# Detailed Spray Measurements in Edinburgh

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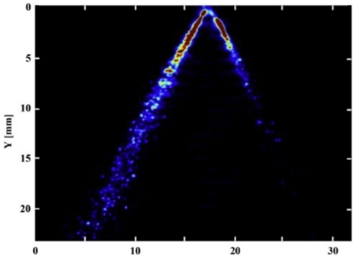
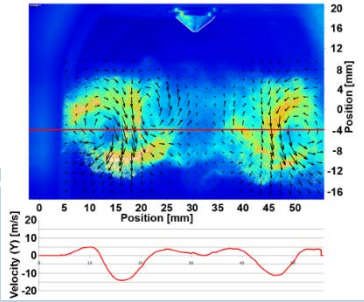
# Topics

- Short overview
- Review of one of our techniques – ballistic imaging
- A new Spray Small Research Facility in Edinburgh

# Short overview

- A group has been formed in Edinburgh to set up a new experimental program based on our individual capabilities and experience from elsewhere.
- Most of our work emphasizes either fuel sprays and their use, or fundamentals of sprays.
- We investigate flows from:
  - Inside the nozzle, at more realistic fuel pressures,
  - Spray formation (aka primary breakup) via ballistic imaging (BI) and structured laser illumination planar imaging (SLIPI),
  - Vaporizing sprays via phase Doppler interferometry and planar imaging techniques,
  - Combustion via planar laser induced fluorescence (PLIF) imaging,
  - And many others (stay tuned).



# Review of Ballistic Imaging (BI)

- Yannis Hardalupas discussed BI at the first SIG meeting, but it is probably useful to add a bit to what he said.
- BI originated in the medical imaging community. There are **many** forms of it described in their literature, but sprays present special challenges when compared to tissue.
- The time-gated variant popular for sprays was developed by the group of Alfano at CCNY. Their first demonstration in sprays was reported at a conference in 1995[1], and later published in Applied Optics[2], but their spatial resolution was very poor. They are interested in tissue, not sprays.
- Paciaroni and Linne then published a paper[3] describing the next generation, single-shot BI, and it achieved much better spatial resolution than the work in references 1 and 2.
- That was followed by demonstration of BI in a Diesel spray[4].

1. P.A. Galland, X. Liang, L. Wang, K. Breisacher, L. Liou, P.P. Ho, R.R. Alfano, Proceedings of the American Society of Mechanical Engineers, HTD-321:585–588, (1995).
2. Y. Xiang, T. Raphan, X. Liang, L. Wang, P. P. Ho, and R. R. Alfano, Applied Optics Vol. 36 No. 5 (1997).
3. M. Paciaroni and M. Linne, Applied Optics, Vol. 43, No. 26 , (2004).
4. M. Linne , M. Paciaroni, T. Hall, and T. Parker, Experiments in Fluids, 40, 836-846, (2006).

# Review of Ballistic Imaging (BI)

- Since then, several variants of BI have been developed and applied by labs around the world. Thanks to that work, we understand much better how to do it well. The groups that have worked on and are now working on BI include:
  - Air Force Research Labs – Sukesh Roy, Terry Meyer
  - Chalmers University – Megan Paciaroni, David Sedarsky, Mark Linne
  - Colorado School of Mines - Megan Paciaroni, Mark Linne, Jason Porter, Terry Parker
  - CORIA – Claude Rozé, Saïd Idlahcen, Loïc Méès, David Sedarsky
  - Ft Lewis College – Megan Paciaroni
  - Iowa State University – Terry Meyer
  - RWTH Aachen University - Florian Mathieu
  - University of Lund – David Sedarsky, Megan Paciaroni, Edouard Berrocal, Mark Linne
  - University of California at Irvine Derek Dunn-Rankin, Jim Trollinger
  - University of Edinburgh – Mark Linne
  - Xi'an Jiaotong University - Wenjiang Tan, Zhiguang Zhou, Xun Hou & others

# Review of Ballistic Imaging (BI)

- Why do this?

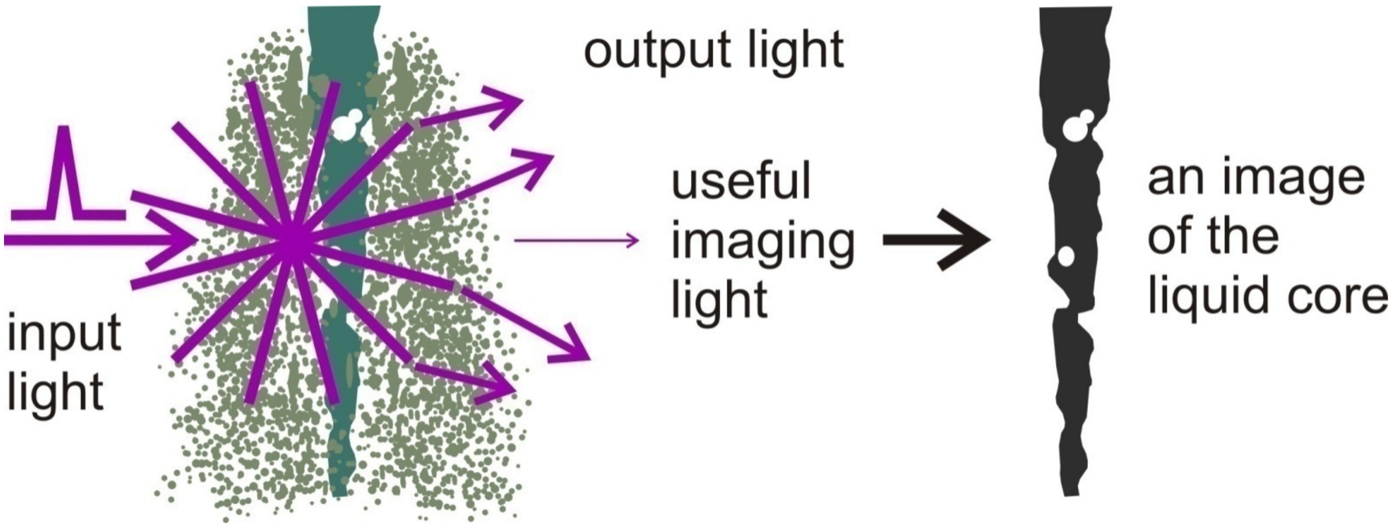
- The problem is to see inside here and observe the fluid dynamics of spray formation as the liquid core breaks up.

