COMBUSTION RESEARCH FACILITY

SAND2018-6060PE

LII particle-size imaging with an ultra-high-speed CMOS camera

Sandia National Laboratories

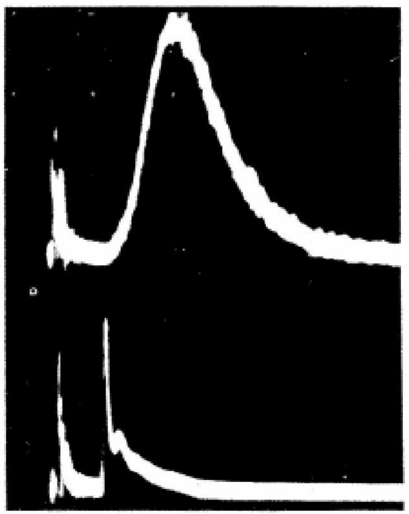
E. Cenker, S. Skeen, Y. Chen, D. Richardson, C. R. Shaddix, D. R. Guildenbecher

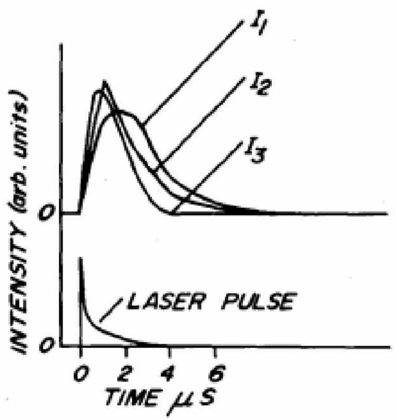
8th International LII Workshop

June 2018

Evolution of hardware for LII

Evolution of LII





Weeks, R. W., & Duley, W. W. (1974). *Aerosol-particle sizes from light emission during excitation by TEA CO2 laser pulses.* Journal of Applied Physics, 45(10), 4661-4662.

Recipe:

- Pulsed TEA CO_2 laser (4 μs pulse width)
- Photomultiplier
- Oscilloscope

Weeks&Duley,1974
(first LII paper)

Sandia National Laboratories

Evolution of hardware for LII

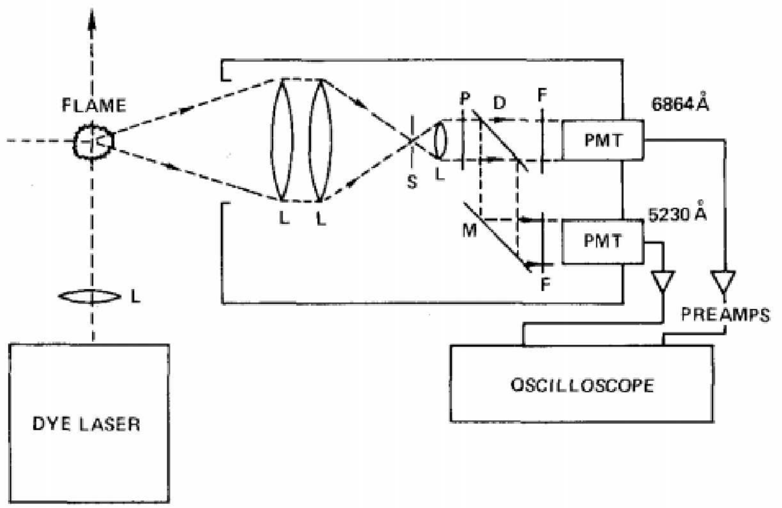


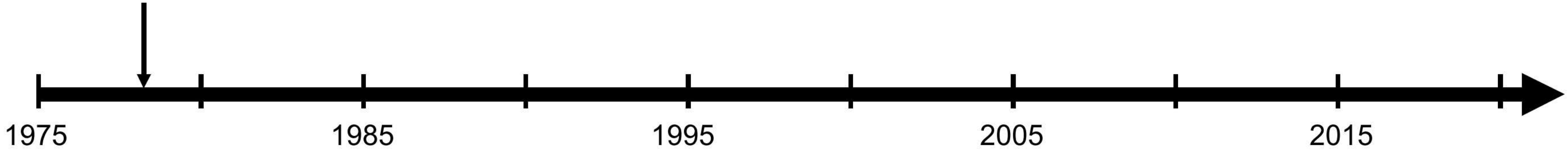
FIG. 2. Two-color optical pyrometer. Symbols: L, lens; S, aperture; P, polarization filter; D, dichroic, M, mirror; F, blocking and narrow-band interference filters; PMT, photomultiplier.

Eckbreth, A. C. (1977).
Effects of laser-modulated particulate incandescence on Raman scattering diagnostics.
Journal of Applied Physics, 48(11), 4473-4479.

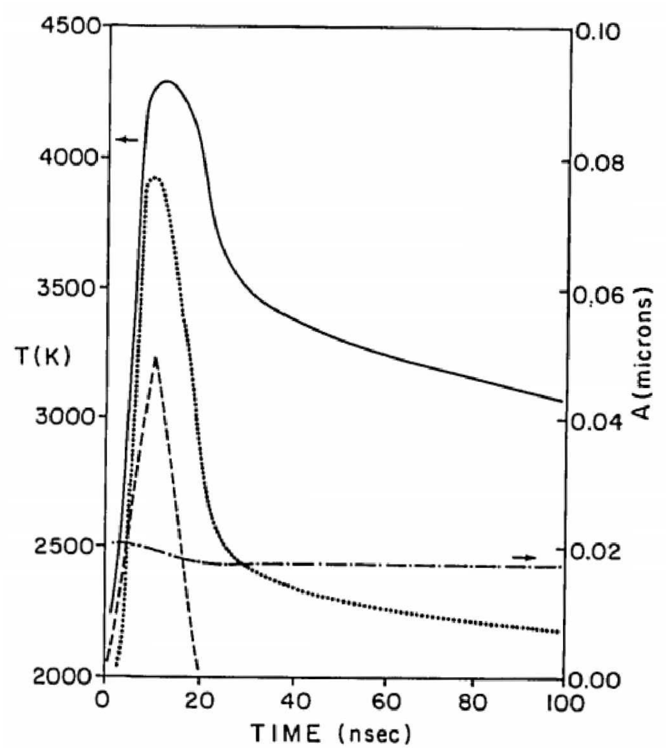
Recipe:

- Pulsed dye laser (1 μs pulse width)
- Photomultiplier
- Oscilloscope

Eckbreth,1977
(first schematic)



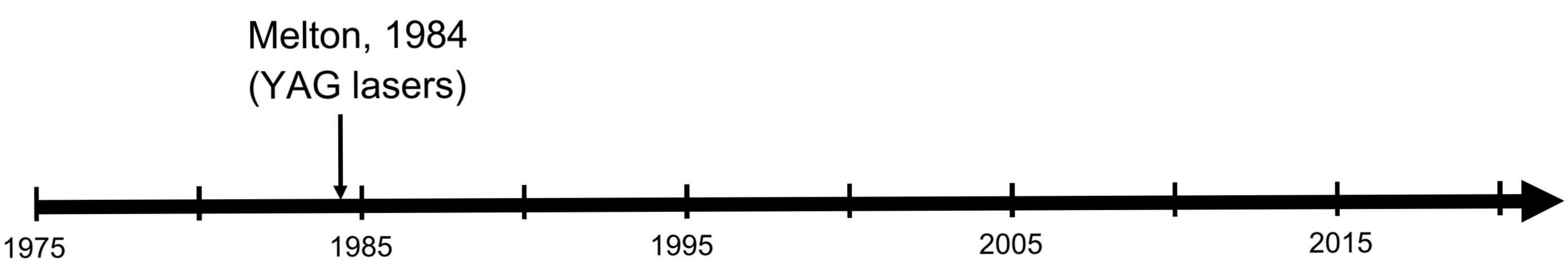
Evolution of hardware for LII



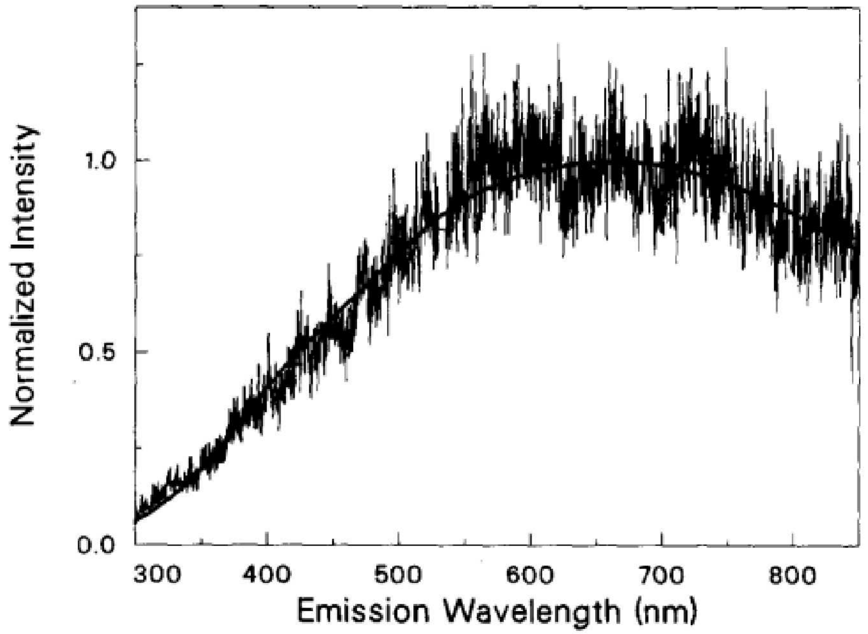
Melton, L. A. (1984).
Soot diagnostics based on laser heating.
Applied Optics, 23(13), 2201-2208.

