The collision front for point and annular colliding plasmas - a new target for XFEL probes ?

John T. Costello

National Centre for Plasma Science & Technology (NCPST)/
School of Physical Sciences, Dublin City University

www.physics.dcu.ie/~jtc

Scientific opportunities of free-electron lasers — Visions for X-ray physics in the 21st century. IAS-TUM. September 2016

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

John T. Costello

National Centre for Plasma Science & Technology (NCPST)/
School of Physical Sciences, Dublin City University

www.physics.dcu.ie/~jtc

TUM-IAS, Munich 12th September 2016

Outline of the Talk

1. Dublin and laser based ‘X-rays’
2. Colliding Point Plasmas – Fundamentals
3. Colliding Annular Plasmas
4. Key properties – potential applications
5. Next Steps

First X-ray Shadowgram - Ireland

Brother Potamian CYReilly: Irish Scientist and X-ray Pioneer

J. P. MURRAY
Department of Radiology
University College, Galway

"It is doubtful if any scientific discovery has excited such an immediate and widespread interest as **Roentgen's discovery of X-rays in November 1895**. Within days of his communication, "On a new form of Radiation" to the Wurzburg Medico- Physical Society on the 28th December, 1895, ...appropriate apparatus to generate and record x-rays, though primitive by today's standards, was already widely available in physics laboratories, even in schools such as De La Salle College in Waterford.

It is generally accepted that **the first recorded clinical x-ray photograph in Ireland, of a girl's hand, was produced by Professor Barratt and Mr. Jefcote at the Royal College of Science (now Government Buildings) on 16th March, 1896,** at the request of Richard Bolton McCausland, surgeon to Dr. Steevens' Hospital,......"

Figure 1: X-Ray taken by Brother Potamian in Waterford on 13th April, 1896, showing needle-like F.B. between heads of middle and ring finger metacarpals [1].

1. Brother Potamian O'Reilly. "The Coming of Age of the X-Ray". The Catholic World, 104, 78-82, New York, Oct. 1916.

Part 1. Laser based 'X-rays' in Dublin

1970s

1980s

1990s + NBS (NIST)

72 OPTICS LETTERS / Vol. 2, No. 3 / March 1978

New continua for absorption spectroscopy from 40 to 2000 Å

P. K. Carroll, E. T. Kennedy, and G. O'Sullivan

Physics Department, University College, Dublin, Ireland

Received November 7, 1977

VOLUME 57, NUMBER 13 PHYSICAL REVIEW LETTERS 29 SEPTEMBER 1986

Giant-Dipole-Resonance Absorption in Atomic Thorium by a Novel Two-Laser Technique

P. K. Carroll

Physics Department, University College Dublin, Dublin 4, Ireland

and

J. T. Costello

National Institute for Higher Education, Glasnevin, Dublin 9, Ireland

(Received 18 June 1986)

PHYSICAL REVIEW A VOLUME 43, NUMBER 3 1 FEBRUARY 1991

3*p* photoabsorption of free and bound Cr, Cr^+, Mn, and Mn^+

J. T. Costello and E. T. Kennedy

Dublin City University, Glasnevin, Dublin 9, Ireland

B. F. Sonntag

II Institute für Experimentalphysik, Universität Hamburg, Hamburg, West Germany

C. W. Clark

National Institute of Standards and Technology, Gaithersburg, Maryland 20899

(Received 16 July 1990)

Paddy Goes to Hamburg…..

Synchrotron – BW3….

1990s

J. Phys. B: At. Mol. Opt. Phys. 28 (1995) L161–L168. Printed in the UK

LETTER TO THE EDITOR

High-resolution photoion yield measurements of 'hollow' atomic lithium

L M Kiernan†, M-K Lee‡, B F Sonntag‡, P Sladeczek§, P Zimmermann§, E T Kennedy‖, J-P Mosnier‖ and J T Costello‖

2000s

EU RTD Project: HRPI-CT-1999-50009
Title: "X-Ray FEL Pump Probe Facility"
Partners: DESY, DCU, Lund, MBI, Orsay & BESSY

1750 OPTICS LETTERS / Vol. 31, No. 11 / June 1, 2006

Spectroscopic characterization of vacuum ultraviolet free electron laser pulses

S. Düsterer, P. Radcliffe, G. Geloni, U. Jastrow, M. Kuhlmann, E. Plönjes, K. Tiedtke, R. Treusch, and J. Feldhaus

Hamburger Synchrotronstrahlungslabor (HASYLAB) at Deutsches Elektronen-Synchrotron (DESY) Notkestrasse 85, D-22603 Hamburg, Germany

P. Nicolosi and L. Poletto

INFM-LUXOR, Department of Information Engineering, University of Padova, Via Gradenigo 6/A, 35131 Padova, Italy

P. Yeates, H. Luna, and J. T. Costello

National Center for Plasma Science and Technology and School of Physical Sciences, Dublin City University, Dublin, Ireland

P. Orr

International Research Centre for Experimental Physics, Queen's University Belfast, BT7 1NN, UK

D. Cubaynes and M. Meyer

LIXAM/CNRS, Centre Universitaire Paris-Sud, Bâtiment 350, F-91405 Orsay Cedex, France

2006 –
1st FEL paper from the DESY collaboration

Paddy Goes on Tour

2012 - FLASH
Cavalieri

ARTICLES

PUBLISHED ONLINE: 18 NOVEMBER 2012 | DOI: 10.1038/NPHOTON.2012.276

nature photonics

Ultrafast X-ray pulse characterization at free-electron lasers

I. Grguraš[1†], A. R. Maier[2,3†], C. Behrens[4†], T. Mazza[5], T. J. Kelly[6], P. Radcliffe[5], S. Düsterer[4], A. K. Kazansky[7,8,9], N. M. Kabachnik[5,9,10], Th. Tschentscher[5], J. T. Costello[6], M. Meyer[5], M. C. Hoffmann[1,11], H. Schlarb[4] and A. L. Cavalieri[1]*

2014 - LCLS
Kienberger

nature photonics

ARTICLES

PUBLISHED ONLINE: 24 NOVEMBER 2014 | DOI: 10.1038/NPHOTON.2014.278

Measuring the temporal structure of few-femtosecond free-electron laser X-ray pulses directly in the time domain

W. Helml[1,2†], A. R. Maier[3,4†], W. Schweinberger[2], I. Grguraš[3,5], P. Radcliffe[6], G. Doumy[7,8], C. Roedig[8], J. Gagnon[2], M. Messerschmidt[9], S. Schorb[9], C. Bostedt[9], F. Grüner[3,4], L. F. DiMauro[8], D. Cubaynes[10], J. D. Bozek[9], Th. Tschentscher[6], J. T. Costello[11], M. Meyer[6,10], R. Coffee[9], S. Düsterer[12], A. L. Cavalieri[3,5] and R. Kienberger[1,2]*

2015 – FERMI
Meyer

Received 6 Dec 2014 | Accepted 2 Mar 2015 | Published 9 Apr 2015 DOI: 10.1038/ncomms7799 OPEN

Sensitivity of nonlinear photoionization to resonance substructure in collective excitation

T. Mazza[1,*], A. Karamatskou[2,3,*], M. Ilchen[1,4], S. Bakhtiarzadeh[1,3], A.J. Rafipoor[1,3], P. O'Keeffe[5], T.J. Kelly[6], N. Walsh[6], J.T. Costello[6], M. Meyer[1] & R. Santra[2,3]

DCU Laser Plasma/Atomic Physics

Laser Plasma @ NCPST - 6 laboratory areas focussed on pulsed laser matter interactions (spectroscopy/ imaging). Off-site collaborations on Synchrotrons and FELs

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), Synchrotron (G3) and Free Electron Laser (XFEL) Light Sources

DCU Laser Plasma-AMO Physics Group

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

Principal Investigators (5): John T. Costello, Eugene T. Kennedy (Emeritus), Lampros Nikolopoulos (T), Jean-Paul Mosnier

Current Research Staff (2): Dr. Pramod Pandey Paddy Hayden (SFI SIRG PI)

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

Recent (ex-DCU) Interns (2012-15): 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), P. Colley (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 & Nicky Walsh

Recent Past Postdocs (2012-2016): Satheesh Krishnamurthy (Open Univ. UK), Pat Yeates (Elekta Oncology UK) & Subhash Singh (U. Allahabad), Colm Fallon (IC4), Mossy Kelly (Hull Univ., UK).

Current focus on ‘D’ in WDM/HDM....

	Experiment	Description
WDM	Warm Dense Matter Creation	Using the XFEL to uniformly warm solid density samples
WDM	Equation of State	Heat / probe a solid with an XFEL to provide material properties
WDM	Absorption Spectroscopy	Heat a solid with an optical laser or XFEL and use XFEL to probe
WDM	High Pressure Phenomena	Create high pressures using high-energy laser, probe with the XFEL
WDM	Surface Studies	Probe ablation/damage processes
HDM	XFEL / Gas Interaction	Create exotic, long-lived highly-perturbed electron distribution in dense plasmas
HDM	XFEL / Solid Interaction	Directly creates extreme states of matter
HDM	Plasma Spectroscopy	XFEL pump/probe for atomic state
	Diagnostic Development	Thomson scattering, SAXS, interferometry, radiography, phase-contrast imaging

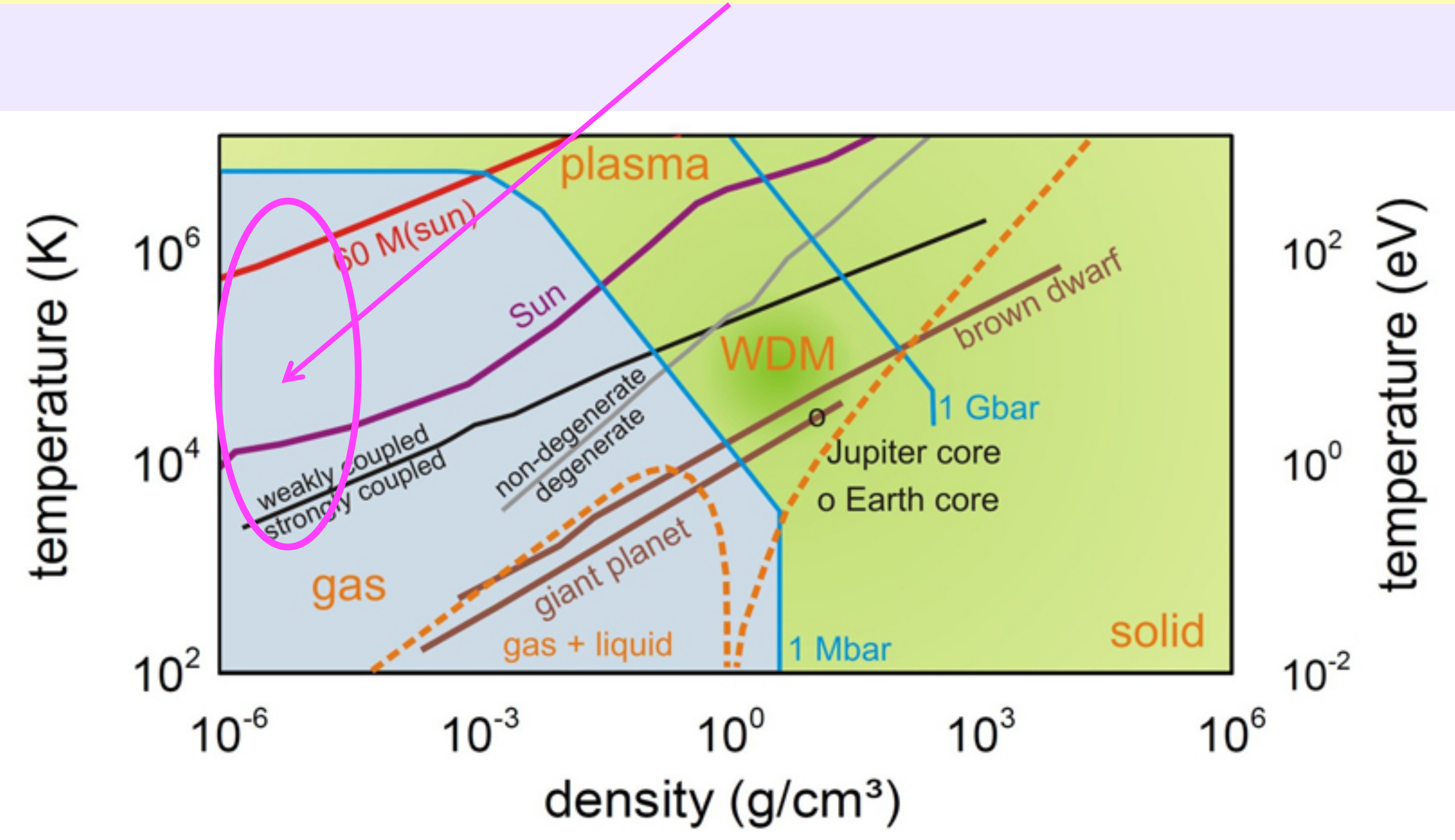
Dense plasmas are strongly coupled and so atomic & molecular species cannot be considered isolated…..

