Chapter 8: High-speed Laser Combustion Diagnostics – General Aspects

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Mechanical Engineering – Reactive Flows and Diagnostics

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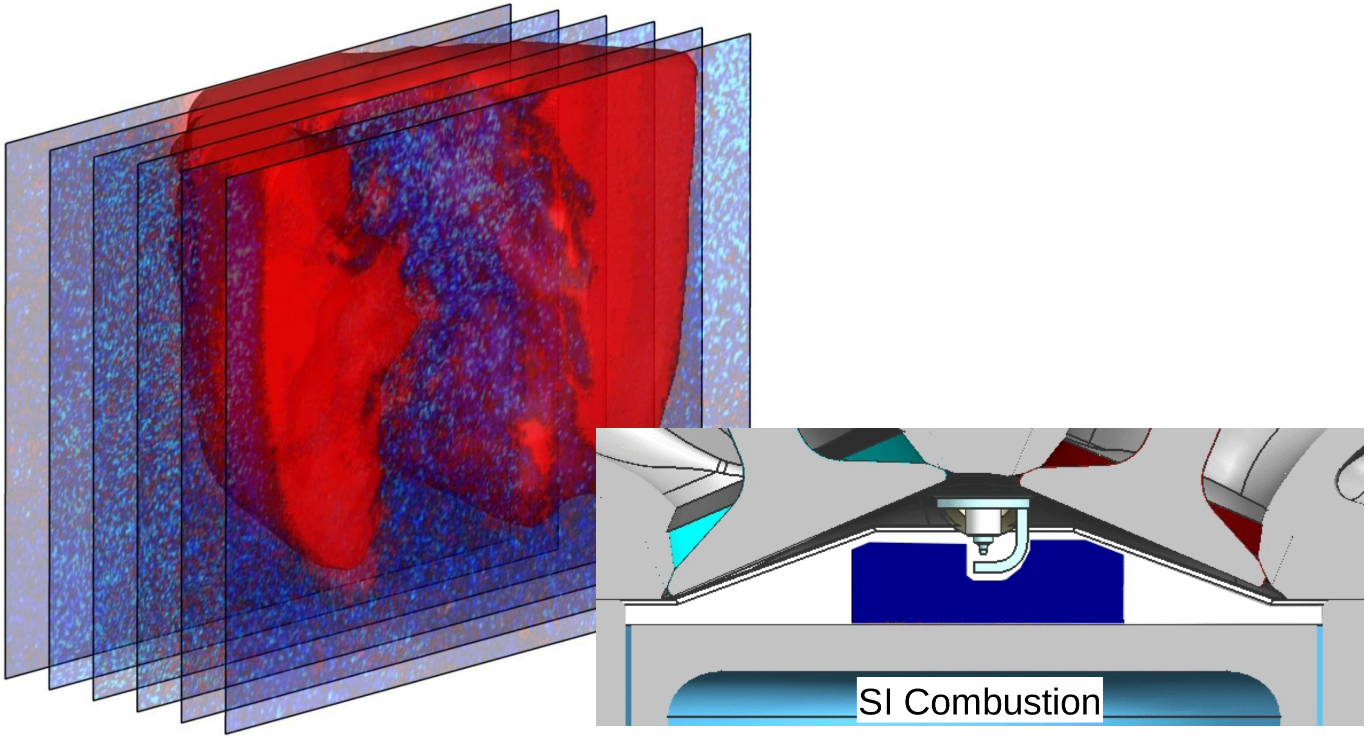
Photron.com



Contents

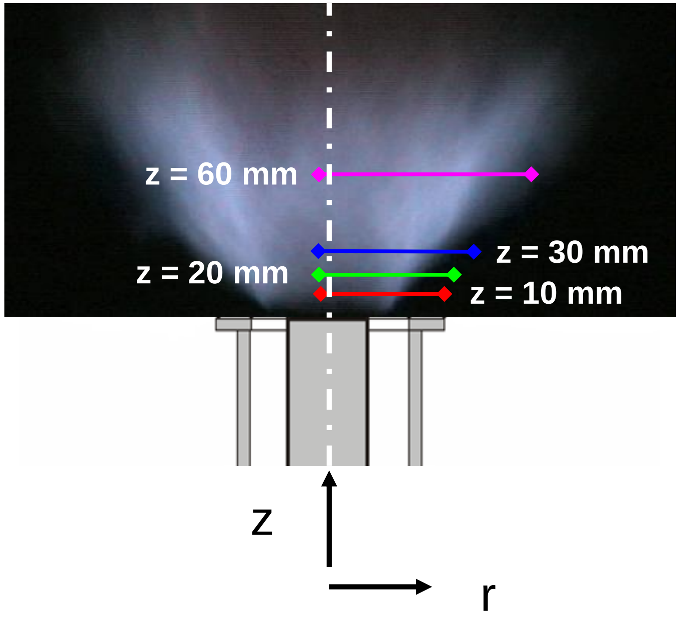
- Why high-speed laser diagnostics?
- Instrumentation
    - High-speed lasers
    - High-speed cameras

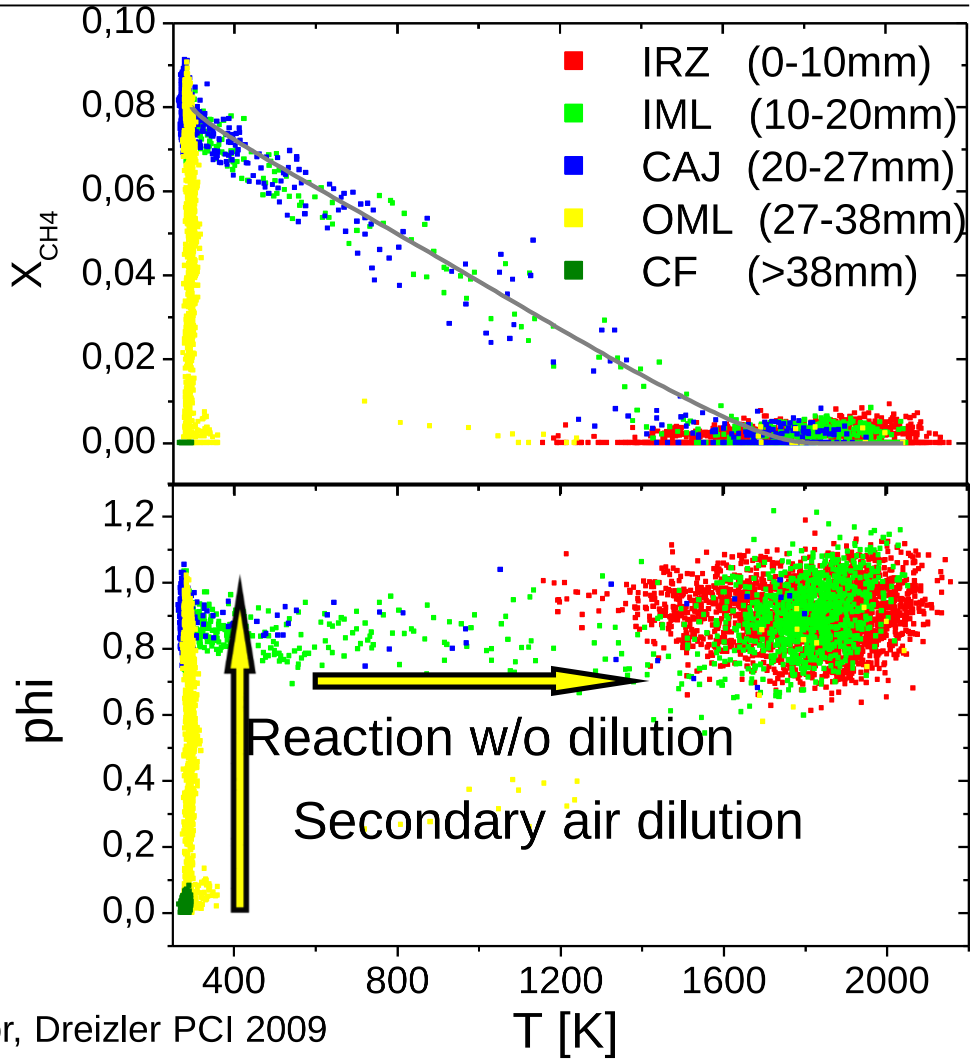
State-of-the-art laser combustion diagnostics

- Flow and multi-scalar measurements
  - Low sampling rates (<100 Hz)
  - High precision and accuracy
  - Good for measuring statistical moments (single-point, two-point statistics)
  - Example: scatter plots by multi-scalar Raman/Rayleigh spectroscopy

State-of-the-art laser combustion diagnostics

- Example: scatter plots by multi-scalar Raman/Rayleigh spectroscopy, lean premixed swirl flame

