

TSINGHUA-PRINCETON-COMBUSTION INSTITUTE

2026 SUMMER SCHOOL ON COMBUSTION

Introduction to Plasma-assisted Combustion

Deanna Lacoste

King Abdullah University of Science and Technology, Saudi Arabia

July 08-10, 2026



TSINGHUA-PRINCETON-COMBUSTION INSTITUTE

2026 SUMMER SCHOOL ON COMBUSTION

Key Activities / 重要活动			
July 5 (Sunday) /7 月 5 日 (周日)	10:00-17:30	Registration 注册	Northeast Gate, Lee Shau Kee Sci. and Tech. Building 李兆基科技大楼东北门
	18:30	Welcome Reception 开班仪式	A-278, Multifunction Room, Lee Shau Kee Sci. and Tech. Building 李兆基科技大楼多功能厅
Class Schedule / 课程安排			
Schedule 时间	Location 地点	Morning 上午 (9:00-9:50/10:00-10:50/11:00-11:50)	Afternoon 下午 (14:00-14:50/15:00-15:50/16:00-16:50)
July 6-10 (Monday-Friday) /7 月 6-10 日 (周一至周五)	Zone A, 6 th Teaching Building 第六教学楼 A 区	Theoretical and Numerical Combustion classroom: 6A018 (0th floor) Thierry Poinsot	Combustion Chemistry: From Fundamentals to Kinetic Modelling for Low-Carbon Technologies classroom: 6A018 (0th floor) Alison Tomlin
July 6-7 (Monday-Tuesday) /7 月 6-7 日 (周一至周二)	Zone A, 6 th Teaching Building 第六教学楼 A 区	Spectroscopic Diagnostics for Combustion Chemistry classroom: 6A203 (2nd floor) Pascale Desgroux	Quantum Mechanics, Statistical Mechanics, and Machine Learning for Molecular Simulations classroom: 6A203 (2nd floor) Alexandre Tkatchenko
July 8-10 (Wednesday-Friday) /7 月 8-10 日 (周三至周五)	Zone A, 6 th Teaching Building 第六教学楼 A 区	Introduction to Plasma-assisted Combustion classroom: 6A203 (2nd floor) Deanna Lacoste	AI for Combustion classroom: 6A016 (0th floor) Matthias Ihme
Special Activities / 特殊活动			
July 5 (Sunday) /7 月 5 日 (周日)	13:30-17:30	Art Museum Visit / 艺术博物馆参观	Tsinghua University Art Museum 清华大学艺术博物馆
July 7 (Tuesday) /7 月 7 日 (周二)	17:00-18:00	Campus Tour / 校园游览	Tsinghua University 清华大学

July 8 (Wednesday) /7 月 8 日 (周三)	17:00-17:30	Group Picture Taking / 暑期学校合影	Mong Man Wai Concert Hall 蒙民伟音乐厅
July 8 (Wednesday) /7 月 8 日 (周三)	18:30-19:30 19:30-21:00	Poster Presentation / 海报展示 Career Panel / 职业发展论坛	B-518, Lee Shau Kee Sci. and Tech. Building 李兆基科技大楼 B-518 会议室
July 9 (Thursday) /7 月 9 日 (周四)	18:00	Farewell Reception / 欢送会	Guan Chou Yuan Restaurant 观畴园餐厅
July 10 (Friday) /7 月 10 日 (周五)	8:00-18:00	Program Certificate Distribution / 学习证 书发放	6 th Teaching Building 第六教学楼
July 11 (Saturday) /7 月 11 日 (周六)	9:30-11:30	CCE Laboratory Tour / 燃烧能源中心实验 室参观	Northeast Gate, Lee Shau Kee Sci. and Tech. Building 李兆基科技大楼东北门

Electronic version of all lecture materials are available at the summer school website





جامعة الملك عبد الله
للعلوم والتقنية
King Abdullah University of
Science and Technology

Introduction to Plasma-Assisted Combustion

Deanna Lacoste

Associate Professor of Mechanical Engineering

Objectives of this Course



- *Provide the basic information to allow any graduate student, researcher or professional in engineering fields to understand the fundamentals of plasma-assisted combustion*
- *Introduce the main challenges and opportunities associated with plasma-assisted combustion*

Agenda



Context & Motivation

- Global Warming
- Consequences & projections
- Actions

Basics of Plasma

- Definitions & properties
- Breakdown mechanisms
- Types of discharges
- Plasma chemistry

Diagnostics

- Electrical properties
- Optical emission spectroscopy
- Laser techniques

History of PAC

- 19th century
- 20th century
- 21st century

Basics of PAC

- Coupling mechanisms
- Ignition
- Combustion enhancement

Modeling Tools

- Plasma-combustion coupling
- 0D PAC
- 1D-3D PAC

Basics of Combustion

- Combustion phenomena
- Premixed & non-premixed
- Turbulent combustion
- Combustion chemistry

Sources and Methods

- DBDs
- Gliding arcs
- NRP discharges
- System integration

Recent Results & Questions

- Carbon-free fuels
- Plasma-assisted detonation
- Three-phase flows

Chapter I: Context & Motivation



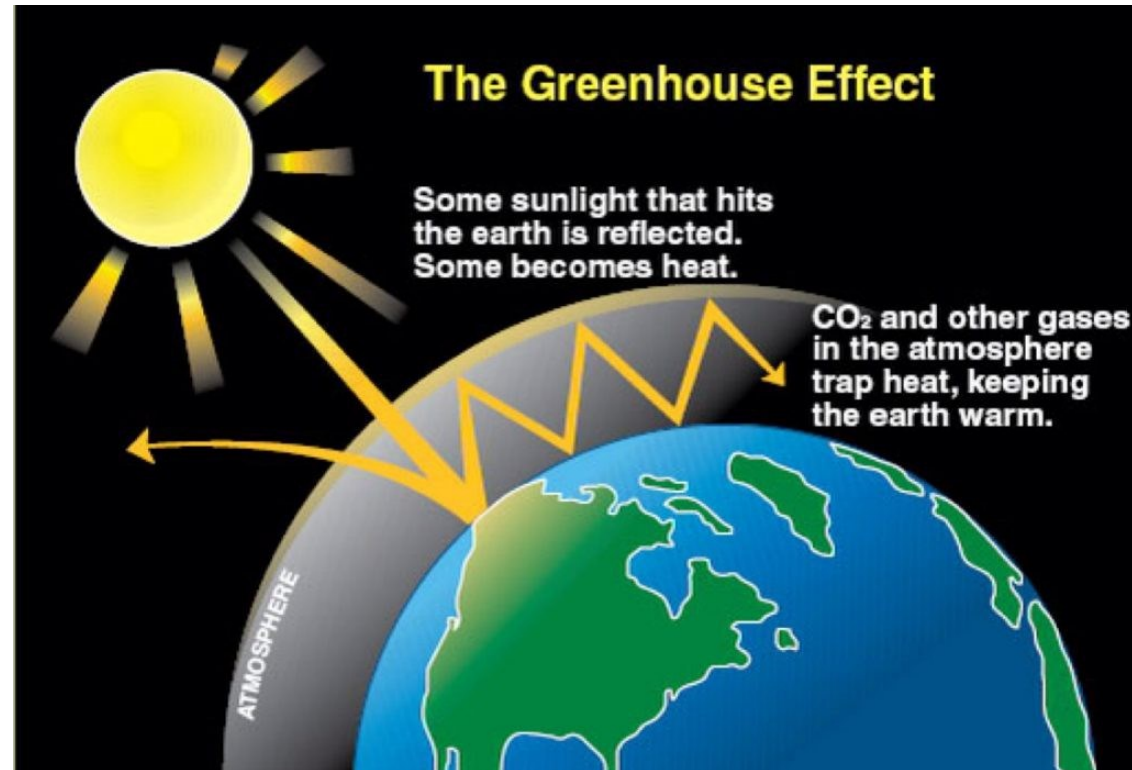
- *Facts*
- *Mechanisms*
- *Consequences and Projections*
- *Actions*
- *References*



Facts



1. Scientists have known since the XIXth century that CO₂ absorbs some of the sun's radiation and that this absorption increases the Earth's temperature:
 - 1850's: John Tyndall measured how much radiant energy the gases in the atmosphere can absorb
 - 1896: Svante Arrhenius estimated by how much CO₂ increases the Earth's temperature



Facts



- Human activity has released vast amounts of CO₂ and other greenhouse gases in the atmosphere



Fossil fuels (coal, oil, natural gas)
For energy and products

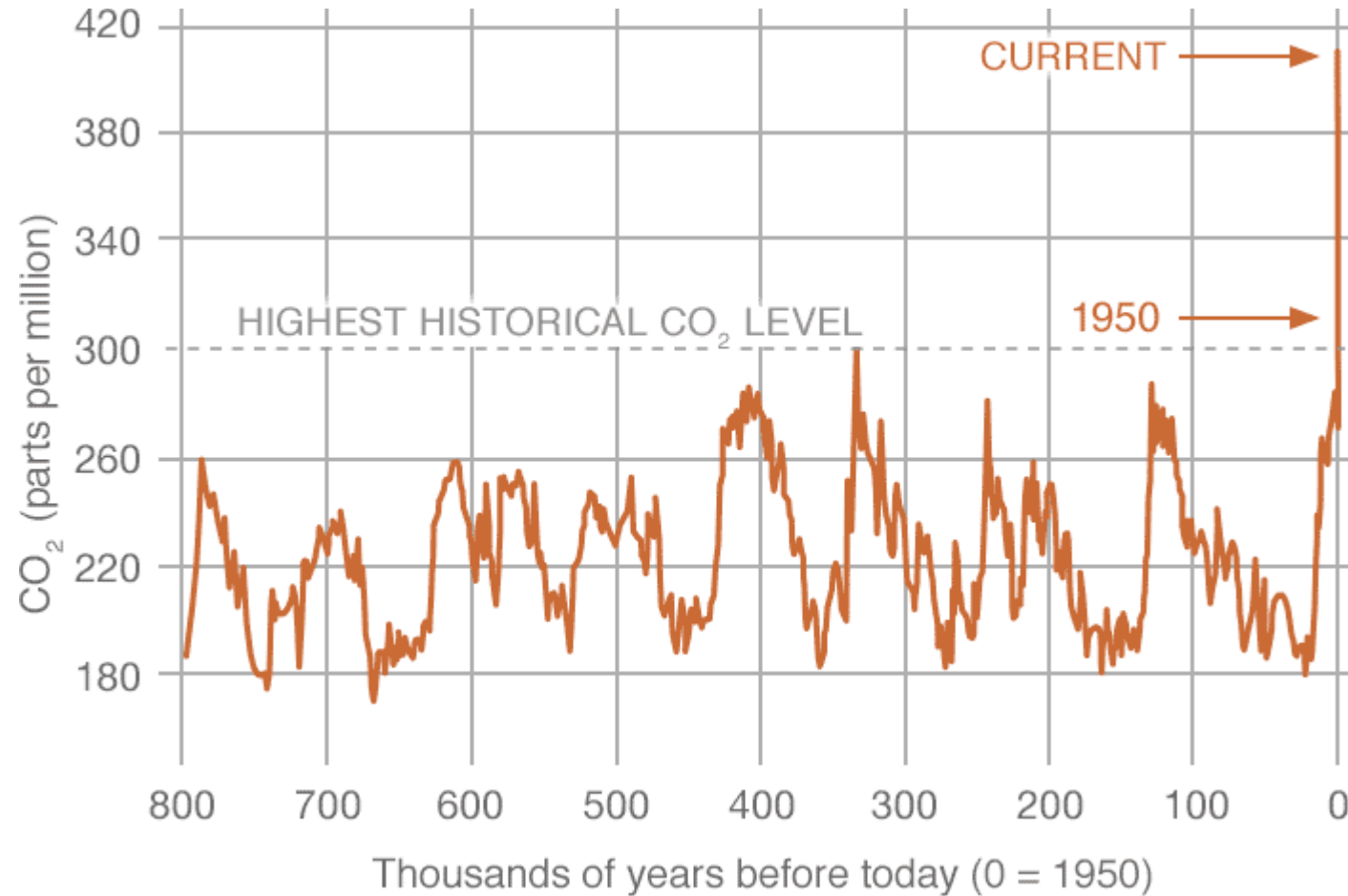


Deforestation
For energy, food, and products

Facts



3. Since the beginning of the industrial revolution, the concentration of CO₂ in the atmosphere has increased from 280 ppm to 428 ppm (Jan 2025) <https://www.co2.earth/daily-co2>

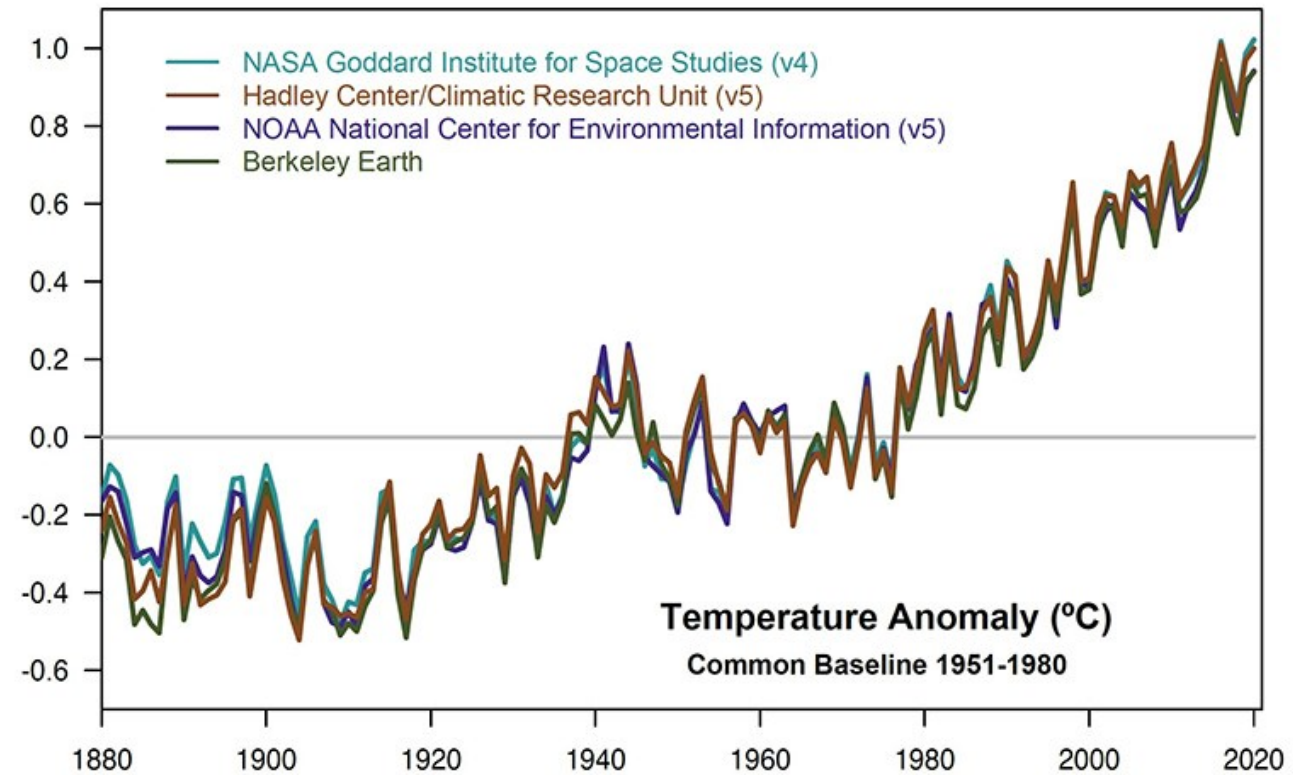
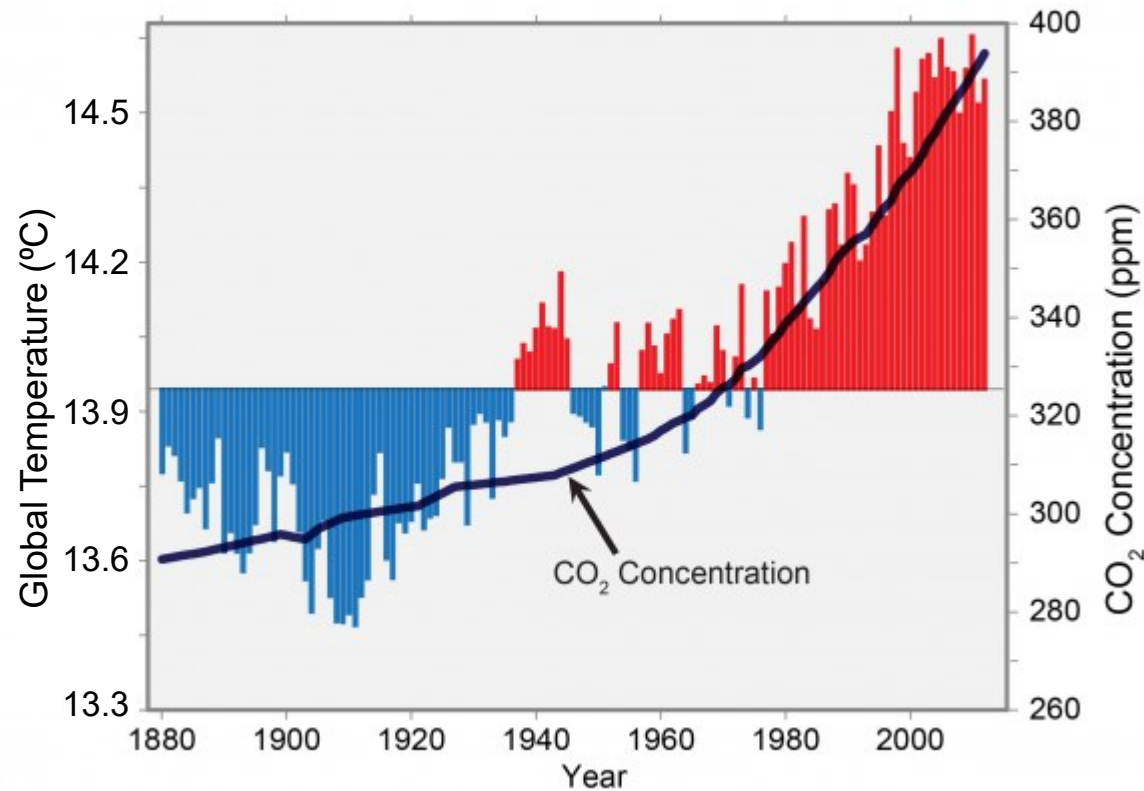


Facts



4. At the same time, the Earth has become warmer (+ 1.55°C in Hawaii Dec 2025)

Global Temperature and Carbon Dioxide



Chapter I: Global Warming



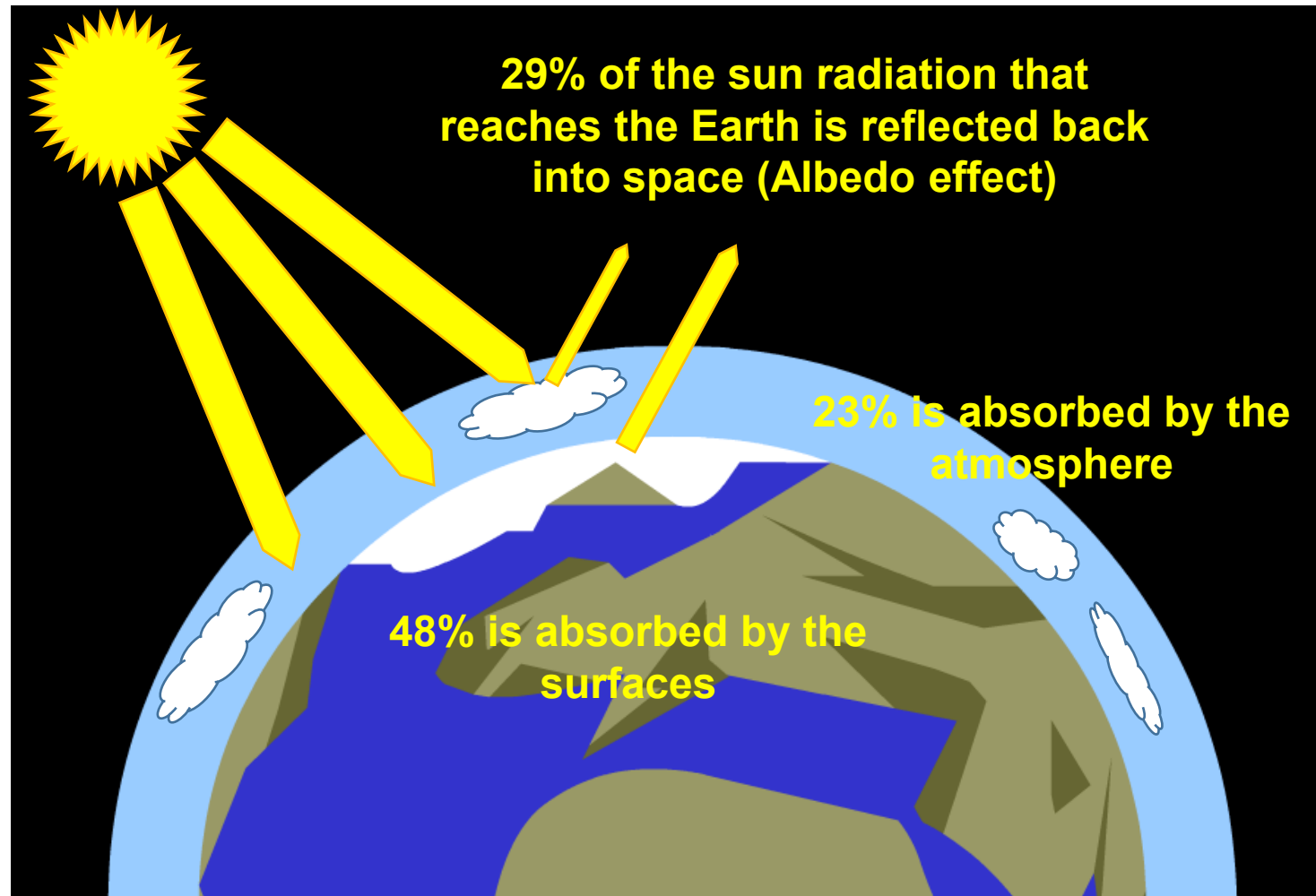
- *Facts*
- ***Mechanisms***
- *Consequences and Projections*
- *Actions*
- *References*



Mechanisms



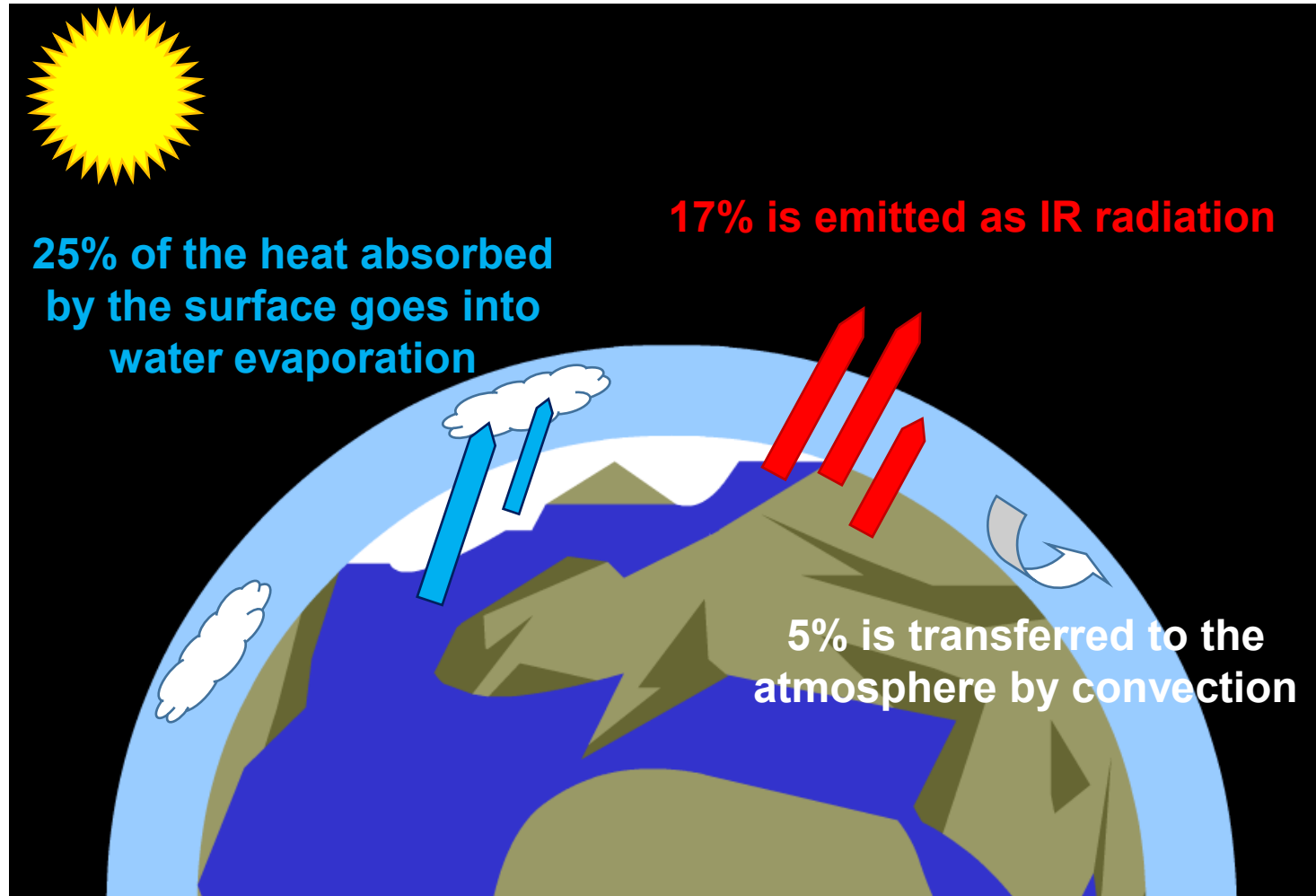
The Greenhouse Effect



Mechanisms



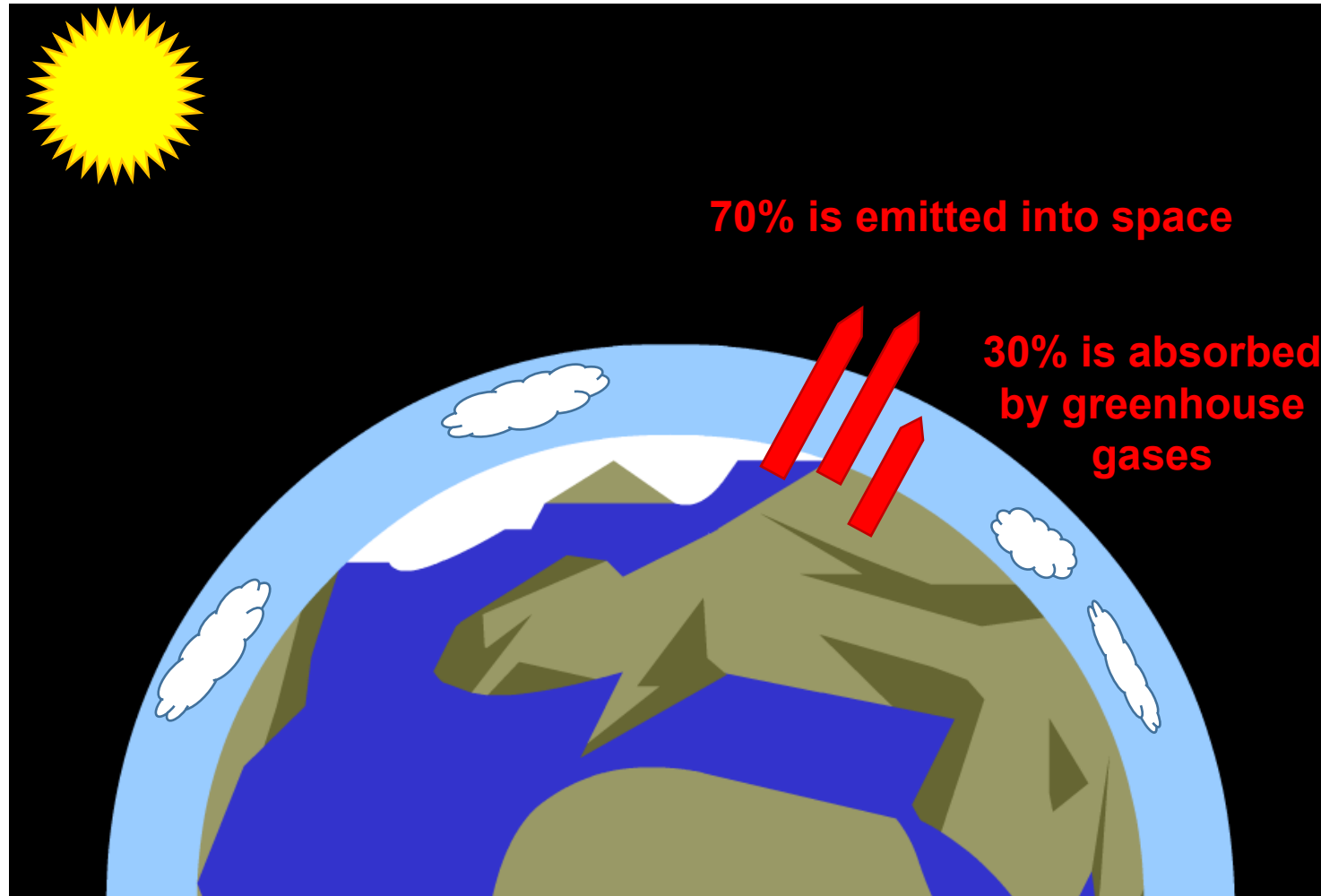
The Greenhouse Effect



Mechanisms



The Greenhouse Effect



Mechanisms



The Greenhouse Effect

Why is the radiation from the Earth more absorbed by greenhouse gases than the radiation from the Sun?

Wien's displacement law: for different temperatures, the black-body radiation peaks at different wavelengths that are inversely proportional to the temperature

$$\lambda_{max} = \frac{b}{T}$$

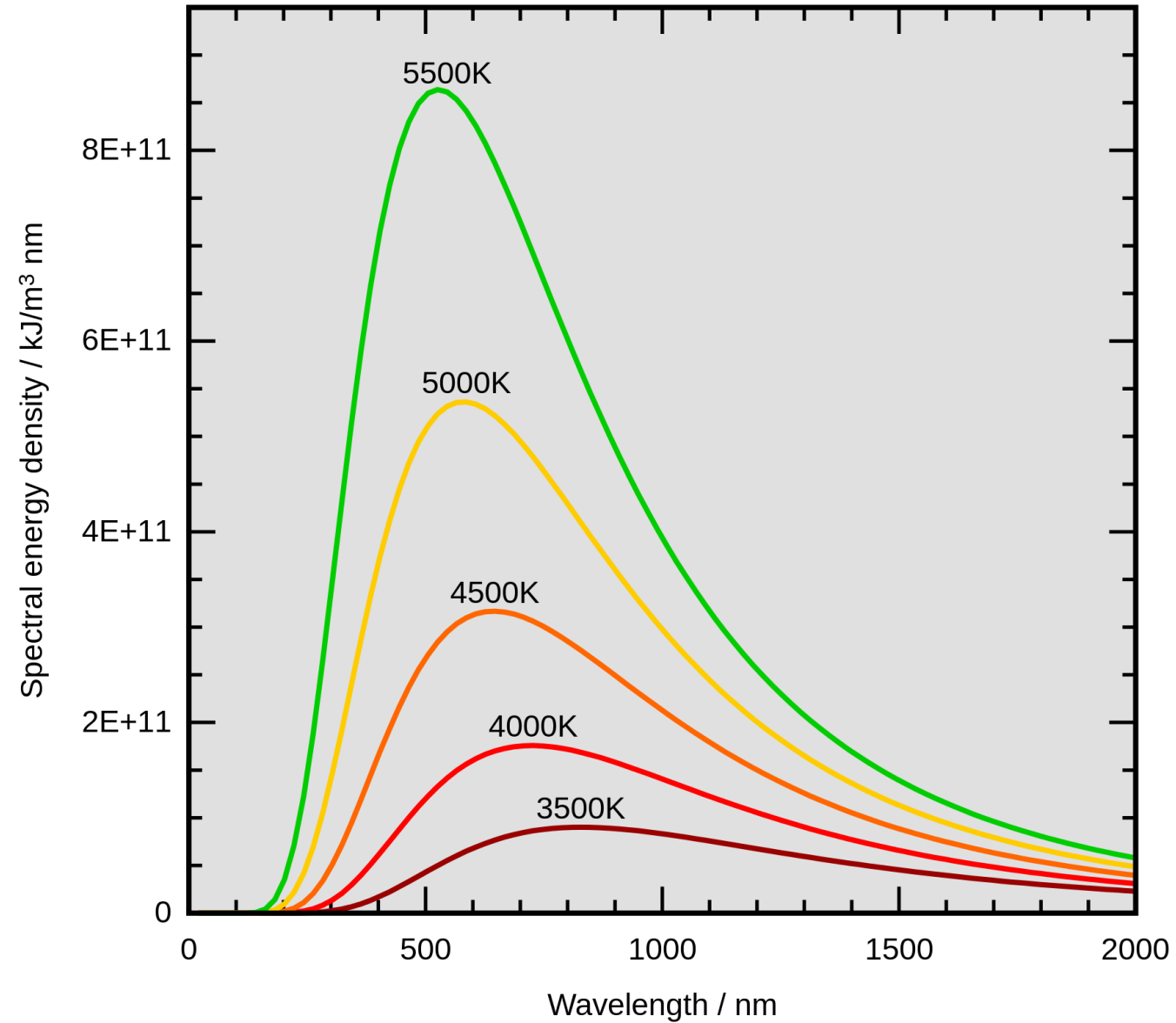
with T, the temperature of the blackbody and $b \approx 2898 \mu\text{m}/\text{K}$

- Sun's surface temperature $\approx 5778 \text{ K}$
- Earth's surface temperature $\approx 288 \text{ K}$



Mechanisms

The Greenhouse Effect



Mechanisms



The Greenhouse Effect

All surfaces that are not at 0 K emit radiations

The radiation emitted by real surfaces is less than the radiation emitted by a **blackbody** at the same temperature:

$$\dot{Q}_{\text{emit}} = \varepsilon \sigma A_s T_s^4 \quad (\text{W})$$

ε : **emissivity** of the surface

σ : Stefan–Boltzmann constant

The sun is a perfect black body: $\varepsilon_{\text{Sun}} = 1$

The effective emissivity of Earth is: $\varepsilon_{\text{Earth}} = 0.62$

Material	Emissivity
Aluminum foil	0.07
Anodized aluminum	0.82
Polished copper	0.03
Polished gold	0.03
Polished silver	0.02
Polished stainless steel	0.17
Black paint	0.98
White paint	0.90
White paper	0.92–0.97
Asphalt pavement	0.85–0.93
Red brick	0.93–0.96
Human skin	0.95
Wood	0.82–0.92
Soil	0.93–0.96
Water	0.96
Vegetation	0.92–0.96

Mechanisms



The Greenhouse Effect

Beer-Lambert law: it relates the attenuation of light to the properties of the material through which the light is travelling

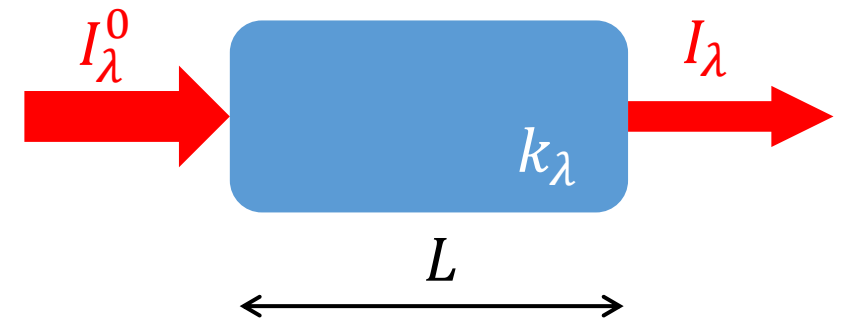
$$I_{\lambda} = I_{\lambda}^0 \exp(-k_{\lambda}L)$$

I_{λ} : radiant flux transmitted

I_{λ}^0 : radiant flux received

k_{λ} : spectral absorption coefficient

L : optical path length



And

$$\sigma_{\lambda} = \frac{k_{\lambda}}{N}$$

σ_{λ} : absorption cross section

N : is the number density



Mechanisms

The Greenhouse Effect

Then for an absorbing species, i , the flux absorbed, $I_{abs,i}$:

$$I_{abs,i} = \int (I_{\lambda}^0 - I_{\lambda,i}) d\lambda = \int I_{\lambda}^0 \left(1 - \exp(-\sigma_{\lambda,i} L N_i) \right) d\lambda$$

And the total absorbed flux, I_{abs} :

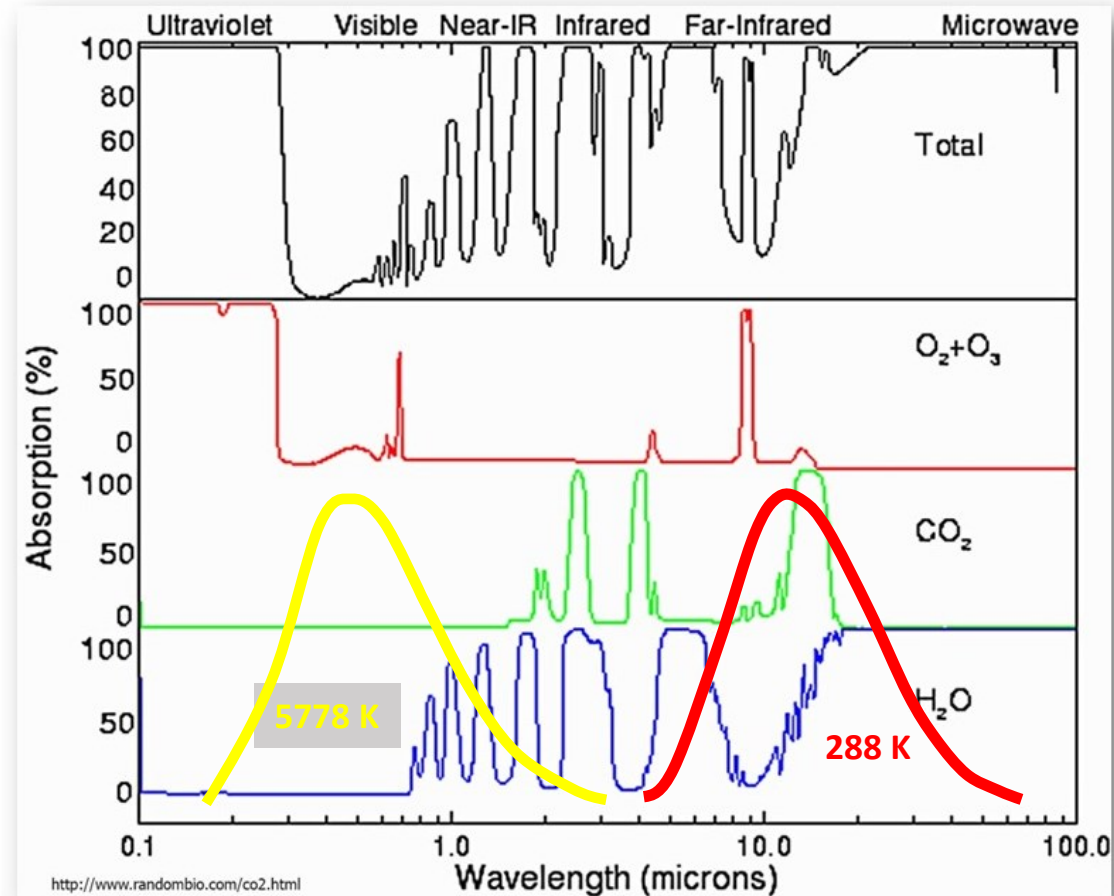
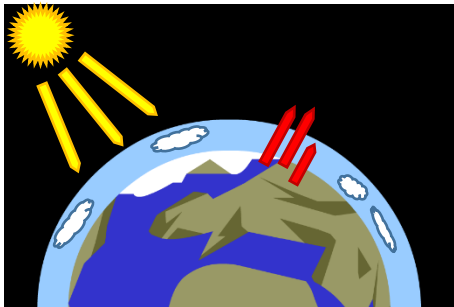
$$I_{abs} = \sum_i I_{abs,i}$$



Mechanisms

Greenhouse Gases

Greenhouse gases are gases with an absorption spectrum of high-value in the range of wavelength radiated by the Earth



Mechanisms



Greenhouse Gases

CO₂ is not the only problem

Substance	Symbol	Concentration in the atmosphere (ppm)	Increase since the beginning of the industrial revolution (%)	Warming potential
Carbon dioxide	CO ₂	410	+45	1
Methane	CH ₄	1.7	+150	67
Nitrous oxide	N ₂ O	0.33	+20	277
Halocarbons	CFCs & HFCs	1 – 65 x 10 ⁻³	Do not exist in nature	174
Tetrafluoromethane	CF ₄	negligible	--	5270
Water vapor	H ₂ O	5 x 10 ³	--	--

Warming potential: over 20 years, the equivalent in warming effect than the same volume (or concentration) than CO₂

Currently, the effect of **all other greenhouse gases** we have emitted is equivalent to the effect of **75 ppm of CO₂**

Mechanisms



Greenhouse Gases

The special case of H₂O

- Unlike other greenhouse gases, H₂O does not accumulate in the atmosphere: it falls to earth as rain or snow
- However, at higher temperature, the atmosphere can hold more water vapor

The specific humidity, ω , is defined as the ratio of mass of water vapor in air, m_v , to the mass of dry air, m_a :

$$\omega = \frac{m_v}{m_a} = \frac{x_v}{1 - x_v}$$

where x_v is the mass fraction of water vapor in moist air



Mechanisms

Greenhouse Gases

$$\omega = \frac{y_v M_v}{(1 - y_v) M_a} = \frac{0.622 y_v}{(1 - y_v)}$$

y_v : mole fraction of vapor in moist air

M_v : molar mass of vapor

M_a : molar mass of dry air

At given p & T , moist air behaves as an ideal-gas mixture at compositions y_v in the range between $y_v = 0$ (dry air) and a maximum value $y_{vs}(T, p)$ at which the mixture is saturated

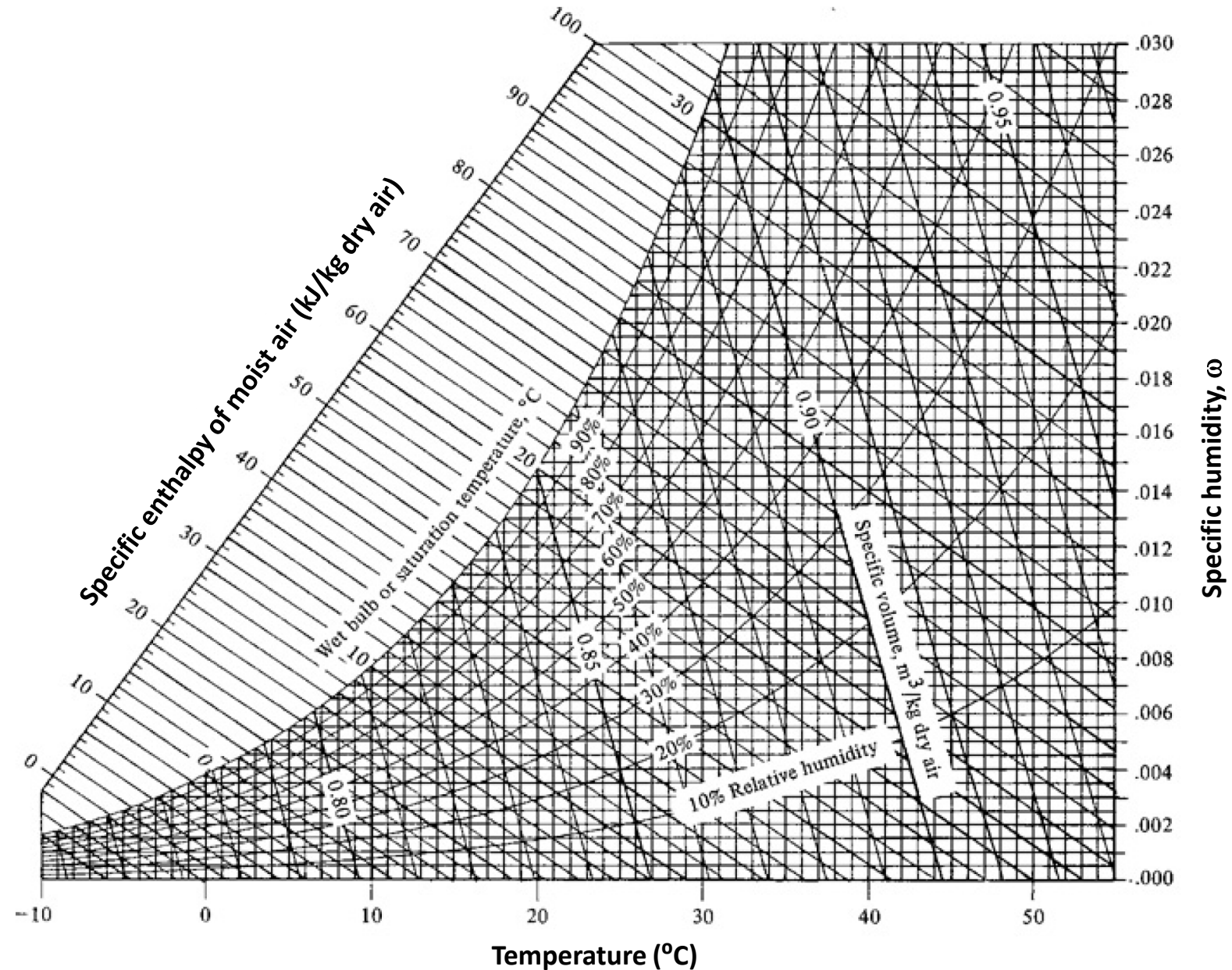
At mole fractions higher than $y_{vs}(T, p)$ the mixture is two-phase (it rains!)

Mechanisms



Greenhouse Gases

Psychrometric chart
for $P = 101.3 \text{ kPa}$



Mechanisms



Greenhouse Gases

If the added amount of CO₂ in the atmosphere is enough to cause 1°C of warming, the actual warming would be 3°C

- +1.5°C from additional water vapor in the atmosphere
- +0.5 °C from the melting of ice

While other greenhouse gases cause warming, ***water vapor amplifies the warming***

Mechanisms



Greenhouse Gases

The special cases of aerosols

- An **aerosol** is a suspension of fine solid particles or liquid droplets in air or another gas
- **Sulfate aerosols**
 - In nature: from volcanoes, biological sources and wildfires
 - From human activities: from combustion
 - Increase since the beginning of industrial revolution + 100%
 - Remain in the atmosphere 3 – 5 days
 - Concentrated in northern hemisphere
 - **Cooling effect** (reflect the sunlight)
 - Currently, their effect is equivalent to reducing by **-60 ppm the concentration of CO₂**



Mechanisms



Greenhouse Gases

The special cases of aerosols

- ***Black soot or black carbon***
 - In nature: from volcanoes and wildfires
 - From human activities: burning coal, diesel fuel, wood and dung
 - Remain in the atmosphere from days to weeks
 - Warming effect (absorb light)
 - Uncertainties about its effect on global warming but recent estimates give equivalent to ***+86 ppm of CO₂***

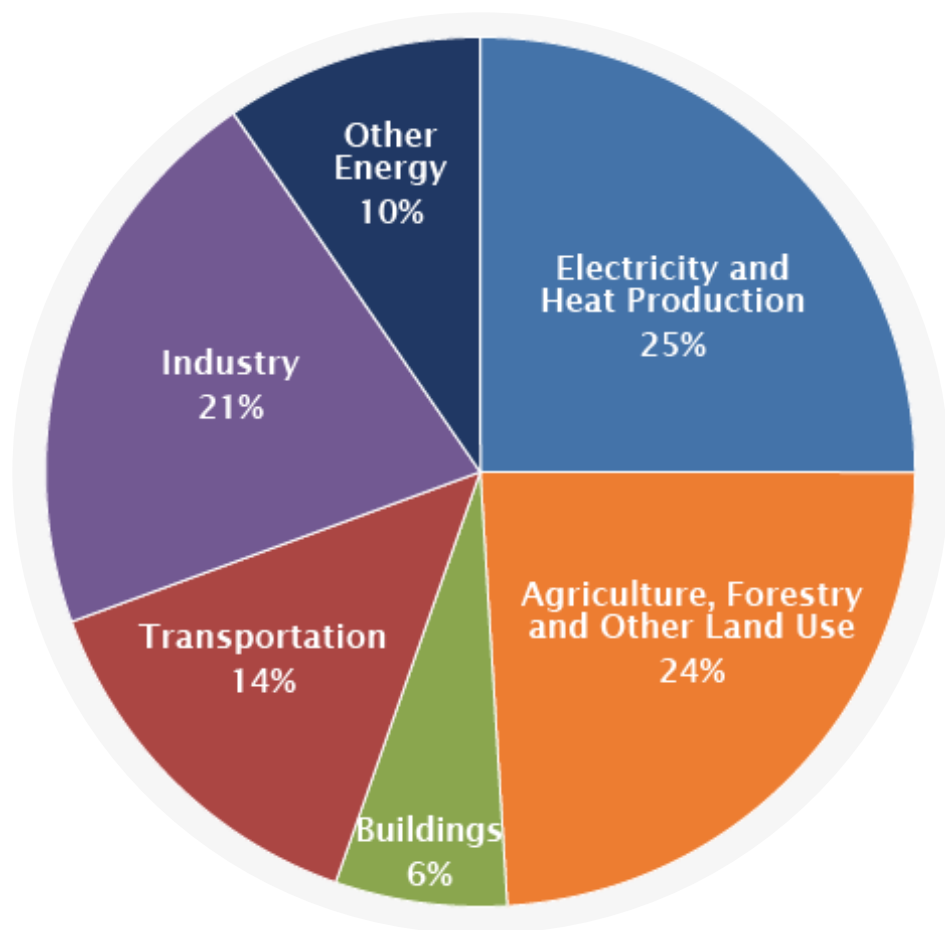


Mechanisms

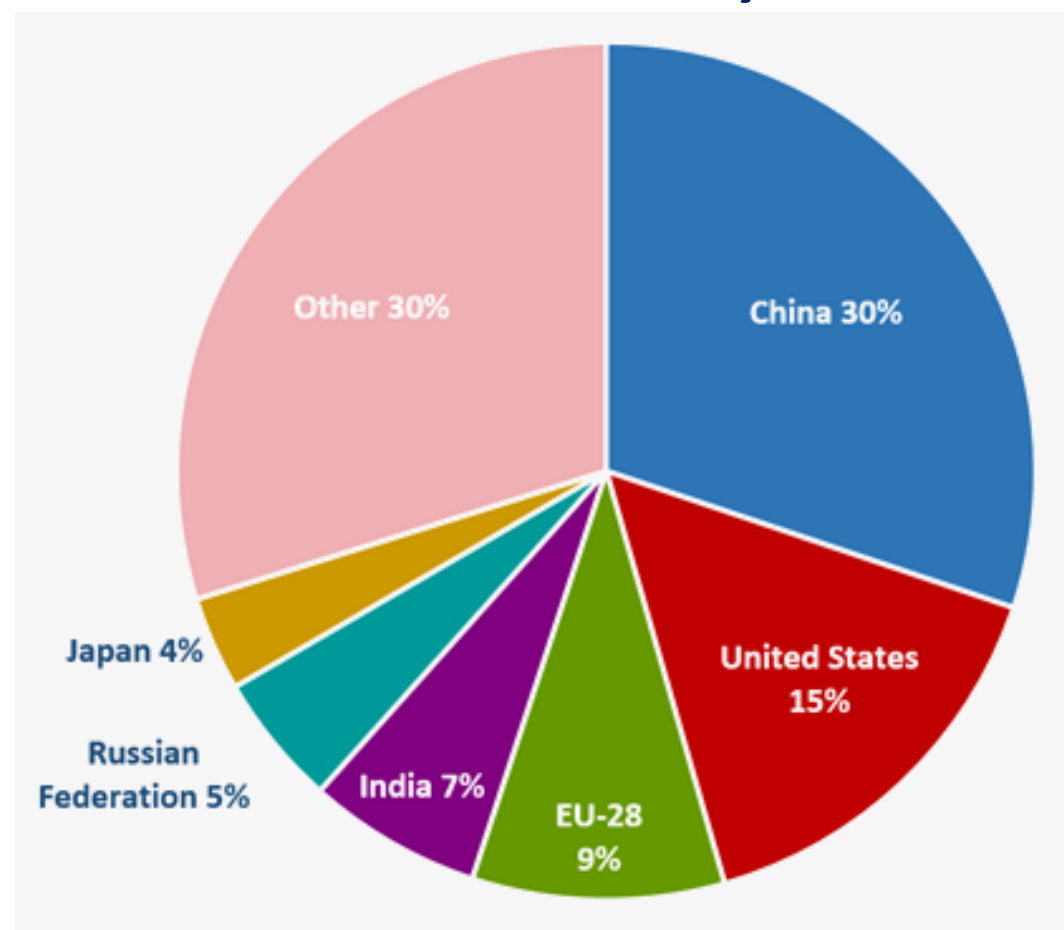


Global Greenhouse Gases (2019)

Per Sector



Per Country



Mechanisms



Self-Reinforcing Warming

- Melting of arctic ice:
 - Albedo of ice = 0.6 – 0.9
 - Albedo of ocean = 0.1

- Dying forests:
 - More wildfires
 - More CO₂ in the atmosphere
 - Less consumption of CO₂ from the atmosphere



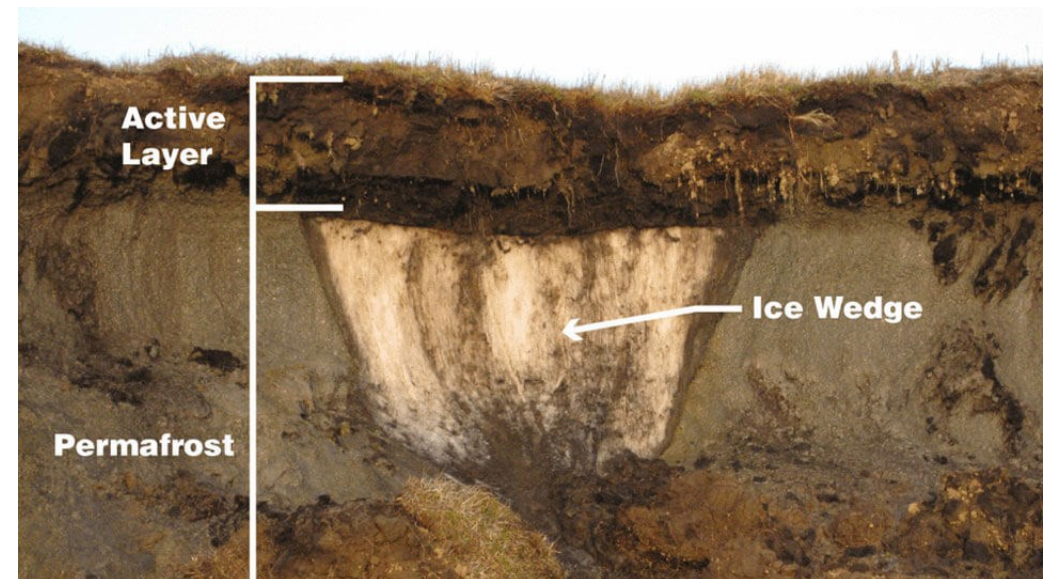
Mechanisms



Self-Reinforcing Warming

- Drying of peatlands:
 - Release the carbon stored (550 billion tons) as CO_2 or CH_4

- Melting of permafrost:
 - Release the carbon stored (1400 billion tons) as CH_4



Mechanisms



Stabilizing Temperatures

- Currently the global warming induced by human activities is +1.5°C

The Intergovernmental Panel on Climate Change, IPCC (www.ipcc.ch) has estimated that:

- ~~• To limit warming to +1.5°C, human-caused CO₂ emissions must reach net zero by 2050~~
- To limit warming to +2°C, human-caused CO₂ emissions must reach net zero by 2070

Chapter I: Global Warming



- *Facts*
- *Mechanisms*
- ***Consequences and Projections***
- *Actions*
- *References*



Consequences and Projections



Summer 2021

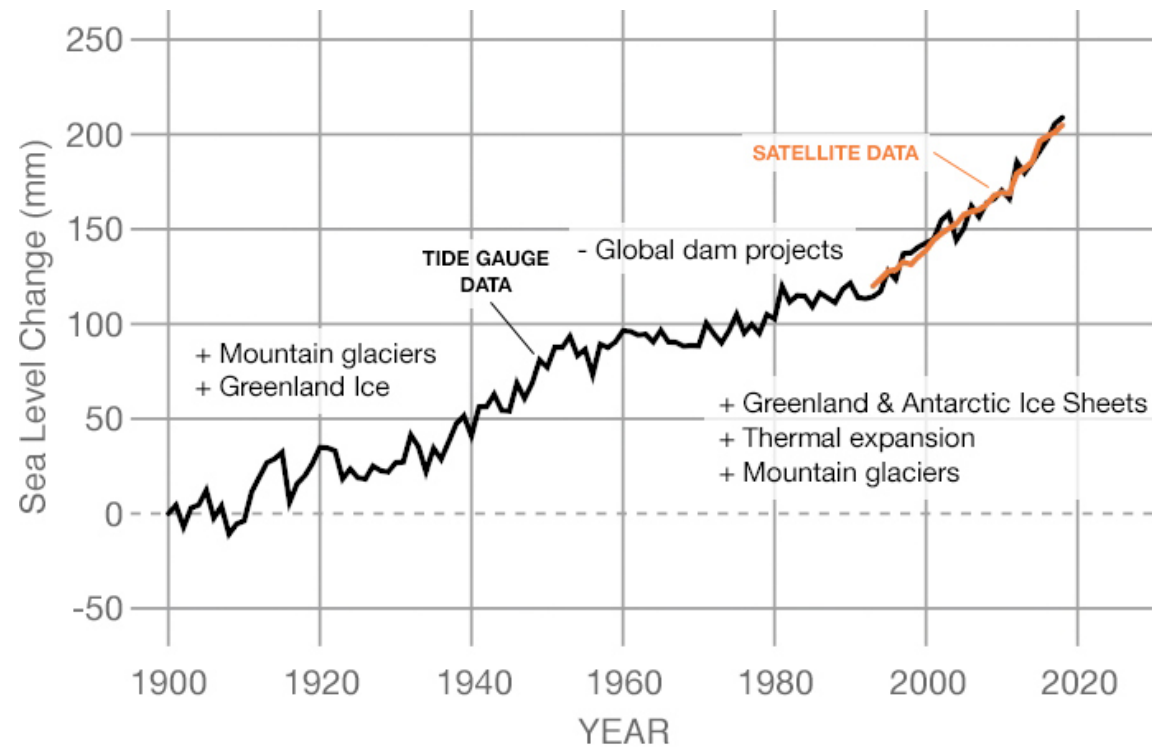
Event	Location	Dates	Increase since the beginning of the industrial revolution	Cost & Casualties
Heat waves	North hemisphere	Since 2000	x 5	50,000 deaths
Wind speed in storms	Tropical areas	Since 2000	+7% (+23% in destructiveness)	394 BUSD
Flooding & Drought	Worldwide	Since 1960	+40% heavy rain x2 drought	500,000 deaths 1,000,000 deaths
Wildfires	Worldwide	Since 1970	x 5	NE
Jet stream pause	North hemisphere	Since 2000	Responsible for major heat & ice waves, floods	NE
Melting Ice & rising sea levels	Worldwide	Since 1900	-50% of arctic ice +0.2 m level of oceans	NE

NE: not evaluated

Consequences and Projections



Global sea level changes



Consequences and Projections



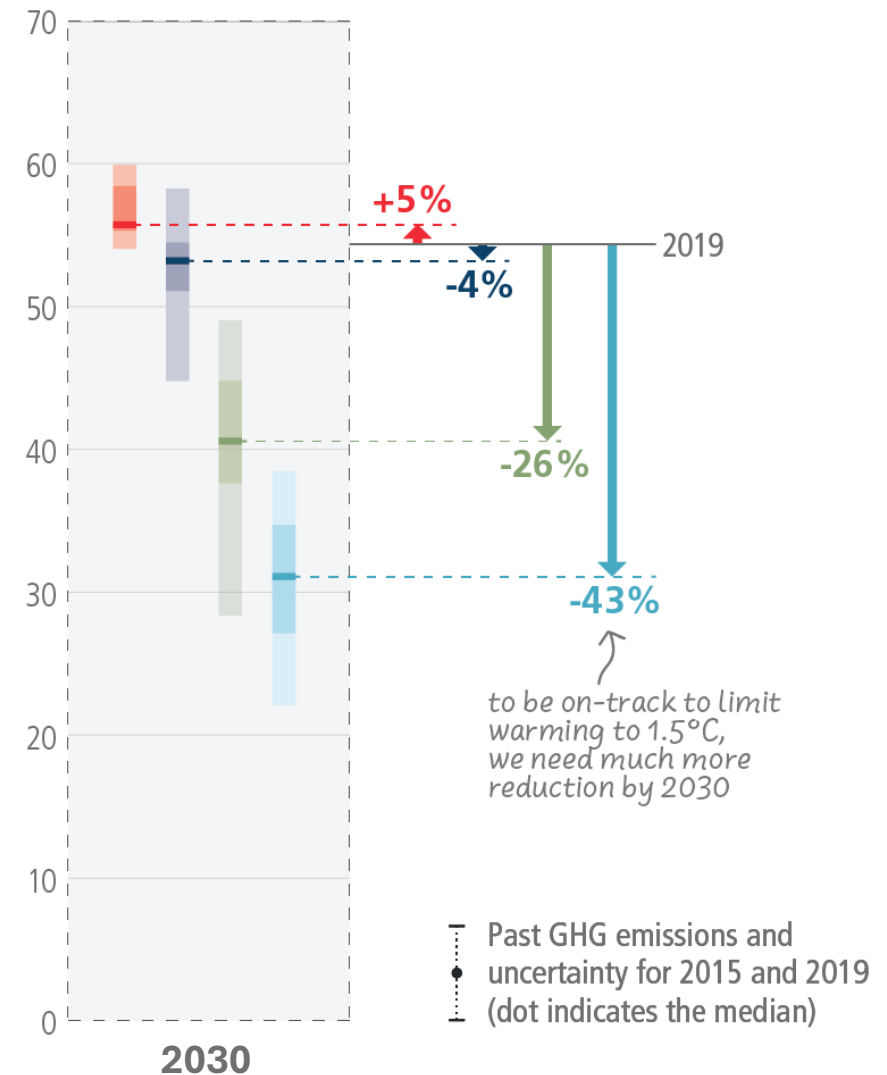
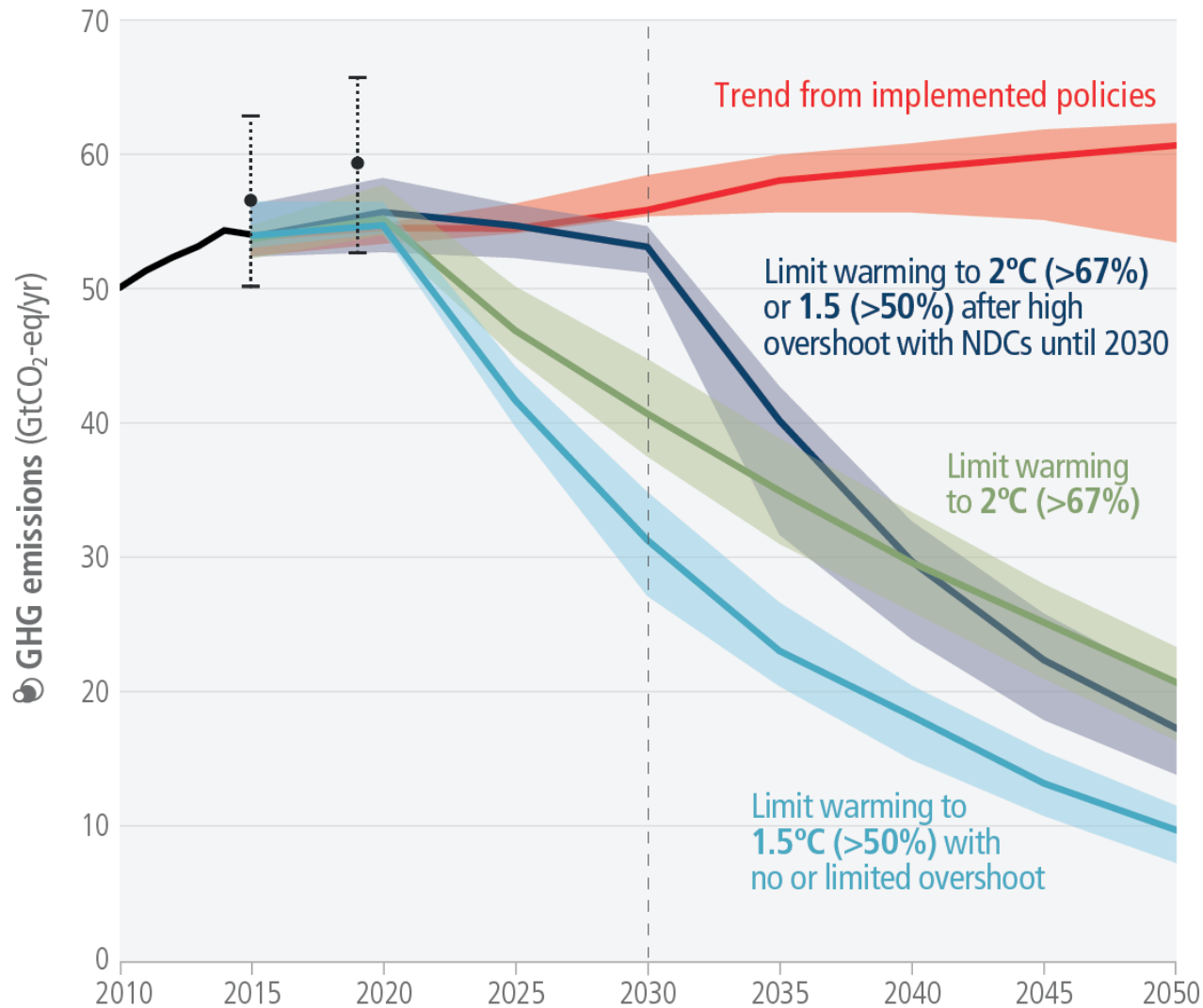
Event	Location	Dates	Increase since the beginning of the industrial revolution	Cost & Casualties
Ocean acidification	Worldwide	Since industrial revolution	+26% more acidic	NE
Extinctions	Worldwide	Since industrial revolution	Decay and extinction of animal and plant populations	NE
Poverty & Insecurity	Sub-tropical areas	Since industrial revolution	Shortage of drinkable water and food (sub tropical), climate refugees (sub tropical), security (e.g., Syria)	NE

NE: not evaluated



Consequences and Projections

Global GHG emissions



Consequences and Projections



In 2100, with the +2°C scenario

- **Extreme heat waves:** 420 million more people frequently exposed
- **Tropical storms:** 50% more destructive than before the industrial revolution
- **Heavy rains:** 36% more frequent than between 1980 and 2010
- **Drought:** twice as many people as nowadays will suffer from water stress
- **Ice melting:**
 - there will be ice-free Arctic summers once every 10 years
 - Increase in sea level by 2 m due to the melting of ice in Antarctic and Greenland
- **Acid oceans:** increase by 17%
- **Extinctions:** 18% of insects, 16% of plants and 8% of vertebrates will lose half of their geographic range
- **Poverty, climate refugees and security:** no reliable projection today

Consequences and Projections



Tipping points

- When warming reaches some point and cannot be reversed for thousands of years:
 - **Polar Ice:** Melting of Antarctic and Greenland ice
 - **Monsoons:** circulation patterns completely shut down
 - **Amazon rain forest:** turn into a grassy savannah
 - **Boreal forest:** turn into open grassland and savannah
 - **Permafrost:** melting and release in the atmosphere of large quantity of methane (comparable with the current amount of CO₂ in the atmosphere)
- According to IPCC probabilities

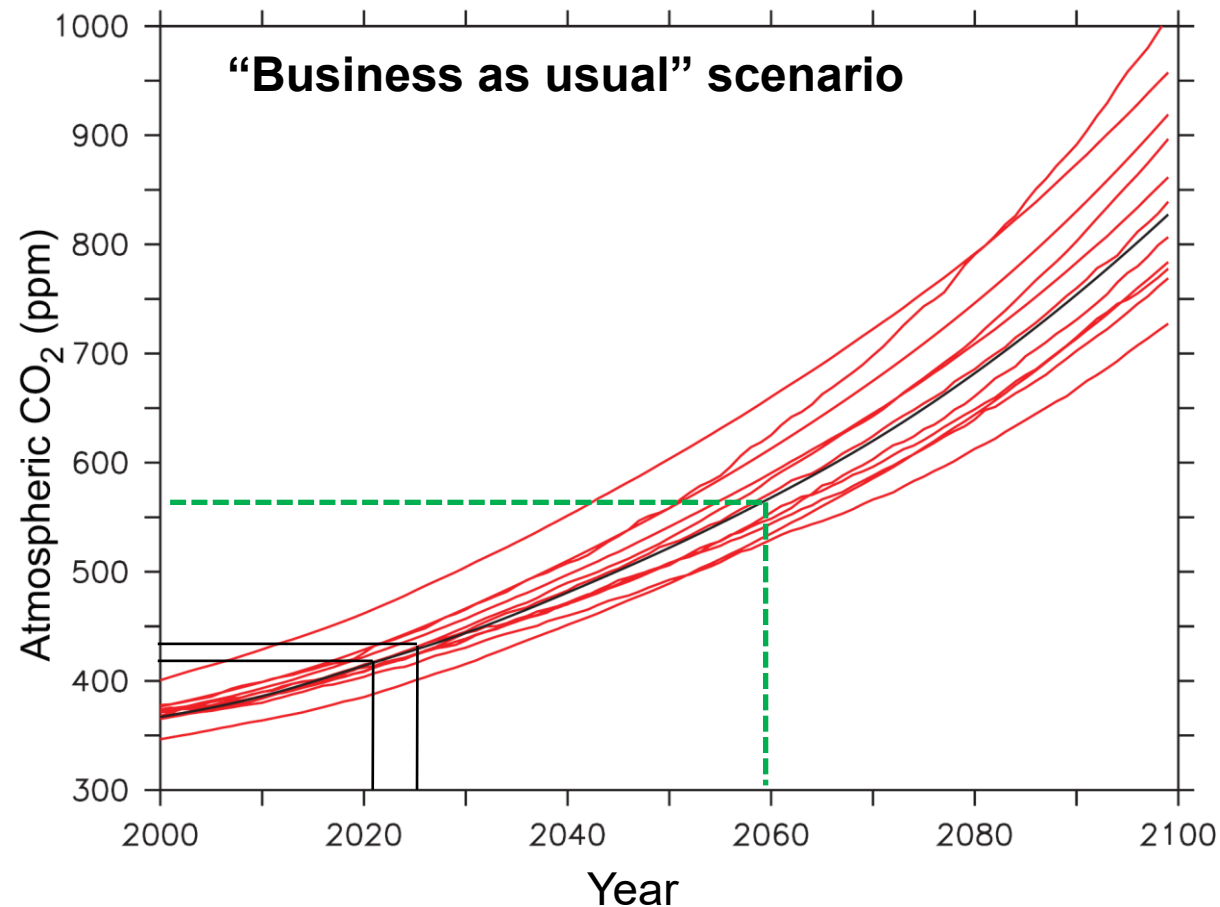
Low risk of reaching tipping points at 2°C warming

For higher increase in temperature, it will not be possible to stabilize

Consequences and Projections



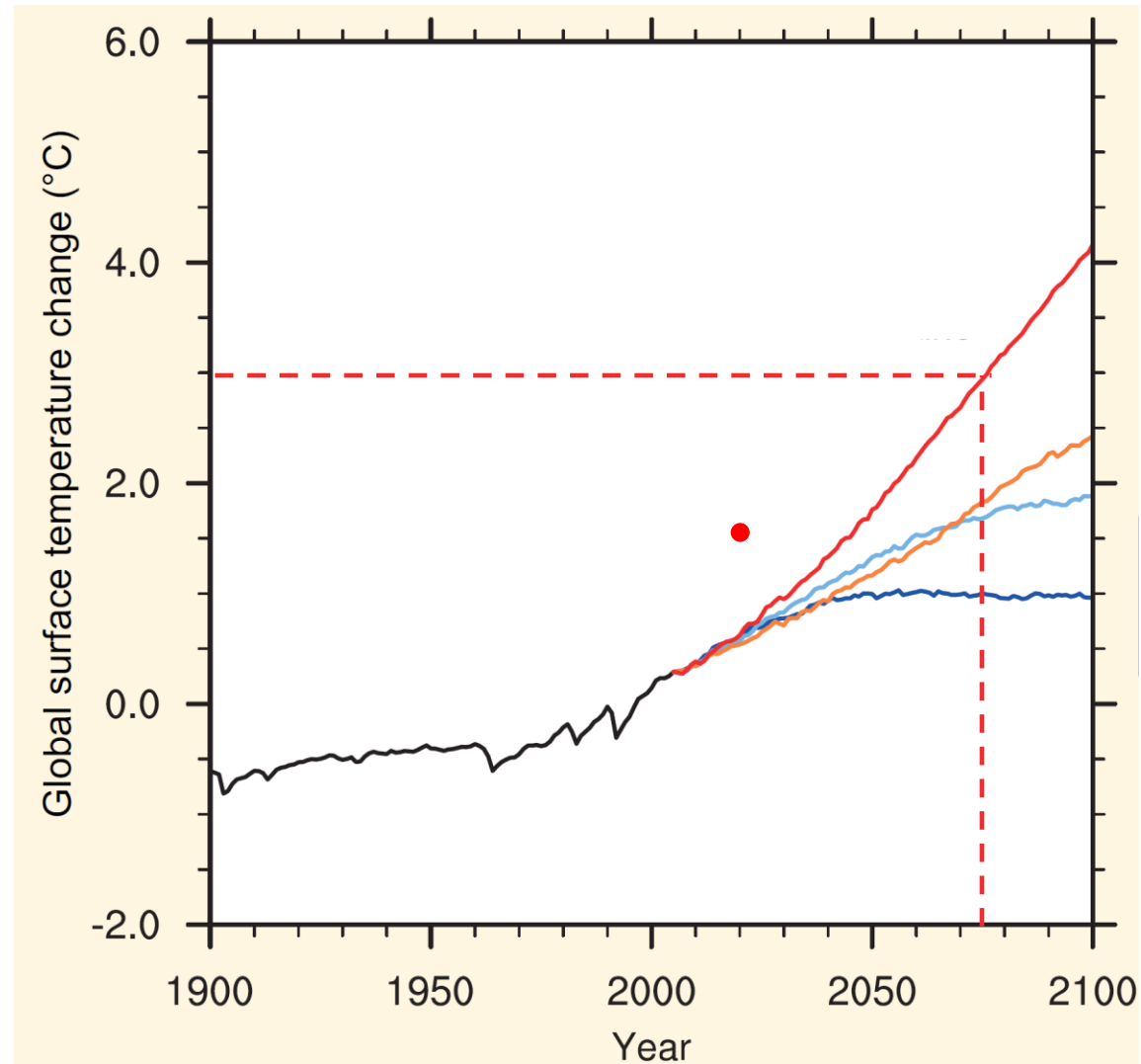
Doubling CO₂ in the atmosphere (560 ppm) will increase temperature by 3°C



Consequences and Projections



Temperature Projections from 2015



Business as usual

Implemented policies

+2°C scenario

+1.5°C scenario

Chapter I: Global Warming



- *Facts*
- *Mechanisms*
- *Consequences and Projections*
- ***Actions***
- *References*



Actions



Mitigation



Adaptation





Actions

What does it take to act?



Actions



Example: Carbon Emission Tax

- A fee for greenhouse gases emissions that increases over time
- Border adjustment with an "emission import tax" on imported goods with equivalent fees than for local production

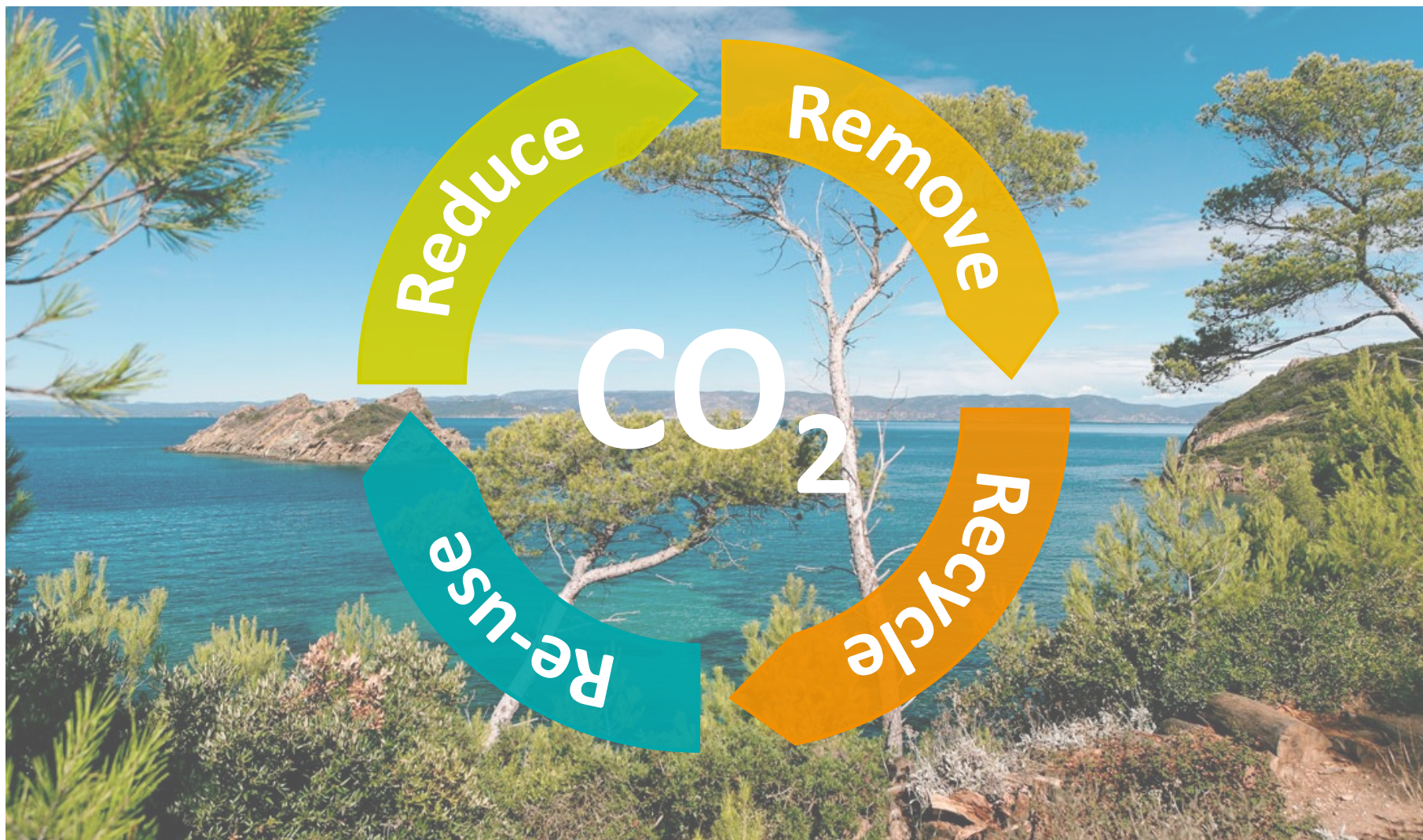
- Advantages:
 - Encourage technological innovation
 - Reduces emissions at the lowest possible cost
 - Easy to adjust
 - Allows multiple carbon offsets



Actions



Example: Circular Carbon Economy

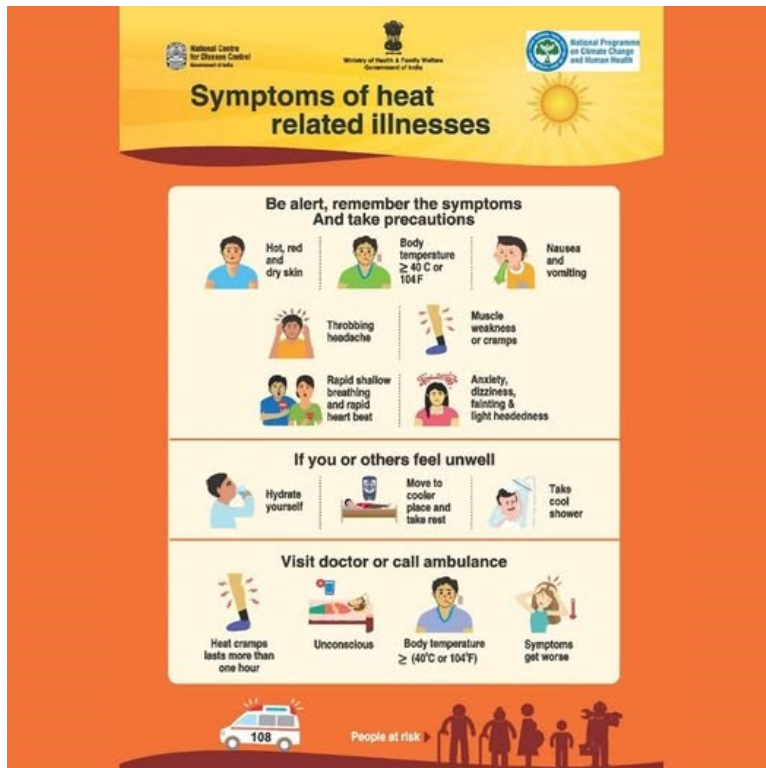




Actions

Example: Heat action plan (since 2017, Ahmedabad, India)

- Cool roofs reflect sunlight and absorb less heat (-5°C in house)
- Heat illness treatment protocol



Actions



Plasma-assisted combustion?

- **Currently, 2 billion+ piston engines are in use**
- **Currently, 60 million electric cars are in use**

- PAC can be an enabler of technical & economical solutions:
 - Carbon-free fuels
 - Opportunity fuels
 - Flexi-fuel
 - Efficiency
 - Retrofit

- **PAC can help for both mitigation and adaptation**



References



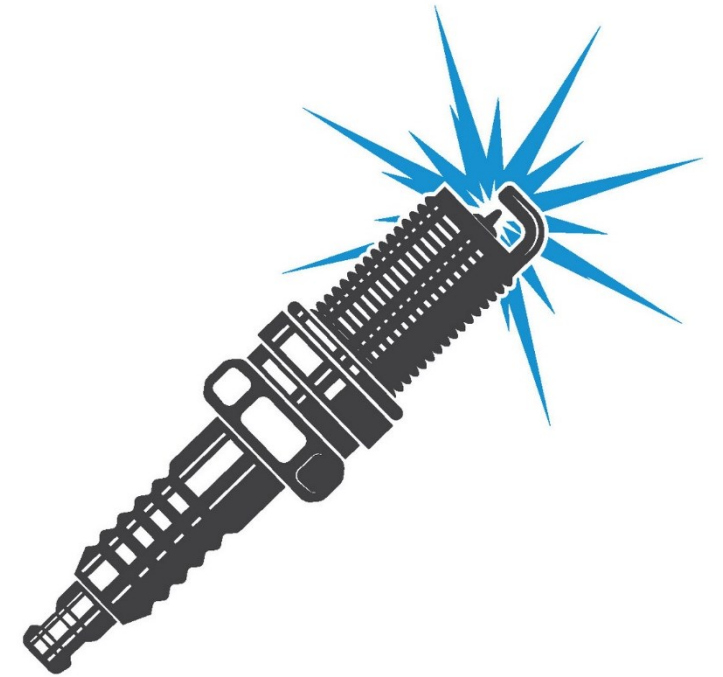
Websites

- *The Intergovernmental Panel on Climate Change:* <https://www.ipcc.ch/>
- *Nasa Global Climate Change:* <https://climate.nasa.gov/>
- *Nasa Sea Level Change:* <https://sealevel.nasa.gov/>
- *U.S. Global Change Research Program:* <https://www.globalchange.gov/>

Chapter II: History of Plasma-Assisted Combustion



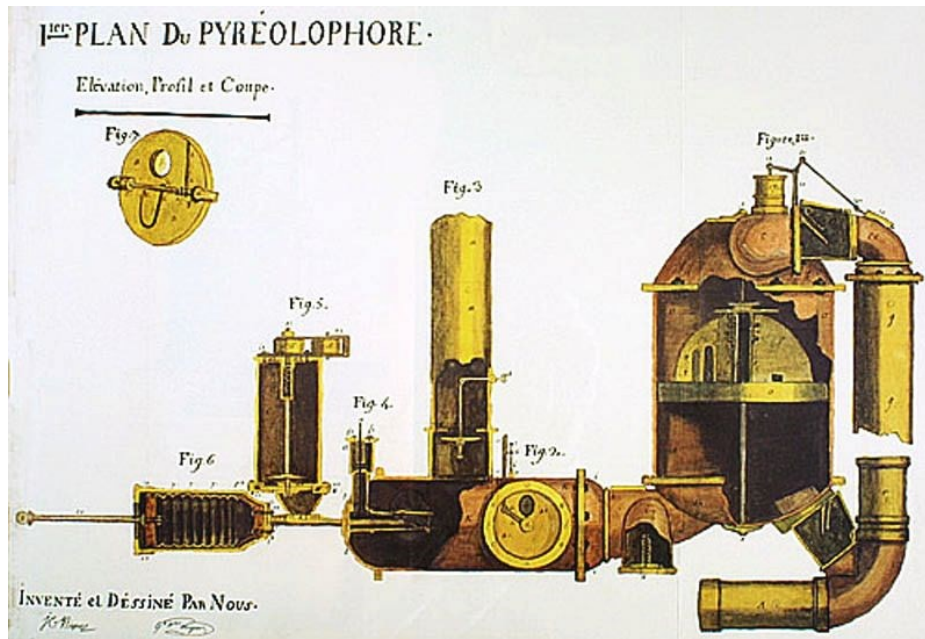
- *19th Century: First Internal Combustion Engines*
- *20th Century: Ignition Systems*
- *21st Century: Science and Opportunities*
- *References*



19th Century: First Internal Combustion Engines



1806: French brothers, Nicéphore and Claude Niépce, built a prototype of internal combustion engine, the **Pyréolophore**



Nic phore Ni pce
Inventor of
photography
in 1827

- It used controlled dust explosions (pulverized coal)
- Ignition by a smoldering fuse

19th Century: First Internal Combustion Engines



1806: the Pyr  lophore is presented at the French Academy of Science by Lazare Carnot



Sadi Carnot
Physicist
Military engineer

- 1824: his only publication (age of 28), *Reflections on the Motive Power of Fire*

$$\eta = 1 - \frac{T_C}{T_H}$$

- H-index: 1



Lazare Carnot
Mathematician
Physicist
Military officer
Politician
Father of Sadi Carnot

19th Century: First Internal Combustion Engines



1807: the Pyr  olophore engine powered a 900 kg boat on the Sa  ne river in France



Charles Motte
*Bridge over the Sa  ne,
around 1800*



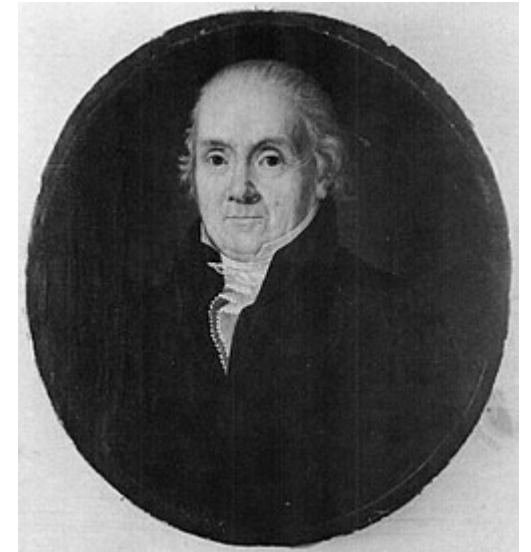
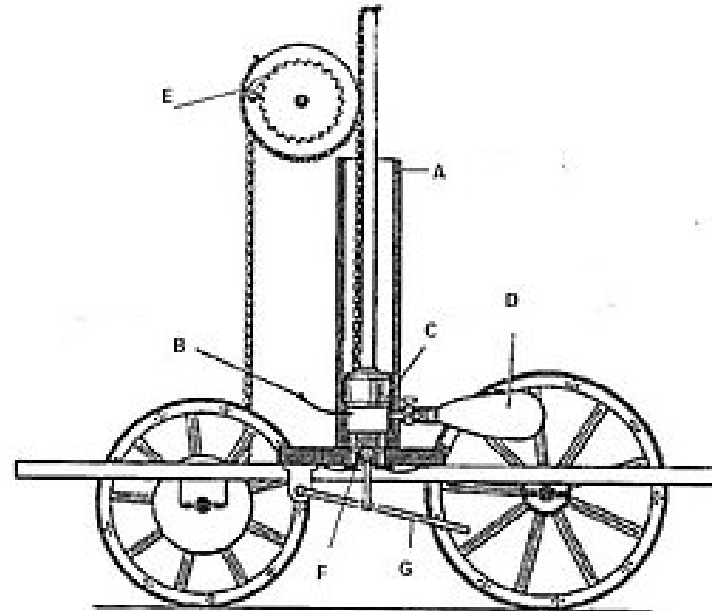
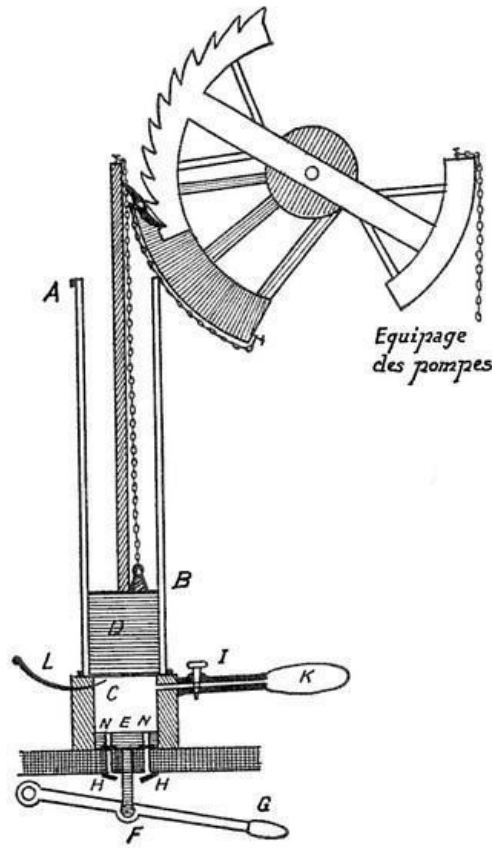
Napoleon Bonaparte
*Emperor of the French
(1804 – 1815)*

- Received a patent from the Bureau of Arts and Trades, signed by Napoleon Bonaparte

19th Century: First Internal Combustion Engines



1807: Swiss engineer François Isaac de Rivaz built and patented a **hydrogen and oxygen-powered internal-combustion engine**



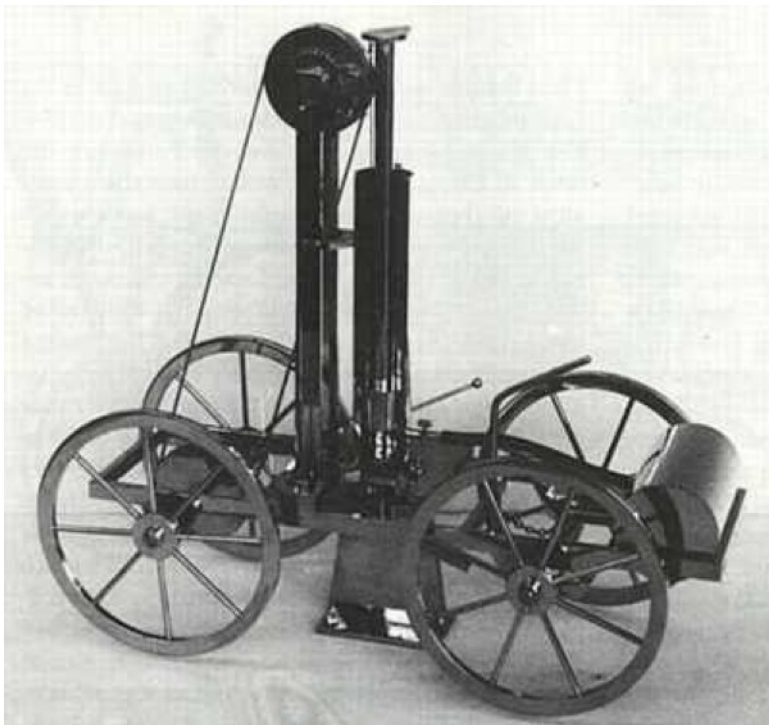
Isaac de Rivaz
Politician
Engineer

➤ Ignition by spark

19th Century: First Internal Combustion Engines



1813: Isaac de Rivaz, age 61, drove 100 meters in the **first automobile** (car-like vehicle)



First hydrogen car

First plasma-assisted ignition car engine

1813



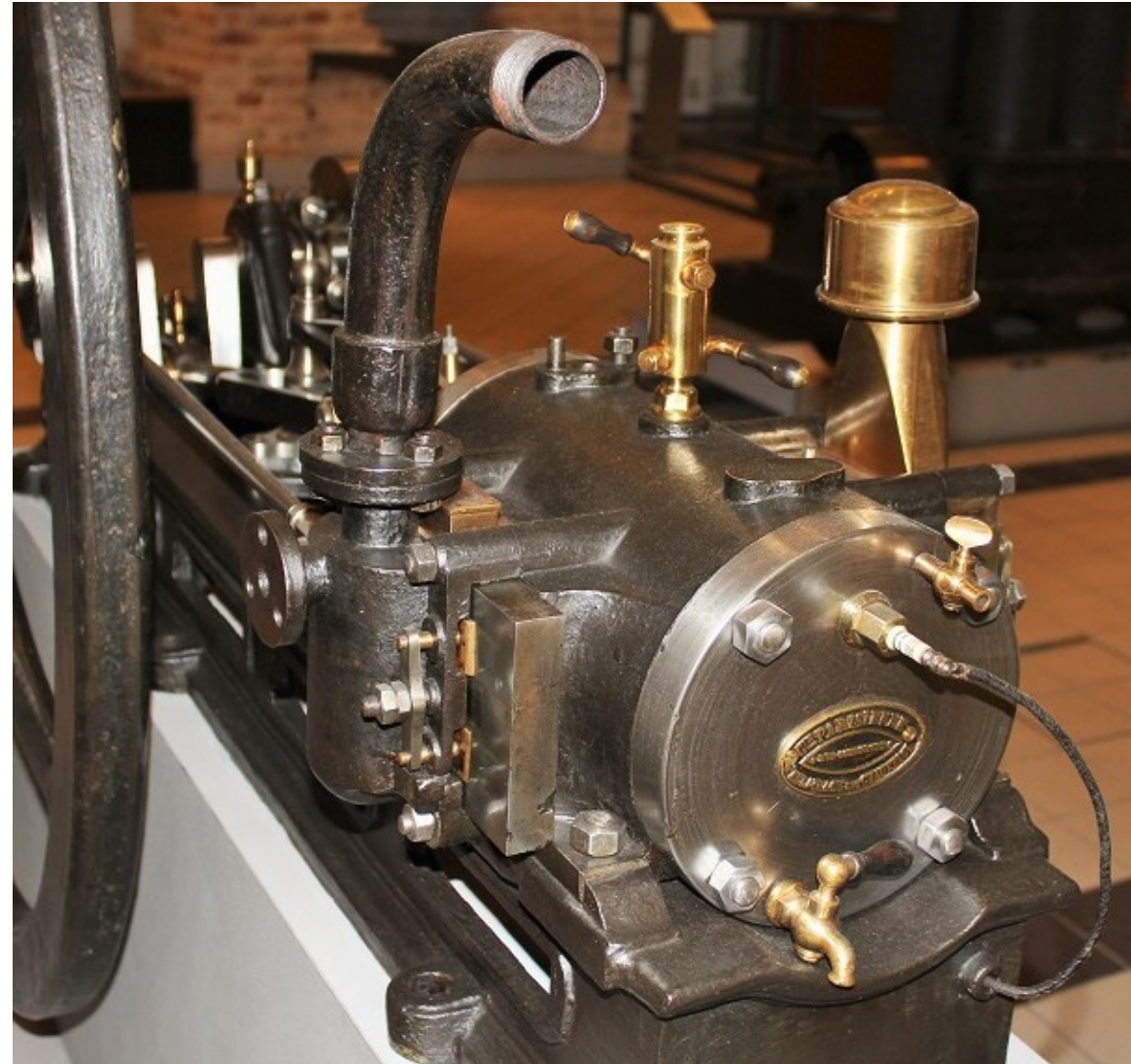
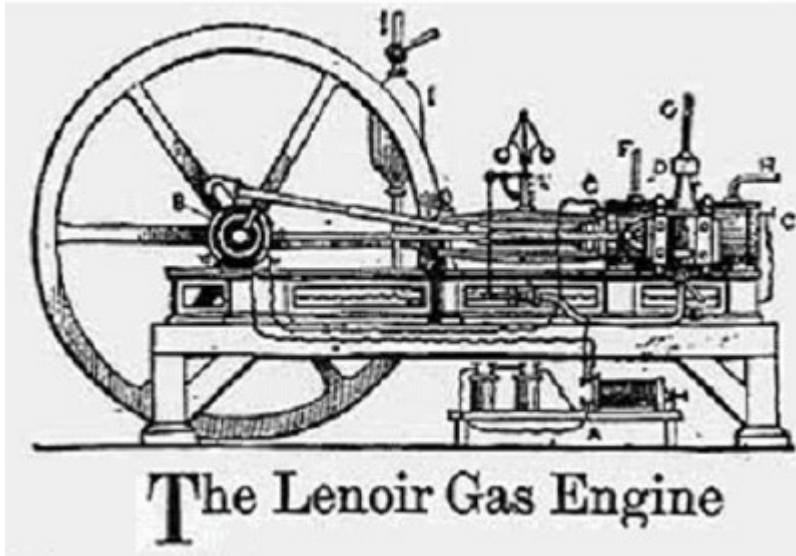
Toyota Mirai

2026

19th Century: First Internal Combustion Engines



1860: Invention of spark plug by Belge engineer Etienne Lenoir

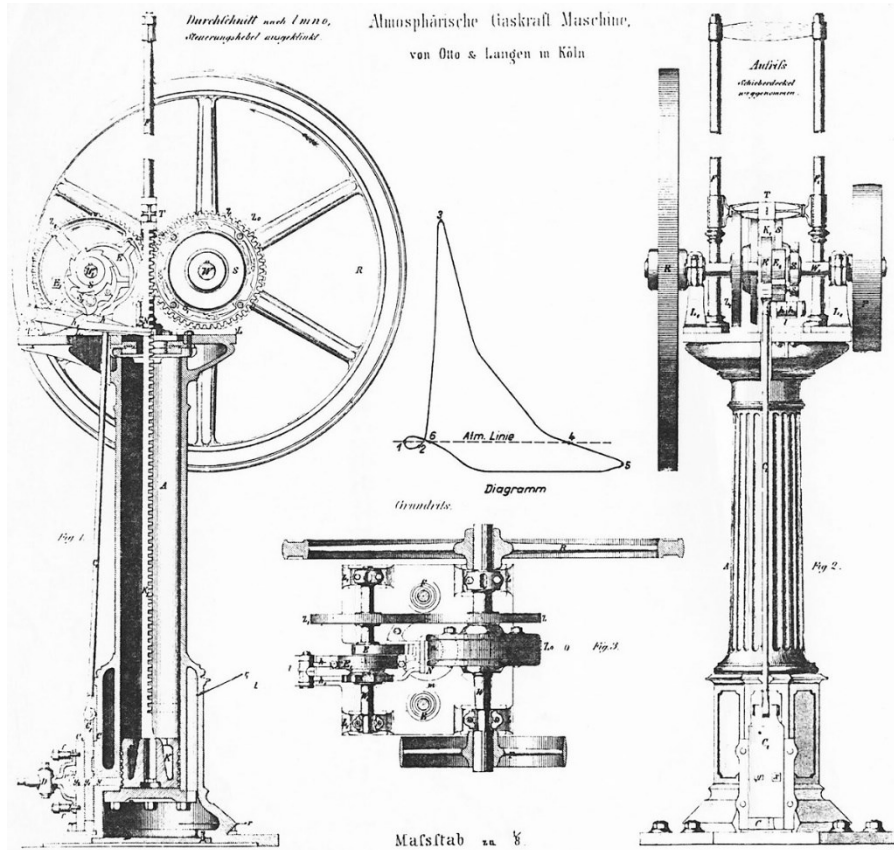


*Etienne Lenoir
Scientist
Engineer*

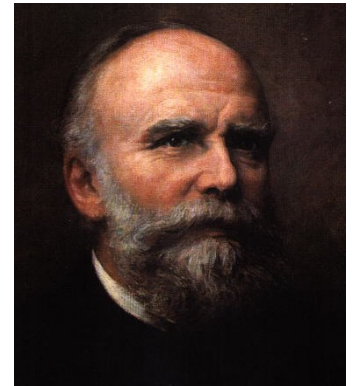
19th Century: First Internal Combustion Engines



1864: First commercially successful internal combustion engine, produced by German engineers Eugen Langen and Nicolaus Otto



Nicolaus Otto
Engineer



Eugen Langen
Engineer

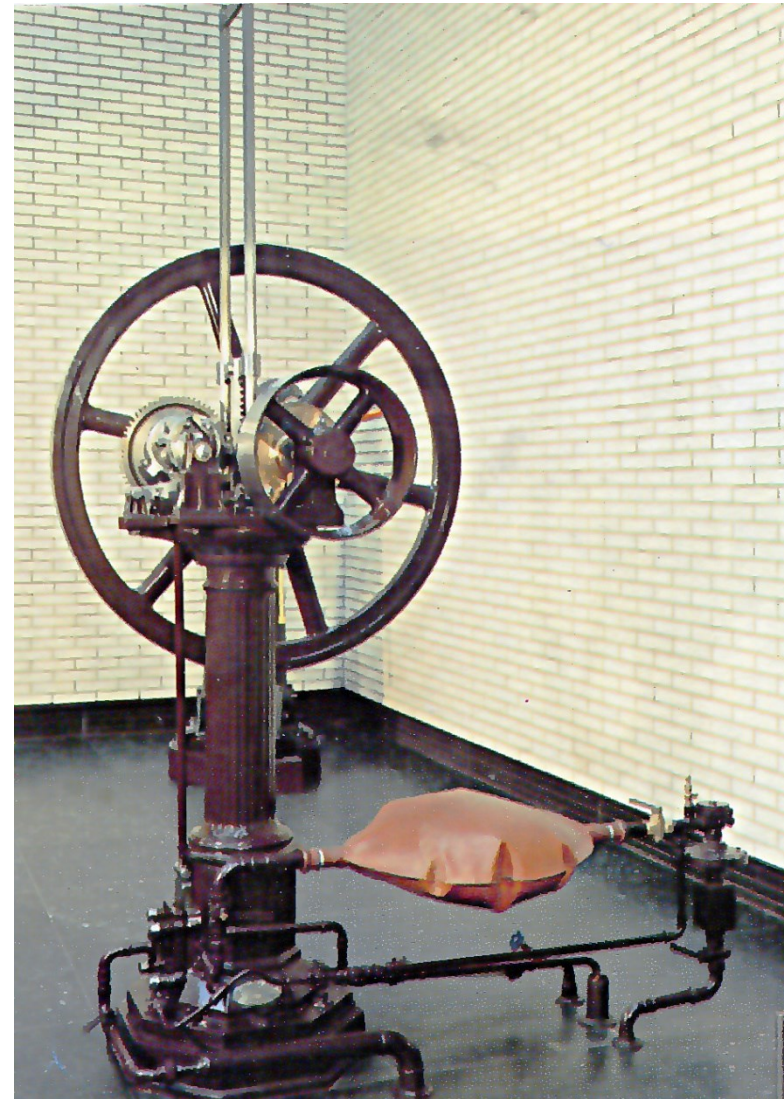
- Coal gas fueled atmospheric pressure engine
- 2.2 kW, 3-4 m height

19th Century: First Internal Combustion Engines



By 1875, 634 engines/year were produced

- Used to power small industrial machinery (printing presses, factory tools...)



19th Century: First Internal Combustion Engines



1876: First functional Otto cycle engine, called the **Otto Silent Engine**, built by Nicholas Otto, Franz Rings and Herman Schumm at the German company Deutz-AG-Gasmotorenfabrik

- The engine compressed the air/fuel mixture before combustion
- Liquid-fueled engine
- Single cylinder
- Four-stroke cycle

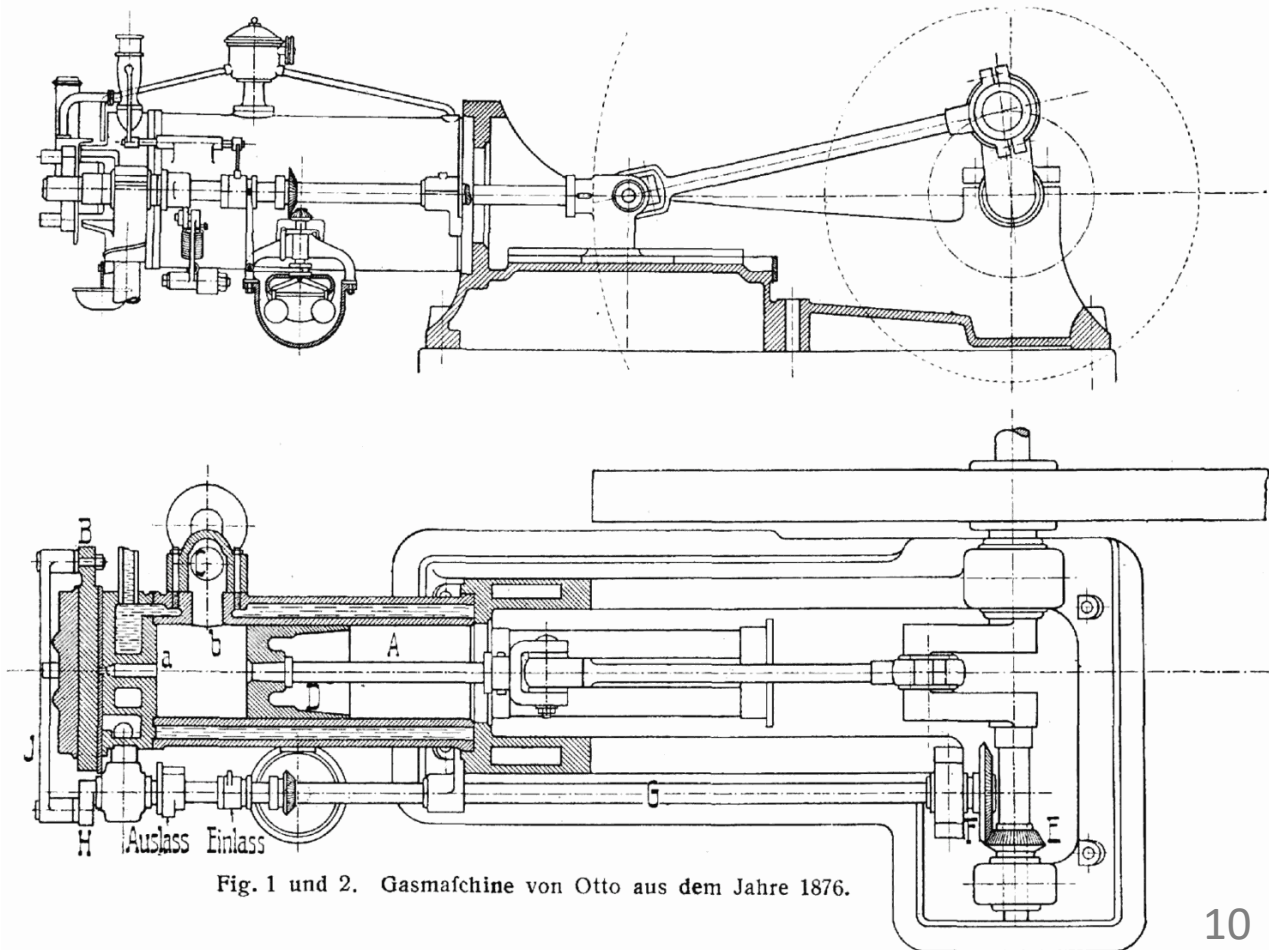


Fig. 1 und 2. Gasmaschine von Otto aus dem Jahre 1876.

