Towards Single Shot Diagnostics in Low Temperature Plasmas

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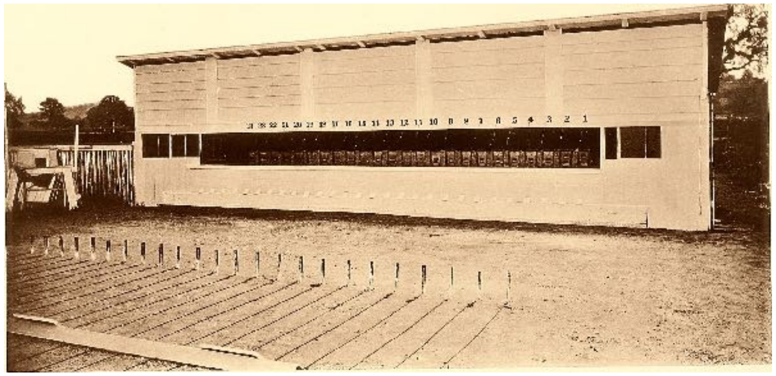
Outline

MONTRÉAL TRANSMEDTECH INSTITUTE LIVING LAB

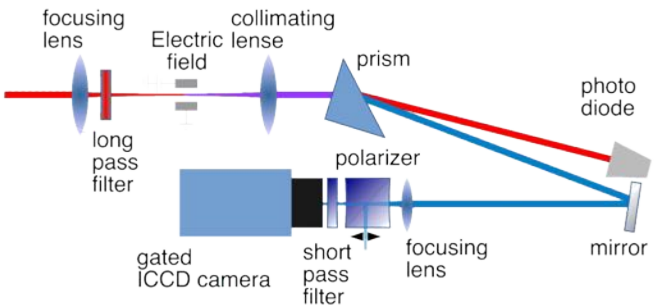
The what and why of single shot



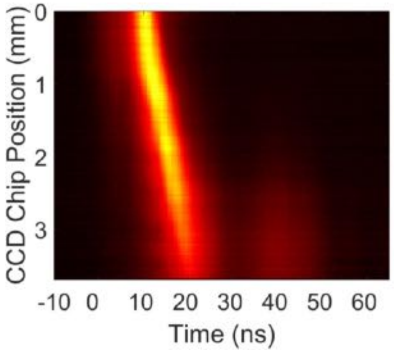
Common single shot techniques

Diagnostic methods used

- E-FISH
- Fleet
- Rayleigh



Towards single shot in low signal measurements



Call for Postdoc Applications

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Acknowledgement

Richard Miles
(Texas A&M,
Princeton)

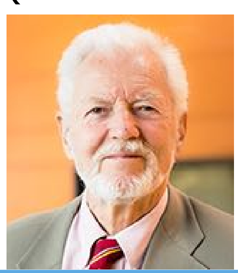
Ben Goldberg
(Rayleigh, E-Fish, Pulse Burst)
(Sandia Nat. Lab, CA)

Arthur Dogariu
(ultrafast spectroscopy)
(Princeton University)

David Feng (Rayleigh)
(Princeton University)

Luka Hansen
(Rayleigh, Pulse Burst)
(Kiel University)

Yibin Zhang (FLEET)
(Sandia Nat. Lab, NM)



Michael Wertheimer
(Polytechnique Montreal)

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CHU Sainte-Justine Le centre hospitalier universitaire mère-enfant
Hôpital général juif Jewish General Hospital
CHUM Centre hospitalier de l'Université de Montréal
Université de Montréal

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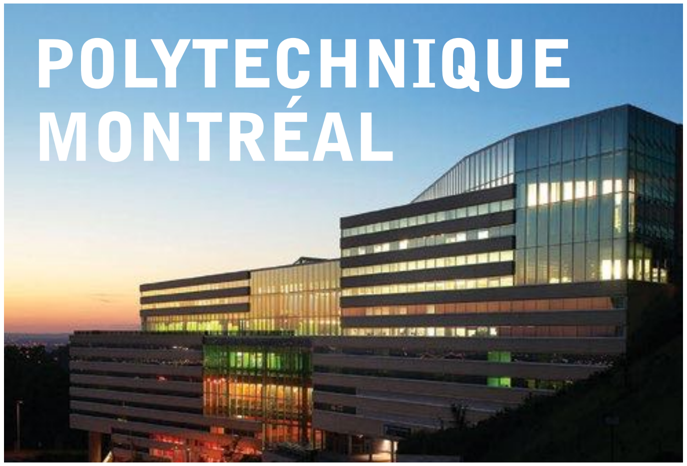
DAAD/PROMOS

Polytechnique Montréal & Institut TransMedTech

Founded in 1873, Polytechnique Montréal is one of Canada's largest engineering Universities.



Engineering Physics Department:

development & **validation** of next generation medical technologies

Three main areas of research

1) **Musculoskeletal disease**
2) **Cardiovascular disease**
3) **Oncology**

for their **implementation** in the health system or industry

Living Lab model:
Transdisciplinary, intersectoral collaborative research, open innovation and creativity

Plasma Physics and Spectroscopy Laboratory

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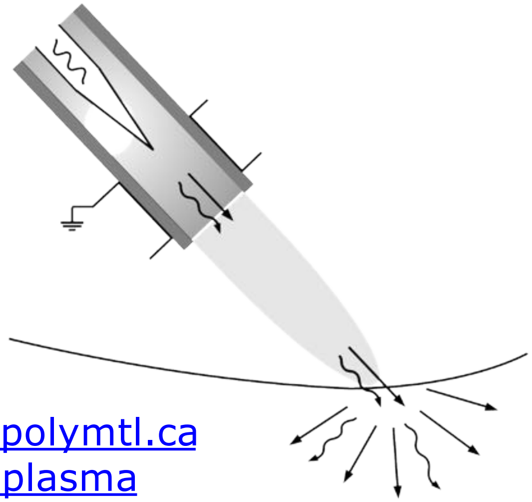

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Sean Watson
Plasma and liquid diagnostics and source development

Justin Hogue
Ultrafast spectroscopy

Julien Bissonette-Dulude
Plasma liquid diagnostics and simulation

Jean-Baptiste Billeau
Microplasmas

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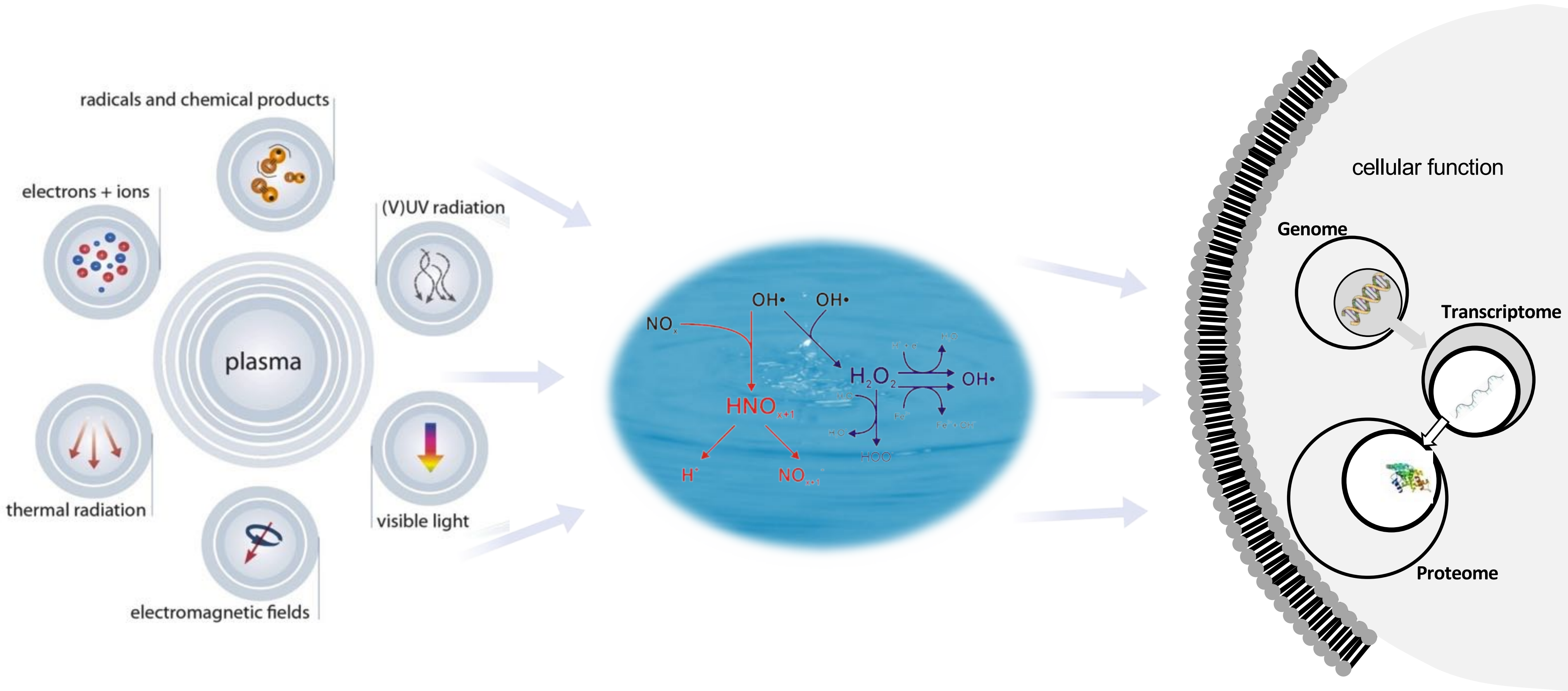
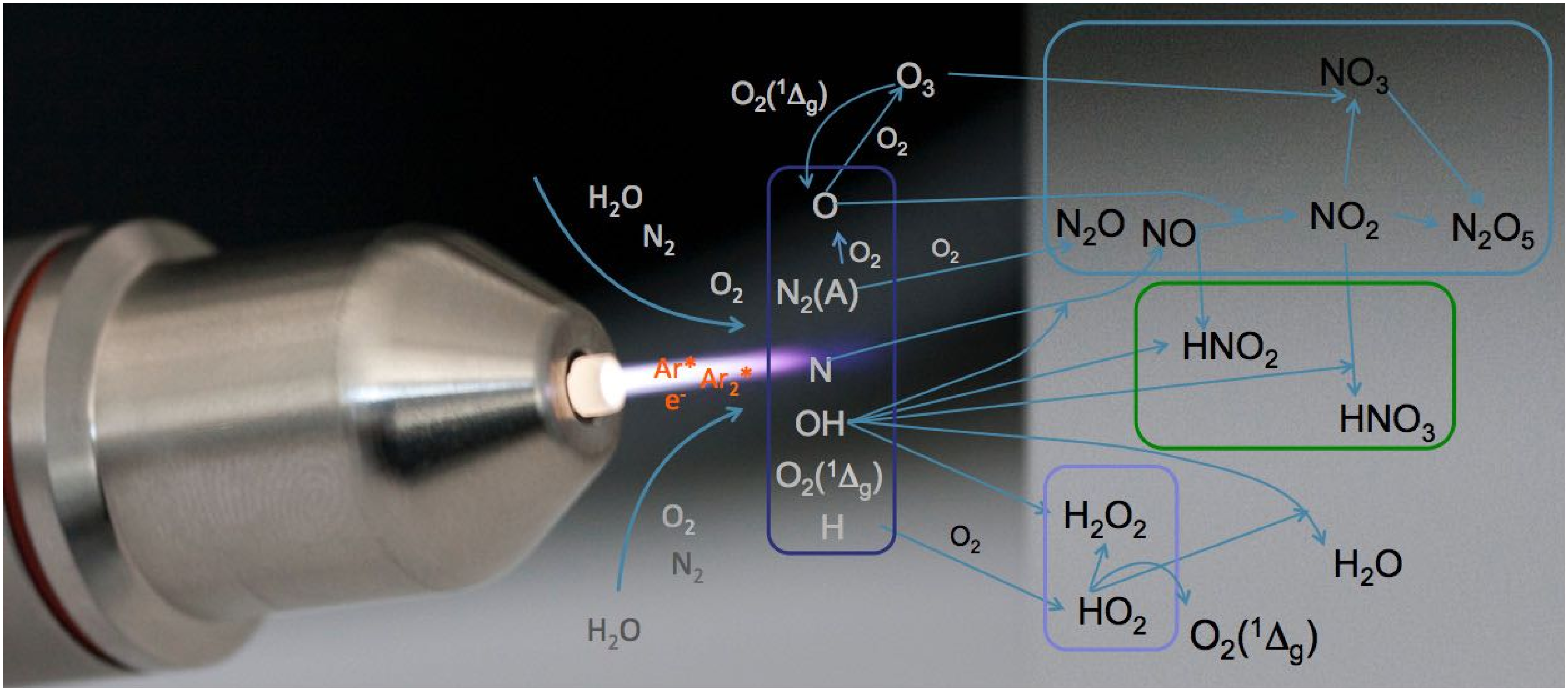
Plasma Medicine – Missing Link



Transition from empirical plasma application to knowledge based plasma therapy is the next step in plasma medicine.

Non-Equilibrium Plasma Chemistry



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Reuter, S., et al. 2018 The kINPen – a Review …
J. Phys D 51 (2018) 233001

Influence of Pressure

increase of pressure

Plasmas at atmospheric pressure quickly become filamentary

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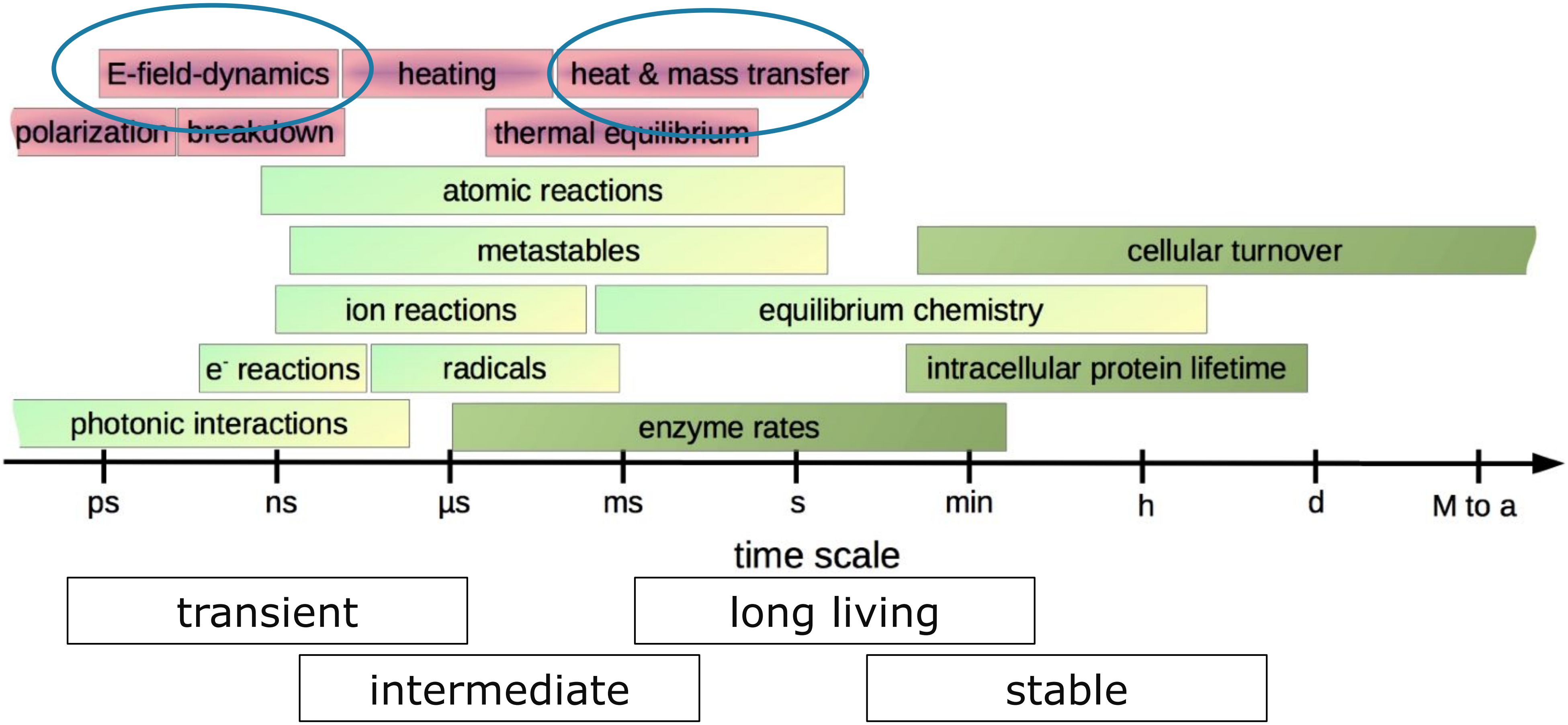
left: NASA
right: j. castells, unsplash

Time scales of Plasma Surface Interaction Processes



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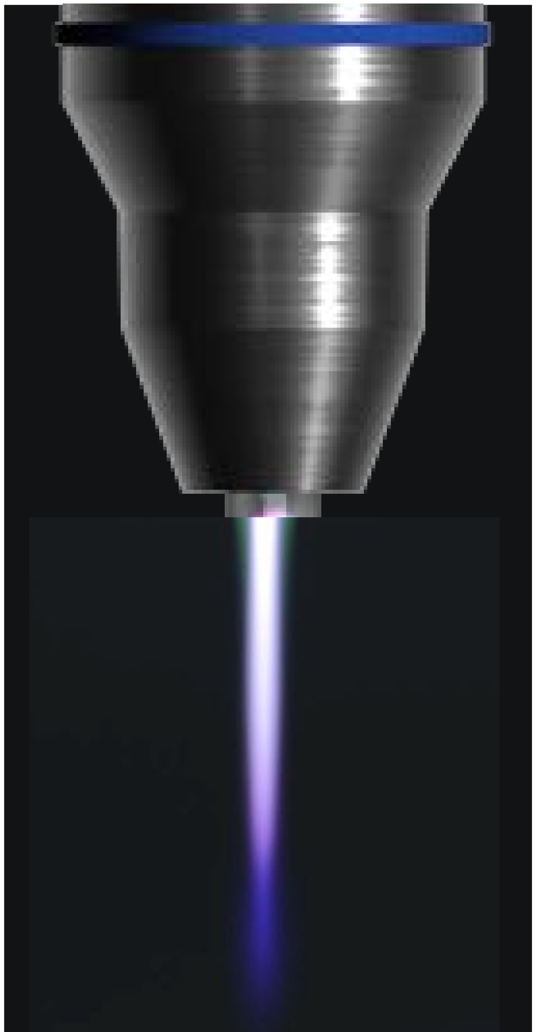
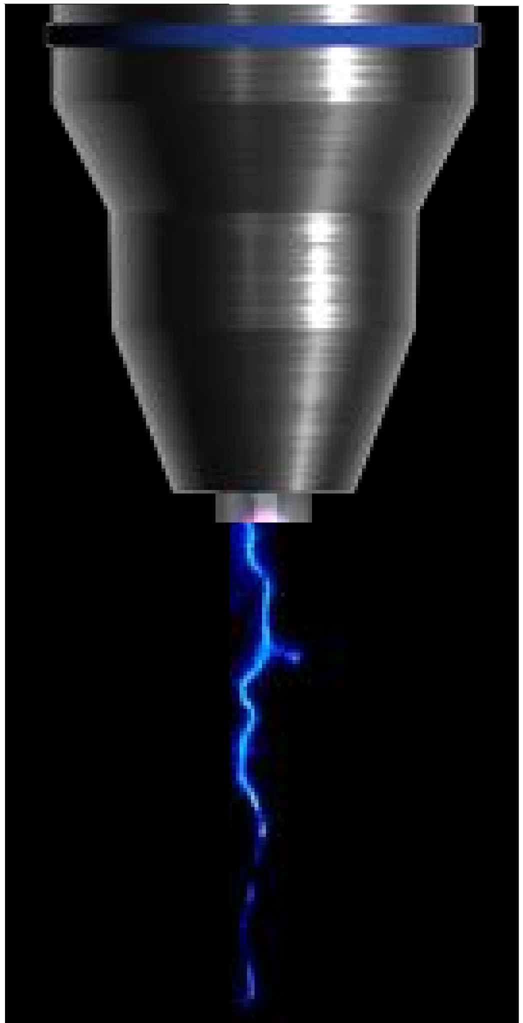
J. Phys D 51 (2018) 233001