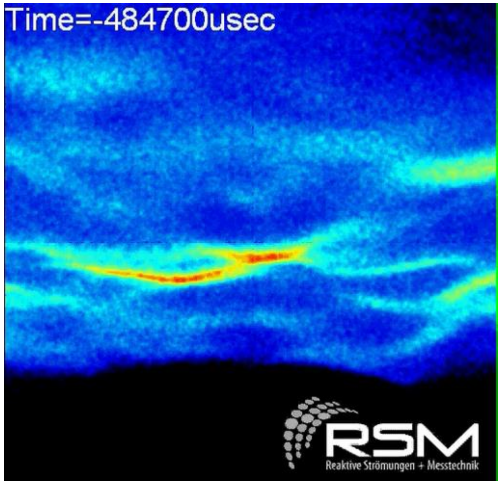




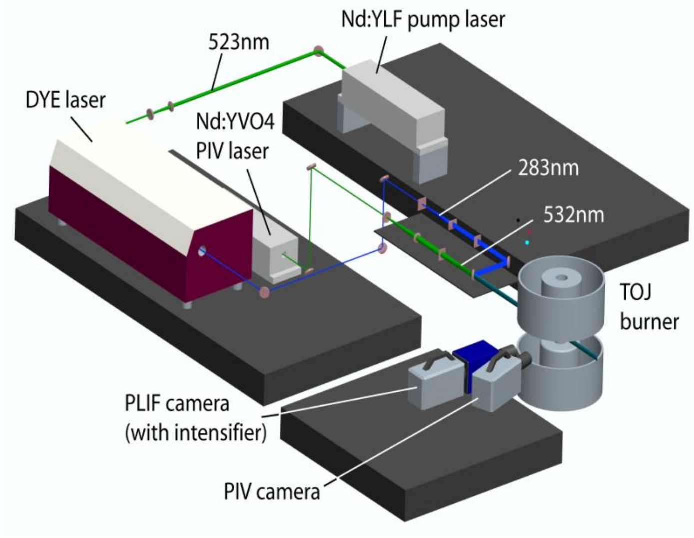
Gregor, Dreizler PCI 2009

Motivation for high speed diagnostics

- Example flame extinction (w/o subsequent re-ignition)
  - Here turbulent opposed jet flows, partially premixed flame
  - Bulk flow rates close to global extinction



Böhm, Dreizler PCI 2009



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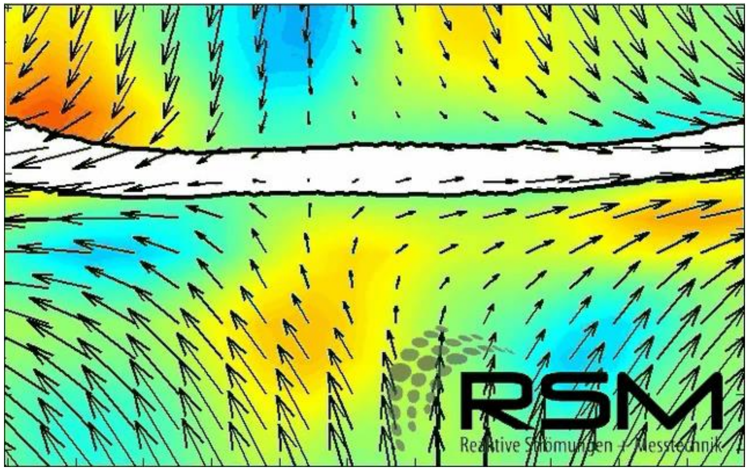
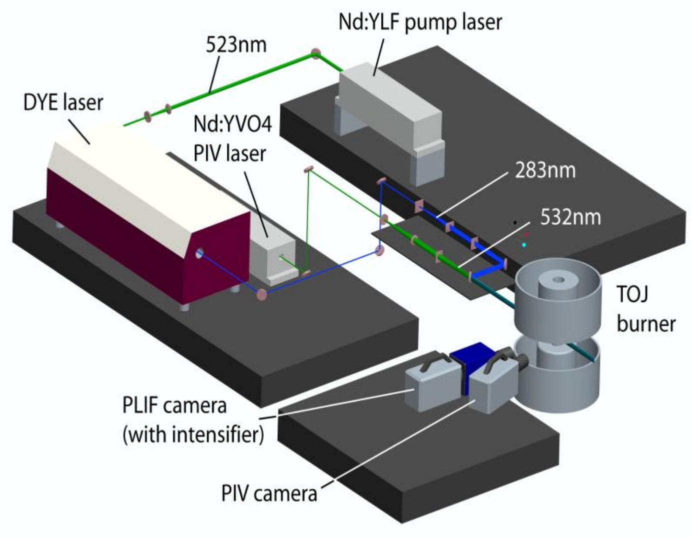
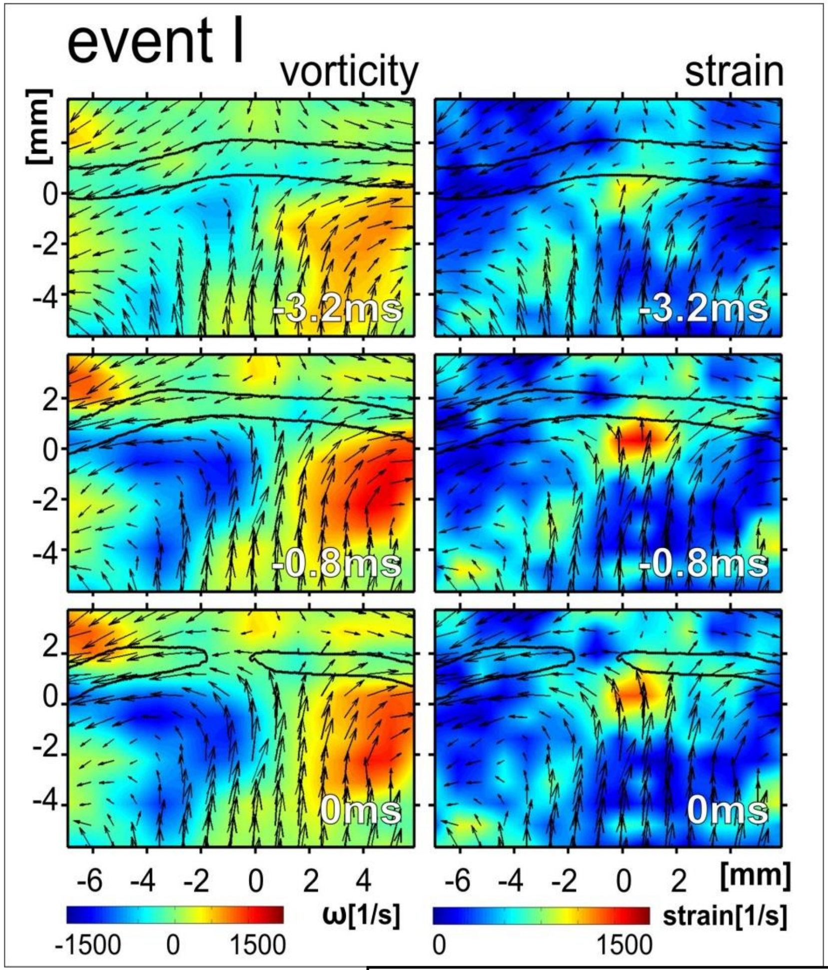


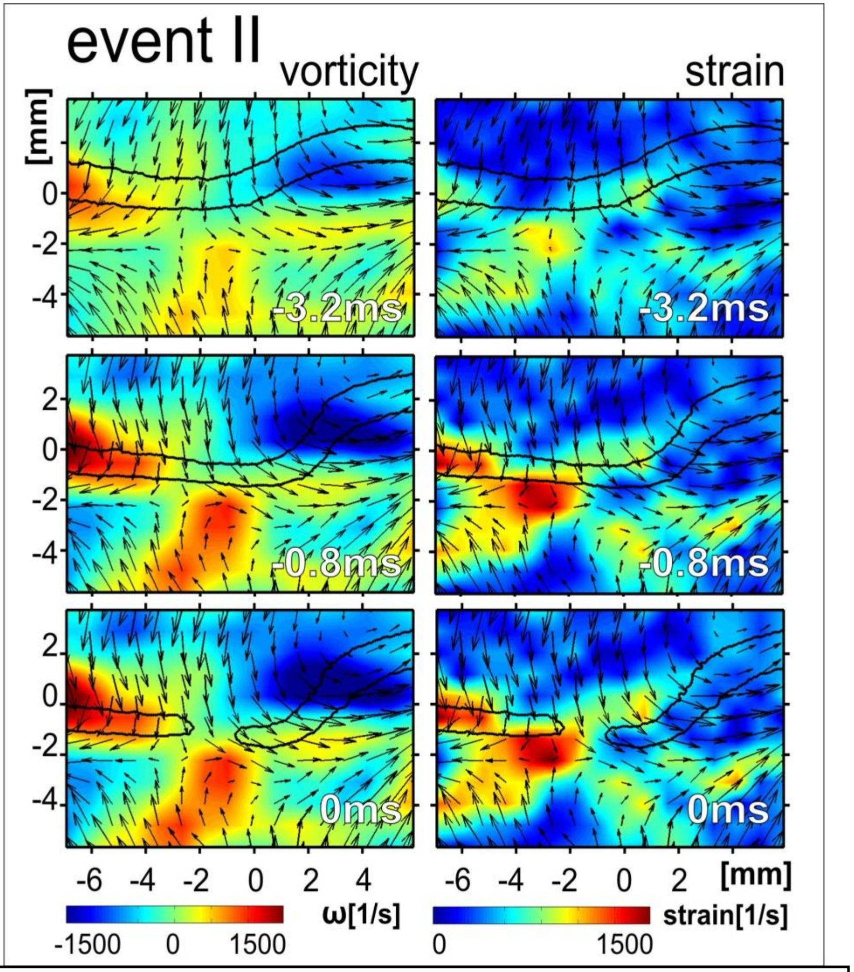


Böhm, Dreizler PCI 2009

→ **Tracking extinction needs high sampling rates, post event-triggering and sequence lengths over 10 – 100ms**