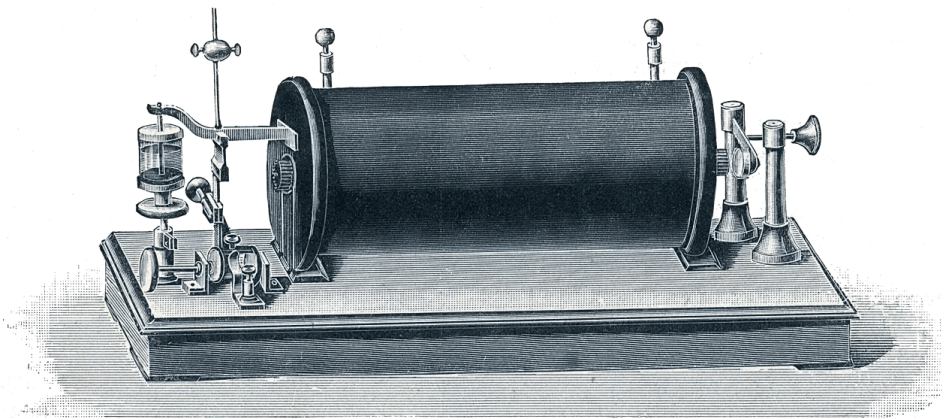
19th Century: First Internal Combustion Engines



1879: A prototype two-stroke gas engine is built by German engineer Carl Benz

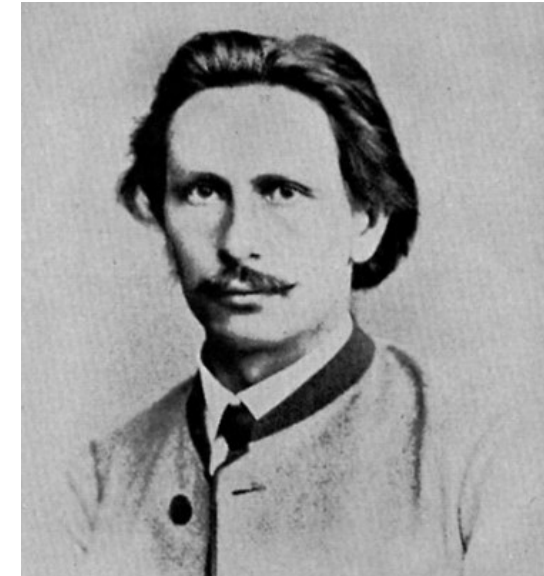
1880-1882: Benz patented

- Speed regulation system
- Ignition system with battery
- Spark plug
- Carburetor
- Clutch
- Gear shift
- Radiator



Induction Coil

By Heinrich Ruhmkorff, 1850s

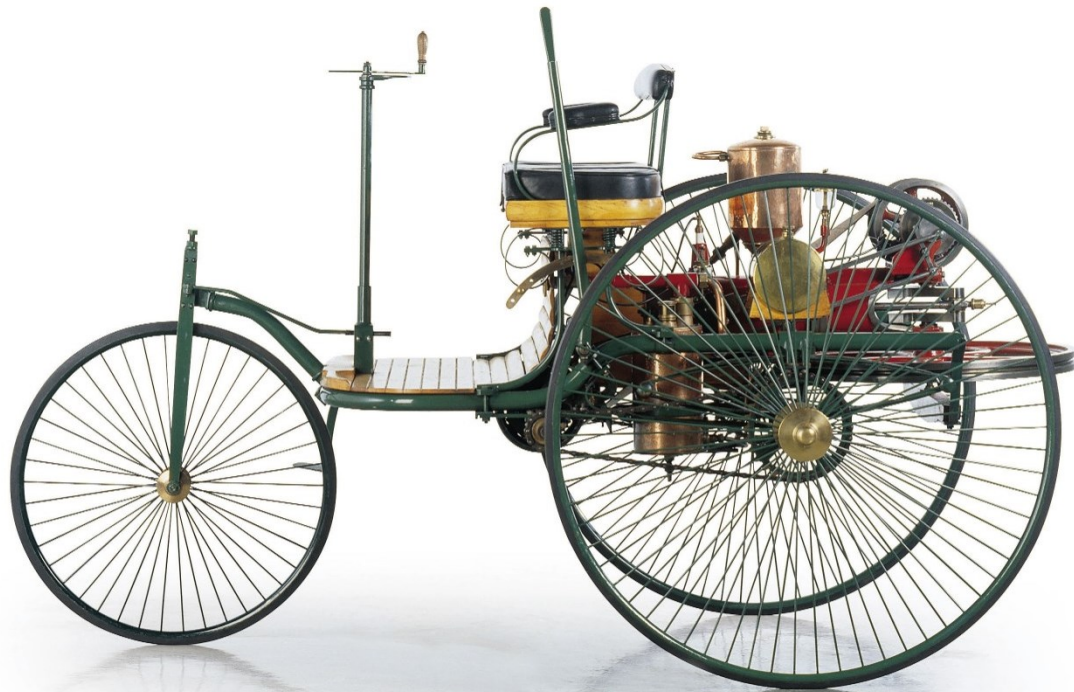


Carl Benz
Engineer
Inventor
Entrepreneur

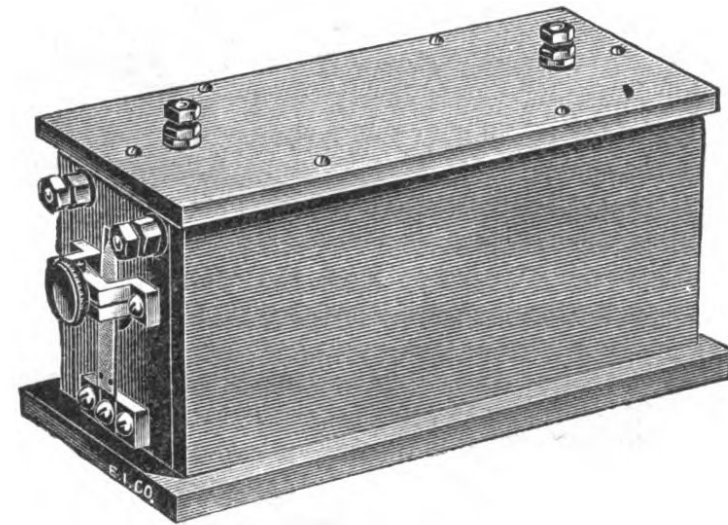
19th Century: First Internal Combustion Engines



1885: First Motorwagen by Carl Benz



- 954 cc single-cylinder four-stroke engine
- Trembler coil ignition



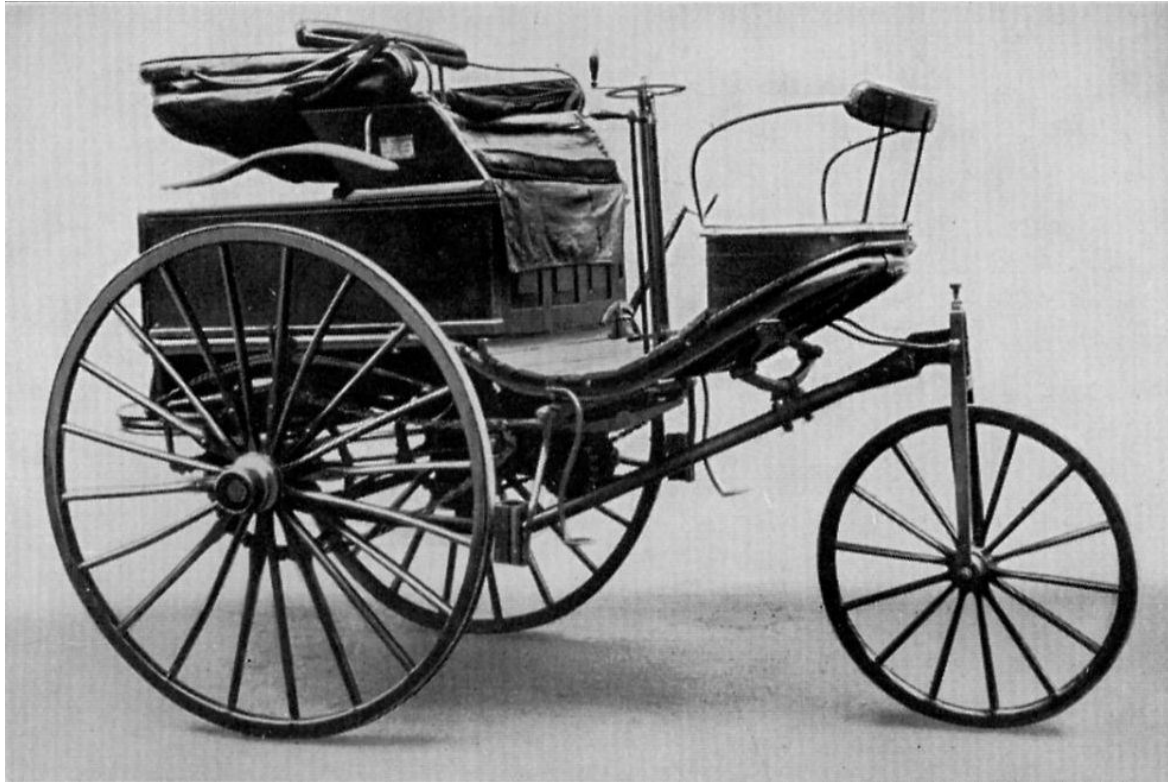
Trembler Coil

With its magnetically-activated contact called a trembler (interrupter), which breaks the primary current, generating multiple sparks during each cylinder's power stroke

19th Century: First Internal Combustion Engines



1886: Benz patent-Motorwagen Nr. 3



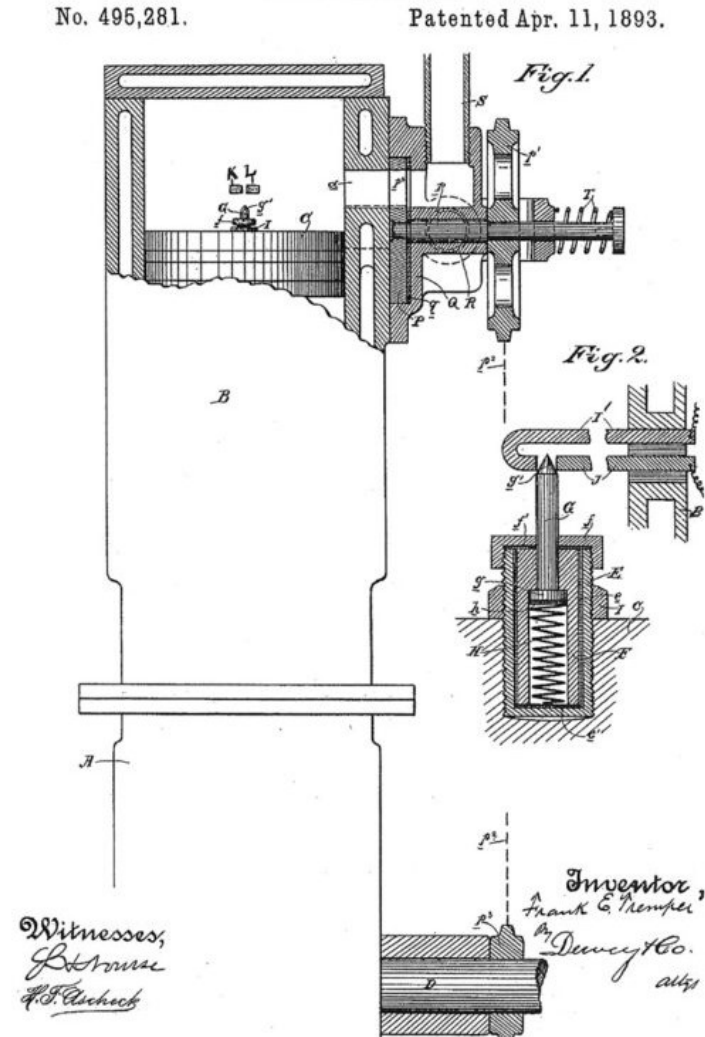
Bertha Benz
*Investor
Entrepreneur
Engineer
First rally car driver*

- **In 1888**, Bertha Benz drove the first long-distance trip between Mannheim and Pforzheim, Germany (106 km)

19th Century: First Internal Combustion Engines



1893: Explosive engine patent including an **original igniter with a spring-loaded contact**, by American engineer Frank Tremper



19th Century: First Internal Combustion Engines



1897: An **ignition magneto** is adapted for use in a motor vehicle engine by German engineer Robert Bosch

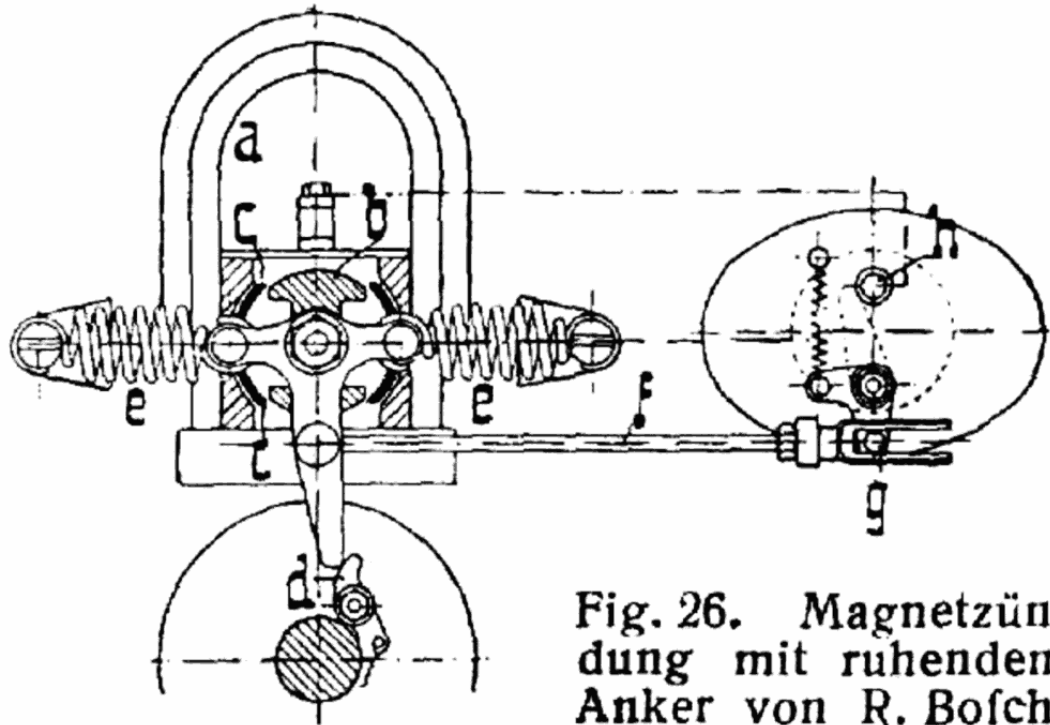
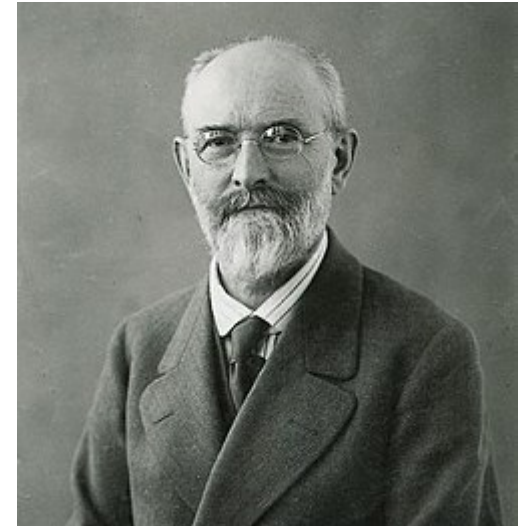


Fig. 26. Magnetzündung mit ruhendem Anker von R. Bosch.

Ignition Magneto

Combined magneto and transformer to make pulses of high voltage for spark plugs



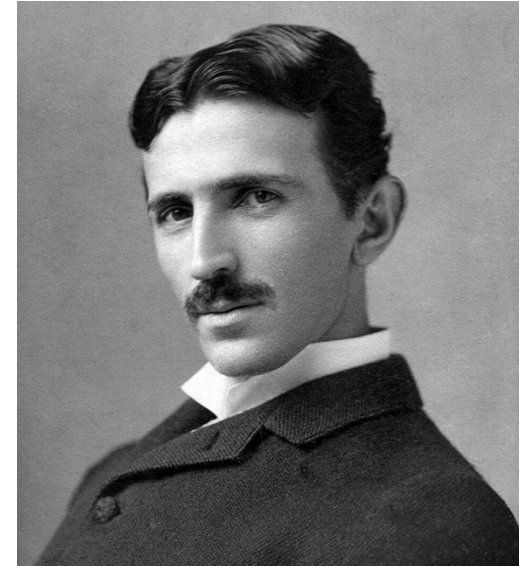
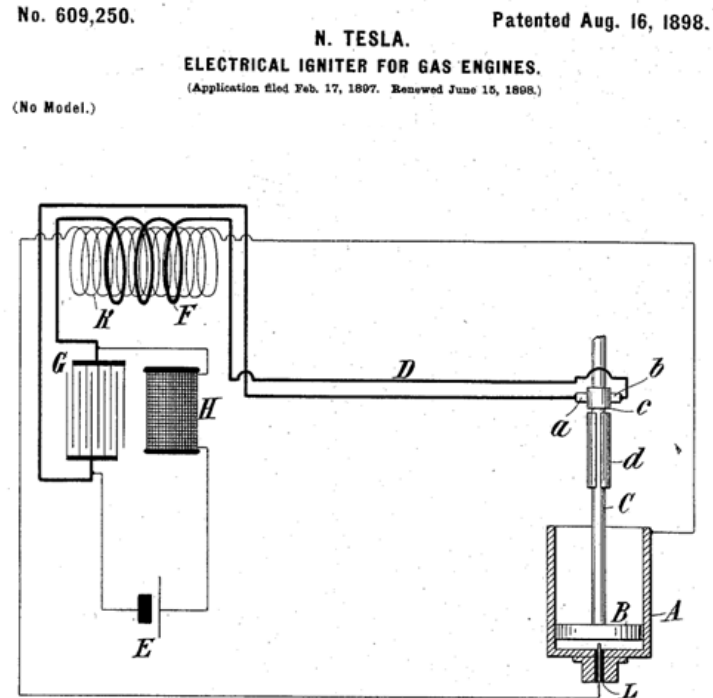
Robert Bosch
*Entrepreneur
Engineer
Inventor*

19th Century: First Internal Combustion Engines



1897: American engineer Nikola Tesla patented a **capacitor discharge ignition (CDI)** system for gas engines

- Main interest: energy released in a very short time ($\sim 100 \mu\text{s}$)



Nikola Tesla
Engineer
Inventor

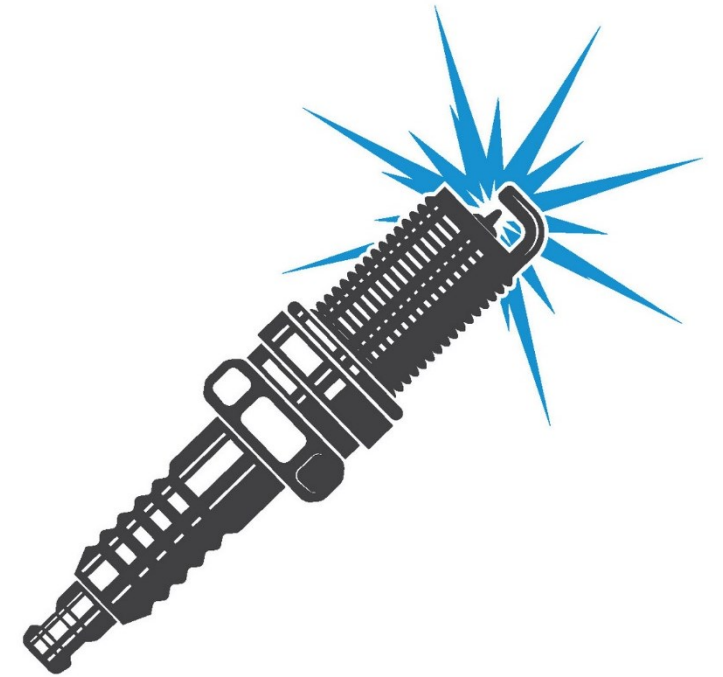
Witnesses:
M. Harmon Syer.
Edwin B. Hopkinson.

Nikola Tesla, Inventor
by Kerr, Curtis & Page 111111

Chapter II: History of Plasma-Assisted Combustion



- *19th Century: First Internal Combustion Engines*
- ***20th Century: Ignition Systems***
- *21st Century: Science and Opportunities*
- *References*



20th Century: Ignition Systems



1902: Patent on a **high-voltage magneto ignition system with spark plug**, by German engineer Gottlob Honold, Chief Engineer at Bosch's workshop



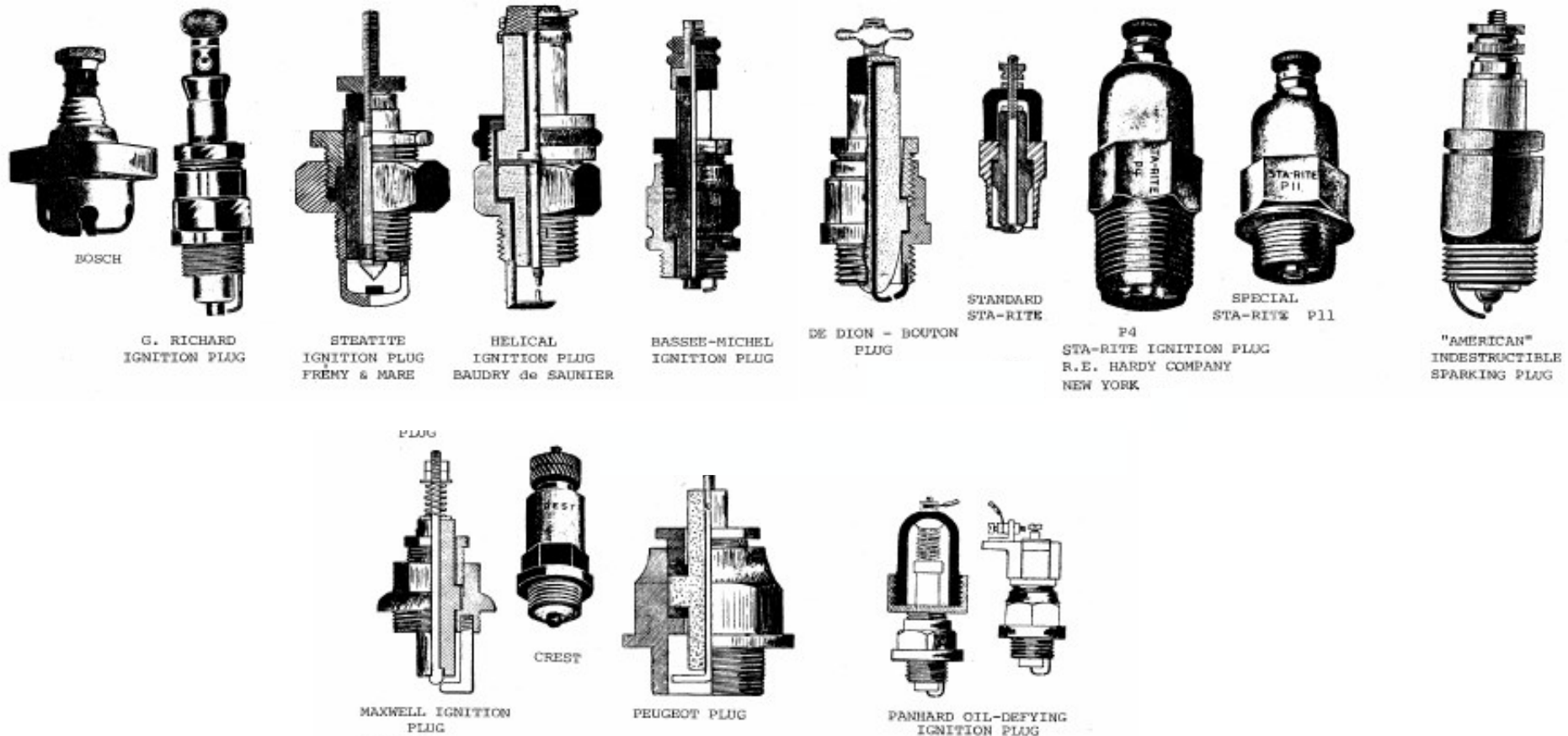
Gottlob Honold
Engineer

20th Century: Ignition Systems



Early 1900s, tens of different ignition systems in Europe and in the US

- Examples of available spark plugs in 1902

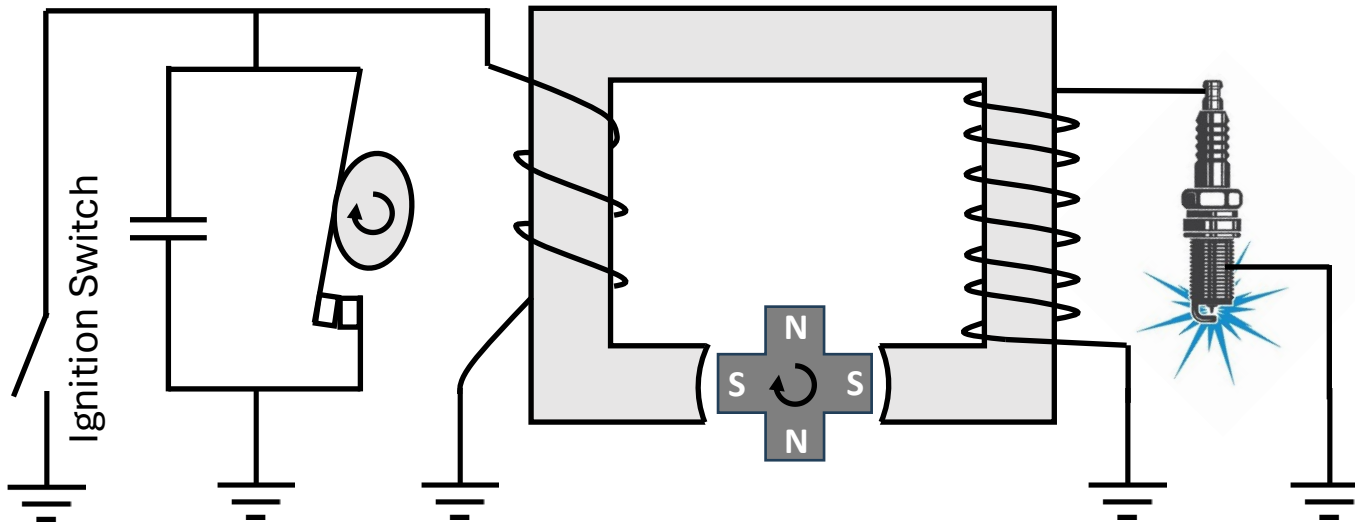


20th Century: Ignition Systems

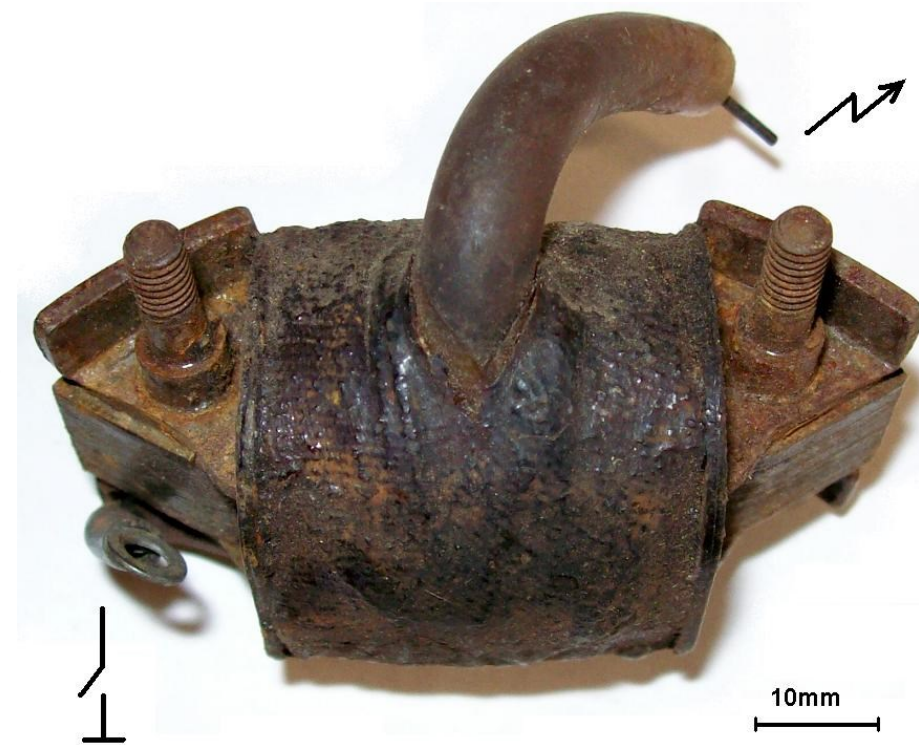


Early 1900s, two main ignition technologies were competing

- Ignition magneto systems:
 - Use a magneto and a transformer to make pulses of high voltage that can generate a spark



- No battery needed
- The strength of the spark depends on the rotation speed



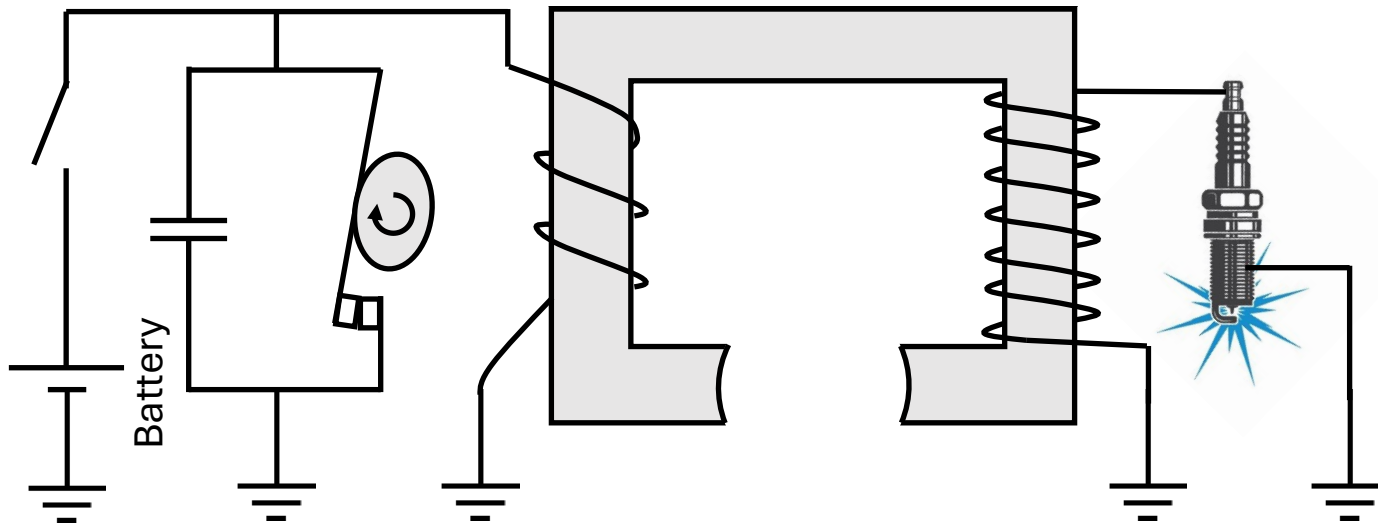
Ignition magneto system

20th Century: Ignition Systems



Early 1900s, two main ignition technologies were competing

- Induction coil (or Trembler coils) ignition systems:
 - Use two coils around an iron core with a vibrating magnetically activated contact breaking the primary current and generating multiple sparks



- Battery
- More controlled spark timing and energy



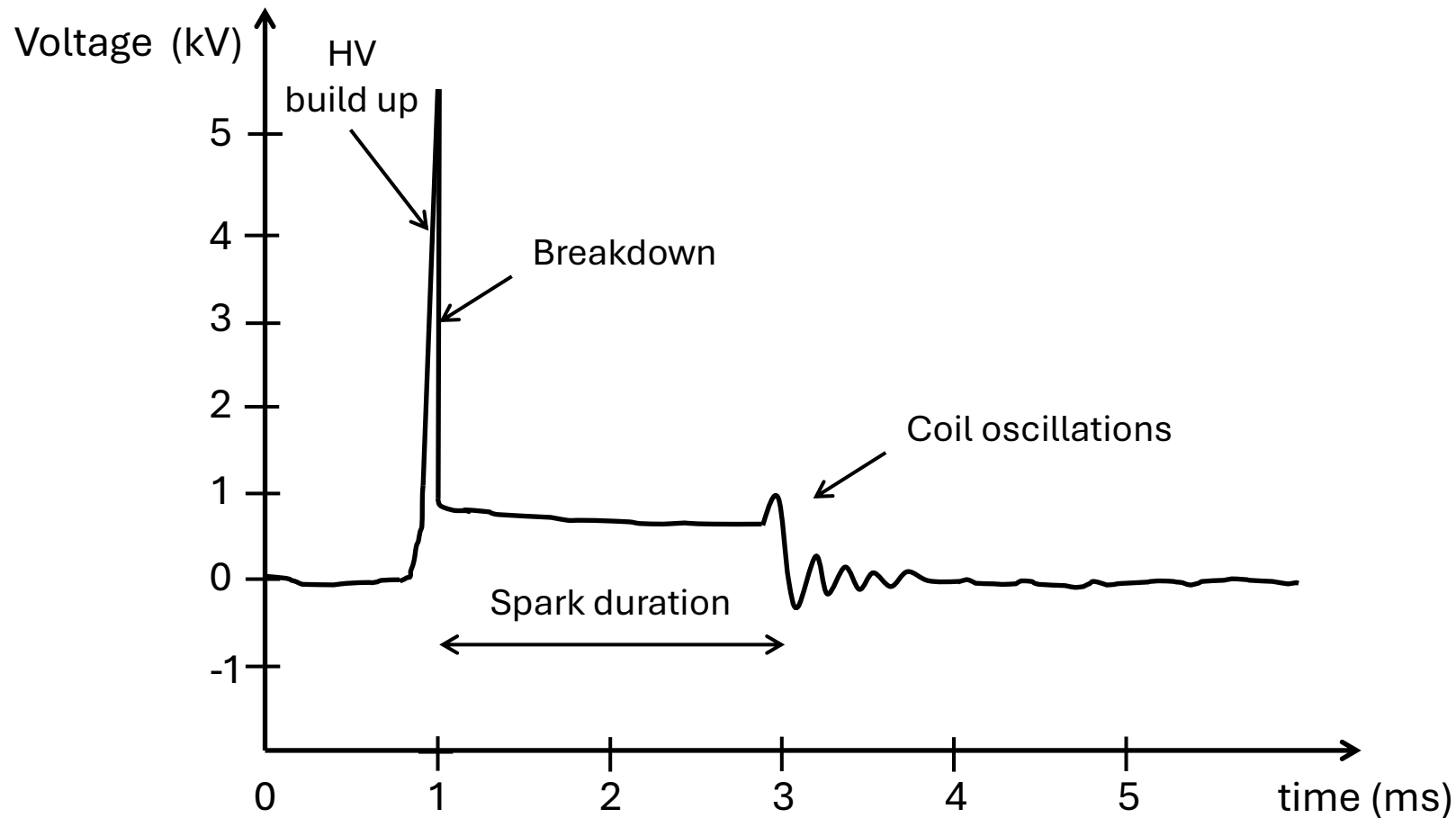
Trembler coil system

20th Century: Ignition Systems



Sparks produced by magneto ignition and induction coil ignition systems

- Typical electrical plots:

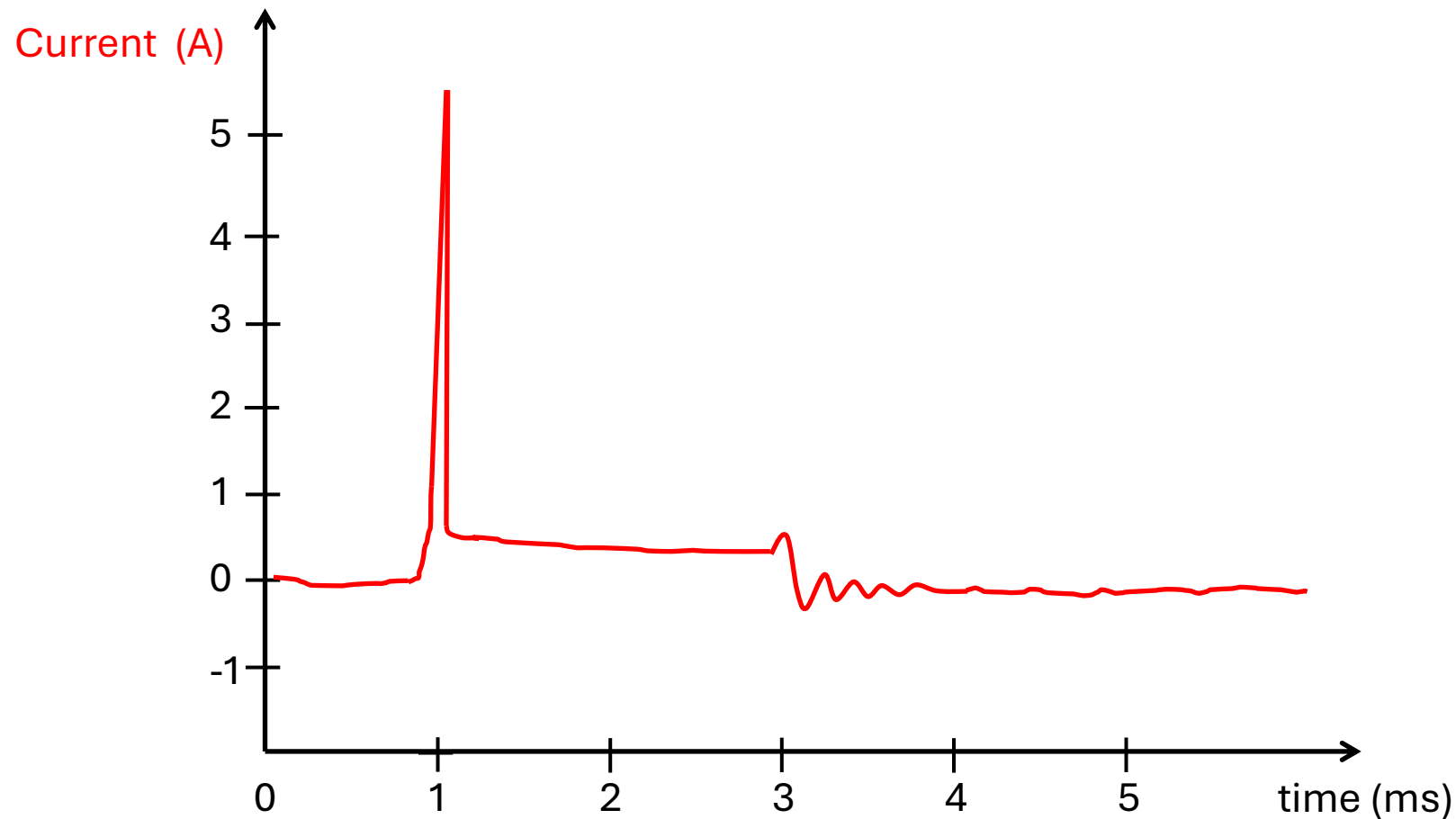


20th Century: Ignition Systems



Sparks produced by magneto ignition and induction coil ignition systems

- Typical electrical plots:

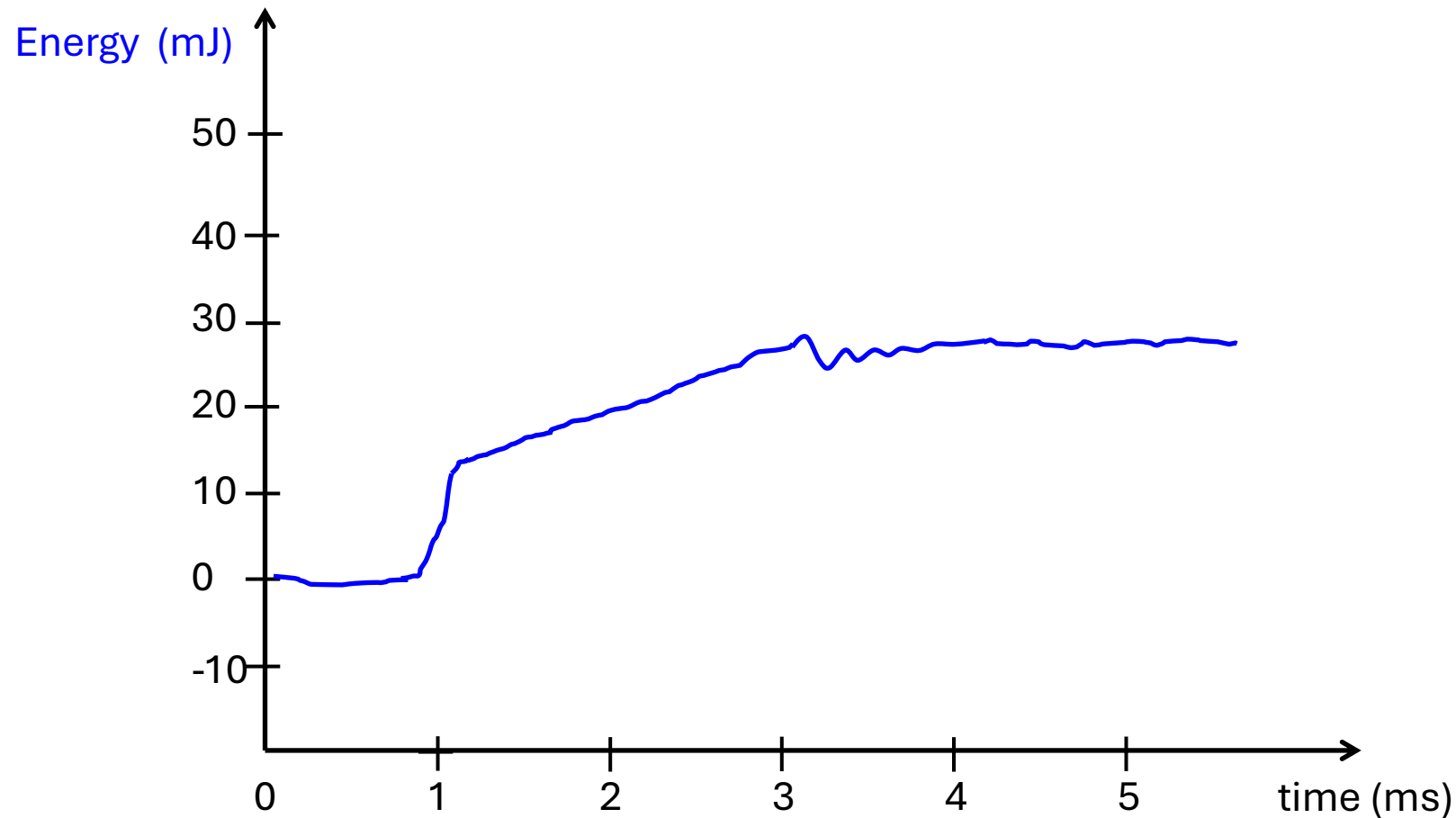


20th Century: Ignition Systems



Sparks produced by magneto ignition and induction coil ignition systems

- Typical electrical plots:



20th Century: Ignition Systems



1906: A **capacitor discharge ignitor (CDI)** combined with a magneto ignition system was used in the Ford Model K

- CDI technology was not very reliable

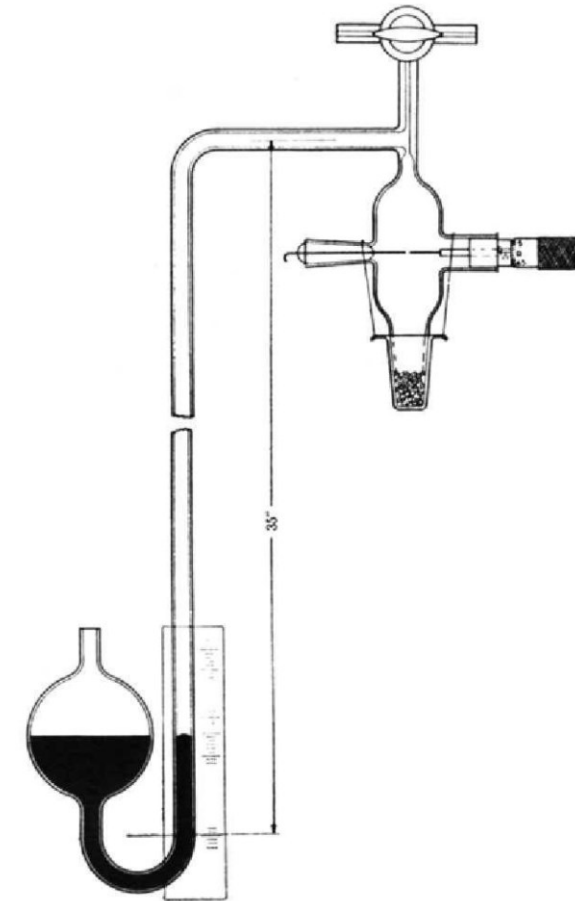
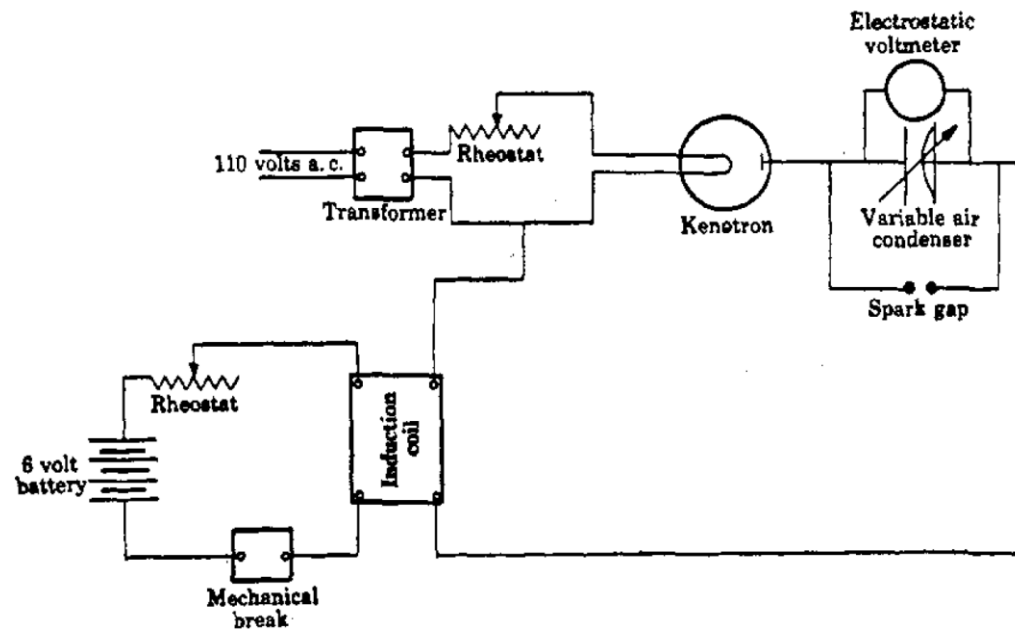


20th Century: Ignition Systems



1927: First scientific experimental paper on the **chemical effect of sparks during ignition** of methane, Bureau of Mines, USA

- Objective: **decrease accidents in mines**



- “... the electric spark acts mainly, perhaps entirely, as a source of thermal energy in igniting a gas mixture.”

H. F Coward and E.G. Meiter, Chemical action in the electric spark discharge. The ignition of methane, Journal of the American Chemical Society 49(2), pp. 396-409, 1927

20th Century: Ignition Systems



1962: American company Tung-Sol marketed a **thyatron CDI system**, Tung-Sol EI-4

1964: Bosch thyatron CDI system was used in NSU Spider, powered by a Wankel rotary engine



Thyatron (gas-filled tube)
High-power electrical switch



NSU Spider (1963-1967)
West Germany

20th Century: Ignition Systems



1965-1970: Deployment of CDI systems using **thyristors** (solid-state semiconductor diode)

- 1965: A CDI is marketed by Prest-O-Lite, with “an unprecedented 50,000 mile warranty”
- 1965: The Delta Mark 10 CDI (most famous aftermarket electronic ignition) was sold assembled or as a kit
- 1967: Delco CDI system optional on Oldsmobile, Pontiac, and GMC vehicles
- 1968: Fiat Dino was the first production car to come standard with an electronic CDI system



Thyristors

First produced in 1956



Delta Mark 10 CDI (1965)

USA



Fiat Dino Coupe (1966-1973)

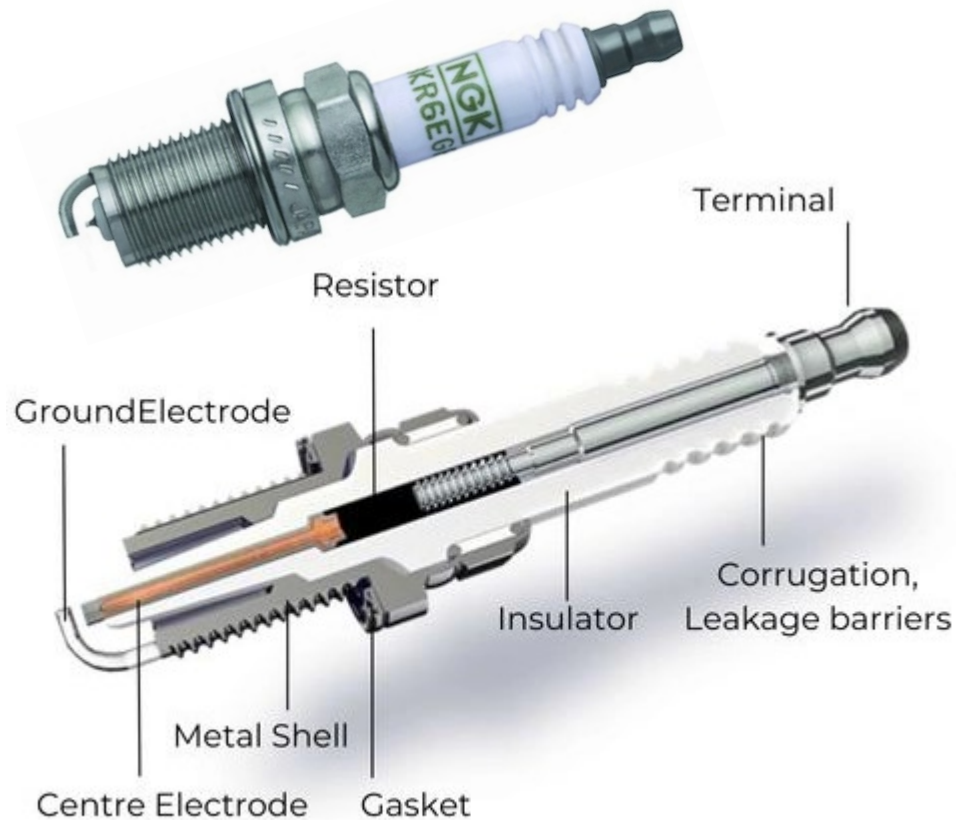
Italy

20th Century: Ignition Systems

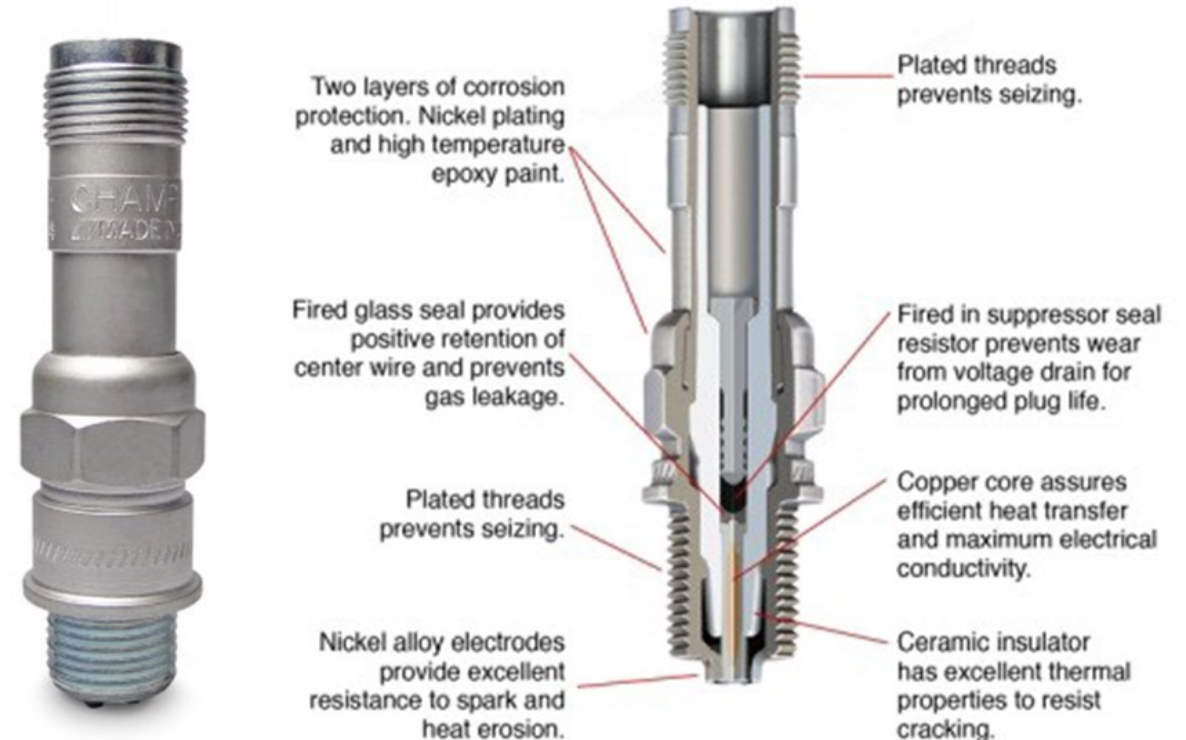


Today's utilization of spark plugs in ignition systems

Spark plug for SI car engines and small piston engines



Spark plugs for SI aircraft engines



20th Century: Ignition Systems



Today's utilization of magneto ignition and induction coil ignition systems

- Car gasoline engines: induction coil ignition and CDI systems
- Motorbikes and planes piston engines: magneto ignition



**Ignition coils and CDI
for cars**



**Magneto ignition for
motorbikes**



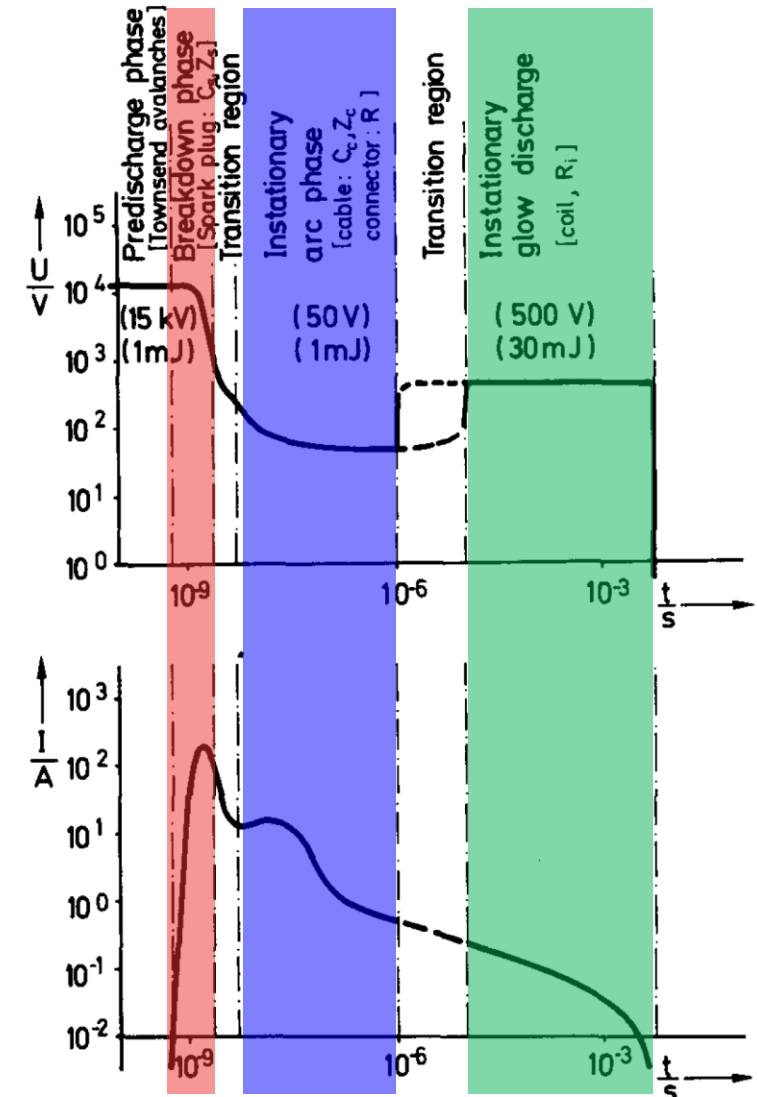
**Magneto ignition for
light aircraft**

20th Century: Ignition Systems



Late 1970s: **Rudolf Maly** (Stuttgart University, Germany) scientifically studied ignition by sparks

- Three phases of spark ignition:
 - Breakdown
 - Arc
 - Glow
- Chemical, thermal and hydrodynamic (shock & gas expansion) effects
- Effect of spark energy and duration on ignition



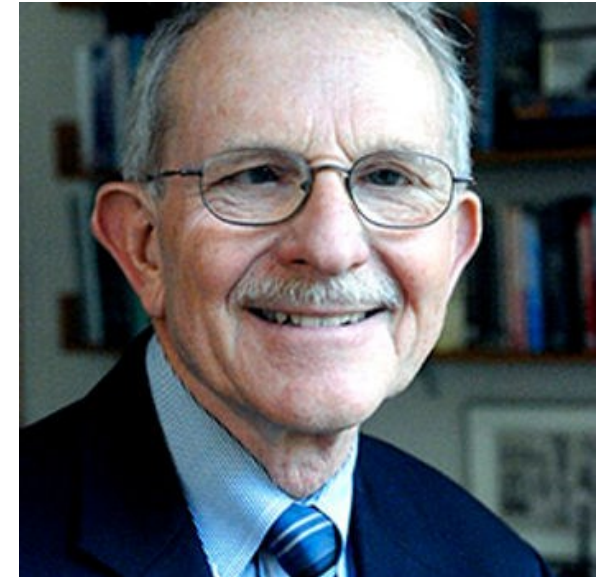
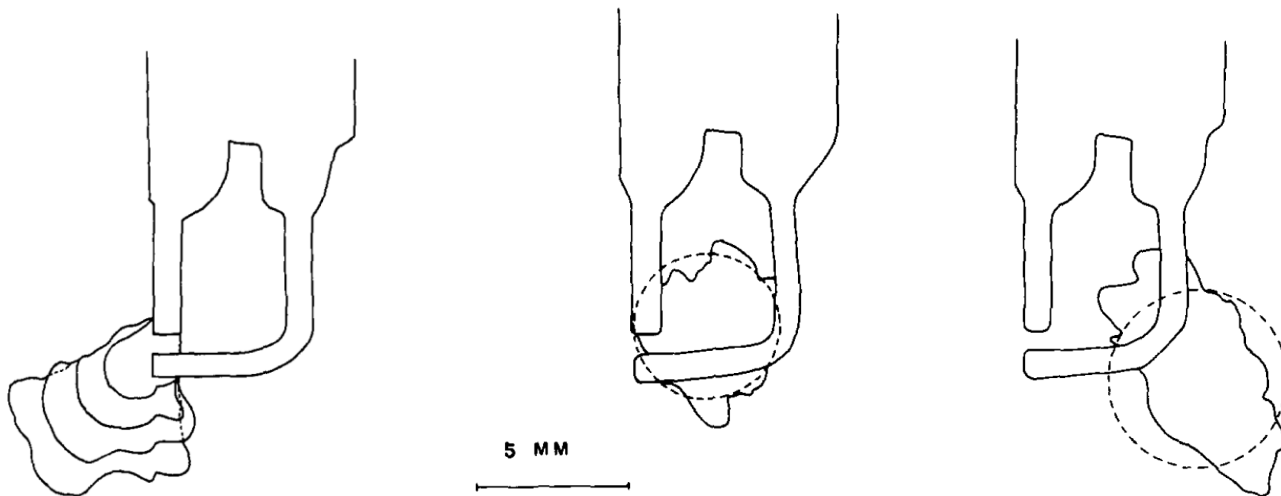
R. Maly and M. Vogel, Initiation and propagation of flame fronts in lean CH₄-air mixtures by the three modes of the ignition spark, Symposium (International) on Combustion, 1979c

20th Century: Ignition Systems



1980s: **John Heywood** (MIT, USA) scientifically studied ignition in spark ignition engines

- Focusing on the ignition kernel
- The spark is mainly treated as a hot spot



John Heywood
Professor
Engineer

J. Tagalian and J.B. Heywood, Flame initiation in a spark-ignition engine, Combustion and Flame 6(2), pp 243-246, 1986

20th Century: Ignition Systems



1990: First paper on plasma assisted combustion (in French), by P. Pasquini from *Electricite de France* (EDF), national French company producing electricity

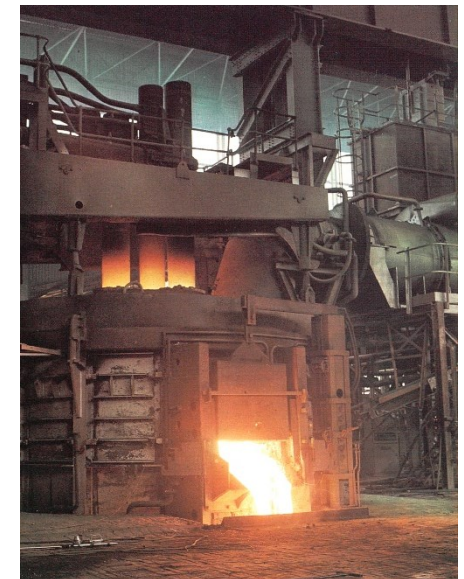
- Combustion of low-grade fuels such as pet coke
- Numerical study of a burner design
- Arc plasma with direct plasma-particle interaction

P. Pasquini, Plasma assisted combustion. Study of different burner design, J. Phys. Colloques 51, C5-101-C5-110, 1990

1992: First experimental paper on a plasma-assisted 4MW burner (in French)

- Very similar design than arc furnace in iron industry

P. Pasquini, A. Bouvier, M. Moneuse, Plasma assisted combustion: Survey of various burners, Congress of the International Union for Electroheat, Montreal (Canada), 14-18 Jun 1992



20th Century: Ignition Systems



1993: First paper on plasma-assisted ignition by thermal plasma jet (in Japanese) from Nippon Steel Corp LTD scientists

- Demonstration that with plasma injection, pulverized coal can be ignited without any addition of auxiliary oil or gas
- The proportion of plasma energy necessary to maintain stable combustion does not exceed **several percentages** of heat input of the coal
- **Suppression of nitrogen oxide formation** can be expected even in the range of high combustion efficiency



K. Takeda, M. Hibi, H. Takeuchi, H. Tsuboi, H. Moridera, K. Tanaka, Effects of plasma injection on stability and nitrogen-oxide formation in combustion of pulverized coal, Tetsu To Hagane – Journal of the Iron and Steel Institute of Japan 79(6), pp 638-644, 1993

20th Century: Ignition Systems



1995: First paper on plasma-assisted cleaning of exhaust gases from the University of Orleans, France

- Multi-electrode reactor producing **gliding arcs**
- Cleaning of highly **soot and NO_x** charged exhaust gas
- Exhaust gas flow rate 200 m³/h and **10 kW electric power** of the gliding arcs

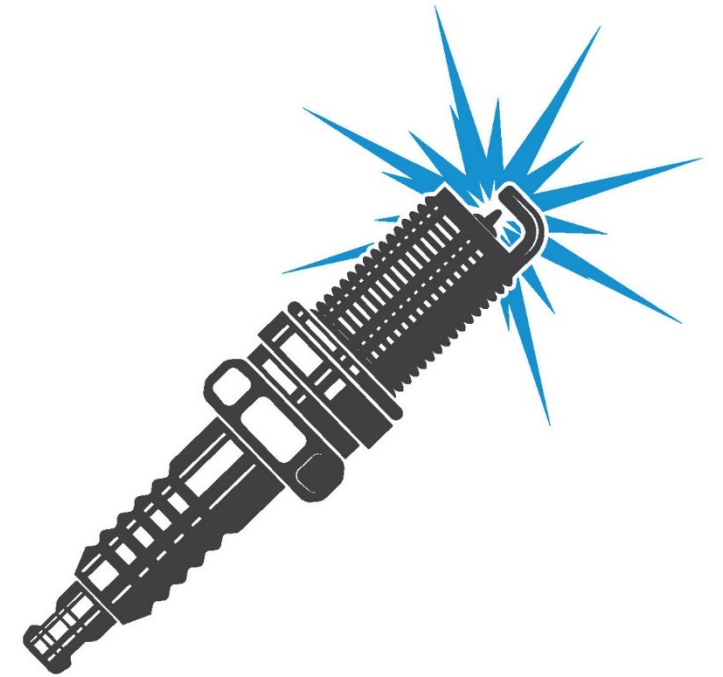


A. Czernichowski, P. Labbe, F. Laval, H. Lesueur, Plasma-assisted cleaning of flue gas from a sooting combustion case of organic nitrates, ACS Symposium Series 607, pp 144-154, 1995

Chapter II: History of Plasma-Assisted Combustion



- *19th Century: First Internal Combustion Engines*
- *20th Century: Ignition Systems*
- ***21st Century: Science and Opportunities***
- *References*



21st Century: Science and Opportunities



Plasma-assisted combustion topics studied since 2000:

- Plasma-assisted ignition
- Flame stabilization:
 - Enhancement of flammability limits
 - Control of thermoacoustic instabilities
- Plasma-assisted detonation:
 - Enhancement of DDT
 - Enhancement of detonation properties
- Fuel cracking
- Exhaust gas treatment:
 - Gaseous pollutant: NO_x, N₂O, CO...
 - Soots



21st Century: Science and Opportunities



Plasma sources considered:

- Dielectric Barrier Discharges (DBD) (known as *silent discharges*, end of 19th century)
- Microsecond pulsed discharges (early 20th century)
- Microwave discharges (1960s)
- Gliding arcs (late 1980s)
- Nanosecond Repetitively Pulsed (NRP) discharges (early 2000s)

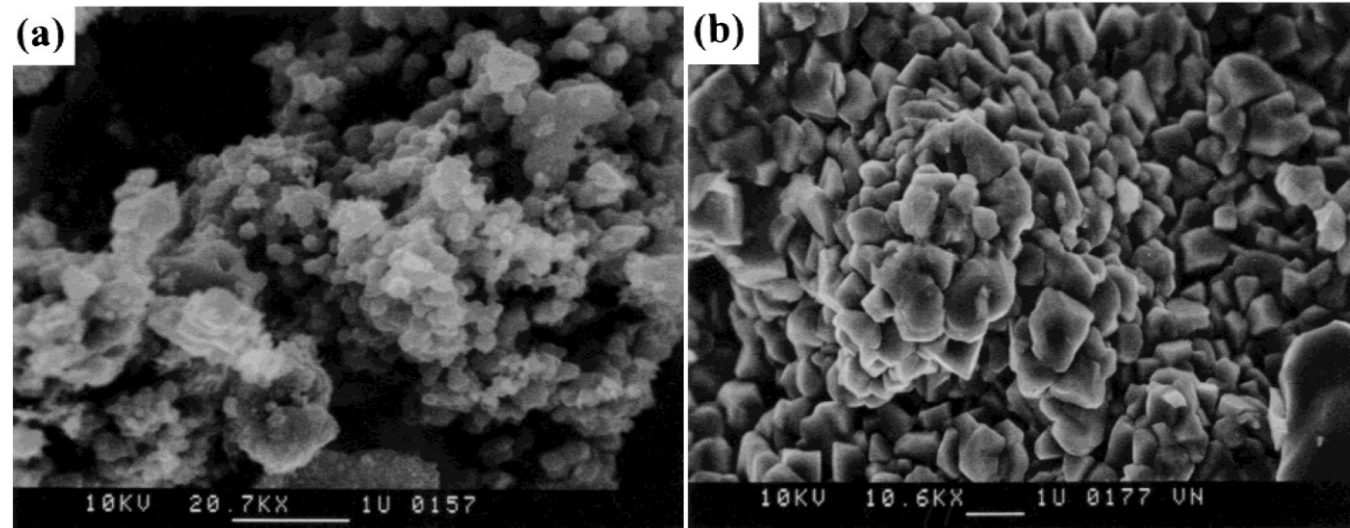
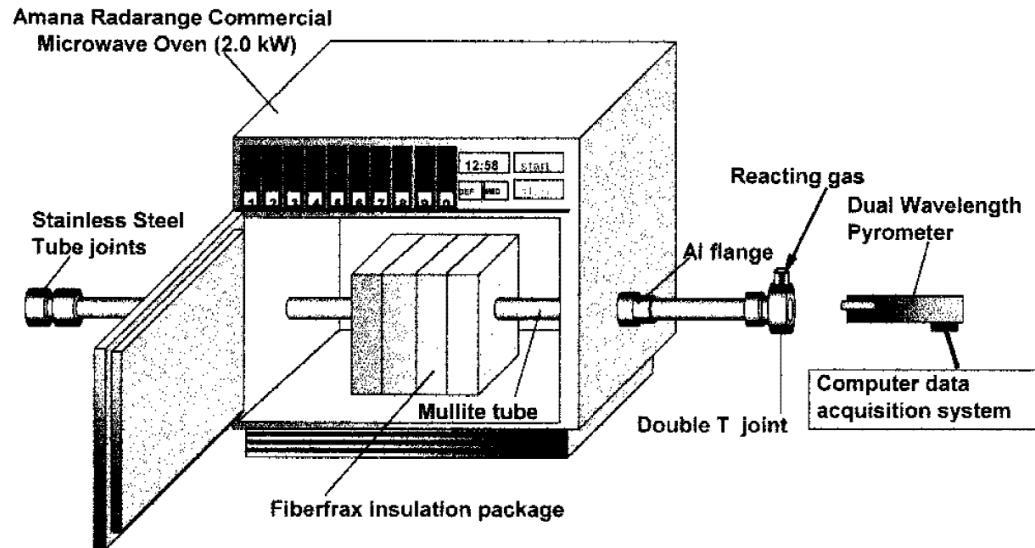


21st Century: Science and Opportunities



2000 First paper on plasma-assisted combustion for synthesis of nitride powders, from Penn state University, USA

- Nitrogen microwave plasma coupled with metal combustion

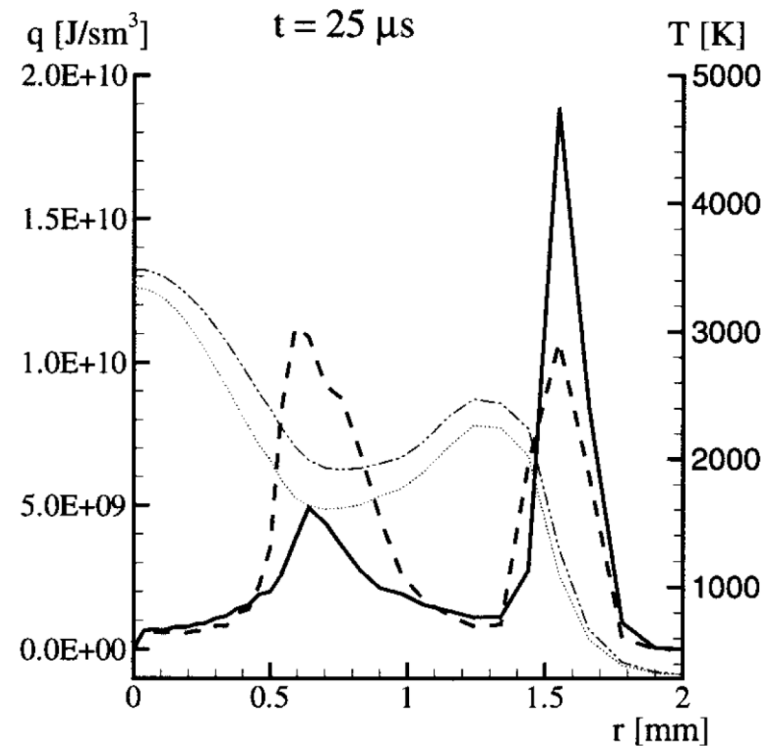
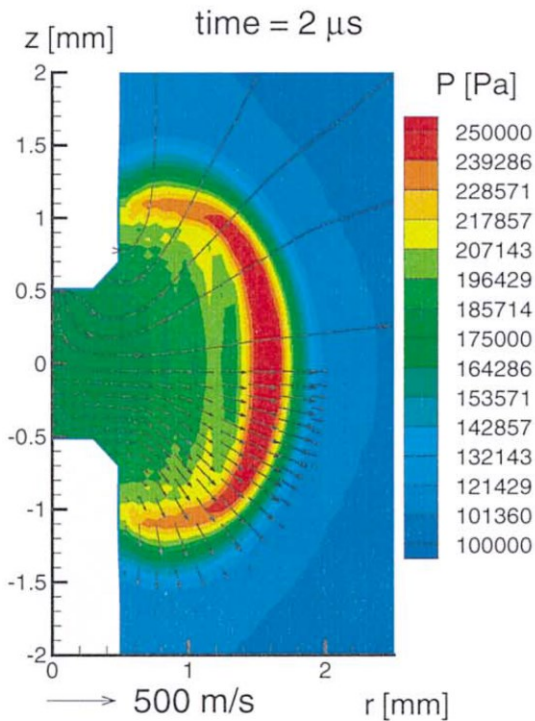


B. Vaidhyathan, D.K. Agrawal, R. Roy, Novel synthesis of nitride powders by microwave-assisted combustion, Journal of Materials Research 15(4), pp 974-981, 2000

21st Century: Science and Opportunities



2000 First paper on numerical simulation of spark ignition including ionization, from Stuttgart University, Germany



Ulrich Maas
Professor

M. Thiele, S. Selle, U. Riedel, J. Warnatz, U. Maas, Numerical simulation of spark ignition including ionization, Proc. Combust. Inst. 28, pp 1177-1185, 2000

21st Century: Science and Opportunities



2001 First techno-economic potential assessment of adaptative plasma-assisted incineration, from McGill University, Canada

- DC thermal plasma afterburner in hazardous waste incineration
- Plasma-assisted processes increases the costs of the process by 50%
- But they offer significant benefits in effectiveness, safety and regulatory compliance



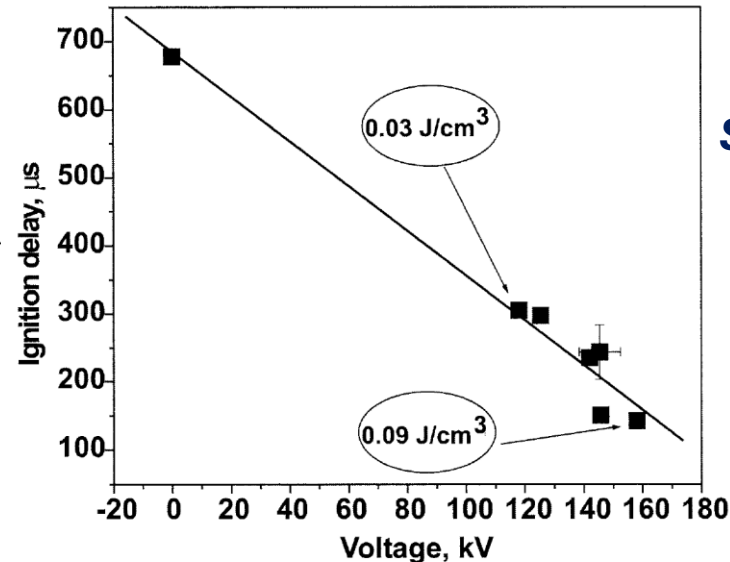
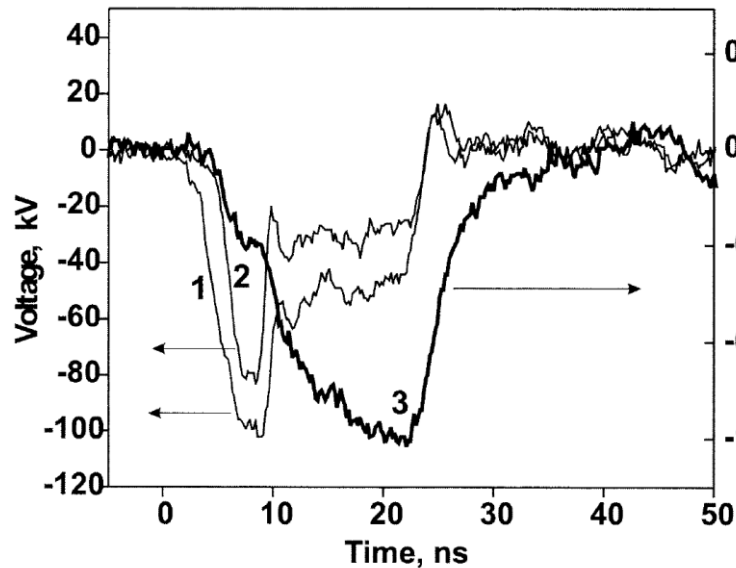
J. Fillion, R.J. Munz, E.D. Salin, A feasibility study of adaptive plasma-assisted incineration, part 2: Techno-economic potential assessment, Canadian Journal of Chemical engineering 79(4), pp 618-625, 2000

21st Century: Science and Opportunities



2003 First paper on a nanosecond discharge ignition from Moscow Institute of Physics and Technology, Russia

- A single nanosecond discharge
- Experimental and numerical results
- Hydrogen and methane fuels
- Ignition delays



Svetlana Starikovskaia
Professor



Andrey Starikovskiy
Professor

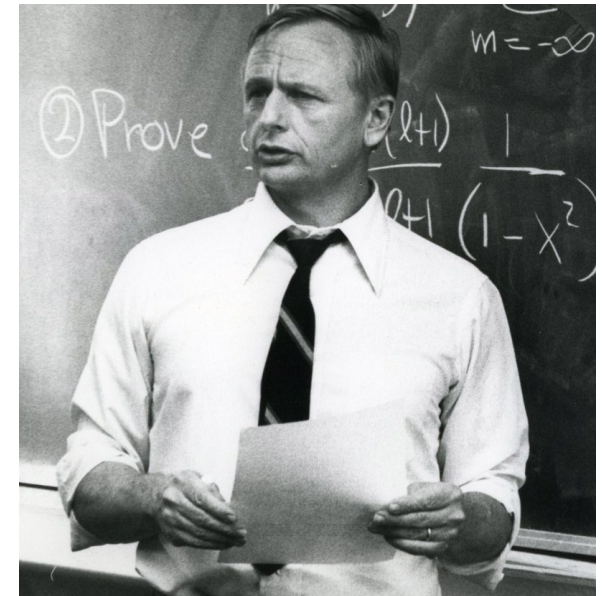
S.A. Bozhenkov, S.M. Starikovskaia, A.Y. Starikovskii, Nanosecond gas discharge ignition of H₂- and CH₄- containing mixtures, Combustion and Flame 133 (1-2), pp 133-146, 2003

21st Century: Science and Opportunities



2004 First paper on a new transient plasma ignition system, from the University of Southern California, USA

- Pseudospark-based high-repetition-rate pulse generator
- Pulses characteristics:
 - 60 – 200 ns duration
 - 15 – 90 kV amplitude
 - Up to 2.6 kHz
- Methods to suppress Electro Magnetic Interference (EMI) and ground noise discussed



Martin A. Gundersen
Professor
Electrical engineer

F. Wang, A. Kuthi, X.D. Wang, M. Gundersen, Compact high-repetition-rate pseudospark pulse generator, IEEE Proc. 26th Int. Power Modulator Symp. pp 137-140, 2004

21st Century: Science and Opportunities



2005 First paper on nonthermal ignition of hydrocarbons by radio frequency (RF) plasma, from Ohio State University, USA

- Large volume ignition kernel produced by the uniform and diffuse RF plasma
- Better ignition compared to both sparks and arc discharges
- Ignition with minimal thermal effect



Igor Adamovich
Professor

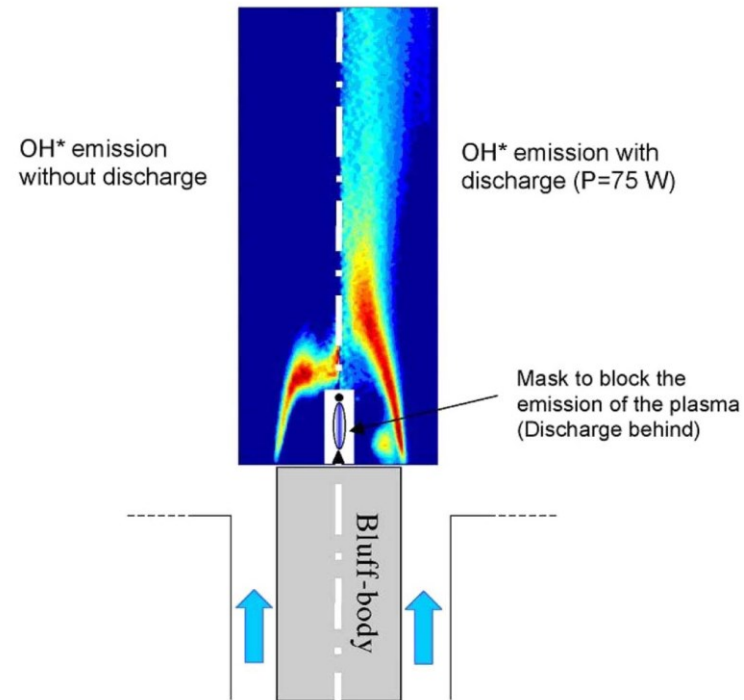
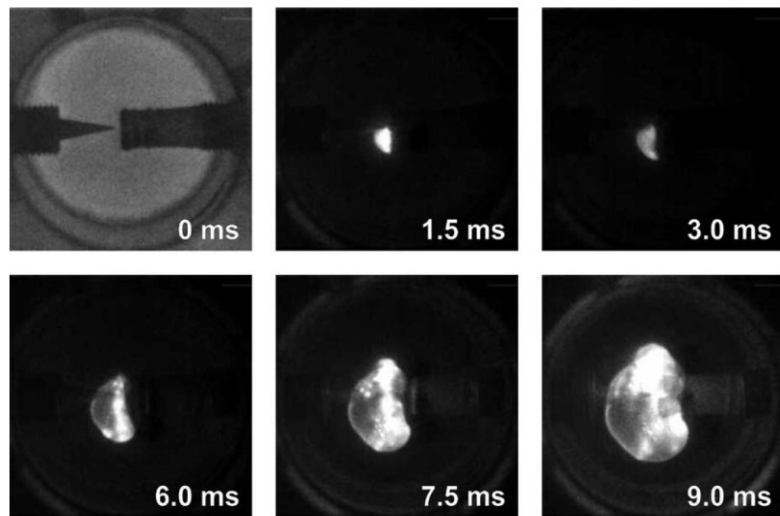
N. Chintala, R. Meyer, A. Hicks, A. Bao, J.W. Rich, W.R. Lempert and I.V. Adamovich, Nonthermal Ignition of Premixed Hydrocarbon-Air Flows by Nonequilibrium Radio Frequency Plasma, Journal of Propulsion and Power 21(2) pp 17-45, 2005

21st Century: Science and Opportunities



2006 First papers on plasma-assisted combustion by nanosecond repetitively pulsed (NRP) discharges from Ecole Centrale Paris, France

- Stabilization of lean premixed flames
- Ignition of gaseous fuels



Christophe Laux
Professor

G. Pilla, D. Galley, D.A. Lacoste, F. Lacas, D. Veynante, C.O. Laux, Stabilization of a turbulent premixed flame using a nanosecond repetitively pulsed plasma, IEEE Transactions on Plasma Science 34(6), pp 2471-2477, 2006

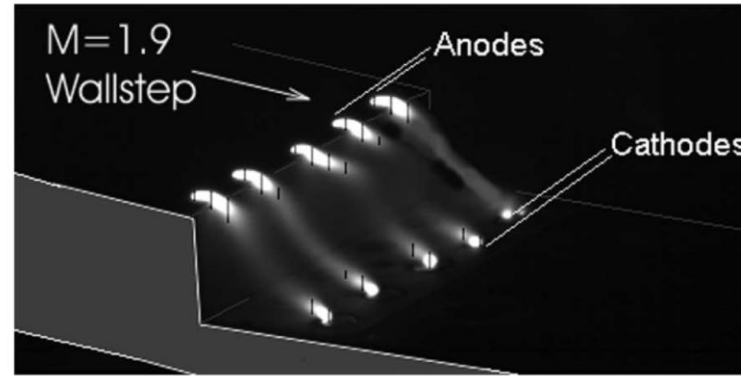
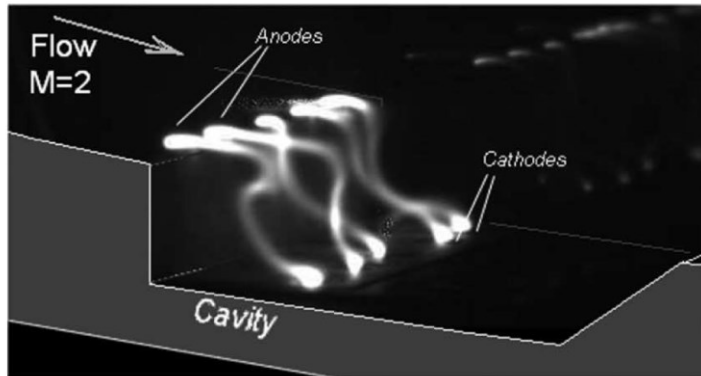
S.V. Pancheshnyi, D.A. Lacoste, A. Bourdon, C.O. Laux, Ignition of propane-air mixtures by a repetitively pulsed nanosecond discharge, IEEE Transactions on Plasma Science 34(6), pp 2478-2487, 2006

21st Century: Science and Opportunities



2006 First paper on plasma-assisted supersonic combustion from the Russian academy of Science, Russia

- Gas flow at Mach 2.5
- Three plasma strategies: plasma-induced ignition, plasma-intensified mixing, and flame-holding by plasma generation



Sergey Leonov
Professor

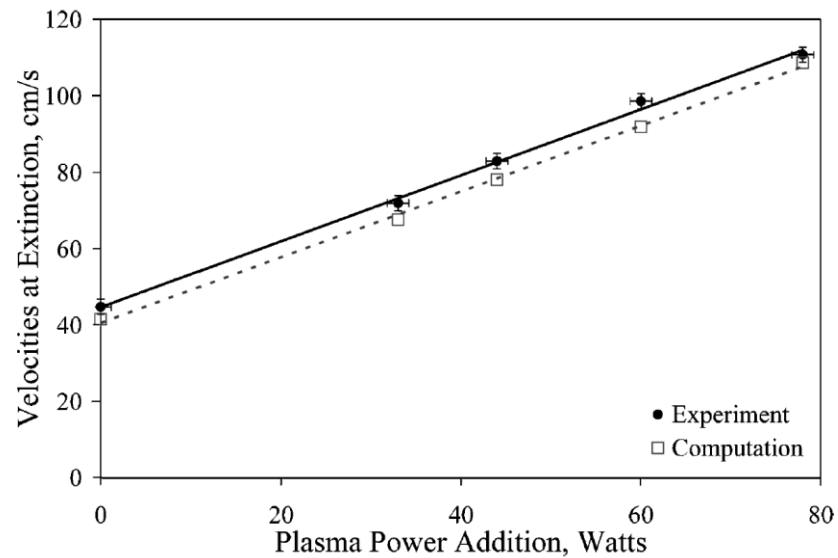
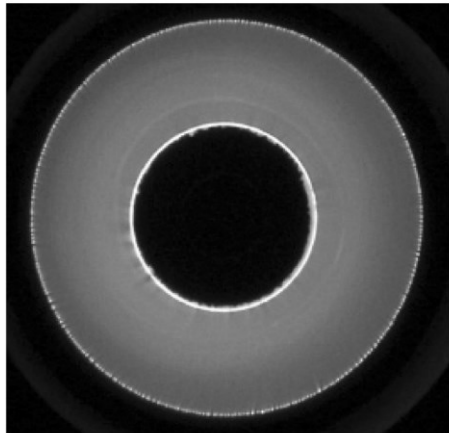
S.B. Leonov, D.A. Yarantsev, A.P. Napartovich, I.V. Kochetov, Plasma-assisted combustion of gaseous fuel in supersonic duct, IEEE Transactions on Plasma Science 34(6), pp 2514-2525, 2006

21st Century: Science and Opportunities



2006 First paper on plasma-assisted combustion by piecewise gliding arc, from Princeton, USA

- Homogeneous plasma in a counterflow burner
- Chemical analysis of the plasma effect



Yiguang Ju
Professor



Tim Ombrello
Researcher

T. Ombrello, X. Qin, Y.G. Ju, A. Gustol, A. Fridman, C. Carter, Combustion Enhancement via Stabilized Piecewise Nonequilibrium Gliding Arc Plasma Discharge, AIAA Journal 44(1), pp 142-150, 2006



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- Ignition systems, Wikipedia:
https://en.wikipedia.org/wiki/Ignition_system#Electronic_systems

Chapter III: Basics of Combustion



- *The Combustion Phenomena*
- *Premixed & Nonpremixed Flames*
- *Turbulent Combustion*
- *Combustion Chemistry*
- *References*



The combustion phenomena



A possible definition of combustion: rapid chemical combination of a substance with oxygen, involving the production of heat and light



Examples:



The combustion phenomena



Scientific disciplines comprising combustion:

1. Thermodynamics:

- How much chemical energy is converted into thermal energy?

2. Chemical Kinetics:

- How long does it take for this chemical reaction to occur?
- How many species are involved? How many reactions?

3. Fluid mechanics:

- How is the flow downstream the reaction front?
- How does the flow affect the chemical reactions?

4. Transport phenomena

- How does the transfer of mass and energy happen across temperature gradients?

The combustion phenomena



Classifications of fundamental combustion phenomena:

- **Premixed vs Nonpremixed Combustion**

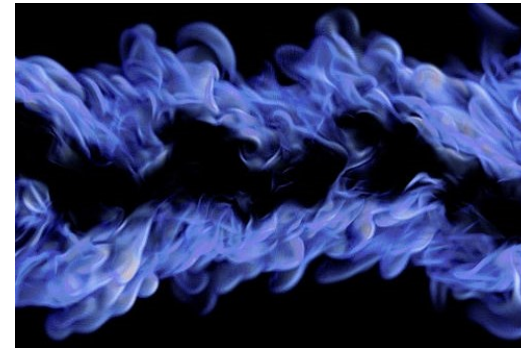


The combustion phenomena



Classifications of fundamental combustion phenomena:

- **Laminar vs Turbulent Combustion**

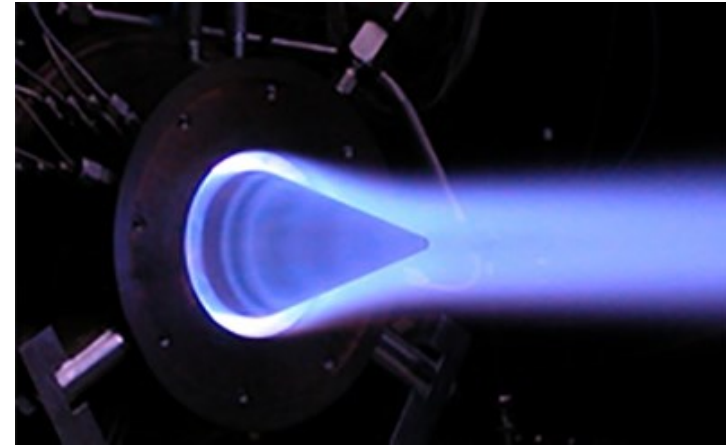


The combustion phenomena



Classifications of fundamental combustion phenomena:

- **Subsonic vs Supersonic Combustion**



The combustion phenomena



Classifications of fundamental combustion phenomena:

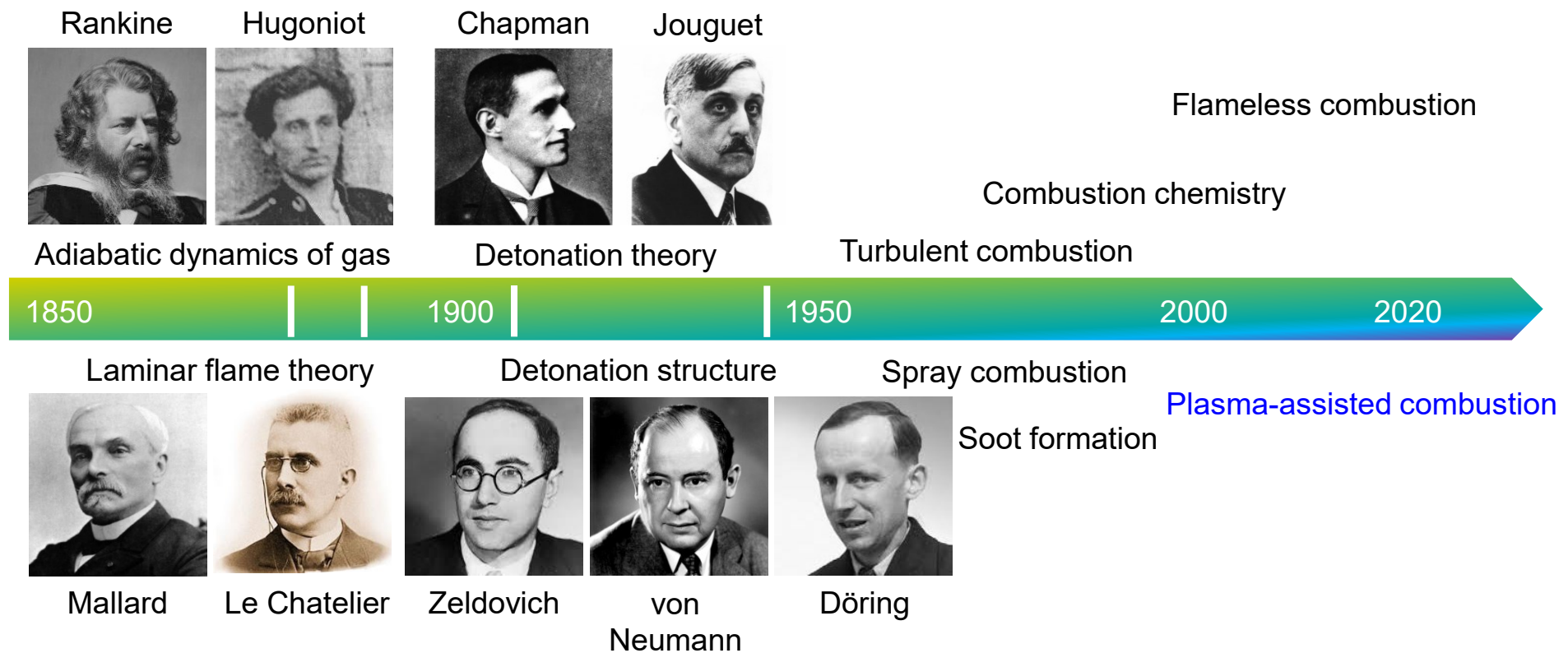
- **Homogeneous vs Heterogeneous Combustion**



The combustion phenomena



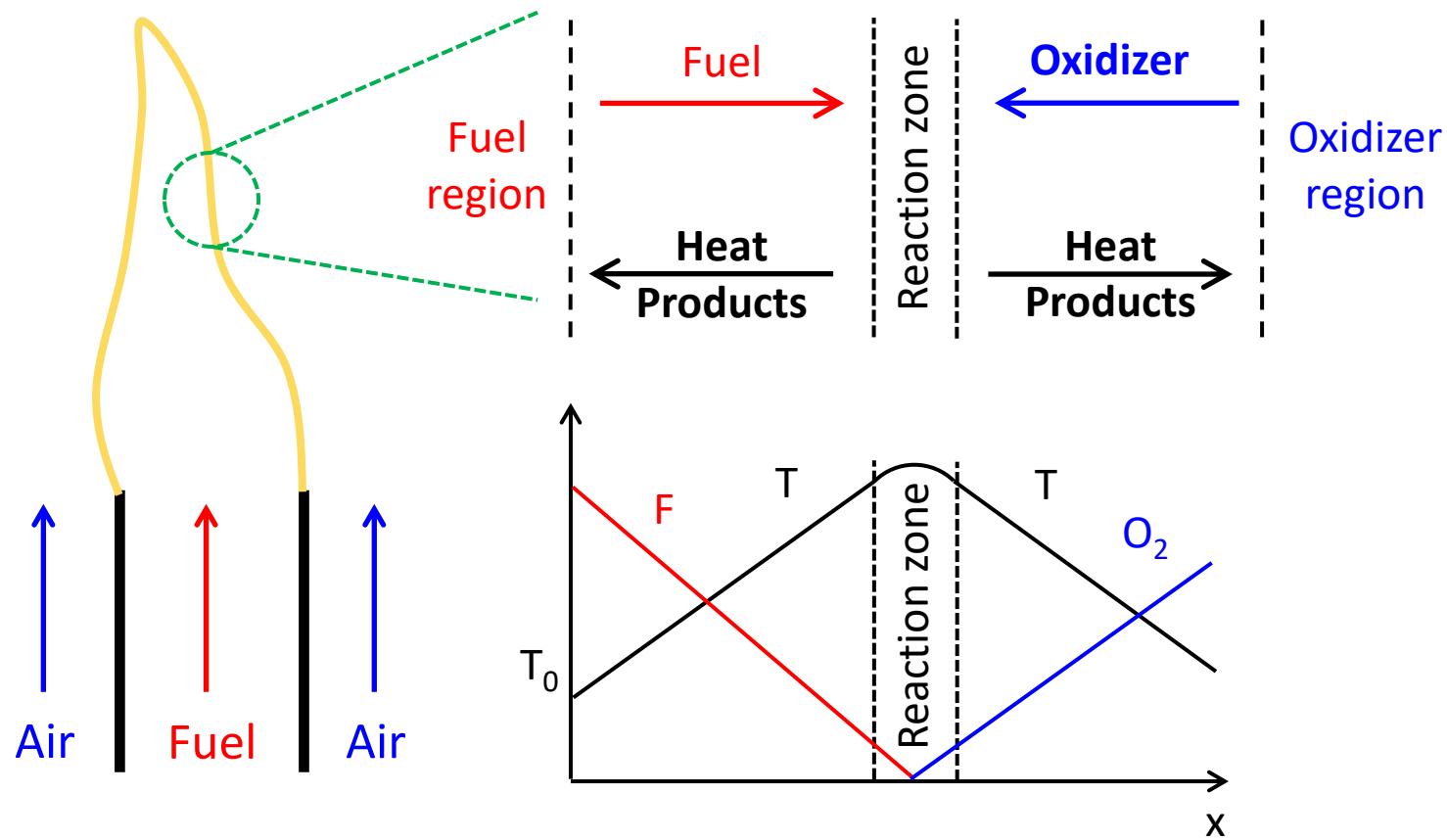
A brief history of combustion science



The combustion phenomena



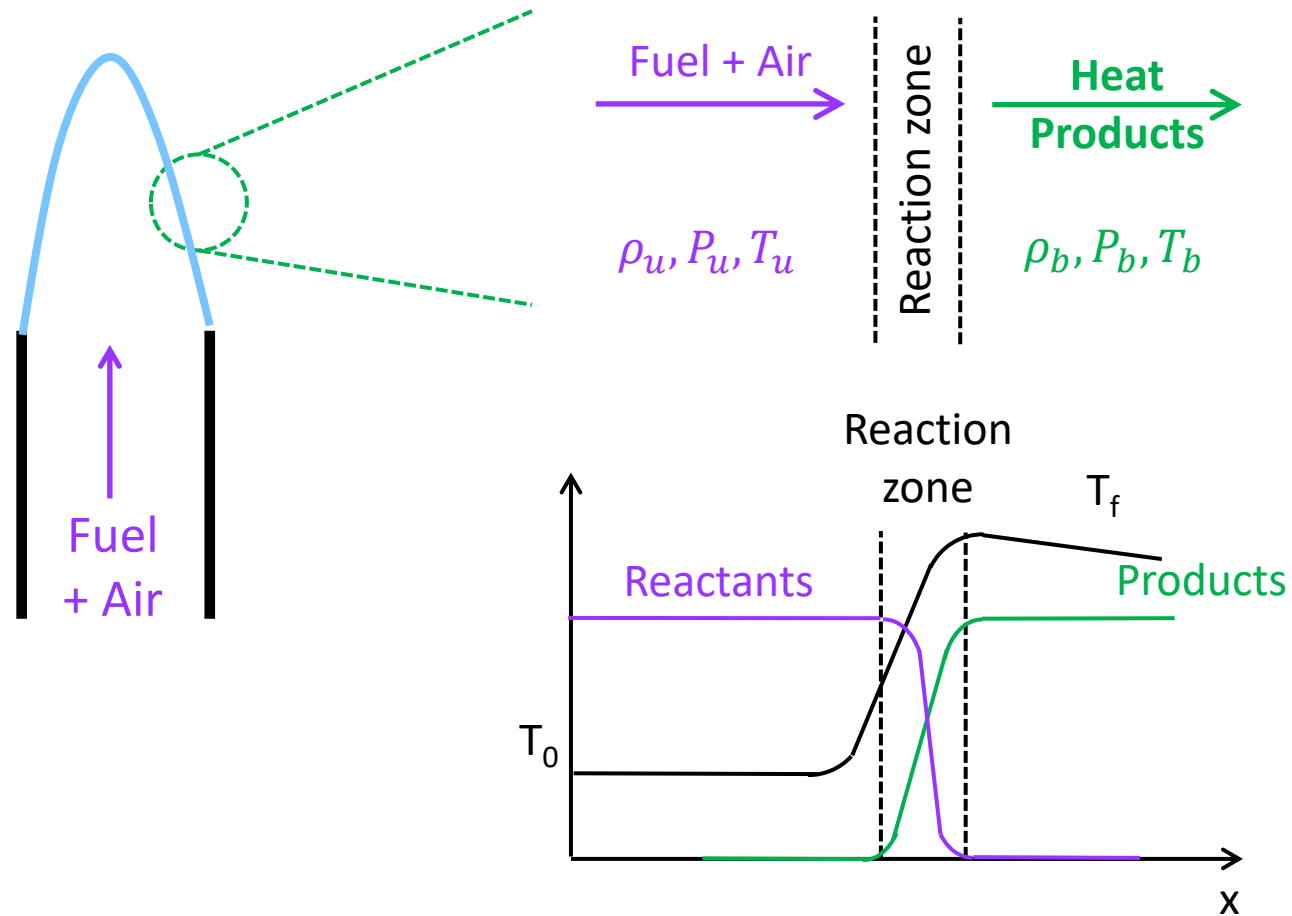
Structure of nonpremixed flames



The combustion phenomena



Structure of premixed flames



The combustion phenomena



Governing equations

- Continuity equation (conservation of total mass):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

ρ : density

\mathbf{v} : mass-averaged velocity of the gas mixture

t : time

The combustion phenomena



Governing equations

- Momentum:

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla \cdot \rho \mathbf{v} \mathbf{v} = -\nabla \cdot \mathbf{P} + \rho \sum_{i=1}^N Y_i \mathbf{f}_i, \quad i = 1, \dots, N$$

ρ : density

\mathbf{v} : mass-averaged velocity of the gas mixture

t : time

Y_i : mass fraction of species i

\mathbf{P} : pressure tensor

\mathbf{f}_i : external body force per unit mass of species i

The combustion phenomena



Governing equations

- Energy:

$$\frac{\partial(\rho e)}{\partial t} + \nabla \cdot \rho \mathbf{v} e = -\nabla \cdot \mathbf{q} - \mathbf{P} : \nabla \mathbf{v} + \rho \sum_{i=1}^N Y_i \mathbf{f}_i \cdot \mathbf{V}_i, \quad i = 1, \dots, N$$

ρ : density

\mathbf{v} : mass-averaged velocity of the gas mixture

t : time

Y_i : mass fraction of species i

\mathbf{P} : pressure tensor

\mathbf{f}_i : external body force per unit mass of species i

e : specific internal energy of the gas mixture

\mathbf{q} : heat flux vector

The combustion phenomena



Governing equations

- Continuity of species (for N species):

$$\rho \frac{\partial(\rho Y_i)}{\partial t} + \nabla \cdot (\rho Y_i(\mathbf{v} + \mathbf{V}_i)) = w_i, \quad i = 1, \dots, N$$

ρ : density

\mathbf{v} : mass-averaged velocity of the gas mixture

t : time

Y_i : mass fraction of species i

\mathbf{V}_i : Diffusion velocity of species i

w_i : mass production rate of species i (mass per unit volume per unit time)

Chapter III: Basics of Combustion



- *The Combustion Phenomena*
- ***Premixed & Nonpremixed Flames***
- *Turbulent combustion*
- *Combustion chemistry*
- *References*

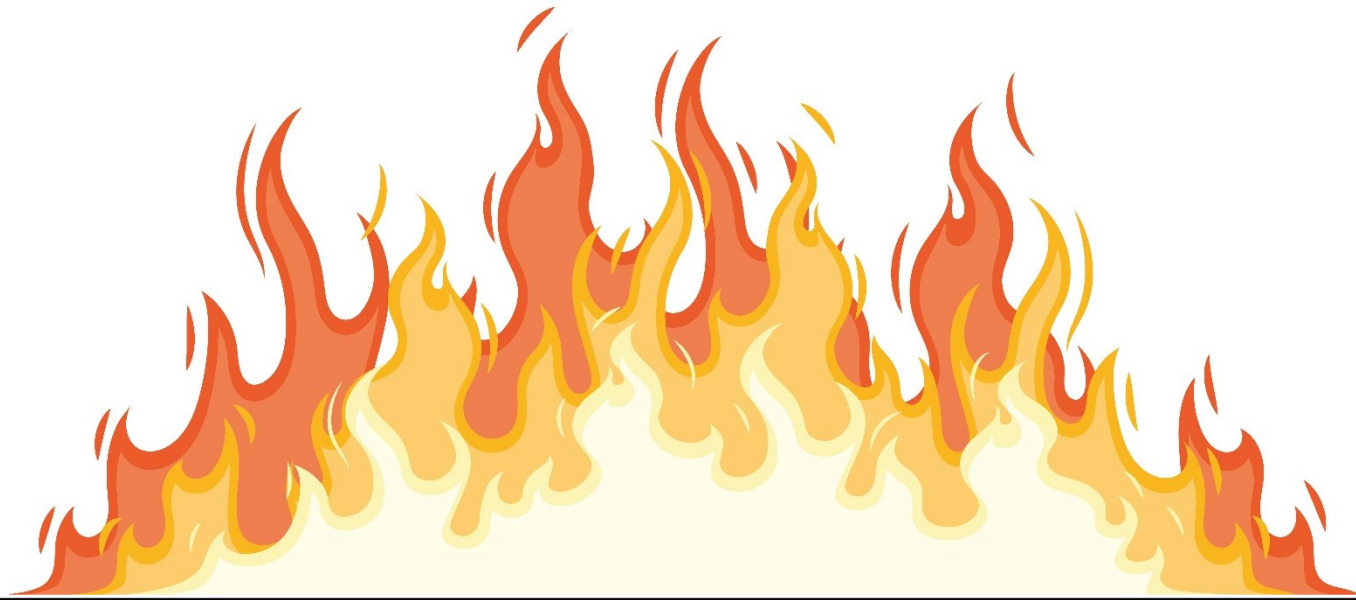


Premixed & Nonpremixed Flames



Quantities of interest to characterize the flames:

- Heat release rate
- Flame temperature
- Burning speed
- Light emission



Premixed & Nonpremixed Flames



Heat release rate:

It can be estimated using the **heating value** of the fuel, assuming an efficiency of combustion of 100% (typically not far from reality)

Lower heating value (also called calorific value): it is the amount of heat released by combusting a specified quantity of fuel initially at 25°C, and returning the temperature of the combustion products to 150°C

- The latent heat of vaporization of water in the product is **not recovered**
- Considered for applications such as piston engines

Premixed & Nonpremixed Flames



Higher heating value (also called gross calorific value): it is the amount of heat released by a specified quantity of fuel initially at 25°C once it is combusted and the products have returned to a temperature of 25°C

- The latent heat of vaporization of water in the product is **recovered**
- Considered for applications such as boilers and gas turbines

For example:

- $LHV_{H_2} = 120 \text{ MJ/kg}$
- $LHV_{\text{Natural Gas}} = 47 \text{ MJ/kg}$
- $HHV_{H_2} = 142 \text{ MJ/kg}$
- $HHV_{\text{Natural Gas}} = 52 \text{ MJ/kg}$

<https://h2tools.org/hyarc/calculator-tools/lower-and-higher-heating-values-fuels>

Premixed & Nonpremixed Flames



Adiabatic flame temperature:

It is the temperature reached by a flame under ideal conditions that can be calculated for a constant pressure or a constant volume combustion process

It is an upper limit of the temperature that is reached in actual combustion processes

Typical assumptions:

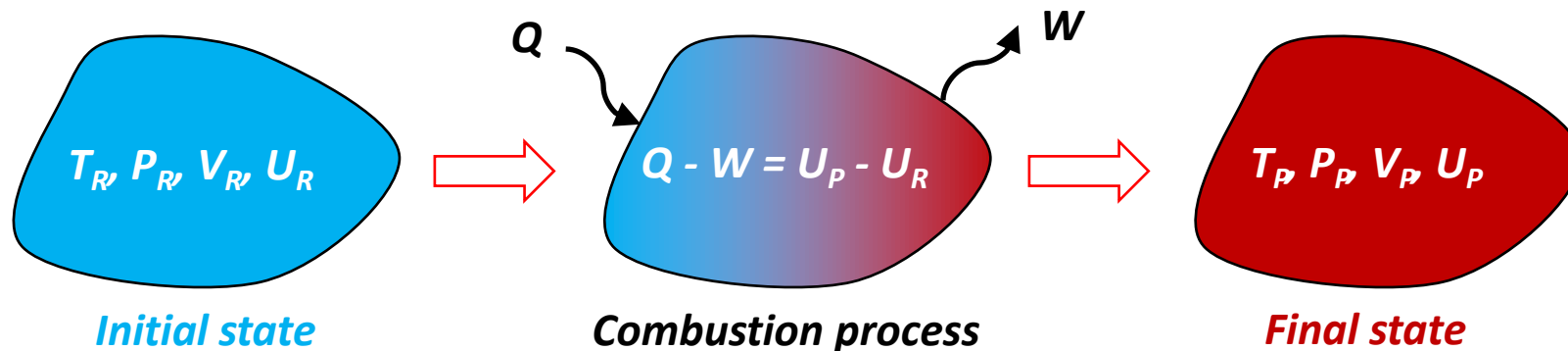
- Equal density-weighted diffusivities
- Unity Lewis number ($Le = \text{thermal diffusivity} / \text{mass diffusivity}$)
- No heat loss (adiabatic)

Premixed & Nonpremixed Flames



Adiabatic flame temperature

- **Premixed flame:** first law of thermodynamics for a closed reacting system



$$Q - W = U_P - U_R$$

Constant volume: $W = 0$, then $U_P = U_R$, and because $m_P = m_R$ (continuity), $u_P = u_R$

Constant pressure: $W = \int_R^P P dV = P(V_P - V_R)$,

then the first law becomes $-P(V_P - V_R) = U_P - U_R$

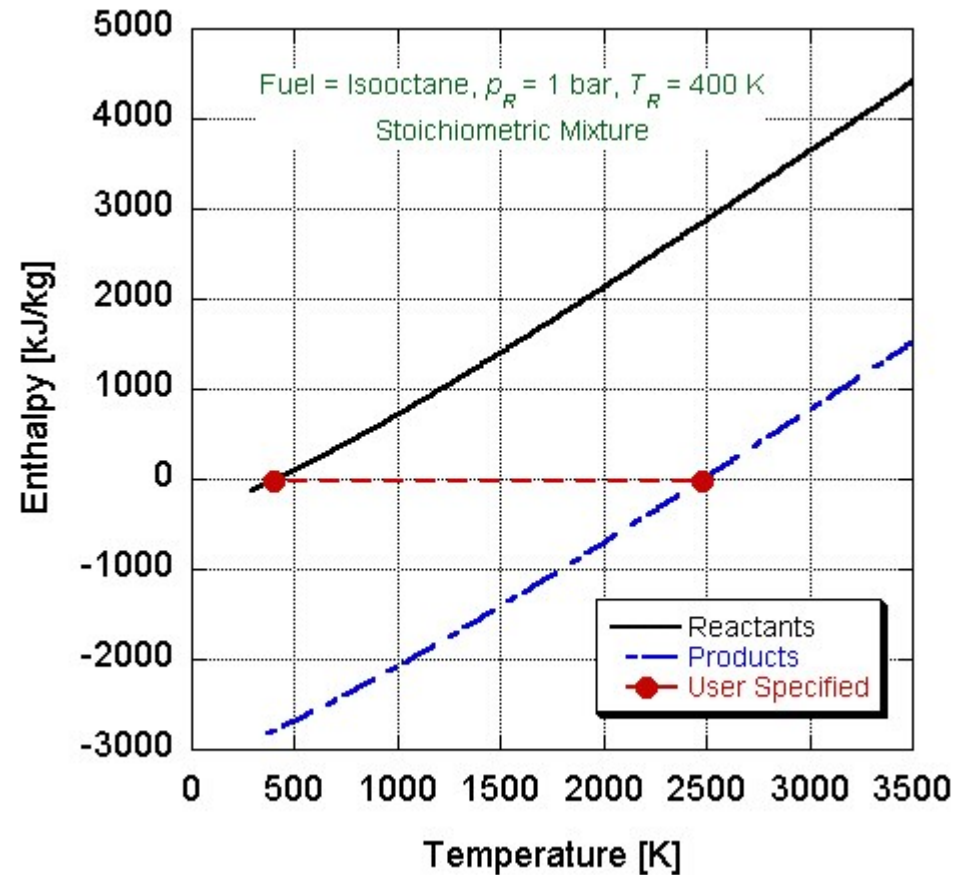
which gives $U_P + PV_P = U_R + PV_R$, then $H_P = H_R$ and (continuity), $h_P = h_R$

Premixed & Nonpremixed Flames



Adiabatic flame temperature

For example, at constant pressure:



For example, stoichiometric combustion of CH_4 -Air at $P = 1$ bar, $T_R = 300$ K:

➤ $T_{ad} = 2222$ K

Premixed & Nonpremixed Flames



Adiabatic flame temperature

- **Nonpremixed flame:** first law of thermodynamics for an open reacting system

At constant pressure:

$$Y_{F,c} q_c = \left(h_f^s - h_{F,c}^s \right) + \left(\frac{Y_{F,c}}{Y_{O,c}} \sigma_O \right) \left(h_f^s - h_{O,c}^s \right)$$

$Y_{F,c}$: mass fraction of fuel at the boundary of the system (cold)

$Y_{O,c}$: mass fraction of oxidizer at the boundary of the system (cold)

q_c : heat of reaction per unit mass of fuel

h_f^s : specific sensible enthalpy at the flame, relative to cold temperature

$h_{F,c}^s$: specific sensible enthalpy of the fuel at the boundary of the system (cold)

$h_{O,c}^s$: specific sensible enthalpy of the oxidizer at the boundary of the system (cold)

σ_O : stoichiometric mass ratio of oxidizer to fuel

Premixed & Nonpremixed Flames



Burning speed of nonpremixed flames: configuration dependent

Burning speed will be a function of the transport of reactants

Classical configurations:

- The Burke Schumann flame
- Pool fire
- Combustion of a fuel droplet
- The counter flow flame

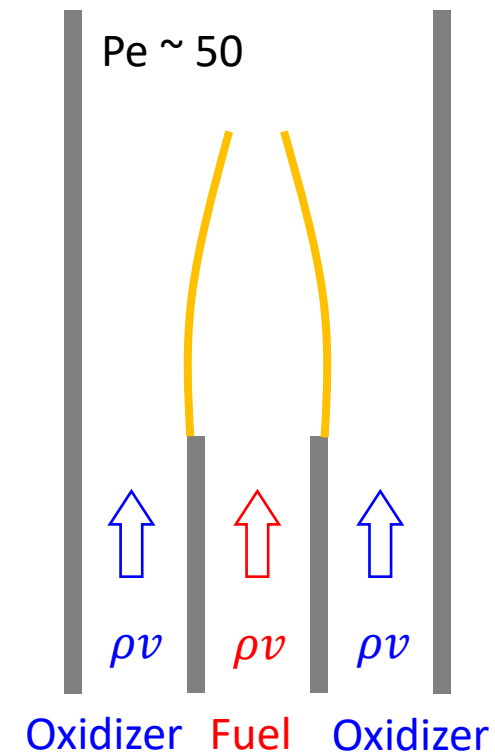
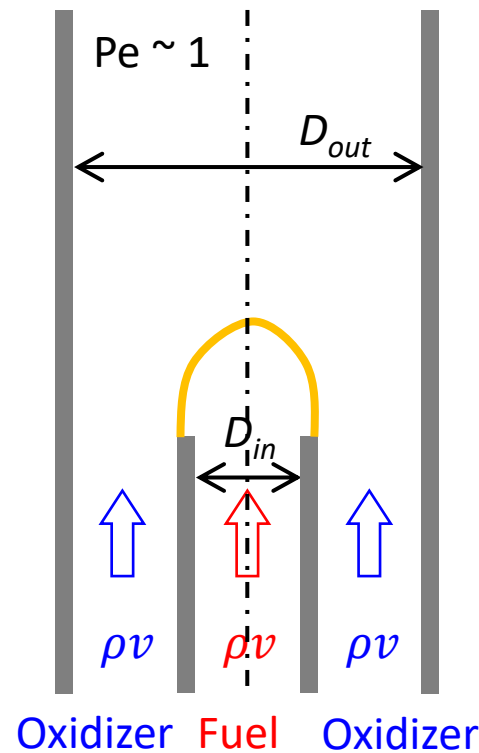




Premixed & Nonpremixed Flames

The Burke Schumann flame (1928)

- Peclet number (convective transport/diffusive transport): $Pe = \frac{\rho v c_p D_{out}}{\lambda}$
- Overventilated flames: rate of oxidizer supply stoichiometrically $>$ rate of fuel supply

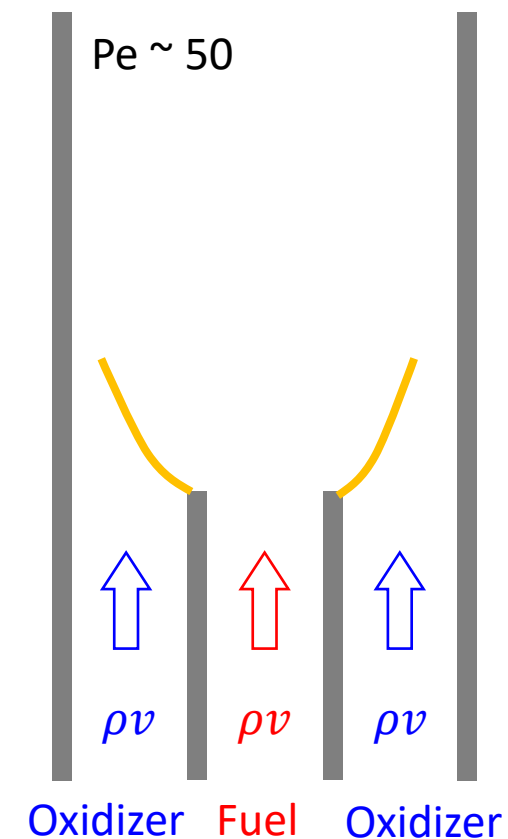
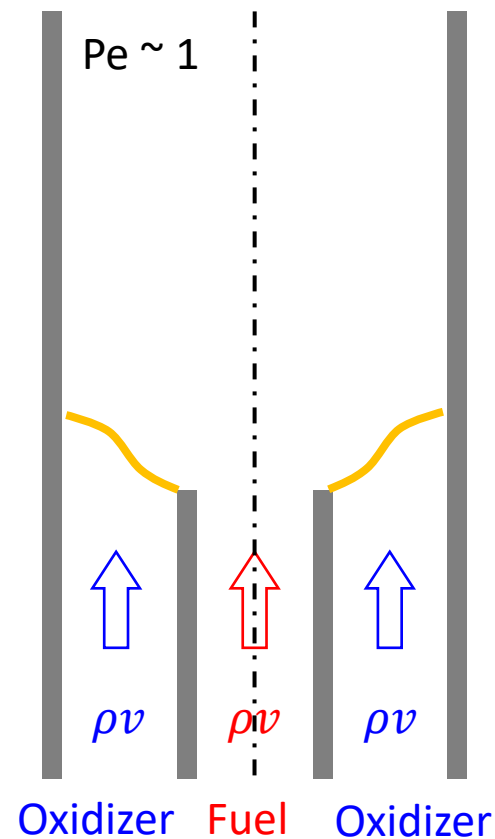