Expanding and colliding plasmas plumes from table top ns laser can cover the weakly to strongly coupled regime..

In the former species are available for AMO studies…..

Source: XFEL Talk by R W Lee

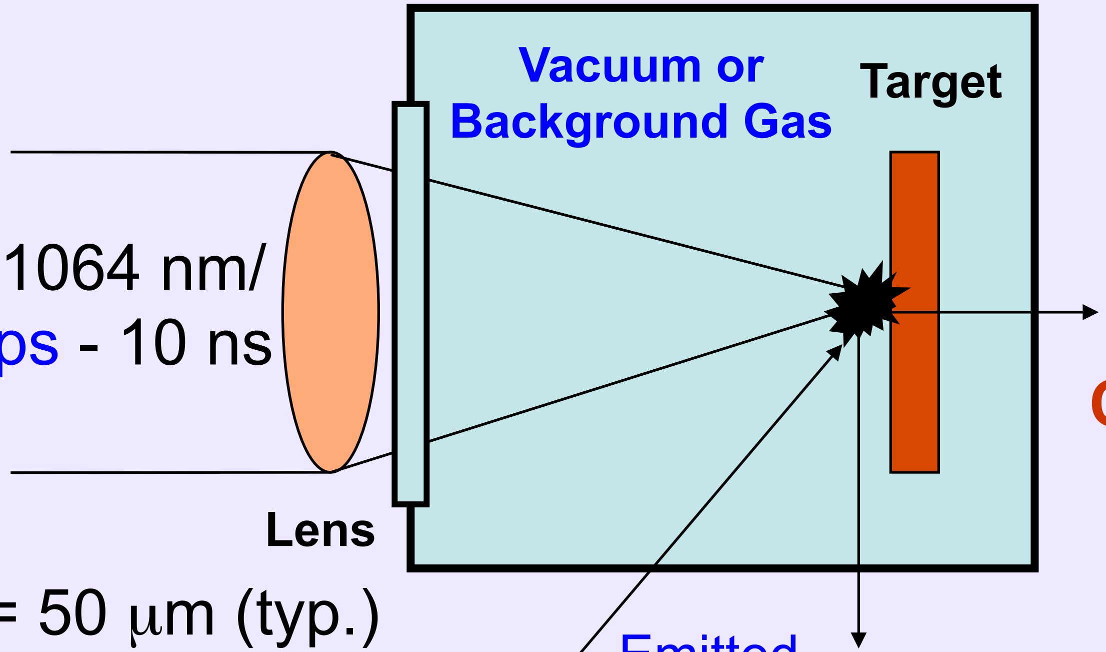
Where table top plasmas reside….



Source: XFEL HED Webpage…

Part II – Table-Top Colliding Plasmas

Laser Pulse 1064 nm/
0.01 - 1 J/ 5ps - 10 ns



Plasma Assisted Chemistry

Spot Size = 50 μm (typ.)

Φ: 10^{11} - 10^{14} $W.cm^{-2}$

T_e : 10 - 1000 eV

N_e: 10^{21} cm^{-3}

$V_{expansion} \geq 10^6$ $cm.s^{-1}$

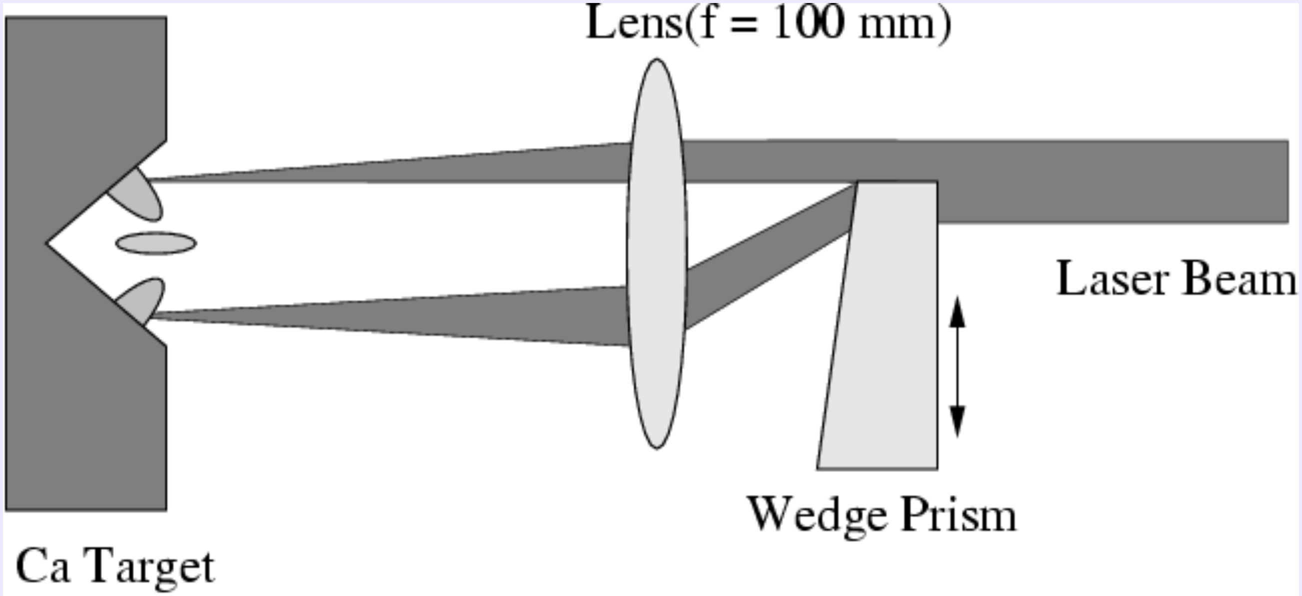
Emitted -

- Atoms
- Ions
- Electrons
- Clusters
- IR - X-ray Radiation

Part II – Table-Top Colliding Plasmas

Typical Colliding Plasma Setup

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



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 II – Table-Top Colliding Plasmas

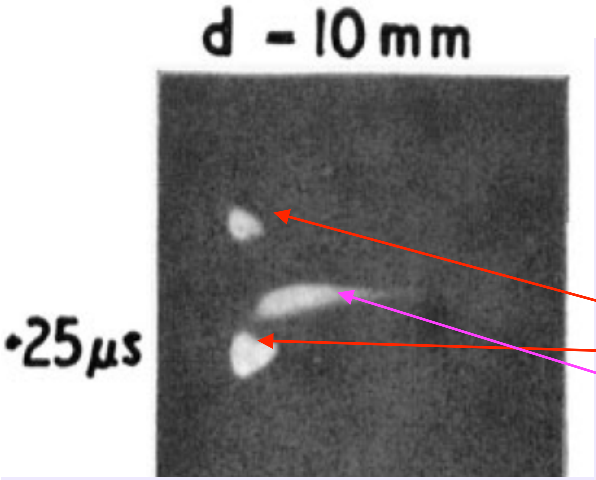
Not a new idea !

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)



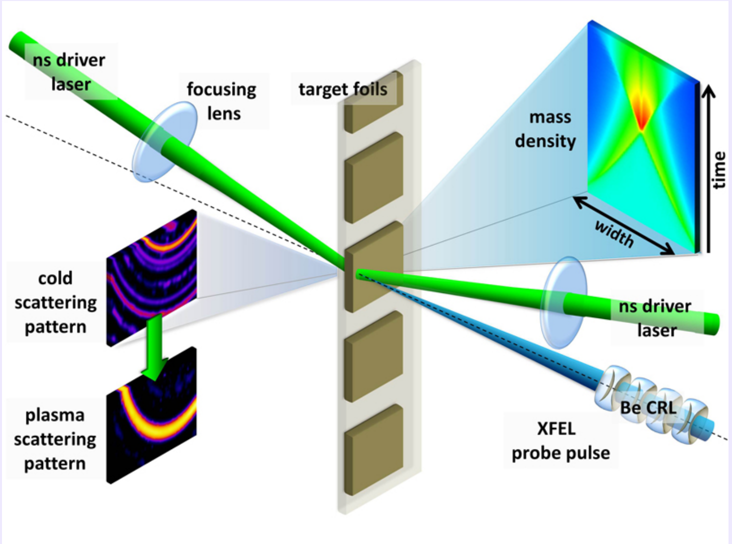
‘Seed’ Plasmas

‘Stagnation Layer’

Part II – Table-Top Colliding Plasmas

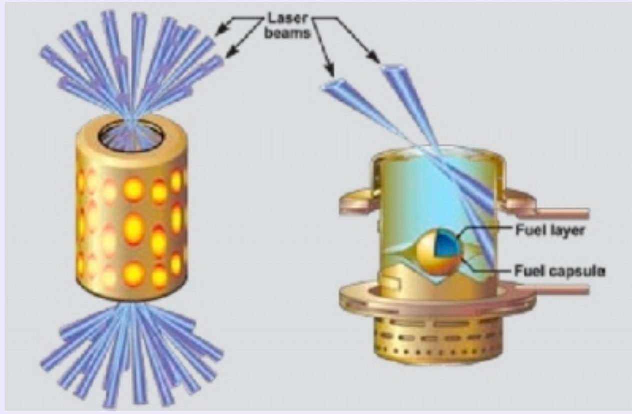
Context…
Large Scale Experiments

Source:
XFEL HED Webpage..



Shock Compressed Matter

Indirect Drive Fusion



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)

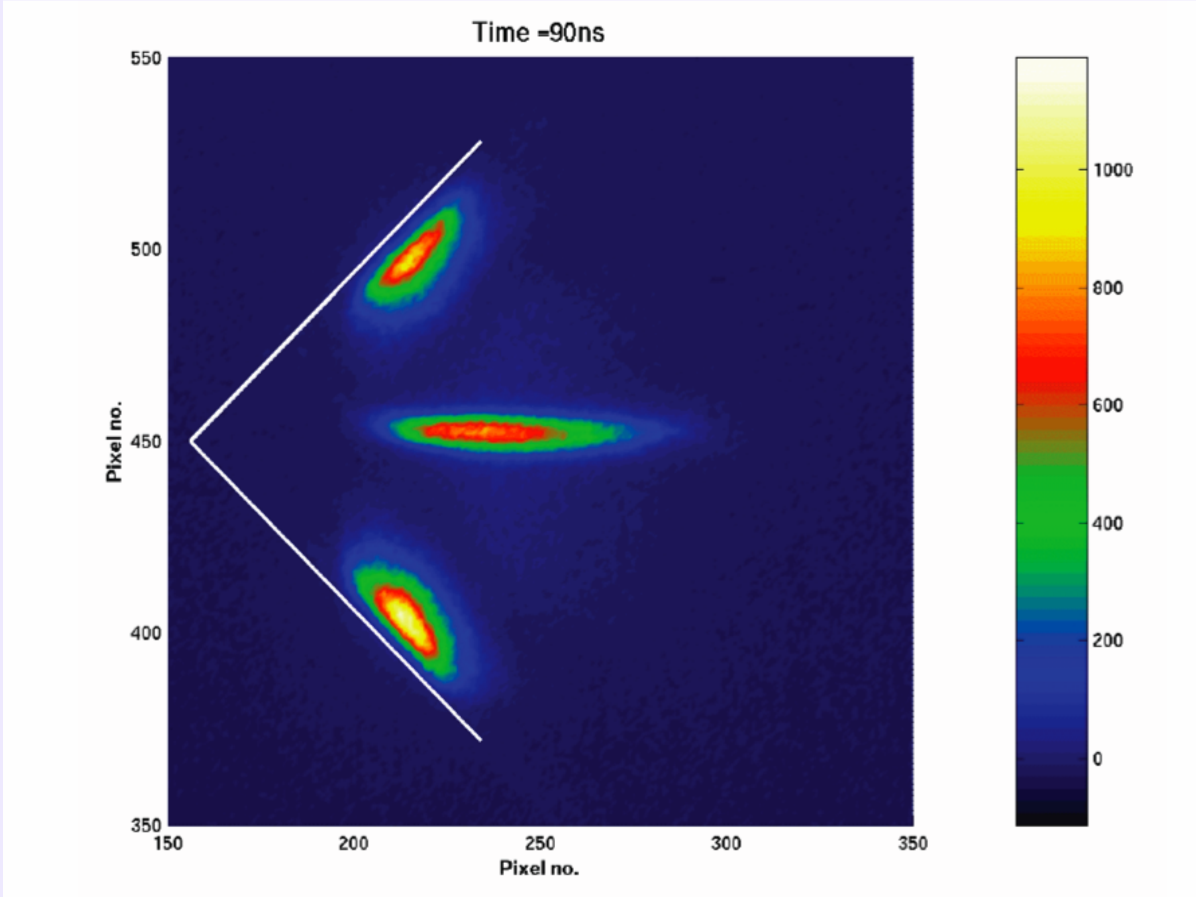
Part II – Table-Top Colliding Plasmas

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 II – Table-Top Colliding Plasmas