- Optical depth is defined in Beer's law:

$$\tau = \frac{I_{out}}{I_{in}} = e^{-OD}$$

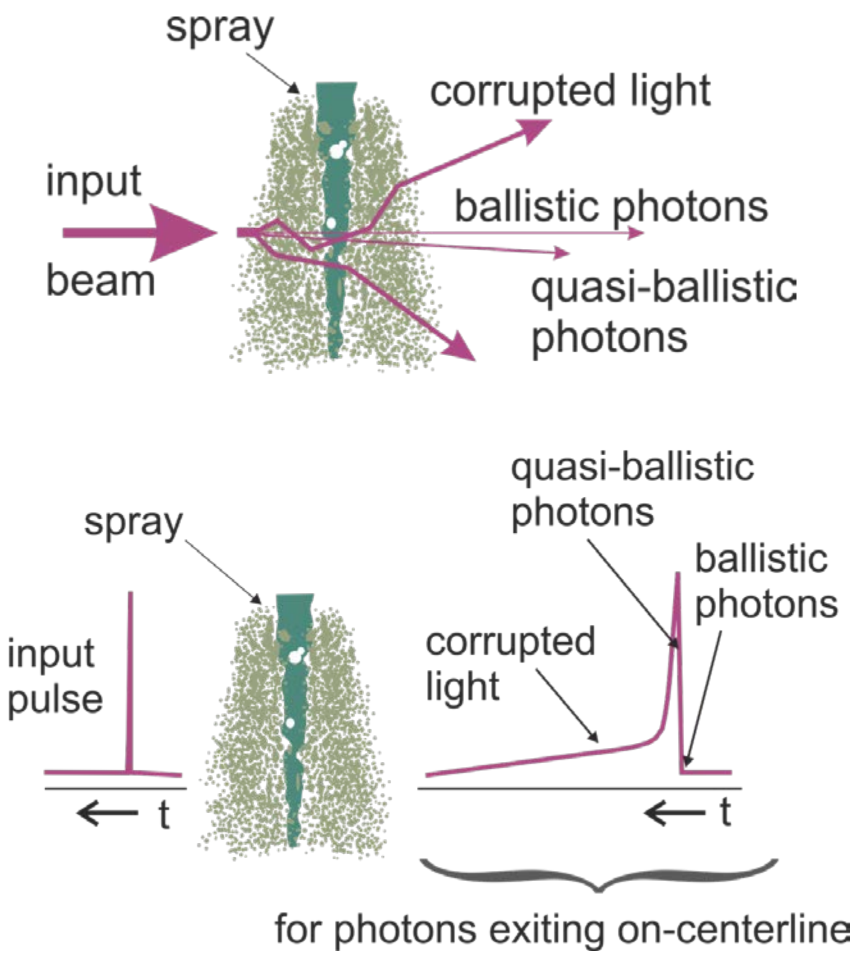
For a Diesel spray, $OD$ can be as large as 12.

# Review of Ballistic Imaging (BI)




- Use what we know about light traversing a turbid medium:
  - Most of it is just spatial noise that corrupts the image – because it was **scattered off-axis** by drops
  - A very small amount of it contains useful image information about structures (e.g. intact liquid) buried inside – it was **refracted** by the larger structures
- We reject most of the light exiting the spray, minimize the amount of corrupted light, and collect as much useful imaging light as possible.

