Table-Top Laser Produced Colliding Plasmas

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Stagnation layers at the collision front between counter-streaming plasma plumes: formation, properties and potential applications

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Outline of the Talk

1. Colliding Plasmas (CPs) – some fundamentals

2. Diagnostics – mapping CPs in space-time

3. Key properties – potential applications

4. Next Steps

DCU Laser Plasma/Atomic Physics

Laser Plasma @ NCPST - 6 laboratory areas focussed on pulsed laser matter interactions (spectroscopy/ imaging)

Research Domains:

1. Colliding Laser Produced Plasmas
2. Optical and Particle Diagnostics of Laser Produced Plasmas
3. Laser Induced Breakdown Spectroscopy (LIBS)
4. Pulsed Laser Deposition (PLD) of Materials
5. Photoionization of Atoms and Ions with Laser Produced Plasma (LPP) and Free Electron Laser (XFEL) Light Sources

Some Current Projects:

1. UV-Vis imaging, spectroscopy and interferometry of colliding laser produced plasmas [with and without laser reheating]
2. Double Pulse VUV-LIBS for Elemental Characterisation in Steel
3. Ion emission from single and colliding laser plasmas
4. PLD of ZnO nanostructures
5. 2 photon and 2 colour photoionization of atoms with X-FELs

DCU Laser Plasma-AMO Physics Group

Laser Plasma/AMO Physics @ NCPST - 6 laboratory areas focussed on pulsed laser matter interactions (spectroscopy/ imagingIparticles)

Principal Investigators (6): John T. Costello, Eugene T. Kennedy (Emeritus), Lampros Nikolopoulos (T), Jean-Paul Mosnier & Paddy Hayden (SFI SIRG PI)

Current Postdocs (2): Dr. Pramod Pandey & Dr. Mossy Kelly

Current PhD students (9): Nichola Walsh, Ben Delaney, Stephen Davitt, Hu Lu, Getasew Wubetu, William Hanks, Muhammed Alli, Sadaf Syedah & Lazaros Varvarezos

Recent Interns (2012-15): K. Nishant/R. Tejaswi, (LNMIIT, Jaipur), C Hand, (NUIM), S Reddy/R Namboodiri/A Neettiyath (IIT Madras), R Singh/S Gupta (IIT Kanpur), S Howard (Notre Dame), I-M Carrasco Garcia (Malaga), R. Black (Notre Dame)

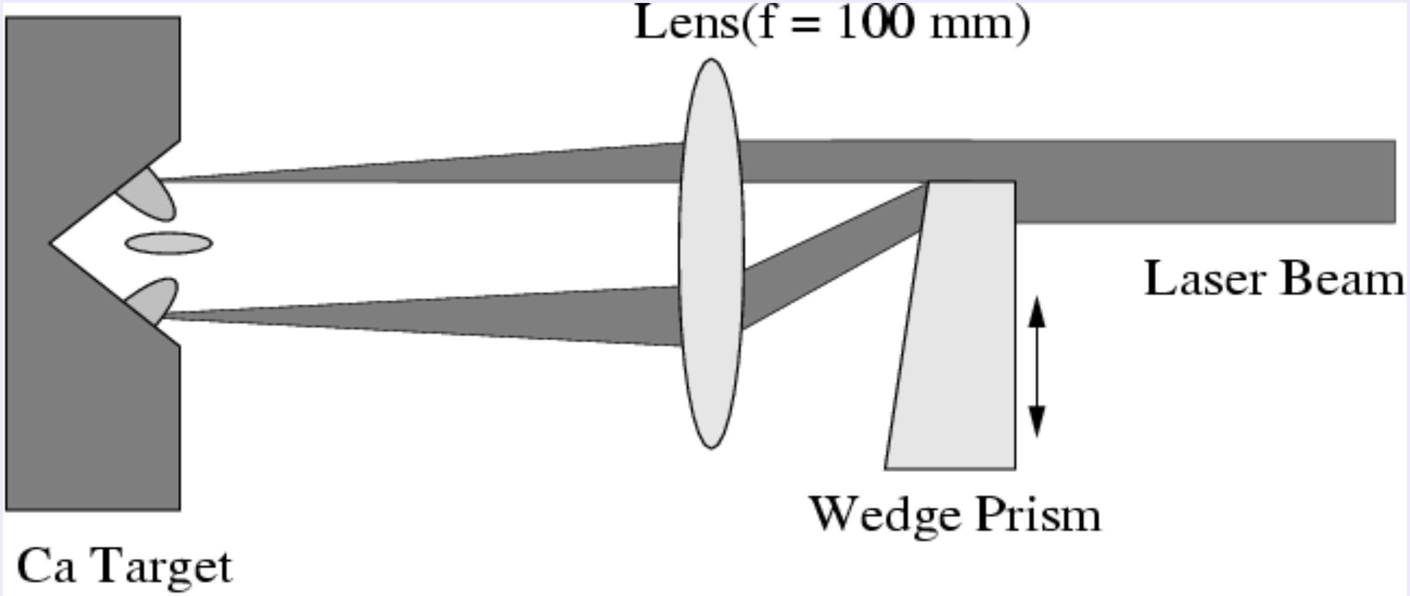
Recent PhD Grads (2009-2016): Padraig Hough, Conor McLoughlin, Rick O'Haire, Vincent Richardson, Dave Smith, Tommy Walsh, Jack Connolly, Jiang Xi, Leanne Doughty, Eanna MacCarthy, Colm Fallon, Mossy Kelly, D Middleton, Cathal O'Broin, Brian Sheehy & Saikumar Inguva

Recent Past Postdocs (2012-2015): Satheesh Krishnamurthy (Open Univ. UK), Pat Yeates (Elekta Oncology UK) & Subhash Singh (U. Allahabad), Colm Fallon (IC4 – DCUBS).

Part I – Table-Top Colliding Plasmas

Making Stagnation Layers

$$d = \gamma f\left(n-1\right)$$



Laser Pulse Energy:	50 - 500 mJ/ beam
Laser Wavelengths:	355nm, 532 nm, 1064 nm
Laser Pulse duration:	170 ps, 6 ns, 15 ns
Focal Spot Size:	~30 - 100 μm
Irradiance:	10^9 - 10^{11} W.cm^{-2}

Part I – Table-Top Colliding Plasmas

Not a new idea !

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

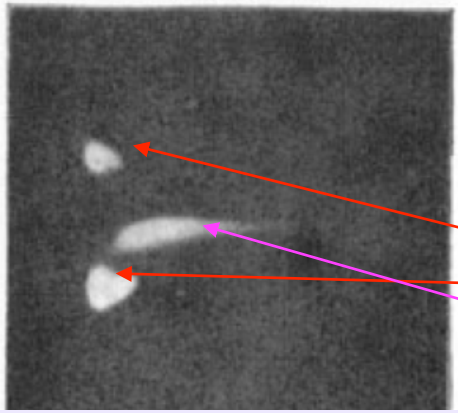
INTERACTIONS BETWEEN TWO COLLIDING LASER PRODUCED PLASMAS

P. T. Rumsby,* J. W. M. Paul and M. M. Masoud†
UKAEA Research Group, Culham Laboratory, Abingdon, Berkshire, England

(*Received* 29 *January* 1974)

d - 10 mm

•25 μs



'Seed' Plasmas

'Stagnation Layer'

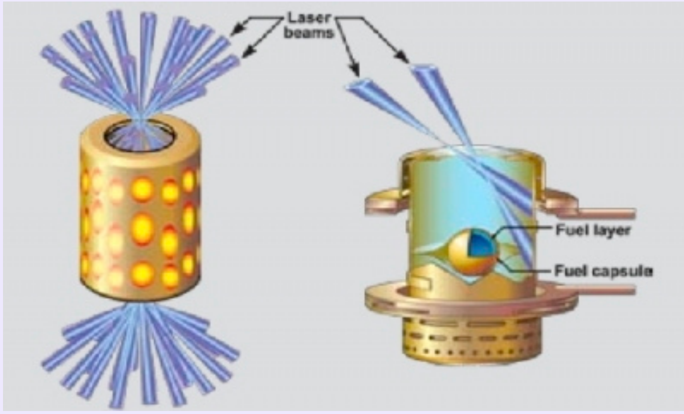
When plasma plumes collide there are two extreme scenarios:

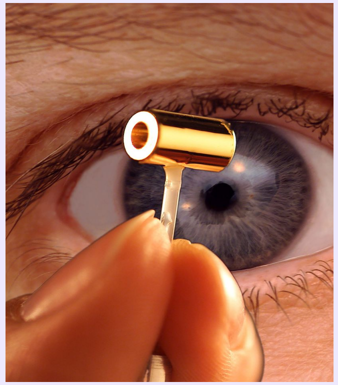
1. Interpenetration - interactions are mostly via binary collisions
2. Stagnation - plumes decelerated at collision plane, rapid accumulation of material, kinetic energy converted into excitation energy (glow), rapid growth of dense (stagnated) layer,………

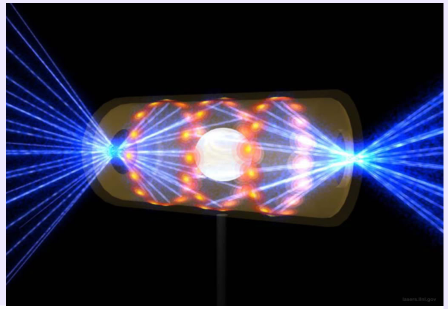
Part I – Table-Top Colliding Plasmas

Not table-top…

Cf. Chris Spindoe talk this morning on ICL shocks…







PRL 110, 145005 (2013) PHYSICAL REVIEW LETTERS week ending 5 APRIL 2013

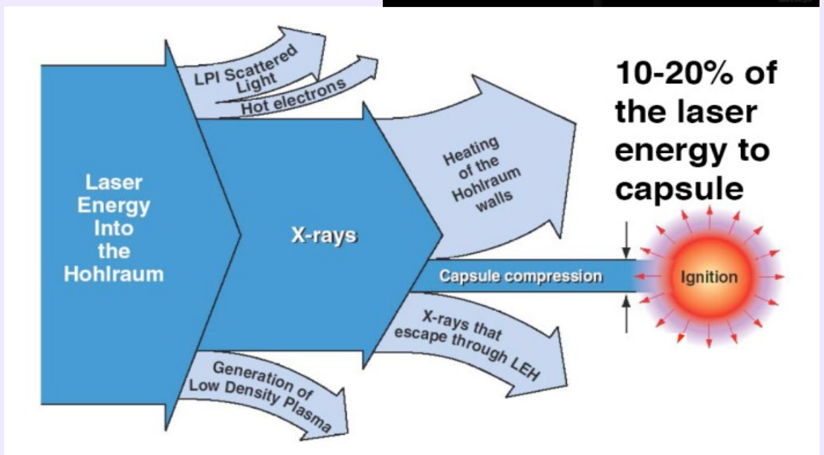
Collisionless Coupling of Ion and Electron Temperatures in Counterstreaming Plasma Flows

J. S. Ross,[1] H.-S. Park,[1] R. Berger,[1] L. Divol,[1] N. L. Kugland,[1] W. Rozmus,[1,2] D. Ryutov,[1] and S. H. Glenzer[1]
[1]*Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, California 94551, USA*
[2]*Department of Physics, University of Alberta Edmonton, Alberta, Canada T6G 2R3*
(Received 22 February 2013; published 2 April 2013)

PRL 111, 085003 (2013) PHYSICAL REVIEW LETTERS week ending 23 AUGUST 2013

Experimental Characterization of the Stagnation Layer between Two Obliquely Merging Supersonic Plasma Jets

E. C. Merritt,[1,2] A. L. Moser,[1] S. C. Hsu,[1,*] J. Loverich,[3] and M. Gilmore[2]
[1]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2]*University of New Mexico, Albuquerque, New Mexico 87131, USA*
[3]*Tech-X Corporation, Boulder, Colorado 80303, USA*
(Received 22 March 2013; published 22 August 2013)



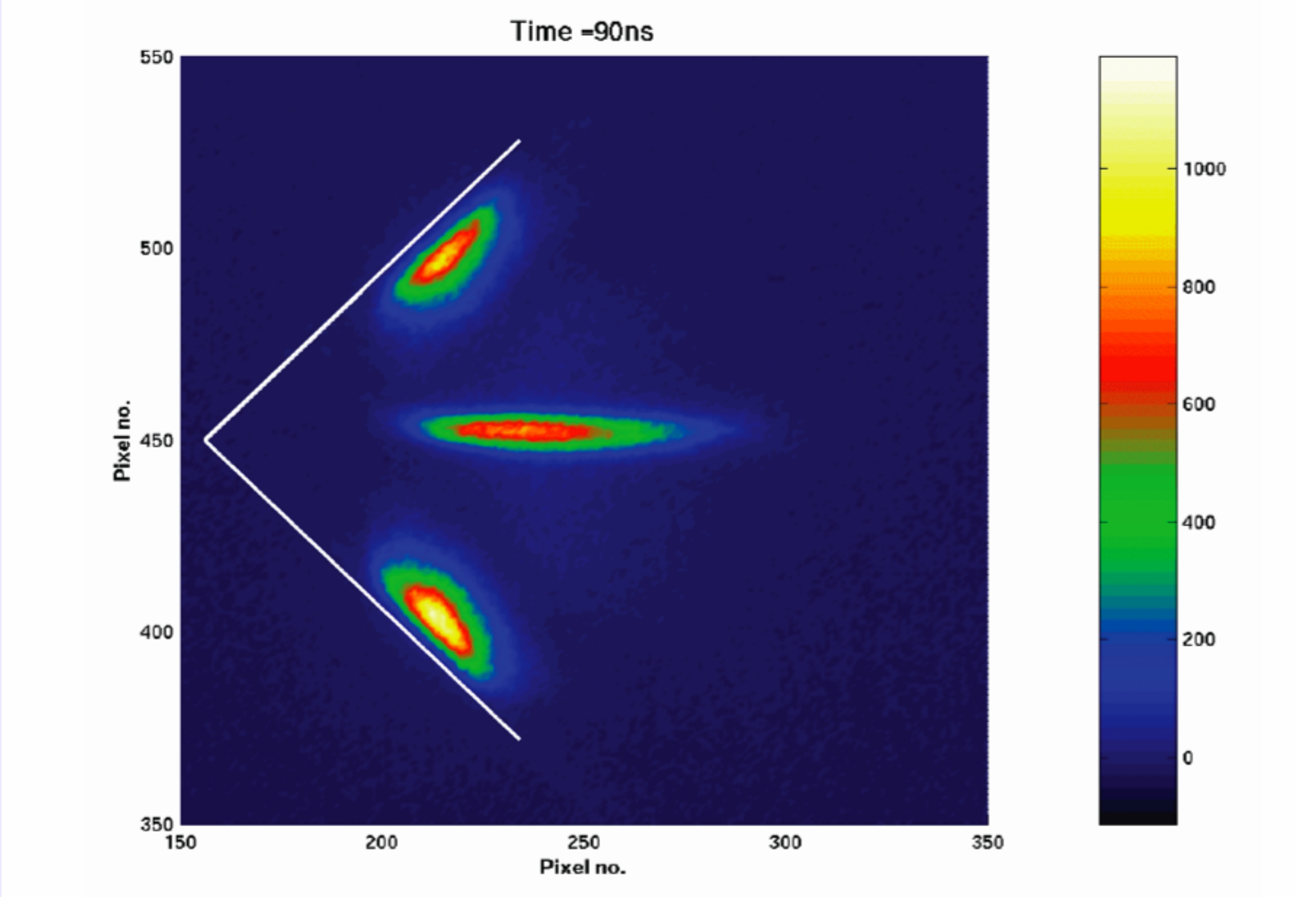
Part I – Table-Top Colliding Plasmas

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)

Part I – Table-Top Colliding Plasmas

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

Plasma - Plasma Separation

Ion - Ion Mean Free Path (mfp)

For collisions between opposing plumes (1, 2)

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

λ_{ii} >> D → Interpenetration
λ_{ii} ~ D → 'Soft' Stagnation
λ_{ii} << D → 'Hard' Stagnation

Slow moving and dense 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)

Part I – Table-Top Colliding Plasmas

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

D – Plasma - Plasma Separation

λ_{ii} – Ion - Ion Mean Free Path (mfp)

For collisions between opposing plumes (1, 2)

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

Key point: *One can engineer stagnation layer characteristics; 'hardness', density, temperature, shape, etc. by varying geometry (D) and laser-target interaction physics (mfp, λ_{ii}) - application specific…..*

Part I – Table-Top Colliding Plasmas

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

Plasma - Plasma Separation

Ion - Ion Mean Free Path (mfp)

For collisions between opposing plumes (1, 2)

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

So perhaps a stagnation layer could be considered to be a useful alternative to single plumes for e.g., - laboratory astrophysics, plasma XRLs (Bleiner et al., Journal of Laser Physics, 23, 056003, (2013), pulsed laser deposition (PLD), pre-heated targets for bright laser plasma light sources (EUVL), LIBS, LA-ICP-MS, etc.

Part II – SL Diagnostics

Stagnation layer growth (evolution)

Time resolved (ICCD) imaging

1. Time-space resolved spectroscopy

Plasma Parameterisation

1. Time-space resolved spectroscopy - n_e & T_e
2. Time resolved interferometry - n_e
3. Time resolved shadowgraphy – shock detection
4. Faraday cup - angle resolved ion current – $i(\theta)$

D Doria, K D Kavanagh, J T Costello and H Luna, Meas. Sci. Technol. **17** 670 (2006)

P Hough, T J Kelly, C Fallon, C McLoughlin, P Hayden, E T Kennedy, J-P Mosnier, S S Harilal and J T Costello, Meas. Sci. Technol. **23** 125204 (2012)

P Yeates, C Fallon, E T Kennedy and J T Costello, Physics of Plasmas **20**, 093106 (2013)

Part II – SL Diagnostics

Stagnation layer evolution/parameterisation

1. Fast Photography - all phases (0 – 1000 ns)
2. Interferometry - usable early phase (0 – 100 ns)
3. Spectroscopy - usable mid phase (50 - 500 ns)
4. Faraday cup - ions and electrons
5. Others: Shadowgraphy, Moire deflectometry, etc.