Individual extinction events

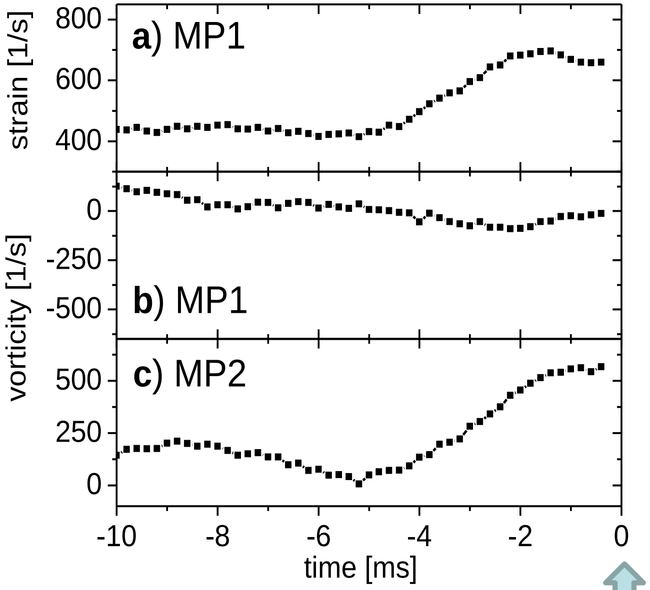




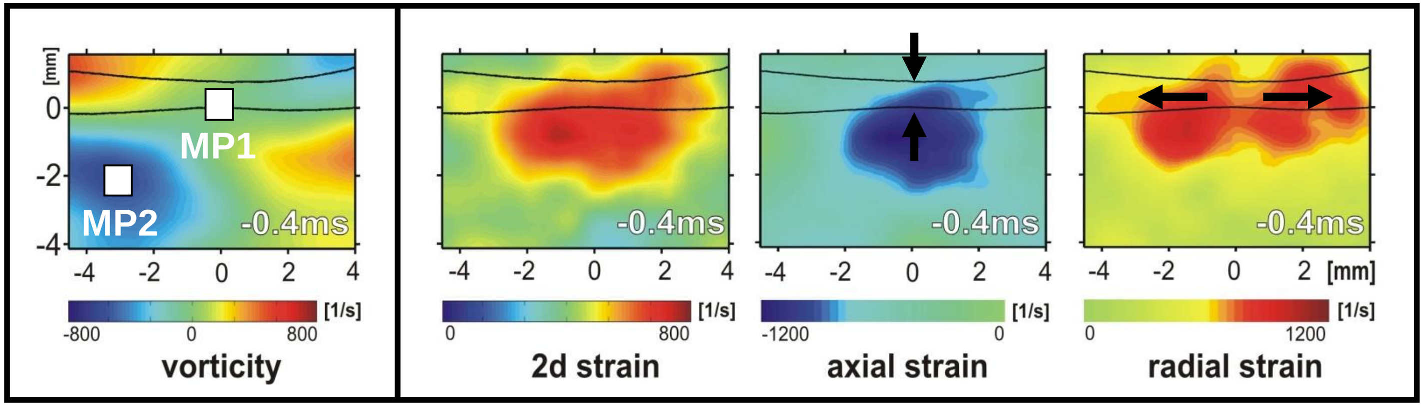
→ multiple vortices act coherently generating regions of high strain close to the flame at the onset of extinction

Conditional averages

- → Maximum of axial strain surrounded by maxima of radial strain
- → Imposed strain requires time to cause extinction
- → Time history is important
- → Diffusion requires time to reduce scalar gradients

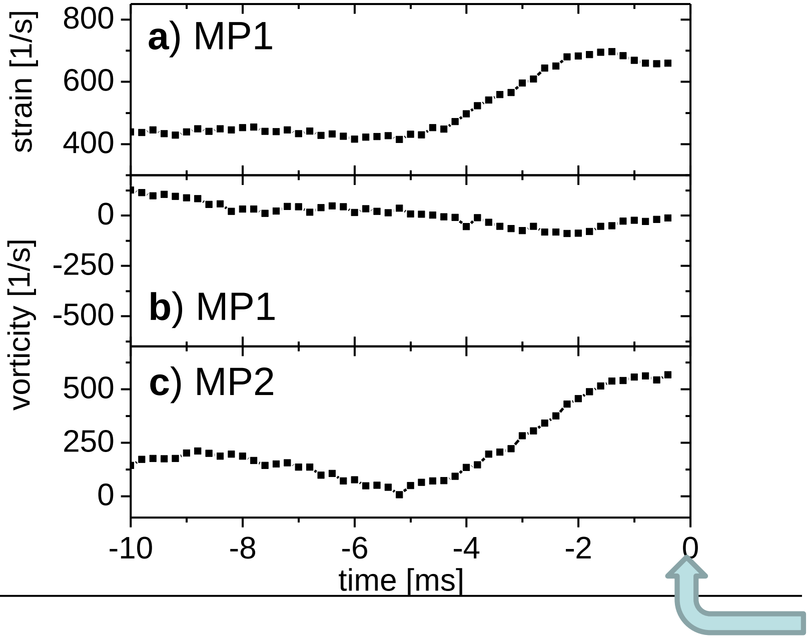


extinction



Multi-parameter diagnostics at high speed

- Simultaneous measurement of velocity fields and qualitative scalar fields that mark features of flames (such as flame fronts) allows determination of <u>conditional velocities</u>:
  - Switch from lab-coordinates to flame-fixed coordinates
  - De-convolute effects from intermittency
  - Better observation of interaction between flow and scalar fields
  - Conditional strain
  - Conditional vorticity



extinction

Transient phenomena in combustion research

- Phenomena requiring high speed diagnostics for better understanding
  - Extinction and re-ignition
  - Flame stabilization of lifted flames and flame propagation
  - Flashback in nozzles
  - Auto- and spark-ignition
  - Cycle-to-cycle variations in IC engines
  - 4D-imaging

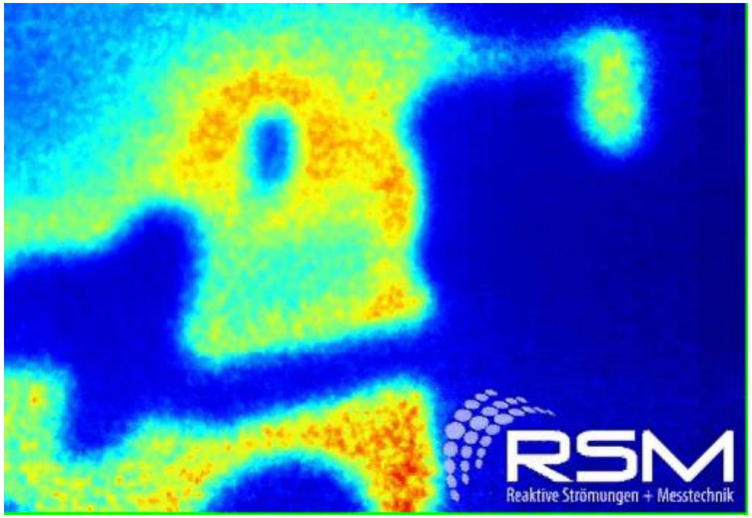
- What repetition rate is needed?

Typical time scales – lab-scale turbulent premixed flame

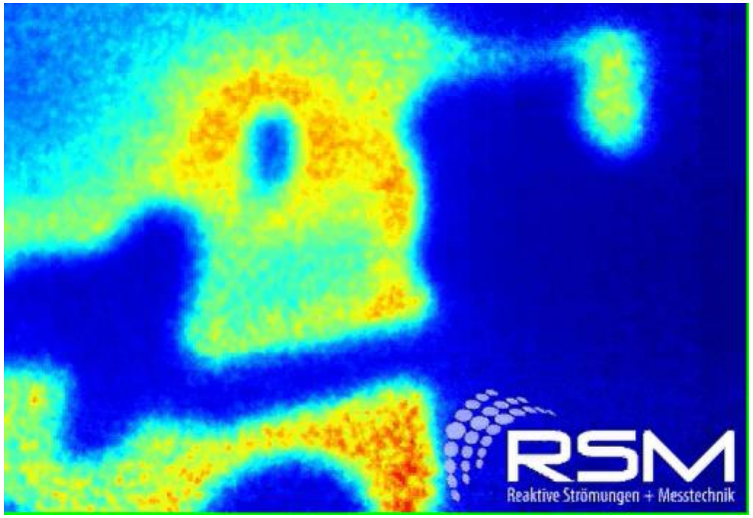
- T_{int} ~ 1.0ms → Sampling rate (0.1 x T_{int}) ~ 100µs → 10 kHz

