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Structured Laser Illumination Planar Imaging, SLIPI, for imaging of dense sprays

Subtask 3.4D: Application of Laser Techniques for Combustion Diagnostics

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Combustion Physics
Lund University, Sweden

IEA-TLM, Nara, Japan, 2010-07-27

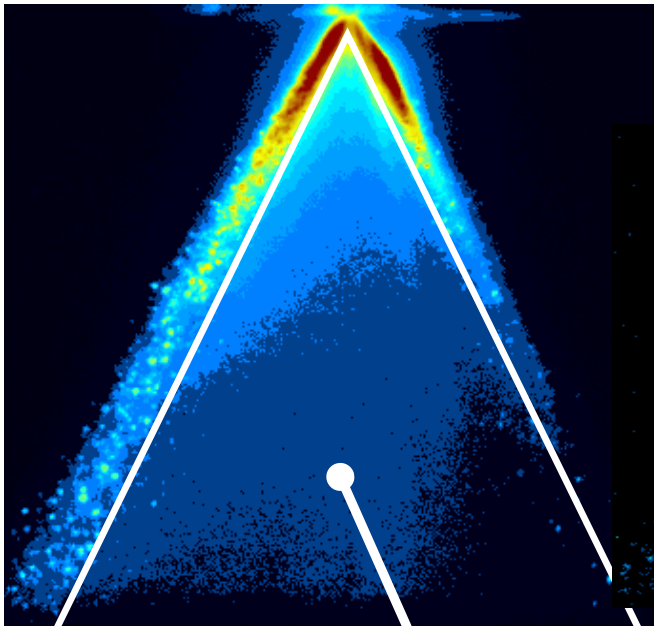
“Attempts to use conventional laser optical techniques to provide information about the internal structure of high-speed jets have been unsuccessful owing to the multiple scattering by droplets and interfaces”

Nature Physics 4, 305 - 309 (2008)



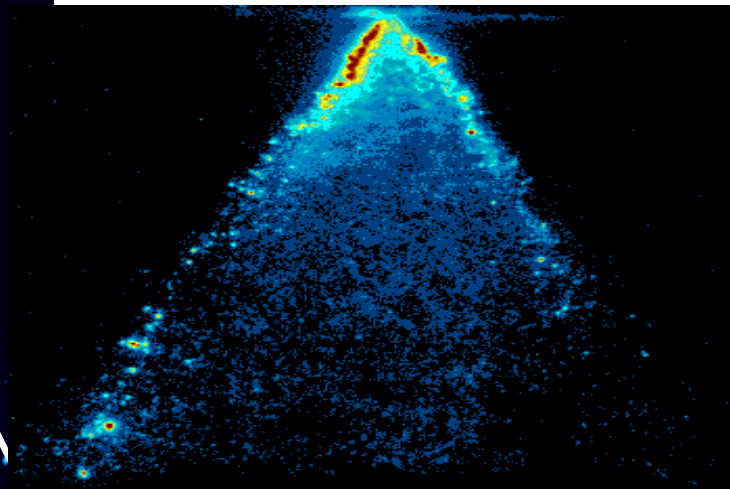
CONVENTIONAL PLANAR LASER IMAGING

Averaged image

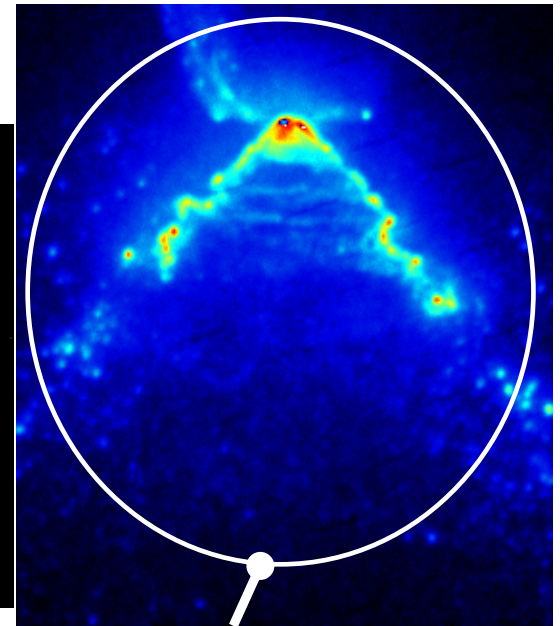


Wrong light intensity contribution

Single shot



Single shot

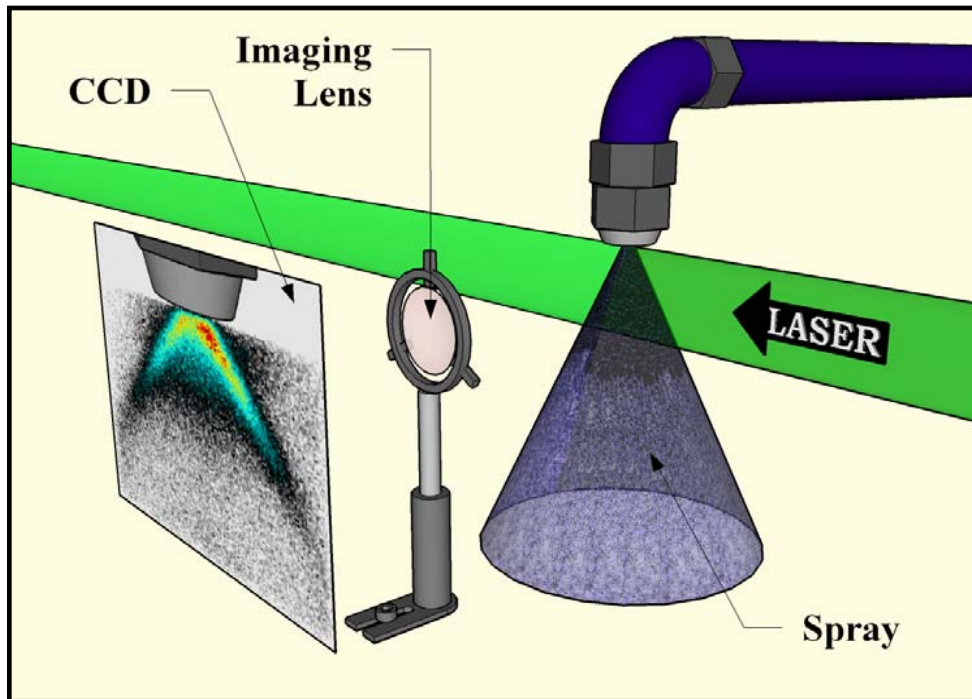


Aureole of light blurring the image

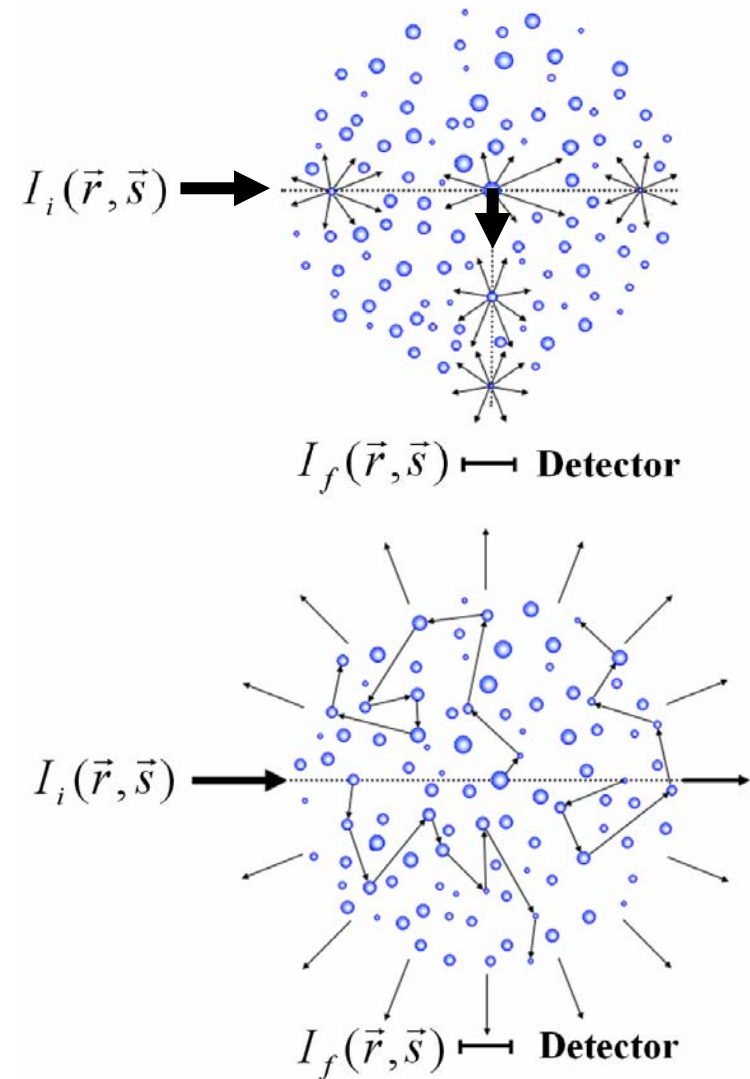
All Laser Diagnostics of Dense Sprays based on **Planar Imaging** are strongly restricted by errors introduced by **Multiple Scattering**