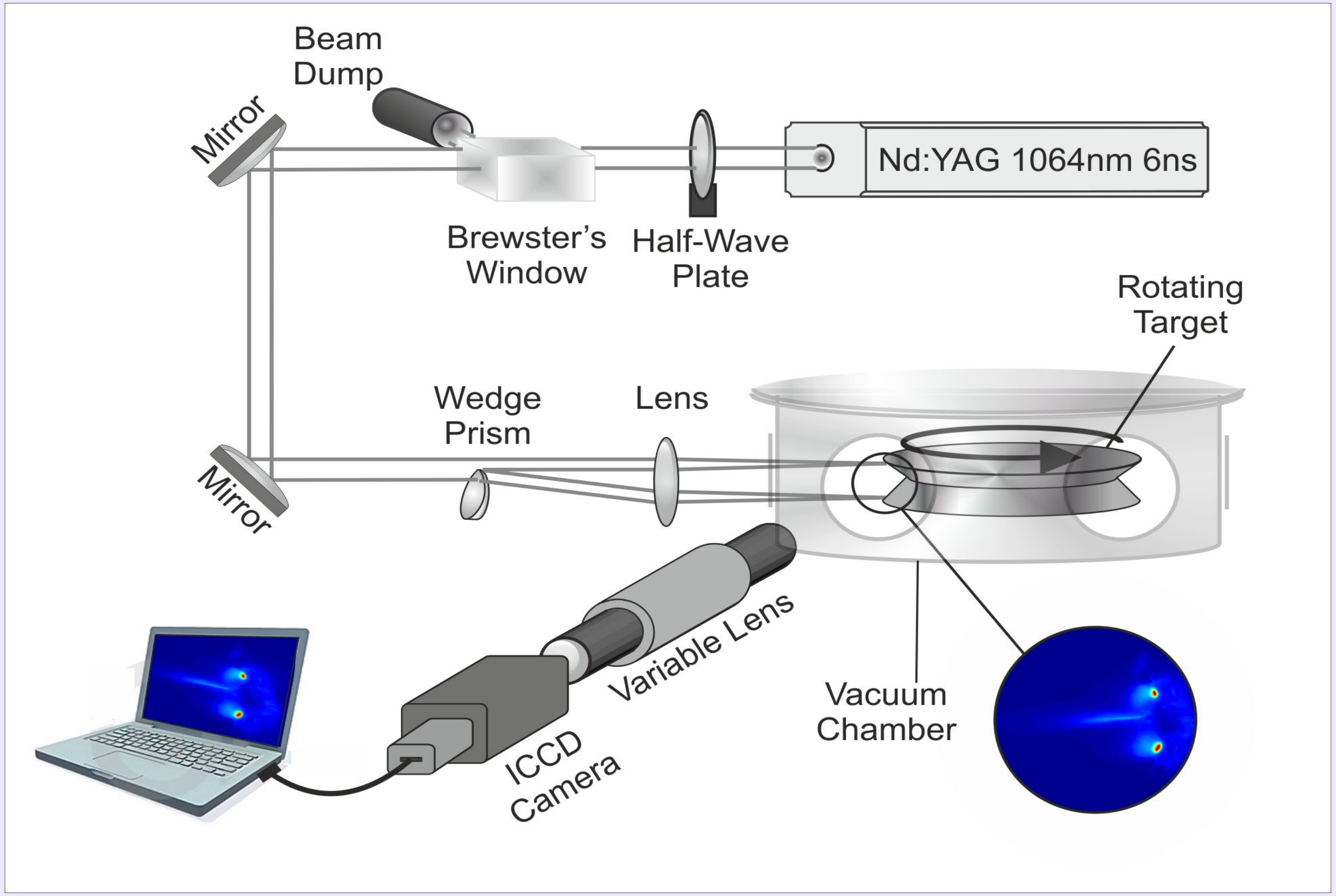
D Doria, K D Kavanagh, J T Costello and H Luna, Meas. Sci. Technol. **17** 670 (2006)

P Hough, T J Kelly, C Fallon, C McLoughlin, P Hayden, E T Kennedy, J-P Mosnier, S S Harilal and J T Costello, Meas. Sci. Technol. **23** 125204 (2012)

P Yeates, C Fallon, E T Kennedy and J T Costello, Physics of Plasmas **20**, 093106 (2013)

Part II – SL Diagnostics

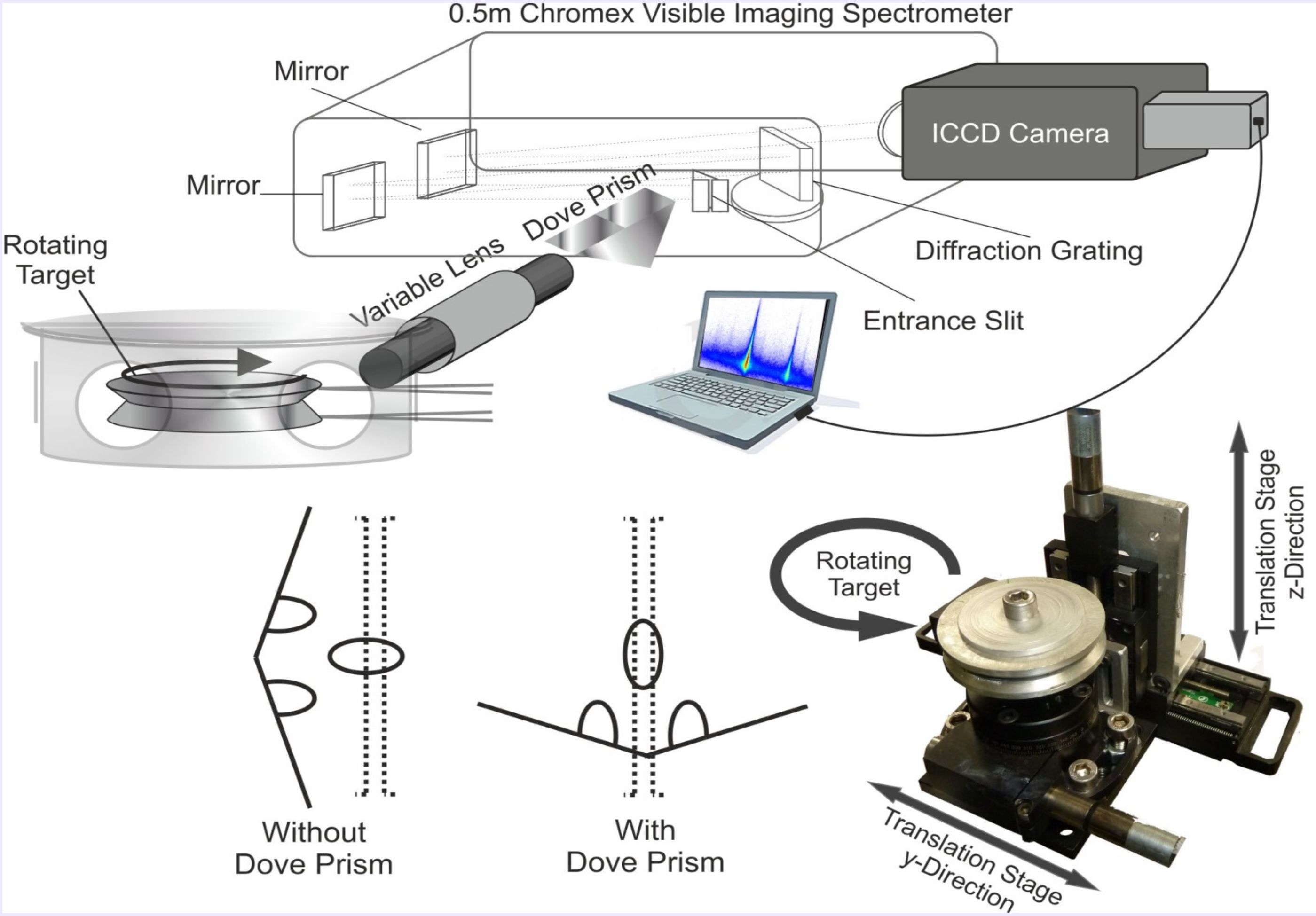
ICCD Photography: Time and angle resolved.



C Fallon, P Hayden, N Walsh, E T Kennedy and J T Costello,
Journal of Physics: Conference Series **548** 012036 (2014)

Part II – SL Diagnostics

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)

Part II – SL Diagnostics

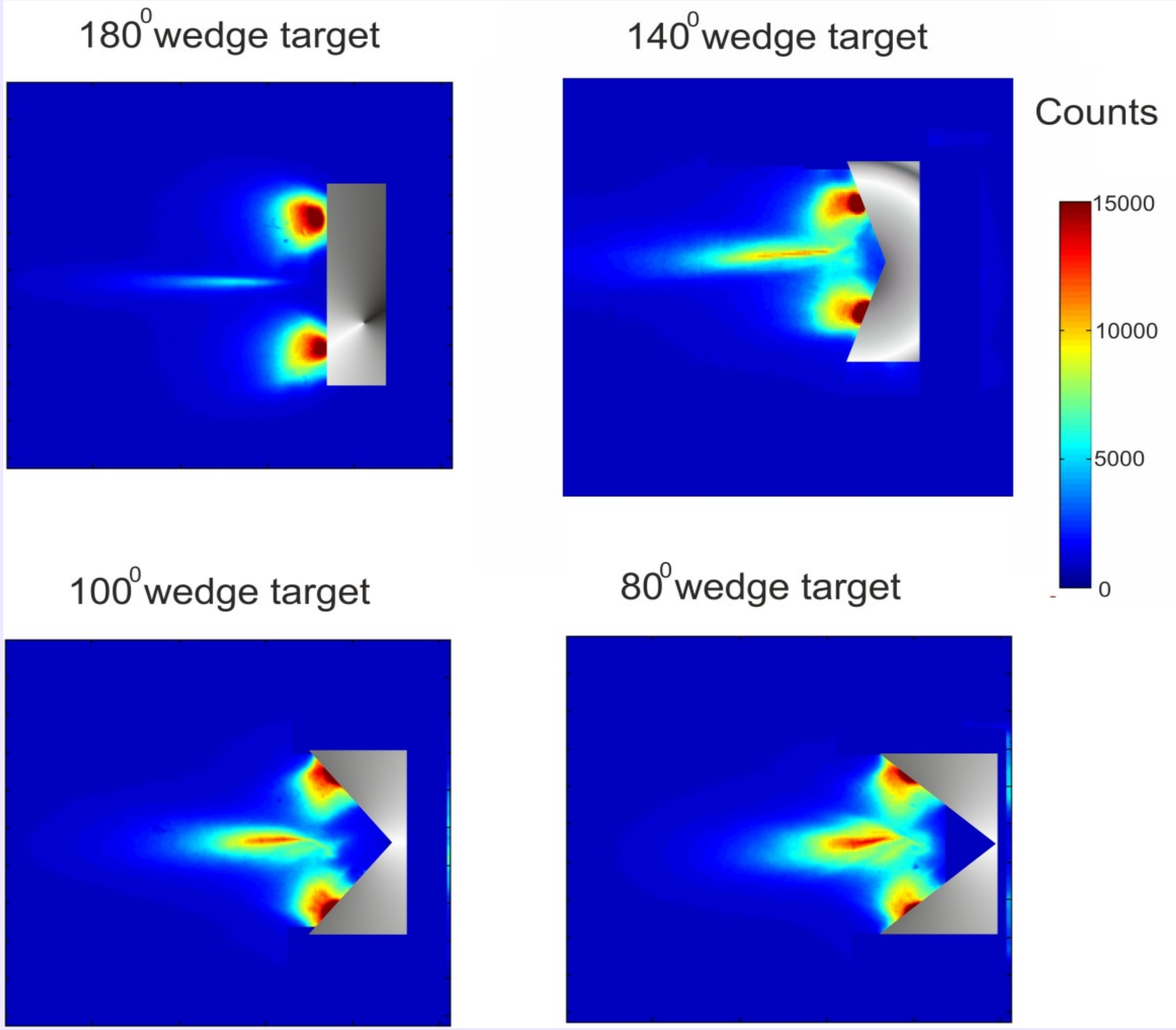
Bespoke Colliding Plasma Laboratory - (Padraig Hough)
Imaging, Spectroscopy, Interferometry, RETOF,….

Part II – SL Diagnostics

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)

Time, Space and Angle-Resolved UV-Vis Spectroscopy

Stigmatic Spectrometer + ICCD

Part II – SL Diagnostics

Extracting Densities and Temperatures

Get densities from Stark broadened lines – assume electron collisions dominant -

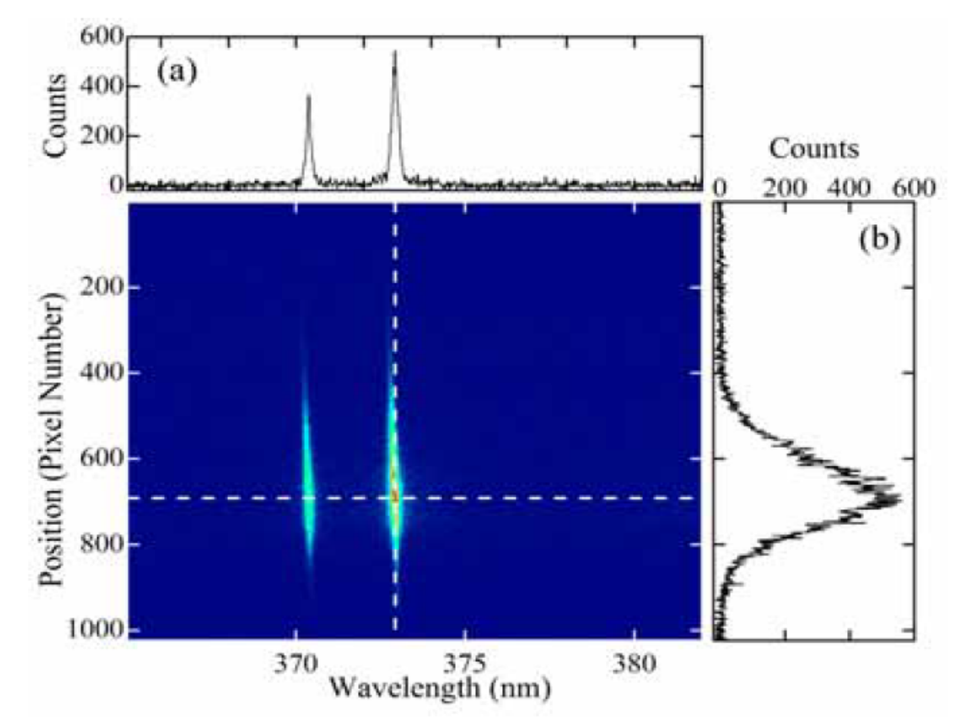
$$\Delta\lambda_{\text{width}} = 2W(Ne/10^{16}) + 3.5A(Ne/10^{16})^{1/4} \times (1 - 1.2N_D^{-1/3})W(Ne/10^{16}),$$

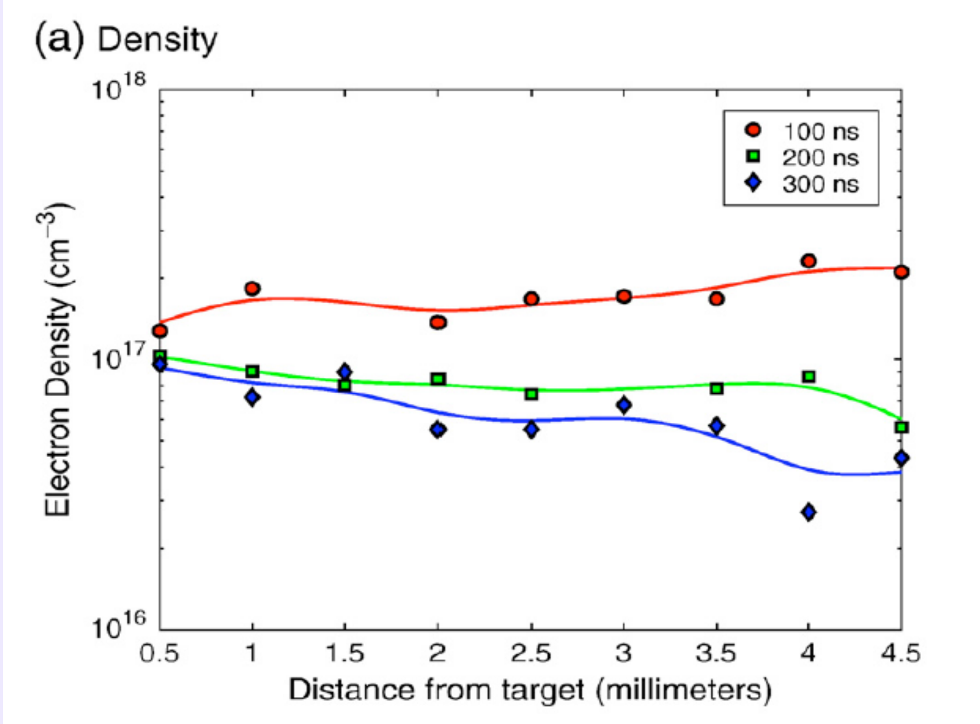
Then temperatures from line intensity ratio for successive ions stages - assumes LTE