# Review of Ballistic Imaging (BI)



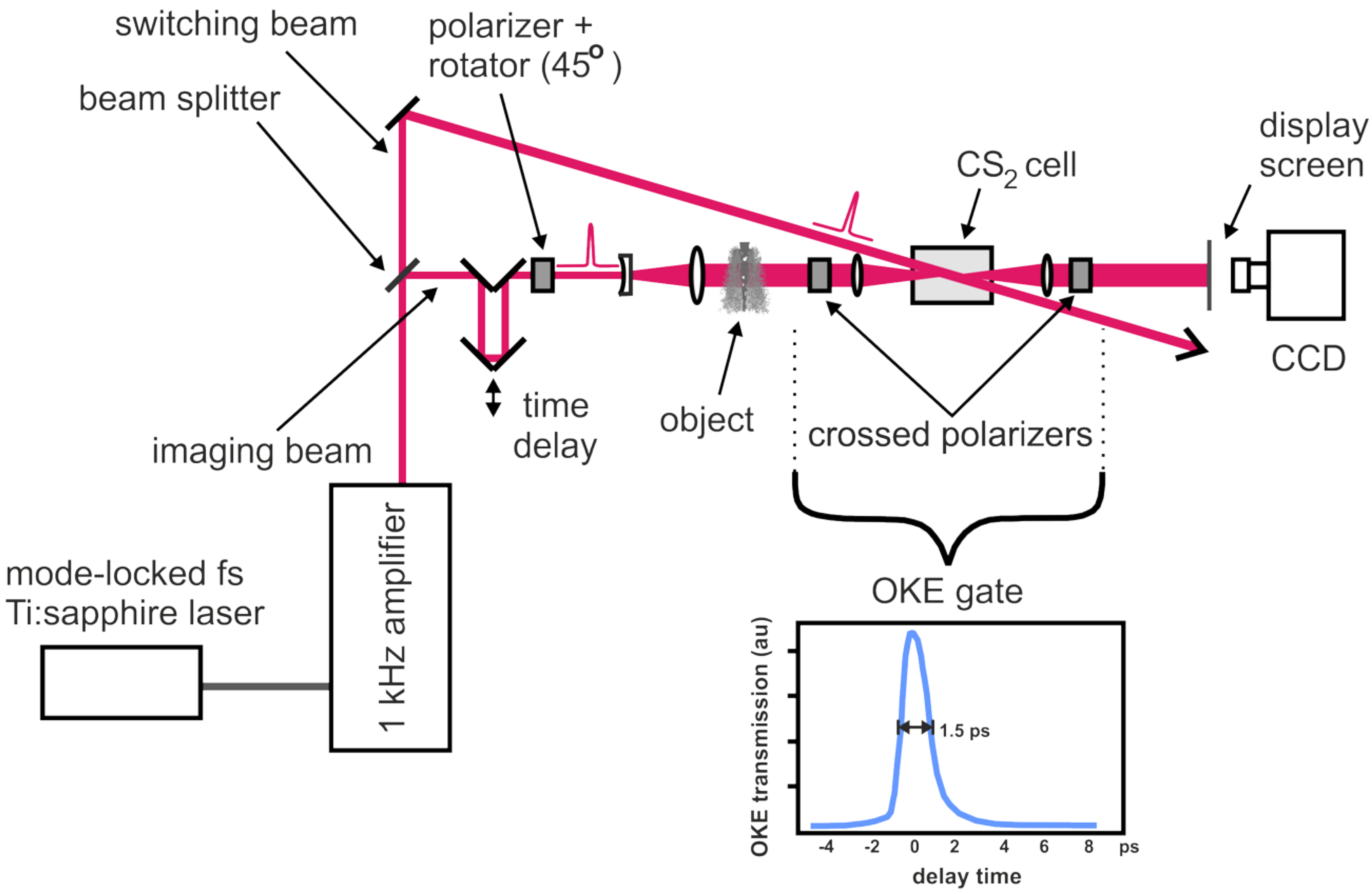

Even in turbid media, some photons do not scatter, passing directly through the medium – called “ballistic photons”. Forward scattered photons can behave almost exactly the same way (they’re “quasi-ballistic”) – all of them together are called useful imaging light

Because they do not scatter at significant angles, useful imaging photons have the shortest path length and exit first

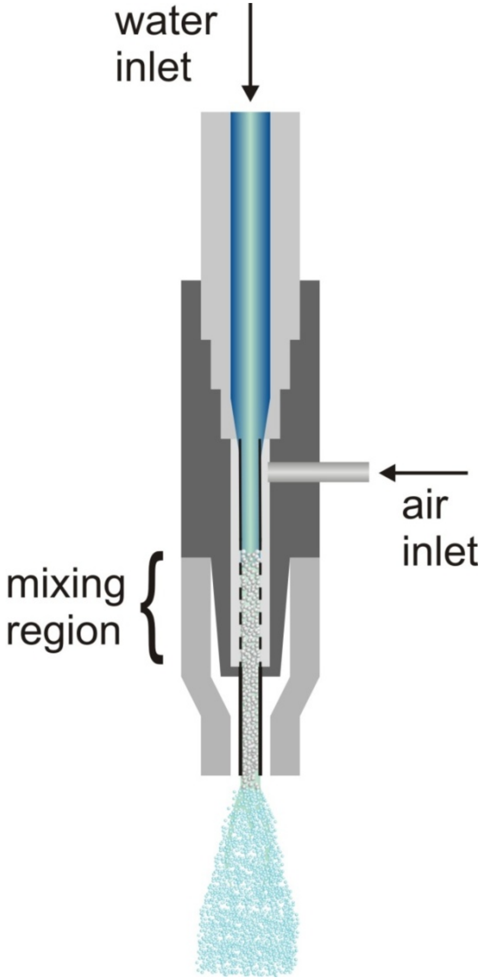
# Review of Ballistic Imaging (BI)

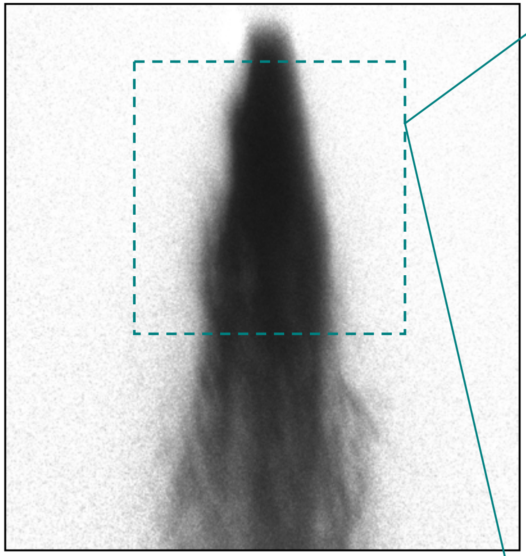
- Useful imaging photons can be used to image the liquid core – if separated from the much more prevalent corrupted light
- This can be done by seeking their signature:
  - Directional orientation (spatial filtering)
  - Preservation of polarization (polarization filtering)
  - First to exit (time gating)
  - Ballistic photons are coherent with the input beam (coherence gating – interferometry, DFWM)