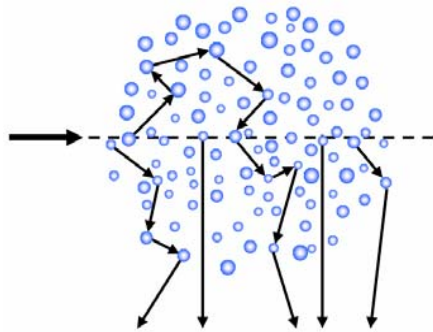
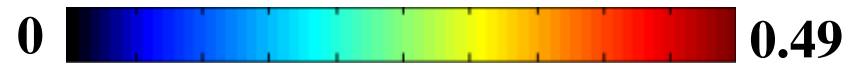
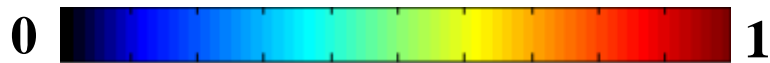
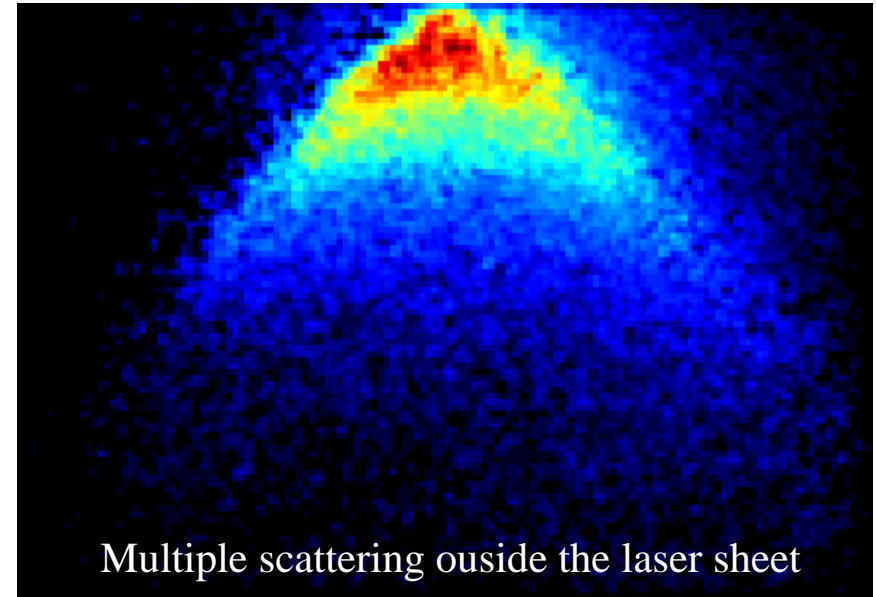
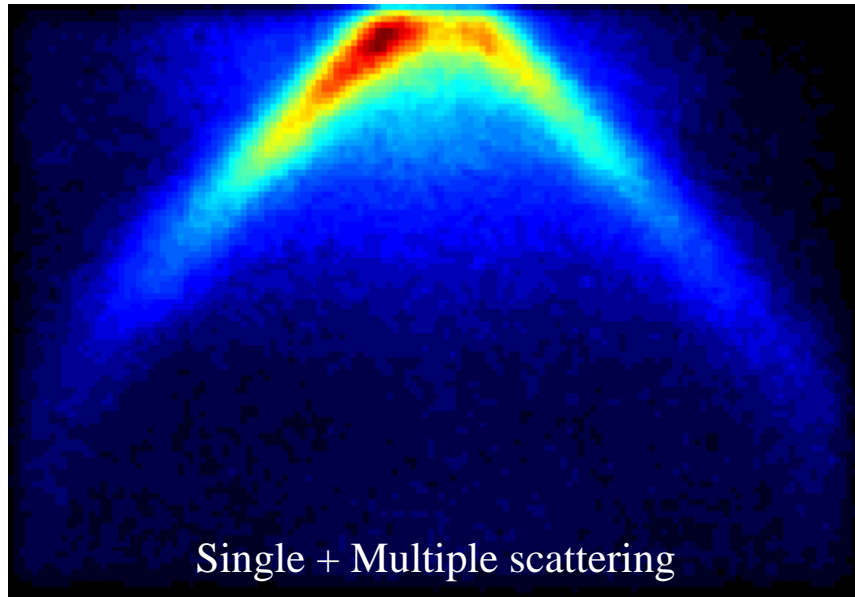
SOURCES OF ERROR IN PLANAR LASER IMAGING



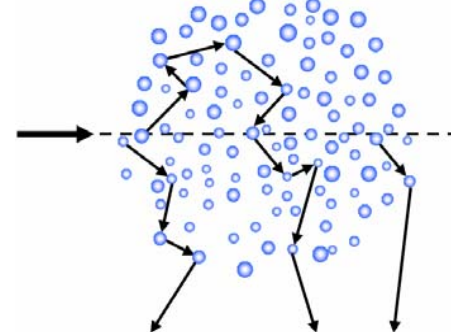
- **Laser Extinction:** Loss of the incident radiation
- **Signal Attenuation:** Loss of the signal
- **Multiple Scattering:** False signal created



SIMULATION OF LASER SHEET IMAGING VIA MONTE CARLO MODELLING



How can multiple scattering be removed experimentally?

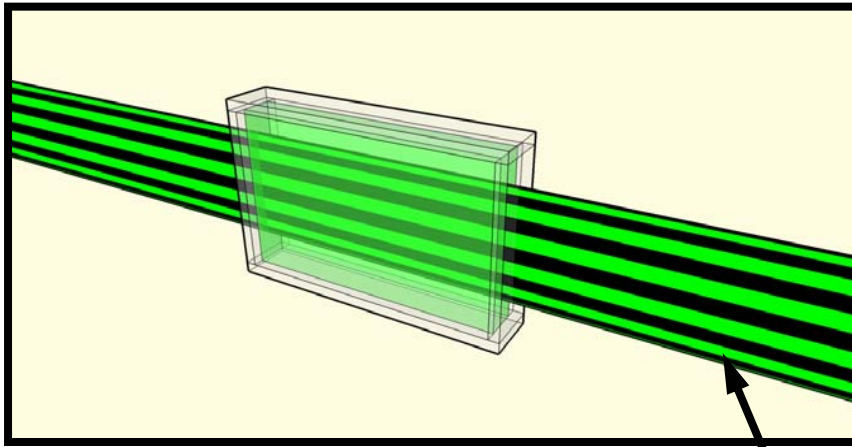


STRUCTURED LASER ILLUMINATION PLANAR IMAGING

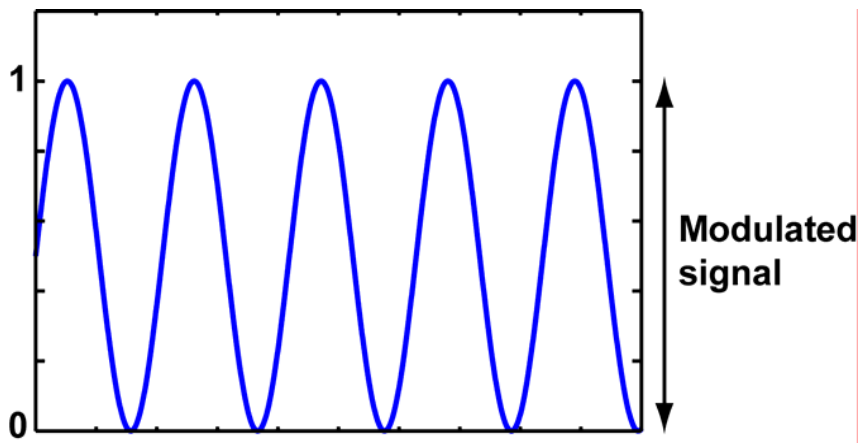
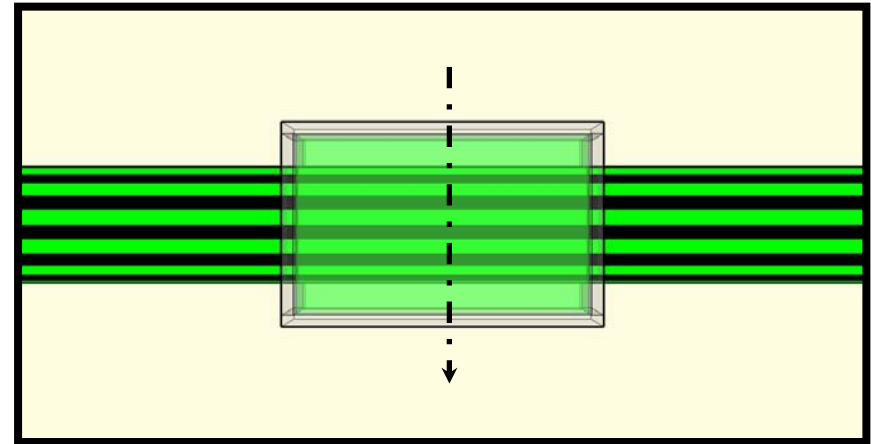
- Part 1: Separation of singly scattered light
- Part 2: Reconstruction of the laser sheet
- Part 3: Suppression of multiple scattering



