25th ICLS, 19th to 24th June – 2022. Caserta, Italy.

Optical Spectroscopy of Self-Colliding Plasmas

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https://dcu-seai-laserab.com http://uf-dynamics.org https://www.dcu.ie/physics/people/john-costello

Talk Outline

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- Colliding Plasmas (a little) History & Fundamentals
- Some Experimental Considerations
- Two Examples of Colliding Plasmas *in Vacuo*
- Getting Plasmas to Collide in Atmospheric Pressure Air
- 'Self-Colliding' Plasmas?
- Preliminary Results (Imaging & Spectroscopy)
- Opacity Effects and the 1D 'Sakka' Model
- Perspective

A Little History

Not a new idea !

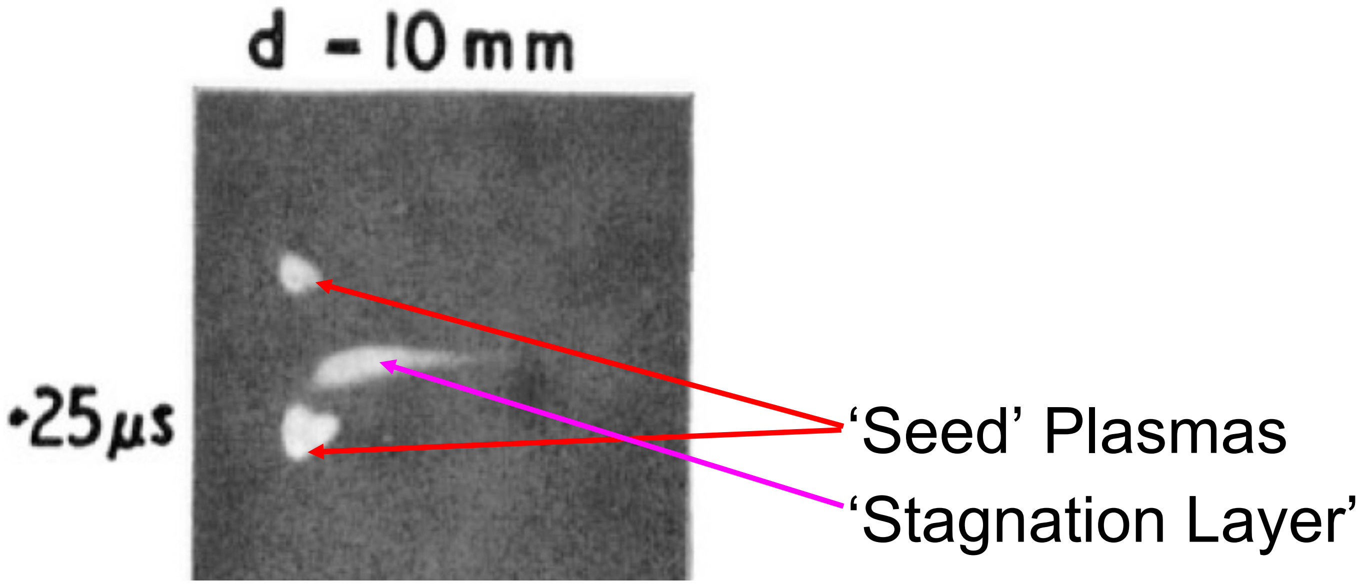
First report - 1974

Plasma Physics, Vol. 16, pp. 969 to 975. Pergamon Press 1974. Printed in Northern Ireland

INTERACTIONS BETWEEN TWO COLLIDING LASER PRODUCED PLASMAS

P. T. RUMSBY,* J. W. M. PAUL and M. M. MASOUD†
UKAEA Research Group, Culham Laboratory, Abingdon, Berkshire, England

(*Received* 29 *January* 1974)



Why colliding plasmas?

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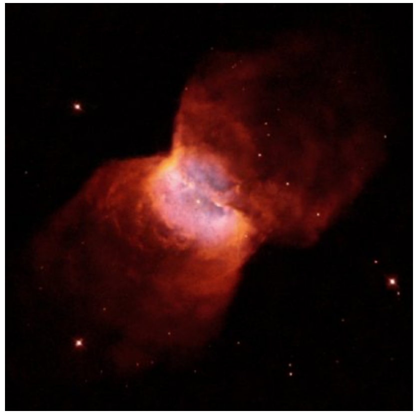
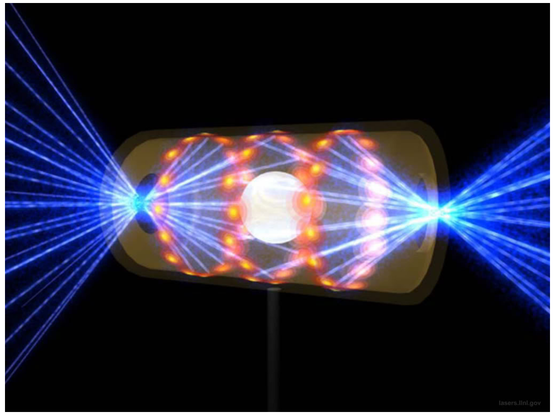
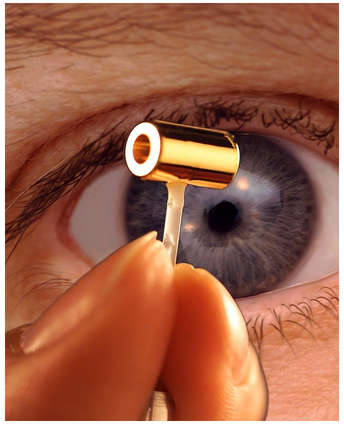
NGC2346 – HST - Colliding Stars'
https://en.wikipedia.org/wiki/NGC_2346

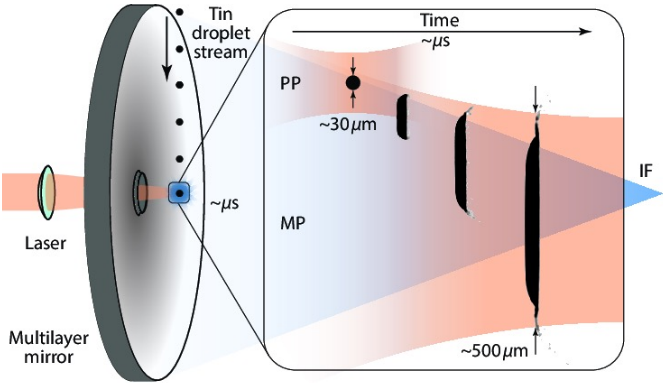


Hohlraum – Indirect Drive Fusion – NIF
https://lasers.llnl.gov



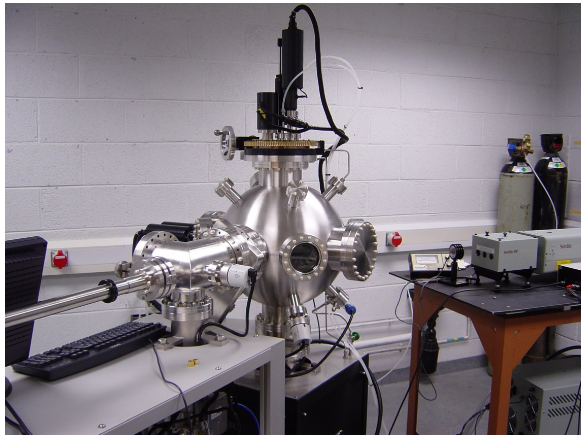


EUV Lithography –
Sn target source

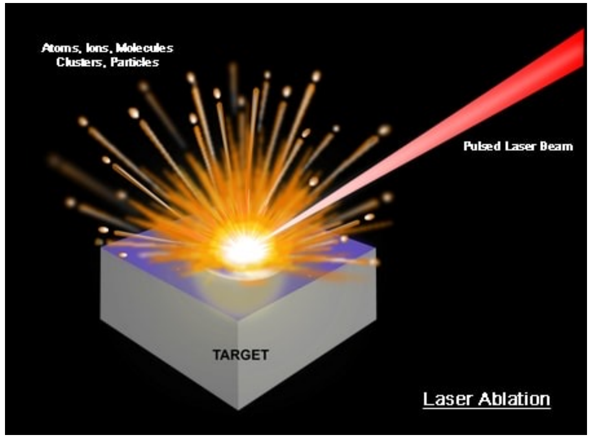


O.O. Versolato, J. Sheil, S.M. Witte, W. Ubachs, R. Hoekstra, J. Opt. **24**, 054014 (2022)

Pulsed Laser Deposition –
J P Mosnier DCU



LIBS – Analytical Sciences –
Applied Spectra Inc.



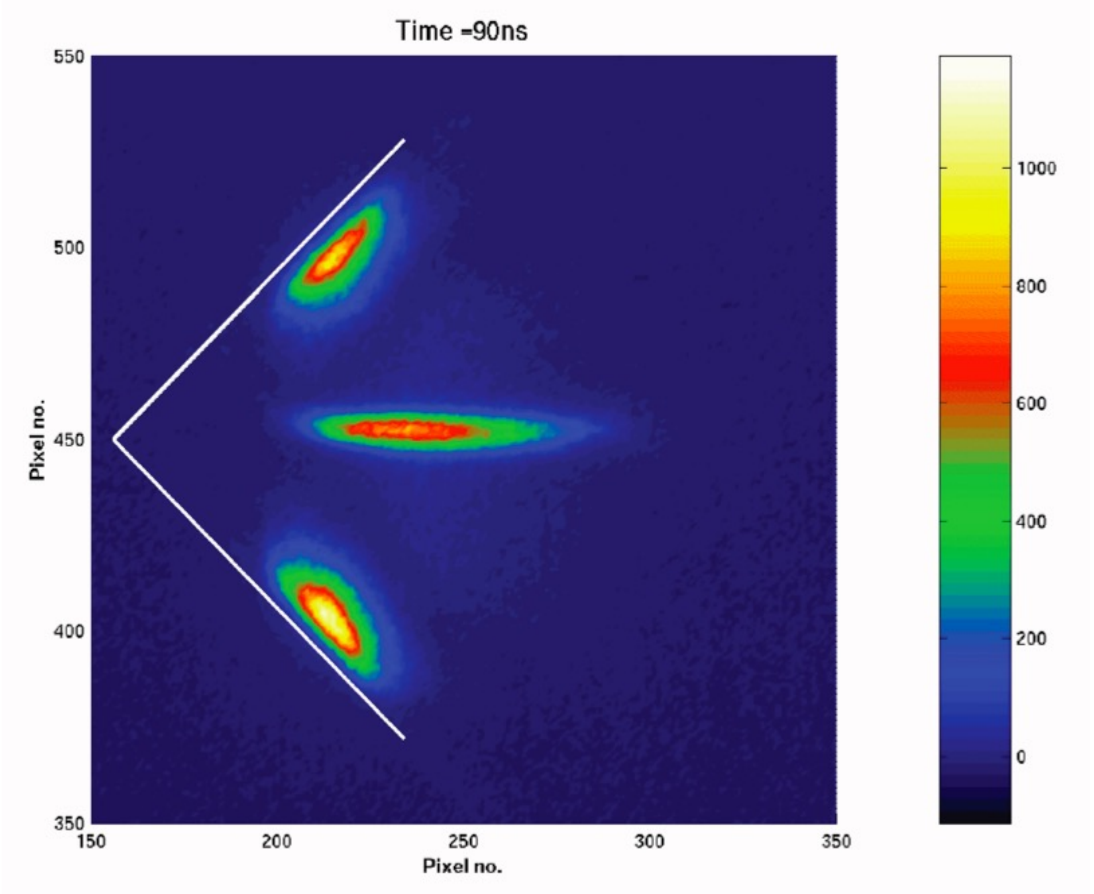
Some Fundamentals

Time Evolution:

Tight point focus on each Ca face:

15 ns/ 120 mJ per 1064 nm beam

ICCD: 5 ns gate
10 ns interval



Atomic Ca - Emission Imaging @ 423 nm

H Luna, K D Kavanagh and J T Costello, J. Appl. Phys. **101** Art No 033302 (2007)

Some Fundamentals

When a pair of laser plasma plumes collide two extreme scenarios can play out:

1. Interpenetration - interactions are mostly via binary collisions

2. Stagnation - plumes decelerate suddenly at the collision plane leading to rapid accumulation of material and the formation of a dense (stagnated) layer. Kinetic energy is converted into excitation energy (layer glow).

