The Abdus Salam International Centre for Theoretical Physics

2369-9

CIMPA/ICTP Geometric Structures and Theory of Control

1 - 12 October 2012

High energy density science (HEDS) experiments with table top terawatt lasers: the why and how

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ICTP-IAEA College on Plasma Physics October 2012
Lectures by G. Ravindra Kumar, TIFR Mumbai

1. Intense Laser- Matter Interaction: Some Basics [mainly for ultrashort (femtosecond) pulses]

2. High energy density science (HEDS) experiments with table top terawatt lasers: the why and how – ***TODAY!***

3. Physics issues and challenges in HEDS with table top lasers: some examples

High energy density science (HEDS) experiments with table top terawatt lasers: the why and how

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ICTP-IAEA College on Plasma Physics, 2012 Oct 01-12; Talk 2

Prashant K. Singh

Sudipta Mondal

Gourab Chatterjee

M. Krishnamurthy

Saima Nafees

Amit D. Lad

V. Narayanan

Fellow Chasers !

Amitava Adak

Malay Dalui

K. P. M. Rishad

R. Rajeev

Madhu Trivikram

J. Jha

P. Brijesh

Collaborators

P. Ayyub and students (DCMP & MS, TIFR)

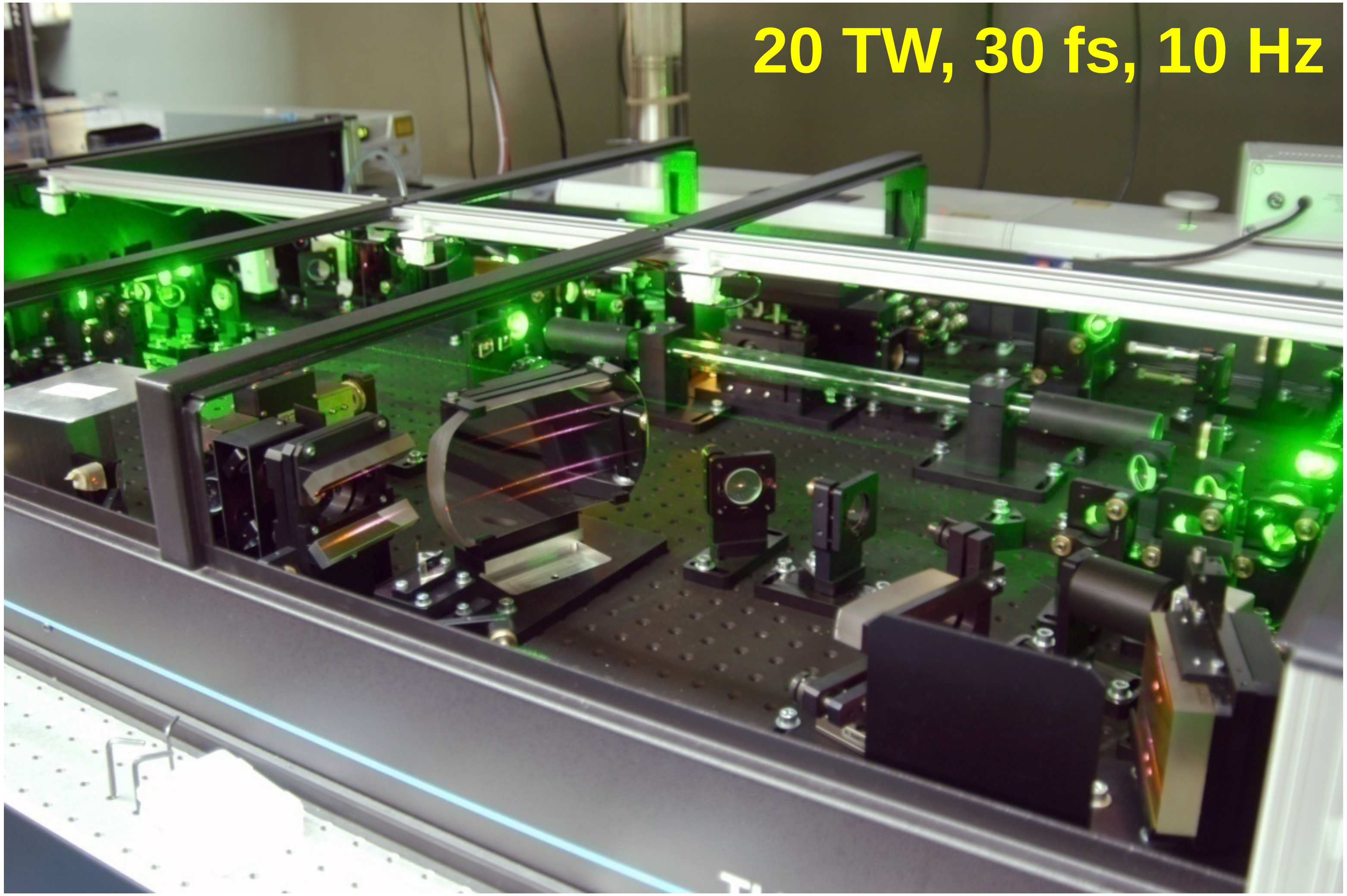
P. K. Kaw , S. Sengupta, A. Das, S. Yadav (IPR): theory and modeling

P. P. Rajeev, A. P. L. Robinson, J. Pasley (Simulation)
(RAL and York, U.K)

K. A. Tanaka, H. Habara, R. Kodama, K. Mima and others (ILE, Osaka)

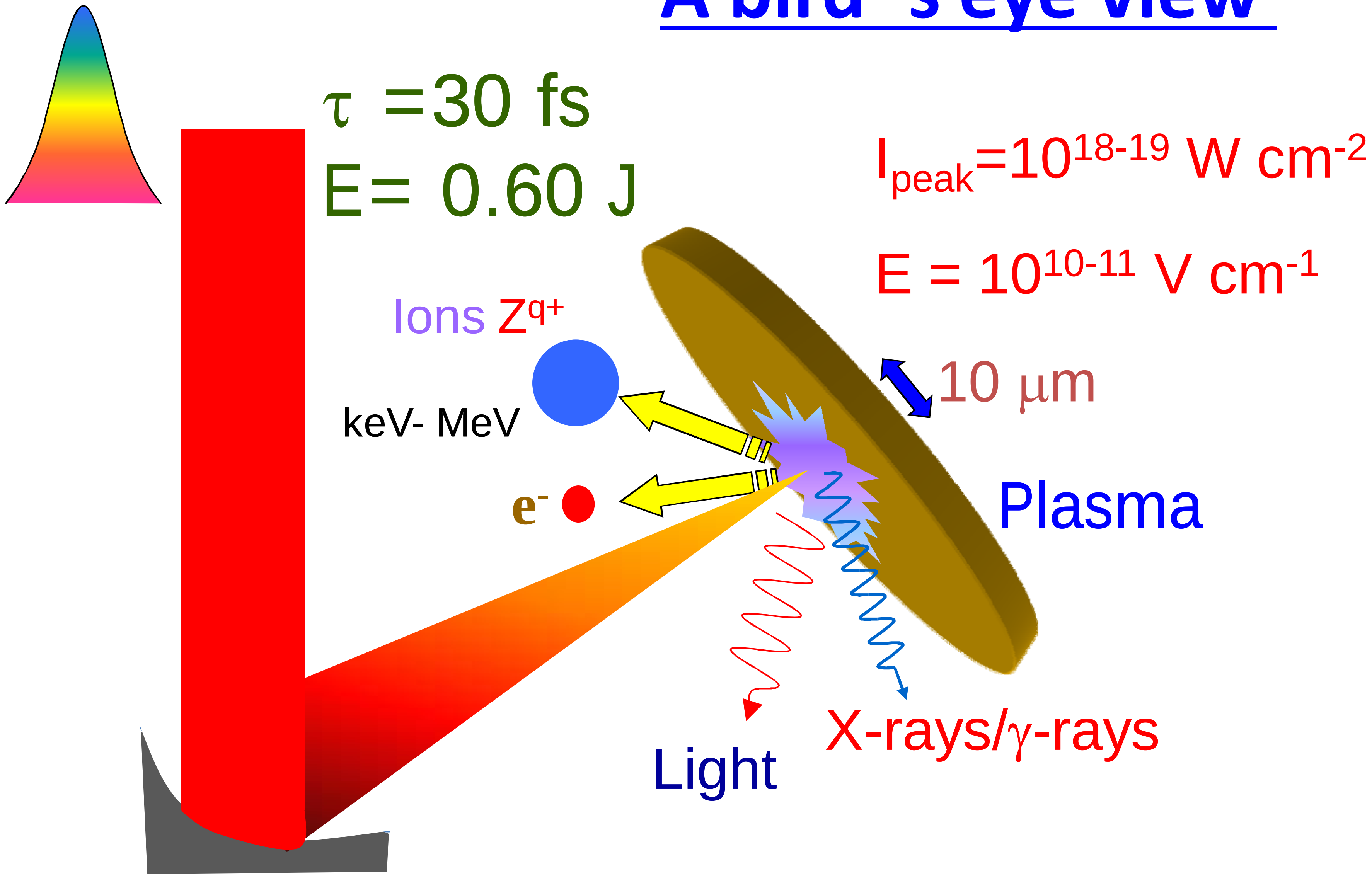
W. M. Wang, Z. M. Sheng (Shanghai)