There are three sides of the coin



Optical Appearance (as observed by eye)

Phase Resolved OES (averaged over many cycles)

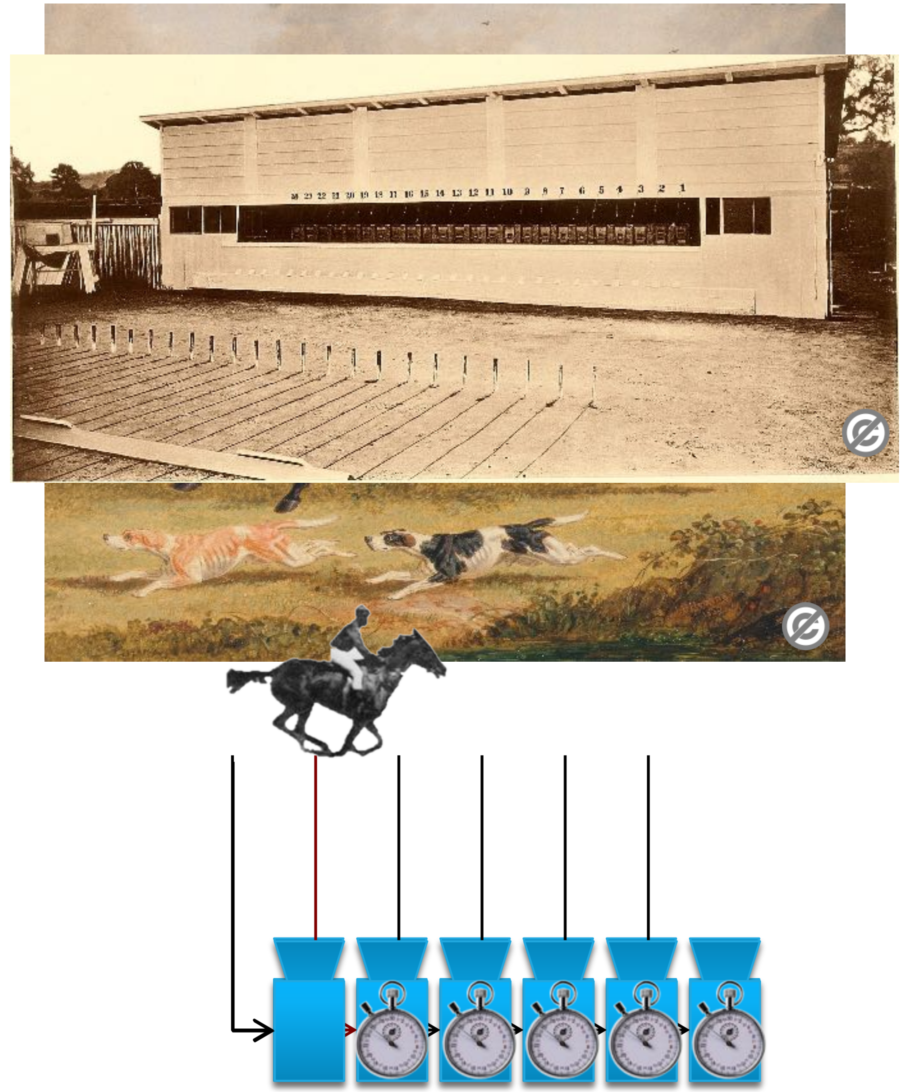


Snapshot (exposure time ≈ one cycle)

Single Shot Diagnostics – the Beginning

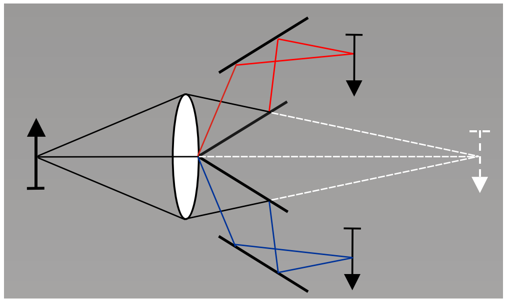
Question 1850s:
At what time does a horse in gallop lift all feet from the ground?

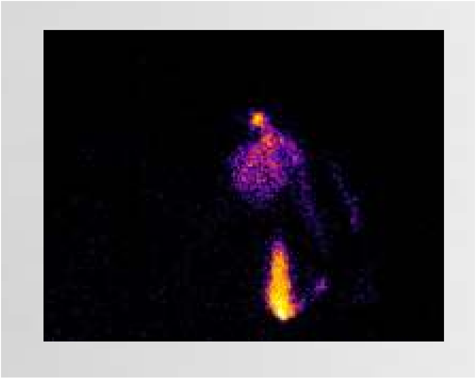
Answer 1877:
Muyebridge Photography



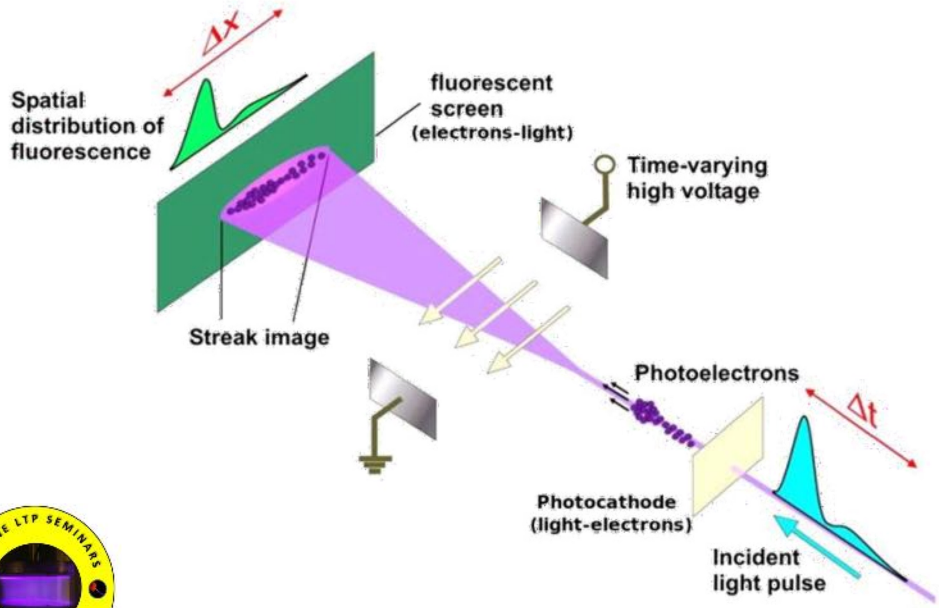
Existing diagnostics with single shot capability

Multi-ICCD Setup

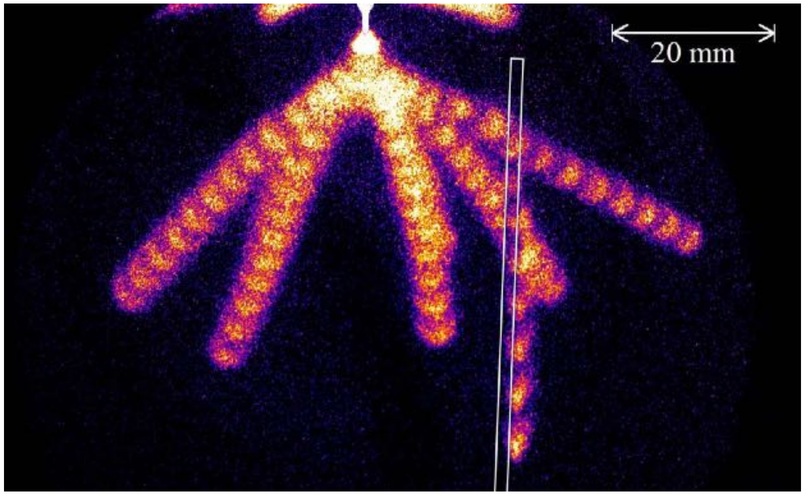




Streak camera



Stroboscope Effect

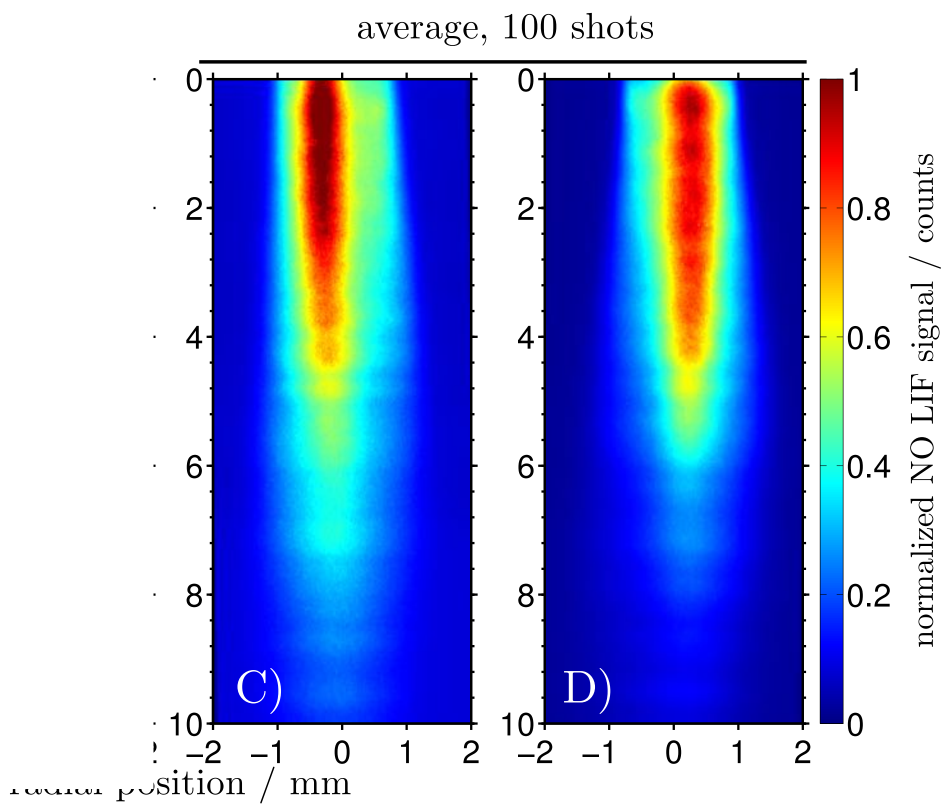


S Nijdam Escampig XII Greifswald

2013 © Paul Hoess KG

Mahgoub et al. Proc. IPAC2012, New Orleans, USA

Single Shot vs. Averaging



Single shot measurements reveal high gradients and locally high densities

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S. Iseni 2014

EVOLUTION OF H_2O_{2aq} and NO_{aq}

H_2O_{2aq} (10^{15} cm^{-3}) | NO_{aq} (10^{15} cm^{-3})

Stationary

1th Pulse | **"Memory-Effect"** | **1th Pulse**

Random

- Stationary: NO_{aq} is consumed by H_2O_{2aq} at the center. In absence of H_2O_{2aq}, NO_{aq} diffuses to the underlying tissue at the edges.
- "Memory-effect": NO_{aq} and H_2O_{2aq} are mixed at selected locations. NO_{aq} survives only where the density of H_2O_{2aq} is smaller.
- Random: H_2O_{2aq} is "well-stirred" with NO_{aq}. Consumed by the H_2O_{2aq} there is little diffusion to the tissue.

Animation Slide

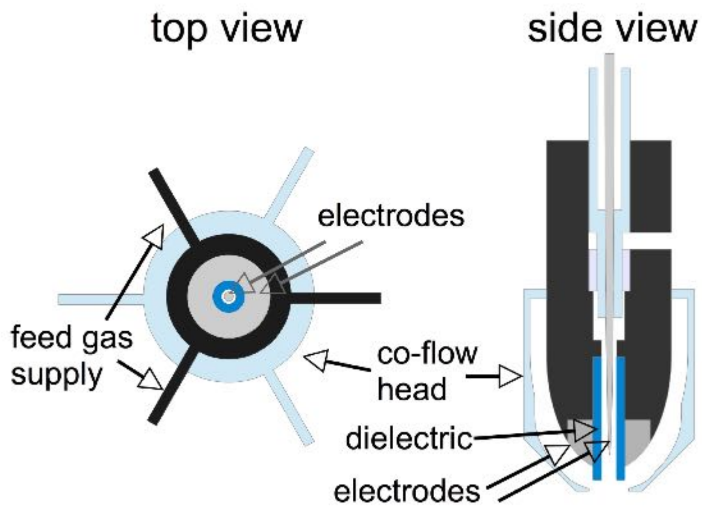
MIN **MAX**

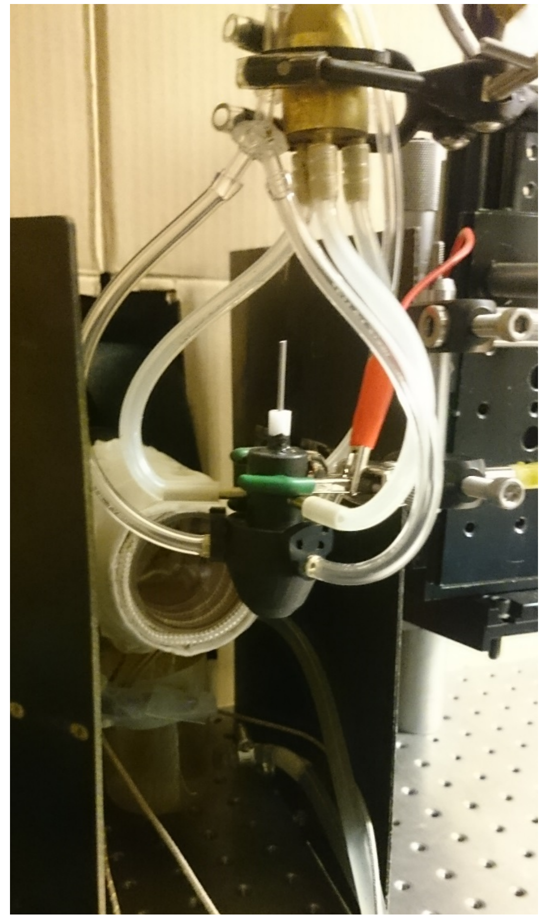
Log scale

University of Michigan
Institute for Plasma Science & Engr.

Tian W. and Kushner M., 67th GEC (2014), Raleigh, USA

“Sentinel” Plasma Jet





- Nanosecond pulsed plasma jet
- 500 sccm Argon
- 500 sccm co-flow (Oxygen/Nitrogen)
- Peak Voltage: ~4 kV
- Pulse Duration: 12 ns FWHM @ 0.5 to 1 kHz

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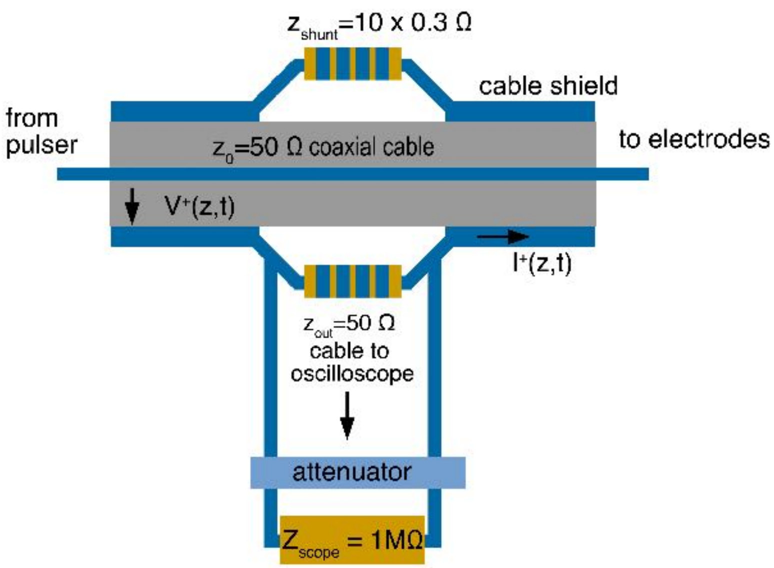
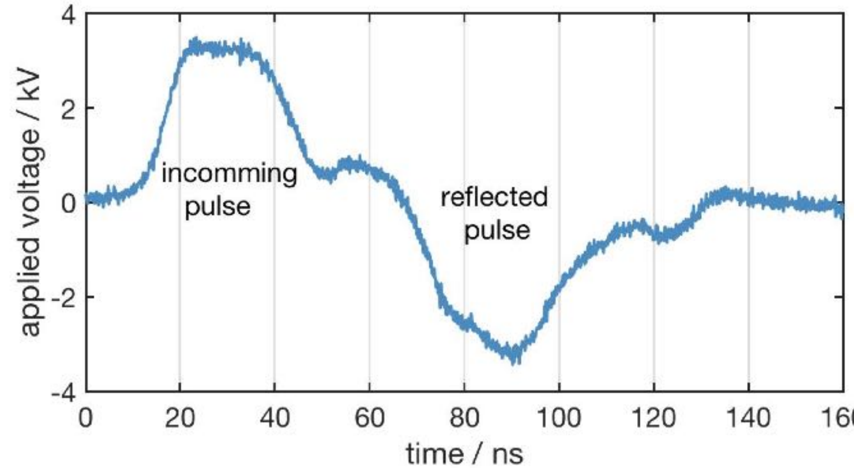
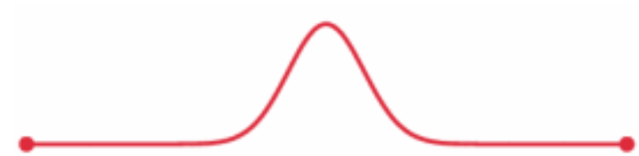
Back current shunt



$$I^+(z,t) = \frac{Z_{out}+Z_{scope}}{Z_{scope}} \frac{V_{scope}}{Z_{shunt}} \times \gamma_{\text{Attenuator}}$$