Some Fundamentals

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Collisionality Parameter: $\xi = \dfrac{D}{\lambda_{ii}}$

Plasma - Plasma Separation

Ion - Ion Mean Free Path (mfp)

For collisions between opposing plumes (1, 2)

$$\lambda_{ii}(1-2) = \frac{m_i^2 v_{12}^4}{4\pi e^4 Z^4 n_e \ln(\Lambda_{12})}$$

$\lambda_{ii} >> D \rightarrow$ Interpenetration

$\lambda_{ii} \sim D \rightarrow$ 'Soft' Stagnation

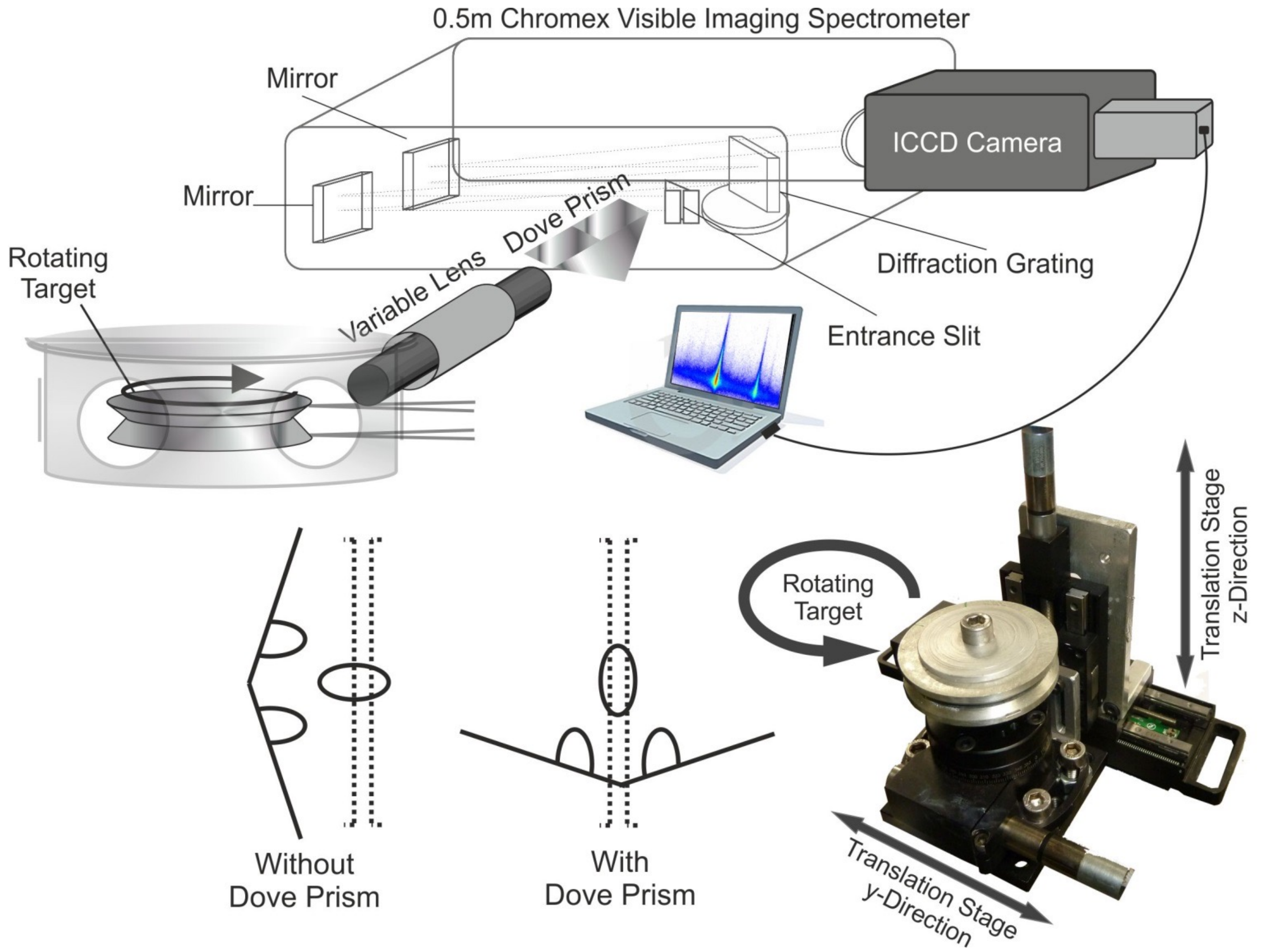
$\lambda_{ii} << D \rightarrow$ 'Hard' Stagnation

Slow moving and dense laser plasma plumes are more likely to stagnate !

P. W. Rambo and J. Denavit, Phys. Plasmas **1** pp 4050 - 4060 (1994)
J Dardis and J T Costello, Spectrochimica Acta Part B **65** pp627-635 (2010)

Some Experimental Considerations

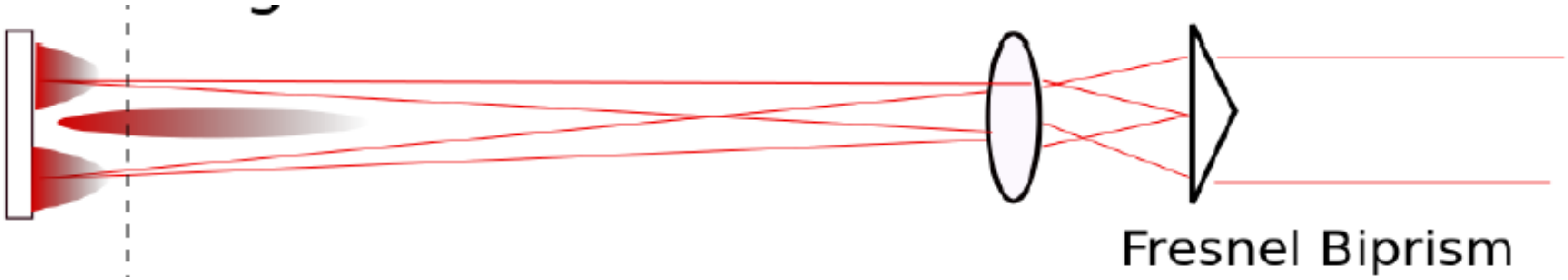
ICCD Spectroscopy: Time and space resolved.



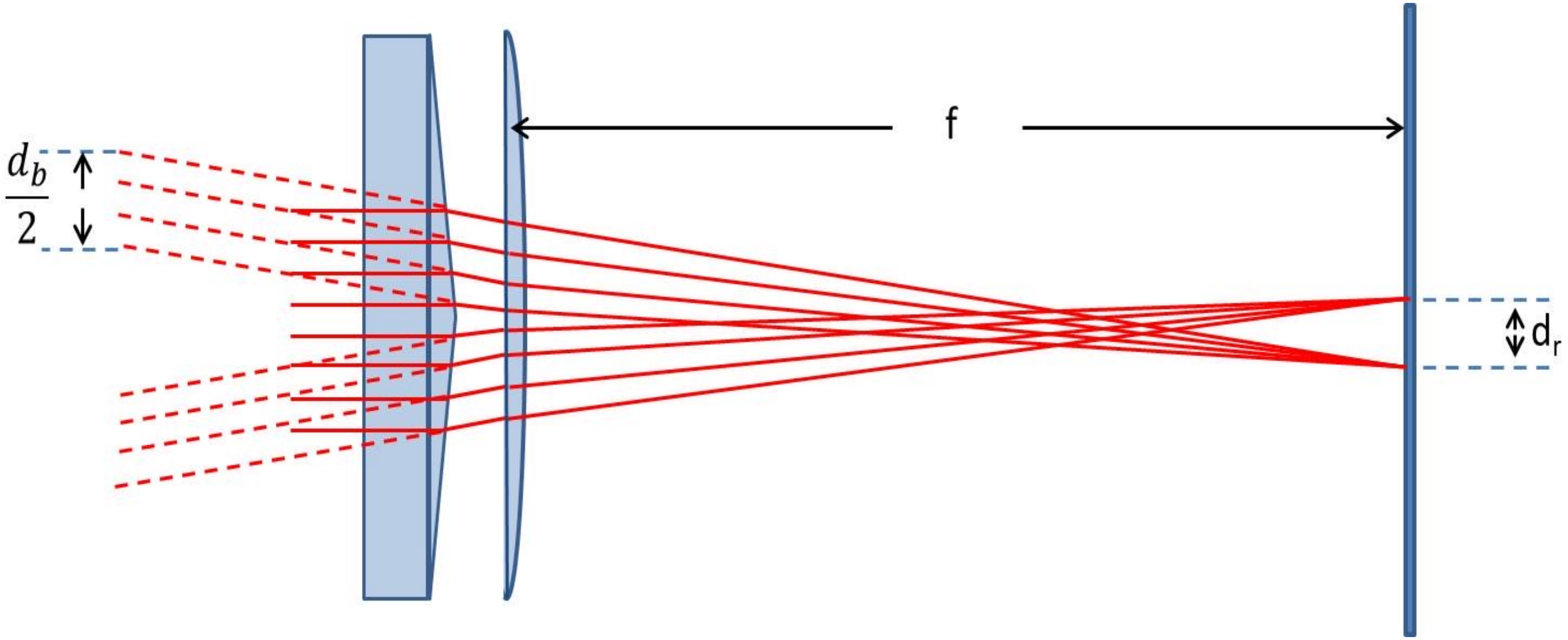
C Fallon, P Hayden, N Walsh, E T Kennedy and J T Costello, Physics of Plasmas 22, 093506 (2015)

Two Examples of Colliding Plasma Setups

Use a Biprism => Symmetric Seed Plasmas



Axicon => Bessel Beam + Focusing => Ring Seed Plasma



Two Examples of Colliding Plasmas *in Vacuo*

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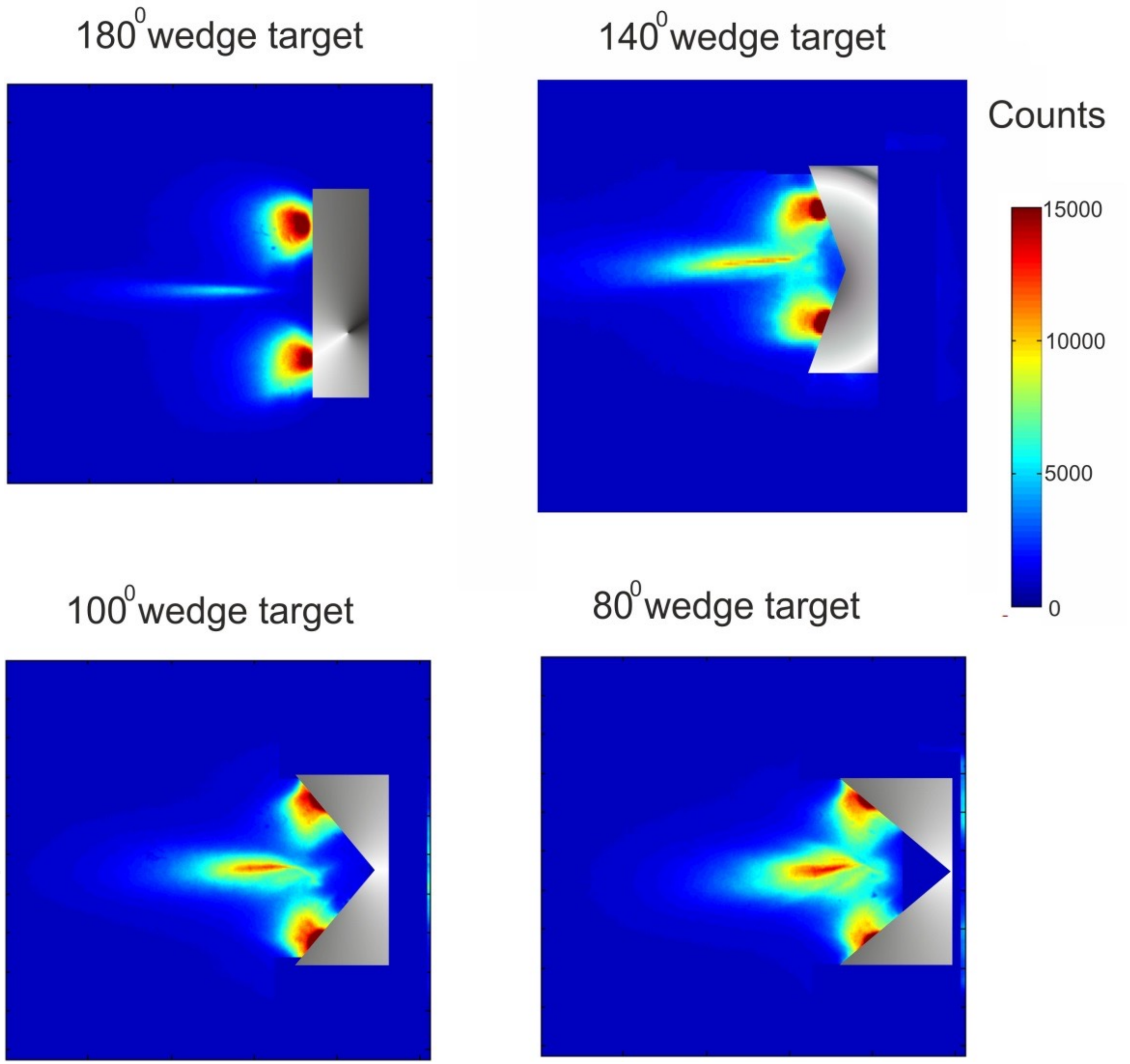
Example 1: Symmetric Seed Plasmas

Imaging - effect of seed collision angle

$$\xi = \frac{D}{\lambda_{ii}}$$

$$\lambda_{ii}(1-2) = \frac{m_i^2 v_{12}^4}{4\pi e^4 Z^4 n_e \ln(\Lambda_{12})}$$