OH PLIF @ 5 kHz

@ 10 kHz



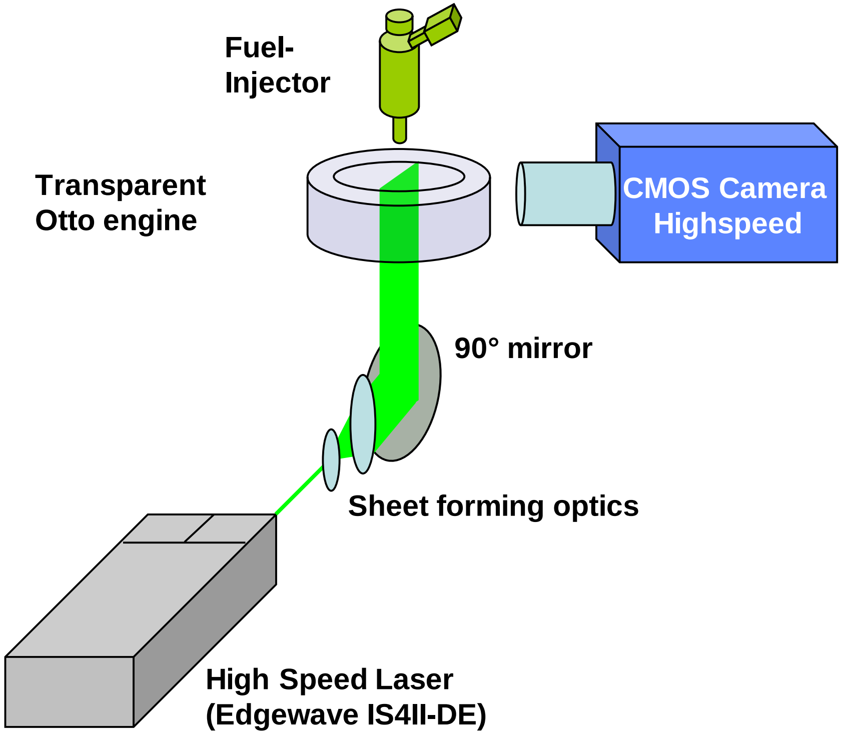
sequence "judders"

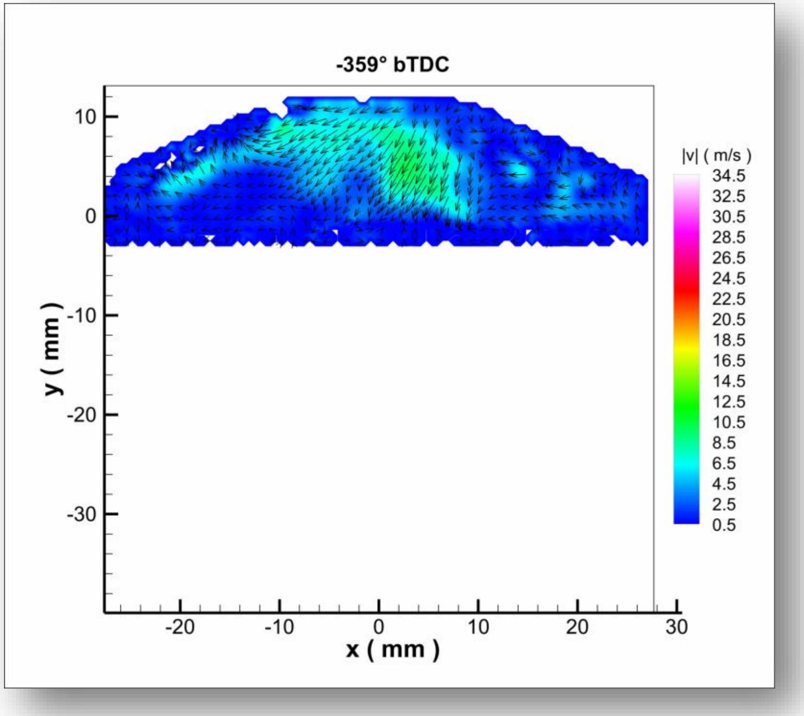


sequence runs "smoothly"

Typical time scales – IC engine

- IC engine operating at 1000 rpm → resolving 1 °CA corresponds to 166 µs → 6 kHz





Flow field during compression
@ 6 kHz 2C-PIV;

E. Baum, et al. *Flow Turbulence Combust.* 92, 269-297 (2014)

Statistically correlated measurements: Scales to be resolved – integral time scale (T_{int})

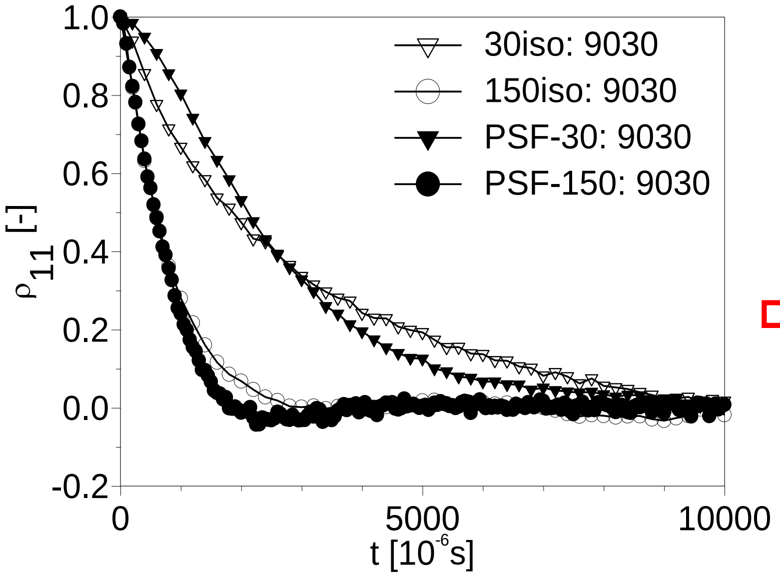
- Swirling annular flow: non-reacting and premixed flame (lab scale)

Iso-pressure surface
Janicka et al. 2007

$Re = 10{,}000 – 40{,}000$

$P_{th} = 30 – 150$ kW

LDV time-series ⇨



⇨ T_{int}~1.0 ms
(Re=10,000)

Schneider et al.
FTaC 2005

Statistically correlated measurements: Scales to be resolved – integral time scale (T_{int})

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Iso-pressure surface
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Re = 10,000 – 40,000

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Nyquist-Shannon theorem $f_{\text{repetition rate}} \geq \frac{2}{T_{\text{int}}} = 2000 \text{ fps}$

Scales to be resolved – Kolmogorov time scale

- Kolmogorov time scale τ_K (integral length scale L_{int} from 2-point correlations)

$$\tau_K = \left(\frac{\nu}{\varepsilon}\right)^{0.5} \; ; \quad \varepsilon = \frac{k^{1.5}}{L_{\text{int}}} \xrightarrow[\text{Swirl flame}]{\text{Example}} \quad \tau_K \sim 100\ \mu\text{s (representative estimate)}$$

Re = 40,000/10,000

- Nyquist-Shannon theorem

$$f_{\text{frame rate}} \geq \frac{2}{\tau_K} \quad \Longrightarrow \quad \underbrace{f_{\text{frame rate}} \geq 20000 \text{ fps}}$$

Imaging:
Fulfilled by state-of-the art CMOS camera technology

Interdependency of time and length scales

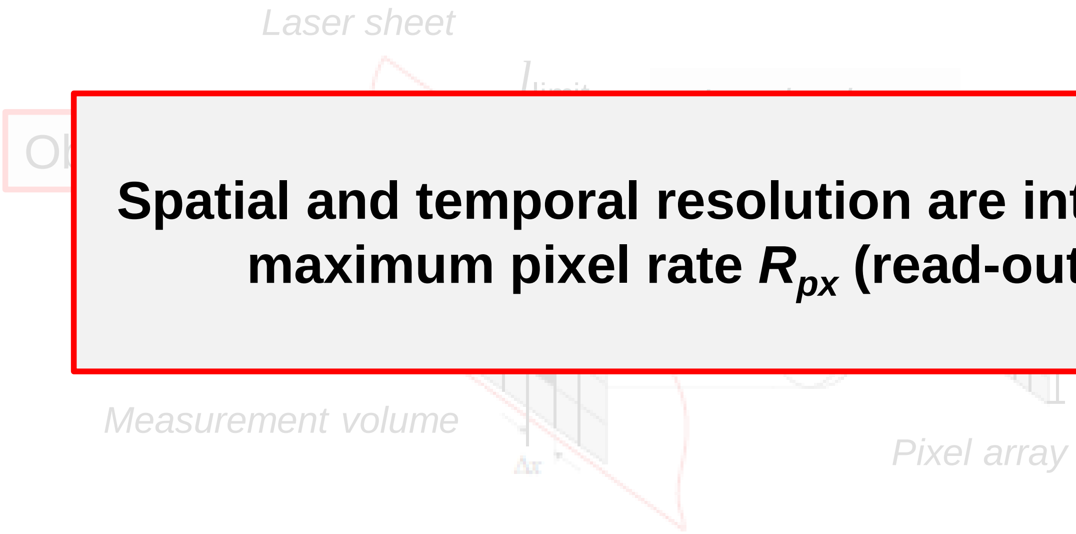
- Field of View: $l_{\text{FOV}} = n_x \cdot \Delta x = n_x \cdot l_{px} \cdot M$
- Nyquist-Shannon: $l_{\text{limit}} \geq 2 \cdot \Delta x$

Pixel rate

Temporal resolution

$$\frac{l_{\text{FOV}}}{l_{\text{limit}}} = \frac{1}{2}\sqrt{\frac{R_{px} \cdot \tau_{\text{limit}}}{2}}$$