Recipe:

- Nd:YAG laser (<10-nsec FWHM)
- Photomultiplier
- Oscilloscope



Evolution of hardware for LII

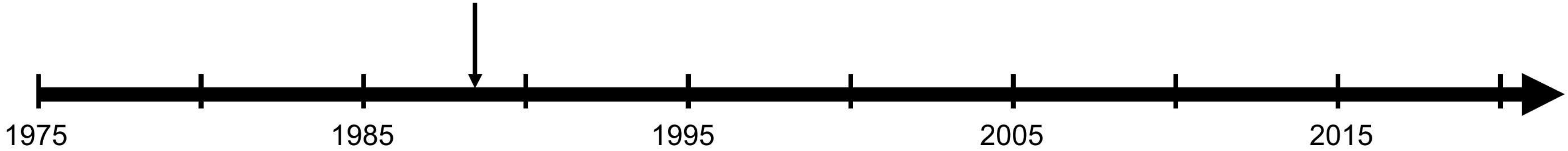


Rohlfing, E. A. (1988).
Optical emission studies of atomic, molecular, and particulate carbon produced from a laser vaporization cluster source.
The Journal of Chemical Physics, 89(10), 6103-6112.

Recipe:

- Nd:YAG laser (<10-nsec FWHM)
- Spectrometer

Rohlfing, 1988
(Spectrometer)



Evolution of hardware for LII

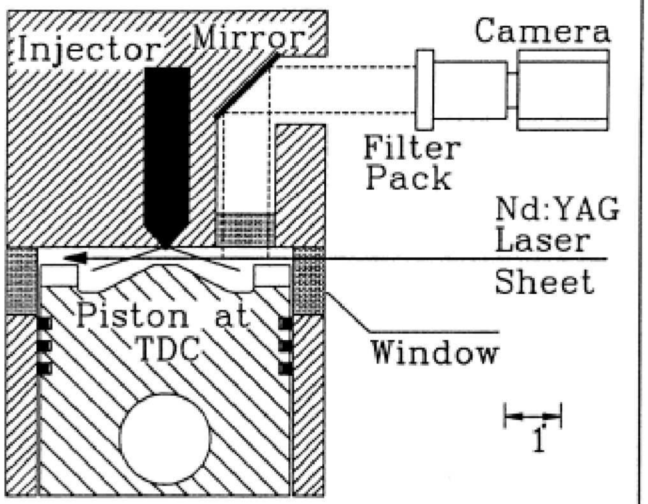


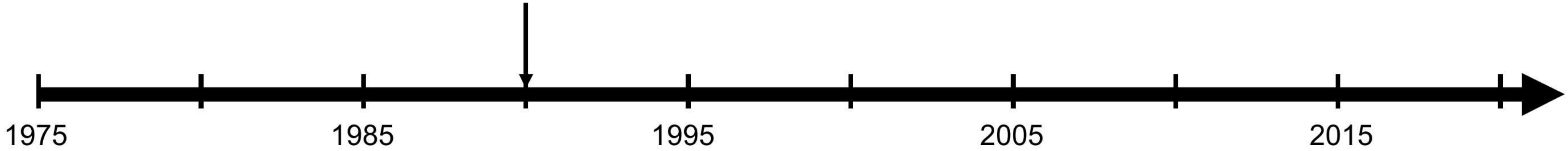
Figure 3 Schematic of the engine's optical configuration.

Zur Loye, A. O., Siebers, D. L., & Dec, J. E. (1990). *2-D soot imaging in a direct injection diesel engine using laser-induced incandescence.* In *COMODIA* (Vol. 90, pp. 523-528).

Recipe:

- Nd:YAG laser (<10-nsec FWHM)
- Camera (intensified CID)

Dec, 1990
(2D LII - ICID)



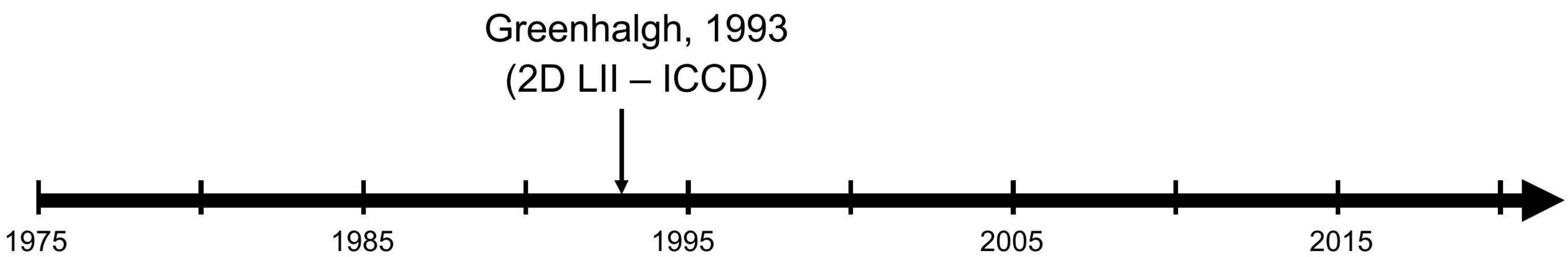
Evolution of hardware for LII

Fig. 9
LII image from a strongly turbulent jet flame

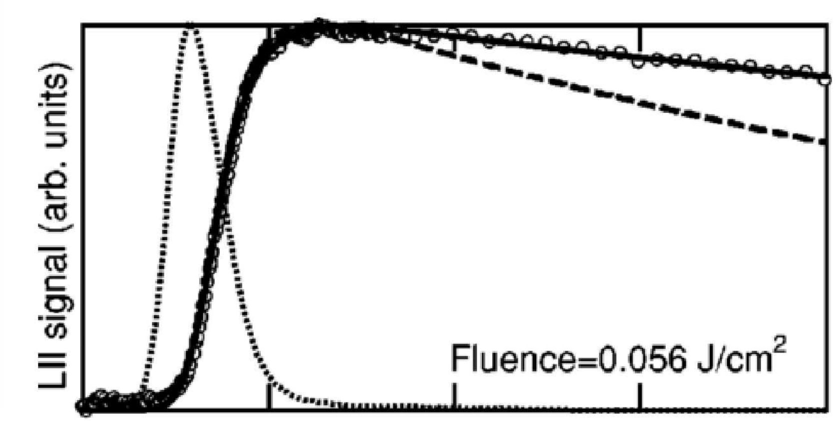
Tait, N.P., & Greenhalgh, D.A. (1993).
PLIF imaging of fuel fraction in practical devices and LII imaging of soot.
Berichte der Bunsengesellschaft fuer Physikalische Chemie, 97(12), 1619-1624.

Recipe:

- Nd:YAG laser (<10-nsec FWHM)
- intensified CCD



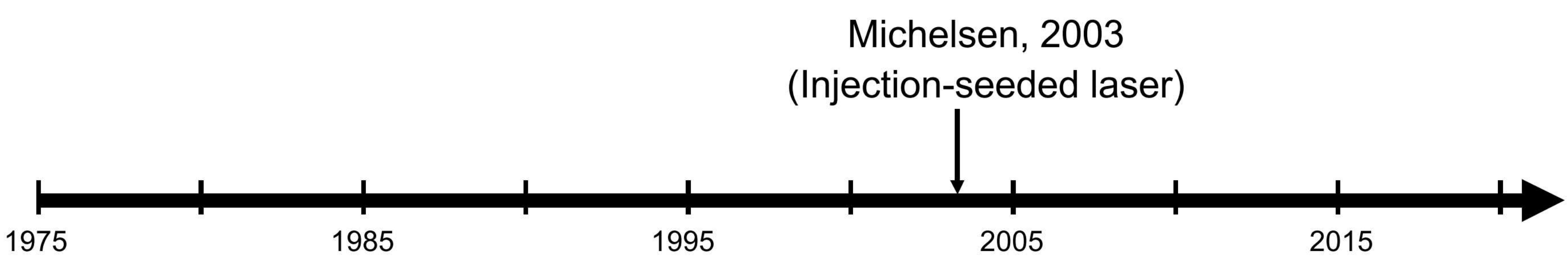
Evolution of hardware for LII



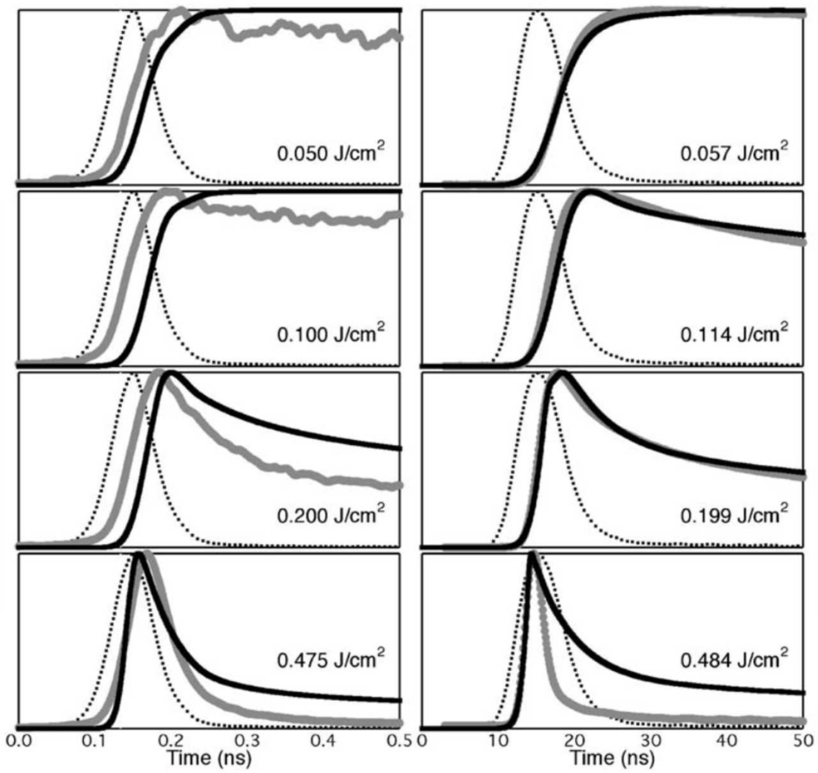
Michelsen, H. A. (2003).
Understanding and predicting the temporal response of laser-induced incandescence from carbonaceous particles
The Journal of Chemical Physics, 118, 7012-7045.

Recipe:

- Nd:YAG laser (injection seeded)
- Photomultiplier
- Oscilloscope



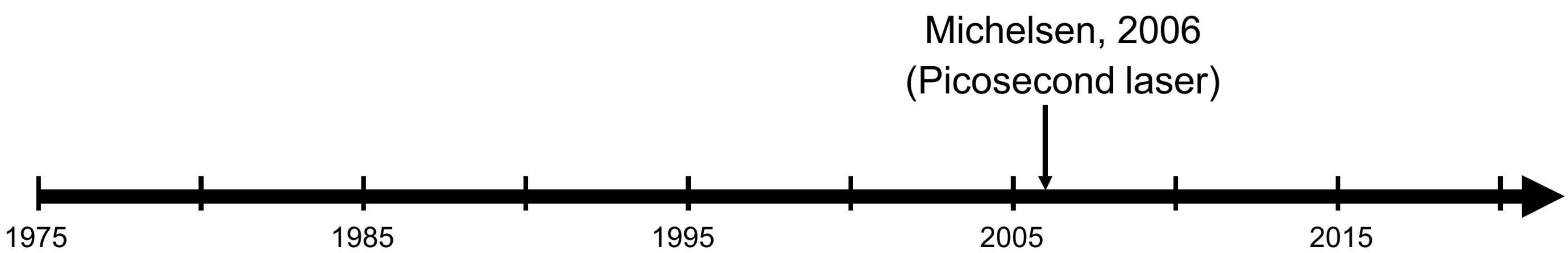
Evolution of hardware for LII



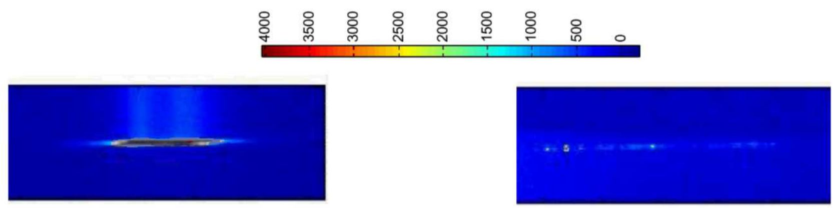
Michelsen, H. A. (2006).
Laser-induced incandescence of flame-generated soot on a picosecond time scale.
Applied Physics B, 83(3), 443.

Recipe:

- Nd:YAG laser (65 ps FWHM)
- Streak camera



Evolution of hardware for LII

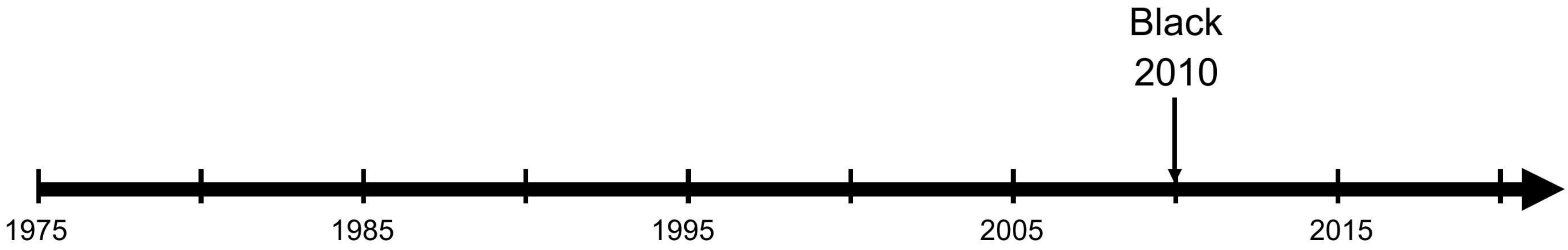


(a) (b)

Black, J. D. (2010).
Fiber Lasers as a Source for Laser-Induced Incandescence in Practical Applications.
OSA Technical Digest Series (CD) paper LWB5.

Recipe:

- High power fiber CW laser
- ICCD



Evolution of hardware for LII

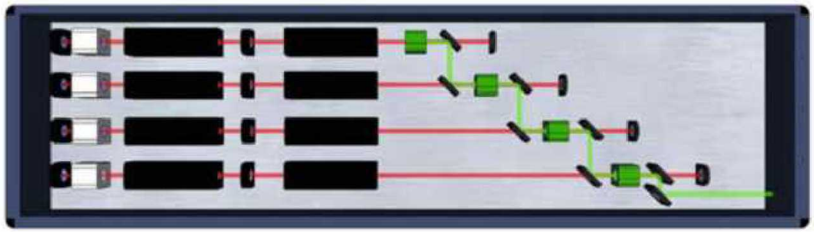
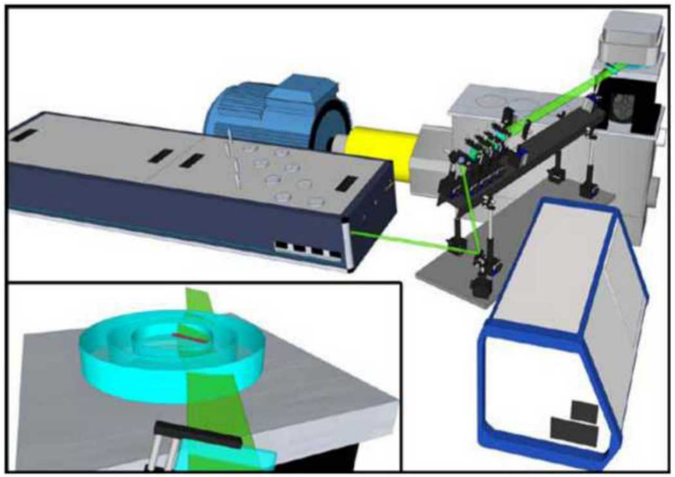


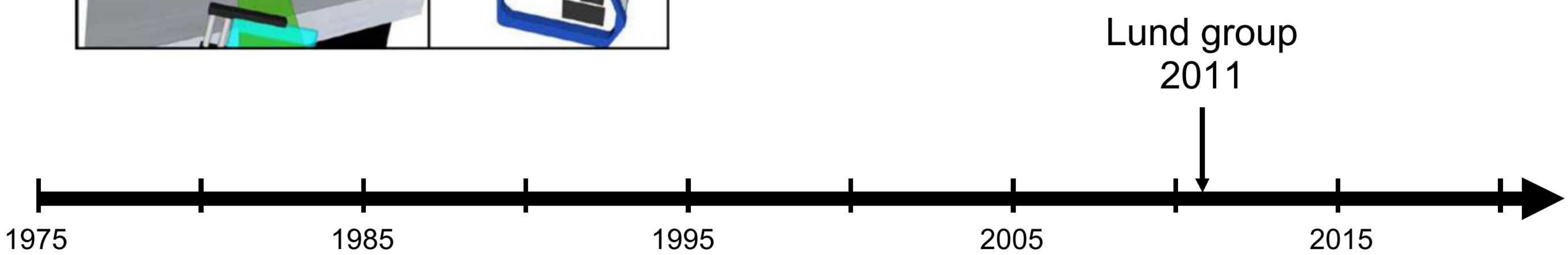
Figure 1. Sketch of the Multi-YAG laser cluster in 532 nm configuration.