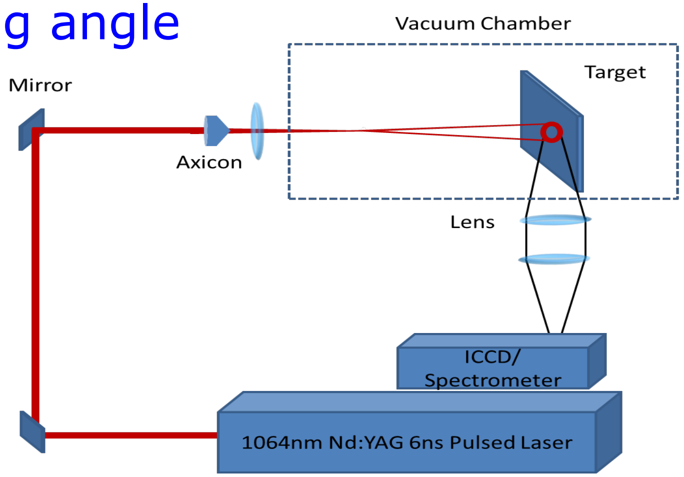


C Fallon, P Hayden, N Walsh, E T Kennedy and J T Costello, J. Phys: Conference Series 548 012036 (2014)

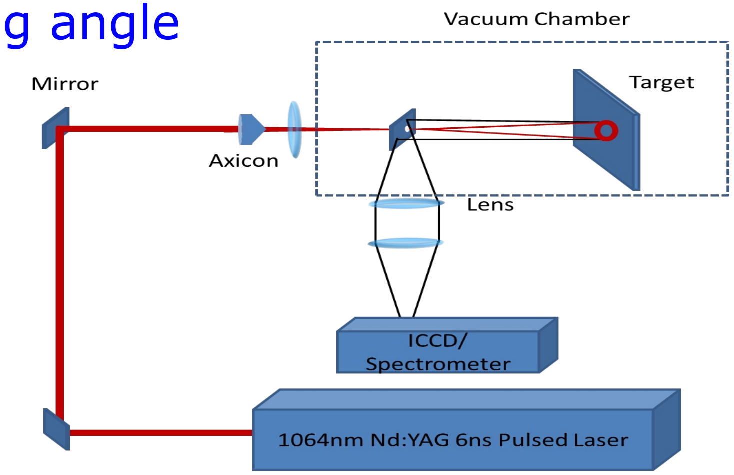
Two Examples of Colliding Plasmas *in Vacuo*

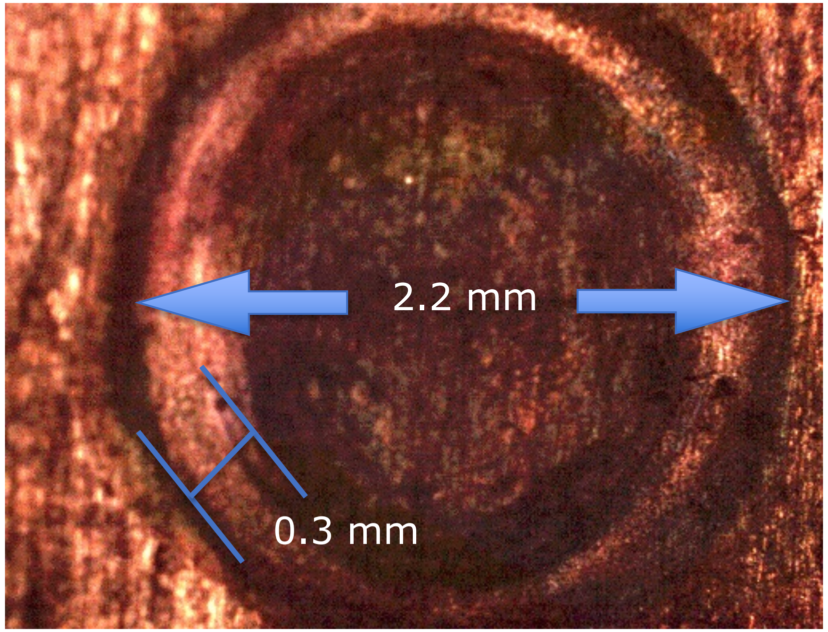
Example 2: Annular Seed Plasma

90° viewing angle



0° viewing angle





Annulus Area: 0.07 cm^2

Power Density: 1.0 GW/cm^2

Two Examples of Colliding Plasmas *in Vacuo*

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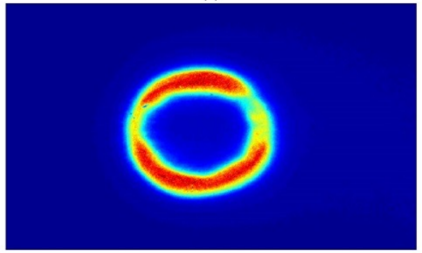
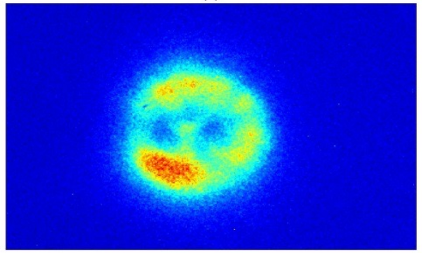
Example 2: Annular Seed Plasma

5ns gate width / 0° viewing angle.

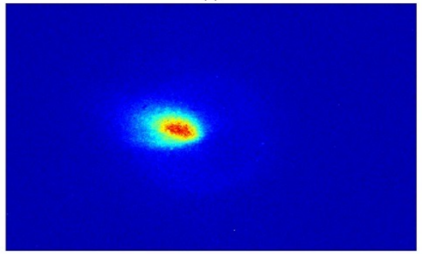
5ns Delay



75ns Delay

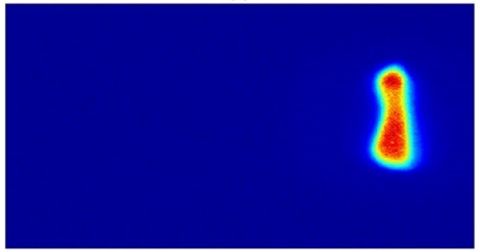


200ns Delay

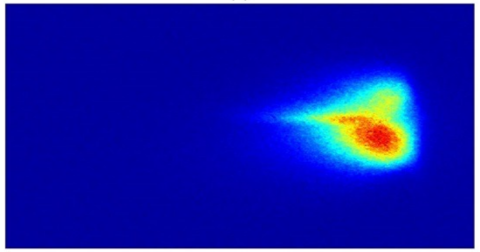


5ns gate width / 90° viewing angle.

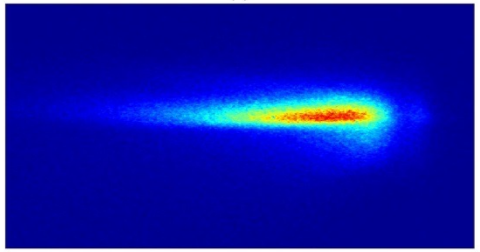
5ns Delay



75ns Delay



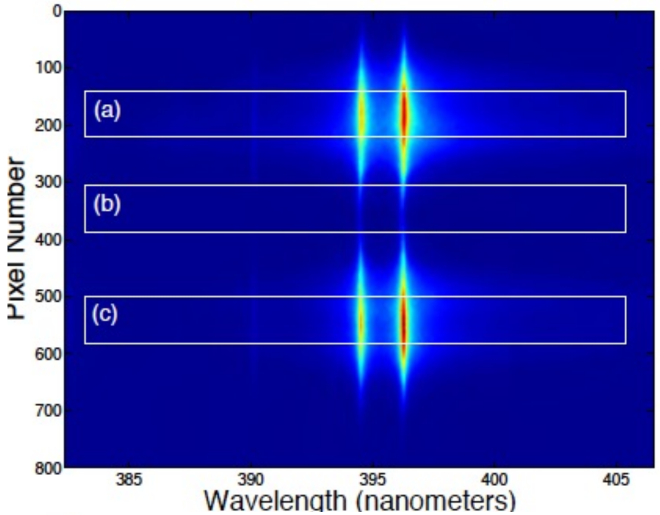
200ns Delay

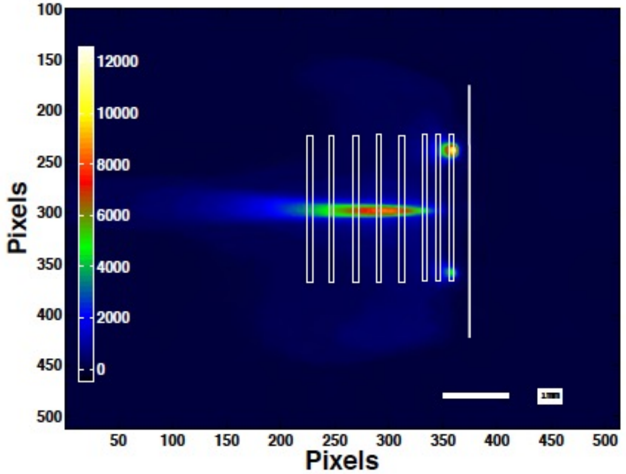


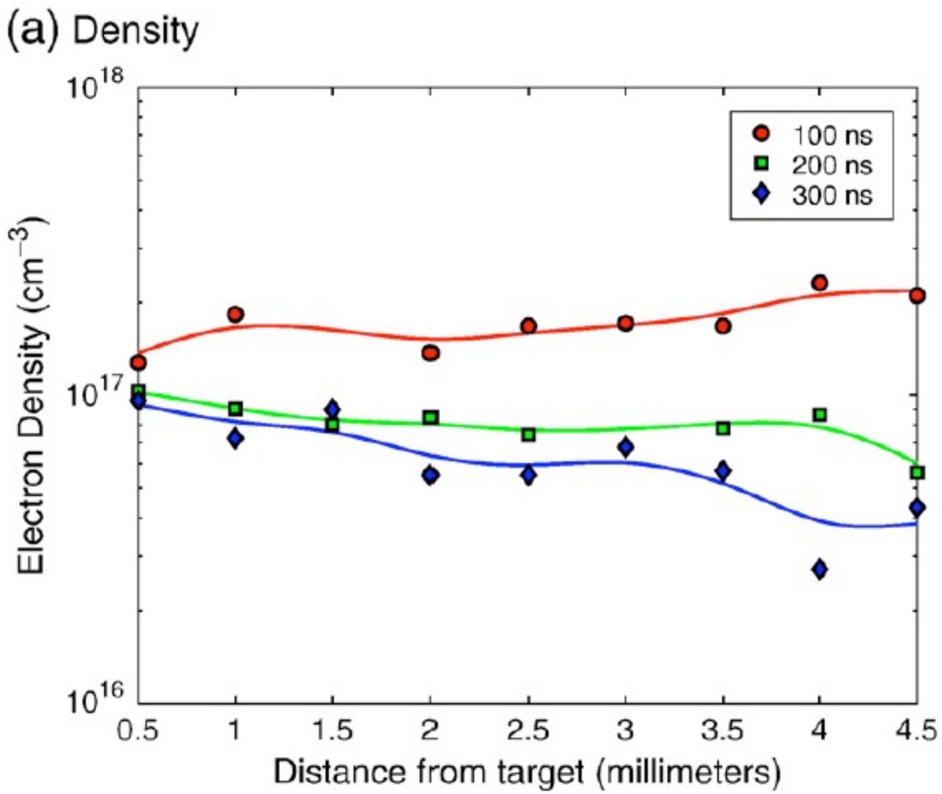
Laser Induced Breakdown Spectroscopy with Annular Plasmas in Vacuo: Stagnation and Limits of Detection.
B Delaney, P Hayden, T J Kelly, E T Kennedy, and J T Costello, Spectrochimica Acta Part B: Atomic Spectroscopy **193** Art. No. 106430 (2022)

Two Examples of Colliding Plasmas *in Vacuo*

Stagnation Layer (Al). *Electron density (Stark, $3s^23p$ ($^2P_{1/2,3/2}$) – $3s^24s$ ($^2S_{1/2}$))*







~100 mJ/170 ps/1064 nm ’seed’ beam

J Dardis and J T Costello, Spectrochimica Acta Part B 65 pp 627-635 (2010)