Ultra short Pulse High Intensity Laser Laboratory, TIFR



www.tifr.res.in/~uphill

A bird's eye view



Pulse `Peak' power
20 x 10^{12} W

Plan of the Talk

- **Introduction and motivation**

  high energy density science

- **High energy density science with ultrashort lasers- how and why?**
- **Illustrative examples**
- **Conclusions**

High Energy Density

External energy density applied to a material ~ comparable to the material's room temperature energy density.

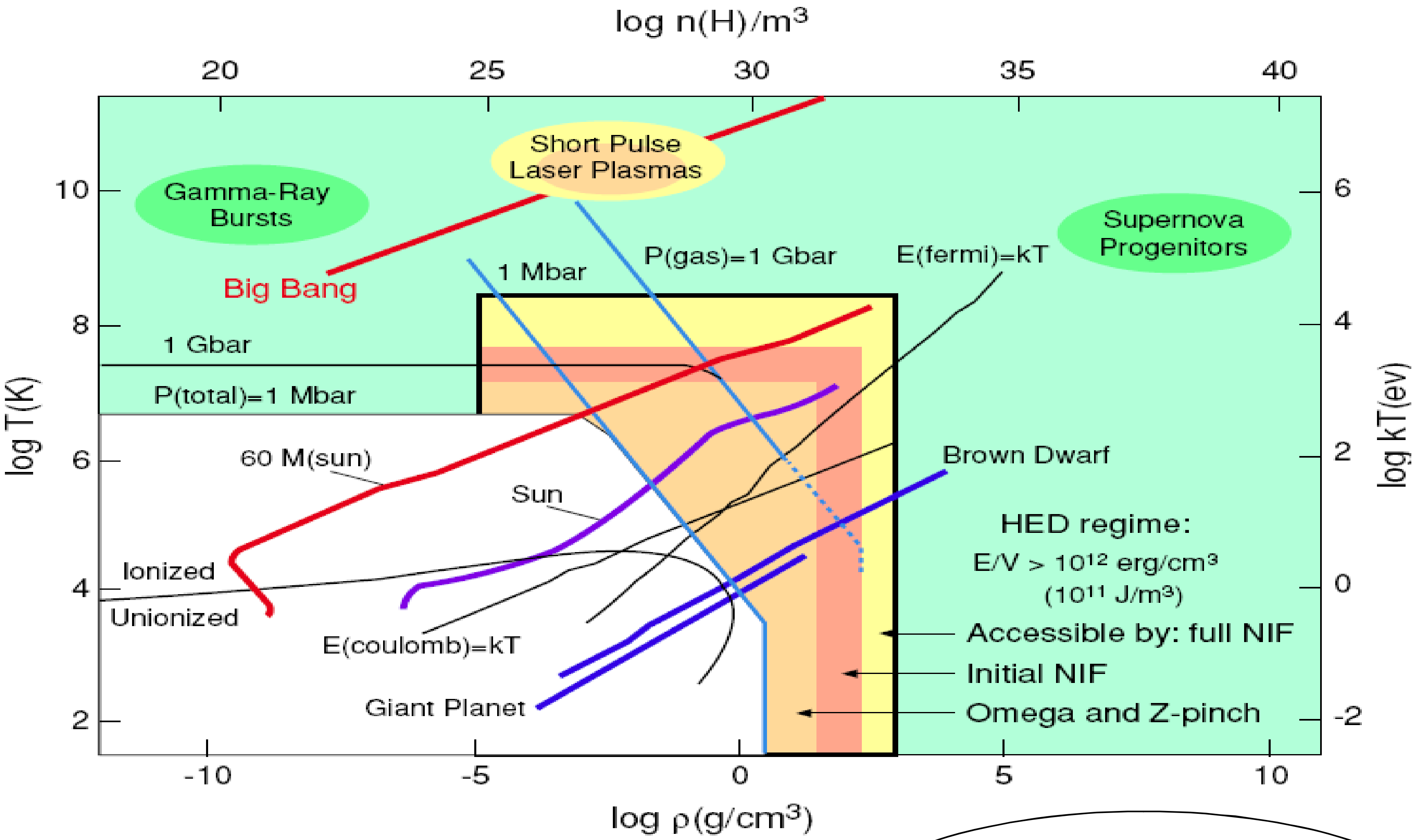
~

bulk moduli of solid-state materials

10^{11} J /m^3

At this energy density, the pressure is 1 Mbar.

What is ‘High Energy Density’?



Shaded- HED region possible to explore

HIGH ENERGY DENSITY SYSTEMS

Physical properties

- **Nonlinear and collective responses**
- **Full or partial degeneracy**

pressure determined by the Pauli exclusion principle rather than by temperature.

- **Dynamic systems**

High Reynolds number-turbulence, ultimate nonlinear response

High Mach no (= kinetic energy / thermal energy)-form and sustain shocks.

Re>10^4 and *Ma* > 0.5 relevant to large scale astrophysical phenomena.

High Energy Density Physics

seeks to answer some of the most basic questions in science…………

- How does matter behave under conditions of extreme temperature, pressure, density, and EM fields?
- What are the **opacities** of the stellar matter?
- What is the nature of the matter at the beginning of the universe?
- How does matter interact with photons and neutrinos under extreme conditions?
- What is the origin of intermediate-mass and high-mass nuclei in the universe?

- Achieve high-yield fusion ignition in the lab?
- Simulate mechanisms for formation of astrophysical jets in laboratory?
- Equation of State for stellar and planetary structures?
- Can electron-positron plasmas relevant to gamma-ray bursts be created in the laboratory?

High Energy Density Science with Small (Tabletop) lasers

=

'High IntensityPhysics'

A study of

Extremely excited states of matter

produced by

Extremely short, energetic pulses of light.

Impulsively kicked physical systems

Energy Scales involved

Photon energy - 1.5 ev (~ 10^0 eV)

Ionization energy of atom (typ.) –

10^1 -10^2 eV >> Photon energy

Energy given to the electron

>>>>>>>>> both the above!