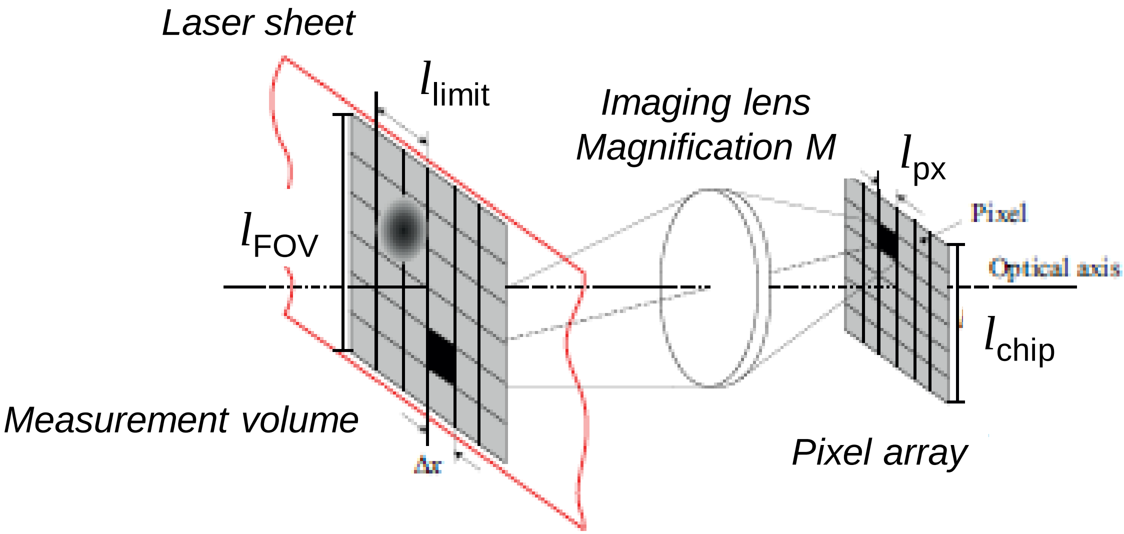
Spatial dynamic range



Spatial and temporal resolution are interconnected via the maximum pixel rate R_{px} (read-out-rate of CMOS)

Interdependency of time and length scales

$$\left.\begin{array}{l} R_{\text{px}} = 20\cdot 10^{9}\ \text{px/s} \\ \text{Magnification} = 1 \\ \tau_{\text{limit}} = \tau_K = 100\ \mu\text{s} \\ l_{\text{FOV}} = 20\ \text{mm} \end{array}\right\} \underbrace{\frac{l_{\text{FOV}}}{l_{\text{limit}}} = 500}_{\text{Spatial dynamic range}} \Rightarrow l_{\text{limit}} = 40\ \mu\text{m}$$



Interdependency of time and length scales

$$R_{\mathrm{px}} = 20 \cdot 10^{9} \ \ \mathrm{px/s}$$

$$\mathrm{Magnification} = 1$$

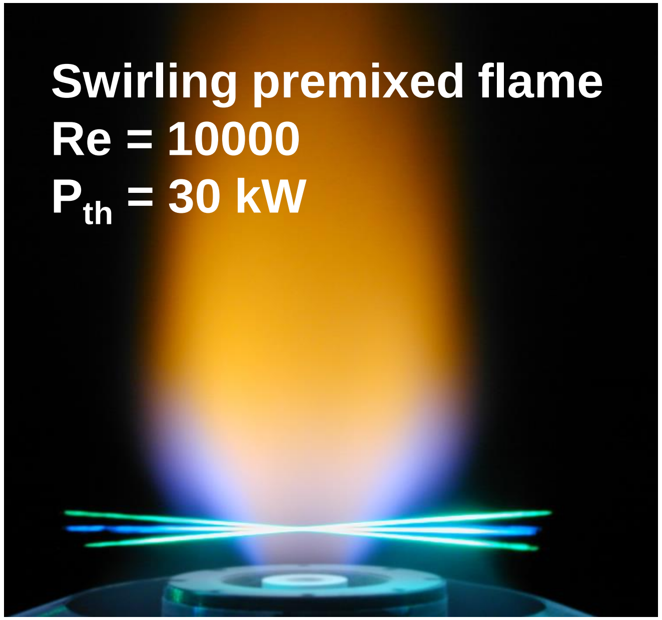
$$\tau_{\mathrm{limit}} = \tau_{K} = 100 \ \mu s$$

$$l_{\mathrm{FOV}} = 20 \ \mathrm{mm}$$

$$\underbrace{\frac{l_{\mathrm{FOV}}}{l_{\mathrm{limit}}} = 500}_{\text{Spatial dynamic range}} \Rightarrow l_{\mathrm{limit}} = 40 \ \mu\mathrm{m}$$

$$l_{K} = \left(\frac{\nu^{3}}{\varepsilon} \right)^{0.25} \Rightarrow l_{K} = 50 \ \mu\mathrm{m}$$

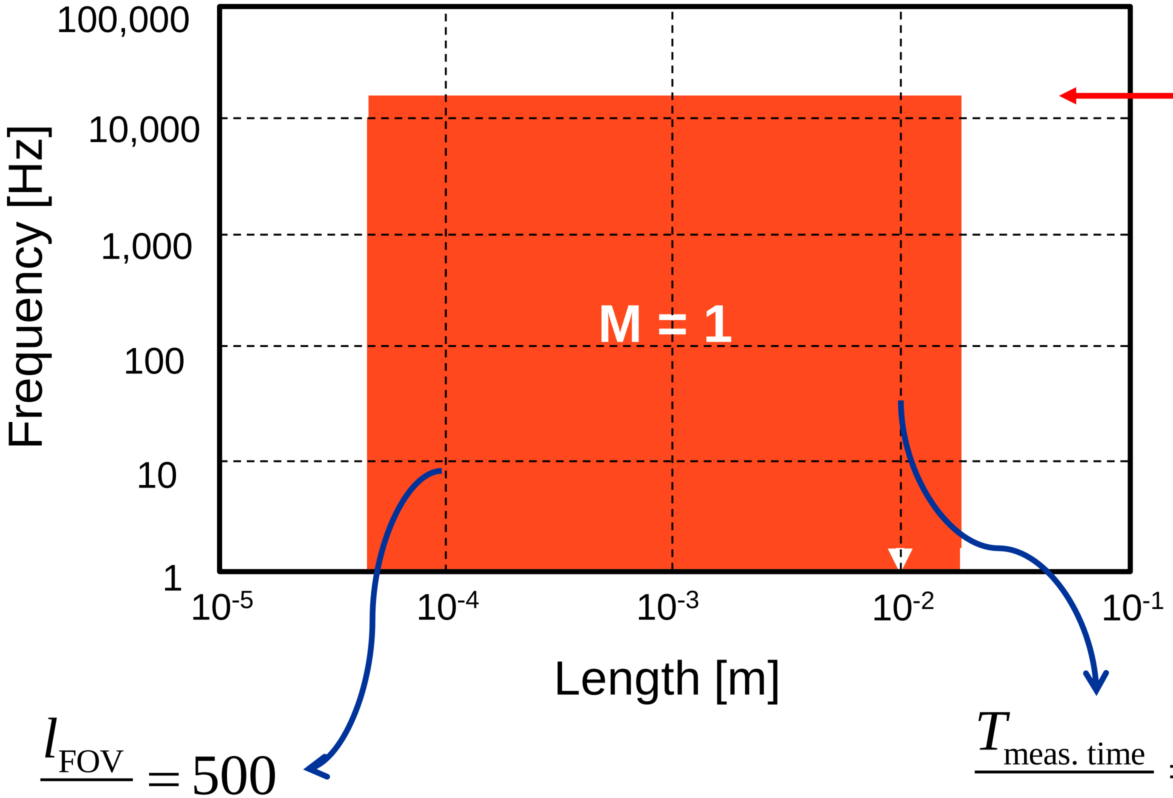
Same range



Swirling premixed flame
Re = 10000
P_{th} = 30 kW

Lab flames, present CMOS technology:
Kolmogorov length and time scales resolvable
FOV contains 2-5 integral length scales

Dynamic ranges – spatial and temporal



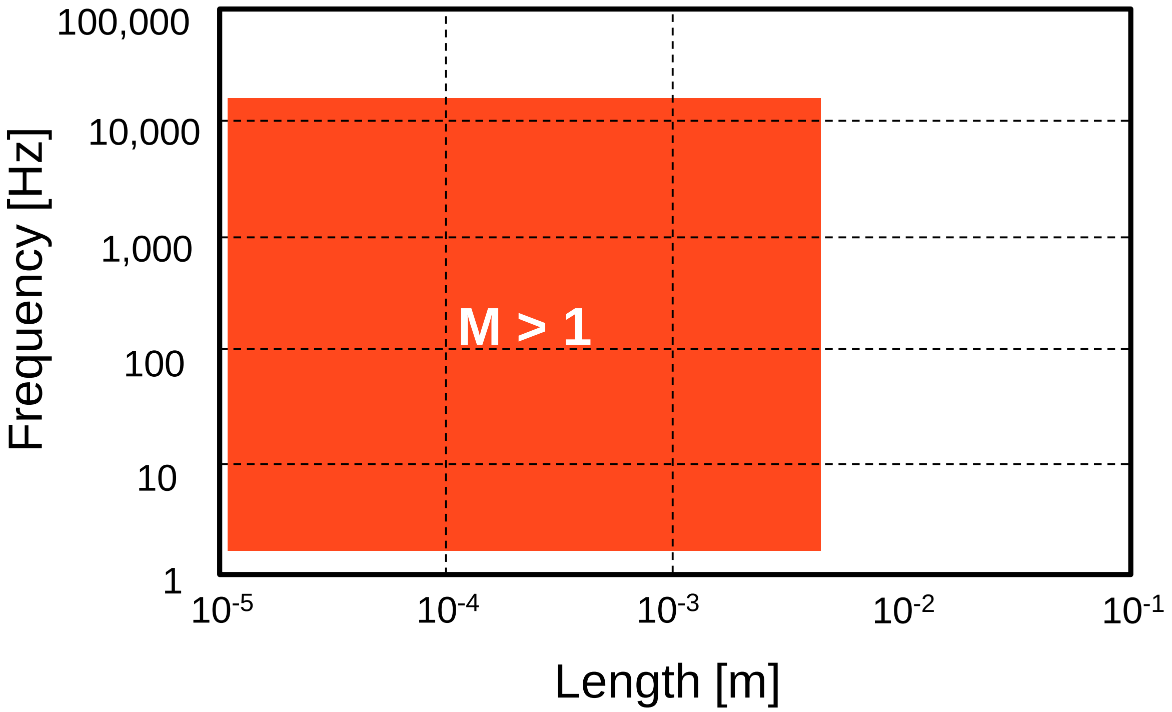
Max. frame rate at full frame
(~ 1 Mio. Pixels)