Two Examples of Colliding Plasmas *in Vacuo*

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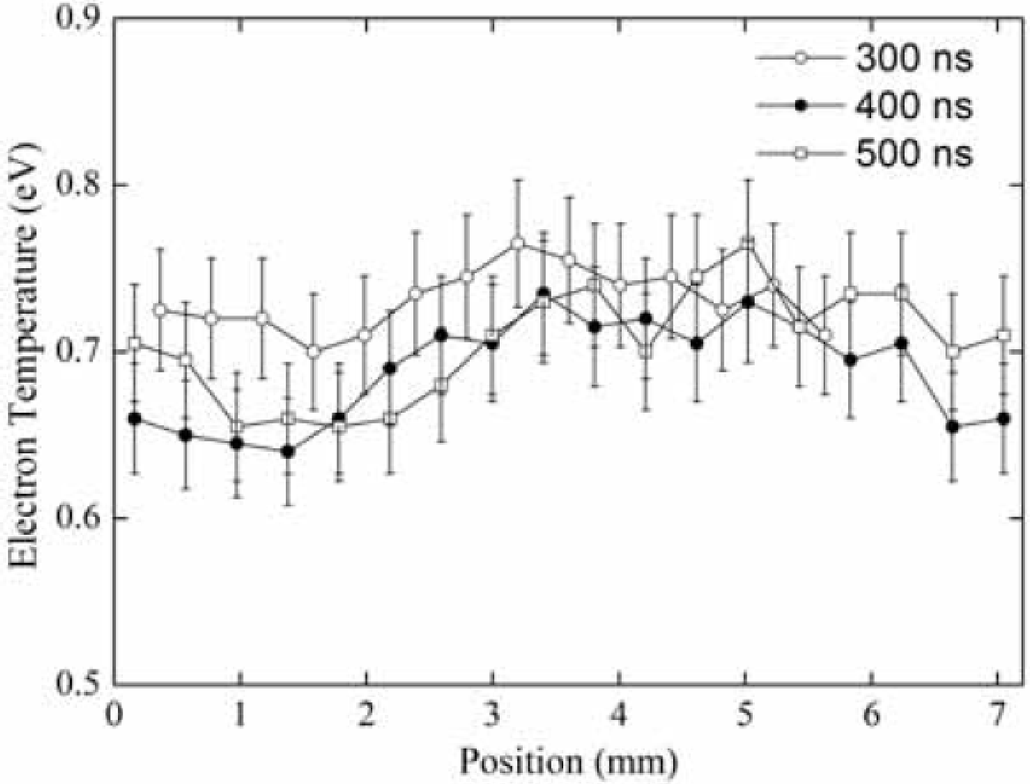
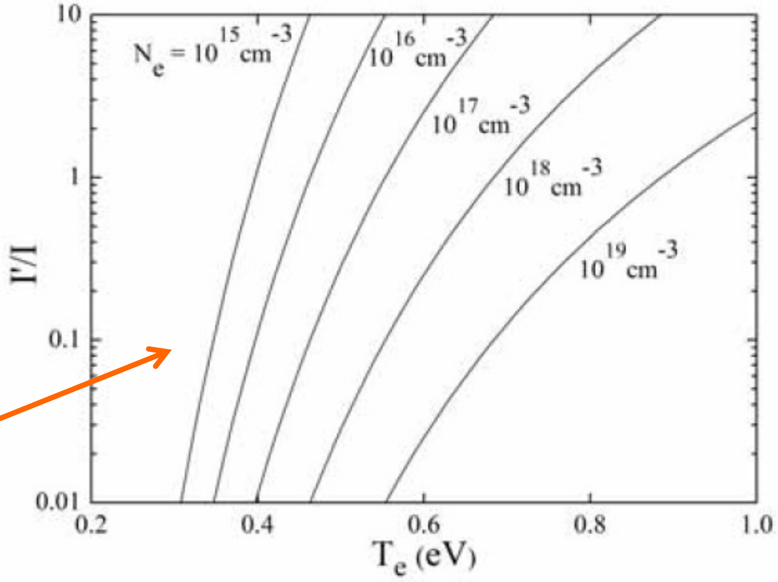
Stagnation Layer (Ca): Electron Temp. – Line ratios

~70 mJ/355 nm/
6 ns/ 'seed' beam

$$T_e \approx 0.7 eV$$



Ratio of 393 nm (Ca+) to 423 nm (Ca) lines



$$\frac{I'}{I} = \frac{f'g'\lambda^3}{fg\lambda'^3}(4\pi^{3/2}a_0^3 Ne)^{-1}\left(\frac{kT}{E_H}\right)^{3/2}\exp\left(\frac{E-E'-E_\infty}{kT}\right)$$

Stagnation layers (SL) *in vacuo* – three take-aways

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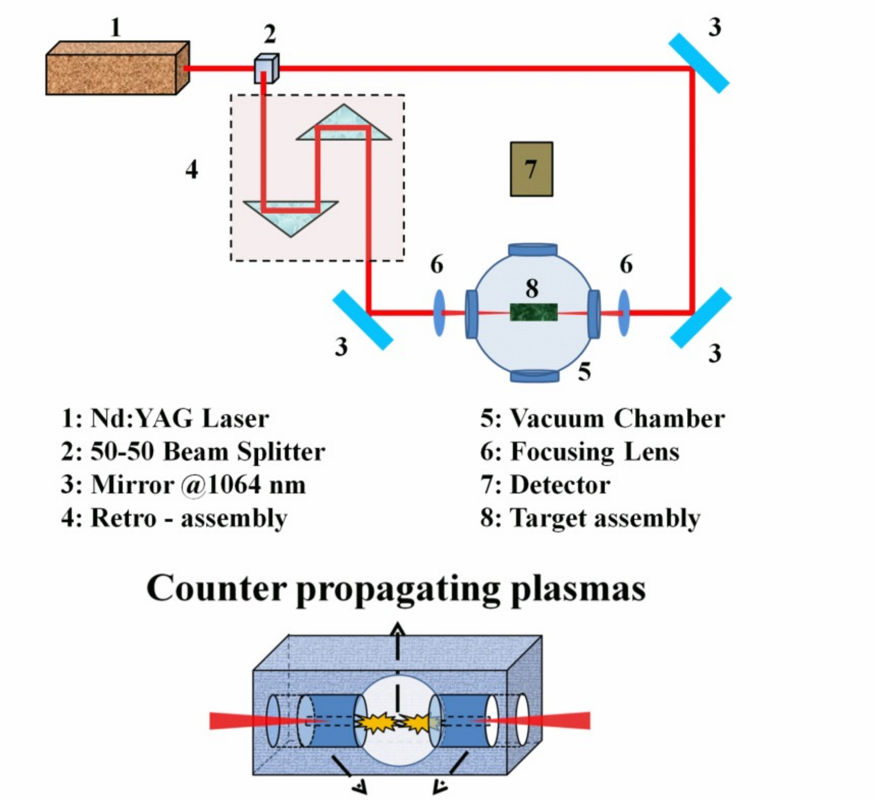
- Stagnation layers becomes quite uniform >100 ns after stagnation layer formation
- Densities and temperatures remain at higher values for longer in stagnation layers
- The duration of self emission from atoms and ions lasts longer than that from single plumes

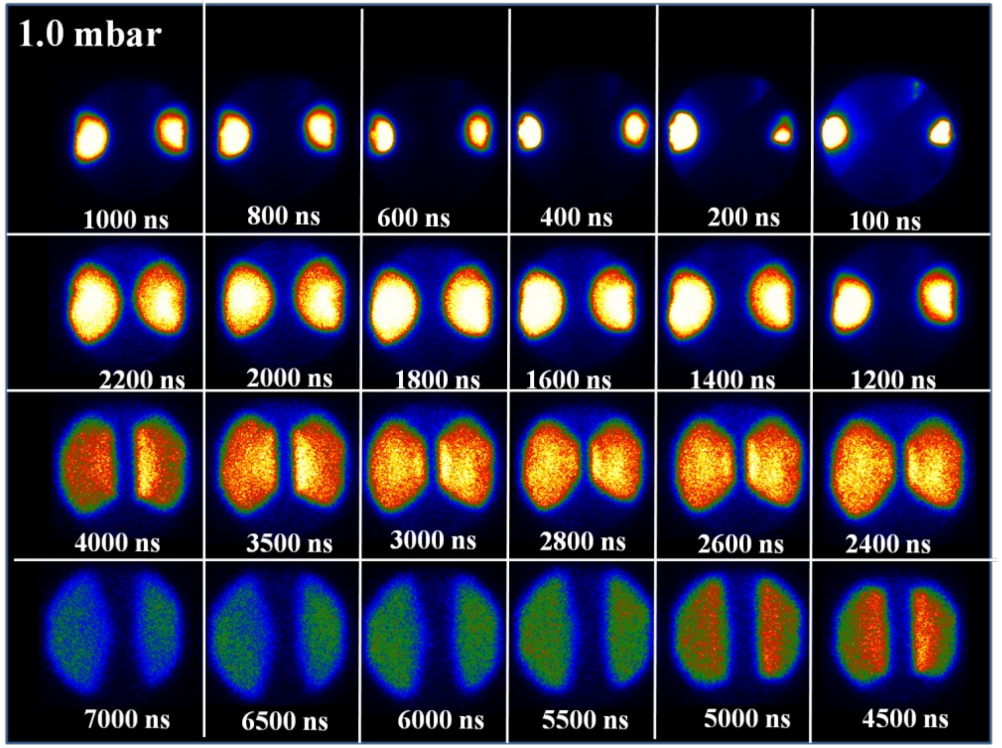
Ergo stagnation layers look potentially attractive for use in laser ablation analytical sciences [LAAS] like LIBS[§] (*Laser Induced Breakdown Spectroscopy*) but only if they can be formed in air !

§ *Laser Induced Breakdown Spectroscopy with Annular Plasmas in Vacuo: Stagnation and Limits of Detection.* B Delaney, P Hayden, T J Kelly, E T Kennedy, and J T Costello, Spectrochimica Acta Part B: Atomic Spectroscopy **193** Art. No. 106430 (2022)

Getting Plasmas to Collide in High Pressure Air



Metal (Al) cylindrical target (φ = 10 mm X l = 10mm) with a hole (φ = 1mm X l = 10mm)



Even an ambient air pressure of 1 mbar (separation D = 10 mm) appears to prevent a significant plume-plume collision rate.

Unpublished – Work associated with P K Pandey, R K Thareja, R Pratap Singh and J T Costello, Applied Physics B, 124, 50 (2018)

‘Self-Colliding’ Plasmas

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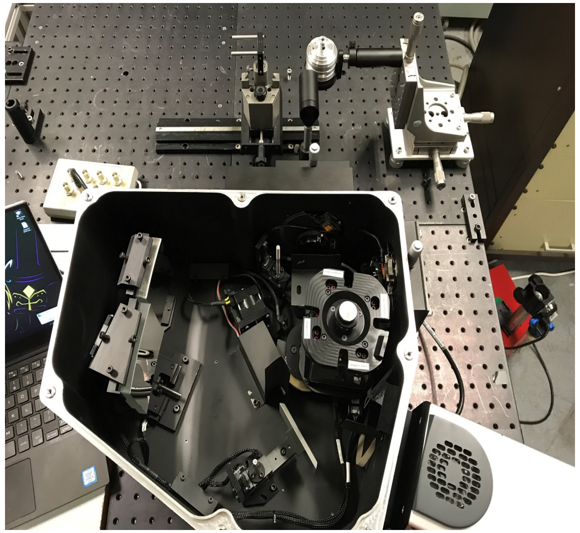
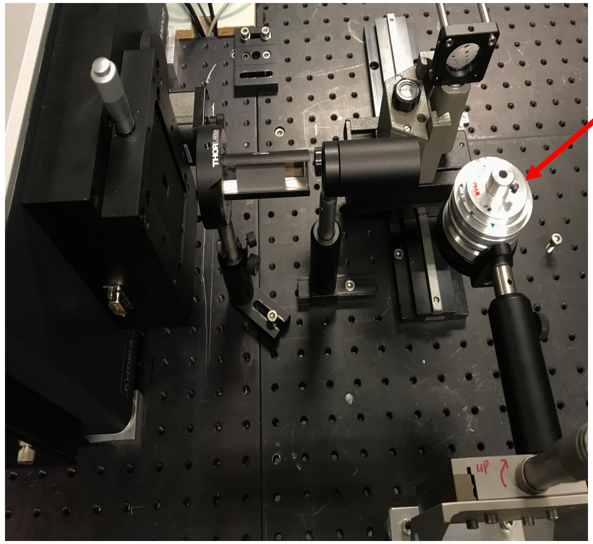
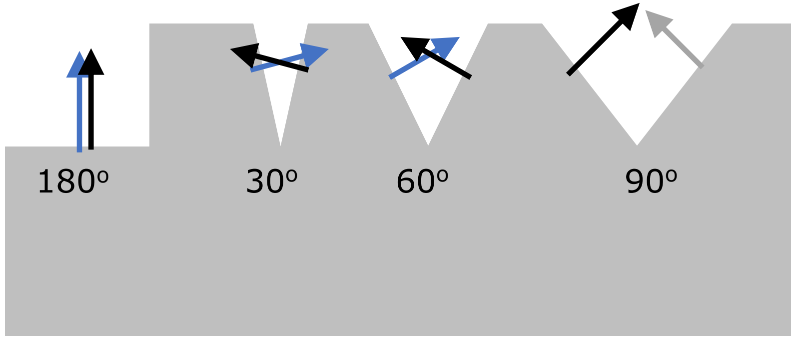
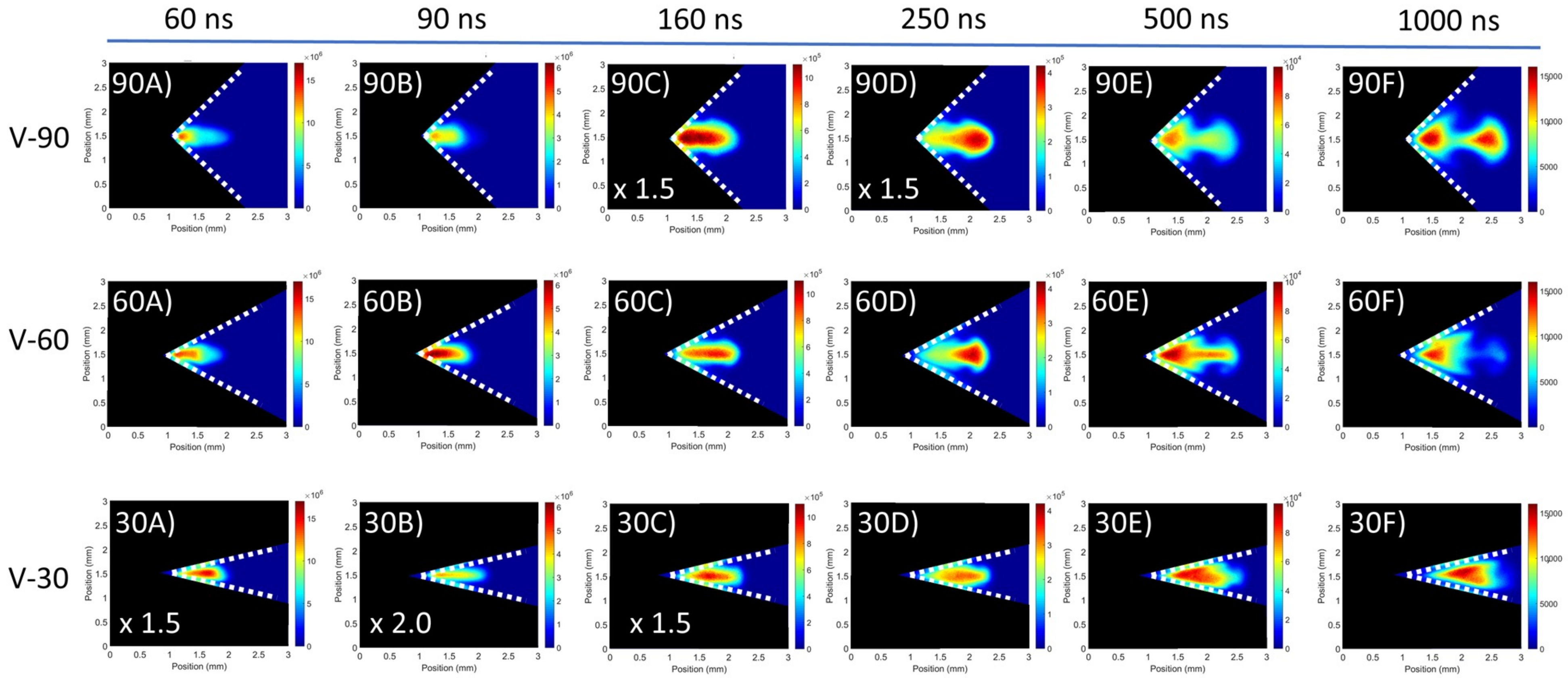