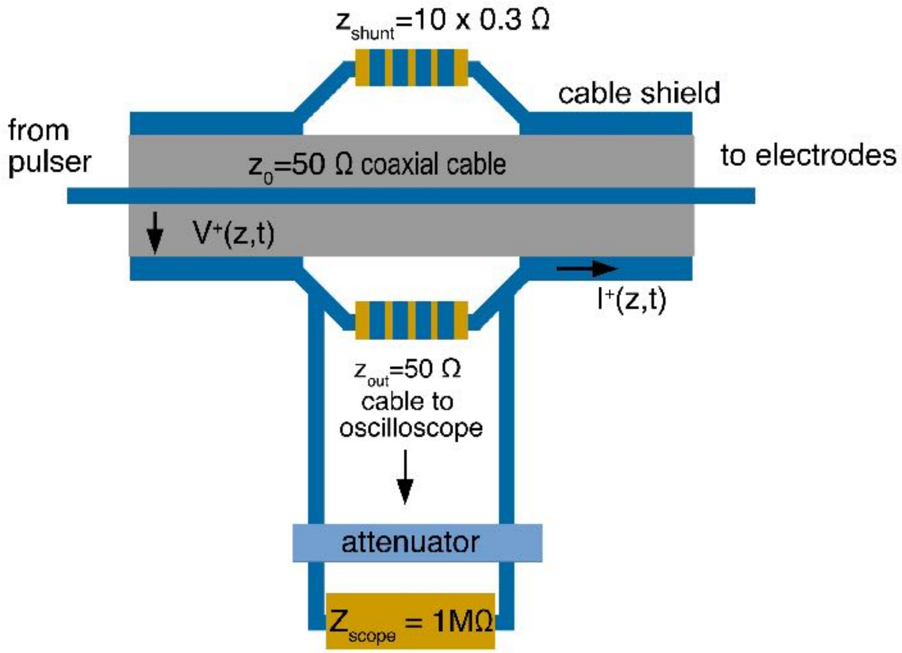
$$V^+(z,t) = I^+(z,t) \times Z_{out}$$

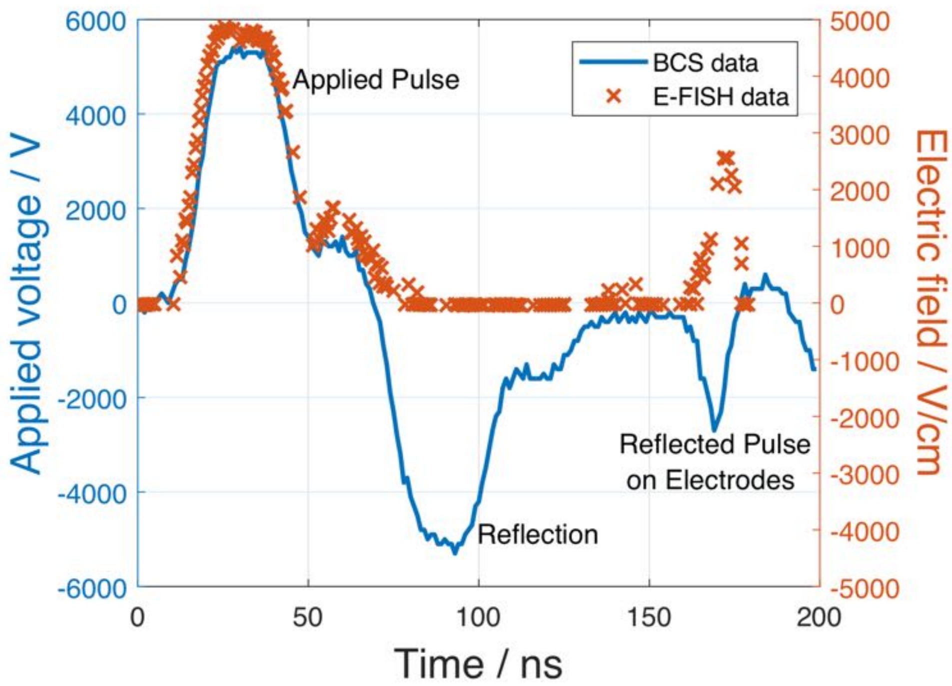




- Resistors soldered into ground shielding of HV cable
- Voltage drop over resistors measures current flowing through cable
- Incoming and reflected pulse measurable

Back current shunt

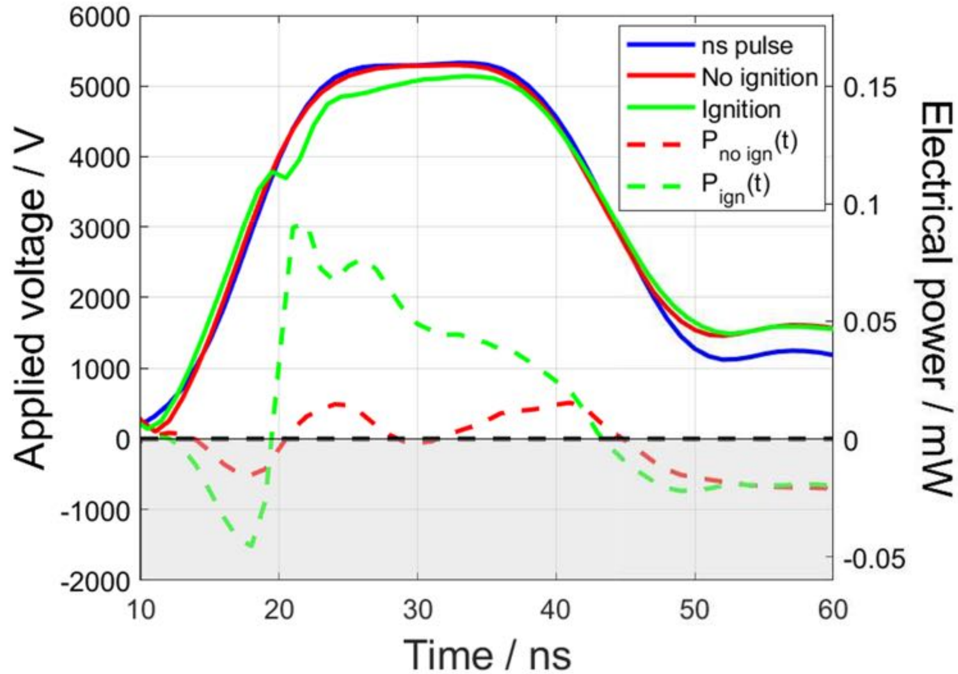




Reflected pulse measured with the BCS exhibits no electric field (red) at the electrodes

L. Hansen, B. Goldberg, D. Feng, D. Miles, H. Kersten, S. Reuter PSST, (Submitted)

Electric Measurements



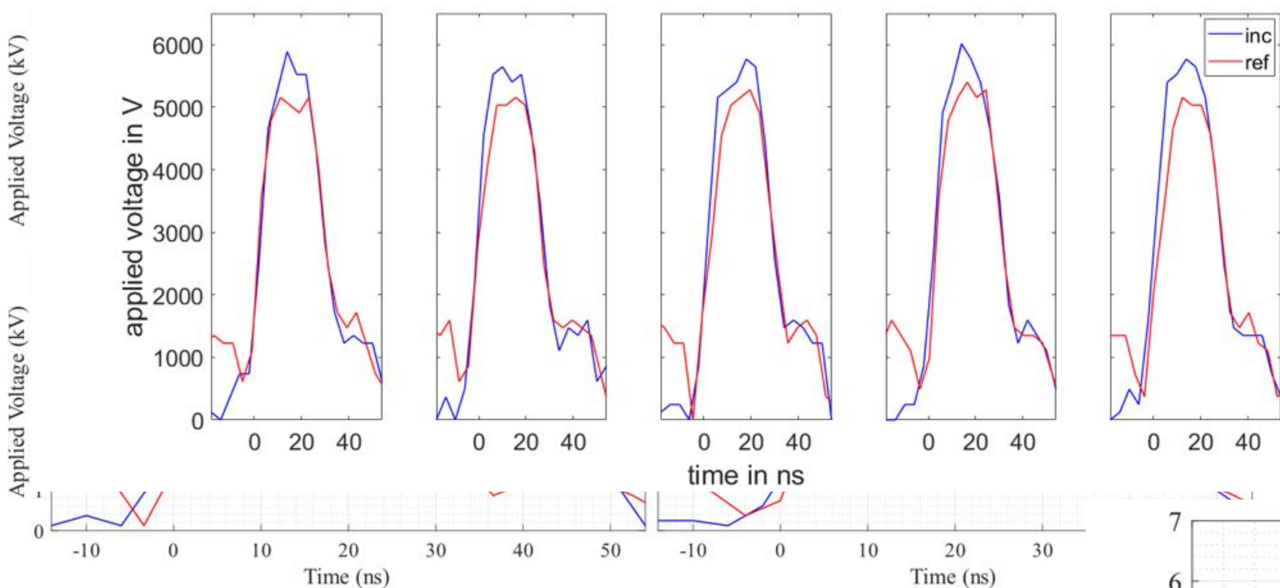
Superimposing applied pulses with reflections shows electrical power dissipated in the discharge

$$W_{BCS} = \frac{1}{Z} \int_{t_o}^{t_{pulse}} \left(U_{inc.}^2 - U_{ref.}^2 \right) dt$$

L. Hansen, B. Goldberg, D. Feng, D. Miles, H. Kersten, S. Reuter PSST, (Submitted)

Back Current Shunt (BCS)

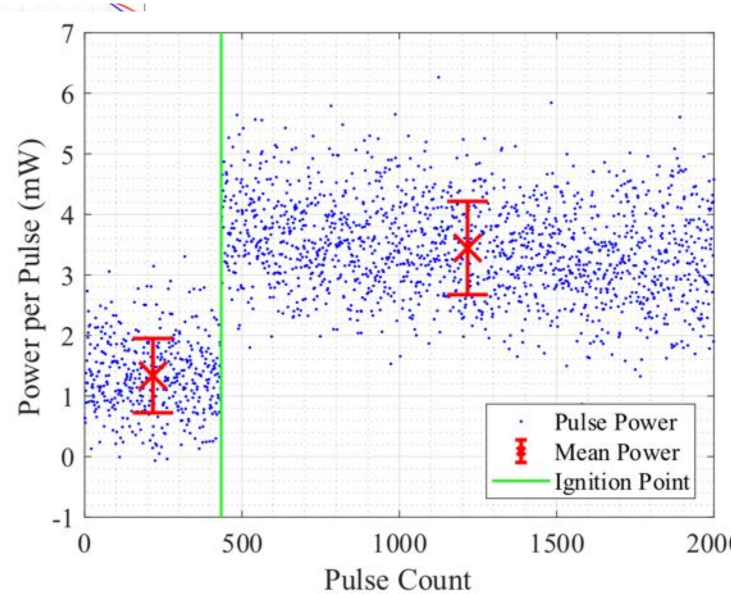
single shot with electric measurements



before plasma ignition

after plasma ignition

Plasma ignition can be observed in real time in single shot BCS evaluation



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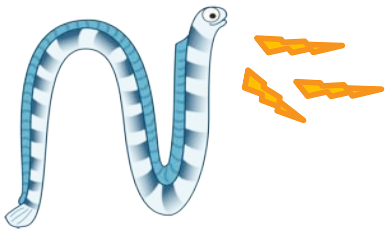
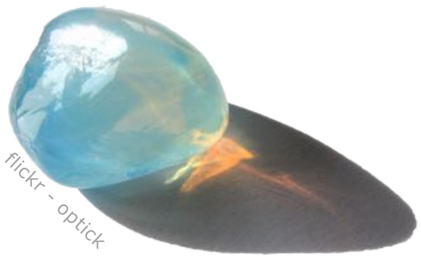
S. Reuter, B. Goldberg, L Hansen, A. Dogariu, D. Miles, in preparation

Measurement Techniques



E-Fish - Electric Field induced second harmonic light generation



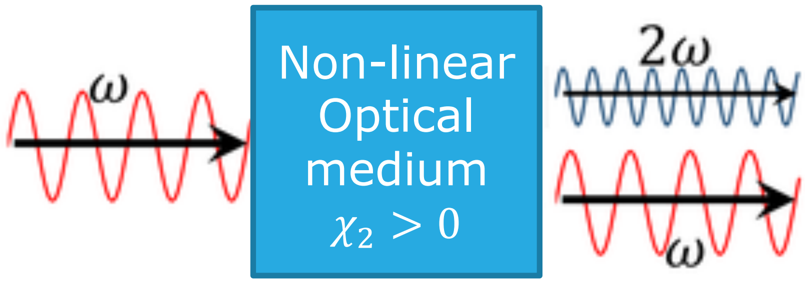
Rayleigh-Scattering

FLEET - Femtosecond Laser Electronic Excitation Tagging

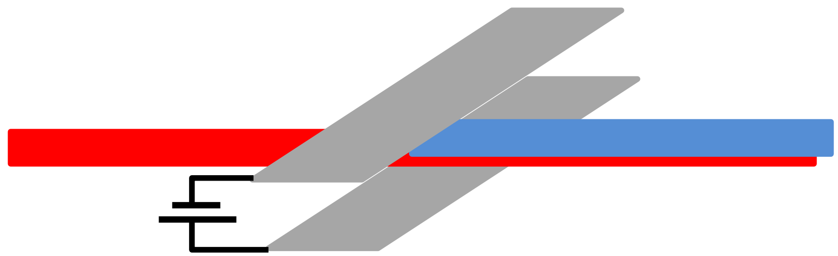
E-FISH

In an isotropic medium, the index of refraction is the same in all directions

Second harmonic generation is only possible in a non-centrosymetric medium and impossible in a symmetric medium



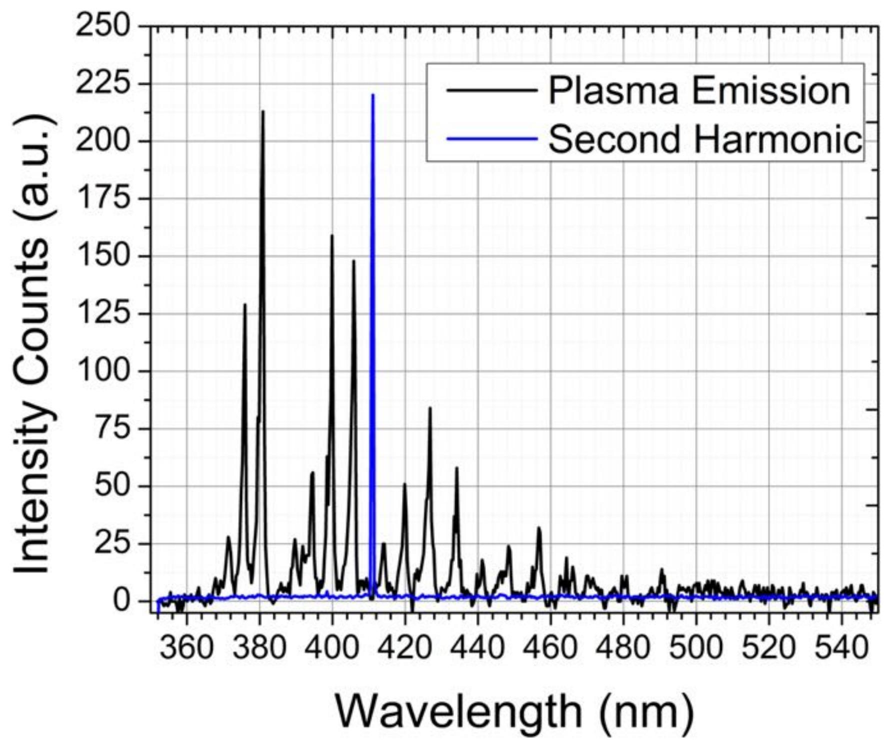
Applying an electric field destroys that symmetry allowing for second harmonic generation



$$I^{(2\omega)} \propto N^2 (E_{Ext})^2 \left(I_{Pump}\right)^2$$

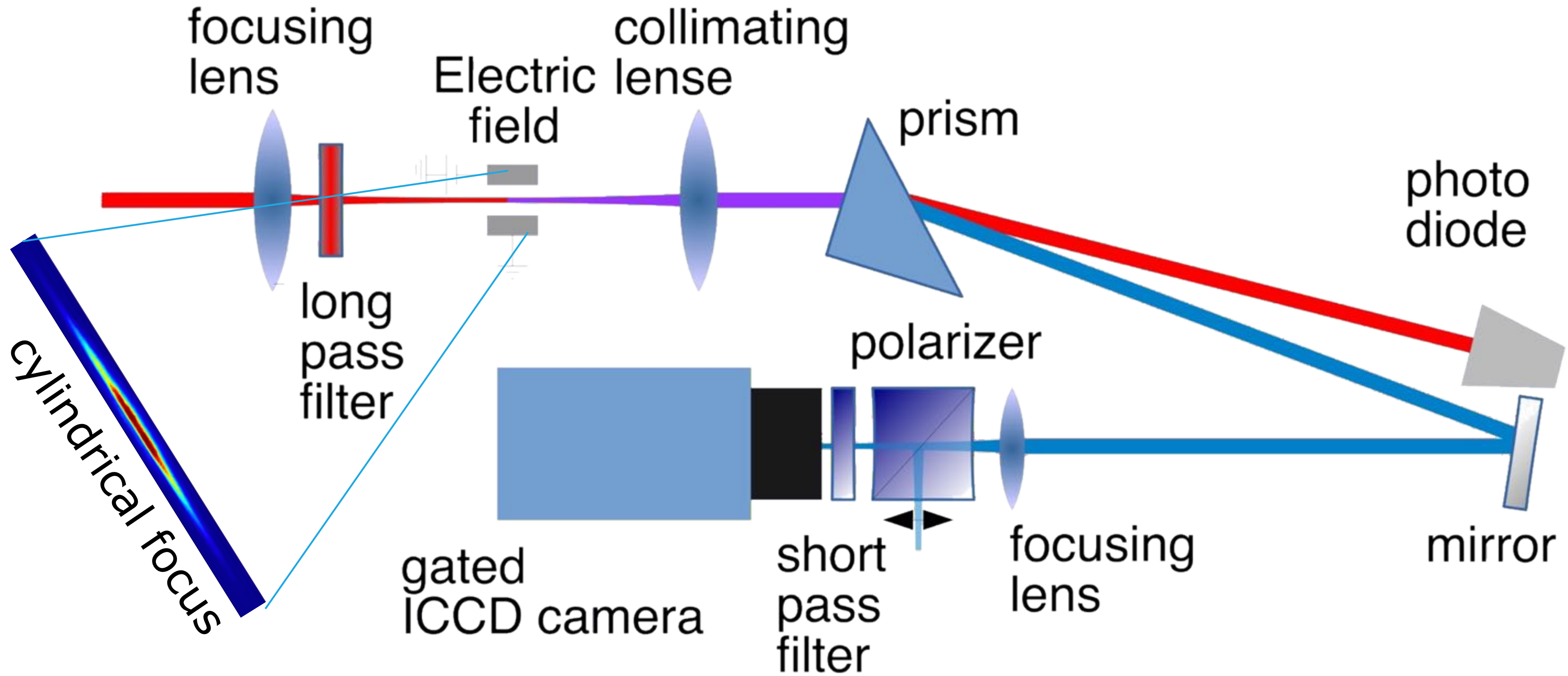
Benefits of E-FISH Method

- Quadratic Dependence upon Electric Field
  - Sensitive down to 100's of V/cm
- Time Resolution
  - fs laser acts as a δ function compared with ns changes in fields
- Non-resonant
  - Wavelength can be chosen to fit experiment



Dogariu, A., et al. *Physical Review Applied*, *7*(2), 024024.