Premixed & Nonpremixed Flames



The Burke Schumann flame (1928)

- Underventilated flames: rate of oxidizer supply stoichiometrically $<$ rate of fuel supply

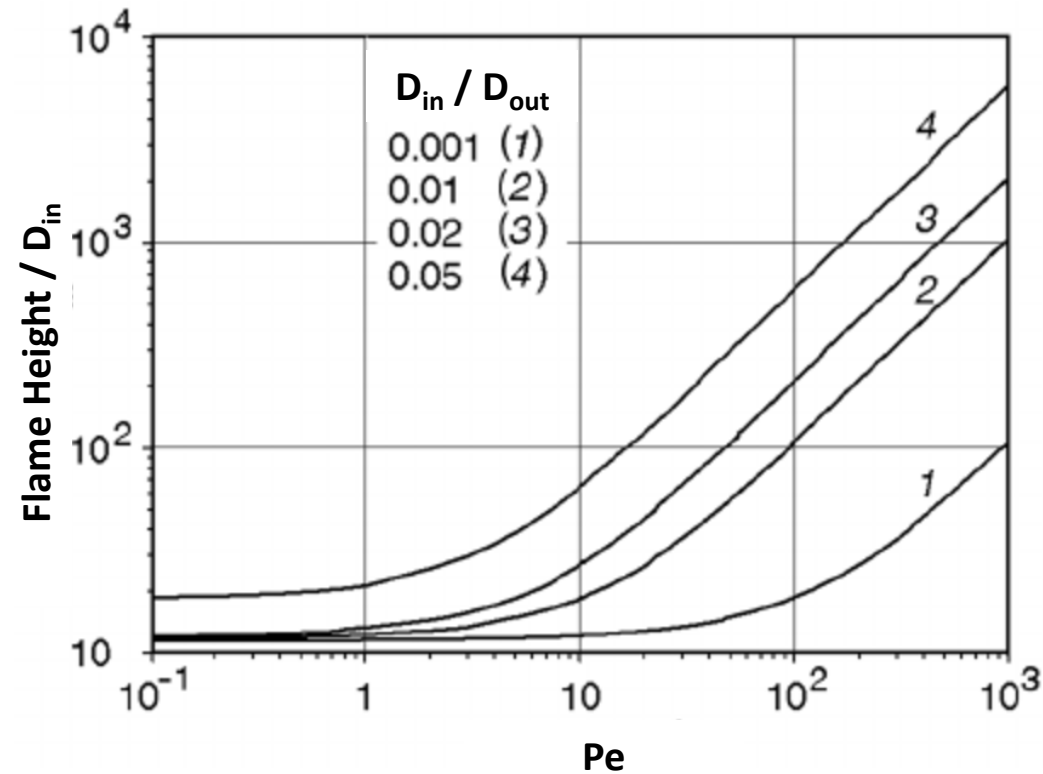


Premixed & Nonpremixed Flames



The Burke Schumann flame (1928)

- Flame height as a function of the Peclet number

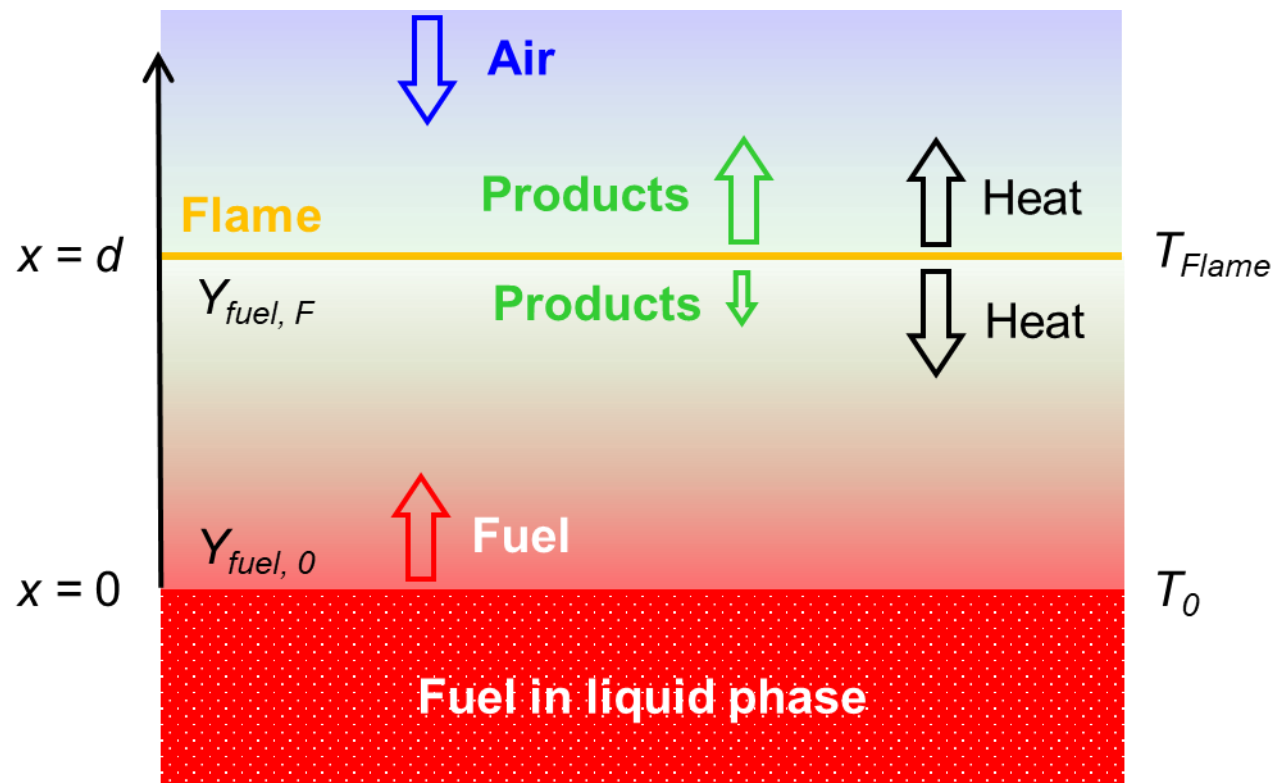


Premixed & Nonpremixed Flames



Pool fire

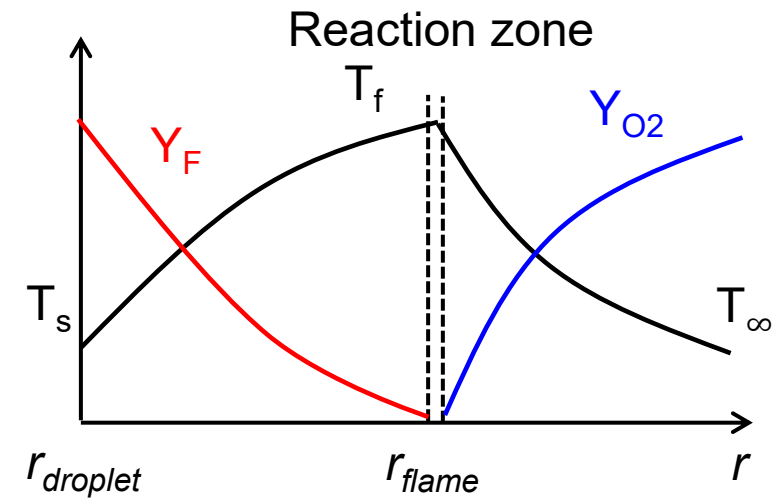
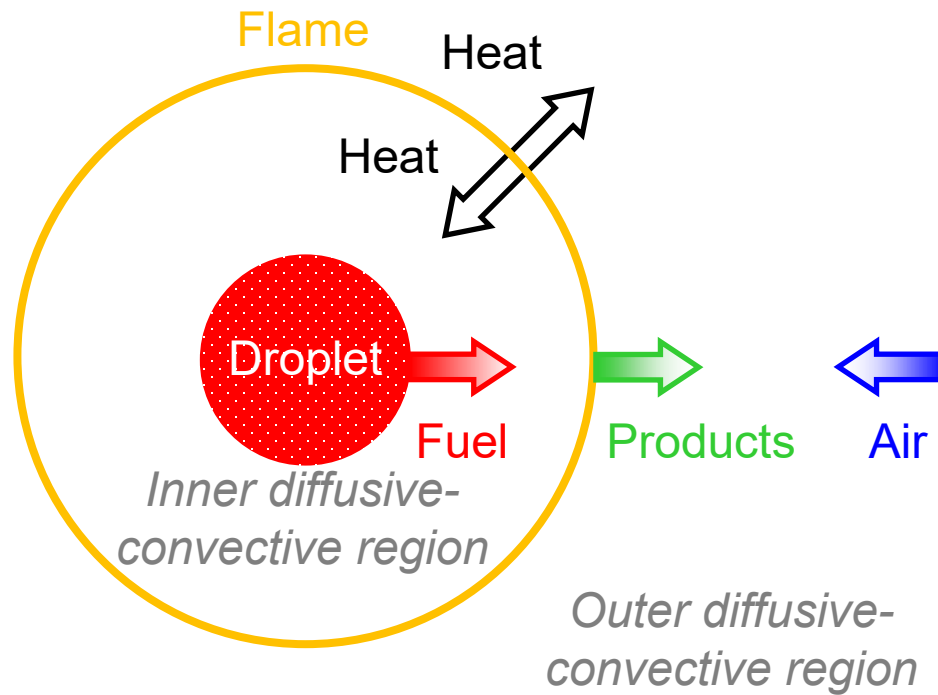
- Condensed fuel vaporization and the Stefan flow (diffusion of the fuel vapor → convection)



Premixed & Nonpremixed Flames



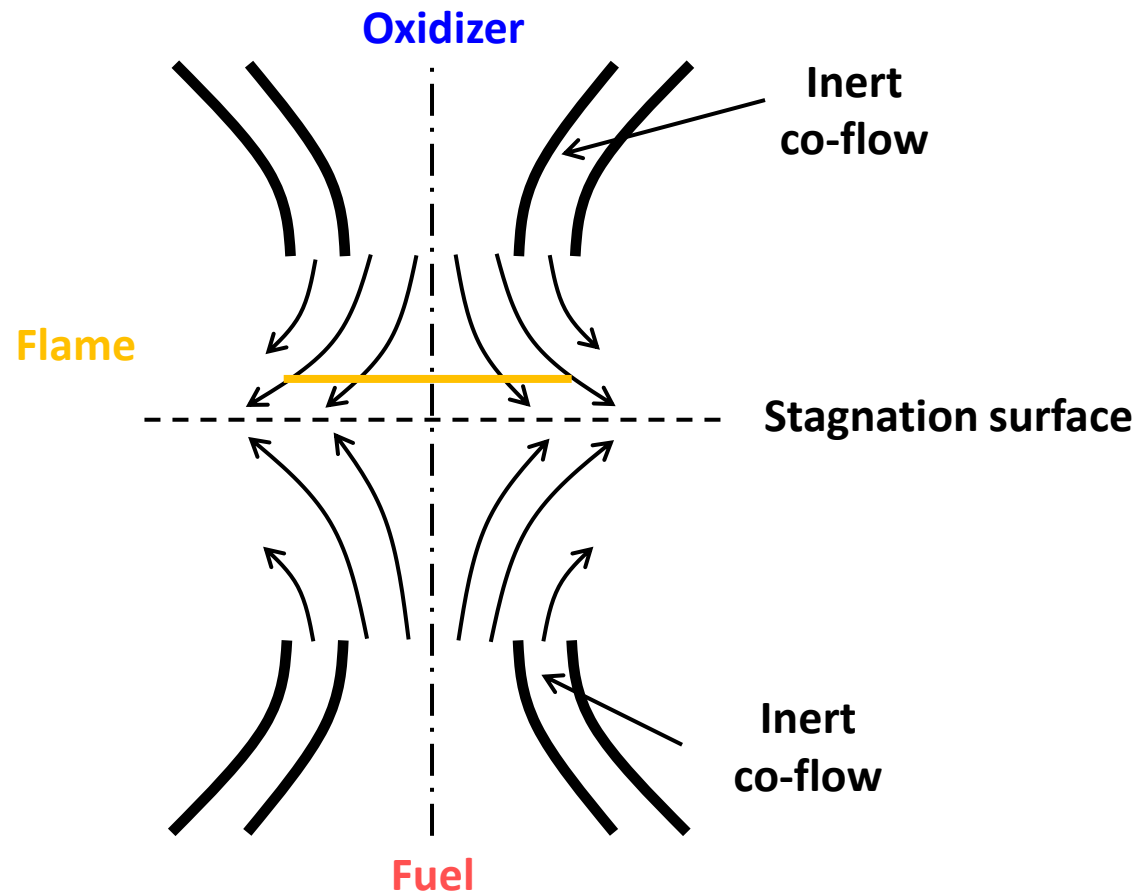
Combustion of a fuel droplet



Premixed & Nonpremixed Flames



The counter-flow flame



Premixed & Nonpremixed Flames



Burning speed of premixed flames: the laminar burning velocity

The **laminar burning velocity**, also called laminar flame speed, S_L , is the speed at which an unstretched one-dimensional laminar flame will propagate through a quiescent mixture of unburned reactants

It is an intrinsic characteristic of the premixed combustible mixture:

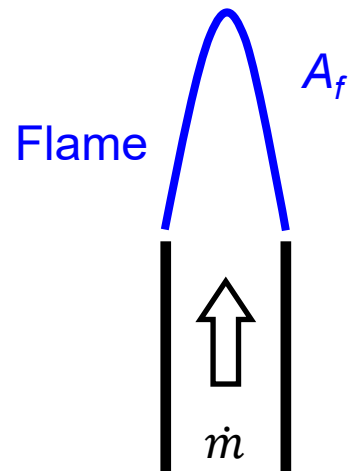
$$S_L = S_L(\text{Fuel, Oxidizer, Dilutant, T, P})$$

It can be determined from one-dimensional calculations, or experimentally



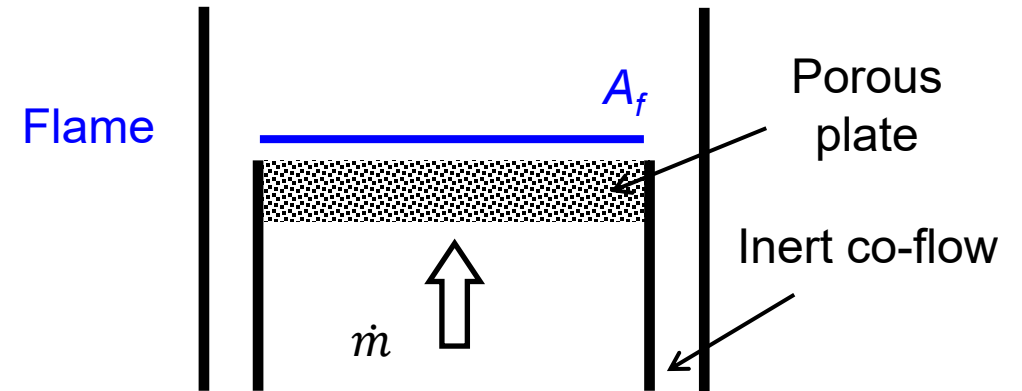
Premixed & Nonpremixed Flames

Experimental methods for determination of S_L



Bunsen flame

$$S_L = \frac{\dot{m}}{\rho_u A_f}$$



Flat flame stabilized over a porous plate

Problems:

- the flame is not flat
- Accurate measurement of flame surface

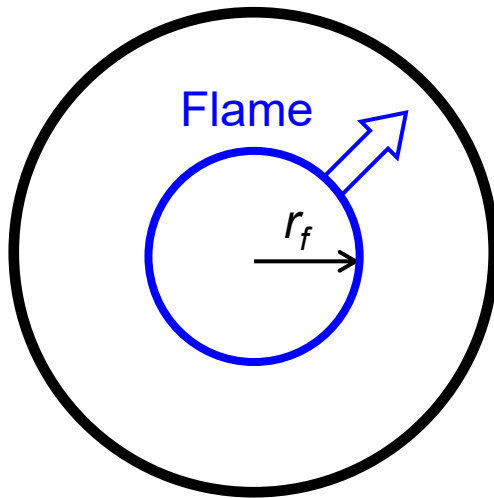
Problems:

- the flame is nonadiabatic

Premixed & Nonpremixed Flames



Experimental methods for determination of S_L

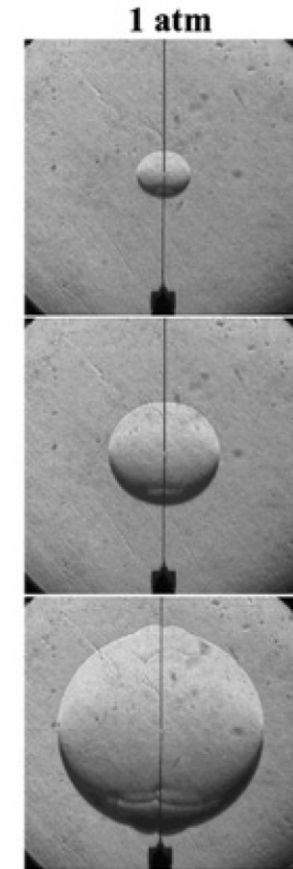


Outwardly propagating
spherical flame

$$S_L = \frac{dr_f}{dt} \times \frac{\rho_b}{\rho_u}$$

Problems:

- the flame is not flat
- pressure is increasing
- Heat loss

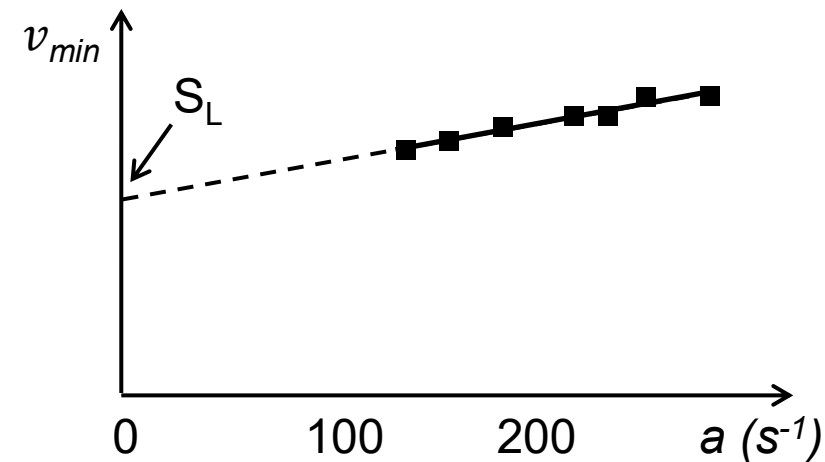
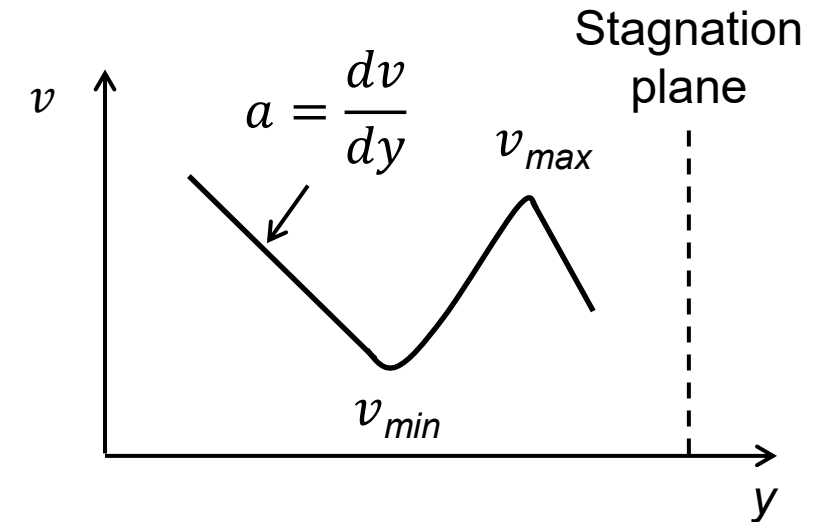
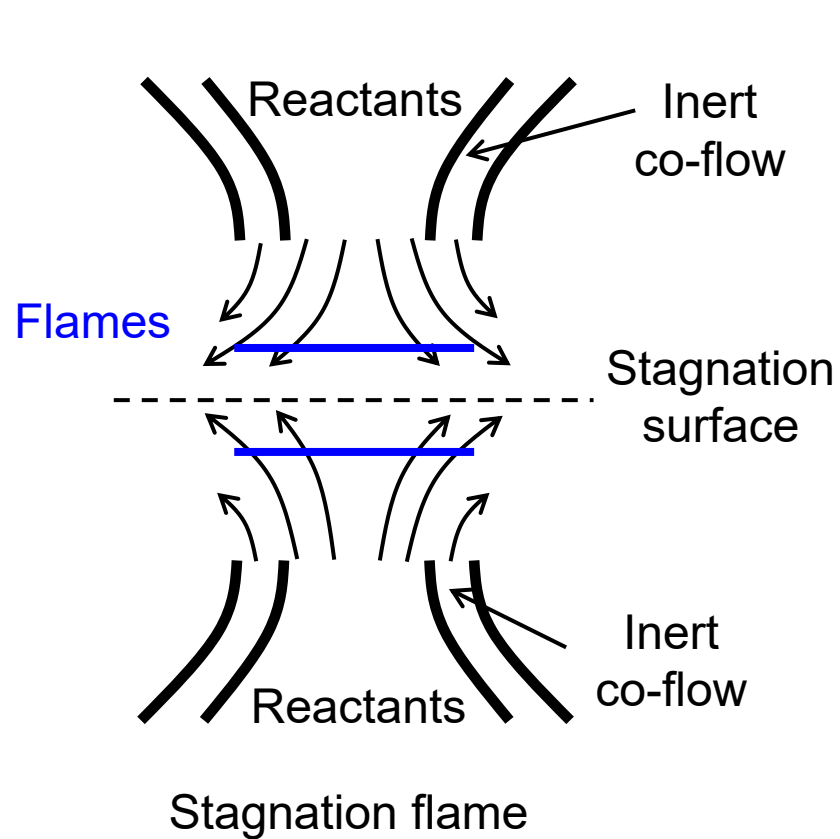


Law et al., PROCI, 2005

Premixed & Nonpremixed Flames



Experimental methods for determination of S_L



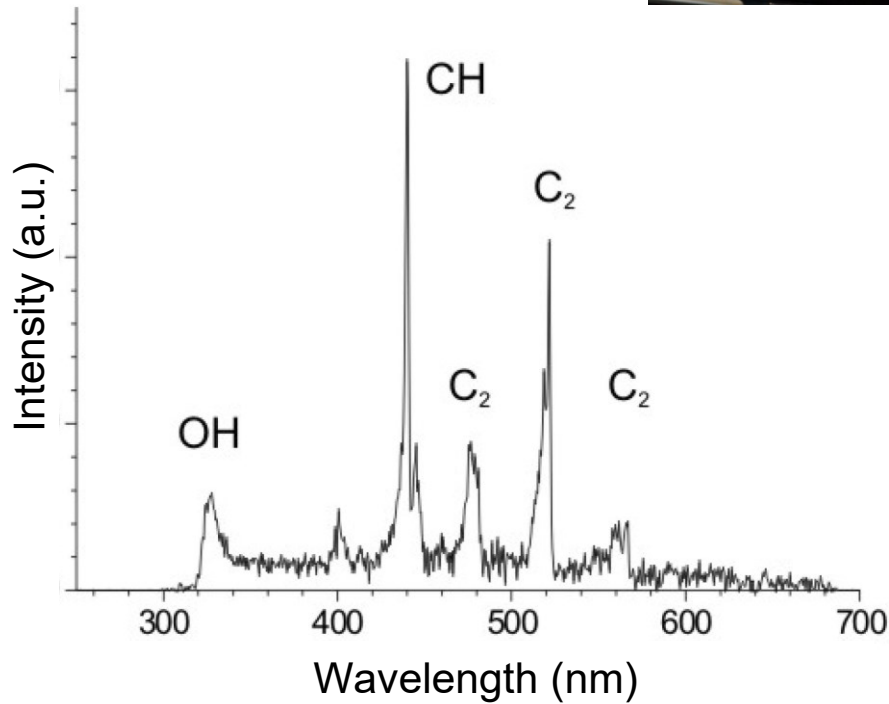
Problems:

- Stretched flames and linear extrapolation
- heat loss

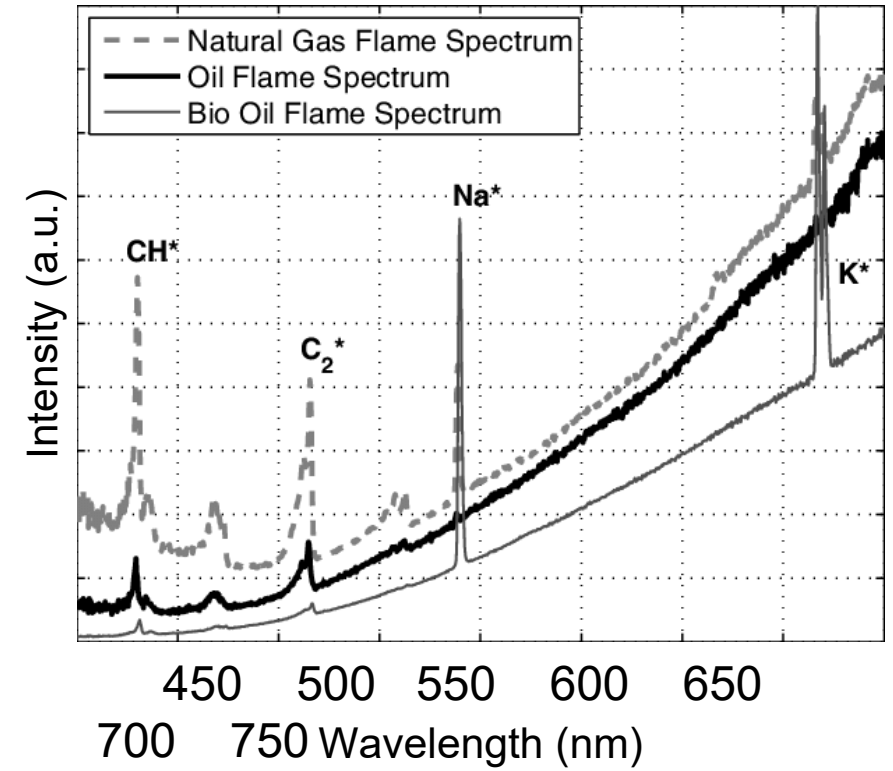
Premixed & Nonpremixed Flames



Light emission



Premixed hydrocarbon-air flame



Nonpremixed hydrocarbon-air flame

Chapter III: Basics of Combustion



- *The Combustion Phenomena*
- *Premixed & Nonpremixed Flames*
- ***Turbulent combustion***
- *Combustion chemistry*
- *References*

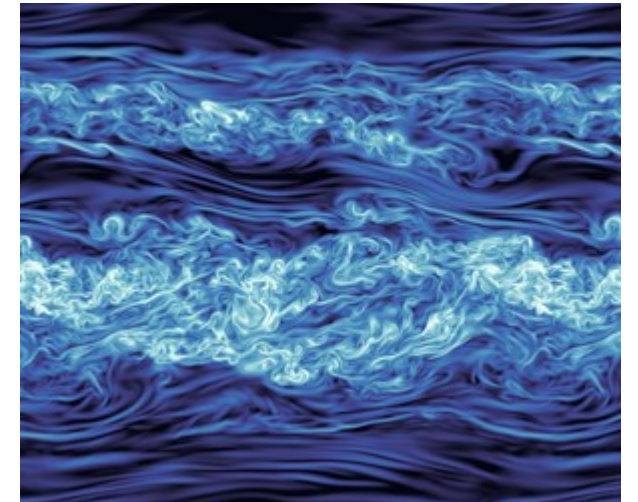


Turbulent Combustion



A turbulent flow is a fluid motion characterized by chaotic changes in pressure and flow velocity

Turbulent combustion is a turbulent reactive flow characterized by the presence of rapid, random fluctuations of the flow velocity and scalar properties at a given point in space



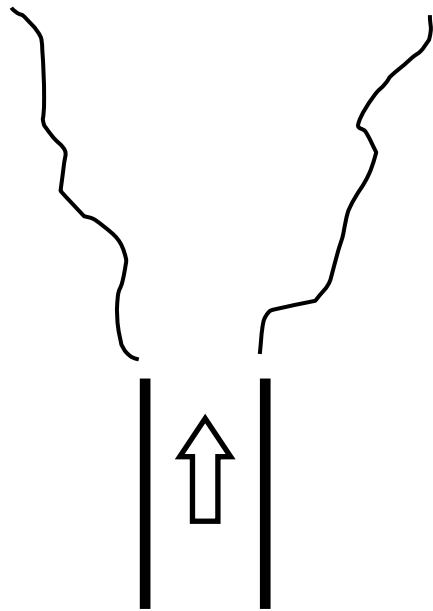
Howland et al., JFM, 2020

In industrial processes, the main objective of turbulent combustion is to **increase the burning speed and heat release rate**

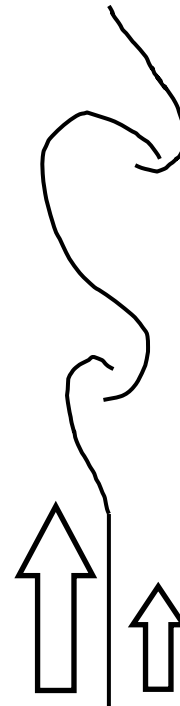
Turbulent Combustion



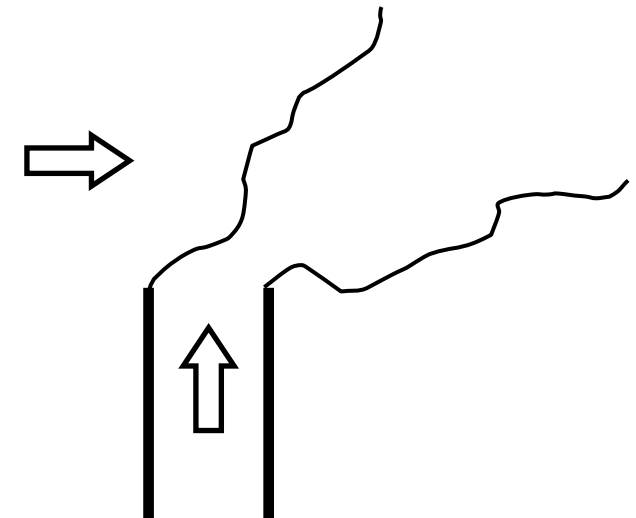
Origin and structure of turbulence: unconfined flows



Jet



Mixing layer

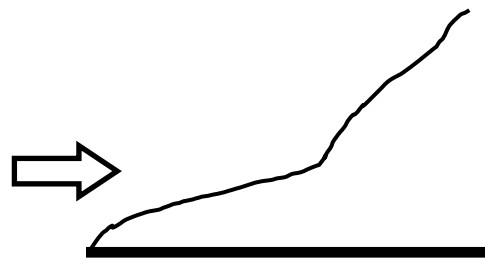


Jet in cross flow

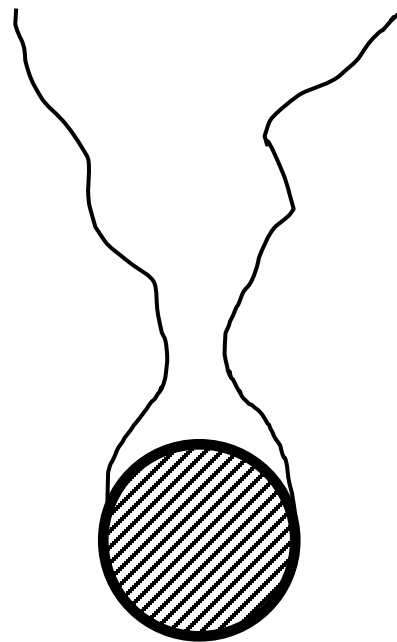
Turbulent Combustion



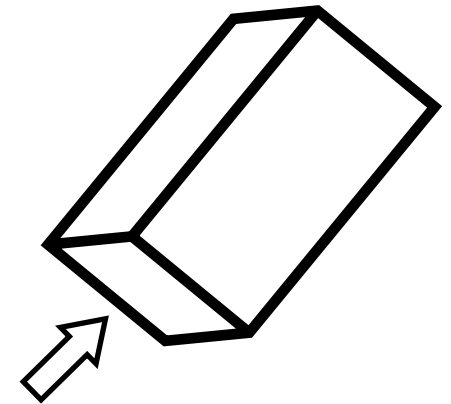
Origin and structure of turbulence: semiconfined and confined flows



Forced convection
boundary layer



Wake flow



Confined flow

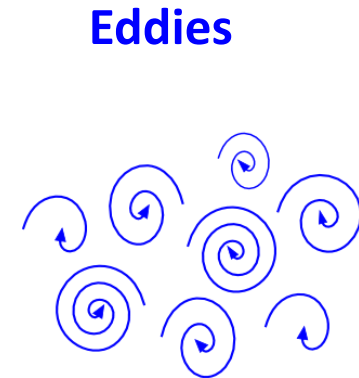
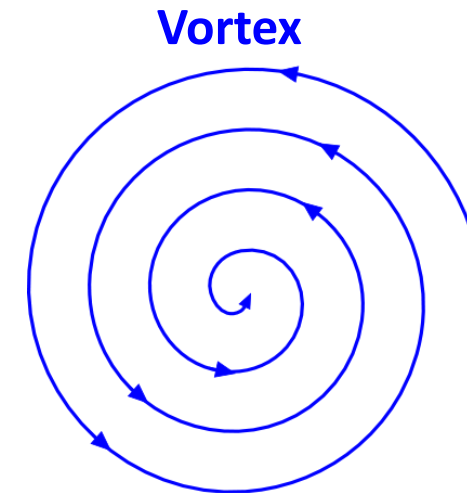
Turbulent Combustion



Turbulence scales:

A turbulent flow is often characterized by a spectrum of eddies

An eddy is a canonical structure represented by a vortical flow unit riding on the mean flow, for which the average rotational velocity and diameter characterize the relevant velocity and length scales



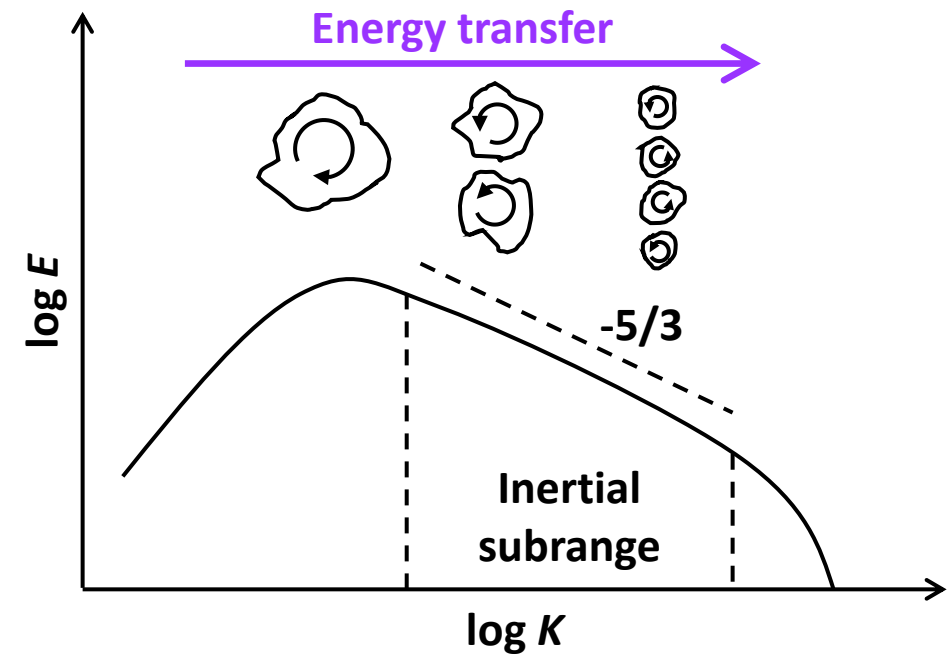
The magnitude of the vortical velocity of an eddy is a measure of the intensity of the turbulent fluctuation

The kinetic energy of eddies at one scale is transferred to another through various modes. This energy cascade concept was first introduced by **Kolmogorov**

Turbulent Combustion



Turbulence scales:



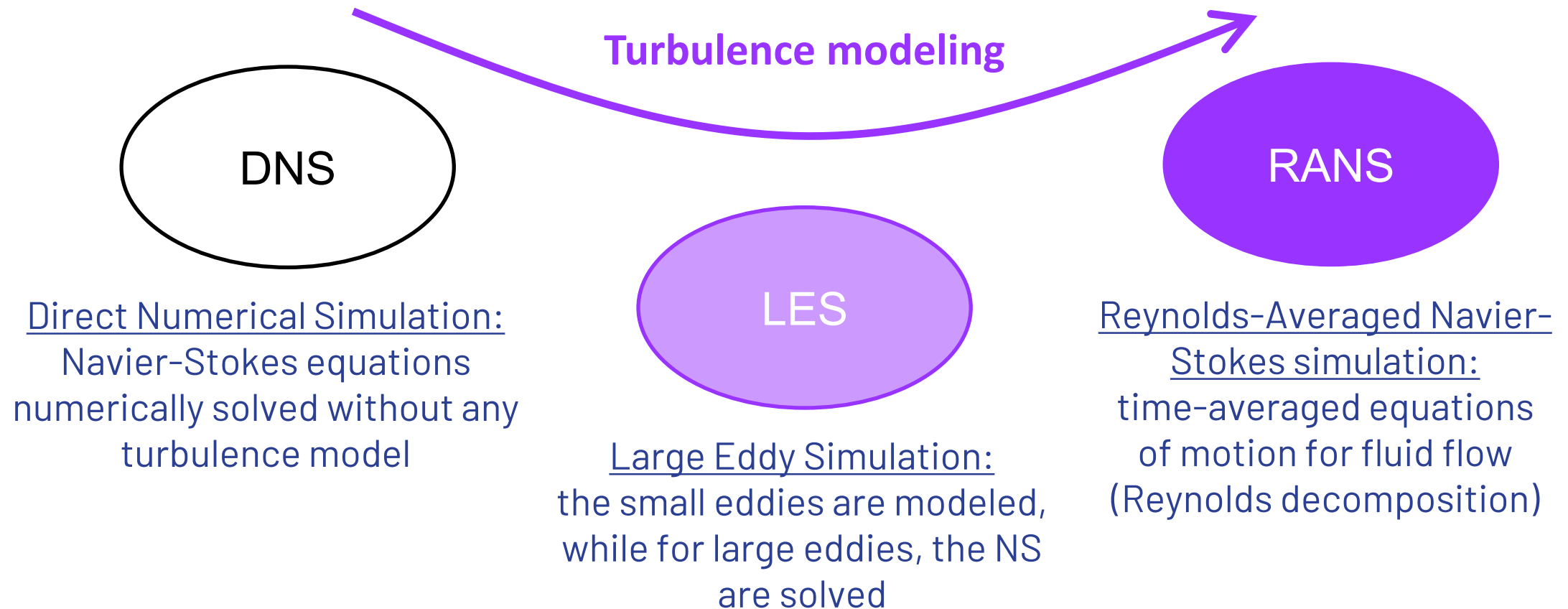
K : wavenumber

E : turbulent kinetic energy spectrum

Turbulent Combustion



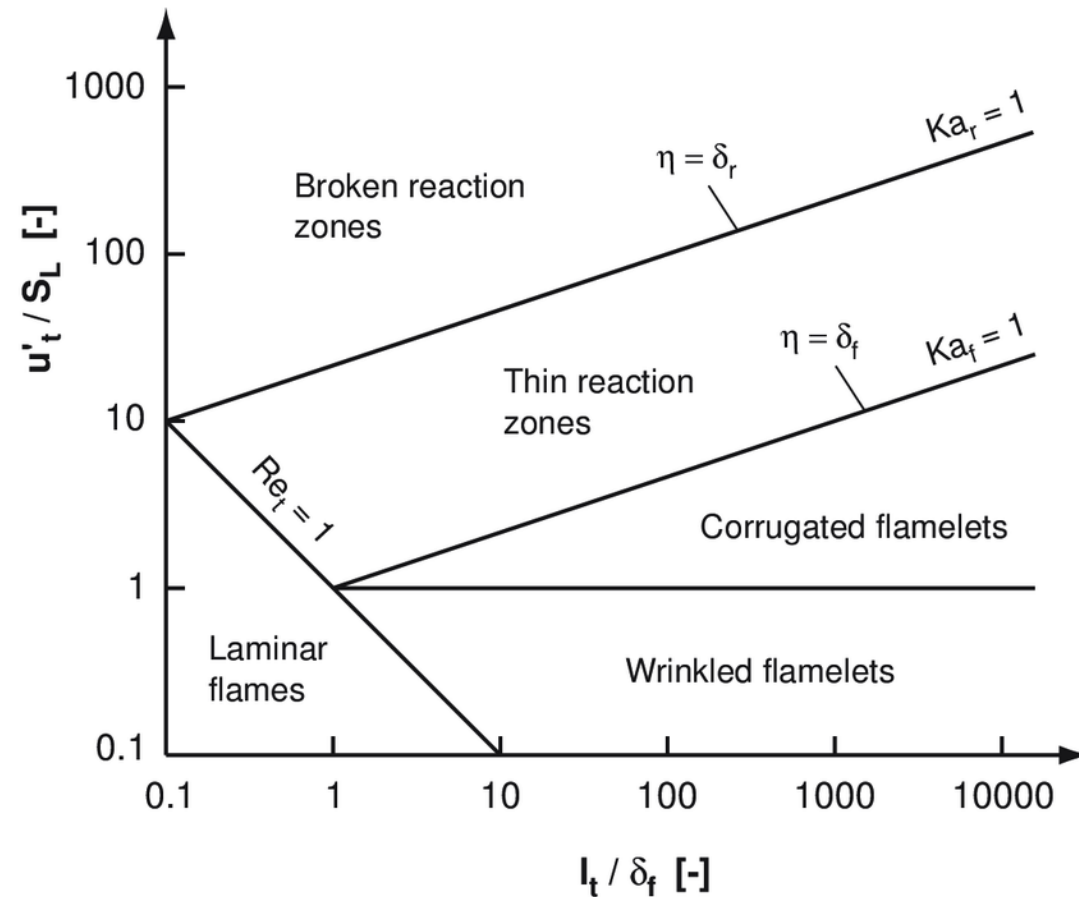
Simulations and modeling



Turbulent Combustion



Regimes of combustion modes: premixed flames



u'_t : turbulent velocity fluctuation

S_L : laminar flame speed

l_t : turbulent length scale

δ_f : flame thickness

$Re_t = \frac{u'_t l_t}{S_L \delta_f}$: turbulent Reynolds number

$Da = \frac{S_L l_t}{u'_t \delta_f}$: Damköhler number

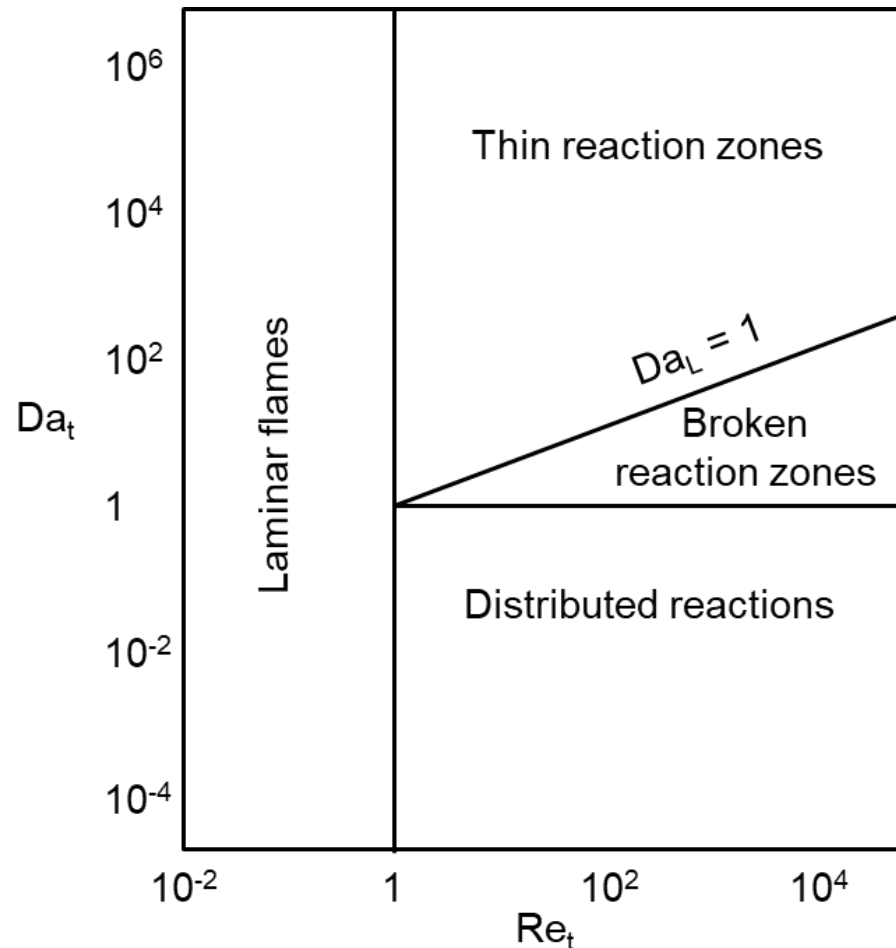
$Ka_f = \frac{\sqrt{Re}}{Da}$: Karlovitz number for the flame

$Ka_\delta = \frac{l_\delta^2}{\eta^2}$: 2nd Karlovitz number, with η the Kolmogorov scale, and l_δ the thickness of the inner layer of the flame

Turbulent Combustion



Regimes of combustion modes: nonpremixed flames



u'_t : turbulent velocity fluctuation

S_L : laminar flame speed

l_t : turbulent length scale

δ_f : flame thickness

$Re_t = \frac{u'_t l_t}{S_L \delta_f}$: turbulent Reynolds number

$Da_L = \frac{\tau_L}{\tau_c}$: flame Damköhler number

τ_L : flame time scale

τ_c : chemical reaction time scale

$Da_t = \sqrt{Re_t Da_L}$: Damköhler number

Chapter III: Basics of Combustion



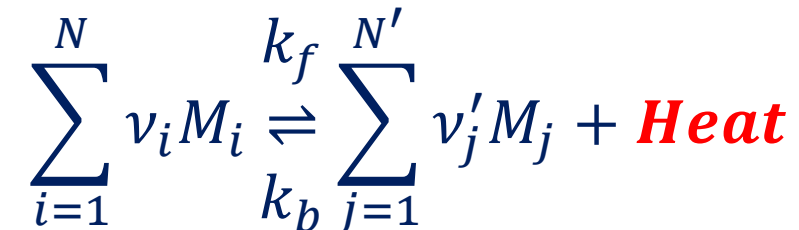
- *The Combustion Phenomena*
- *Premixed & Nonpremixed Flames*
- *Turbulent combustion*
- ***Combustion chemistry***
- *References*



Combustion Chemistry



An elementary direct reaction between species M_i and a reverse reaction between species M_j with stoichiometric coefficients ν_i and ν'_j can be written as:



Heat > 0 for exothermic reactions and **Heat** < 0 for endothermic reactions

Equilibrium is established for a given ratio of the concentrations of reactants $[M_i]$ and products $[M_j]$ defined by the equilibrium constant K

$$K = \left(\prod_{j=1}^{N'} M_j^{\nu'_j} \right) / \prod_{i=1}^N M_i^{\nu_i}$$

Combustion Chemistry



Elementary reactions occur in both directions (forward and backward)

The rates of the forward reaction, W_f , and backward reaction, W_b , are defined as

$$W_f = k_f \prod_{i=1}^N M_i^{\nu_i} \quad \text{and} \quad W_b = k_b \prod_{j=1}^{N'} M_j^{\nu'_j}$$

k_f and k_b are the rate constants of the forward and backward reaction, that depend on the temperature T as

$$k = \mathcal{A}T^{\mathcal{b}} \cdot \exp\left(-\frac{E_a}{RT}\right)$$

\mathcal{A} and \mathcal{b} : constants

R : universal gas constant

E_a : activation energy corresponding to an energy barrier to be overcome during the reaction

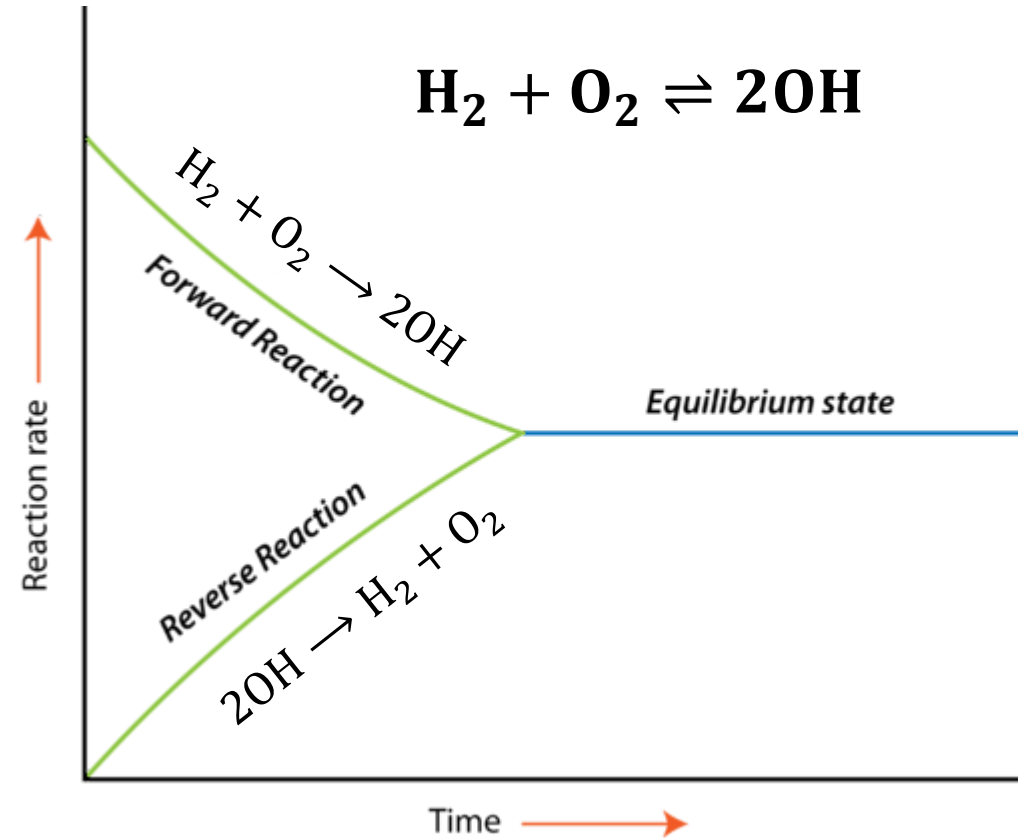
Combustion Chemistry



At equilibrium, the rates of the forward and the backward reactions are equal $W_f = W_b$

The equilibrium constant K is a function of the gas temperature and can be expressed as

$$K = k_f/k_b$$

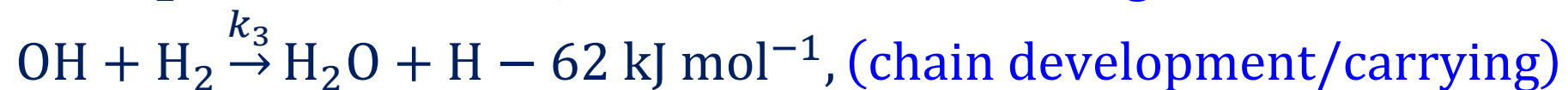


Combustion Chemistry



Branched-chain reactions: mechanism that model well combustion kinetics at relatively high temperatures and pressures

For example, combustion of hydrogen with oxygen



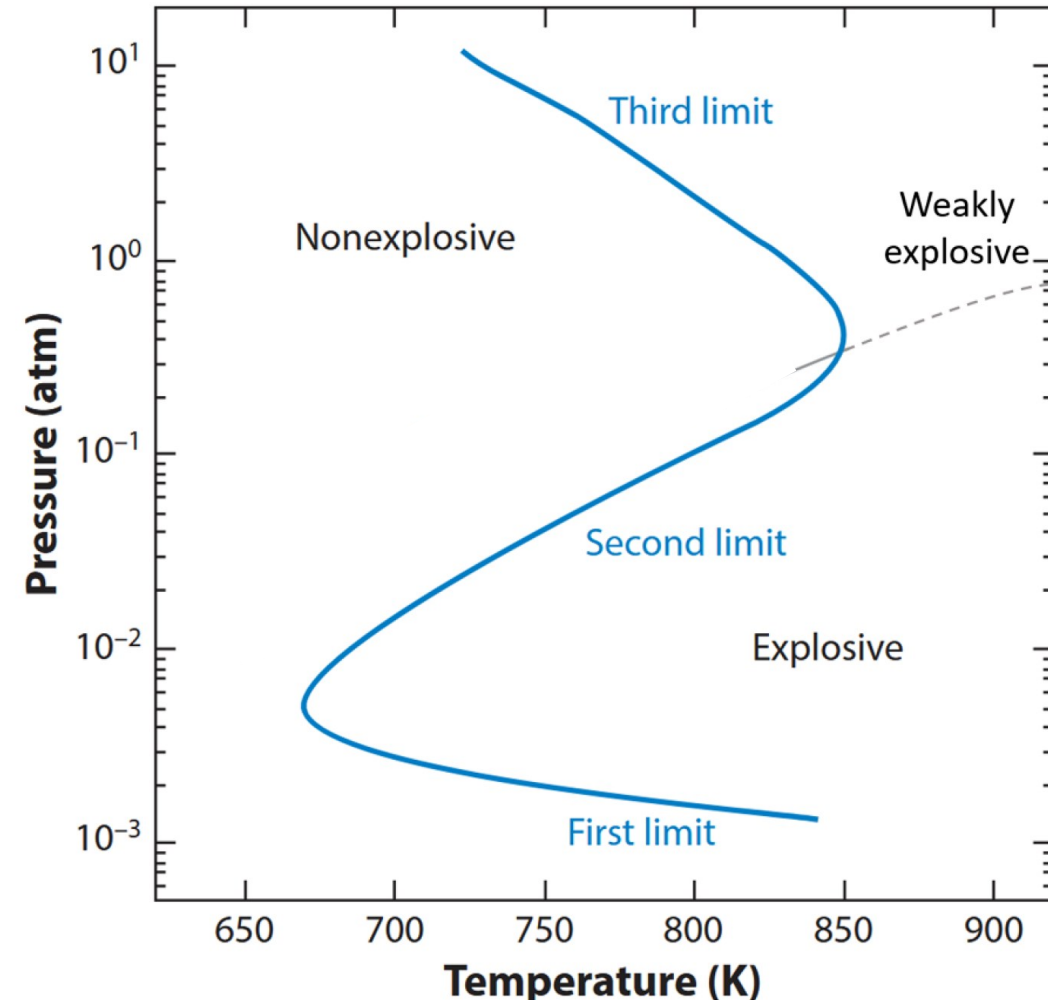
} Chain-branching
cycle

Combustion Chemistry



Limits of autoignition (or explosion limits): pressure and temperature conditions at which a mixture is explosive

- The first limit is governed by the balance of H
- The second explosion limit is caused by a competition between the chain branching and the chain termination reaction of H
- The third explosion limit is due to a reaction that overtakes the stability of HO_2 , (a suggested reaction is $\text{HO}_2 + \text{H}_2 \rightarrow \text{H}_2\text{O}_2 + \text{H}$)



Combustion Chemistry



Example of detailed hydrogen-oxygen reaction mechanism (units are cm³, mol, sec, kcal, K)

		<i>A</i>	<i>n</i>	<i>E_a</i>
1.	H + O ₂ = O + OH	3.55 × 10 ¹⁵	-0.41	16.6
2.	O + H ₂ = H + OH	5.08 × 10 ⁴	2.67	6.29
3.	H ₂ + OH = H ₂ O + H	2.16 × 10 ⁸	1.51	3.43
4.	O + H ₂ O = OH + OH	2.97 × 10 ⁶	2.02	13.4
5.	H ₂ + M = H + H + M ^a	4.58 × 10 ¹⁹	-1.40	104.38
6.	O + O + M = O ₂ + M ^a	6.16 × 10 ¹⁵	-0.50	0.00
7.	O + H + M = OH + M ^a	4.71 × 10 ¹⁸	-1.0	0.00
8.	H + OH + M = H ₂ O + M ^b	3.8 × 10 ²²	-2.00	0.00
9.	H + O ₂ + M = HO ₂ + M ^c	k _O 6.37 × 10 ²⁰	-1.72	0.52
10.	HO ₂ + H = H ₂ + O ₂	1.66 × 10 ¹³	0.00	0.82
11.	HO ₂ + H = OH + OH	7.08 × 10 ¹³	0.00	0.30
12.	HO ₂ + O = OH + O ₂	3.25 × 10 ¹³	0.00	0.00
13.	HO ₂ + OH = H ₂ O + O ₂	2.89 × 10 ¹³	0.00	-0.50
14.	HO ₂ + HO ₂ = H ₂ O ₂ + O ₂ ^e	4.20 × 10 ¹⁴	0.00	11.98
	HO ₂ + HO ₂ = H ₂ O ₂ + O ₂	1.30 × 10 ¹¹	0.00	-1.63
15.	H ₂ O ₂ + M = OH + OH + M ^f	k _O 1.20 × 10 ¹⁷	0.00	45.5
		k _∞ 2.95 × 10 ¹⁴	0.00	48.4
16.	H ₂ O ₂ + H = H ₂ O + OH	2.41 × 10 ¹³	0.00	3.97
17.	H ₂ O ₂ + H = H ₂ + HO ₂	4.82 × 10 ¹³	0.00	7.95
18.	H ₂ O ₂ + O = OH + HO ₂	9.55 × 10 ⁶	2.00	3.97
19.	H ₂ O ₂ + OH = H ₂ O + HO ₂ ^e	1.00 × 10 ¹²	0.00	0.00
	H ₂ O ₂ + OH = H ₂ O + HO ₂	5.8 × 10 ¹⁴	0.00	9.56

$$k = AT^n \exp(-E_a/RT)$$

Li et al., Int. J. Chem. Kinetics, 2004

References



Websites

- elearning.cerfacs.fr/combustion

Books

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- Turbulent Combustion, N. Peters, 2000, Cambridge University Press, New York, USA
- Theoretical and Numerical Combustion, T. Poinsot and D. Veynante, 2012

Chapter IV: Basics of Plasma

- *Definitions & Properties*
- *Breakdown Mechanisms*
- *Types of Discharges*
- *Plasma Chemistry*
- *References*

Definitions & Properties



A **plasma** can be defined as a **quasineutral** gas of charged and neutral particles which exhibits **collective behavior**

A system is **quasineutral** if its characteristic dimension is much larger than the **Debye length, r_D**

$$r_D = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}}$$

T_e : electron temperature

n_e : electron density

ϵ_0 : vacuum permittivity

k_B : Boltzmann constant equal to 8.617×10^{-5} eV/K

e : electron charge

→ For PAC conditions, $r_D \sim 1 \mu\text{m}$

Definitions & Properties



Collective behavior: the motions of particles depend not only on local conditions (by collisions) but on the state of the plasma in remote regions (by electric or magnetic fields)

→ The motion of particles depends on the electron density and energy/temperature

Examples



✓ *Plasma*

Lightning

$$n_e = 10^{18} \text{cm}^{-3}, T_e = 30,000 \text{ K}$$



✓ *Plasma*

Flame

$$n_e = 10^{10} \text{cm}^{-3}, T_e = 2000 \text{ K}$$



✗ *Not a plasma*

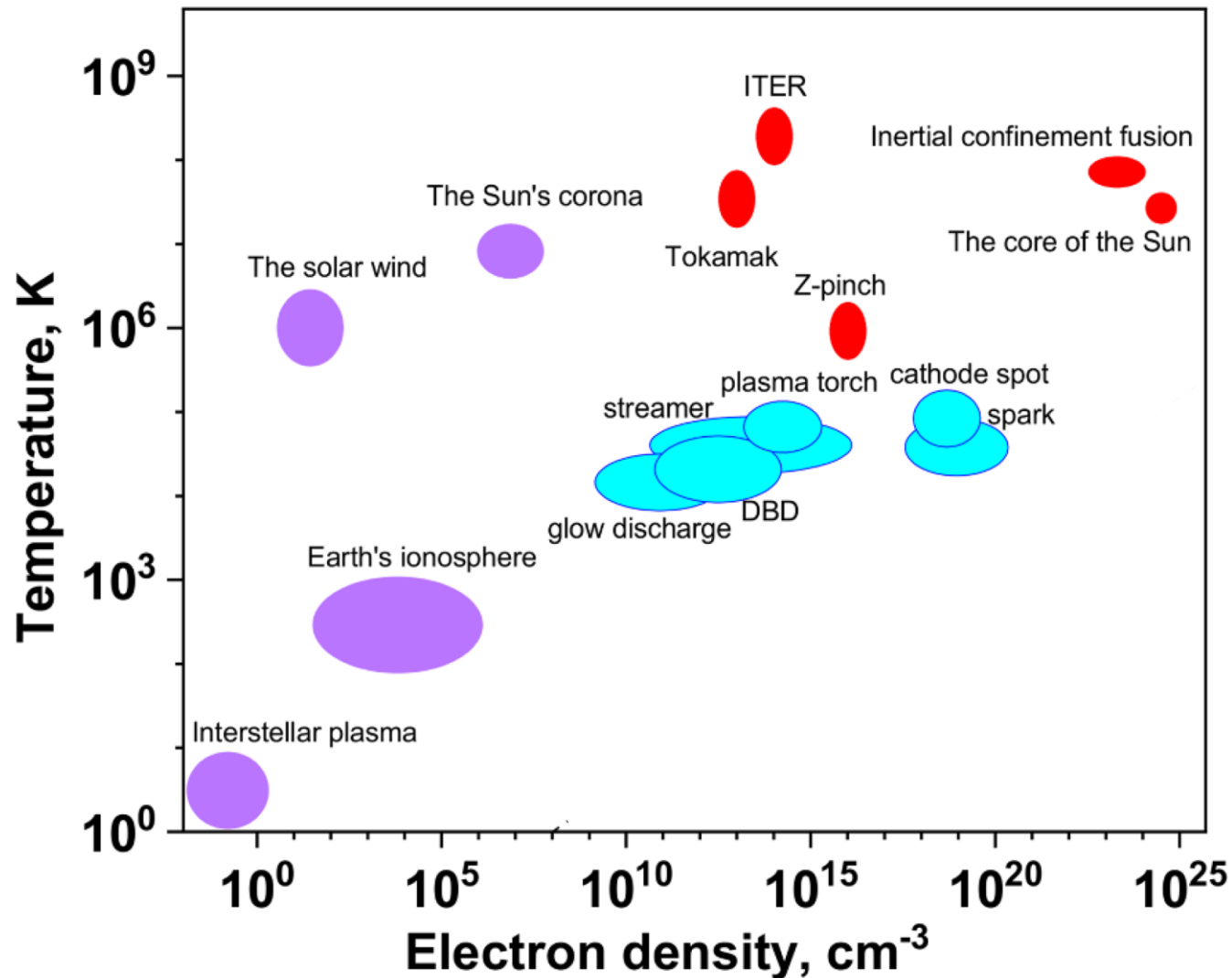
Ambient air




$$n_e = 10^3 \text{cm}^{-3}, T_e = 300 \text{ K}$$

Definitions & Properties



Examples of plasma parameters in nature and human made



-  *Space plasmas*
-  *Fusion plasmas*
-  *Low temperature plasmas*

Starikovskaia et al, PSST, 2026

Definitions & Properties



The electron temperature T_e can be expressed in electron-volt (eV) or in kelvin (K)

The conversion factor from eV to K is given by equating the energy gained by an electron accelerated by a potential difference of 1 V to the characteristic thermal energy $k_B T_e$

$$T_e(\text{K}) = \frac{e(\text{eV})}{k_B} \approx 11,610 \text{ K}$$

In plasma, all particles can have different temperatures:

- T : temperature of neutral particles
- T_i : ion temperature
- T_e : electron temperature

Definitions & Properties

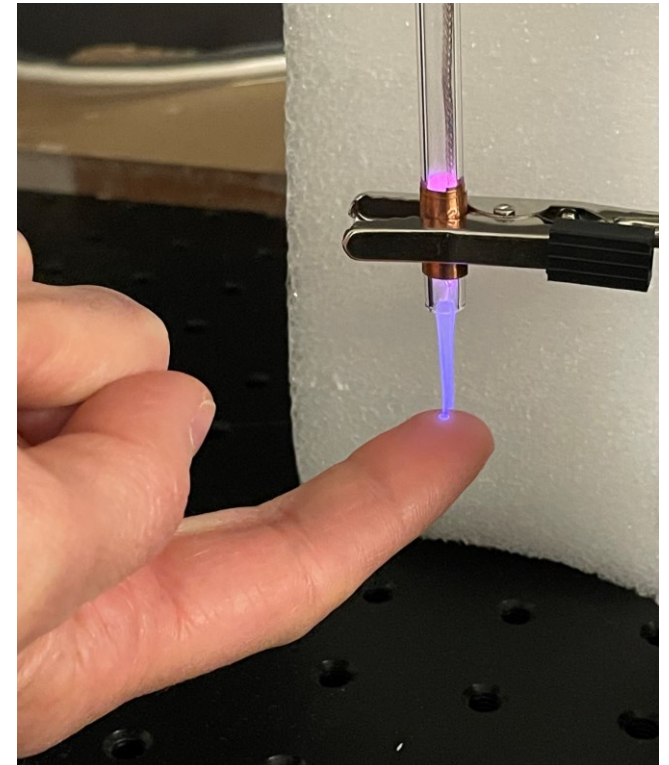


Low temperature plasmas can be

- At equilibrium: $T = T_i = T_e$
- At nonequilibrium: $T \ll T_i \ll T_e$

In PAC, mainly nonequilibrium plasmas are used, for three reasons:

1. Control of the gas temperature
2. Low electrical energy cost
3. Strong chemical effect



Definitions & Properties



The average electron energy in a gas $\langle \epsilon \rangle$, or electron temperature T_e , is a function of the **reduced electric field**:

$$T_e = \mathcal{F}(E/N)$$

E : electric field (difference of potential / distance)

N : gas number density

In many textbooks on low temperature plasma physics, the reduced electric field is presented as E/P , with P the gas pressure

With most experimental data obtained at room temperature, it implicitly assumes the established relation $P = Nk_B T$ at $T \approx 300$ K

E/N is a more physically meaningful quantity for plasma-assisted combustion, using the usual non-standard unit Townsend, Td:

$$1 \text{ Td} = 10^{-17} \text{ V}\cdot\text{cm}^2$$

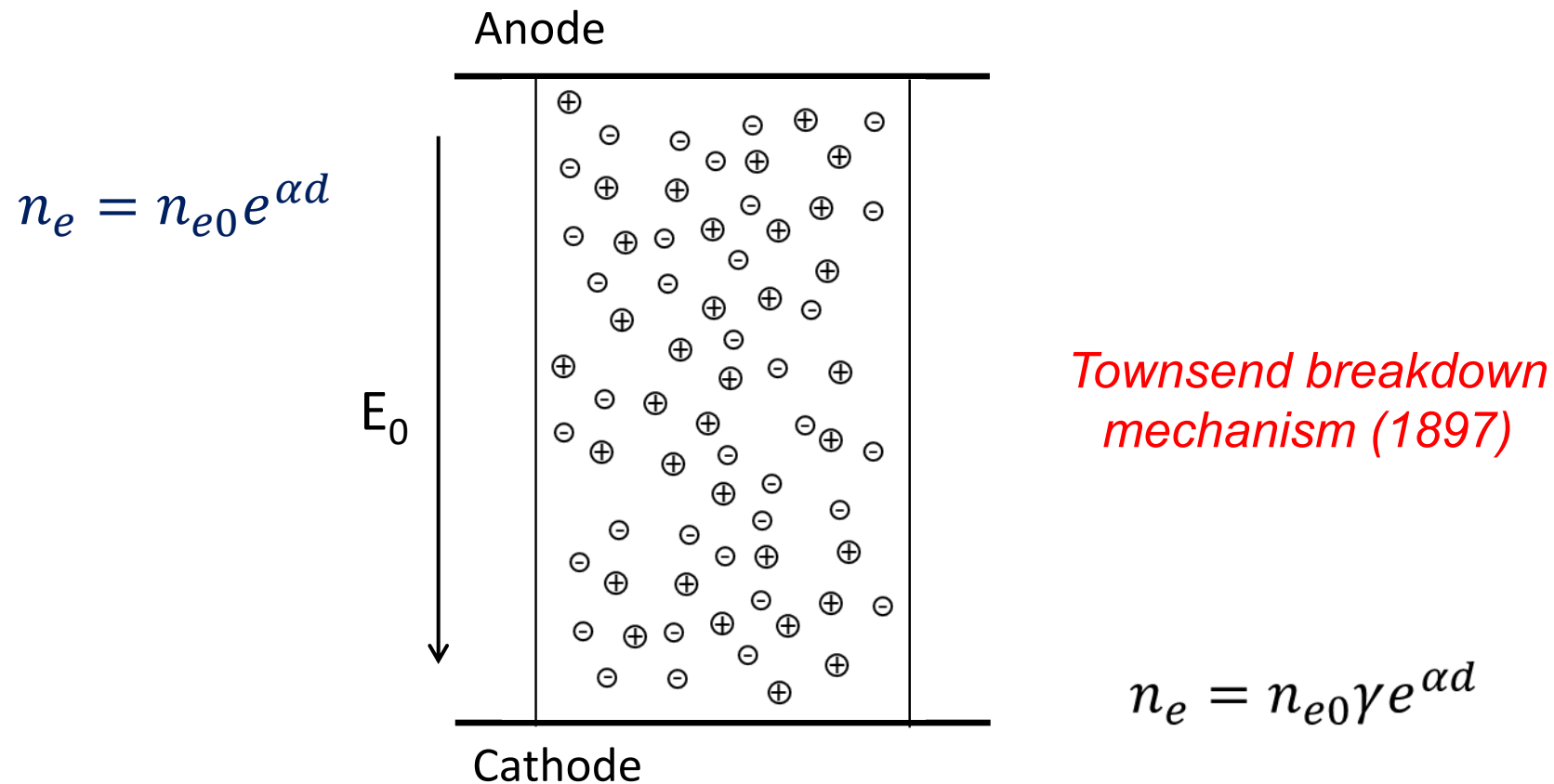
Chapter IV: Basics of Plasma

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Breakdown Mechanisms



Electric gas discharges, process of turning a gas into a conductive media by applying an electric field, E , produce low temperature plasmas



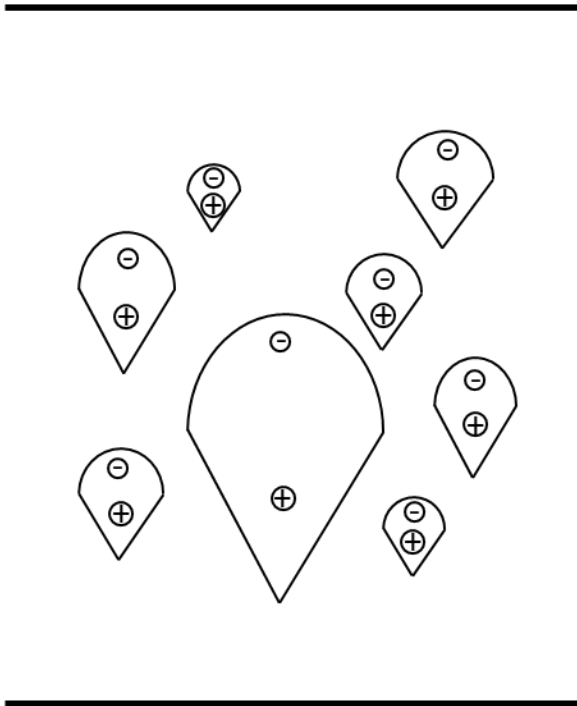
On Earth, in gases at P_{atm} : $[e^-] \approx 10^3 \text{ cm}^{-3}$

Breakdown Mechanisms



Different breakdowns

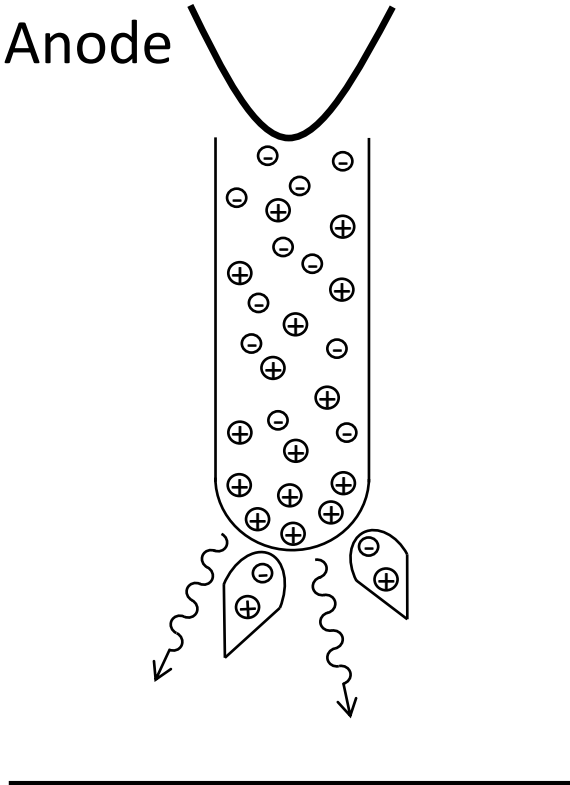
Anode



Cathode

Townsend breakdown

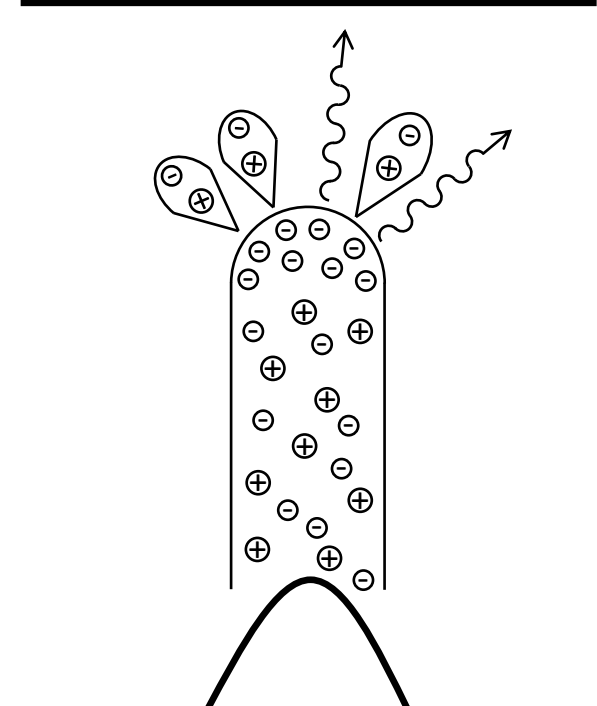
Anode



Cathode

Positive streamer

Anode



Cathode

Negative streamer

Breakdown Mechanisms



Electron impact ionization: when seed electrons in the gap are accelerated and collide with heavy particles to produce additional electrons

- Characteristic ionization energies are on the order of 10 eV or higher

Species	Ionization energy (eV)
O ₂	12.07
O	13.62
H ₂	15.43
H	13.60
CH ₄	12.98
NH ₃	10.16
N ₂	15.58
N	14.53
Ar	15.76
He	24.59
H ₂ O	12.61
CO ₂	13.79

Breakdown Mechanisms



The energy of electrons depends on their **transport coefficients (or swarm parameters)**, which include

- the drift velocity
- the longitudinal and transverse diffusion coefficients (with respect to the direction of E)
- the first Townsend ionization coefficient
- Attachment coefficients (loss of electrons due to formation of negative ions)

Drift velocity, v_{dr} : average velocity of electrons in the opposite direction of electric field (typically much lower than the thermal velocity)

Electron mobility, μ : proportionality coefficient between the drift velocity and the electric field, it is a weak function of the reduced electric field E/N (sometimes taken as a constant)

$$v_{dr} = -\mu \times E$$

μ : from calculations or experiments

Breakdown Mechanisms



Townsend coefficients: empirically derived parameters that describe the development of a discharge in a given gas mixture under a specified electric field

First Townsend coefficient, α_i : is the number of ionization events performed by an electron in a 1 cm path along the field. It characterizes electron multiplication in a gas

$$\alpha_i = \mathcal{A}N \exp\left(-\frac{\mathcal{B}}{E/N}\right)$$

\mathcal{A} and \mathcal{B} : empirical constants

N : gas density

Second Townsend coefficient, γ : quantifies the electron yield from the cathode under bombardment by positive ions

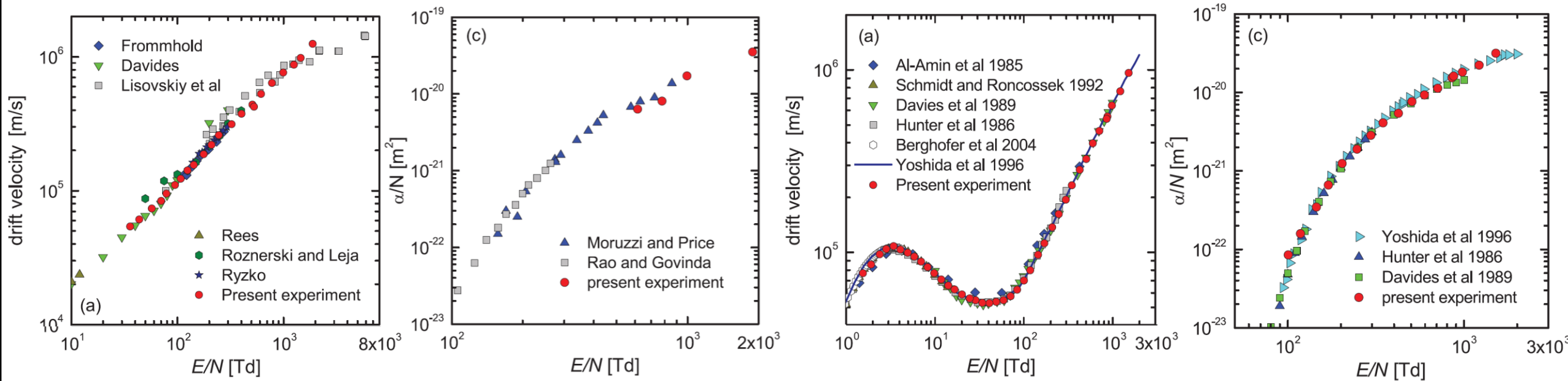
Breakdown Mechanisms



Examples of electron drift velocity v_{dr} and reduced effective ionization coefficient α/N

Synthetic air

Methane

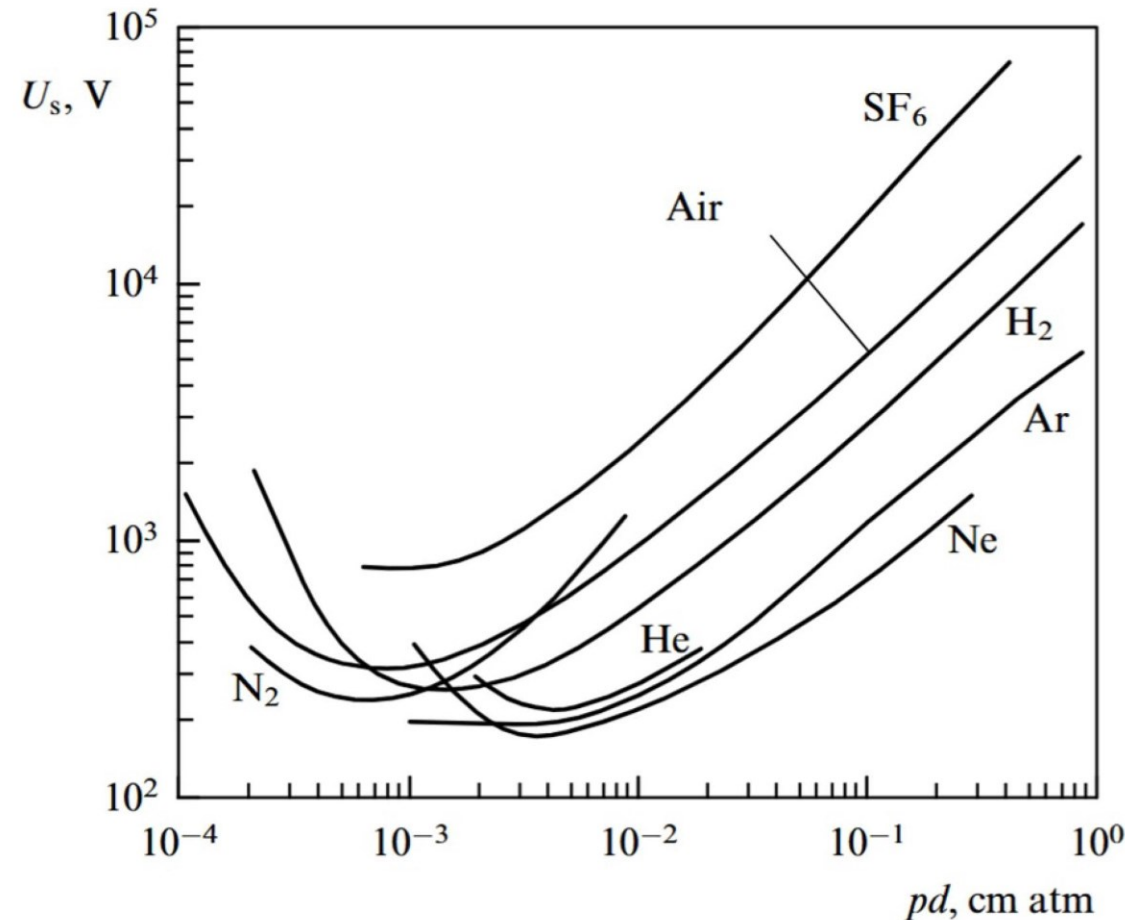


Breakdown Mechanisms



Breakdown voltage: defined as the voltage at which plasma ignites under an **infinitely slow increase of the applied voltage across the gap**, with other parameters fixed

→ Paschen curves



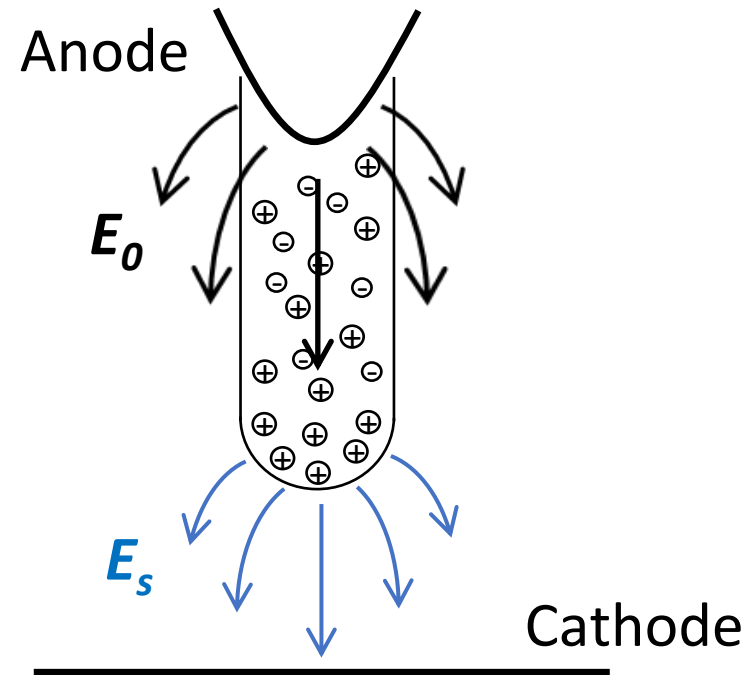
Starikovskaia et al, PSST, 2026



Breakdown Mechanisms

In **pulsed voltage**, the situation is different

The **streamer mechanism of breakdown dominates** when the electric field in the head of a single avalanche becomes comparable to the external electric field



The modified Paschen's law should take into account an **overvoltage** as a function of pd

Chapter IV: Basics of Plasma

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Types of Discharges

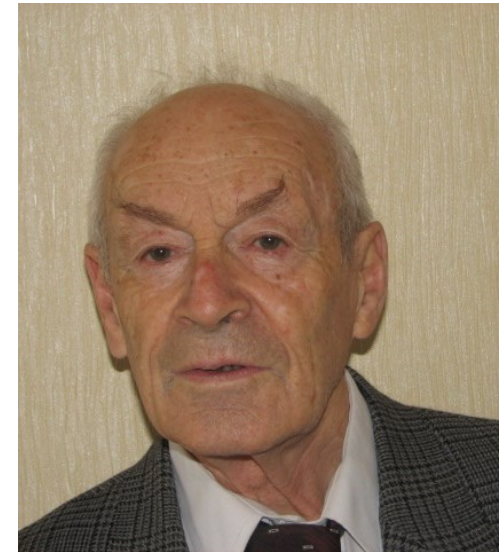


In engineering applications, the most common method of producing plasma is a gas discharge

Gas discharge = Breakdown + electric current flowing through the plasma

Note that '*plasma discharge*' is sometimes used in papers, however, it is improper, as the plasma is the result of a discharge

Accurate terms include '*gas discharge plasma*' or '*discharge induced plasma*'



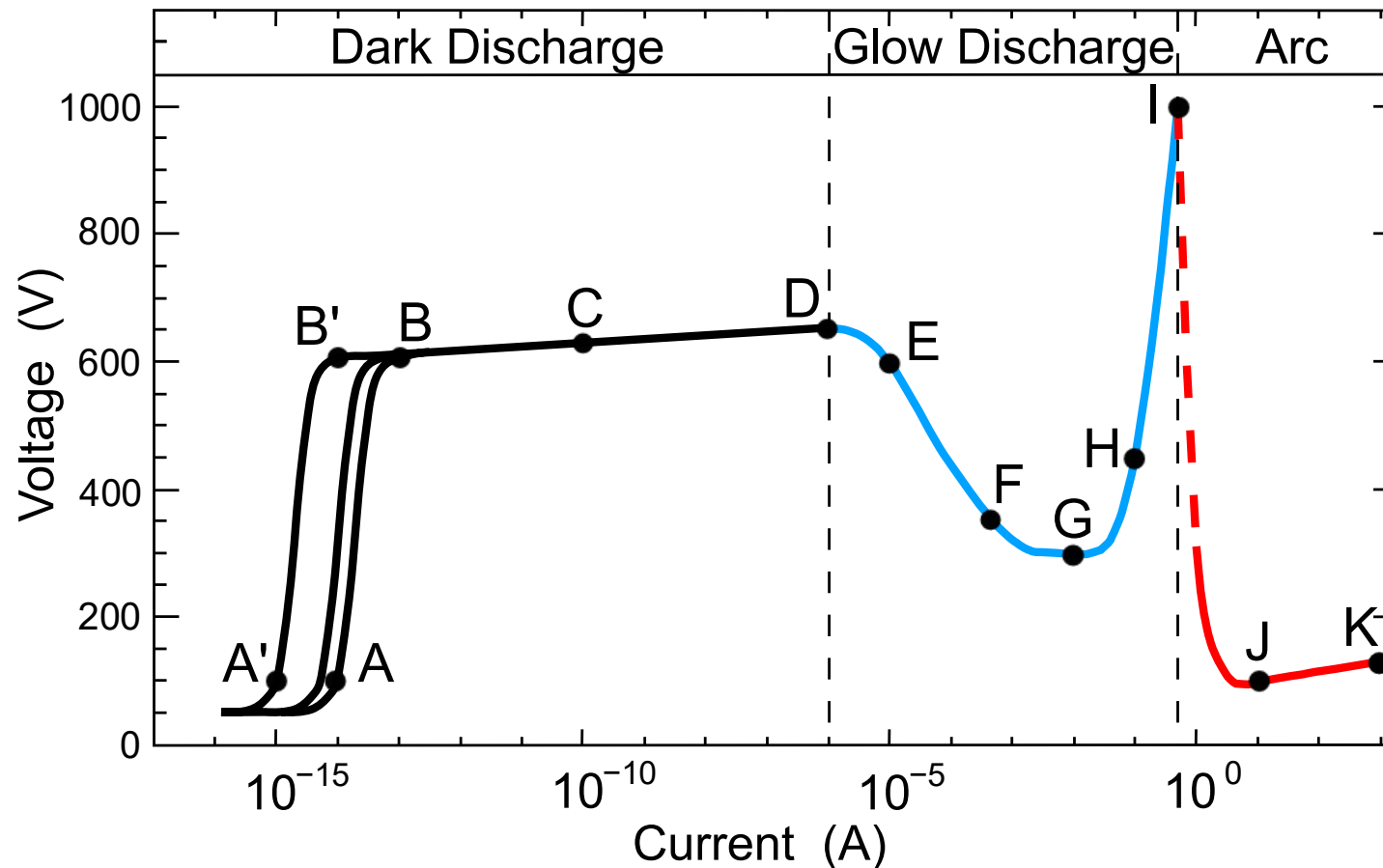
Yuri P. Raizer
Plasma Physicist
(1927-2021)

Types of Discharges



For continuous applied voltages (DC), several types of discharges have been defined

Example of voltage-current characteristics of gas discharges in neon at 1 torr (1.3 mbar)



Types of Discharges



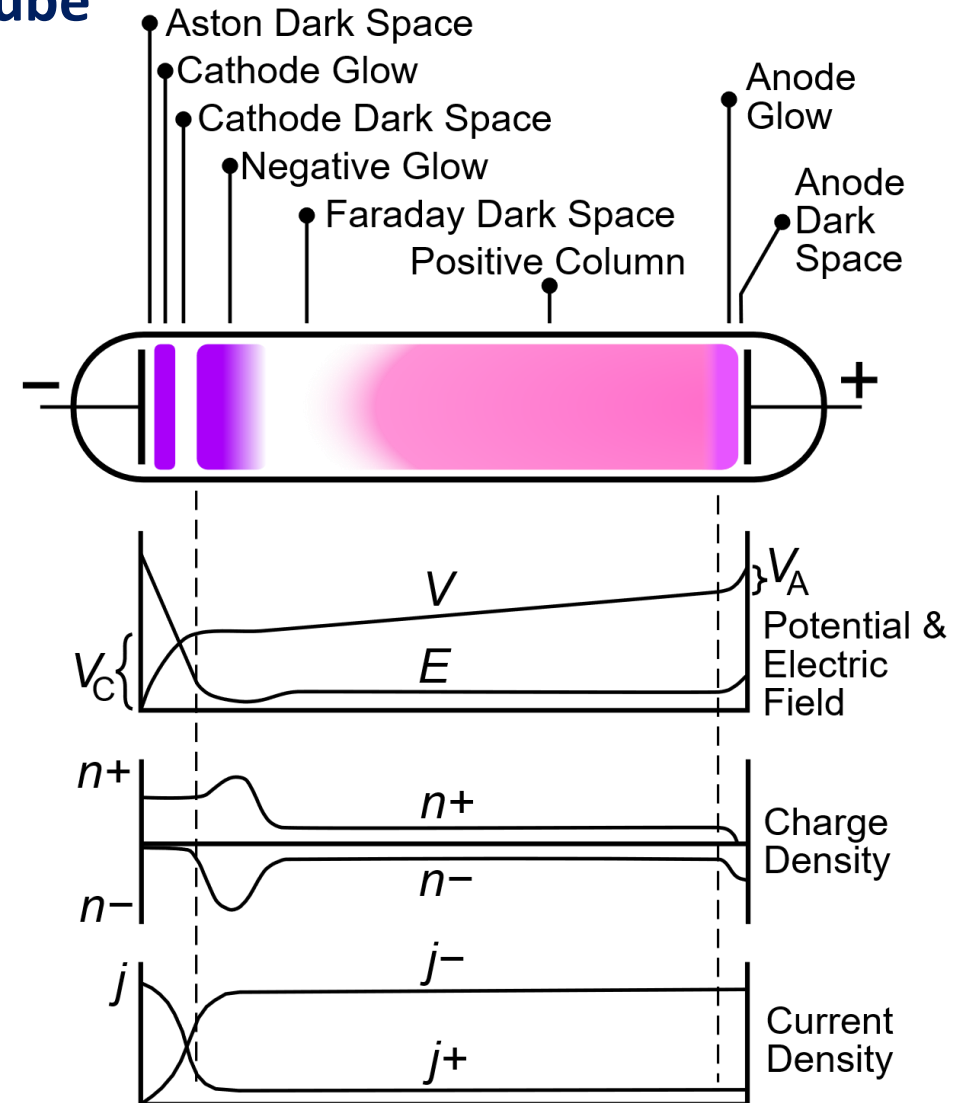
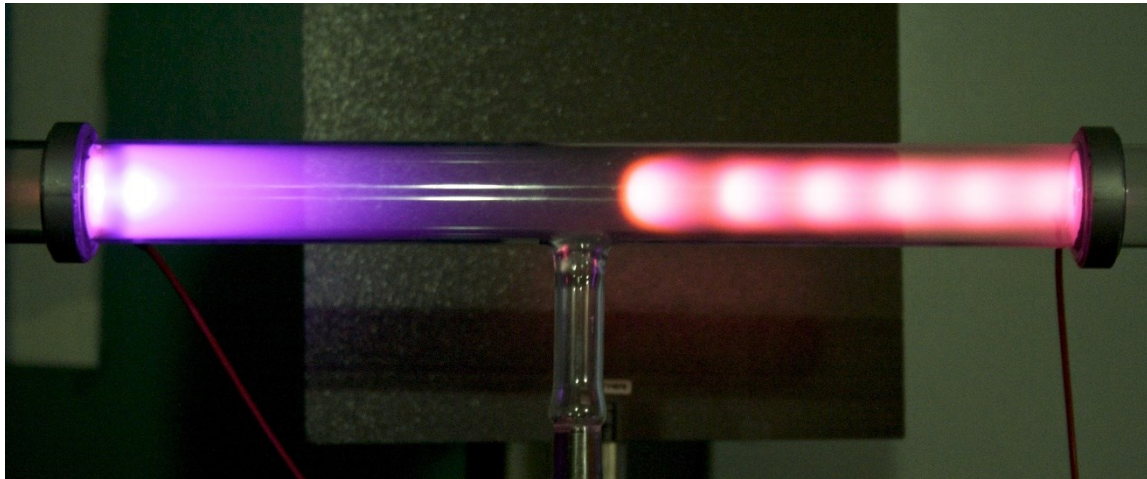
Glow discharge: self-sustaining discharge with a cold cathode emitting electrons due to secondary emission, mostly due to positive ion bombardment

- Glow discharges have a **layer of large positive space charge at the cathode**, with a strong field at the surface and a potential drop that can reach 100-400 V, known as the **cathode fall**
 - The thickness of the cathode fall layer is inversely proportional to the pressure of the gas
- If the interelectrode gap is large enough, an electrically neutral plasma region with a weak electric field is formed between the cathode layer and the anode, called the **positive column**
 - The positive column of a DC glow discharge is an example of **weakly ionize nonequilibrium plasma**

Types of Discharges



Example of a DC glow discharge in a low-pressure tube



Glow discharge in a Crookes tube

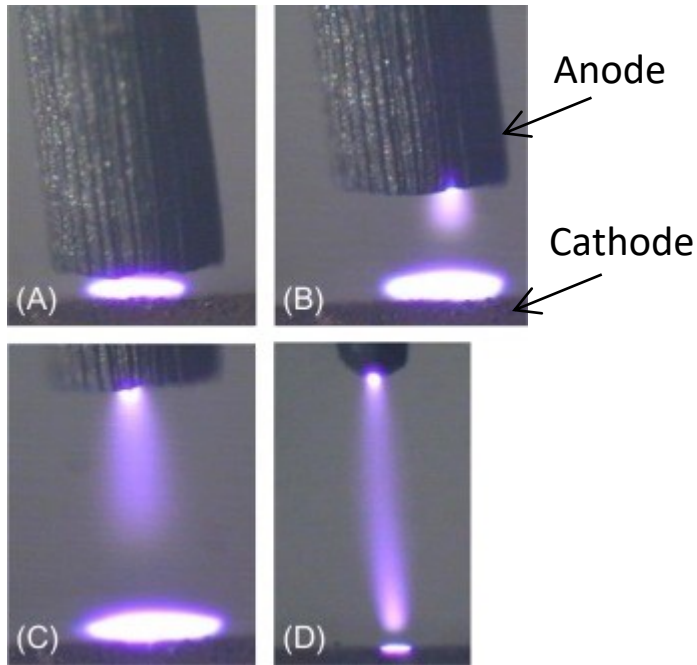
Pressure $\sim 10^{-6}$ torr (10^{-9} bar), Applied voltage ~ 5 kV

Distance between electrodes ~ 30 cm



Types of Discharges

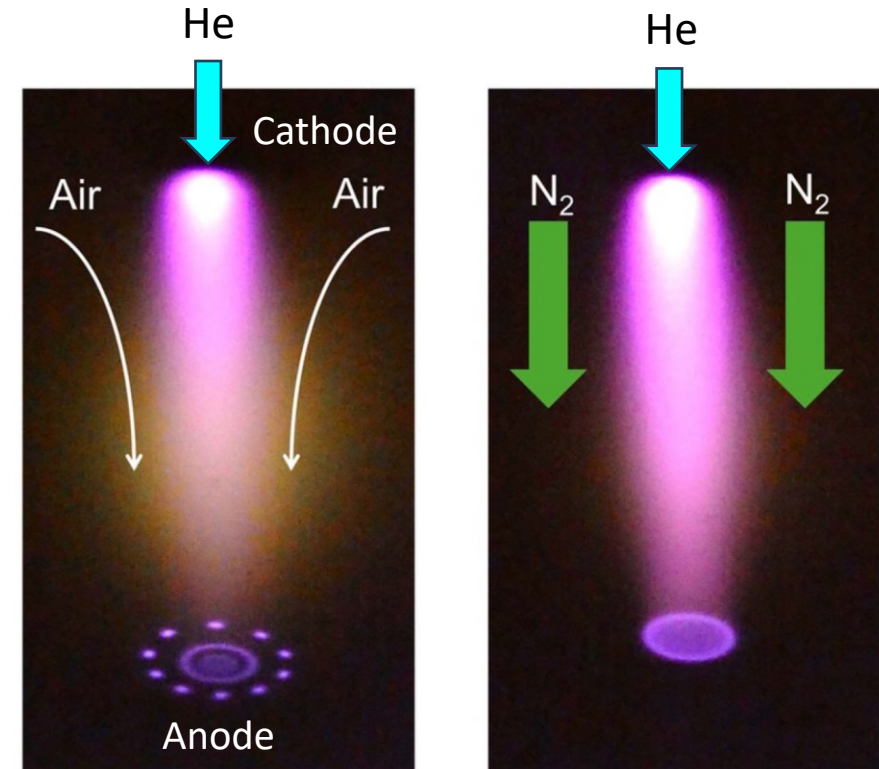
Examples of DC glow discharges at atmospheric pressure



Glow discharge in atmospheric pressure air

Distance between electrodes (A) 0.1 mm,
(B) 0.5 mm, (c) 1 mm, (D) 3 mm

Staack et al, PSST, 2005



Helium glow discharge at atmospheric pressure

Distance between electrodes ~ 1 cm

Miyazaki et al, PSST, 2024

Types of Discharges



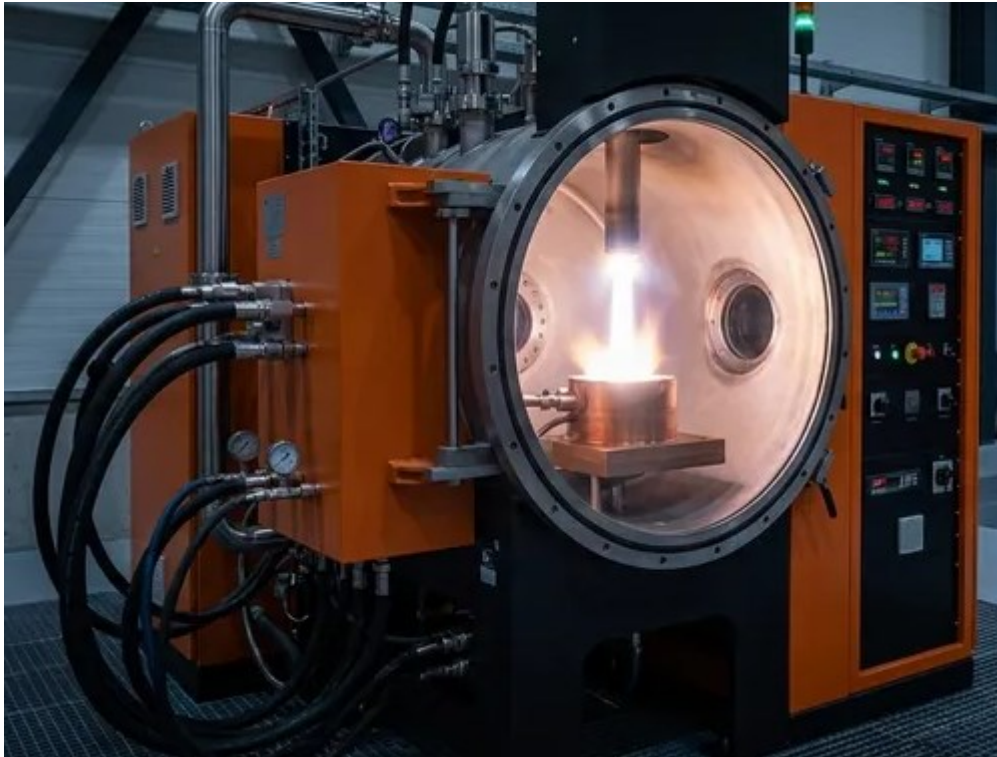
Arc: self-sustaining discharge with a high-temperature cathode emitting electrons due to thermionic, field electron, and thermionic field emission, resulting in a low cathode fall

- Arcs have low voltages (less than 20–30 V) and high current
- Arc plasma (plasma produced by an arc discharge) may be in thermal equilibrium or in nonequilibrium, depending on the pressure
 - Equilibrium plasma is found only in arcs, while nonequilibrium plasma is characteristic of both glow and arc discharges
- At **atmospheric pressure** and above, arcs produce **dense low-temperature equilibrium plasmas** ($T = 6000 - 12,000$ K)

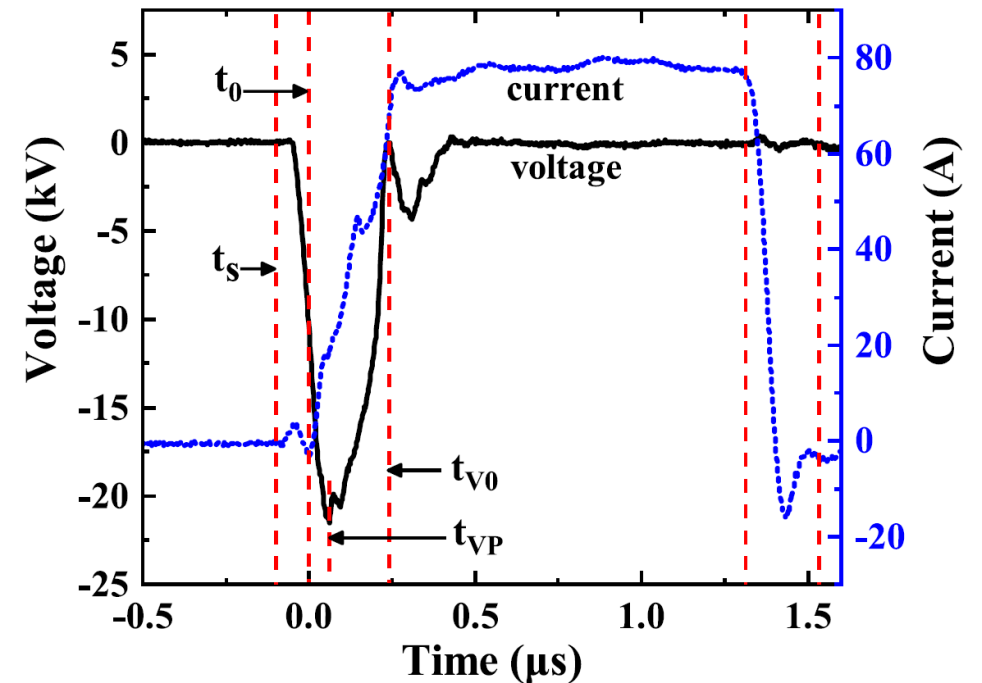
Types of Discharges



Examples of vacuum arcs



Industrial Vacuum Arc Remelting
For high purity metals



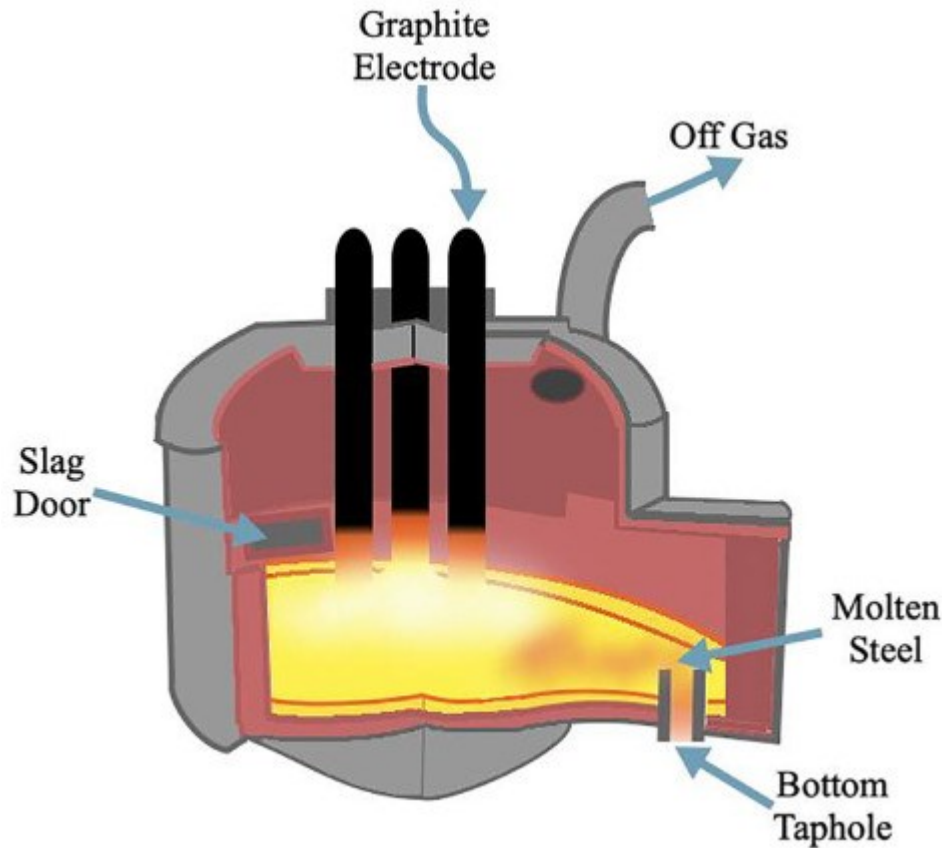
Arc discharge at pressure $10^{-3} - 10^{-1}$ Pa ($10^{-8} - 10^{-6}$ bar)
Copper electrodes, gap 5 mm

Zhou et al, Sci. Reports, 2019

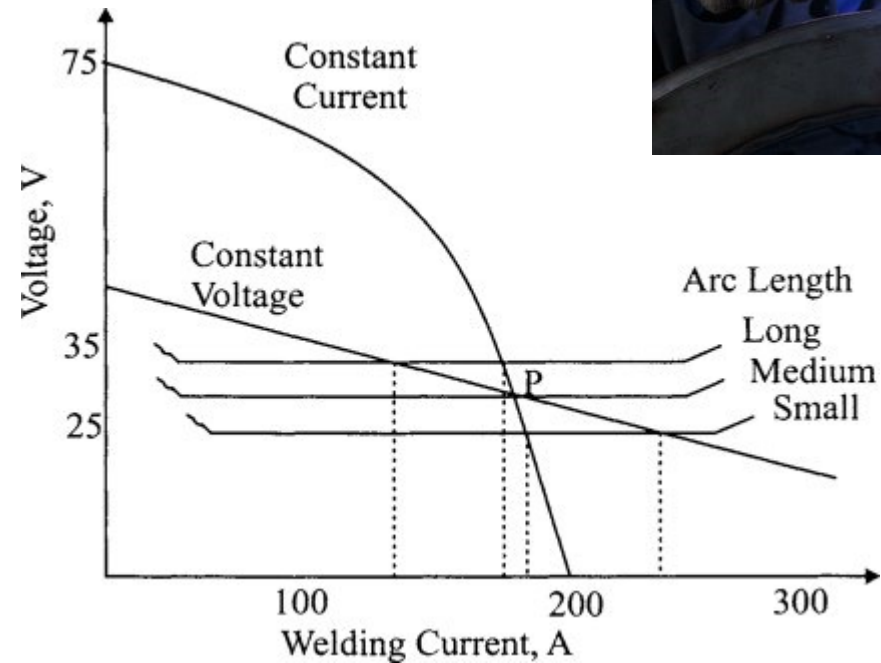
Types of Discharges



Examples of arcs at atmospheric pressure



Electric Arc Furnace (EAF) process
For steel production



*Modeling, Sensing and Control of Gas
Metal Arc Welding, 2003*



Types of Discharges



When the voltage is not applied continuously, **transient processes** happen, with additional terminologies for the resulting discharges

The two most common transient discharges are called **sparks** and **coronas**



Example of spark



Example of corona

Types of Discharges



Spark discharges (or sparks): occurs at voltage above the breakdown level at pressures above atmospheric in gaps of the order of centimeter or above, i.e., $pd \gtrsim 1$ bar.cm

- Sparks have characteristics **cracking sounds** coming from the shock waves produced by a sharp pressure increase due to an **intense release of Joule heating** in the spark channel
- Sparks can occur in **any electrode geometry**, e.g., plane-plane, wire-plane, pin-pin, wire-cylinder, etc.
- Current in spark can reach $10^2 - 10^5$ A for a short period of time (nanoseconds)
- If the strong current can be sustained long enough, the **spark turns into an arc**

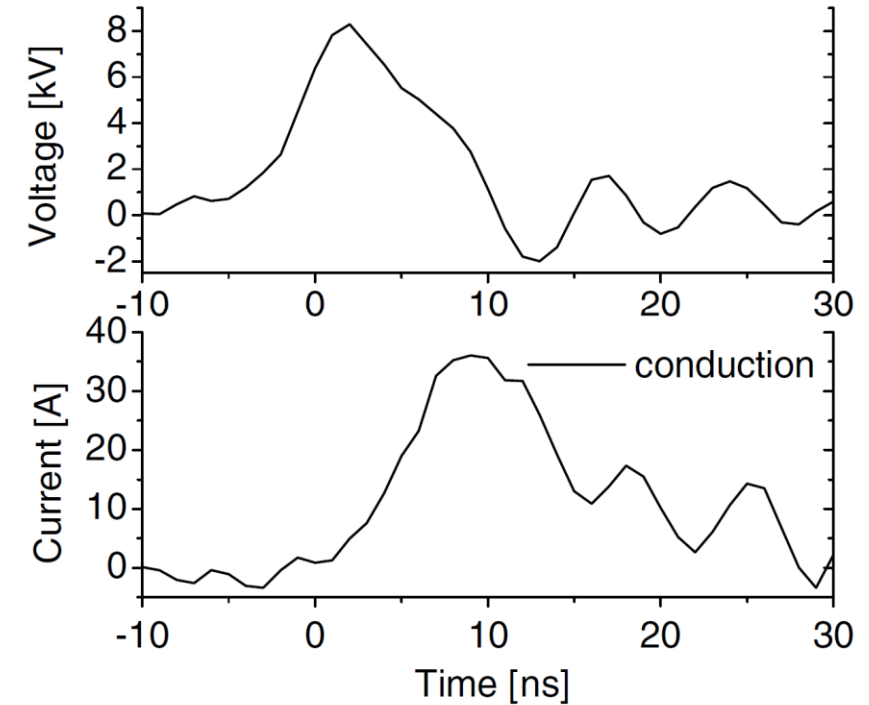
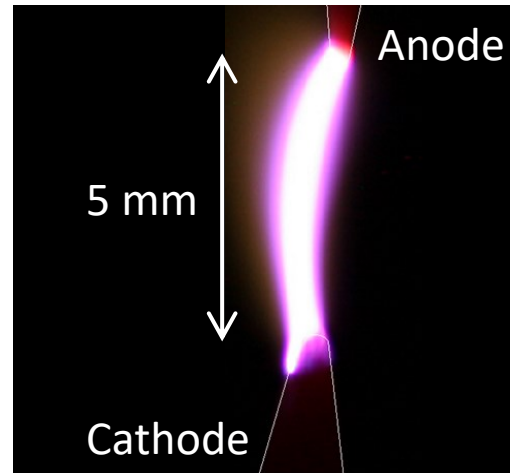
Types of Discharges



Examples of sparks in atmospheric pressure air



Lightning
Arnaud Lery, KAUST



Spark in preheated air
Nanosecond repetitively pulsed voltage

Pai et al., PSST, 2010

Types of Discharges



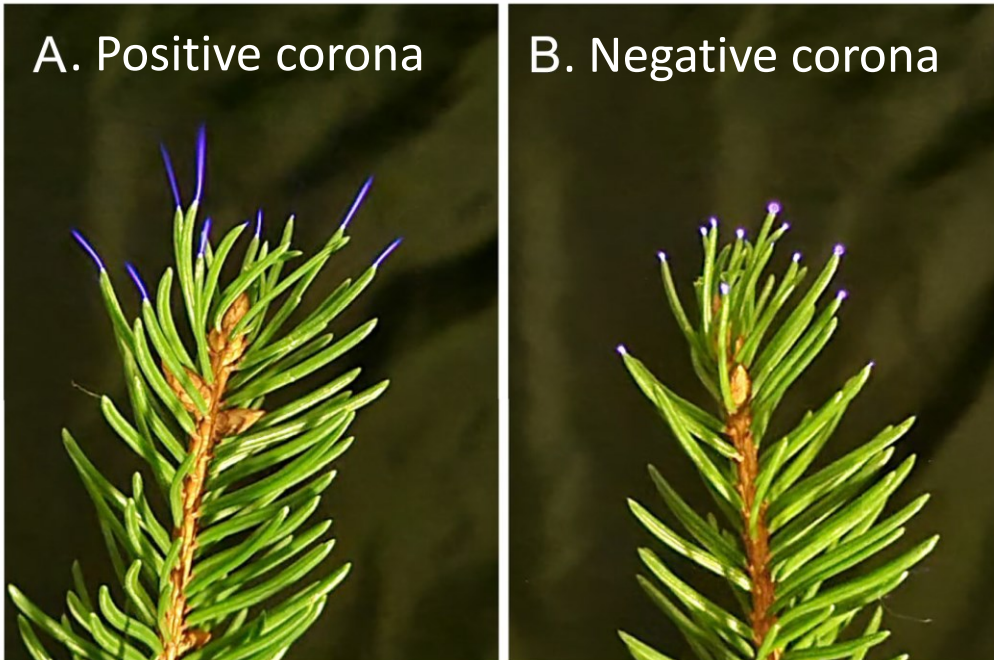
Corona discharge: weakly luminous discharge that appear in the neighborhood of a point or a thin wire, where the field is greatly enhanced

- **Ionization takes place only locally**, and the gas there emits light
- The electric current (very small) is closed by a flux of charges of a specific sign (depending on the polarity of the point/thin electrode)
- These charges are **produced in the self-sustaining-discharge zone at the point**, and are **dragged by a relatively weak field to the other electrode**
- If the voltage is further increased, the **corona turns into a spark**

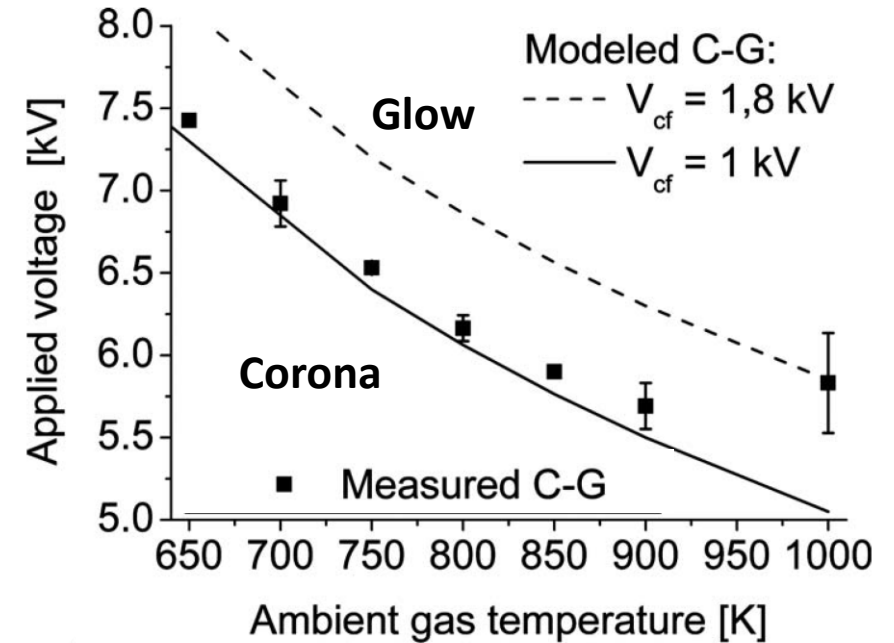
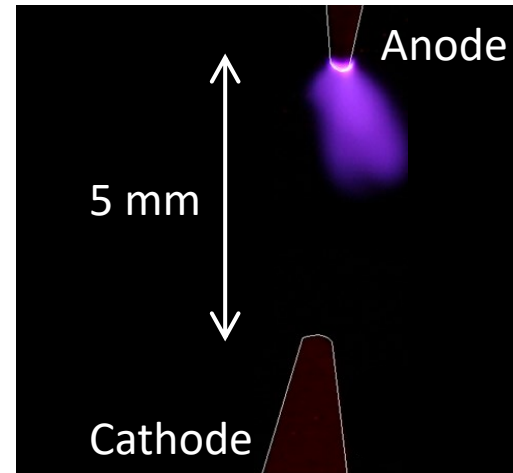


Types of Discharges

Examples of corona discharges in atmospheric pressure air



Corona discharges from needle leaves
Applied voltage ~ 10 kV



Corona in preheated air
Nanosecond repetitively pulsed voltage

Chapter IV: Basics of Plasma

- *Definitions & Properties*
- *Breakdown Mechanisms*
- *Types of Discharges*
- ***Plasma Chemistry***
- *References*

Plasma Chemistry



The most chemically active species in low temperature plasmas are the electrons

For a given gas, the electron-induced chemistry depends on the electron density n_e , and the electron energy T_e

Even in a homogeneous electric field, the electrons do not have a single energy, but rather a distribution of energy, that is called the **Electron Energy Distribution Function (EEDF)**

To perform 0-D calculations of the chemistry induced by the electrons in weakly ionized plasmas, you need to know:

- Initial gas composition (including n_e)
- Thermodynamic conditions
- Electric field
- Electron impact kinetic model
- Collision cross-sections (including ionization, attachment, dissociation, excitation)

Plasma Chemistry



Electron Energy Distribution Function (EEDF): can be found by solving a balance equation for the number of electrons in an elementary volume defined by spatial coordinates and velocities, called the **electron Boltzmann equation (EBE)**

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \frac{\mathbf{F}}{m_e} \cdot \nabla_{\mathbf{v}} f = \left(\frac{\partial f}{\partial t} \right)_{col}$$

$f(\mathbf{r}, \mathbf{v}, t)$: distribution function of electrons

\mathbf{v} : electron velocity vector

\mathbf{r} : electron location vector

\mathbf{F} : external electric force vector ($\mathbf{F} = -e\mathbf{E}$)

m_e : electron mass

$\nabla_{\mathbf{v}}$: gradient in velocity space

$\left(\frac{\partial f}{\partial t} \right)_{col}$: collision term comprising all kinds of binary collisions with electrons

Plasma Chemistry



$$\left(\frac{\partial f}{\partial t}\right)_{col} = S_{en}^{el} + S_{en}^{inel} + S_{ei} + S_{ee}$$

S_{en}^{el} : elastic electron collisions with neutral atoms and molecules

S_{en}^{inel} : inelastic electron collisions with neutral atoms and molecules

S_{ei} : electron-ion collisions

S_{ee} : electron-electron collisions

The EBE is a 7-dimensional equation then it can be solved only for very specific conditions, or by simplifying it to 1D in energy space

Plasma Chemistry



Conditions at which EBE can be solved

1. Assuming constant collision frequency between electrons and neutral species ($\nu_{en} = \text{const.}$), the **Maxwellian distribution** is obtained (equilibrium plasma)

$$f_{\text{Maxwell}} \sim \exp(-\epsilon/T_e)$$

ϵ : electron energy

The mean electron temperature for the Maxwellian distribution is equal to

$$T_e(\text{Maxwell}) = \frac{e^2 E^2 M}{3m_e^2 (\nu_{en})^2} \sim \left(\frac{E}{N}\right)^2$$

M : mass of the heavy particle participating in the collision

e : electron charge

Plasma Chemistry



2. Assuming constant mean free path length for the electrons, the solution of the Boltzmann equation is the **Druyvesteyn distribution**

$$f_{\text{Druyvesteyn}} \sim \exp\left(-\epsilon^2 / (eE\lambda_e)^2\right)$$

λ_e : mean free path length of electrons

The Druyvesteyn distribution decreases with energy much faster than the Maxwellian distribution for the same mean energy

The electron temperature is then proportional to the reduced electric field

$$T_e(\text{Druyvesteyn}) \sim \frac{E}{N}$$

Plasma Chemistry



The more general situation of a low temperature nonequilibrium plasma **with inelastic losses** cannot be described within the model cases $\nu_{en} = \text{const.}$ or $\lambda_e = \text{const.}$

No simple analytical solution exists for the mean electron energy/temperature in this case, but **T_e is always a monotonically increasing function of the reduced electric field**

The function depends upon the gas mixture composition, the cross-sections of electron impact, the ionization degree, etc.