Part 1: Separation of singly scattered light



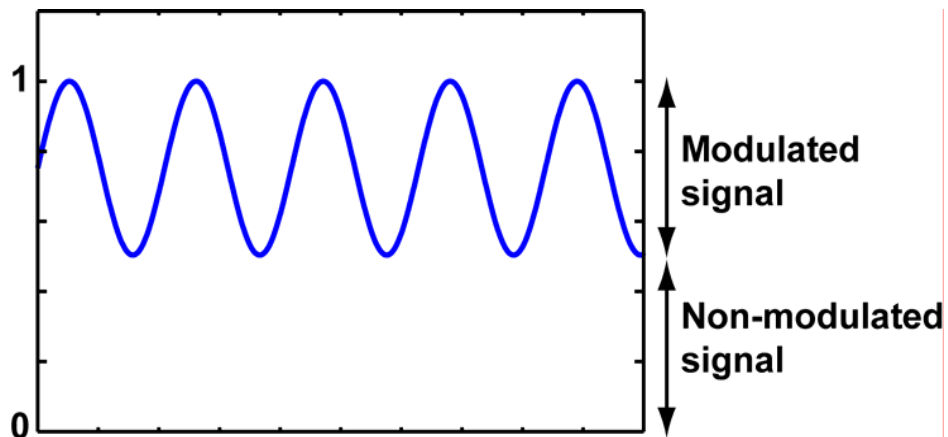
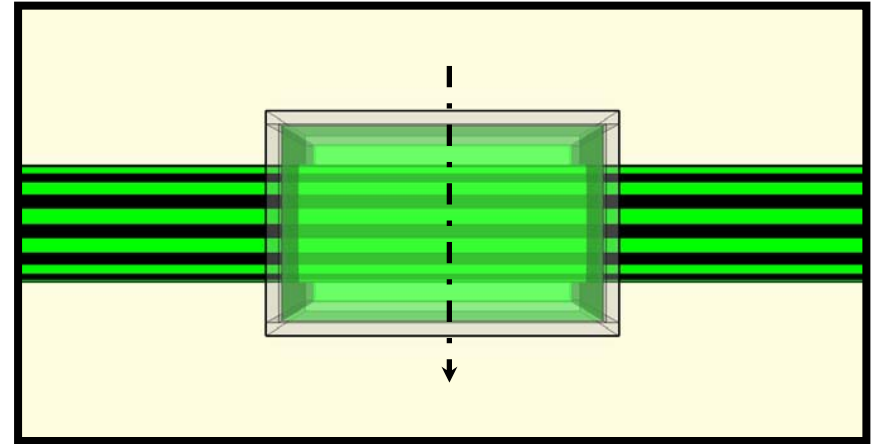
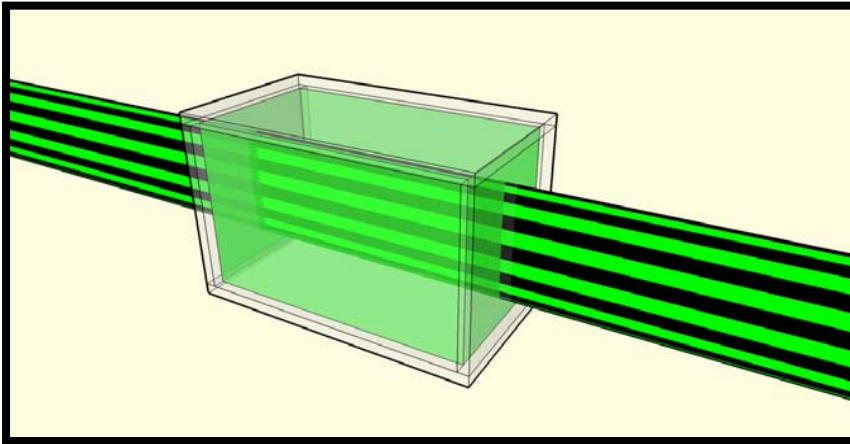
Structured laser sheet



Almost all light is modulated, i.e. directly scattered. No multiple scattering.



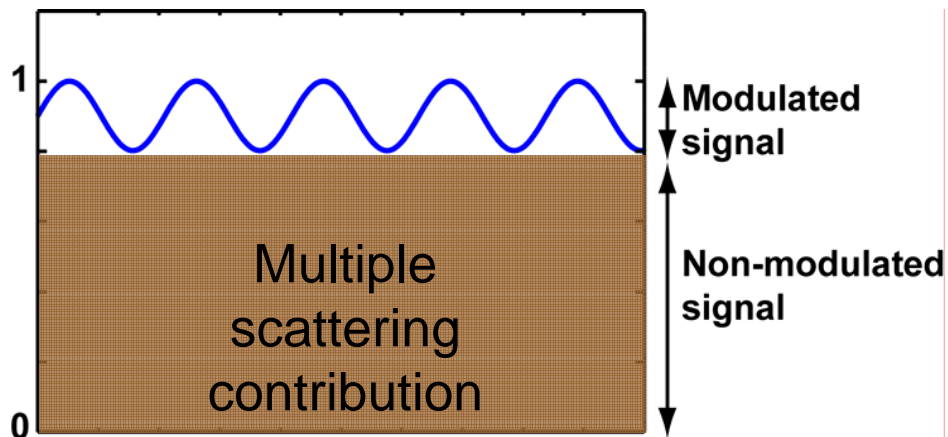
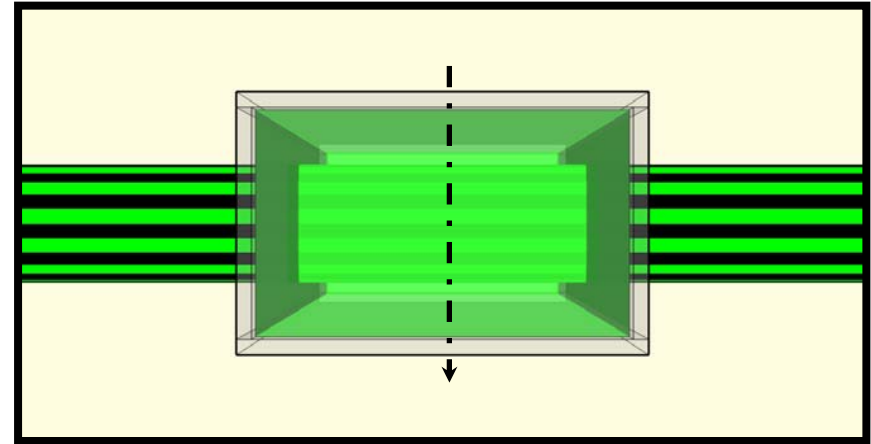
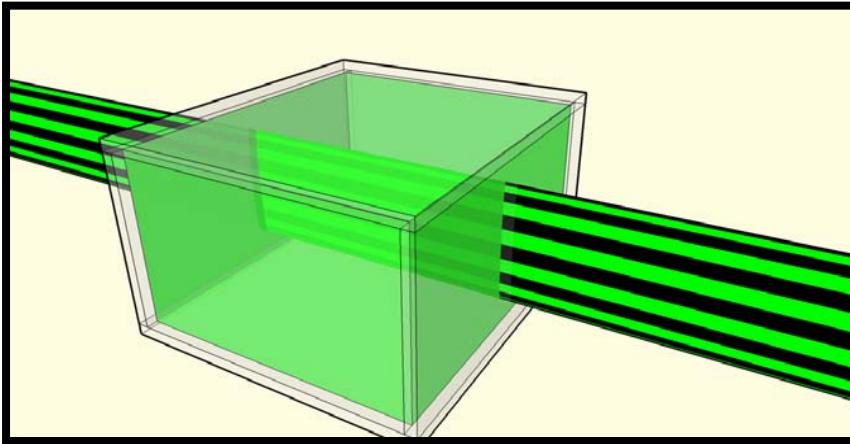
Part 1: Separation of singly scattered light



Modulation is reduced,
due to light being
multiply scattered.



Part 1: Separation of singly scattered light



Almost no light is modulated, only a small portion is directly scattered.

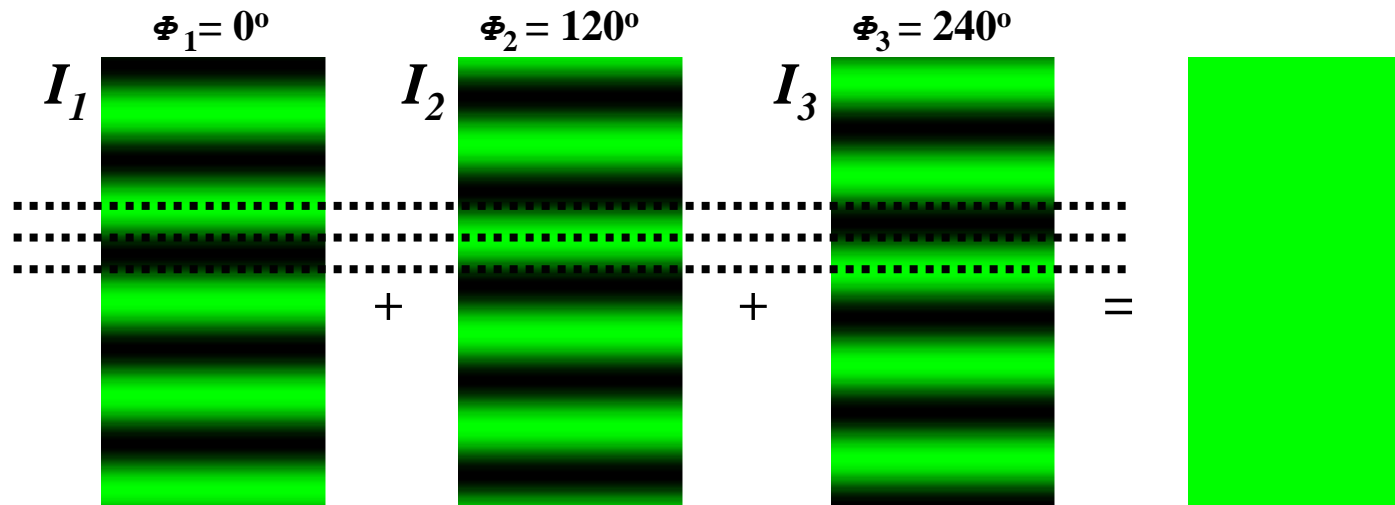


STRUCTURED LASER ILLUMINATION PLANAR IMAGING

- Part 1: Separation of singly scattered light
- Part 2: Reconstruction of the laser sheet
- Part 3: Suppression of multiple scattering