Experimental Setup



Spectra-Physics Solstice Ace laser 800 nm @ 50 fs up to 6 mJ per pulse
a wave plate and polarizer are used to vary the energy

w_0 ~10µm z_R~100µm. L_{coh}~10 mm

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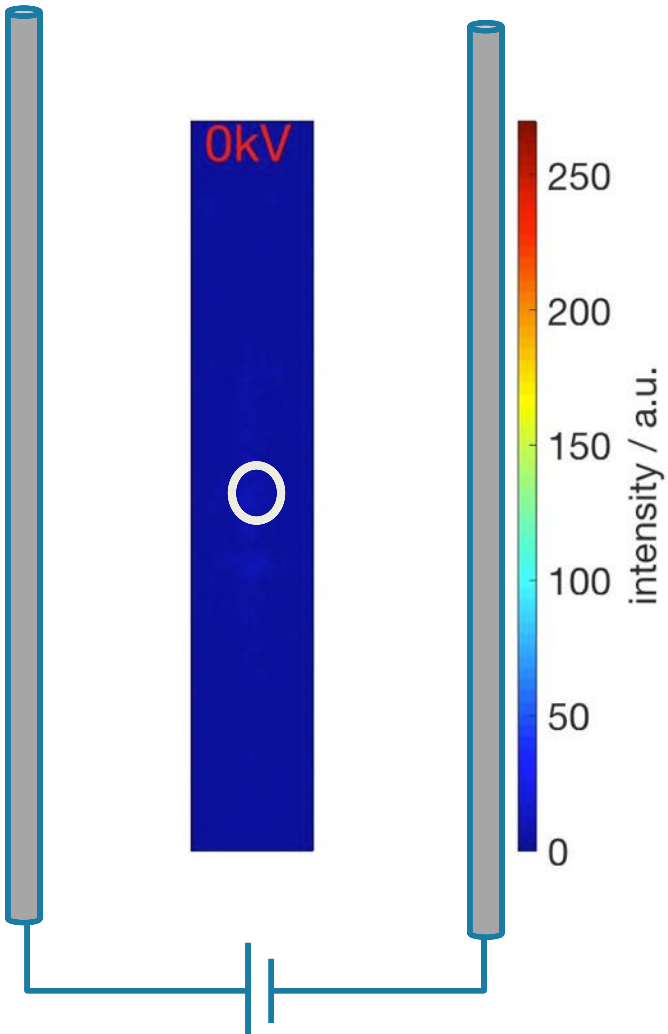
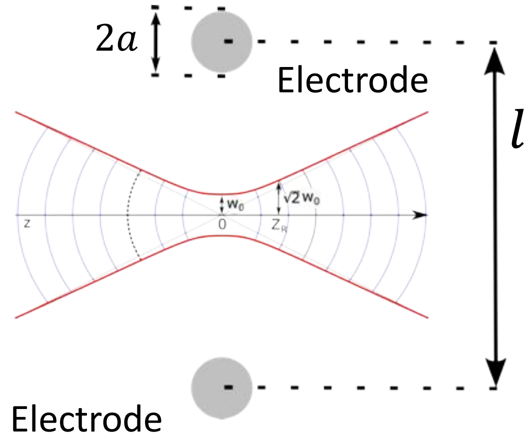
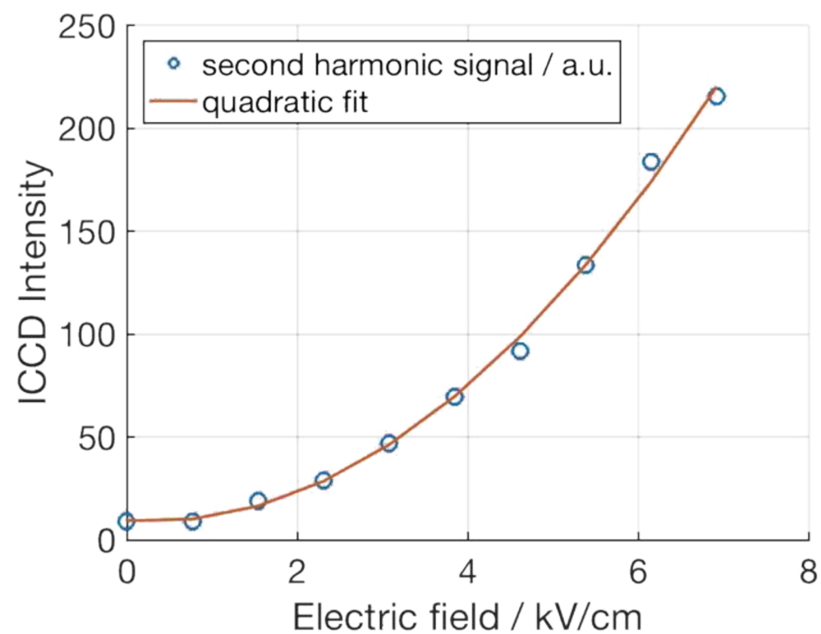
Calibration



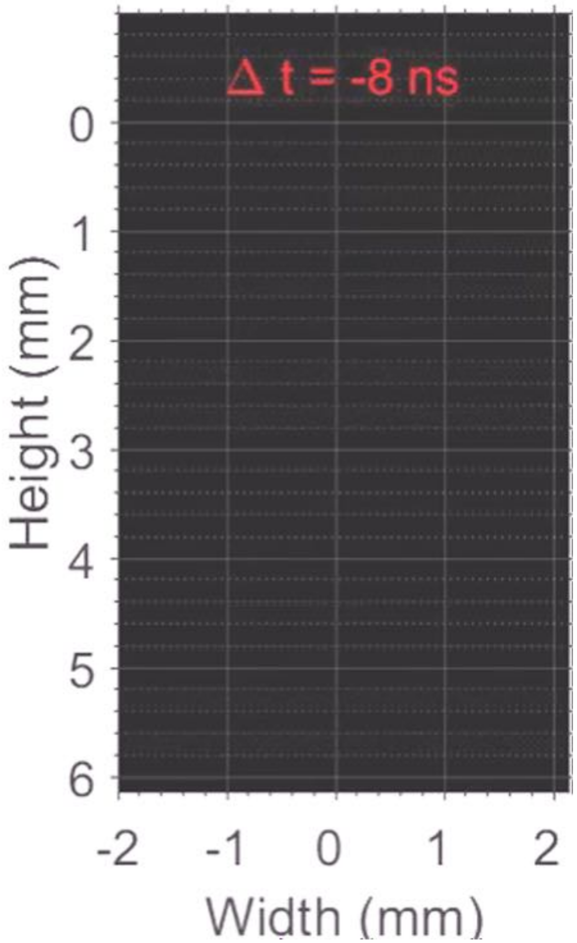


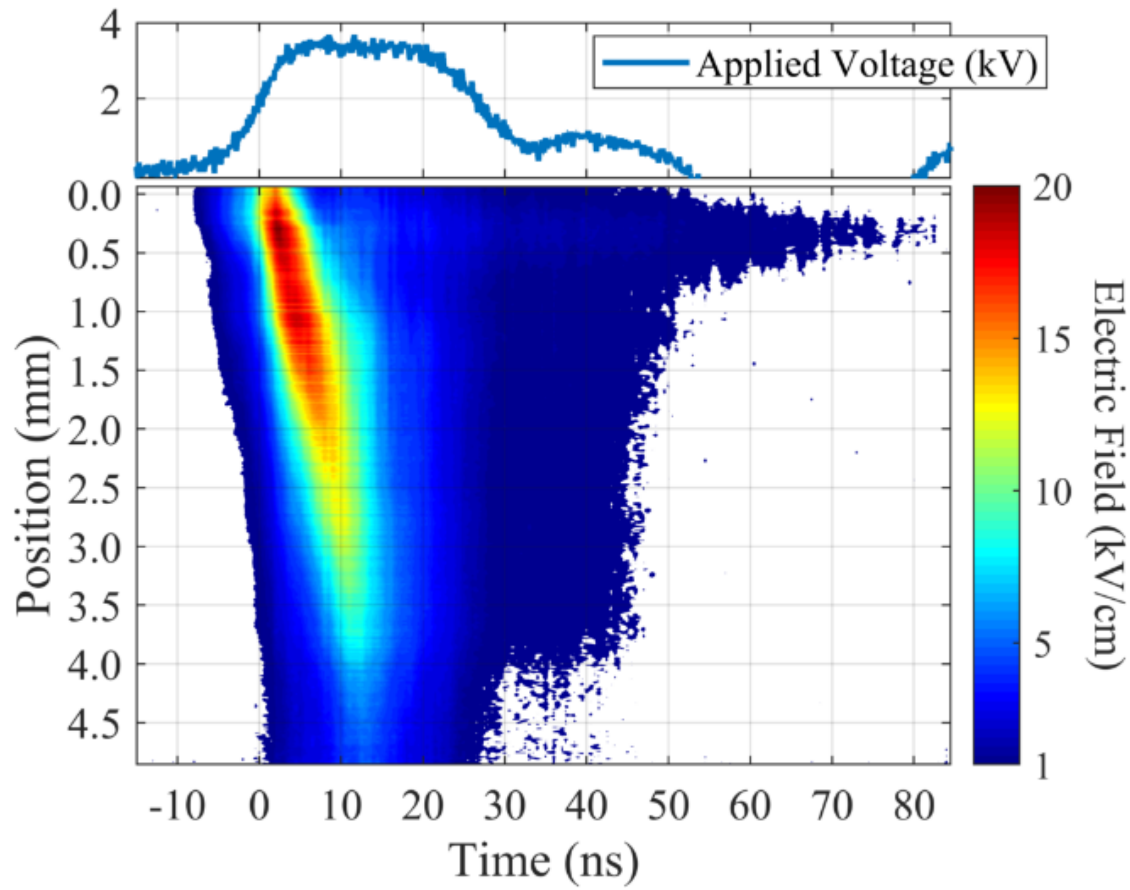
$$E(z) = \frac{2 \cdot V_{Applied}}{d \cdot \cosh^{-1} {}^{l}/_{2a}} \cdot \frac{1}{\left[1 + 4\,{}^{(z - z_0)^2}/_{d^2}\right]}$$



to be continued…

Electric Field in Streamer Propagation





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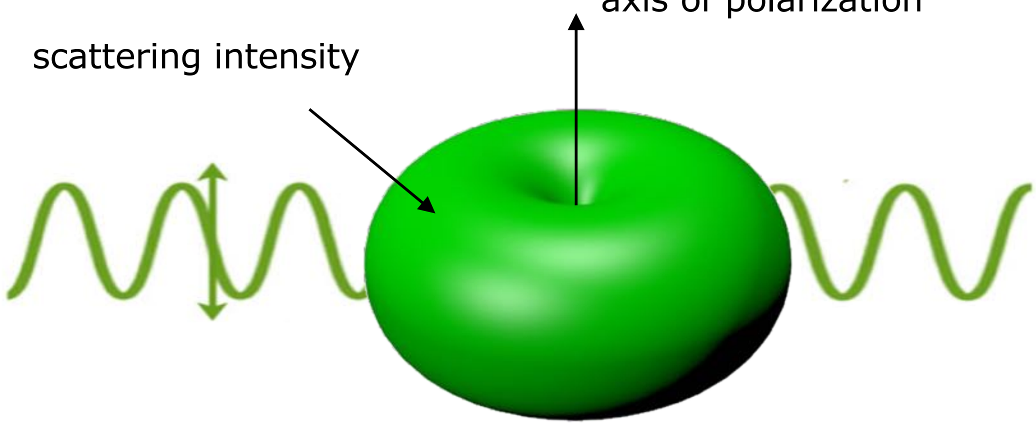
B.M. Goldberg, S. Reuter et al., Opt Lett, 3853, 44 (2019)

Rayleigh Scattering

- Rayleigh scattering is the scattering of light on particles with diameter d smaller than the wavelength: $d<<\lambda$
- Electron displacement by the incident electric field creates a dipole that emits the Rayleigh scattered light.



dipole radiation pattern

laser intensity

number density

$$S_{RS} \propto I_L n V \sigma_{RS}$$

scattering cross section

mixture fraction

$$\sum_{i=1}^{N} \chi_i \sigma_i$$

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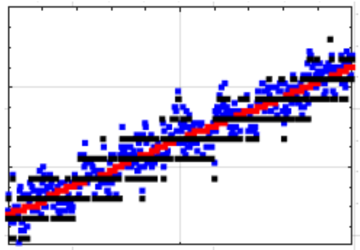
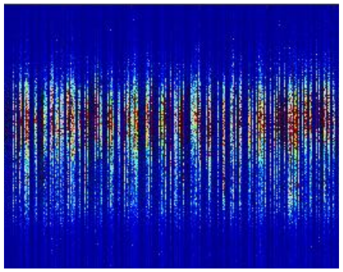
Towards single shot in low signal measurements

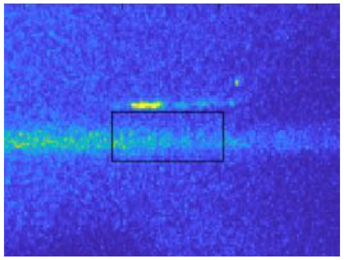
1. time binning



2. advanced averaging



3. space slicing



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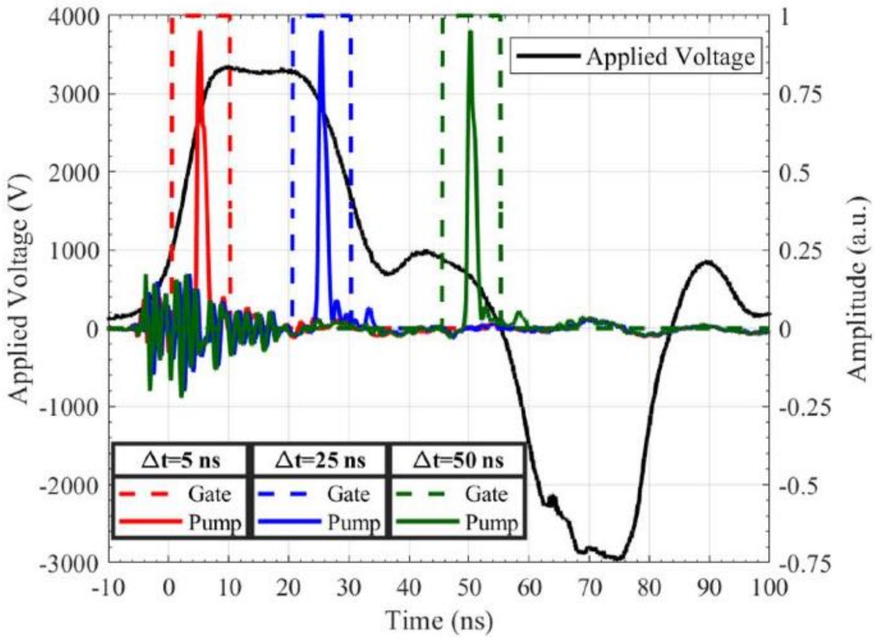
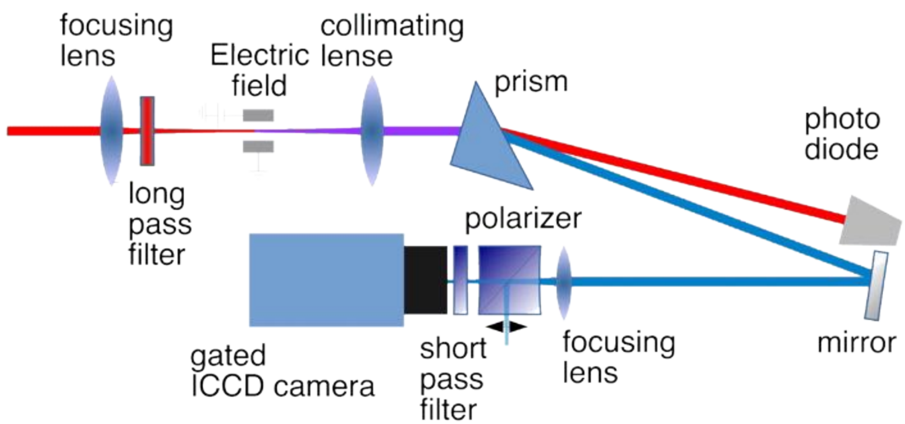
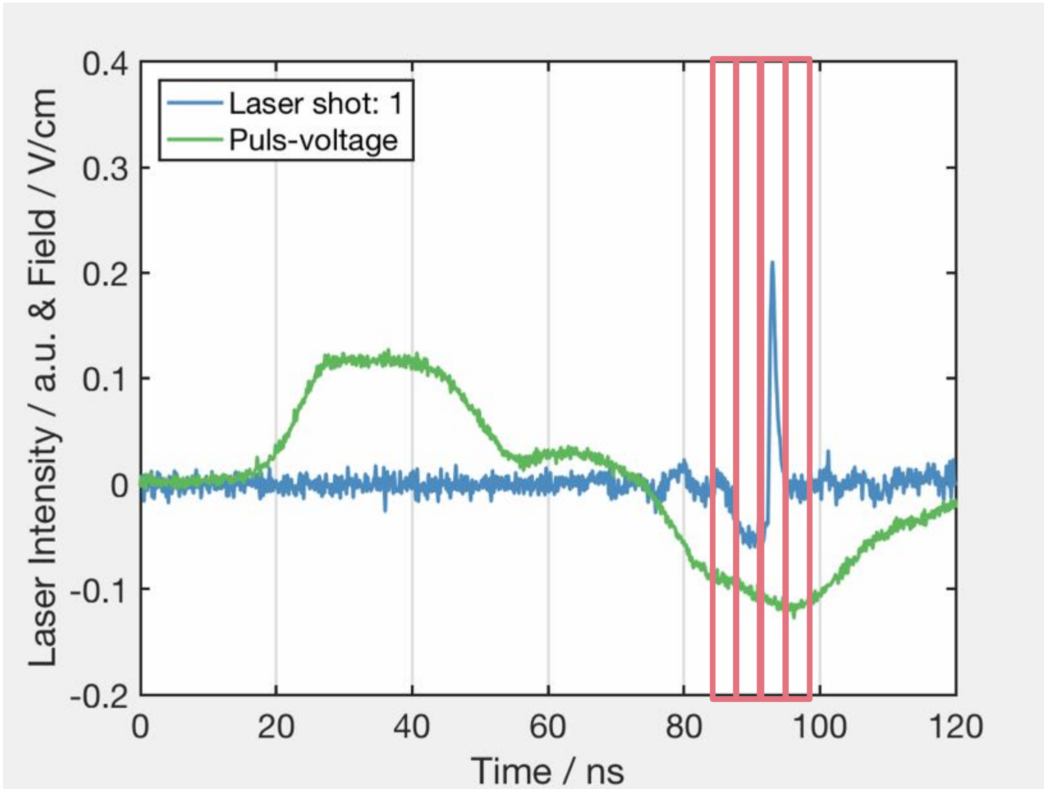
Time Binning (E-FISH)