When 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, rapid accumulation of material, kinetic energy converted into excitation energy (glow), rapid growth of dense (stagnated) layer,

Part II – Table-Top Colliding Plasmas

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

D ← Plasma - Plasma Separation

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

For collisions between opposing plumes (1, 2)

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

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 II – Table-Top Colliding Plasmas

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

D ← Plasma - Plasma Separation

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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 II – Table-Top Colliding Plasmas

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

D ← Plasma - Plasma Separation

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

For collisions between opposing plumes (1, 2)

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

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 – Table-Top Colliding Plasmas

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 – $i(\theta)$

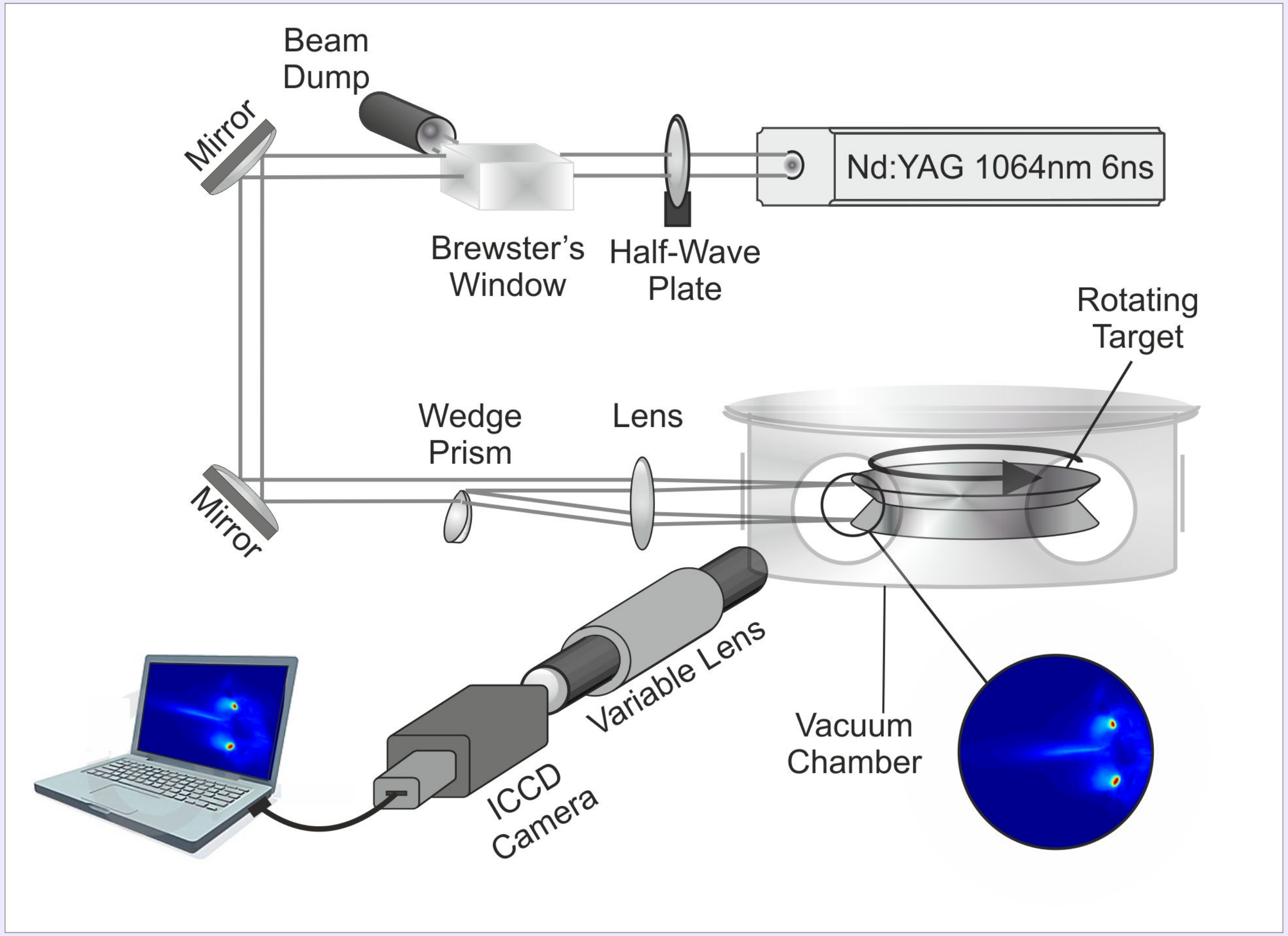
D Doria, K D Kavanagh, J T Costello and H Luna, Meas. Sci. Technol. **17** 670 (2006)

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 – Table-Top Colliding Plasmas

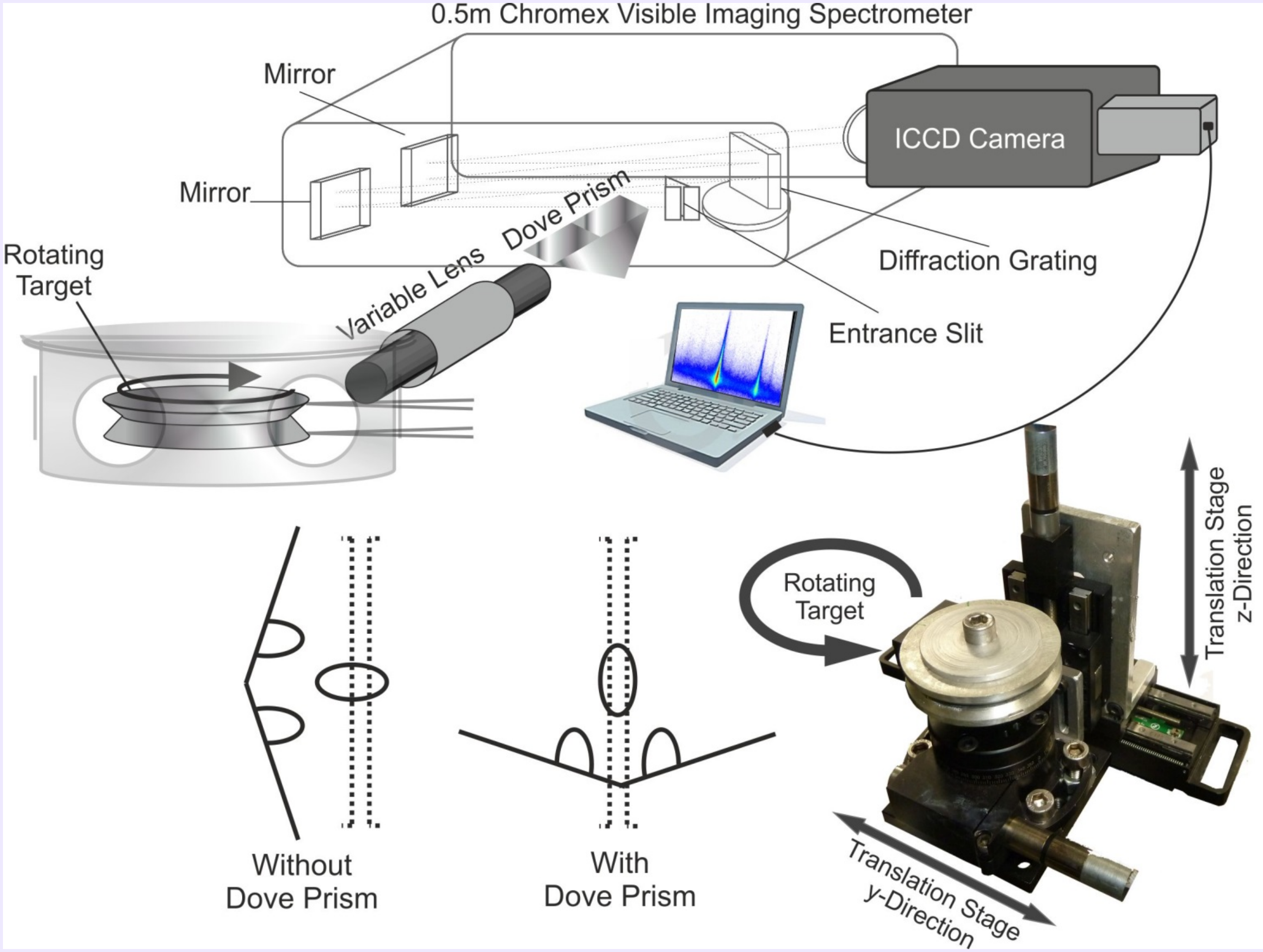
ICCD Photography: Time and angle resolved.



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

Part II – Table-Top Colliding Plasmas

ICCD Spectroscopy: Time and space resolved.



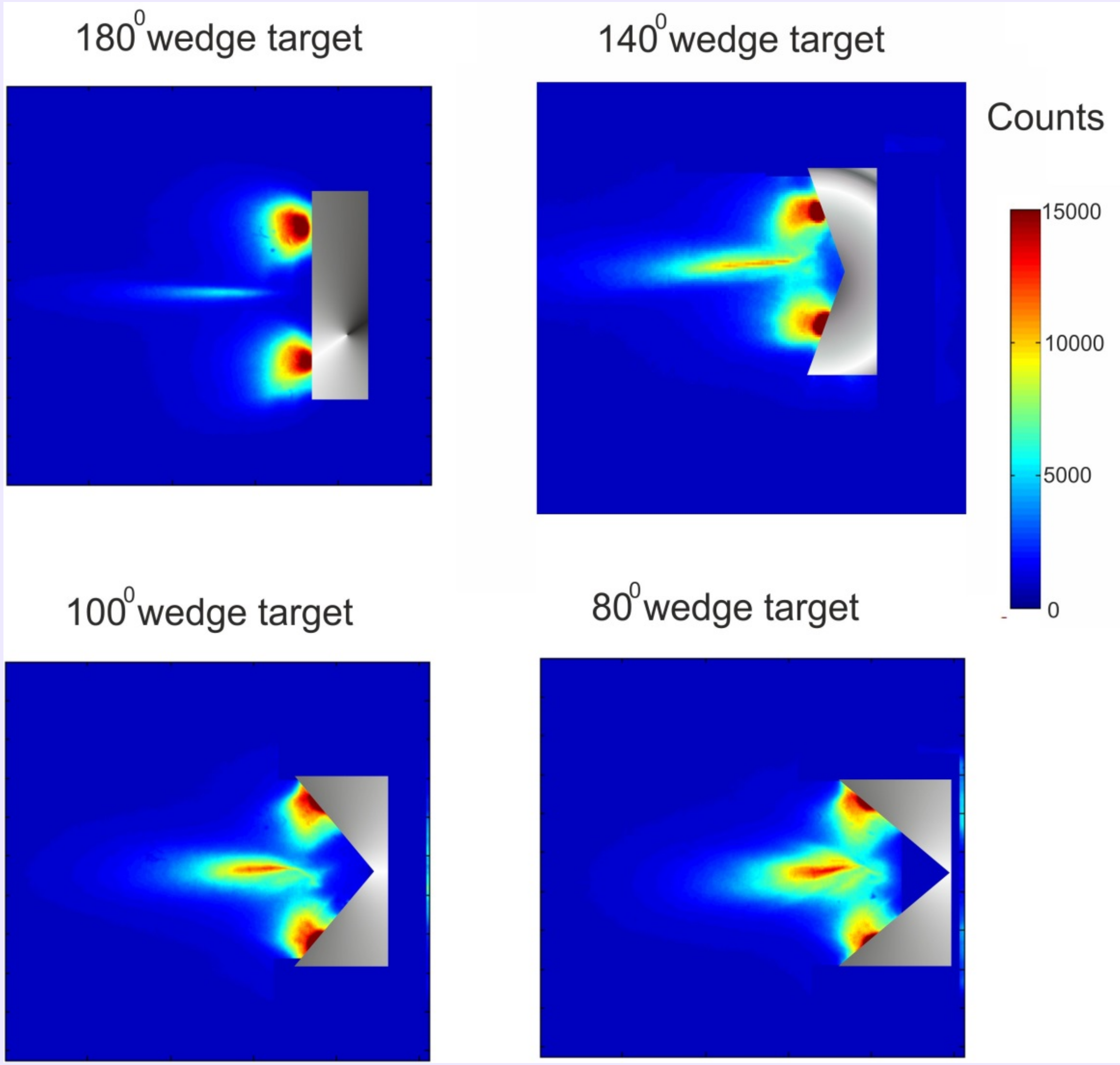
C Fallon, P Hayden, N Walsh, E T Kennedy and J T Costello, Physics of Plasmas **22,** 093506 (2015)