# Review of Ballistic Imaging (BI)

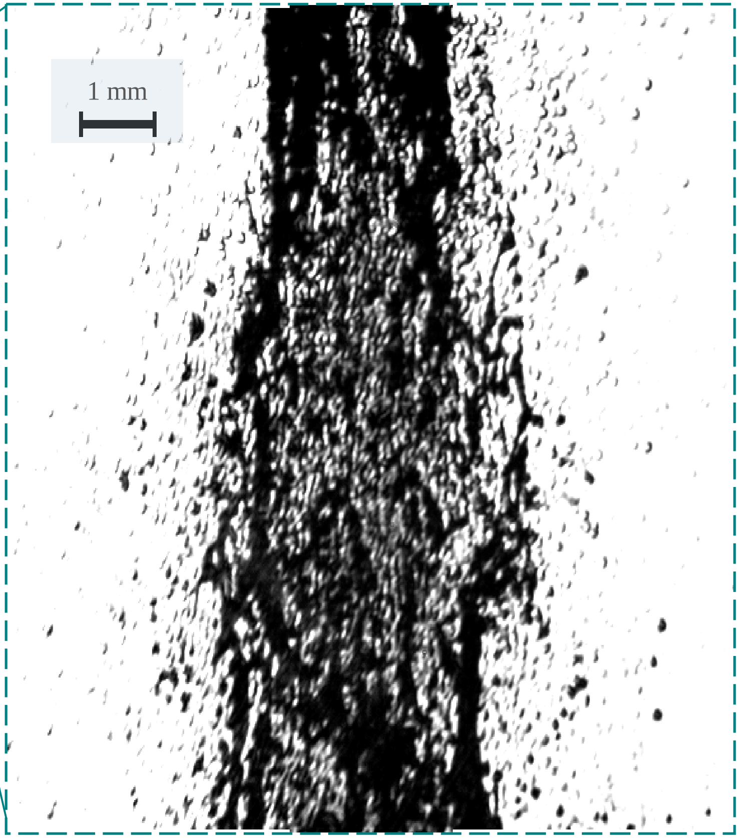


# Review of Ballistic Imaging (BI)



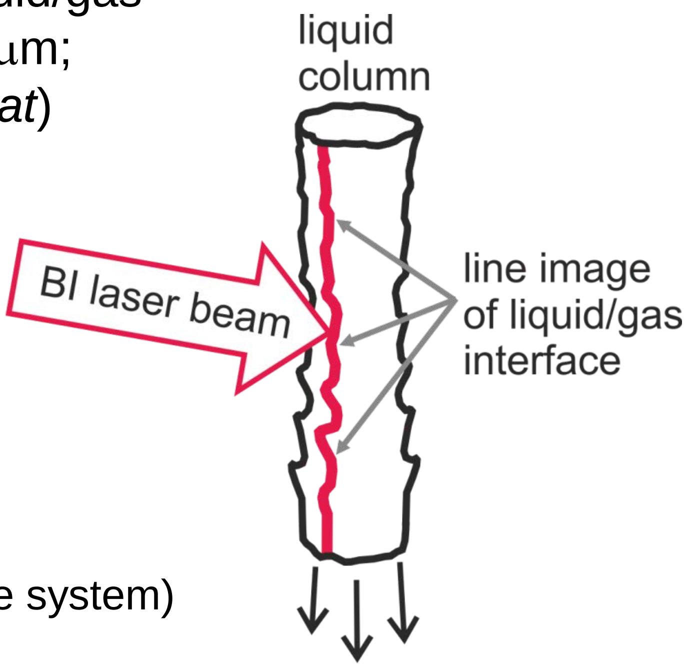
White light shadowgram




Time gated ballistic image

# Review of Ballistic Imaging (BI)

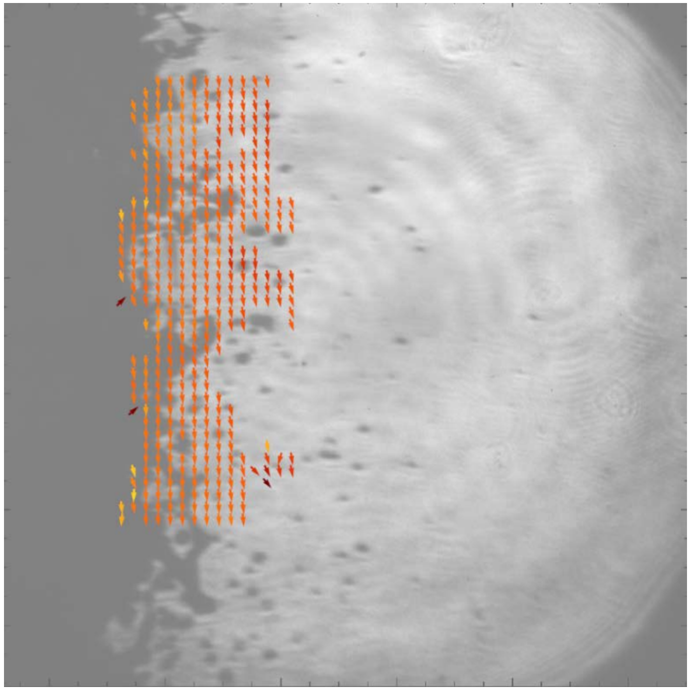
- Yannis mentioned some theory work by Loïc Méès showing differences between scattering orders depending on drop size, but that doesn't actually matter in BI because we are just collecting **all** forward scattered light and looking **only** at the liquid/gas interface
- BI is a line-of-sight technique, but it captures the liquid/gas interface with good spatial resolution (from 20 – 30 $\mu$m; FWHM of the PSF, and *we don't want better than that*)
- Images <u>all</u> refractive structures
- Not a drop size technique
- Can go up to OD = 14
- Can extract statistics on:
  - o Ligament size distributions
  - o Void size distributions
  - o Surface curvature distribution
  - o Surface wave spectra
  - o Velocity (2-pulse system) and/or acceleration (3-pulse system)
- Does not detect liquid mass
- Overkill for simpler sprays



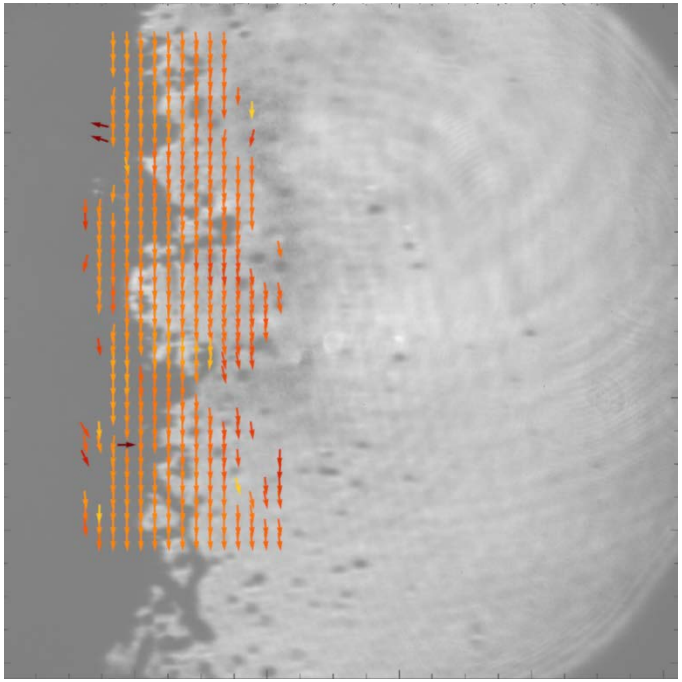
# Review of Ballistic Imaging (BI)