Plasma Chemistry



In plasma-assisted combustion (relatively high pressure) it is possible to consider:

- The EEDF is approximately equal to the **local EEDF** only, i.e., at a given point, the electron velocity distribution is not influenced by electric field from other regions
- There is an immediate response of the EEDF to the electric field

This is called the **Local Field Approximation (LFA)**

When the LFA holds, the EEDF, $g(\epsilon)$, is related to the velocity distribution function $f(\mathbf{v})$ as

$$g(\epsilon)d\epsilon = 4\pi v^2 f(\mathbf{v})dv$$



Plasma Chemistry

Using the relation between ϵ and v , it is possible to write the EEDF

$$g(\epsilon) = 2\pi \left(\frac{2e}{m_e} \right)^{3/2} \sqrt{\epsilon} f(v(\epsilon)) = \rho(\epsilon) f(v(\epsilon)) \sim \sqrt{\epsilon} f(v(\epsilon))$$

ϵ : electron energy in eV

$\rho(\epsilon) \sim \sqrt{\epsilon}$: is the density of electron states along the energy axis

The average electron energy $\langle \epsilon \rangle$ is given by

$$\langle \epsilon \rangle = \frac{1}{n_e} \int_0^{\infty} \epsilon g(\epsilon) d\epsilon = \frac{3}{2} T_e$$

T_e : electron temperature in eV

Plasma Chemistry



Solving the Boltzmann equation for the EEDF generally requires the use of numerical methods

In most studies, a solution is expressed in the form of an expansion in spherical harmonics, considering the first two terms of the expansion

This is known as the **two-term approximation of the Boltzmann equation**, given by

$$f(\mathbf{v}, t) = f^{(0)}(v, t) + f^{(1)}(v, t) \cos \Theta$$

$f^{(0)}$: isotropic part of the solution

$f^{(1)}$: anisotropic part of the solution

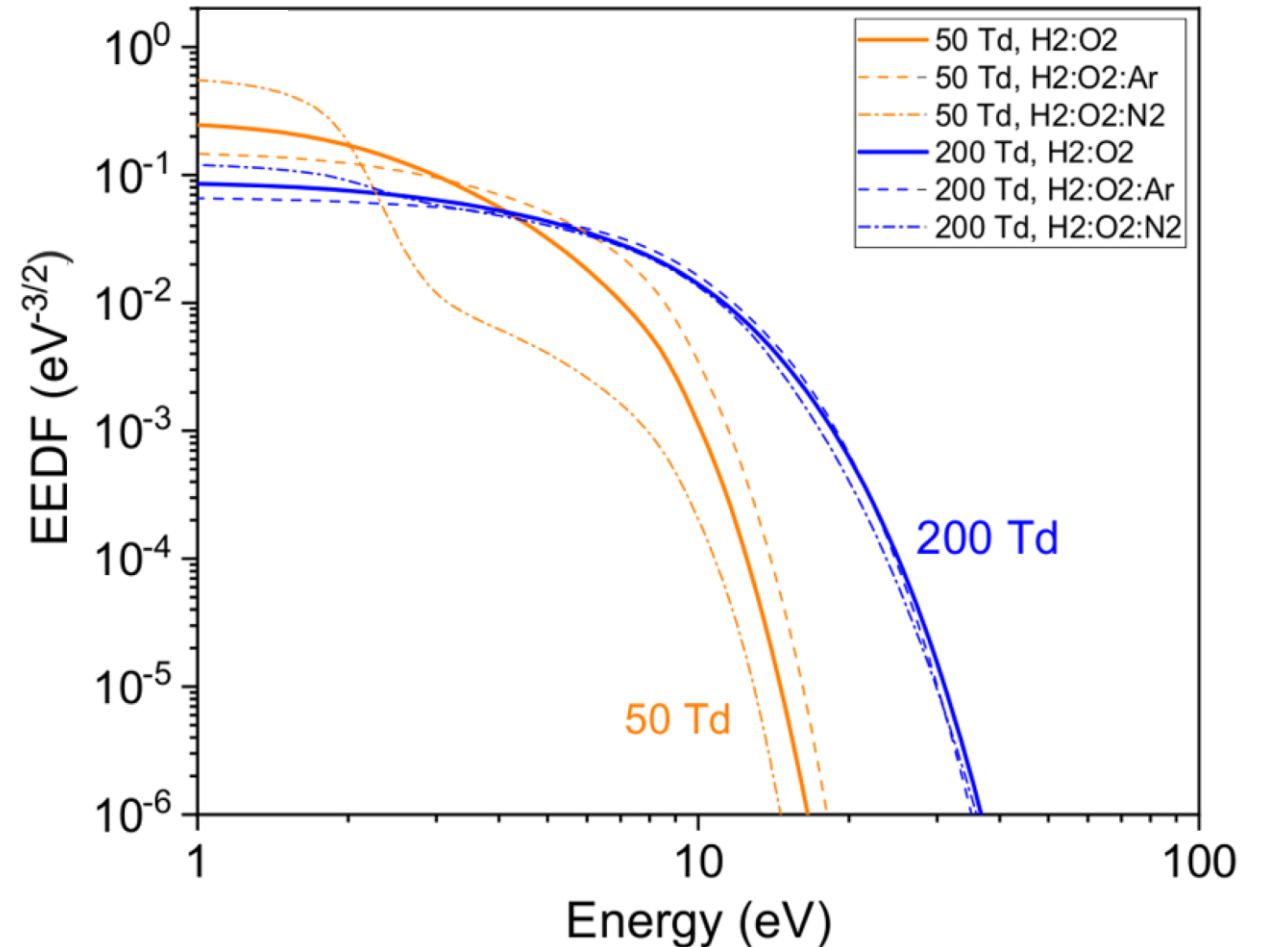
Θ : angle between the directions of the electron velocity vector \mathbf{v} and the electric field vector \mathbf{E}

Plasma Chemistry



Examples of EEDFs

- Depend on reduced electric field
- Depend on gas composition (inelastic processes)
 - **Need cross-sections of electron collisions with atoms and molecules**
- The EEDF is then used to calculate the electron impact reaction rates



Starikovskaia et al., PSST, 2026

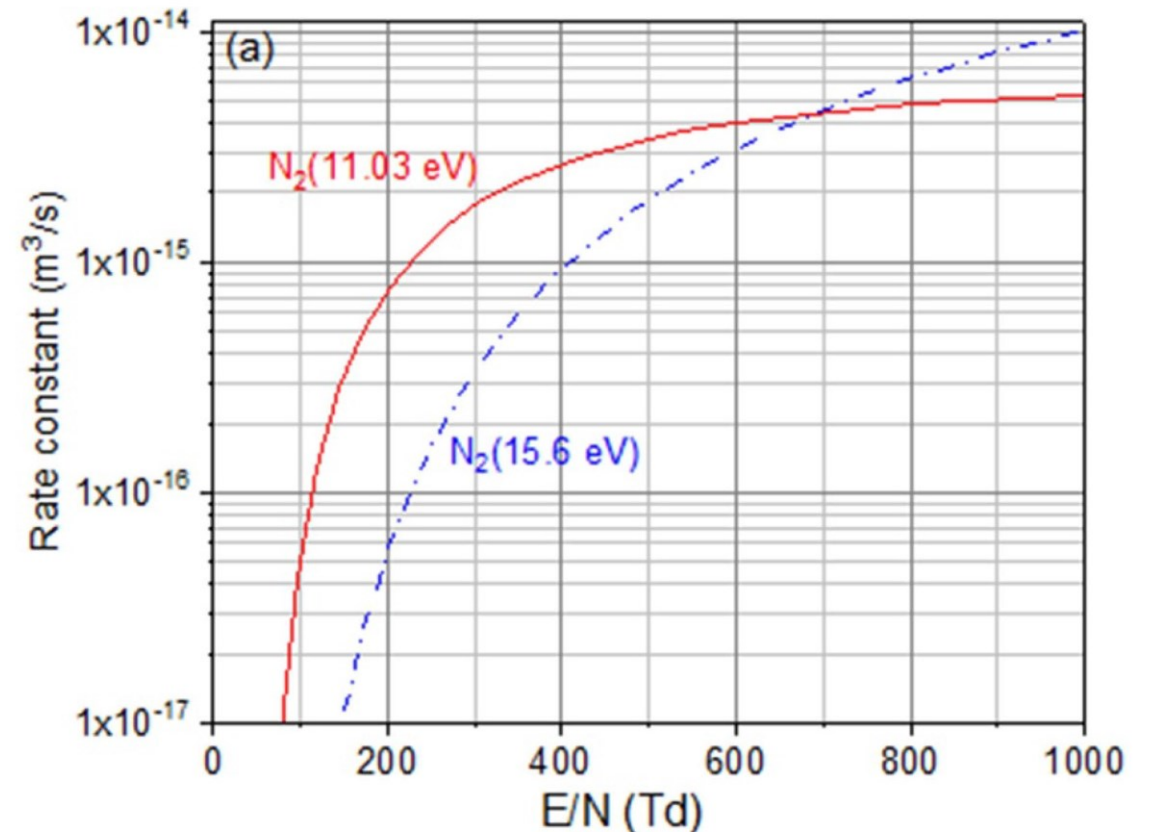
Plasma Chemistry



Examples of rate constants

- Rate constants of excitation of $N_2(C^3\Pi_u)$ (threshold 11.03 eV) and ionization of N_2 (threshold 15.6 eV)

→ Strong functions of the reduced electric field



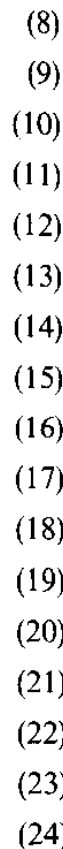
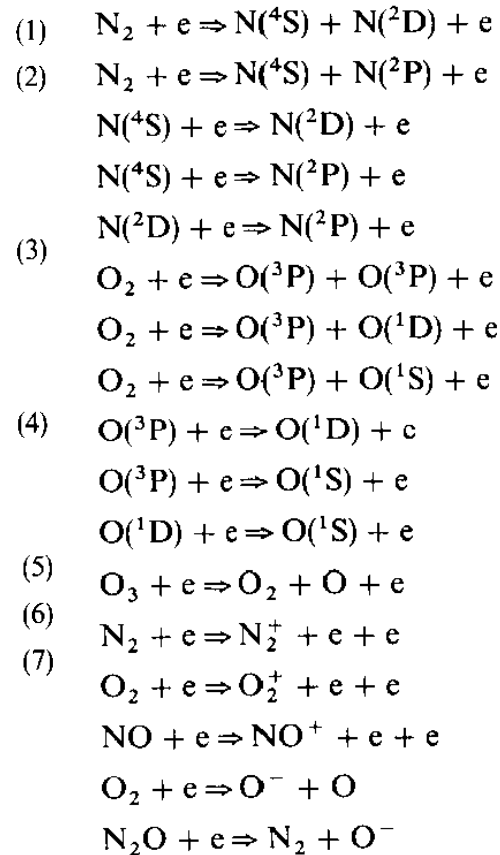
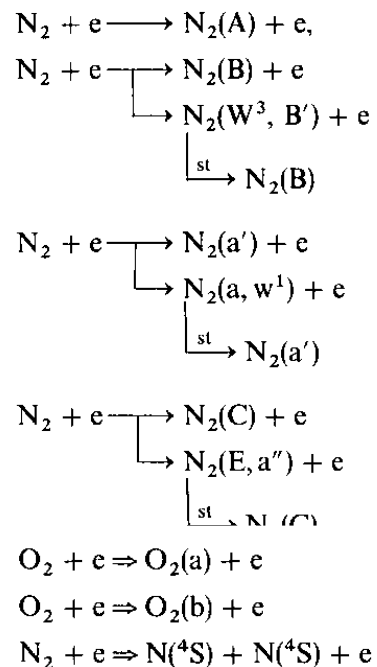
Starikovskaia et al., PSST, 2026

Plasma Chemistry



For some gases, simplified chemical kinetic models are available in the literature (then no need for EEDF calculations)

Example of electron impact chemical kinetic model for synthetic air ($4N_2 + O_2$)



$$\begin{aligned}
 \log k_1 &= -8.4 - 14/\vartheta \\
 k_2 &\simeq k_{e-B} + k_{e-w^3} + k_{e-B'} \\
 \log k_{e-B} &= -8.2 - 14.8/\vartheta \\
 \log k_{e-w^3} &= -8.3 - 15.4/\vartheta \\
 \log k_{e-B'} &= -8.7 - 16.8/\vartheta; \\
 k_3 &\simeq k_{e-a'} + k_{e-a} + k_{e-w^1} \\
 \log k_{e-a'} &= -8.8 - 16.7/\vartheta \\
 \log k_{e-a} &= -8.5 - 17.4/\vartheta \\
 \log k_{e-w^1} &= -8.7 - 17.5/\vartheta \\
 k_4 &\simeq k_{e-C} + k_{e-E} + k_{e-a''} \\
 \log k_{e-C} &= -8.2 - 21.1/\vartheta \\
 \log k_{e-E} &= -10.1 - 25.4/\vartheta \\
 \log k_{e-a''} &= -9.2 - 26.2/\vartheta \\
 \log k_5 &= \begin{cases} -9 - 5.2/\vartheta & \text{at } \vartheta < 4 \\ -10.2 - 0.35/\vartheta & \text{at } \vartheta > 4 \end{cases} \\
 \log k_6 &= \begin{cases} -9.5 - 6/\vartheta & \text{at } \vartheta < 3 \\ -11.2 - 0.72/\vartheta & \text{at } \vartheta > 3 \end{cases} \\
 \log k_{13} &\simeq \log k_{(X \rightarrow A + e^1 + C^3)} = -7.9 - 13.4/\vartheta \\
 \log k_{14} &\simeq \log k_{(X \rightarrow B^3 + ^3\Pi_g)} = -8 - 16.9/\vartheta \\
 \log k_{15} &\simeq \log k_{(X \rightarrow 9.7 - 12.1 eV)} = -8.8 - 11.9/\vartheta
 \end{aligned}$$

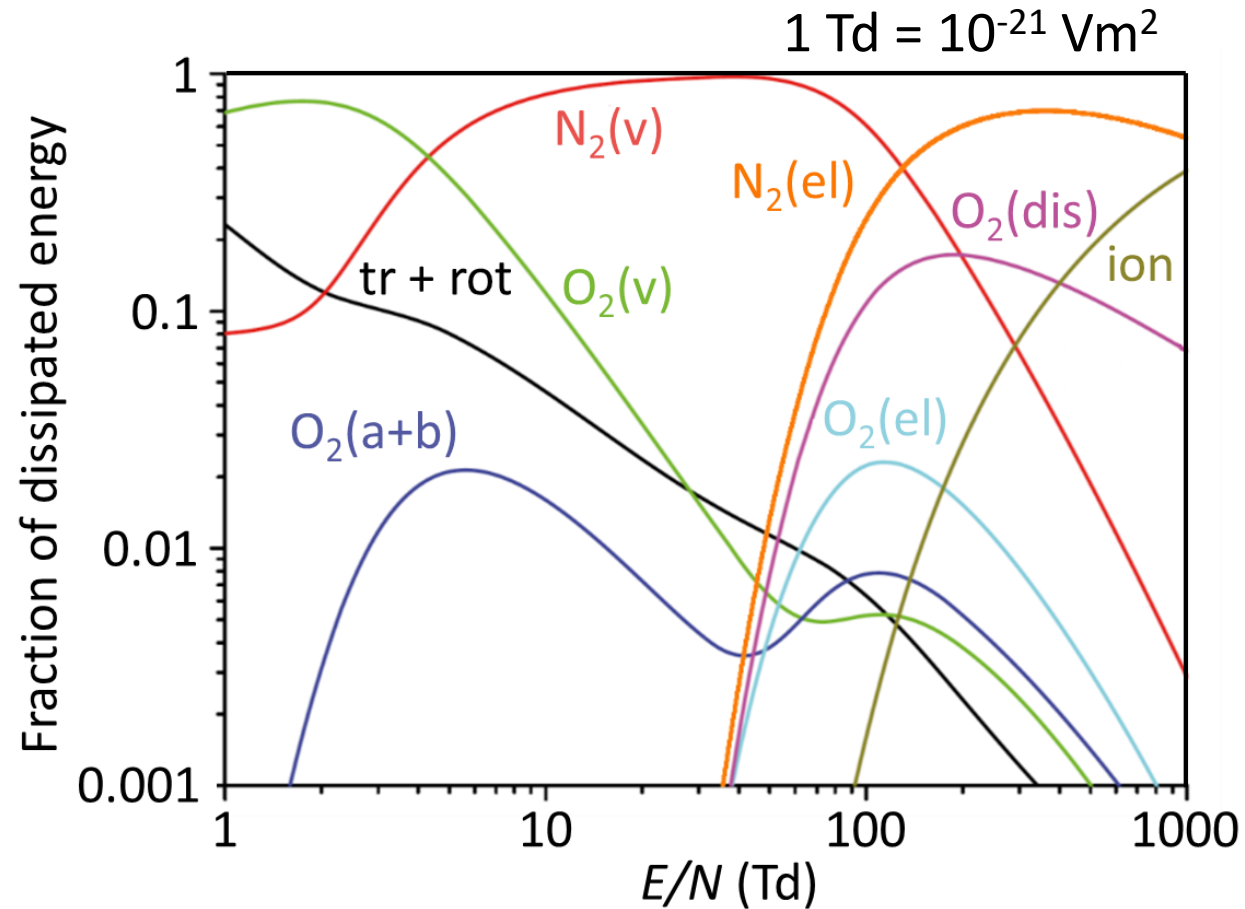
$$\begin{aligned}
 \log k_{20} &= -8.3 - 36.5/\vartheta \\
 \log k_{21} &= -8.8 - 28.1/\vartheta \\
 \log k_{23} &= \begin{cases} -9.3 - 12.3/\vartheta & \text{at } \vartheta > 8 \\ -10.2 - 5.7/\vartheta & \text{at } \vartheta > 8. \end{cases}
 \end{aligned}$$

With $\vartheta = E/N$

Plasma Chemistry



Example of electron energy loss fraction in air



Plasma Chemistry



But plasma chemistry involves more than electron impact chemistry

Electron impact reactions

- Excitation:
 - $e + M \rightarrow M(\text{rot}) + e$
 - $e + M \rightarrow M(\text{v}) + e$
 - $e + M \rightarrow M(\text{el}) + e$
- Dissociation:
 - $e + M_2 \rightarrow M + M + e$
- Ionization:
 - $e + M \rightarrow M^+ + 2e$
- Attachment:
 - $e + M \rightarrow M^-$

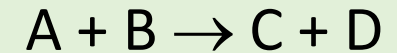
$$k_e(E/N)$$

Ion reactions

- Positive ion recombination:
 - $e + M^+ \rightarrow M$
 - $M^+ + M \rightarrow 2M + e$
- Electron detachment:
 - $M^- + M \rightarrow M + M + e$
- Associative ionization:
 - $M(\text{el}) + M(\text{el}) \rightarrow M_2^+ + e$

$$k_i\left(\frac{E}{N}, T\right)$$

Neutral particle reactions



$$k_n(T, p)$$

Plasma Chemistry



Examples of open-source numerical tools

- **Bolsig+**: electron Boltzmann equation (EBE) solver (Windows application)
→ <https://www.bolsig.laplace.univ-tlse.fr/index.html>
- **BOLOS**: library for solutions of the Boltzmann equation for electrons (Python)
→ <https://github.com/aluque/bolos>
- **ZDPlasKin**: zero-dimensional plasma kinetics solver (Fortran 90)
→ <http://www.zdplaskin.laplace.univ-tlse.fr/index.html>
- **LXCat**: platform for archiving and manipulating collections of data related to electron scattering and transport in cold, neutral gases
→ <https://nl.lxcat.net/home/>

References



Papers

- *D.A. Lacoste, Flames with plasmas, Proc. Combust. Inst. 39, 5405-5428, 2023*
- *S.M. Starikovskaia, V. Lafaurie, J.-B. Perrin-Terrin, C.O. Laux, Foundations of plasma-assisted combustion: I. Fundamentals of combustion and plasma, Plasma Sources Sci. Technol. 35, 023001, 2026*

Books

- *Gas discharge physics, Yu. P. Raizer, Springer-Verlag, Berlin Heidelberg, Germany, 1991*
- *Plasma Assisted Combustion and Chemical Processing, Yiguang Ju & Andrey Starikovskiy, CCRC Press, Taylor and Francis Group, Boca Raton, FL, USA, 2025*

Chapter V: Basics of Plasma-Assisted Combustion



- *Coupling Mechanisms*
- *Ignition*
- *Combustion Enhancement*
- *References*



Coupling Mechanisms

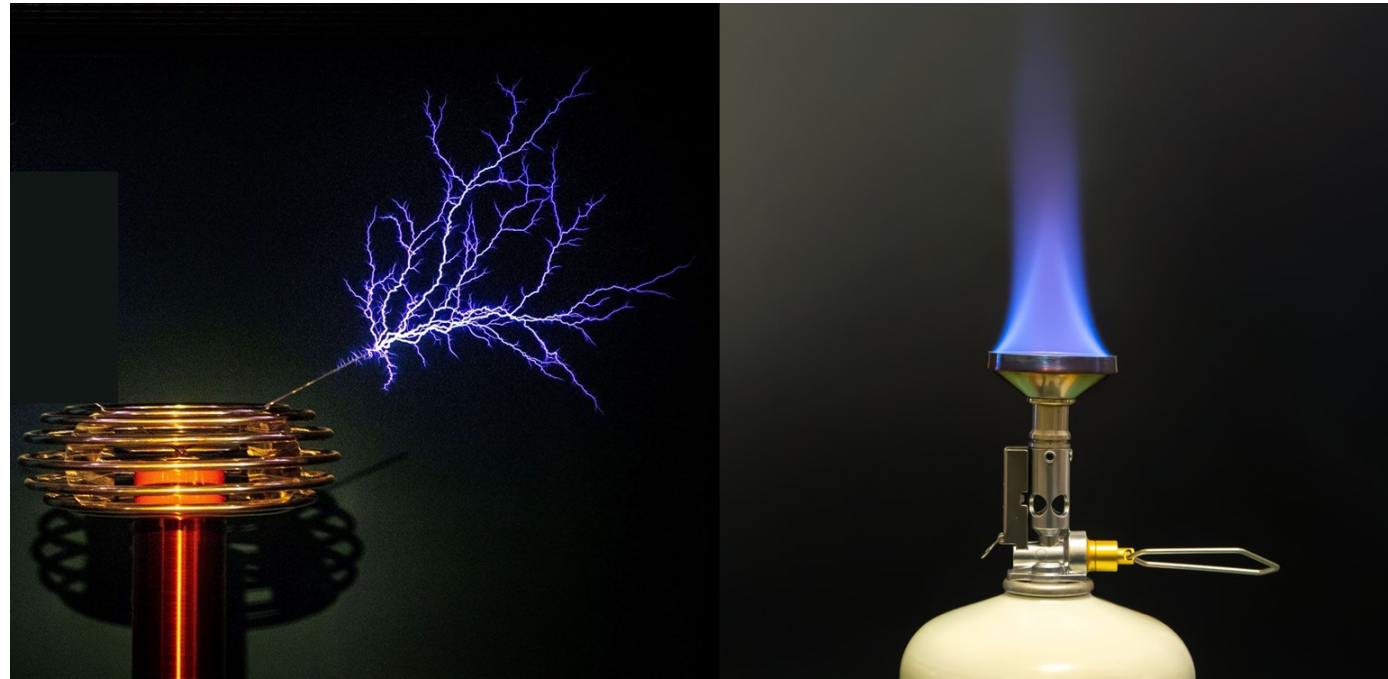


Both flames and electric discharges of gases are highly reactive exothermic environments

Their physics is different, but they both change

- The chemical composition
- The temperature
- The transport properties

Plasma-assisted combustion studies mainly focus on the effect of the discharges on combustion/ignition



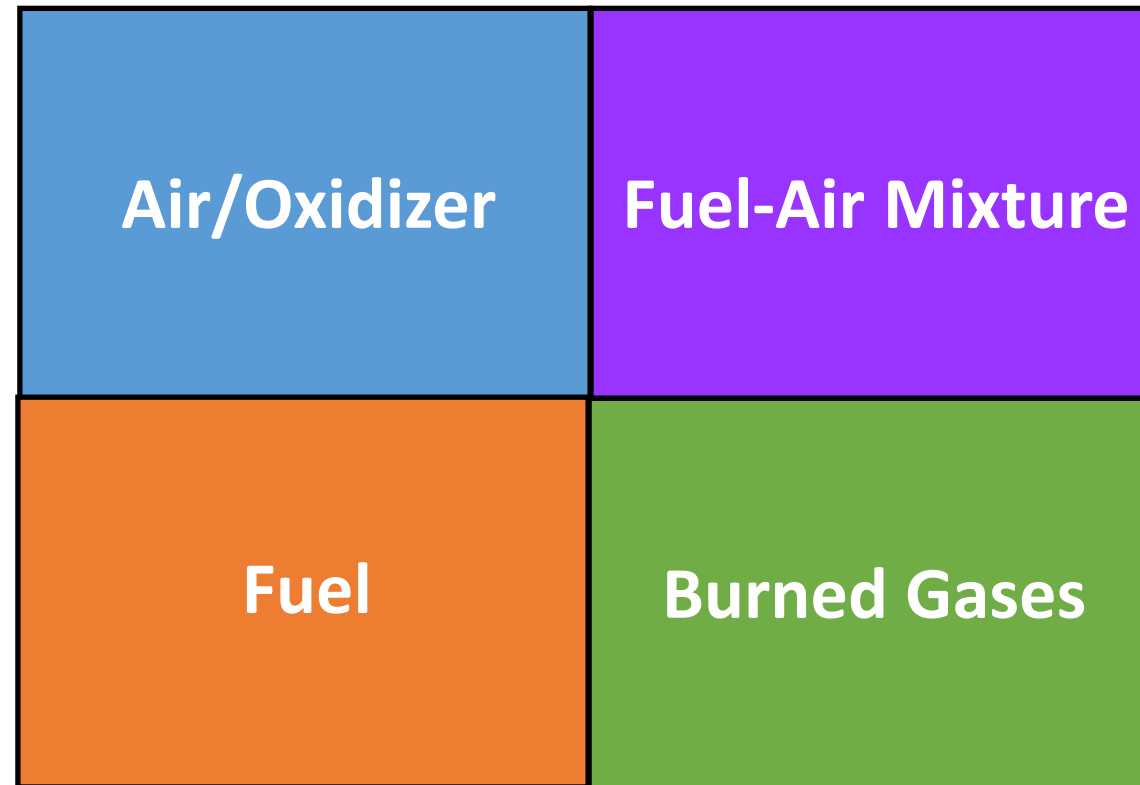
However, it is important to keep in mind that combustion can also affect gas discharge plasma

Coupling Mechanisms



Because electric discharges depend on the gas composition and thermodynamic conditions, the location of the plasma actuator in the combustion system is crucial

Four main options:

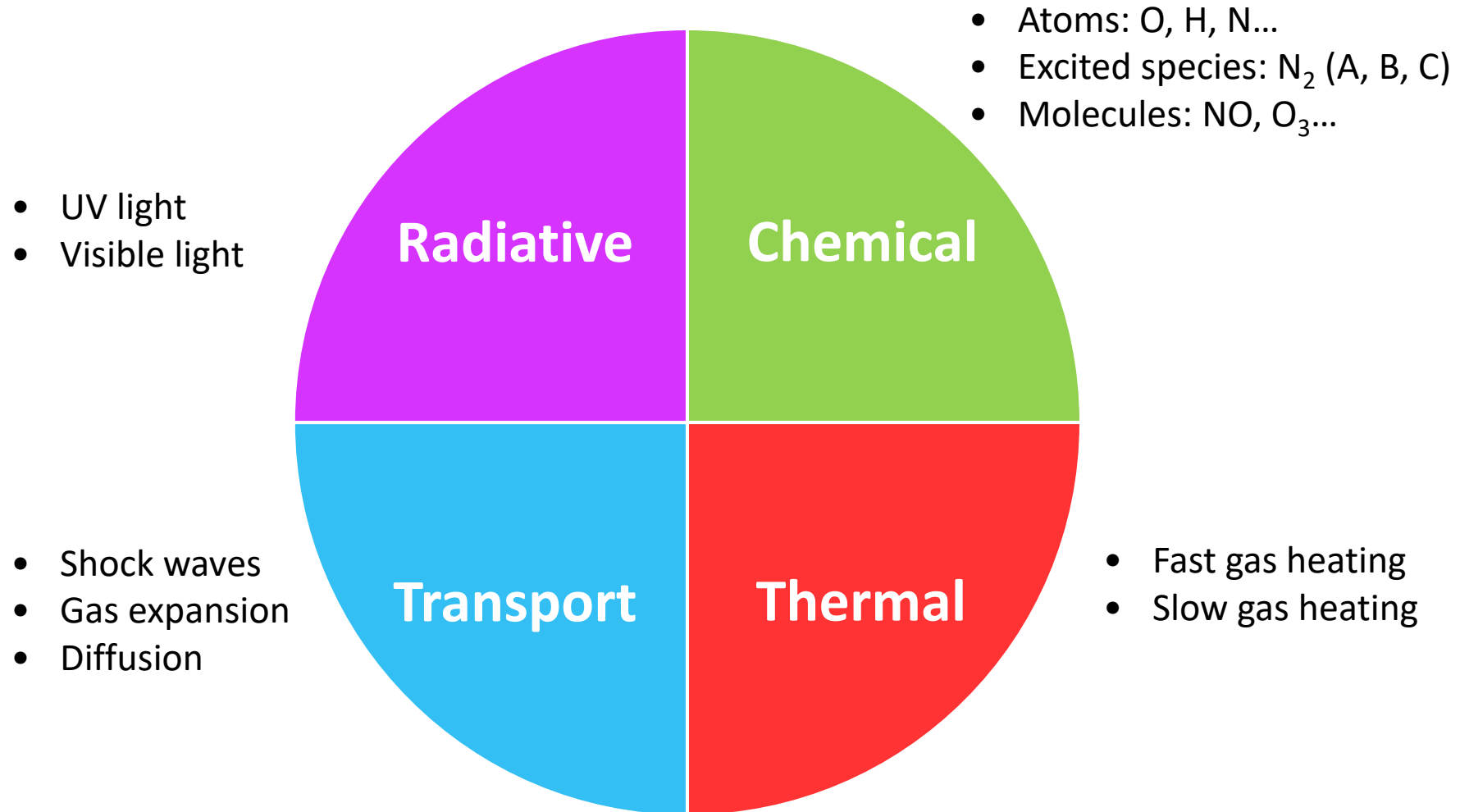


The best location depends on the targeted effect and on the combustion system

Coupling Mechanisms



Four coupling mechanisms



Coupling Mechanisms



Chemical effect

Depending on the reduced electric field, electron impact reactions produce different chemical species that are more or less efficient in enhancing combustion

The species produced by the discharges of interest to enhance combustion are:

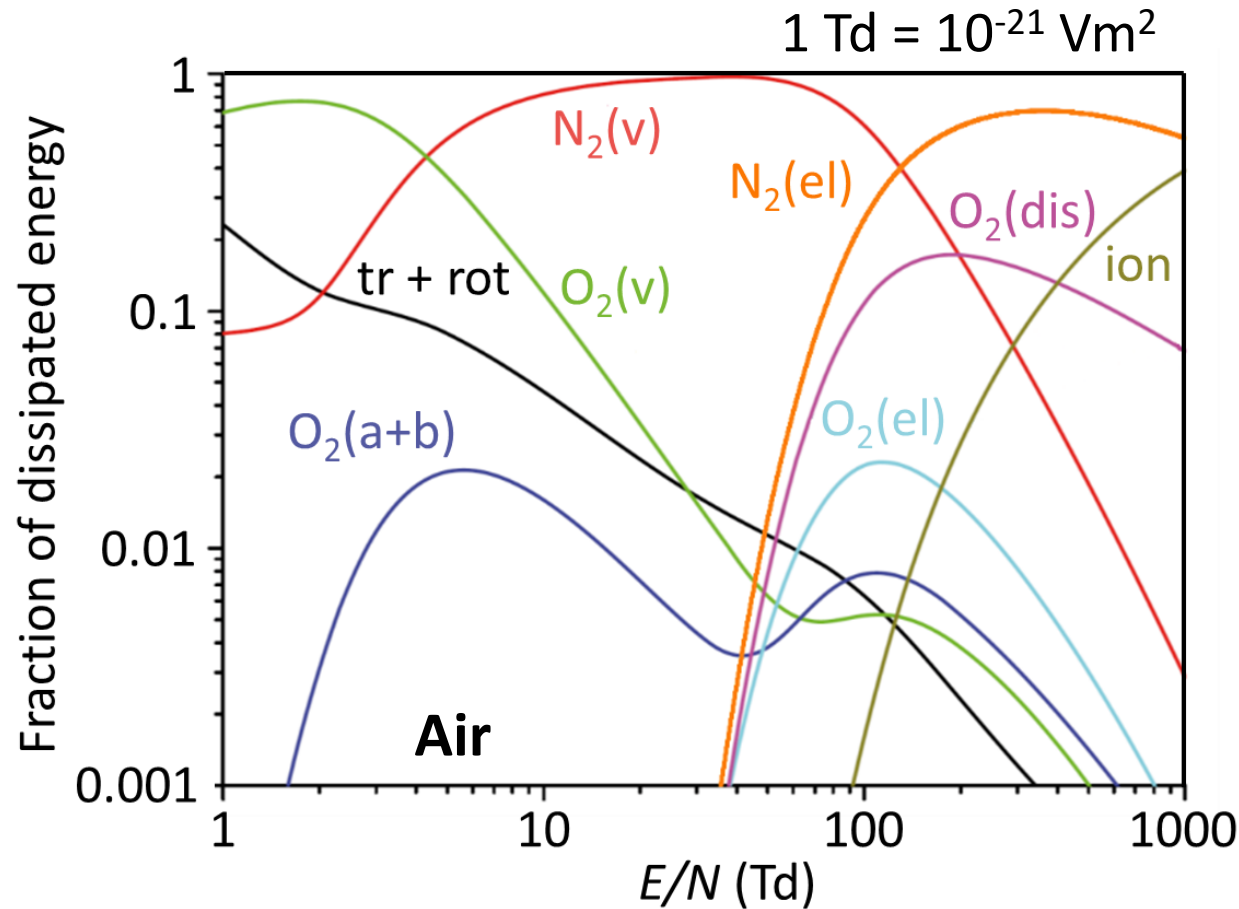
- combustion species that contribute to chain initiation and chain branching reactions
- similar but more energetic than combustion species
- species that produce combustion species during fast/exothermic processes

In air containing mixtures, these key chemical species are produced for reduced electric field in the range 80 – 1000 Td

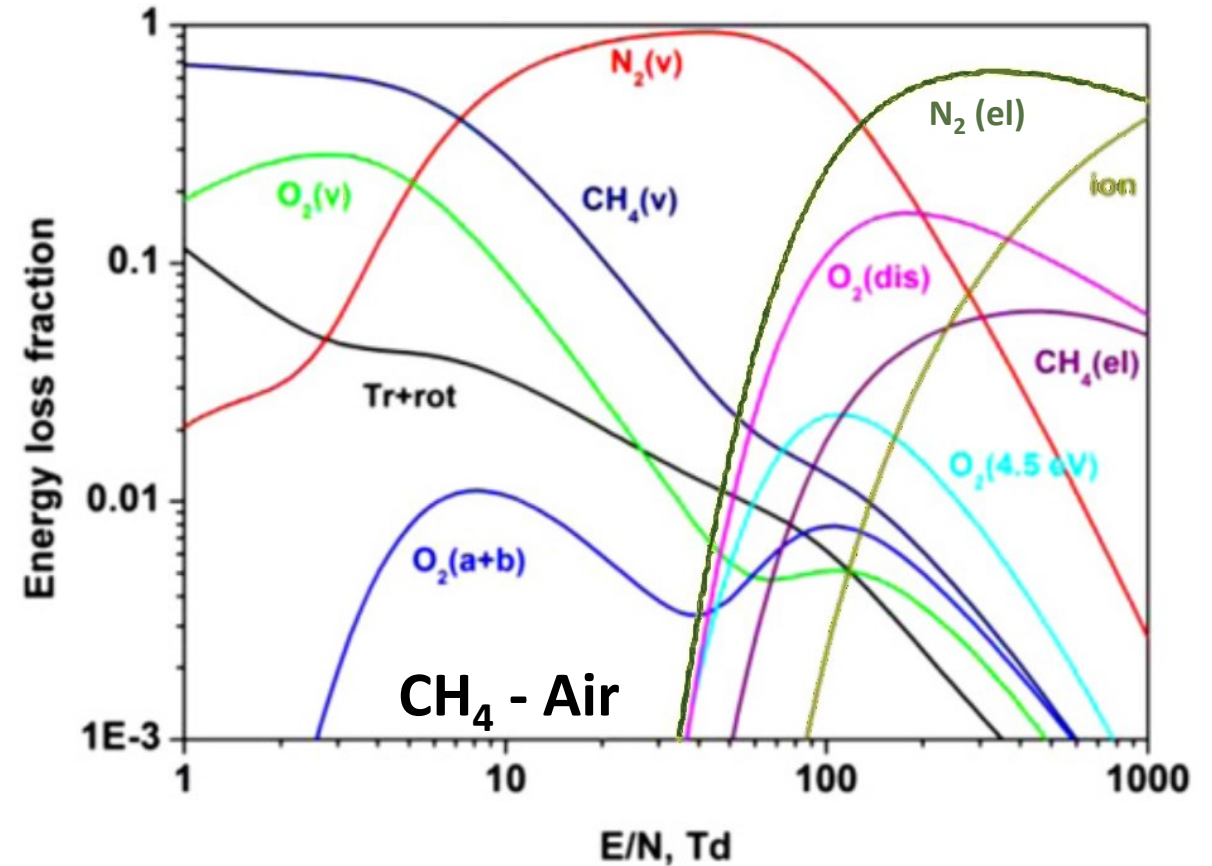
Coupling Mechanisms



Examples of species of interest for combustion enhancement



Starikovskiy et al., *Phil. Trans. R. Soc. A*, 2012



Starikovskiy and Aleksandrov, *PECS*, 2013

Coupling Mechanisms



Examples of species of interest for combustion enhancement

In **air containing gases** (air, fuel/air mixture, exhaust gases of lean combustion), the **main key species** produced by electrical discharges are:

- Atomic oxygen (O)
- Singlet oxygen ($^1\text{O}_2$)
- Ozone (O_3), that will dissociate into $\text{O} + \text{O}_2$
- Electronically excited N_2 (A, B, C...), that will dissociate O_2 into molecular O by dissociative quenching

In addition, in **fuel-air mixtures** or in the **burned gases of lean combustion**:

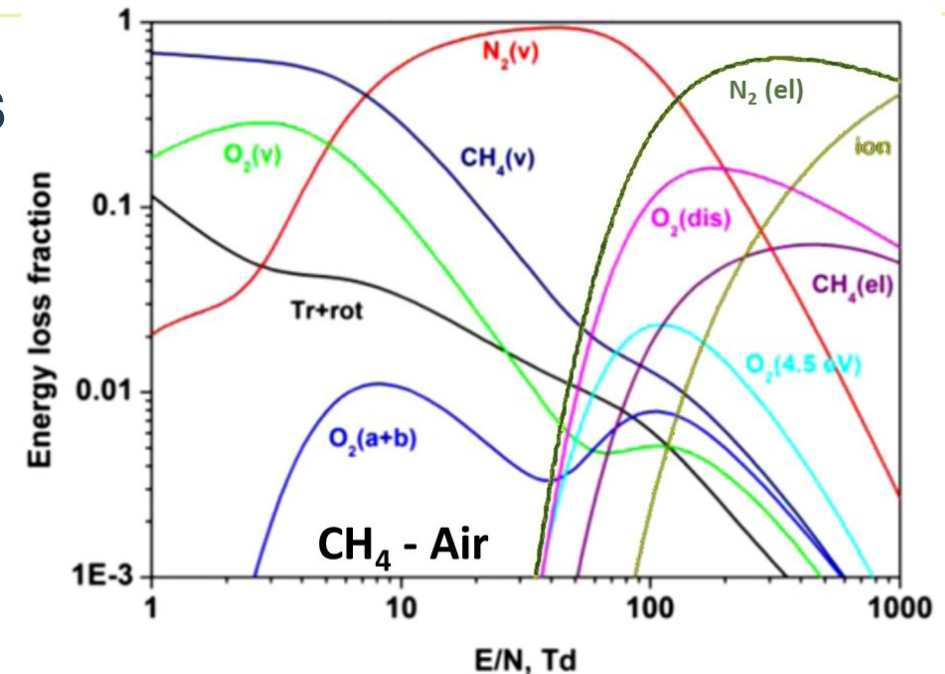
- Atomic hydrogen (H)
- Hydroxyl radical (OH)
- Methyl radical (CH_3) - (fuel-air mixtures)
- Methylidyne radical (CH) - (fuel-air mixtures)
- Carbon monoxide (CO) - (burned gases)

Coupling Mechanisms

Thermal effect

In PAC, two different thermal effects are considered:

- Slow heating
- Fast heating



The thermal effect of the discharges will also be controlled by the electron impact chemistry

- At $E/N < 10$ Td, about 10% of the electron energy goes into direct heating of the gas, the rest goes into vibrational excitation of molecules
 - These vibrationally excited molecules can affect the chemistry or release their energy as heat on characteristic time scales of VT-relaxation, τ_{VT}
 - In conditions of PAC applications, $\tau_{VT} \sim 10\text{--}100 \mu\text{s}$
 - **This is generally considered as slow gas heating**

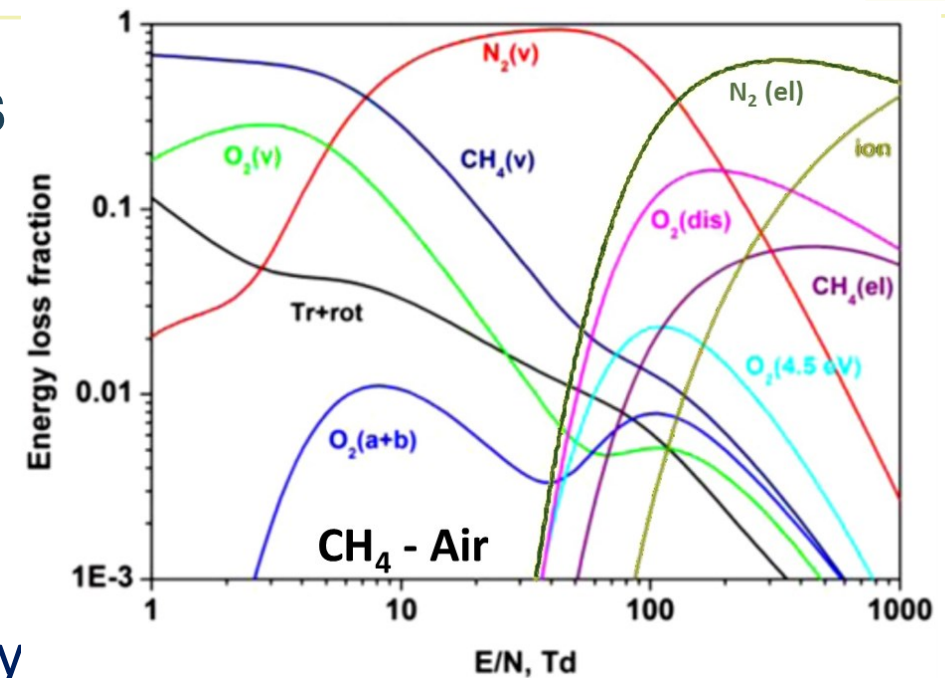
Coupling Mechanisms

Thermal effect

- At $10 < E/N < 80$ Td, the main part of electron energy goes into vibrational excitation of nitrogen
 - **Slow gas heating**
- At $80 < E/N < 1000$ Td, the main part of electron energy goes into electronic excitation of nitrogen
 - These energetic states of nitrogen reacts quickly (~ 10 ns) with oxygen, releasing a significant amount of heat



→ **Fast gas heating**



Coupling Mechanisms

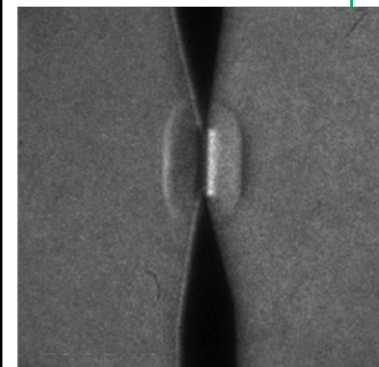


Transport effect: a consequence of the plasma chemistry

- Change in chemical composition → Change of diffusion properties
- Increase in gas temperature:
 - Slow gas heating → Gas expansion → Plasma induced flow, including jets and vortices
 - Fast gas heating → Shock wave and gas expansion

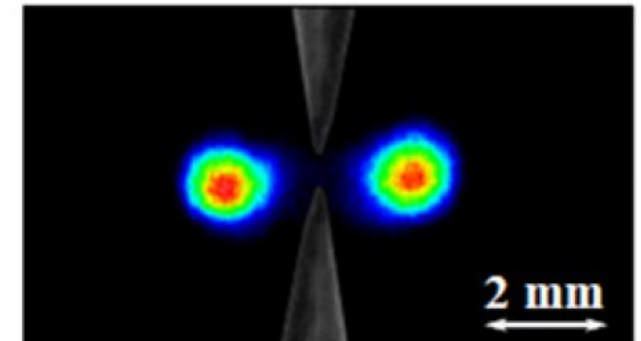
- Flow/Flame perturbations
- Part of the discharge energy will be moved away from the plasma channel by the shock

Plasma induced flow, including jets and vortices



Xu et al.
Appl. Phys. Lett., 2011

Stepanyan et al
J Phys D: Appl. Phys., 2019

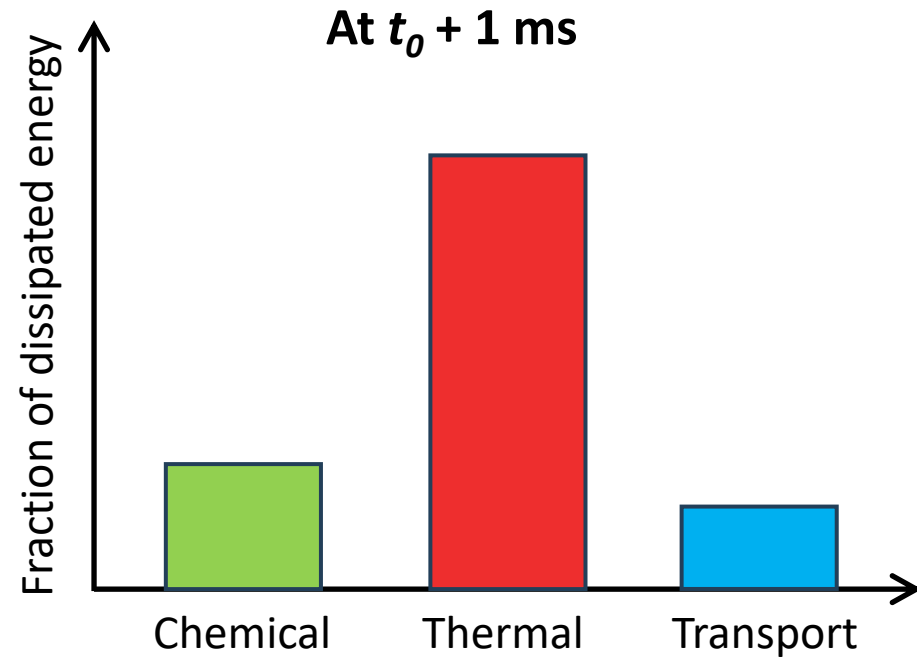
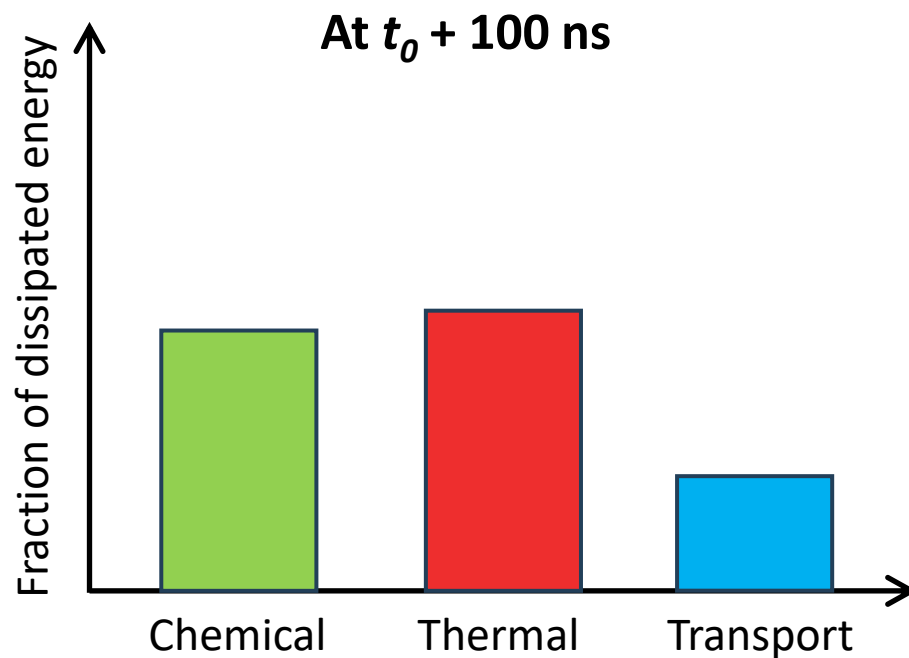


Coupling Mechanisms



In real life, chemical, thermal and transport effects are coupled

However, by playing with the discharge parameters, it is only possible to play with the energy branching (i.e., which fraction of the electron energy goes into each effect)



The energy branching is a function of time

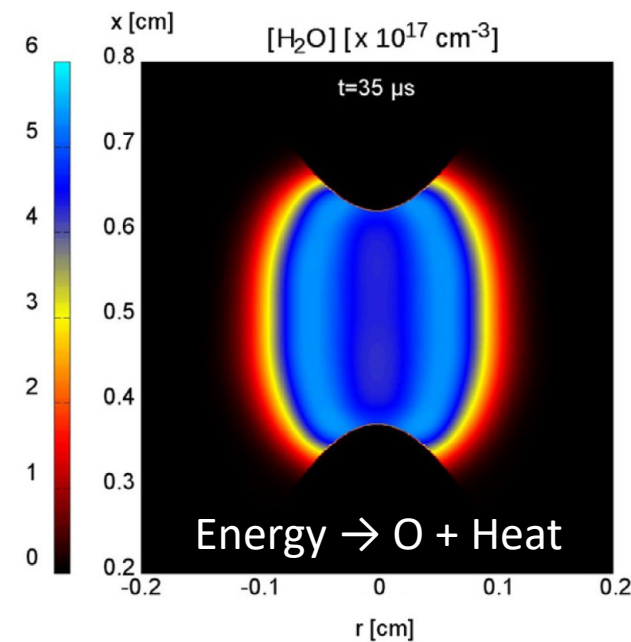
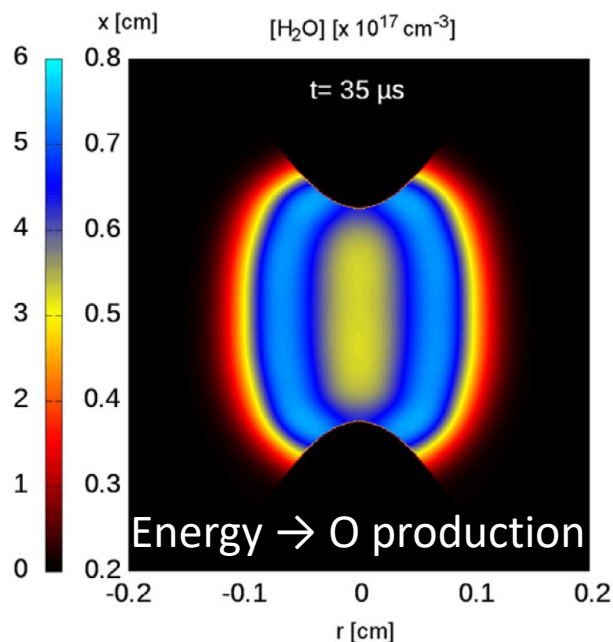
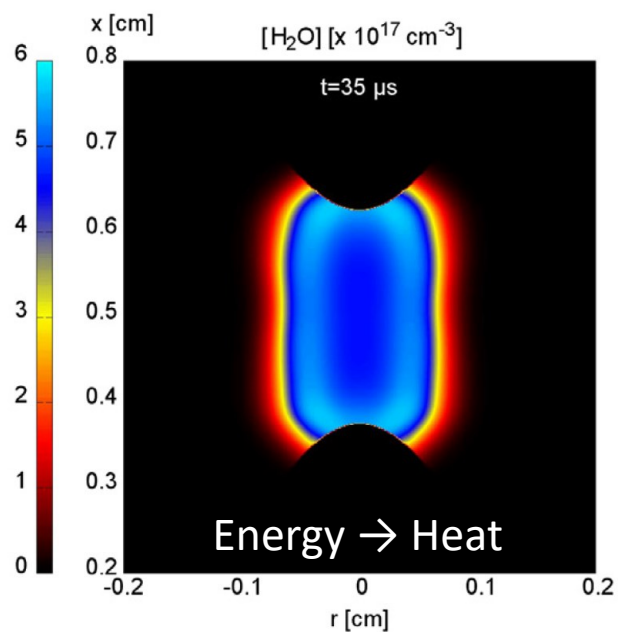
Coupling Mechanisms



In numerical life, it is possible to decouple the chemical, thermal and transport effects

- provide guidance on which effect should be promoted to achieve a targeted goal
- challenges in modeling and in coupling plasma and combustion codes

Example of 2D simulations of $\text{H}_2\text{-O}_2$ ignition with different energy branching



Tholin et al., *Combust. Flame*, 2014

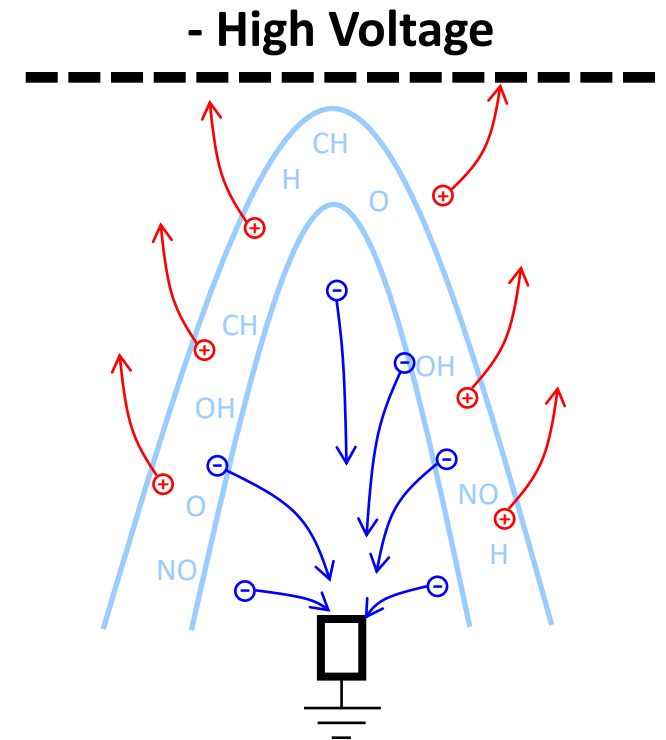
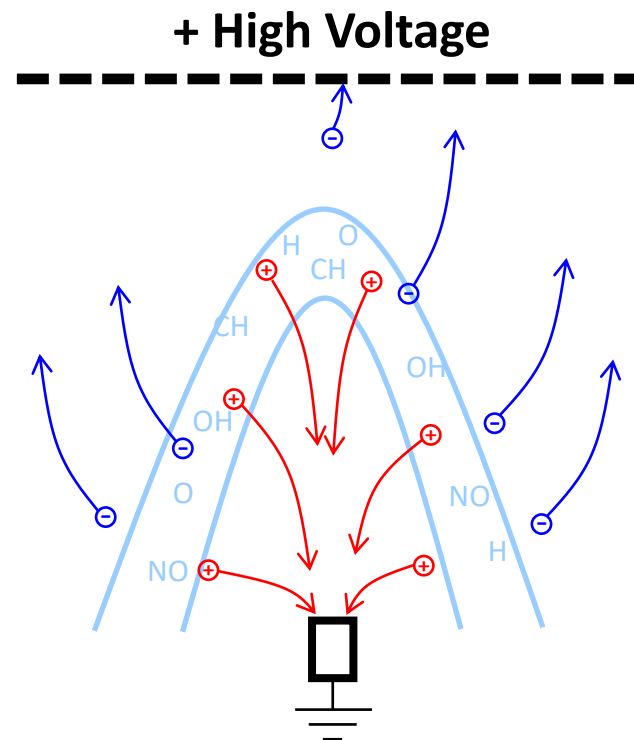
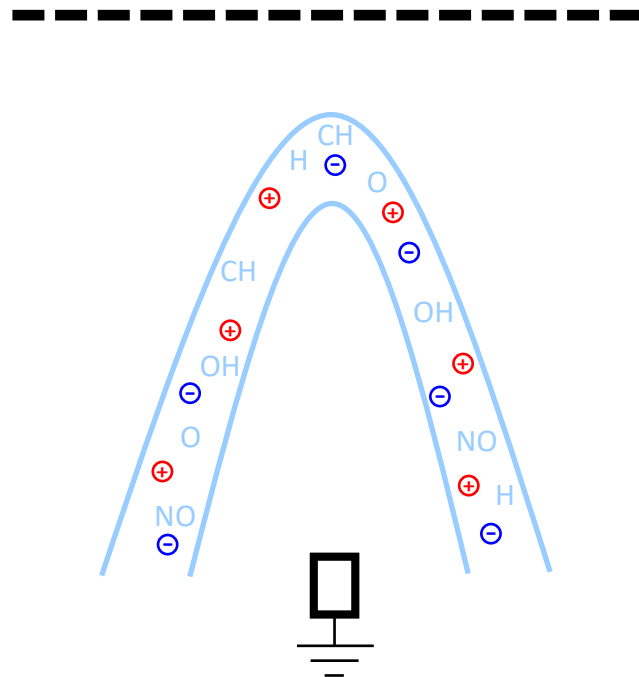
Coupling Mechanisms



Transport effect: the special case of ionic wind

- PAC without any additional discharge → the flame itself is the plasma
- The response time of the flame is ~ 1 ms, then ionic wind is noticeable only for DC, AC and μ s-pulsed applied voltages
- Ionic wind effect on turbulent flames is marginal

$$E < E_{breakdown}$$



Chapter V: Basics of Plasma-Assisted Combustion



- *Coupling Mechanisms*
- ***Ignition***
- *Combustion Enhancement*
- *References*



Ignition



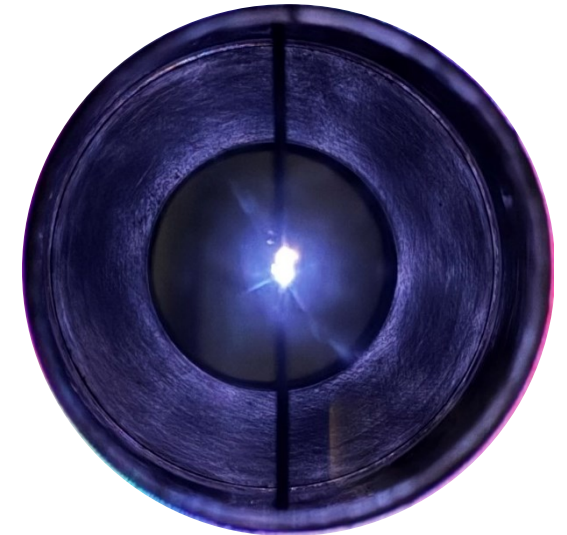
Ignition of flammable mixtures by sparks has been used for more than a century (see Chapter II)

Plasma-assisted ignition (PAI) refers to any ignition strategy that are produced by discharges that are not generated by a high-voltage pulse of duration $\sim 10 \mu\text{s} - 5 \text{ms}$

The goal of these new ignition sources is to allow ignition of mixtures that are difficult to ignite with conventional systems or to improve combustion properties (including pollutant emissions)

Four parameters are commonly used to characterize ignition:

- The ignition delay time
- The Minimum Ignition Energy (MIE)
- The flammability limits (lean, rich, diluted...)
- The reproducibility of ignition

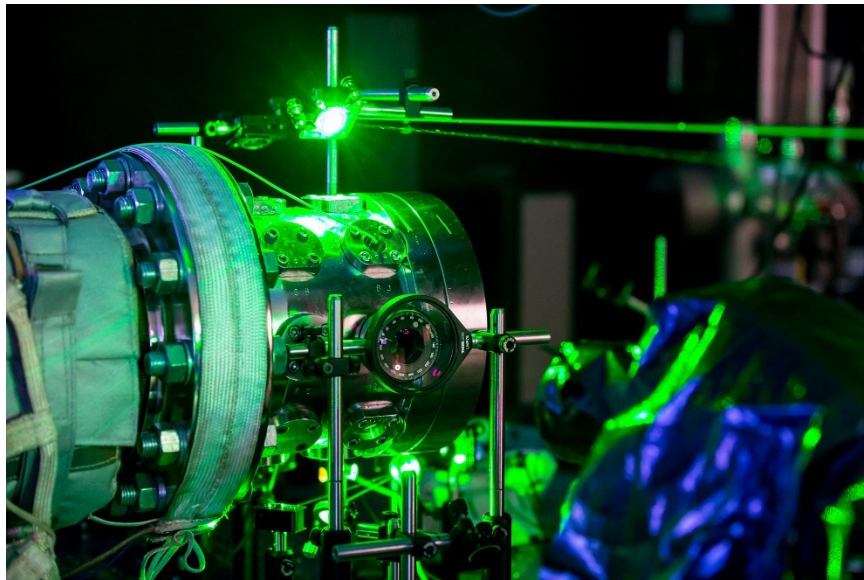




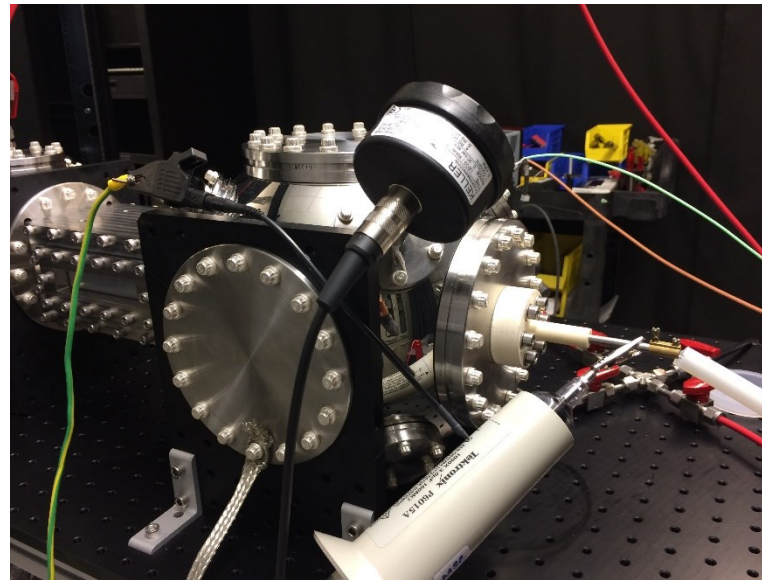
Ignition

PAI studies can be grouped in three large families:

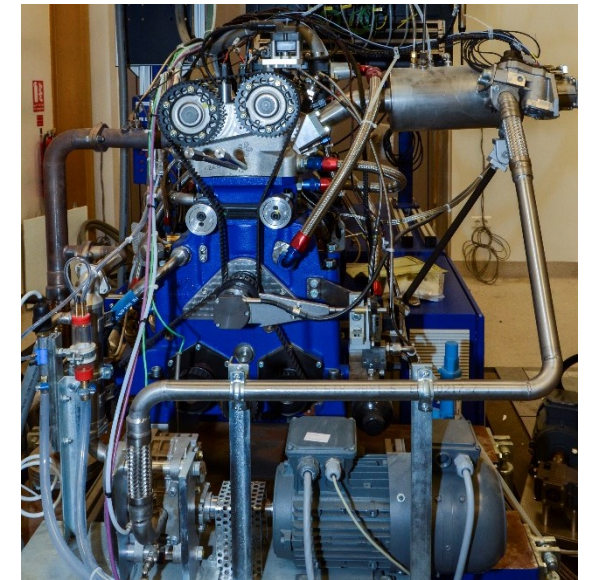
1. Fundamental: in shock tubes and rapid compression machines (RCM)
2. Model systems: constant volume combustion chambers (CVCC) and continuous-flow burners
3. Applied: piston engines or scramjets



Shock tube with laser diagnostics
KAUST



CVCC for ignition studies
KAUST



Test engine
KAUST

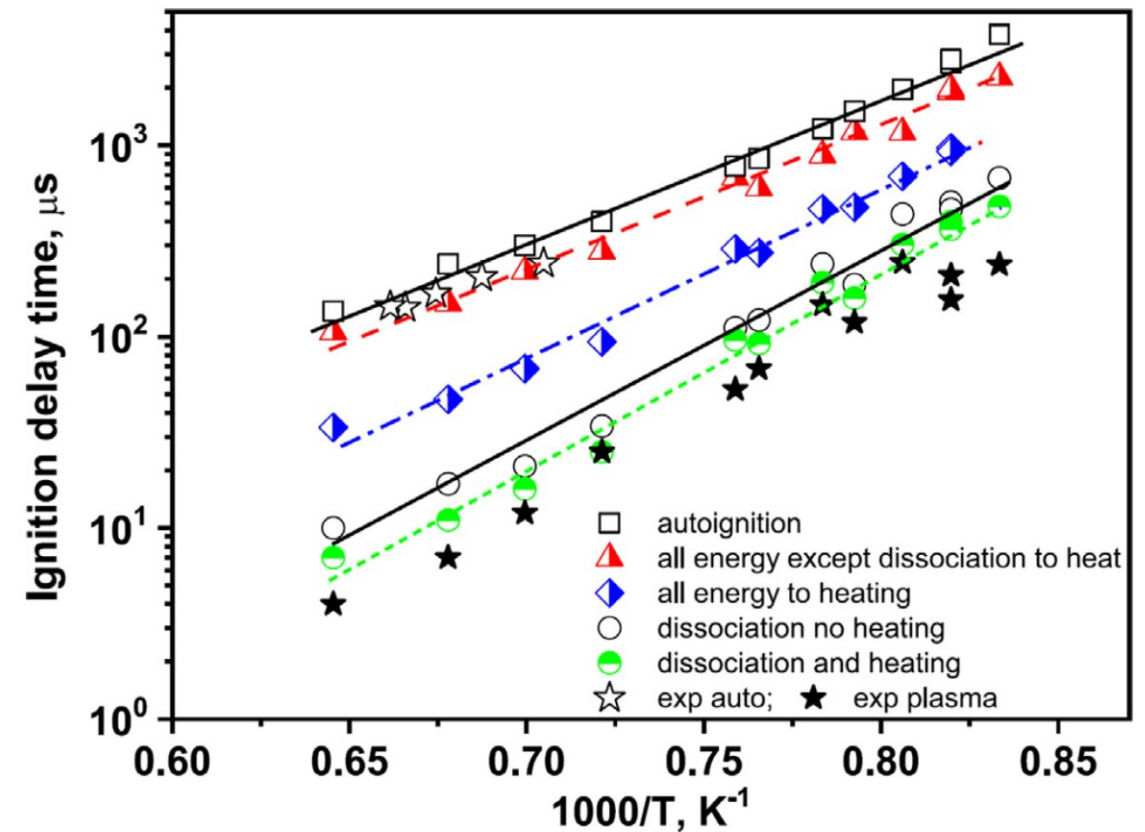
Ignition



PAI studies in shock tubes: controlled high temperature and pressure conditions

- Plasma effect on ignition (autoignition) delay time
- Usually coupled with chemical modeling and simulations
- Only a few plasma sources and fuels have been studied

→ **More shock tube/RCM experiments are needed!**

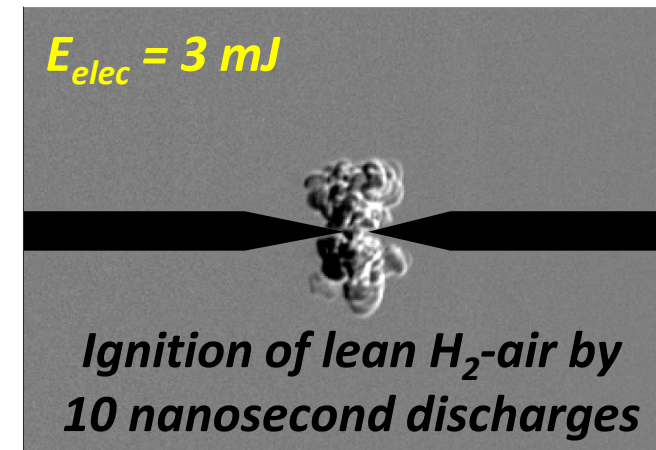
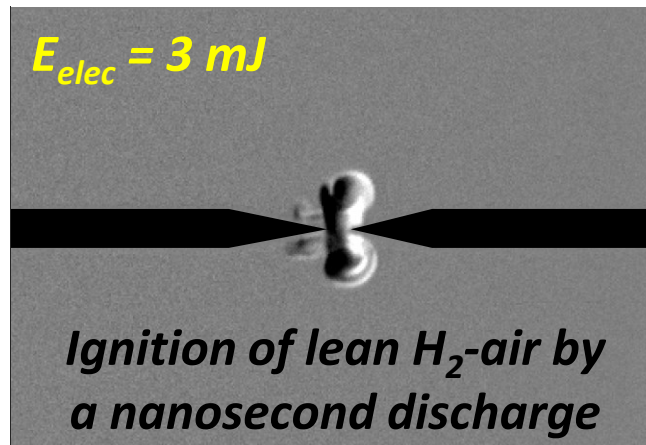




Ignition

PAI studies in CVCC or lab burners: controlled temperature, pressure and flow

- Plasma effect on ignition delay time and MIE
 - Most common studies in PAI
 - Large ranges of conditions, fuels & discharges have already been covered
 - Precise understanding of the plasma action is difficult because all plasma effects are coupled
- Useful to study plasma-induced flow (transport effect)



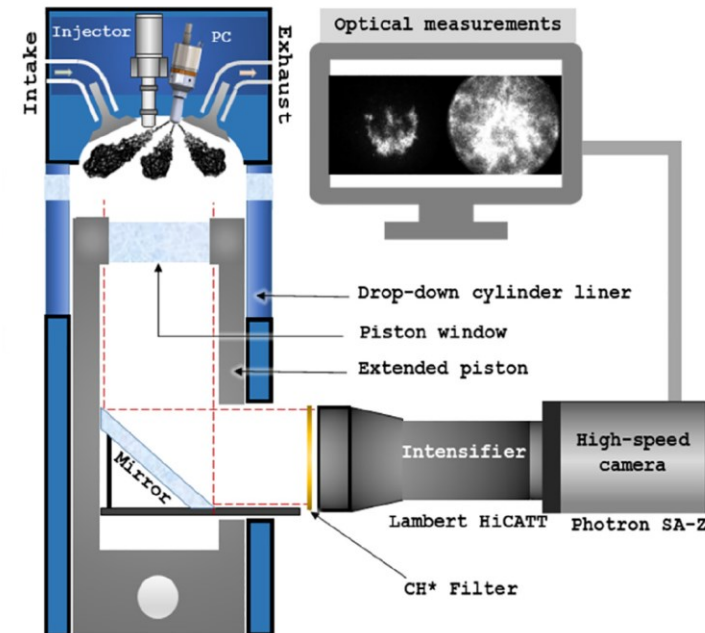
Ignition



PAI studies in engines: demonstration of ignition capability in realistic environments

- Effect on the coefficient of variation (COV) of indicated mean effective pressure (IMEP)
- Effect on ignition delay time
- Effect on heat release rate (HRR)
- Only a few engine studies, with surrogate or real fuels
- Ignition systems tested: microwave, microwave-spark, multiple nanosecond discharges

→ More collaboration with engine manufacturers is needed!



Ignition



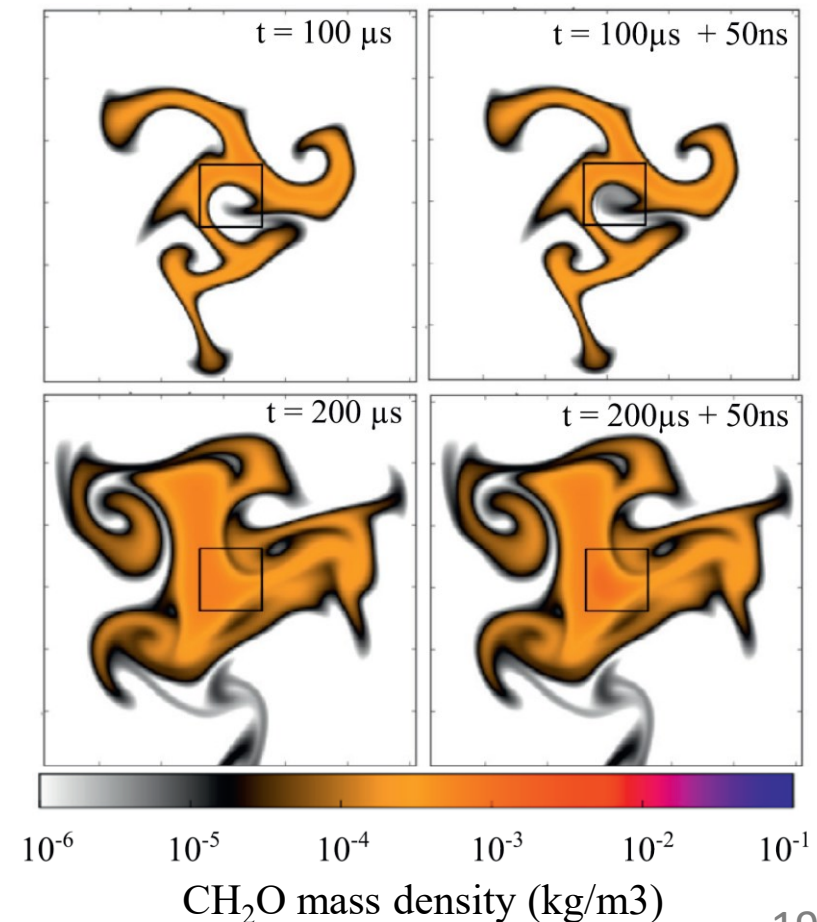
PAI main mechanisms

Three effects of nonequilibrium gas discharge plasma have proven to be important in plasma-assisted ignition:

- The decrease of ignition delay time due to the production of active **chemical species**
- The acceleration of chain branching and chain prolongation reactions due to **fast temperature increase**
- The **hydrodynamic** perturbations and resulting mixing, induced by gas heating (not always beneficial!)

2D simulations of ignition by multiple nanosecond discharges in turbulent flow

Castela et al, Combust. Flame, 2016



Chapter V: Basics of Plasma-Assisted Combustion



- *Coupling Mechanisms*
- *Ignition*
- ***Combustion Enhancement***
- *References*



Combustion Enhancement



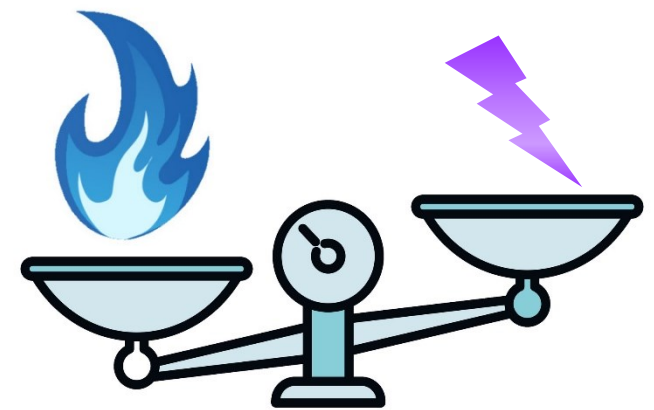
Plasma-assisted combustion studies focus on enhancing combustion with the lowest amount of electrical energy/power

→ **Strong advantage of discharges producing nonequilibrium plasma compared to equilibrium plasma**

For combustion systems with a permanent flame such as boilers or gas turbine engines, the **plasma power** should be as low as possible compared to the **flame thermal power**

Four groups of PAC studies have shown interesting results:

- Enhancement of lean flammability/stability limits
- Control of flame dynamics
- Reduction of pollutant emissions
- Enhancement of supersonic combustion/detonation



Combustion Enhancement



Early PAC studies focused on:

- solving a combustion problem (combustion stability, pollutant emissions, or flammability limits)
- providing fundamental understanding on the PAC mechanisms at play
- demonstrating the usefulness of a specific tool, either numerical or experimental

Recent PAC studies almost always:

- propose a comprehensive investigation of the plasma actuator (e.g., effect on combustion & on pollutant emissions)
- showcase a strong PAC result with progress in the understanding of plasma-flame coupling
- combine numerical and experimental tools to study a specific problem
- combine different tools to propose new investigation capabilities (e.g., coupled plasma and combustion numerical tools)

Combustion Enhancement



Enhancement of lean flammability/stability limits by PAC

- Very mature research area, with a large range of conditions and plasma sources studied

Burner	Fuel	Pressure (bar)	Flame power (kW)	Plasma source	Plasma location	Plasma power (W)	LBO / stability extension
Bluff-body stabilized	Propane Methane	1	11	NRP discharges	Burned gases	70	10%
Jet	Methane	3.3	50	NRP discharges	F-A mixture	500	25%
Swirl	Kerosene Methane Ammonia Hydrogen	1- 5	2-50	NRP discharges DBD Gliding arc	F-A mixture Fuel	10-500	5-50%
Swirled staged	Propane Methane	1	11-150	NRP discharges	F-A mixture	350-370	25-70%
Swirled spray	Heptane Dodecane	1	5	NRP discharges	Burned gases	100	10%
Flat-flame	Methane	1	0.75	Microwave discharges	Flame	75	50%

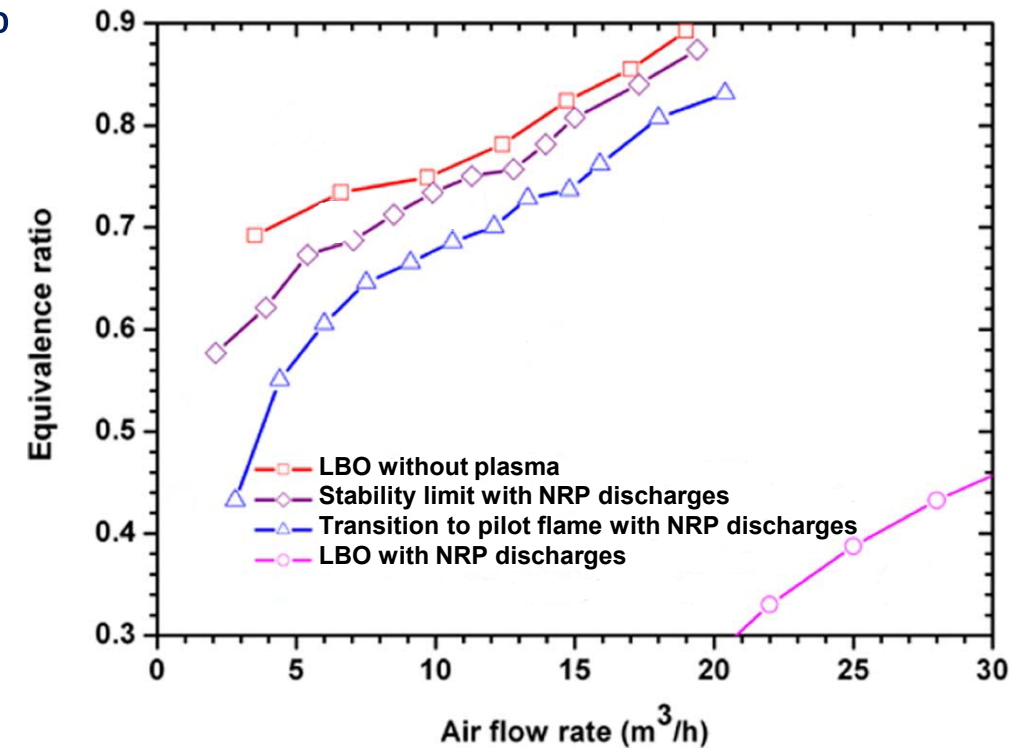
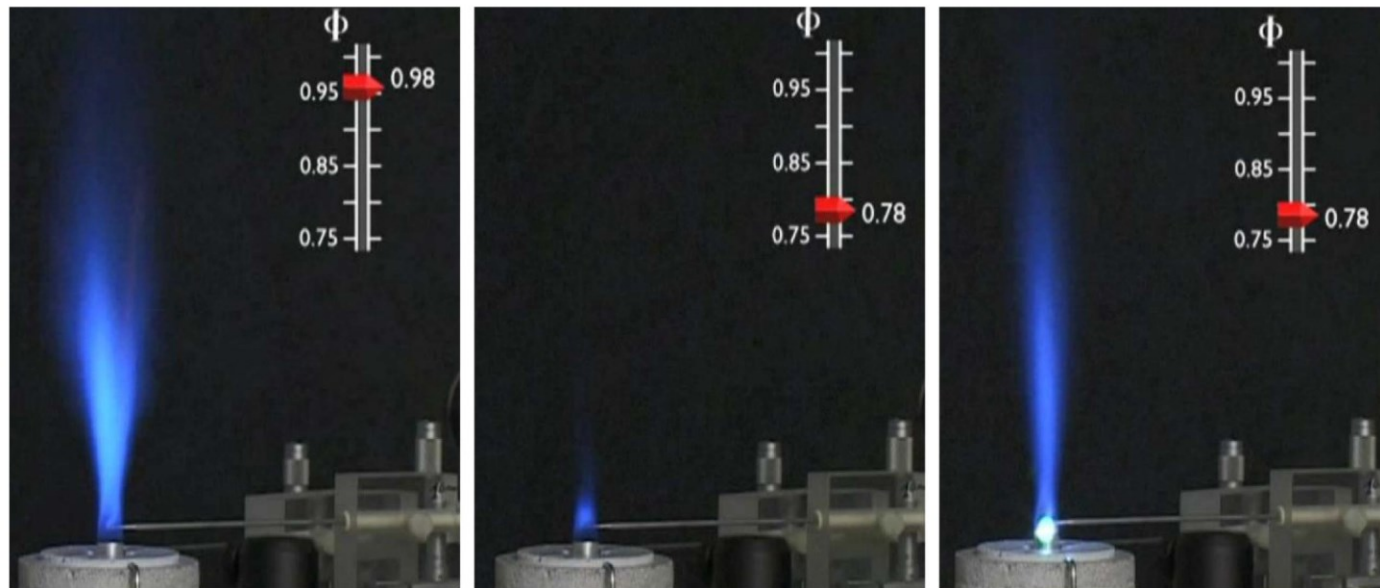
Adapted from Laux et al, PSST, 2026

Combustion Enhancement



Example of early study on enhancement of lean flammability/stability limits by PAC

- 11-kW atmospheric pressure bluff-body stabilized propane-air flame enhanced with NRP discharges: $P_{\text{plasma}}/P_{\text{flame}} = 0.75\%$
- Extension of Lean Blow Off (LBO) limit by up to 60%



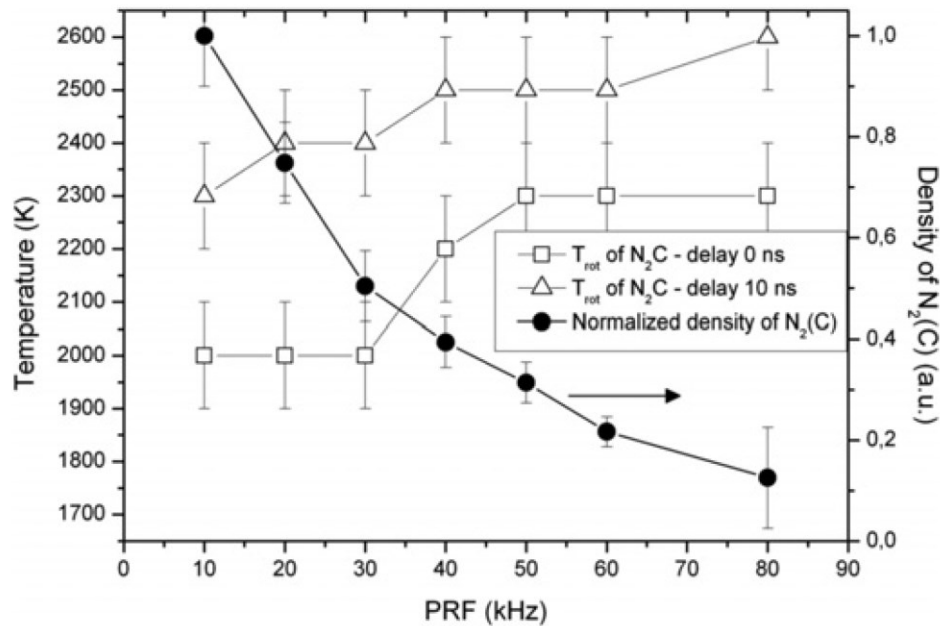
Pilla et al, IEEE Trans. Plasma Sci, 2006

Combustion Enhancement

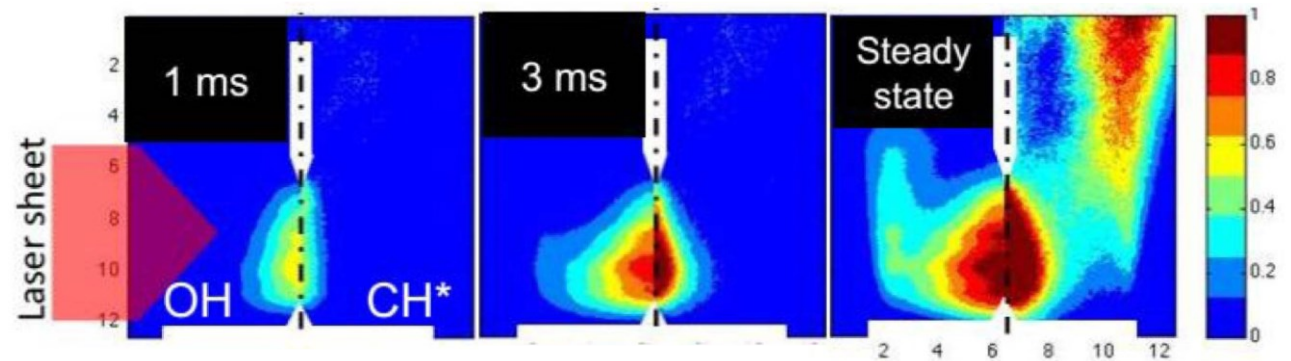


Example of early study on enhancement of lean flammability/stability limits by PAC

- 11-kW atmospheric pressure bluff-body stabilized propane-air flame enhanced with NRP discharges: $P_{\text{plasma}}/P_{\text{flame}} = 0.75\%$
- Results explained by a **coupled thermal and chemical effect**



Lacoste et al, PROCI, 2013



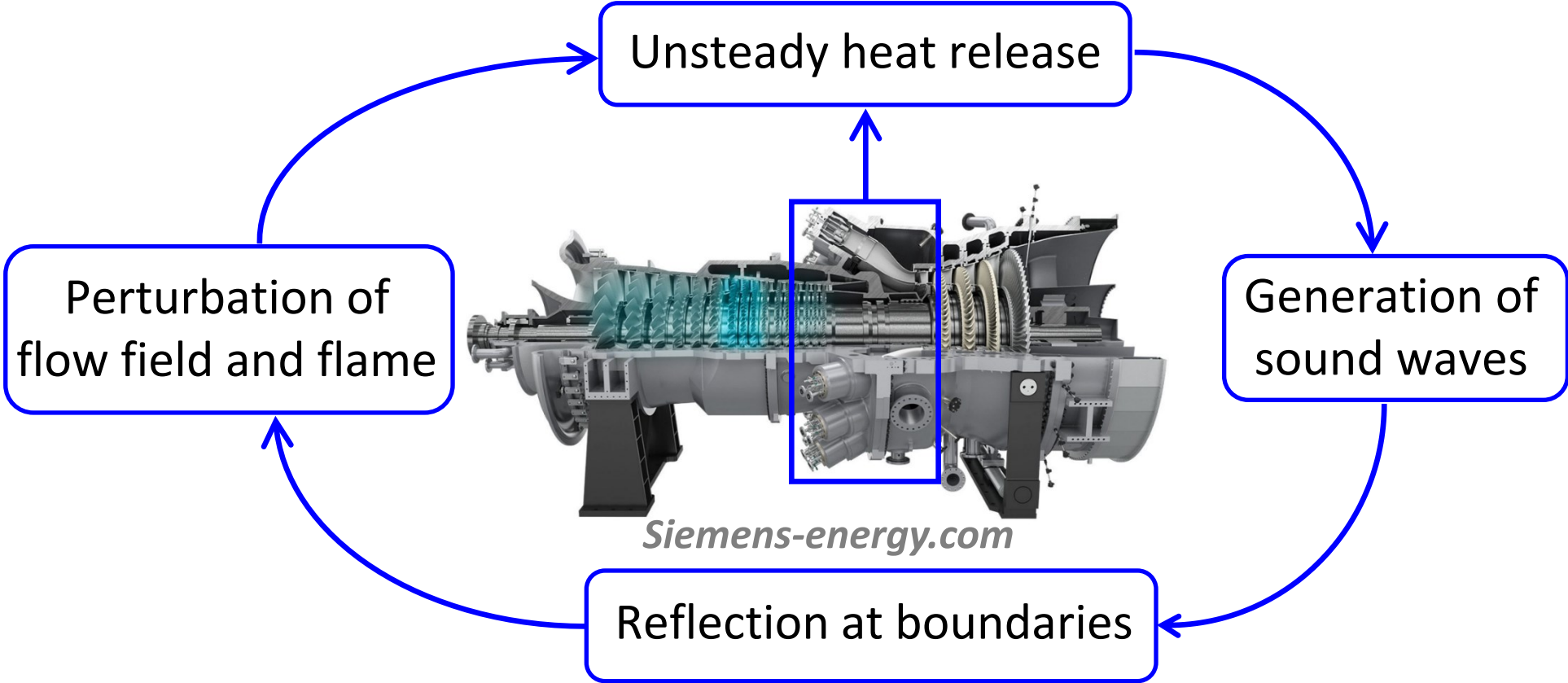
Xu et al, AIAA 2013-0895, 2013

Combustion Enhancement



Control of flame dynamics by PAC

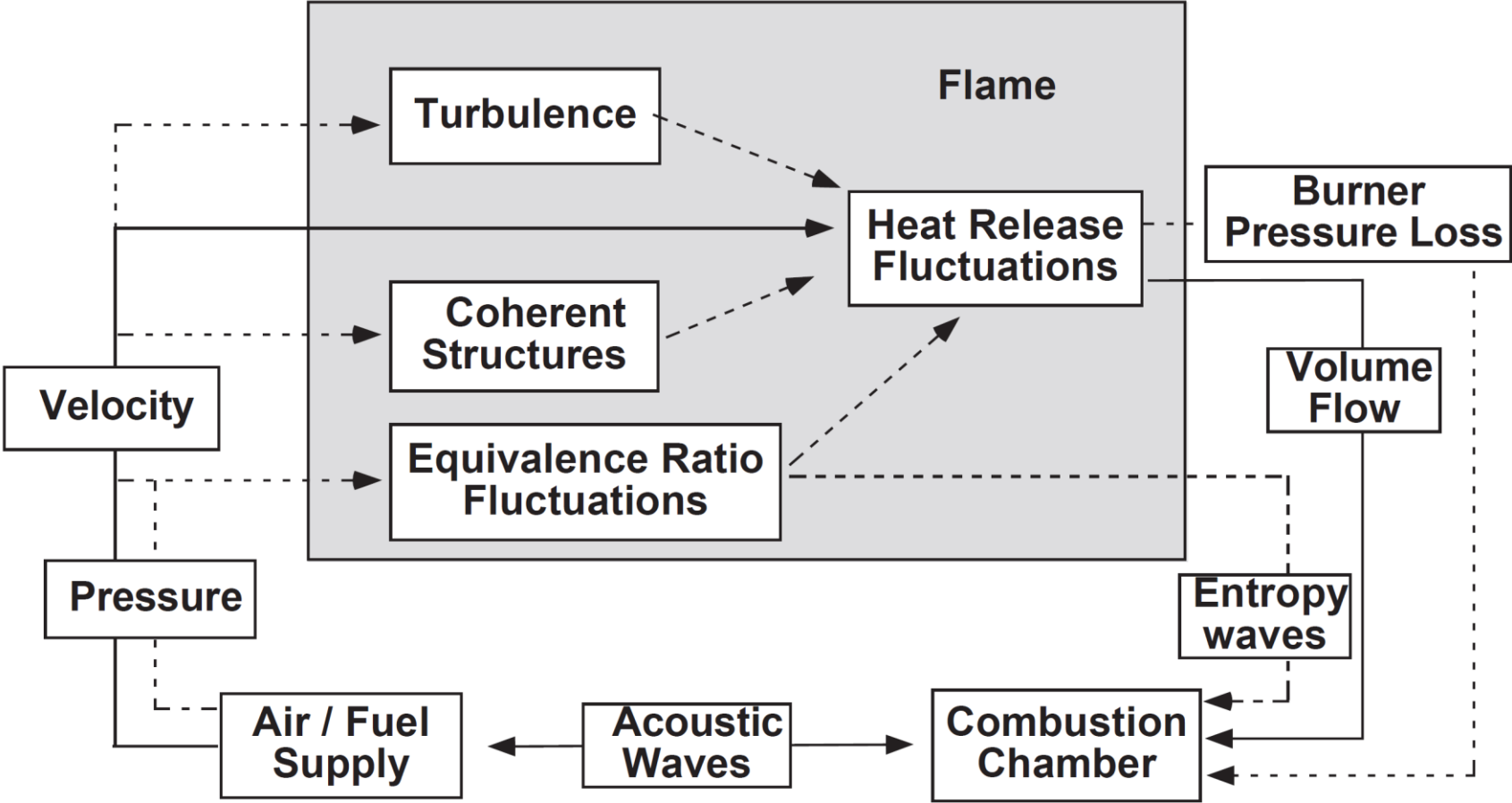
Thermoacoustic instabilities: coupling between unsteady heat release rate and acoustic modes of an engine



Combustion Enhancement



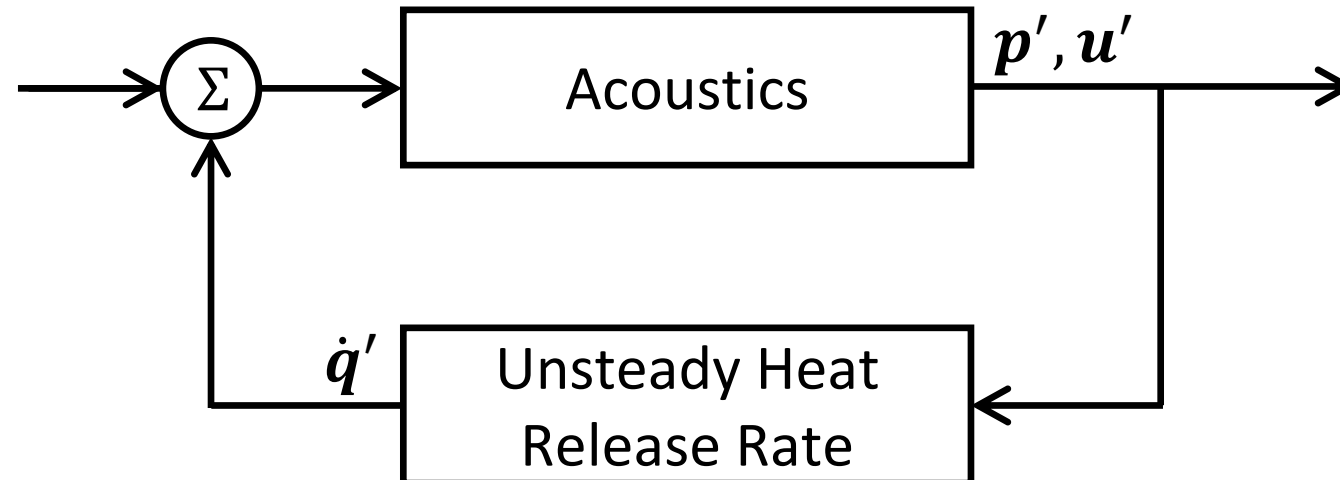
Control of flame dynamics by PAC



Combustion Enhancement



Control of flame dynamics by PAC

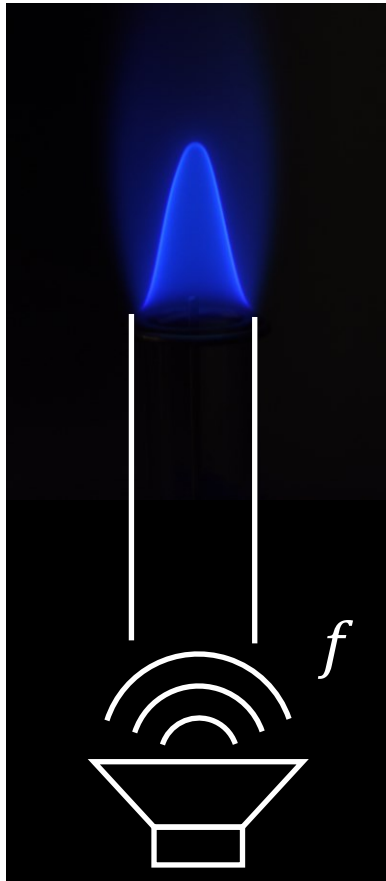


Combustion Enhancement

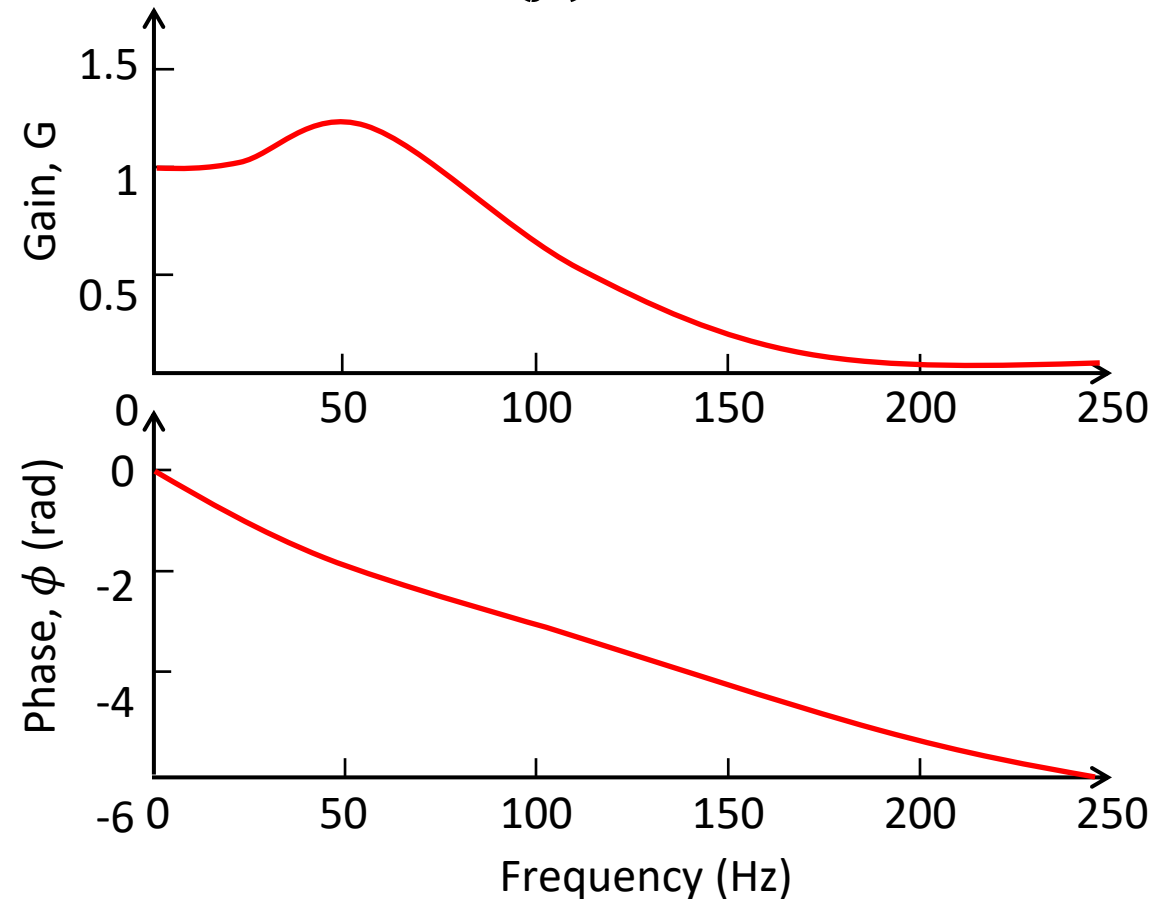


Control of flame dynamics by PAC

- Flame response to acoustic perturbations



$$F(f) = \frac{\dot{Q}'(f)/\bar{Q}}{u'(f)/\bar{u}}$$

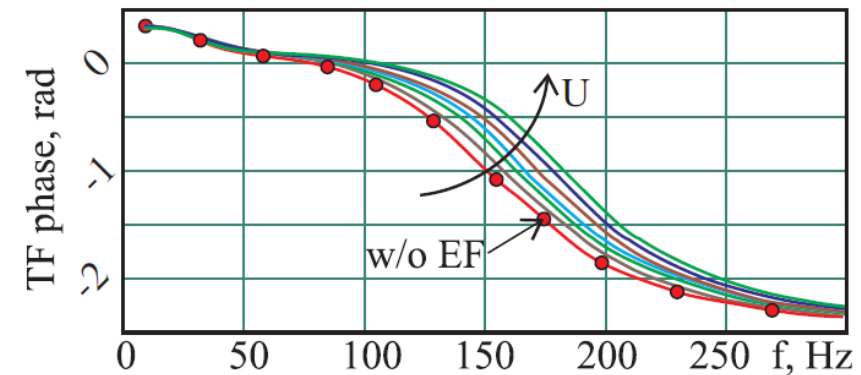
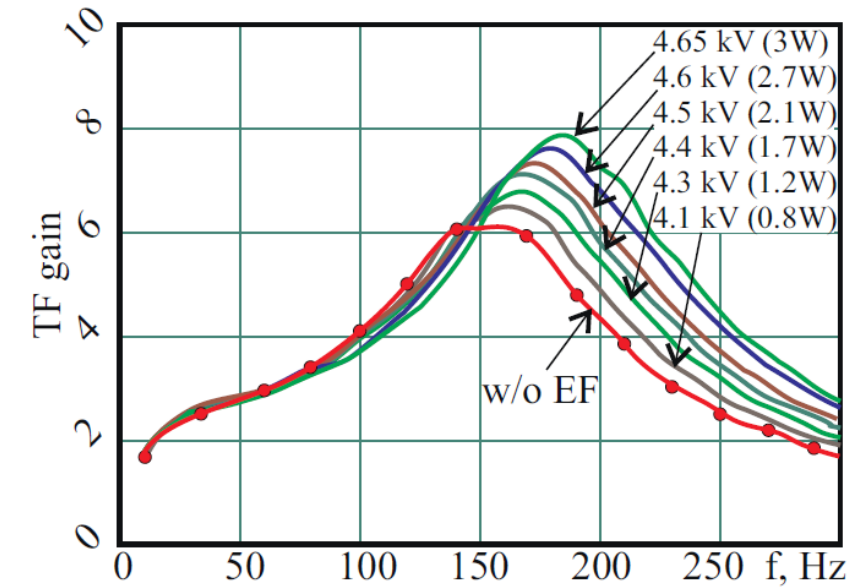
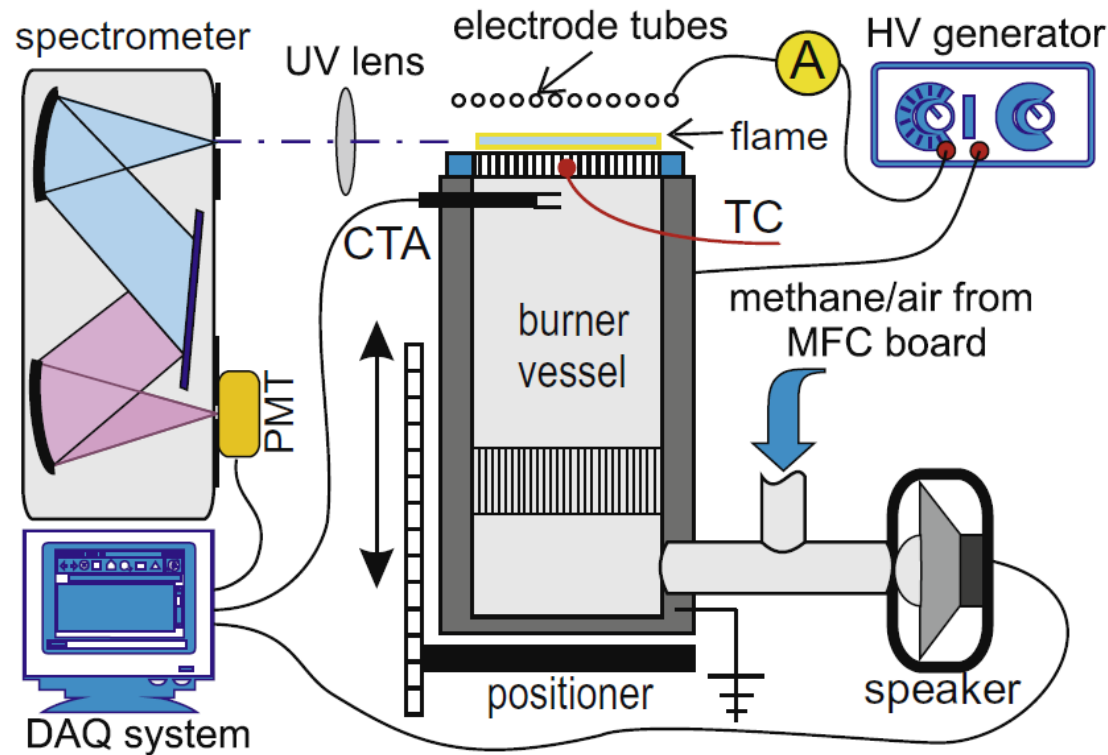