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

Part II – SL Diagnostics

Stagnation Layer (Al): ***Electron density (Stark Analysis)***



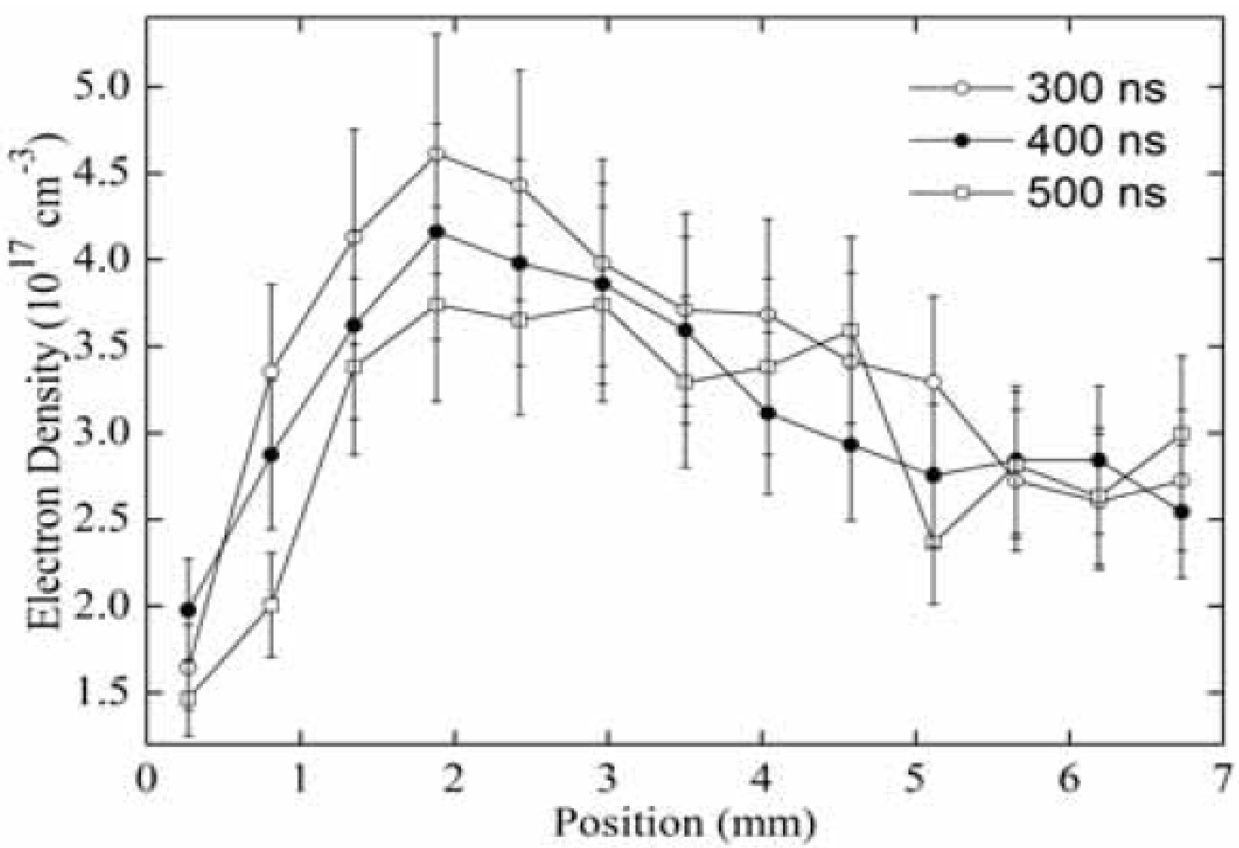


~100 mJ/170 ps/1064 nm 'seed' beam

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

Part II – SL Diagnostics

Stagnation Layer (Ca): ***Electron density (Stark Analysis)***

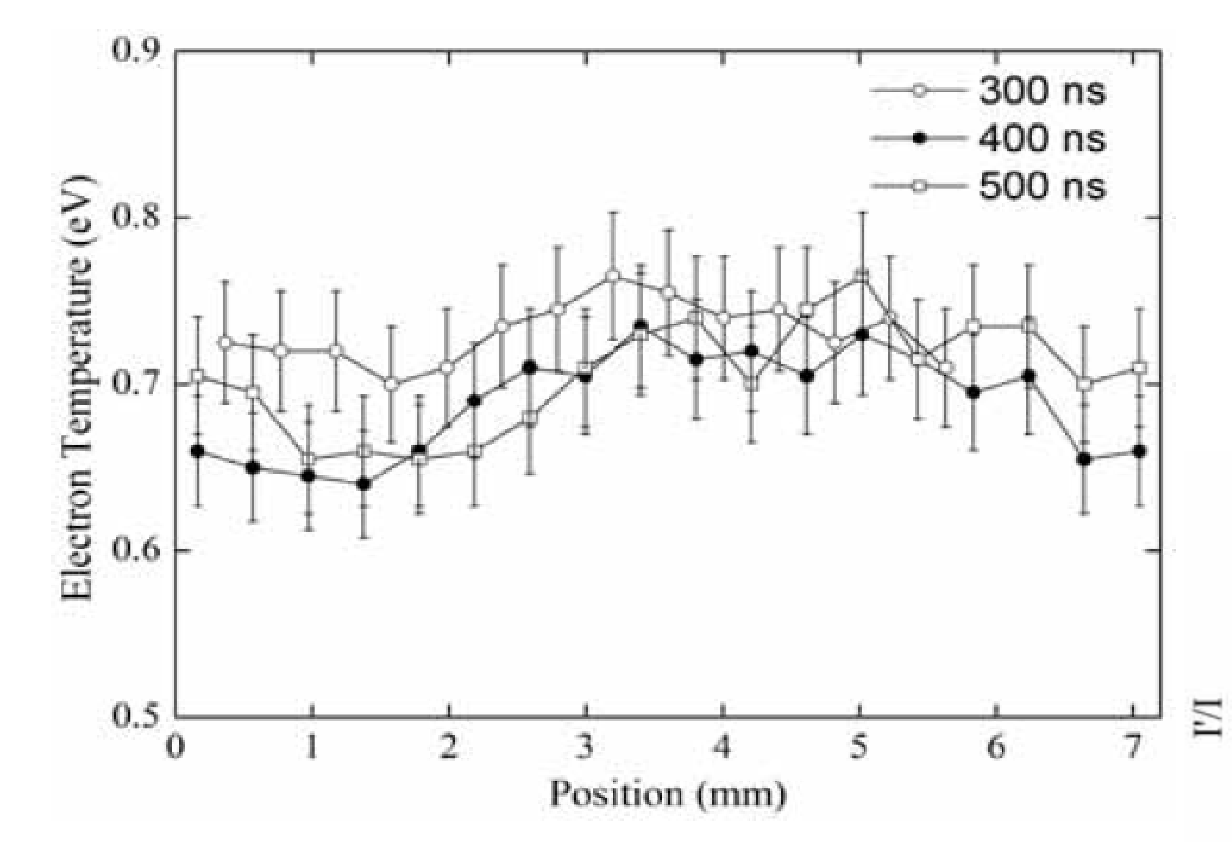


~70 mJ/**355 nm**/
6 ns/ 'seed' beams

$$n_e \approx 3x10^{17} cm^{-3}$$

Part II – SL Diagnostics

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

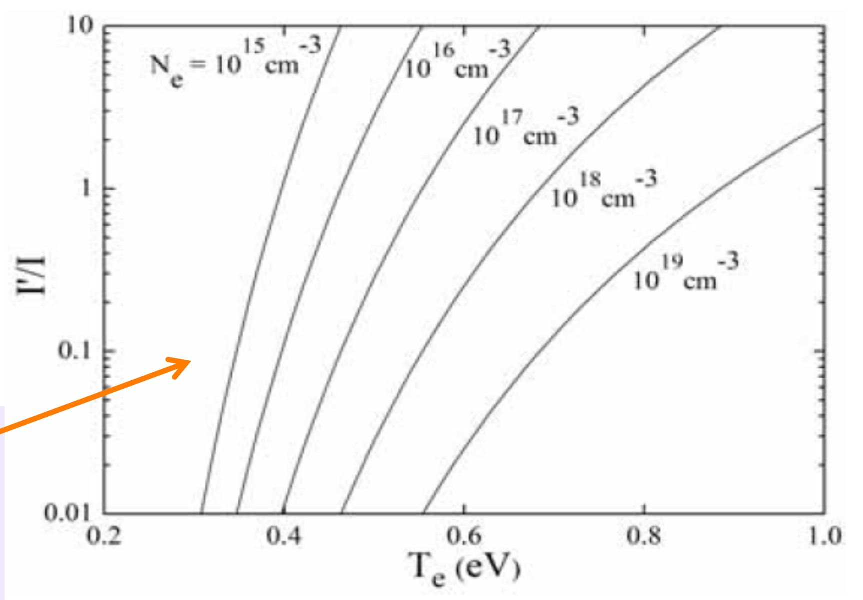


~70 mJ/**355 nm**/
6 ns/ 'seed' beam

$$T_e \approx 0.7eV$$

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

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

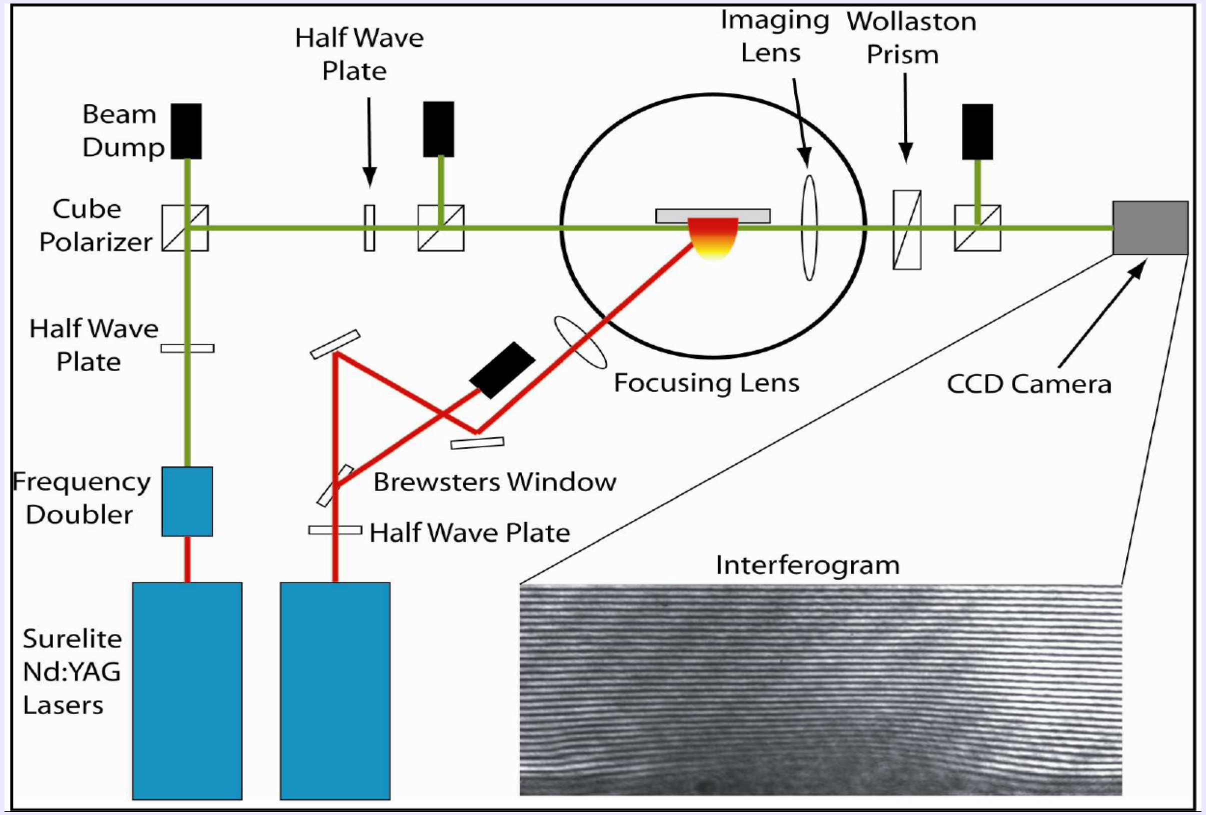


Part II – SL Diagnostics

***Stagnation Layer (Al):** Electron density & temperature*

Spectroscopy - only works well for Δt > 100 ns

Spectra dominated by continuum emission - *solution - time resolved interferometry*



Experimental Setup-

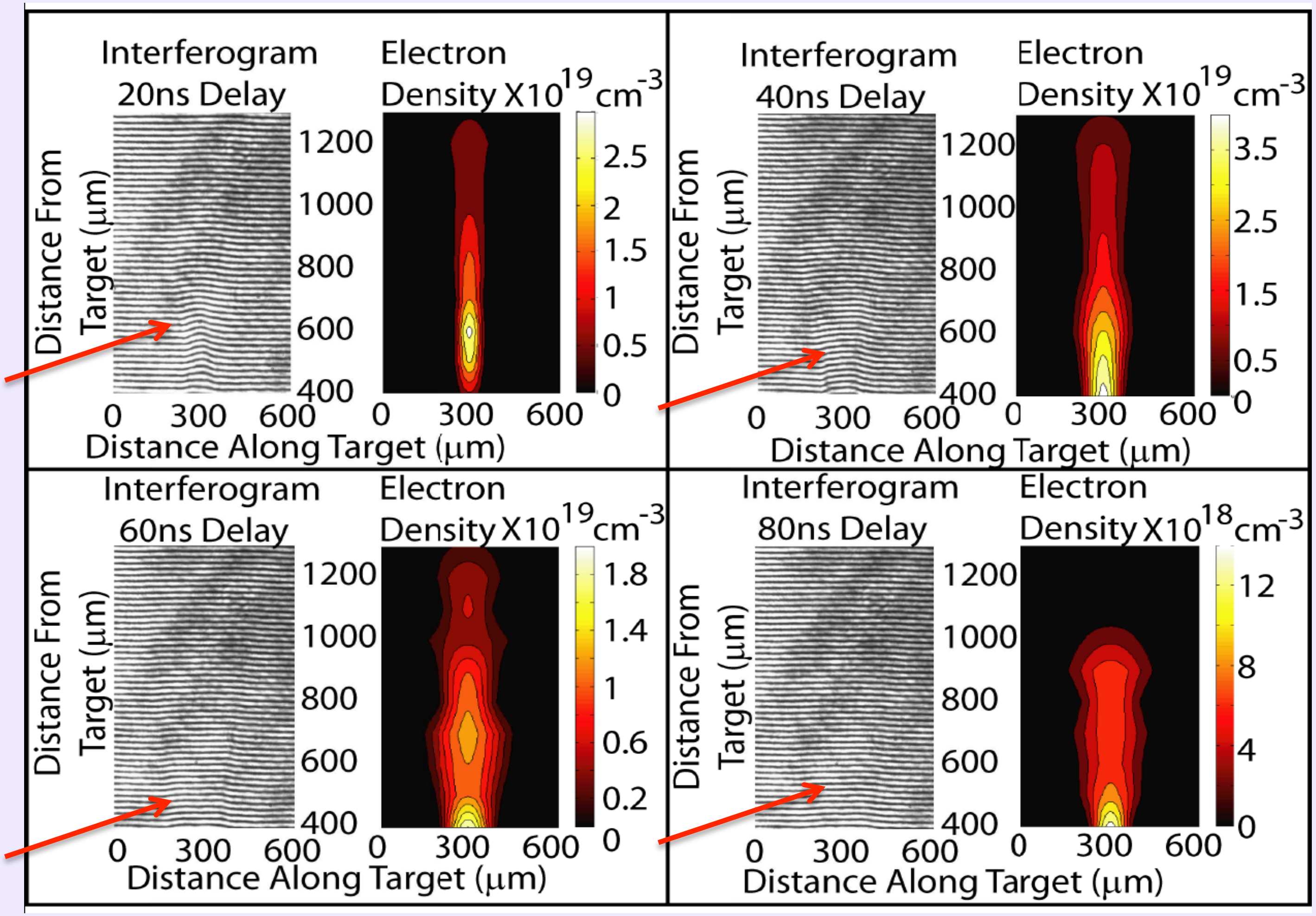
Nomarski Interferometer

P Hough, C McLoughlin, T J Kelly, S S Harilal, J-P Mosnier and J T Costello, Appl. Surf. Sci. **255** 5167 (2009)

Part II – SL Diagnostics

Electron Stagnation at the Collision Plane

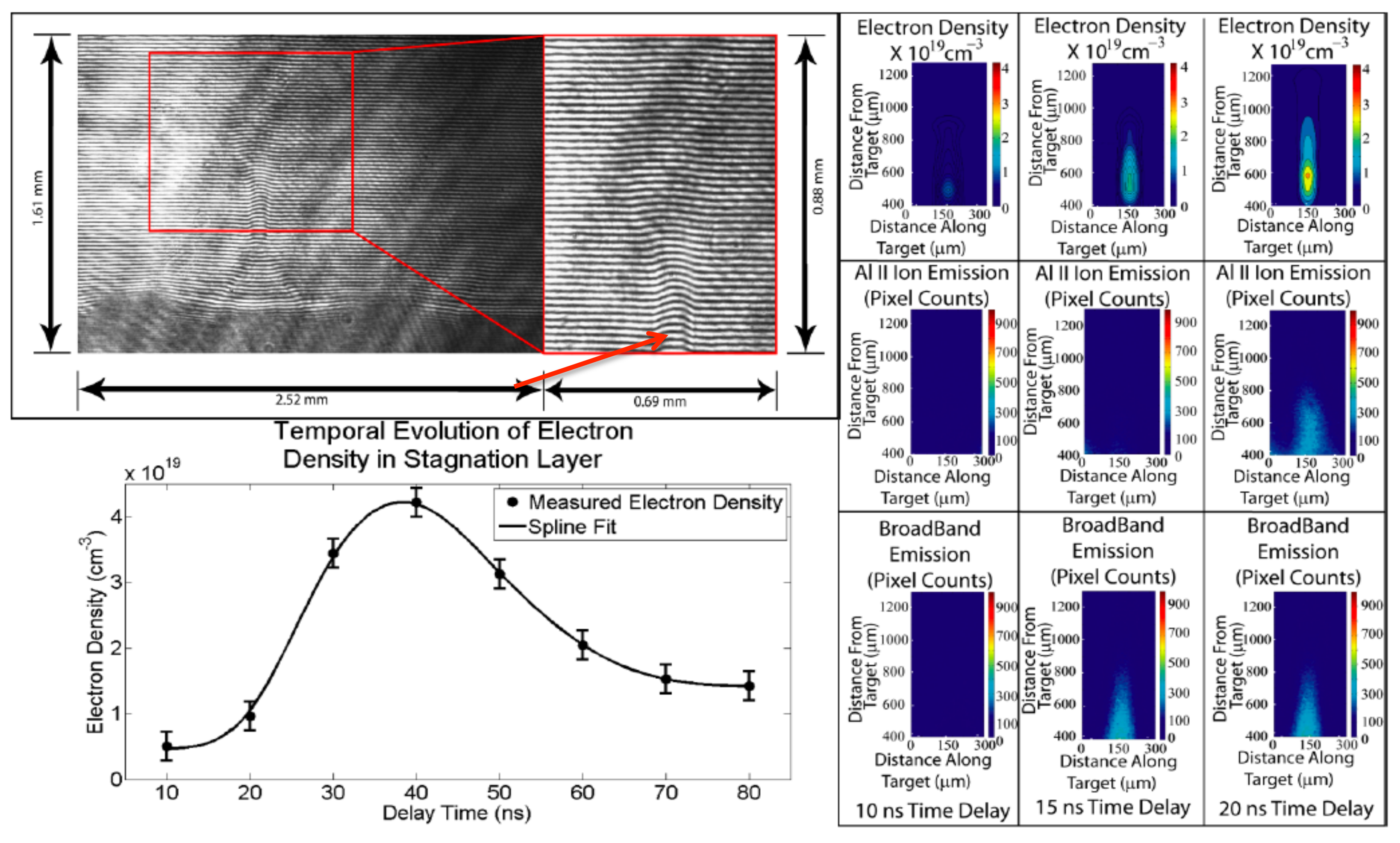
P Hough, C McLoughin, T J Kelly, S S Harilal, J P Mosnier and J T Costello, J. Phys. D: Appl. Phys. **42** 055211 (2009)