Part 2: Reconstruction of the laser sheet



Record three images, with a phase shift of a third of a period between each image

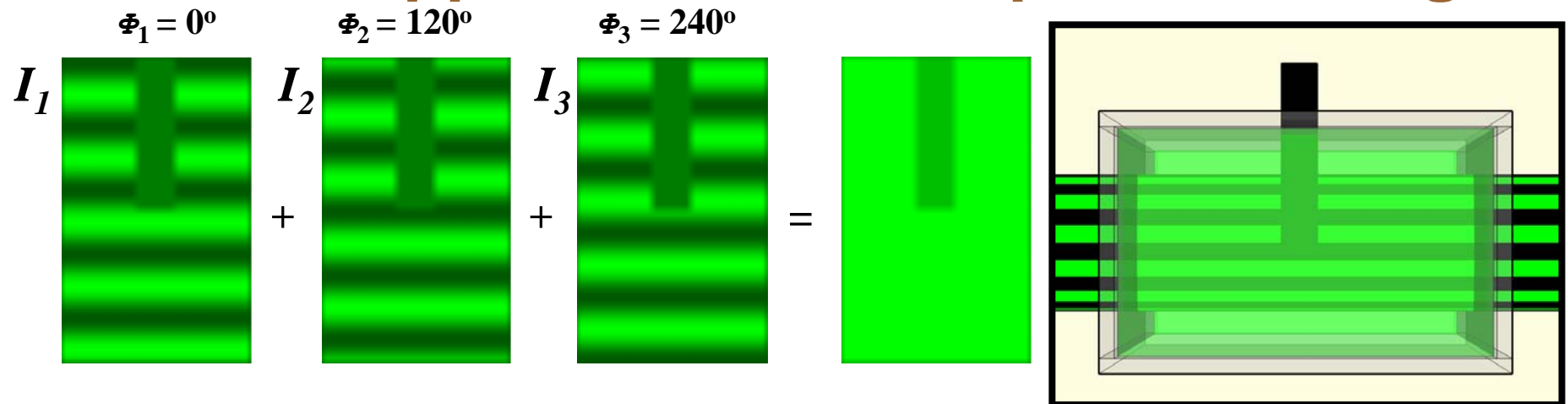


STRUCTURED LASER ILLUMINATION PLANAR IMAGING

- Part 1: Separation of singly scattered light
- Part 2: Reconstruction of the laser sheet
- Part 3: Suppression of multiple scattering



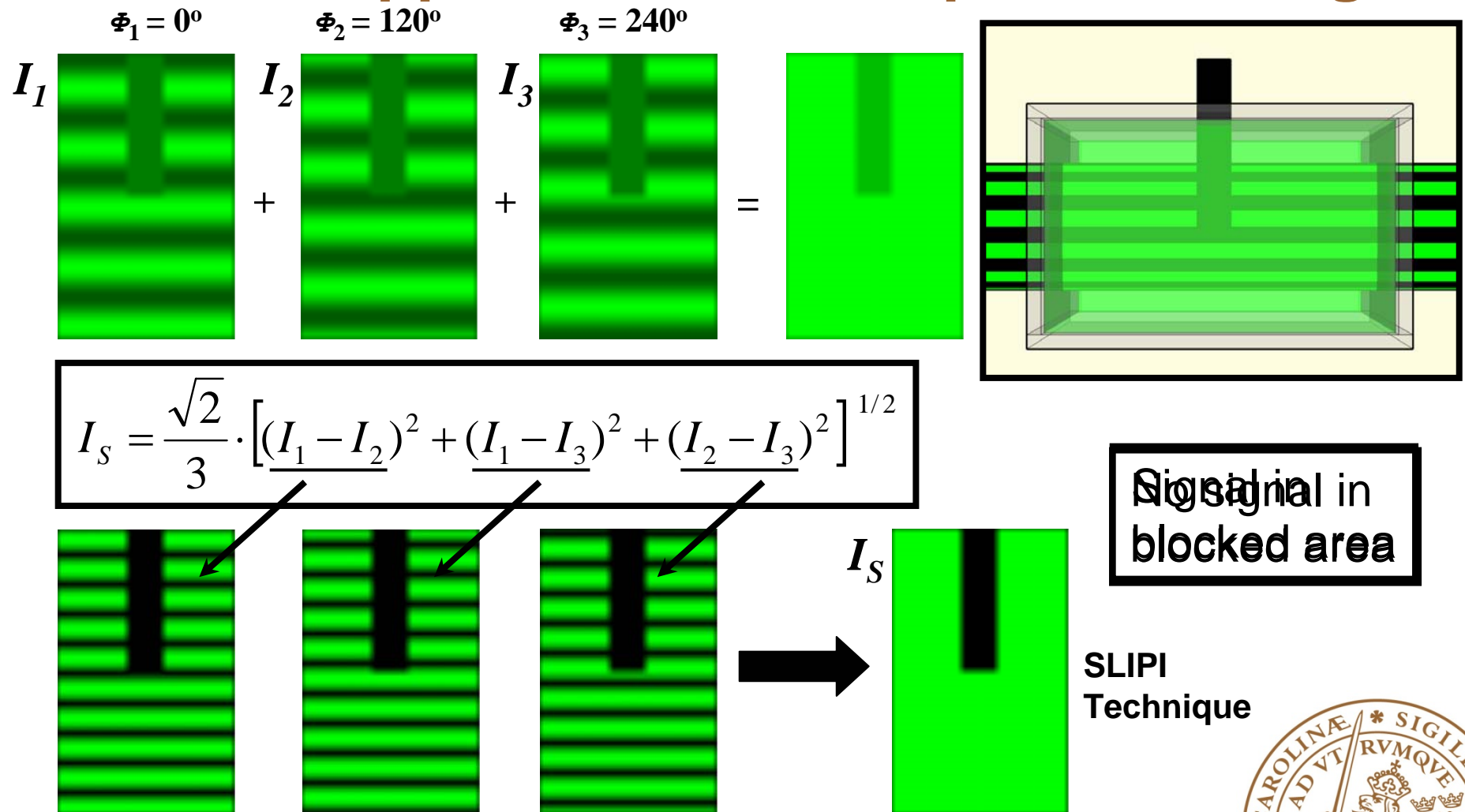
Part 3: Suppression of multiple scattering



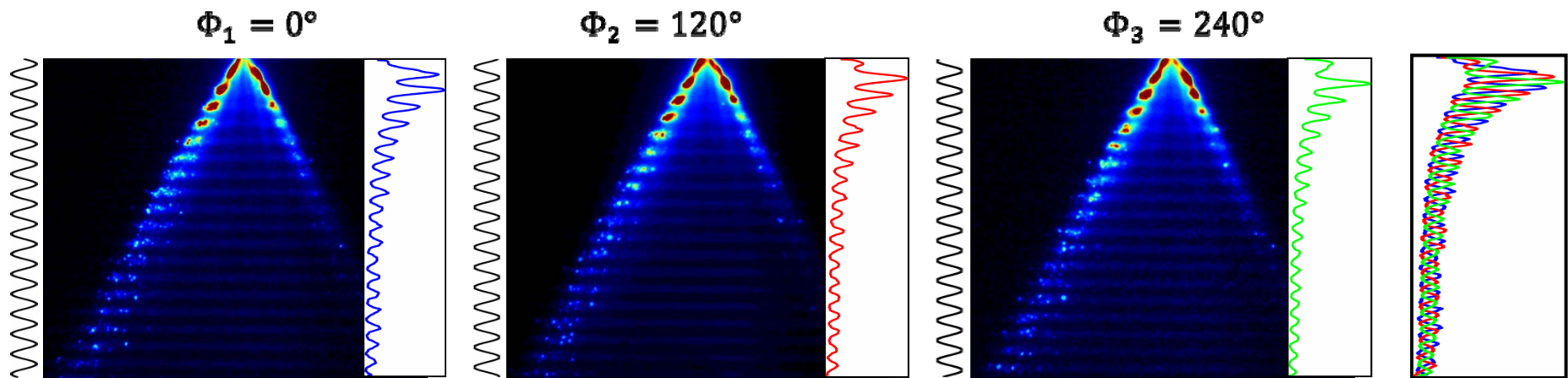
Signal in
blocked area



Part 3: Suppression of multiple scattering

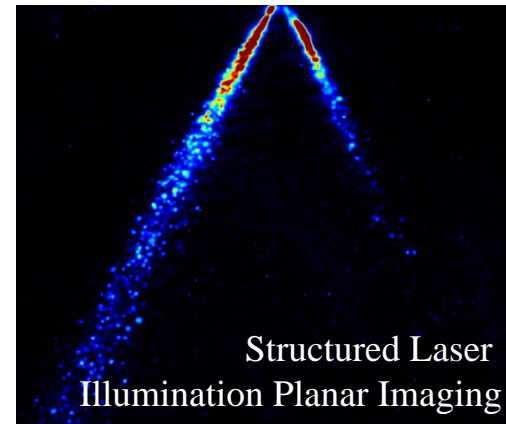
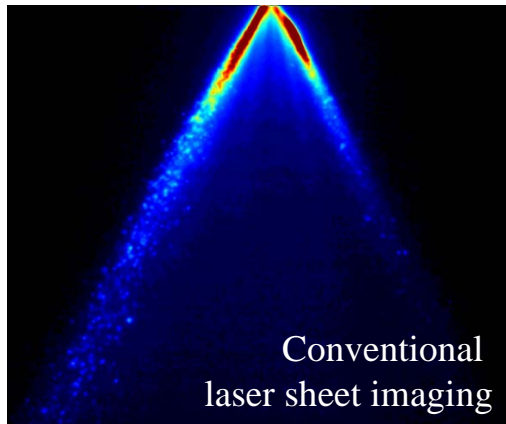