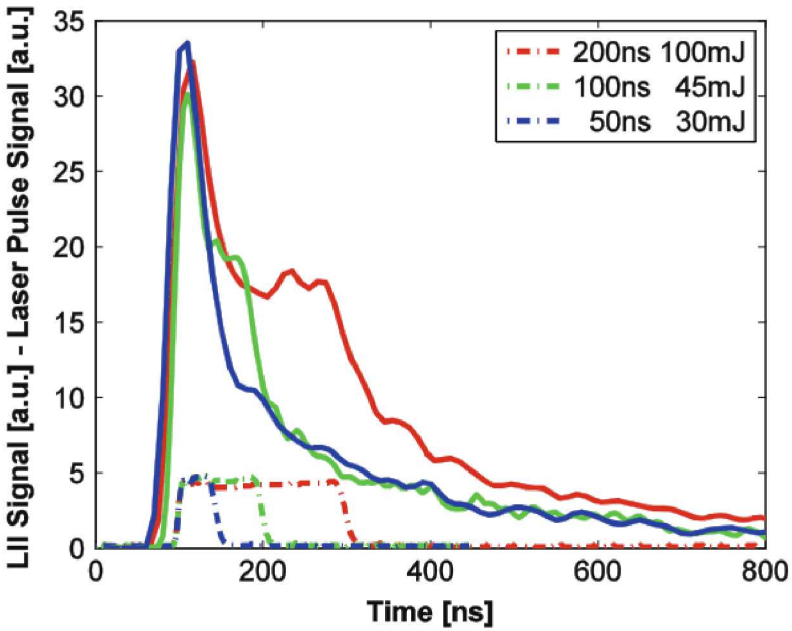
Sjöholm, J., Wellander, R., Bladh, H., Richter, M., Bengtsson, P. E., Alden, M., Johansson, B. (2011). *Challenges for in-cylinder high-speed two-dimensional laser-induced incandescence measurements of soot.* SAE International Journal of Engines, 4(2011-01-1280), 1607-1622.

Recipe:

- 8 Nd:YAG laser (<10-nsec FWHM)
- SIM 8 Camera (1 intensifier and 8 CCD)



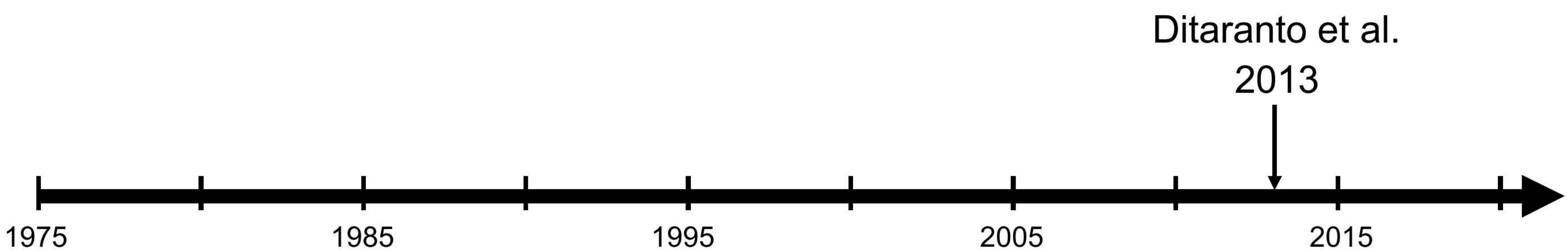
Evolution of hardware for LII



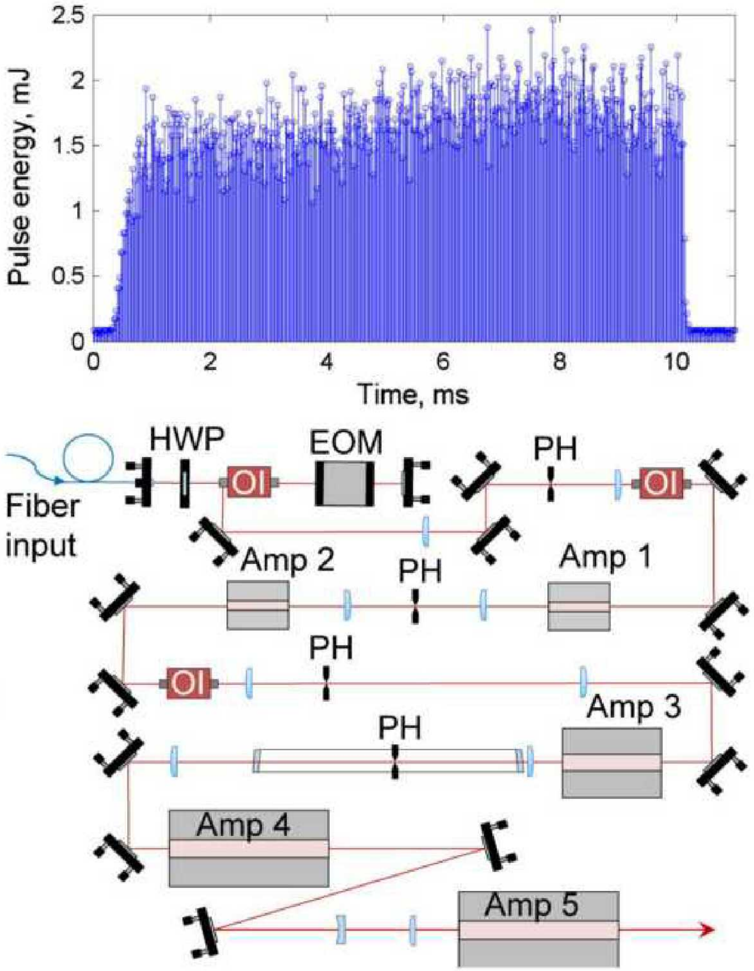
Ditaranto, M., Meraner, C., Haugen, N.E.L., and Saanum, I. (2013).
Influence of long pulse duration on time-resolved laser-induced incandescence.
Appl. Phys. B 112: 359–367.

Recipe:

- Nd:YAG laser with temporal shaping capabilities (50 – 1500 ns)
- Spectrometer and PMT



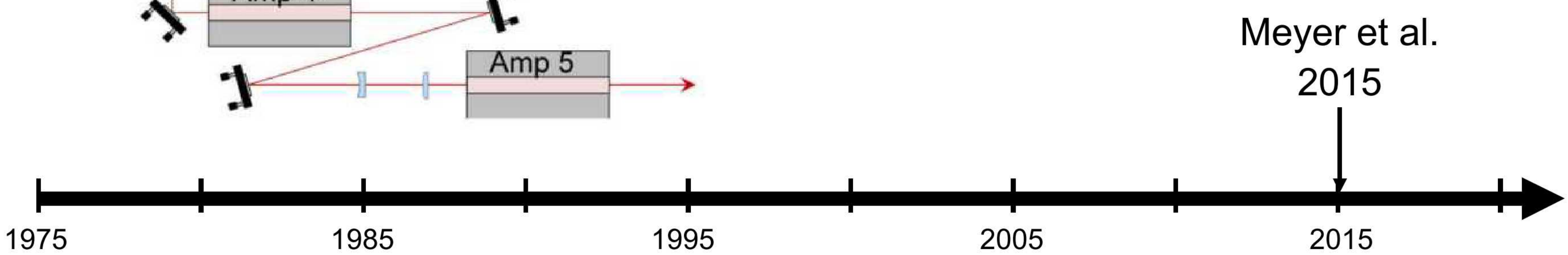
Evolution of hardware for LII



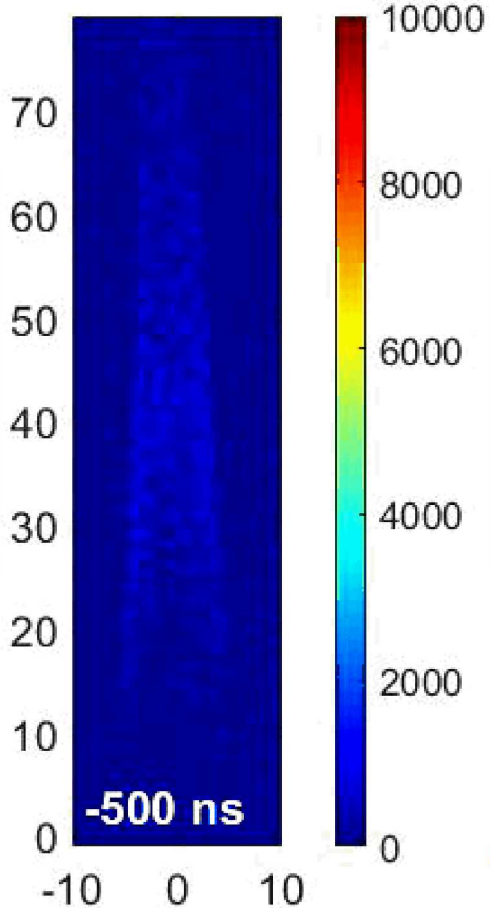
Michael, J. B., Venkateswaran, P., Shaddix, C. R., & Meyer, T. R. (2015).
Effects of repetitive pulsing on multi-kHz planar laser-induced incandescence imaging in laminar and turbulent flames.
Applied Optics, 54(11), 3331-3344.