Plasma formation in a DENSE medium

Initial ionization of valence electrons by light field

↓

Acceleration of ionized electrons by light (Oscillation)

Repetitive processes

Collisional absorption

Collisions of these individual electrons with other particles `Inverse bremsstrahlung'

Resonance Absorption

Excitation of a plasma wave (Collective effect)

↓

Damping of wave

Hot electrons and finally Hot ions →

Hot,dense plasma

Physics In ULTRA-INTENSE Light Fields

Matter totally ionized → Large charge densities (> 10^{24} cm^{-3})

→ Energetic electrons (10^3 - 10^6 eV)

Sun

Nonequilibrium dynamics - violently driven systems

Gigantic magnitudes

Magnetic fields 10^9 G Electric field 10^{10} V cm^{-1}

Pressure 10^9 bars Temperature 10^8 K (for e^-)

neutron star

Relativistic and QED effects

multiphoton Compton scattering, pair production

Nuclear excitation and fusion

Laboratory Astrophysics

HED with a Table Top TW Laser (HEDS-T^3)

Why???

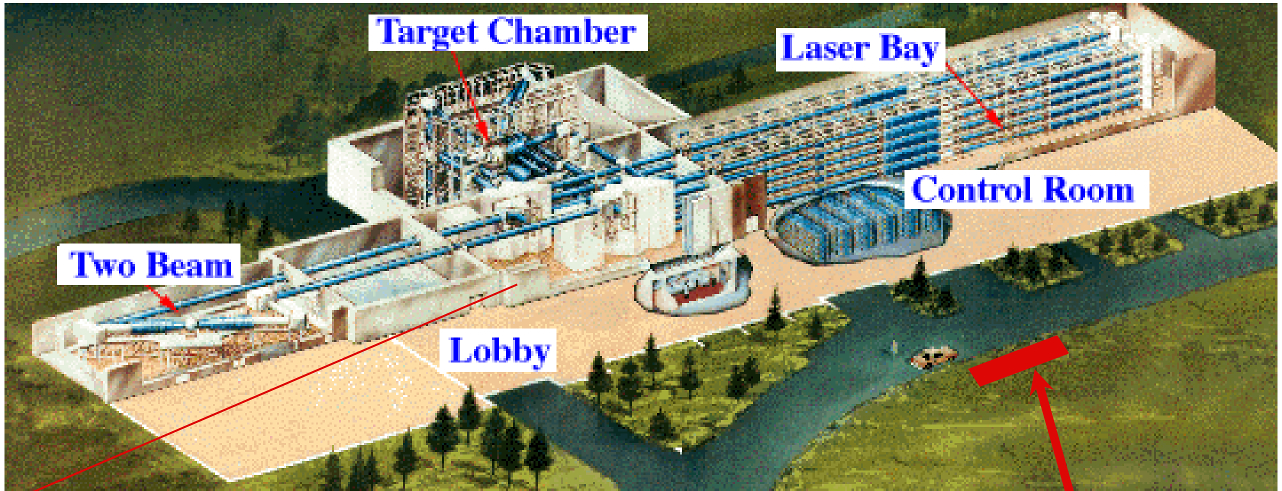
Experimental:

- **Simplicity**
- **Repetition Rates**
- **Easier verifiability/reproducibility**
- **All the above lead to 'robustness' of the experiment (averaging, systematics …)**

- **Larger participation (multiple groups, cross referencing)**

Ultrafast CPA Characteristics

- Compactness and high repetition rate



Nova
Pulse duration 1 ns
10 kJ/beam
10 beams @ 10 TW/beam = 100 TW
1 shot/hour

Ultrafast Ti:S Amplifier
Pulse duration 15 fs
1.5 J/beam
100 TW/pulse
36,000 shots/hour

HEDS –T^3

Why ???

Physics

- ➢Ultrafast excitations(<<100fs)
- ➢Easier temporal and Spatial Manipulation of Laser beam

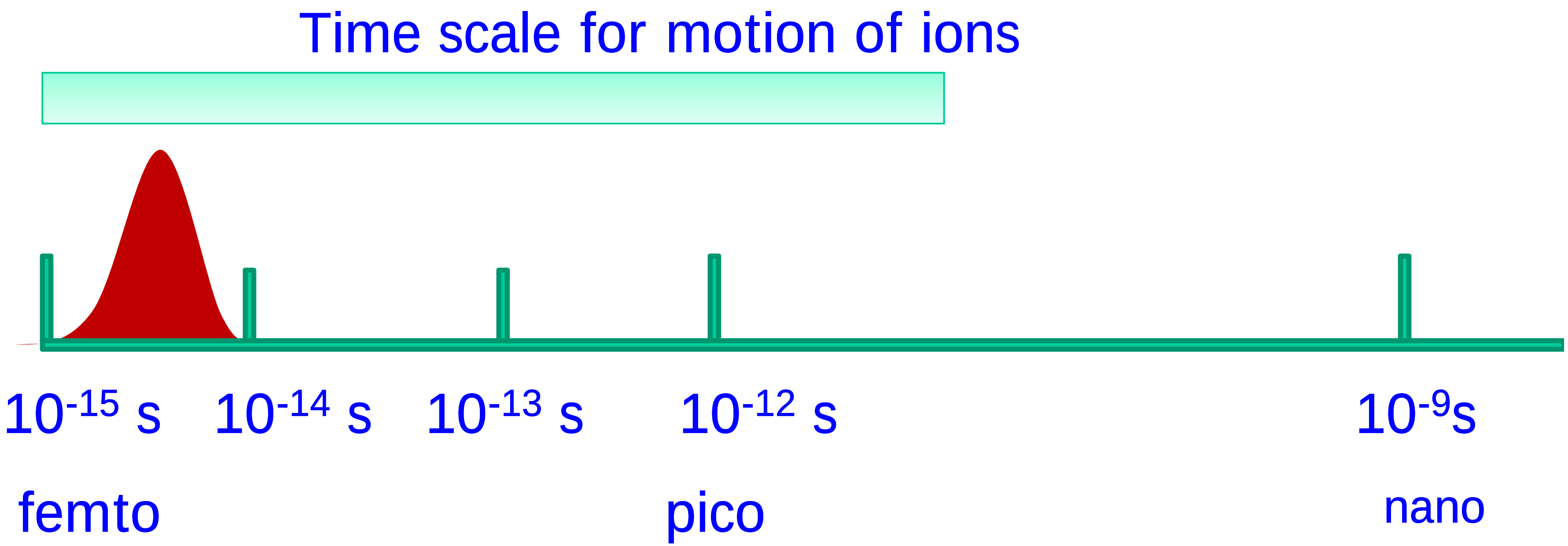
T^3 Spatial Profile (10-15 cm)

Non-T^3 Laser Spatial profile (0.5 to 1.0 meter!)

- ➢Steep gradient plasma [Ultrahigh contrast pulses (10^{-10})]
- ➢High repetition rates (0.1- 10 shots/sec as opposed to 1 shot/hour!)

Testing/matching/pushing PIC Simulations.

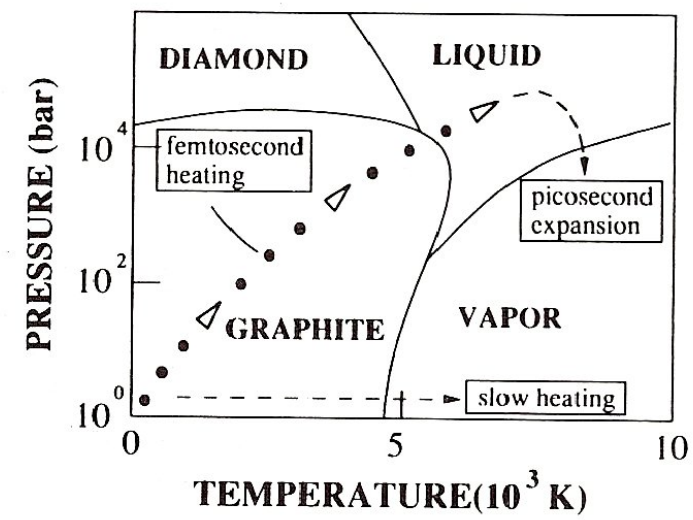
Femtosecond pulses excite matter before ions can move



HEDS-T ^{3}: Creating unusual states

Liquid carbon sighted !