$$\frac{l_{\mathrm{FOV}}}{l_{\mathrm{limit}}} = 500$$

$$\frac{T_{\mathrm{meas.\ time}}}{\tau_{\mathrm{limit}}} = \frac{T_{\mathrm{meas.\ time}}}{2} f_{\mathrm{frame\ rate}} = 10,000$$

Nyquist, on-board memory CMOS

Dynamic ranges – spatial and temporal



Application high speed diagnostics – examples

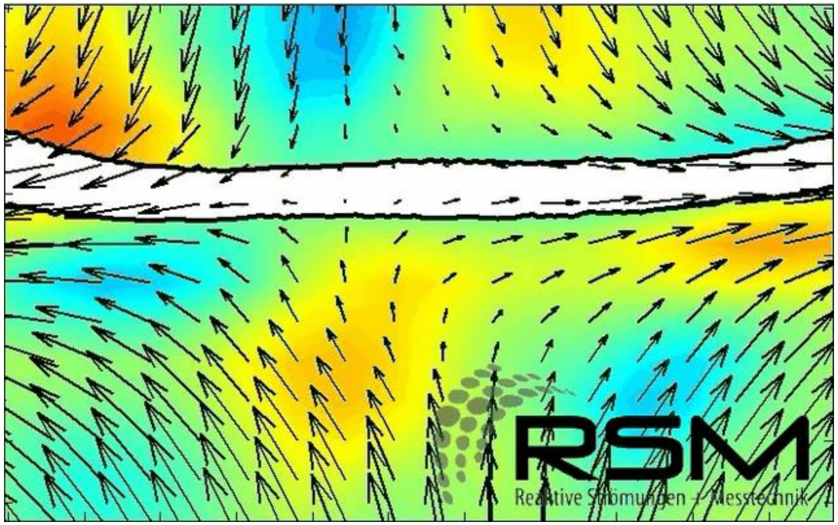
- Field of application
  - Experiments where only few realizations or short measurement periods are available (shock tubes, IC engines, …)
  - Transients in combustion
    - ignition, extinction
    - blow off, flashback
    - flame propagation, cyclic variations …

  } (conditional) statistics

- Instrumentation specific to spectral range and diagnostic method
  - Towards 4D imaging (3D in space + time) → new high speed lasers and CMOS cameras

Ex2: High speed imaging

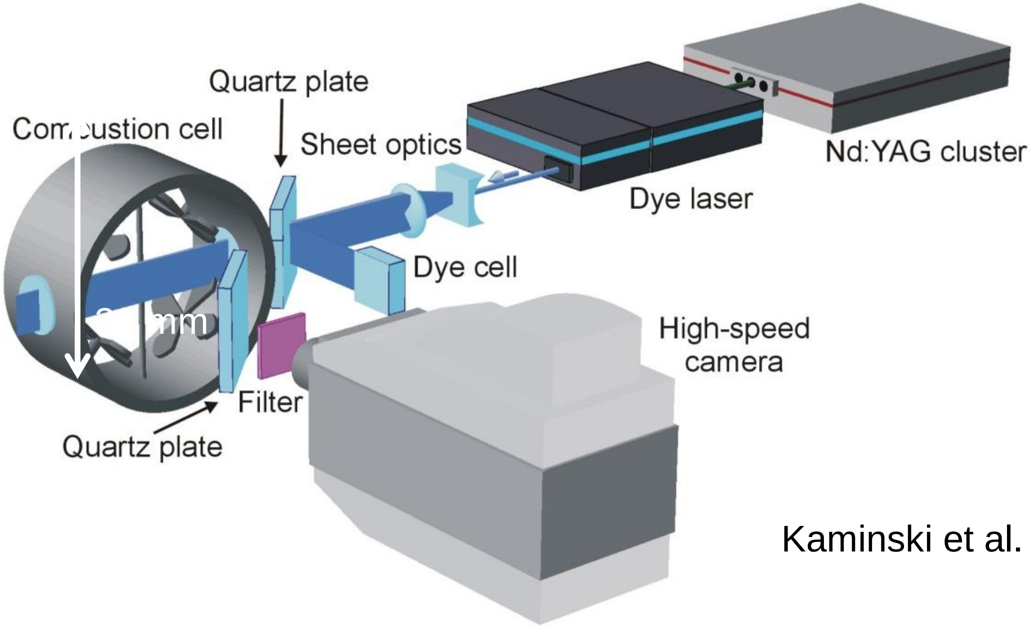
- Rapid progress of laser and camera technology over the last 6-8 years
- Recent reviews on high speed imaging
  - Böhm et al. (FTaC 2011)
  - Thurow et al. (MST 2013)
  - Sick (PCI 2013)
- Requirements
  - High power lasers
  - High frame rate cameras



Extinction in turbulent opposed jet flame
B. Böhm et al. PCI 2009

Burst lasers for high speed imaging

- Low duty cycle, high pulse energies
  - Aldén group (Lund)
    - Cluster of 4 Nd:YAG lasers, frequency doubled
    - 4 – 8 pulses/burst, <500mJ/pulse
    - Use of harmonics directly or for pumping a dye laser/dye laser cluster



Kaminski et al. PCI 2000

Lund multi-YAG

Burst lasers for high speed imaging

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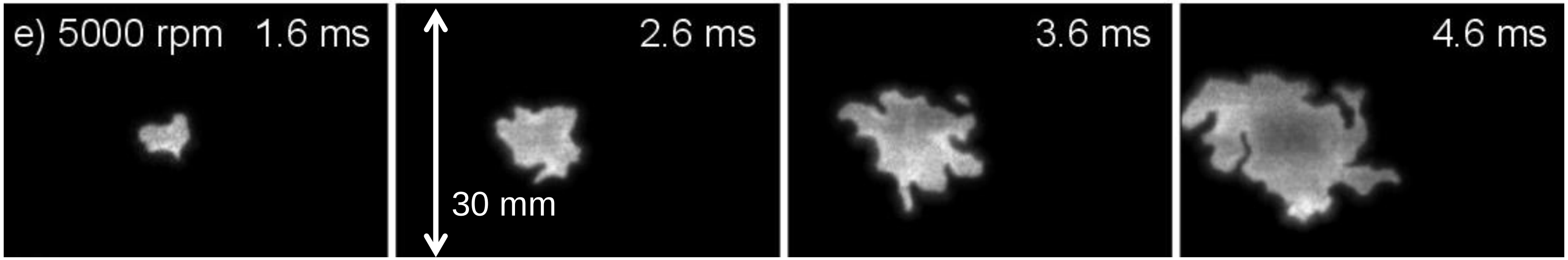
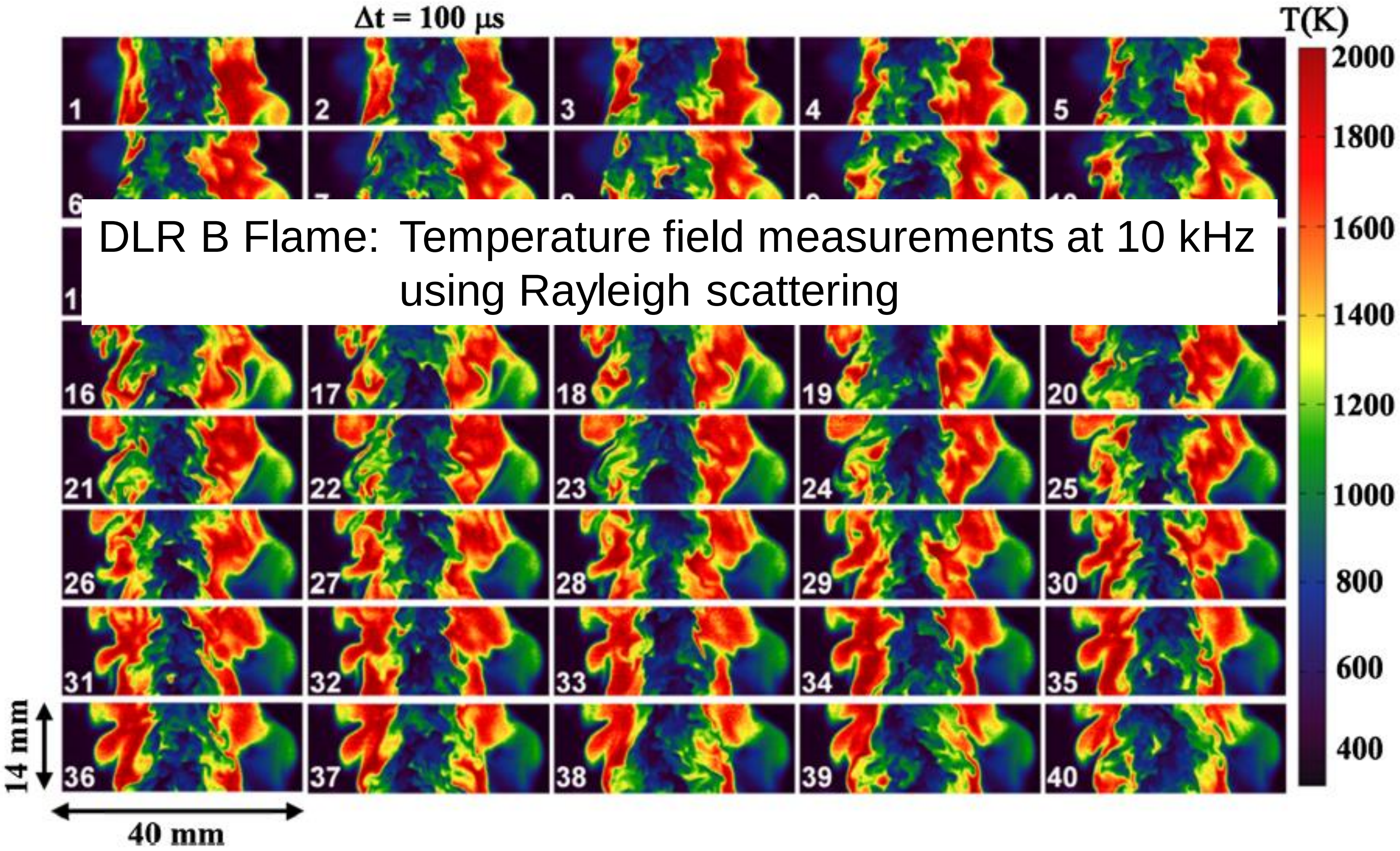
OH-PLIF, $\Delta t = 1$ ms