Part II – Table-Top Colliding 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)

Part II – Table-Top Colliding Plasmas

Time, Space and Angle-Resolved UV-Vis Spectroscopy

Stigmatic Spectrometer + ICCD

Part II – Table-Top Colliding Plasmas

Extracting Densities and Temperatures

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

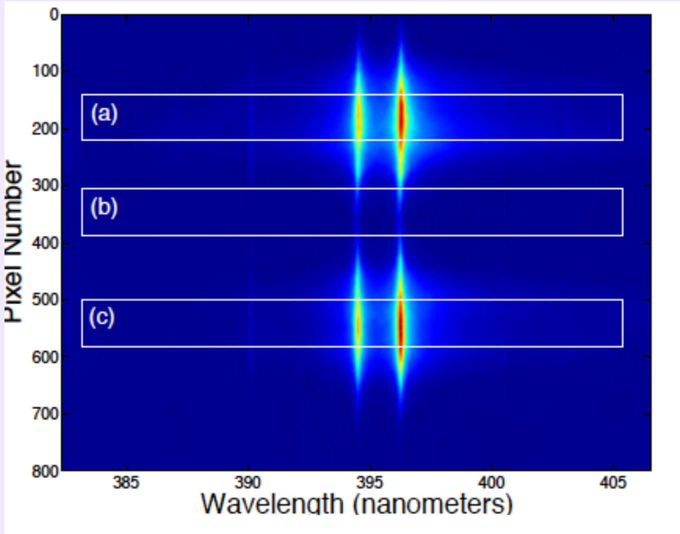
$$\Delta\lambda_{\text{width}} = 2W(Ne/10^{16}) + 3.5A(Ne/10^{16})^{1/4} \times (1 - 1.2N_D^{-1/3})W(Ne/10^{16}),$$

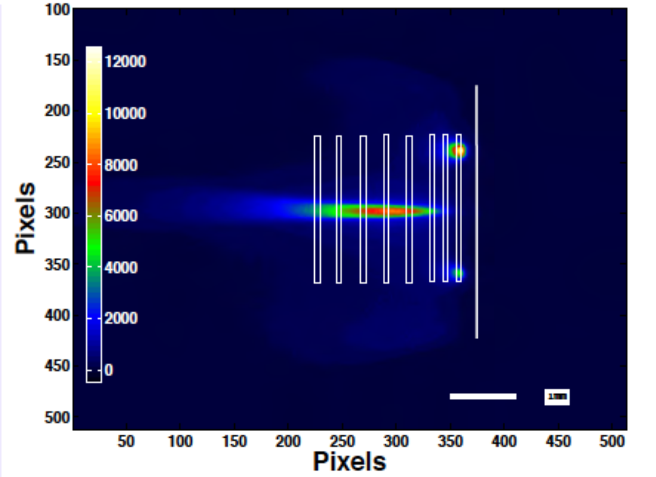
Then temperatures from line intensity ratio for
successive ions stages - assumes LTE

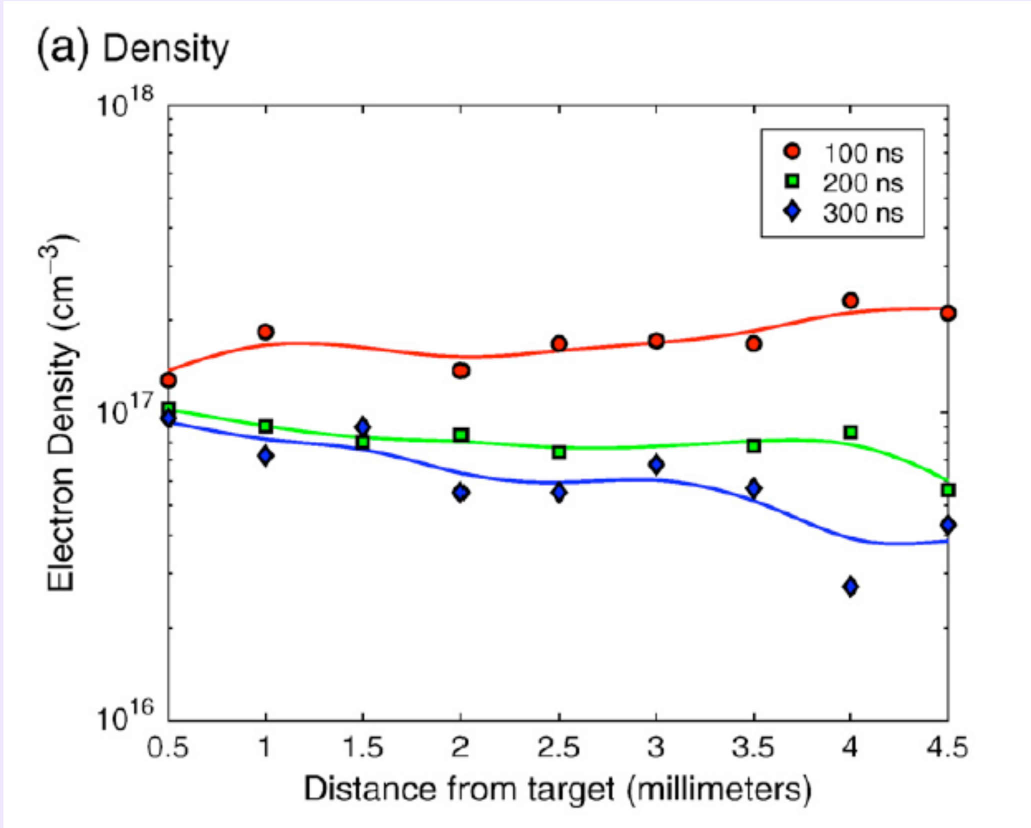
$$\frac{I'}{I} = \frac{f'g'\lambda^3}{fg\lambda'^3}(4\pi^{3/2}a_0^3 Ne)^{-1}\left(\frac{kT}{E_H}\right)^{3/2} \exp\left(\frac{E - E' - E_\infty}{kT}\right)$$

Part II – Table-Top Colliding Plasmas

Stagnation Layer (Al): Electron density (Stark, Al Doublet)