- Three amplifiers provide 3 BI in rapid succession, allowing one to acquire two velocity images with known time separation:

Processed BI of ligaments and large refractive drops, acquired on the side of a water jet undergoing turbulent primary breakup



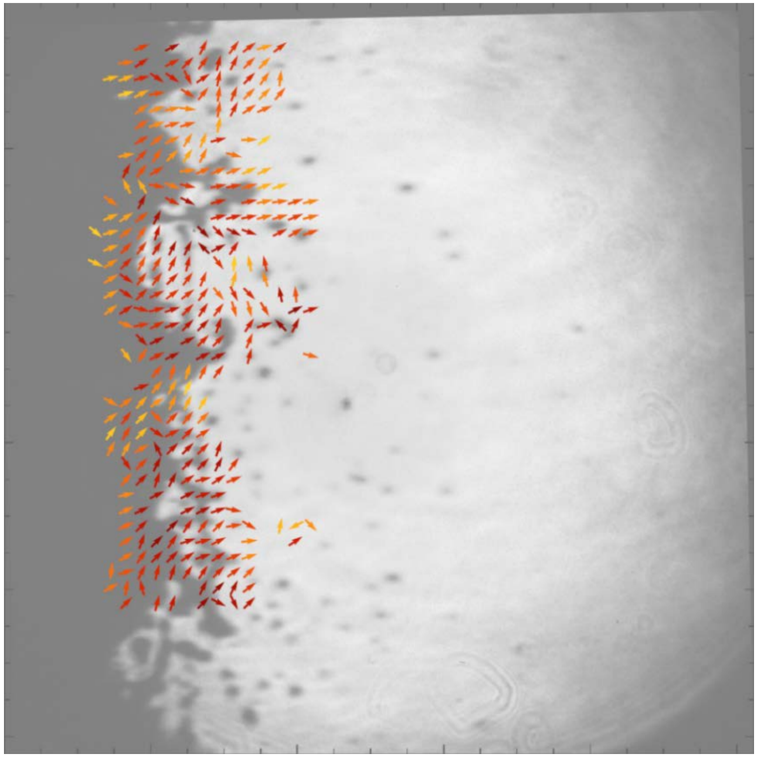
velocity 1-2



velocity 2-3

# Review of Ballistic Imaging (BI)

- The two images can be differenced to infer acceleration (for known image time separation)[5]:



high to low:
yellow-to-orange-to-red,
orange is ~ 5 $m/s^2$

- Because densities are constant, these are images of the forces acting on the fluid features

5. D. Sedarsky, M. Rahm, and M. Linne, Optics Letters, Vol. 41, No. 7, 1404 – 1407, (2016).

# Review of Ballistic Imaging (BI)

- The major disadvantage of BI is that it requires an expensive femtosecond laser, a low-light-level camera, and understanding of how to set it up.
- Many labs in the UK study sprays, and many of them might like to have access to BI.
- In fact, many labs might like to have access to a variety of laser diagnostics.
- For that reason we are opening a new Small Research Facility (SRF) on Sprays in Edinburgh.

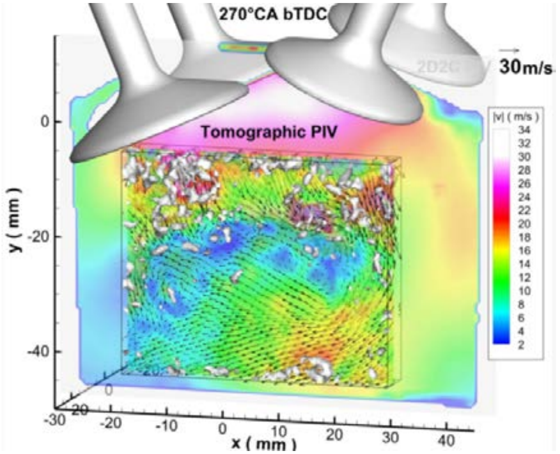
# Spray SRF

- This Small Research Facility is currently under development, based upon:
  - £1.8 million in support from the university, and
  - £1.7 million from EPSRC.
- It can host visitors from universities and companies to make measurements in our facilities using our diagnostics.
  - Our goal is not to compete with researchers across the UK. The idea is to complement work you do in your own lab (or with others) by providing access to additional measurement techniques.
  - There are various EPSRC-approved costing structures depending on how much of the facility is used and whether or not the work is proprietary.
- The lab will be set up with a video-conferencing facility and high-rate data sharing so that PIs can sit at their desks at their home organizations and communicate in real time about methods and results with researchers in place in Edinburgh.

# The SRF staff

- Mark Linne

  Laser diagnostics
  Spray research




- Brian Peterson

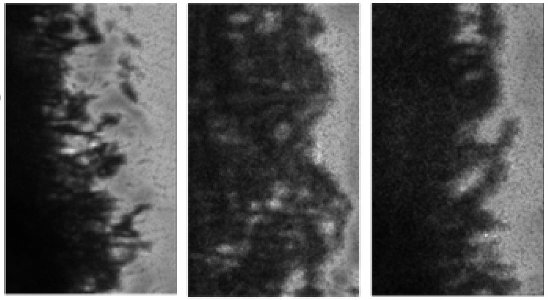
  Laser diagnostics
  IC engines & sprays