Part II – SL Diagnostics

Distinguishing electron and ion stagnation - 1064 nm/ 6 ns/ 100 mJ

P Hough, C McLoughin, T J Kelly, S S Harilal, J P Mosnier and J T Costello, J. Phys. D: Appl. Phys. **42** 055211 (2009)



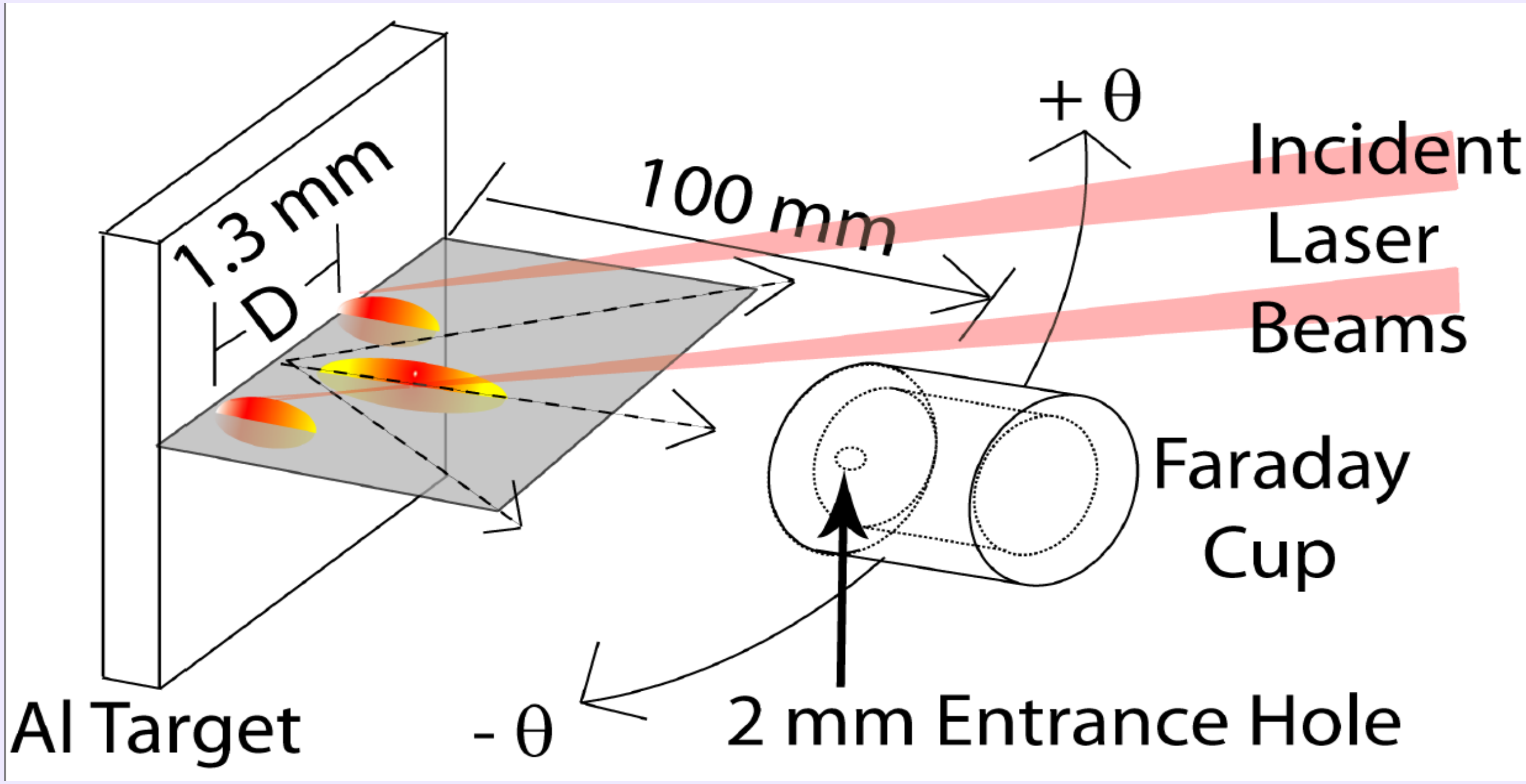
Electrons - 'Nomarski'

Al^+ ions - ICCD

Al plume - ICCD

Part II – SL Diagnostics

Motivation – colliding plasmas as **laser ion sources** - LIS



Angle Resolved Ion Emission Experiment

Part II – SL Diagnostics

Motivation – colliding plasmas as laser ion sources – *LIS ?*

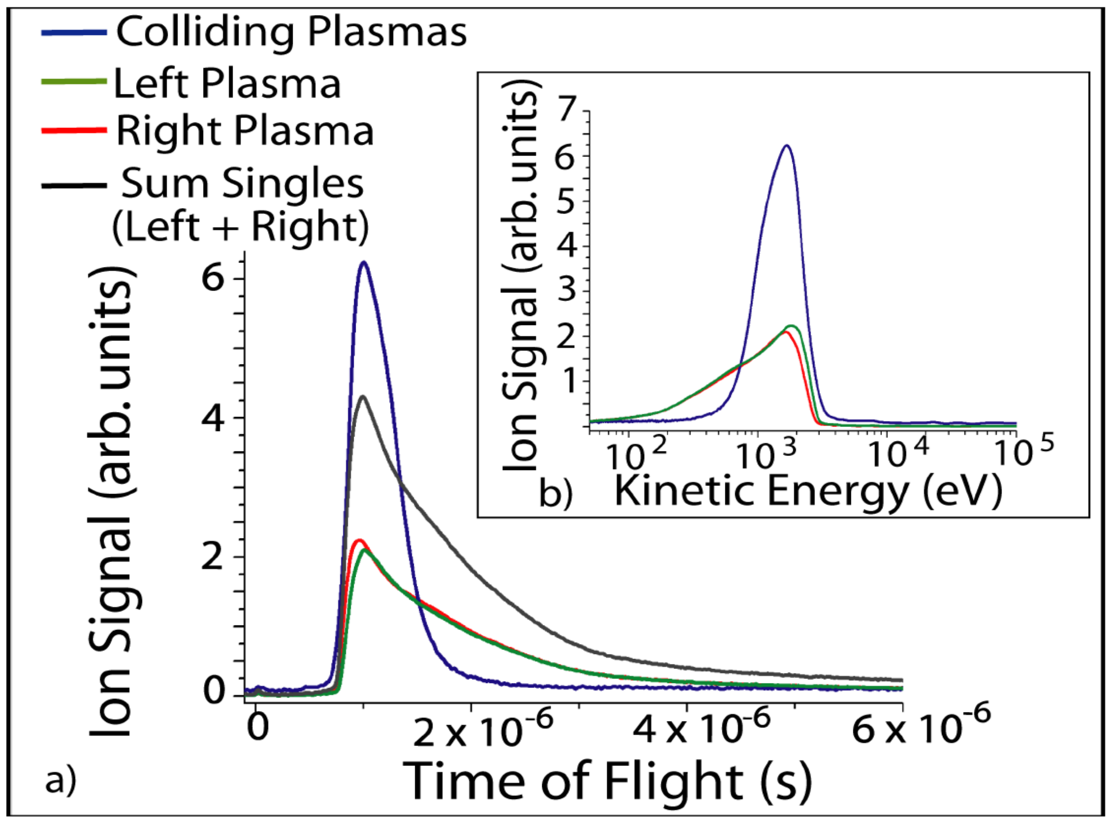
Some interest arising from potential applications in:

1. Fundamental Interactions with Particles/Fields
2. Ion implantation
3. Injector systems for ion accelerators
4. Heavy ion therapy in oncological studies

1. www.pearl2009.org
2. E Woryna et al., Rev. Sci. Instrum **72** 2 (2000)
3. B Sharkov and R Scrivens, IEEE Trans. Plasma. Phys **33** 1778 (2005)
4. A. Denker et al., NIM B **240** 61 (2005)
5. P Yeates, J T Costello and E T Kennedy, Plasma Sources Sci. Technol. **19** 065007 (2010)
6. P Yeates, J T Costello and E T Kennedy, Physics of Plasmas **17** 123115 (2010)
7. P Yeates, J T Costello and E T Kennedy, J. Phys. D: Appl. Phys. **44** 135204 (2011)

Part II – SL Diagnostics

We observe quite significant narrowing of the TOF distribution compared to single plasma plumes….!

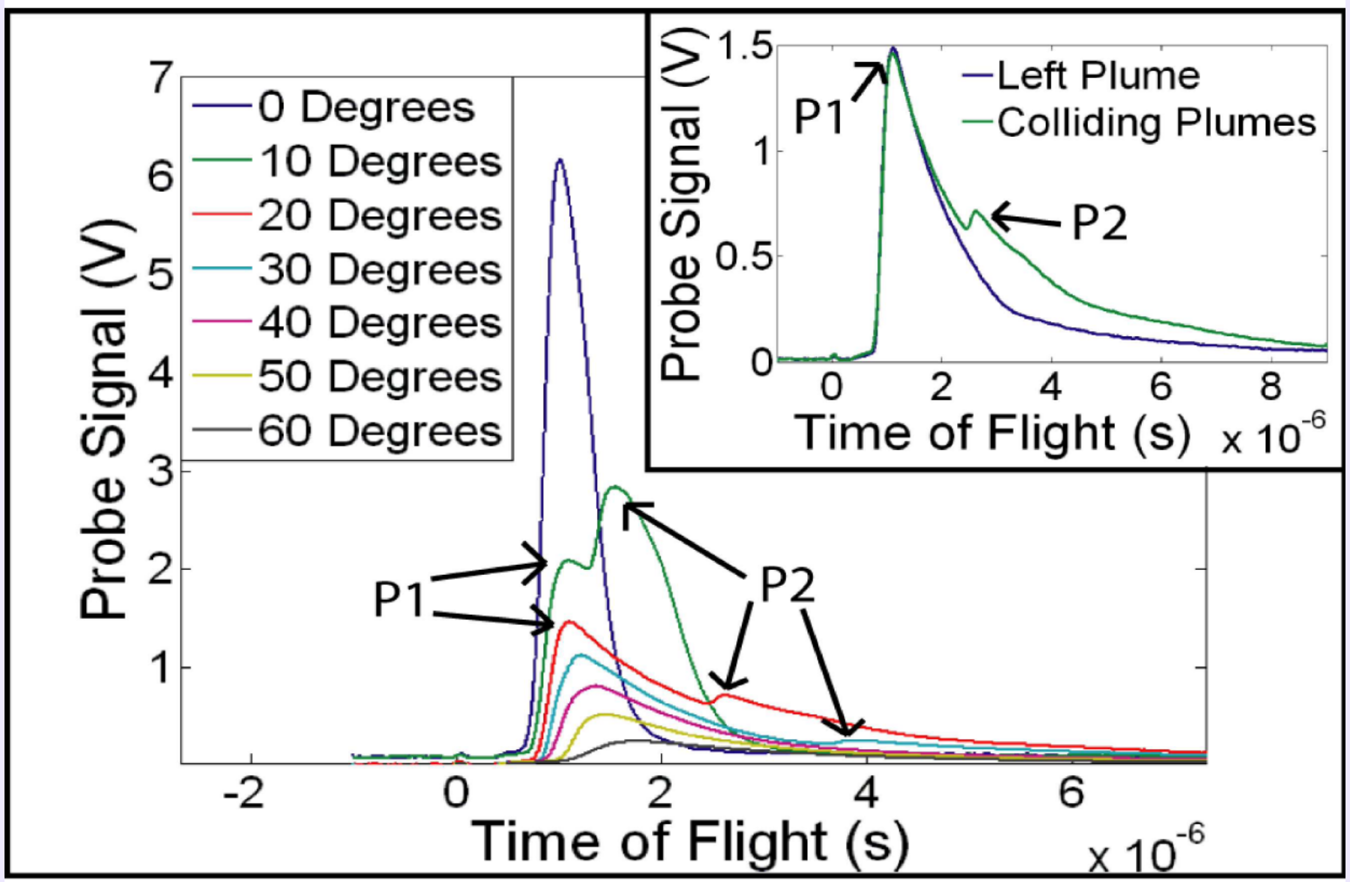


'Plasma ion bunch compression…'

P Hough, P Hayden, C Fallon, T J Kelly, C McLoughin, P Yeates, J-P Mosnier, E T Kennedy, S S Harilal and J T Costello, J. Phys. D: Appl. Phys. 44 355203 (2011)

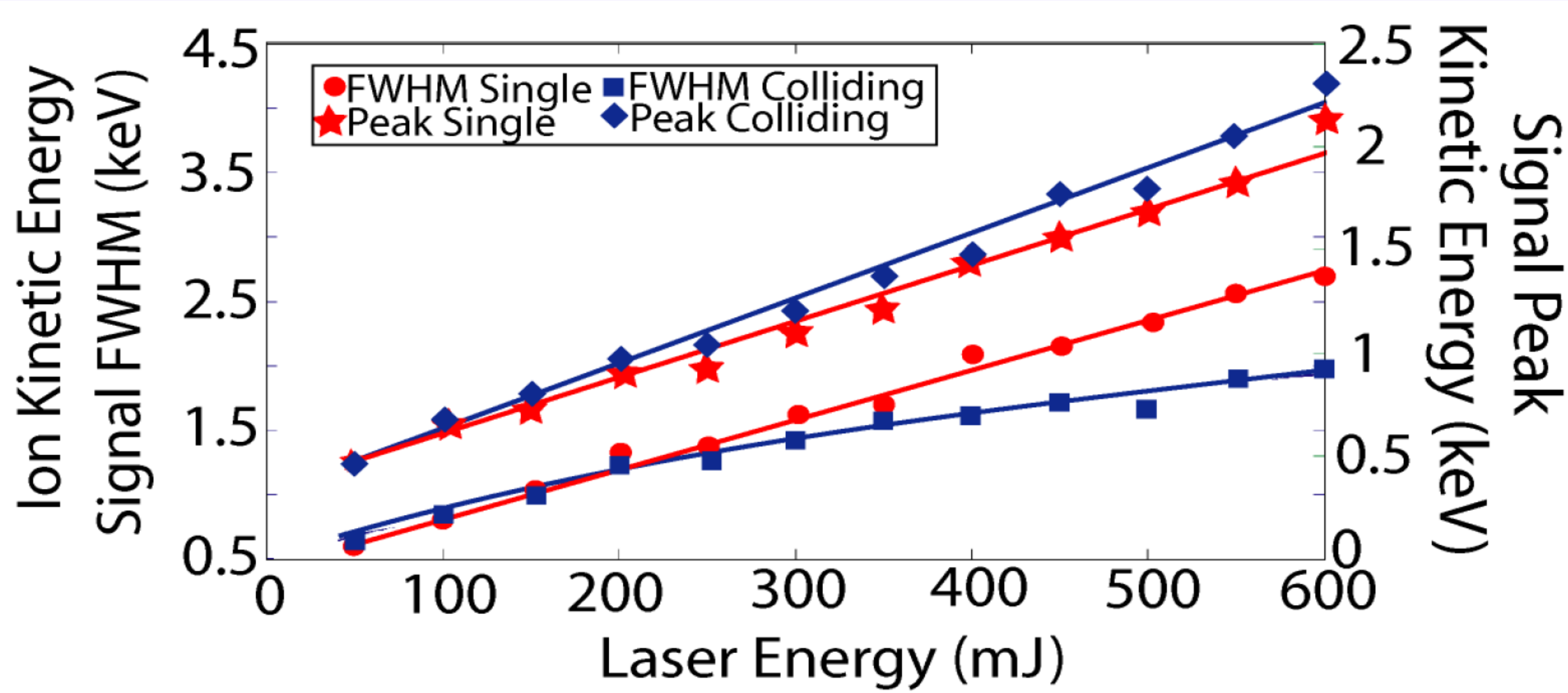
Part II – SL Diagnostics

As we move the detector off normal emitted ion flux from each (left or right hand side) single plume dominates => weak lateral emission from stagnation layer - fewer damaging fast ions and perhaps less plasma debris ? (EUVL)



Part II – SL Diagnostics

One can also tune the width and peak energy of the 'total ion' TOF distribution with the laser energy (6ns/1064nm)



P Hough, P Hayden, C Fallon, T J Kelly, C McLoughin, P Yeates, J-P Mosnier, E T Kennedy, S S Harilal and J T Costello, J. Phys. D: Appl. Phys. 44 355203 (2011)

CP Ion Emission – Summary So Far

1. The Faraday cup entrance aperture is 2 mm in diameter and so we see all paraxial ions coming from the complete colliding plasma system.

2. Ergo the stagnation layer (stagnant field) appears to have the effect of accelerating (or suppressing) the slow ions that are a feature of single plumes – no tail.

3. Right now we cannot say anything about the ions coming exclusively from the stagnation layer – need better spatial resolution.

4. Looks promising but much to left to do to prove potential.

What have we learned in general ?

1. Strong stagnation in table-top colliding plasmas due to large value of the collisionality parameter (ζ)

2. Degree of confinement/hardness of the stagnation layer can be controlled by designing the value of ζ

3. Density and temperature are strongly dependent on the seed laser wavelength – so can be selected/controlled via laser parameters

4. Both temperature and density increase with decreasing wedge angle – so can be selected/controlled controlled via target geometry

5. Densities and temperatures remain at higher values for longer in stagnation layers

What have we learned in general ?