STRUCTURED LASER ILLUMINATION PLANAR IMAGING

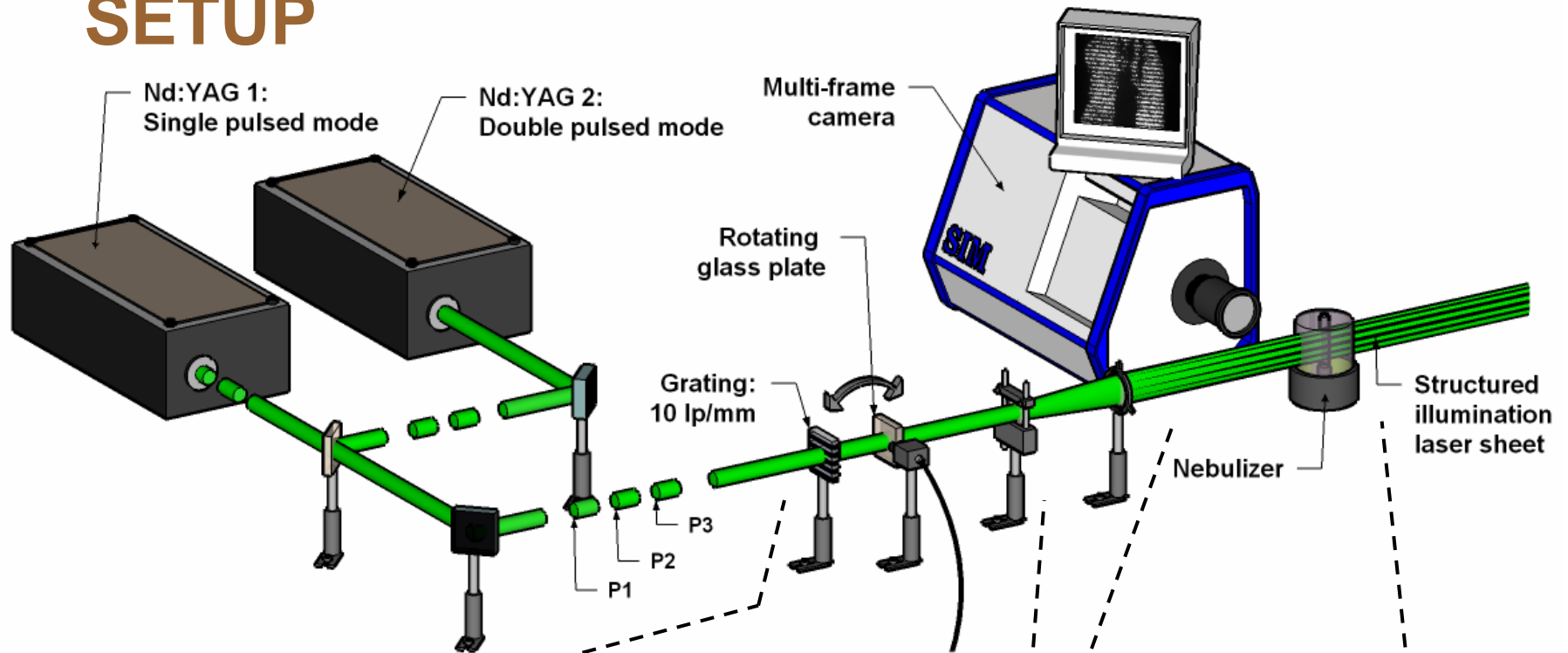


$$I_G = \frac{I_1 + I_2 + I_3}{3}$$

$$I_S = \frac{\sqrt{2}}{3} \cdot \sqrt{(I_1 - I_2)^2 + (I_1 - I_3)^2 + (I_2 - I_3)^2}$$

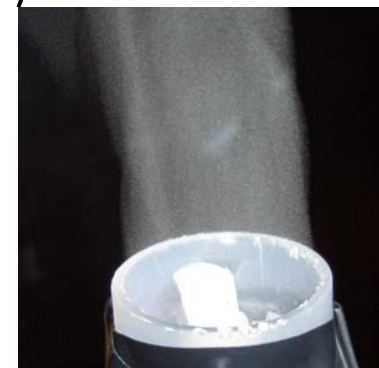
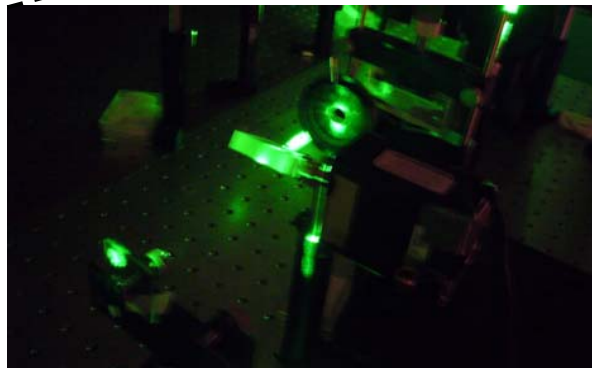


FIRST SINGLE-SHOT EXPERIMENTAL SETUP



Capabilities:

- Single-shot imaging
- Flows up to 25 cm/s
- Study of a nebulizer
- Limit: Rotating glass plate
- 12-bit intensified CCDs

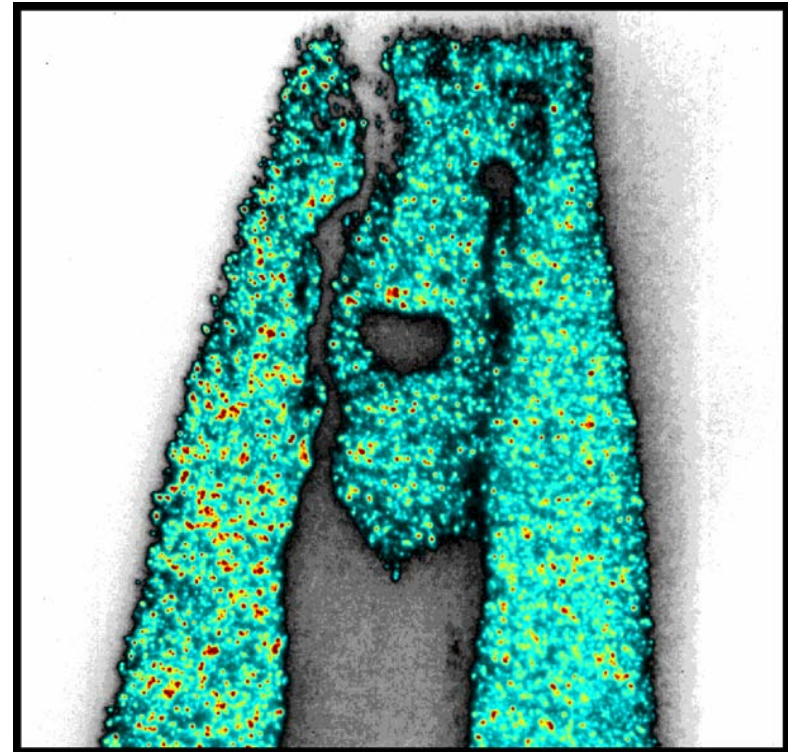


FIRST SINGLE-SHOT SLIPI

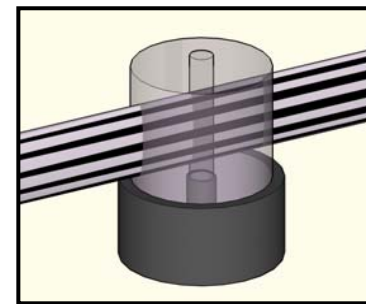
SLIPI



Conventional Laser Sheet

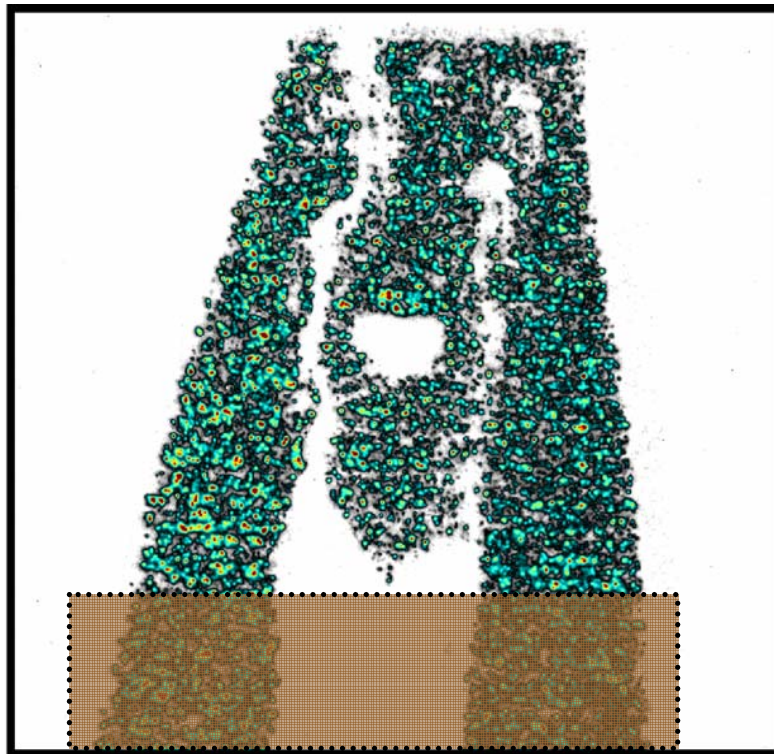


- **Slow flow** of water droplets
- Additional inner **flow of nitrogen** for quantification
- **55 μ s** pulse separation, velocities up to **25 cm/s**
- Separated liquid structures, **voids** more visible