- Laser shot is shifted with respect to ns-pulse
- gated camera records second harmonic signal

Time Binning (E-FISH)



example: Laser jitter
triggering on previous laser pulse leads to jitter ~20ns

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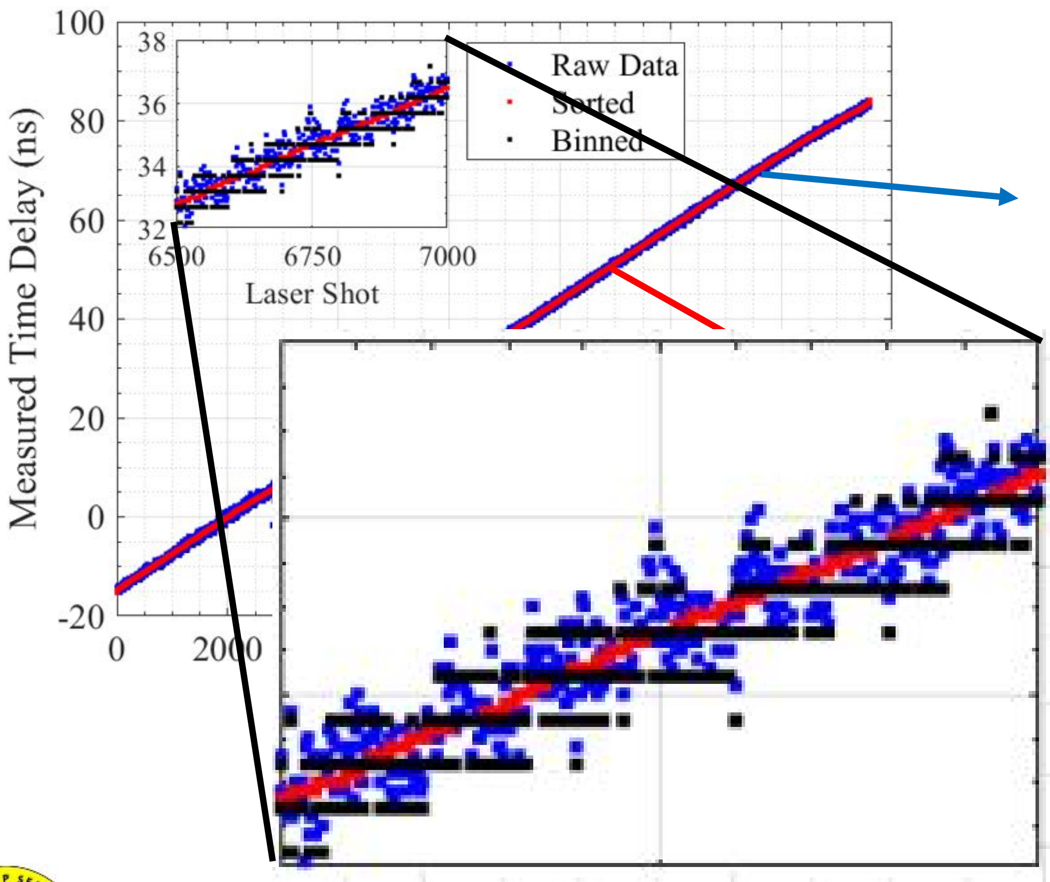
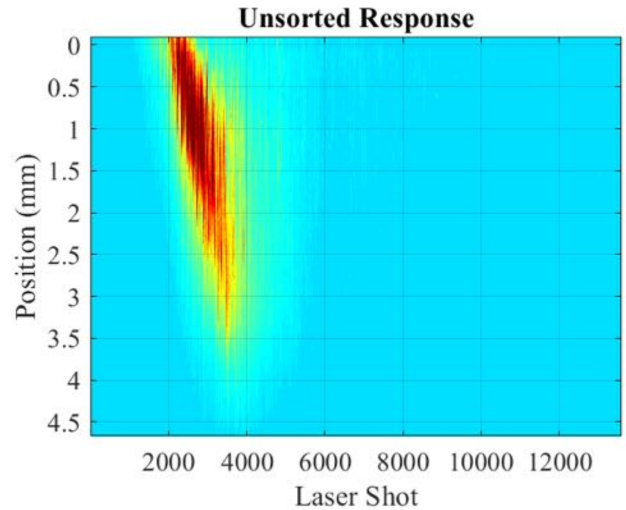
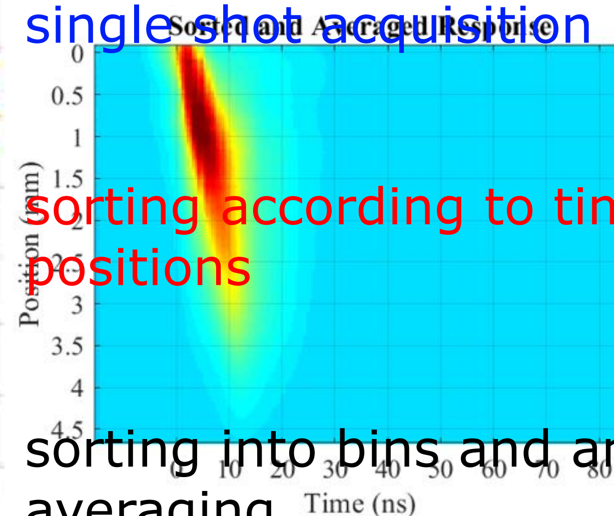
Time Binning (E-FISH)





single shot acquisition

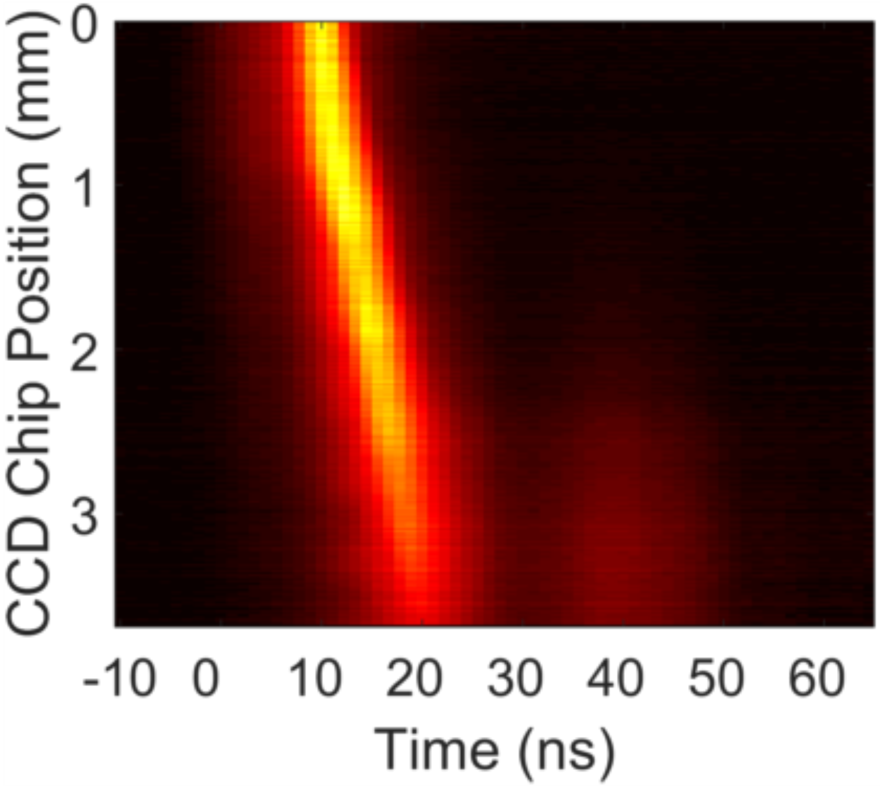


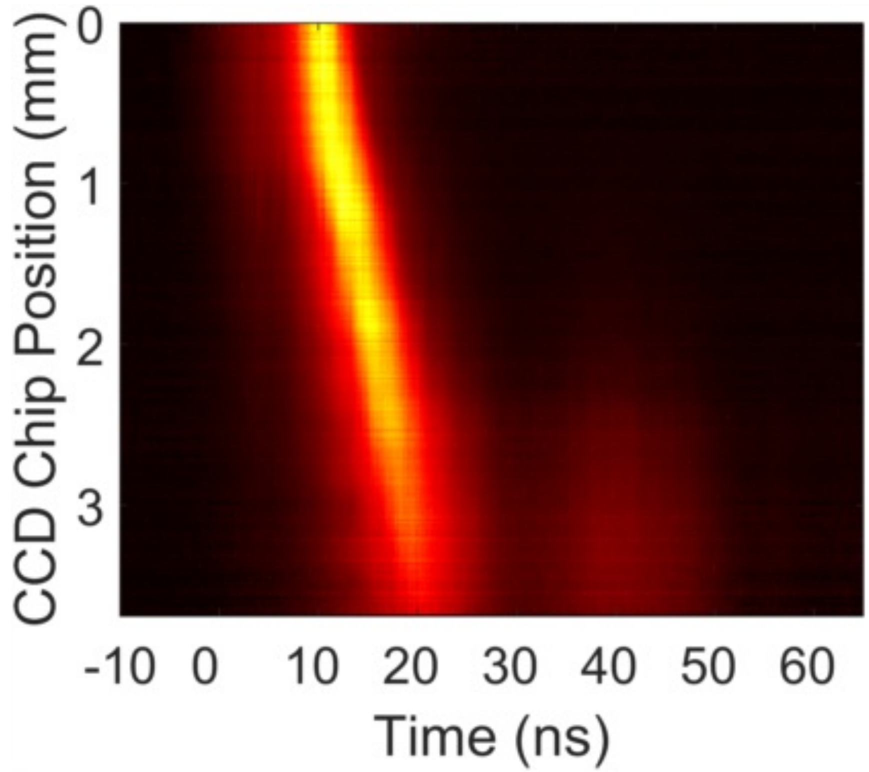
sorting according to time positions

sorting into bins and and averaging

S. Reuter, B. Goldberg, L Hansen, A. Dogariu, D. Miles, in preparation

Time Binning (E-FISH)





~1 ns resolution ⟹ ~100 ps resolution

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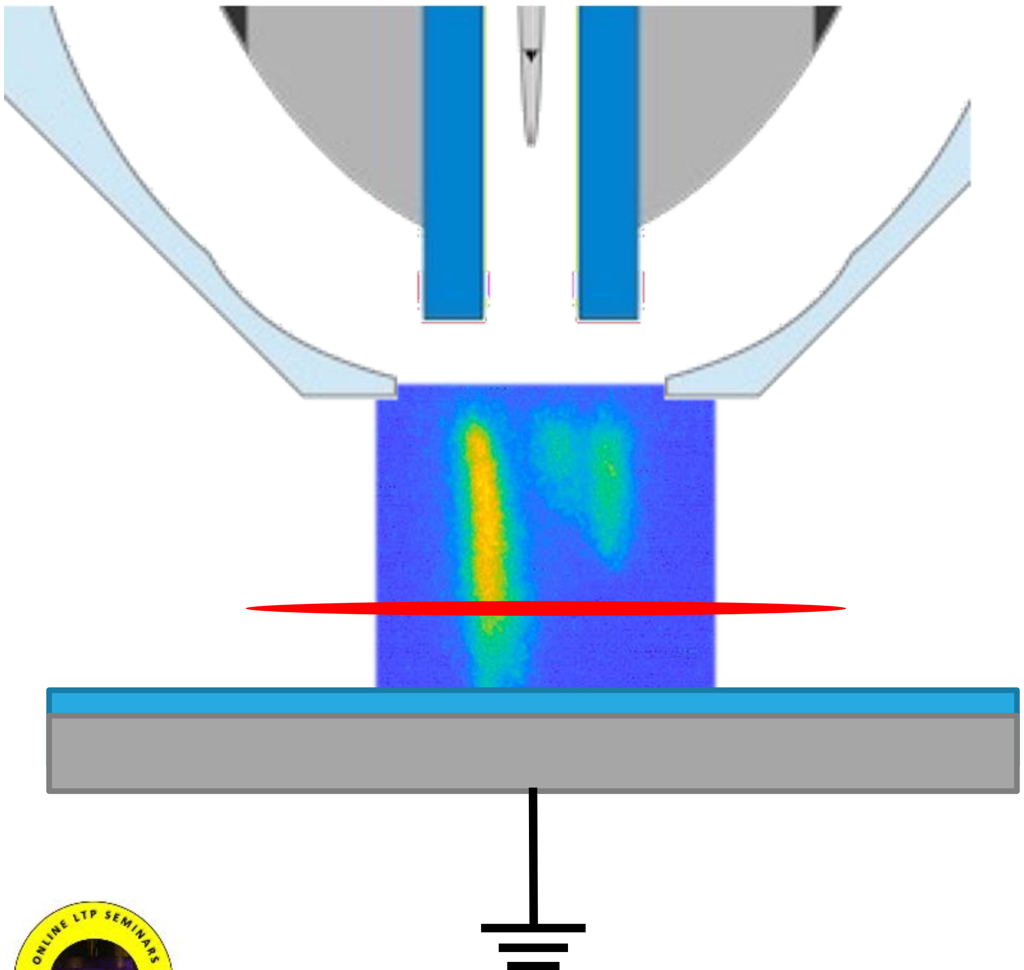
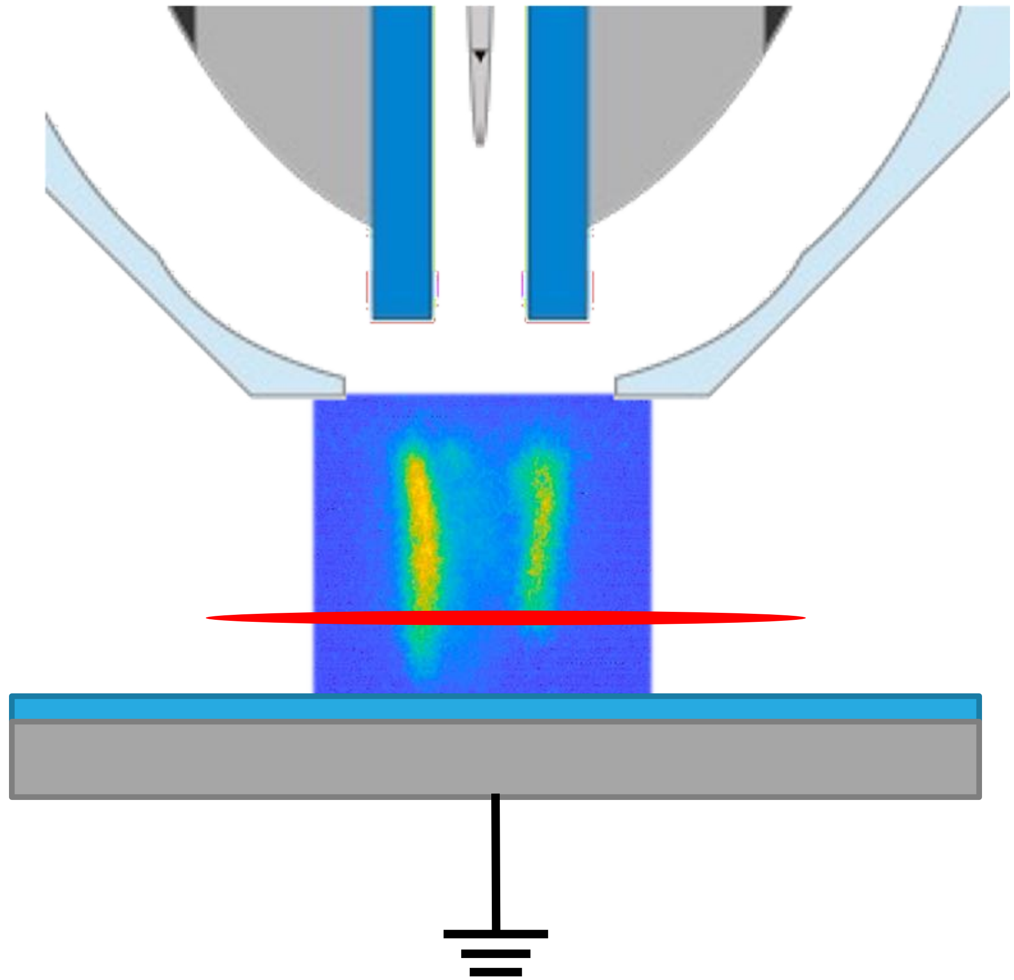
Advanced Averaging