6. Compared to single plume the duration of self emission from atoms and ions lasts longer than form single plumes

7. Stagnation layers becomes quite uniform >100 ns after SL formation

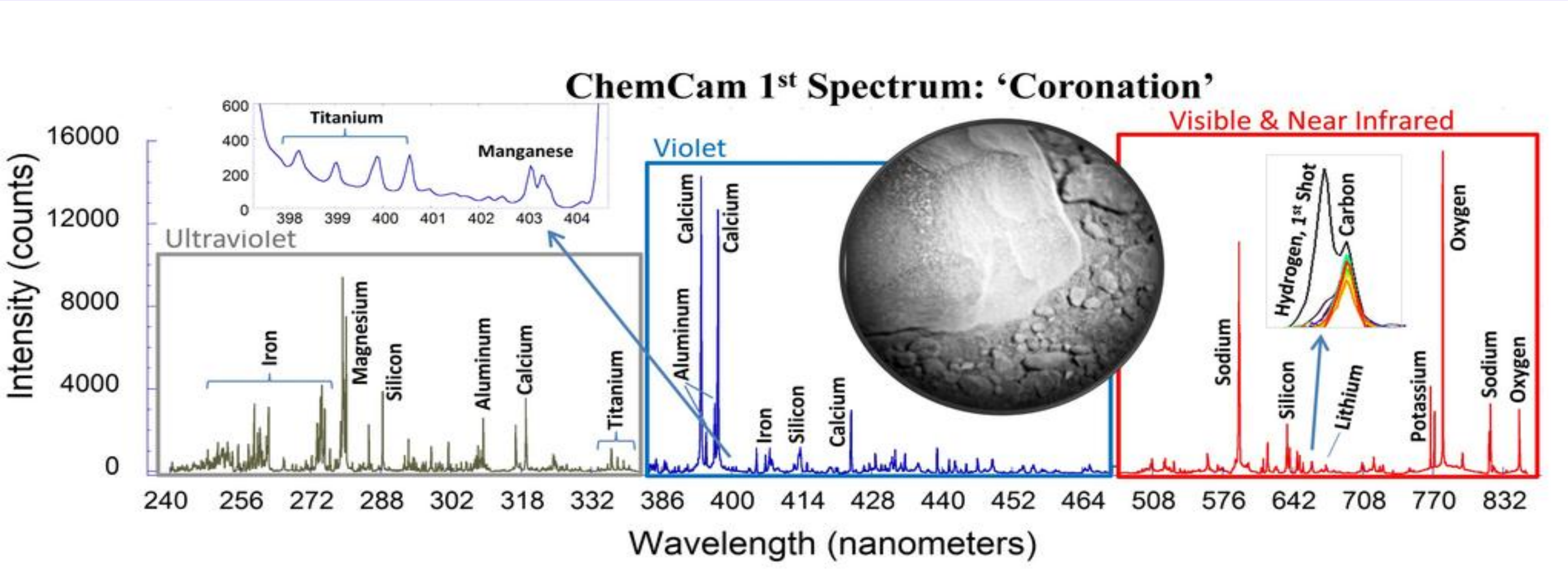
8. Ergo SLs look potentially attractive for applications in laser ablation analytical sciences [LAAS] and perhaps as an alternative [PLD] source

9. We believe that more than one process determines species transport in SL (not shown but discussed in Fallon et al (2015))

10. 'Velocities' of SL species drop as the wedge angle decreases - ion/neutral 'velocity' ratio generally >3 (not shown but discussed in Fallon et al. (2015))

Part III. Key Properties–Potential Applications

LIBS Spectrum of ‘Coronation Rock – N165’



LIBS provides both classification and quantification possibilities

Received from Mars by NASA’s *Curiosity Rover* on *19th Aug 2012*
(*Picture source: http://mars.jpl.nasa.gov/msl/multimedia/images/?ImageID=4541*)

Part III. Key Properties–Potential Applications

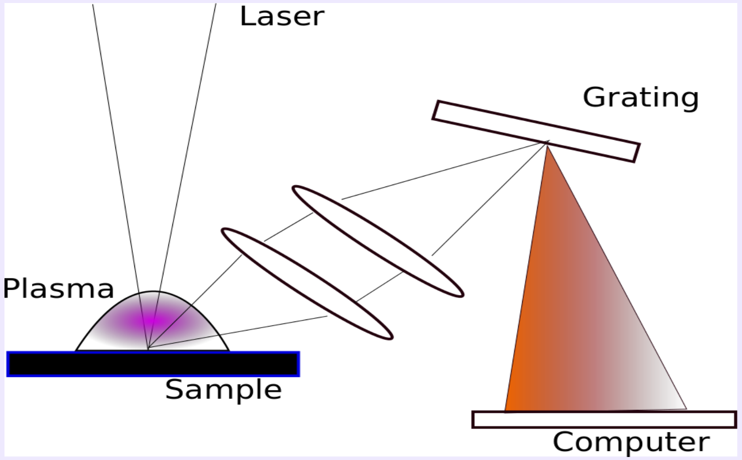
1. The most important of these is flexibility. Since a stagnation layer is a partially ionized plasma, it has many free parameters, which can be tuned for specific applications
2. Opacity is a problem in LIBS as radiation from the core is reabsorbed in the cooler corona - we know that the stagnation layer can be heated uniformly to reduce/eliminate opacity
3. The stagnation layer requires mainly some additional focusing optics and novel target designs and so it is easily retrofitted to existing experiments or commercial systems.
4. The emitting size of a re-heated stagnation layer can be geometrically engineered to readily match the acceptance angle of both optical and mass spectrometric systems.
5. The stagnation layer is already a pre-heated or proxy plasma for e.g., double pulse LIBS.
6. We have good preliminary evidence that we can preferentially generate high nanoparticle fluxes in nanosecond colliding plasmas
7. The position of the layer in space can be adjusted by the target geometry and relative energy in each of the seed plasma laser beams
8. It also **does not suffer from clogging** as happens in some EUVL Tin-Drop and biomolecule injector system applications
9. As we have seen stagnation layer electron densities ranging up to a few 10^{19} cm^{-3} are readily obtained while even higher densities are possible with frequency tripled Nd-YAG seed lasers.
10. We also have preliminary signs that we can control the ion energy spectrum to improve the resolution in TOF applications, reduce ion / debris damage in EUV optical systems, etc.

Part III. Key Properties–Potential Applications

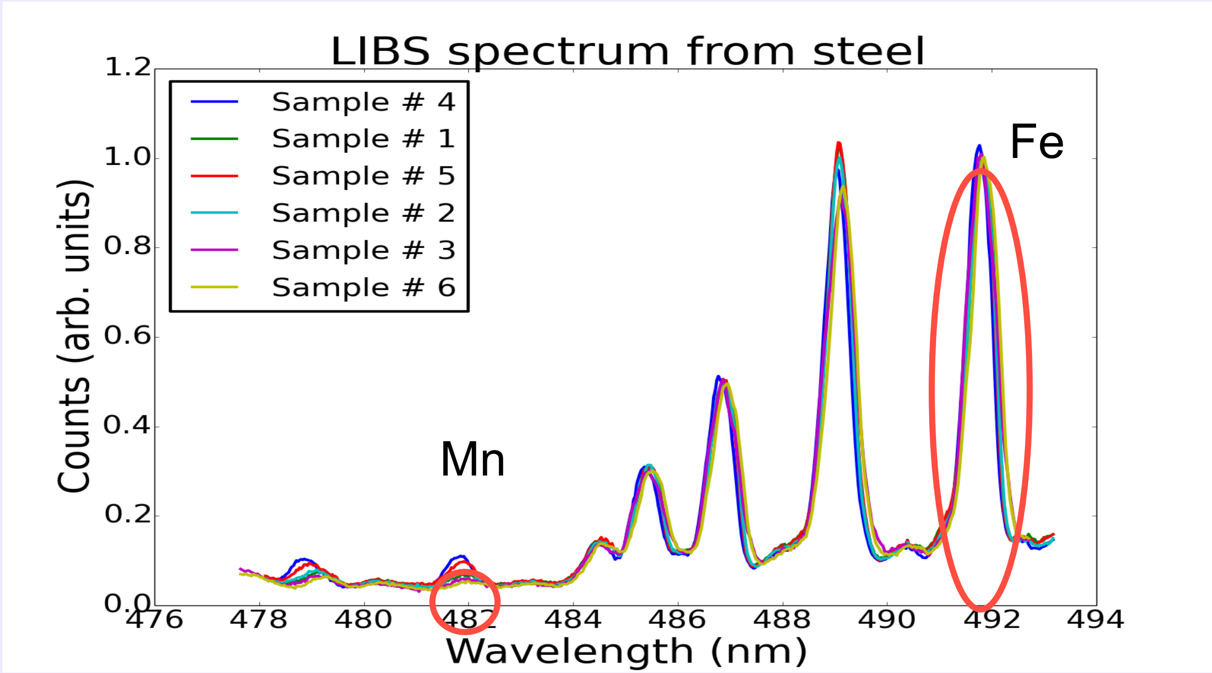
Laser Induced Breakdown Spectroscopy - LIBS

- LIBS is is a powerful analytical tool for analysing the composition of samples (Classification and Quantification)

- In principle, the concentration any element can be measured and the technique is minimally invasive with little sample preperation required



This is a nice way of measuring light elements in steel e.g., Mn



Part III. Key Properties–Potential Applications

Laser Induced Breakdown Spectroscopy - LIBS

The usefulness of LIBS is determined by its sensitivity

The key parameter in LIBS that determines the limit-of-detection (LOD) is the signal-to-background ratio (SBR)

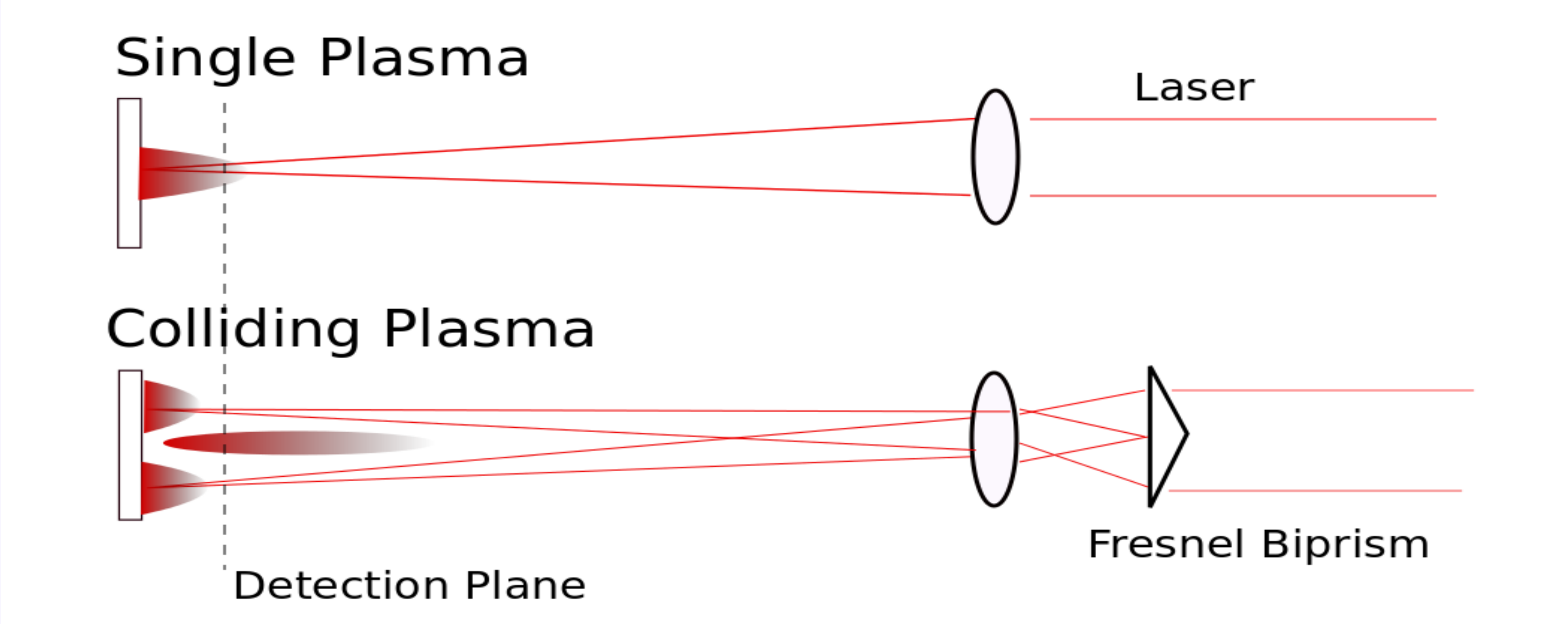
Our goal: Minimise variation in background and increase dynamic range and concomitantly the SBR – LOD

Can be this be done in a way that retro-fits to existing LIBS systems to make it cost effective and wdiely adopted ?

One candidate is colliding plasma LIBS

Part III. Key Properties–Potential Applications

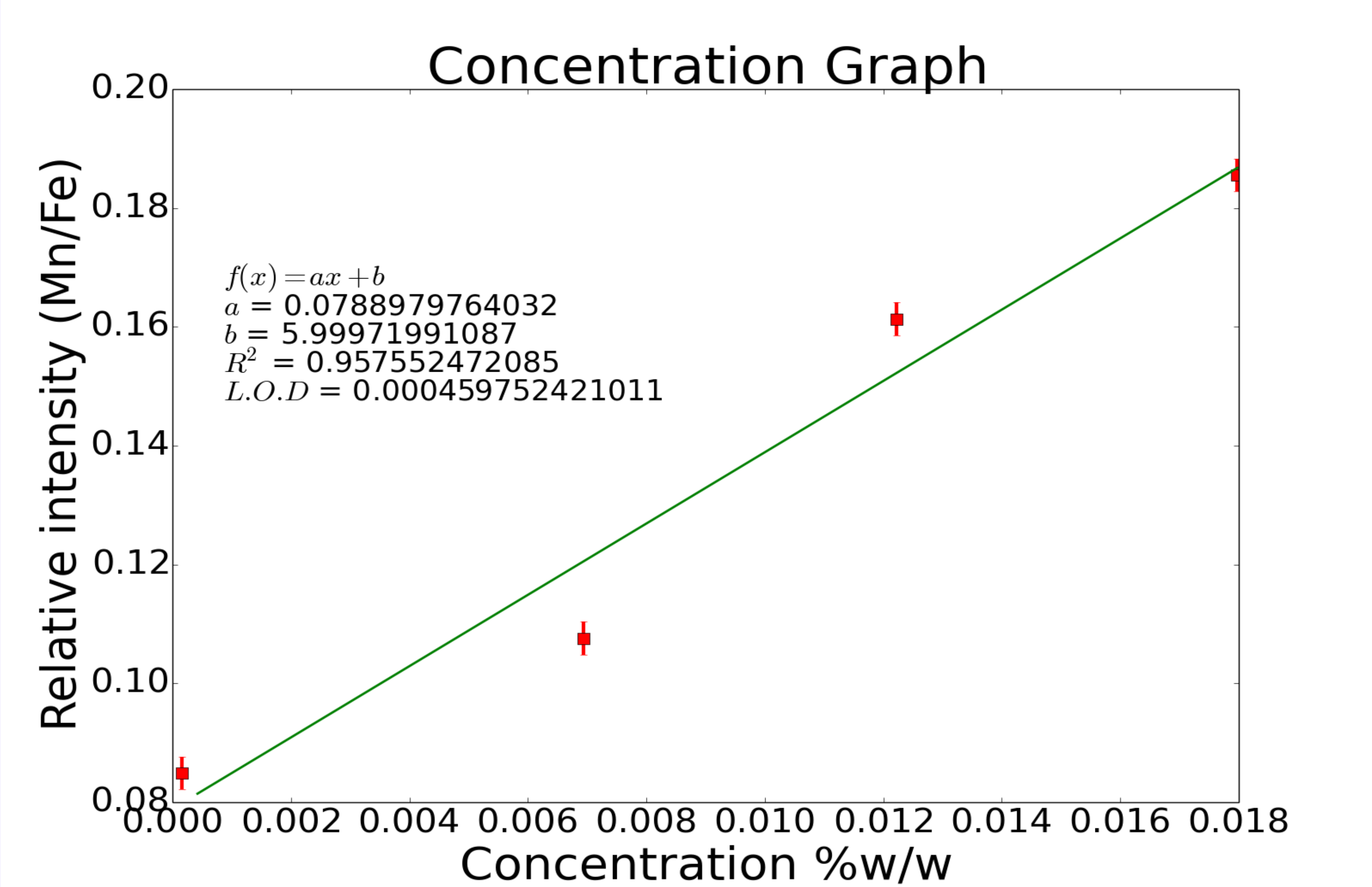
Compare two different plasma creation methods.



1. Measure four steel samples of known Mn and Fe concentration
2. Plot ratio of Mn signal to Fe signal against Mn/Fe concentration
3. Slope of concentration graph = S
4. L.O.D = 3σ / S. σ = standard deviation of the background.

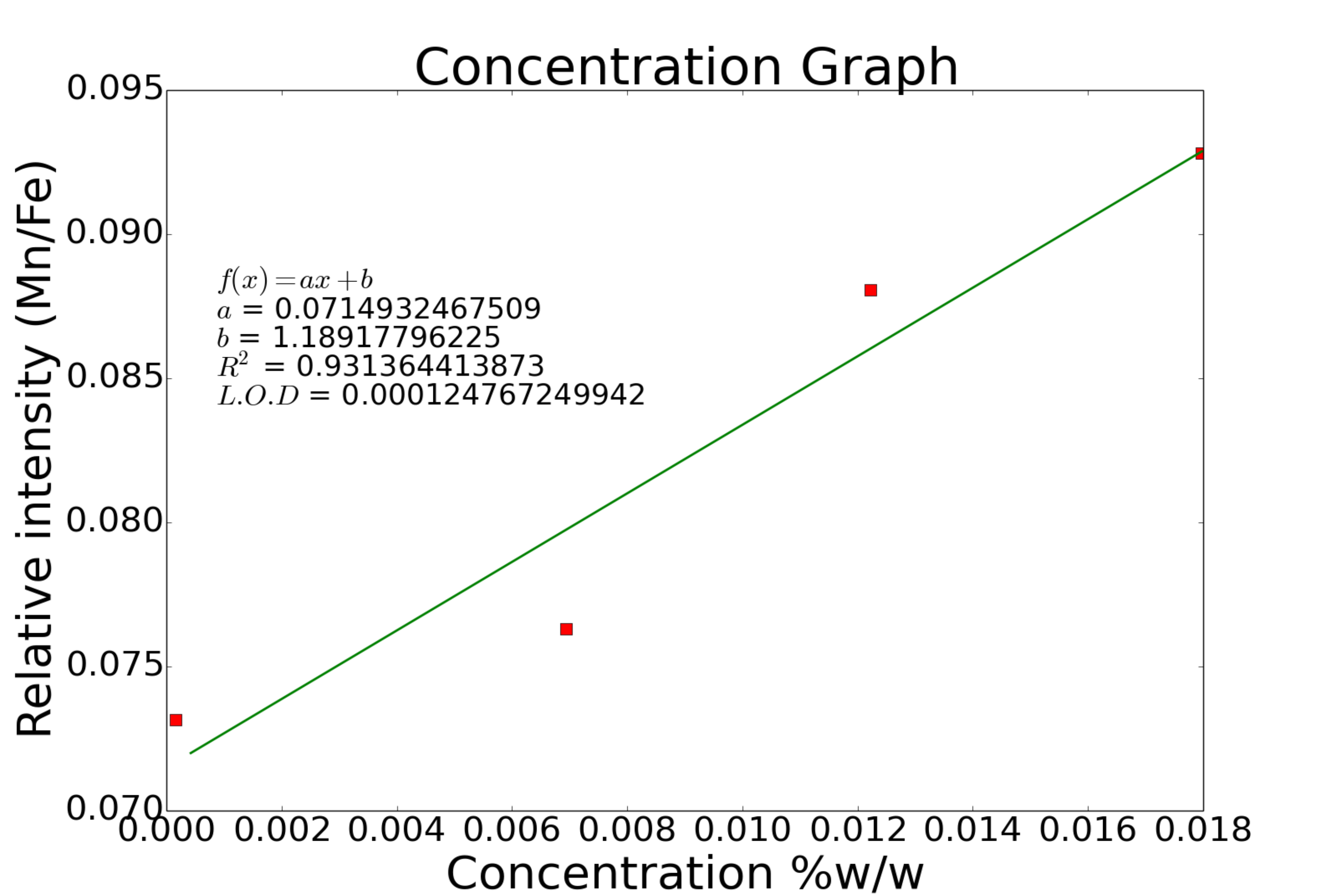
Part III. Key Properties–Potential Applications