Combustion Enhancement



Control of flame dynamics by PAC

- Effect of a DC electric field on CH₄-air flame at P = 1 bar

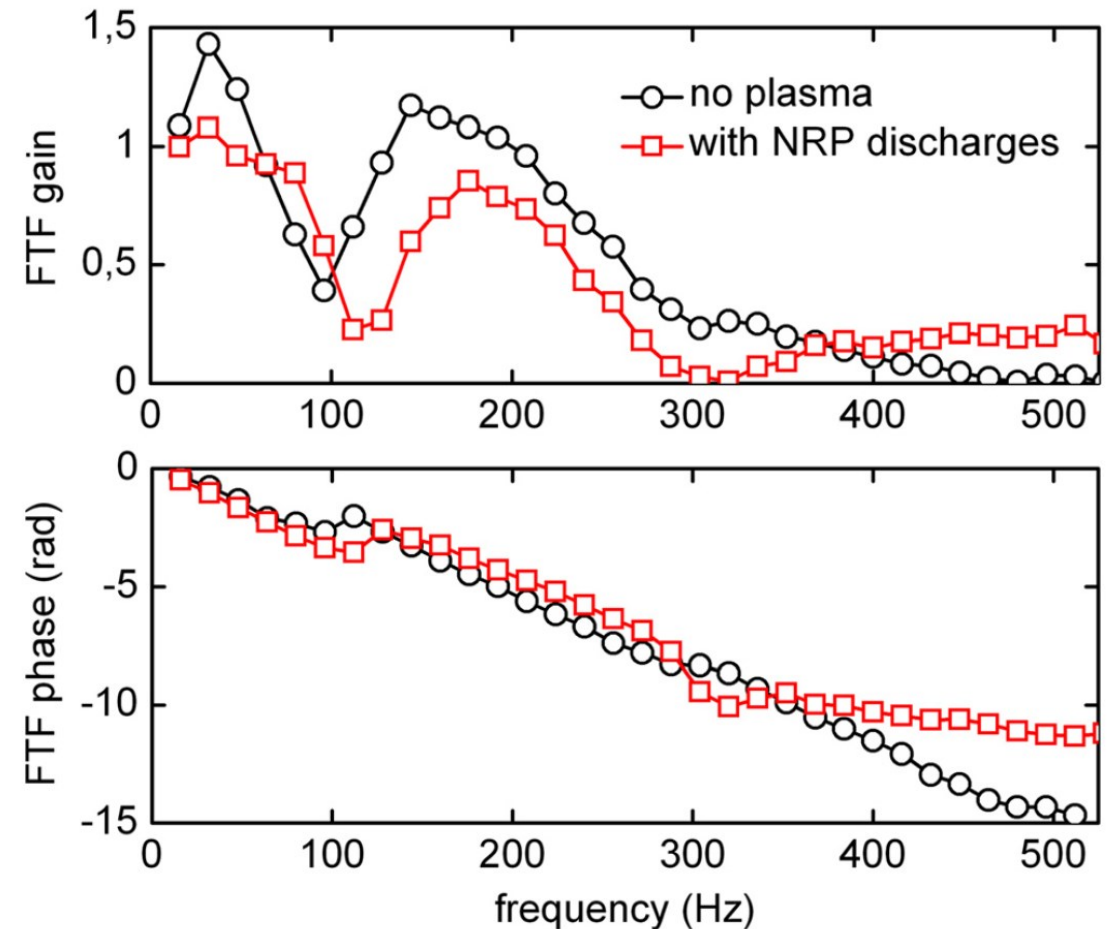
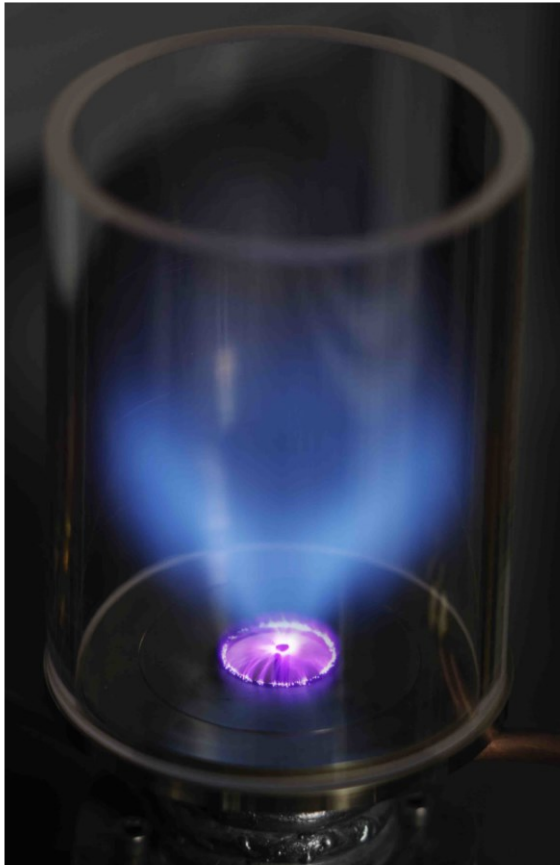


Combustion Enhancement



Control of flame dynamics by PAC

- Effect of 40-W NRP spark discharges on a 4-kW CH₄-air flame at P = 1 bar

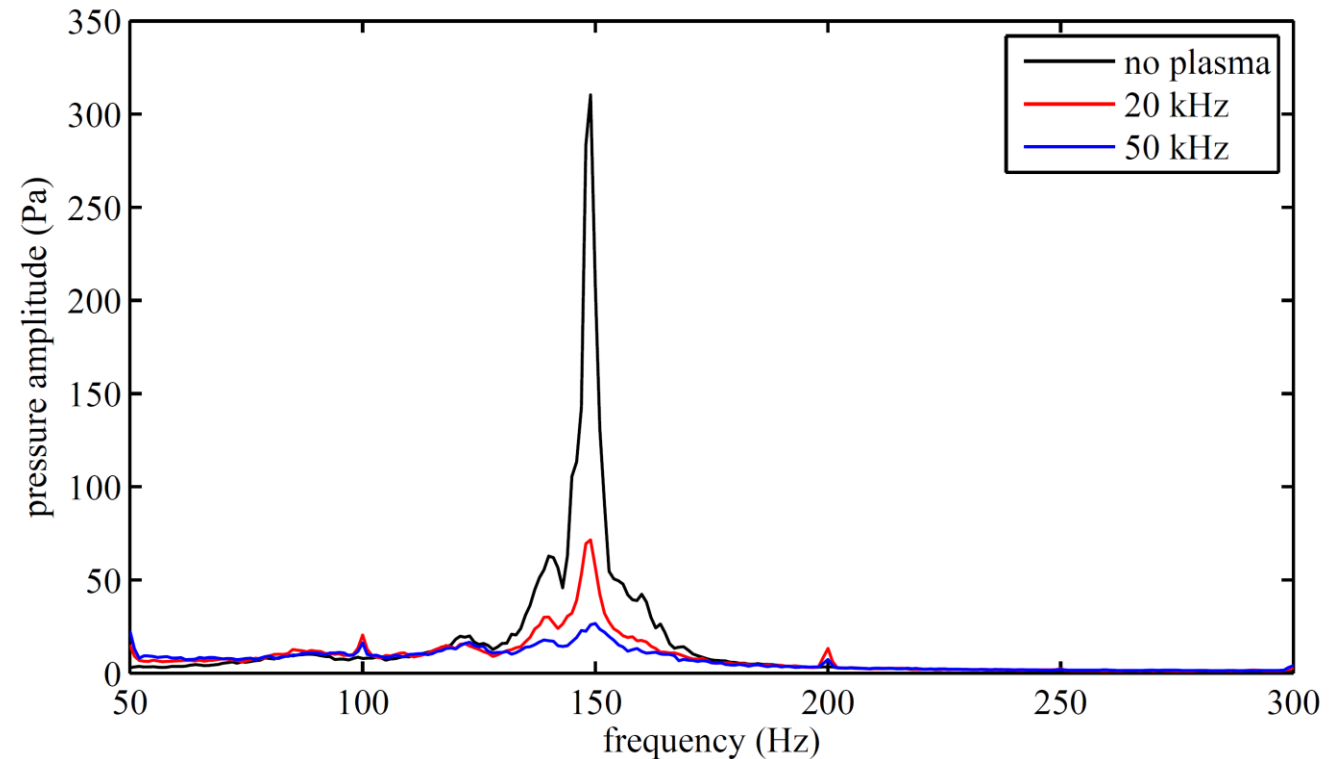
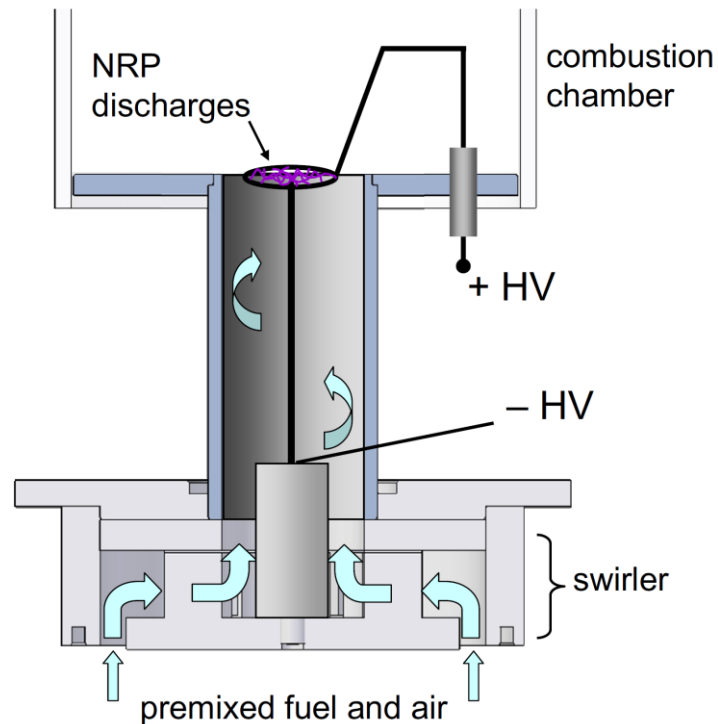


Combustion Enhancement



Control of flame dynamics by PAC

- Effect of 350-W NRP spark discharges on a 43-kW CH₄-air flame at P = 1 bar



→ Today, still no proof of the dominant plasma effect(s)

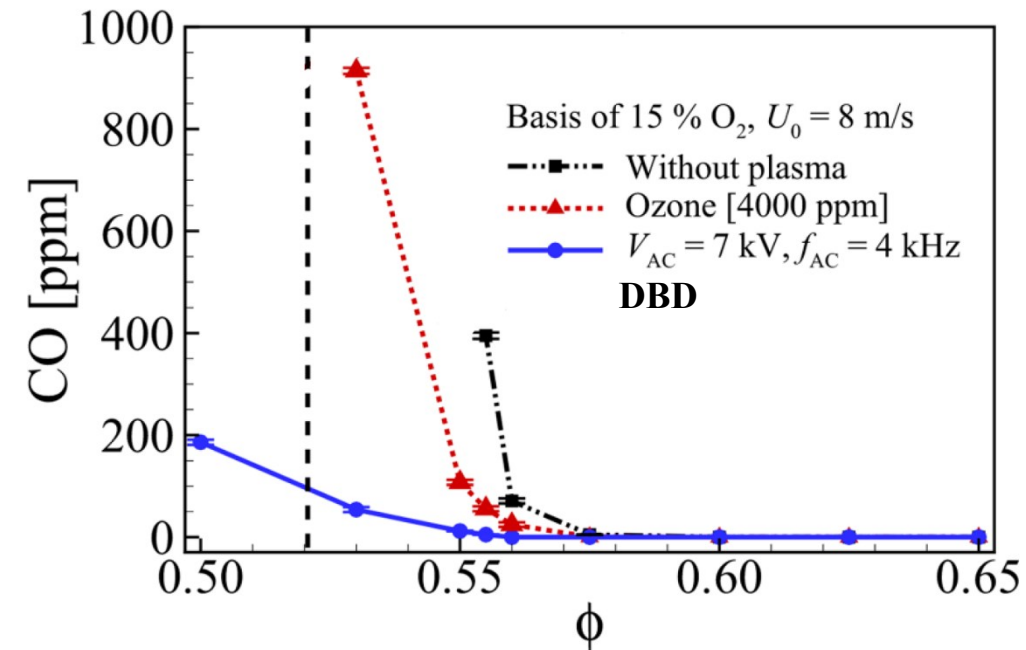
Combustion Enhancement



Reduction of pollutant emissions by PAC

- The main targeted species are:
 - Unburned fuel
 - CO
 - NO_x
 - Soot

Reduction of unburned fuel and CO in the exhaust gases is relatively **easy to achieve** because with plasma, flames burn better



Kim et al., Combust. Flame, 2020

Combustion Enhancement

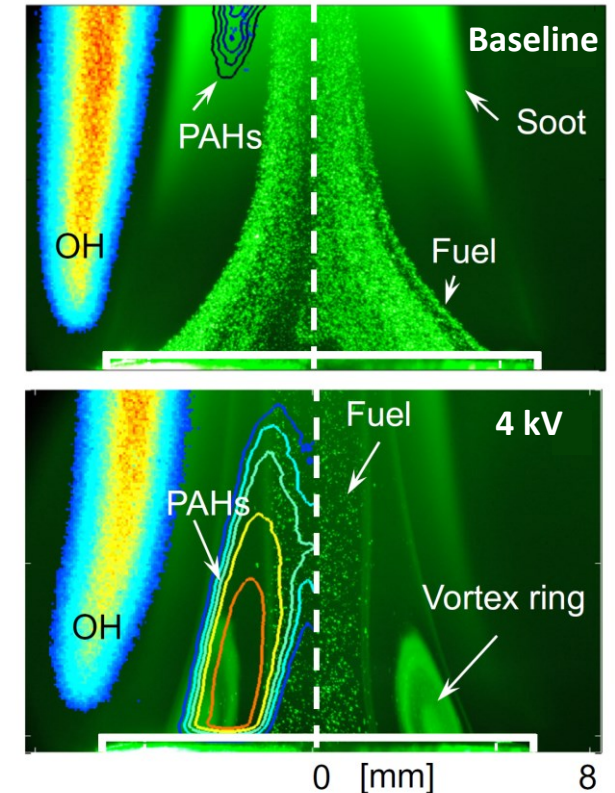
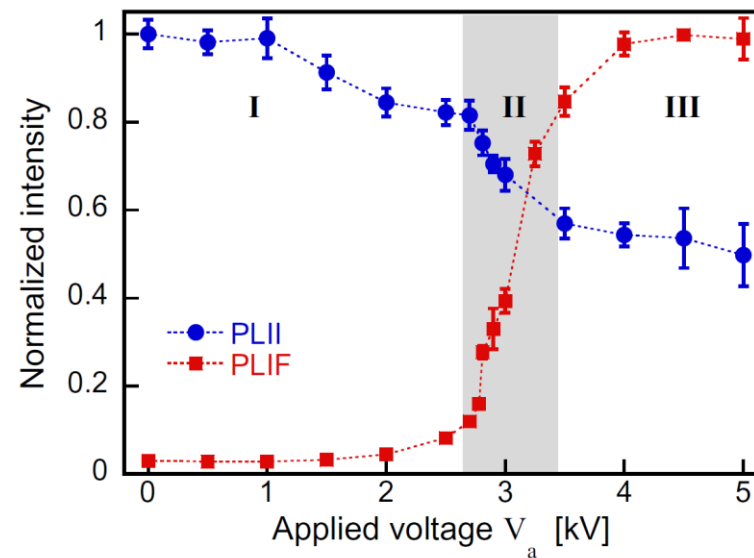
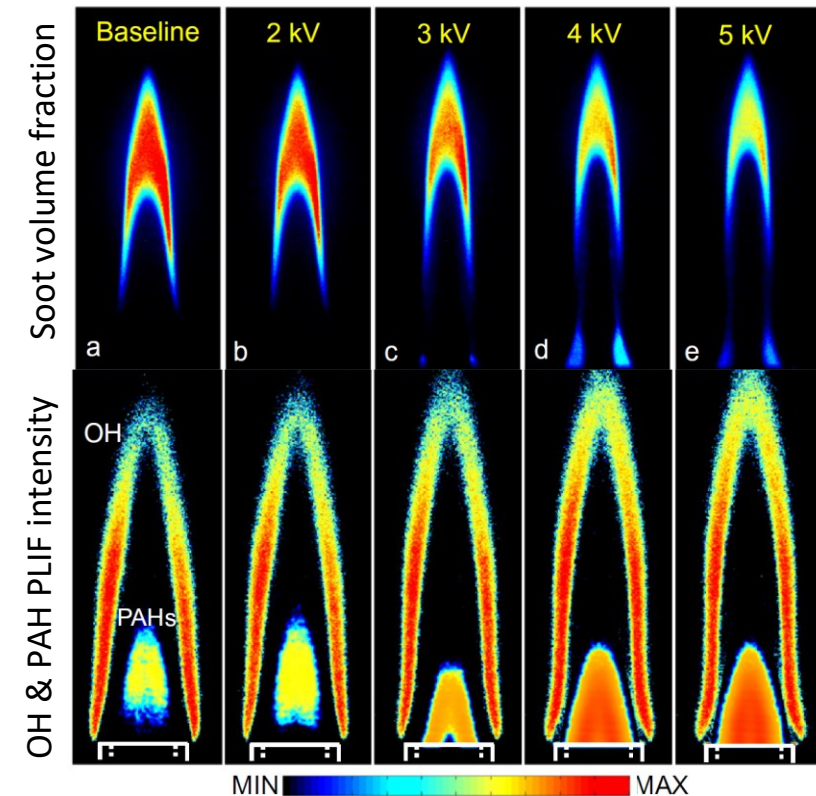


Reduction of soot emissions

Two important parameters in soot formation are the residence time and the temperature

→ Ionic wind can change the time PAH/soot spend in different areas

Example: Non-premixed propane flame subjected to an AC electric field (sub-breakdown)



Xiong et al., PROCI, 2015

Combustion Enhancement



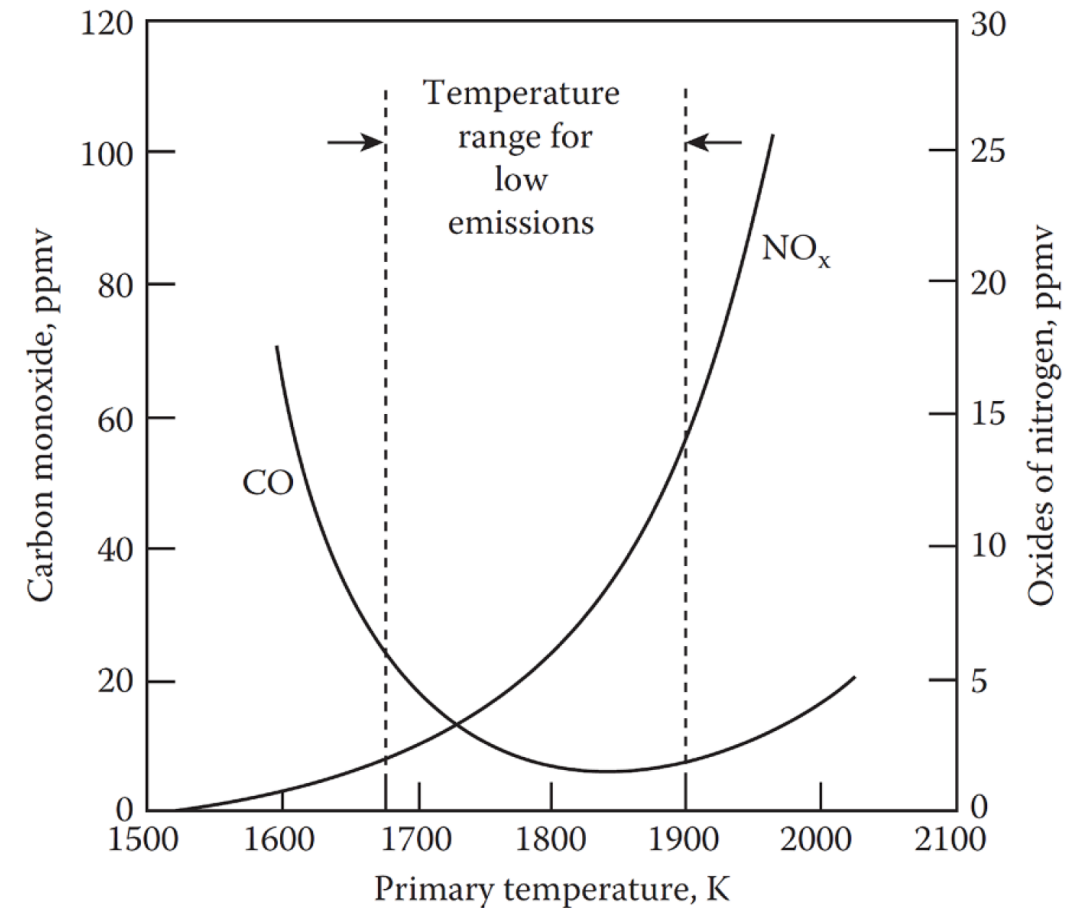
Reduction of NO_x in PAC: That's the hard part!

- The concentration of NO₂ is usually negligible compared to the concentration of NO

→ Focus on reduction of NO in PAC

- Mechanisms of NO formation in combustion

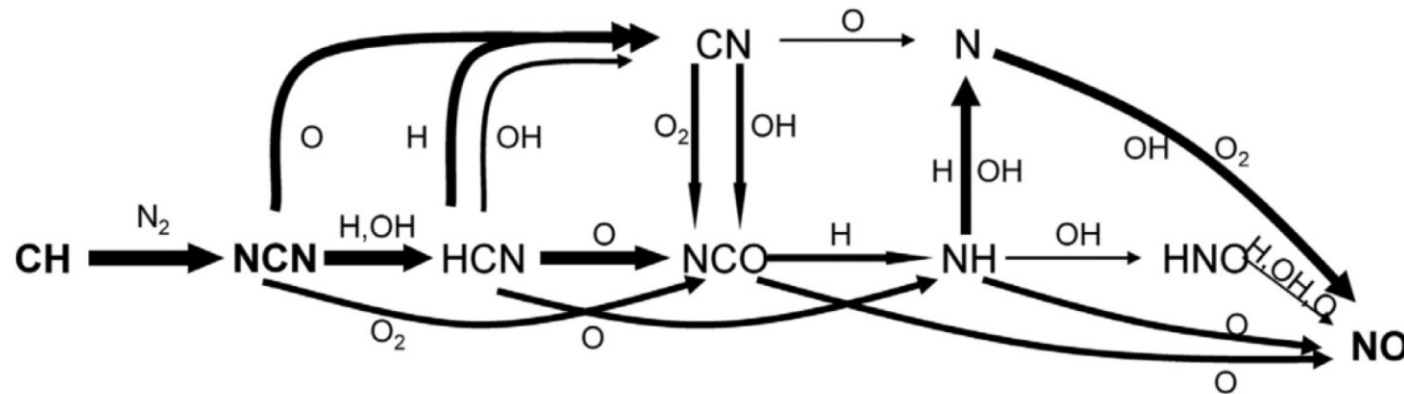
- Thermal NO (Zeldovich):



Combustion Enhancement



- Mechanisms of NO formation in combustion
 - Thermal NO (Zeldovich)
 - Prompt NO: involve numerous reactions, not present in carbon-free flames



*Lamoureux et al.,
Combust. Flame, 2010*

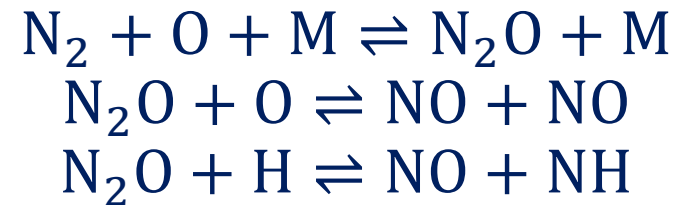
- NO via NNH: non negligible in H_2 and NH_3 flames

$$\text{O} + \text{NNH} \rightleftharpoons \text{NO} + \text{NH}$$

Combustion Enhancement



- Mechanisms of NO formation in combustion
 - Thermal NO (Zeldovich)
 - Prompt NO: involve numerous reactions, not present in carbon-free flames
 - NO via NNH: non negligible in H₂ and NH₃ flames
 - NO via N₂O: non negligible in lean or low-temperature combustion



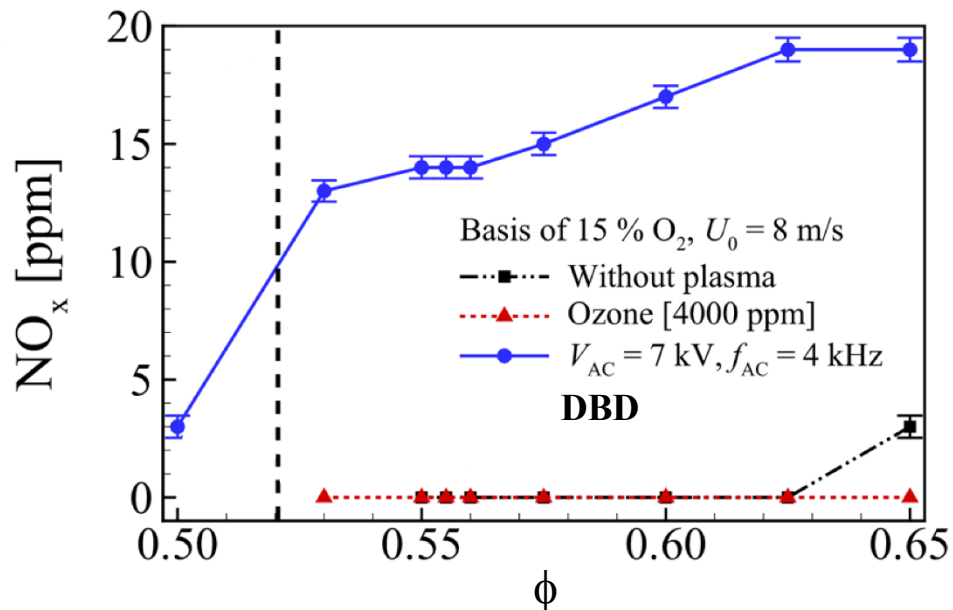
- Fuel NO: non negligible for fuels containing nitrogen atoms (e.g., complex HC or NH₃)

Combustion Enhancement

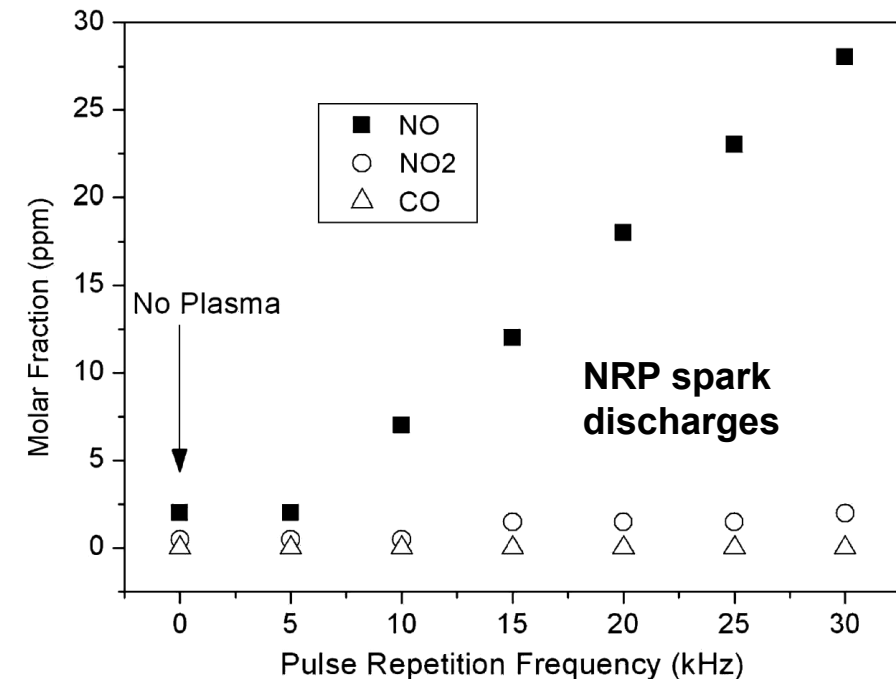


The production of NO in plasma-assisted flames is highly sensitive to the plasma power
→ The higher the plasma power, the higher the NO produced by the discharge

Examples of NO concentrations in the exhaust of PAC experiments (methane-air, P = 1 bar)



Kim et al., Combust. Flame, 2020



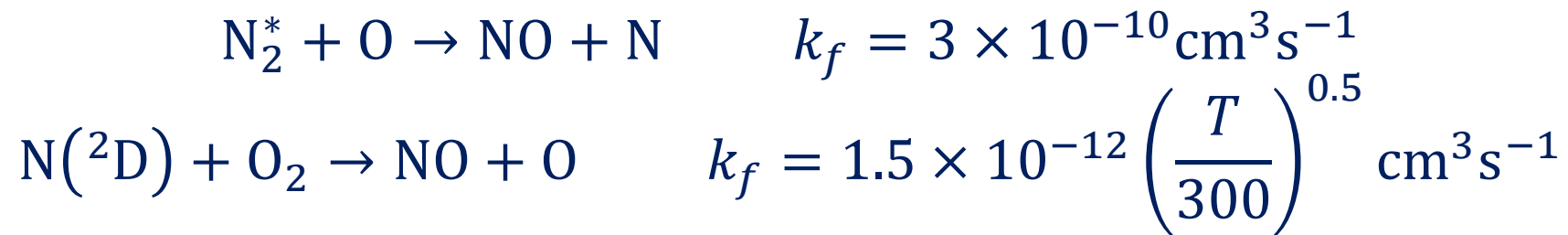
Lacoste et al., J. Propulsion Power, 2013

Combustion Enhancement



Mechanisms of NO formation in PAC

- Increase in gas temperature and in concentration of O, N, and OH, increasing the thermal NO
- NO formation by dissociative quenching of excited electronic states of N_2^* and N, the 'excited Zeldovich reactions'



Combustion Enhancement



Mechanisms of NO formation in PAC

- In NH₃ flames, plasma can **decrease** NO emissions via two potential reaction pathways

1. The HO₂ formed in the plasma region reacts with NO and NO₂ through reactions



2. NO is consumed by reactions with NH₂ (thermal de-NO_x process)



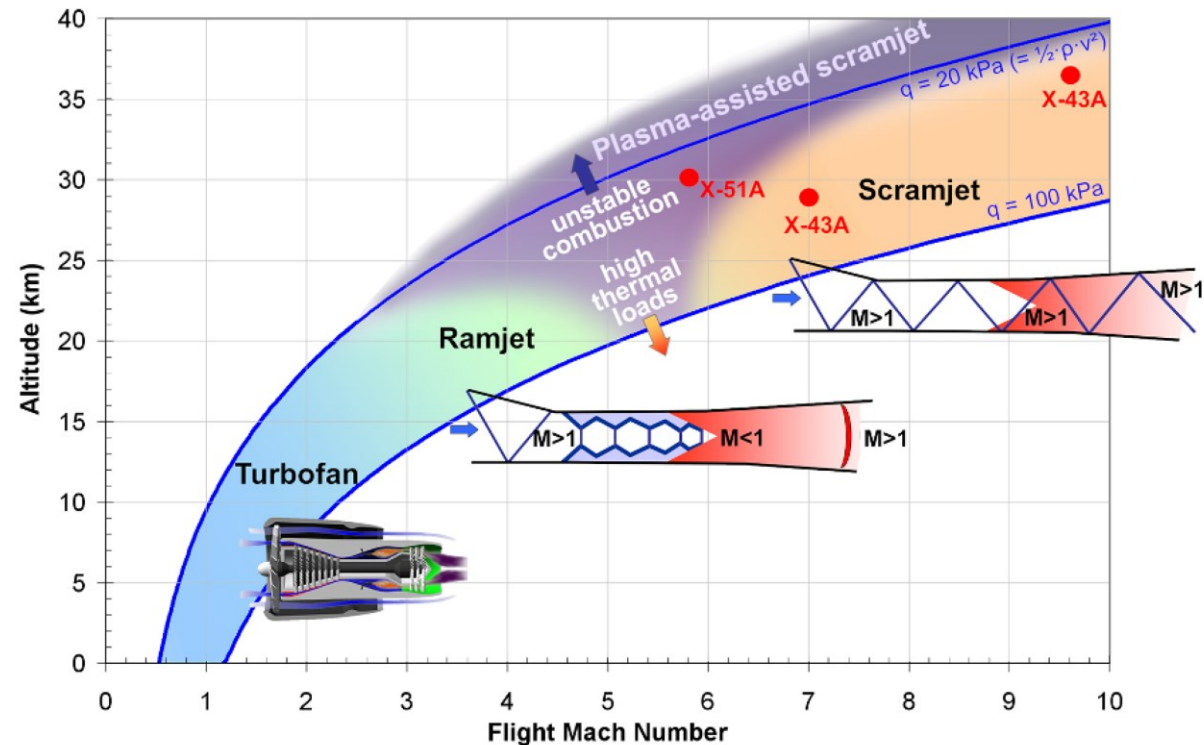
- However, the **thermal NO and the excited Zeldovich reactions routes are still active**, therefore, depending on the conditions, discharges can increase or decrease NO emissions of NH₃ flames



Combustion Enhancement

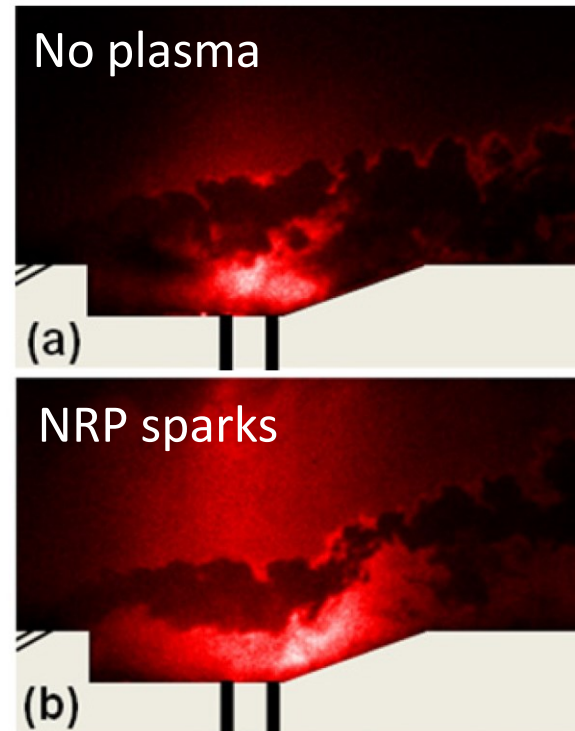
Enhancement of supersonic combustion by PAC

- The main objective is to extend the operation range of air breathing vehicles
- Discharges are typically used to anchor the flame



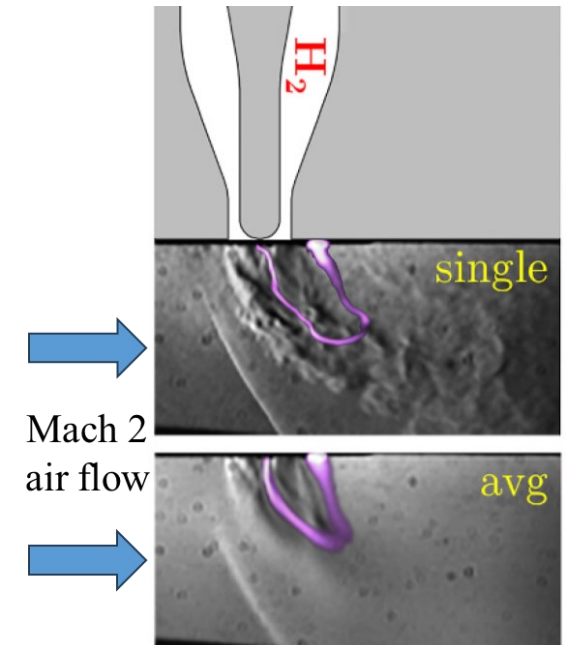
Laux et al., PSST, 2026

Scramjet cavity, H_2 in air, NRP discharges



Do et al., Combust. Flame, 2010

H_2 injector coupled with a DC arc in a ramjet



Vincent-Randonnier et al.,
Int. J. Hydrogen Energy, 2024

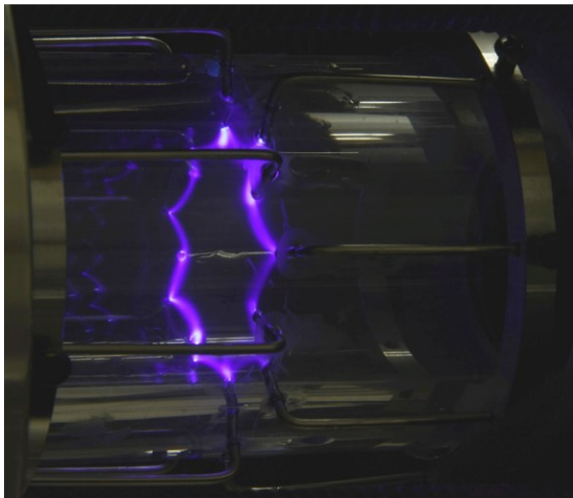
Combustion Enhancement



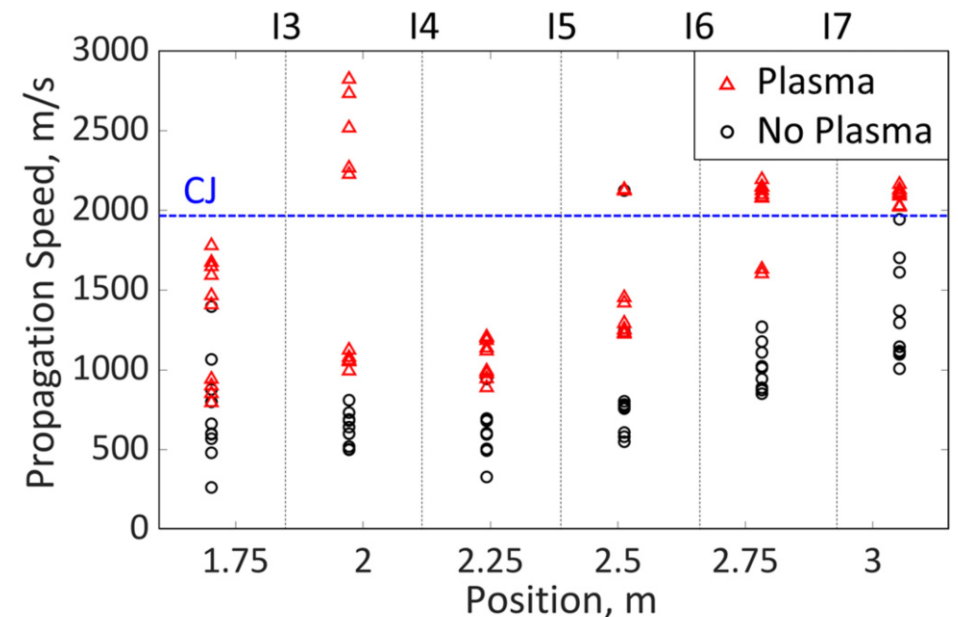
Enhancement of detonation by PAC

- Three different types of studies:
 - For ignition of detonation tubes or engines (RDE)
 - For enhancement of the deflagration-to-detonation transition (DDT)
 - For enhancement of detonation properties (e.g., cell size, CJ speed...)

Example of plasma assisted DDT of an H₂-air turbulent flame by NRP discharges



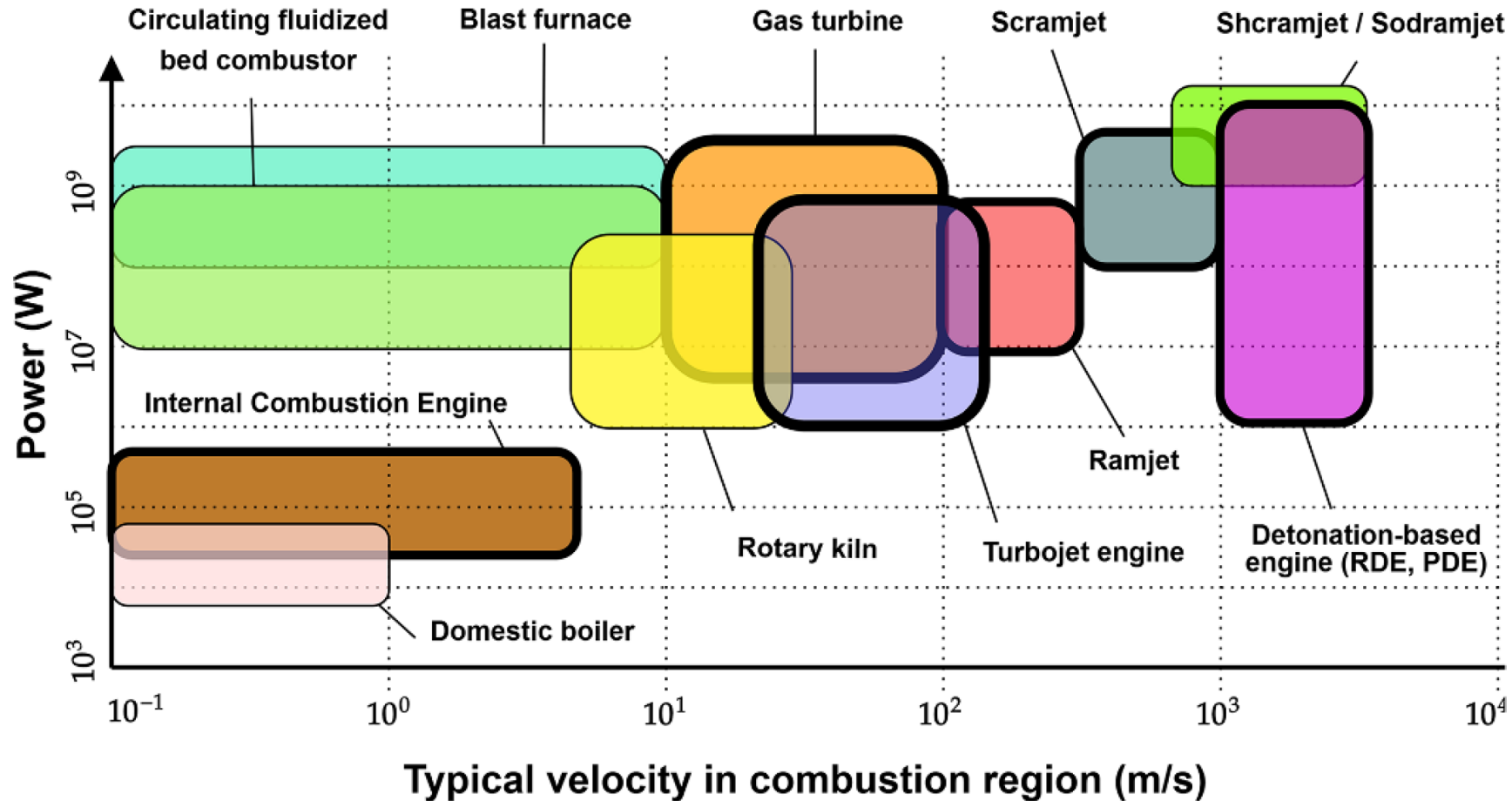
Gray and Lacoste, PROCI, 2021





Combustion Enhancement

Ranges of powers and flow velocities in combustion systems



References



Papers

- *D.A. Lacoste, Flames with plasmas, Proc. Combust. Inst. 39, 5405-5428, 2023*
- *S.M. Starikovskaia, V. Lafaurie, J.-B. Perrin-Terrin, C.O. Laux, Foundations of plasma-assisted combustion: I. Fundamentals of combustion and plasma, Plasma Sources Sci. Technol. 35, 023001, 2026*
- *C.O. Laux, J.-B. Perrin-Terrin, V. Lafaurie, S.M. Starikovskaia, Foundations of plasma-assisted combustion: II. Mechanisms and applications, Plasma Sources Sci. Technol. 35, 023002, 2026*

Book

- *Plasma Assisted Combustion and Chemical Processing, Yiguang Ju & Andrey Starikovskiy, CCRC Press, Taylor and Francis Group, Boc Raton, FL, USA, 2025*

Chapter VI: Sources and Methods



- *Strategies*
- *Dielectric Barrier Discharges*
- *Gliding Arcs*
- *NRP Discharges*
- *Microwave Discharges*
- *System Integration*
- *References*



Strategies



After a breakdown, the two electrodes are connected by a conductive channel

- The flow of electrons is controlled by the source (power supply)
- If the amount of electrons is large enough, then the plasma thermalizes
 - equilibrium plasma (arc)

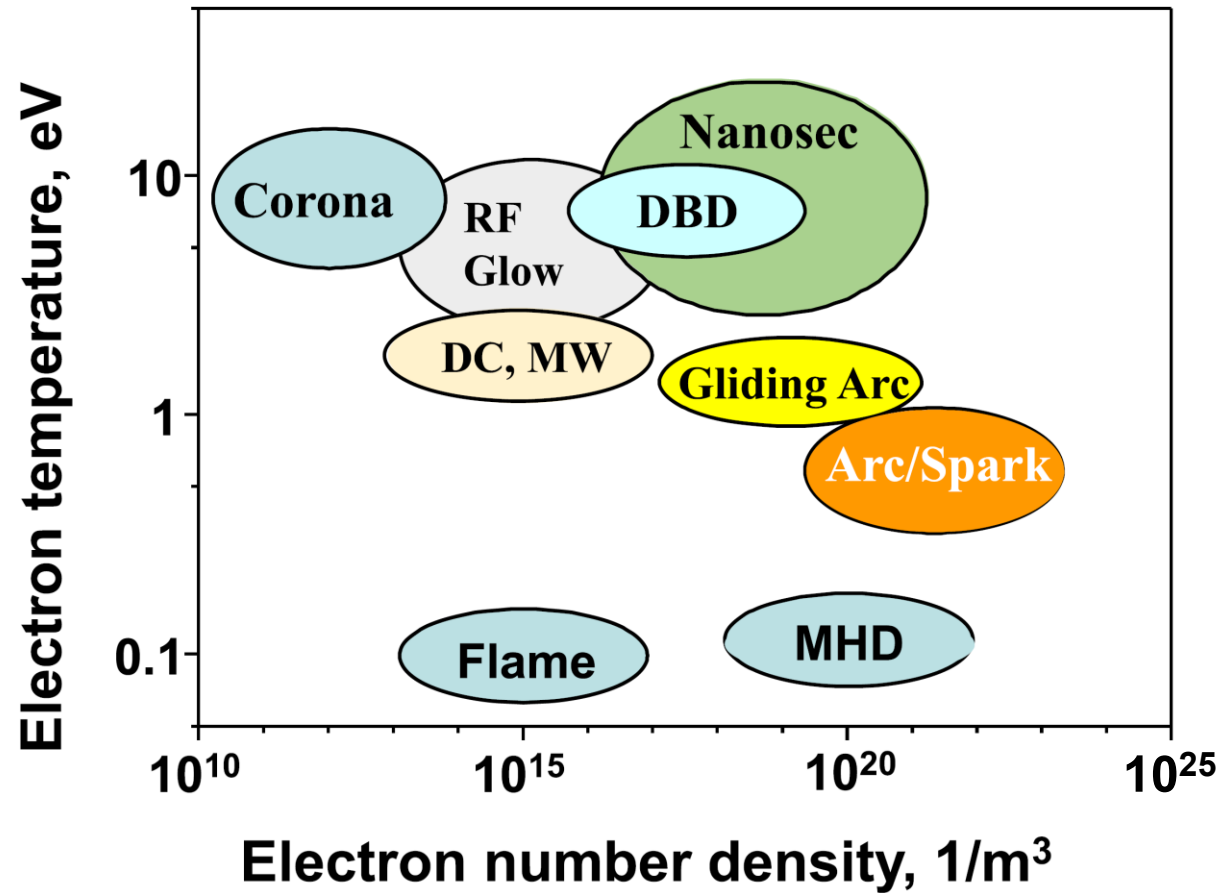
Strategies to obtain a non-equilibrium plasma at atmospheric pressure

1. Avoid thermalization by limiting the current
 - Dielectric barrier discharges (DBD)
 - Gliding/elongated arc (GA)
2. Avoid thermalization by stopping the applied voltage
 - Nanosecond discharges
 - Single/low frequency nanosecond discharges
 - Nanosecond Repetitively Pulsed (NRP) discharges
 - Pulsed microwave discharges

Strategies



Plasma characteristics



Ju and Sun, PECS, 2015

Strategies



Typical nonequilibrium plasma sources for PAC

Source	Electrode features	Power range (W)	Thermal effect	Chemical effect	Cost
DBD	Covered with dielectric	$10^{-3} - 10$	Low	High	Low
Gliding/elongated arc	Specific/large gap distances	100 – 1000	High	Low	Low
Nanosecond (< 1kHz)	Metal	$10^{-3} - 10$	Low to High	Low to High	Moderate
NRP discharges (> 5kHz)	Metal	10 – 1000	Low to High	Low to High	High
Pulsed microwave discharges	Antenna	10 – 1000	High	Low	Moderate

Cost depends on:

- Energy/Power
- Accuracy/Repeatability
- Ranges of operation

Chapter VI: Sources and Methods



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- *Gliding arcs*
- *NRP discharges*
- *Microwave discharges*
- *System integration*
- *References*



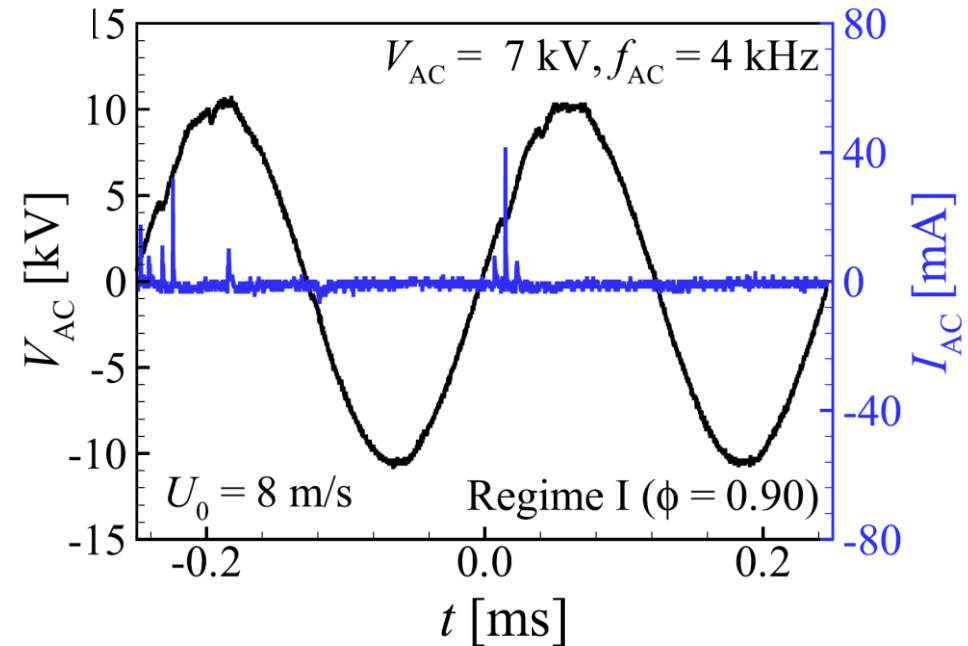
Dielectric Barrier Discharges



Avoid thermalization by limiting the current

- High-voltage AC power supply $\sim 5\text{--}50\text{ kV}$
- Typical range of frequencies $\sim 5\text{--}30\text{ kHz}$

Cathode



Kim et al., Combust. Flame, 2020

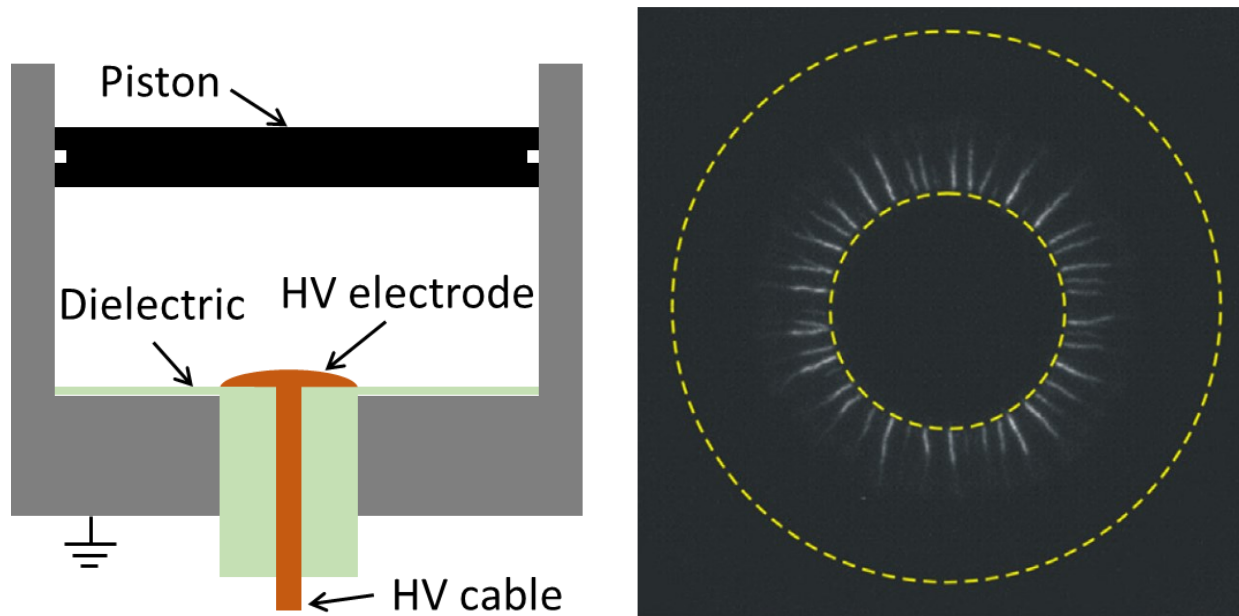
Anode

Dielectric Barrier Discharges



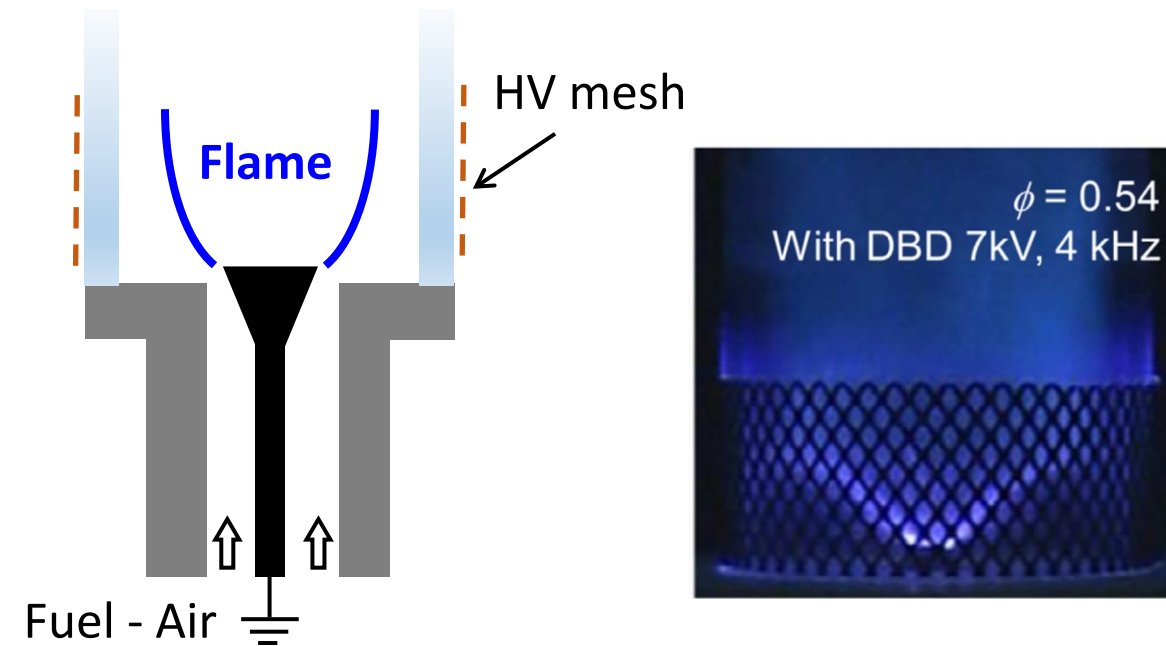
Examples of DBD in PAC

Pulsed DBD for ignition in engine



Boumevdi et al., Combust. Flame, 2015

DBD for enhancement of LBO limit



Kim et al., Combust. Flame, 2020

Dielectric Barrier Discharges



Why should I choose a DBD?

✓ PROS

- ✓ Low power/energy deposition
- ✓ Minimal/negligible heating
- ✓ High-reduced electric field
- ✓ Relatively large plasma volume
- ✓ Best source for ionic wind

✗ CONS

- ✓ Low power/energy deposition
- ✓ Dielectric material
- ✓ No control on streamer inception

Chapter VI: Sources and Methods



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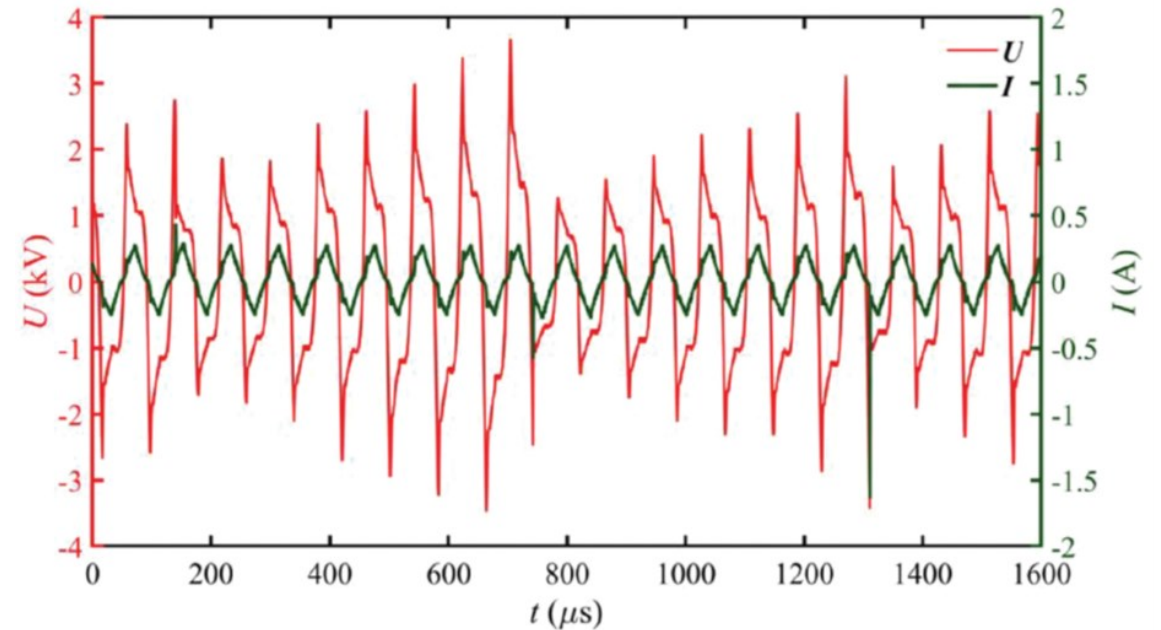
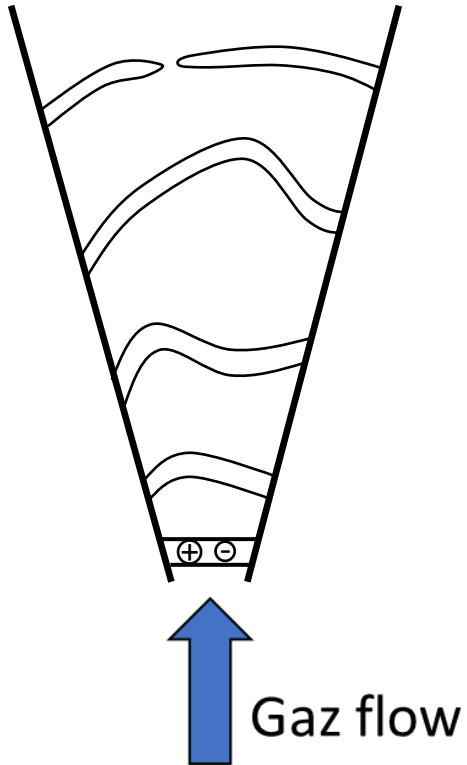




Gliding Arcs

Avoid thermalization by limiting the current

- High-voltage AC or DC power supply $\sim 2\text{--}10\text{ kV}$
- Typical range of current peak $\sim 0.1\text{--}10\text{ A}$



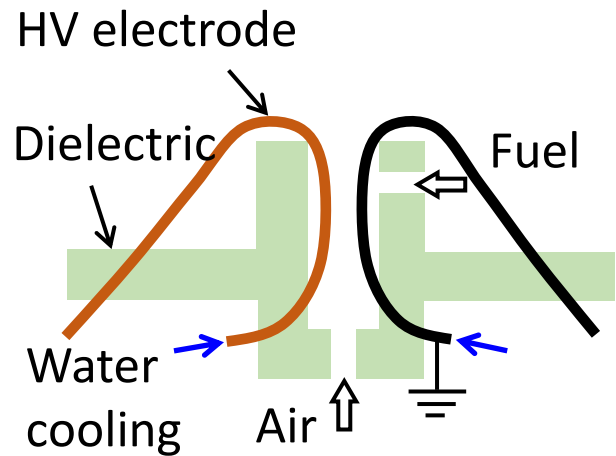
Tang et al., Fuel, 2022

Gliding Arcs



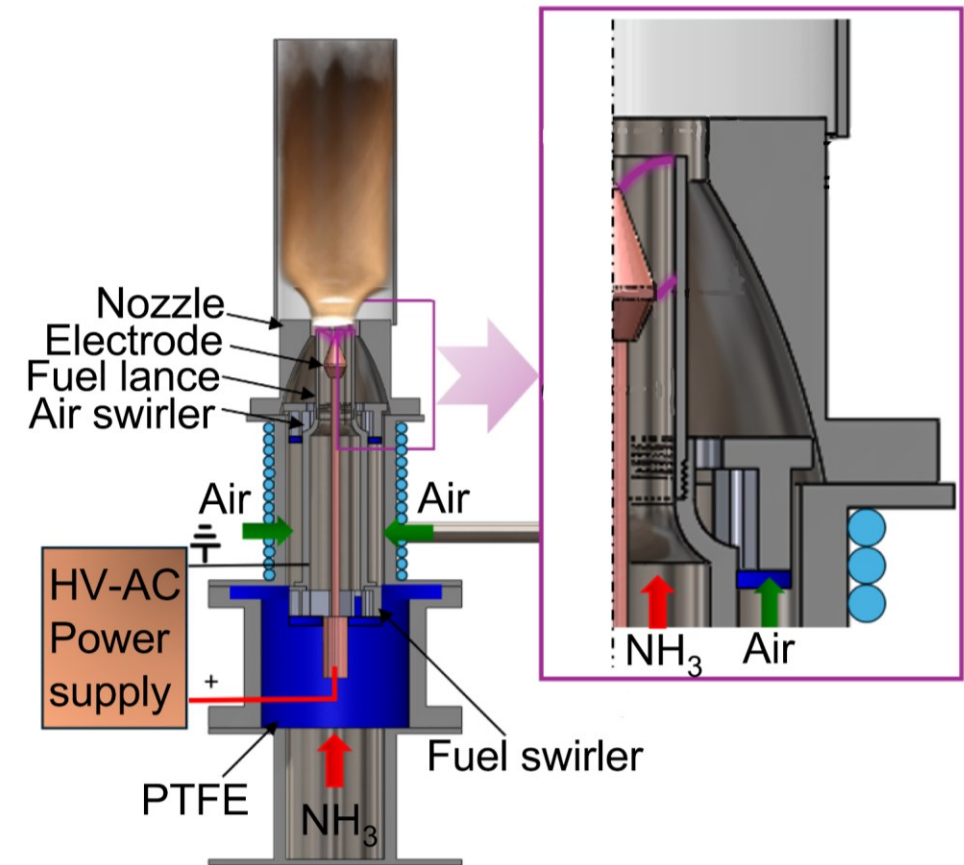
Examples of GA or elongated arc in PAC

GA for turbulent jet flame stabilization



Gao et al., Proc. Combust. Inst., 2019

GA for swirled flame stabilization



Aravind et al., Proc. Combust. Inst., 2025

Gliding Arcs



Why should I choose a GA / elongated arc?

✓ PROS

- ✓ High power/energy deposition
- ✓ Strong heating
- ✓ Minimal electrode erosion
- ✓ Relatively large plasma volume
- ✓ Can be a source of ionic wind

✗ CONS

- ✓ Low reduced electric field
- ✓ Design and location of electrodes
- ✓ No control on plasma location

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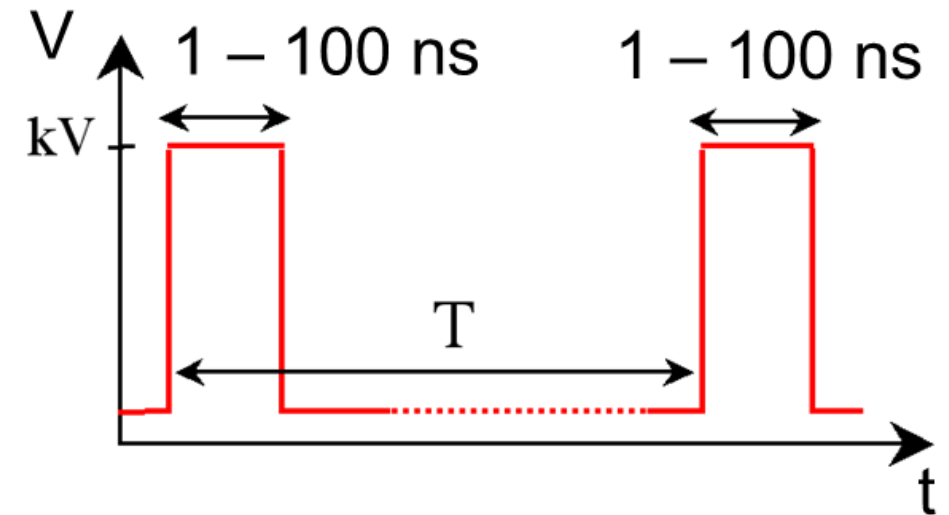


NRP Discharges



Avoid thermalization by stopping the applied voltage

- High-voltage pulser $\sim 3\text{--}50$ kV
- Typical range of current peak $\sim 0.1\text{--}100$ A
- Pulse Repetition Frequency (PRF) $\sim 5\text{--}100$ kHz
→ $T = 1/\text{PRF} \sim 10\text{--}200$ μs

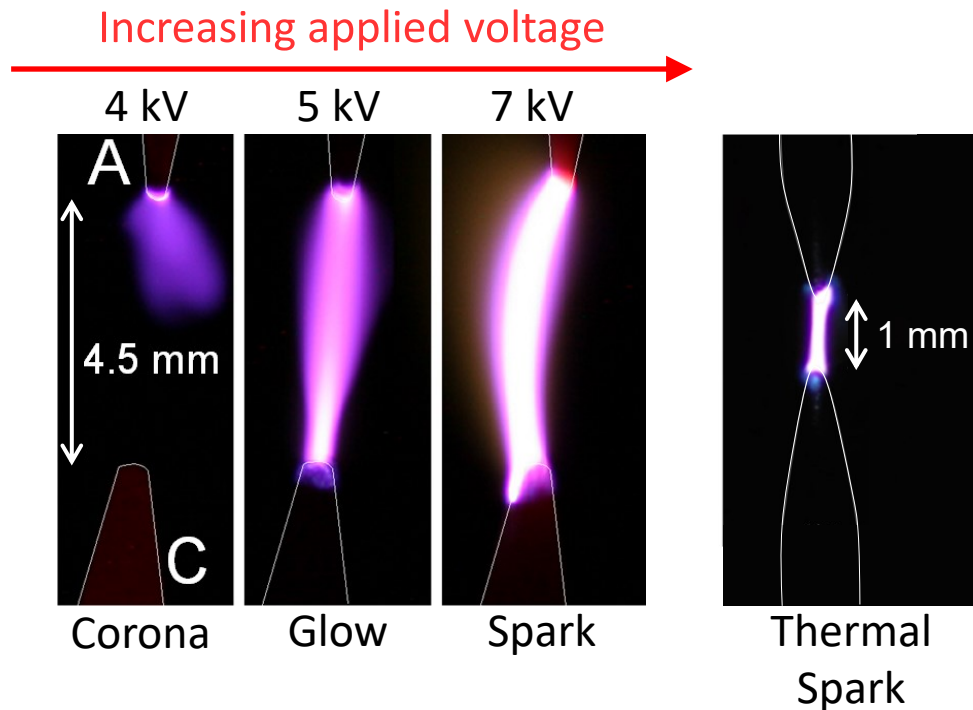


- Four types of usage
 - Single pulse (mainly for ignition or fundamental studies)
 - Burst of XX pulses (mainly for ignition)
 - Duty-cycle (mainly for flame stabilization or enhancement of flammability)
 - Continuous mode

NRP Discharges



In ambient air



Pai et al., PSST, 2010 *Minesi et al., PSST, 2020*

Regime	Glow	Spark	Thermal Spark
Conduction current	negligible	1–100 A	1–100 A
Energy per pulse	<100 μ J	1–20 mJ	1–20 mJ
Gas heating	negligible	1000 – 4000 K	> 10,000 K
O ₂ dissociation	up to 5%	50%	TBD
Transport effect	negligible	Gas expansion & shocks	Jets & shocks

Pai et al., PSST, 2009

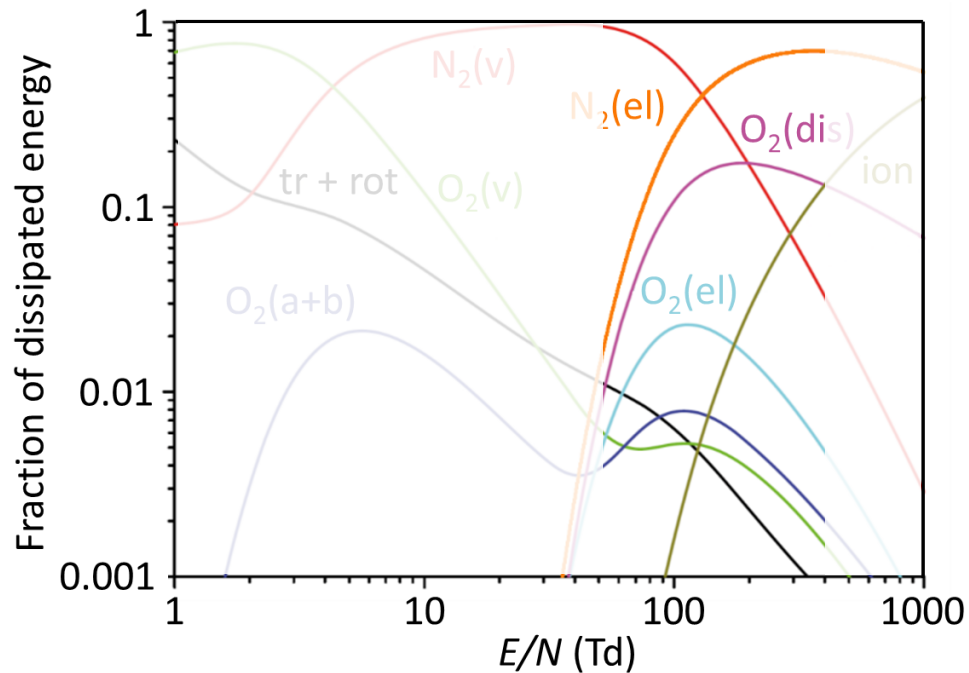
Stancu et al., J. Phys. D: Appl. Phys., 2010

Minesi et al., PSST, 2020

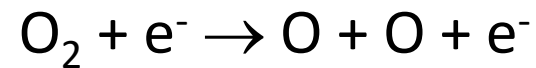
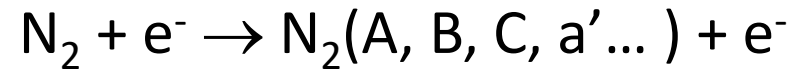
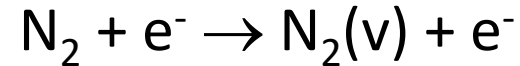
NRP Discharges



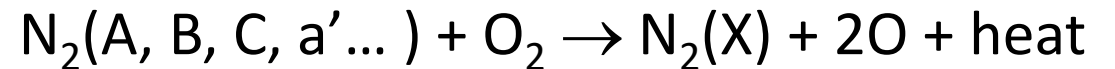
In ambient air



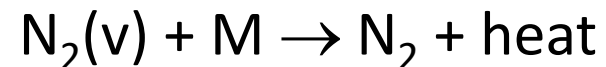
During a ns-pulse (~ 10 ns):



Just after a pulse (~ 20 ns):



In between pulses (~ 10 μs):



NRP Discharges

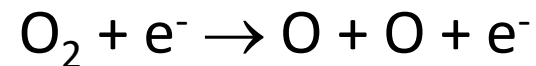
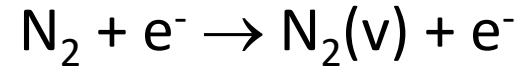


In ambient air

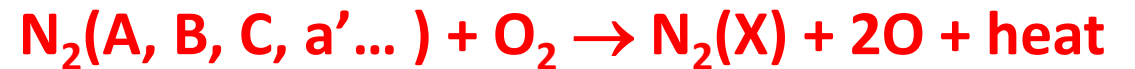
Two-step mechanism of fast gas heating and atomic oxygen production

Popov, Plasma Phys. Rep., 2001

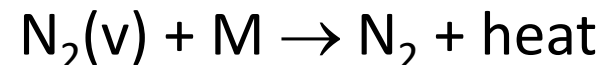
During a ns-pulse (~ 10 ns):



Just after a pulse (~ 20 ns):



In between pulses (~ 10 μs):



NRP Discharges

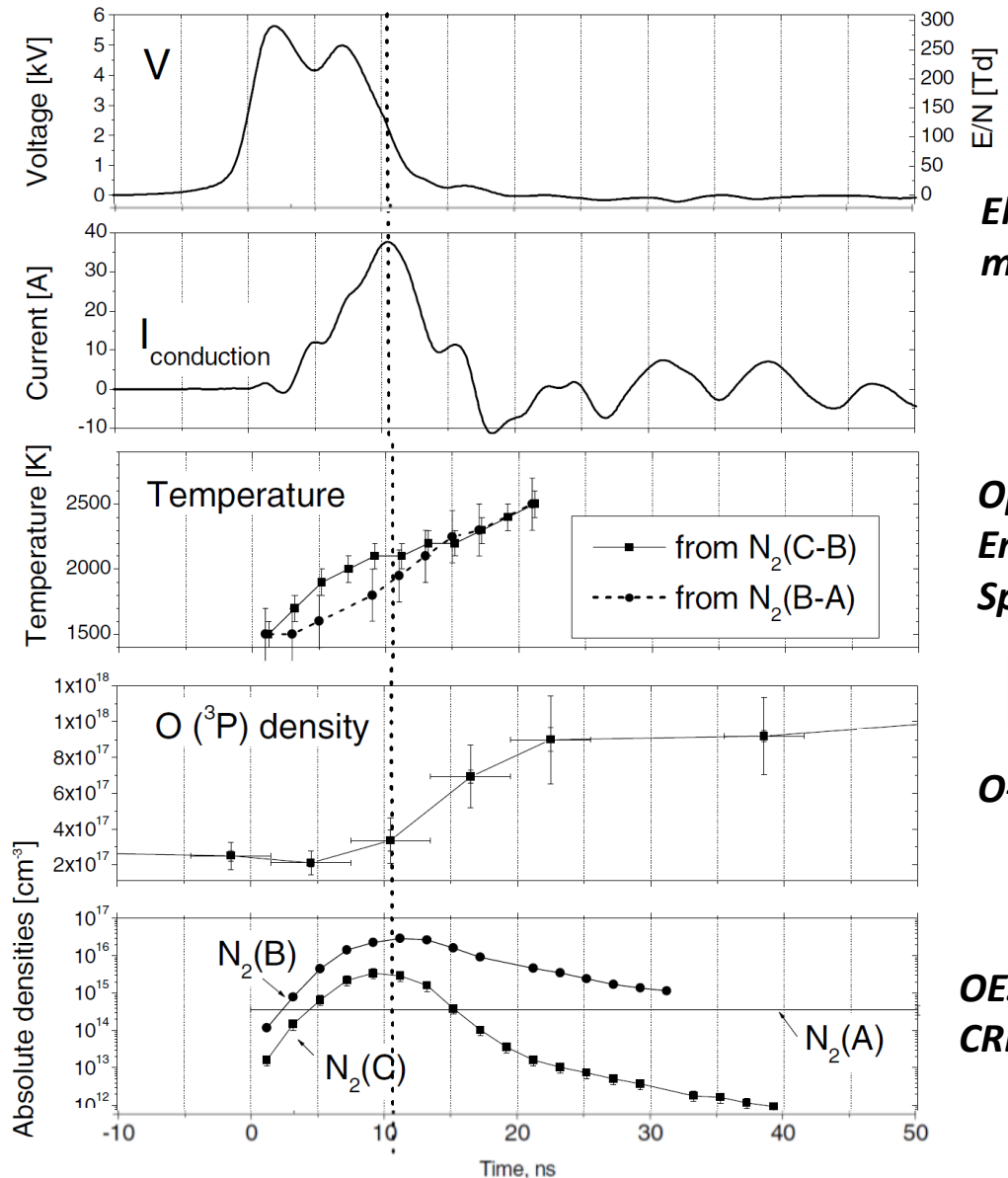


In ambient air

Two-step mechanism of fast gas heating and atomic oxygen production

Popov, Plasma Phys. Rep., 2001

Rusterholtz et al., J. Phys. D: Appl. Phys., 2013



Electrical measurements

Optical Emission Spectroscopy

O-TALIF

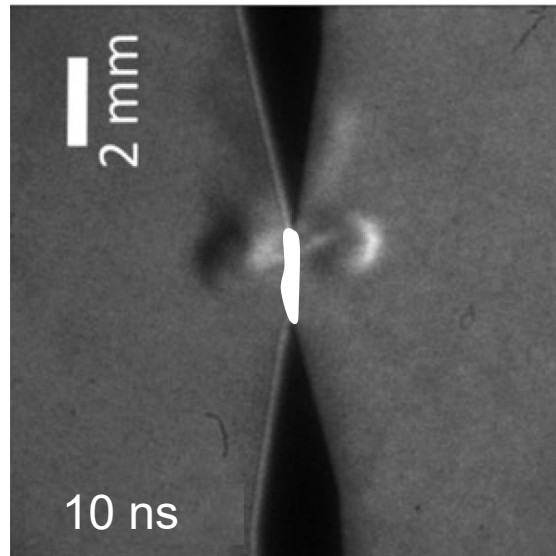
OES CRDS

NRP Discharges

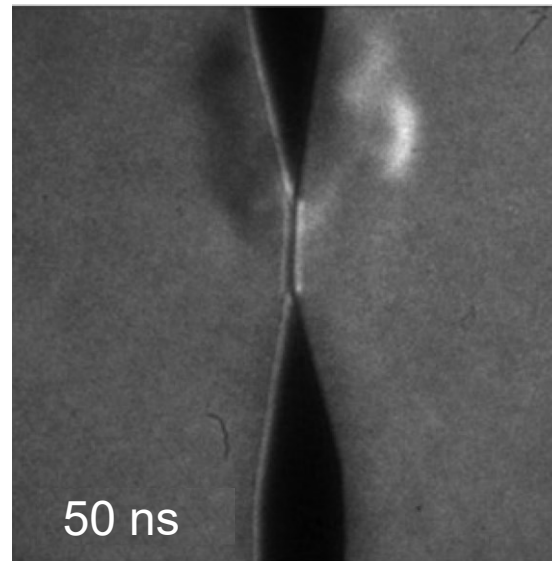


In ambient air

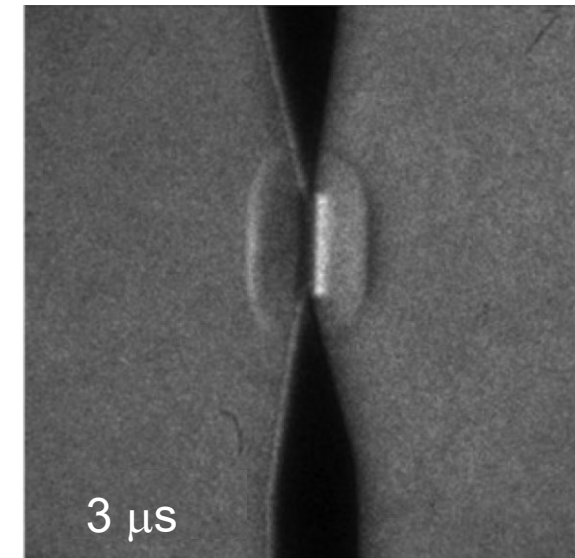
NRP spark discharges at 1 kHz, schlieren imaging



Light emission



Heated channel



Shock wave

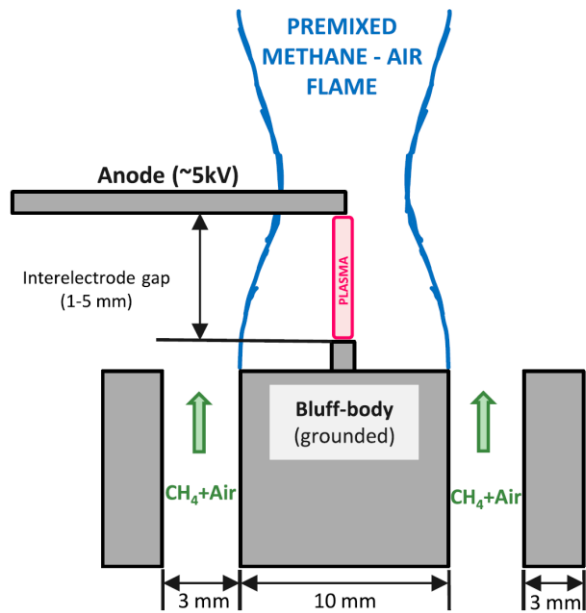
Xu et al., J. Appl. Phys. Lett., 2011

NRP Discharges



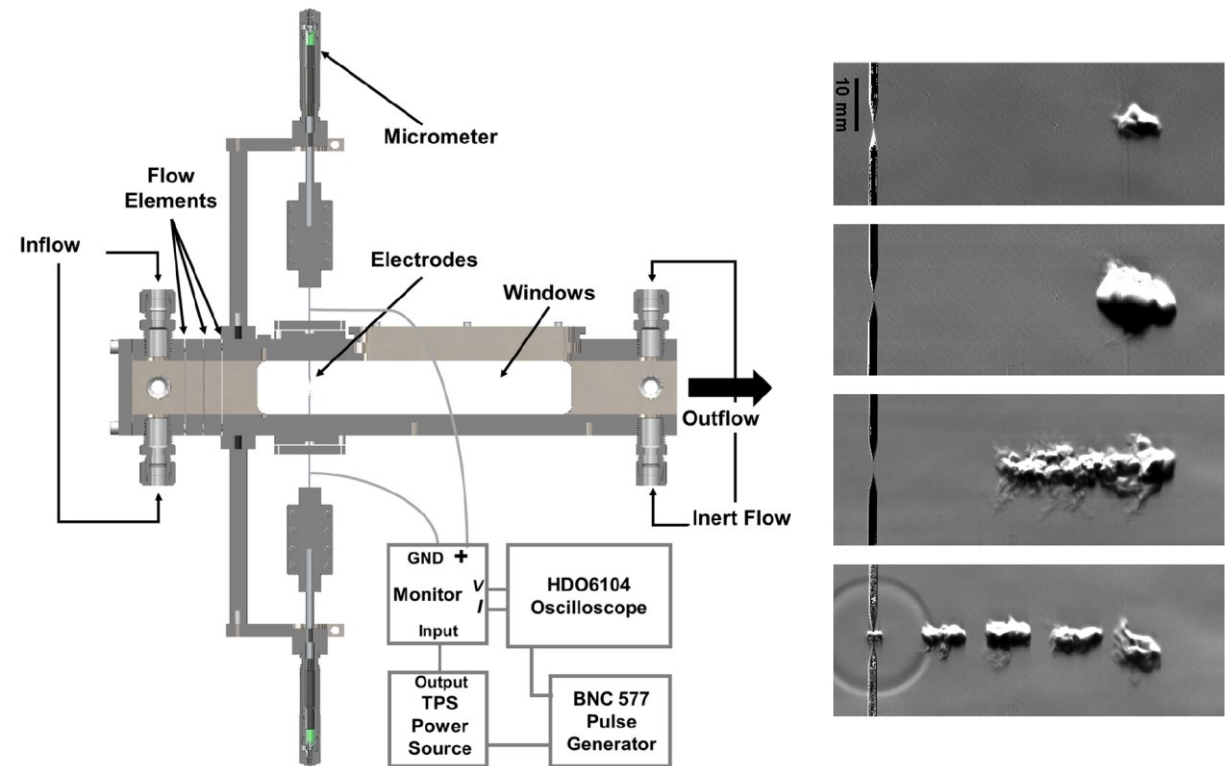
Examples of NRP discharges in PAC

NRP discharges for turbulent jet flame stabilization



Renaud Gablier, PhD thesis, 2026

Bursts of NRP discharges for ignition



Lefkowitz & Ombrello, Combust. Flame, 2017

NRP Discharges



Why should I choose NRP discharges?

✓ PROS

- ✓ High power/energy deposition
- ✓ Strong heating
- ✓ High reduced electric field
- ✓ Minimal electrode erosion
- ✓ Relatively large plasma volume
- ✓ Control of streamer inception

✗ CONS

- ✓ Risk of Electro-Magnetic Interferences (EMI)

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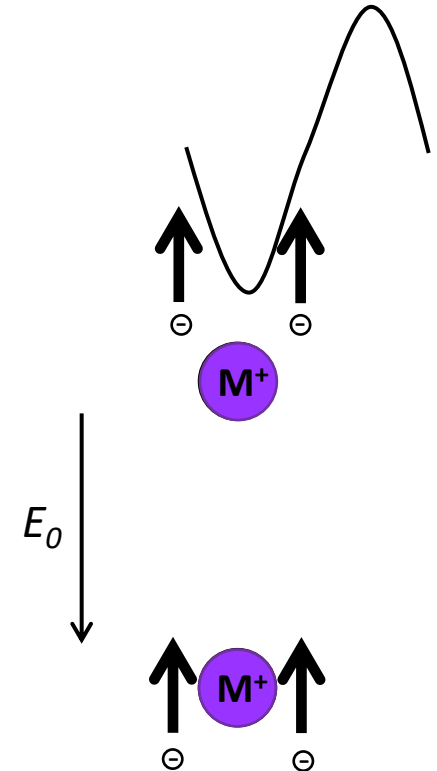


Microwave Discharges



Avoid thermalization by stopping the applied voltage

- Typical frequency 2.45 GHz
- Oscillations of the electrons on a 0.4-ns period
 - electrons move back and forth (no real current)
 - ions don't move
- Electrons can be accelerated by a magnetic field (inductive coupling) or by an electric field (capacitive coupling)
- Always a thermal effect (at low power or transient)
- Three different technologies to generate microwave discharges
 - Resonant cavity
 - Waveguide and antenna
 - Free expanding torch

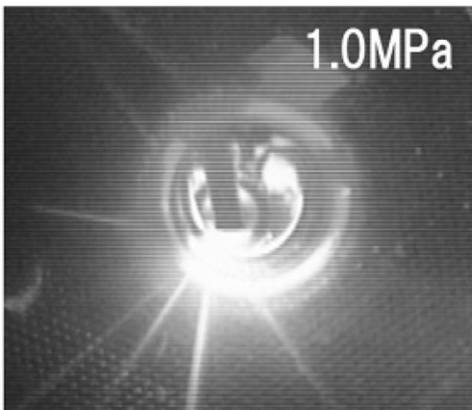
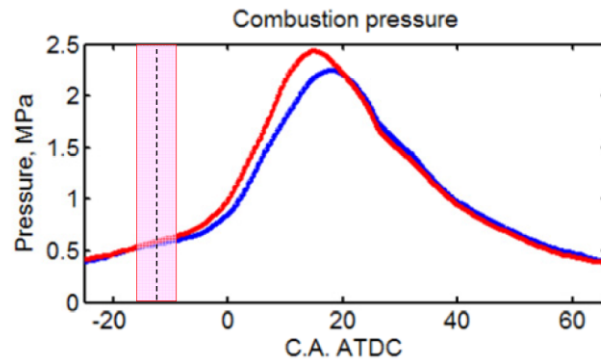


Microwave Discharges



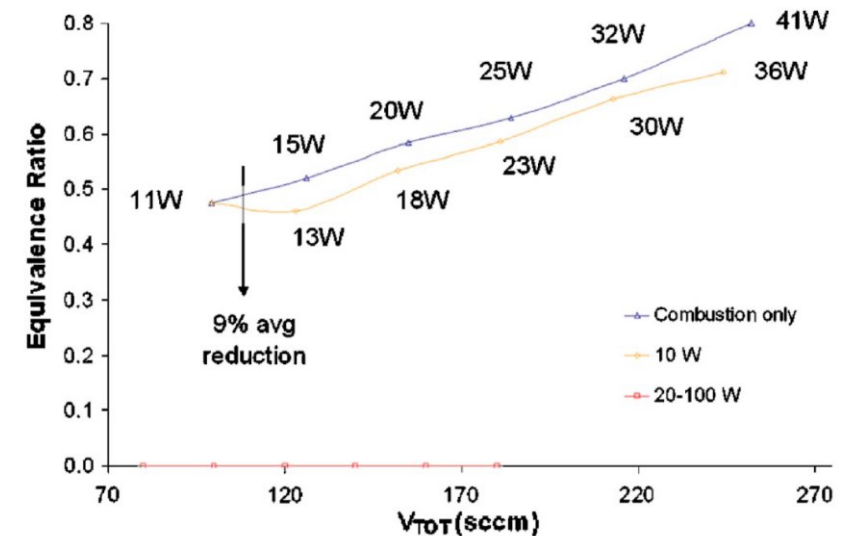
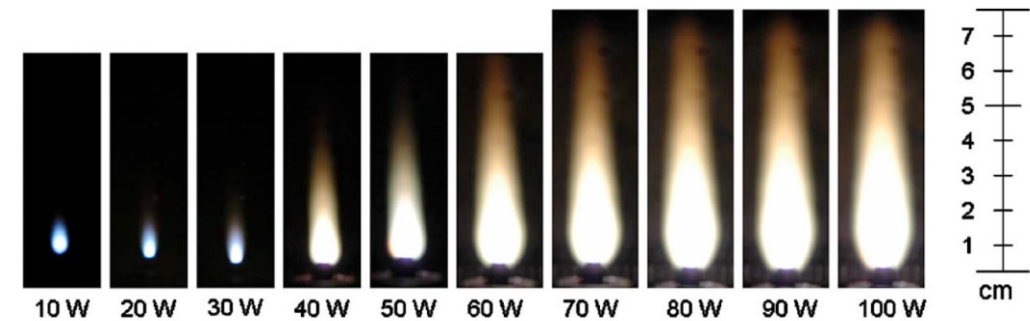
Examples of microwave discharges in PAC

Pulsed microwave-spark discharges for ignition



Ikeda et al., AIAA 2009-223, 2009

Microwave plasma torch for enhancement of LBO



Hemawan et al., Appl. Phys. Lett., 2006

Microwave Discharges



Why should I choose microwave discharges?

✓ PROS

- ✓ Strong heating
- ✓ No electrode erosion
- ✓ Large plasma volume

✗ CONS

- ✓ Always strong heating
- ✓ Complicated systems
- ✓ Microwave radiation

Chapter VI: Sources and Methods



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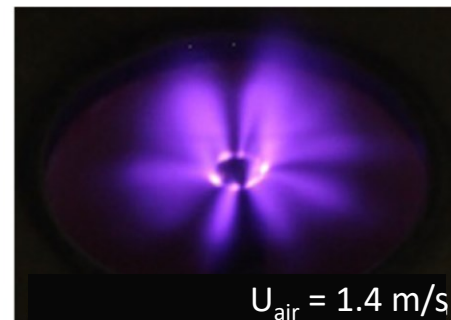
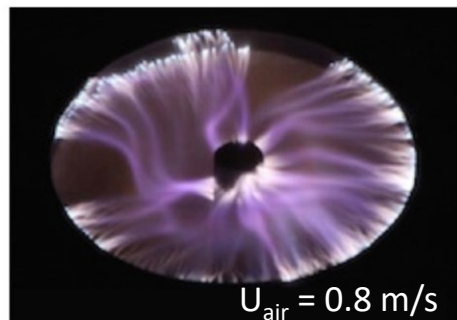
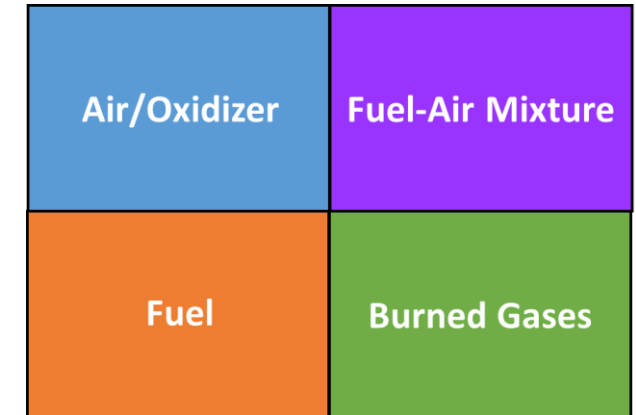


System Integration



Where to install a plasma actuator in the combustion system?

- Parameters to consider:
 - Gas composition
 - discharge physics (e.g., breakdown voltage)
 - chemical species produced (O, OH, NO, CH, CO...)
 - gas heating
 - Flow (e.g., quiescent, laminar, turbulent, supersonic)
 - discharge physics (e.g., discharge regime)
 - volume of gas treated by the discharges
 - convection/residence time → chemical species



NRP discharges in various flows of air

System Integration

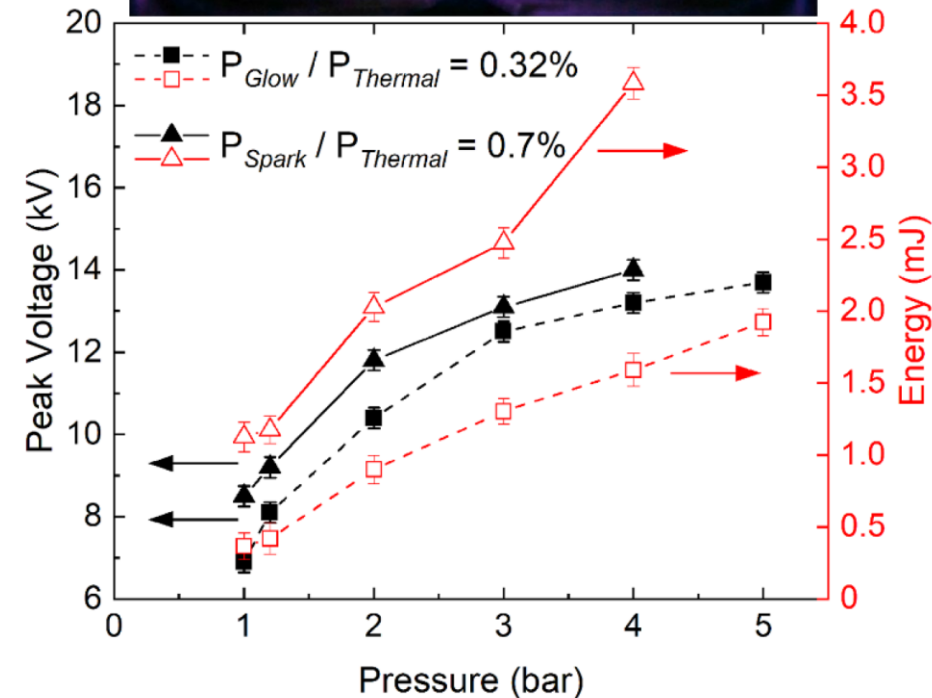


Where to install a plasma actuator in the combustion system?

- Parameters to consider:
 - Pressure and temperature
 - E/N → discharge physics, chemistry, heating
 - Post-discharge chemistry (e.g., recombination reactions)
 - Electrode integration
 - Electrical insulation
 - Thermal protection
 - Available volume/space



NRP discharges in swirl flames



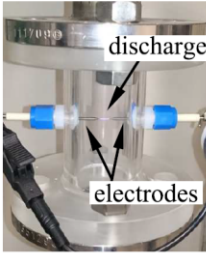
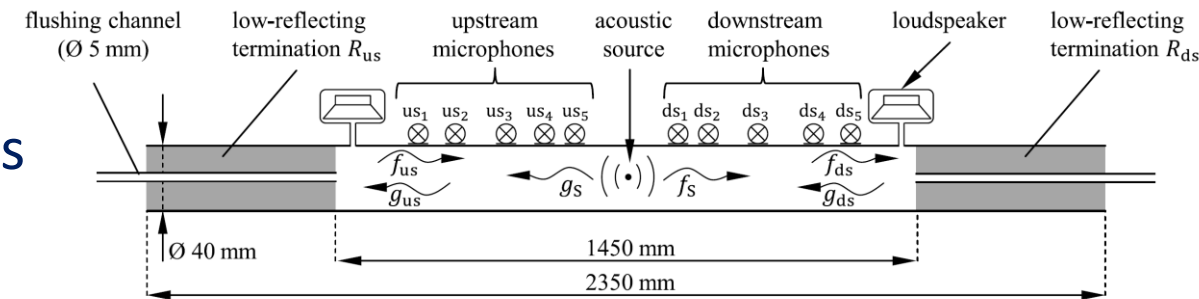
System Integration



Where to install a plasma actuator in the combustion system?