First evidence - by fs, INTENSE light



NEWS AND VIEWS

Nature 1992

CONDENSED STATE

First light on fluid carbon

Nicolaas Bloembergen

RESEARCHERS at the University of Texas, Austin, may have caught the first, fleeting glimpse of fluid carbon. D. H. Reitze, H. Ahn and M. C. Downer describe in *Physical Review* (**B45**, 2677–2693; 1992) how both graphite and diamond can be melted momentarily by intense laser irradiation before expanding as a hot plasma.

The liquid phase of the element carbon is elusive, as it appears to exist in equilibrium only at temperatures of about 5,000 K and at pressures above several hundred atmospheres. The phase cannot be contained in any vessel, because all other materials melt or chemically react before the temperature required for the liquid state of carbon is reached. Clearly the structure of this state is of interest to those studying condensed matter physics, but because these conditions can be found in planetary interiors, it is also important for geophysics and astrophysics.

The first evidence for this phase came from experiments using pulsed ohmic heating of graphite electrodes. Shock-wave studies and pulsed-laser heating of graphite and diamond have also been tried (see F. B. Bundy's review in *Physica* **156A**, 169–178; 1989). Downer and colleagues used laser pulses lasting less than a picosecond (10^{-12} s) in their new experiments, both to create and to probe their fluid carbon.

It is well known that short, intense laser pulses are capable of turning any substance into a high-temperature, high-density plasma. By careful control of the energy fluence in the pump pulse it is possible to determine a threshold for melting as the first stage in the process of plasma formation. A second, probe pulse will be reflected or will generate second-harmonic (or frequency-doubled) light, and the change in either of these can be followed as a function of the pump fluence, the time elapsed, and the wavelength, polarization and angle of incidence of the probe. This parameterization gives detailed information on the changes in electronic structure of the

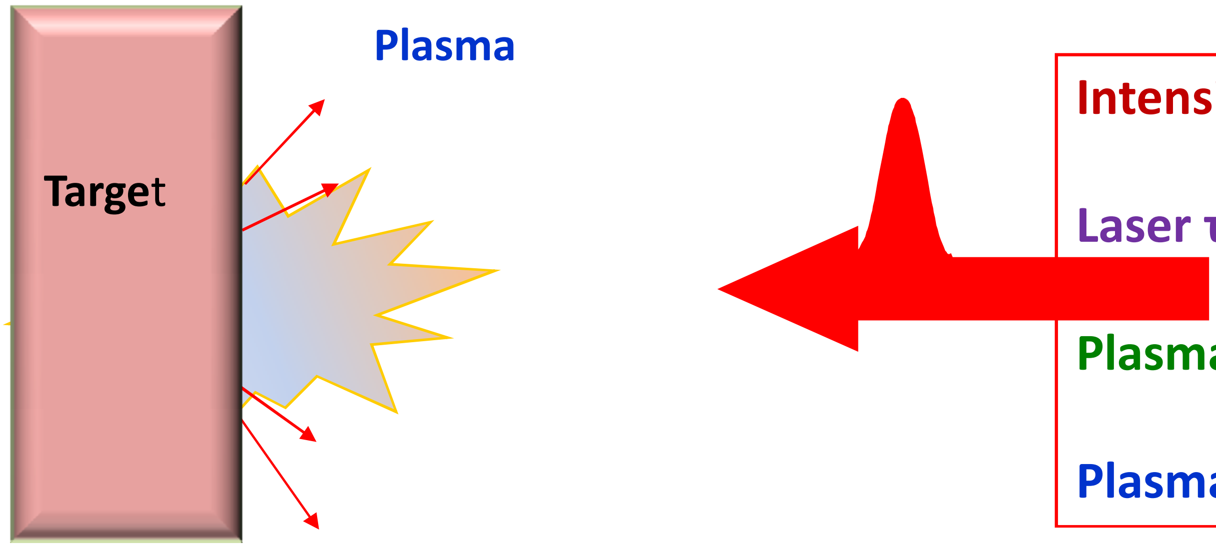
HEDS –T^3

HOW ???

Here is one example

Real Time Ultrafast Dynamics of Dense, Hot Matter Measured by Pump-Probe Doppler Spectrometry