The Effect of Confinement Angle on Self-Colliding Aluminium Laser Plasmas Using Spectrally Resolved Fast Imaging
L Varvarezos, S J Davitt, J T Costello and T J Kelly, Materials 13, 5489 (2020); doi:10.3390/ma13235489

'Self-Colliding' Plasmas



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L Varvarezos, S J Davitt, J T Costello and T J Kelly, Materials **13**, 5489 (2020); doi:10.3390/ma13235489

Preliminary Results – Time Resolved Imaging

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Some observations from imaging experiments.

- Around 160 ns, the 90° and 60° V-channel targets were seen to form two distinct components, the stationary plasma and the 'plasma lobe'.
- The stationary plasma appeared to exhibit some of the characteristics expected of a stagnation layer (need to confirm).
- Spectrally filtered images showed the Al^{2+} species moving towards/ occupying the leading edge of the plasma while the neutral Al species tended to remain close to the target surface in each case.
- Potentially (a degree of) forced recombination was evident for plasma plumes formed within the V-channel targets showing points of intense Al emission due to interactions with the target walls.

The Effect of Confinement Angle on Self-Colliding Aluminium Laser Plasmas Using Spectrally Resolved Fast Imaging
L Varvarezos, S J Davitt, J T Costello and T J Kelly, Materials **13**, 5489 (2020); doi:10.3390/ma13235489

Very Preliminary Results – Time Resolved Spectroscopy

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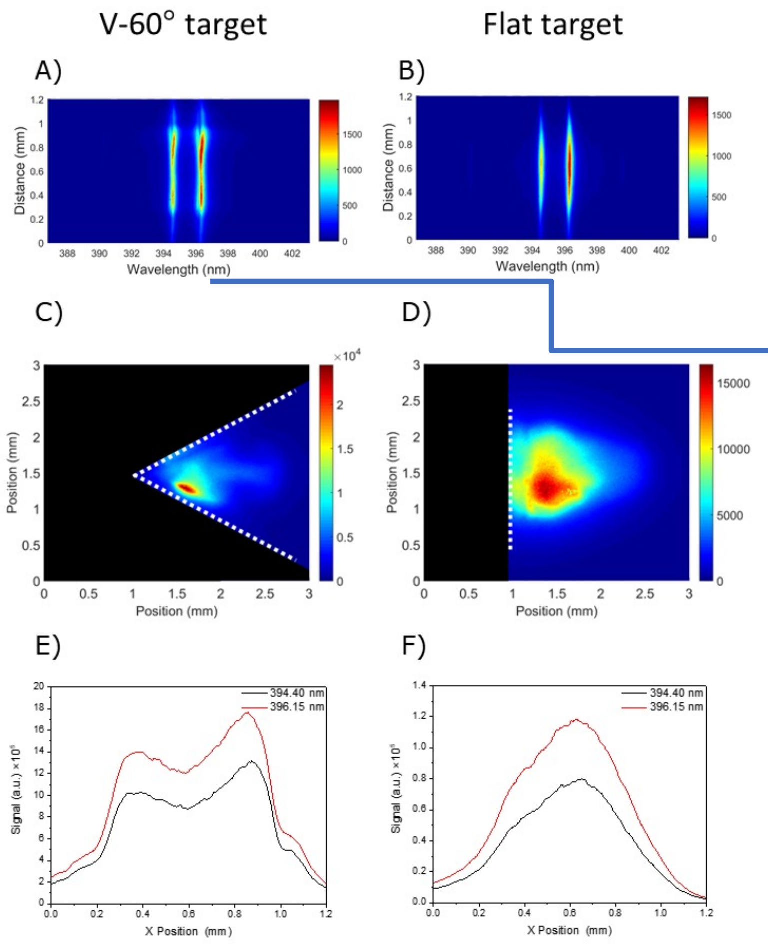
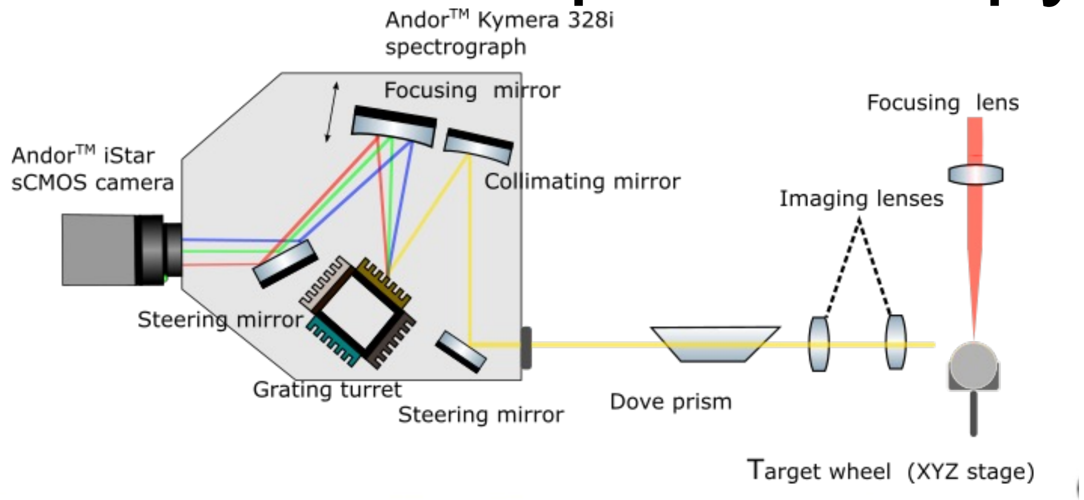
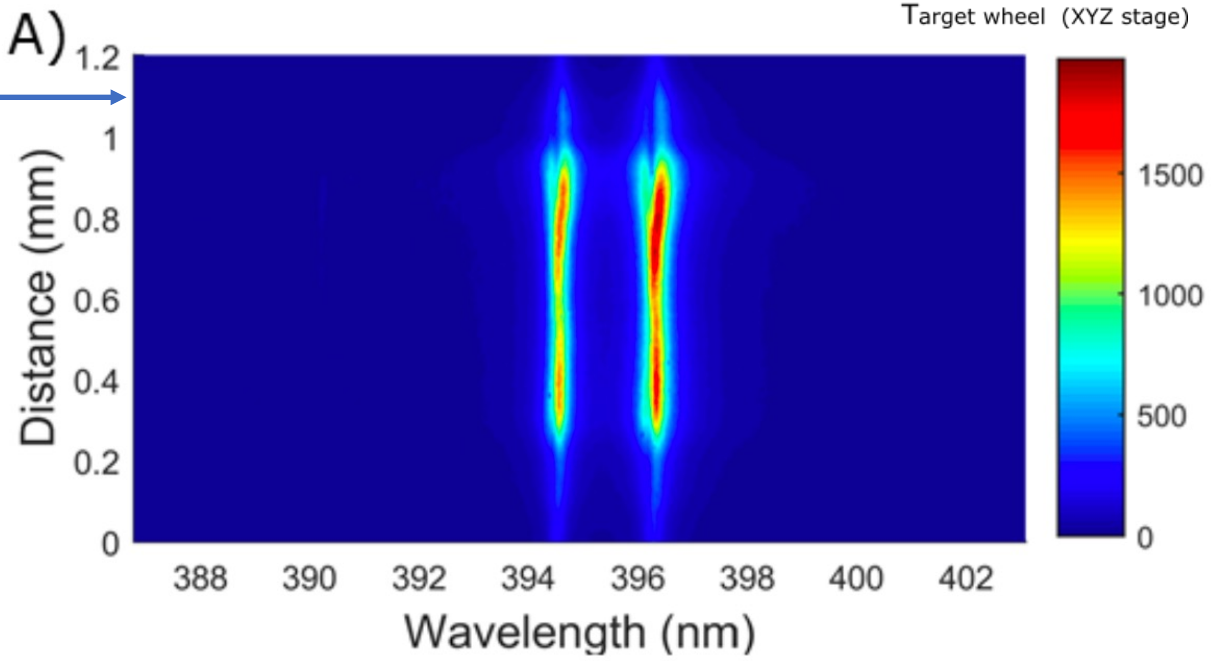
Immediate problem…..







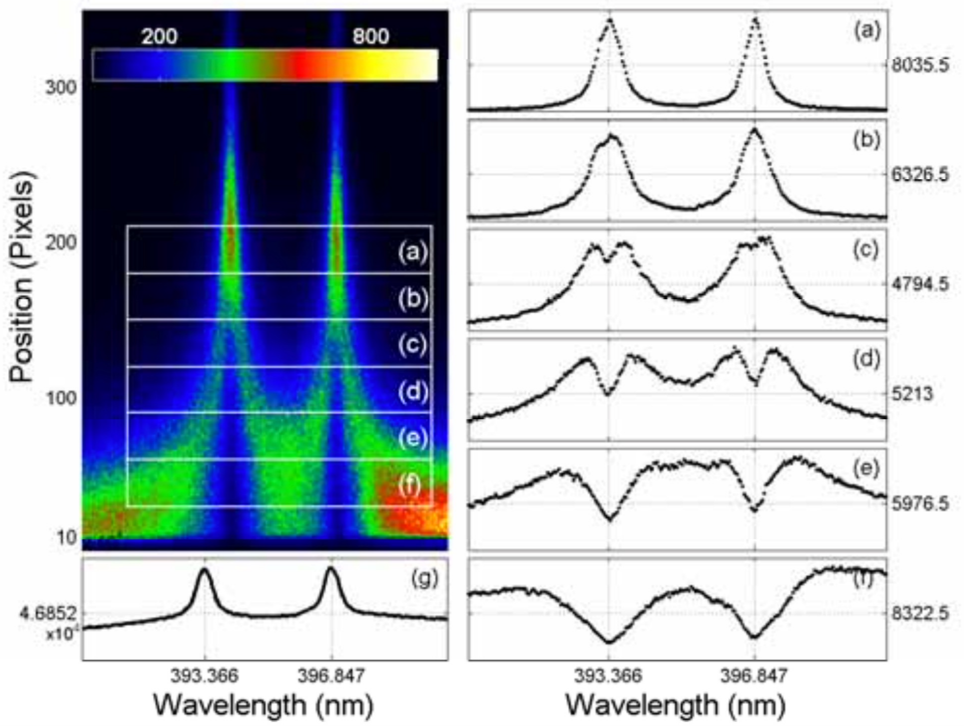
Al I doublet. $3s^23p\ (^2P_{1/2,3/2}) - 3s^24s\ (^2S_{1/2})$)

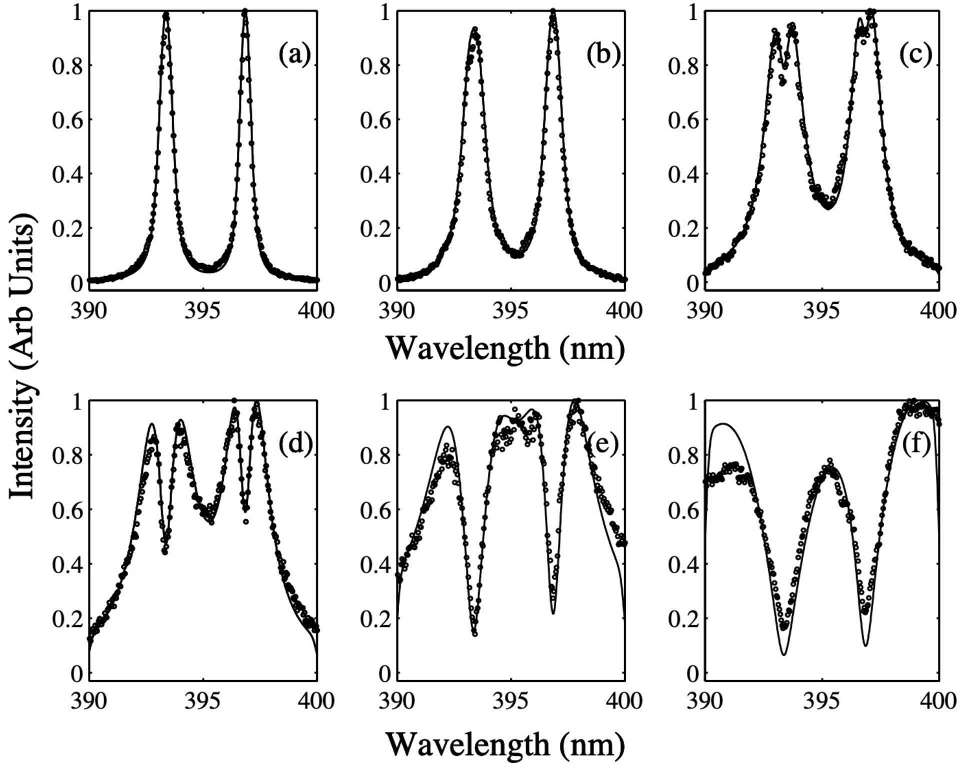
Very Preliminary Results – Time Resolved Spectroscopy

Solution – use a simple (1D) model of radiation transport.