Advanced Averaging. (E-FISH)

left position



both sides



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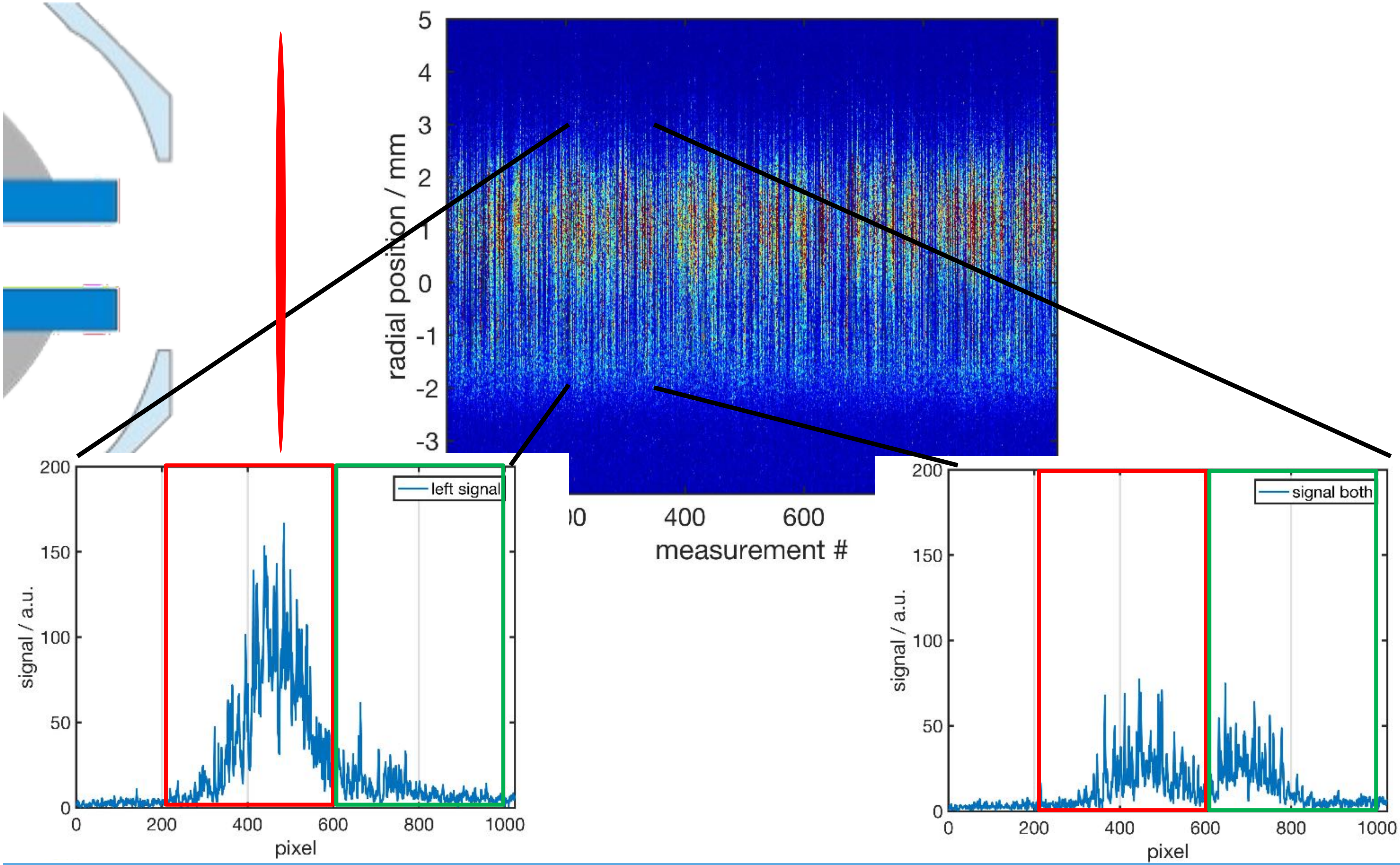
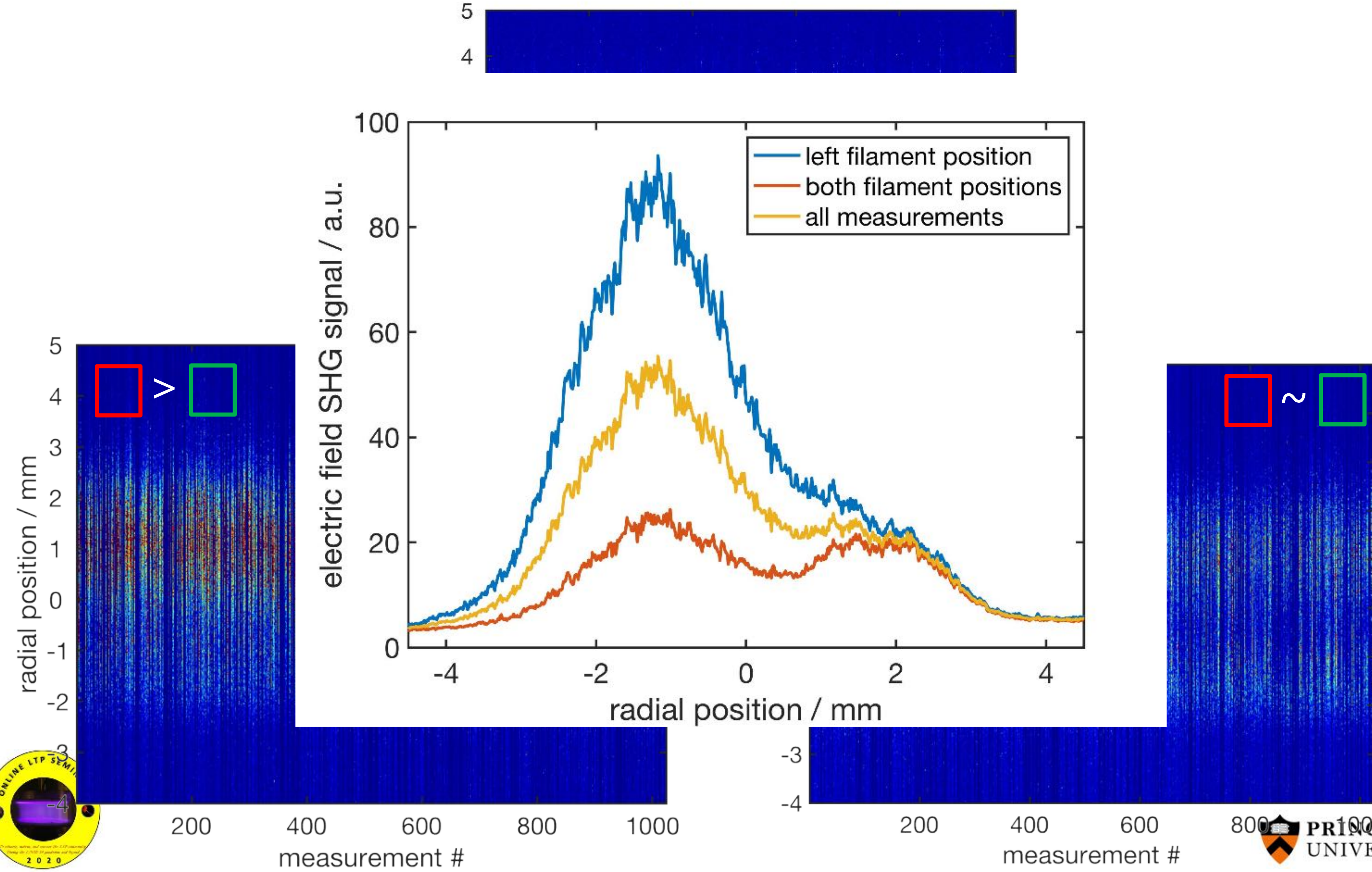
Advanced Averaging



S. Reuter et al. Proc. 22nd Int. Conf. GD2018, NoviSad

S. Reuter, B. Goldberg, L Hansen, A. Dogariu, D. Miles, in preparation

Advanced Averaging



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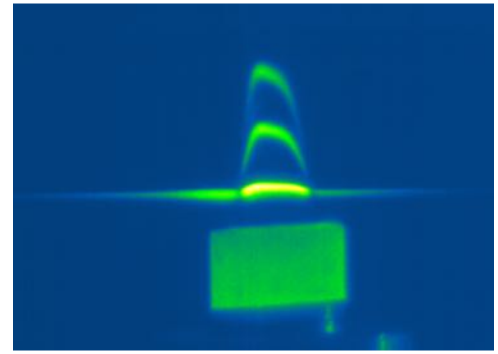
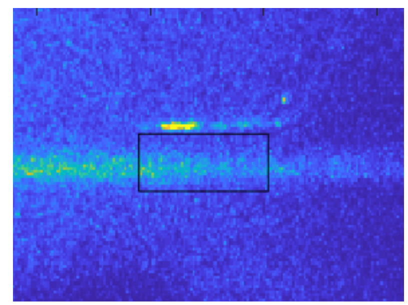
S. Reuter, B. Goldberg, L Hansen, A. Dogariu, D. Miles, in preparation

Flow measurements

- Femtosecond laser tagging with stroboscopic detection



- Planar Rayleigh-Scattering



- Space Slicing

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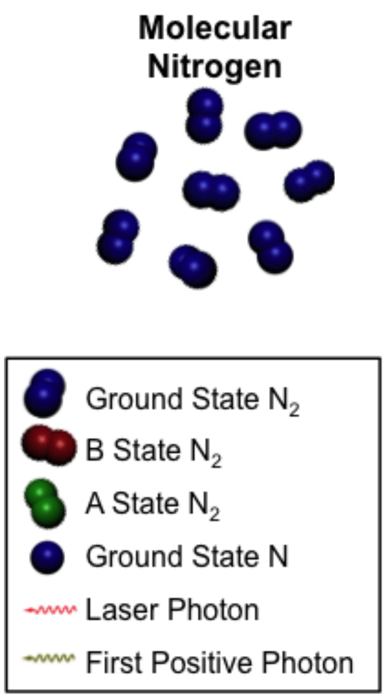
FLEET

Femtosecond **l**aser **e**lectronic **e**xcitation **t**agging



- Laser pulse ionizes molecular nitrogen—dissociation via e-ion recombination
- Atomic nitrogen recombines into excited molecular nitrogen
  - 1^{st} positive (520-780 nm) signal: ~10 μs in air, >60 μs in pure nitrogen, >100μs in Ar
  - 3-body recombination limits overall rate

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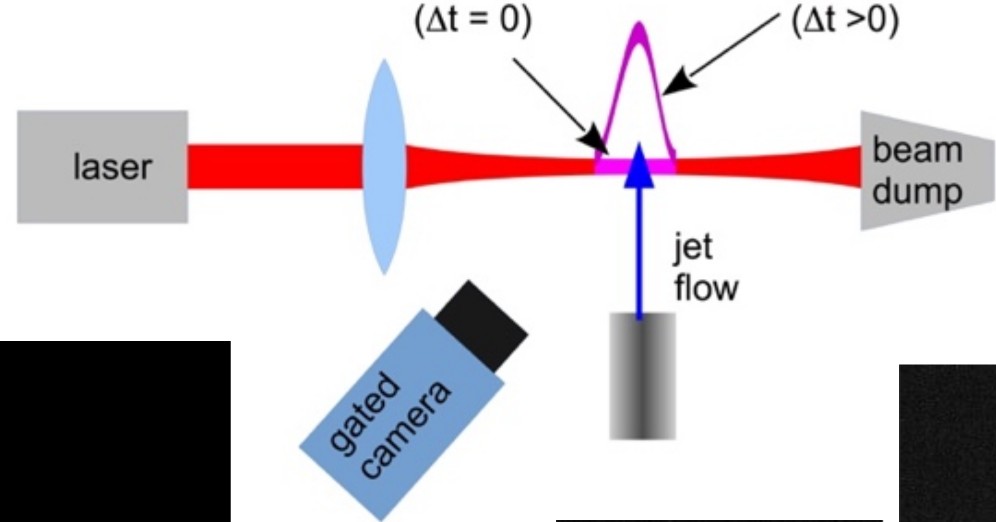
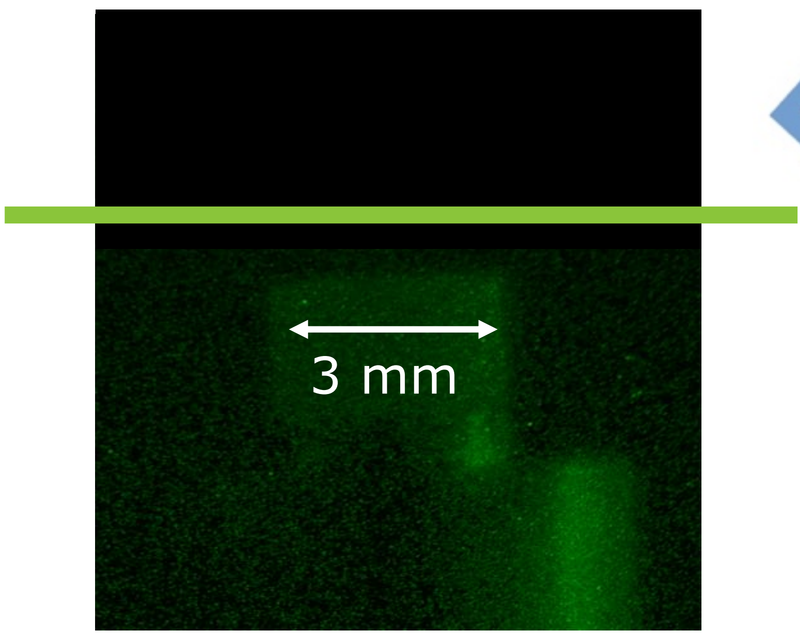
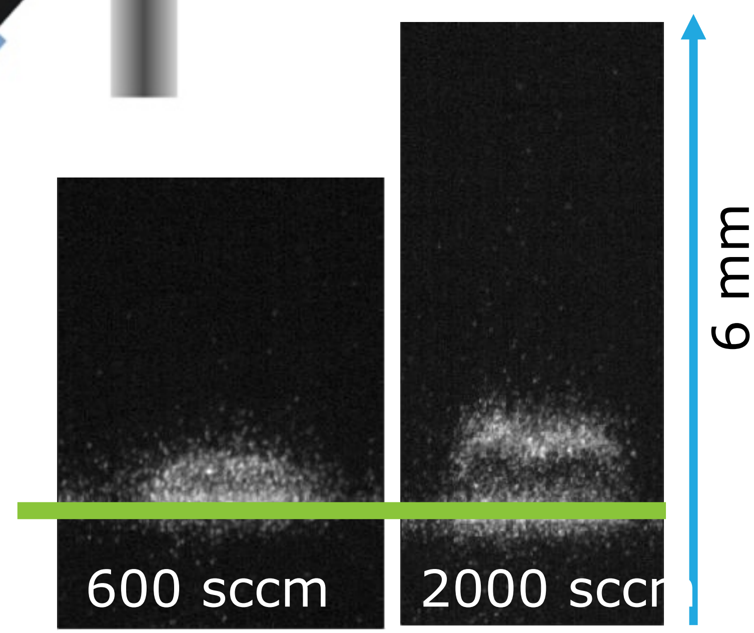
R. Miles et al., American Institute for Aeronautics Applications 2013-0340

FLEET







Flow velocity is calculated by known dimensions and time of camera gating after laser tagging

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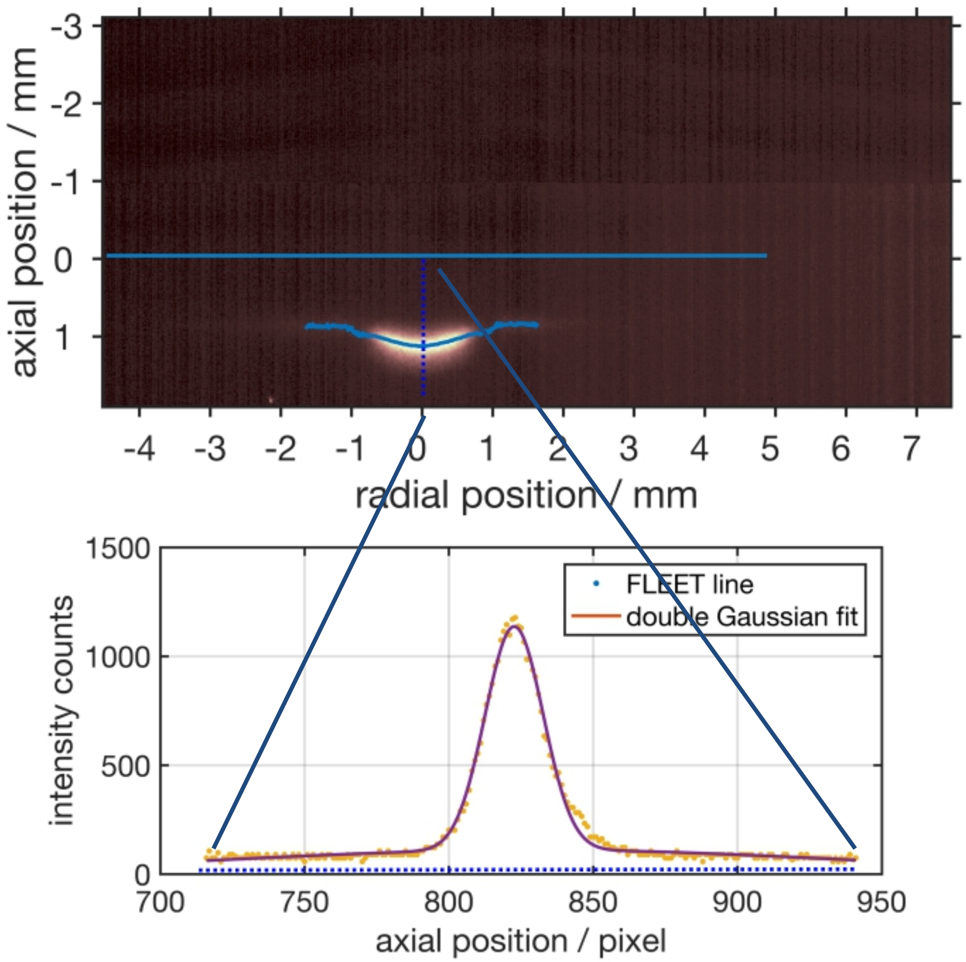
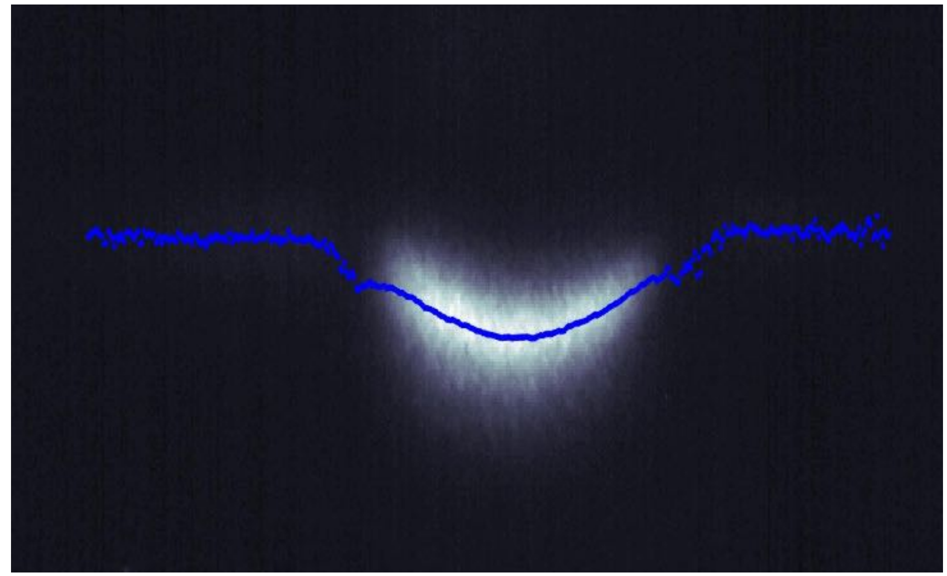
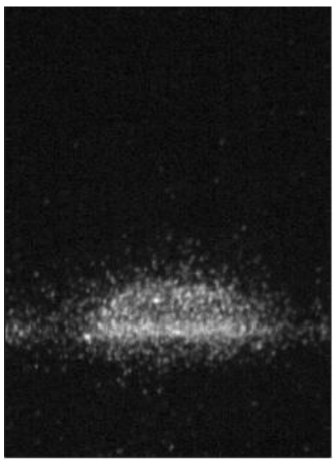
FLEET Evaluation