Turbulent flame kernel propagation following spark ignition, stoich. CH_4/air

Lund multi-YAG

Burst lasers for high speed imaging



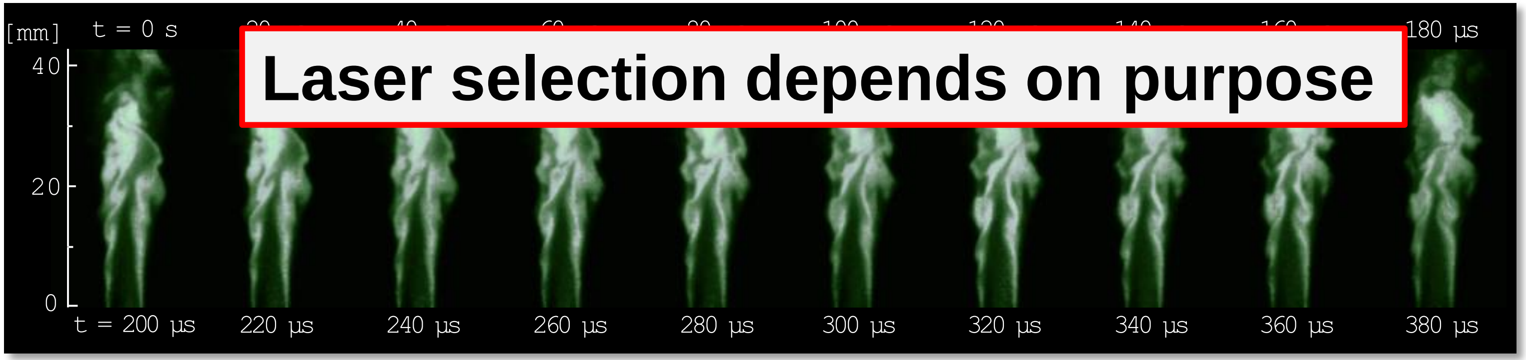
DLR B Flame: Temperature field measurements at 10 kHz using Rayleigh scattering

Continuously pulsed high speed lasers

- High duty cycle, low pulse energies
  - Long pulse-lasers: $\Delta t_{laser} > 100$ns → intra-cavity conversion for VIS, UV generation
  - Short pulse-lasers: $\Delta t_{laser} < 20$ns → extra-cavity conversion for VIS, UV generation
    - Suitable to pump dye lasers
    - Most recent specifications:
      - 50 kHz, 200 W pump power @ 532 nm → 7 W @ 283nm (2-step SHG)

S. Hammack, C. Carter, C. Wünsche, T. Lee: Appl. Optics (2014)

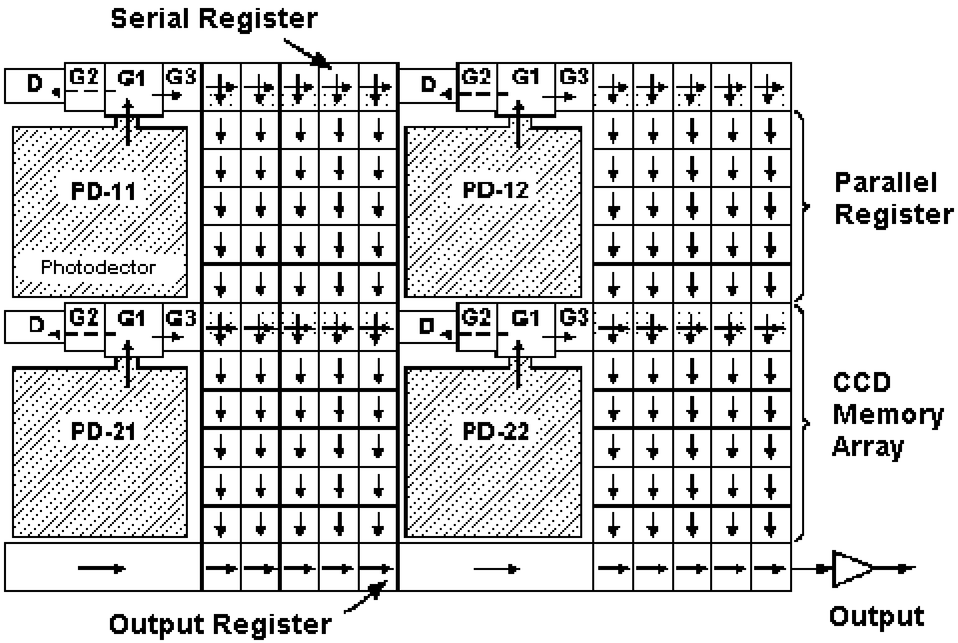
plasma-torch stabilized CH_4/air flame



Laser selection depends on purpose

Instrumentation – cameras

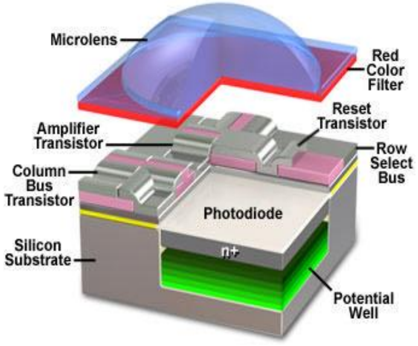
- High speed cameras
  - Multi-frame CCD´s cameras
    - Example: Princeton Scientific Instruments PSI 4
      (28 frames, 3 MHz, 80x160 pixels, 14 bit)

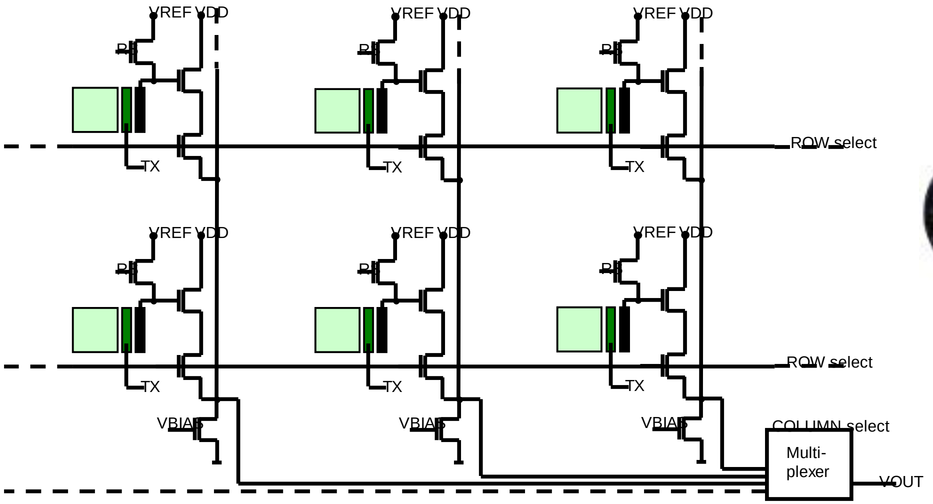


Instrumentation – cameras

- High speed cameras
  - Multi-frame CCD´s cameras
  - CMOS cameras
    - Example: Phantom v2512

      (1280 x 800@ 25,000 fps, 128 x 16 pixels @ 1,000,000 fps)
    - Other providers: PCO, Photron