Spatial population distribution of laser ablation species determined by self-reversed emission line profile.
T. Sakka, T. Nakajima, and Y.H. Ogata, Journal of Applied Physics **92**, pp2296–2303 (2002)

Single Al plasma plume (30 ns gate, 260 ns delay)



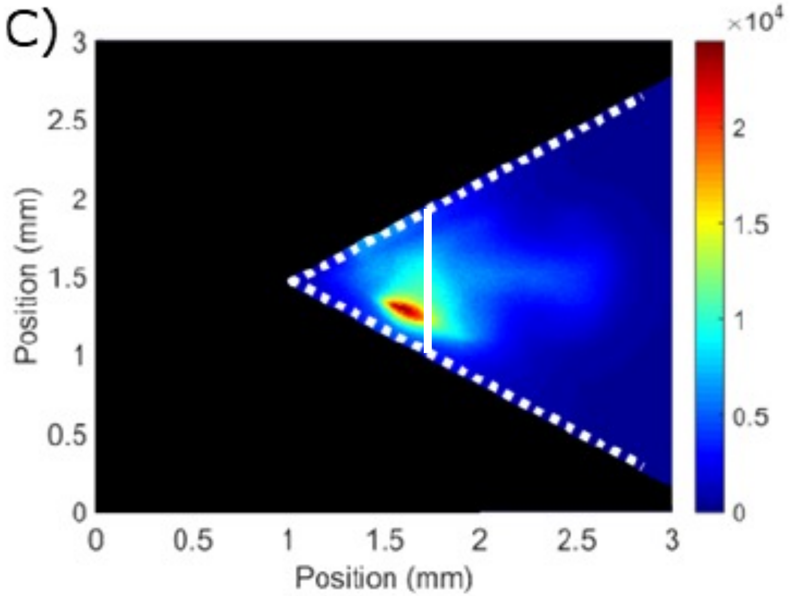


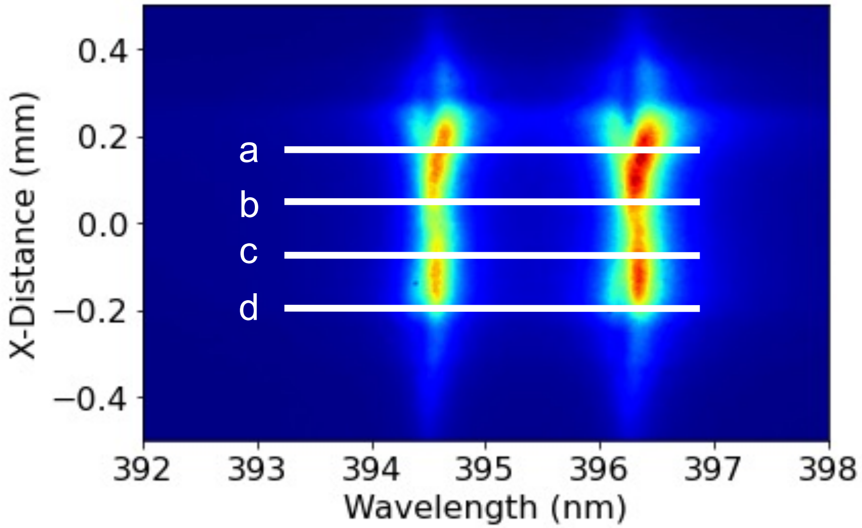
Kevin Kavanagh, PhD Thesis, DCU.

Ca II doublet. $3p^6 4s\ (^2S_{1/2}) – 3p^6 4p\ (^2P_{1/2,3/2})$

Very Preliminary Results – Time Resolved Spectroscopy

Mossy Kelly





Al I doublet. $3s^2 3p$ ($^2P_{1/2,3/2}$) – $3s^2 4s$ ($^2S_{1/2}$))

500 ns delay, 30 ns gate width, 60^0 wedge angle,
Spectrometer slit to record ca. 1.6 mm from the apex.

Very Preliminary Results – Time Resolved Spectroscopy

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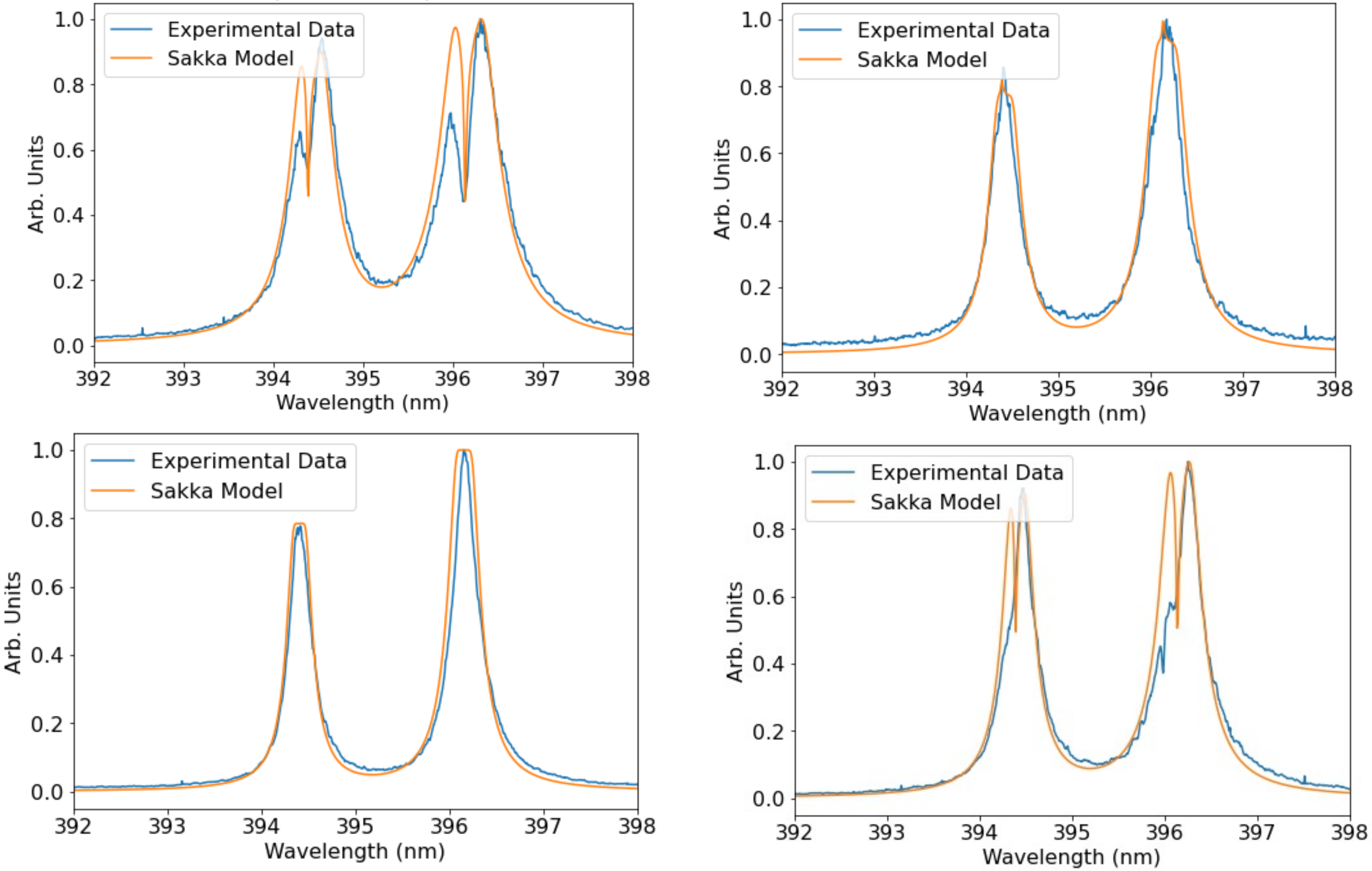
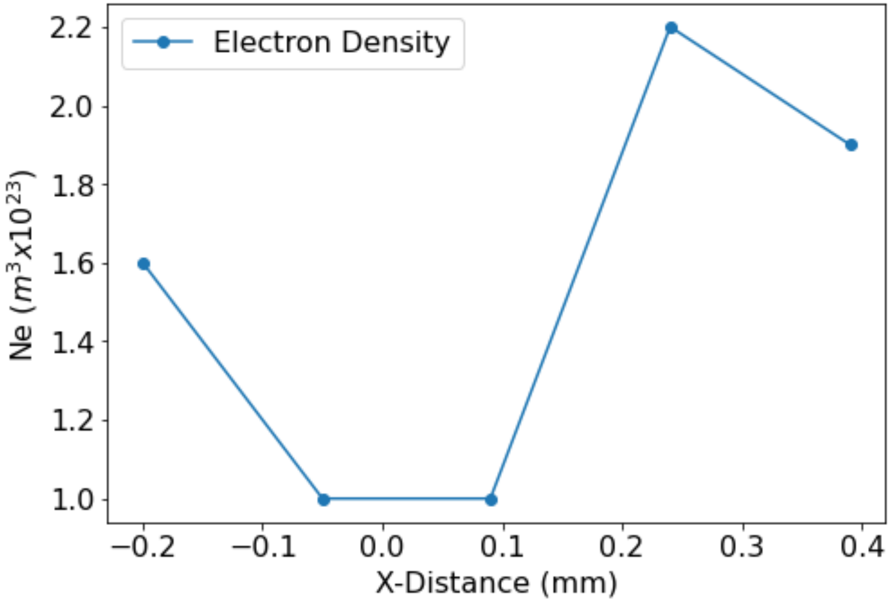
WORK IN PROGRESS

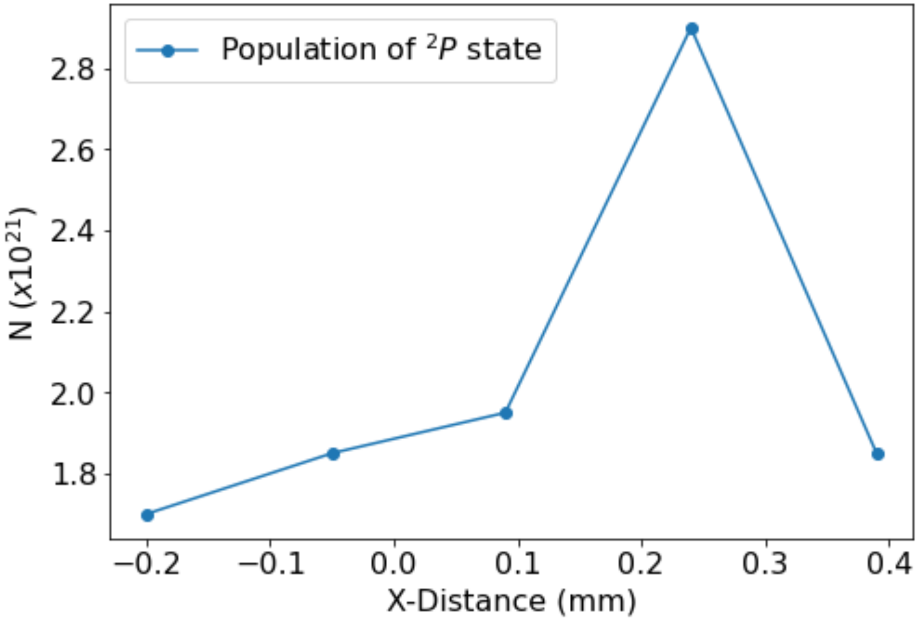
Mossy Kelly



Very Preliminary Results – Time Resolved Spectroscopy

Mossy Kelly





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Very Preliminary Results – Time Resolved Spectroscopy

Some observations from spectroscopy experiments.