Single Plasma LIBS - Preliminary



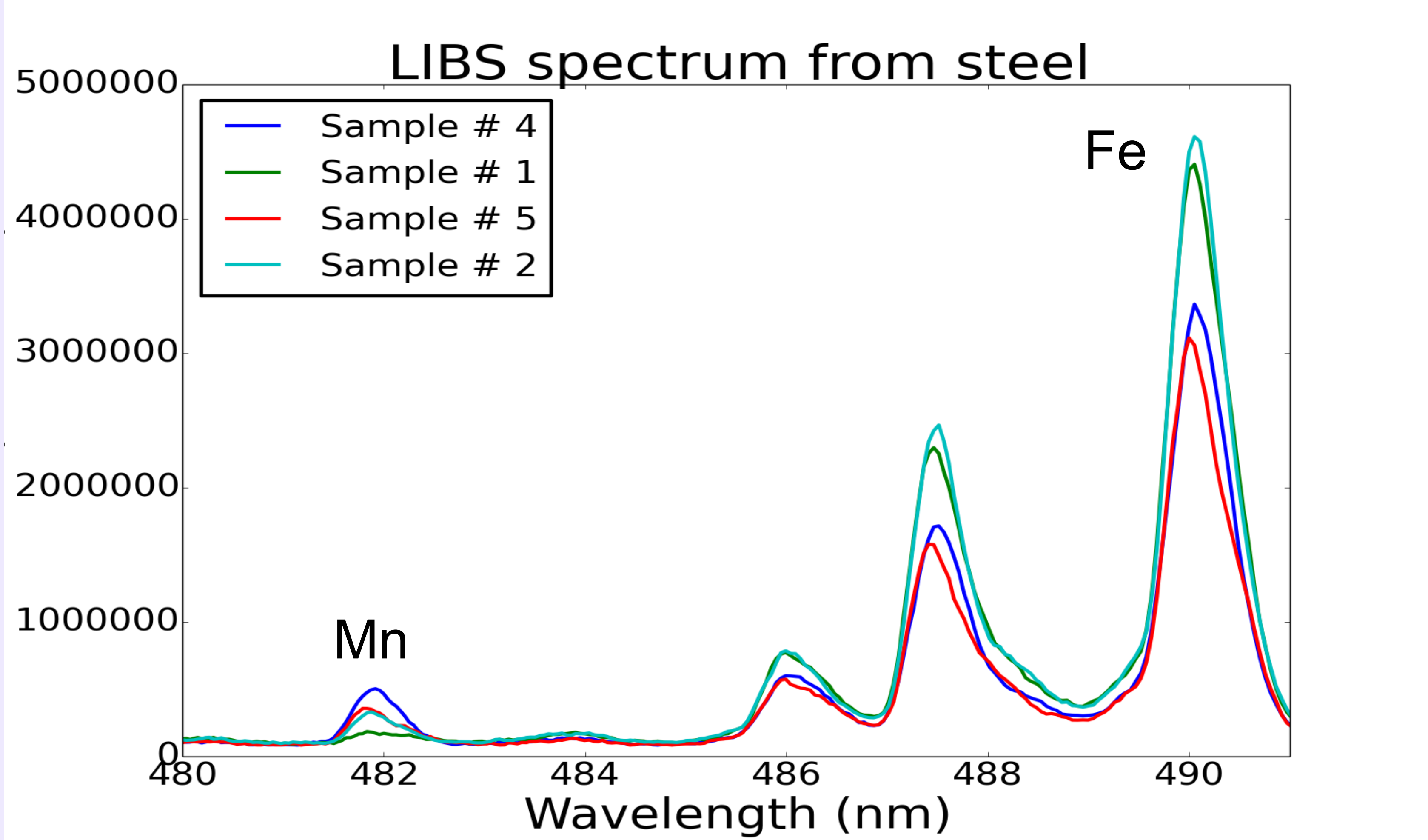
Part III. Key Properties–Potential Applications

Colliding Plasma LIBS - Preliminary



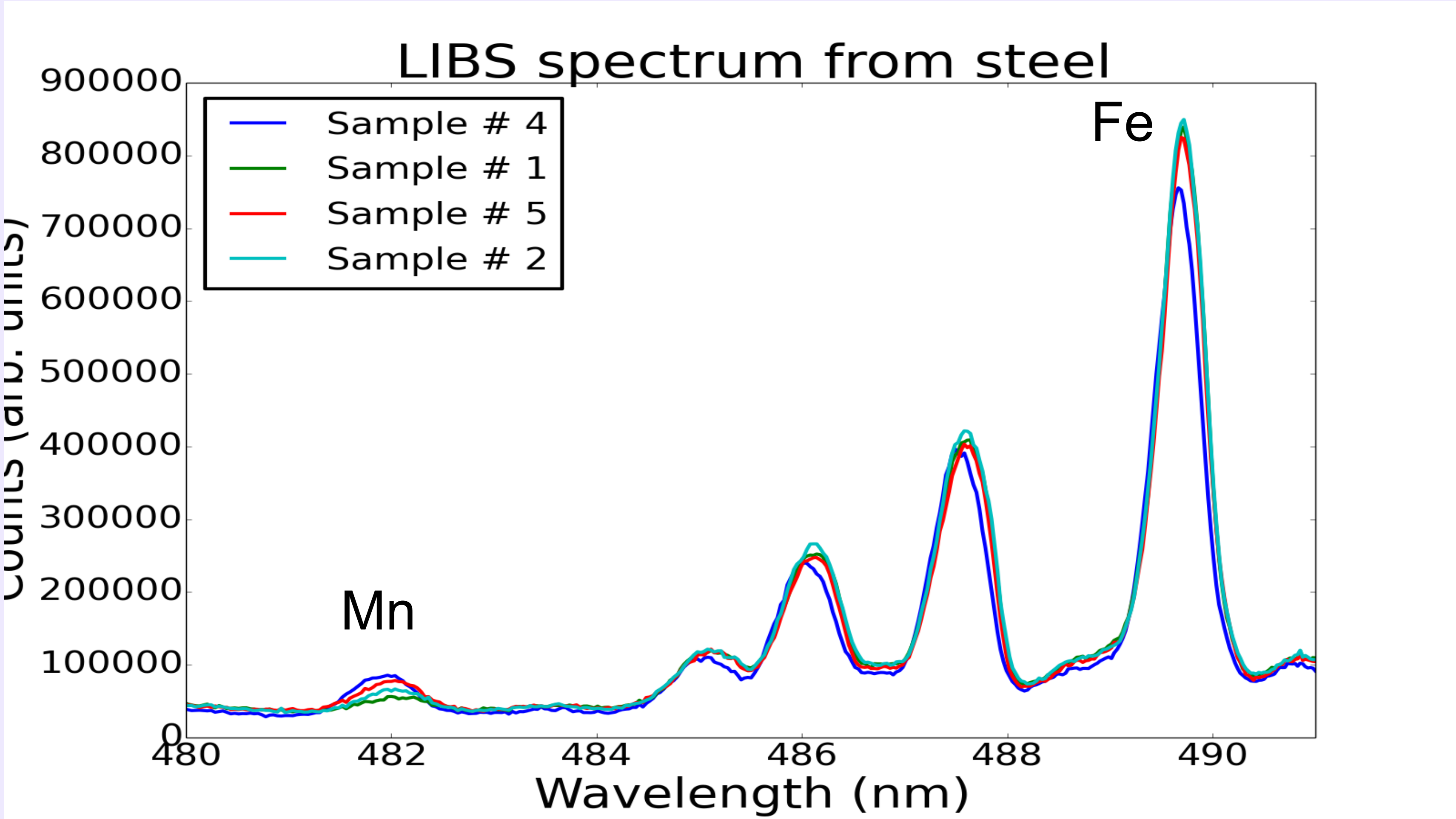
Part III. Key Properties–Potential Applications

Single plume spectra show high fluctuation (cf. Iron lines)



Part III. Key Properties–Potential Applications

Colliding plasma (stagnation layer) spectra show much reduced fluctuation (cf. Iron lines)



Part III. Key Properties–Potential Applications

Conclusions

1. Setup shows improved limit of detection (LOD) for colliding plasmas over single plume LIBS – looks promising

2. Comparison of spectra shows greater fluctuation of background signal in single plume case leads to lower LOD

Future Work

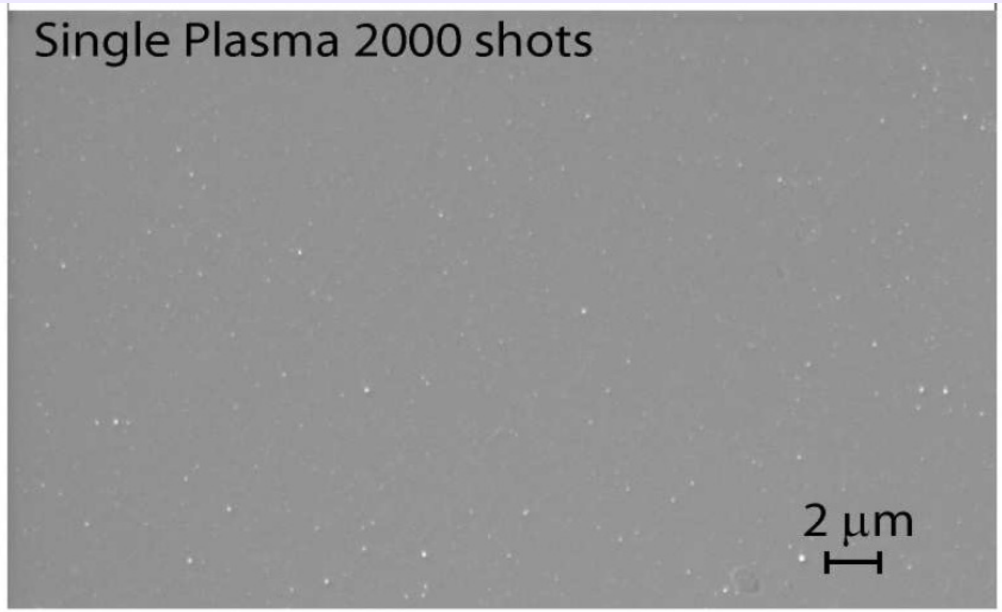
4. Better determination of signal fluctuation sources, spatial and temporal investigation of stagnation layer

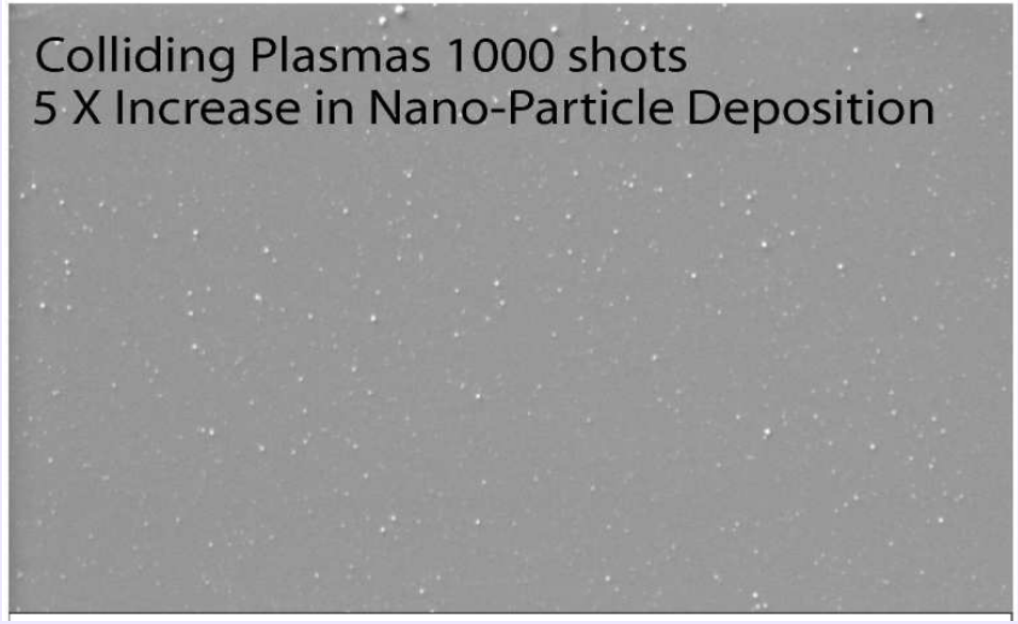
5. Extend to double pulse LIBS

Part III. Key Properties–Potential Applications

ZnO nanoparticle Deposition – ZnO target in 10 mbar O_2

SEM IMAGES



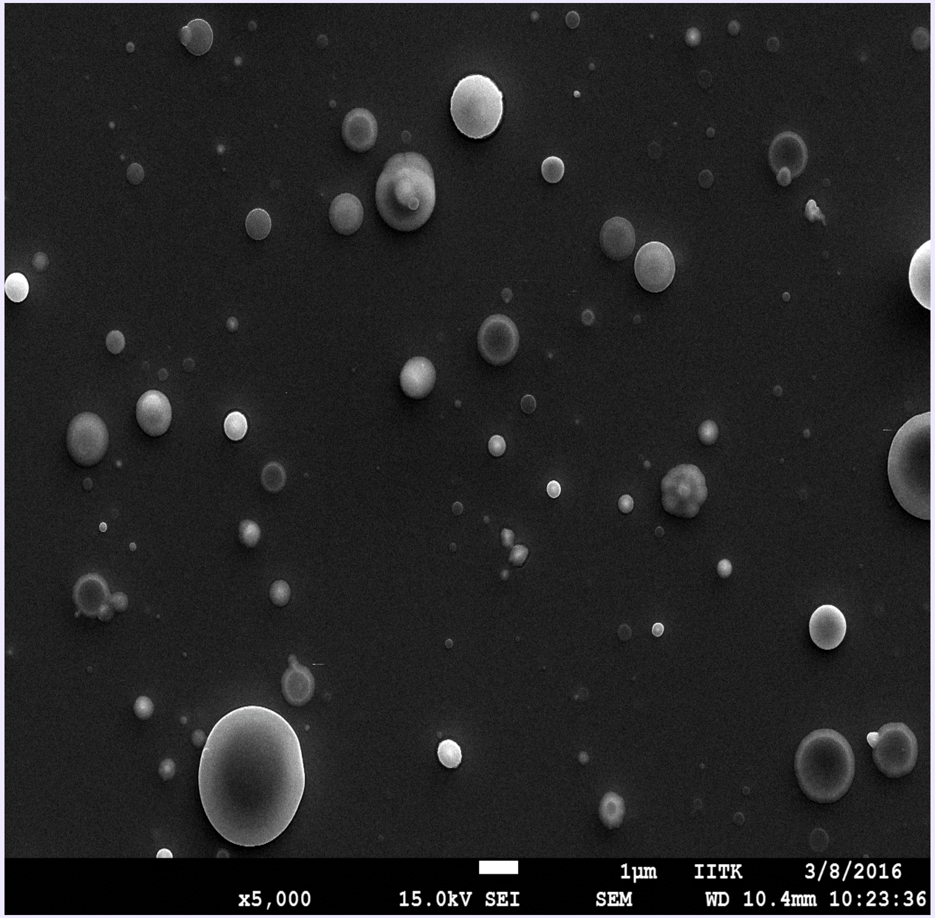


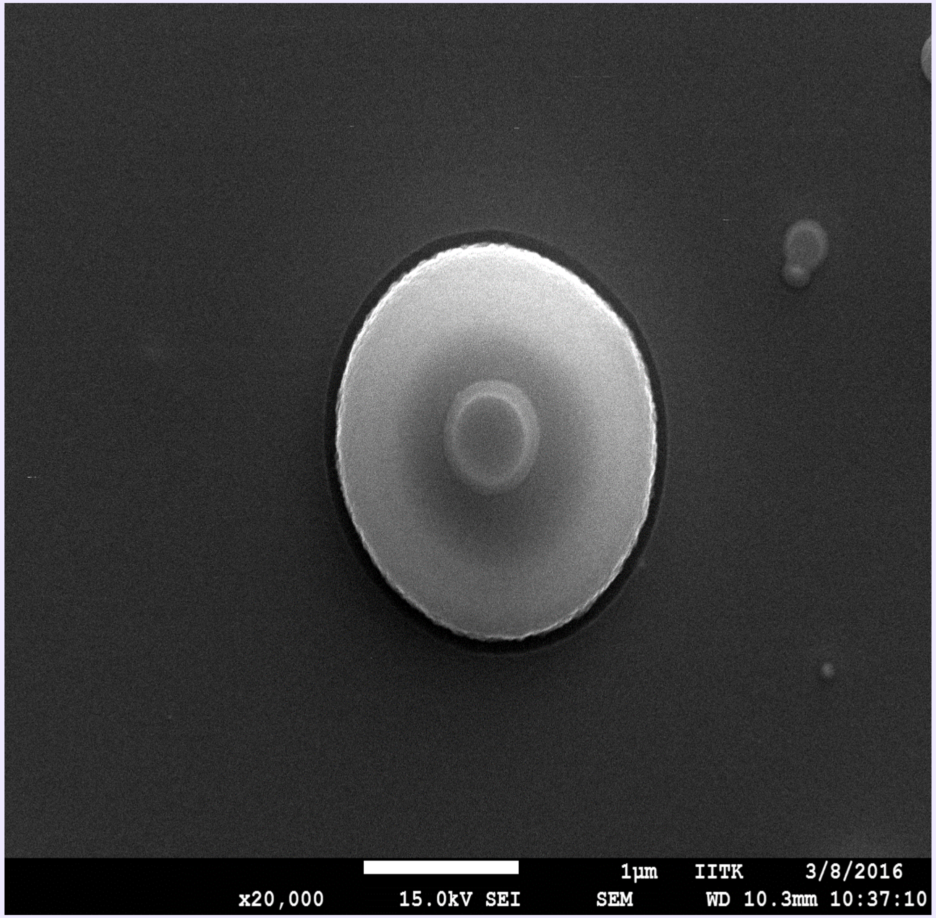
Padraig Hough – PhD thesis 2010

Cf. also Photoluminescence of nanoparticles in vapor phase of colliding plasmas
S L Gupta, and R K Thareja, J. Appl. Phys **113** 143308 (2013)