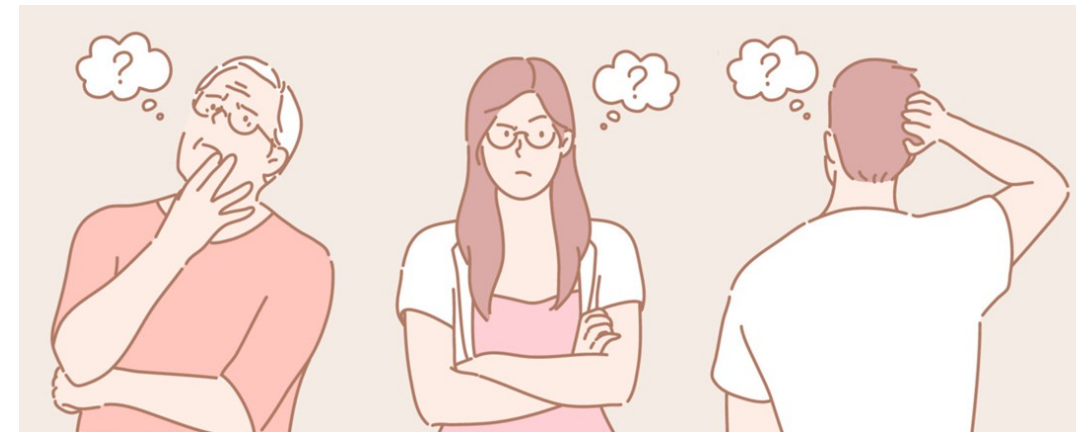
- Desired outcomes:
 - Goal of the plasma actuation
 - Ignition
 - Flammability limit enhancement
 - Control of thermoacoustic instabilities
 - Control of soot/pollutant emissions

NRP discharges in an acoustic tube



Bölke et al., J. Phys. D: Appl. Phys., 2018

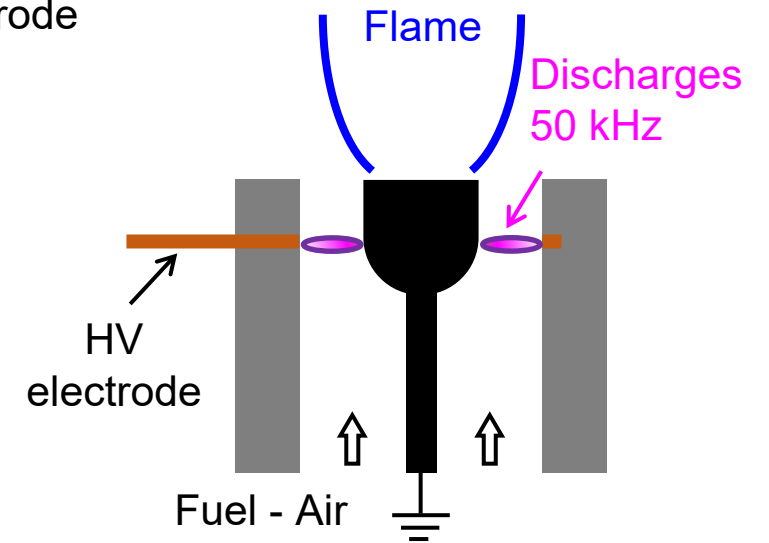
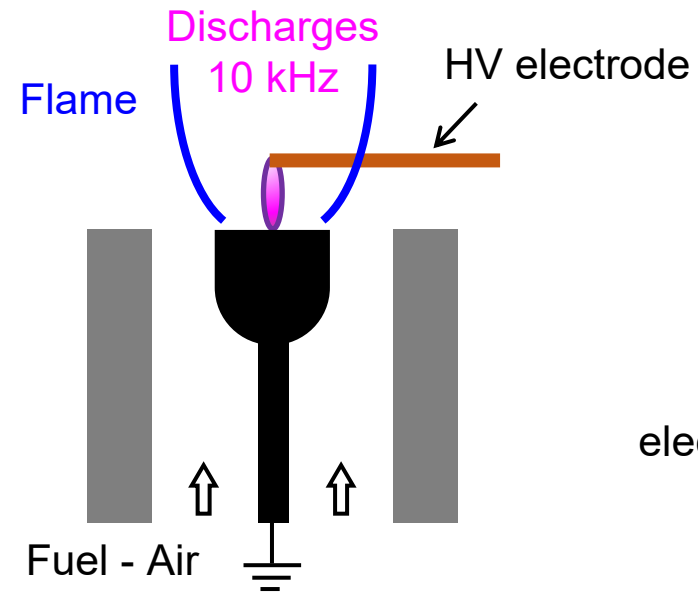
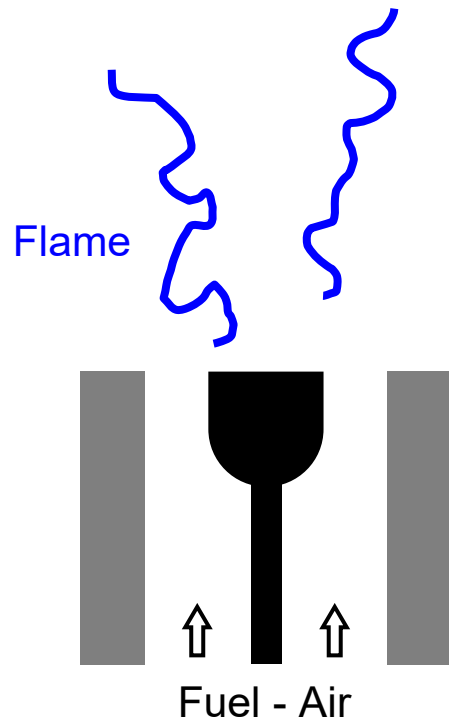
- Your personal goal
 - Obtain a good plasma effect to graduate, get a grant, convince an industrial partner...
 - Answer a scientific question
 - Become a recognized expert in PAC



System Integration



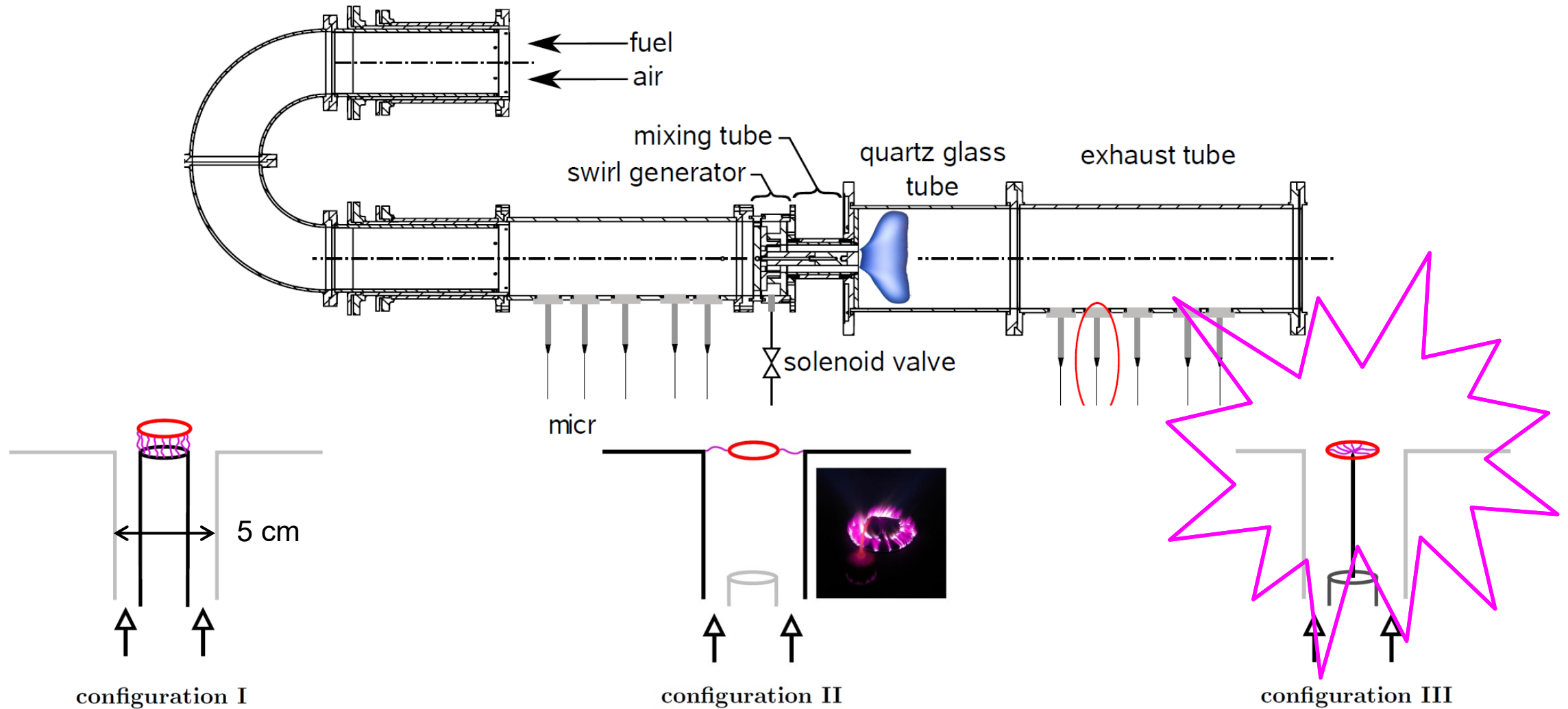
Example 1: anchoring a flame stabilized over a bluff-body



System Integration



Example 2: control of thermoacoustic instabilities in a swirl flame



References



Papers

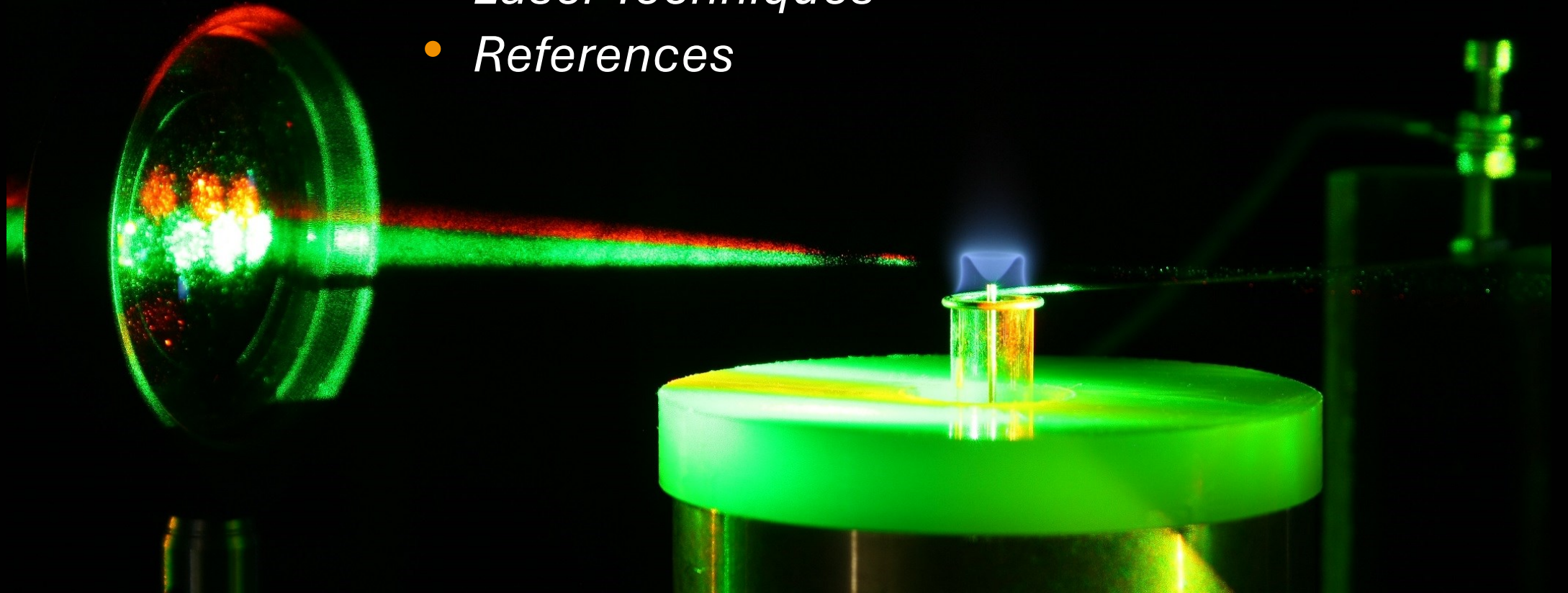
- *D.A. Lacoste, Flames with plasmas, Proc. Combust. Inst. 39, 5405-5428, 2023*
- *S.M. Starikovskaia, V. Lafaurie, J.-B. Perrin-Terrin, C.O. Laux, Foundations of plasma-assisted combustion: I. Fundamentals of combustion and plasma, Plasma Sources Sci. Technol. 35, 023001, 2026*
- *C.O. Laux, J.-B. Perrin-Terrin, V. Lafaurie, S.M. Starikovskaia, Foundations of plasma-assisted combustion: II. Mechanisms and applications, Plasma Sources Sci. Technol. 35, 023002, 2026*

Book

- *Plasma Assisted Combustion and Chemical Processing, Yiguang Ju & Andrey Starikovskiy, CCRC Press, Taylor and Francis Group, Boc Raton, FL, USA, 2025*

Chapter VII: Diagnostics

- *Electrical Properties*
- *Optical Emission Spectroscopy*
- *Laser Techniques*
- *References*





Electrical Properties

Discharge properties that are important for combustion applications are:

- Energy/power
 - Duration
 - Volume/dimensions
 - Gas temperature
 - Chemical composition
- } → **electrical measurements**

The energy deposited by the discharge, ϵ_{plasma} , can be obtained by measuring the voltage, V , and current, I , and integrating their product

$$\epsilon_{plasma} = \int V \times I dt$$

- Different plasma sources require different techniques to measure energy
- Each probe affects the electrical circuit



Electrical Properties

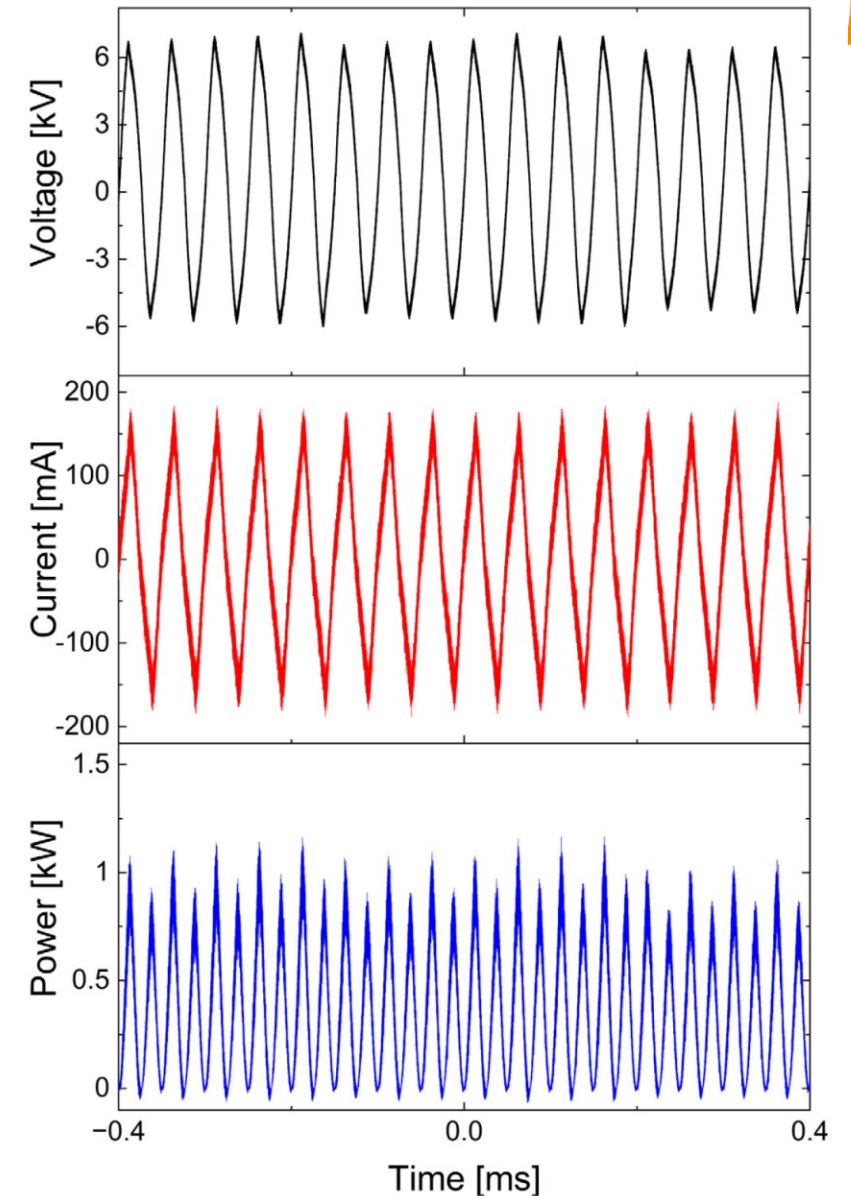
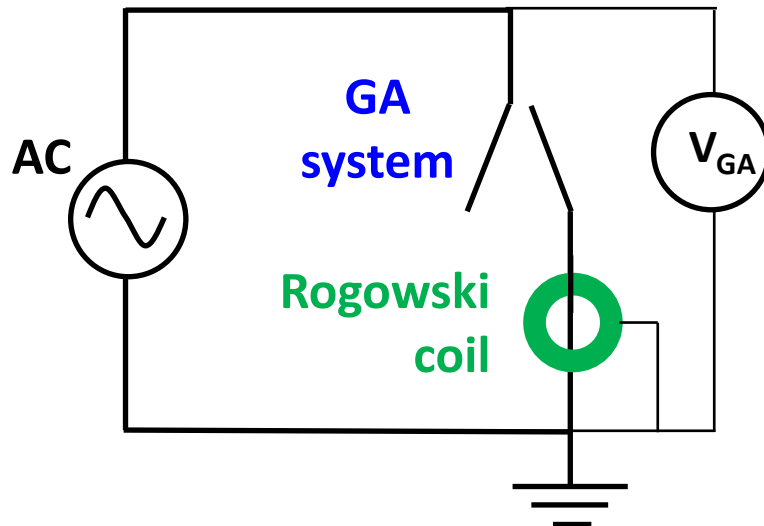


Power measurements in gliding/elongated arcs

- With the correct probes, relatively easy to measure
- The instantaneous power is given by the product of voltage across the gliding arc, V_{GA} , and the current, I , typically measured with a Rogowski coil

$$P_{GA} = V_{GA} \times I$$

Electrical circuit for inductive current measurement method



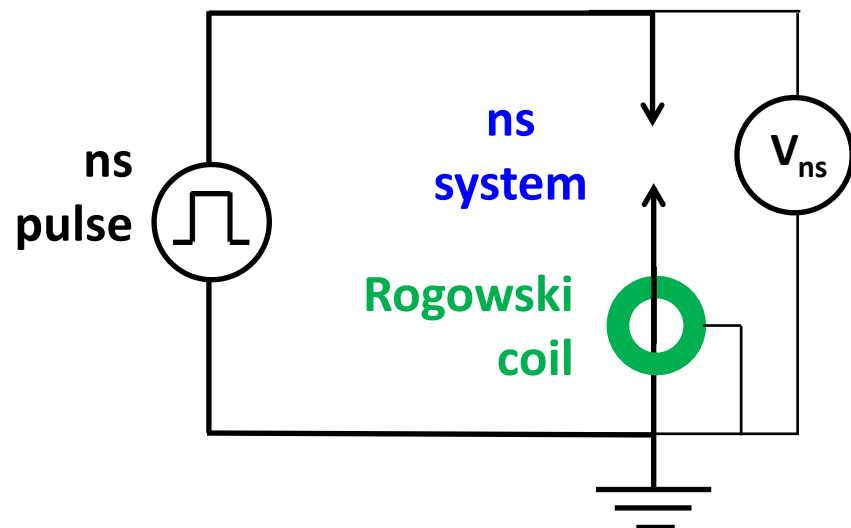
Electrical Properties



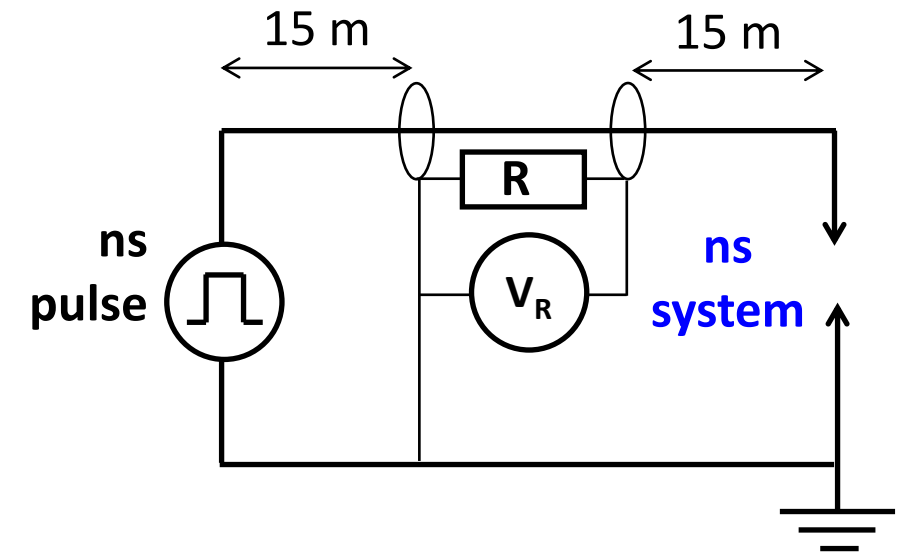
Energy measurements in nanosecond discharges

- In principle, easy, in practice challenging
- The propagation speed of an electric signal in a wire is about 1 m/5 ns
- When an electric signal travels across medias of different impedances, a part of the signal will be reflected at the interface
- In practice, two different techniques are used

Electrical circuit for inductive current measurement method



Electrical circuit for back current shunt resistor measurement method



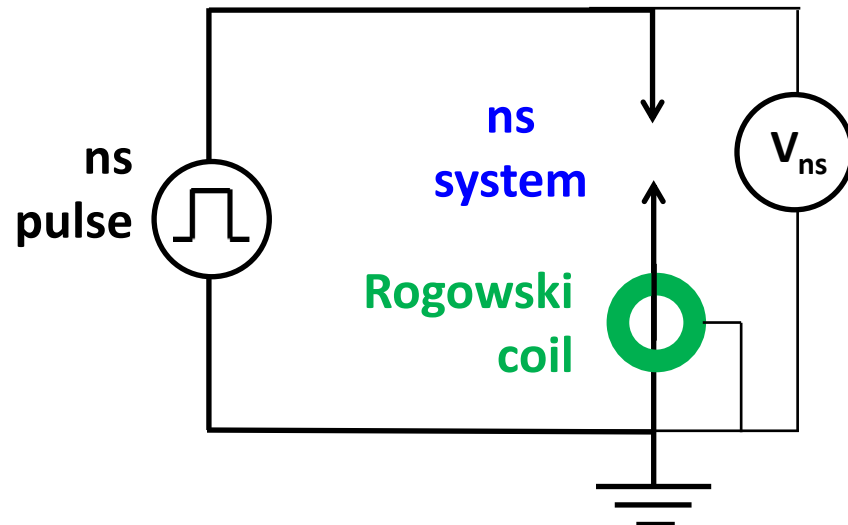
Electrical Properties



Energy measurements in nanosecond discharges

- Inductive current method
- The voltage, V_{ns} , and the current, I , signals must be **synchronized** because the response times of the measurement circuits (probes, wires, attenuators...) are different
- Two different synchronization techniques, both based on **measurements without plasma**

Electrical circuit for inductive current measurement method



- Without discharges $\varepsilon_{plasma} = 0$ J, then Δt is adjusted such that $\varepsilon_{plasma} = \int V(t) \times I(t + \Delta t) dt = 0$

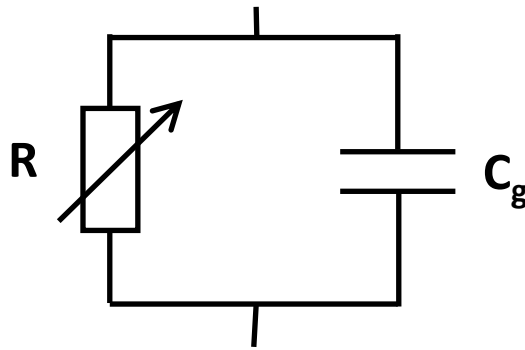
Electrical Properties



Energy measurements in nanosecond discharges

- Inductive current method
- The voltage, V_{ns} , and the current, I , signals must be **synchronized** because the response times of the measurement circuits (probes, wires, attenuators...) are different
- Two different synchronization techniques, both based on **measurements without plasma**

Simplified electrical circuit for ns system



- Without discharges $\varepsilon_{plasma} = 0$ J, then Δt is adjusted such that $\varepsilon_{plasma} = \int V(t) \times I(t + \Delta t) dt = 0$
- Without plasma, the system (electrodes + gas) behaves as a capacitor and Δt is adjusted such that
$$I(t + \Delta t) = C_g \frac{dV(t)}{dt}$$
- More details in *Rusterholtz et al., J. Phys. D: Appl. Phys., 2013*

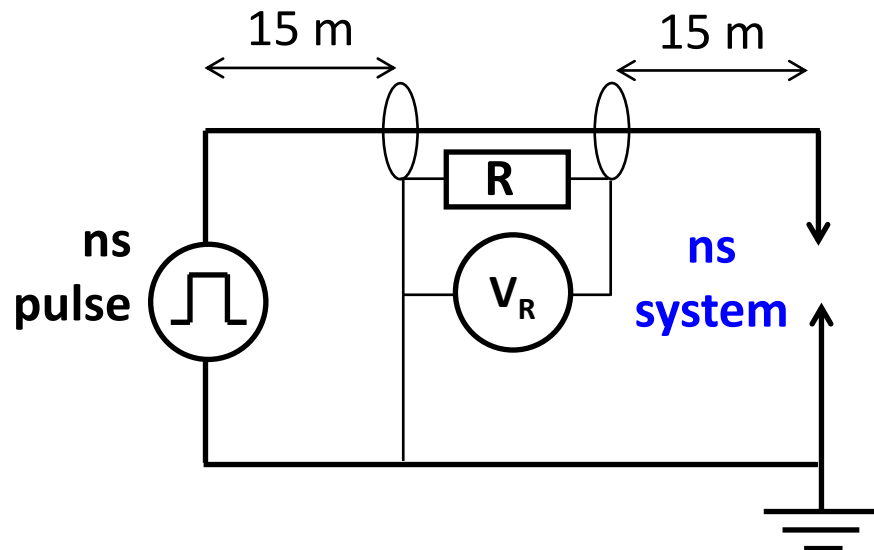
Electrical Properties



Energy measurements in nanosecond discharges

- Back current shunt resistor method: a resistor is installed in the shielding of the high voltage coaxial cable
- Very long coaxial cable (> 15 m) is used to separate the incident and reflected pulse
- The current across the resistor is measured with a voltage probe $I_R = U_R/R$

Electrical circuit for back current shunt resistor measurement method



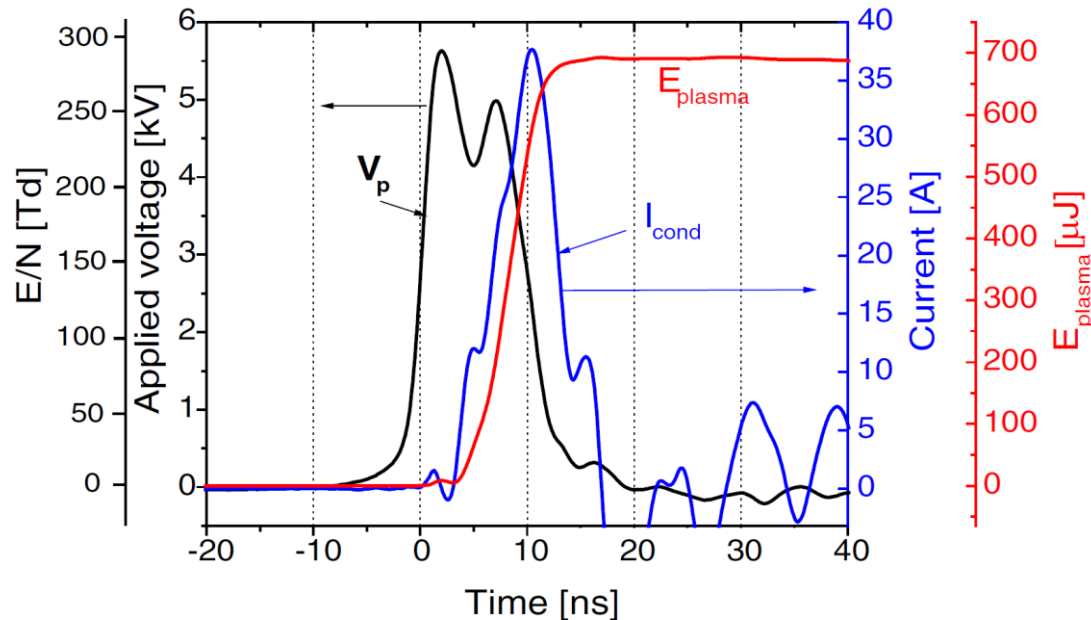
- The incident pulse carries the energy of the power supply $\epsilon_{incident} = RI_R^2_{incident}$
- The reflected pulse carries the energy that is not dissipated in the discharges $\epsilon_{reflected} = RI_R^2_{reflected}$
- $\epsilon_{plasma} = \epsilon_{incident} - \epsilon_{reflected}$
- More details in *Anikin et al., Plasma Phys. Rep., 2004*

Electrical Properties



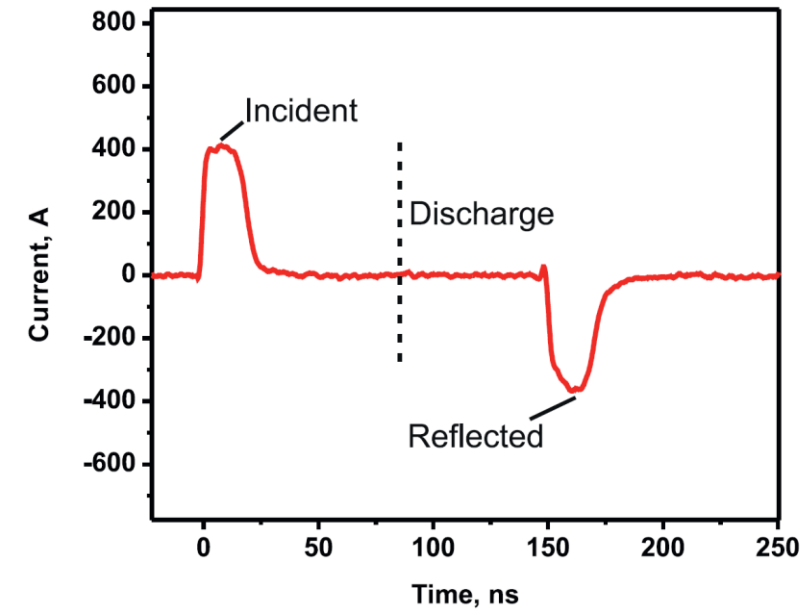
Examples of energy measurements in NRP discharges

Electrical measurements using inductive current method



Rusterholtz et al., J. Phys. D: Appl. Phys., 2013

Electrical measurements using back current shunt method



Shcherbanev et al., Combust. Flame, 2017

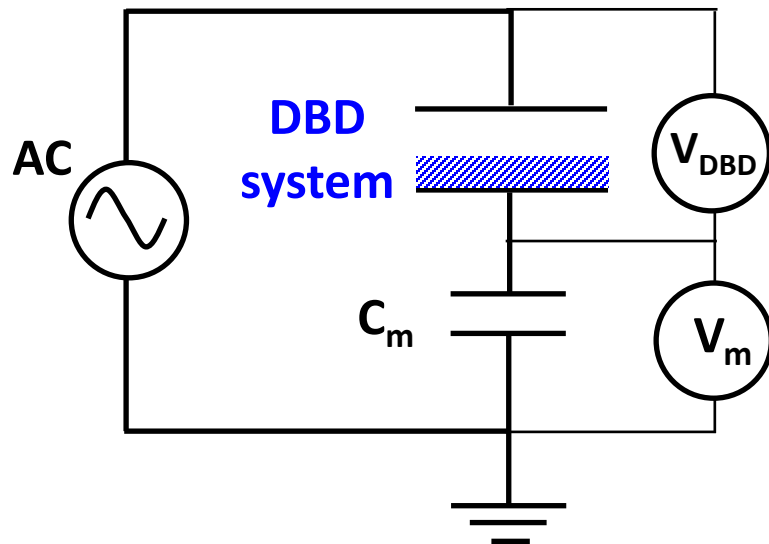
Electrical Properties



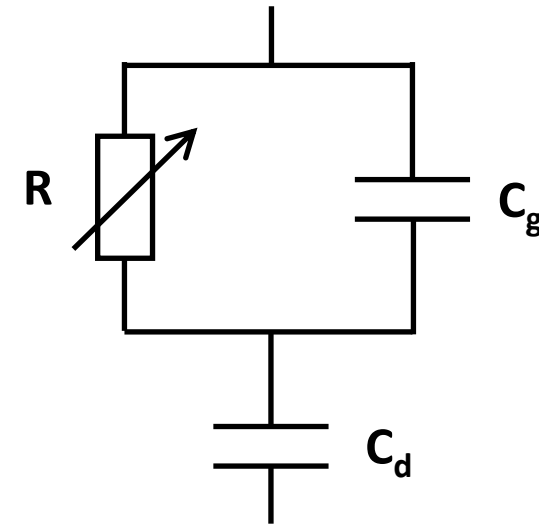
Power measurements in AC DBD

- Methods consisting of measuring the voltage and the current (using a shunt resistor or an inductive coil) are not precise enough for DBD discharges
- Instead, electric charge method using a capacitor is utilized

Electrical circuit for a monitor capacitor method



Electrical circuit for DBD system



Pipa et al., Rev. Sci. Instrum., 2012

- $C_m \gg \frac{C_g C_d}{C_d + C_g}$ without discharges (typically $C_m \sim 100$ nF)

Electrical Properties



Power measurements in AC DBD

- Capacitor-based charge method:

- The instantaneous charge of the monitor capacitor is $Q_m(t) = C_m V_m(t)$

- The current through the capacitor is $I_m(t) = C_m \frac{dV_m(t)}{dt}$

- The instantaneous power dissipated by the DBD is then

$$P_{DBD}(t) = V_{DBD}(t) \times I_m(t) = V_{DBD}(t) \times C_m \frac{dV_m(t)}{dt}$$

- And the average power over a period T is

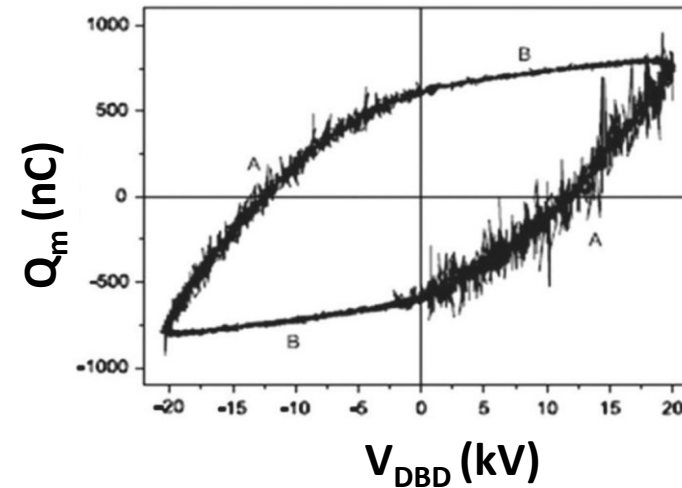
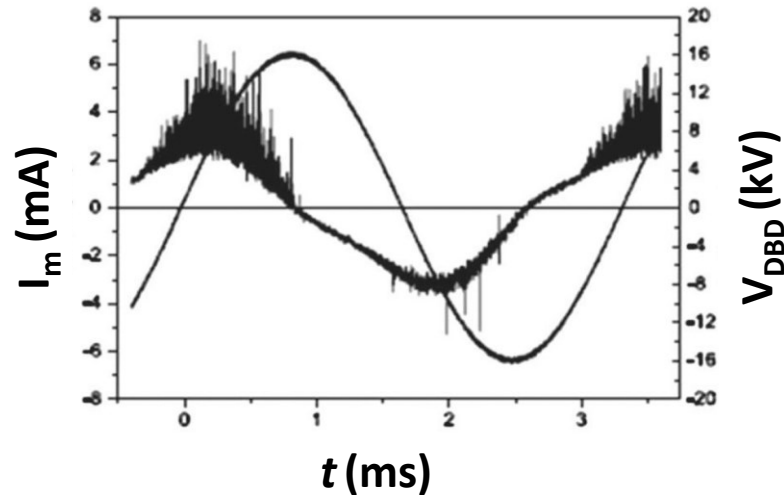
$$\bar{P}_{DBD} = \frac{1}{T} \int_0^T V_{DBD}(t) \times C_m \frac{dV_m(t)}{dt} dt = \frac{1}{T} \int V_{DBD} C_m dV_m = \frac{1}{T} \oint V_{DBD} dQ_m$$

Electrical Properties



Power measurements in AC DBD

- The instantaneous capacitor charge Q_m and the instantaneous DBD voltage V_{DBD} plotted against each other generate a **Lissajous curve** in the $Q_m - V_{DBD}$ plane



Pons et al., J. Phys. D: Appl. Phys., 2005

- The area inside the closed Lissajous curve divided by the AC cycle period T is equal to the DBD power

Electrical Properties



Power measurements in microwave discharges

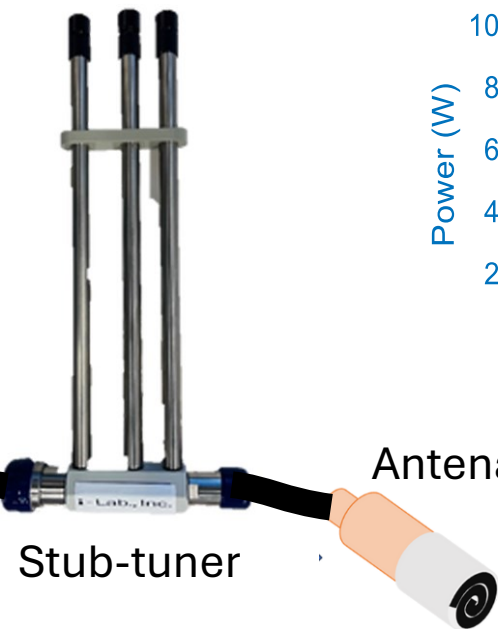
- The microwave losses in the discharge, P_{plasma} , can be defined from the power balance between the incident power, $P_{forward}$, and the reflected power, $P_{reflected}$

$$P_{plasma} = P_{forward} - P_{reflected}$$

Microwave generator

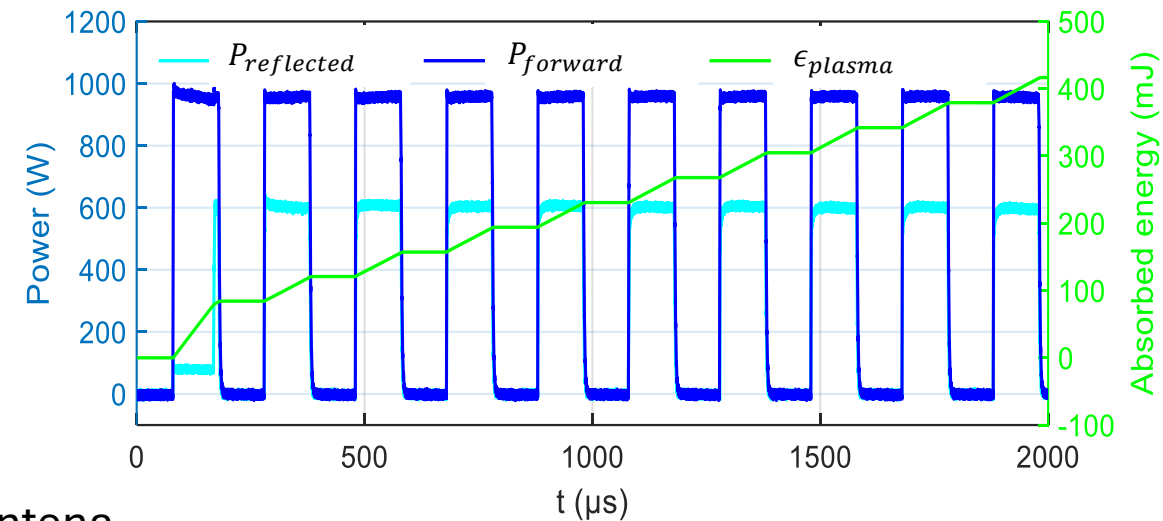


Coupler



Stub-tuner

Antenna



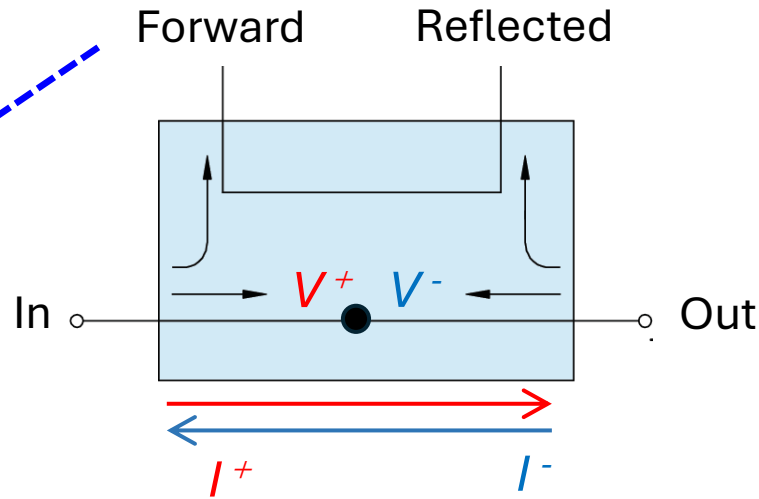
Electrical Properties



Power measurements in microwave discharges



Coupler



- **Main line**
 $V = V^+ + V^-$
 $I = I^+ - I^-$
 $Z_0 I = V^+ - V^-$

- **Coupled line**

$$V_{forward} = v_E + v_H \propto \frac{d(V + Z_0 I)}{dt} = 2 \frac{dV^+}{dt}$$

$$V_{reflected} = v_E - v_H \propto \frac{d(V - Z_0 I)}{dt} = 2 \frac{dV^-}{dt}$$

$$v_E \propto \frac{dV}{dt}: \text{electric-field coupling}$$

$$v_H \propto \frac{d(Z_0 I)}{dt}: \text{magnetic-field coupling}$$

Electrical Properties



Probe requirements

- Ranges (input, output)
- Bandwidth/Response time
- Calibration

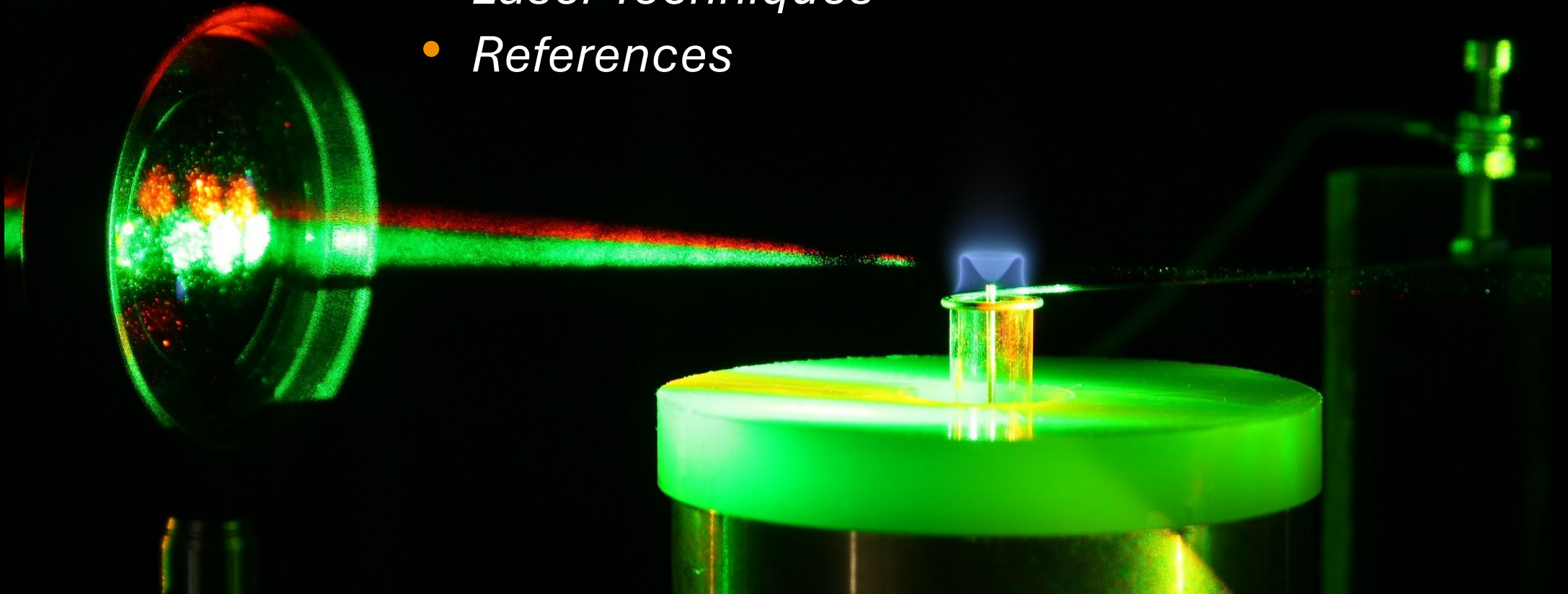
Typical probes used in PAC studies

- Passive high-voltage probes: attenuation 1000:1, maximum input voltage 20 kV, bandwidth 75 MHz
- Rogowski coil current monitor: attenuation 1:1, maximum input current 500 A, bandwidth 250 MHz
- Attenuator: attenuation 10:1, maximum input voltage 1.25 kV, maximum peak power 31 kW, bandwidth DC to 7 GHz
- Oscilloscope: Bandwidth 2 GHz, 4 channels, acquisition 5 GS/s



Chapter VII: Diagnostics

- *Electrical Properties*
- ***Optical Emission Spectroscopy***
- *Laser Techniques*
- *References*



Optical Emission Spectroscopy



THE plasma diagnostic

- Nonintrusive
- Works relatively well for PAC conditions
- For some conditions, allow quantitative measurements of
 - Electron density
 - Electron temperature
 - Temperatures of excited species
 - Density of excited species
- Limitation: light-of-sight integrated



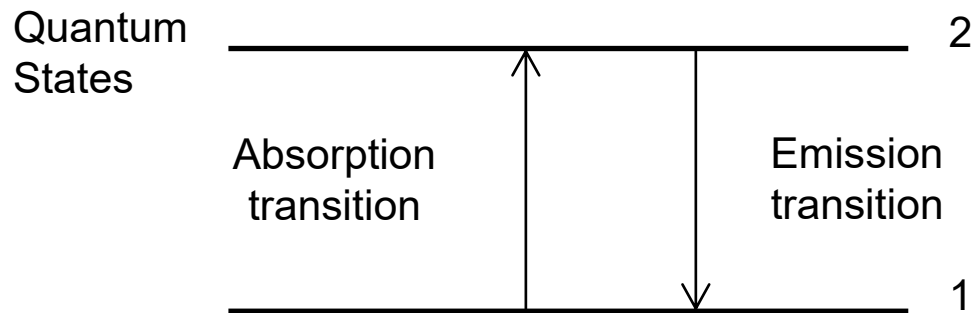
The Dark Side of the Moon
Pink Floyd, 1973

Optical Emission Spectroscopy



Principle of optical emission spectroscopy (OES)

- Optical emission occurs when a molecule or atom changes quantum states from higher to lower energy and, in the process, release a photon

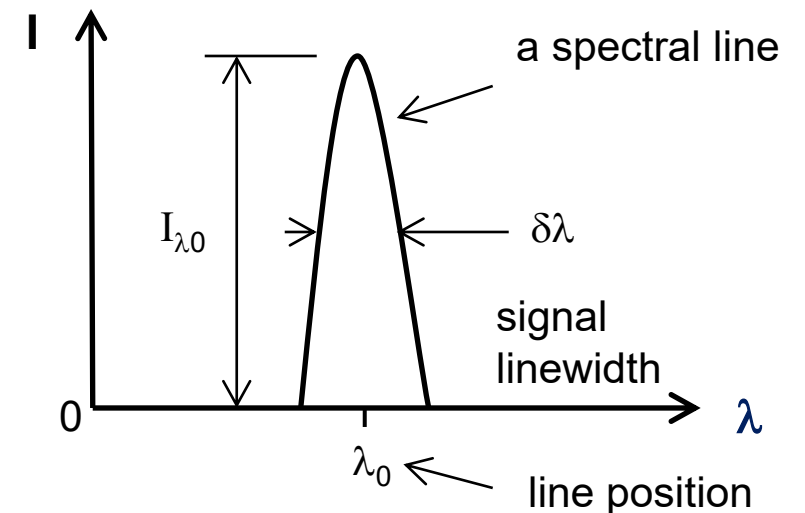


- Planck's law: $\Delta\varepsilon = \varepsilon_{upper} - \varepsilon_{lower} = h\nu$

$h = 6.63 \times 10^{-34} \text{ J} \cdot \text{s}$, the Planck's constant

ν : photon frequency, with $c = \lambda\nu$, $c = 3.0 \times 10^8 \text{ m/s}$

λ : wavelength

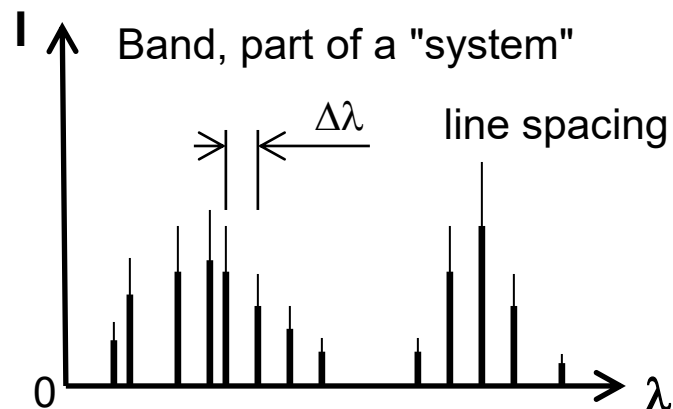


Optical Emission Spectroscopy



Principle of optical emission spectroscopy (OES)

- Emission spectra of diatomic molecules



- Intensity of a rotational line

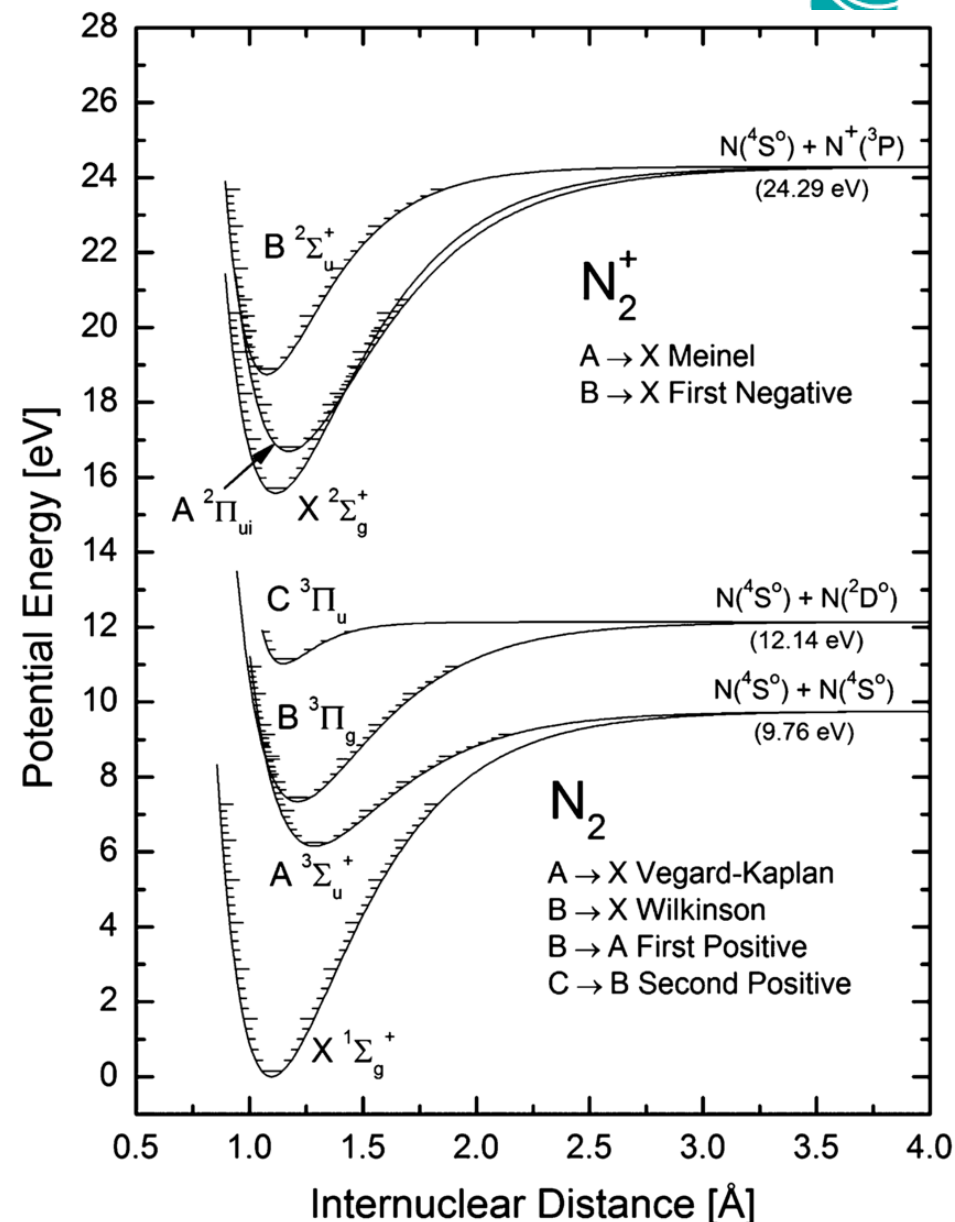
$$I(\lambda) = n_{e'v'J'} A_{e'v'J'-e''v''J''} h\nu \Phi(\lambda-\lambda_0)$$

$n_{e'v'J'}$: molecule density in the upper state

$A_{e'v'J'-e''v''J''}$: Einstein coefficient

$h\nu = \varepsilon_{e'v'J'} - \varepsilon_{e''v''J''}$

$\Phi(\lambda-\lambda_0)$: normalized lineshape function



Optical Emission Spectroscopy



Principle of optical emission spectroscopy (OES)

- At local equilibrium, the distribution of molecules per energy level can be calculated with the Boltzmann's equation

$$F_i = \frac{n_i}{n} = \frac{g_i \exp\left(-\frac{\epsilon_i}{kT}\right)}{Q}$$

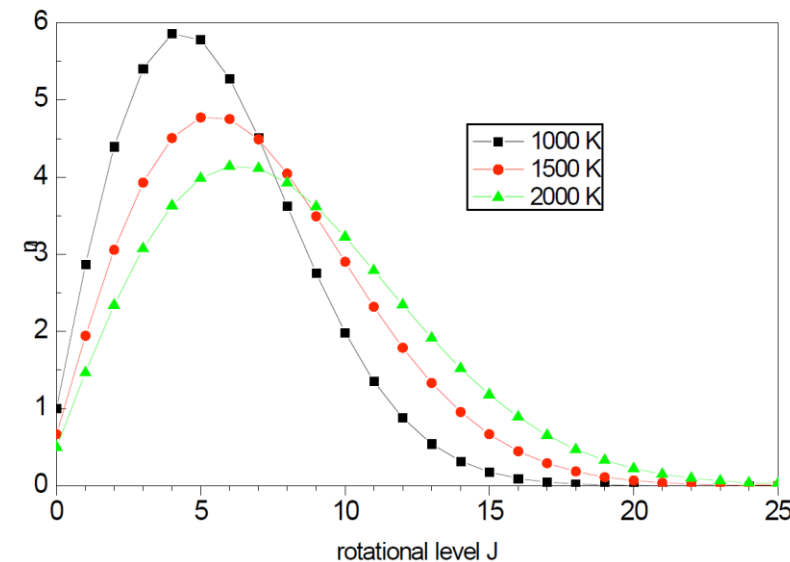
Q : partition function given by $Q = \sum_i g_i \exp\left(-\frac{\epsilon_i}{kT}\right)$

g_i : degeneracy of level i

ϵ_i : energy of level i

$k = 1.38 \times 10^{-23} \text{ J K}^{-1}$, Boltzmann constant

T : temperature



→ The relative intensity of the lines is a function of the temperature

Optical Emission Spectroscopy



Principle of optical emission spectroscopy (OES)

- Molecular emission lines never appear to be Dirac functions in spectra because there are different mechanisms that lead to broadening spectroscopic transitions
 - **Natural broadening** (Heisenberg Uncertainty Principle): Lorentzian form, weaker than other broadenings
 - **Doppler broadening** (molecular random velocities): Gaussian form, gas temperature dependent only, becomes predominant at low pressure
 - **Van der Waals broadening**: Lorentzian form, pressure and temperature dependent
 - **Resonance broadening** (self broadening): Lorentzian form
 - **Stark broadening** (in presence of charged particles) : Lorentzian form
 - **Instrument broadening**: caused by the way a measurement is made (spectral resolution), Gaussian form

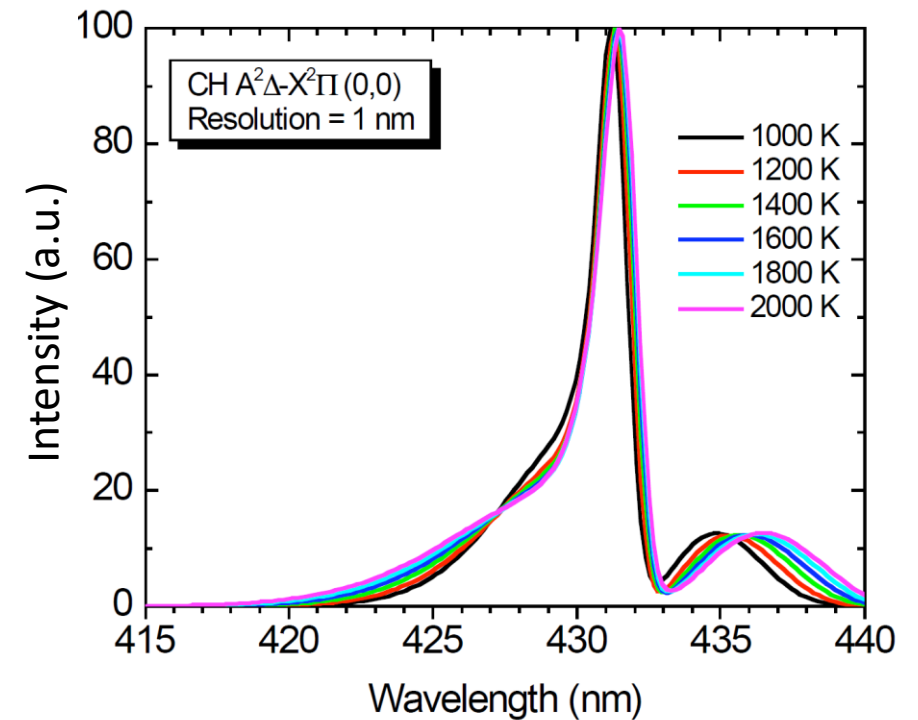
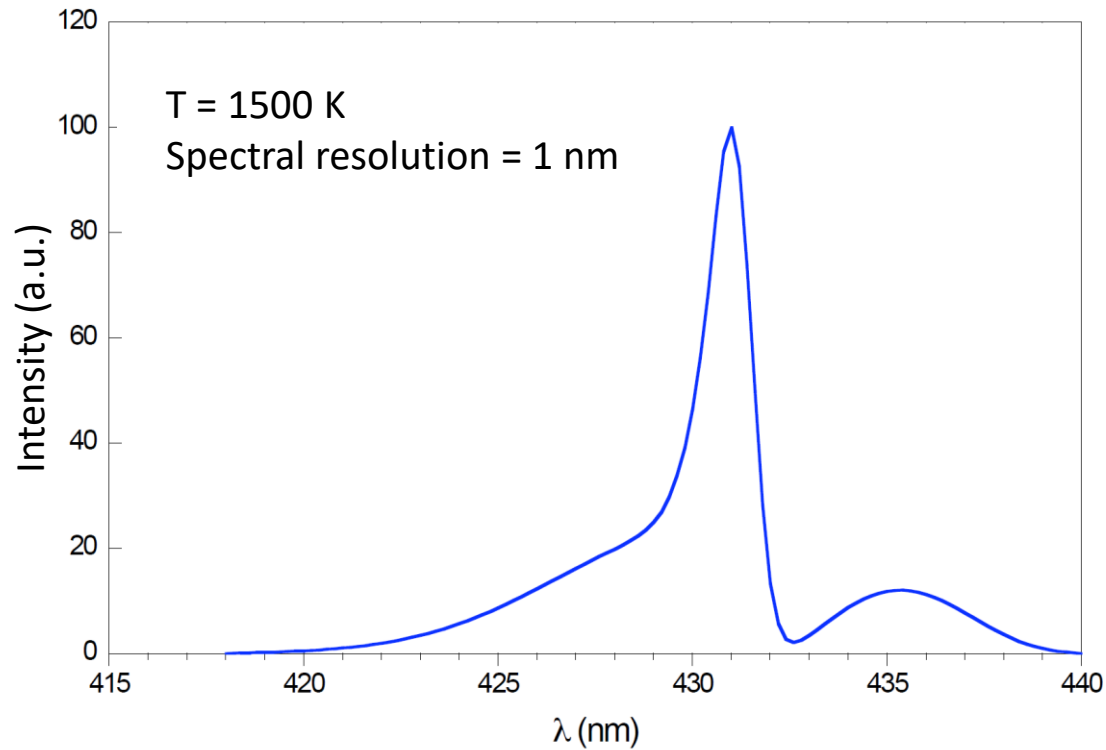
→ Line broadening is often used in OES to determine electron density

Optical Emission Spectroscopy



Examples of simulated emission spectra

- Simulations of CH A-X (0,0) with LIFBASE



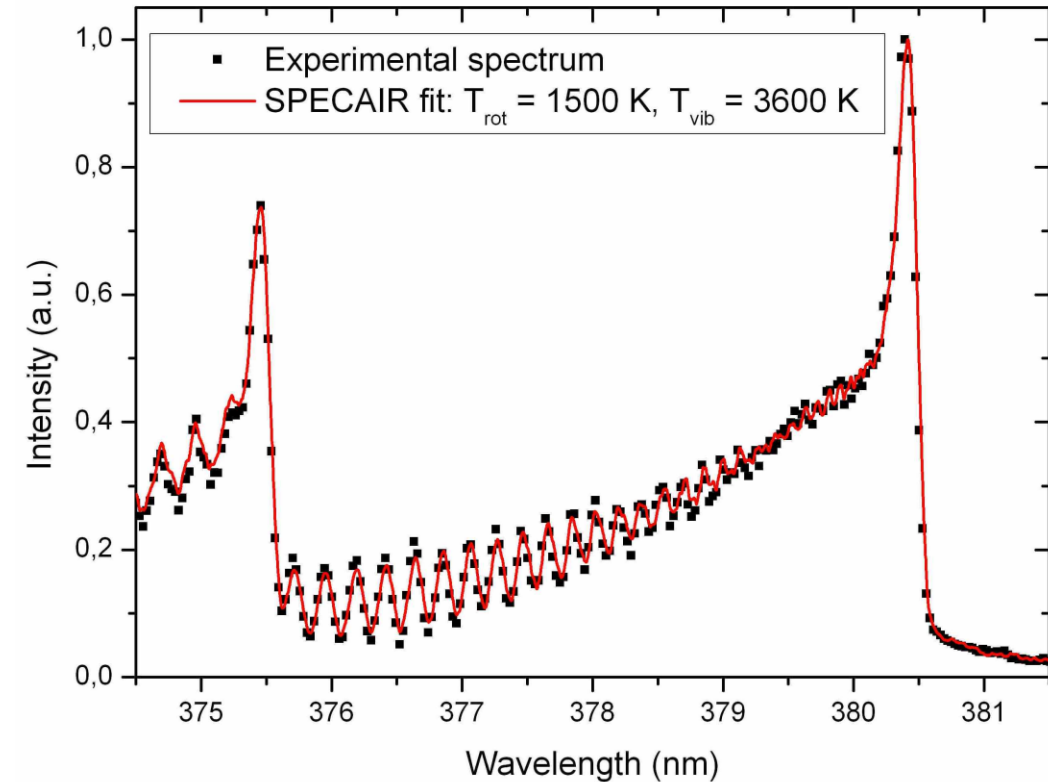
Optical Emission Spectroscopy



OES of N_2 for gas temperature measurements in PAC

- Assumptions:
 - N_2 C is populated by electron impact of N_2 X
 - $T_{rot N2C} = T_{rot N2X} = T_{gas}$
- Validity domain of these assumptions can be found in *Tibère-Inglesse et al., PSST, 2023*
- Good spectral resolution is important
- For this thermometry technique, an accuracy of ± 100 K is good
- Simulations with SPECAIR (commercial software)
- In absence of N_2 , other species can be used (e.g., H_2)

OES of N_2 for thermometry in PAC Spectral resolution 0.11 nm



Lacoste et al., PROCI, 2013

Optical Emission Spectroscopy



OES of atomic H for electron density in PAC

- Stark broadening of an atomic H line, $\Delta\lambda_S$, can be used to determine the electron density
- For example, using this equation for H_α

$$\Delta\lambda_S = 1.78 \times \left(\frac{n_e}{10^{17}} \right)^{1.5}$$

Hofmann et al., PSST, 2011

- $\Delta\lambda_S$ can be obtained from the measured H_α line, by fitting the line with a Voigt profile (combination of Gaussian and Lorentzian profiles)
- The FWHM of the Gaussian broadening, $\Delta\lambda_G$, is coming from Doppler and Instrumental broadening

$$\Delta\lambda_G^2 = \Delta\lambda_{Doppler}^2 + \Delta\lambda_{Instr}^2$$

- $\Delta\lambda_{Instr}$ is measured by recording the emission of a monochromatic source
- $\Delta\lambda_{Doppler}$ is calculated (different models available in the literature)

Optical Emission Spectroscopy



OES of atomic H for electron density in PAC

- For example:
$$\Delta\lambda_{Doppler} = 2 \times \left[\frac{2kT_{gas}\ln(2)}{Mc^2} \right]^{0.5} \lambda$$

M : radiation mass in kg/molecule

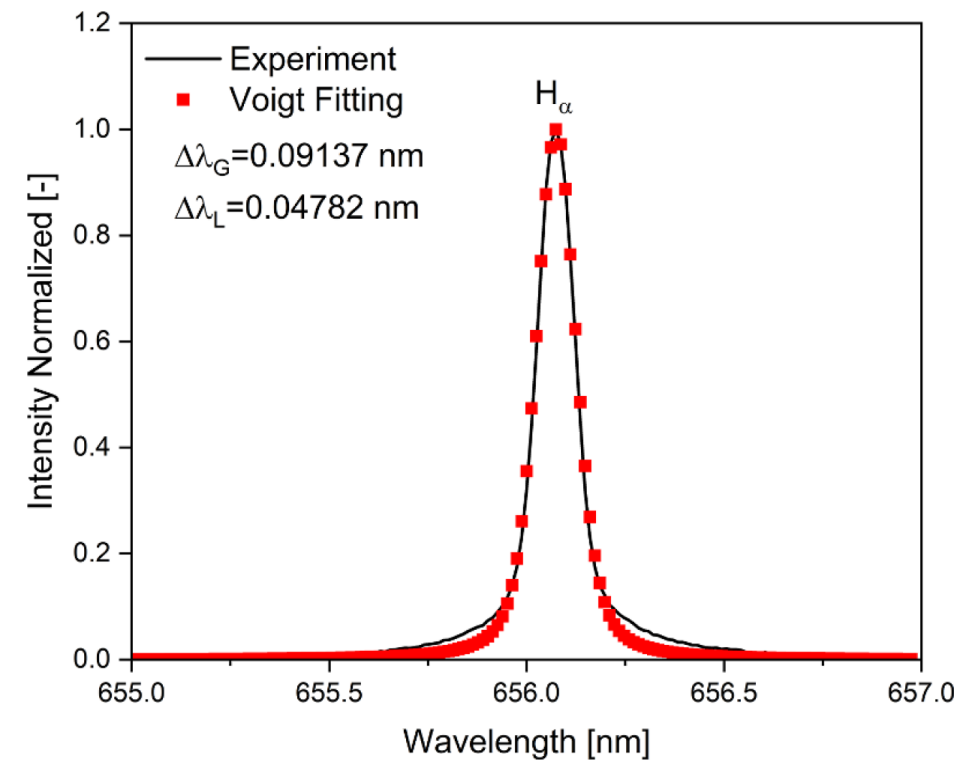
c : speed of light

- Then the H_α line can be fitted using a Voigt profile with a known Gaussian FWHM
- The Stark broadening is calculated from the obtained Lorentzian FWHM, $\Delta\lambda_L$

$$\Delta\lambda_S = \Delta\lambda_L - \Delta\lambda_{nat} - \Delta\lambda_R - \Delta\lambda_{VdW}$$

- Different models available in the literature for $\Delta\lambda_{nat}$, $\Delta\lambda_R$, and $\Delta\lambda_{VdW}$
- Some contributions might be negligible, but you need to calculate them first to know

Ashkenazy et al., Phys. Rev. A, 1991



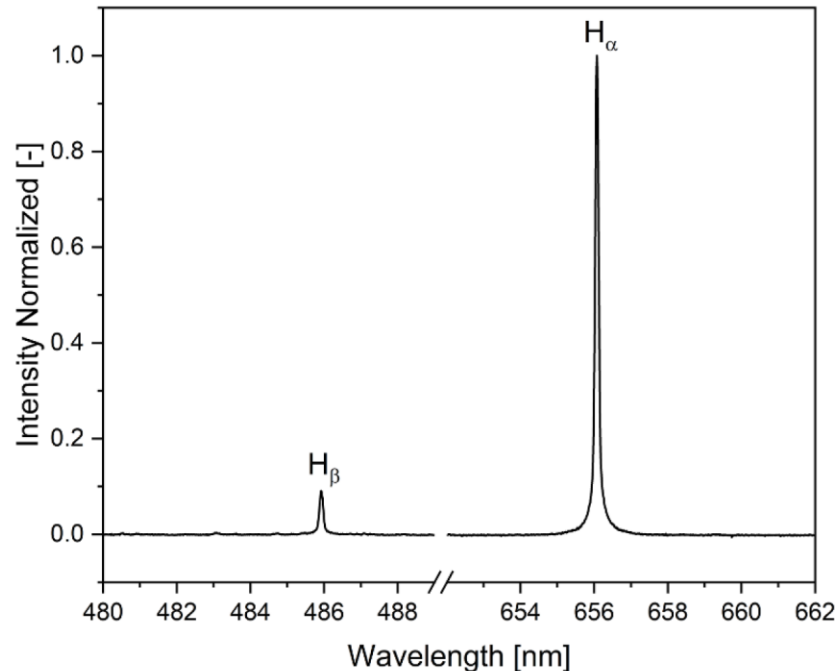
Figueiredo et al., J. Phys. D: Appl. Phys., 2025

Optical Emission Spectroscopy



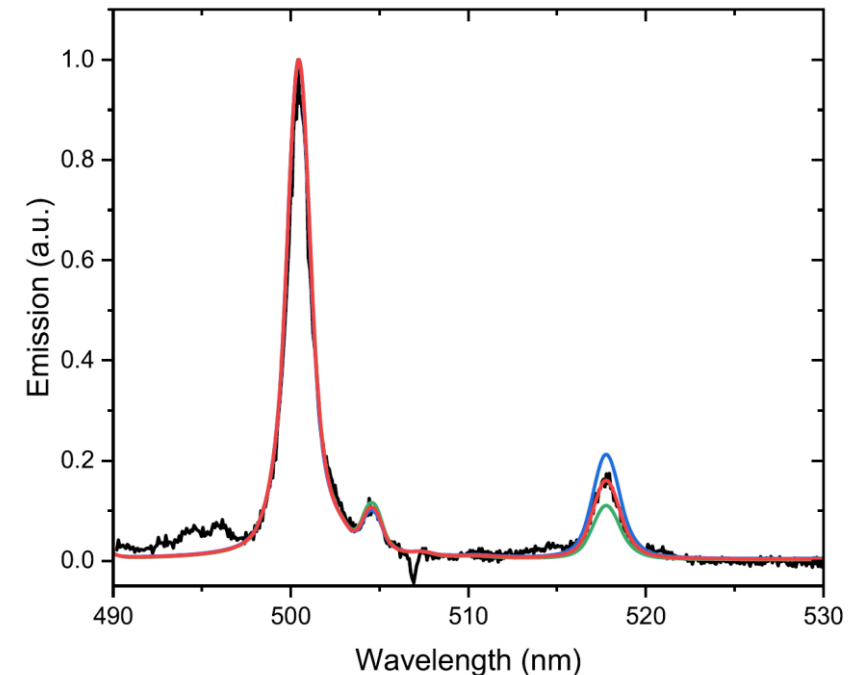
Examples of OES spectra used for electron density measurements

OES of H for measurements of electron density
Spectral resolution 0.09 nm



Figueiredo et al., J. Phys. D: Appl. Phys., 2025

OES of N⁺ for measurements of electron density



Gablier et al., Combust. Flame, 2026

→ Note that the uncertainty can be as large as a factor of 2

Optical Emission Spectroscopy



OES of atomic lines for electron temperature in PAC

- The electron temperature, T_e , can be calculated assuming $T_e = T_{elec}$, with T_{elec} the electronic temperature of atomic species (since free electrons cause the excitation and their energies should be described by a Boltzmann distribution at a given temperature)
- For example, using a Boltzmann plot of the H_α (3d \rightarrow 2p) and H_β (4d \rightarrow 2p) lines
 - The electron temperature is calculated using

$$\ln\left(\frac{I\lambda}{g_{i'}A_i}\right) = -\frac{\varepsilon_{i'}}{T_e} + C \quad \text{Staack et al., PSST, 2008}$$

I : intensity of the line

$g_{i'}$: degeneracy of the upper state

A_i : transition probability

$\varepsilon_{i'}$: upper state energy

C : constant

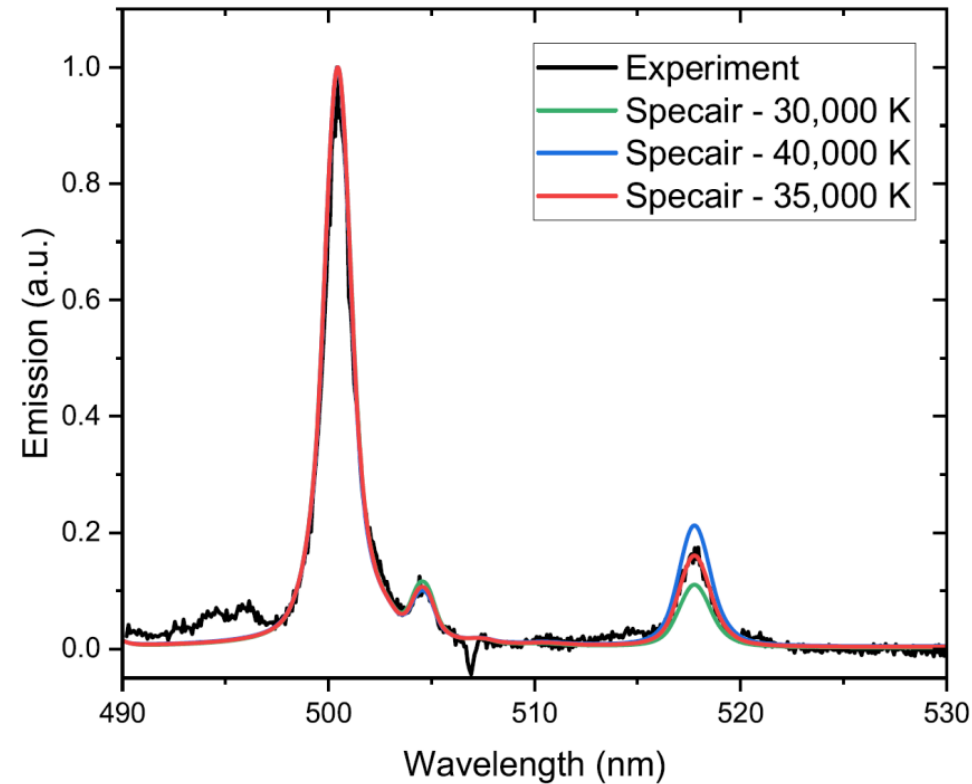
Peak	Transition	λ (nm)	$E_{i'}$ (eV)	$g_{i'}$	A_i (1 s^{-1})
H_α	3d \rightarrow 2p	656.28	12.087	6	44 101 000
H_β	4d \rightarrow 2p	486.13	12.748	6	8419 300

Optical Emission Spectroscopy



OES of atomic lines for electron temperature in PAC

- For example, fitting the N⁺ lines in air plasma



Gablier et al., Combust. Flame, 2026

→ Typical accuracy is ± 1000 K

Optical Emission Spectroscopy



Density of excited species in PAC

- The local emissivity, e_λ , of a volumetric light source such as a plasma is

$$e_\lambda = \frac{1}{4\pi} h\nu A_{21} N_2 \phi(\lambda) \quad \text{unit: Wcm}^{-3}\text{sr}^{-1}\text{nm}^{-1}$$

$h\nu$: photon energy (J)

A_{21} : Einstein coefficient (s^{-1})

N_2 : density of the upper state

$\phi(\lambda)$: normalized profile function, measured recording the spectral line of a narrow laser source (assuming other broadening are negligible)

- The wavelength-dependent intensity, I_λ , measured using a spectrometer corresponds to the line-of-sight integration of emissivity

Optical Emission Spectroscopy

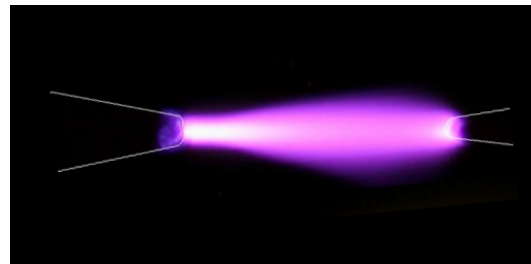


Density of excited species in PAC

- If the emission volume is uniform and optically thin, then the measured line intensity as a function of wavelength is

$$I_{\lambda} = \int_l e_{\lambda}(l) dl = \frac{1}{4\pi} L h \nu A_{21} N_2 \phi(\lambda)$$

- Electric discharges are usually not uniform, then OES could not be used to measure species densities
- However, in cylindrical geometry such as in a discharge straight filament, the species have a radial distribution with maximum at the discharge center



Optical Emission Spectroscopy



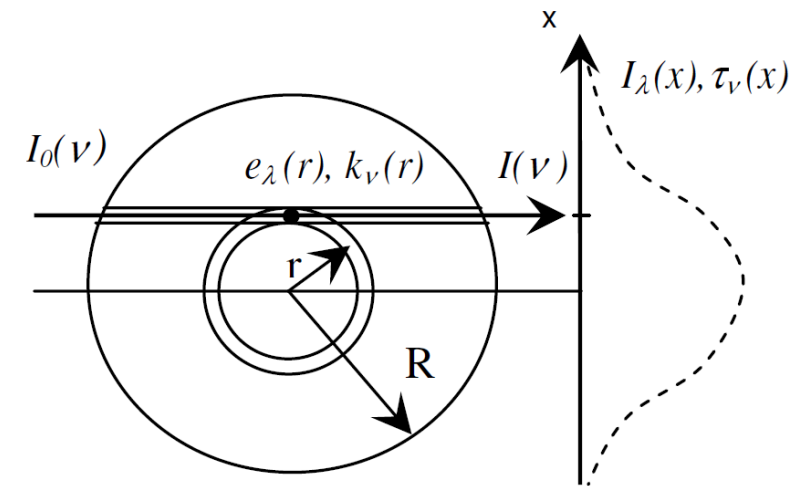
Density of excited species in PAC

- The local distribution of emissivity can be obtained from the Abel inverted intensity profile $I'_\lambda(x)$, obtained from a lateral scan

$$e_\lambda(r) = -\frac{1}{\pi} \int_r^R \frac{I'_\lambda(x)}{\sqrt{x^2 - r^2}} dx$$

- And the local concentration is given by

$$N_2(r) = \frac{4\pi e_\lambda(r)}{h\nu A_{21} \phi(\lambda)}$$



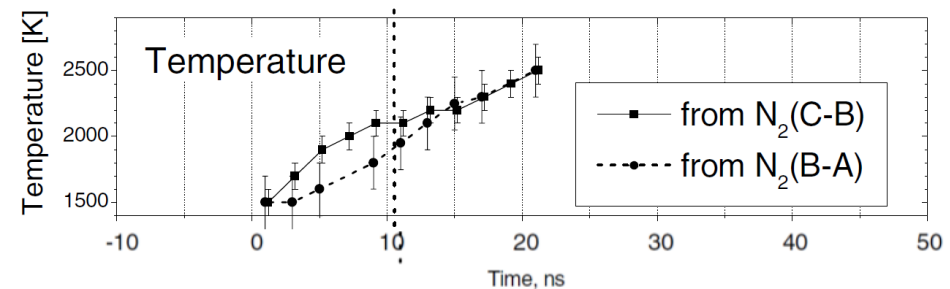
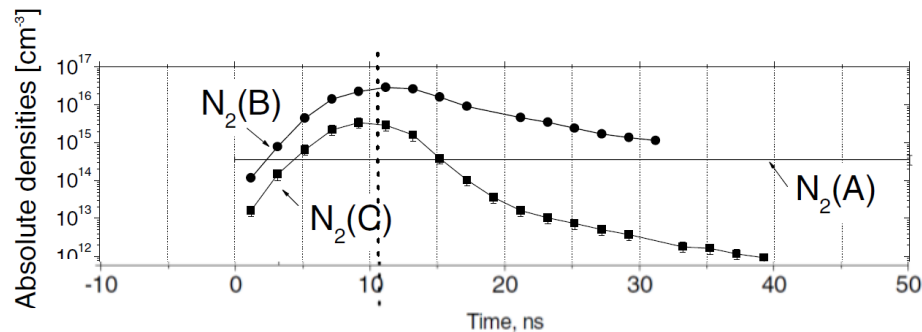
Optical Emission Spectroscopy



Density of excited species in PAC

- To convert the measured spectra in arbitrary units (usually volts or counts), a calibrated light source (e.g., tungsten strip lamp) is used in place of plasma while keeping all experimental parameters identical
- Calibration can be as involved as measurements of the emission from the plasma

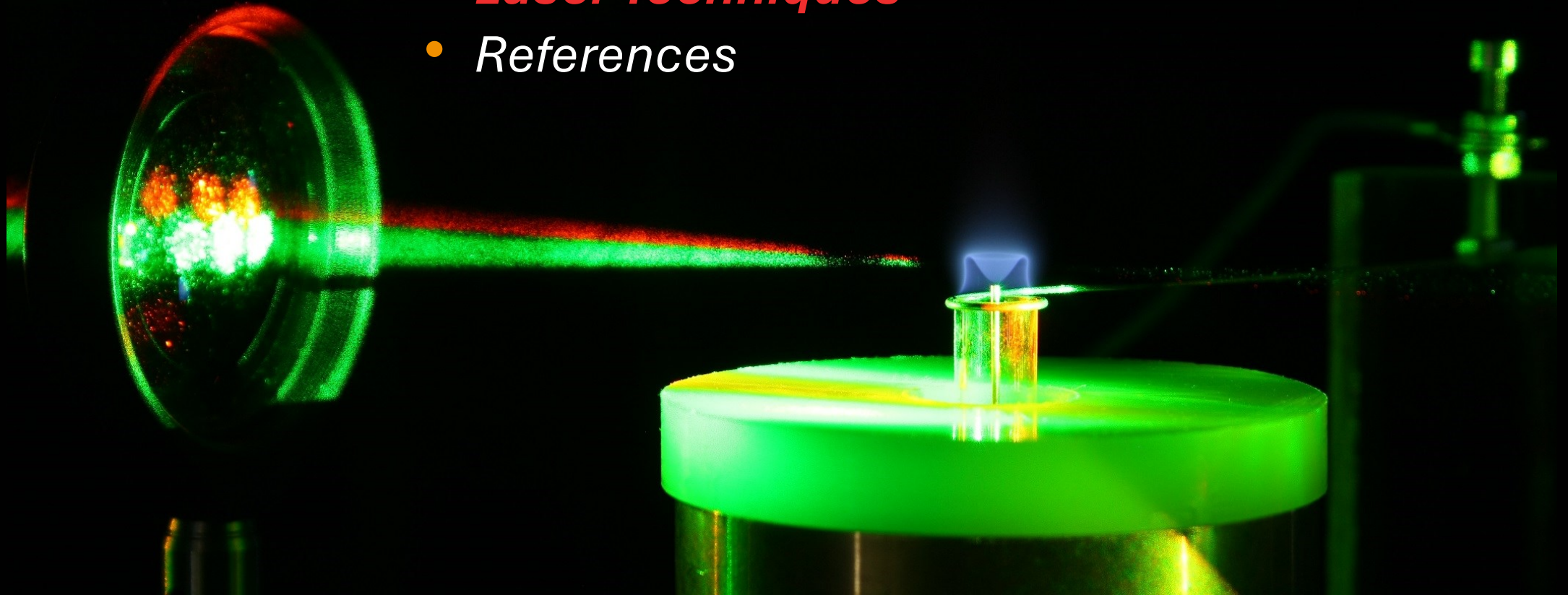
Examples of absolute densities of N_2 B and N_2 C measured by OES



Rusterholtz et al., *J. Phys. D: Appl. Phys.*, 2013

Chapter VII: Diagnostics

- *Electrical Properties*
- *Optical Emission Spectroscopy*
- ***Laser Techniques***
- *References*



Laser Techniques



Typical laser techniques used in combustion can also be used in PAC (with minor adjustments)

- Laser absorption techniques, for concentration of species
- Laser Induced Fluorescence (LIF), for distribution and concentration of radicals (e.g., OH, CH, NH...)
- Two photon Laser Induced Fluorescence (TALIF), for concentration of atoms (e.g., O, H...)
- Photo-fragmentation LIF, for concentration of radicals (e.g., CH₃)
- Thermometry by Coherent Anti-Stokes Raman Spectroscopy (CARS)
- Rayleigh scattering, Filtered Rayleigh scattering, for measurements of density / imaging of gradient density
- Raman scattering for concentration of species and temperature

Additional laser techniques have been specifically developed for measurements in plasma

Laser Techniques

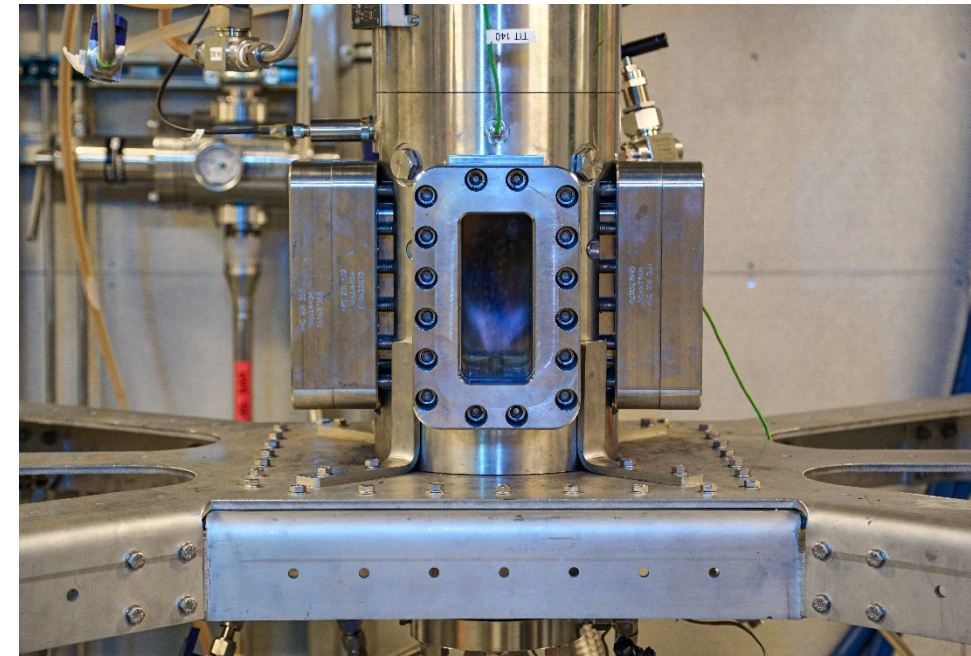


These techniques typically target one of the three main quantities of interest

- electric field E
- electron density n_e
- electron temperature T_e

They have been developed in plasma labs, and are usually challenging to utilize in PAC due to complex environment

- electrode geometry
- elevated pressure
- single shot events
- soot or droplets



However, they are worth the effort for a deep understanding of PAC

Laser Techniques



Electric Field Induced Second Harmonic Generation (E-FISH) is a technique developed to measure the electric field in gaseous/plasma environments

- In the presence of an electric field, E , second-harmonic generation connected to the 3rd order non-linear susceptibility, $\chi^{(3)}$, can happen
- The intensity of the second harmonic signal, $I^{2\omega}$, is then

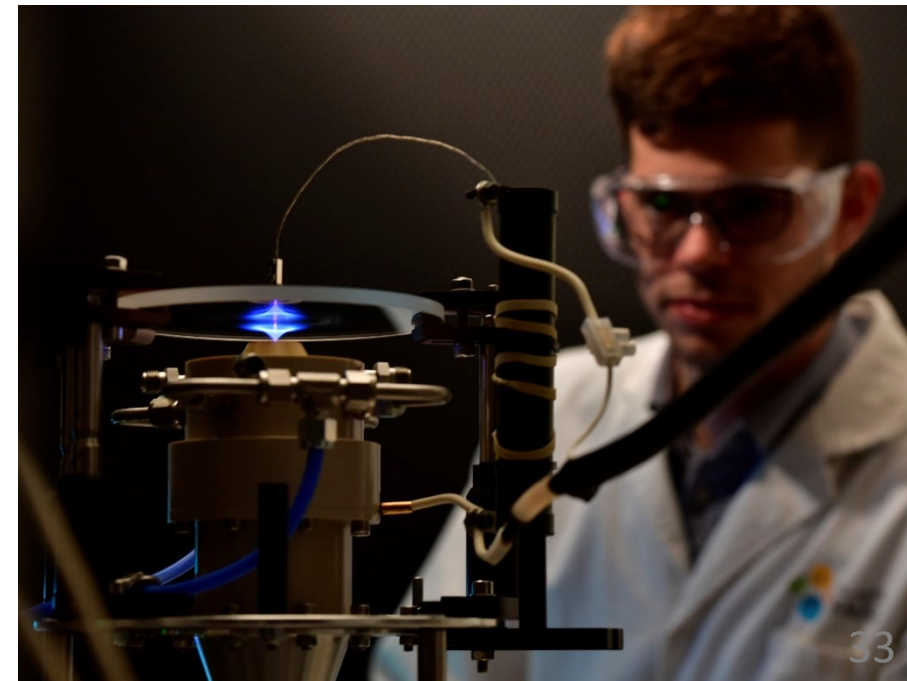
$$I^{2\omega} = A \times N^2 E^2 I_{\omega}^2$$

I_{ω} : intensity of the incident laser beam

N : gas number density

A : calibrated constant using a known electric field

- In practice, $I^{2\omega}$ is affected by many parameters, and advanced data processing techniques are necessary for quantitative E measurement by E-FISH in PAC

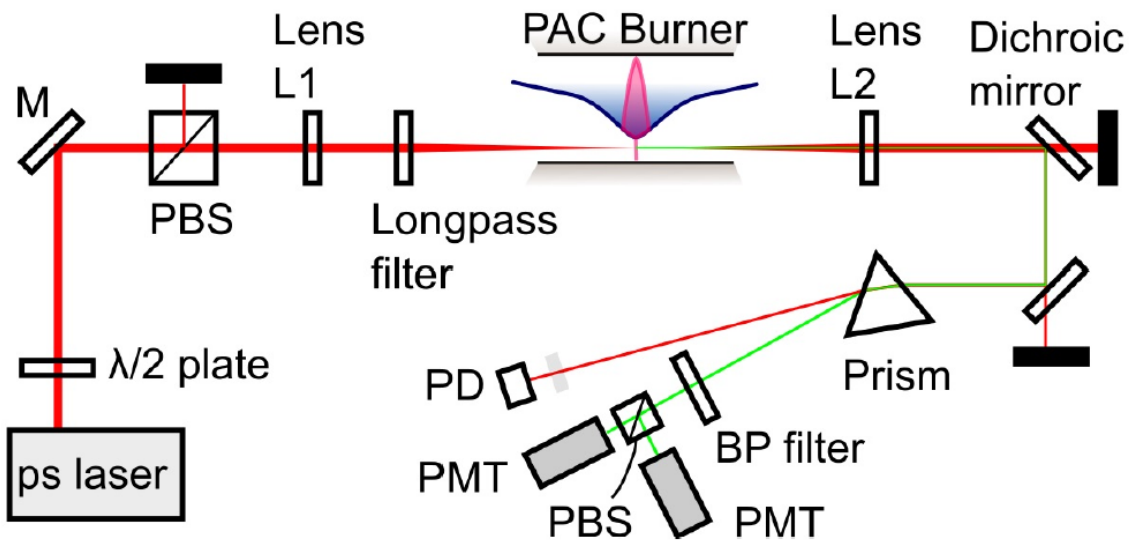


Laser Techniques

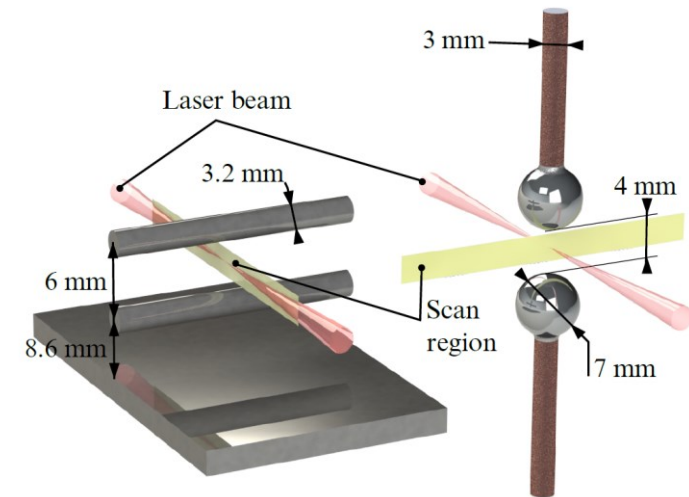


Electric Field Induced Second Harmonic Generation (E-FISH)

Typical E-FISH experimental setup



Examples of electrode arrangements producing a known electric field for calibration



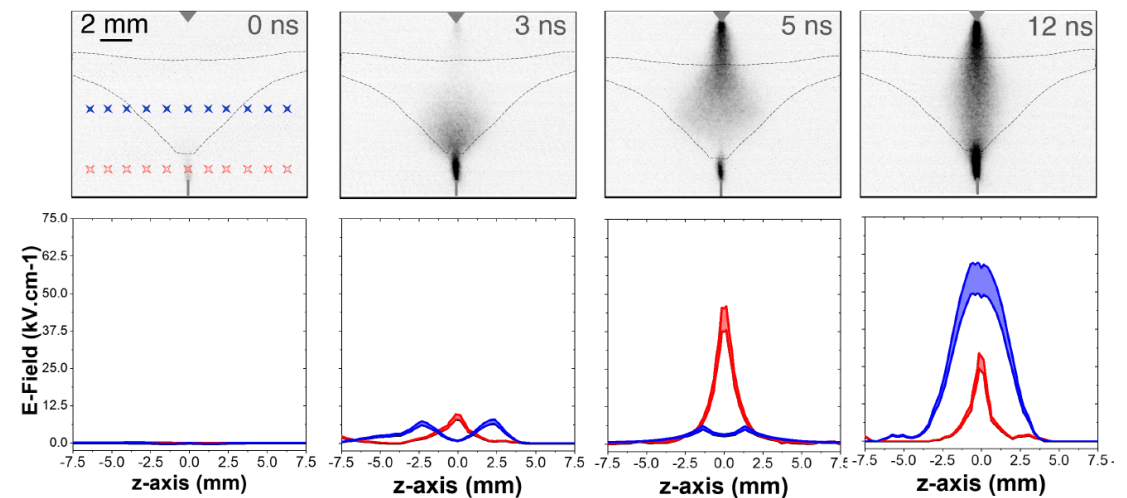
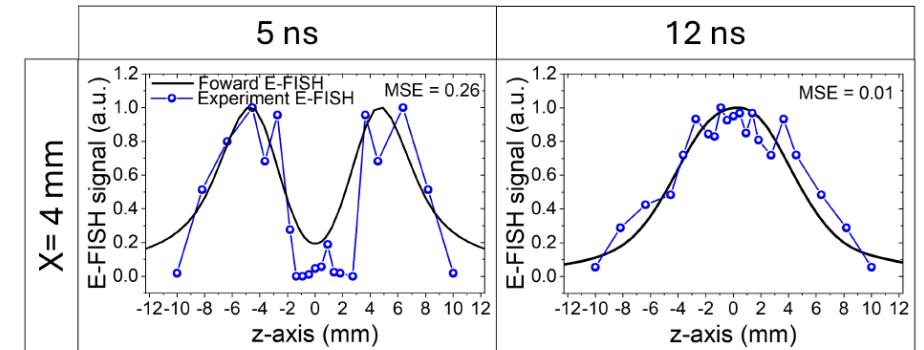
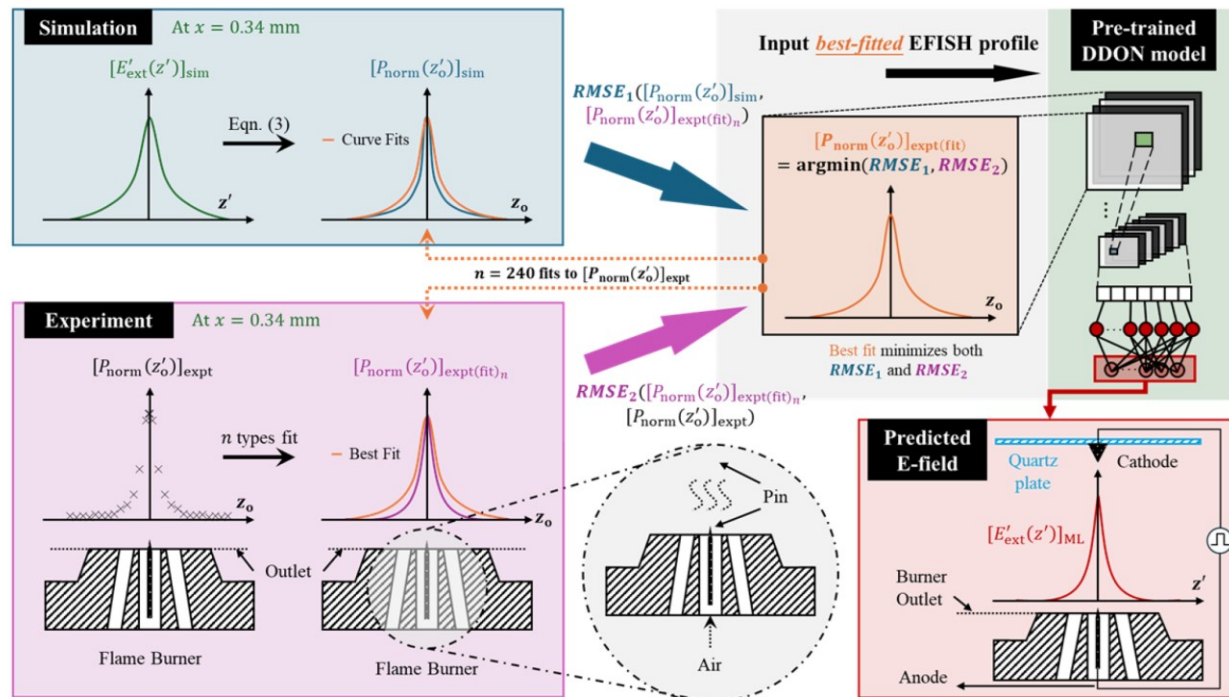
- 30-ps laser @1064 nm, energy per pulse 4 mJ
- Using polarized beam splitters (PBS) two directions of E can be measured simultaneously

Laser Techniques



Example of electric field measurements by E-FISH in PAC

Calibration procedure for Machine-Learning-Assisted Inverse E-FISH



Laser Techniques



Thomson scattering can be used to measure electron density and electron temperature in gaseous/plasma environments

- Based on elastic scattering of electrons
- Happens in parallel of Rayleigh & Raman scattering (scattering from molecules)
- Necessitates the use of special filtering of scattering, large laser fluences, and sensitive detection for Thomson scattering
- Works well for $n_e > 10^{13} \text{ cm}^{-3}$
- If a laser is incident on a plasma with electron density n_e , the amount of scattered power per wavelength, $P_s(\lambda)$, is linearly dependent on n_e as

$$P_s(\lambda) = P_0 n_e \eta \frac{d\sigma_e}{d\Omega} \Delta\Omega S(\lambda) L$$

P_0 : incident laser power

η : transmission efficiency of the detection optics

L : length of the detection volume

$\Delta\Omega$: collection solid angle

$S(\lambda)$: normalized scattering spectral distribution

$\frac{d\sigma_e}{d\Omega}$: differential Thomson scattering cross section

Laser Techniques



Thomson scattering

- For example, in a nitrogen-diluted nonequilibrium plasma, the **absolute electron number density** n_e can be determined by the ratio of the integrated Thomson scattering \hat{P}_e to the integrated N_2 rotational Raman scattering \hat{P}_{N_2} , for calibration with the population f at the J rotational state

$$n_e = \frac{\hat{P}_e \left(\frac{d\sigma_{N_2}}{d\Omega} \right)_{\text{Raman, 532nm}}}{\frac{d\sigma_e}{d\Omega}} n_{N_2} f_J$$

- The **electron temperature** can be found from the Doppler-shifted Thomson scattering spectrum (width of a fitted Gaussian profile)

$$T_e = \frac{c^2 m_e}{8k_B \sin^2(\theta/2)} \left(\frac{\Delta\lambda_{1/e}}{\lambda_i} \right)^2$$

c : speed of light

λ_i : laser wavelength

θ : scattering angle

$\Delta\lambda_{1/e}$: 1/e half-width of the Gaussian spectral shape

m_e : mass of electron

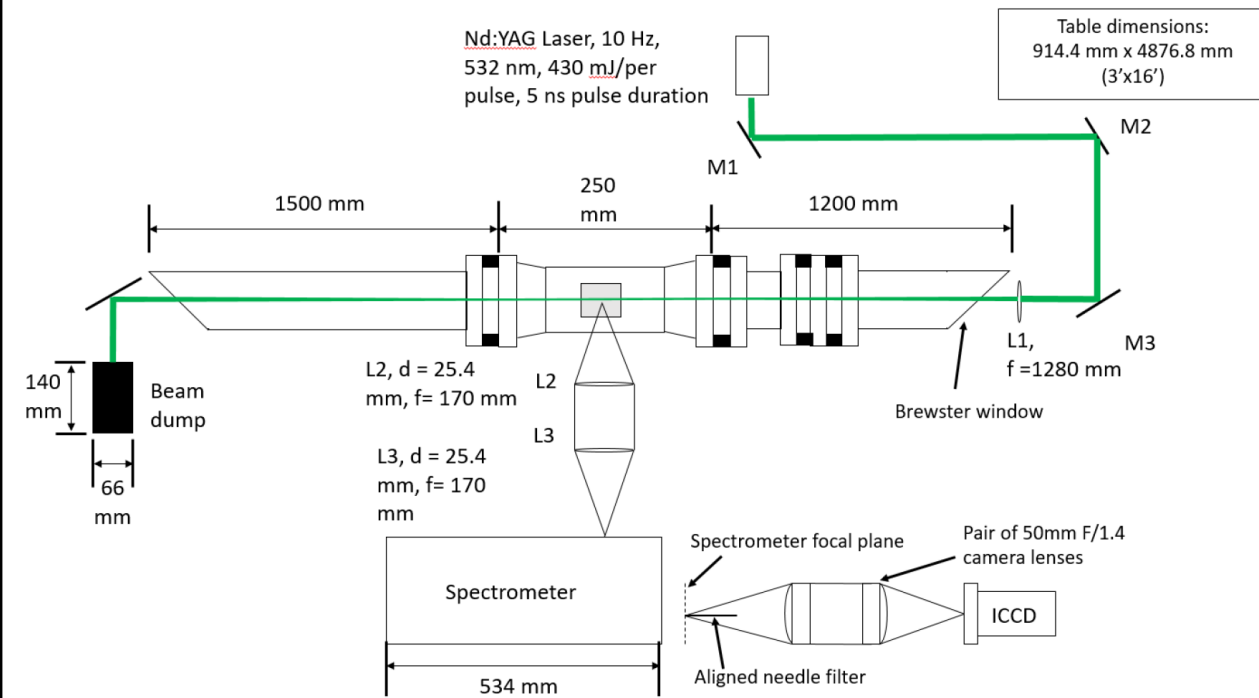
k_B : Boltzmann constant

Laser Techniques



Thomson scattering

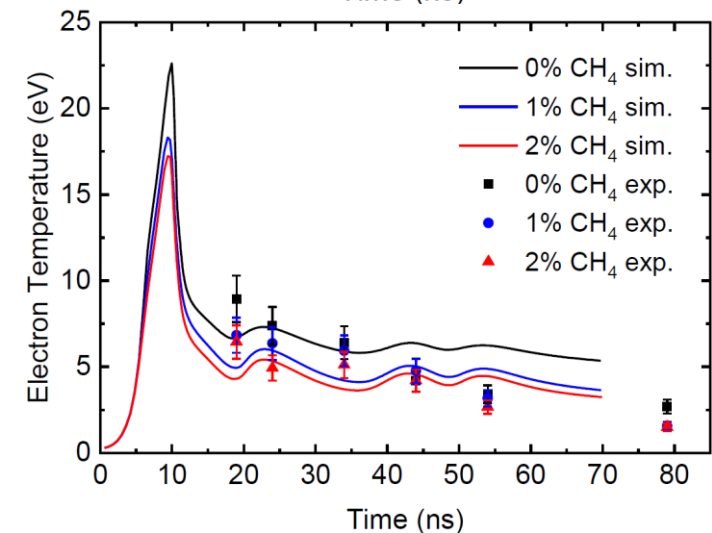
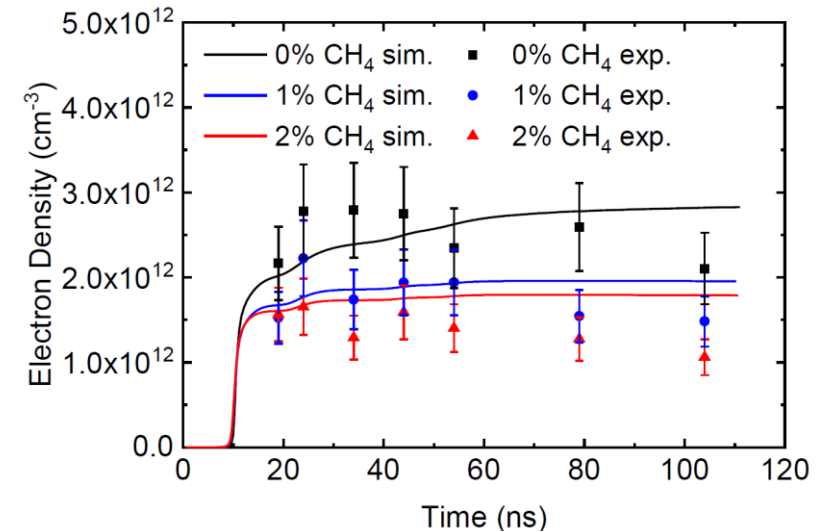
Typical Thomson scattering experimental setup



Timothy Chen, PhD thesis, Princeton, 2017

Chen et al., PROCI, 2021

n_e and T_e measurements by Thomson scattering in a ns-DBD of He-CH₄ at 75 Torr



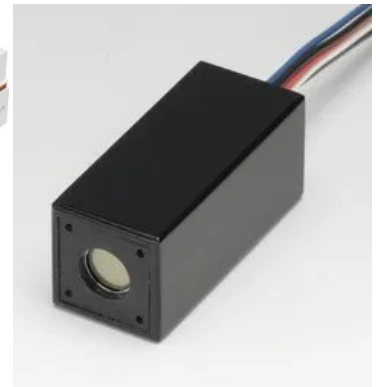
Laser Techniques



Laser techniques as well as advanced imaging techniques can be sensitive to electro-magnetic interferences (EMI) produced by electrical discharges

EMI can add some noise to the measurements and/or can even damage sensitive equipment

- Main sources of EMI in PAC:
 - Electric discharges
 - High-voltage cables
 - Poor quality electrical connections of HV parts/cab
- From their source, EMI can propagate:
 - In cables
 - In open air

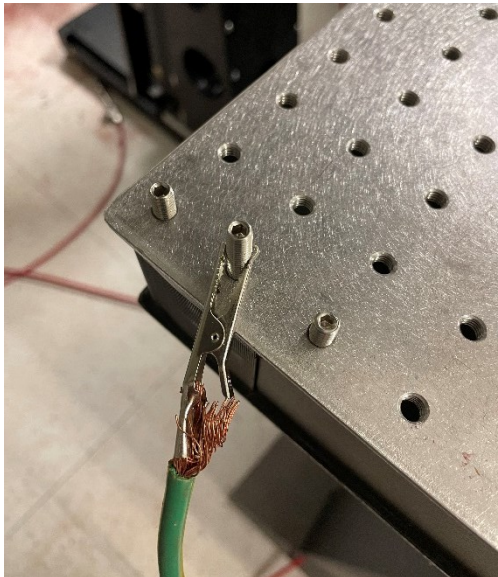


Laser Techniques



The three weapons for a successful battle against EMI

- **Grounding**
 - Ground any metallic part that should not be connected to an electric source (chassis, optical table, burner, MFC, casing of oscilloscope, camera, laser...)
 - Add direct grounding cables between each metallic devices and a ground plug
 - Separate the ground of your sensitive equipment (oscilloscope, camera, laser, computer) from the ground of your high-voltage source, e.g., using separated plugs



Laser Techniques



The three weapons for a successful battle against EMI

- **Shielding / distance**
 - Put the sensitive equipment as far as possible from the EMI source (2 m is better than 50 cm)
 - Metallic screens between the sensitive equipment and EMI source (aluminum foil, thick metallic plate...)
 - Faraday cage
- **Avoid propagation through electric cables (low voltage)**
 - Add ferrites near the connections of the cables
 - Ensure clean electrical connection (avoid poorly done soldering)



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- D.L. Rusterholtz, D.A. Lacoste, G.D. Stancu, D.Z. Pai, C.O. Laux, *Ultrafast heating and oxygen dissociation in atmospheric pressure air by nanosecond repetitively pulsed discharges*, *J. Phys. D: Appl. Phys.* 46, 464010, 2013
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- A.C. Tibère-Inglesse, S.D. McGuire, C.O. Laux, *Inferring Gas Temperature from N₂ Emission via Rotational Distribution of the N₂ B₃ Π_g and C₃ Π_u States*, *Plasma Sources Sci. Technol.* 32 (7), 075018, 2023

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- LIFBASE 2.1: <https://lifbase.software.informer.com/>
- SPECAIR: <http://www.specair-radiation.net/>

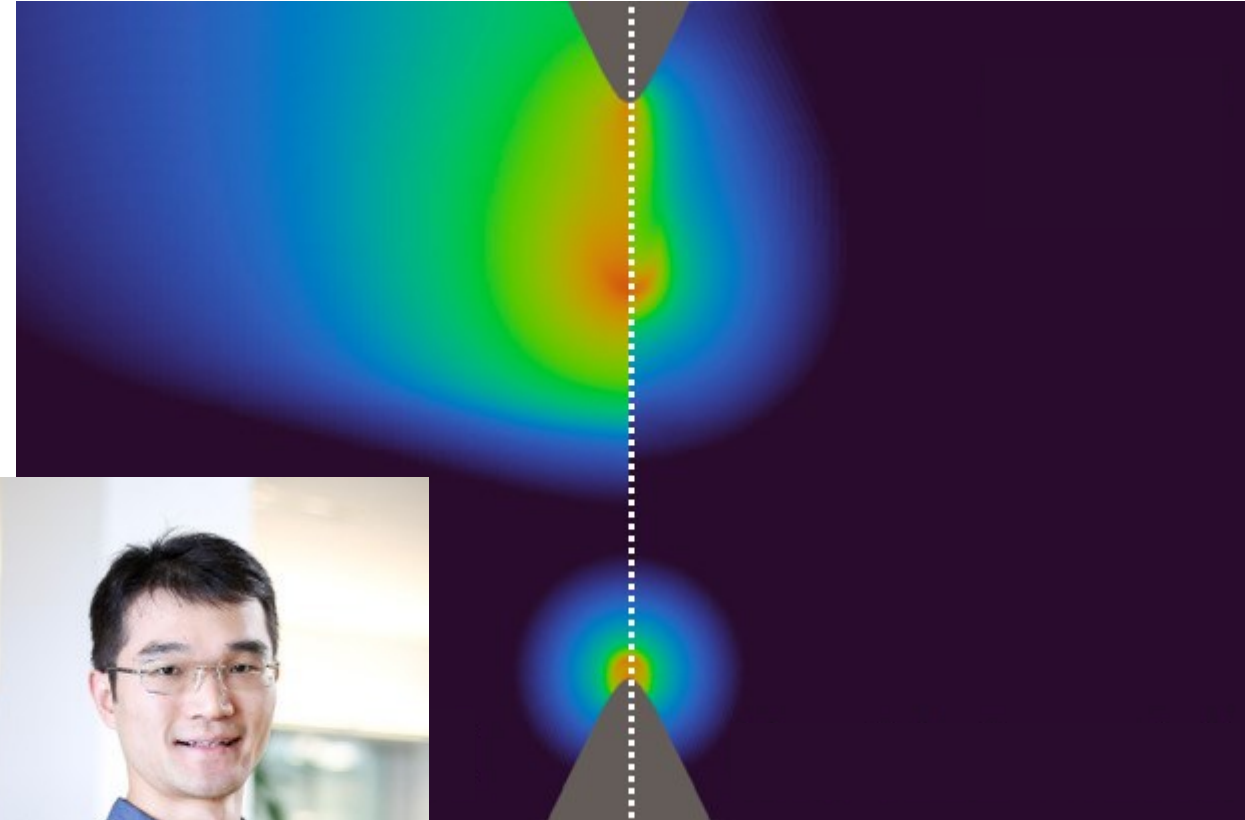
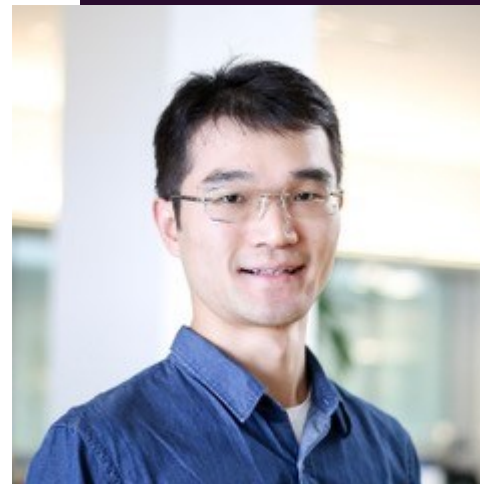
Book

- *Plasma Assisted Combustion and Chemical Processing*, Yiguang Ju & Andrey Starikovskiy, CCRC Press, Taylor and Francis Group, Boca Raton, FL, USA, 2025

Chapter VIII: Modeling Tools



- *Plasma-Combustion Coupling*
- *0D PAC*
- *MultiD PAC*
- *References*



Many thanks to Dr. Xiao Shao, KAUST

Plasma-Combustion Coupling



Both plasma simulations and combustion simulations require to choose:

- Mixture composition
- Thermodynamic conditions
- Governing equations
- Chemical kinetic models
- Numerical methods
- Time steps
- Mesh

In each field, the state-of-the-art numerical simulations are **predictive tools** that capture the mechanisms at play and provide data that can be used in **engineering applications**

However, because the physics involved is different, coupling plasma and combustion requires an **additional step of modeling**

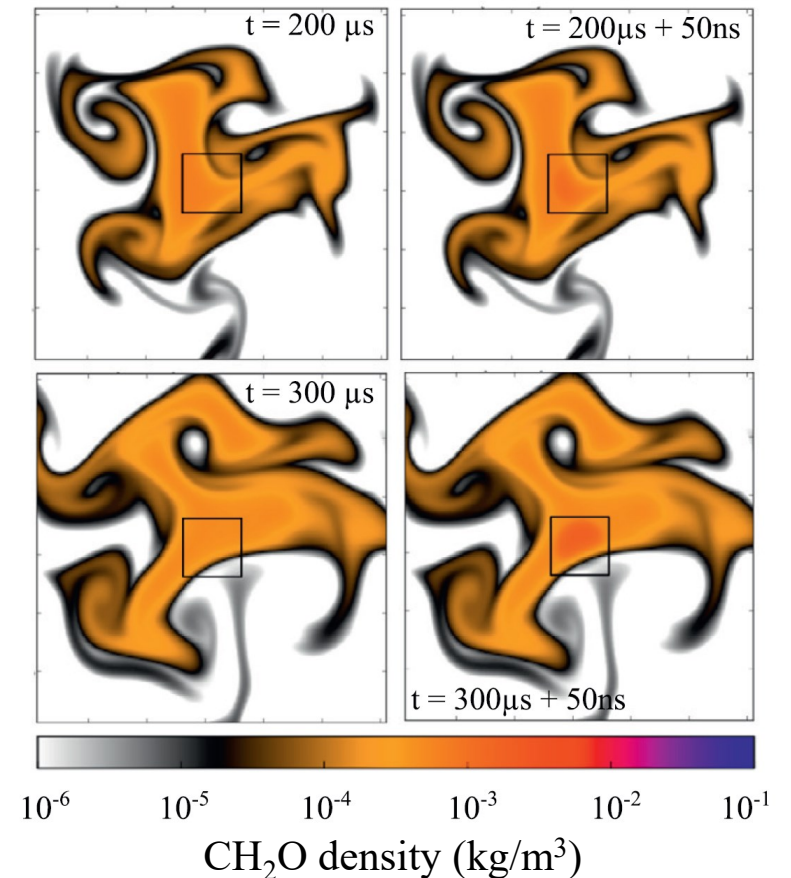
Plasma-Combustion Coupling



Models of plasma-combustion coupling

- **Fully modelled discharge (Phenomenological model):** conditions produced by the discharges are modeled (volume of gas, temperature, concentration of chemical species), and used as an input for the combustion code
- First PAC simulations

PAC simulations using a phenomenological model for the discharge



Plasma-Combustion Coupling



Models of plasma-combustion coupling

- **Temporal split (Operator splitting):** because the plasma time is much shorter than the combustion time, an option is to consider that plasma and combustion happen in series
 - 1) Perform plasma simulation
 - 2) Use its output as input of the combustion code
 - 3) Perform combustion simulation
 - 4) If a new discharge is produced (e.g., in NRP discharges), use its output as input of the plasma code
 - 5) Repeat
- The plasma is modeled as an instantaneous process for the combustion, and combustion being slow, it is modeled as frozen during plasma process
- Two options for the plasma simulations
 - Plasma phenomenological model
 - Plasma detailed chemistry

Plasma-Combustion Coupling

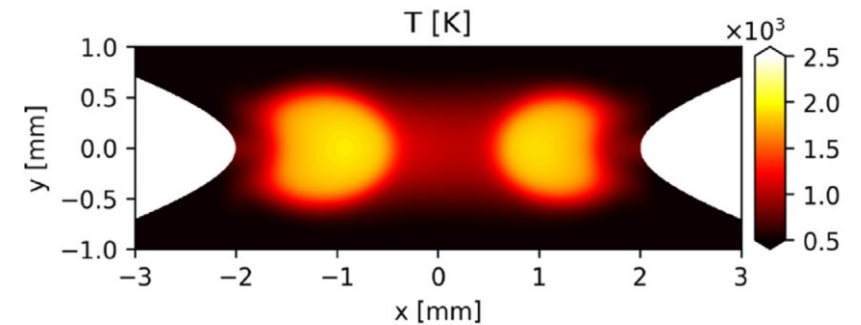


Models of plasma-combustion coupling

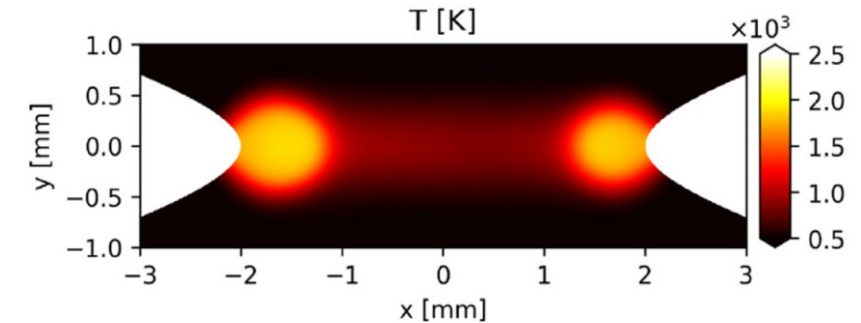
- **Fully coupled (Two-way coupled):** at each time step, combustion and plasma chemistry are calculated → high fidelity PAC simulations

Example of Ignition simulations using a phenomenological model and a fully coupled PAC code

Barleon et al., Combust. Flame, 2023



(a) Detailed - 100 μ s



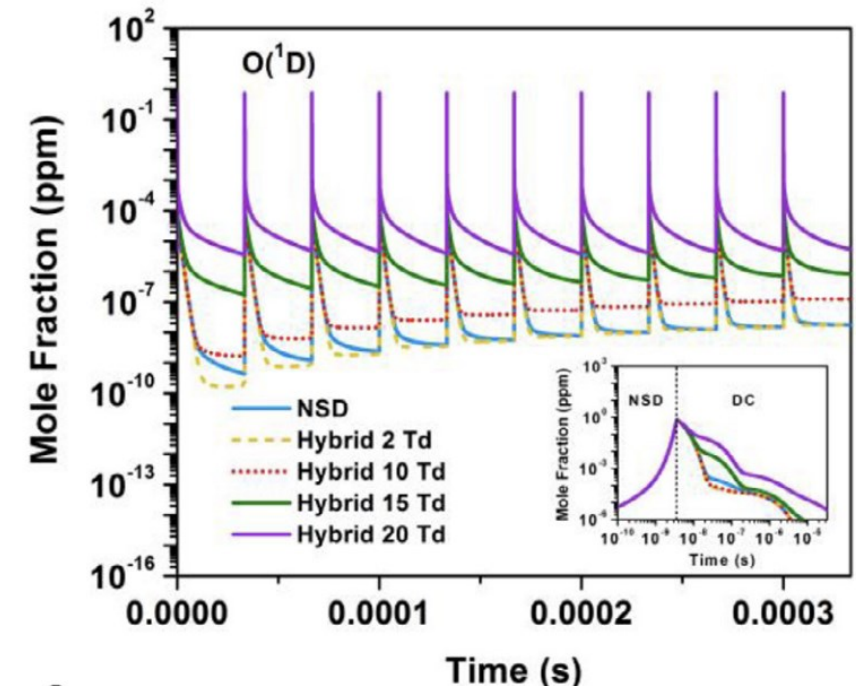
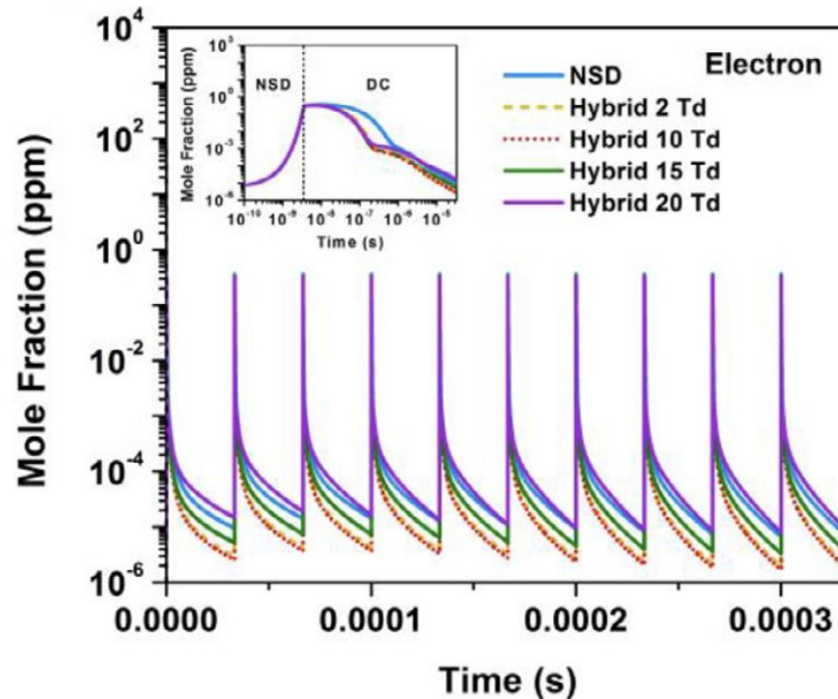
(e) CASTELA - 100 μ s

Plasma-Combustion Coupling



Models of plasma-combustion coupling

Dimension	Plasma model	Pros	Cons	Applications
0D	Kinetics	Low cost Detailed chemistry	Homogeneous No transport Need experimental E/N and n_e	Mechanism development Pathway analysis



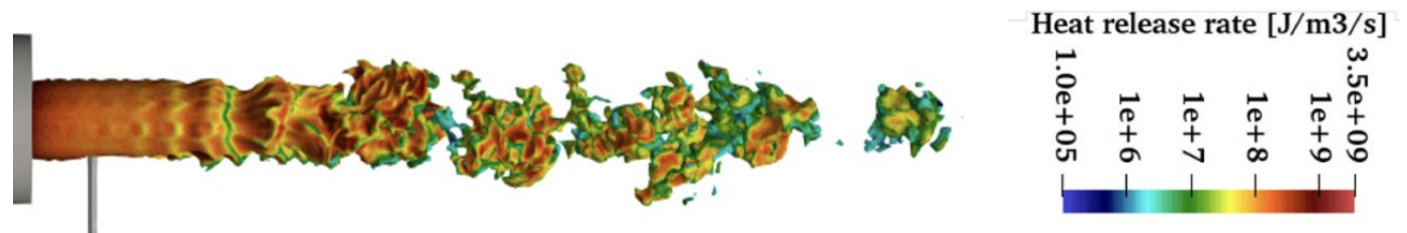
Plasma-Combustion Coupling



Models of plasma-combustion coupling

Dimension	Plasma model	Pros	Cons	Applications
0D	Kinetics	Low cost Detailed chemistry	Homogeneous No transport Need experimental E/N and n_e	Mechanism development Pathway analysis
MultiD	Phenomenological	Low cost Easy to implement	Predefined discharges No plasma dynamics	Ignition Plasma-flame interactions
	Kinetics & Dynamics	High fidelity Two-way coupling	Complex implementation High cost	Plasma-flame interactions Benchmark for reduced-order models