- The jury is still out on whether we can make 'stagnation layers' in air with desirable properties
- Looks like we have two distinct regions in the plasma and so, even if we have a system that could exhibit flat density/temperature over periods of 100s ns, it may only apply to a limited space region.
- For applications where the region can be isolated – e.g., LIBS, this may not be a problem.
- For stagnation layers *in vacuo* the situation is more positive… double-pulse LIBS[1], PLD[2], etc.

1. ***Laser Induced Breakdown Spectroscopy with Annular Plasmas in Vacuo: Stagnation and Limits of Detection.*** B Delaney, P Hayden, T J Kelly, E T Kennedy, and J T Costello, Spectrochimica Acta Part B: Atomic Spectroscopy 193 Art. No. 106430 (2022) - https://doi.org/10.1016/j.sab.2022.106430
2. ***Deposition of nanocomposite Cu–TiO2 using heterogeneous colliding plasmas,*** P K Pandey, R K Thareja, R Pratap Singh and J T Costello, Applied Physics B, 124, 50 (2018) - https://doi.org/10.1007/s00340-018-6919-8

Our Colliding Plasma Papers

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Bhaile Átha Cliath
Dublin City University

Laser Induced Breakdown Spectroscopy with Annular Plasmas in Vacuo: Stagnation and Limits of Detection, B Delaney, P Hayden, T J Kelly, E T Kennedy, and J T Costello, Spectrochimica Acta Part B: Atomic Spectroscopy 193 Art. No. 106430 (2022) - https://doi.org/10.1016/j.sab.2022.106430

The Effect of Confinement Angle on Self-Colliding Aluminium Laser Plasmas Using Spectrally Resolved Fast Imaging, L Varvarezos, S J Davitt, J T Costello and T J Kelly, Materials 13, 5489 (2020); doi:10.3390/ma13235489

Deposition of nanocomposite Cu–TiO2 using heterogeneous colliding plasmas, P K Pandey, R K Thareja, R Pratap Singh and J T Costello, Applied Physics B, 124, 50 (2018) -

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Colliding Plasma People

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Stephen Davitt
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Padraig Hough
Kevin Kavanagh
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Jean-Paul Mosnier
Pramod Pandey
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Extra Slides

Fits to colliding Ca plasmas *in vacuo*

Ollscoil Chathair Bhaile Átha Cliath
Dublin City University

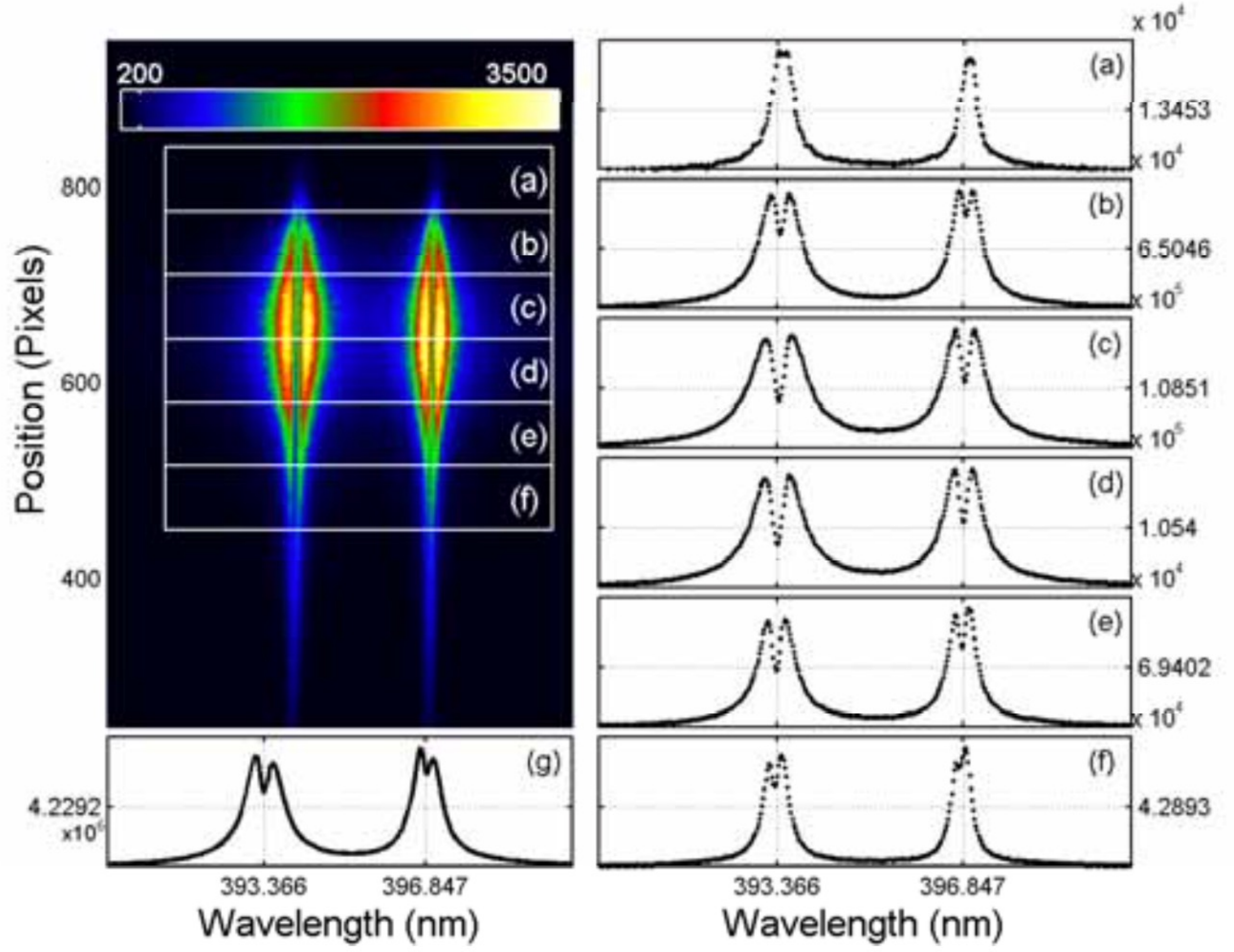

Figure 7.16: Spectral image showing the $3p^6 4s(^2S_{1/2})$-$3p^6 4p(^2P_{3/2,1/2})$ at 393.36 and 396.84 nm recorded 400 ns after plasma initiation with a 30 ns gate width.

Kevin Kavanagh
PhD Thesis - DCU

Fits to colliding Ca plasmas *in vacuo*

Ollscoil Chathair Bhaile Átha Cliath
Dublin City University

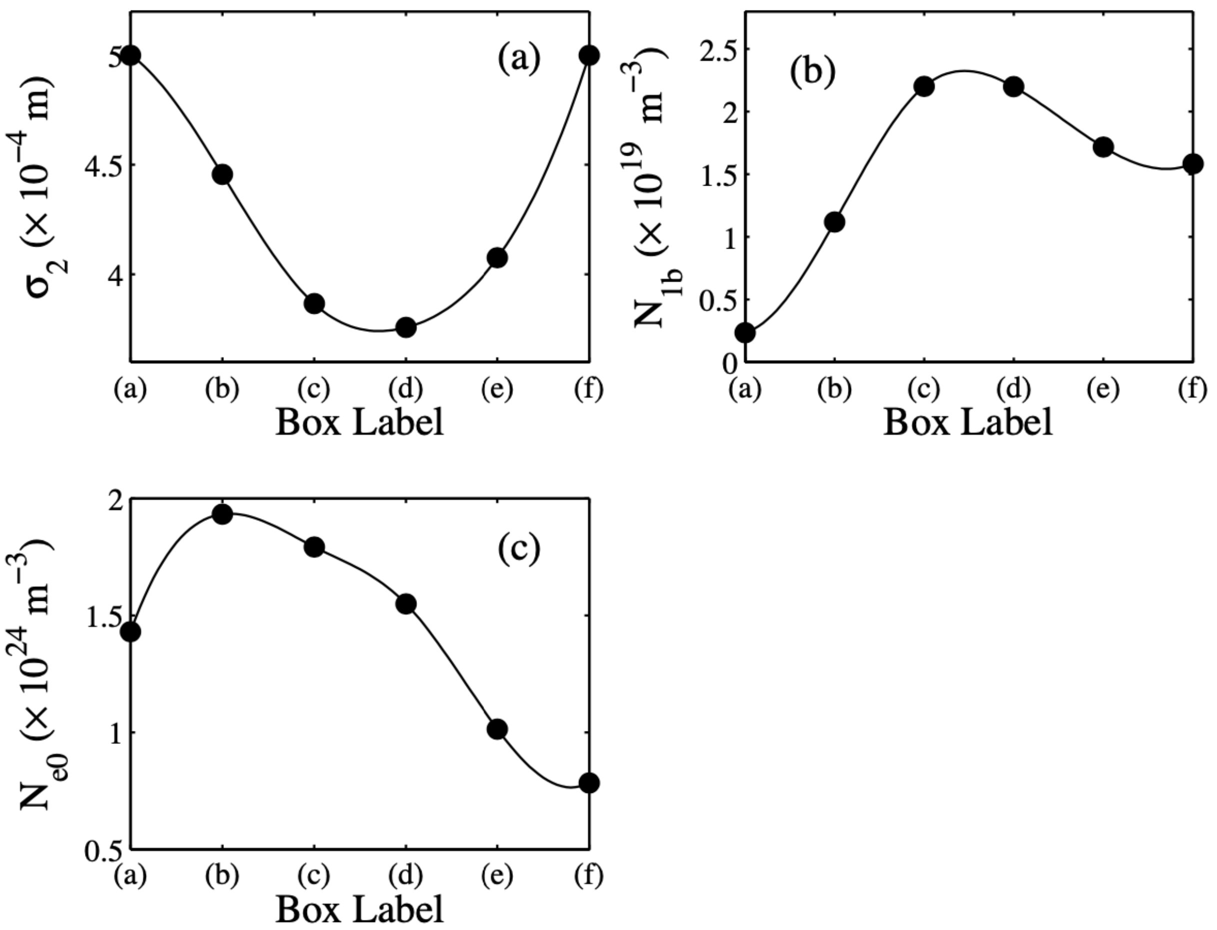

Figure 7.18: Best-fit input parameters calculated during the model comparison with a 400 ns spectroscopic image (figure 7.16).

Kevin Kavanagh
PhD Thesis - DCU

Laser Plasma (Optical) Diagnostics Lab

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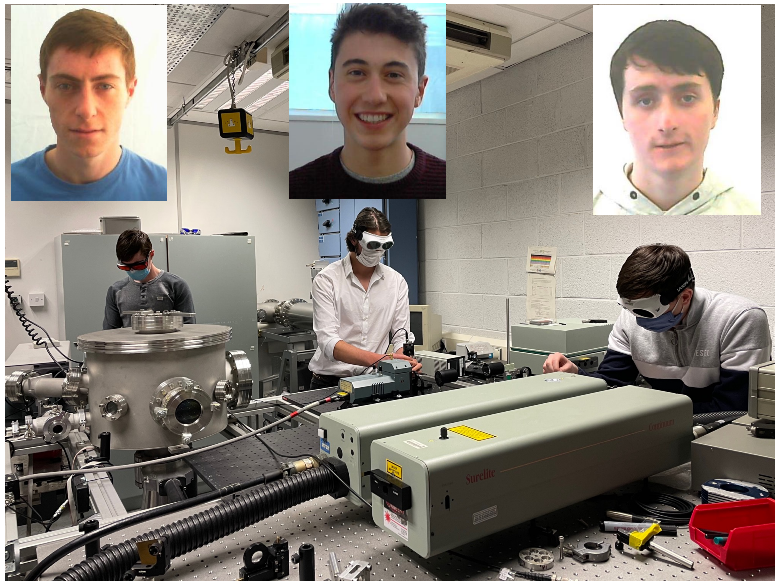
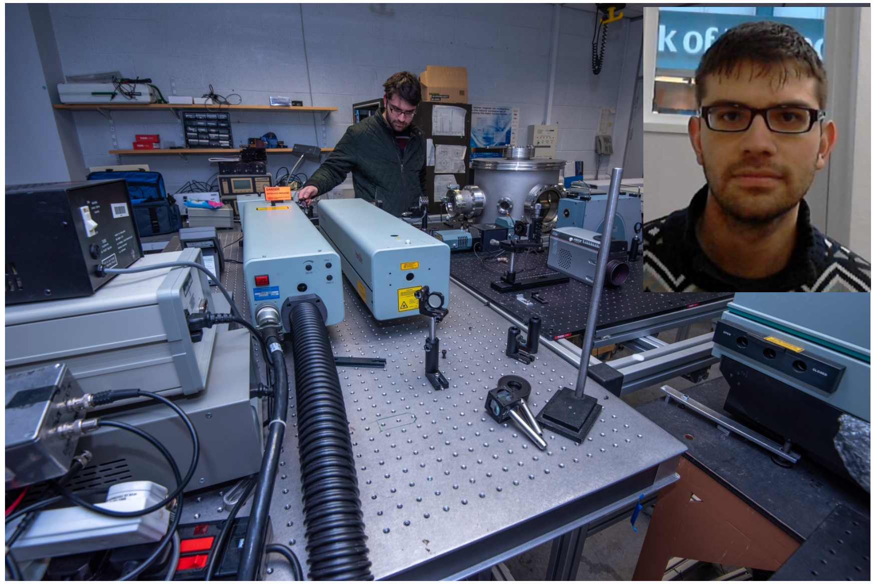