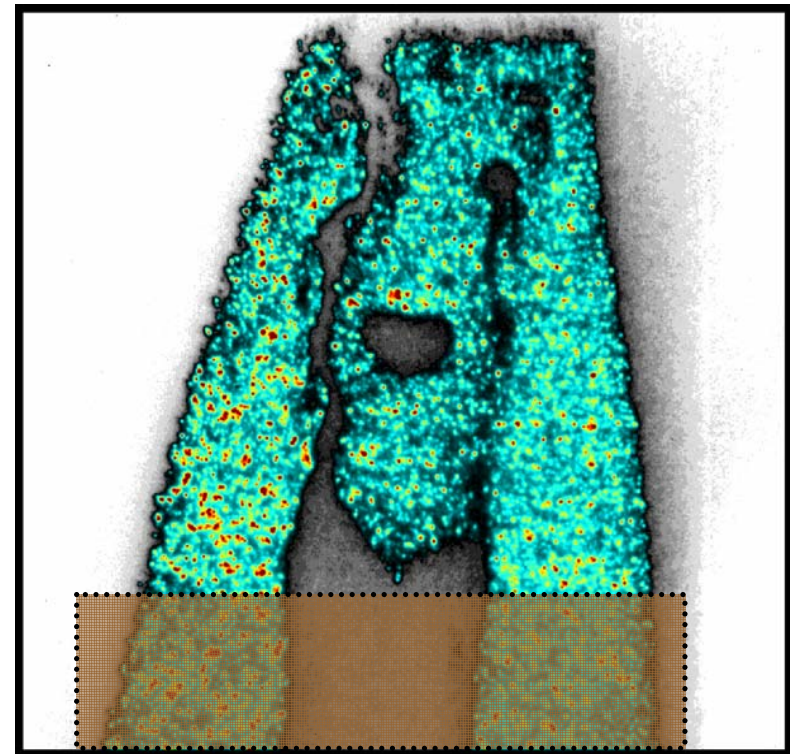


FIRST SINGLE-SHOT SLIPI

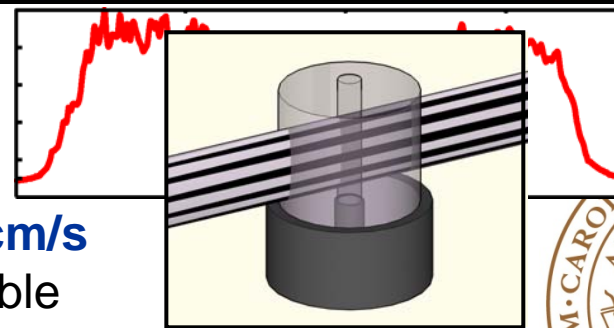
SLIPI



Conventional Laser Sheet

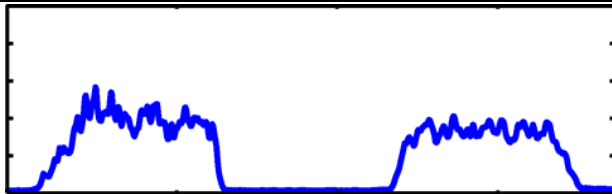
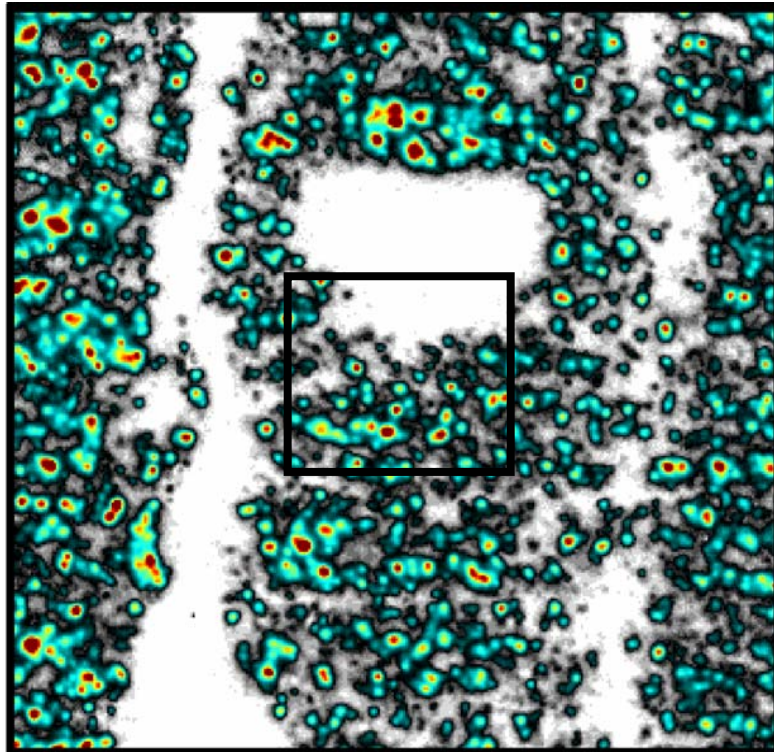


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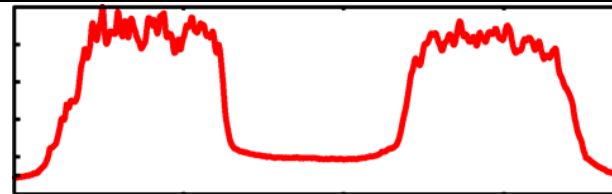
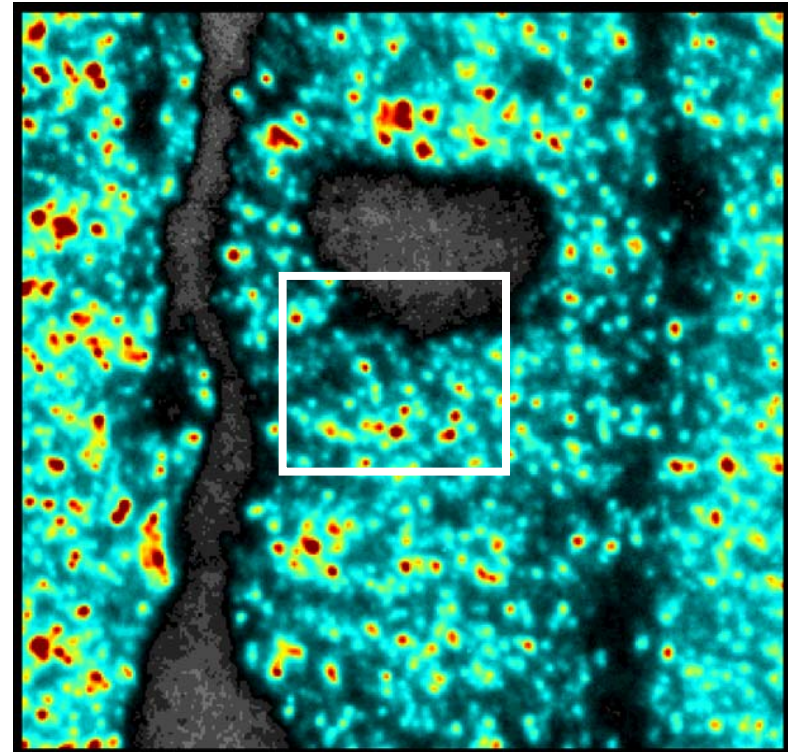