Laser Plasma Interaction

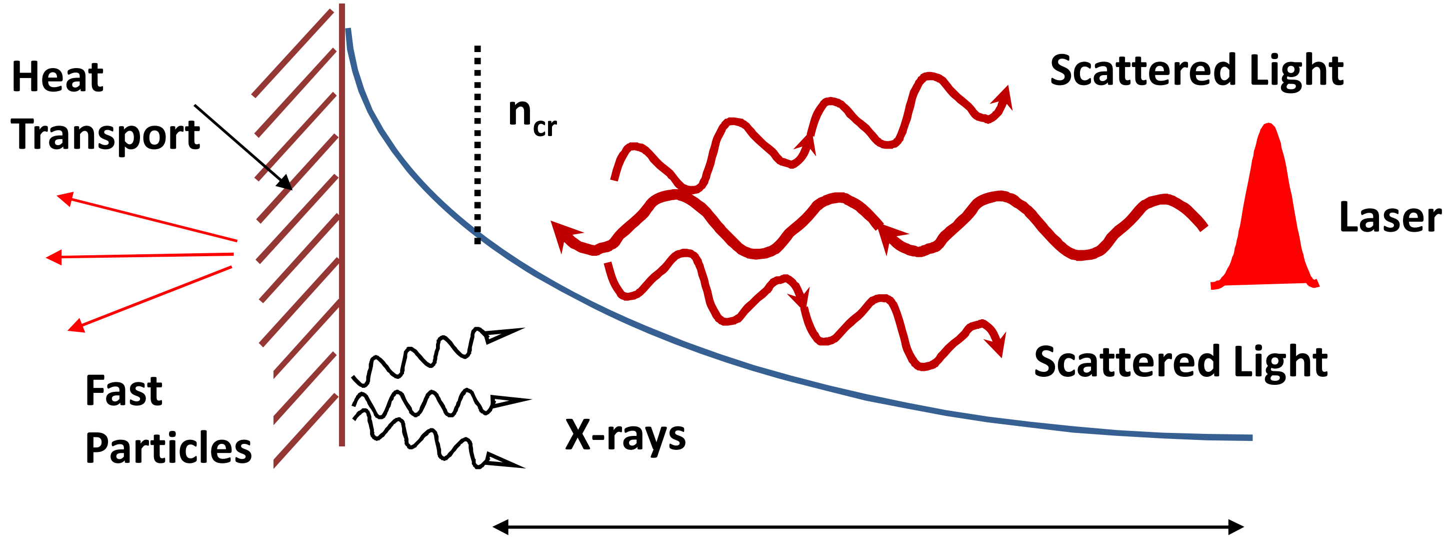


Intensity : 10^{18} W/cm^2

Laser τ : 30 X 10^{-15} s

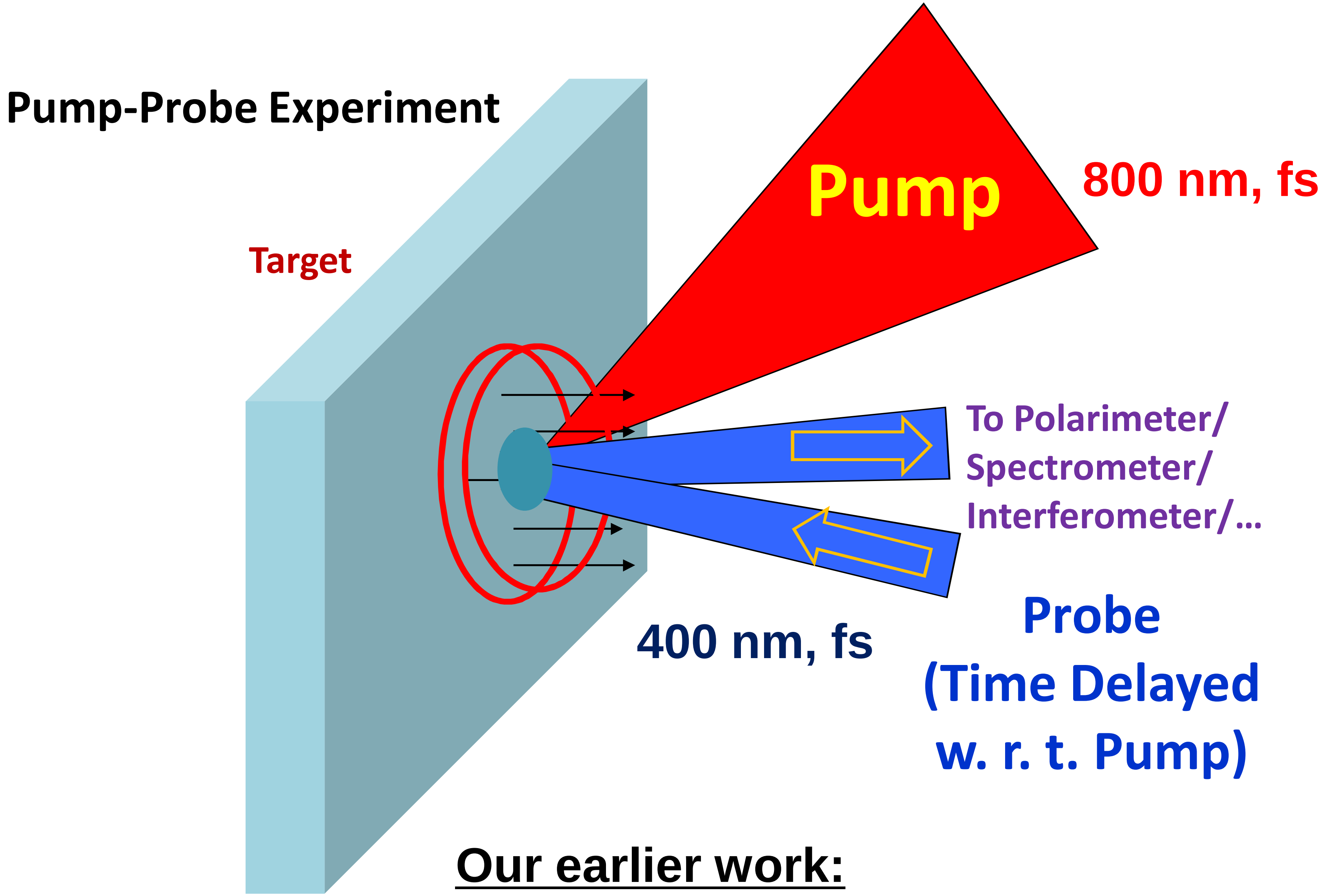
Plasma T : 10^2 / 10^5 eV

Plasma Velocity : 10^7 -10^8 cm/s



Plasma Dynamics – Extremely Important

Need to See Plasma Dynamics "as it happens"



Our earlier work:

PRL (2002): PRE (2006); POP (2009)

Ultrafast Plasma Dynamics

Plasma motion occurs at very high velocity

(> 10^7 cm/sec)