Stephen Durkan / Séamus Cummins/
James Campbell - all PhD students



Lazaros Varvarezos (PD)

Standoff LIBS Prototype – Under Construction

Ollscoil Chathair Bhaile Átha Cliath
Dublin City University

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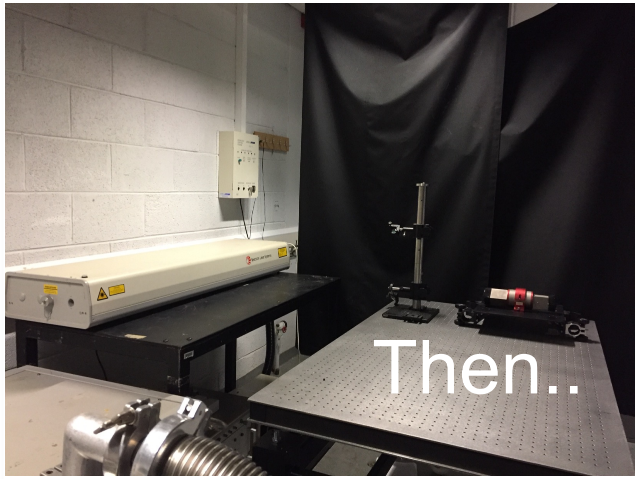
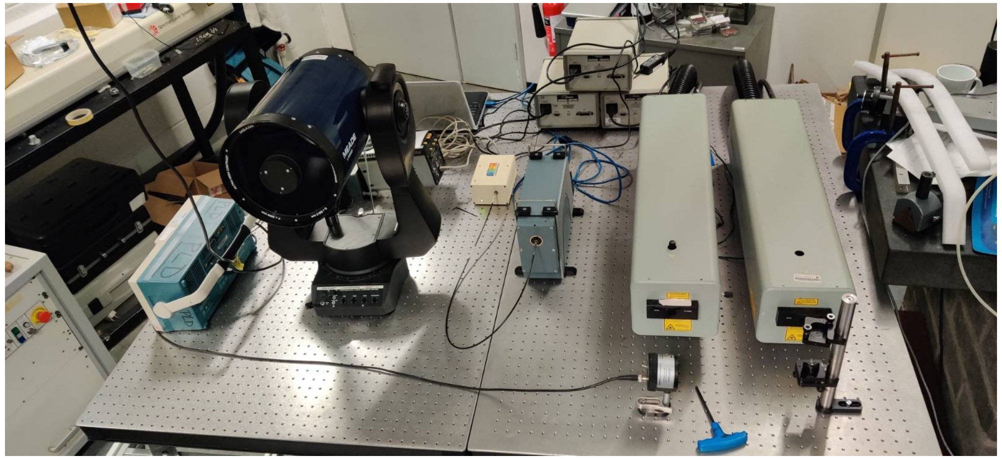
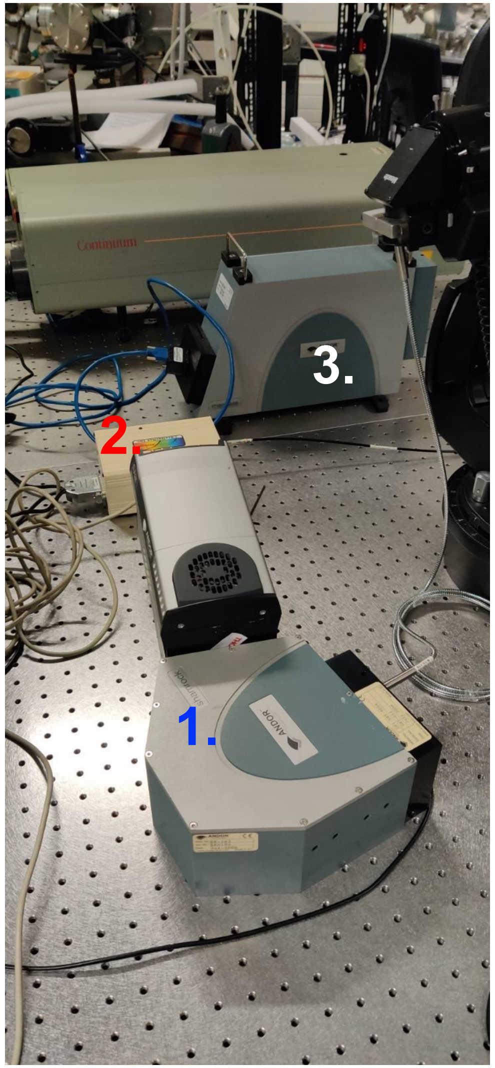
First in pictures….





Top view showing double pulse laser setup with telescope.

Split tables with laser PSUs



Spectrometers for WP1
1. Time-Gated
2. Continuous-Readout
3. Wide-Spectral Range

Ultrafast (UF) Laser Spectroscopy Lab

Ultrafast Laser Spectroscopy

DCU
Ollscoil Chathair Bhaile Átha Cliath
Dublin City University

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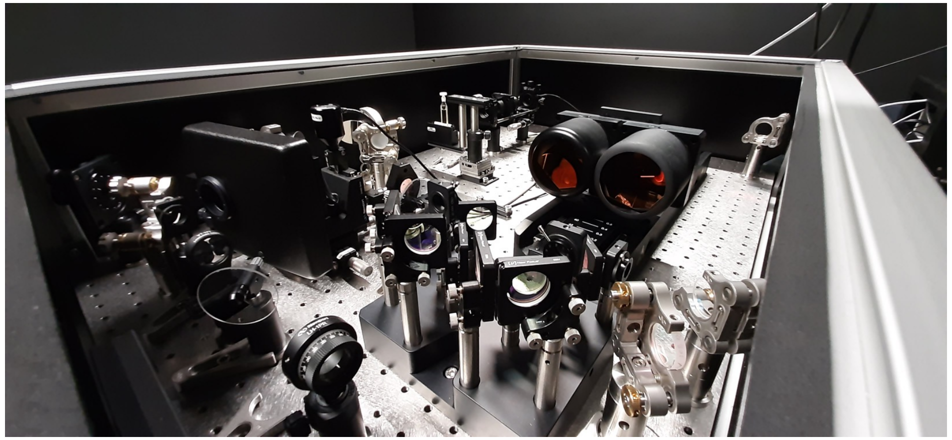
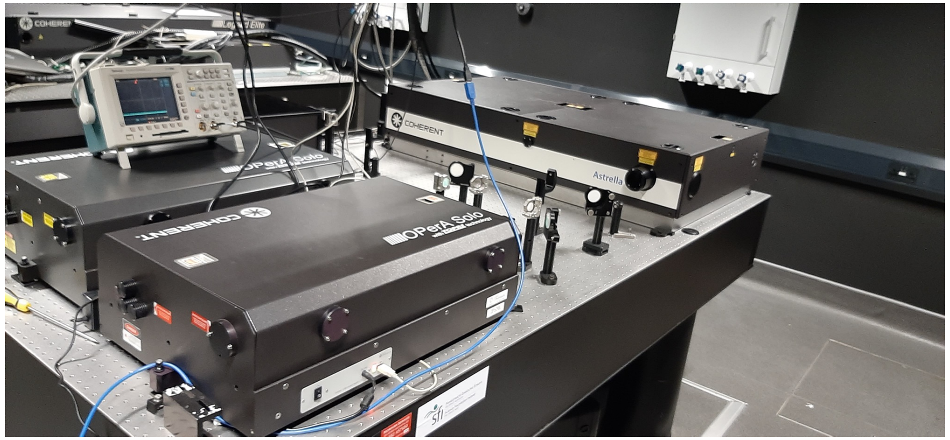
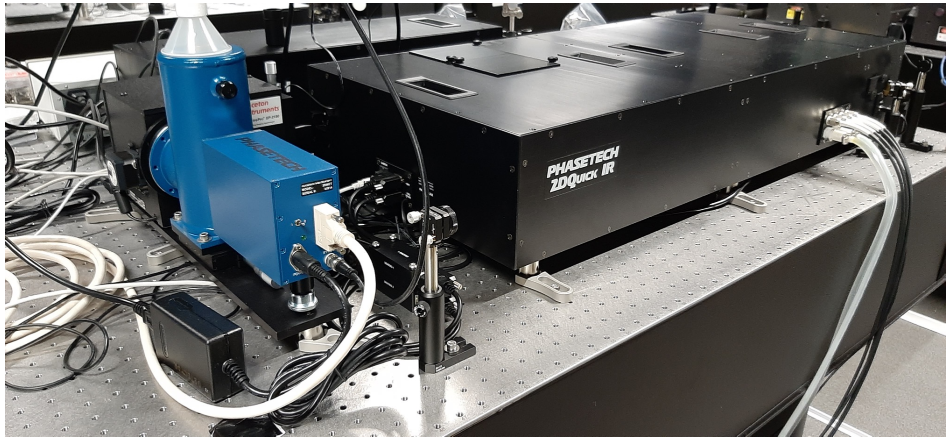
WP4. UF Laser Spectroscopy Laboratory @ DCU



WP4. Inside the UF Transient Spectrometer



WP4. UF Laser Table with Astrella Amplifier & OPAs



WP4. UF Time Resolved IR Spectrometer

VUV LIBS (and Photoabsorption)

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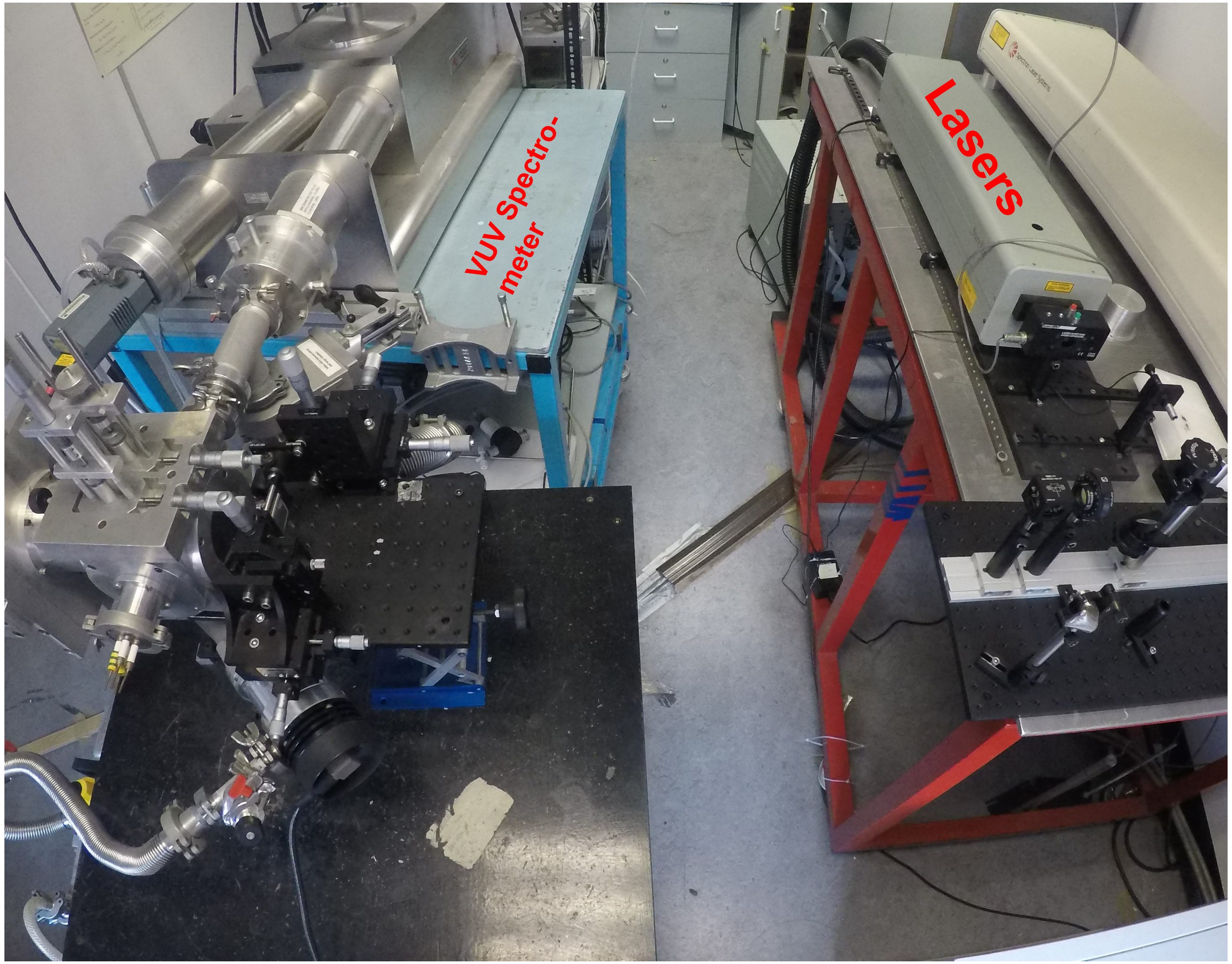

Dual Pulse Vacuum-UV (VUV) LIBS Lab.