Bechane and Fiorina, PROCI, 2023



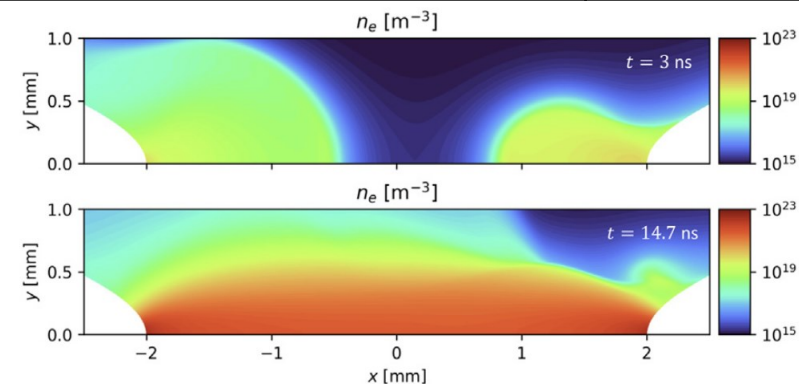
Plasma-Combustion Coupling



Models of plasma-combustion coupling

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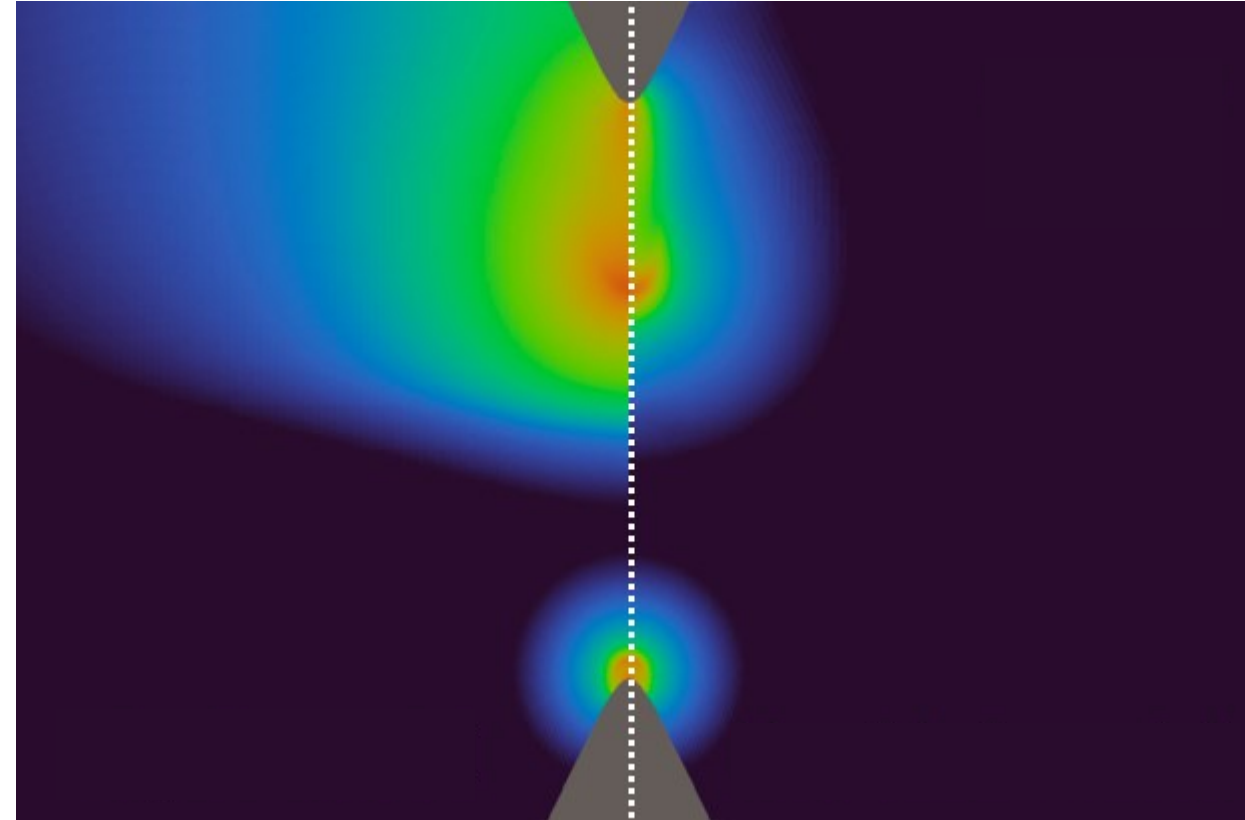
Barleon et al., PROCI, 2023



Chapter VIII: Modeling Tools



- *Plasma-Combustion Coupling*
- **0D PAC**
- *MultiD PAC*
- *References*



0D PAC



0D PAC kinetics solver requires the determination of species reaction rates for the gas-phase and the plasma

- For the gas phase reactions, the reactions rates, k , are given by an Arrhenius law

$$k = A \exp\left(-\frac{E_a}{RT}\right)$$

- For plasma, the EEDF is used for determining reaction rate coefficients of electron-induced processes and electron temperature
 - In nonequilibrium plasma, because of non negligible inelastic collisions, EEDF deviates from Maxwellian and **no simple analytical solution** exists for the mean electron temperature
 - f depends upon the gas mixture composition, the cross-sections of electron impact, the ionization degree, and so on
- Dedicated electron Boltzmann equation (EBE) solvers



0D PAC

- The EBE can be written as (see Chapter IV)

$$\frac{\partial f}{\partial t} + \mathbf{v}\nabla f + \frac{\mathbf{F}}{m_e} \cdot \nabla_{\mathbf{v}} f = \left(\frac{\partial f}{\partial t}\right)_{col}$$

$f(\mathbf{r}, \mathbf{v}, t)$: distribution function of electrons

\mathbf{F} : external electric force vector ($\mathbf{F} = -e\mathbf{E}$)

m_e : electron mass

$\left(\frac{\partial f}{\partial t}\right)_{col}$: collision term comprising all kinds of binary collisions with electrons

- Assuming spatial uniformity and steady state, a **two-term approximation** can be used to obtain the EEDF

$$f(\mathbf{v}, t) = f^{(0)}(v, t) + f^{(1)}(v, t)\cos \Theta$$

$f^{(0)}$: isotropic part of the solution

$f^{(1)}$: anisotropic part of the solution

Θ : angle between the directions of the electron velocity vector \mathbf{v} and the electric field vector \mathbf{E}



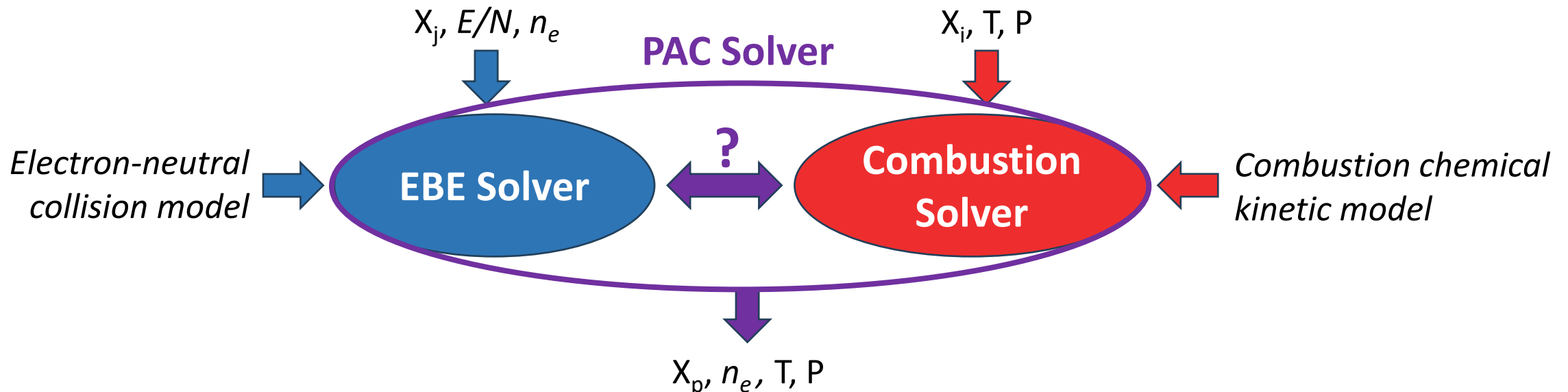
0D PAC

- Reaction rate coefficients for collisions, k_j , are derived from $f^{(0)}$ and cross-section, σ_j , by integrating over electron energy ϵ

$$k_j = \sqrt{2e/m_e} \int_0^\infty \epsilon \sigma_j f^{(0)} d\epsilon$$

- And the electron temperature, T_e , is given by

$$T_e = \frac{2}{3} \int_0^\infty \epsilon^{3/2} f^{(0)} d\epsilon$$



OD PAC



Progress in development of PAC chemical kinetics code

Method		Gas mixture	Research group	Year	
Bolsig + CHEMKIN	Tabulated	Air-H ₂ , Air-HC	Ohio State U	2015	
ZDPlasKin + CHEMKIN		CH ₄ -Air	UC Berkeley	2016	
Bolsig + CHEMKIN		CH ₄ -Air, C ₂ H ₄ -Air	UT Austin	2021	
ZDPlasKin + CHEMKIN	Operator splitting	CH ₄ -Air, H ₂ -O ₂ -He, CH ₄ -O ₂ -He, n-dodecane-O ₂ -N ₂ , NH ₃ -O ₂ -He, NH ₃ -Air, n-pentane-air	Princeton	2018-2024	
ZDPlasKin + Cantera		DME-O ₂ -Ar, C ₃ H ₈ -O ₂ -Ar	USC	2017	
ZDPlasKin + CHEMKIN		DME-O ₂	Tsinghua	2021	
ZDPlasKin + CHEMKIN		NH ₃ -Air	UMN	2021	
ZDPlasKin + CHEMKIN		H ₂ -O ₂	KAUST	2022	
ZDPlasKin + Cantera		NH ₃ -N ₂ -O ₂ -He	Birmingham	2022	
ZDPlasKin + Cantera		CH ₄ -Air	MIT	2023	
ZDPlasKin + In house		NH ₃ -N ₂ -O ₂	XJTU	2023	
BOLOS + Cantera		Fully coupled	CH ₄ -Air	CERFACS	2022
CppBOLOS + Cantera			H ₂ -Air, CH ₄ -Air, NH ₃ -Air	KAUST	2024-2026

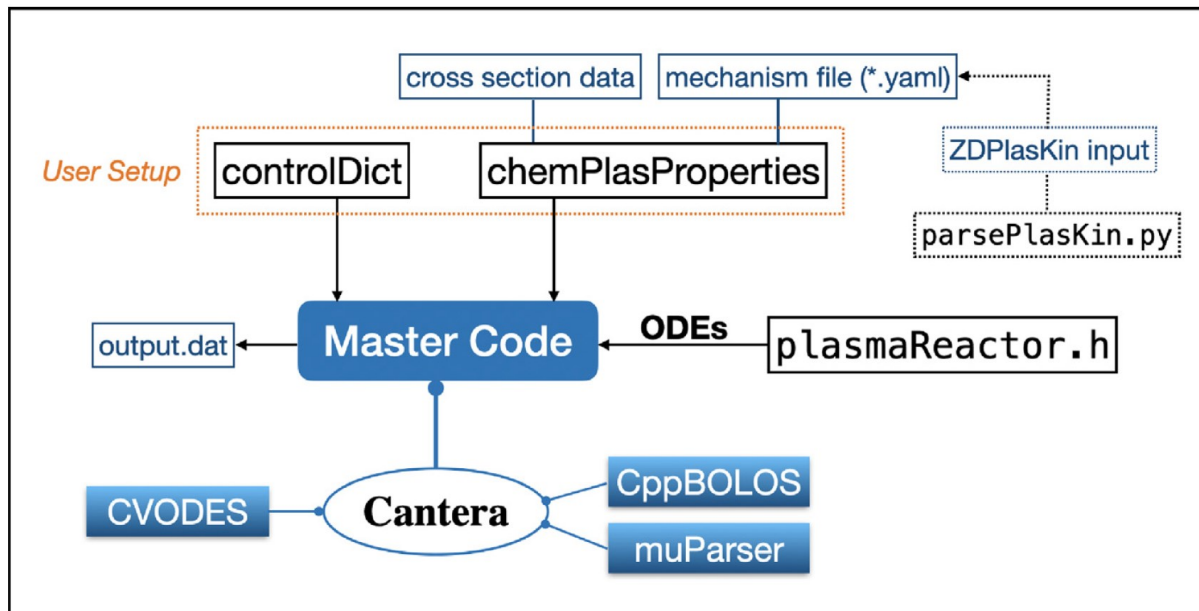
OD PAC



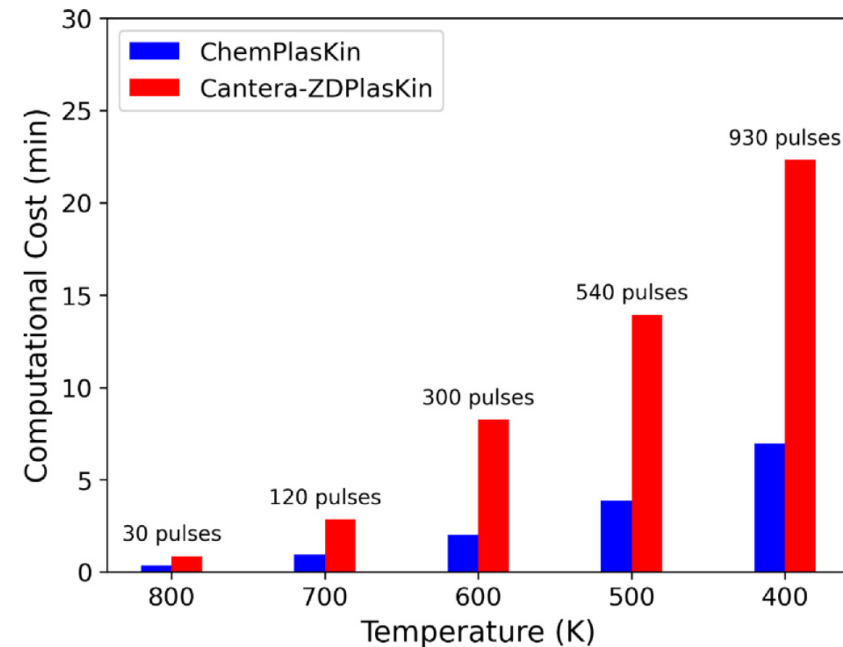
ChemPlasKin: A general-purpose program for unified gas and plasma kinetics simulations

- Incorporates an EBE solver directly into Cantera library
- Solves all reactions and thermal effects (combustion & plasma) in a unified ODE system
- High performance design for CFD integration

Code architecture of ChemPlasKin



Shao et al., *Appl. Energy Combust. Sci.*, 2024



OD PAC



Example of ChemPlasKin chemical kinetic model

- Based on GRI3.0 mechanism and CH₄-air plasma-combustion mechanism developed by *Cheng et al. Combust. Flame, 2022*
- Thermo: ideal gas, Model NASA7
- Elements: electron, H, C, O, N, Ar
- Species (100)
 - Electron
 - Ground state: O, O₂, OH, H, H₂, HO₂, H₂O₂, CH, CO, CH₂, HCO, CH₂(S), CH₃, CH₂O, CH₄, CO₂, CH₂OH, CH₃O, CH₃OH, C₂H, C₂H₂, HCCO, C₂H₃, CH₂CO, C₂H₄, C₂H₅, C₂H₆, H₂O, N, N₂, AR, C, HCCOH, NO, N₂O, NO₂, NO₃, O₄, NH, HNO, NH₂, NNH, CN, NCO, HCN, HOCN, HNCO, H₂CN, HCNN, HCNO, NH₃, CH₂CHO, CH₃CHO, C₃H₈, C₃H₇
 - Excited states: N(2D), N₂(A₃), N₂(B₃), N₂(a₁), N₂(C₃), O₂(a₁), O₂(b₁), O₂(A₃), O(1D), O(1S), NO(A), NO(D), N(2P), O₂(B₃), AR*
 - Ions: AR⁺, H⁺, H₂O⁺, OH⁺, H₂⁺, NO₂⁻, N₂O⁻, NO₃⁻, OH⁻, H⁻, N⁺, N₂⁺, CH₄⁺, CH₃⁺, CH₂⁺, N₄⁺, O₄⁺, O₄⁻, N₃⁺, N₂O⁺, NO₂⁺, O₃⁻, O⁻, O₂⁻, O₂⁺, O⁺, O₃, NO⁻, NO⁺



ChemPlasKin heat loss model for NRP discharges

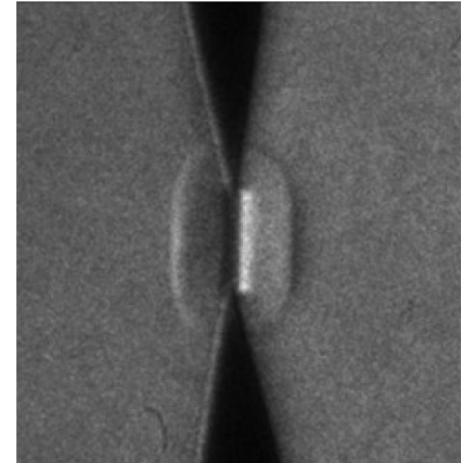
- In NRP spark discharges: ultrafast gas heating → constant volume heat addition → shock wave and thermal energy loss due to gas expansion
- In 0D simulations, those phenomena are not accounted for and could lead to **overestimations of the temperature increase**

→ **Need for a heat loss model**

1. Isentropic expansion after the discharge

$$T_{after\ expansion} = \left(\frac{P_{ambient}}{P_{plasma}} \right)^{\frac{\gamma-1}{\gamma}} T_{before\ expansion}$$

γ : heat capacity ratio





ChemPlasKin heat loss model for NRP discharges

2. Radial thermal conduction from the hot discharge kernel to the ambient environment

$$\dot{q}_{loss} \approx -\lambda C_0 \frac{T_{discharge} - T_{ambient}}{r_{discharge}^2}$$

\dot{q}_{loss} : heat loss in W/m³

λ : thermal conductivity (calculated by Cantera's transport module)

$r_{discharge}$: effective radius of the cylindrical discharge

C_0 : dimensionless empirical coefficient

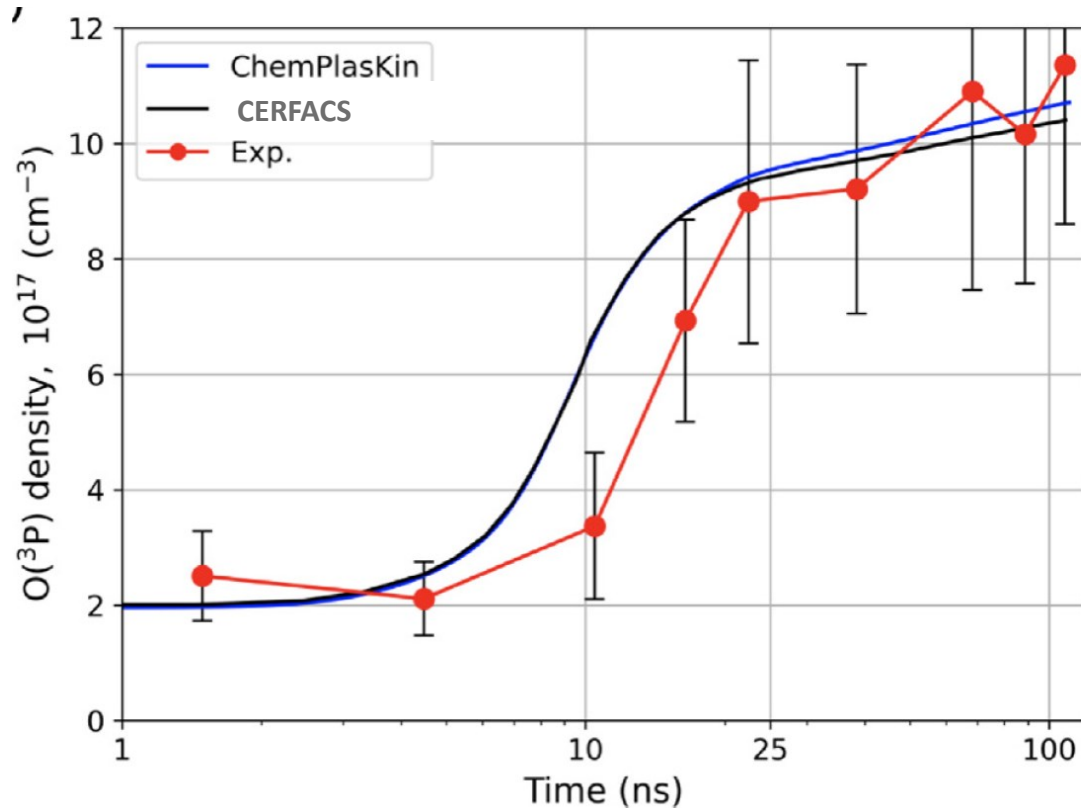
→ After calibration for a given condition, this heat loss model gives good results in terms of gas temperature of the discharge volume

0D PAC

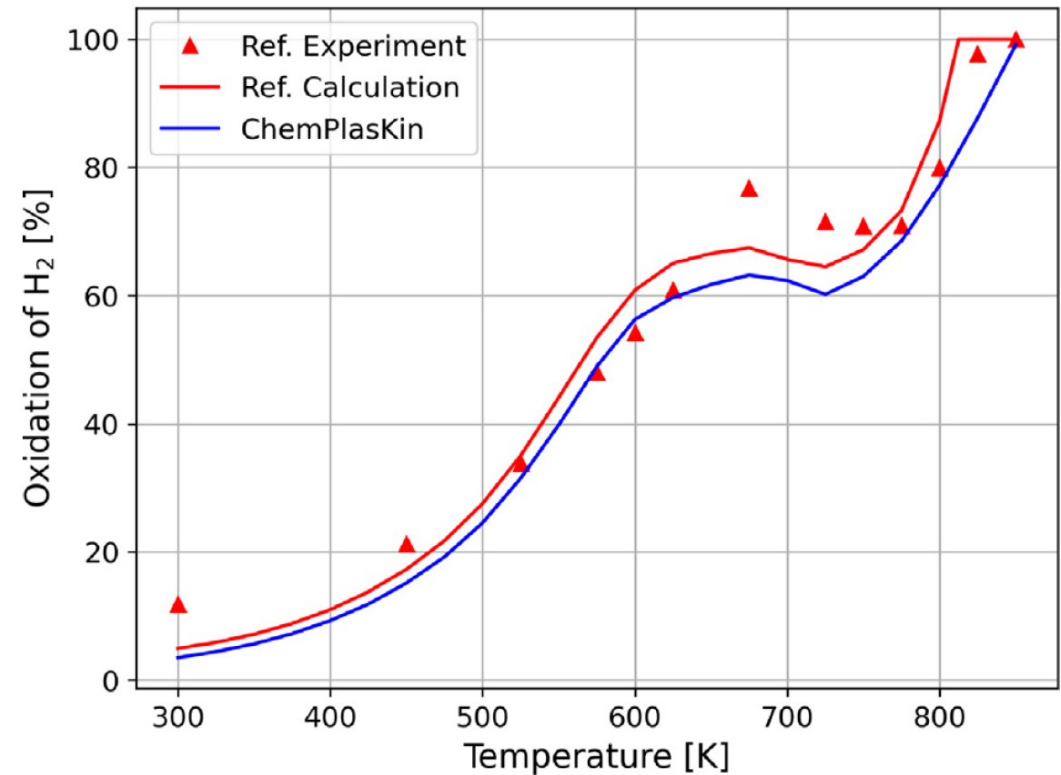


Examples of results obtained with ChemPlasKin for 0D simulations

Nanosecond discharge in air



DBD in H₂-air

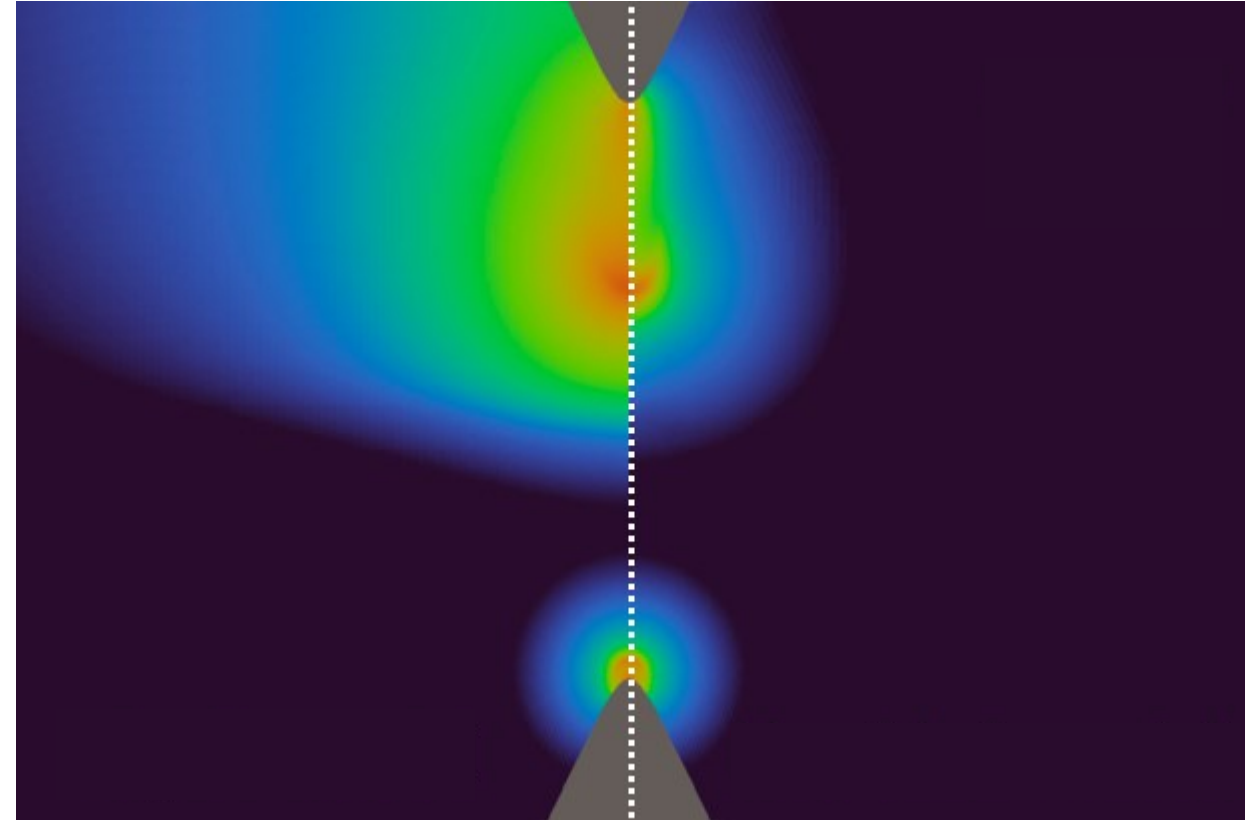


Shao et al., Appl. Energy Combust. Sci., 2024

Chapter VIII: Modeling Tools



- *Plasma-Combustion Coupling*
- *0D PAC*
- ***MultiD PAC***
- *References*

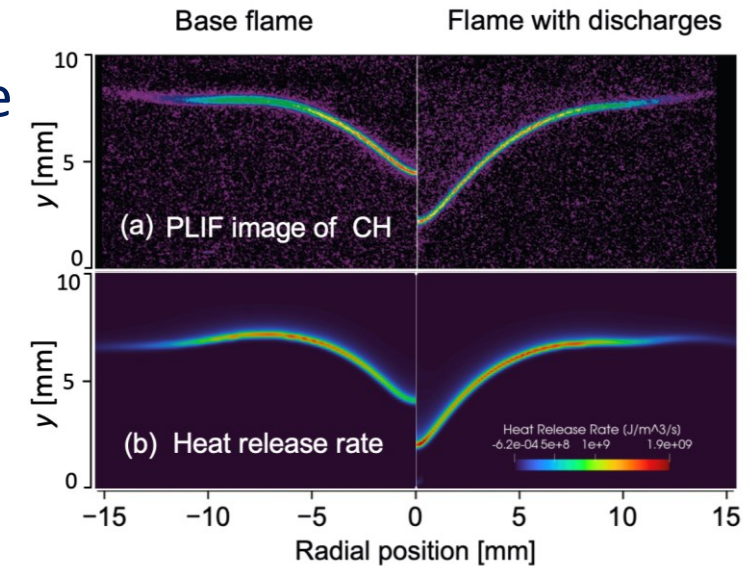


MultiD PAC

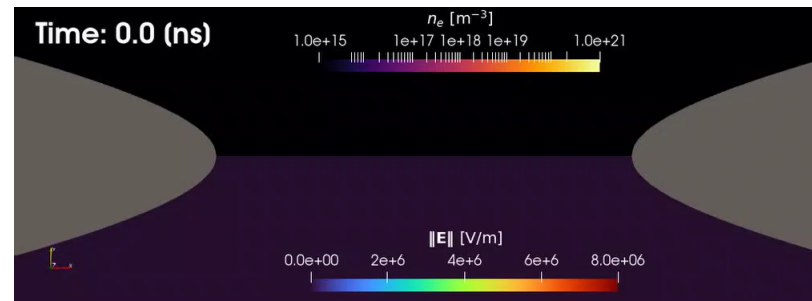


Multi-dimensional PAC solvers

1. Phenomenological model coupled with RANS/LES/DNS code
 - Capture major plasma enhancement pathways
 - Semi-empirical, simple and low-cost
2. Fully coupled plasma-fluid code
 - High-fidelity predictive simulations
 - Complex and higher cost



Shao et al., J. Phys. D: Appl. Phys., 2024



Shao et al., PSST, 2025



Phenomenological model (Castela's model)

1. The energy of a nanosecond discharge is transferred to the gas within two characteristic time scales
 - τ_{pulse} : relaxation time of electronically excited N_2 molecules ($\sim ns$)
 - τ_{VT} : vibrational–translational relaxation time of N_2 molecules ($\sim 1-100 \mu s$)
2. The fraction of the discharge energy deposited within τ_{pulse} leads to
 - Ultrafast dissociation of certain species and, therefore to the change of the chemical energy at a rate of \dot{E}_{chem}^p
 - Ultrafast increase of the gas temperature leading to an increase of the sensible energy at a rate of \dot{E}_{heat}^p
 - Ultrafast increase of the vibrational energy of the gas at a rate of \dot{E}_{vib}^p
3. e_{vib} relaxes into the translational modes, increasing the gas energy within τ_{VT} at a rate \dot{R}_{VT}^p

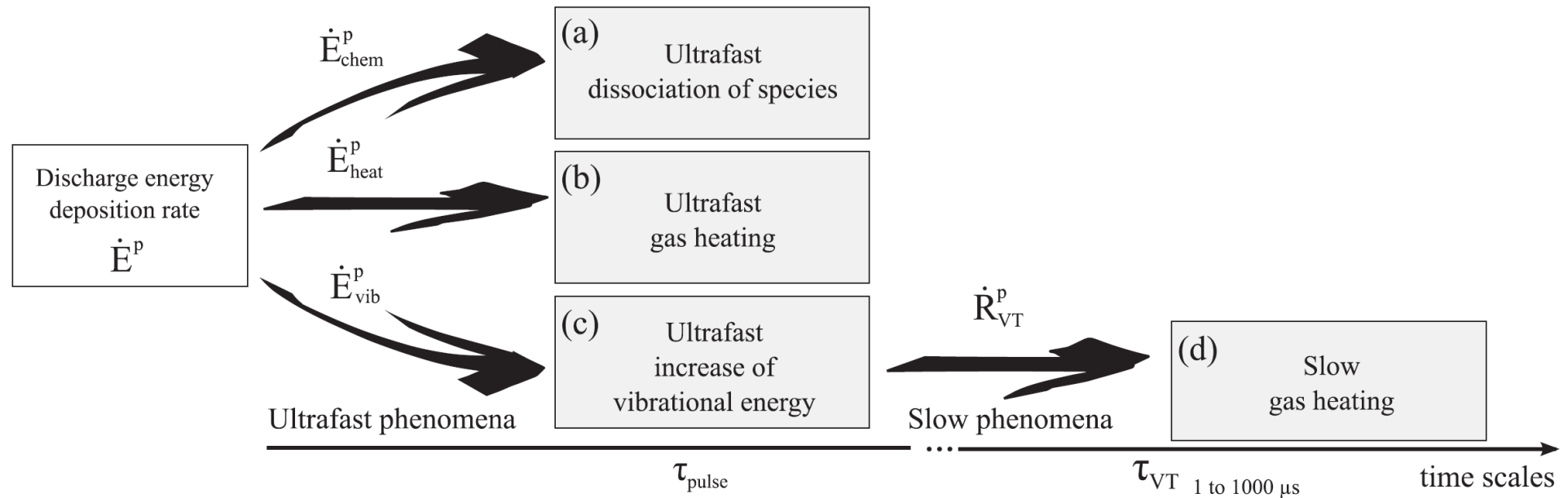


MultiD PAC

Phenomenological model (Castela's model)

The rate of energy deposited by each plasma pulse \dot{E}^p can be written as the sum of the three energy pathways

$$\dot{E}^p = \dot{E}_{chem}^p + \dot{E}_{heat}^p + \dot{E}_{vib}^p$$



MultiD PAC



Phenomenological model (Castela's model)

The set of governing equations that include the plasma model are

Continuity $\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0$

Momentum $\frac{\partial(\rho u_j)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_i}$

Energy $\frac{\partial(\rho e)}{\partial t} + \frac{\partial(\rho u_i e)}{\partial x_i} = -\frac{\partial q_i}{\partial x_i} + \frac{\partial(\sigma_{ij} u_i)}{\partial x_i} + \dot{E}_{chem}^p + \dot{E}_{heat}^p + \dot{R}_{VT}^p$

Vibrational energy $\frac{\partial(\rho e_{vib})}{\partial t} + \frac{\partial(\rho u_i e_{vib})}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\rho \mathcal{D} \frac{\partial e_{vib}}{\partial x_i} \right) + \dot{E}_{vib}^p + \dot{R}_{VT}^p$

Species $\frac{\partial(\rho Y_k)}{\partial t} + \frac{\partial(\rho u_i Y_k)}{\partial x_i} = -\frac{\partial(\rho V_{k,i} Y_k)}{\partial x_i} + W_k \dot{\omega}_k^c + W_k \dot{\omega}_k^p$

Relaxation rate of vibrational energy



Molar production rate by the plasma





MultiD PAC

Phenomenological model (Castela's model)

- Energy branching:

$$\begin{aligned}\dot{E}_{chem}^p &= \alpha \dot{E}^p \\ \dot{E}_{heat}^p &= \beta \dot{E}^p \\ \dot{E}_{vib}^p &= \gamma \dot{E}^p\end{aligned}$$

With

$$\alpha(E/N) + \beta(E/N) + \gamma(E/N) = 1$$

- Relaxation rate of vibrational energy into total energy:

$$\dot{R}_{VT}^p = f(X_{i=1\dots N}, T, P, e_{vib})$$

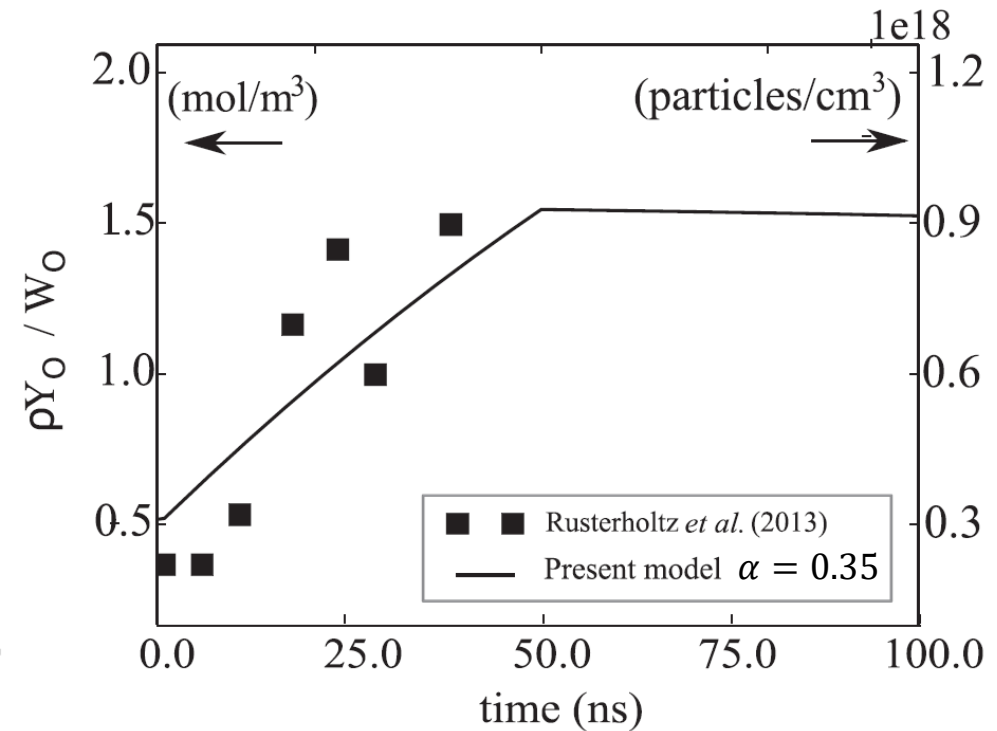
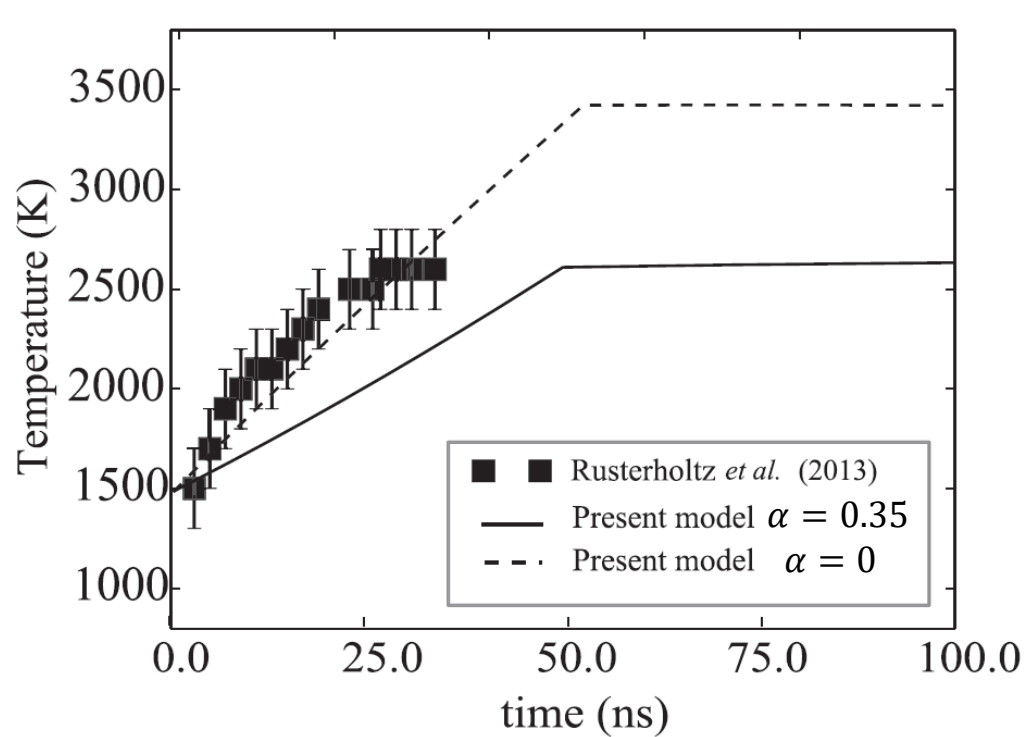
- Only the dissociation process of oxygen is considered $O_2 \rightarrow 2O$

$$\begin{aligned}\dot{\omega}_{O_2}^p &= -\frac{W_O}{W_{O_2}} \dot{\omega}_O^p \\ \dot{\omega}_k^p &= 0 \quad \text{if } k \neq O_2, O\end{aligned}$$



Phenomenological model (Castela's model)

- Validation against experimental results in air

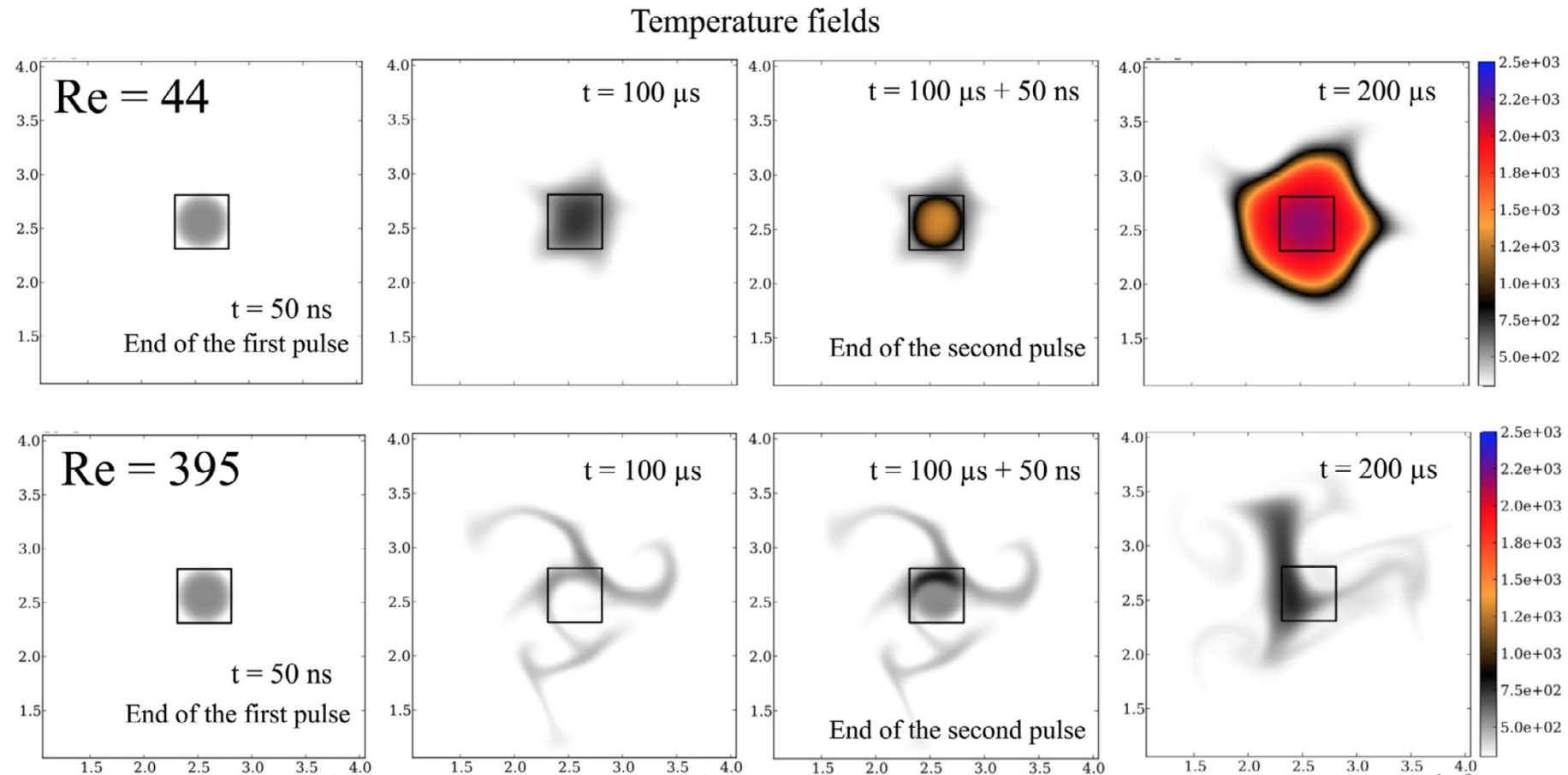


MultiD PAC



Phenomenological model (Castela's model)

- Example of results: impact of turbulence on temperature fields in methane-air (2D DNS)



MultiD PAC



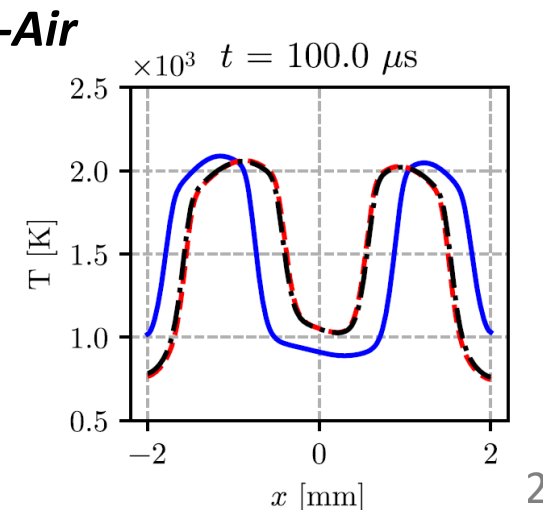
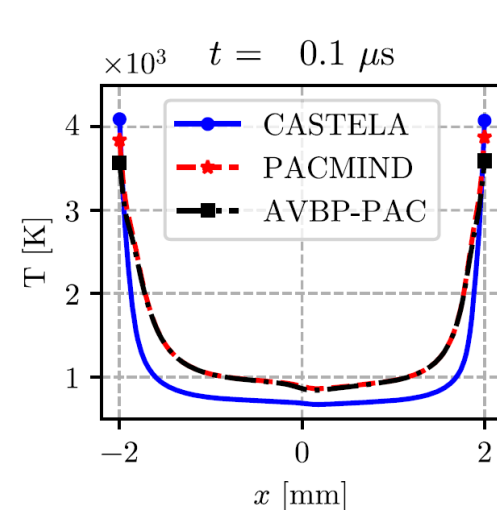
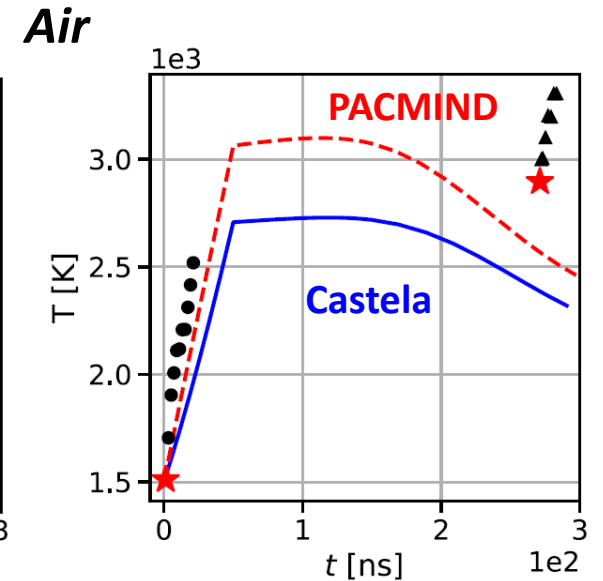
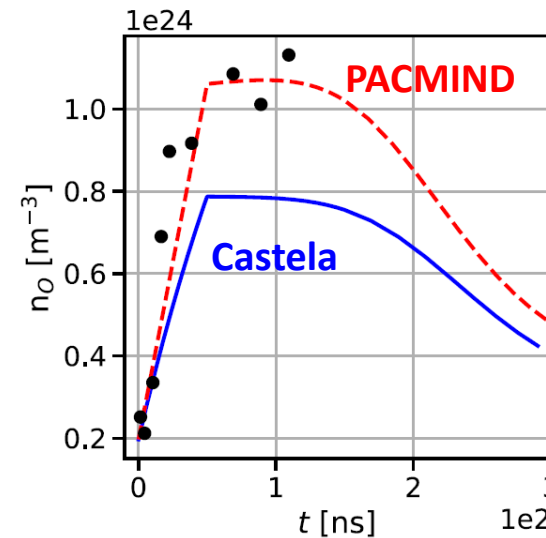
Updates of the phenomenological model

- Include additional chemical processes

Example of updated phenomenological model
Process considered for CH₄-air mixtures: PACMIND



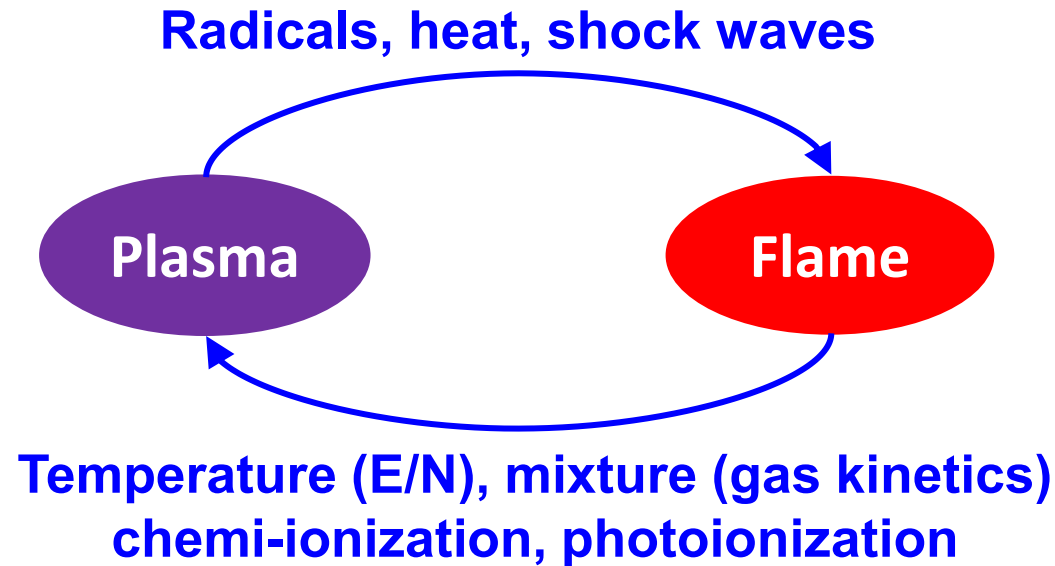
Barleon et al., Combust. Flame, 2023



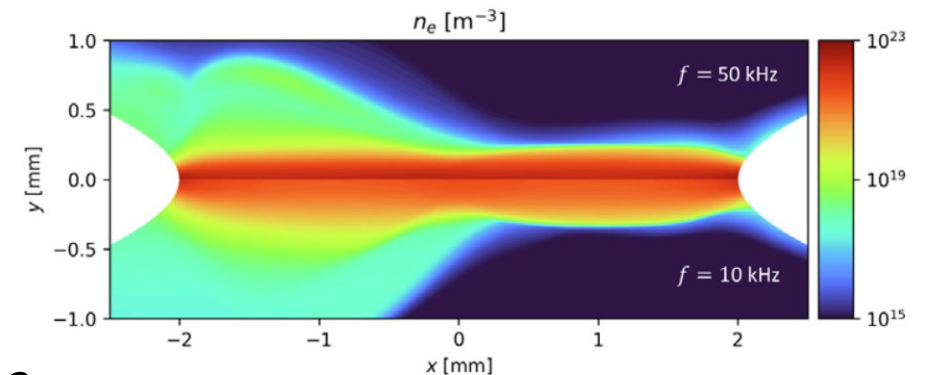
MultiD PAC



Fully coupled plasma-fluid model



- CERFACS: first group demonstrating fully coupled PAC code (AVIP coupled with AVBP) in 2022

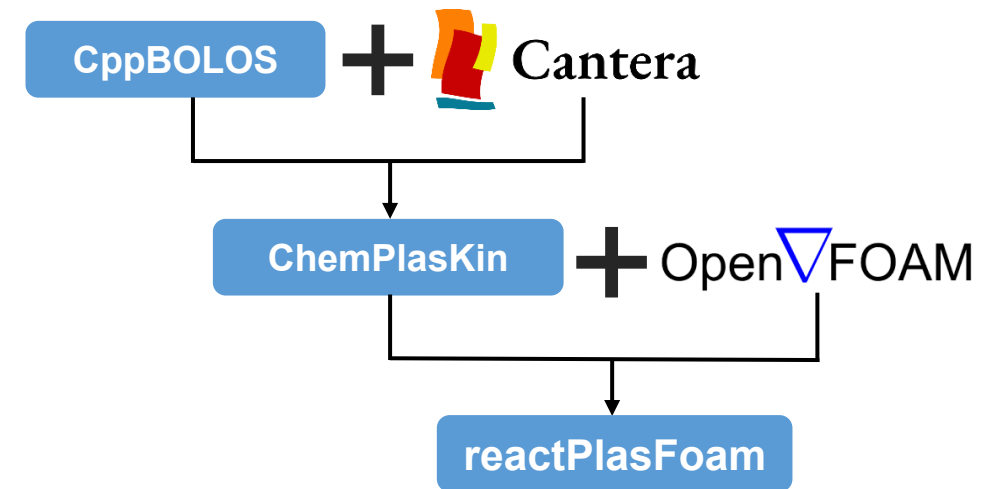


MultiD PAC



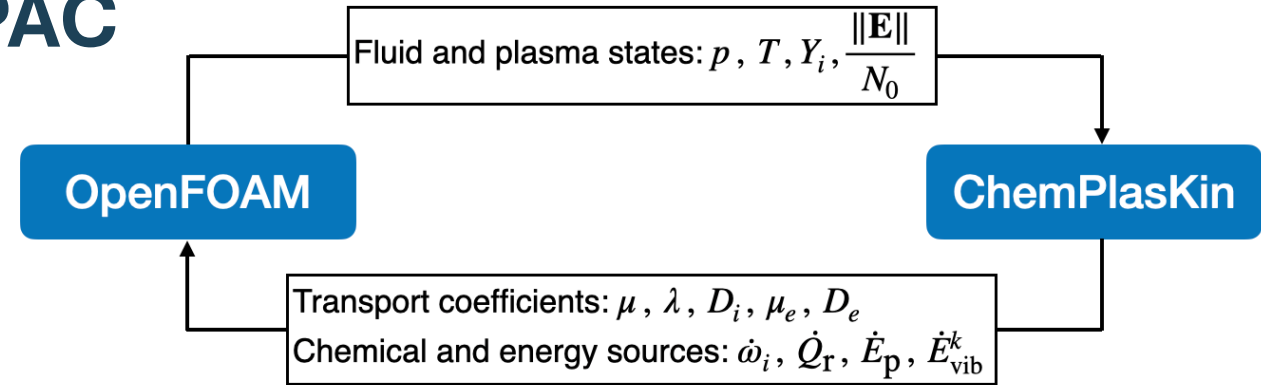
reactPlasFoam: A fully coupled unified plasma-fluid model

- Combine ChemPlasKin with OpenFOAM
- Simulate streamer discharges in reacting flows
- On-the-fly solution of EBE at the cell level
- Adaptative mesh refinement (AMR)
- Dynamic load balancing for solving EBE
- Suitable for calculations of
 - Streamer discharges
 - Spark discharges (with strong gas heating)
 - Combustion
 - Ionic wind
- Not yet available on GitHub...



MultiD PAC

reactPlasFoam's governing equations



Continuity $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$

Momentum $\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v} + p \mathbf{I} - \boldsymbol{\tau}) = \sum_{i=1}^N q_i e \mathbf{E} n_i \rightarrow$ Electro-hydrodynamic force

Species $\frac{\partial \rho Y_i}{\partial t} + \nabla \cdot [\rho (\mathbf{v} + \mathbf{V}_i) Y_i] = W_i \dot{\omega}_i + \frac{W_i S_{\text{ph},i}}{N_A} \rightarrow$ Photoionization source

Enthalpy $\frac{\partial \rho h^s}{\partial t} + \nabla \cdot (\rho \mathbf{v} h^s + \mathbf{q}) = \frac{\partial p}{\partial t} + \mathbf{v} \cdot \nabla p + \dot{Q}_r + \dot{E}_p \rightarrow$ Chemical and plasma heating

Electric potential $\nabla^2 \phi = -\frac{n_c}{\epsilon_0} = -\frac{\sum_{i=1}^N q_i e n_i}{\epsilon_0}$ with $\mathbf{E} = -\nabla \phi$

Diffusion-drift velocity $\mathbf{V}_i = -D_i \nabla \ln Y_i + \frac{q_i}{|q_i|} \mu_i \mathbf{E}$

$$\dot{Q}_r = -\sum_{i=1}^N h_i^0 \dot{\omega}_i$$

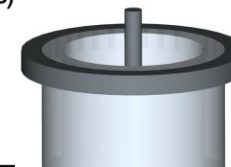
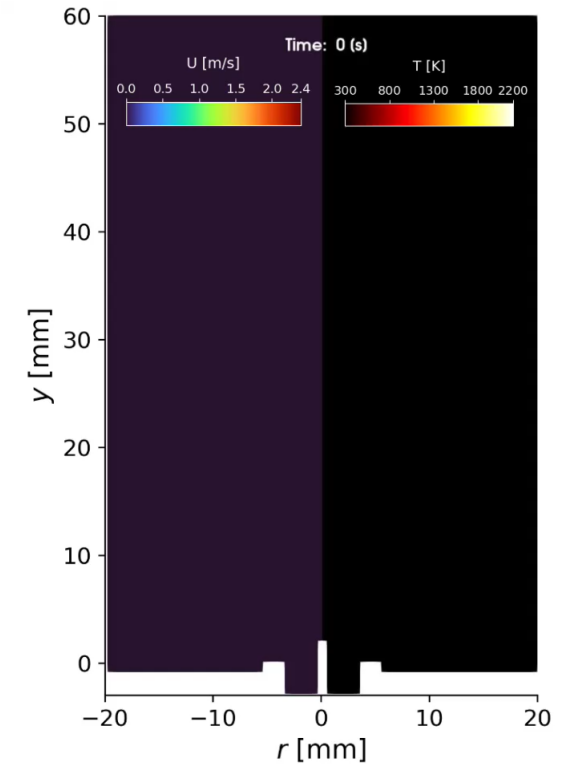
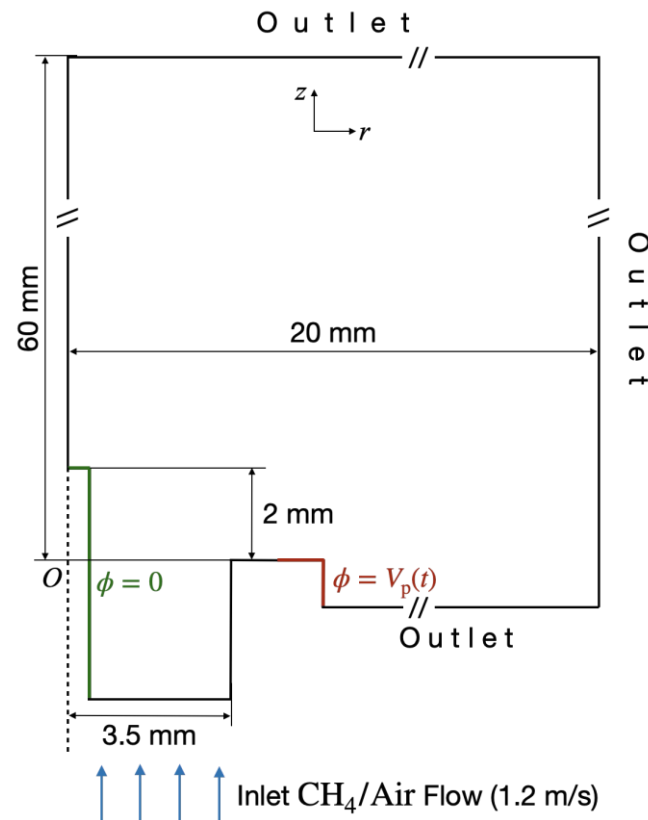
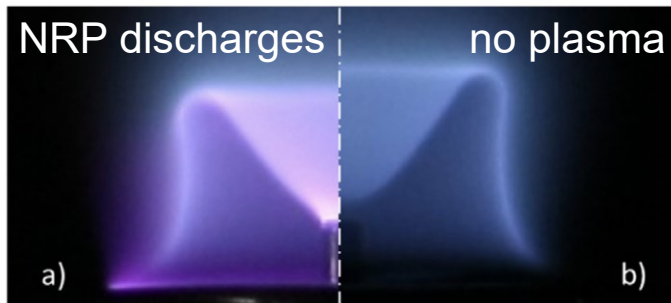
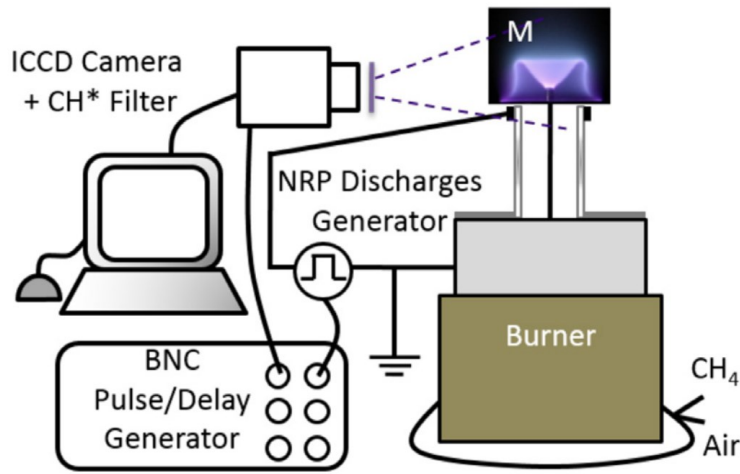
$$\dot{E}_p = \sum_{j \in \mathcal{B}} \epsilon_{\text{th}}^j r_{\text{B}}^j n_e n_{[j]}$$



MultiD PAC

Example of result obtained with reactPlasFoam

- Dynamics of a CH₄-air flame enhanced by NRP discharges (glow regime)

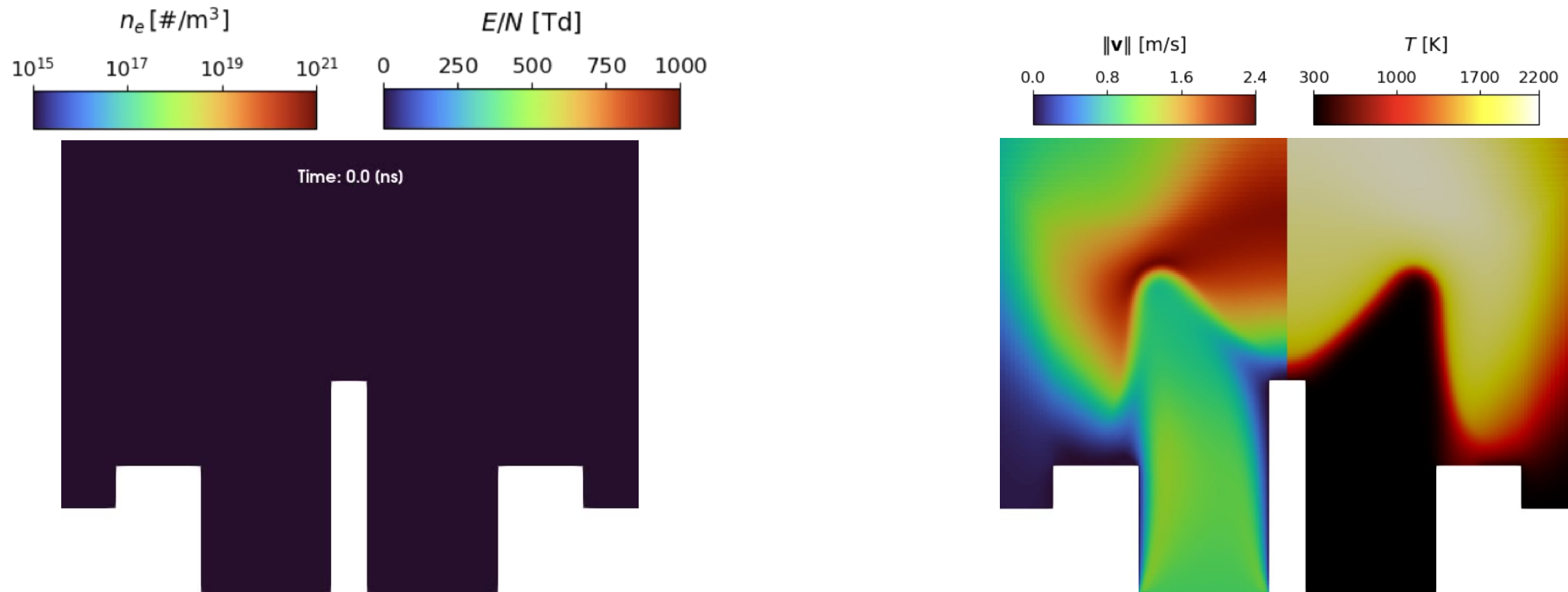


MultiD PAC



Example of result obtained with reactPlasFoam

- Apply an 8 kV nanosecond pulse (12 ns), very low pre-ionization level, $n_e(t = 0) = 10^3 \text{ cm}^{-3}$



- The streamer propagation follows the flame front → flame-guided streamer

References



Papers

- M. Castela, B. Fiorina, A. Coussement, O. Gicquel, N. Darabiha, C.O. Laux, Modelling the impact of non-equilibrium discharges on reactive mixtures for simulations of plasma-assisted ignition in turbulent flows, *Combust. Flame* 166, 133-147, 2016
- N. Barleon, L. Cheng, B. Cuenot, O. Vermorel, A phenomenological model for plasma-assisted combustion with NRP discharges in methane-air mixtures: PACMIND, *Combust. Flame* 253, 112794, 2023
- N. Barleon, L. Cheng, B. Cuenot, O. Vermorel, A. Bourdon, Investigation of the impact of NRP discharge frequency on the ignition of a lean methane-air mixture using fully coupled plasma-combustion numerical simulations, *Proc. Combust. Inst.* 39, 5521-5530, 2023
- X. Shao, D.A. Lacoste, H.G. Im, ChemPlasKin: A general-purpose program for unified gas and plasma kinetics simulations, *Appl. Energy Combust. Sci.*, 100280, 2024
- X. Shao, D.A. Lacoste, H.G. Im, A unified fluid model for nonthermal plasmas and reacting flows, *Plasma Sources Sci. Technol.* 34, 085016, 2025

Websites

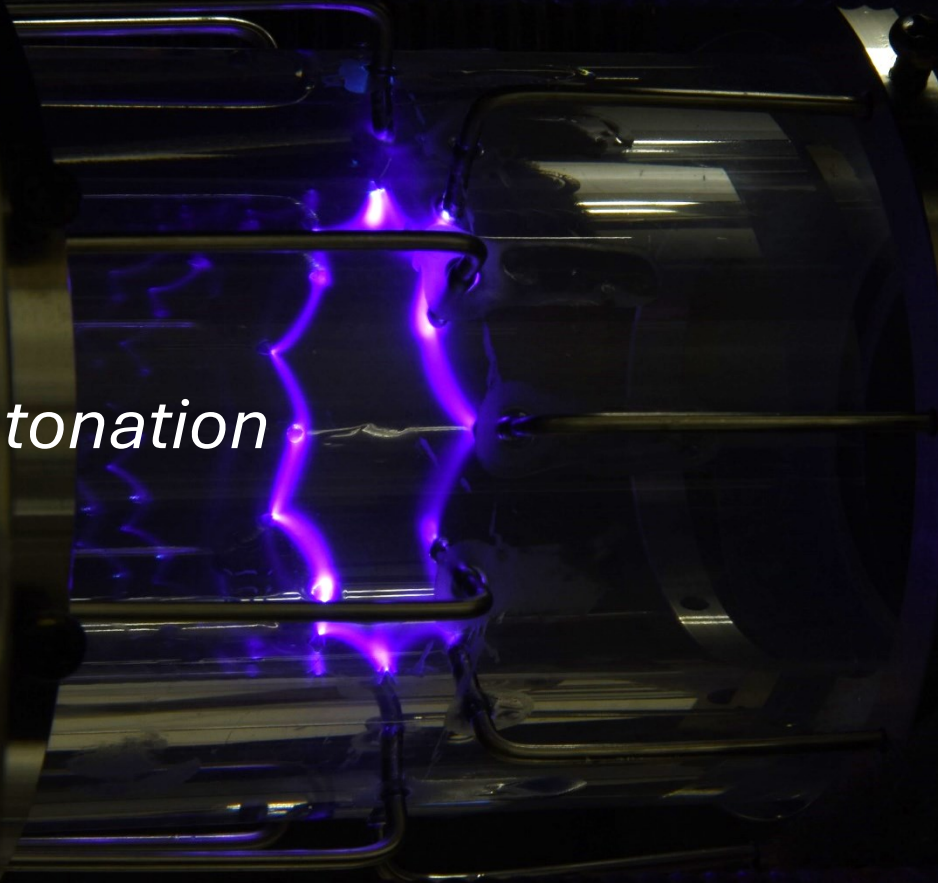
- ChemPlasKin: <https://github.com/ShaoX96/ChemPlasKin>

Book

- *Plasma Assisted Combustion and Chemical Processing*, Yiguang Ju & Andrey Starikovskiy, CCRC Press, Taylor and Francis Group, Boca Raton, FL, USA, 2025

Chapter IX: Recent Results & Questions

- *Carbon-Free Fuels*
- *Plasma-Assisted Detonation*
- *Three-Phase Flows*
- *References*



Carbon-Free Fuels

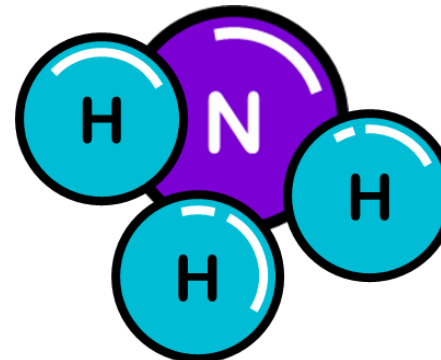
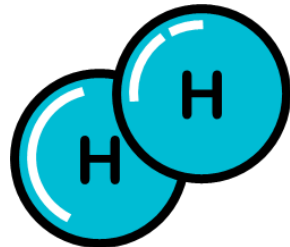


Wish list for a perfect carbon-free fuel

- ✓ Cheap
- ✓ Available at large scale
- ✓ Safe
- ✓ Easy to store and to transport
- ✓ No greenhouse gas emissions during production
- ✓ No greenhouse gas emissions during utilization
- ✓ Similar combustion properties than hydrocarbon fuels



Best candidates

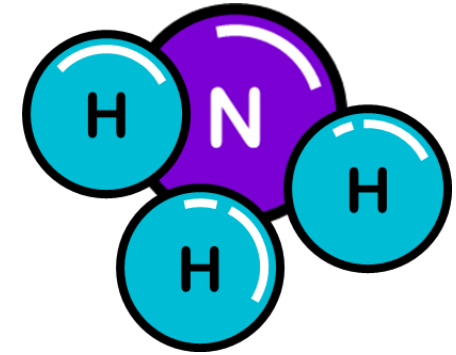


Carbon-Free Fuels



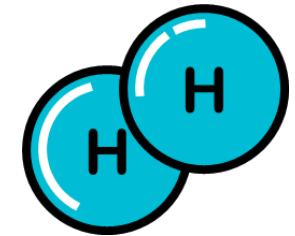
Main challenges of ammonia combustion

- ✗ Narrow flammability range
- ✗ Very low burning speed
- ✗ Emissions of NO_x (regulated)
- ✗ Emissions of N₂O (greenhouse potential about 300 × CO₂ equivalent)



Main challenges of hydrogen combustion

- ✗ Very large flammability range
- ✗ Very high burning speed
- ✗ Emissions of NO_x
- ✗ Storage



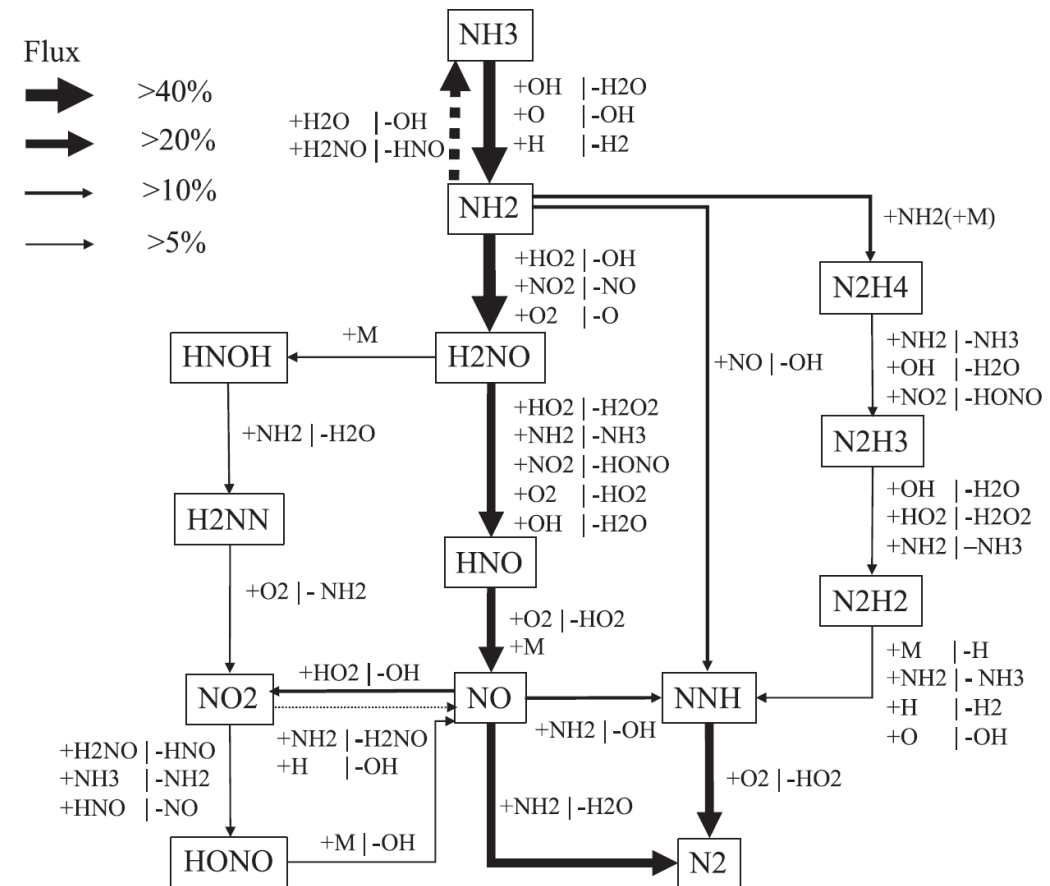
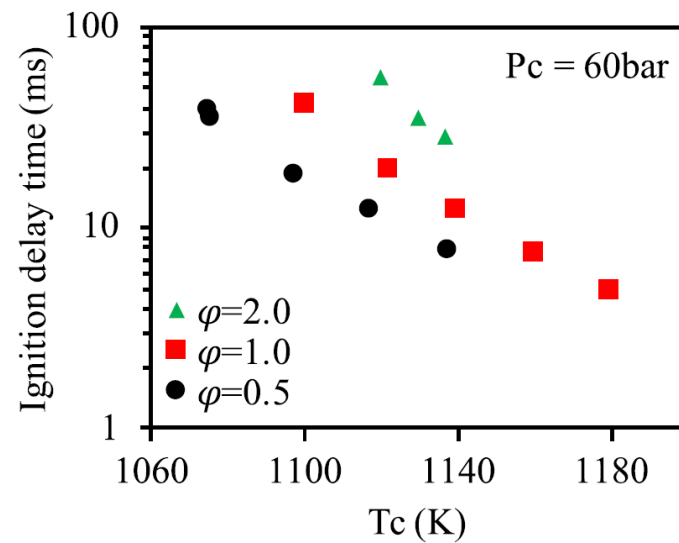
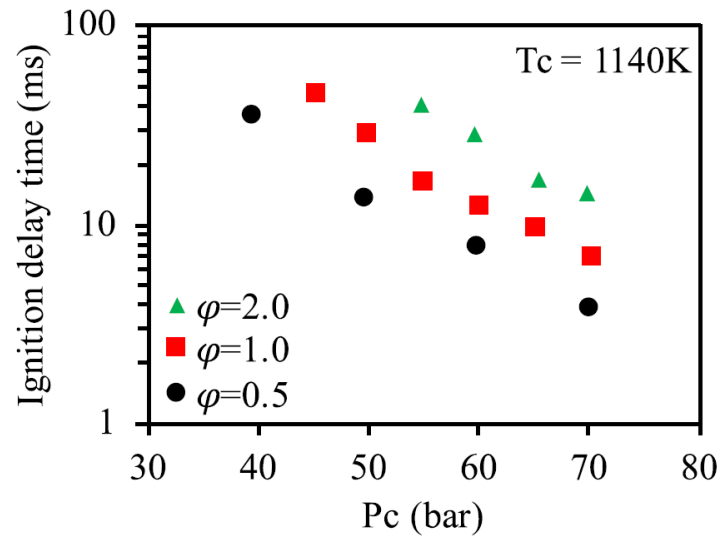
Carbon-Free Fuels



Plasma-assisted ignition of ammonia

- Need of data for NH_3 ignition and combustion

Experimental and numerical investigation of NH_3 and $\text{NH}_3\text{-H}_2$ auto-ignition at high pressure



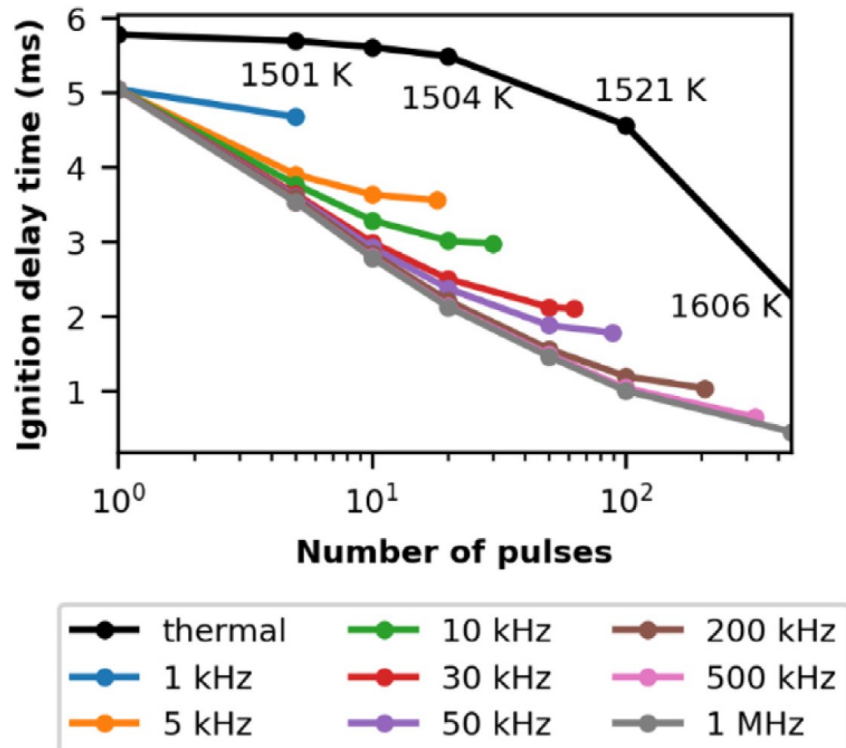
Carbon-Free Fuels



Plasma-assisted ignition of ammonia

- Need of PAC model for NH₃ ignition

Numerical investigation of NH₃/O₂/He ignition limits by NRP discharges



Faingold & Lefkowitz, PROCI, 2021

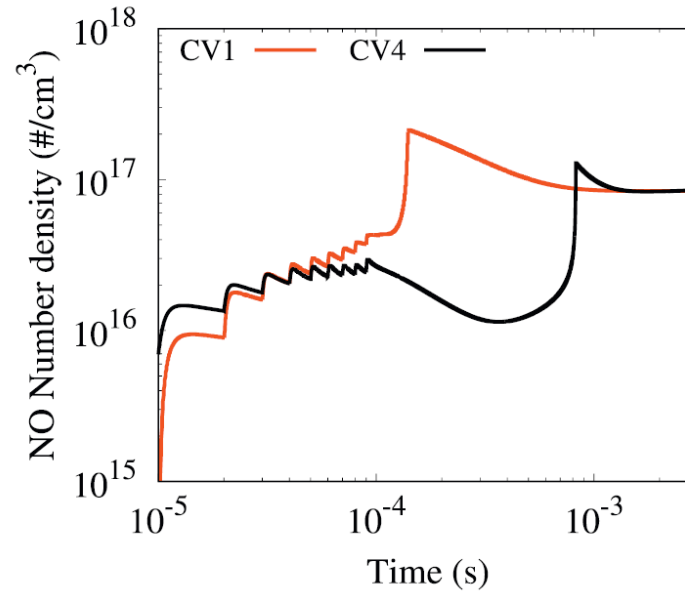
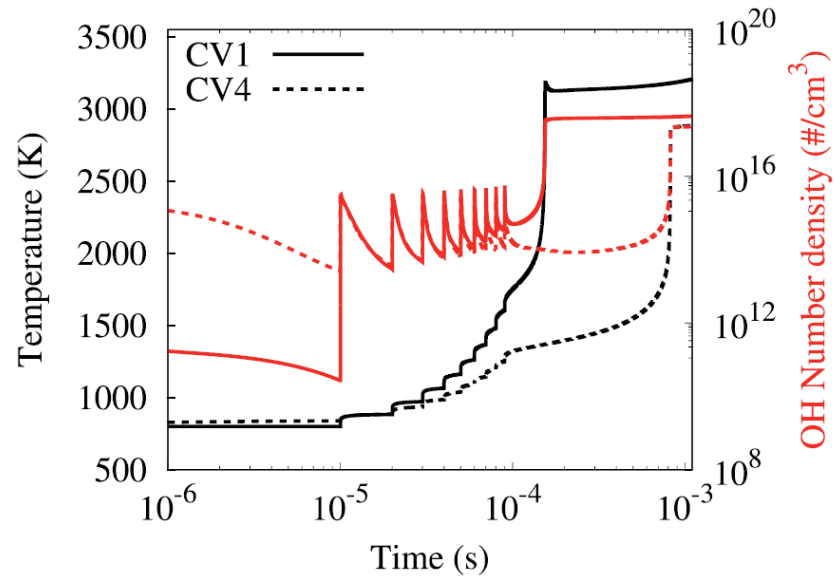
Reaction	Rate constant (cm ³ molecule ⁻¹ s ⁻¹)
Electron impact with NH₃	
1 $e + \text{NH}_3 \rightarrow e + \text{NH}_2 + \text{H}$	σ
2 $e + \text{NH}_3 \rightarrow e + \text{NH} + \text{H} + \text{H}$	σ
3 $e + \text{NH}_3 \rightarrow e + e + \text{NH}_3^+$	σ
Quenching of excited species	
4 $\text{O}(^1\text{D}) + \text{NH}_3 \rightarrow \text{OH} + \text{NH}_2$	$0.9 \times 2.51 \times 10^{-10}$
5 $\text{O}(^1\text{D}) + \text{NH}_3 \rightarrow \text{H}_2\text{O} + \text{NH}$	$0.06 \times 2.51 \times 10^{-10}$
6 $\text{O}(^1\text{D}) + \text{NH}_3 \rightarrow \text{H}_2 + \text{NOH}$	$0.001 \times 2.51 \times 10^{-10}$
7 $\text{O}(^1\text{D}) + \text{NH}_3 \rightarrow \text{H}_2\text{NO} + \text{H}$	$0.04 \times 2.51 \times 10^{-10}$
8 $\text{O}_2(a^1\Delta_g) + \text{NH}_3 \rightarrow \text{O}_2 + \text{NH}_3$	8.92×10^{-18}
9 $\text{He}^* + \text{NH}_3 \rightarrow \text{NH}^+ + \text{H} + \text{H} + \text{He} + e$	$0.08 \times 2.0 \times 10^{-9}$
10 $\text{He}^* + \text{NH}_3 \rightarrow \text{NH}_2^+ + \text{H} + \text{He} + e$	$0.80 \times 2.0 \times 10^{-9}$
11 $\text{He}^* + \text{NH}_3 \rightarrow \text{NH}_3^+ + \text{He} + e$	$0.12 \times 2.0 \times 10^{-9}$
Electron-ion Recombination	
12 $\text{NH}^+ + e \rightarrow \text{N} + \text{H}$	$4.30 \times 10^{-8} (0.026/T_e)^{0.5}$
13 $\text{NH}_2^+ + e \rightarrow \text{NH} + \text{H}$	$1.02 \times 10^{-7} (0.026/T_e)^{0.5}$
14 $\text{NH}_2^+ + e \rightarrow \text{N} + 2\text{H}$	$1.98 \times 10^{-7} (0.026/T_e)^{0.5}$
15 $\text{NH}_3^+ + e \rightarrow \text{NH} + 2\text{H}$	$1.55 \times 10^{-7} (0.026/T_e)^{0.5}$
16 $\text{NH}_3^+ + e \rightarrow \text{NH}_2 + \text{H}$	$1.55 \times 10^{-7} (0.026/T_e)^{0.5}$
17 $\text{N}_2\text{H}^+ + e \rightarrow \text{N}_2 + \text{H}$	$7.1 \times 10^{-7} (0.026/T_e)^{0.72}$
Charge exchange	
18 $\text{H}^+ + \text{NH}_3 \rightarrow \text{NH}_3^+ + \text{H}$	5.20×10^{-9}
19 $\text{H}_2^+ + \text{H} \rightarrow \text{H}_2 + \text{H}^+$	6.4×10^{-10}
20 $\text{H}_2^+ + \text{H}_2 \rightarrow \text{H}_3^+ + \text{H}$	2.00×10^{-9}
21 $\text{H}_2^+ + \text{NH}_3 \rightarrow \text{NH}_3^+ + \text{H}_2$	5.70×10^{-9}
22 $\text{H}_2^+ + \text{N}_2 \rightarrow \text{N}_2\text{H}^+ + \text{H}$	2.00×10^{-9}
23 $\text{H}_3^+ + \text{N} \rightarrow \text{NH}^+ + \text{H}_2$	2.6×10^{-10}
24 $\text{H}_3^+ + \text{N} \rightarrow \text{NH}_2^+ + \text{H}$	3.9×10^{-10}
25 $\text{H}_3^+ + \text{N}_2 \rightarrow \text{N}_2\text{H}^+ + \text{H}_2$	1.86×10^{-9}
26 $\text{N}^+ + \text{H}_2 \rightarrow \text{NH}^+ + \text{H}$	5.00×10^{-10}
27 $\text{N}^+ + \text{NH}_3 \rightarrow \text{NH}_2^+ + \text{NH}$	$0.20 \times 2.35 \times 10^{-9}$
28 $\text{N}^+ + \text{NH}_3 \rightarrow \text{NH}_3^+ + \text{N}$	$0.71 \times 2.35 \times 10^{-9}$
29 $\text{N}^+ + \text{NH}_3 \rightarrow \text{N}_2\text{H}^+ + \text{H}_2$	$0.09 \times 2.35 \times 10^{-9}$
30 $\text{NH}^+ + \text{H}_2 \rightarrow \text{H}_3^+ + \text{N}$	$0.15 \times 1.23 \times 10^{-9}$
31 $\text{NH}^+ + \text{H}_2 \rightarrow \text{NH}_2^+ + \text{H}$	$0.85 \times 1.23 \times 10^{-9}$
32 $\text{NH}^+ + \text{NH}_3 \rightarrow \text{NH}_3^+ + \text{NH}$	$0.75 \times 2.40 \times 10^{-9}$
33 $\text{NH}^+ + \text{N}_2 \rightarrow \text{N}_2\text{H}^+ + \text{N}$	6.50×10^{-10}
34 $\text{NH}_2^+ + \text{H}_2 \rightarrow \text{NH}_3^+ + \text{H}$	1.95×10^{-10}
35 $\text{NH}_2^+ + \text{NH}_3 \rightarrow \text{NH}_3^+ + \text{NH}_2$	$0.5 \times 2.30 \times 10^{-9}$
36 $\text{N}_2^+ + \text{H}_2 \rightarrow \text{N}_2\text{H}^+ + \text{H}$	2.00×10^{-9}
37 $\text{N}_2^+ + \text{NH}_3 \rightarrow \text{NH}_3^+ + \text{N}_2$	1.95×10^{-9}

Carbon-Free Fuels



Plasma-assisted ignition of ammonia

Numerical investigation of NH_3 -air ignition delays and NO_x emissions by NRP discharges



Reaction	Enthalpy of reaction, ΔH_r (kJ/mol)
$\text{E} + \text{NH}_3 \rightarrow \text{E} + \text{NH}_2 + \text{H}$	456.1
$\text{O}(^1D) + \text{NH}_3 \rightarrow \text{OH} + \text{NH}_2$	28.1
$\text{N}_2(\nu1) + \text{NH}_3 \rightarrow \text{N}_2 + \text{NH}_3(\nu2)$	-17.6
$\text{N}_2(\nu2) + \text{NH}_3 \rightarrow \text{N}_2 + \text{NH}_3(\nu2)$	-46.5
$\text{N}_2(\nu3) + \text{NH}_3 \rightarrow \text{N}_2 + \text{NH}_3(\nu2)$	-75.5
$\text{N}_2(\nu4) + \text{NH}_3 \rightarrow \text{N}_2 + \text{NH}_3(\nu2)$	-94.8
$\text{N}_2(\nu5) + \text{NH}_3 \rightarrow \text{N}_2 + \text{NH}_3(\nu2)$	-123.7
$\text{N}_2(\nu6) + \text{NH}_3 \rightarrow \text{N}_2 + \text{NH}_3(\nu2)$	-152.6
$\text{N}_2(\nu7) + \text{NH}_3 \rightarrow \text{N}_2 + \text{NH}_3(\nu2)$	-181.6
$\text{N}_2(\nu8) + \text{NH}_3 \rightarrow \text{N}_2 + \text{NH}_3(\nu2)$	-200.9

Taneja et al., Combust. Flame, 2022

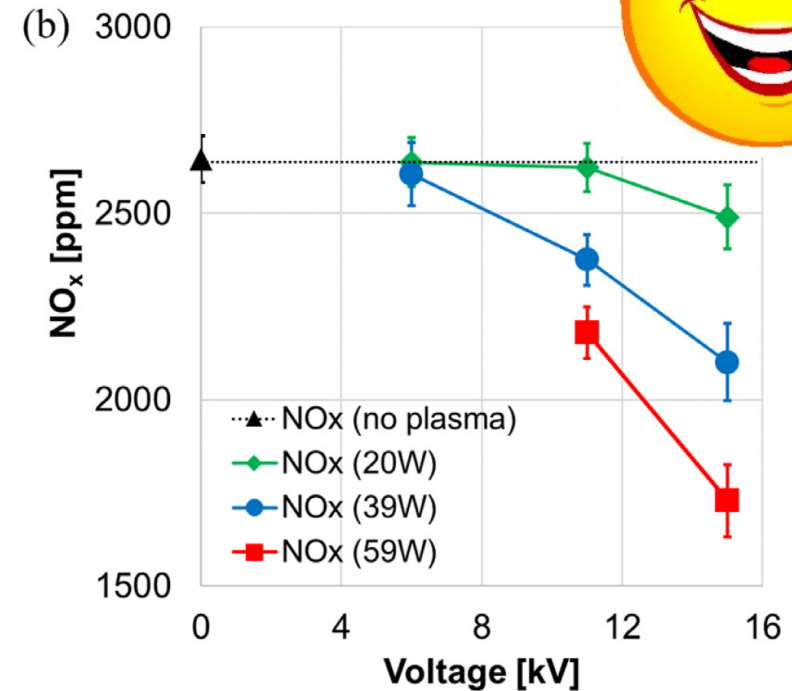
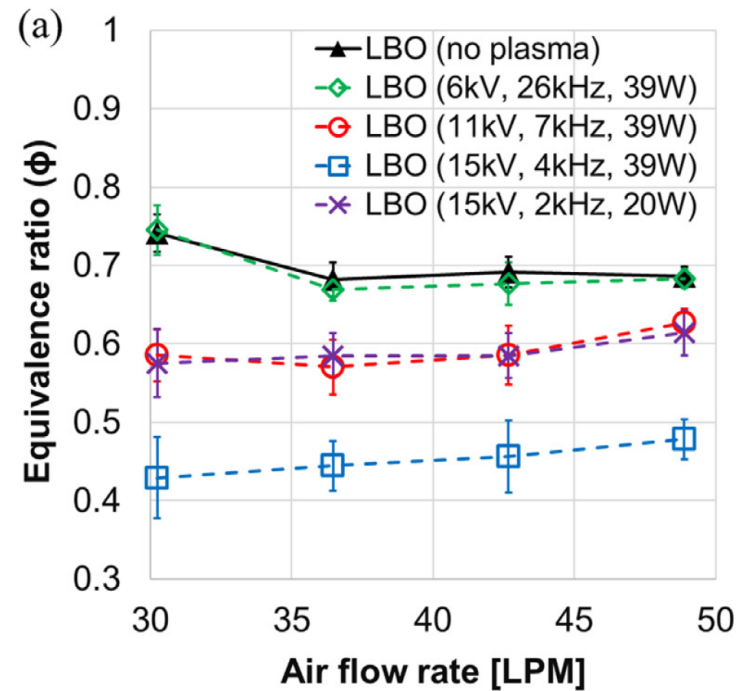
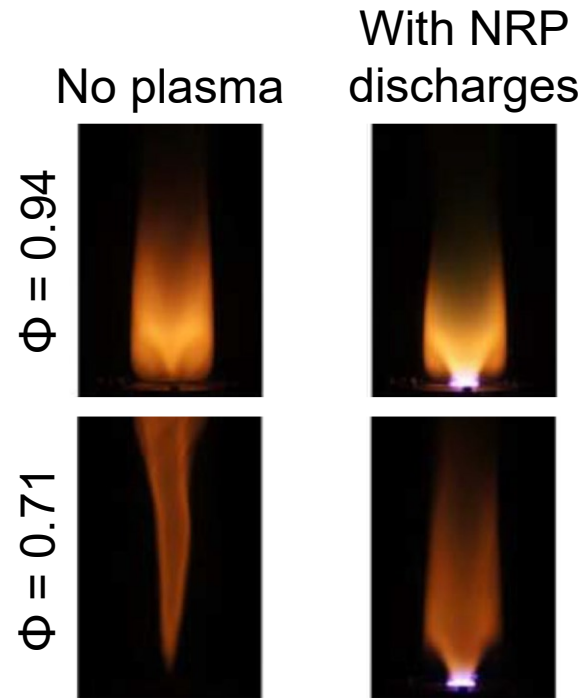
→ More effort is needed to have a reliable PAC model for NH_3 -air mixtures

Carbon-Free Fuels



Plasma-assisted ammonia combustion (PAAC)

First paper on experimental effect of NRP discharges on LBO and NO_x emissions of NH₃-air swirl flame

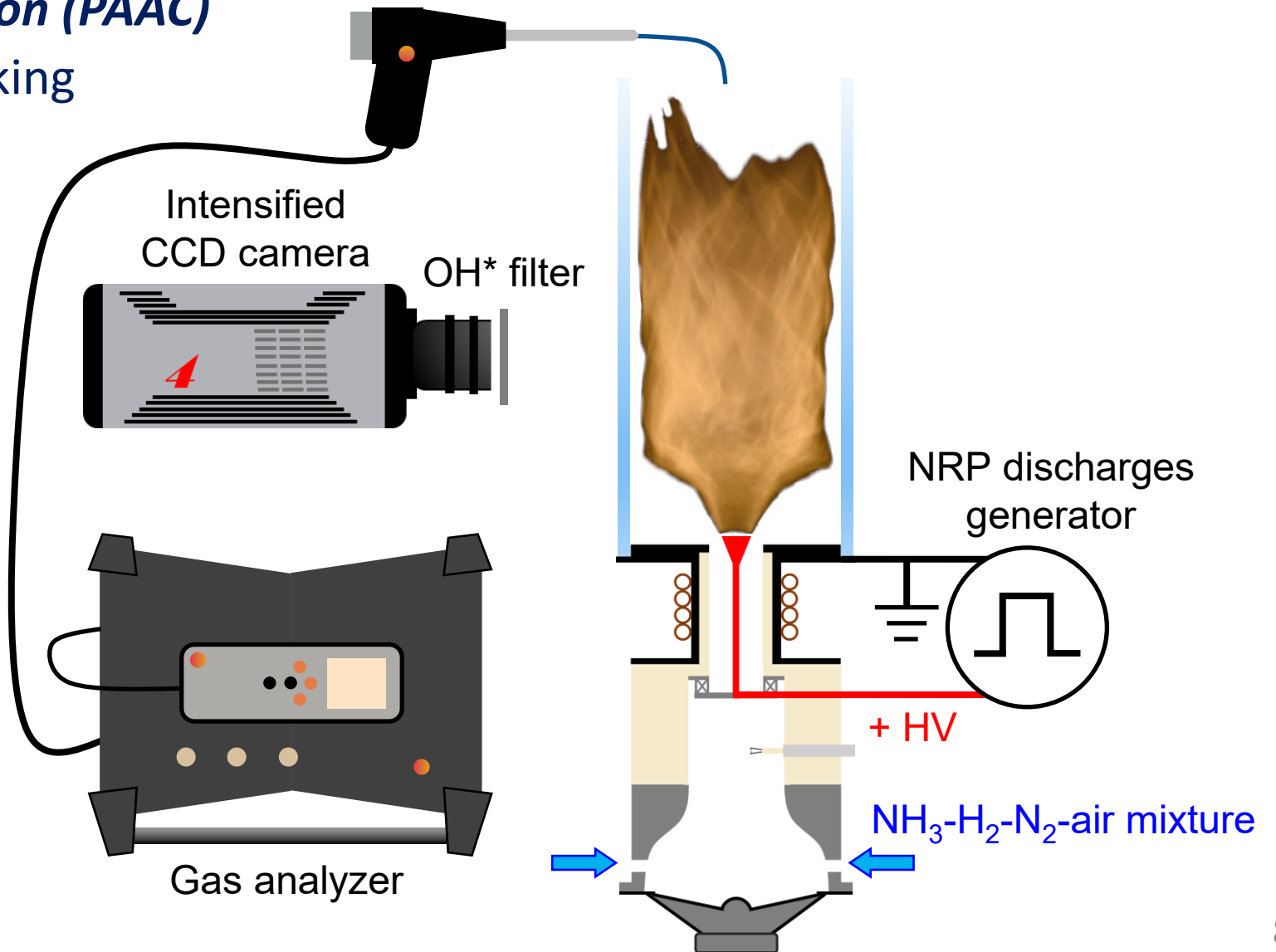
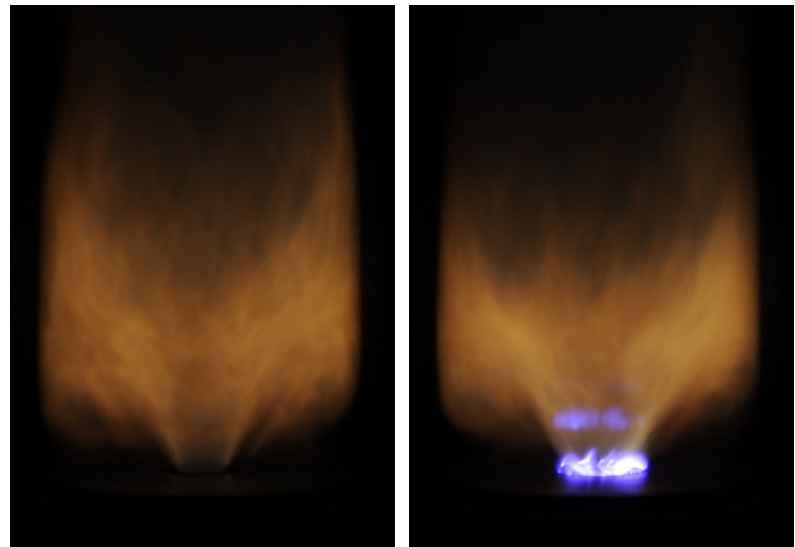


Carbon-Free Fuels



Plasma-assisted ammonia combustion (PAAC)

- Comparison between NH_3 cracking and PAAC

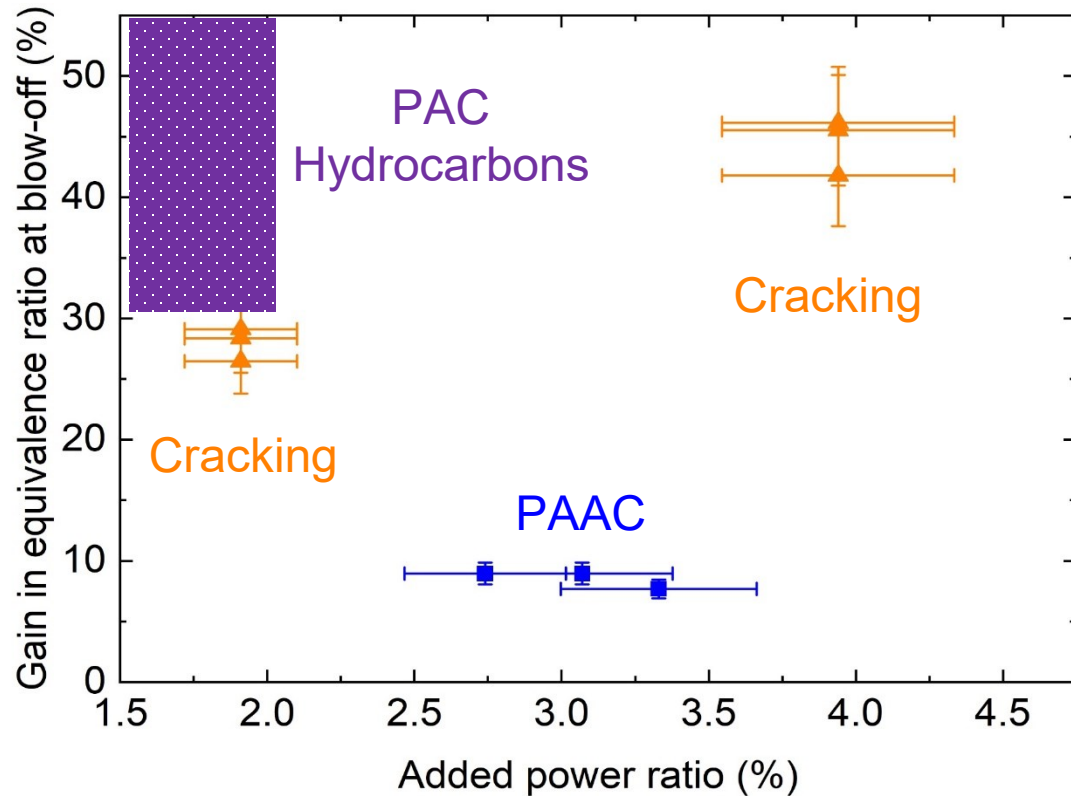


Carbon-Free Fuels



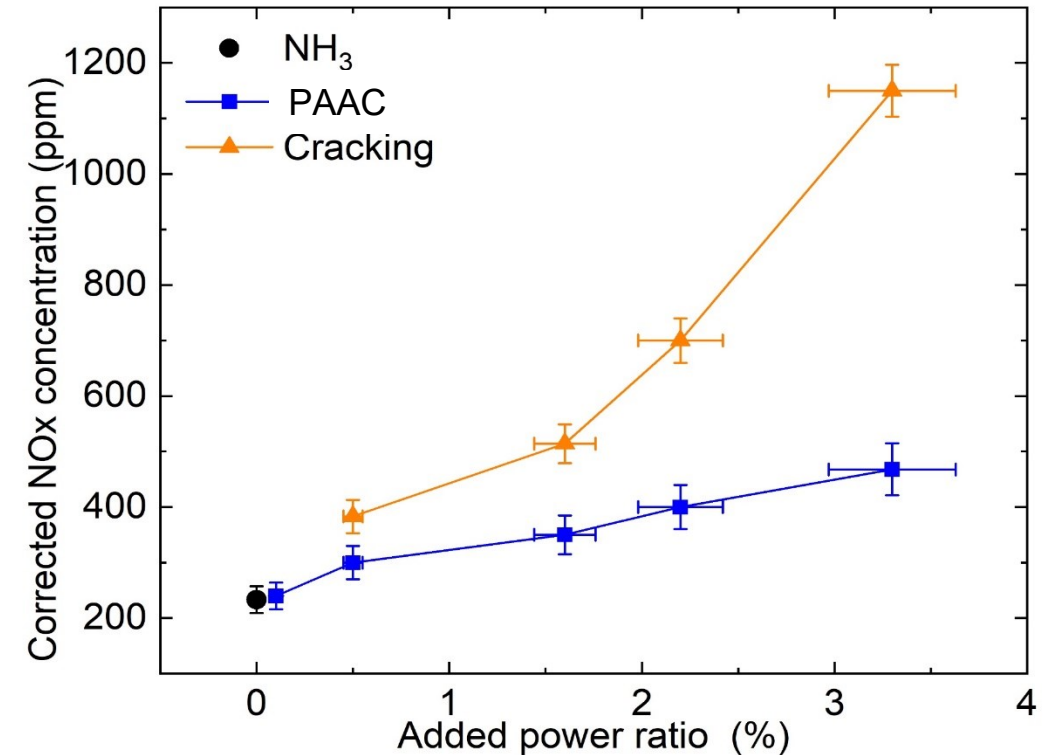
Plasma-assisted ammonia combustion (PAAC)

- Enhancement of the LBO limit



→ Thermal cracking more efficient than PAAC

- Effect on NO_x emissions



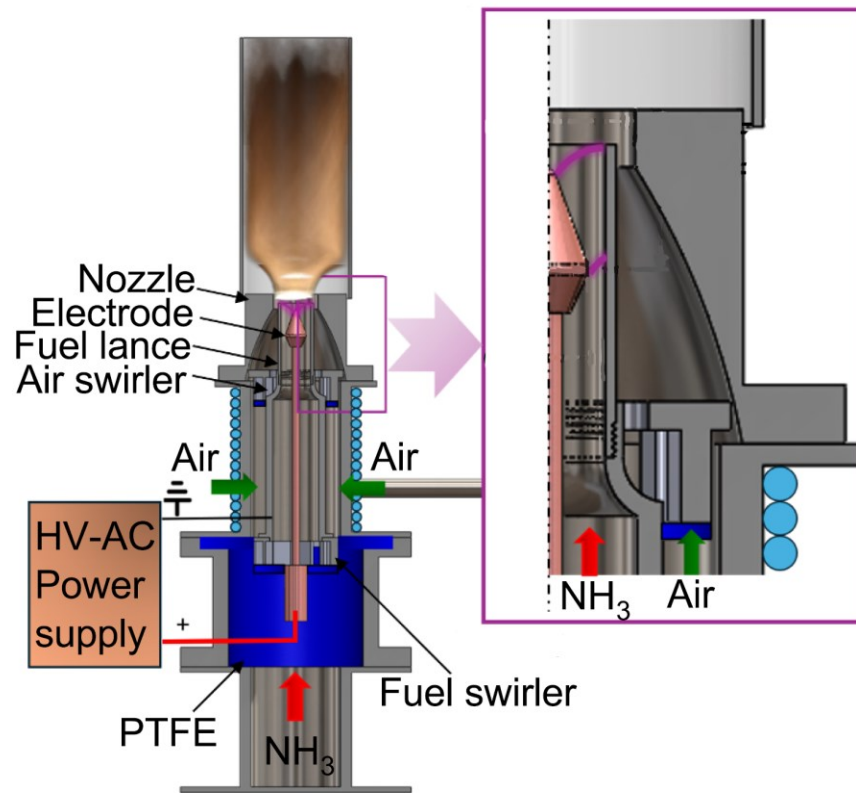
→ Higher NO_x penalty for thermal cracking than for PAAC

Carbon-Free Fuels

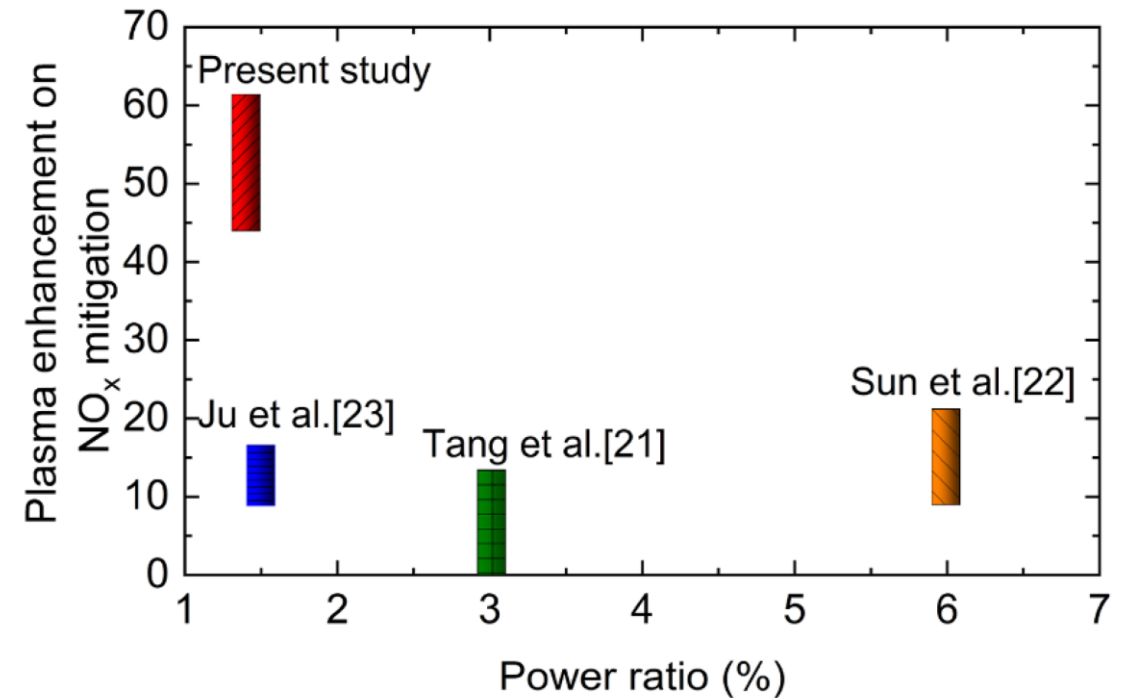


Plasma-assisted ammonia combustion (PAAC)

- New PAAC strategy 1 → Gliding arc in the fuel stream



Aravind et al., PROCI, 2025



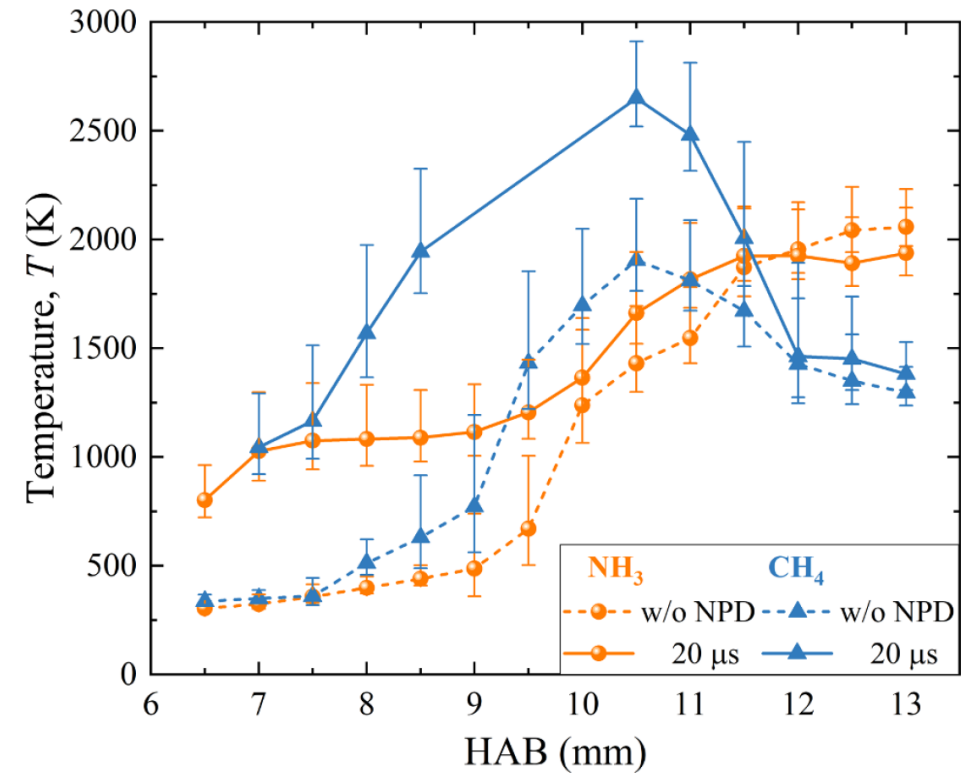
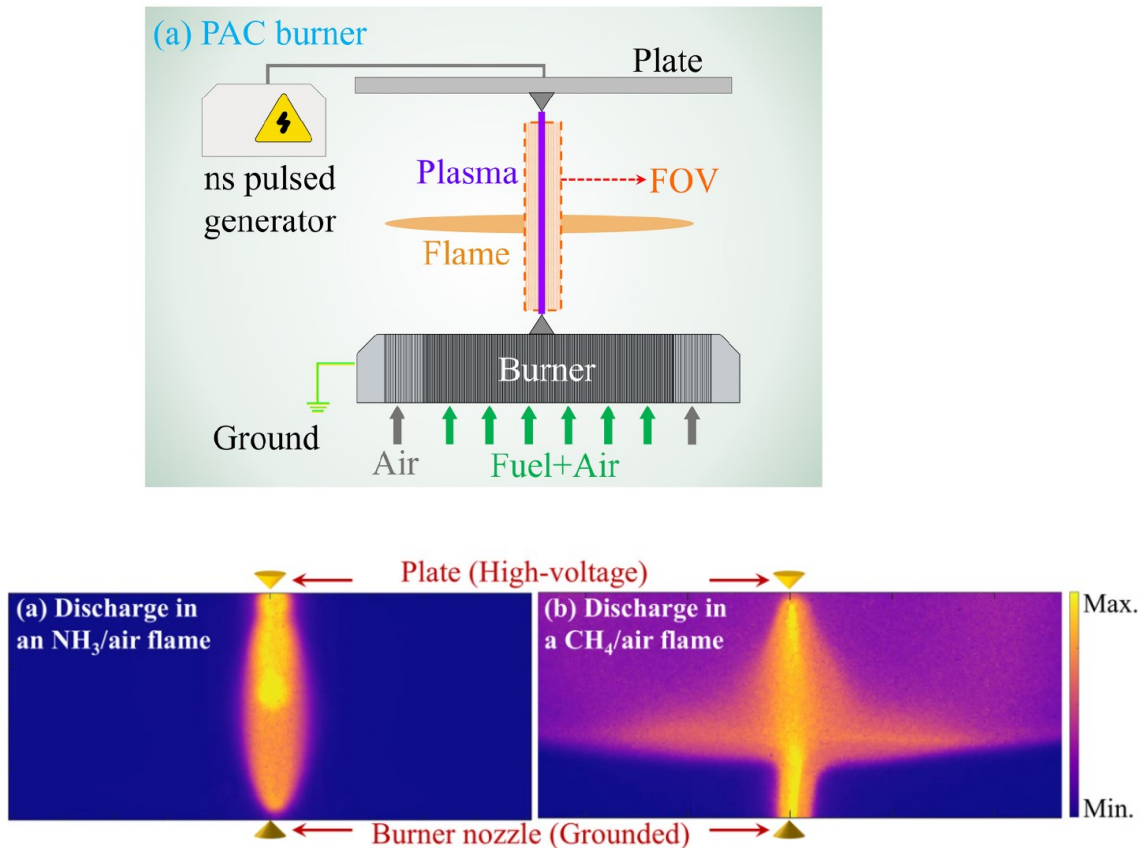
→ Best PAAC results reported

Carbon-Free Fuels



Plasma-assisted ammonia combustion (PAAC)

- New PAAC strategy 2 → Adding a bit of carbon



→ CH chemistry might be key in PAC

Carbon-Free Fuels



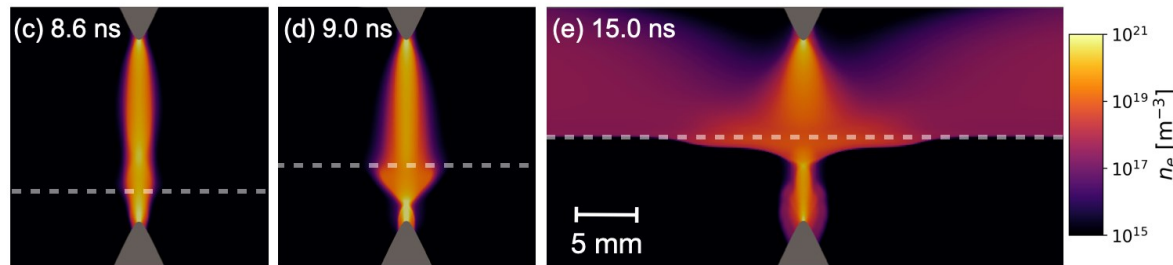
Plasma-assisted ammonia combustion (PAAC)

- New PAAC strategy 2 → Adding a bit of carbon

→ Confirms that for CH-driven chemi-ionization promotes discharges and chemistry

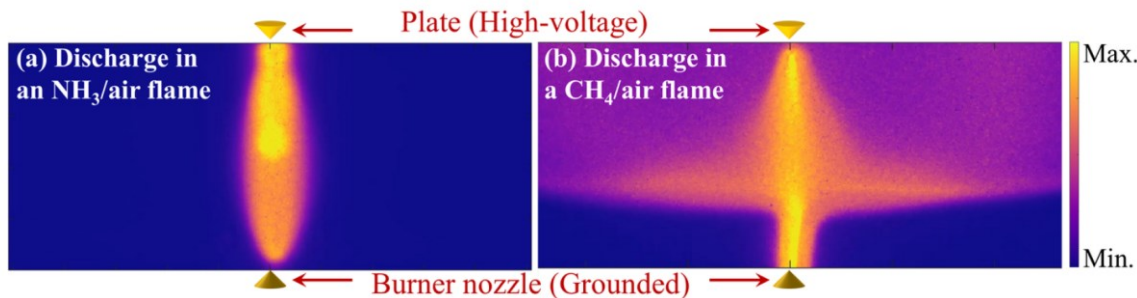
→ In NH_3 , lack of flame pre-ionization and weaker photoionization in burned gases induce smaller discharges

Simulations with reactPlasFoam

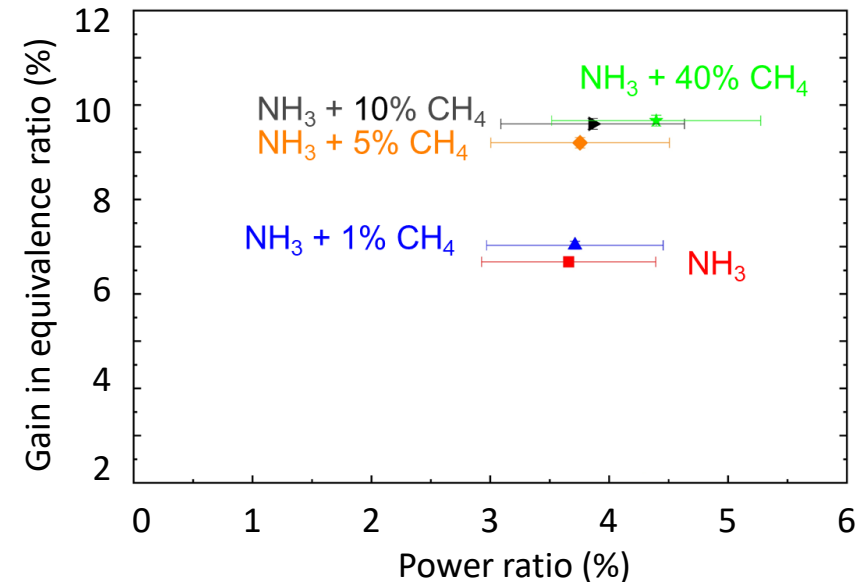


In NH_3 /air flames (different height)

In a CH_4 /air flame



Shao et al., Accepted in PROCI

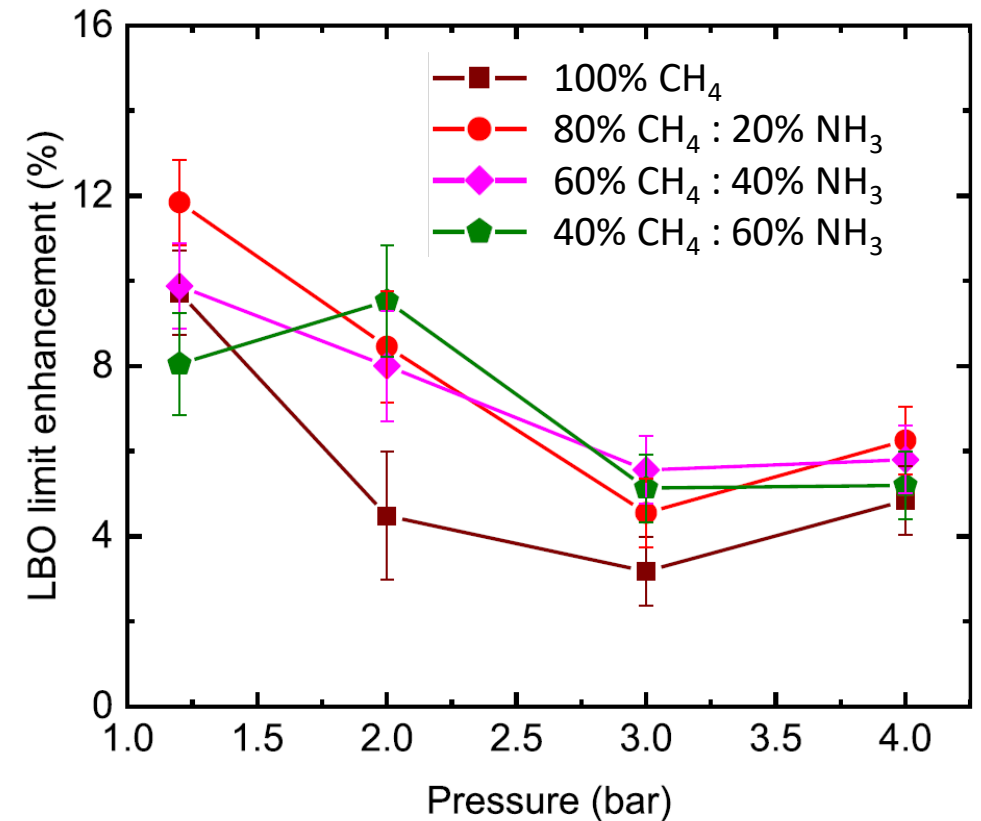
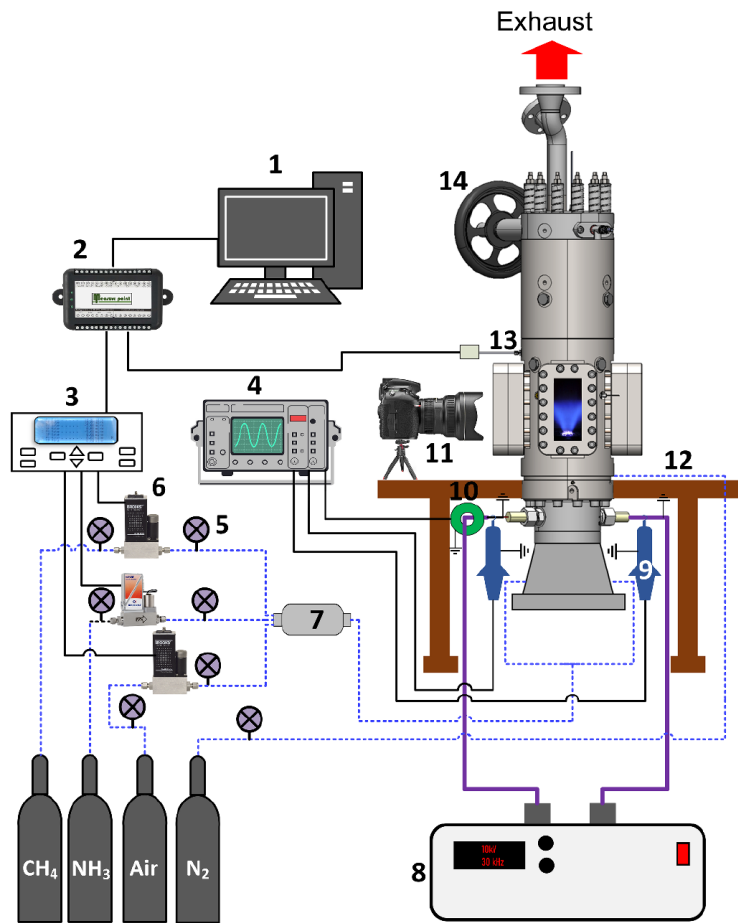


Carbon-Free Fuels



Plasma-assisted ammonia combustion (PAAC)

- New PAAC strategy 2: At elevated pressure?