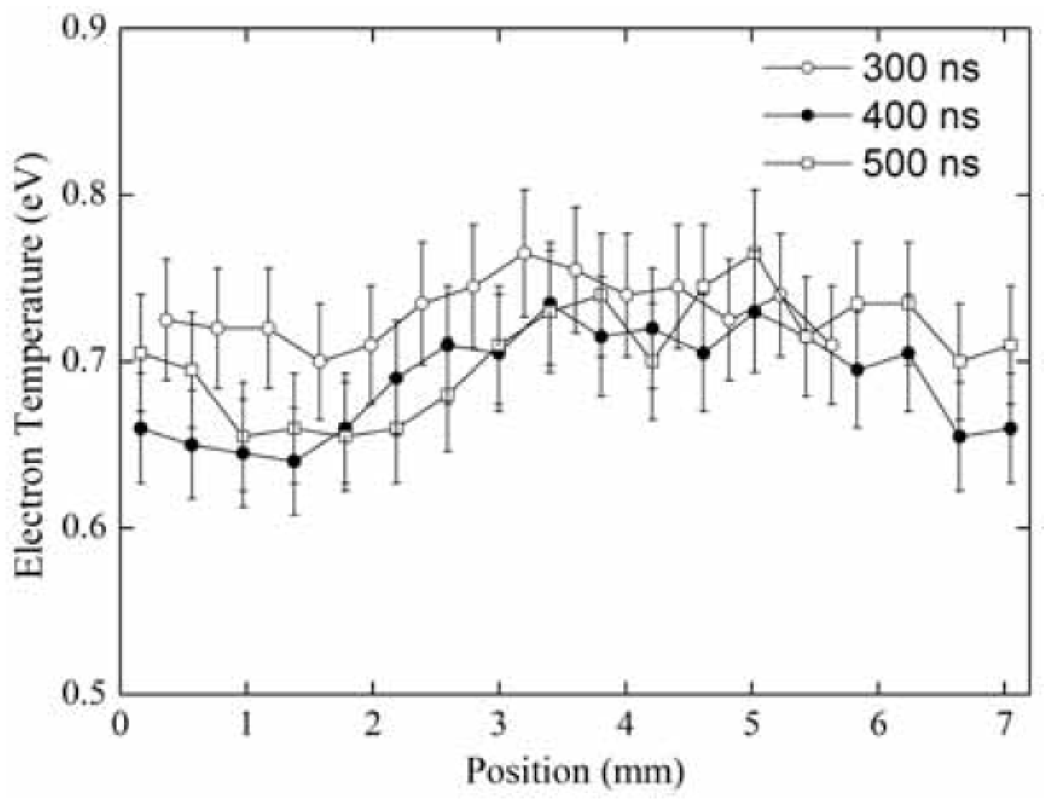


~100 mJ/170 ps/1064 nm 'seed' beam

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

Part II – Table-Top Colliding Plasmas

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

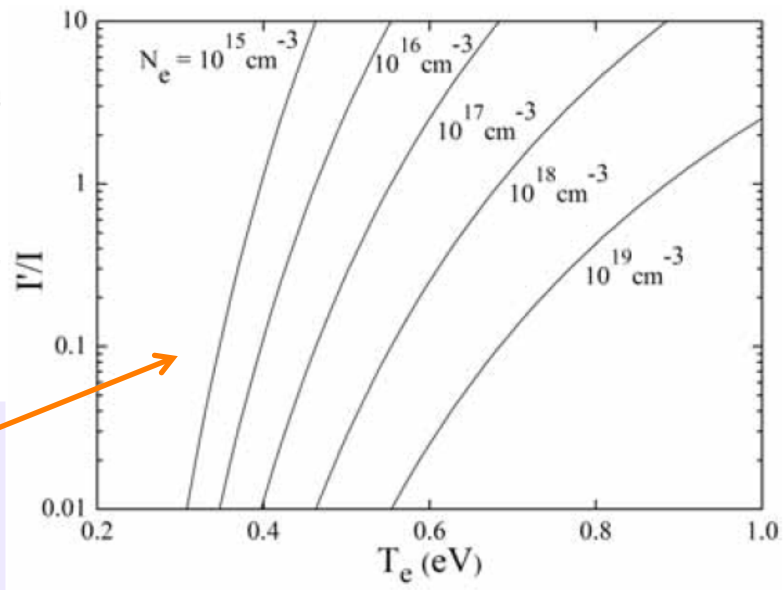


~70 mJ/**355 nm**/
6 ns/ 'seed' beam

$$T_e \approx 0.7eV$$

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

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

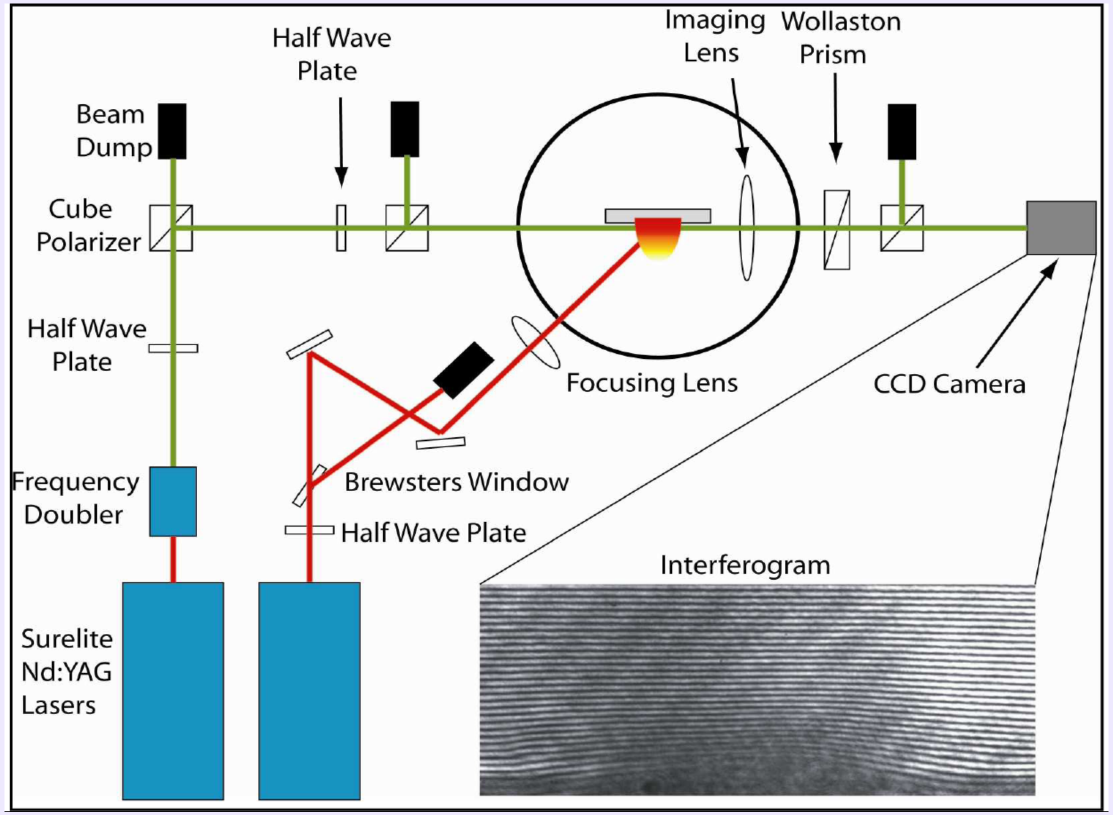


Part II – Table-Top Colliding Plasmas

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-

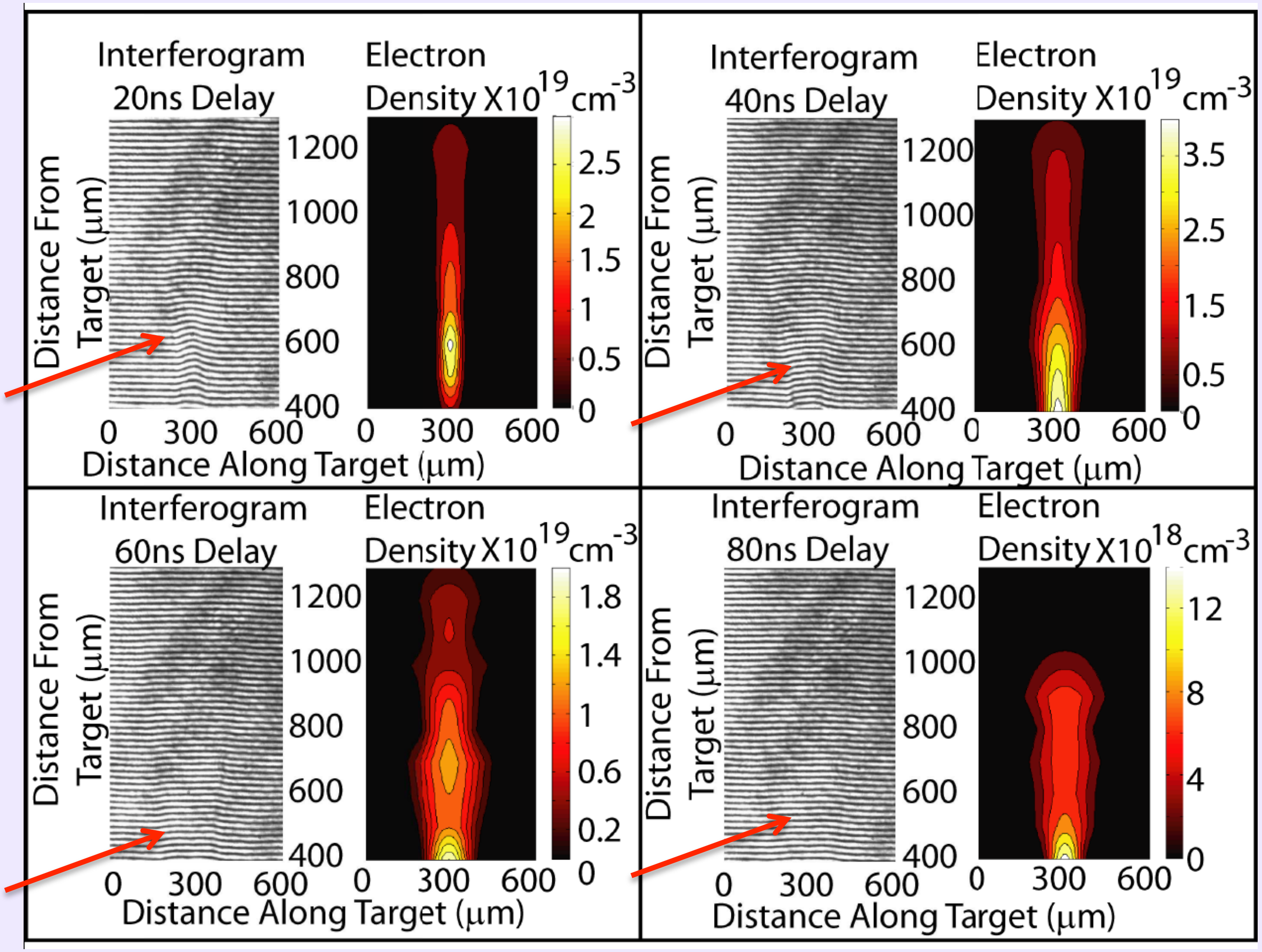
Nomarski Interferometer

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 – Table-Top Colliding Plasmas

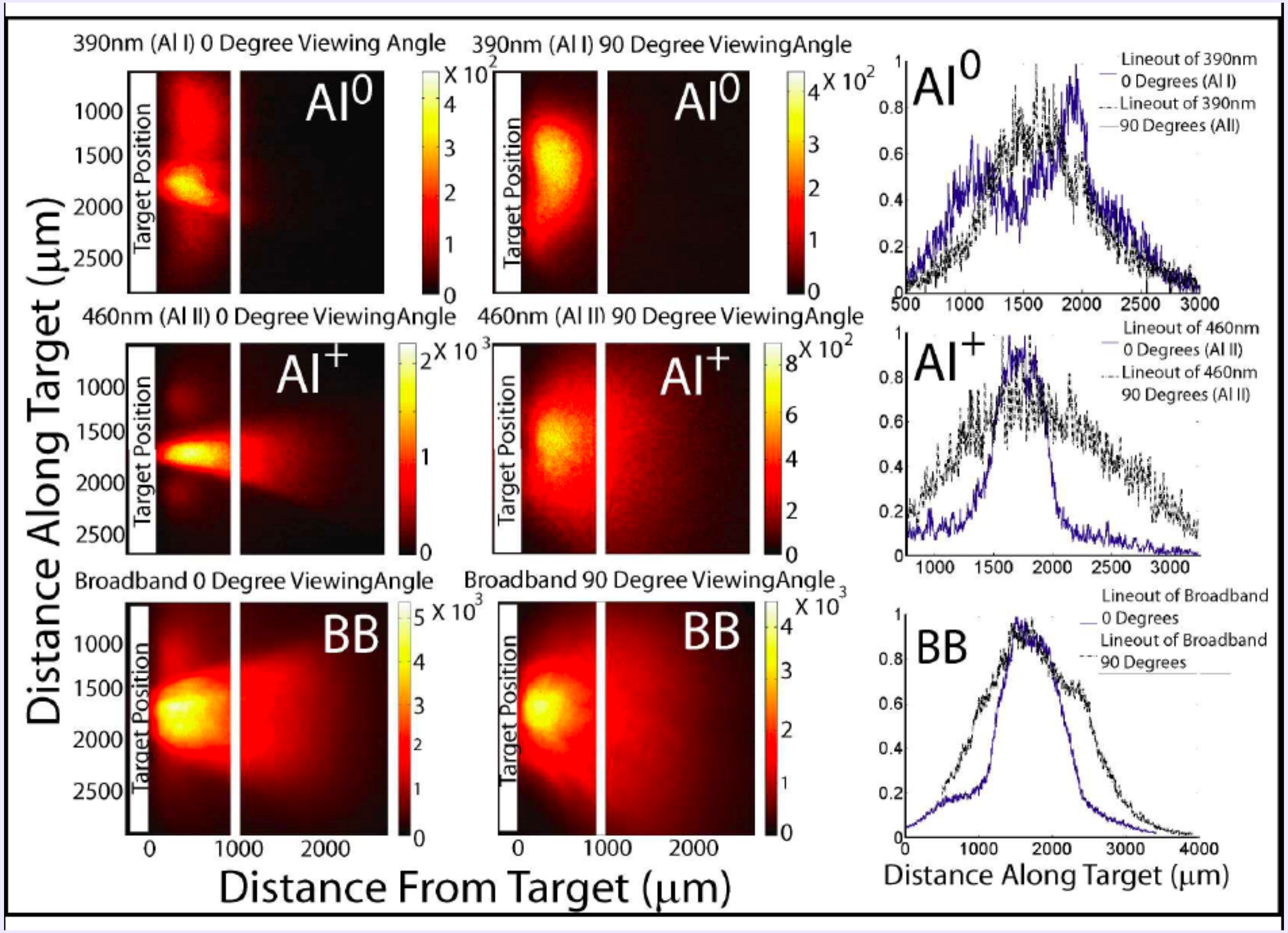
Electron Stagnation at the Collision Plane

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 III – Colliding Annular Plasmas

Colliding Aluminium Plasmas - Individual Fluid Asymmetry - cf: Al^+



Angle Resolved Imaging:

Al, Al^+ & Broadband

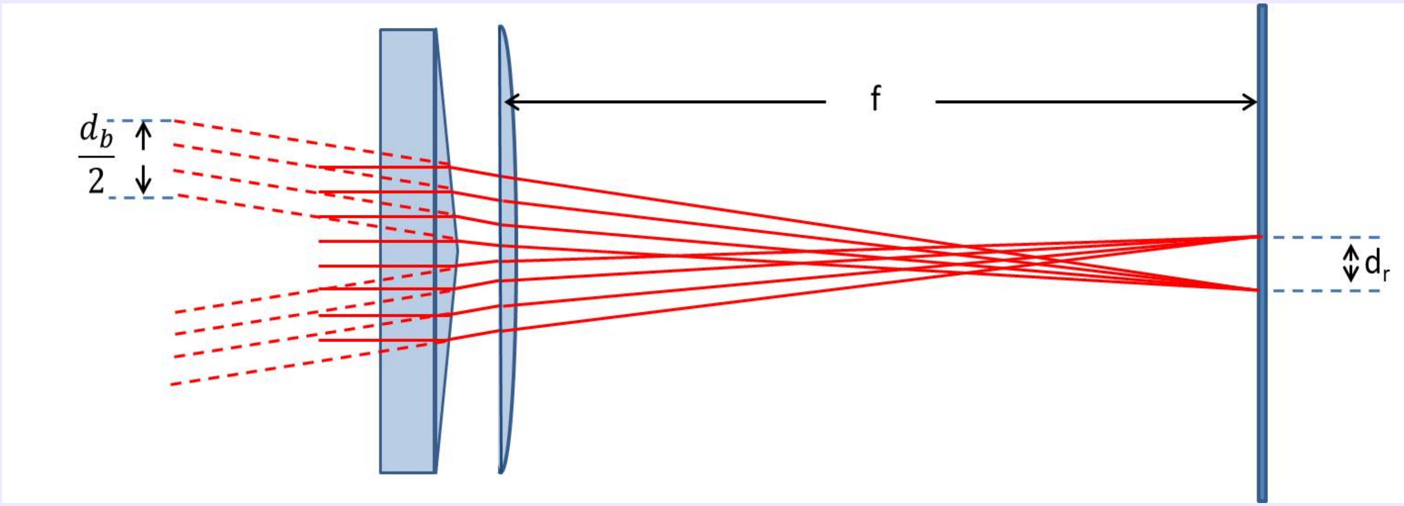
~300 mJ/ 6 ns/ 1064 nm 'seed' beam

P Hough, C McLoughlin, S S Harilal, J-P Mosnier and J T Costello, J. Appl. Phys. **107** 024904 (2010)

Part III – Colliding Annular Plasmas

Symmetric seed plasmas…. Use a Biprism…

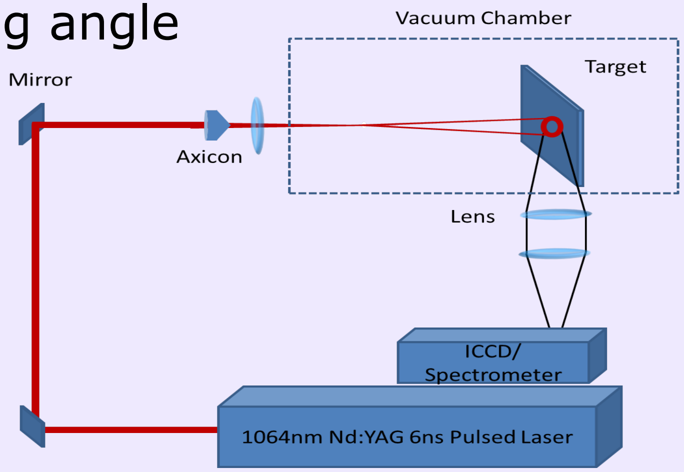
Axicon => Bessel Beam + Focusing => Ring Plasma