Recipe:

- 100 kHz using a burst-mode laser system
- High-speed intensifier
- High-speed CMOS camera



Evolution of hardware for LII

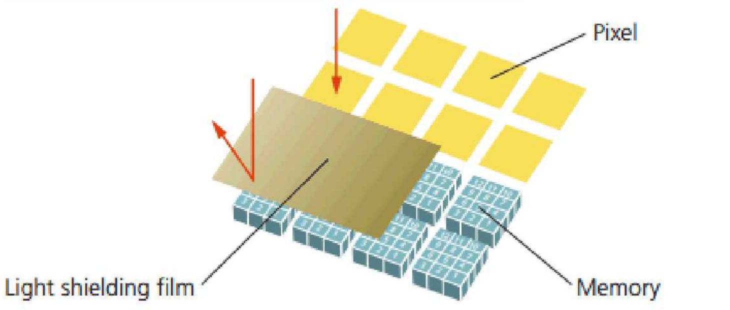


Recipe:

- Nd:YAG (injection seeded)
- Ultra-high-speed CMOS camera (10 million fps)

FTCMOS2 burst image sensor
Extreme sensitivity (**ISO 16,000**)

Max. Recording Speed	10 million frames/second
Resolution	400 (horizontal) × 250 (vertical) pixels
Number of Frames Recorded	256
Exposure time	50 ns

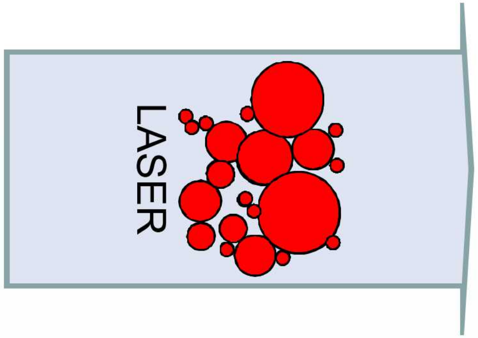


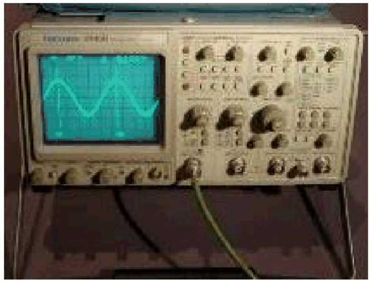
Burst Image Sensor Using Next-Generation CMOS Technology

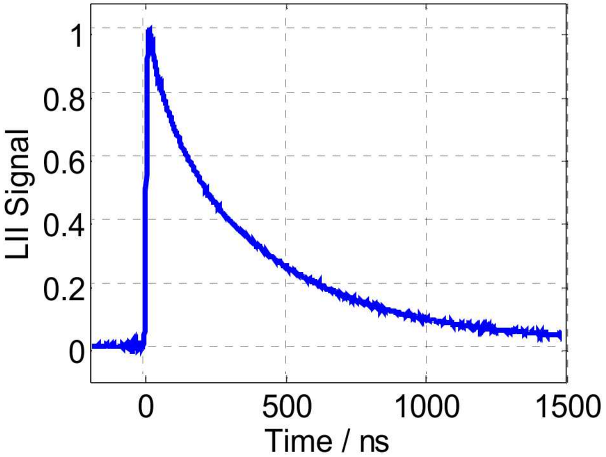
Sandia National Laboratories

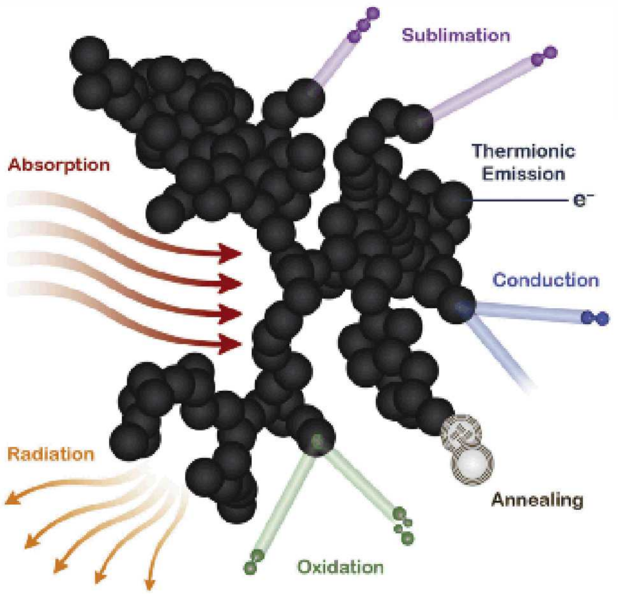
Particle sizing with LII

Time-resolved laser-induced incandescence (TiRe-LII)





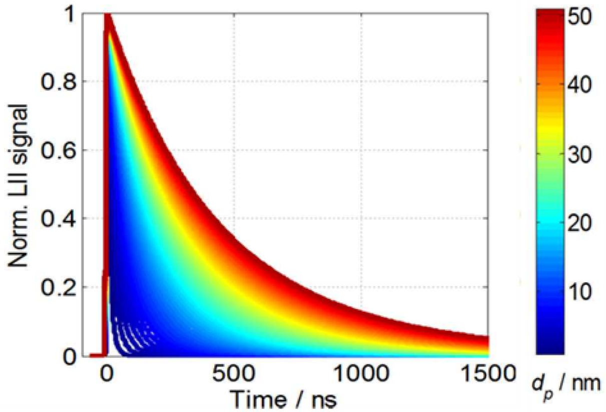




Michelsen, H.A., et al. Prog. Energy Combust. Sci. 51 (2015) 2–48

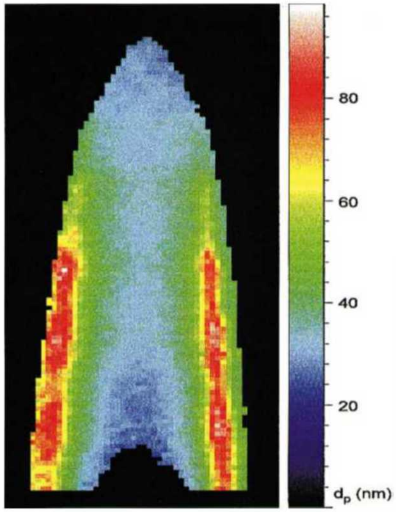
$$\frac{dU_{int}}{dt} = \dot{Q}_{abs} + \dot{Q}_{rad} + \dot{Q}_{cond} + \dot{Q}_{sub} + \dot{Q}_{ox} + \dot{Q}_{ann} + \dot{Q}_{therm}$$

$$\frac{dM}{dt} = \left(\frac{dM}{dt}\right)_{sub} + \left(\frac{dM}{dt}\right)_{ox}$$



Sandia National Laboratories

Particle-size imaging with LII



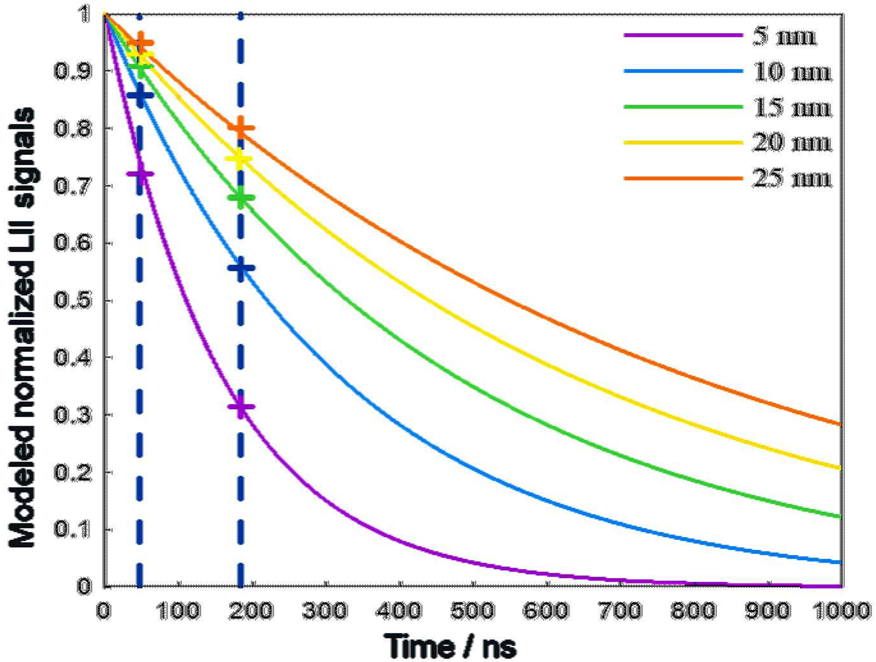
Particle-size imaging

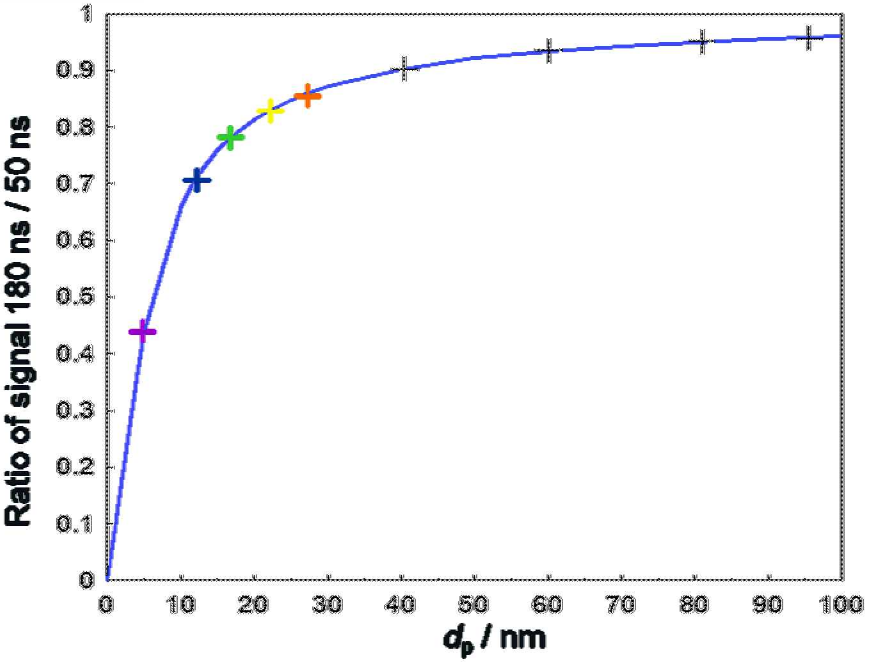
Determine the spatial distribution of d_p

Will, S., Schraml, S., and Leipertz, A. (1995).