So plasma profile changes rapidly

This implies, plasma conditions change significantly during laser interaction

Motivation

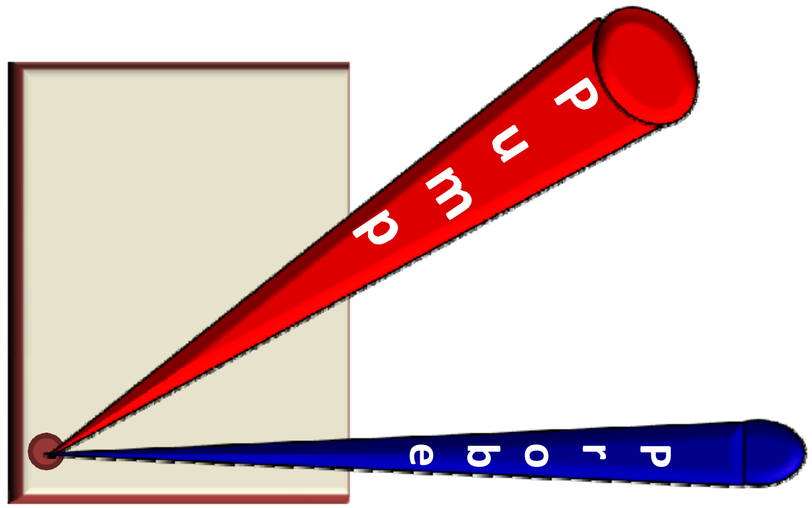
To Estimate

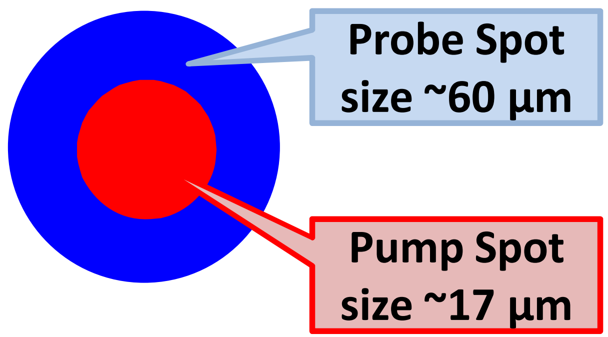
the Plasma Expansion Velocity and

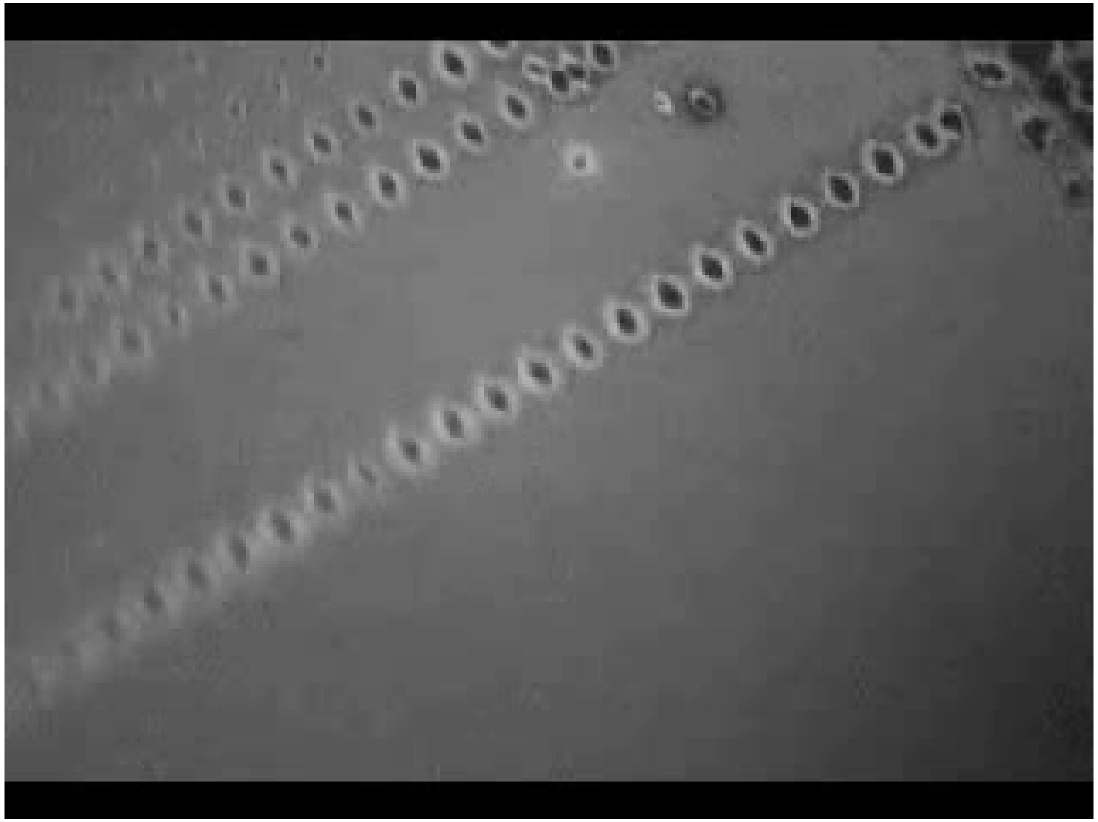
thereby

the Instantaneous Plasma Profile

Spatial Matching of Two Beams







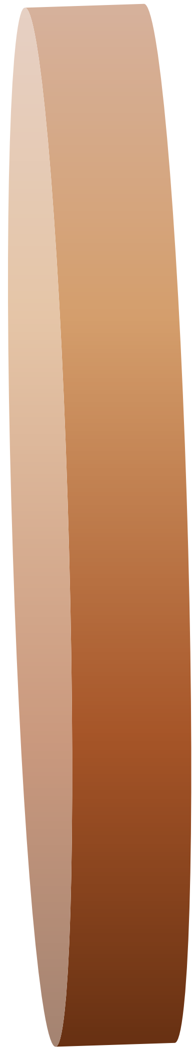
Idea of pump-probe geometry

Probe ahead of pump
Reflects from Metal

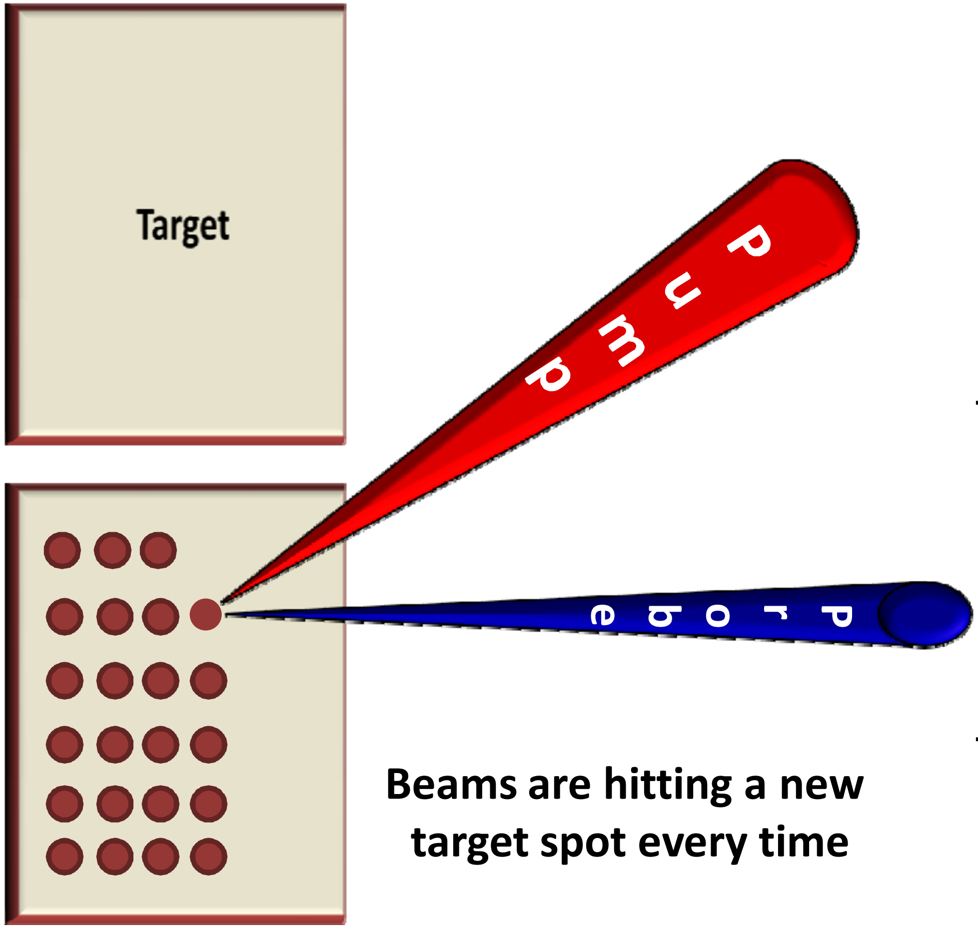
No plasma contribution as yet

Pump Probe Overlapped
Time = 0
Partly reflected from plasma

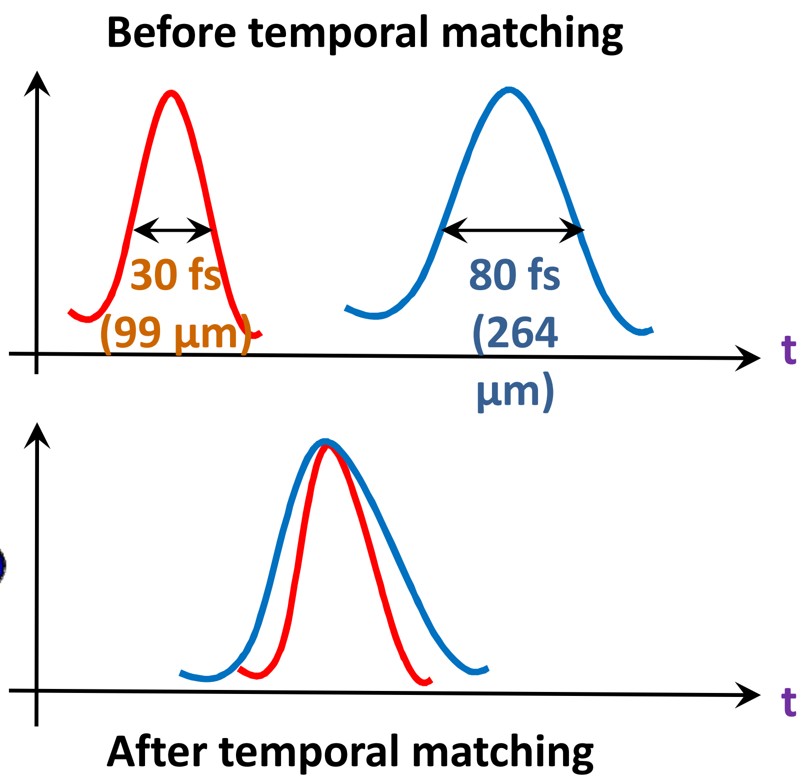
Now probe reflected from plasma
formed by the pump
Studying evolution of plasma