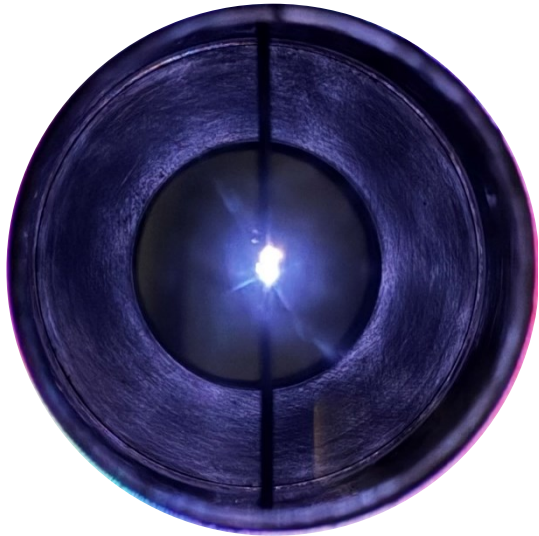
→ PAC of CH₄-NH₃ mixtures works better or similarly than PAC of CH₄ for pressures up to 4 bar

Carbon-Free Fuels

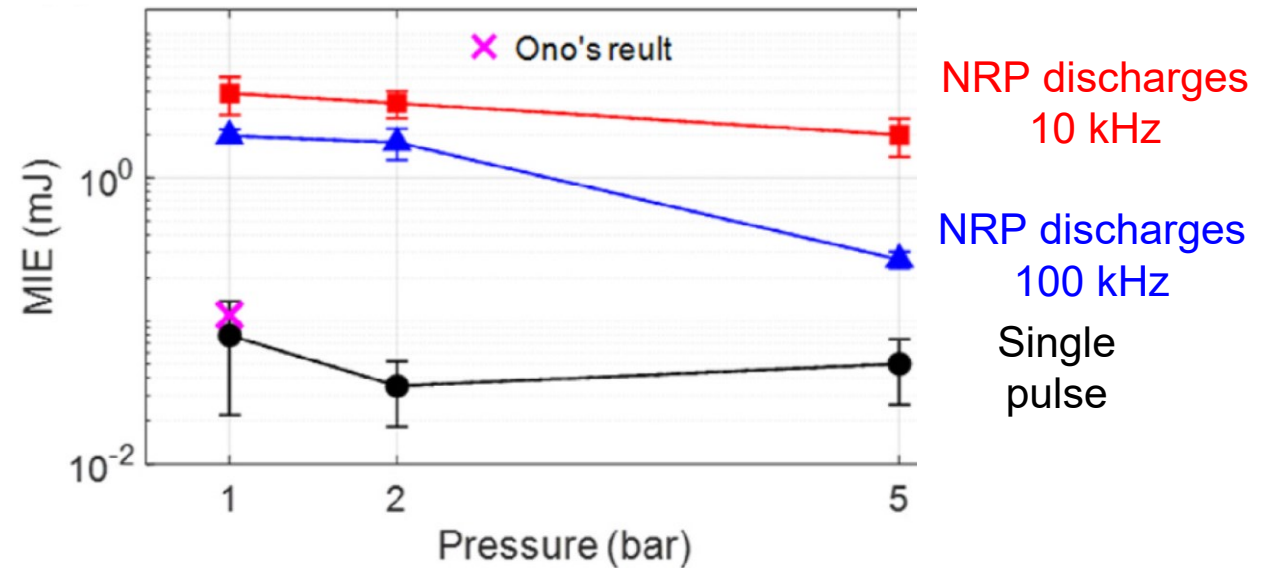


Plasma-assisted ignition of hydrogen

- Ignition of ultra-lean H₂ by NRP discharges
- Minimum Ignition energy (MIE) as a function of pressure



- Equivalence ratio: 0.18
- Initial pressure: 1-5 bar
- Electrode gap distance: 1.2 mm



- MIE by single pulse lower than by NRP discharges
- Opposite trends compared to HC fuels. Why?

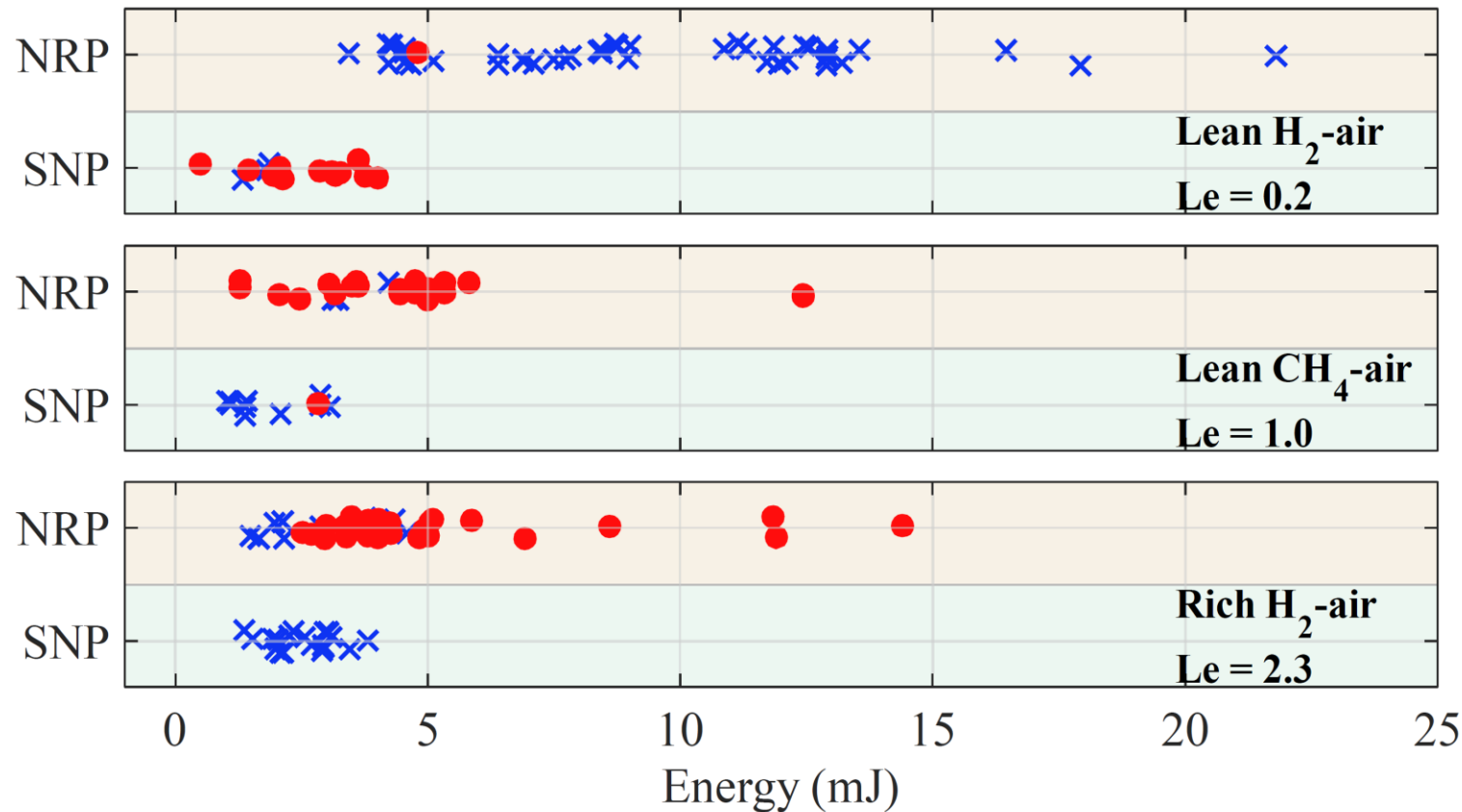
Carbon-Free Fuels



Plasma-assisted ignition of hydrogen

- One-to-one comparison of ignition of mixtures with different Lewis number

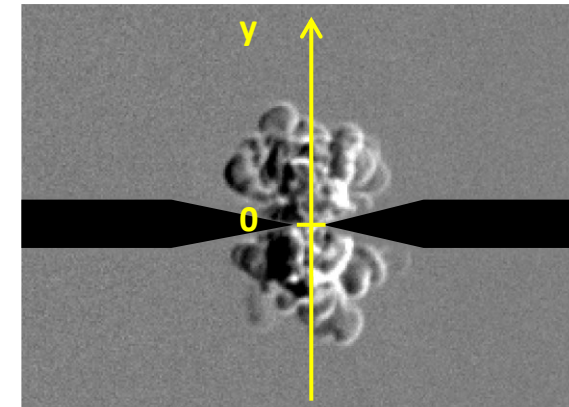
● Ignited × No-ignition



$$Le = \frac{\alpha}{D} = \frac{\lambda}{\rho c_p D}$$

- NRP discharges are better for ignition of $Le \geq 1$ mixtures
- Why?

→ Hydrodynamic effect

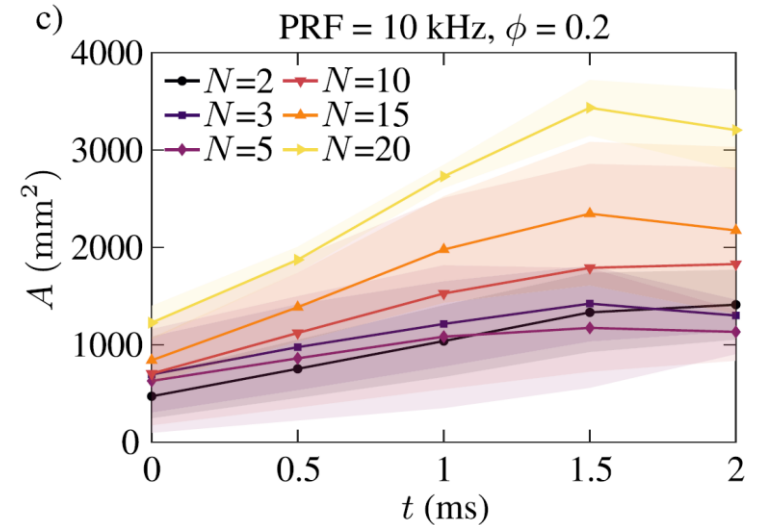
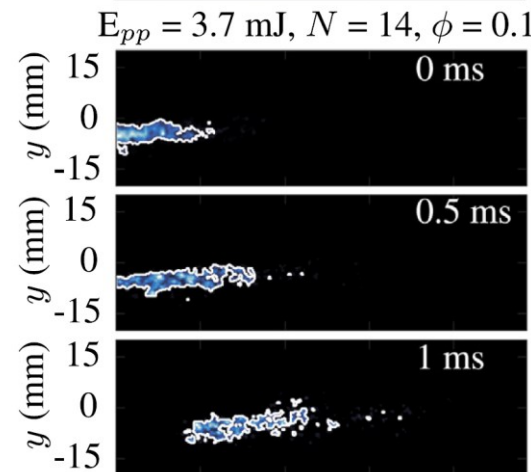
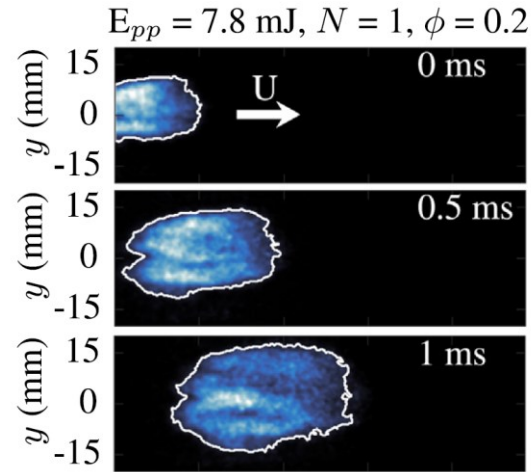
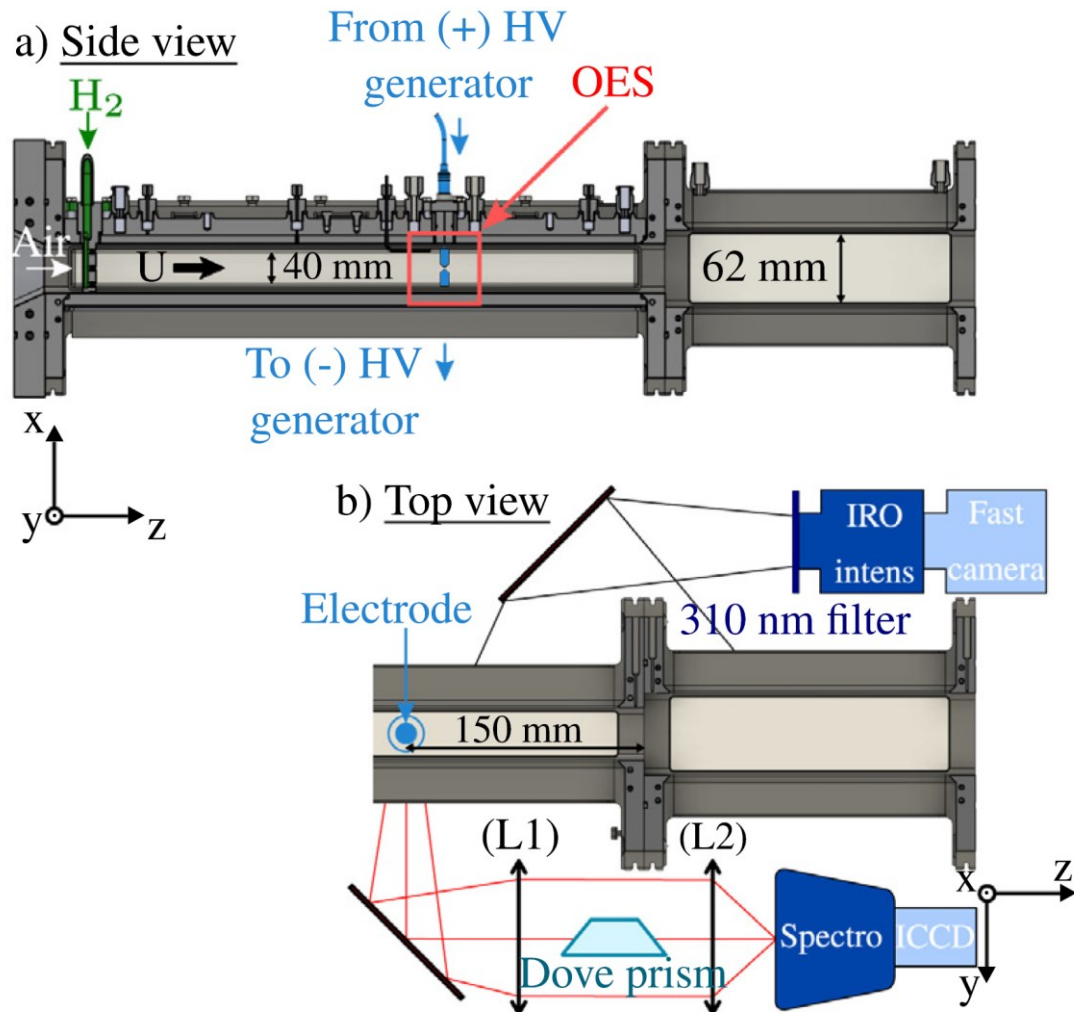


Carbon-Free Fuels



Plasma-assisted ignition of hydrogen

- NRP discharges for reliable ignition of ultra-lean hydrogen-air turbulent flow ($P = 1$ atm)



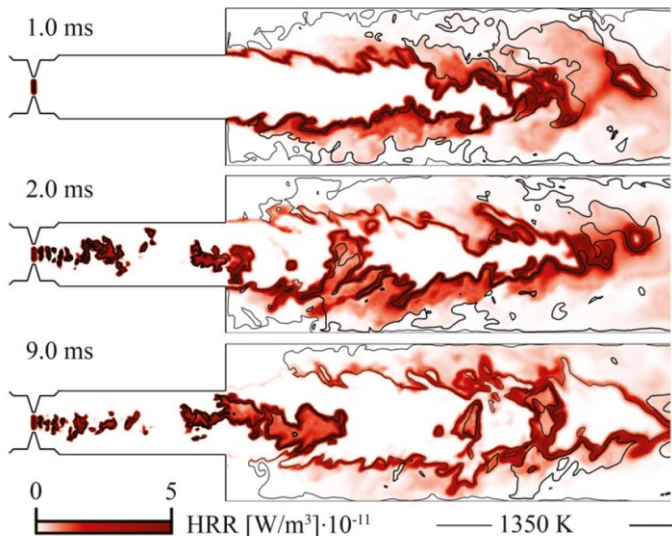
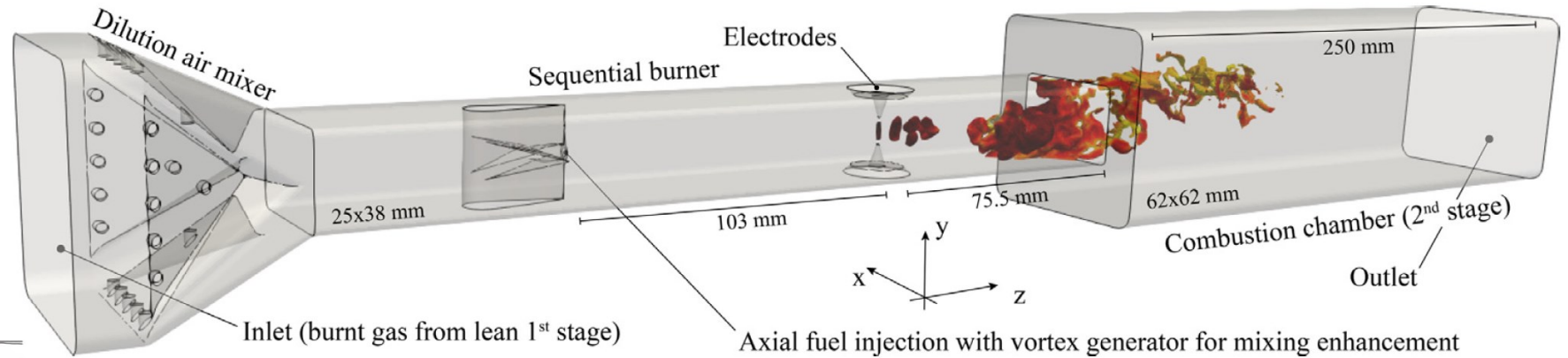
- In turbulent flow, similar ignition results than in hydrocarbon fuels

Carbon-Free Fuels



Plasma-assisted ignition of hydrogen

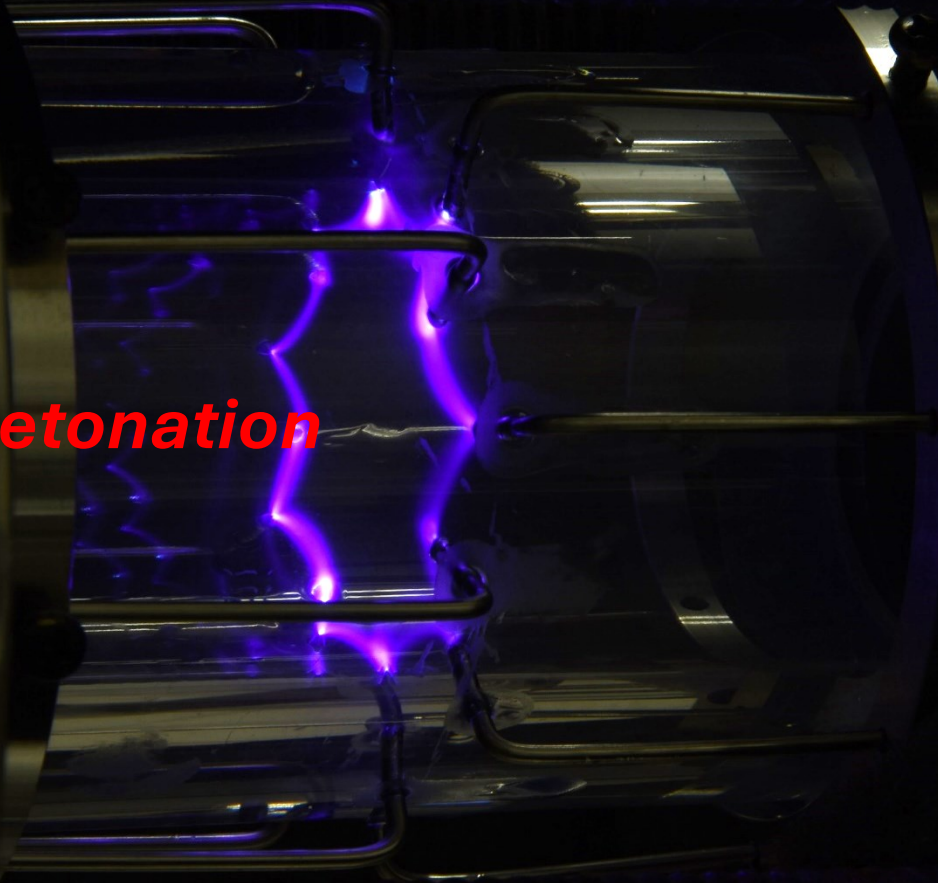
- NRP discharges for PAC in a sequential combustor fed with H₂-CH₄ mixtures
- LES with phenomenological model



- Experimental results reproduced, validating LES + Castela's model to capture PAC in a sequential combustor
- Reveals that ignition kernels are initiated almost instantaneously after each discharge

Chapter IX: Recent Results & Questions

- *Carbon-Free Fuels*
- ***Plasma-Assisted Detonation***
- *Three-Phase Flows*
- *References*

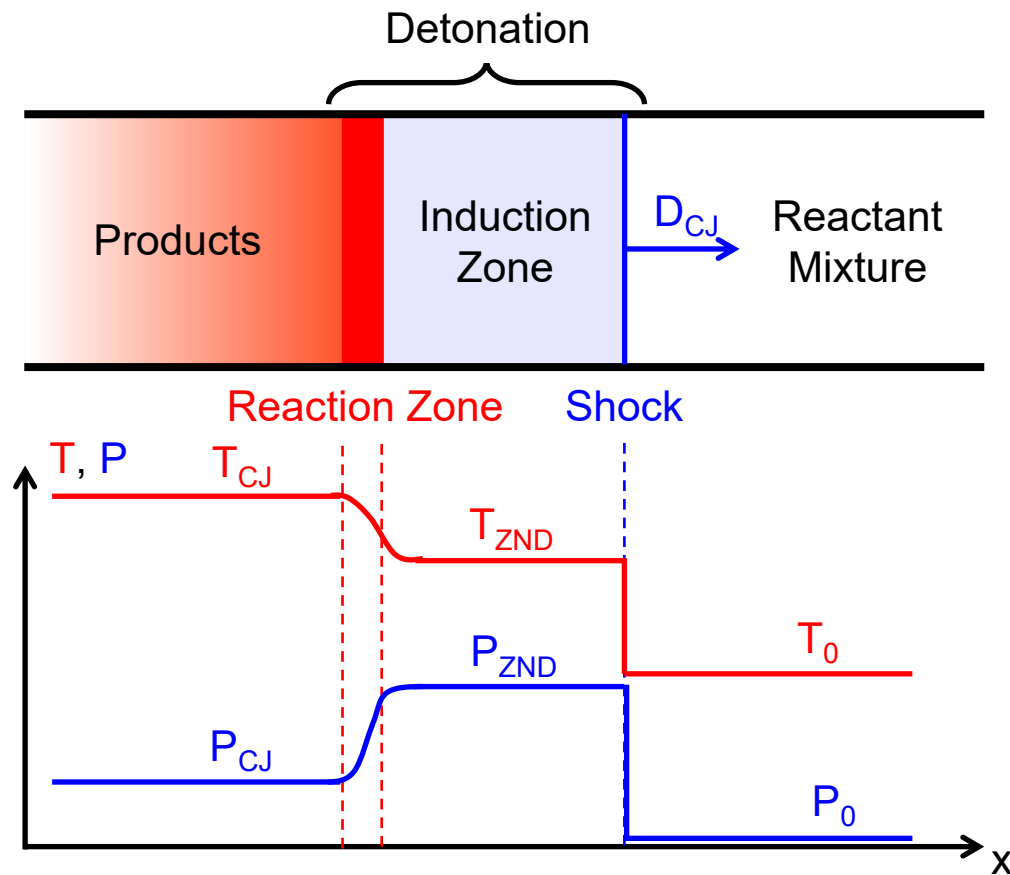


Plasma-Assisted Detonation



What is a detonation?

- A detonation is a combustion front that is coupled with a shock, and propagates at $\text{Mach} > 1$



Conditions to obtain a detonation depend on:

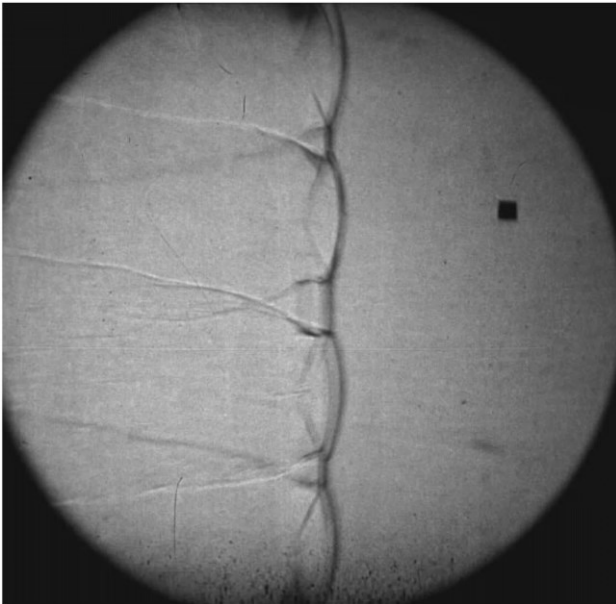
- Reactant mixture
- Duct/apparatus dimensions
- Initiation method (Direct vs Transition to)

Plasma-Assisted Detonation

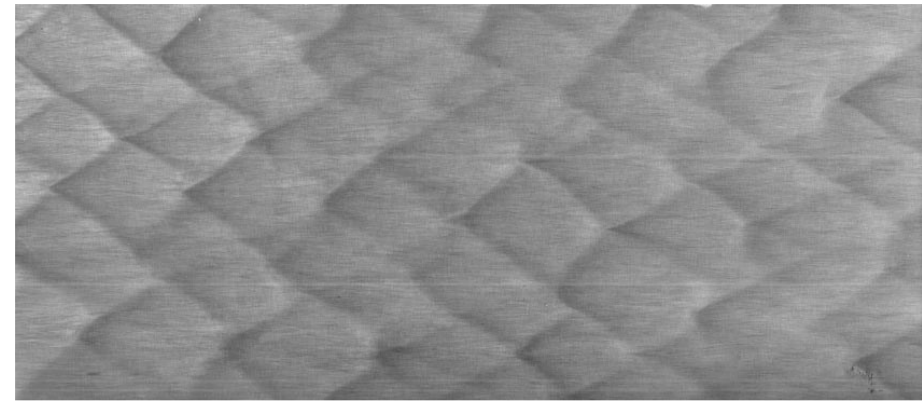


What is a detonation?

- The real detonation structure is 3D



*Schlieren visualization
Austin, PhD thesis, 2003*



*Soot foil measurements: detonation footprint
Austin, PhD thesis, 2003*

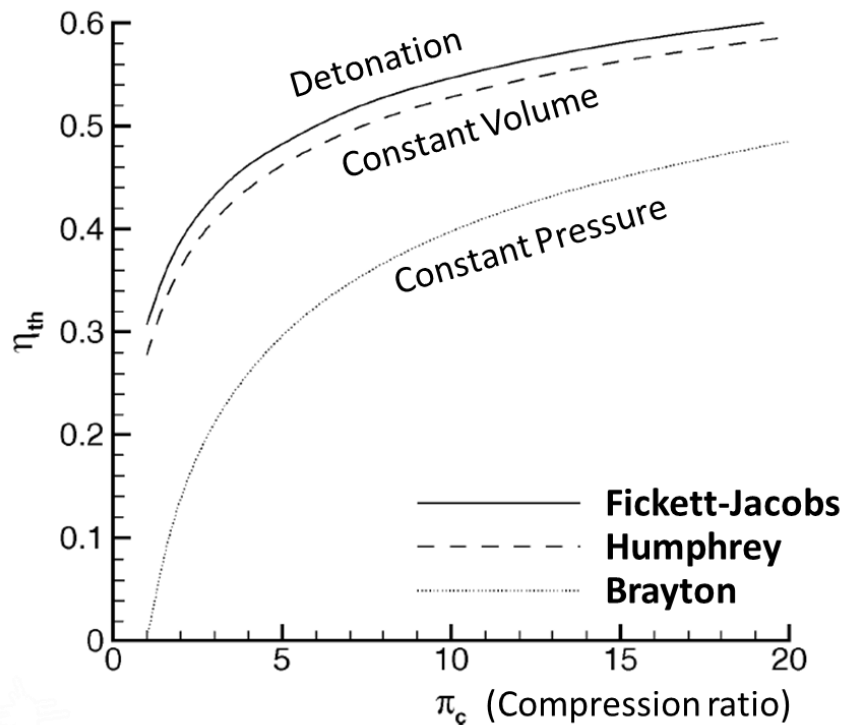
→ Detonation structure results from the shock-dynamics and chemistry coupling

Plasma-Assisted Detonation



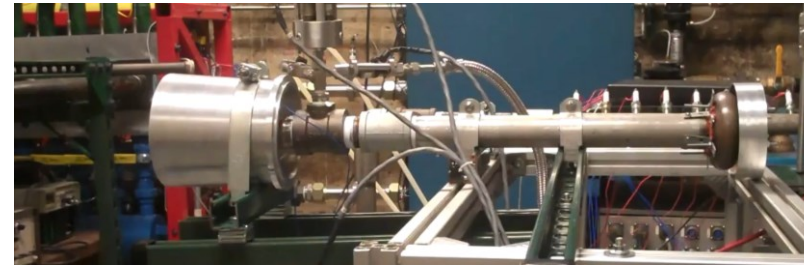
Detonation engines are under development

- Thermodynamic cycles based on detonations have high thermal efficiency



Adapted from Forman, 1985

Pulse Detonation Engines (PDE)



Adapted from UC.Detlab, Youtube Channel

Rotating Detonation Engines (RDE)



Adapted from Bohon, TU Berlin, Youtube channel

Plasma-Assisted Detonation

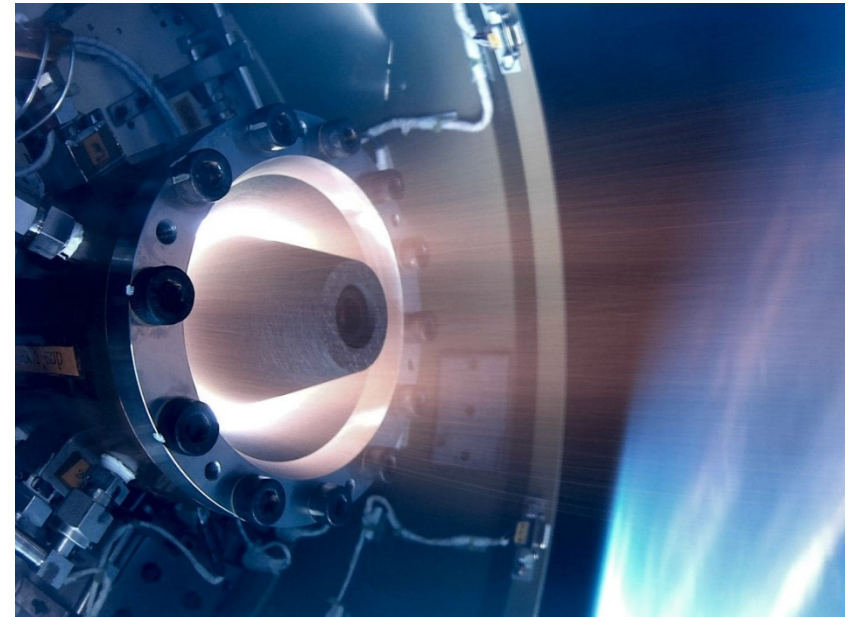


Three main types of plasma-assisted detonation studies

1. Ignition of detonation tube or engine
2. Enhancement of DDT
3. Enhancement of detonation properties

Types of electrical actuation tested

1. Electric field (no plasma)
2. NRP discharges
3. Sparks (μs)
4. Arcs
5. DBD



Nagoya University / JAXA

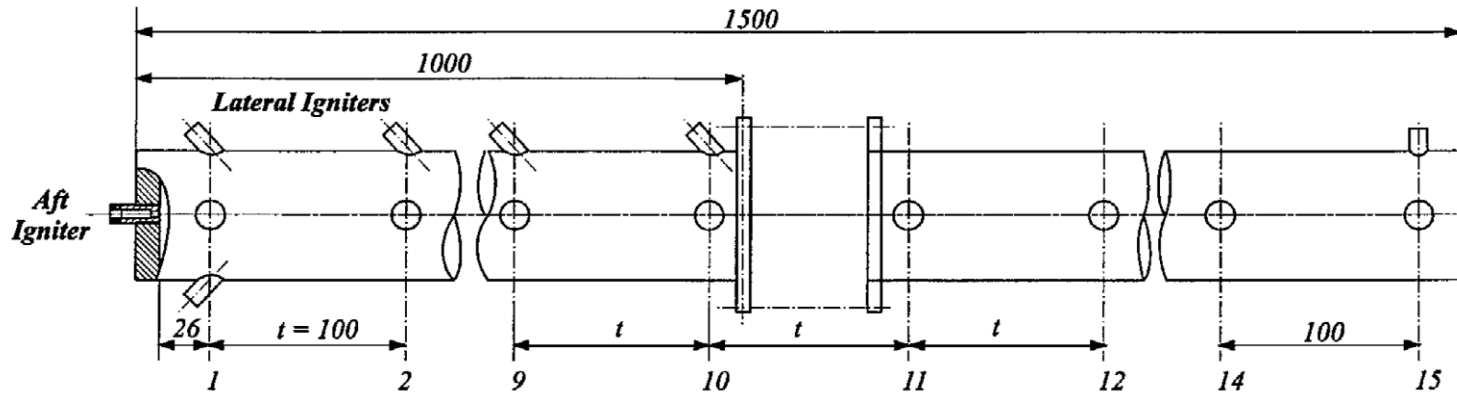
Many studies are not published in scientific journals due to proximity with defense applications/funding



Plasma-Assisted Detonation

2000's First studies on plasma-assisted detonation

- Detonation initiation by controlled triggering of spark discharges



Booster Section

Test Section

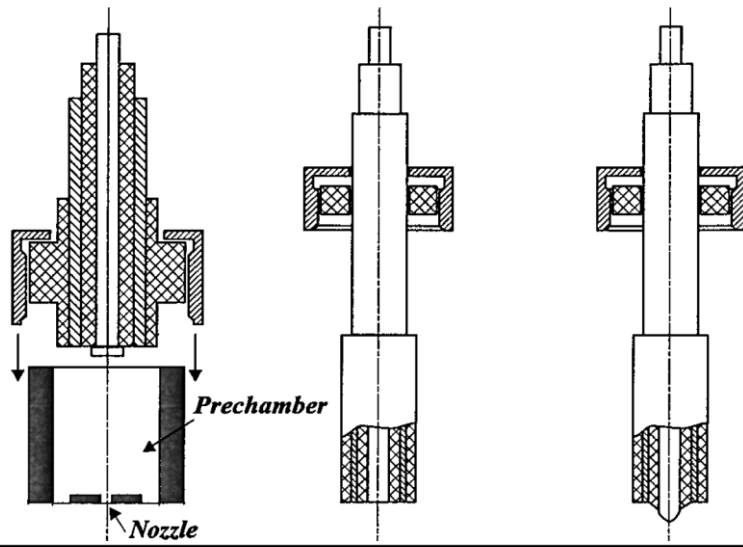


Table 2 Effect of capacitor voltage on accelerating a shock wave in the stoichiometric propane–oxygen-enriched air mixture

Capacitor voltage, V	Velocity, m/s		No. of capacitors (100 μ F)	Remarks ^c
	Base 1 ^a	Base 2 ^b		
2500	1767	1805	9	Detonationlike mode
2300	1606	1748	9	Marginal detonationlike mode
2100	565	648	9	No detonationlike mode

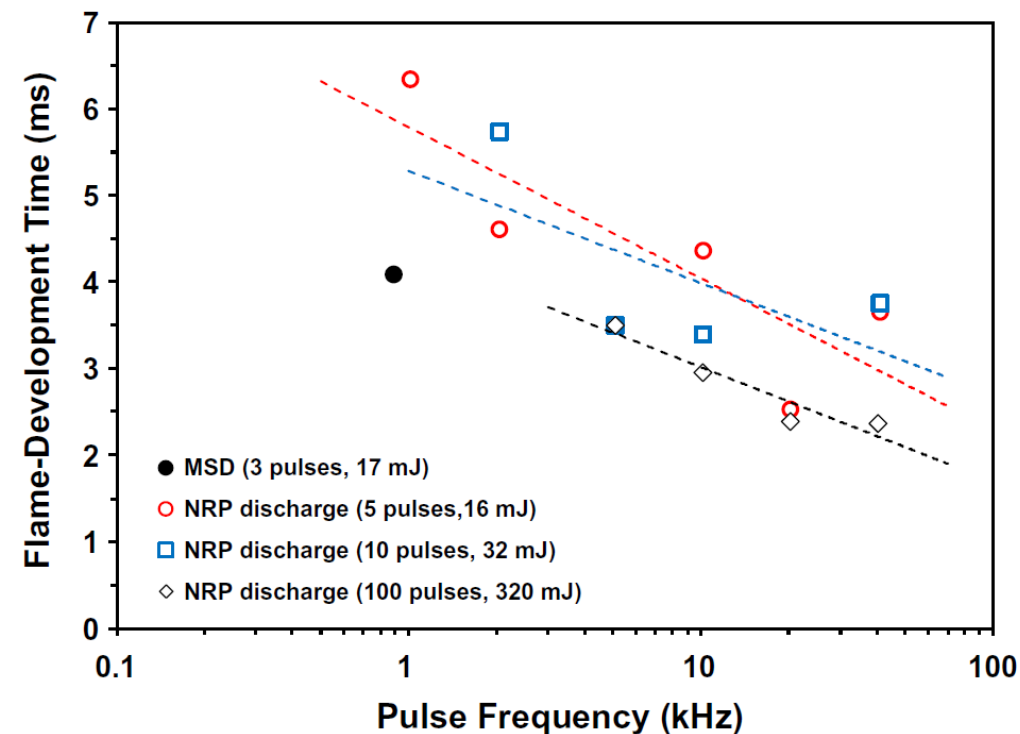
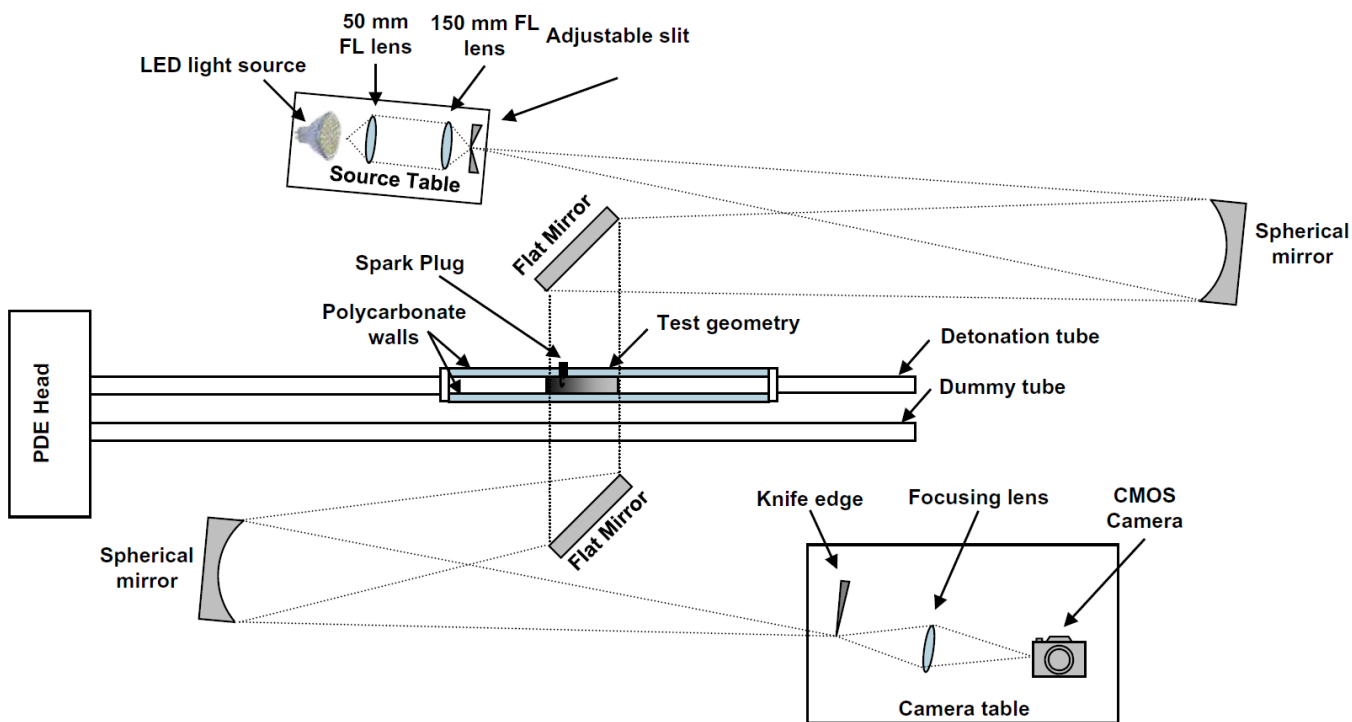
Frolov et al., *J. Propulsion Power*, 2003



Plasma-Assisted Detonation

Ignition of a pulsed detonation engine (PDE) by NRP discharges

- Comparisons of NRP discharges with multiple spark discharges (μs)
- Methane-air mixture at atmospheric pressure



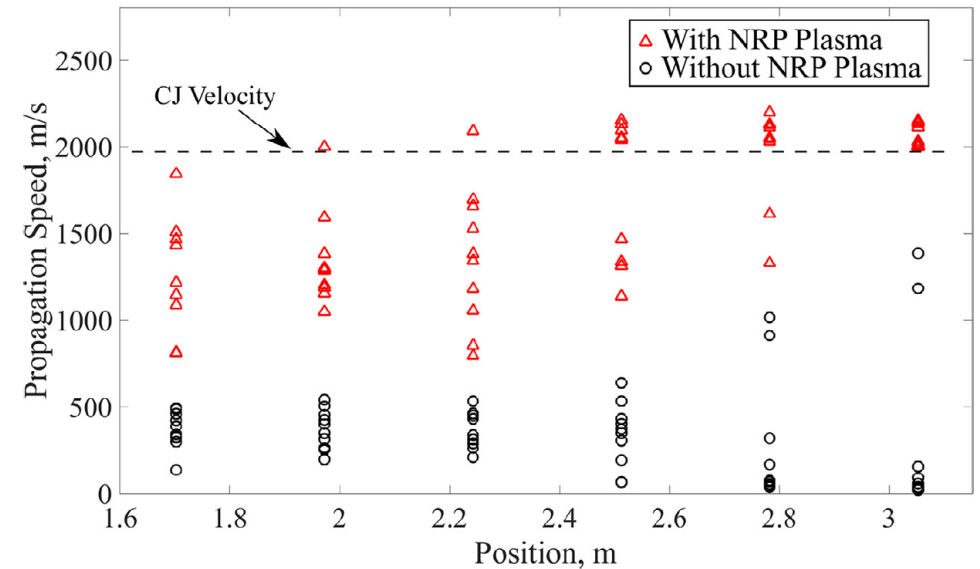
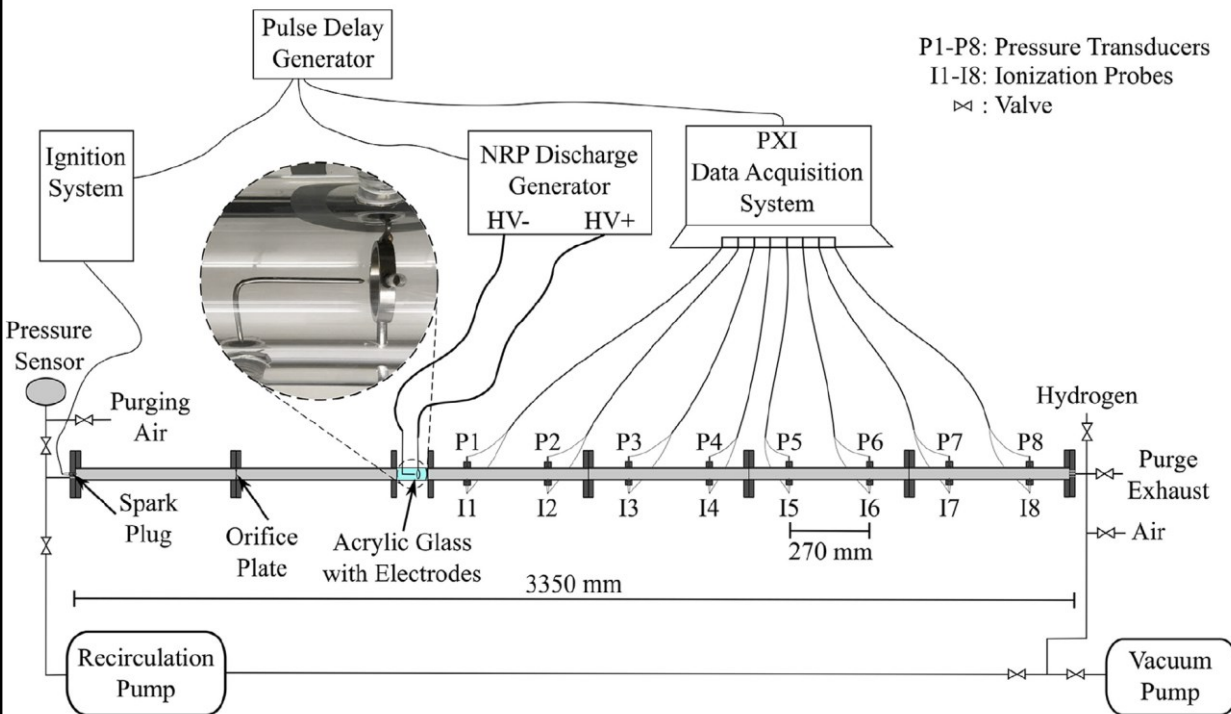
- For a same energy deposition, the flame development time is shorter the higher the PRF

Plasma-Assisted Detonation



Enhancement of Deflagration-to-Detonation Transition (DDT) by NRP discharges

- Stoichiometric hydrogen-air mixture at atmospheric pressure
- Pin-ring electrodes in the center of the tube



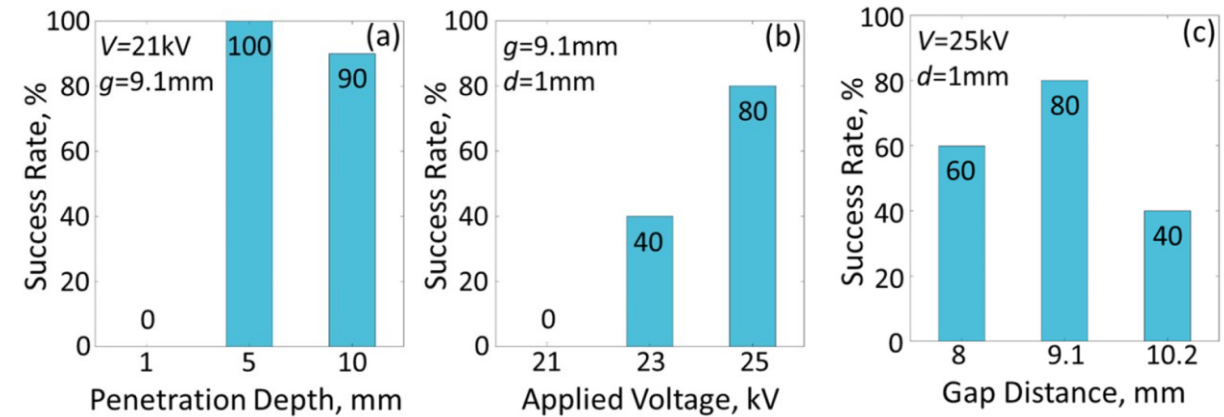
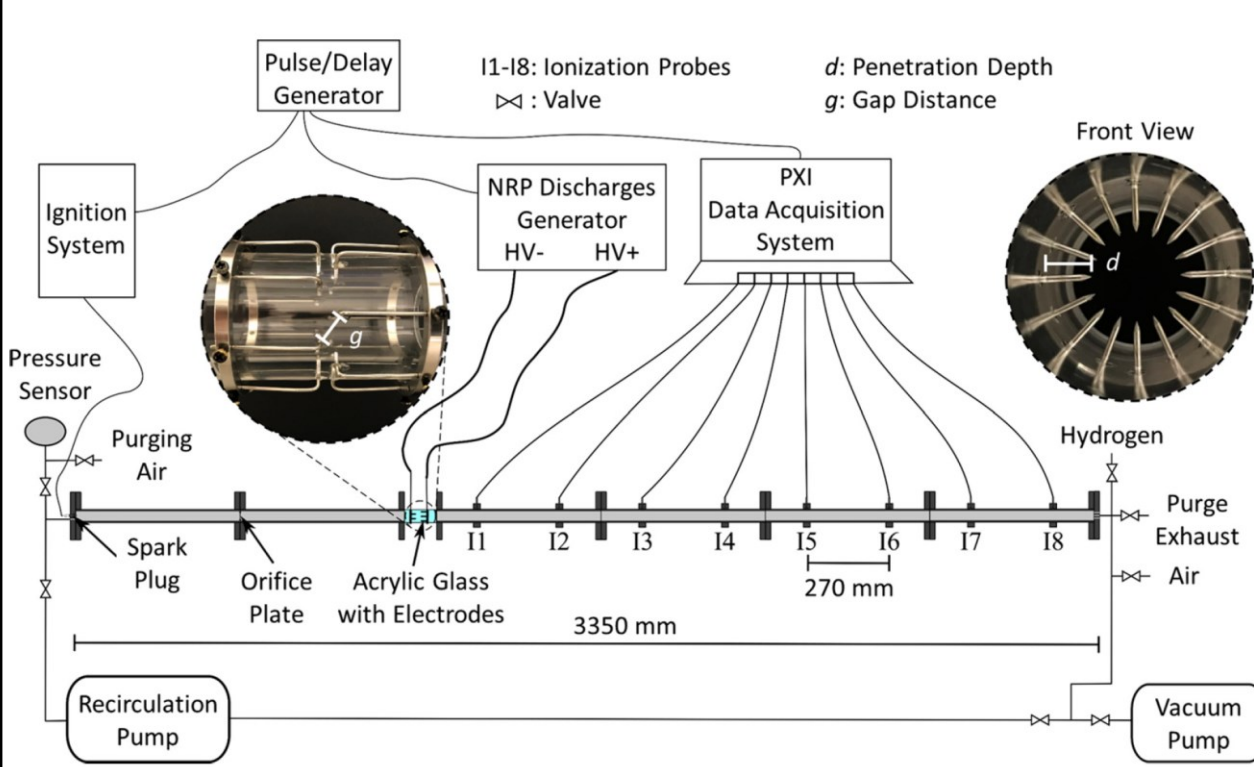
- Split electrical energy into ignition and flame acceleration is efficient in enhancing DDT
- No need for precise synchronization
- Large PRF (100 kHz) better than low PRF (30 kHz)

Plasma-Assisted Detonation



Enhancement of Deflagration-to-Detonation Transition (DDT) by NRP discharges

- Stoichiometric hydrogen-air mixture at atmospheric pressure
- **Electrodes near the tube wall**



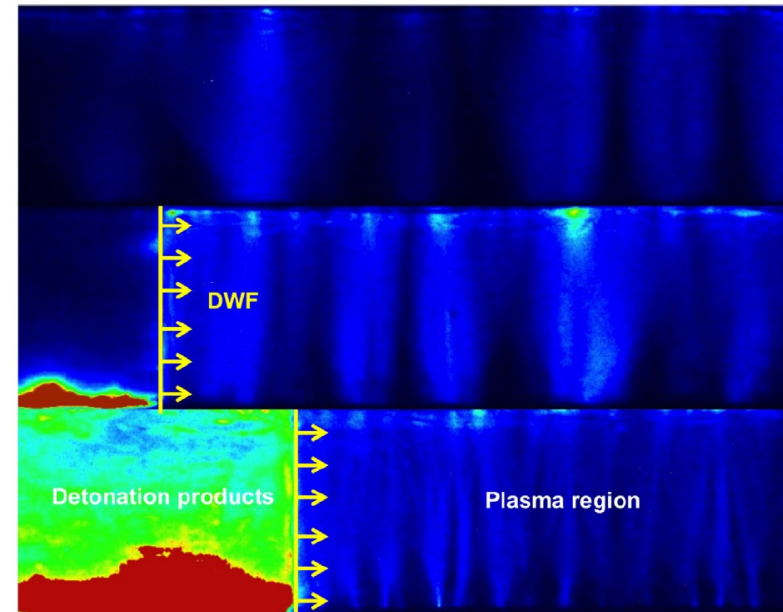
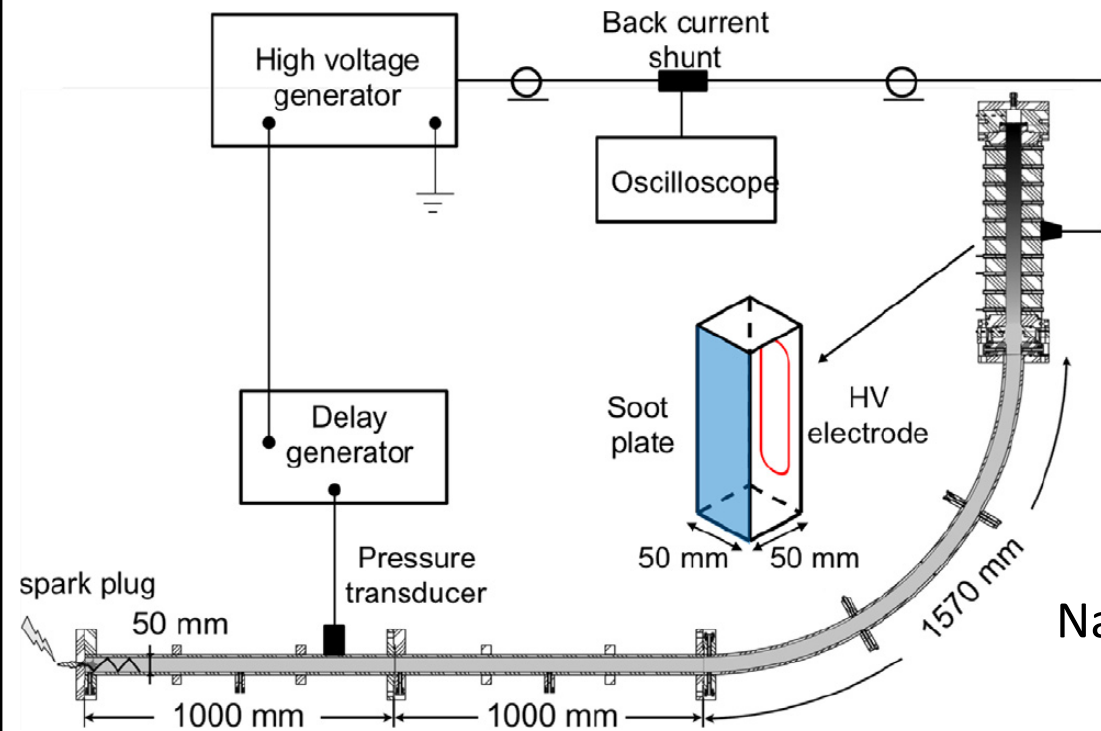
- Enhancing DDT with discharges near the wall is harder than with discharges in the middle
- Different enhancement mechanisms

Plasma-Assisted Detonation



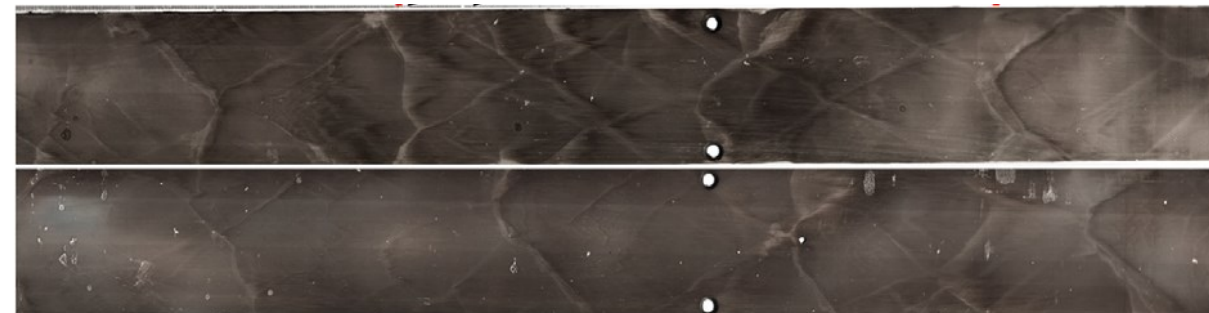
Effect of nonequilibrium plasma on developed detonations

- Decrease of the cell size of CH_4 and $\text{CH}_4:\text{H}_2$ detonations ($T = 295 \text{ K}$, $P < 0.2 \text{ bar}$) by nanosecond discharges



Nanosecond discharges

No plasma



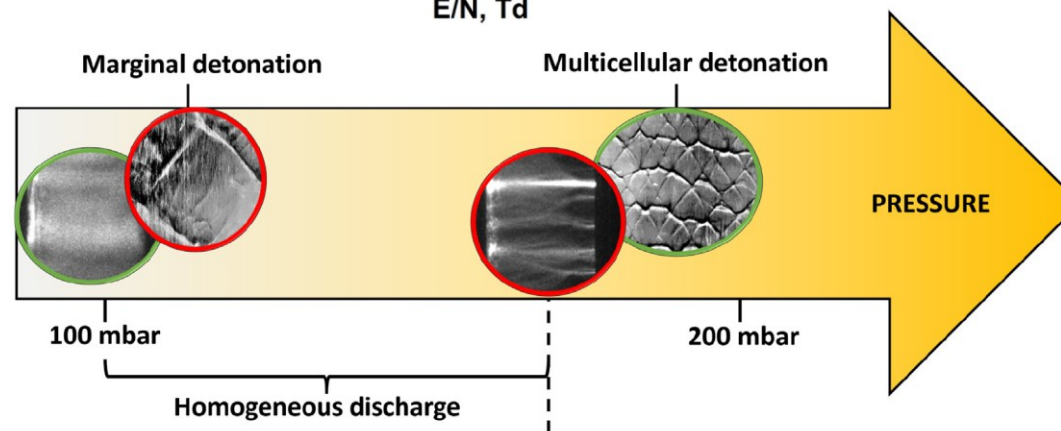
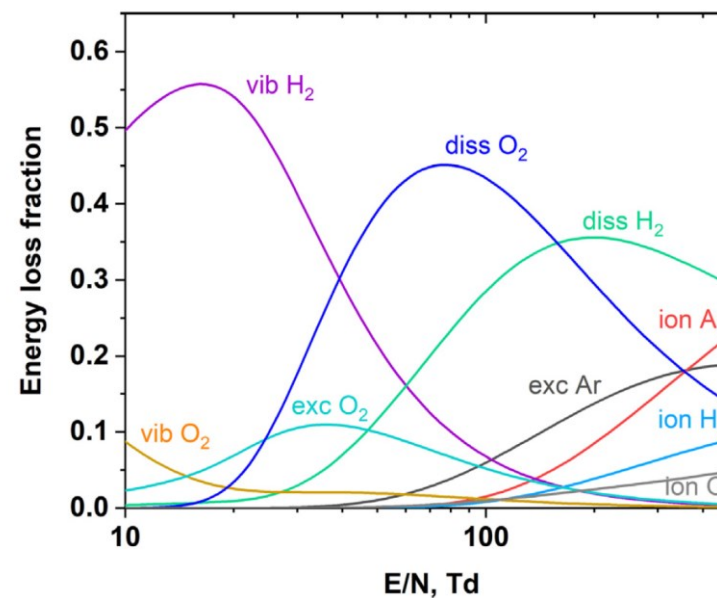
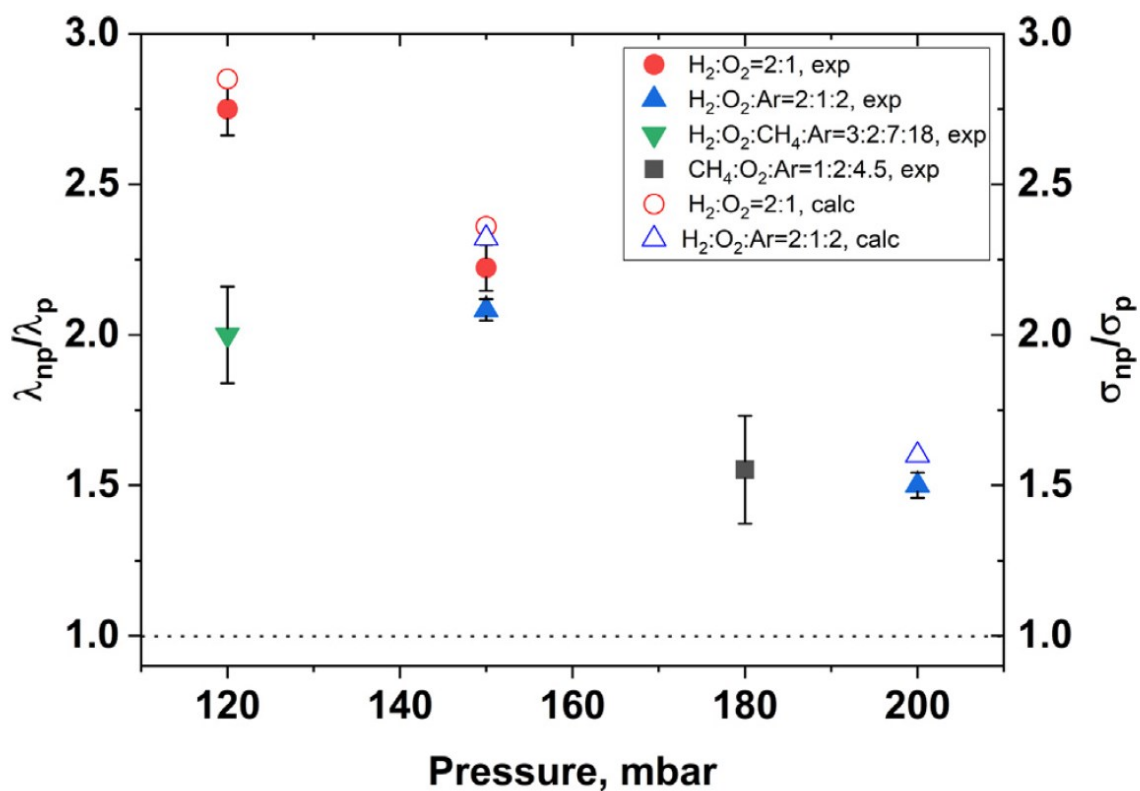
120mbar $\text{O}_2:\text{Ar}:\text{CH}_4:\text{H}_2$ (7:8:3:2)

Plasma-Assisted Detonation



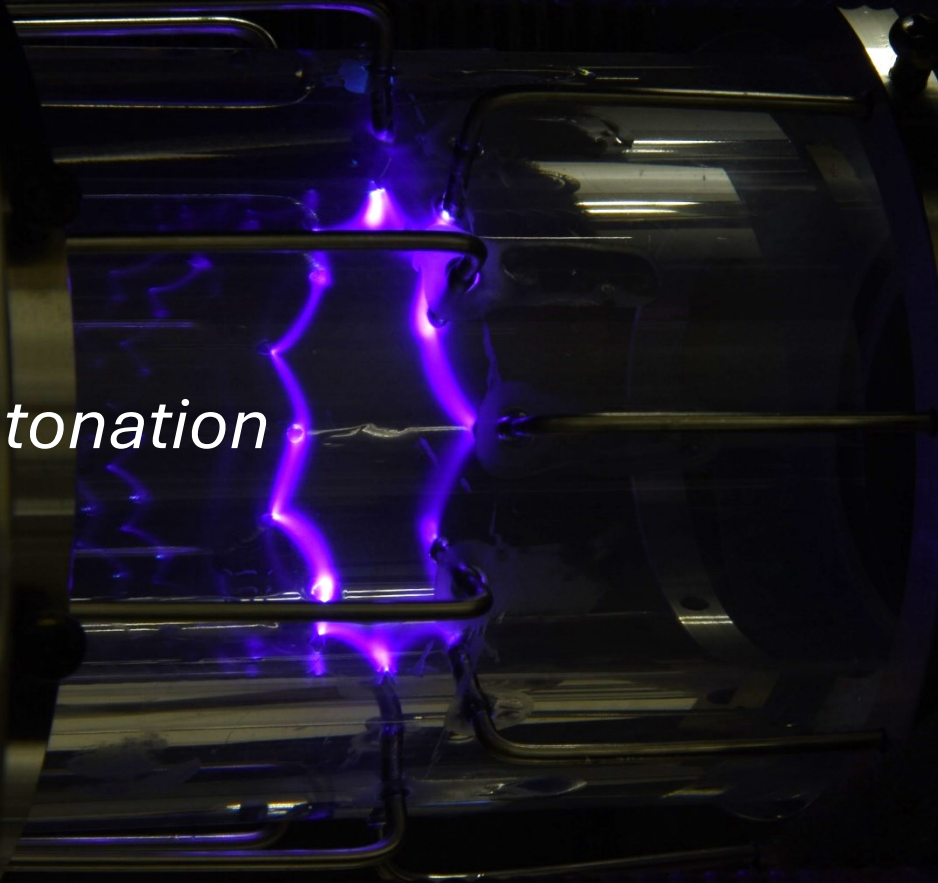
Effect of nonequilibrium plasma on developed detonations

- Understanding of the plasma effect with 0D (plasma) and 1D (ZND) simulations



Chapter IX: Recent Results & Questions

- *Carbon-Free Fuels*
- *Plasma-Assisted Detonation*
- ***Three-Phase Flows***
- *References*

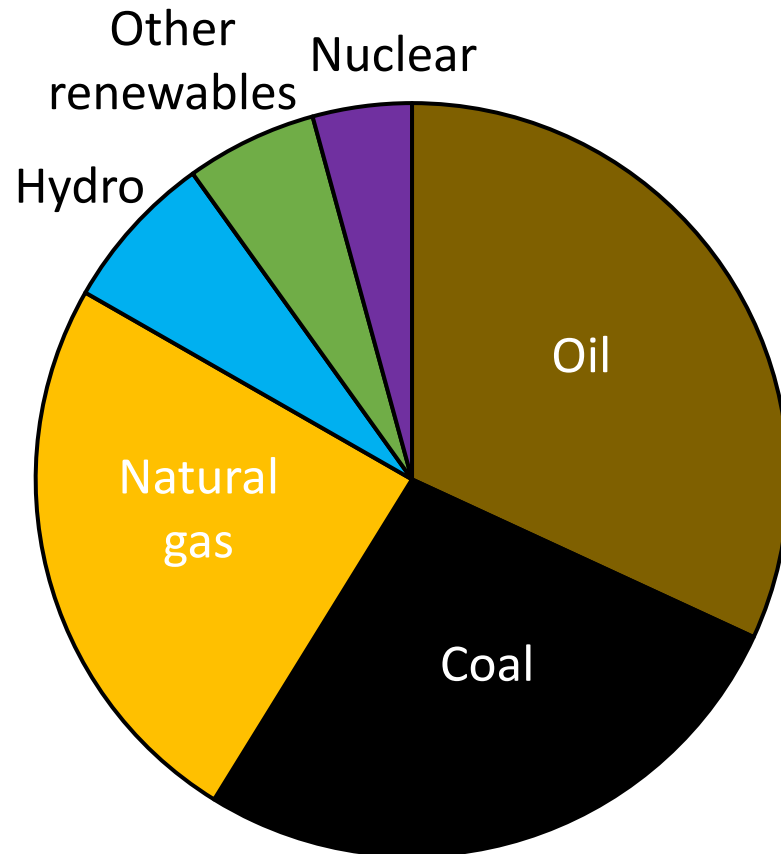




Three-Phase Flows

Liquid/solid fuels and nonequilibrium plasma

- World total primary energy consumption by type in 2020



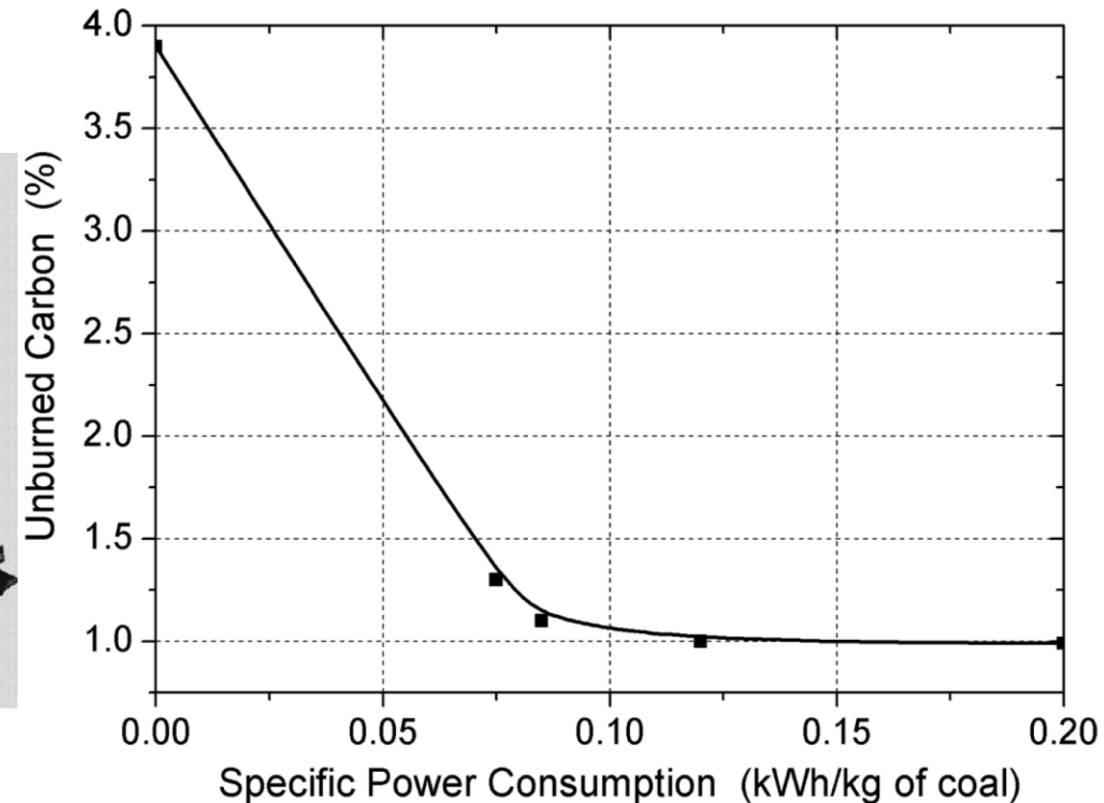
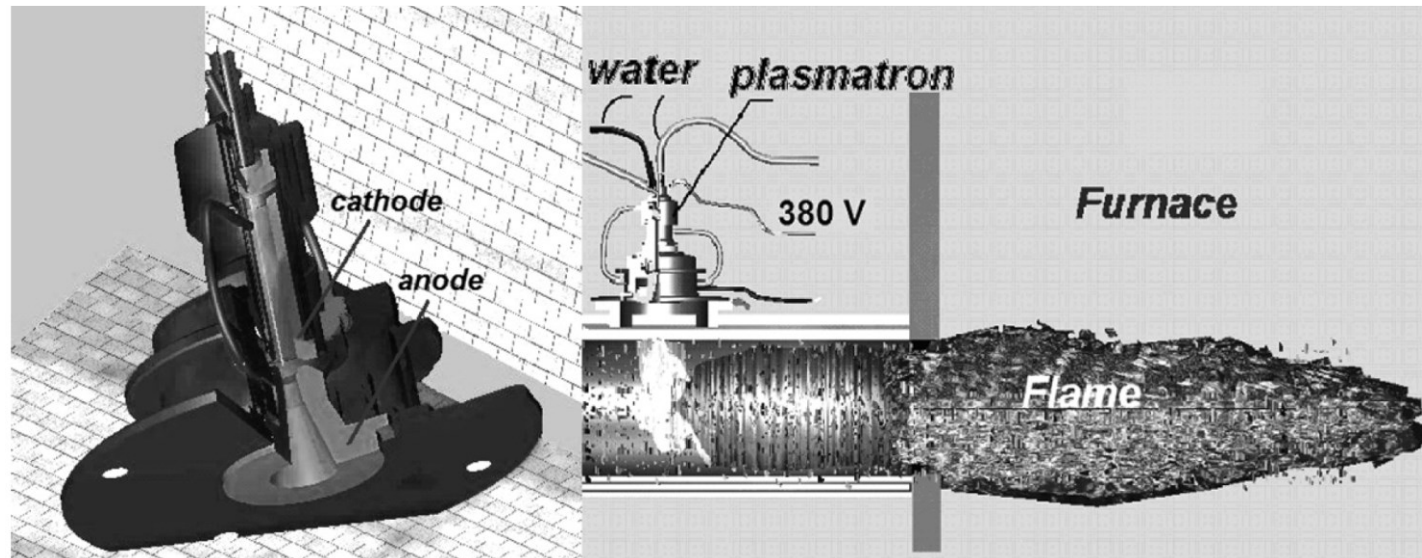
- 70% of the fuels used in combustion systems are solid or liquid
- Less than 10% of PAC studies use liquid or solid fuels



Three-Phase Flows

2007: Plasma-assisted coal combustion

- Enhancement of pulverized coal combustion by plasma technology
- Arc discharge is used in a rich coal-air flow to produce CO and increase the temperature, helping in stabilizing a flame in the furnace
- Experimental and numerical study

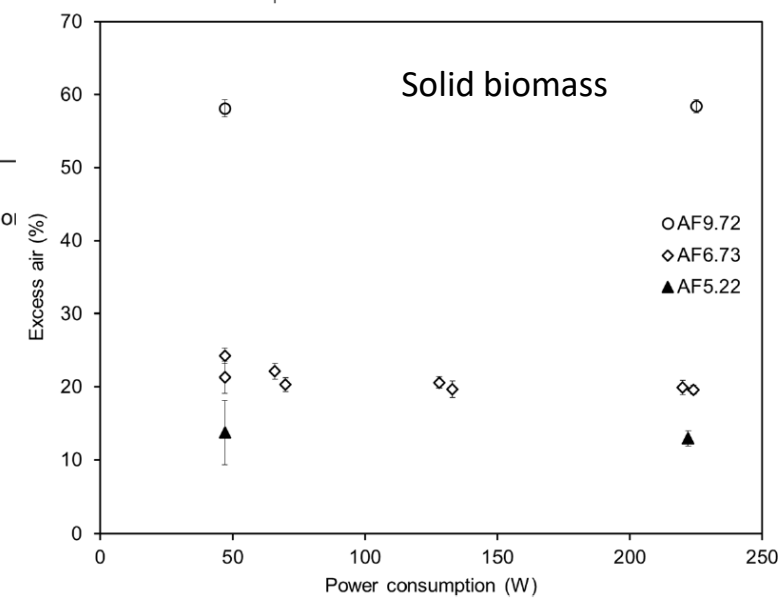
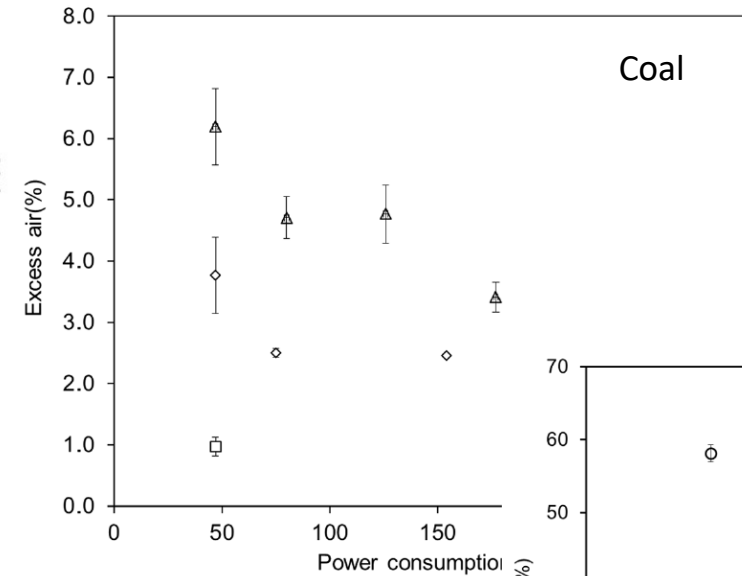
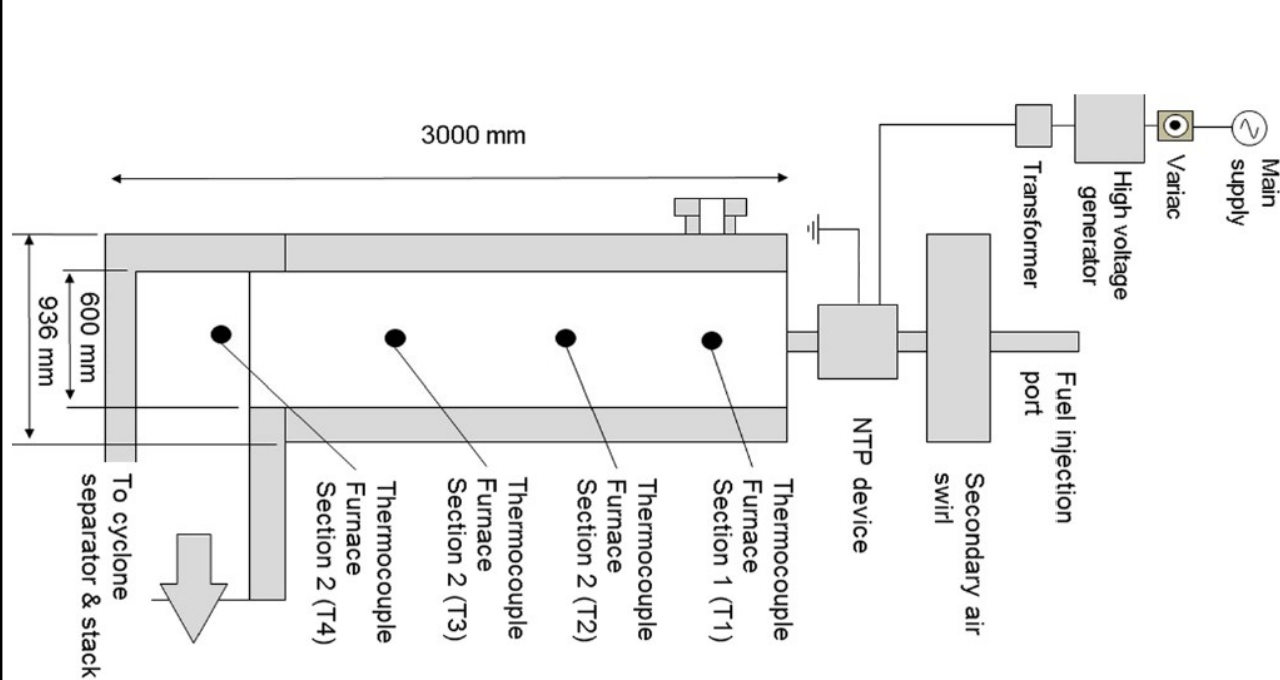




Three-Phase Flows

Plasma-assisted combustion of solid biomass and coal

- Effects on flue gas composition and efficiency
- 2 kW DBD reactor used to produce ozone in a 150-kW furnace

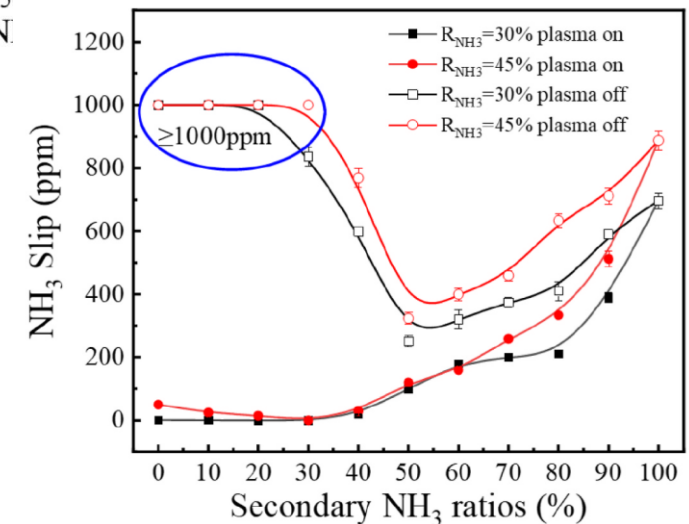
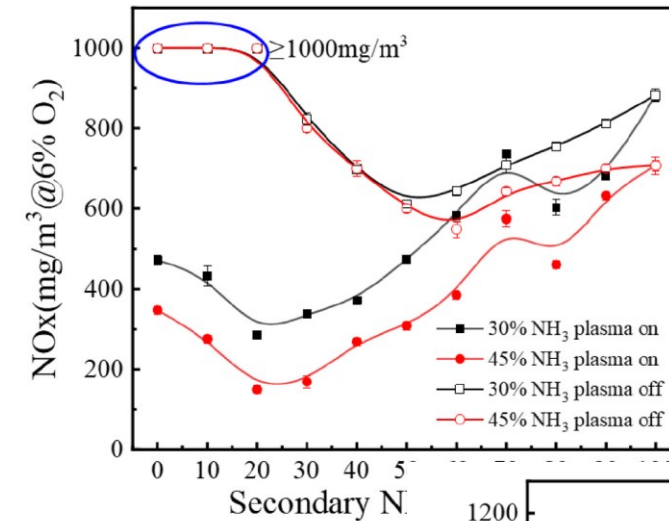
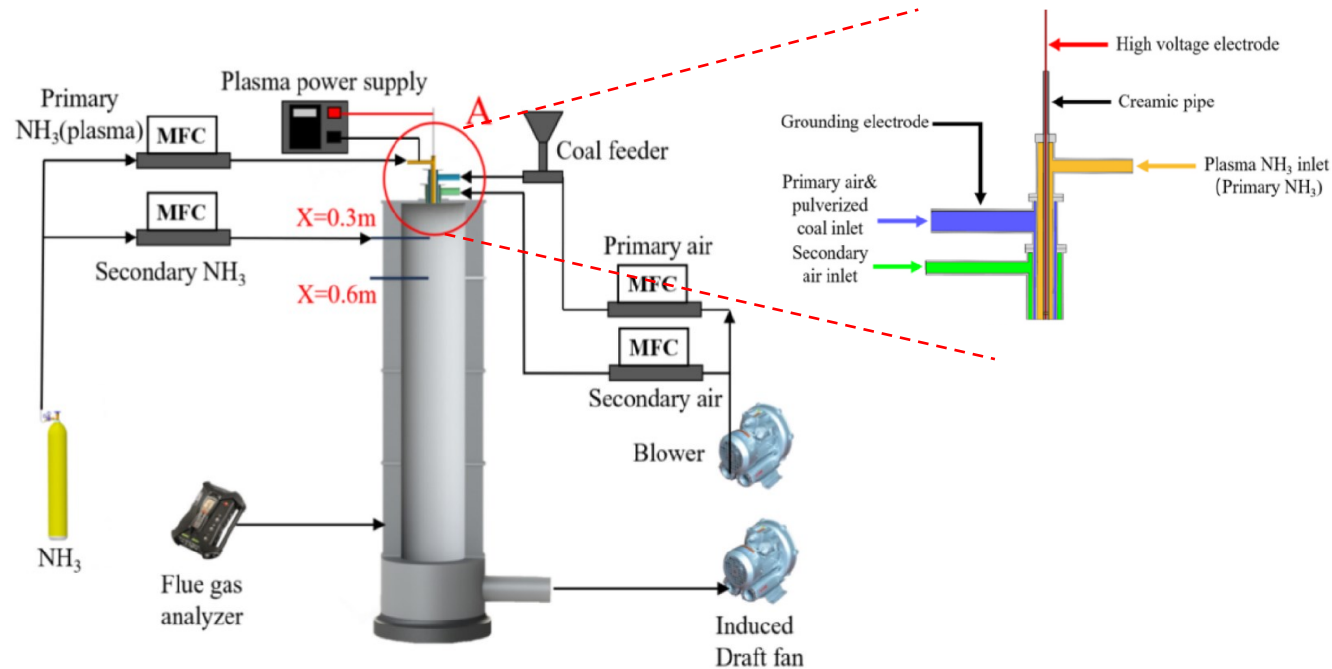




Three-Phase Flows

Plasma-assisted ammonia-coal co-combustion

- Synergistic NO_x reduction: Roles of staging ratio and injection position
- DBD reactor on the NH₃ stream

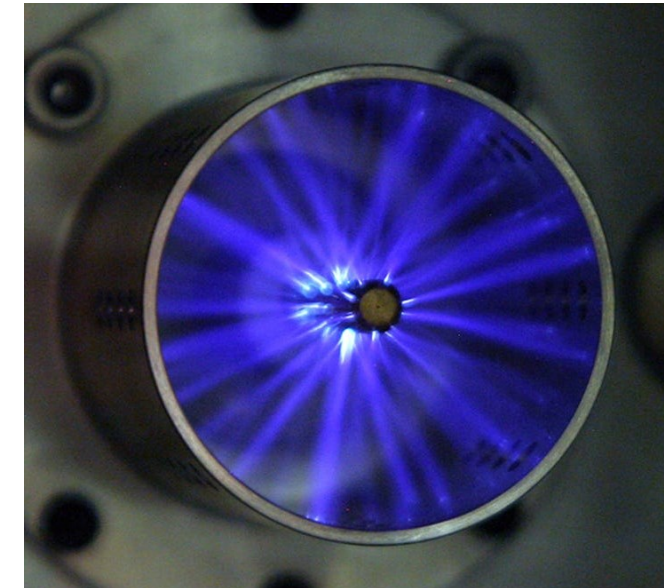
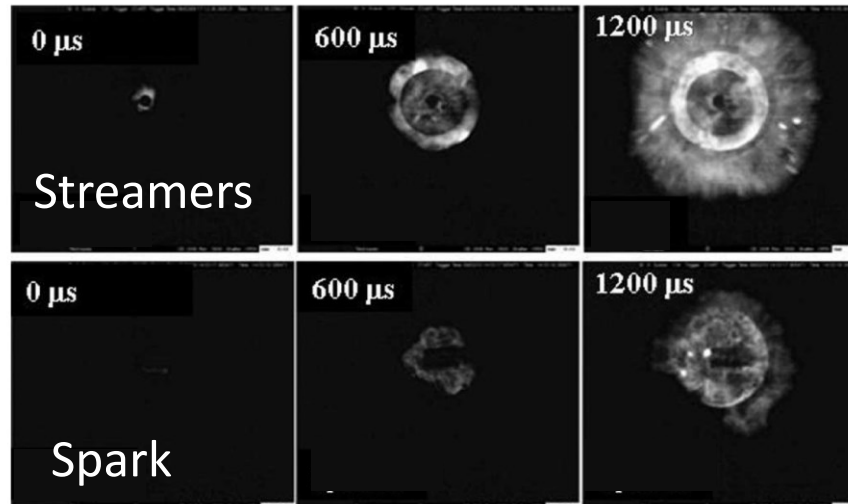
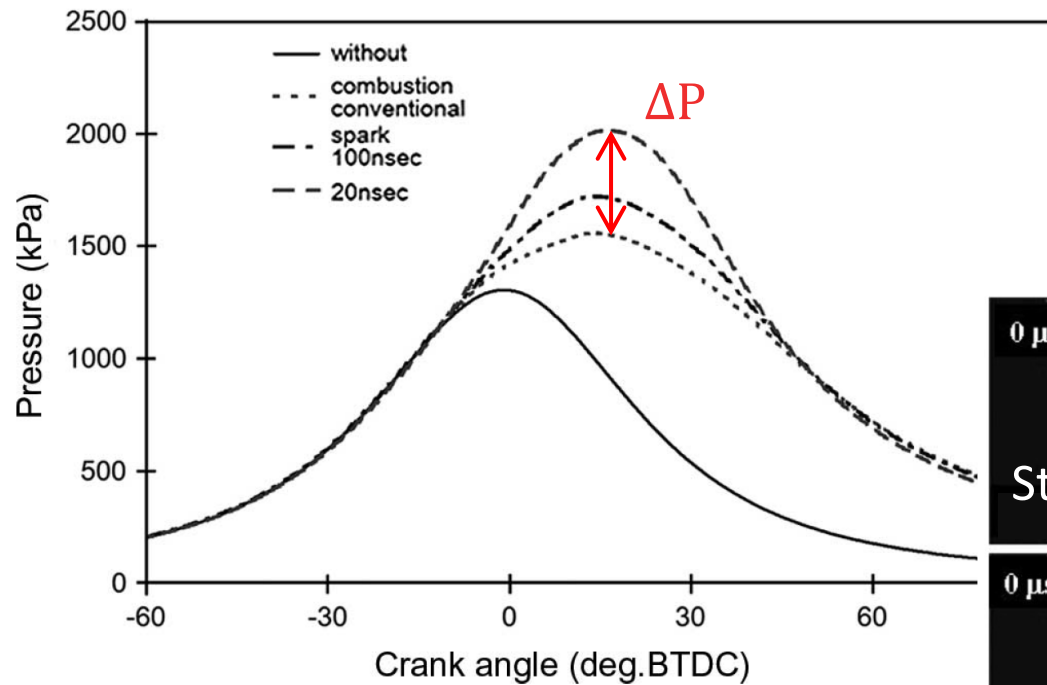




Three-Phase Flows

2007: Plasma-assisted ignition of gasoline IC engines

- Comparison of different nanosecond-discharge configurations: spark, DBD, streamers
- Single cylinder SI engine: tests with isoctane



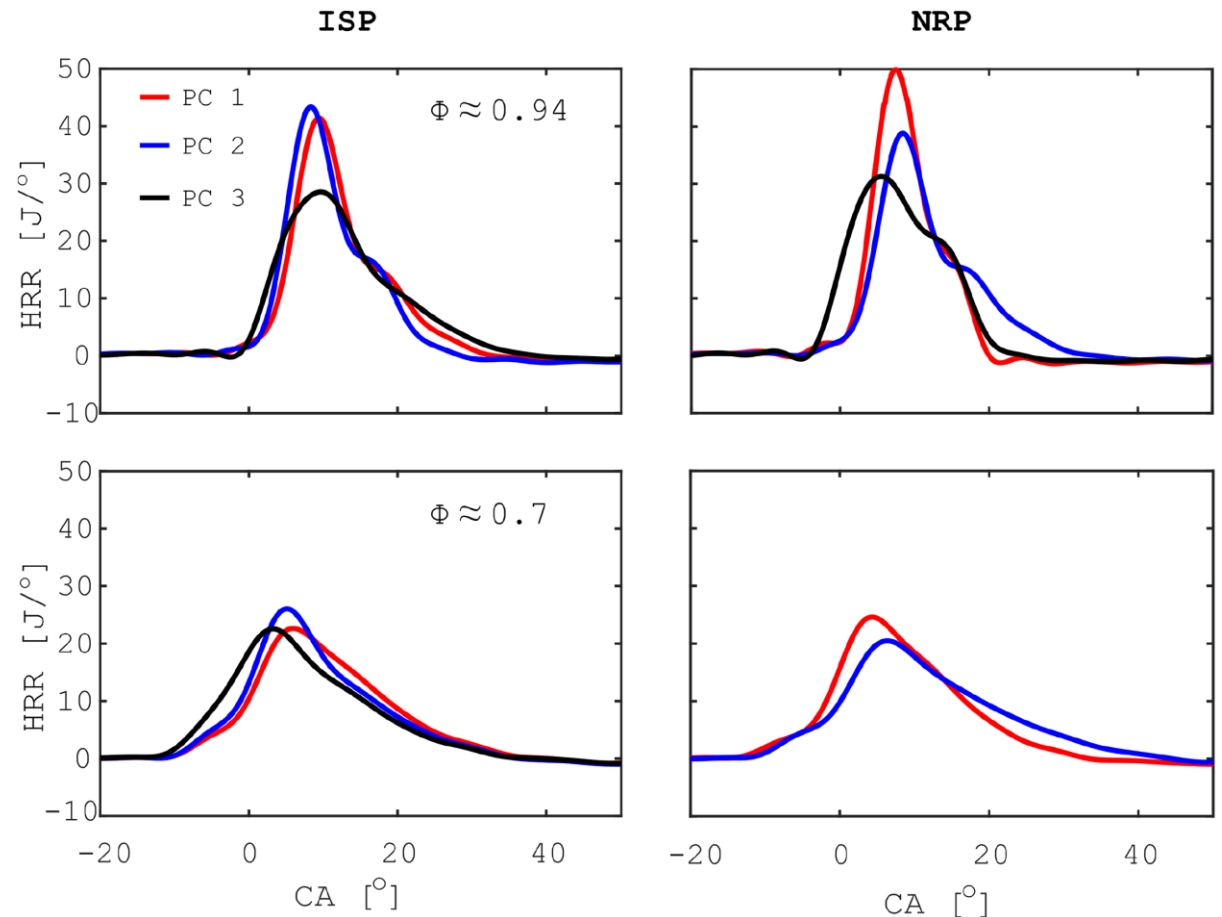
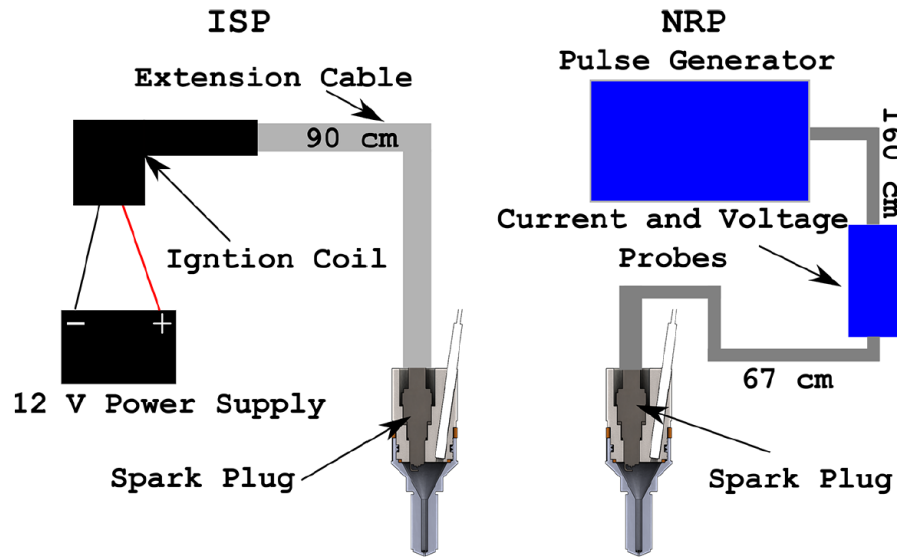
www.tpsignition.com



Three-Phase Flows

Plasma-assisted ignition of gasoline IC engines

- Coupling between nanosecond discharges and prechambers
- Single cylinder SI engine: tests with research grade gasoline (RD5-87)

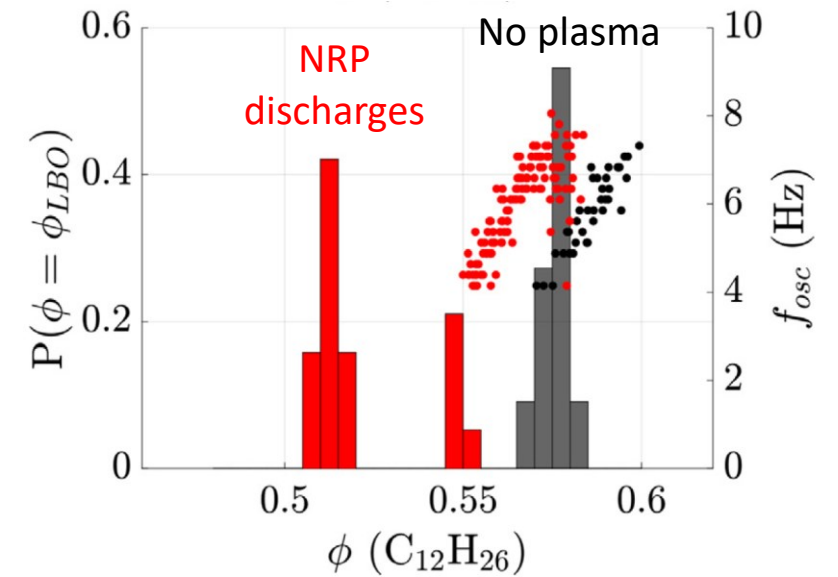
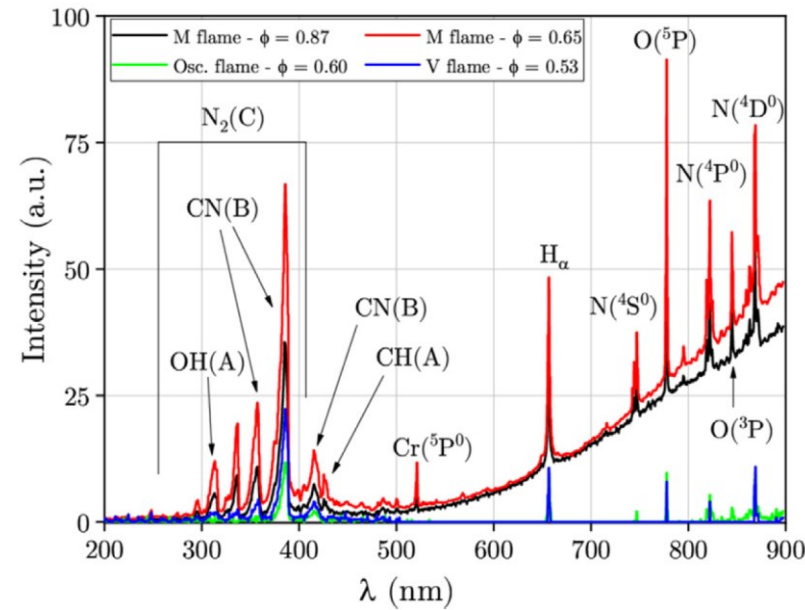
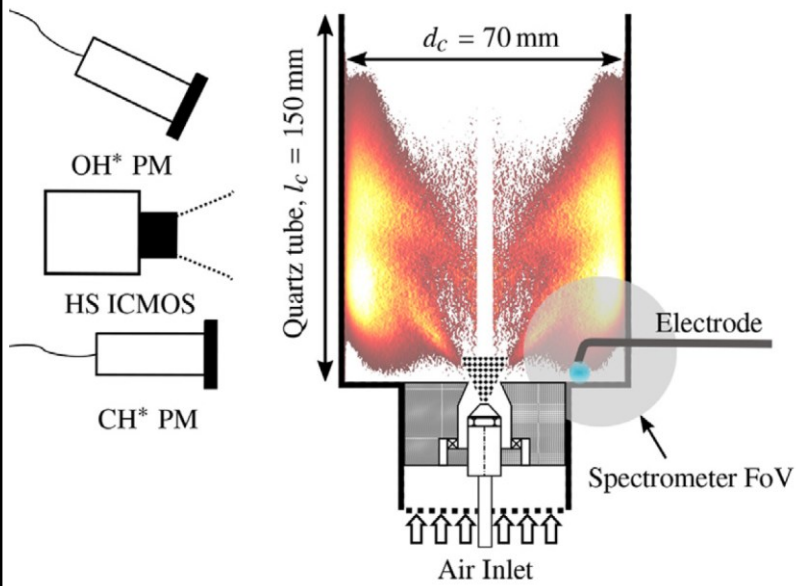




Three-Phase Flows

Plasma-assisted combustion of spray swirl flames

- Improvement of lean blow out performance with NRP discharges
- Swirl burner of n-heptane & dodecane, with discharges in the outer recirculation zone

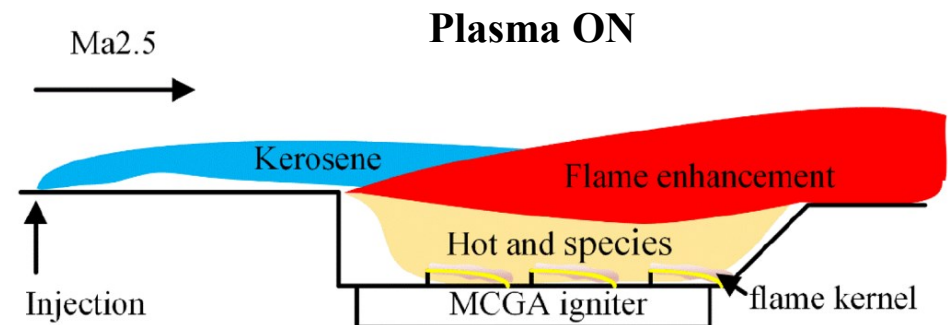
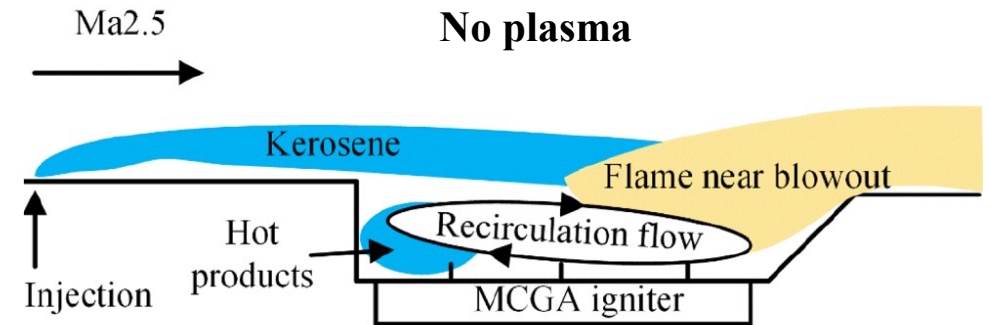
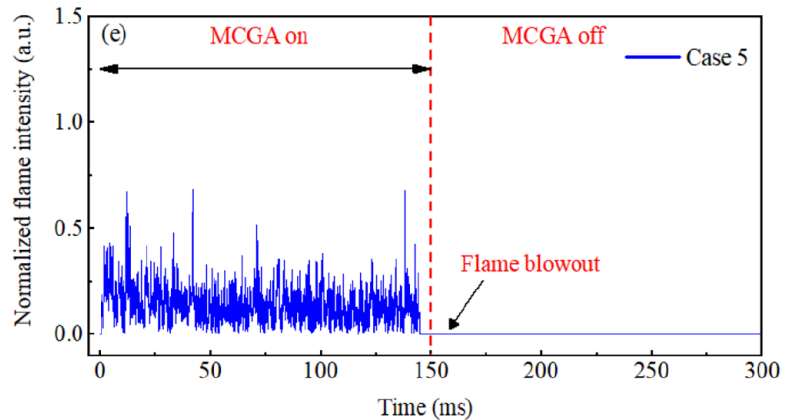
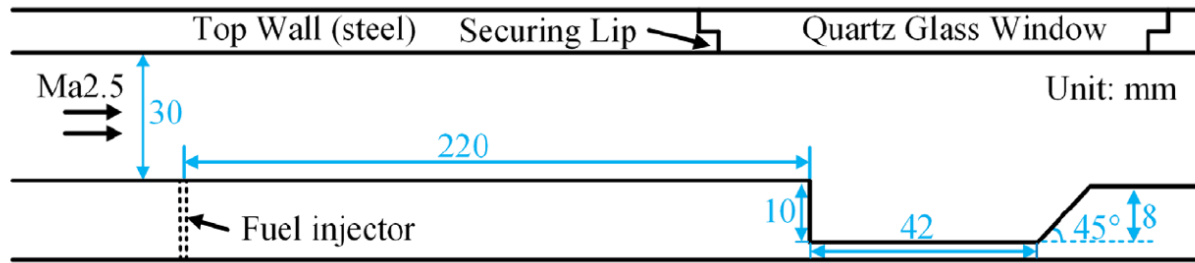




Three-Phase Flows

Plasma-assisted combustion of spray kerosene-fueled scramjet

- Multi channel gliding arc (MCGA) discharges to enhance flame holding in a cavity-based scramjet (inlet airflow at Mach 2.5)
- Injection pressure: 0.16 – 1.91 MPa



References



Paper

- D.A. Lacoste, *Flames with plasmas*, *Proc. Combust. Inst.* 39, 5405-5428, 2023
- C.O. Laux, J.-B. Perrin-Terrin, V. Lafaurie, S.M. Starikovskaia, *Foundations of plasma-assisted combustion: II. Mechanisms and applications*, *Plasma Sources Sci. Technol.* 35, 023002, 2026

Website

- D.A. Lacoste, *Plasma Assisted Ammonia Flames*, YouTube video: <https://www.youtube.com/watch?v=chYQmXIRx0k>
- Flight CO2 footprint calculator: https://co2.myclimate.org/en/flight_calculators/new

Book

- *Plasma Assisted Combustion and Chemical Processing*, Yiguang Ju & Andrey Starikovskiy, CCRC Press, Taylor and Francis Group, Boca Raton, FL, USA, 2025



清华大学燃烧能源中心
Center for Combustion Energy