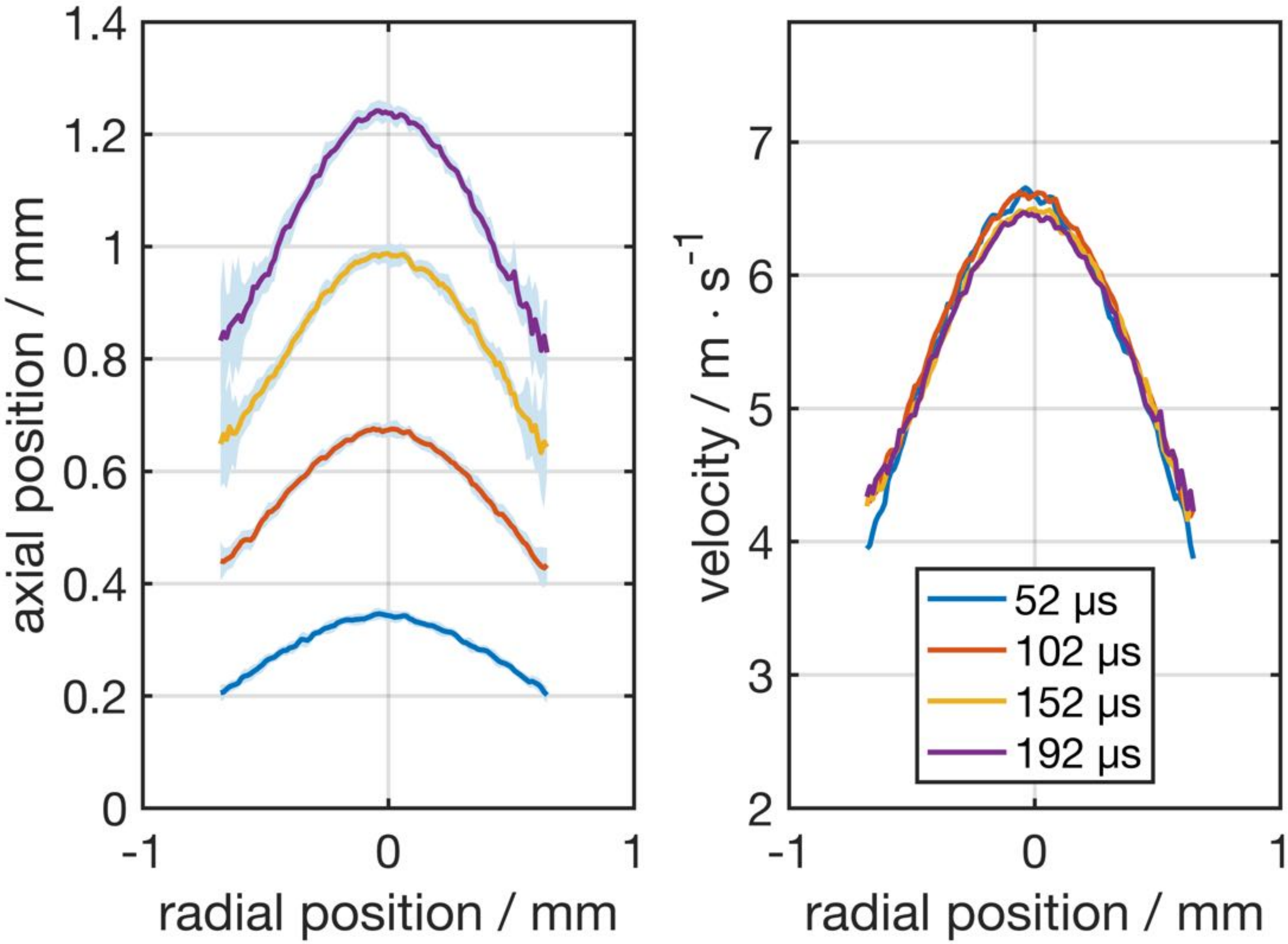




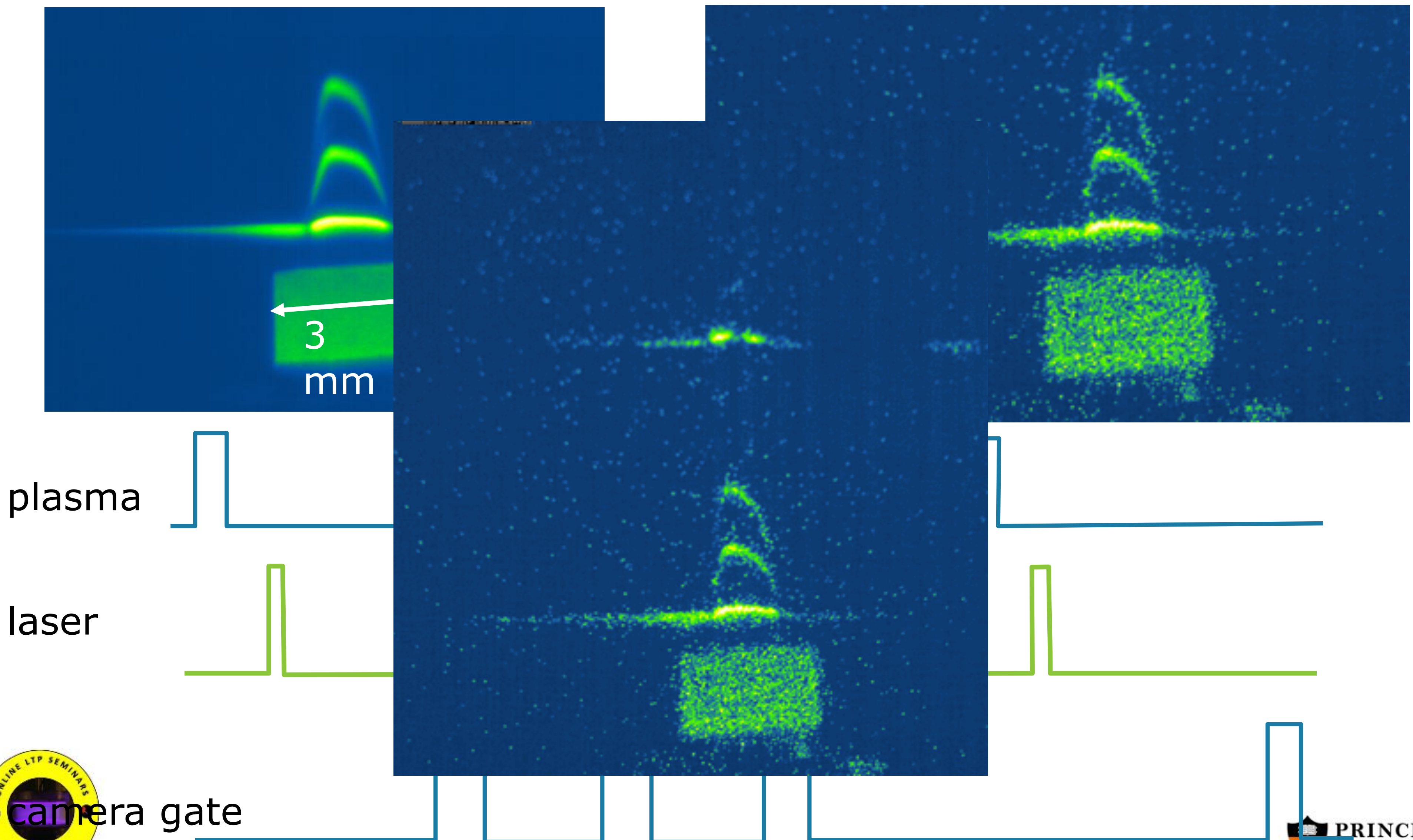
Gaussian fit of line profile at each position yields FLEET line displacement

FLEET Evaluation





Space and time Resolved Flow Field



S. Reuter et al. J. Phys. D, in preparation

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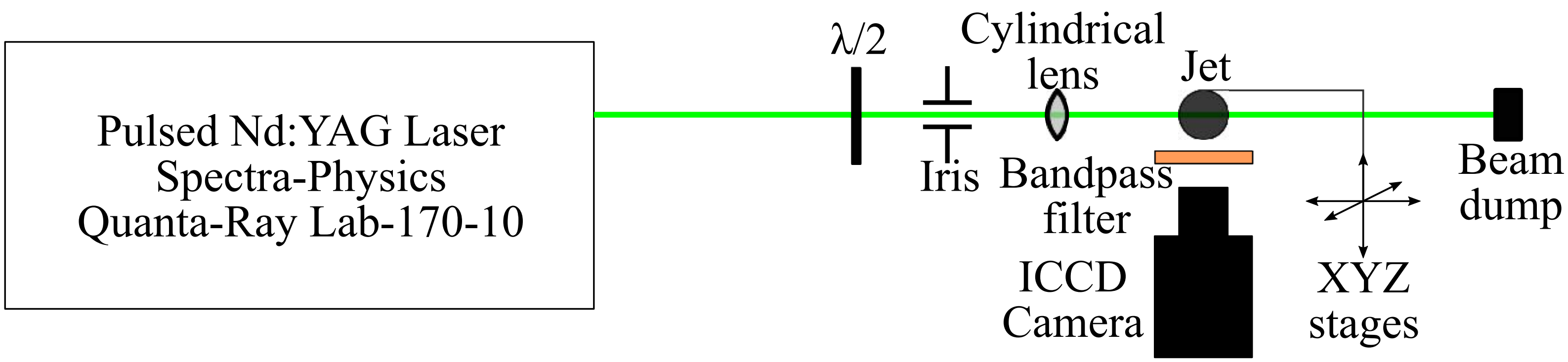
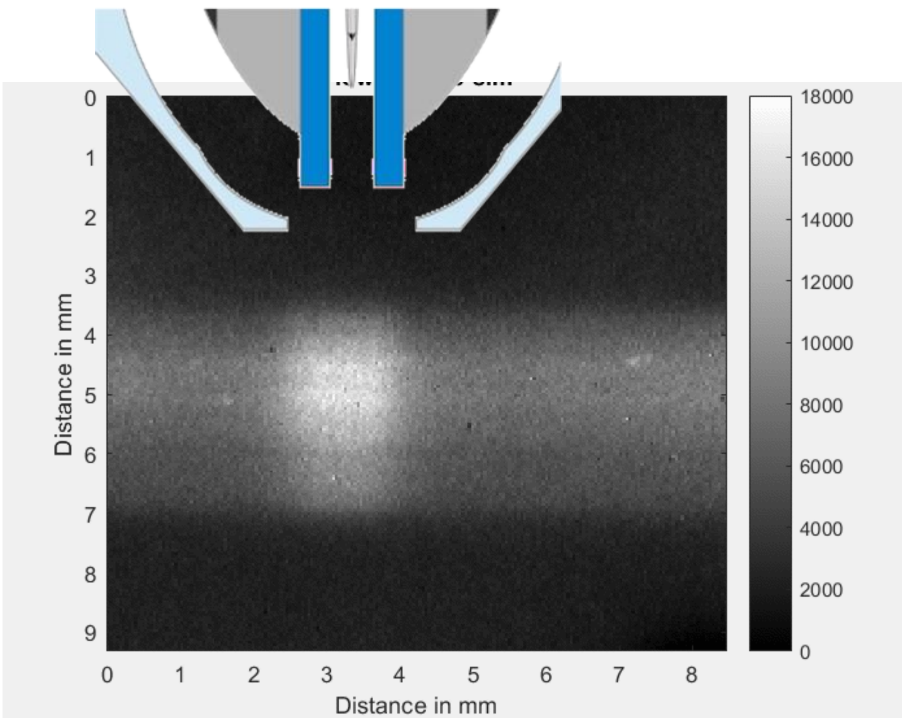
Planar Rayleigh Scattering



~ 3 mm wide laser sheet



400 sccm CO_2 (laminar flow)

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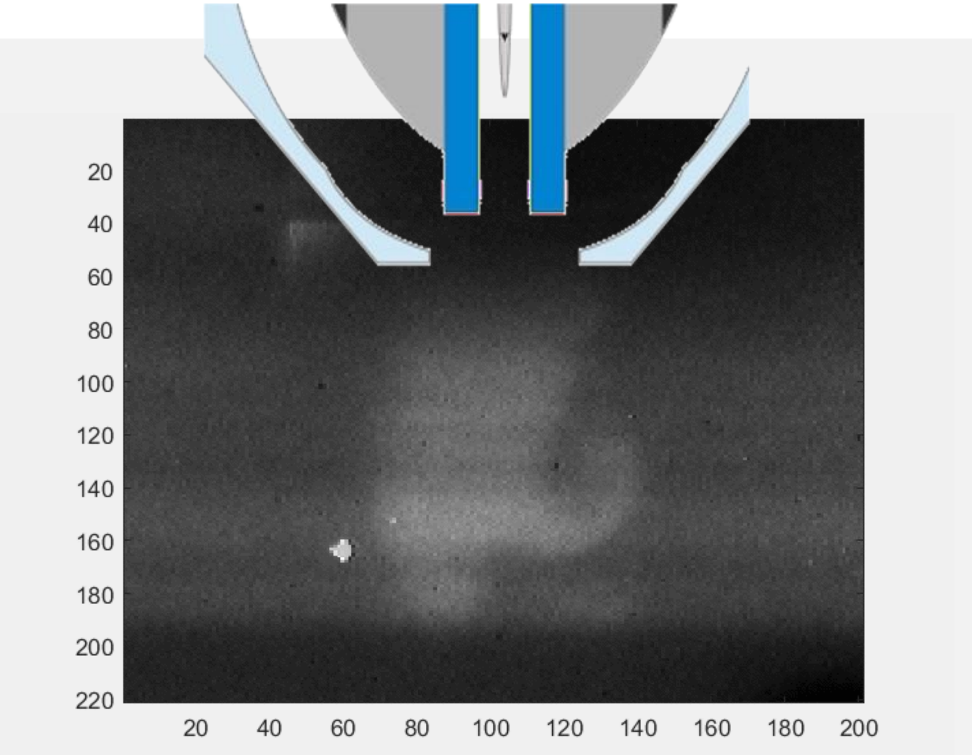
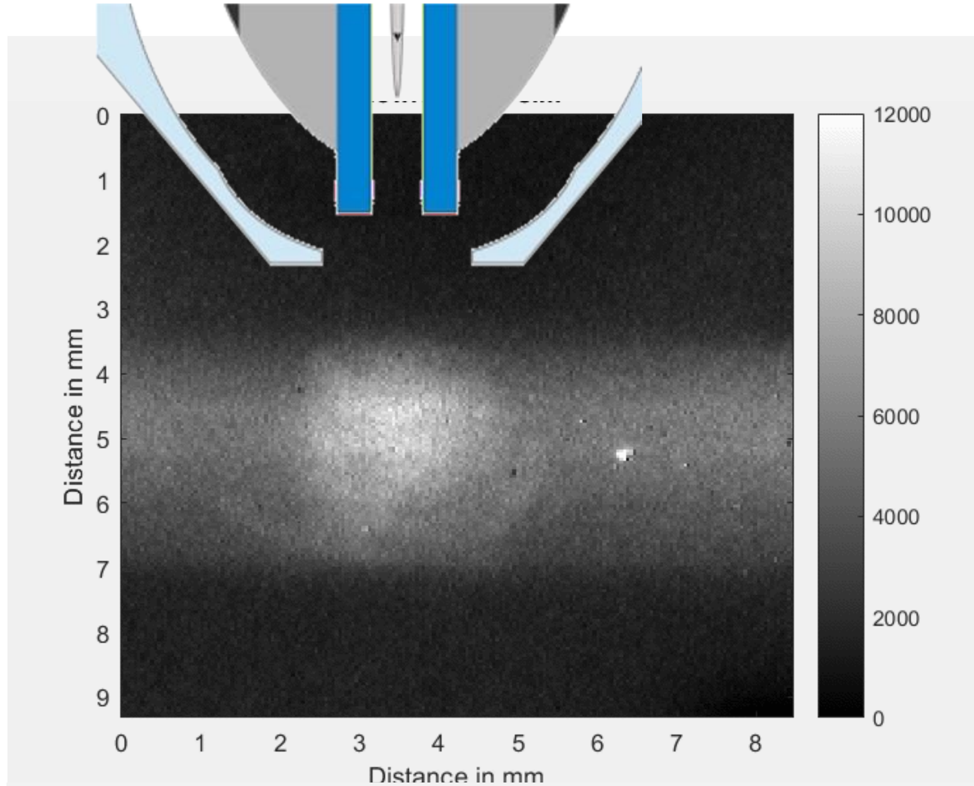
L. Hansen, B. Goldberg, D. Feng, D. Miles, H. Kersten, S. Reuter PSST, (Submitted)

Planar Rayleigh Scattering



650 sccm CO_2 (transition laminar - turbulent)



2000 sccm CO_2 (turbulent flow)

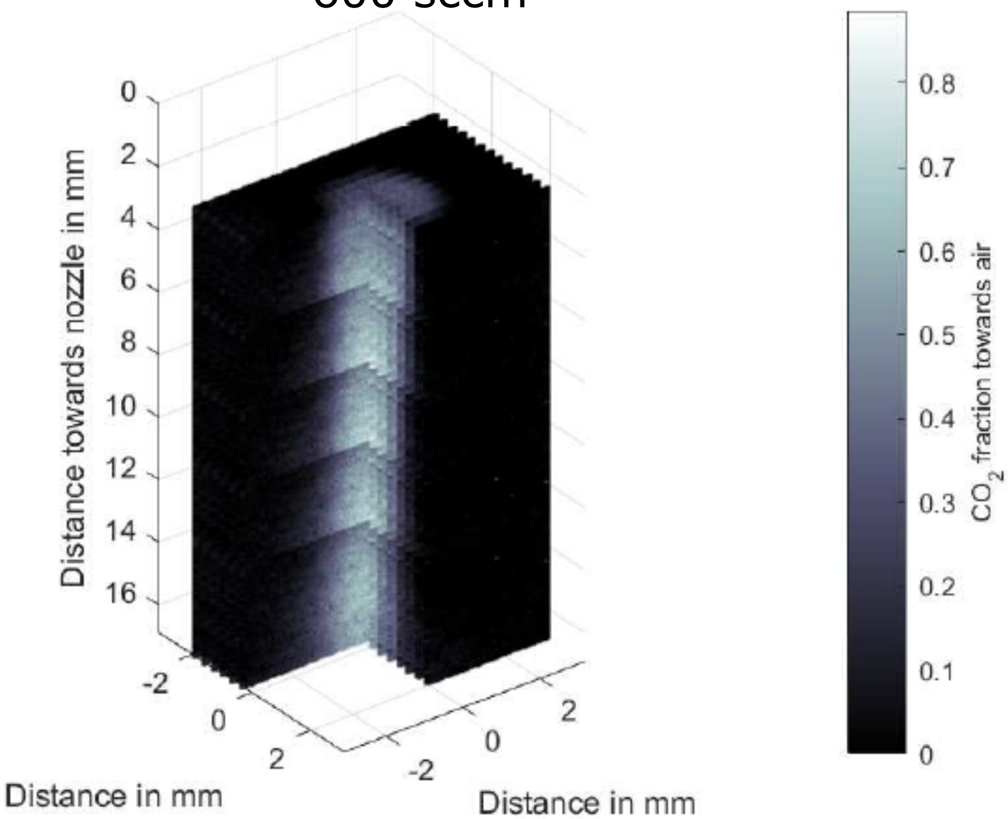
Kelvin-Helmholtz instability
(with aliasing)