Temporal Matching of Two Beams

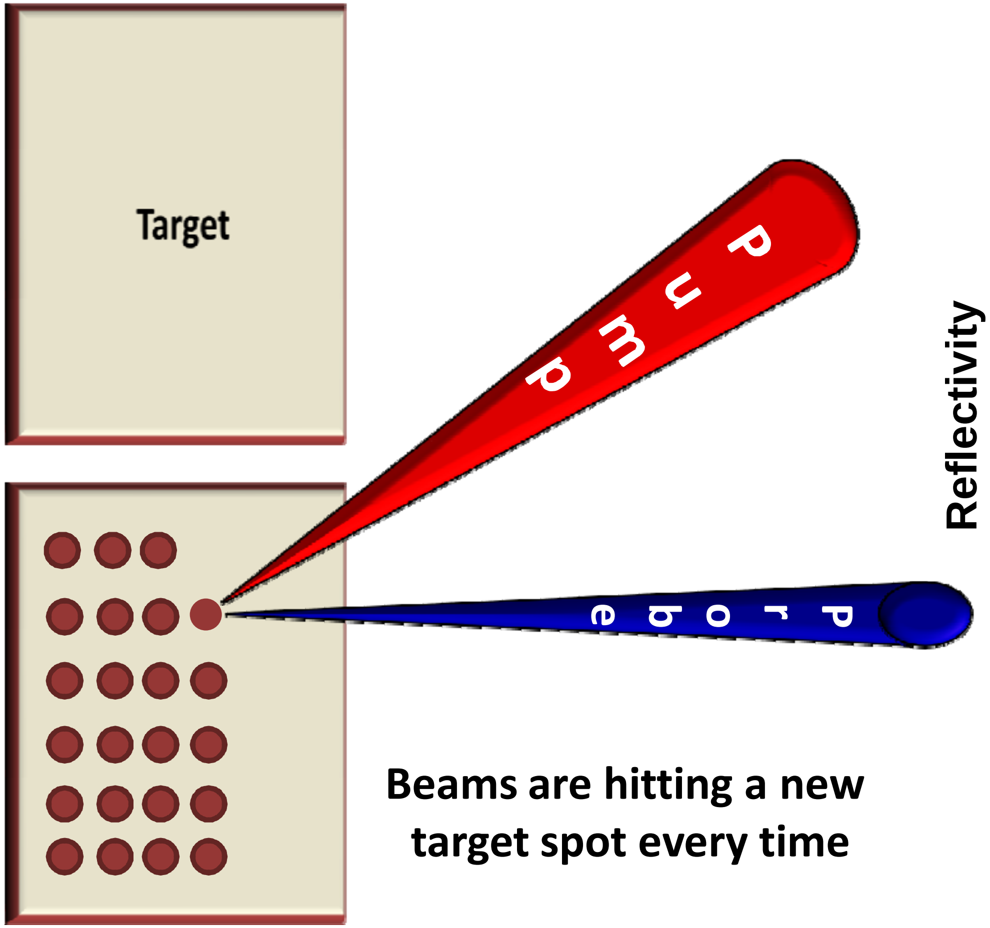


Beams are hitting a new target spot every time

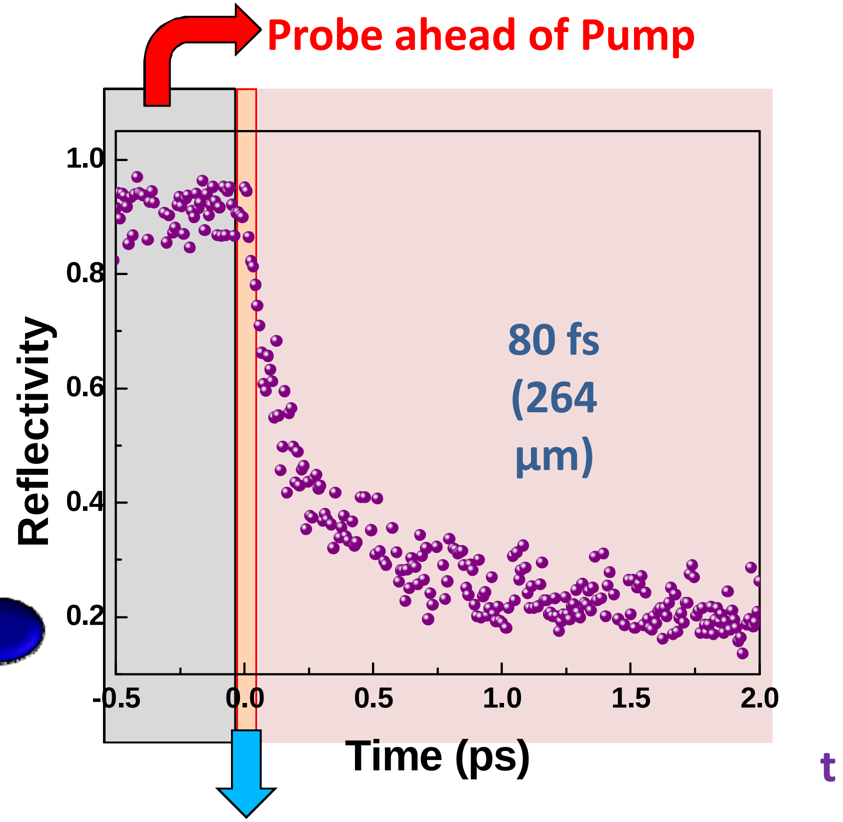


Many Interesting results on time resolved reflectivity
in the *Posters of Prashant K. Singh and Gourab Chatterjee on Thursday*

Temporal Matching of Two Beams



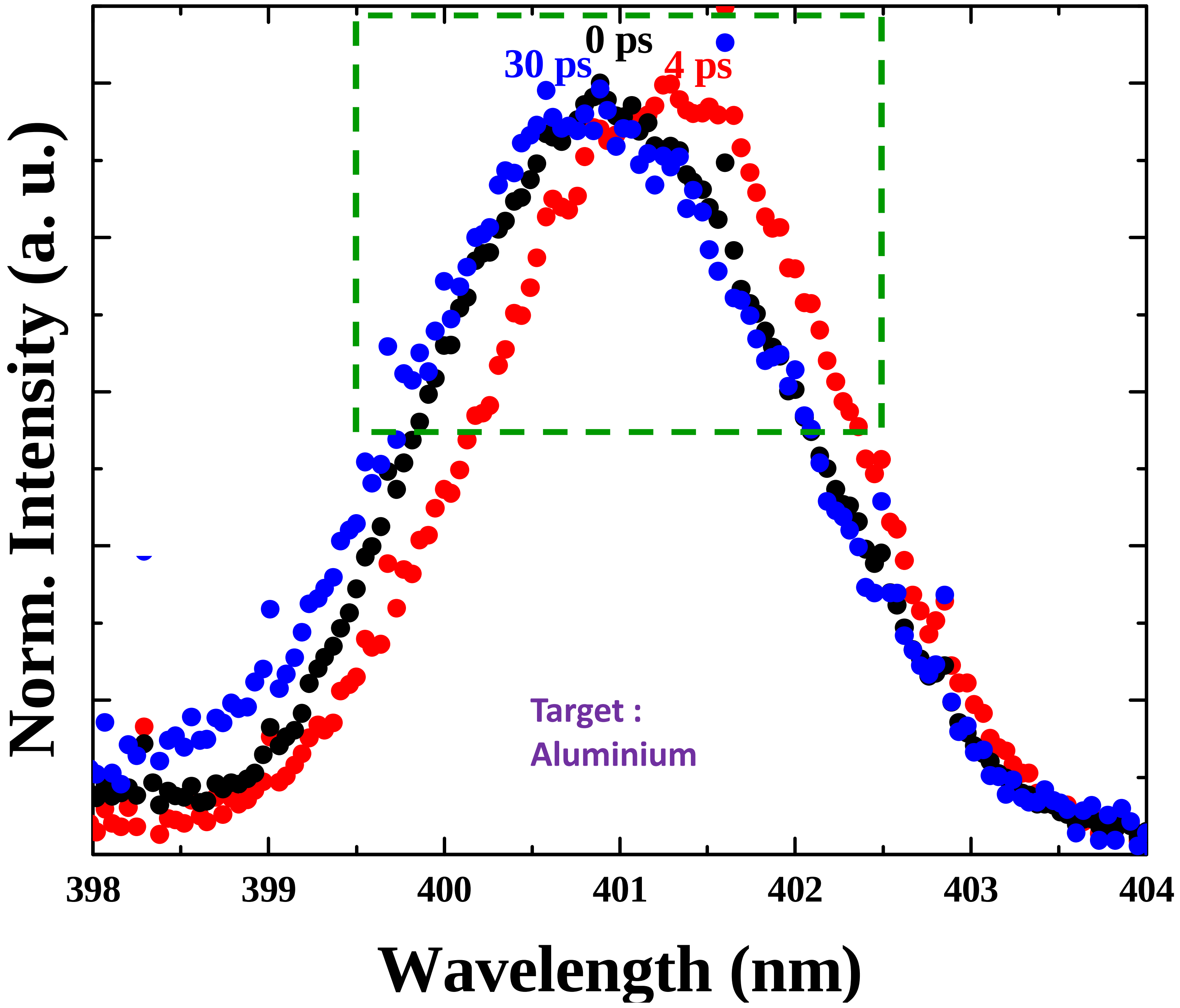
Beams are hitting a new target spot every time