- Zachary Falgout

  Laser diagnostics
  Sprays & supercritical flows

- Lars-Christian Johansen

  PhD-level Experimental Officer

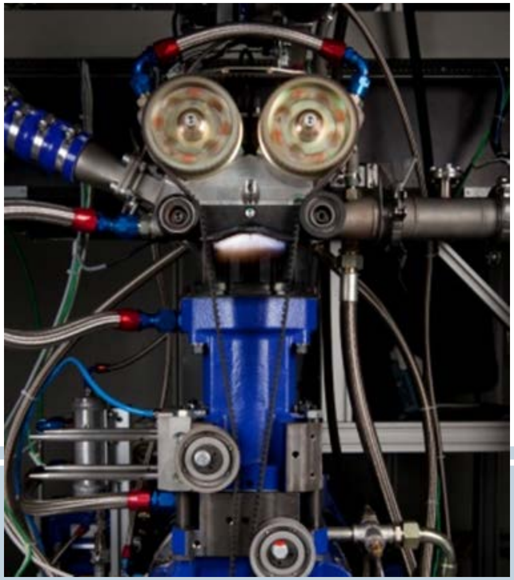


- Other post-docs and graduate students

# SRF Facilities

- The SRF will be equipped with:
  - A high pressure (up to 120 bar) and temperature (up to 1000 K) spray research vessel from Aachen.

    We will collaborate with the group in Aachen to develop a way to inject (and afterwards filter) PIV particles, which would be unique and important for e.g. spray induced turbulence.
  - An optically accessible single-cylinder engine.



# SRF Facilities

- The SRF will b… …ipped with:
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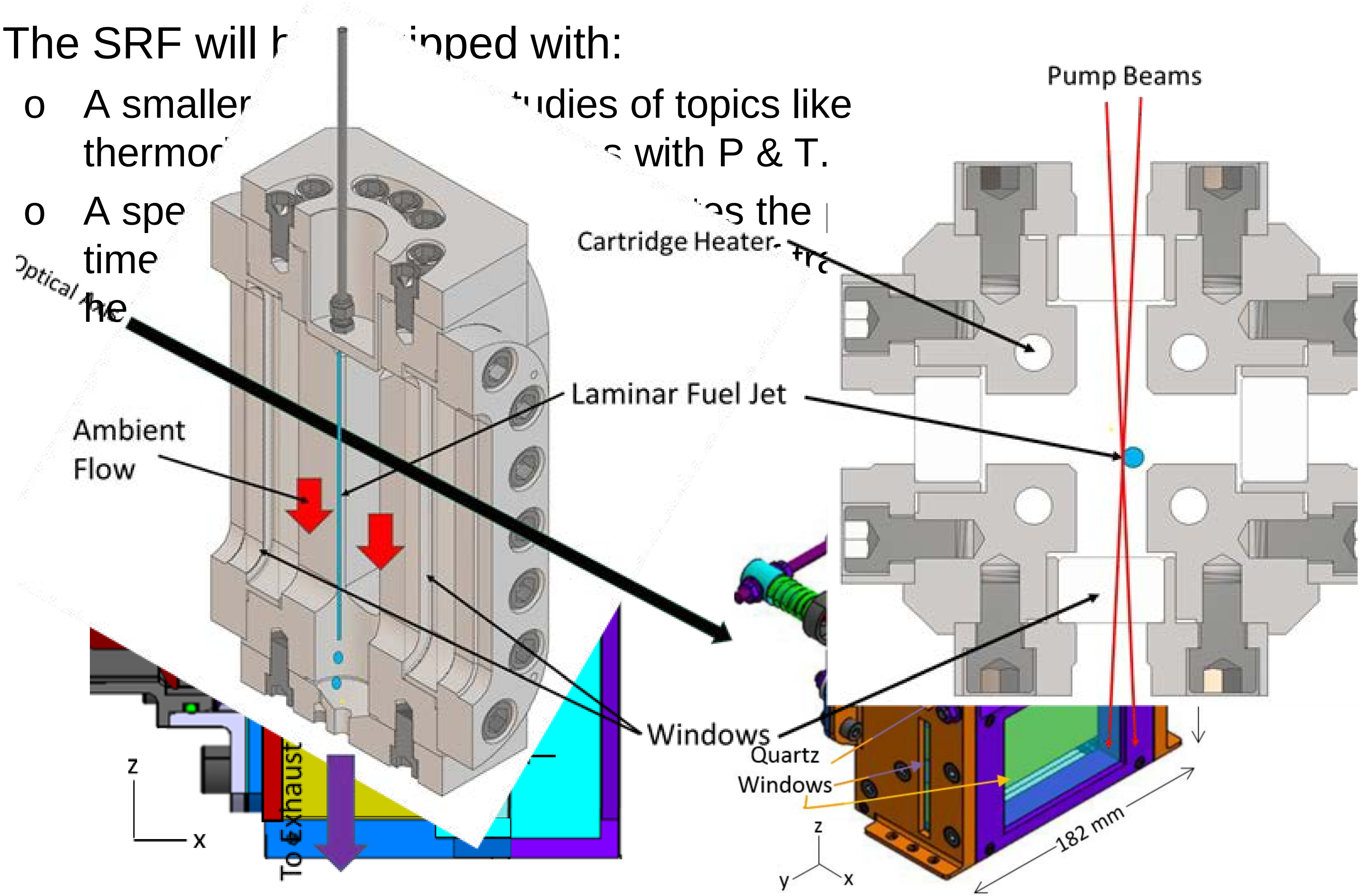


# SRF Facilities

- The measurement equipment will include:
  - o Injector mass flow meters (ROI meters) together with single-hole impingement.
  - o Two high speed cameras (10 kHz – 100 kHz) with one lens-coupled intensifier for low light level imaging.
  - o Two high-speed (10 kHz) Nd:YAG lasers: a two-pulse version at the second harmonic (532 nm) and a high-speed single-pulse version with all harmonics (532, 355 & 266 nm).
  - o A 10 Hz 2-pulse (e.g. for PIV) Nd:YAG laser with all harmonics + a dye laser & wavelength shifting (e.g. for OH PLIF).