L. Hansen, B. Goldberg, D. Feng, D. Miles, H. Kersten, S. Reuter PSST, (Submitted)

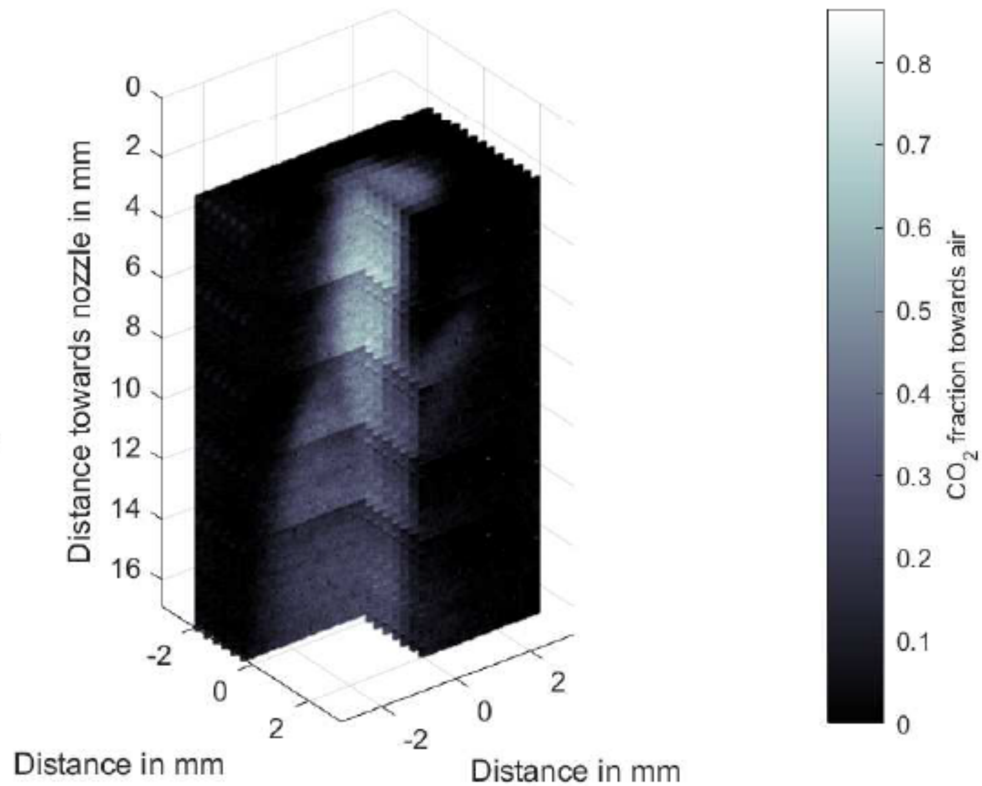
Planar Rayleigh Scattering

Plasma jet (not ignited) with
CO_2 flowing into room air

600 sccm



700 sccm



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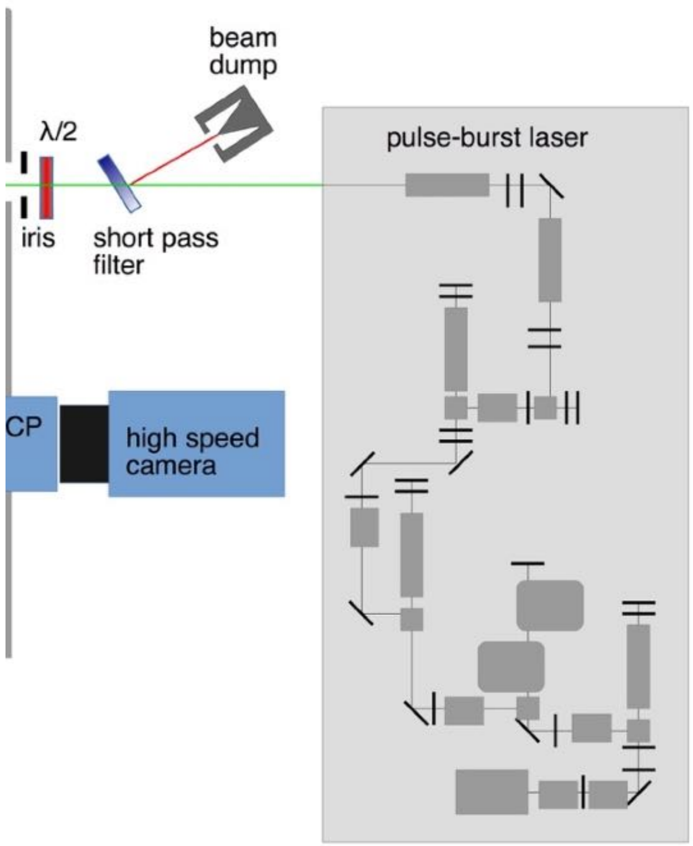
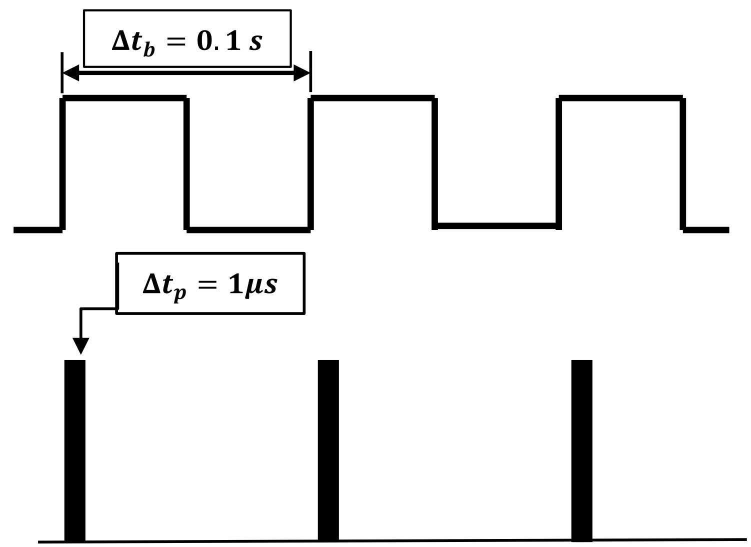
Space slicing: 3D filtered Rayleigh Scattering

very first pulse burst system (20 years ago)





- 15 – 30 pulses at MHz repetition.
  each FWHM: 12 ns

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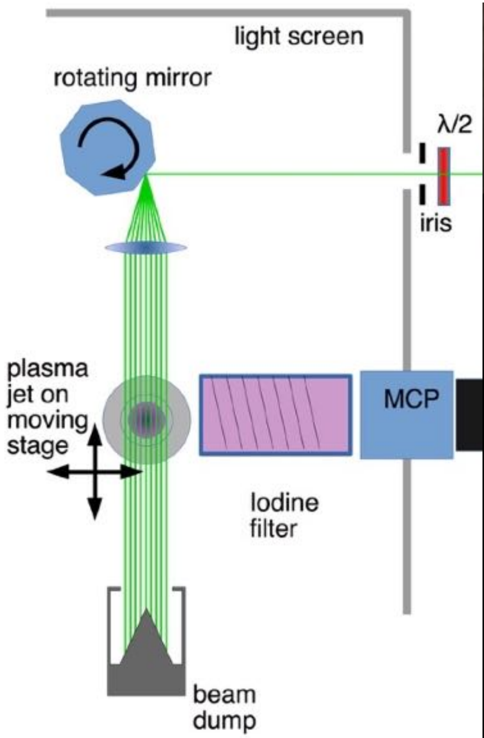
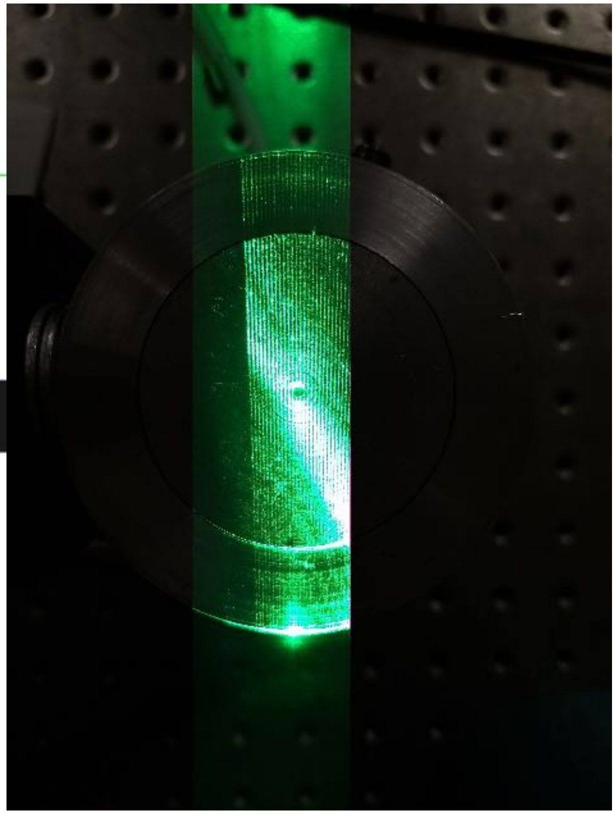
Wu, Lempert, Miles, AIAAJ 38,2000
P. Wu, R.B. Miles, Opt Lett, **1639**, 25 (2000)

Space slicing: 3D filtered Rayleigh Scattering

15 slightly shifted laser sheets utilizing a pulse-burst laser with a rotating mirror





Laser sheet fan

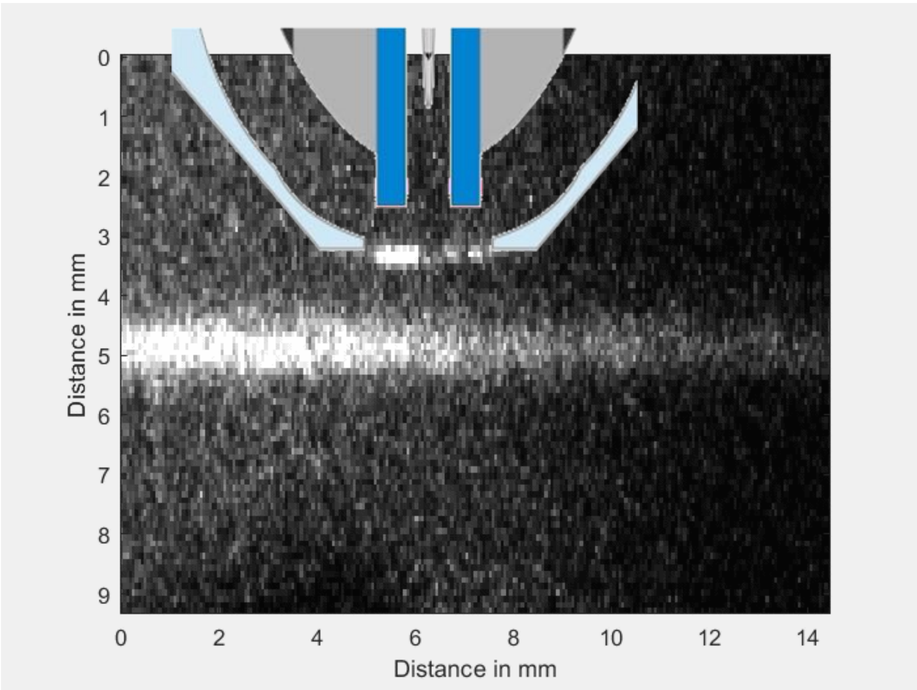
- Height: 5 mm
- Width: 0.3 mm
- Mirror rotation 333.3 Hz
- Width: 8.7 mm
- Sheets displaced by 0.3 mm

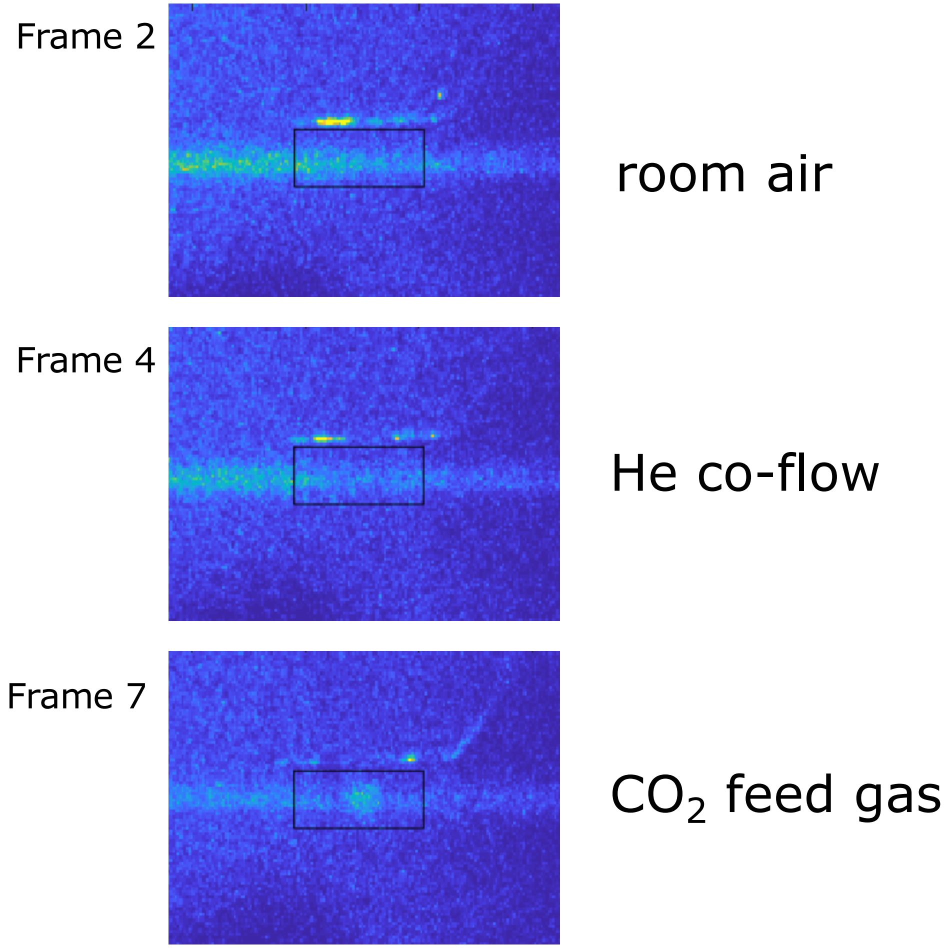
Gas displacement

- Flow speed 2 m/s @ 500sccm
- 30 µs burst time
- 6.25 µm average movement

S. Reuter, B. Goldberg, L Hansen, A. Dogariu, D. Miles, in preparation

Space slicing: 3D filtered Rayleigh Scattering





Feed gas: 500 sccm CO_2; Shielding gas: 500 sccm He

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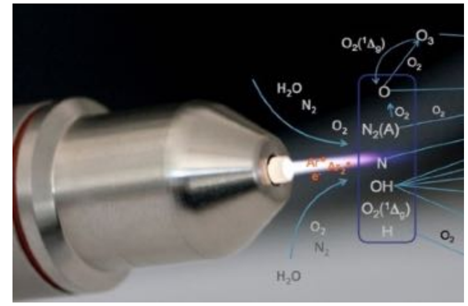
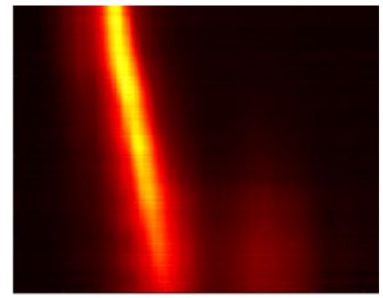
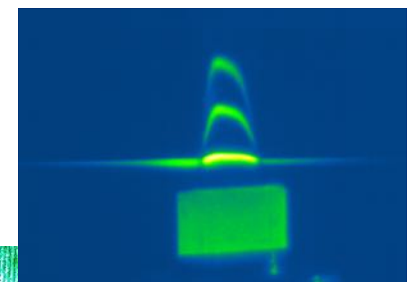
Summary



- Tailored plasma reactivity requires insight into real time processes
- ultrafast diagnostics & sensitive space resolved methods
- Novel diagnostics & computing power -> detailed single shot space and time resolved measurements
- Low signal measurements –> advanced evaluation





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Open PostDoc Position

Postdoctoral Position: Spectroscopy on Atmospheric Pressure Plasmas for Medicine

Plasma Physics and Spectroscopy Laboratory (PPSL www.polymtl.ca/plasma) of Stephan Reuter, TransMedTech Chair for Plasma Medicine, within the Department of Physics Engineering at Polytechnique Montréal and the TransMedTech Institute offers a Postdoctoral Fellow position. Successful applicants should have hands-on experience in spectroscopy of plasmas and/or plasma liquid systems, plasma source design, and/or laser spectroscopy. They should have an interest or experience in plasmas for medicine.

You will work on an interdisciplinary project involving aspects of physics, biophysics, chemistry, and medicine. In this position, you are expected to contribute to proposal and report writing, and to preparation of presentations and publications.

Your profile:

- Ph.D. in physics, chemistry, mechanical-, electrical-, biomedical engineering, or a related discipline.
- excellent theoretical and practical knowledge within the fields of plasma physics and diagnostics, biomedical applications of plasmas, or redox biological processes relevant for plasma medicine.
- outstanding scientific track record demonstrating well-organized design and execution of research.
- ability to work independently and in a collaborative team.
- strong communication skills.
- strong motivation to collaborate with researchers in the medical field
- your excellent grades should allow you to apply for grants under Canadian funding schemes.

We will especially consider applications under the aspect of equity, diversity, and inclusion.

You will be employed at Polytechnique Montréal, a francophone engineering University in the heart of Montréal. You will interact with colleagues within Engineering Physics Department and the Institut Biomédicale of Polytechnique Montréal and Université de Montréal and the Institute TransMedTech and its collaborating research hospitals.

Please send your application in a first application stage as a single PDF file including a full CV, a cover letter describing research interests and goals (max. 2 pages), full list of publications highlighting your most relevant peer reviewed works, as well as the names and contact information of three references. **Applications should be sent to Prof. Stephan Reuter (stephan.reuter@polymtl.ca) using the subject line "*PPSL-Postdoctoral Fellow*".** The successful candidate of the first stage must send a full application including a research project to the Institute TransMedTech de Montréal (fall competition deadline: 1st stage **10th of Sept. 2020**; full application 21st of Sept. 2020 – spring competition deadline: to be announced).