Part III. Key Properties–Potential Applications

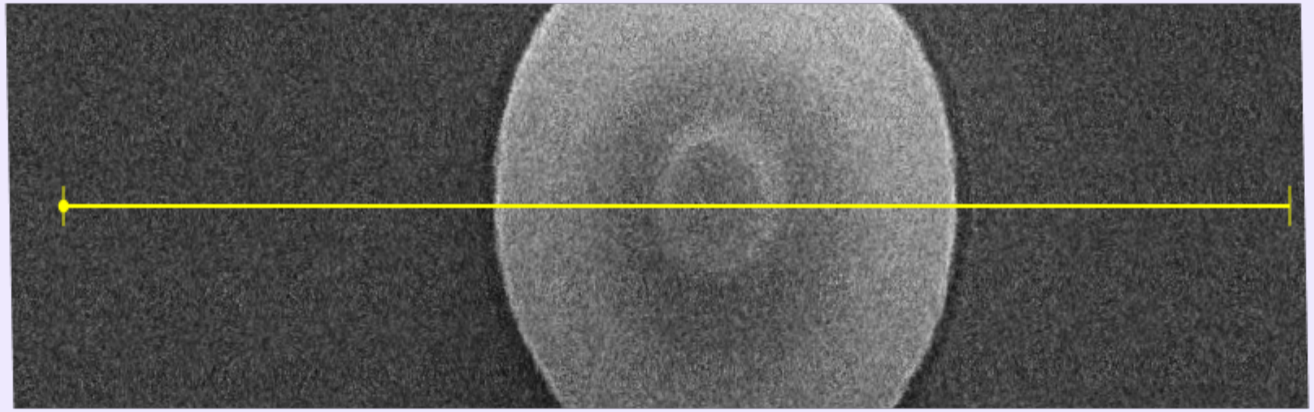
TiCu alloy formation by colliding Ti and Cu plasmas – Collaboration with IIT Kanpur – Raj Thareja

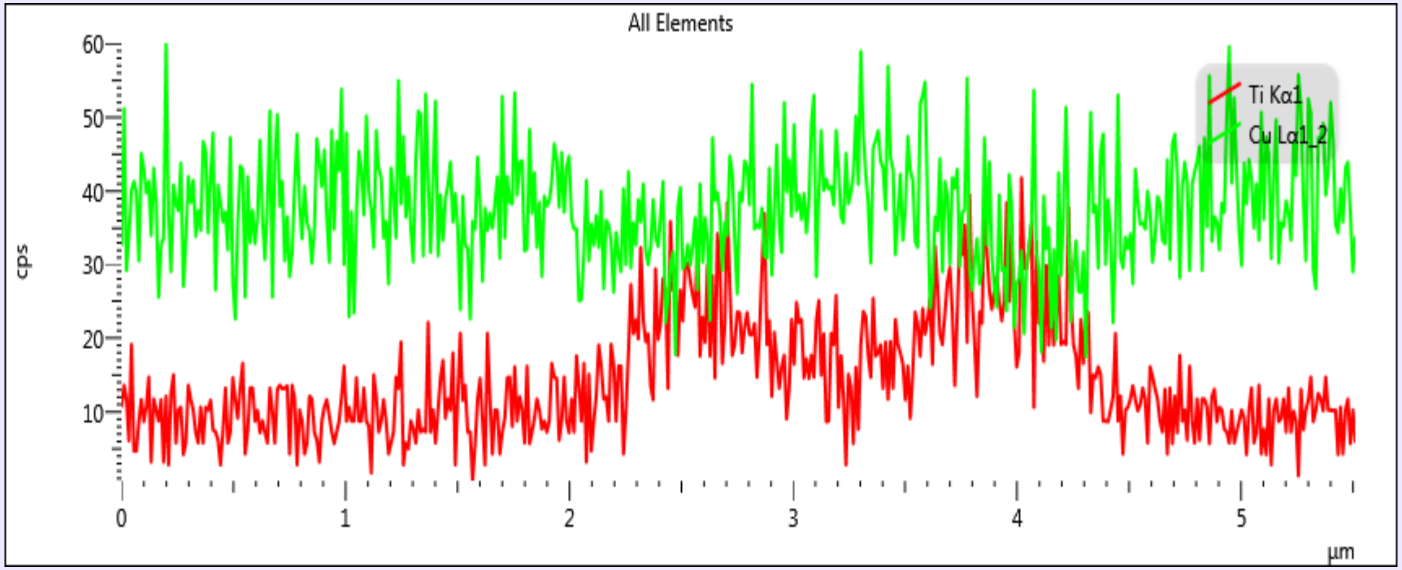




Part III. Key Properties–Potential Applications

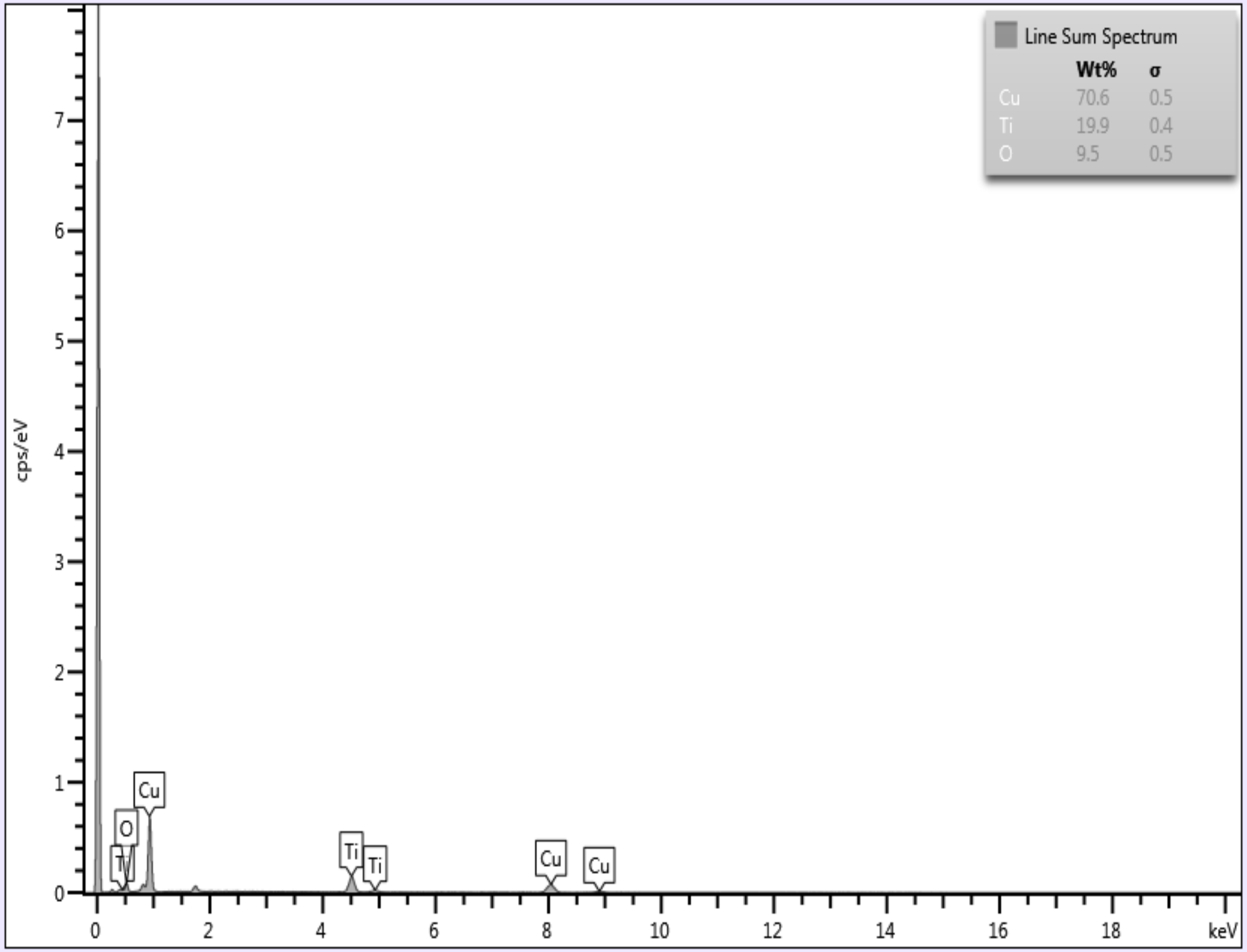
Energy dispersive X-ray analysis (EDX)





Part III. Key Properties–Potential Applications

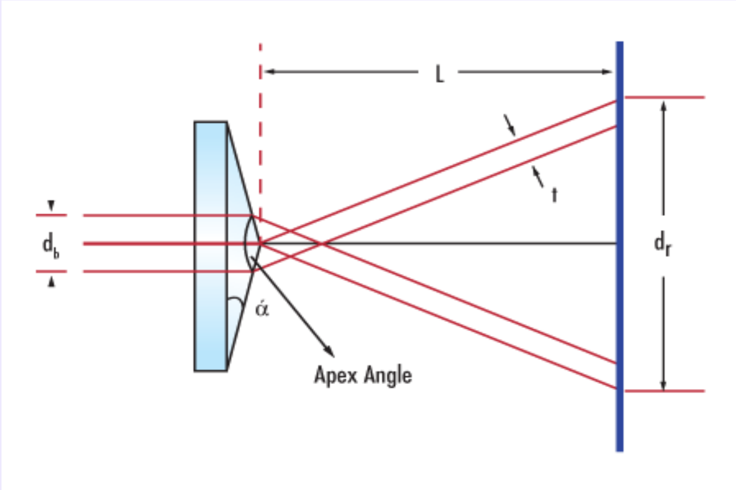
Energy dispersive X-ray analysis (EDX)



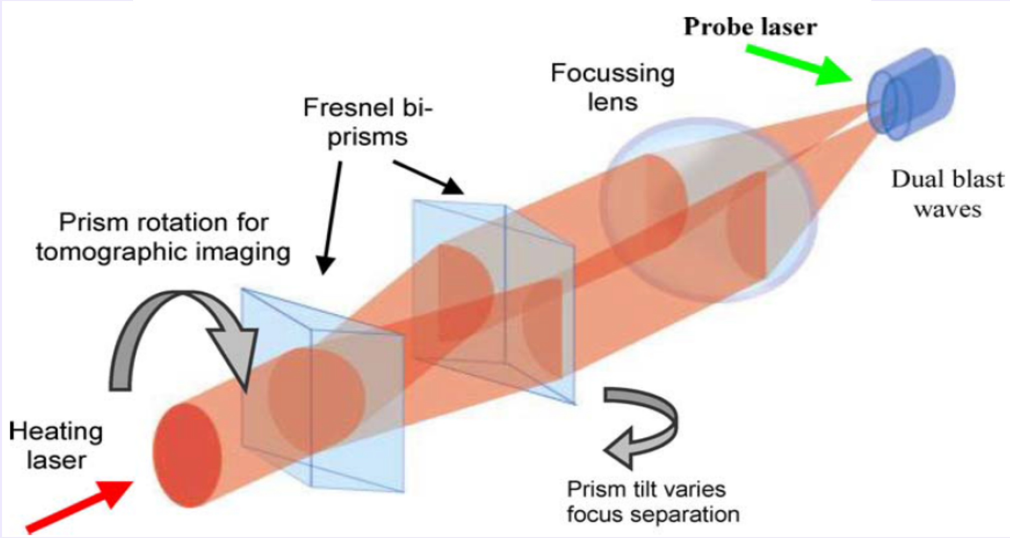
Part IV. Summary I – Next Steps

Symmetric seed plasmas….

Axicon =>
Bessel Beam + Focusing =>
Ring Plasma



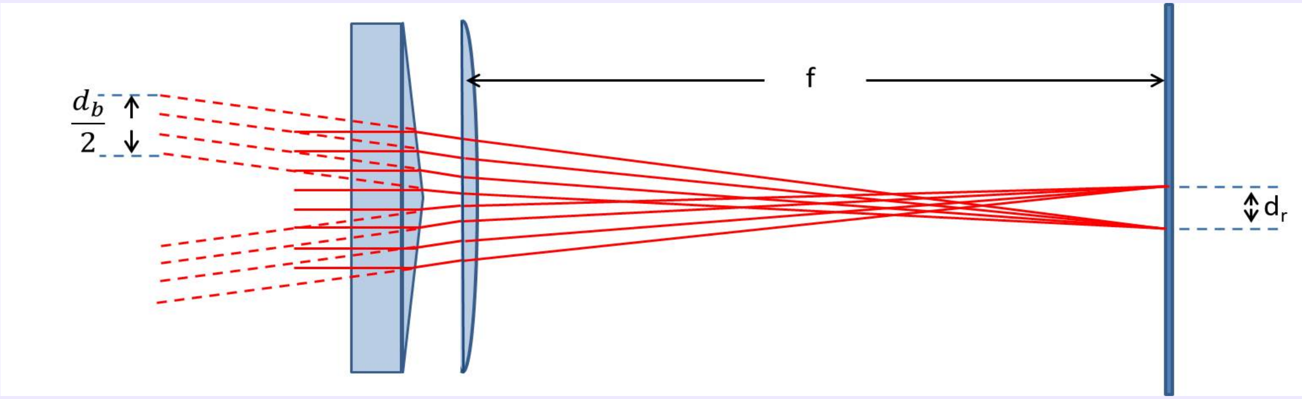
Matched Fresnel Bi-prisms
=> Symmetric Beams
+ Focusing =>
Symmetric 'Seed' Plasmas

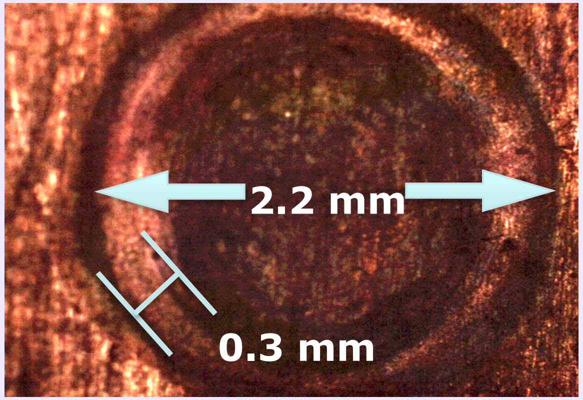


R A Smith et al., Astrophys. Space Sci. **307** pp131–137 (2007)

Part IV. Summary I – Next Steps

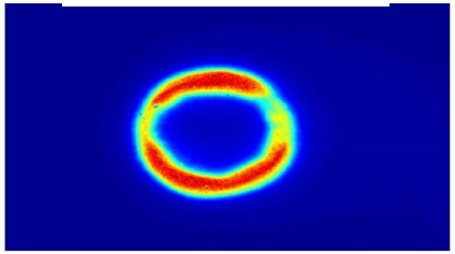
Colliding annular plasma – first images



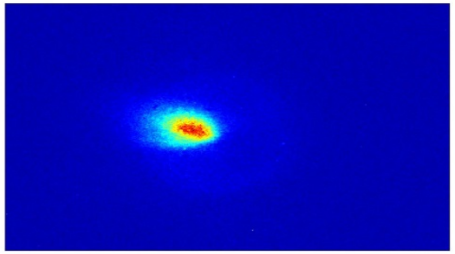


$$d_r = 2.f.Tan\{(n-1)\alpha\}$$

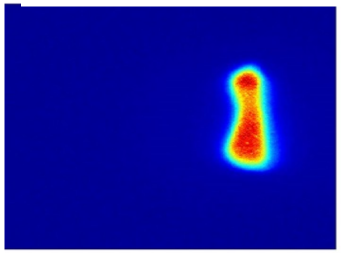
5ns Delay



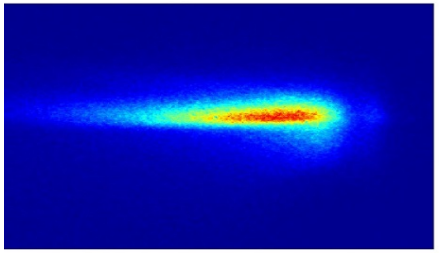
200ns Delay



5ns Delay



200ns Delay



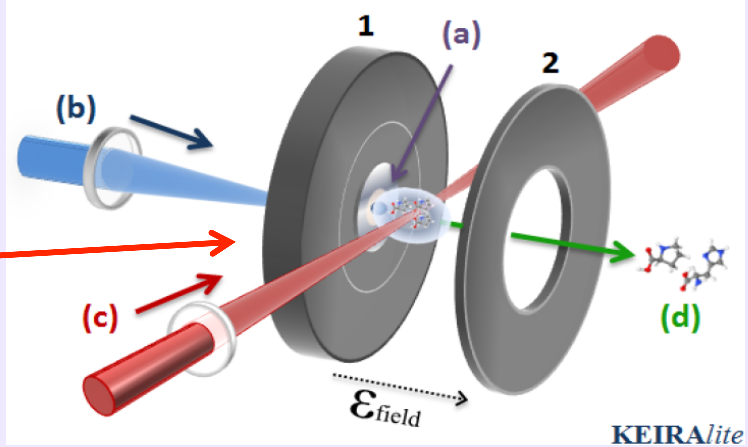
Part IV. Summary I – Next Steps

1. Analytical Sciences: Applications of Stagnation Layers in LIBS and LA-ICP-MS for LOD enhancements (NPs)

2. Bio-molecular Sciences:

Stagnation Layers as 'getters' for biomolecule aggregation in LIAD

C R Calvert, L Belshaw, M J Duffy, O Kelly, R B King, A G Smyth, T J Kelly, J T Costello, D J Timson, W A Bryan, T Kierspel, P Rice, I C E Turcu, C M Cacho, E Springate, I D Williams and J B Greenwood, Phys. Chem. Chem. Phys. **14**, 6289–6297 (2012)



3. EUV Lithography: Stagnation Layers as self suspended targets, preheated targets (reduced opacity, ion energy narrowing, debris, etc.)