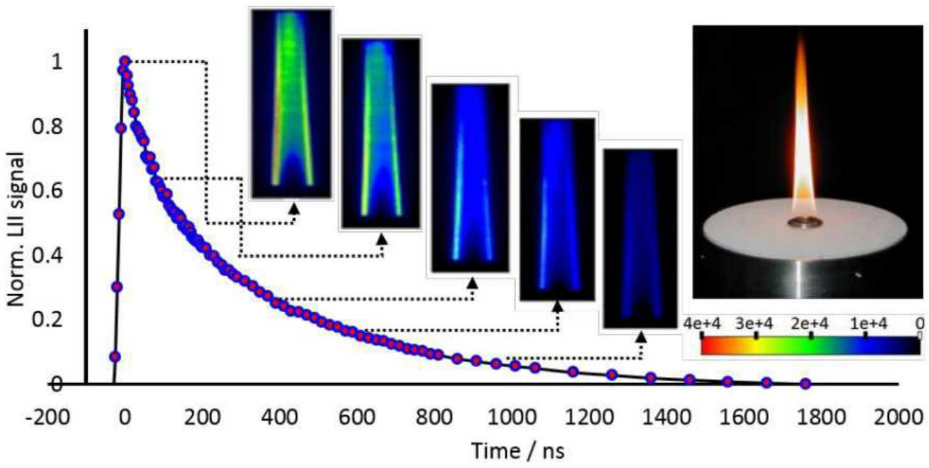
Two-dimensional soot-particle sizing by time-resolved laser-induced incandescence. *Opt. Lett.* 20: 2342–2344.

- Image ratio



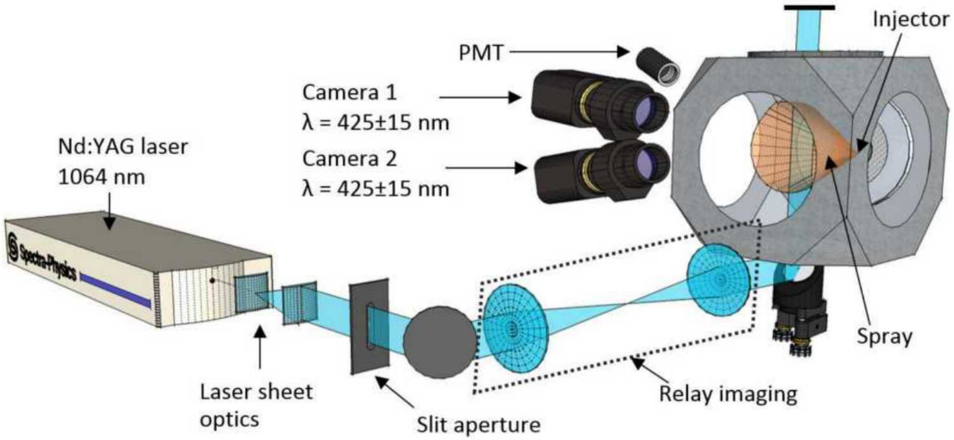


Particle-size imaging with LII



Time-gate sweeping:

- Only works for steady flames/flows
- Flame perturbations
- Laser shot-to shot variations
- Extended data acquisition duration



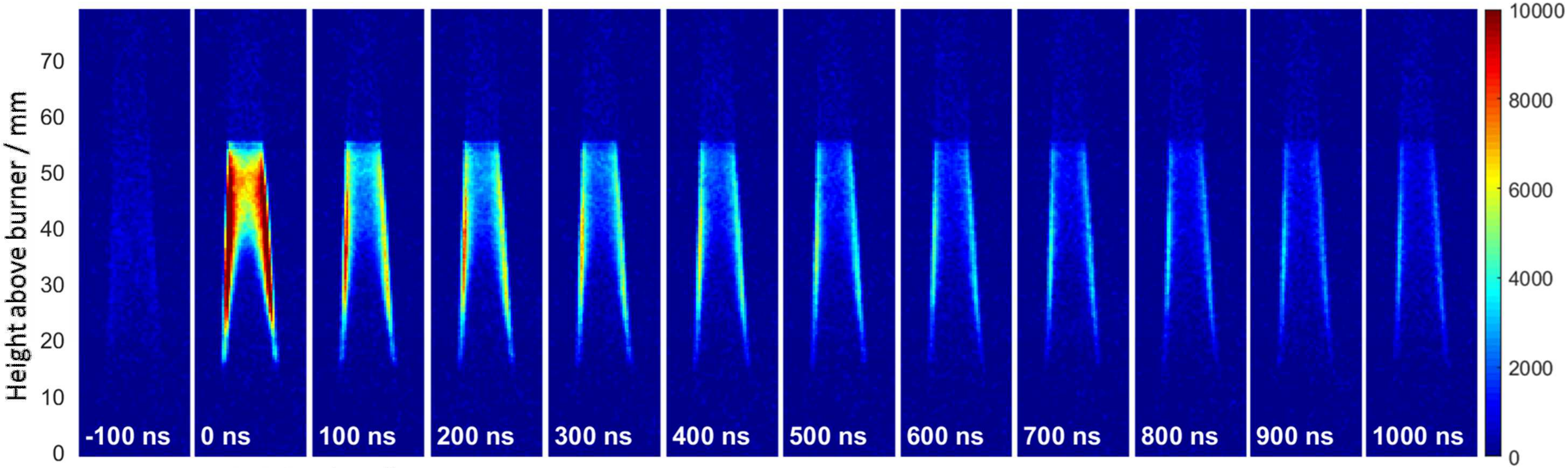
Multiple camera:

- Image mapping
- Different light-to-signal linearity
- Packaging

LII imaging at 10 million fps

The proof of concept measurements:

- Co-annular non-premixed laminar ethylene/air flame (Santoro burner)
- 1064-nm (injection seeded) laser sheet
- Fluences from 0.03 to 0.15 J/cm^2.
- Detection wavelength band: 608-674
- Experiments were done in New Mexico. Altitude: 5000 ft → P_{atm} = 0.84 bar