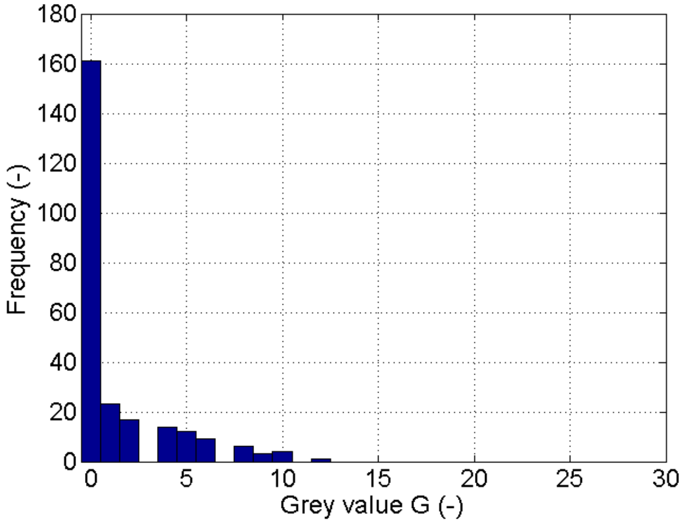


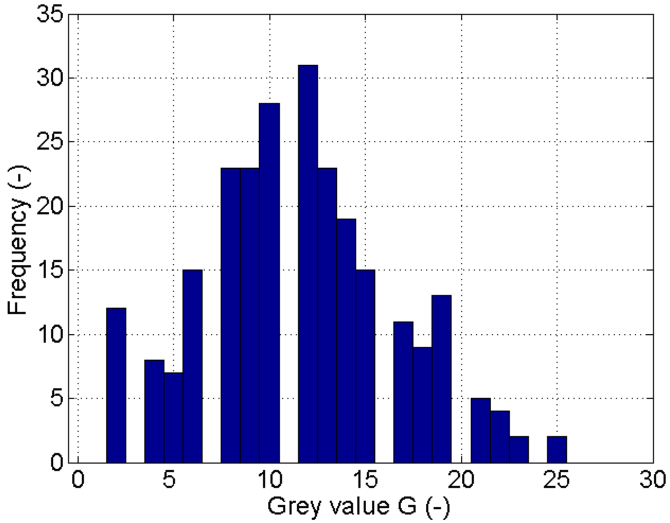


Photron

CMOS – basic sensor checks

- High speed CMOS not yet temp. stabilized
  - → Significant temperature drift, independent on illumination
  - → Wait for thermal equilibrium
- Truncated dark noise with “intensity calibration”
  - → Switch off intensity calibration
- Vacancies in grey value resolution due to pixel gain
  - → Reduces dynamic range
  - → Introduces larger digitization noise





Weber, Dreizler APB 2011

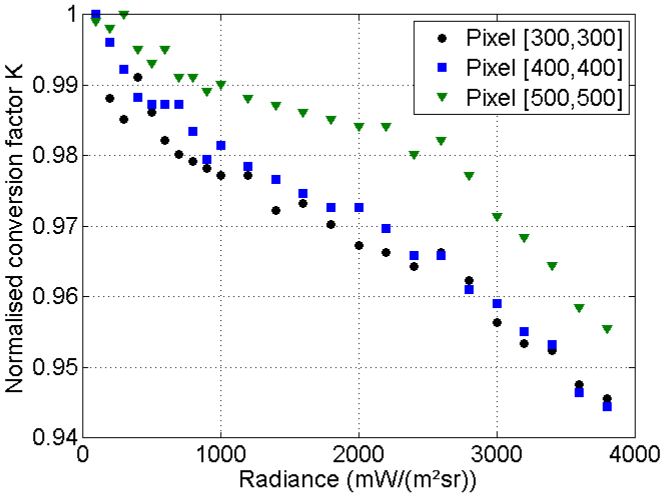
CMOS – Non-linearity

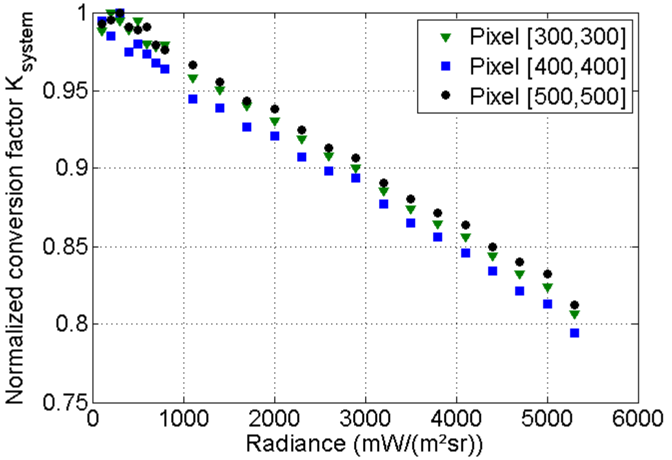
- Checking camera response (pixelwise)
  → Homogenous calibrated light source (Ulbricht sphere)
- Model for pixel response as

$$G_i = G_{0,i} + K_{i,N_{e,i}} N_{e,i}$$

→ Inherent non-linear response
→ Deviations from linearity < 6%

- Inclusion of image 2-stage-intensifier (MCP + booster)
  → Significantly increased non-linearity





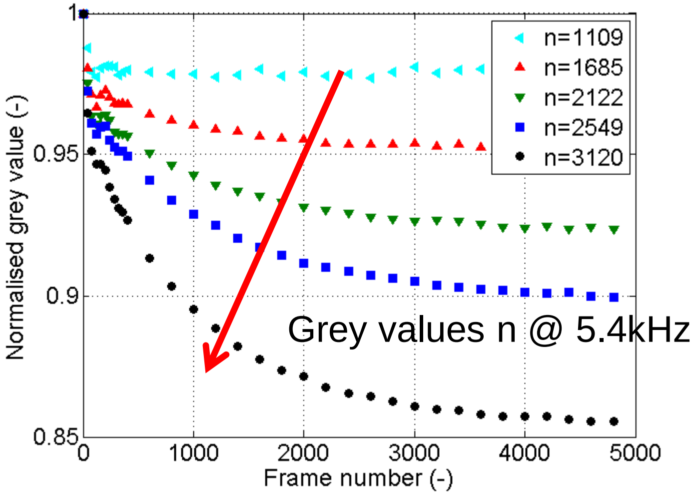
CMOS – image intensifier signal depletion

- Intensified systems suffer from signal depletion
- Full sensor illumination: Depletion increases with signal intensity (grey value n) and repetition rate

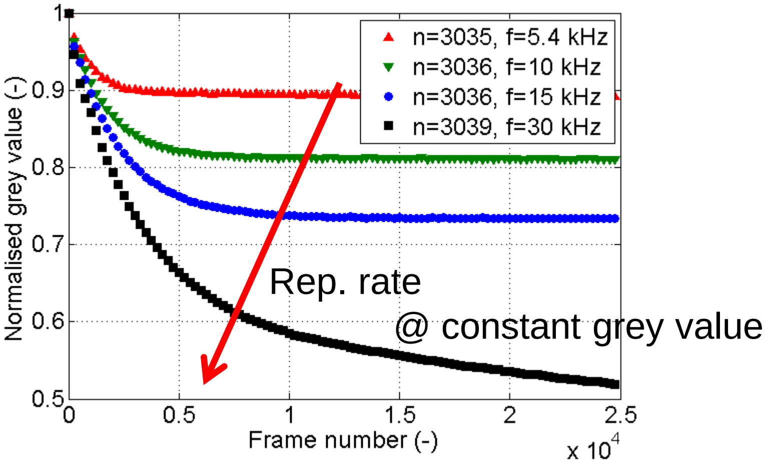
→ Without correction: device is unable to reproduce a constant signal within the first few 2000 frames

- Dependent on
  - Signal intensity
  - Frame rate
  - Exposure time
  - Illuminated area

→ <u>In-situ calibration required</u>



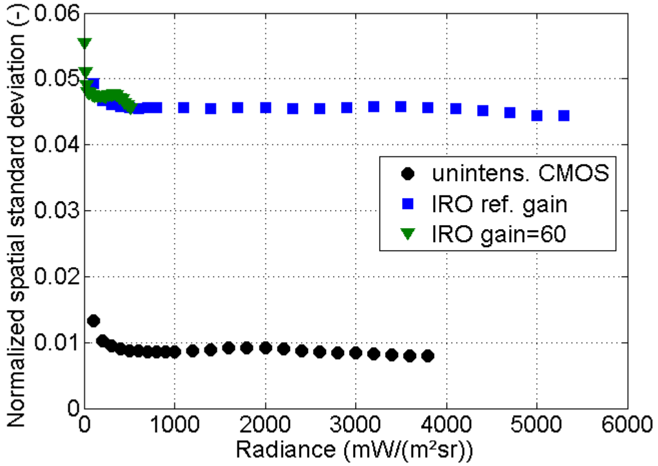
Grey values n @ 5.4kHz



Rep. rate

@ constant grey value

CMOS – quantitative measurements



- Unintensified CMOS camera (preferred)
  - Resolve dark signal (disable IC)
  - (Pixelwise) correction of nonlinearity
- Intensified CMOS
  - Pixelwise correction of nonlinearity
  - Signal depletion. No best practice advice available

  → Solution: monitor depletion with spot of known illumination?
  - “Halos” (steep intensity gradients cause cross-talk to neighboring pixels)?

→ Each CMOS camera/ intensifier has unique characteristics
→ Need for common calibration procedure
→ EMVA 3.0 not suitable for our needs