4. XUV/X-ray sources:

Applications of Stagnation Layers in double pulse experiments (especially opacity reduction in high-Z materials to enhance spectral line emission)

P K Carroll et al., Opt. Letts. **2**, 72 (1978)

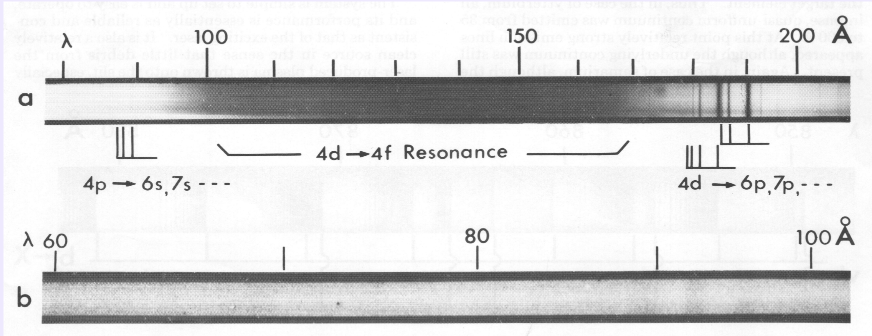


Fig. 1. (a) Absorption spectrum of xenon from 80 to 200 Å. The xenon pressure in the spectrograph was 0.05 Torr, and the number of laser pulses used was 30. For details of the xenon spectrum in this region see Madden and Codling.[5] The unmarked weak lines near 200 Å are due to 0 v. Oxygen present in the target gives rise to some emission lines as well. (b) The ytterbium continuum from 60 to 100 Å. The number of laser shots was 20. As in (a), the spectrum was obtained on a Kodak SC5 plate.

Financial Support to DCU Group

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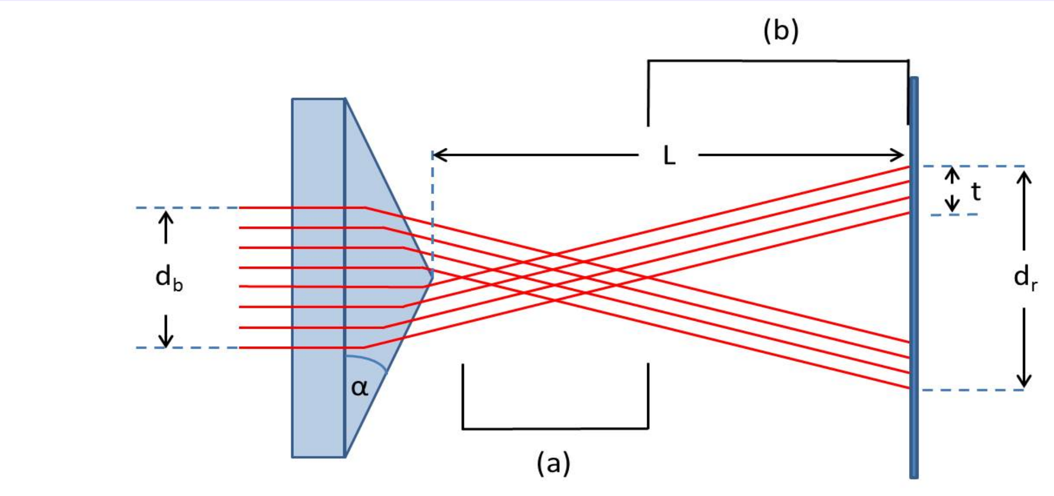
Irish Research Council (PhD Scholarships / Postdoctoral Fellowships)

EU FP7 Erasmus Mundus Joint Doctorate 'EXTATIC' – EUV and X-ray Technology and Training for Interdisciplinary Cooperation – Grant No. FPA 0033-2012

Extra Slides

Extra Slides

Axicon........



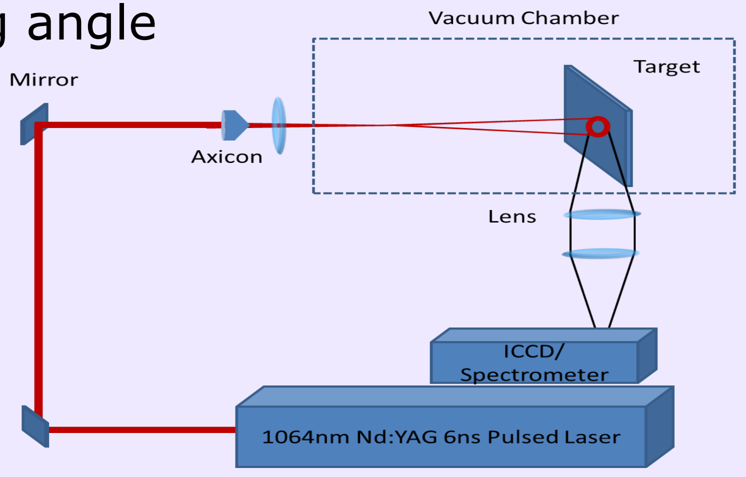
$$DOF = R/\{(n-1)\alpha\}$$

$$t = d_b/2$$

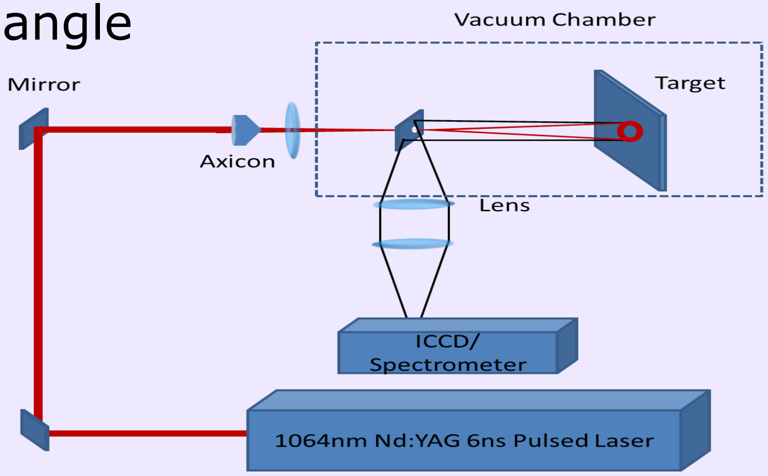
$$d_r = 2.L.Tan\{(n-1)\alpha\}$$

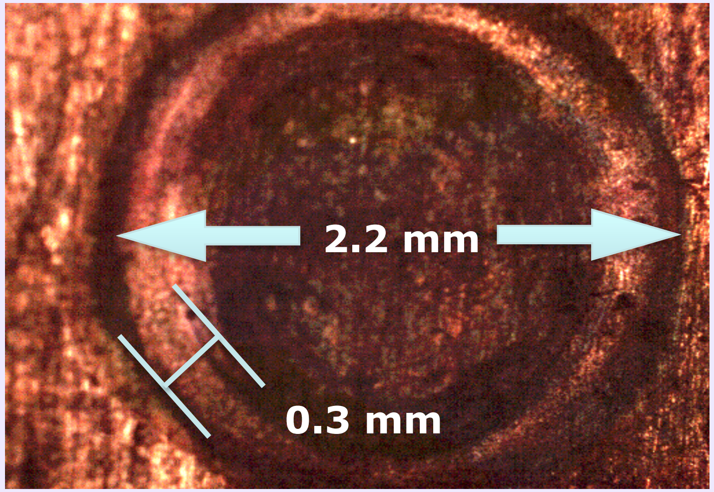
Extra Slides

90° viewing angle



0° viewing angle



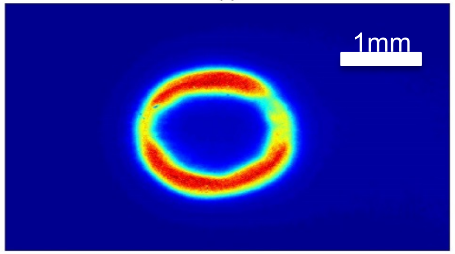


- Area of annulus: 0.07 cm^2
- Power Density: 0.29 GW/cm^2

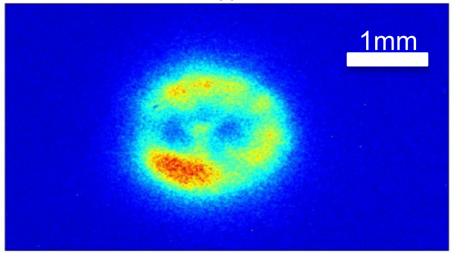
Extra Slides

- 5ns gate width, 0° viewing angle imaging.

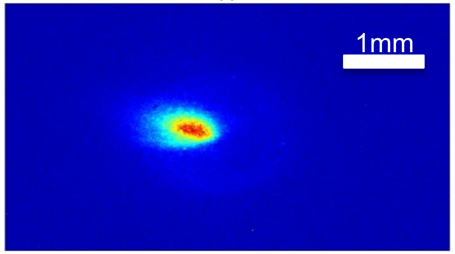
5ns Delay



75ns Delay

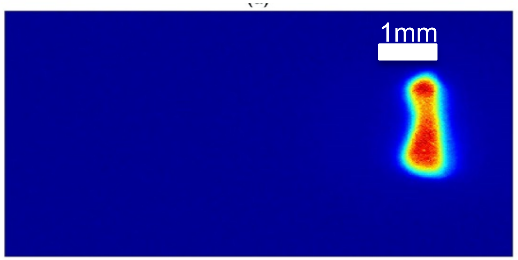


200ns Delay

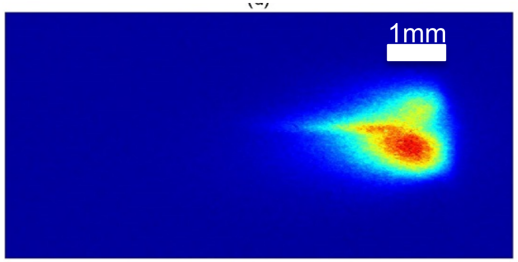


- 5ns gate width, 90° viewing angle imaging.

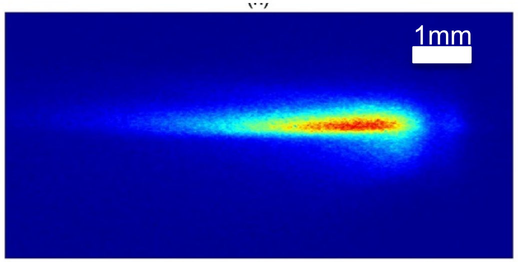
5ns Delay



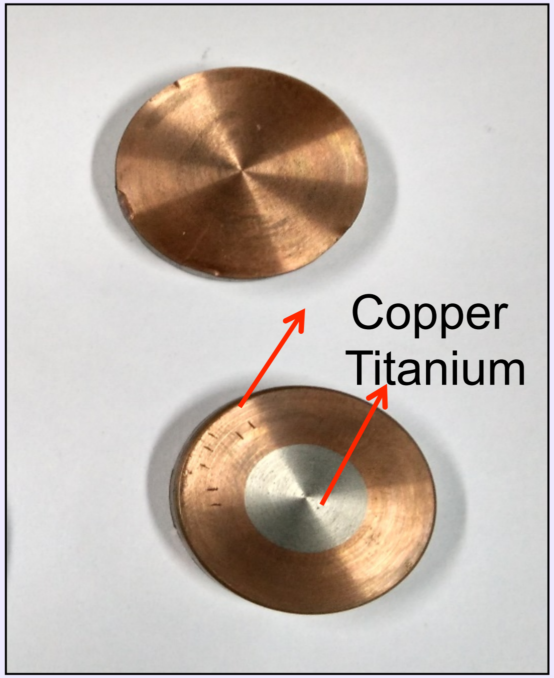
75ns Delay



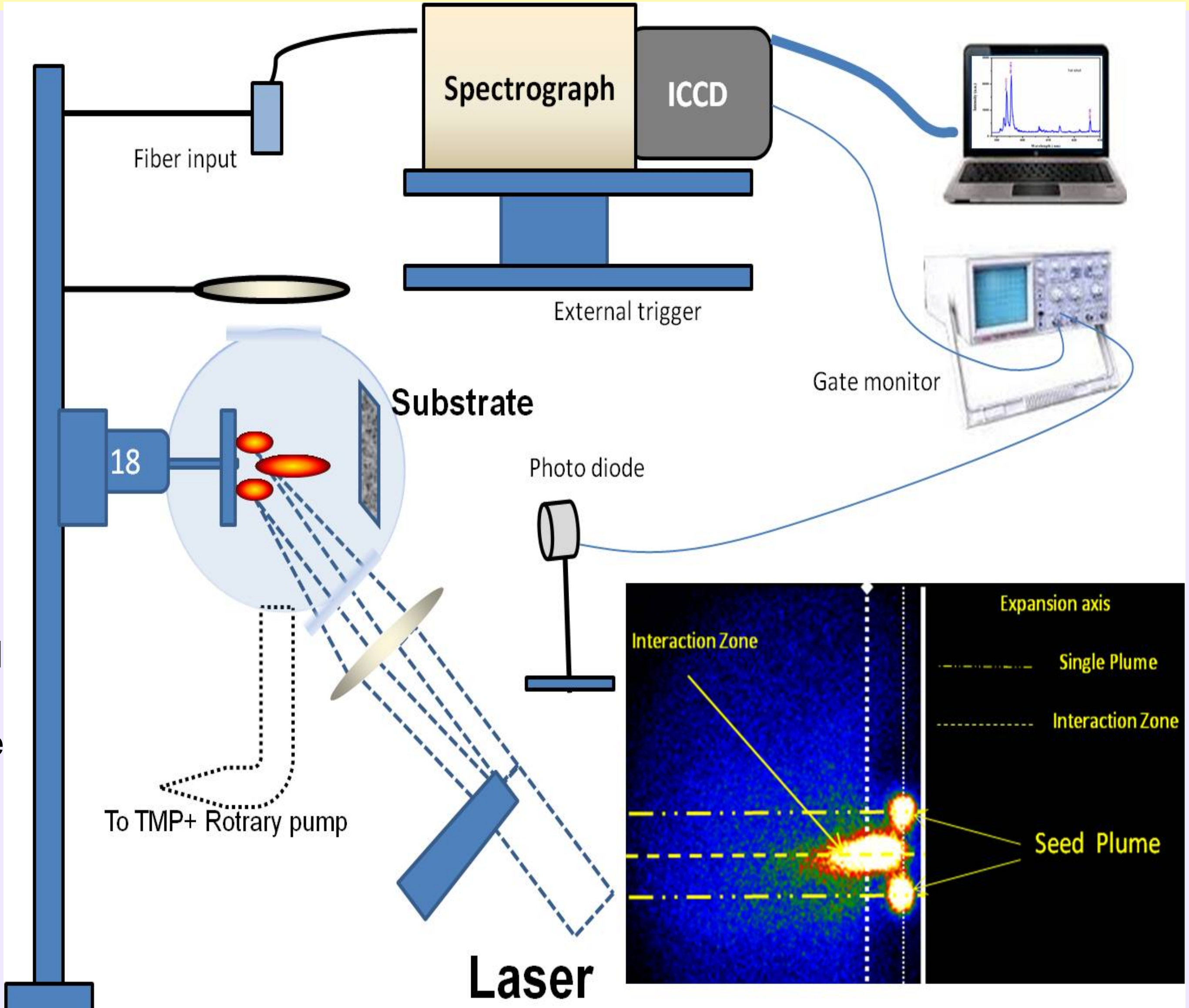
200ns Delay



Extra Slides

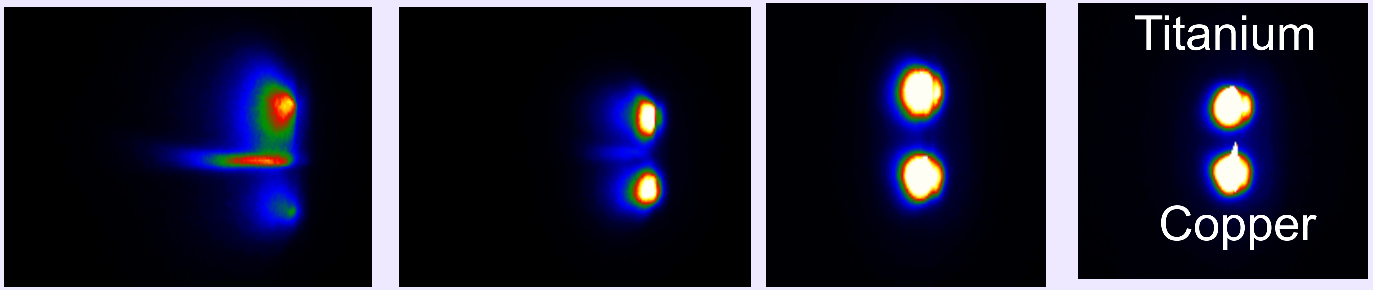


1. Distance between target and substrate= 4 cm
2. Laser energy = 50 mJ /Pulse for each splitted beam
3. Focal spot size = 300 micron.
4. Beam incident at target surface at 45 degree.

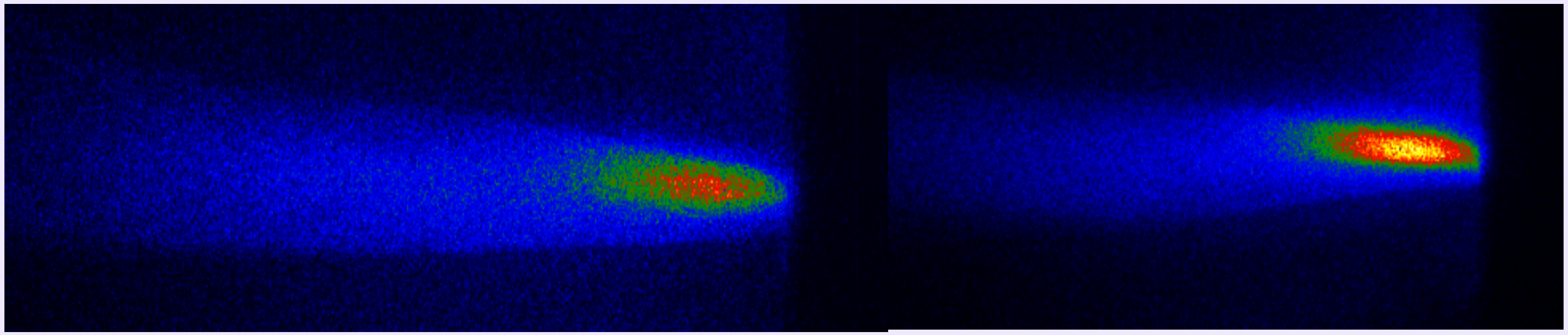


Extra Slides

Plume dynamics of the Cu-Ti colliding plasmas



100 ns 50 ns 20 ns 10 ns



500 ns 400 ns

Extra Slides

1mm

Extra Slides

1mm

Extra Slides

1mm