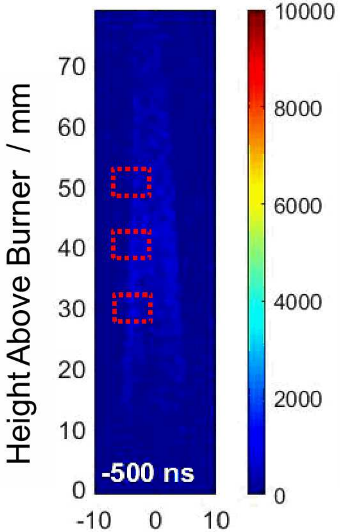


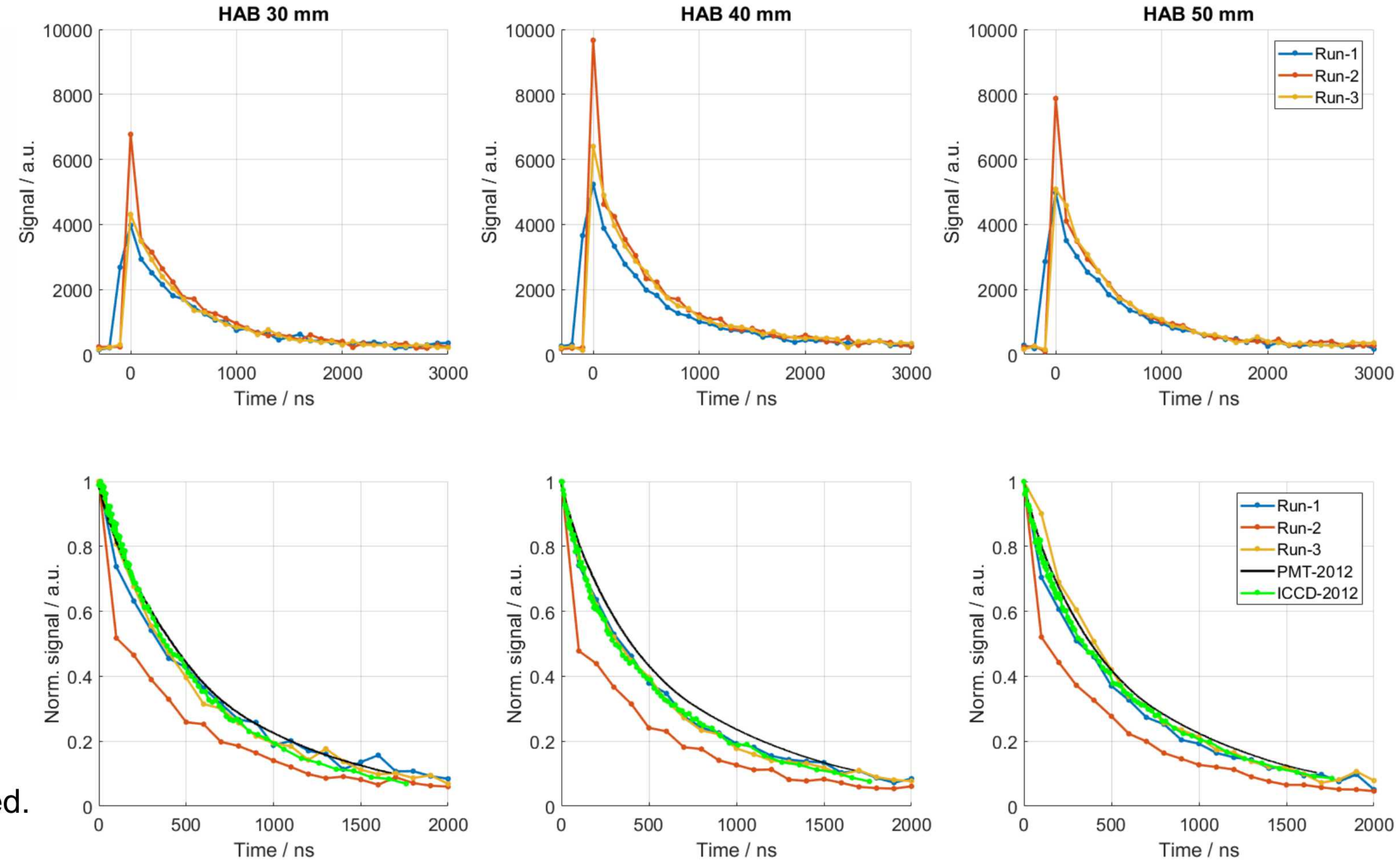
Fluence: 0.08 J/cm^2

The first 10 to 20 images following laser excitation show LII signal that is clearly above the background signal and sufficiently strong to compare to the modeled LII decay.

Benchmarking signal decay

- 3 single shots (Run#2 is an outlier).
- PMT and ICCD (gate sweeping, 92 nodes) data are acquired in 2012 at IFPEn (at 1 bar, 0.08±0.01 J/cm^2, 655±20 nm).

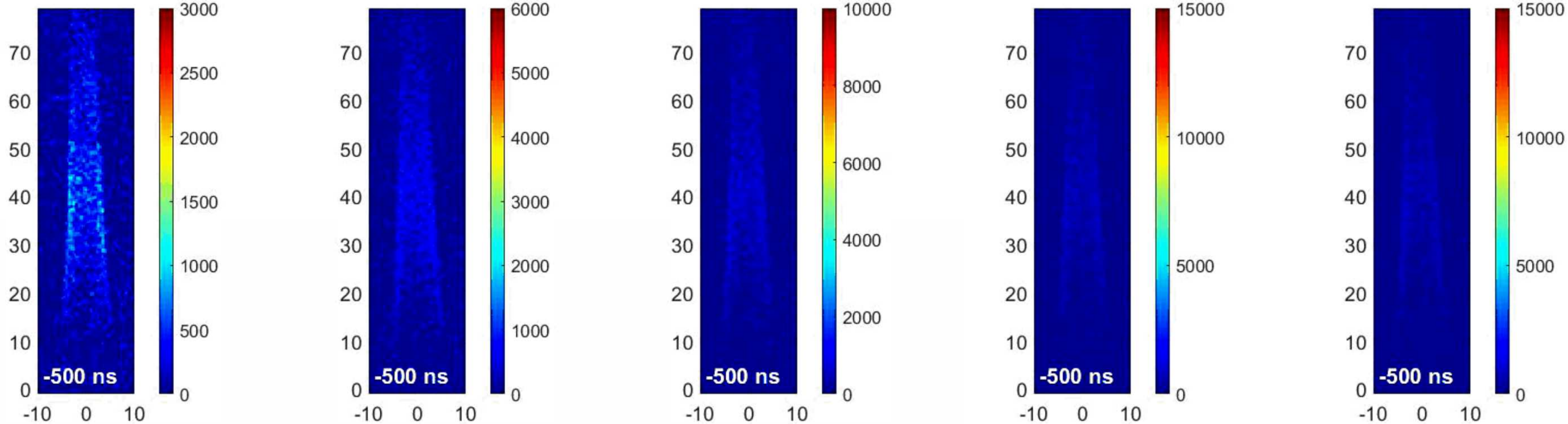




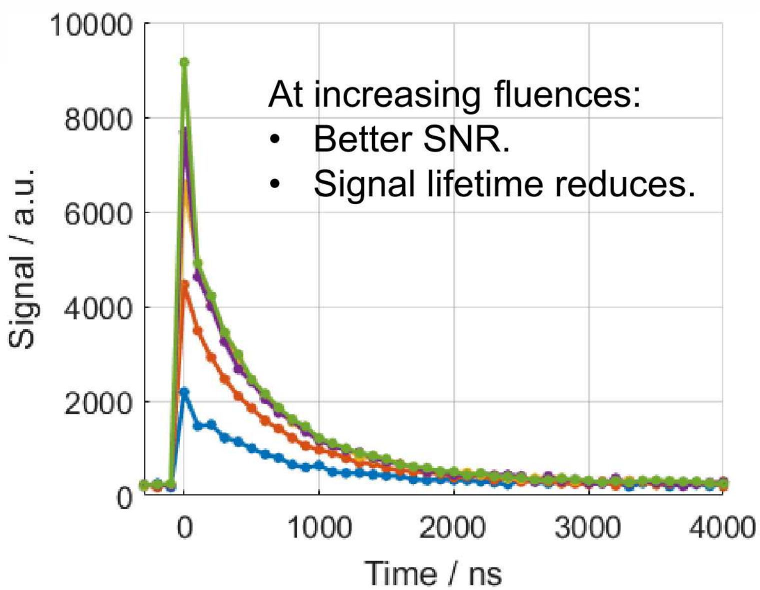
Mean value of 5x12 (60 px ROI).

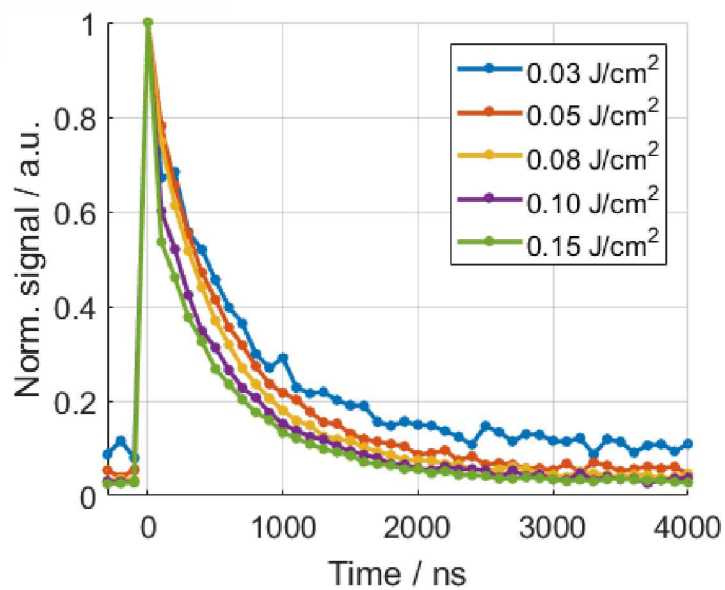
Background correction:
97% of the natural luminosity subtracted.