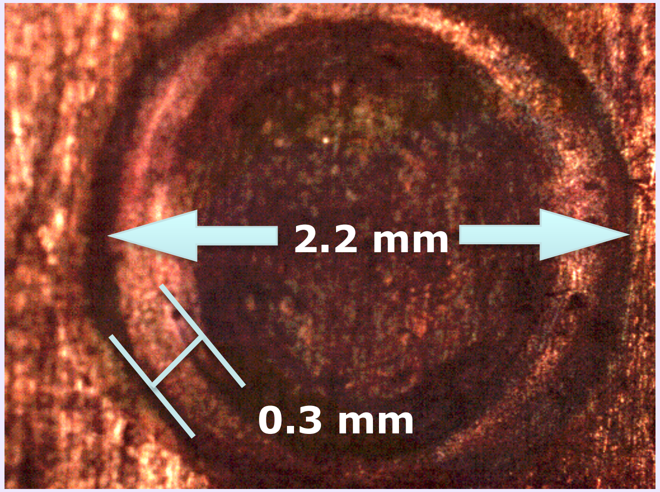


$$d_r = 2.f.Tan\{(n-1)\alpha\} \qquad \alpha = \text{apex angle}$$

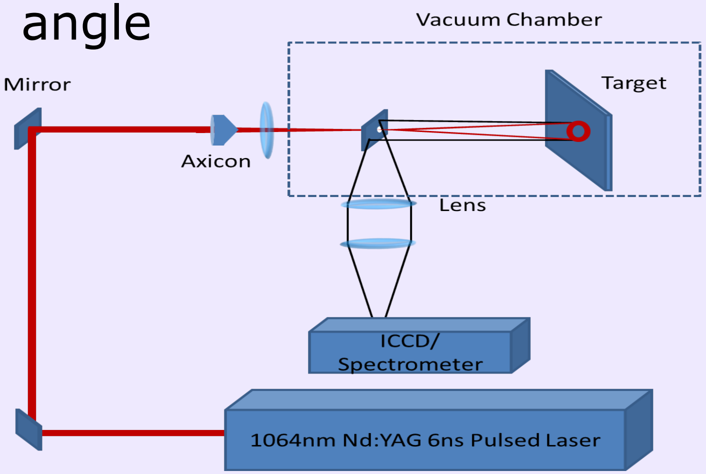
Part III – Colliding Annular Plasmas

90° viewing angle





0° viewing angle

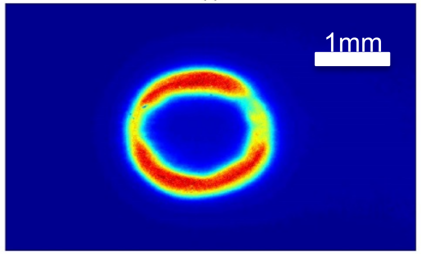


- Area of annulus: 0.07 cm^2
- Power Density: 1.0 GW/cm^2

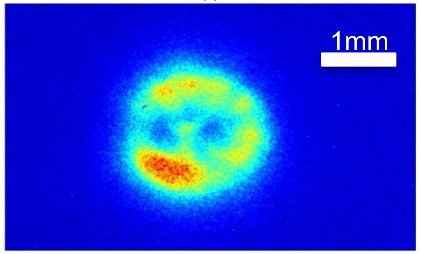
Part III. Colliding Annular Plasmas

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

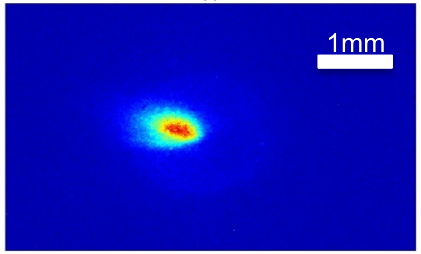
5ns Delay



75ns Delay

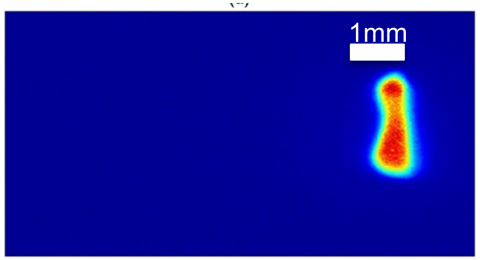


200ns Delay

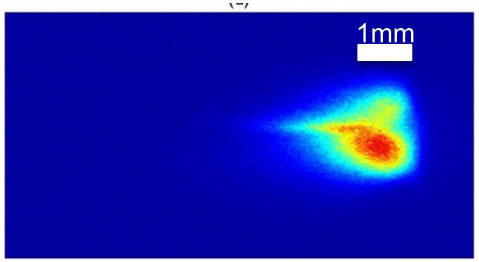


- 5ns gate width, 90° viewing angle imaging.

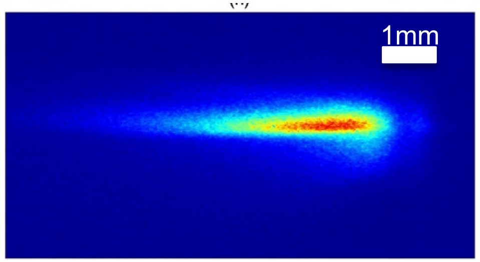
5ns Delay



75ns Delay



200ns Delay



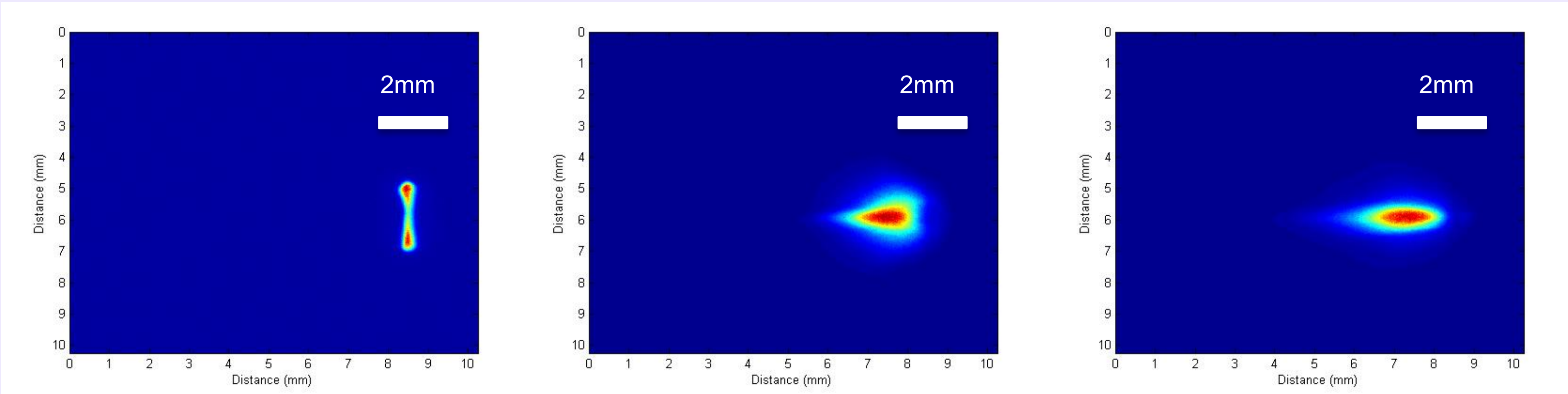
Part III. Colliding Annular Plasmas

Delay: 10 ns
Gate W: 5ns

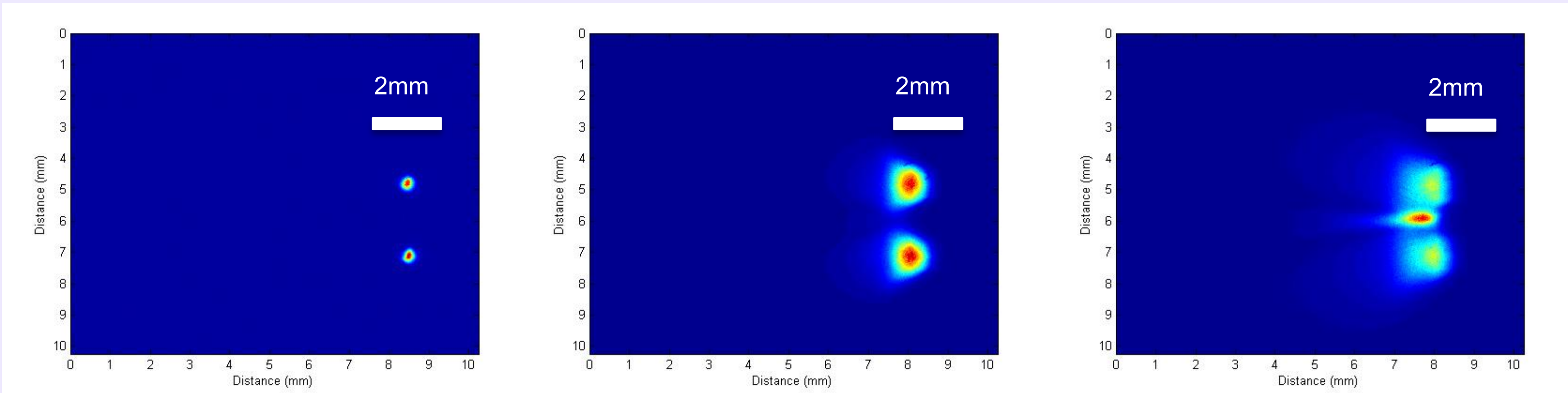
Delay: 30 ns
Gate W: 5ns

Delay:60 ns
Gate W: 5ns

Axicon



Bi-prism



What have we learned so far?

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 – stagnation layers tend to be stable

What have we learned so far ?

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 - stagnation layers tend to be stable

8. Ergo SLs look potentially attractive for applications in laser ablation analytical sciences [LAAS] and perhaps as an alternative [PLD] source and as sources of atoms, ions, clusters,…

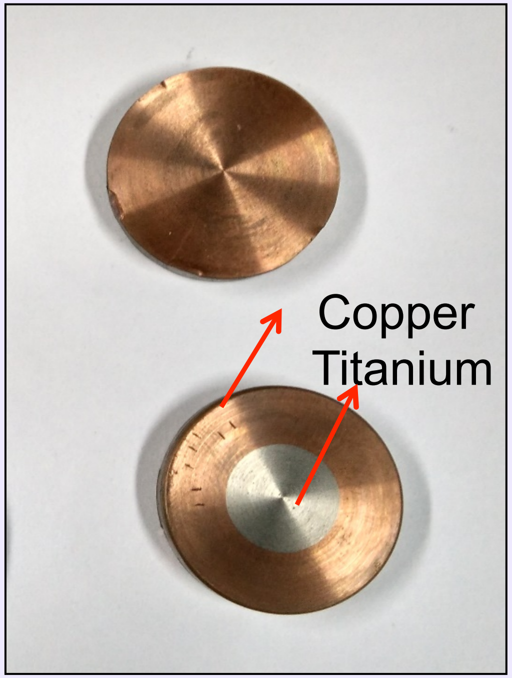
9. We believe that more than one process determines species transport in SL (not shown but discussed in Fallon et al (2015))