# SRF Facilities

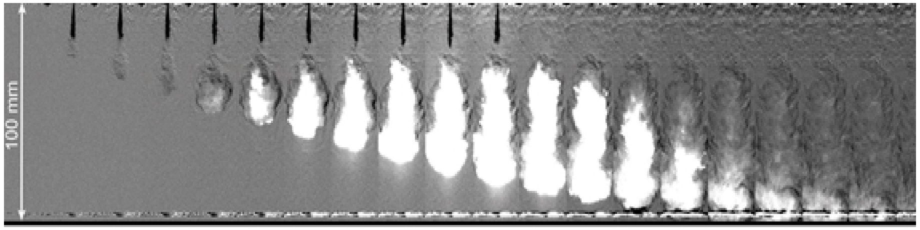

- The measurement equipment will include:
    - o A mode-locked femtosecond (40 fs) Ti:sapphire oscillator and regenerative amplifier.
    - o A 30 ps Nd:YAG laser at the second harmonic (532 nm).
    - o Phase Doppler interferometer.

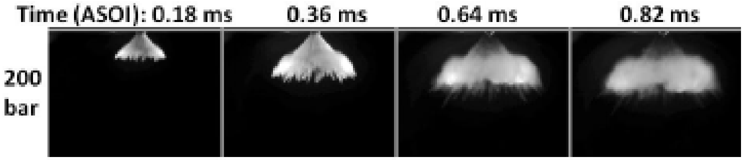


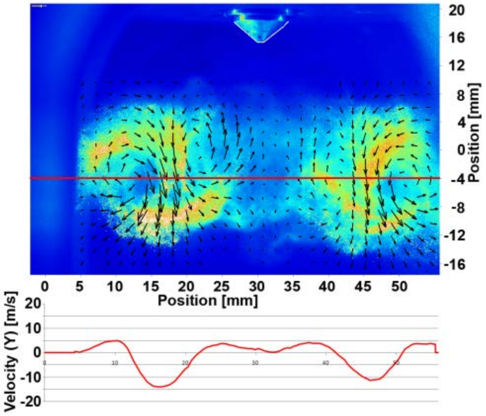
- o Ancillary equipment such as fuel pumps and controllers, an imaging spectrometer and imager, other cameras and small lasers, mass flow meters, data acquisition etc.

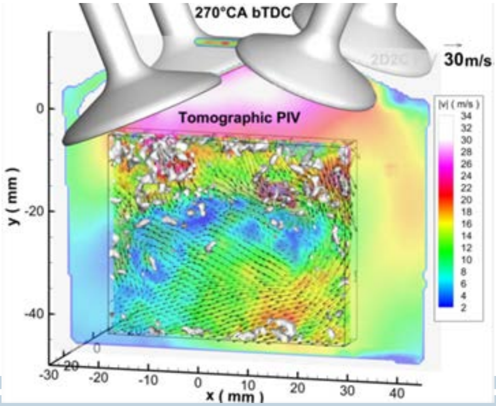
# SRF Diagnostic techniques

- The techniques will include:
  - o Injector mass flow and impingement measurements.
  - o High-speed passive imaging: light-field/dark-field, Schlieren, chemiluminescence, and luminescence (including 2$\lambda$).
  - o Stereoscopic PIV at high and low speeds, and tomographic PIV at low speeds.
  - o Spontaneous Raman for major species and temperature, can be done along a line often.



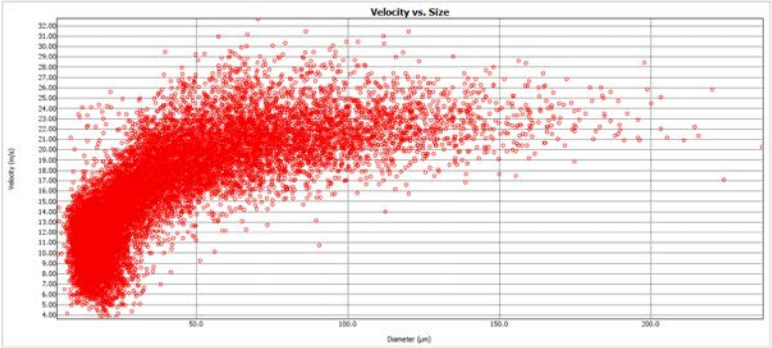



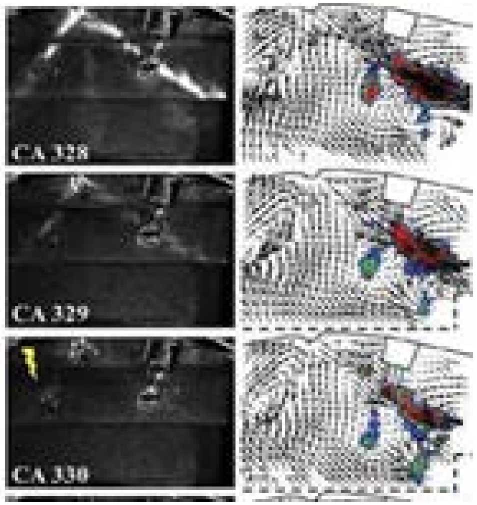



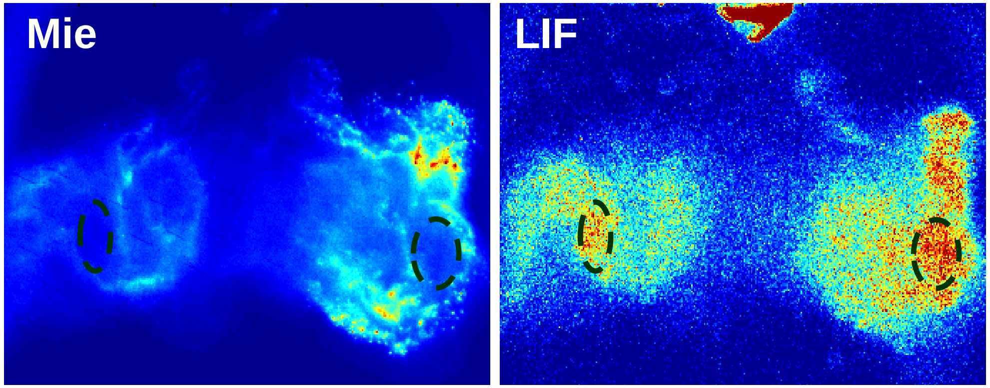



# SRF Diagnostic techniques

- The techniques will include:
  - o Phase Doppler interferometry (for drop size distributions and velocity in 2 directions measured at a single point).
  - o Planar laser induced fluorescence imaging (here simultaneous fuel PLIF coupled with PIV here).
  - o Elastic scattering + planar laser induced fluorescence for drops and vapour (or exclipex fluorescence)