FIRST SINGLE-SHOT SLIPI

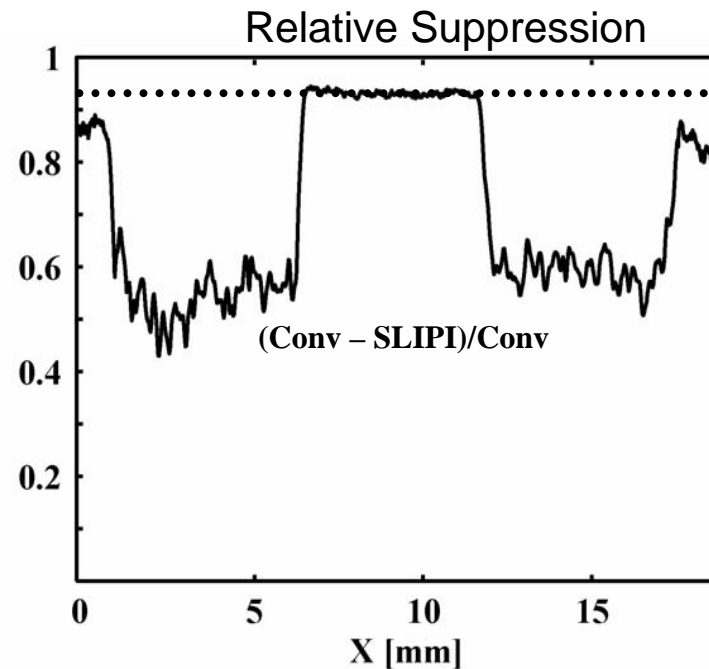
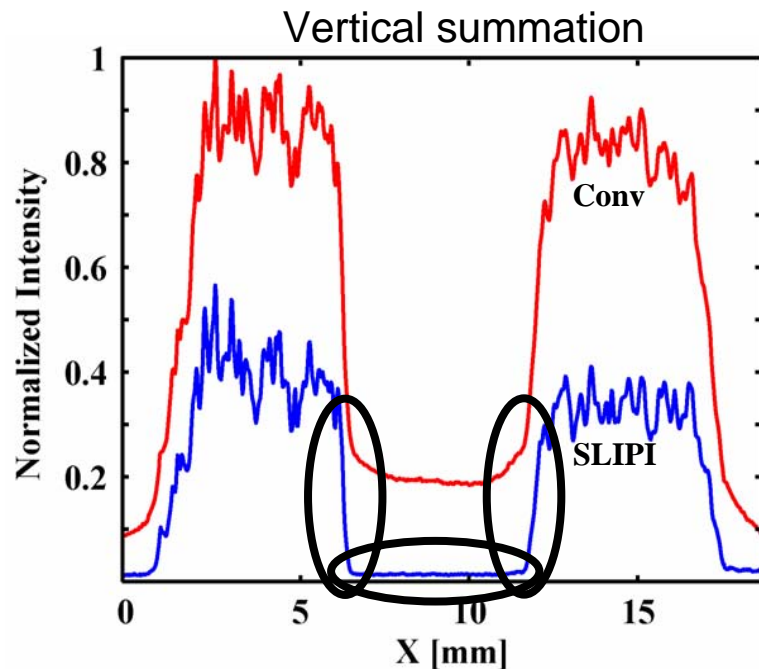
SLIPI



Conventional Laser Sheet



SUPPRESSION ANALYSIS



- Droplet-free region **tends to zero** for SLIPI
- Sharper "on-off" **gradient**
- ~**93 %** suppression in droplet-free region

Laser sheet



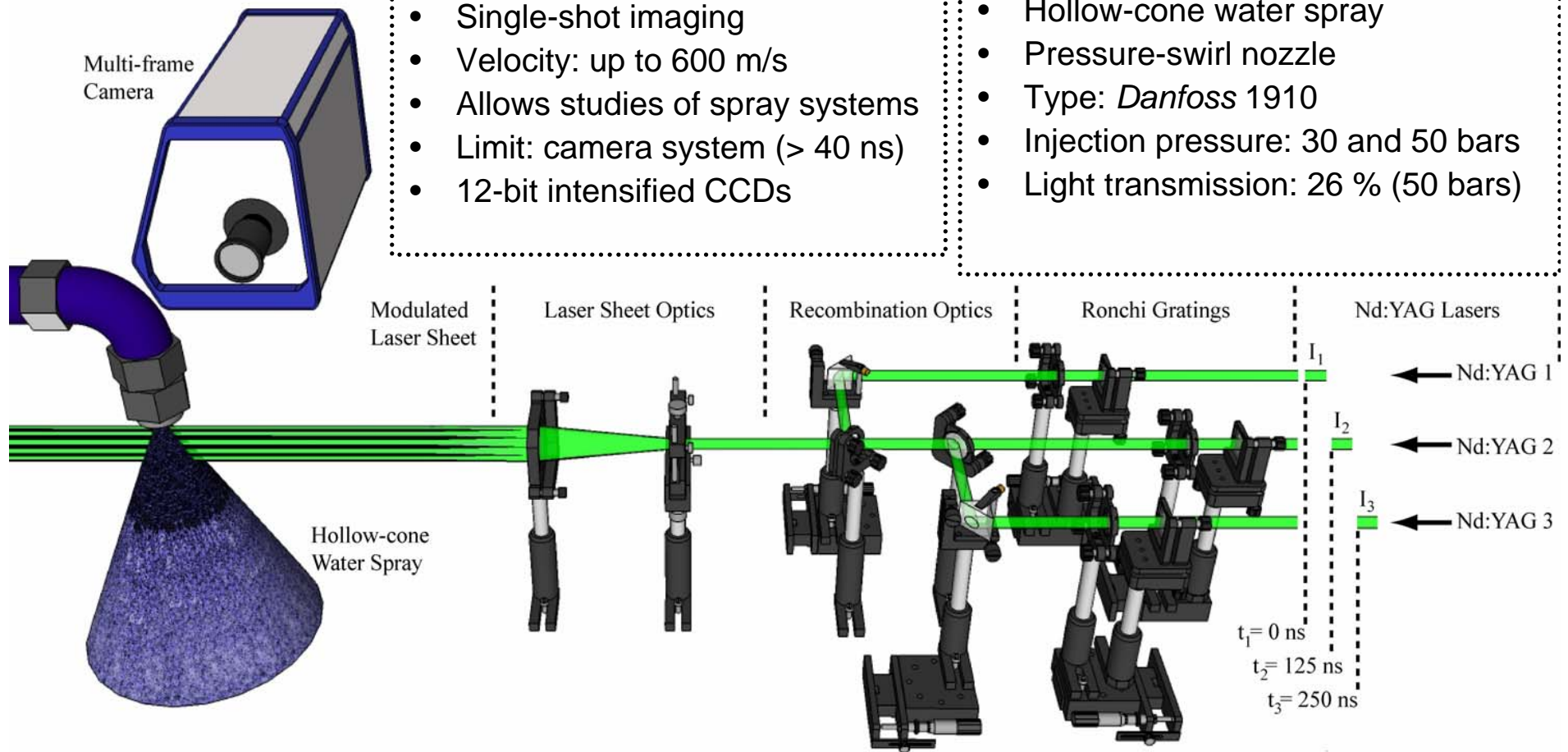
ULTRA-FAST SLIPI – OPTICAL ARRANGEMENT

Capabilities:

- Single-shot imaging
- Velocity: up to 600 m/s
- Allows studies of spray systems
- Limit: camera system (> 40 ns)
- 12-bit intensified CCDs

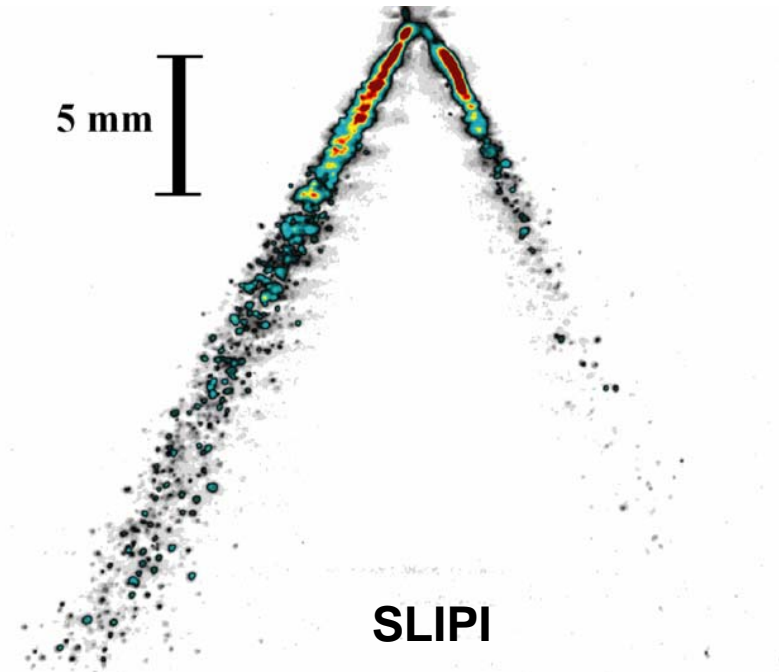
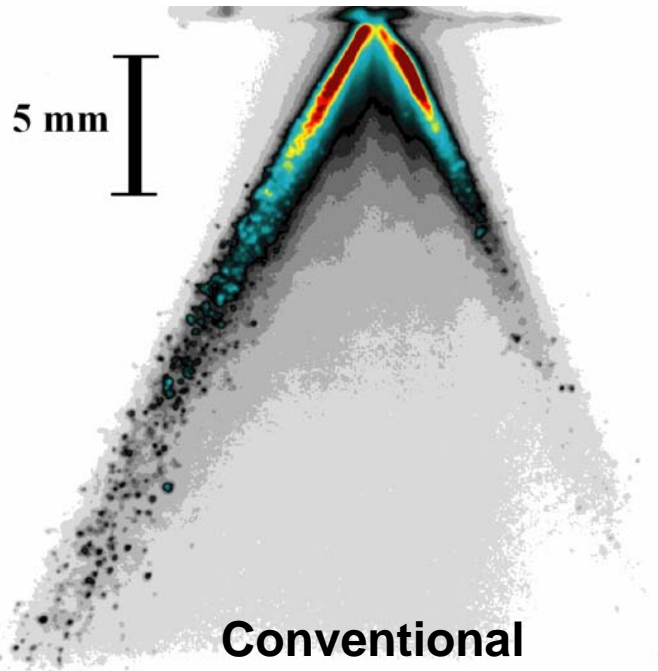
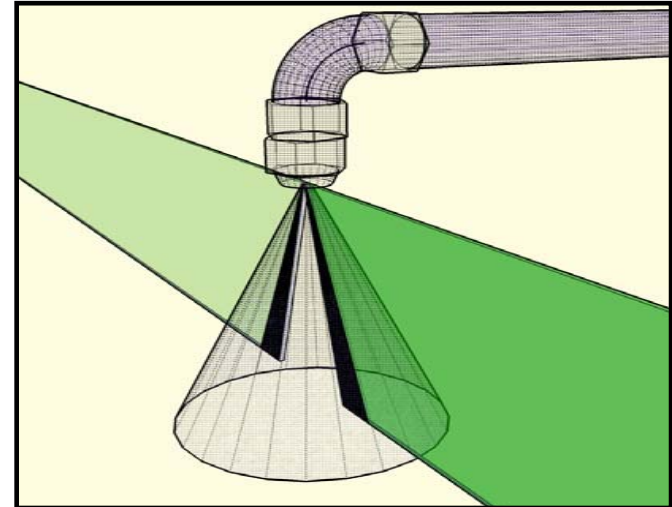
Spray information:

- Hollow-cone water spray
- Pressure-swirl nozzle
- Type: *Danfoss* 1910
- Injection pressure: 30 and 50 bars
- Light transmission: 26 % (50 bars)



AVERAGED IMAGES Hollow-Cone Spray

OFF-AXIS ILLUMINATION



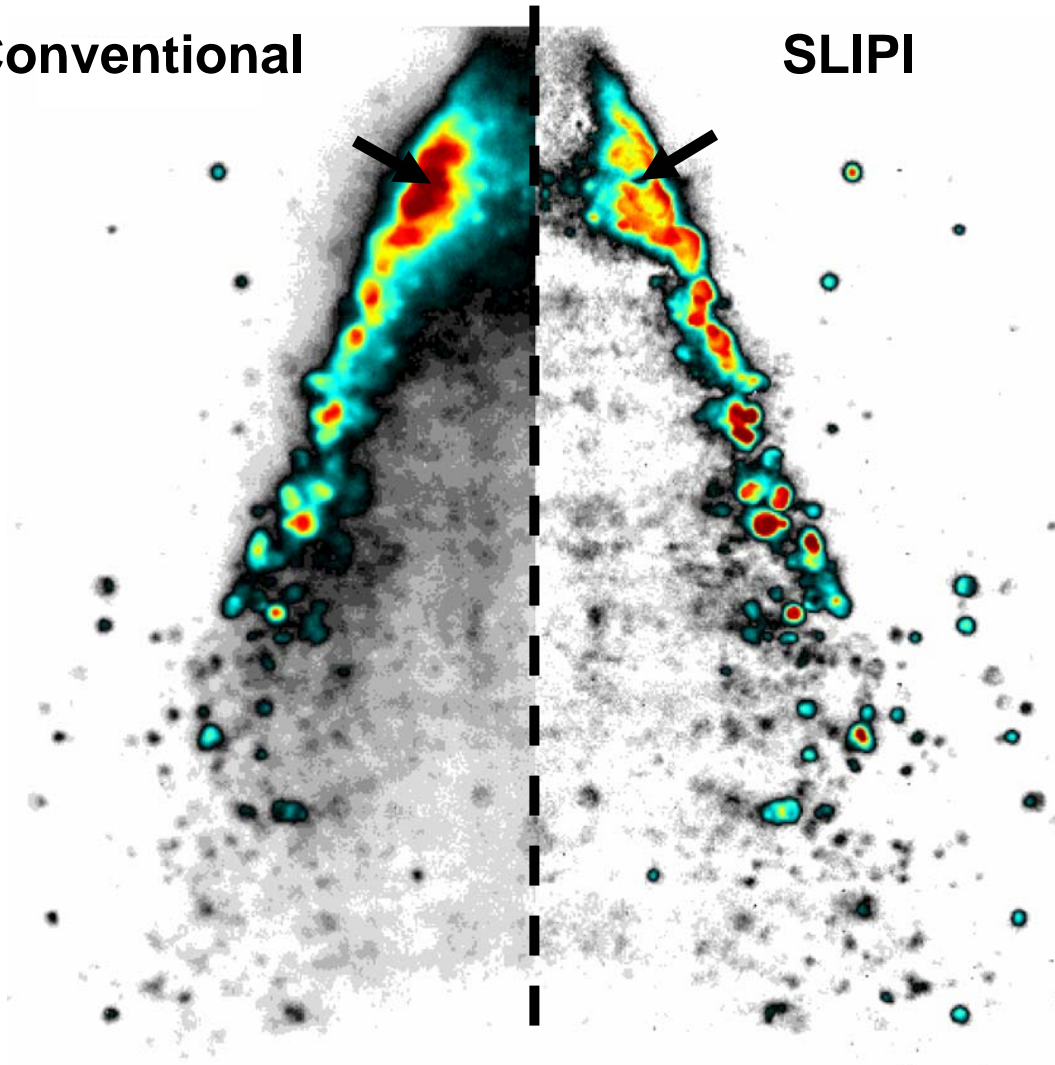
SINGLE-SHOT - Hollow-Cone Spray

Conventional

SLIPI

COMPARISON:

Voids becomes visible



SINGLE-SHOT - Hollow-Cone Spray

Conventional

SLIPI

COMPARISON:

Voids becomes visible

Droplets more enhanced



SINGLE-SHOT - Hollow-Cone Spray

Conventional

SLIPI

COMPARISON:

Voids becomes visible

Droplets more enhanced

Central region appears hollow



SINGLE-SHOT - Hollow-Cone Spray

Conventional

SLIPI

COMPARISON:

Voids becomes visible

Droplets more enhanced

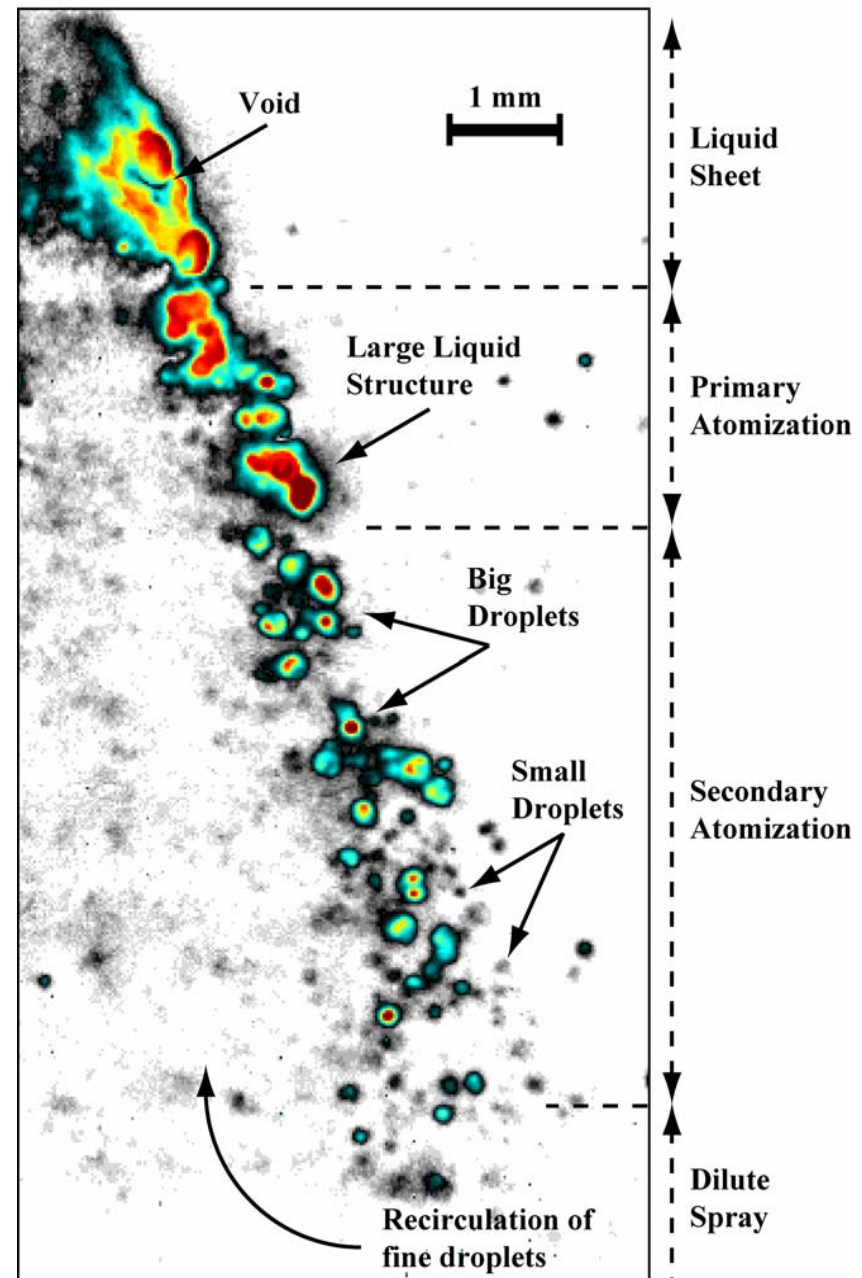
Central region appears hollow

Interfaces become sharp



**SPRAY
BREAKUPS
ANALYSIS
FROM HIGH
RESOLUTION
IMAGES**

**PROVIDE
VALUABLE DATA
FOR THE VALIDATION
OF CFD MODELS**



CONCLUSIONS

- Novel technique for **multiple scattering suppression** in planar laser imaging
- First time applied for **single-shot** imaging of a spray
- Provide visualization of primary and secondary **atomizations** in the **dense spray** region
- Allows a better estimation of the **liquid sheet/liquid core** length
- Direct application for **PIV** and **PLIF**



ACKNOWLEDGEMENTS

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Lund Laser Centre (LLC), SSF and
STEM through CECOST for financial
support



Presentation at 33rd Symposium on Combustion in Beijing:

E. Kristensson et al.: Structured illumination for 3D Mie imaging and 2D attenuation measurements in optically dense sprays