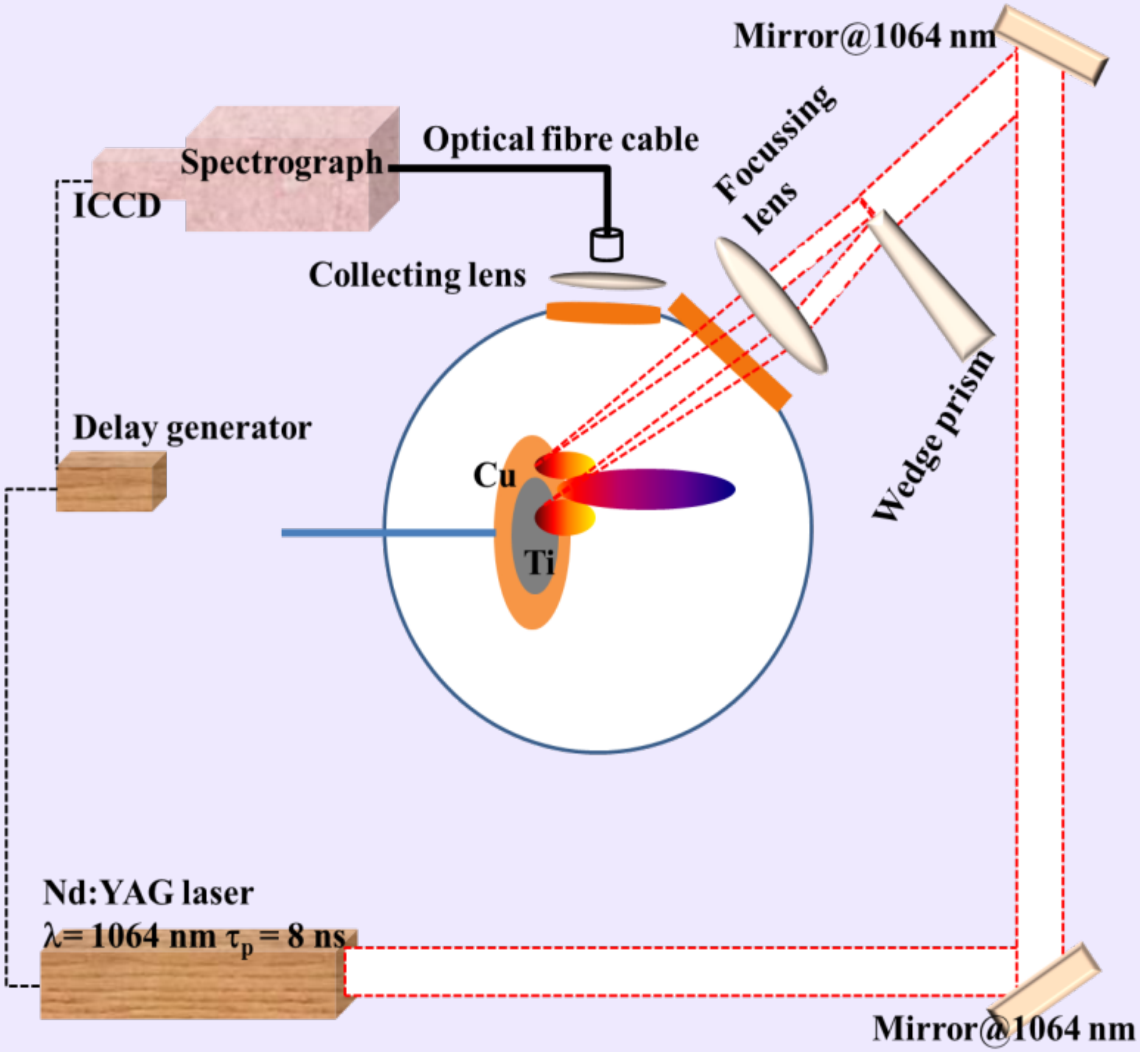
10. 'Velocities' of SL species drop as the wedge angle decreases - ion/ neutral 'velocity' ratio generally >3 (not shown but discussed in Fallon et al. (2015))

Part IV. 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 new experimental evidence that we can **preferentially generate high nanoparticle fluxes** in nanosecond colliding plasmas (Pandey et al., Physics of Plasmas, submitted)
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 Sn-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** - even higher densities are possible with 3ω 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 IV. Key Properties–Potential Applications

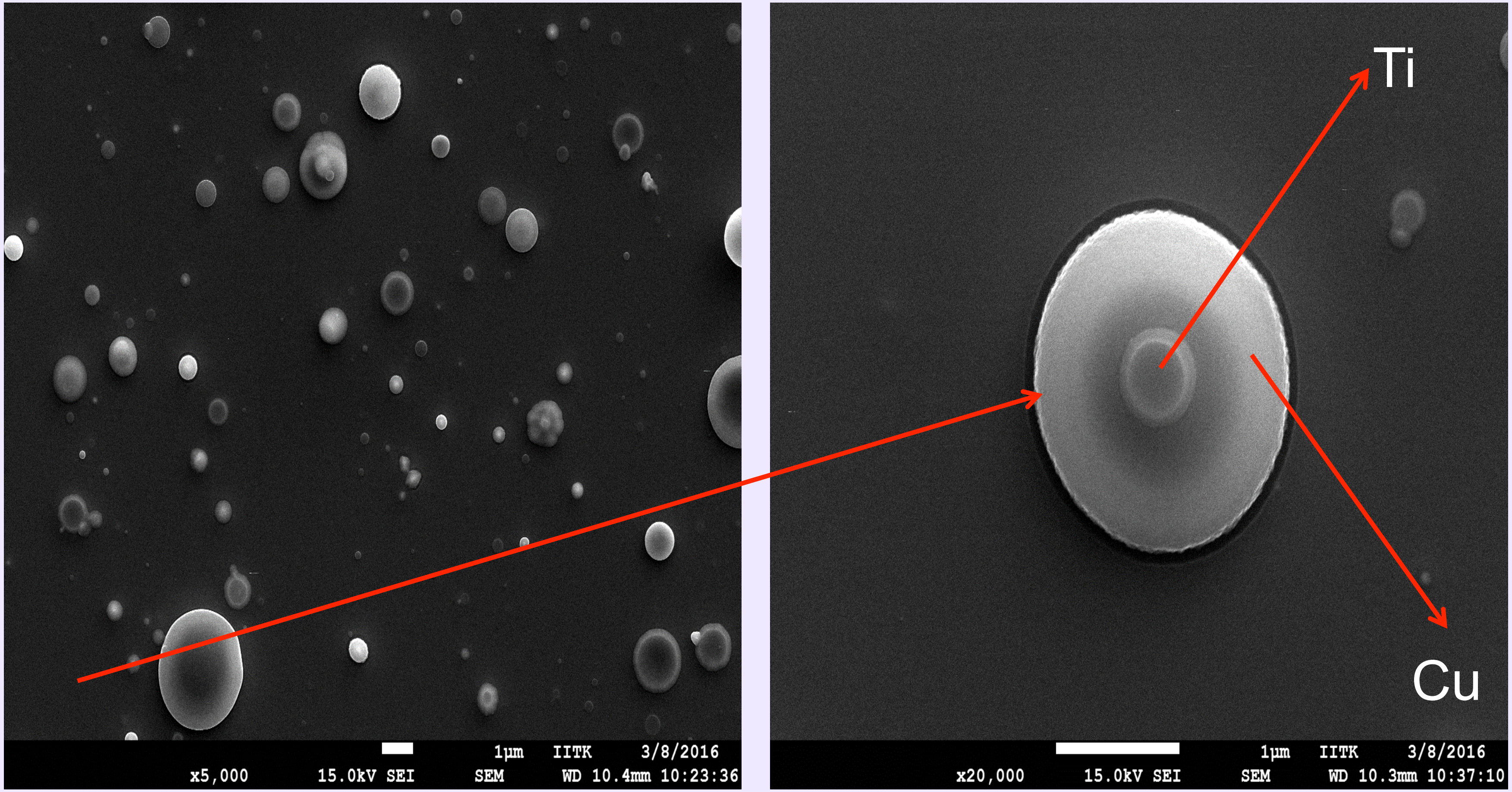




1. Distance between target and substrate= 4 cm
2. Laser energy = 50 mJ / Pulse for each splitted beam
3. Focal spot size = 300 μm
4. Beam incident on target surface at 45 degree.

Part IV. Key Properties–Potential Applications

TiCu alloy formation by colliding Ti and Cu plasmas – Collaboration with IIT Kanpur – SEM and EDX



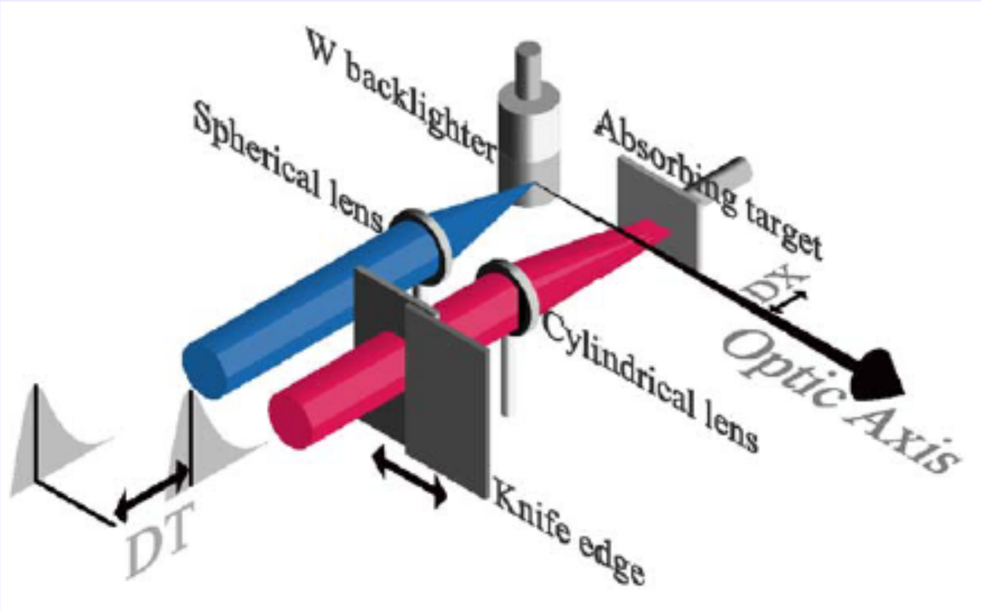
Part IV. Key Properties–Target for XFELs