Effects of laser fluence



F: 0.03 J/cm^2 F: 0.05 J/cm^2 F: 0.08 J/cm^2 F: 0.10 J/cm^2 F: 0.15 J/cm^2

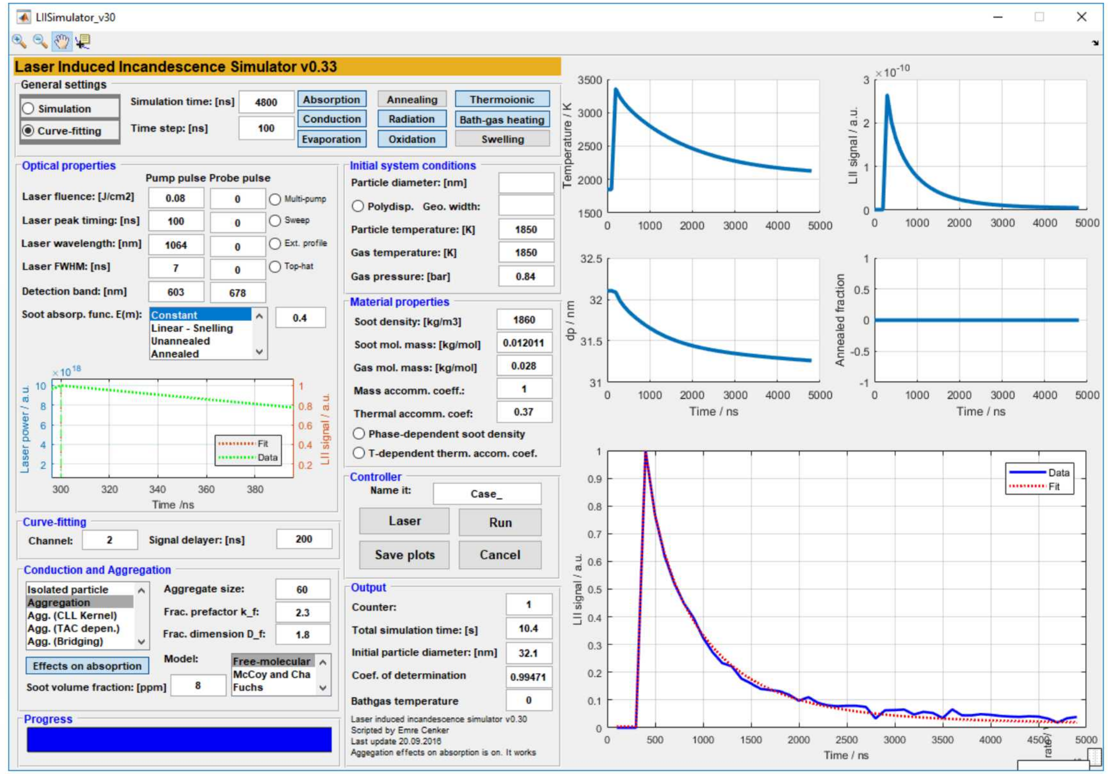


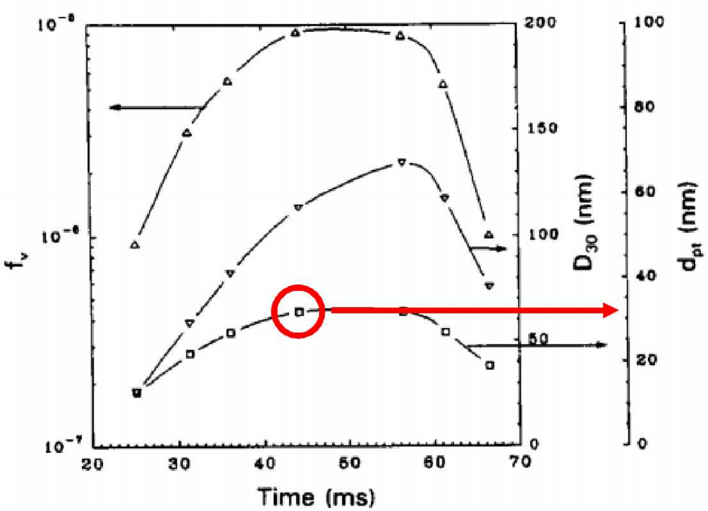


Particle-size prediction with LII model

LII model:

HAB	40 mm
Gas temperature	1850 K (pyrometry)
Pressure	0.84 bar (5000 ft)
Laser fluence	0.08 J/cm^2
$E(m)$	0.4 (literature)
TAC	0.37 (literature)
Aggregate size	60 (TEM)
Time domain	4500 ns (aLaser)
Detection band	603 – 678 nm
Annealing	Off
Bath-gas heating	On (f_v = 6 ppm)



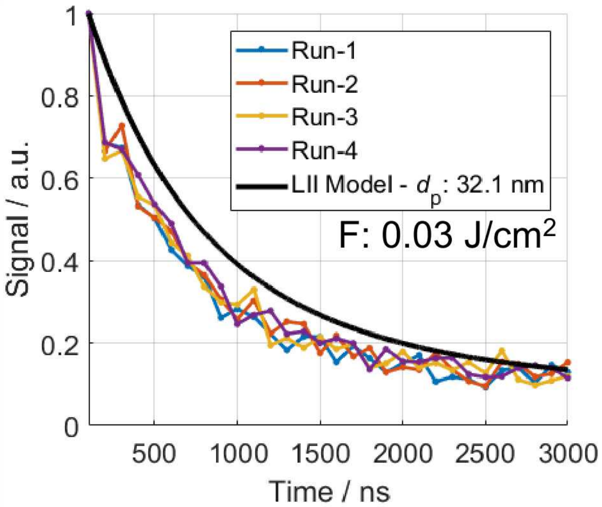


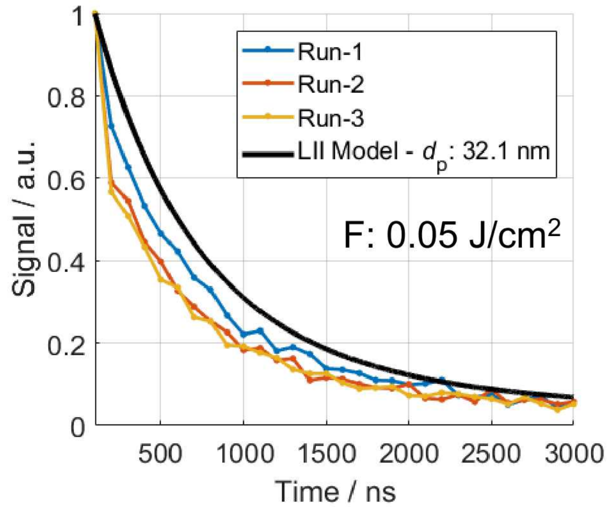
Puri, R., Richardson, T. F., and Santoro, R. J. (1993). Aerosol Dynamic Processes of Soot Aggregates in a Laminar *Combust. Flame* 92: 320–333.

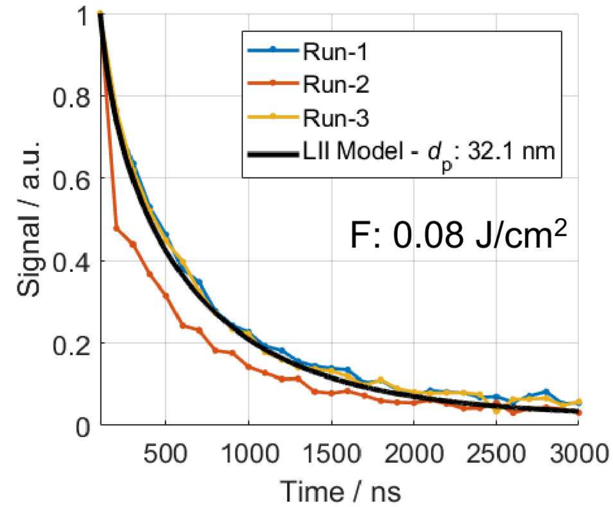
- Successful fit: R^2>0.99
- Predicted $\boldsymbol{d_p}$ **= 32.1 nm**

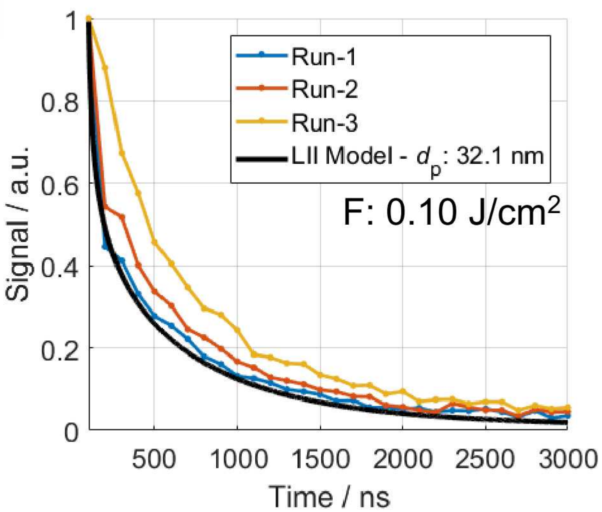
Sandia National Laboratories

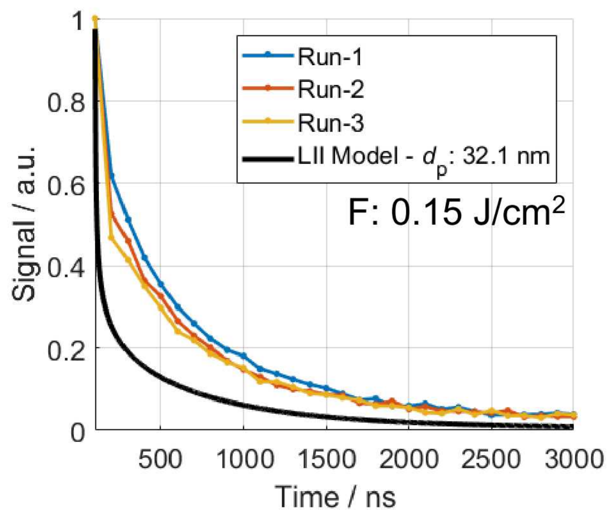
Particle-size prediction with LII model











- Optimized for 0.08 J/cm^2
- 0.15 J/cm^2 fails because of the Gaussian laser profile.

The model is simulating a homogenous heating (top-hat laser profile) and due to the strong evaporation, solid material vanishes and signal drops.

Experiments, on the other hand, were performed with 1D Gaussian laser sheet where evaporated soot at the center is compensated with heated soot at the wings.

Conclusion

- The new CMOS technologies provide sufficient sensitivity for (delayed) LII imaging.
- Temporally and spatially resolved LII signal can be acquired at 10 million fps. The state of the art cameras provide very short gating capabilities.

- Signals from the ultra-high-speed camera are in good agreement with the previous PMT measurements.
- Evaluated particle sizes show good agreement with those reported in the literature.
- Compared to imaging with multiple sensors or time-gate sweeping strategies, this new ultra-high-speed LII imaging reduces uncertainties due to
  - image mapping
  - flame perturbations
  - laser shot-to-shot variations.

Thank you.