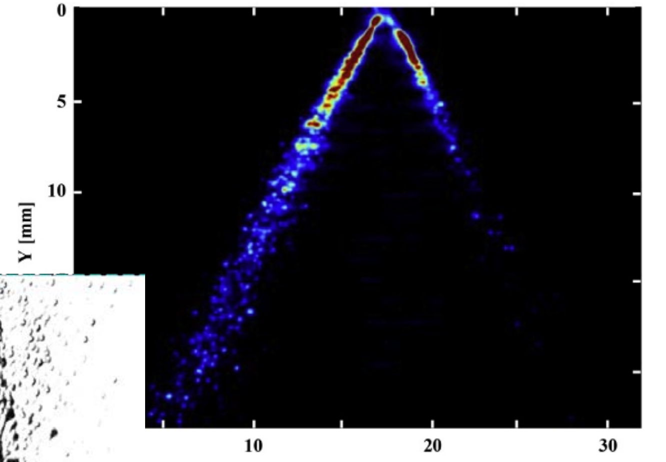


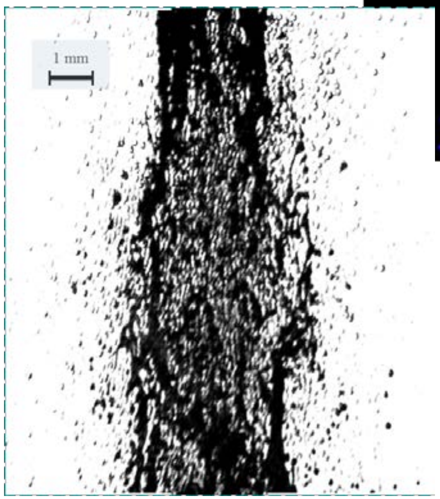



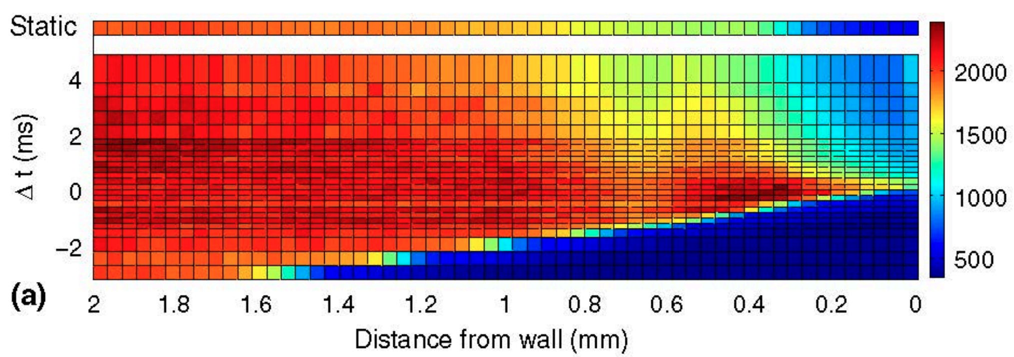



# SRF Diagnostic techniques

- The techniques will include:
  - o Structured laser illumination planar imaging (SLIPI) for planar imaging in dense sprays (for OD < 6), and for planar laser dropsizing (gives an image of Sauter mean diameter distribution).
  - o Ballistic imaging for dense sprays with OD > 6.
  - o Hybrid fs/ps rotational coherent anti-Stokes Raman scattering (CARS), can provide line-images of temperature (with very high accuracy) and sometimes species concentrations.



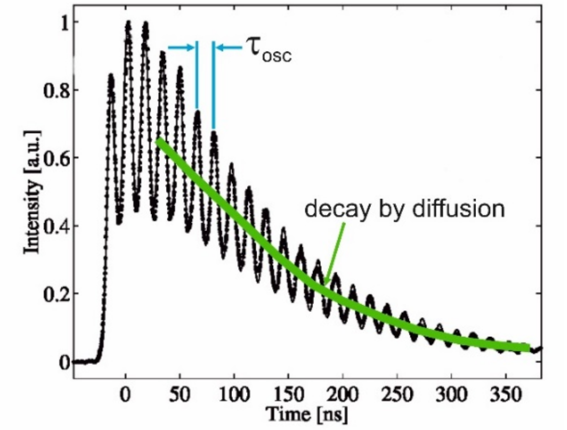




A. Bohlin, M. Mann, B. Patterson, A. Dreizler, C. Kliewer, Proceedings of the Combustion Institute 35, 3723–3730, (2015).

# SRF Diagnostic techniques

- The techniques will include:
  - Laser induced incandescence for soot imaging.
  - Laser induced thermal acoustics for sound speed (e.g. for transcritical fluids).
  - Dynamic light scattering for diffusion rates.
  - Digital 2-pulse holography for larger drop fields (giving drop size and velocity for a drop field in one instant) and micro-holography for cavitation bubbles.
  - + others

# Collaboration

- This SRF could be of use for:
  - Evaluation of existing injectors (e.g. effect of coking) using mass flow and imaging of the burning jet.
  - Spray-wall interactions (mount a quartz cylinder around the jet inside the chamber).
  - Effects of various fuels, including alternative fuels, by parametric comparison of spray combustion (mass flow, soot luminescence imaging, liquid length, lift-off length etc.)
  - More detailed investigation (e.g. planar laser dropsizing).
  - Spray induced turbulence using PIV.
  - More basic studies such as interior flows correlated with breakup and overall spray behaviour.
  - Development of extended or new injector concepts.
  - Much more.

# Thanks for your attention

If you want to discuss how you could use the SRF, just contact me at mark.linne@ed.ac.uk