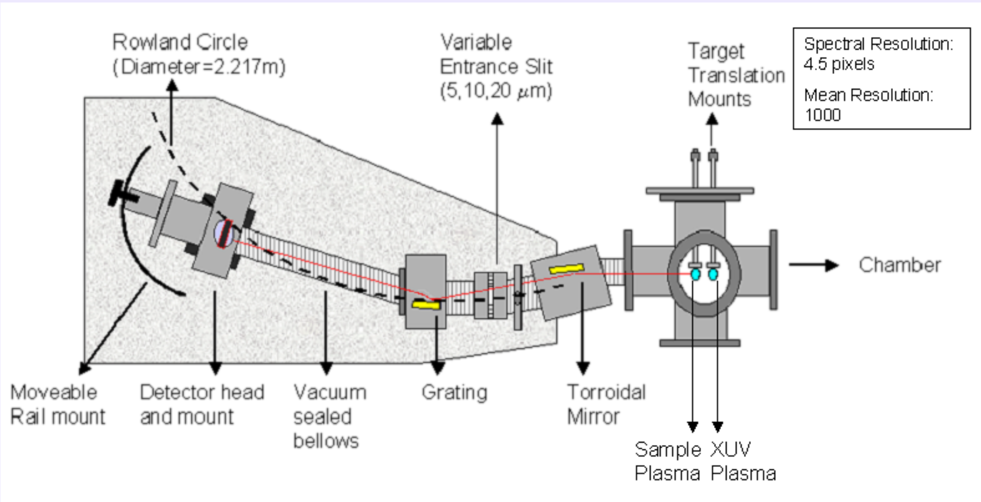
Ti

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……

Cu

Part IV. Key Properties–Target for XFELs





No tuning required
No vapour required

Neutrals (atoms & mols)/
Multiply charged ions/
Refractory Elements

Δx, ΔT, I(W/cm^2)
➔ Species choice

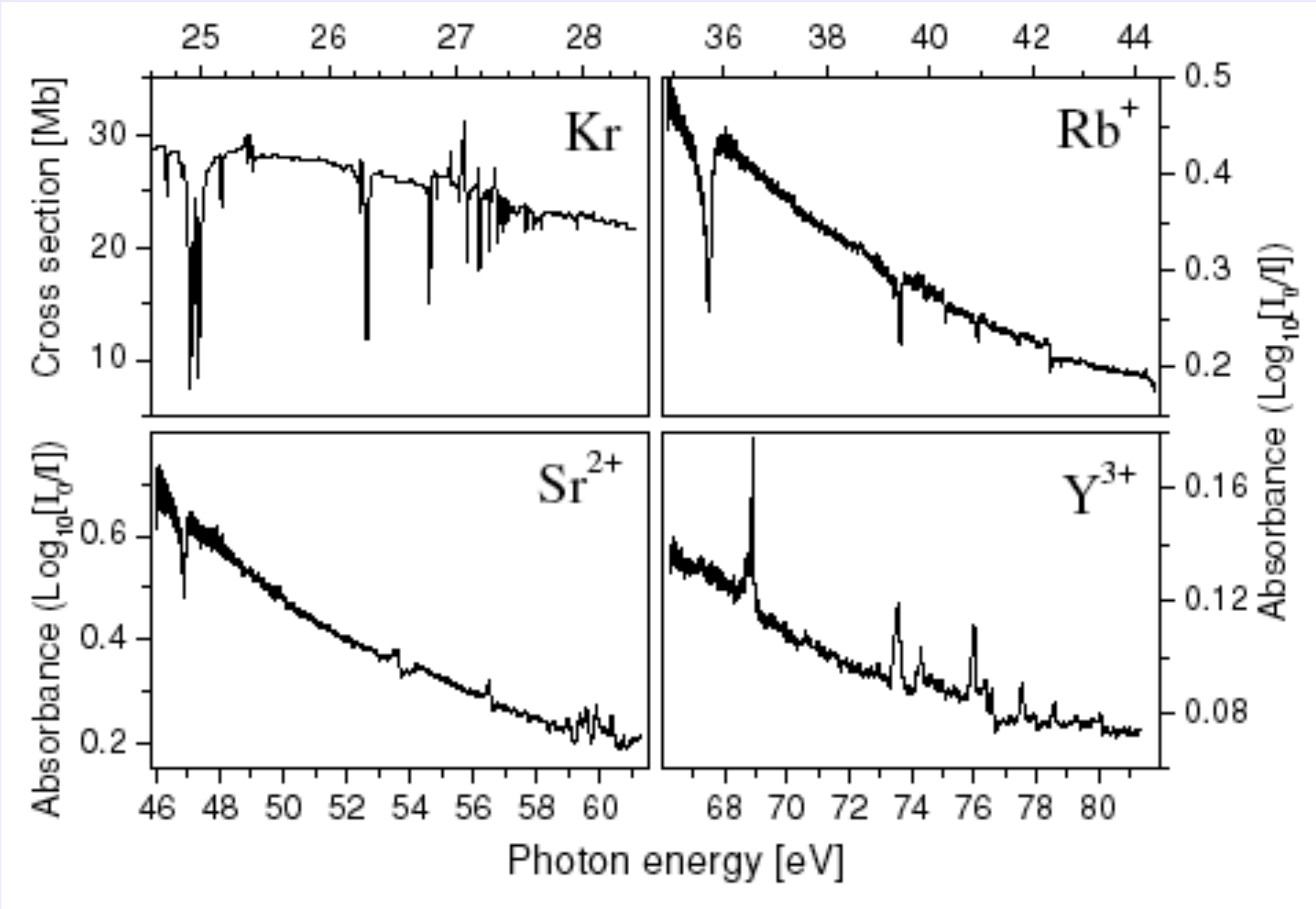
Backlighting Plasma I_o
Both Plasmas $I = I_o e^{-\sigma n L}$

Relative Absorption
Cross Section $\sigma NL = Ln(Io/I)$

J T Costello et al., Phys.Scr. **T34**, 77 (1991),
E T Kennedy et al., Opt.Eng **33**, 3984 (1994)

Part IV. Key Properties–Target for XFELs

$4s^2 4p^6 + h\nu_{XUV} \rightarrow 4s4p^6 np + 4s^6 4p^4 nln'l' \rightarrow Kr^+(4s^2 4p^5) + \varepsilon' l$

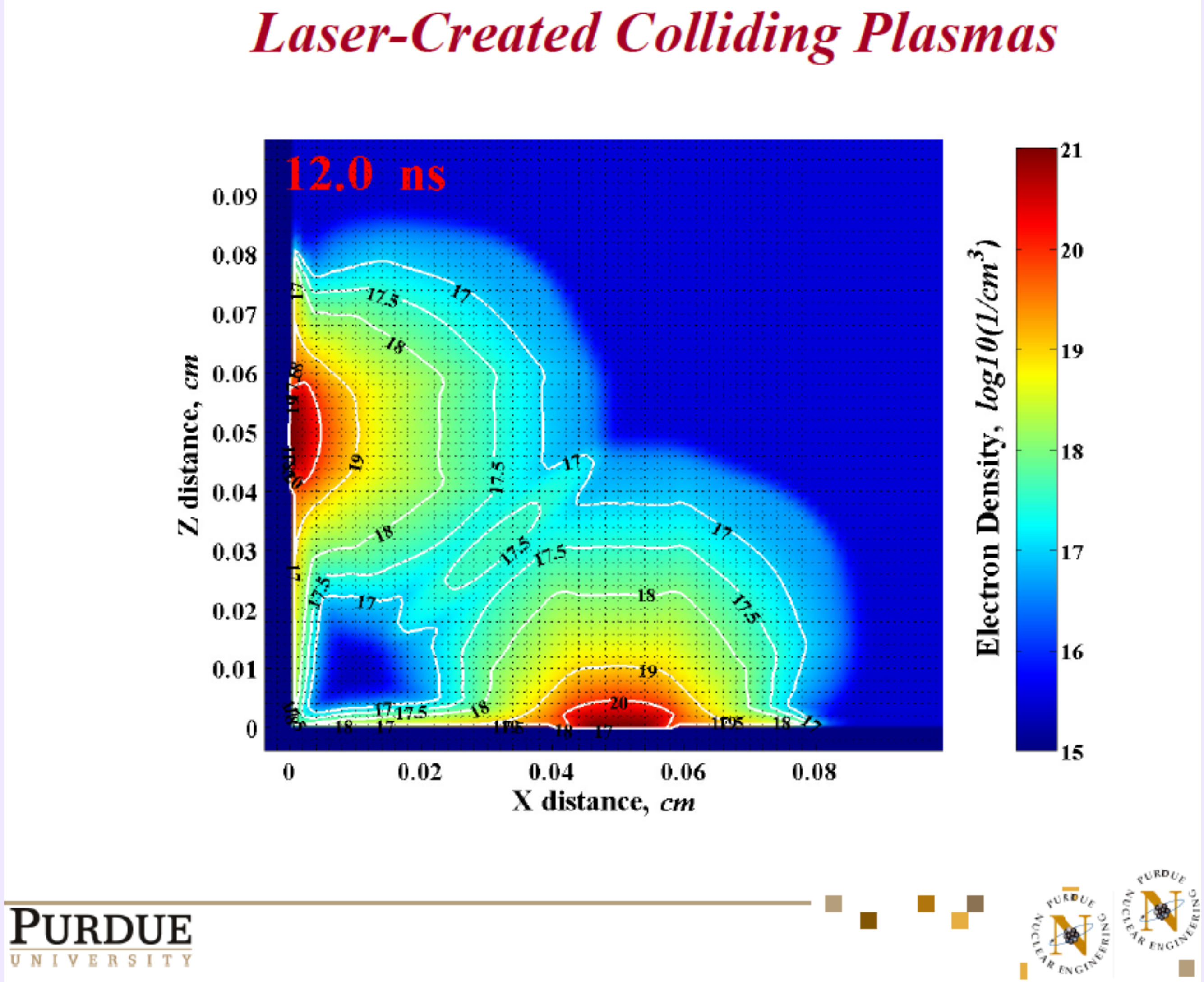


Ti

Cu

A Neogi et al., Phys.Rev.A **67**, Art. No. 042707 (2003)
P Yeates et al., J. Phys. B: At. Mol. Opt. Phys. **37**, 4663 (2004)

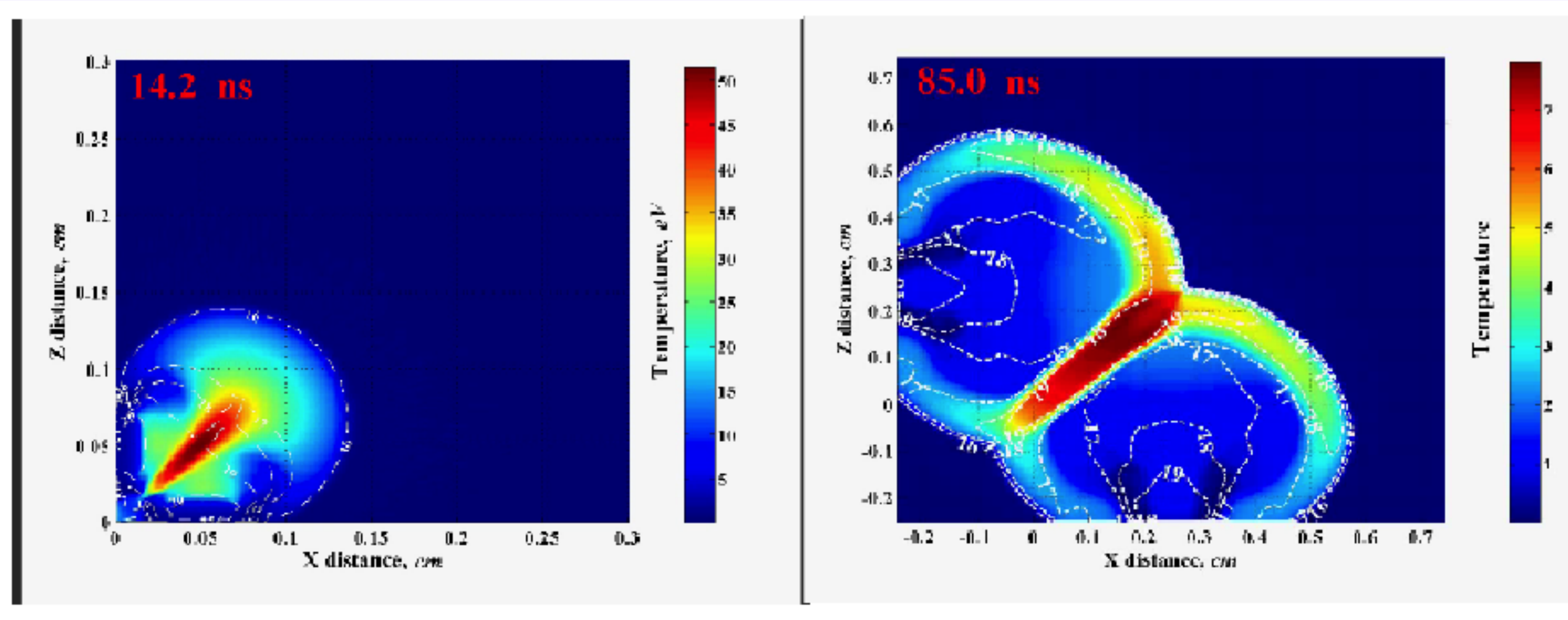
Part V. Next Steps



Density Simulation with 'HEIGHTS' code from Ahmed Hassanein Purdue University

Part V. Next Steps

Colliding plasmas from C – Nd:YAG, 10^{10} W/cm^2. 6 ns pulses



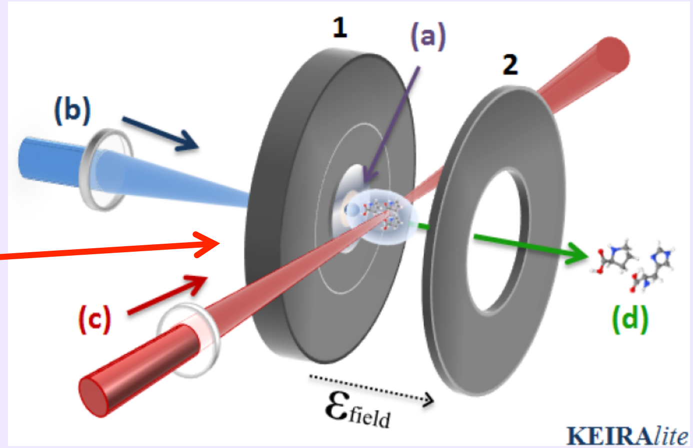
Temp. Simulation with 'HEIGHTS' code - Ahmed Hassanein, Purdue Univ.

Part V. Next Steps

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

2a. 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)

2b. Femtosecond colliding plasmas – nanoparticle stagnation for biomolecular capture…….

3. XUV/X-ray sources:
Applications of Stagnation Layers in double pulse experiments (especially opacity reduction in high-Z materials to enhance spectral line emission)

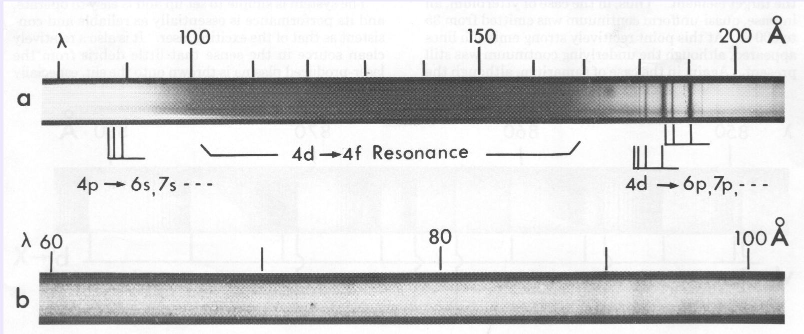


Fig. 1. (a) Absorption spectrum of xenon from 80 to 200 Å. The xenon pressure in the spectrograph was 0.05 Torr, and the number of laser pulses used was 30. For details of the xenon spectrum in this region see Madden and Codling.[5] The unmarked weak lines near 200 Å are due to 0 v. Oxygen present in 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.

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

STEP
Science & Technology Enhancement Platform

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Local Organiser: John Costello – www.physics.dcu.ie/~jtc

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