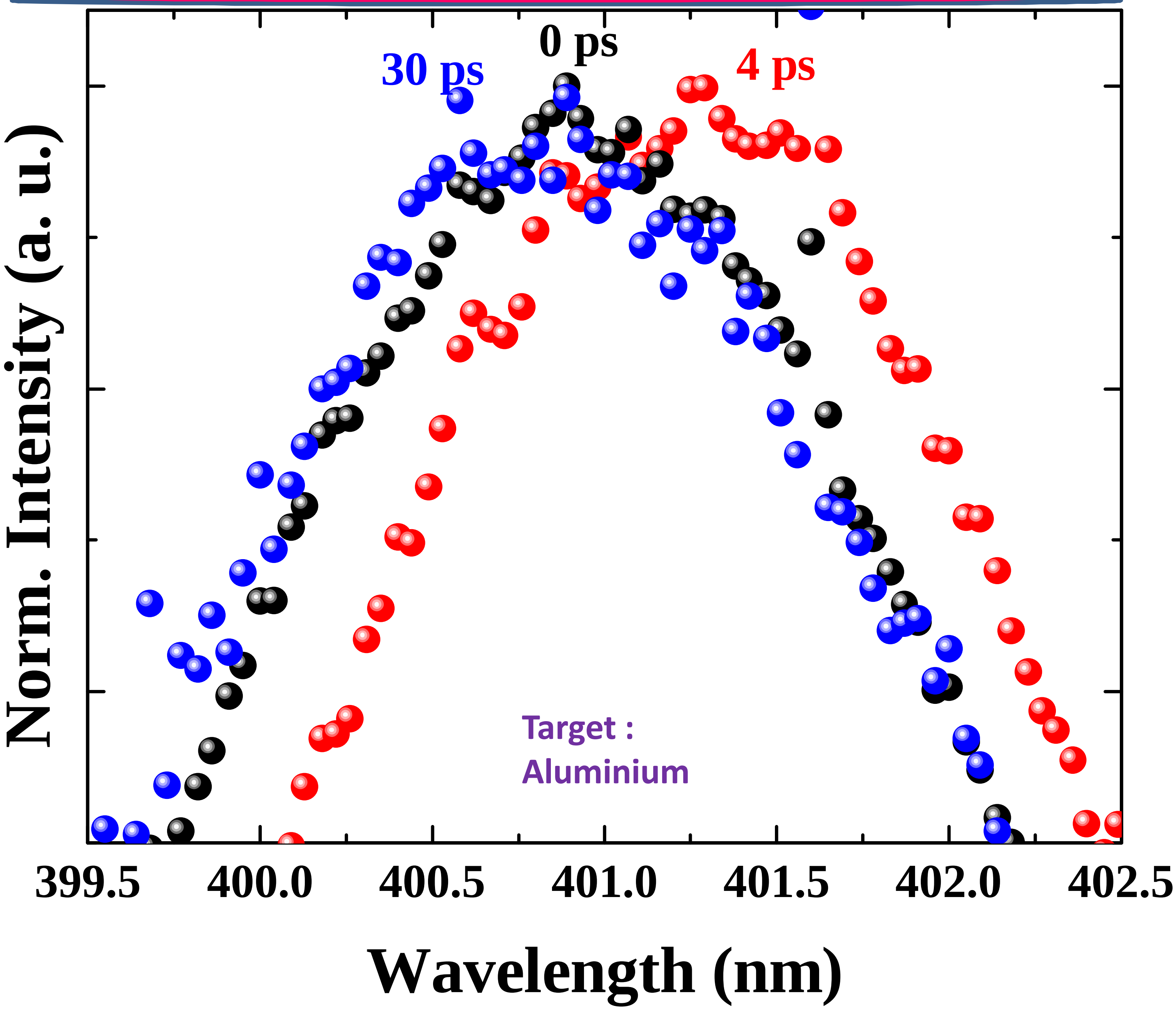
Pump and Probe arrive at the same time

Many Interesting results on time resolved reflectivity
in the *Posters of Prashant K. Singh and Gourab Chatterjee on Thursday*

Time Delayed Spectra



Time Delayed Spectra

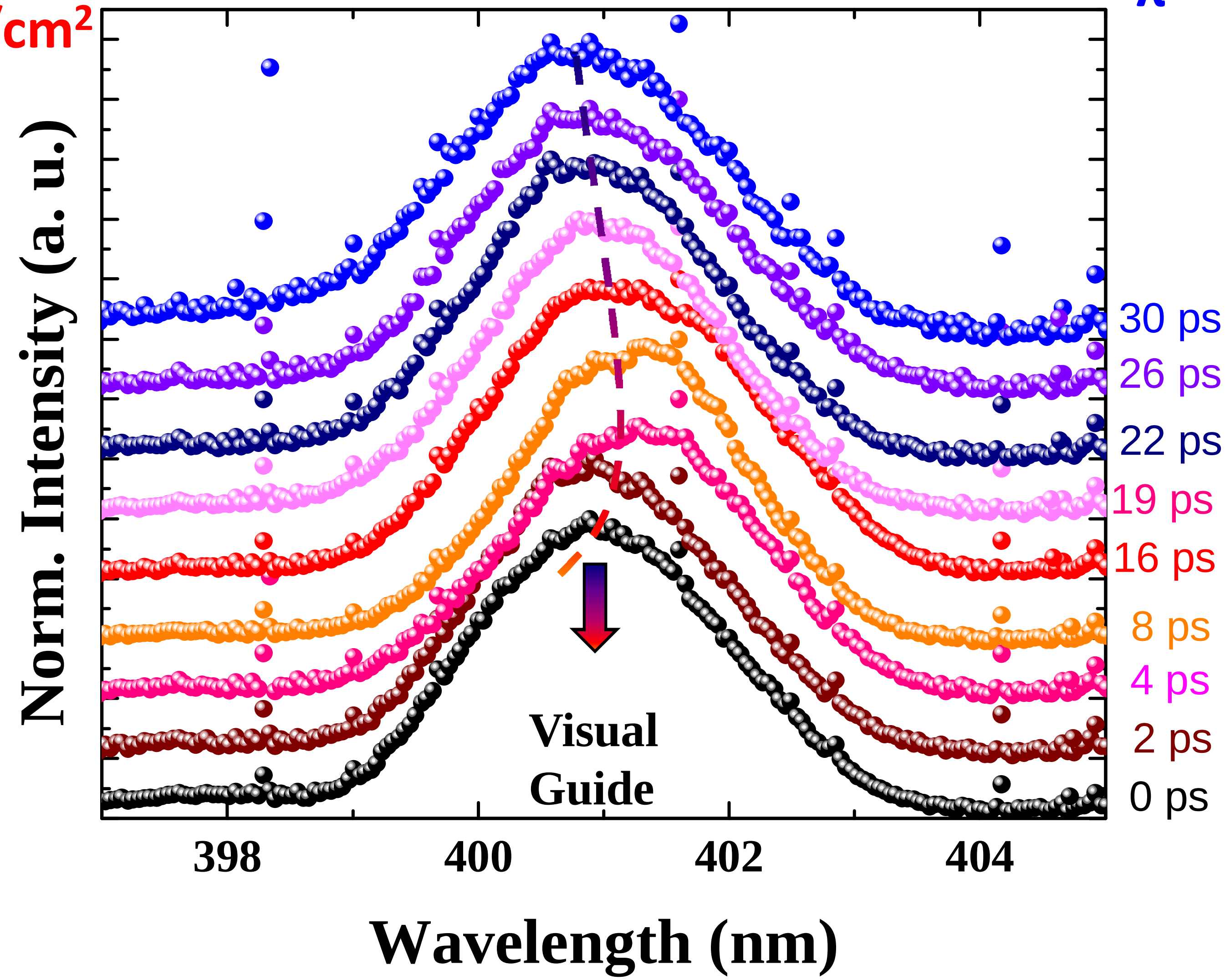


Dynamics Over 30 ps

Pump:
800 nm,
3 x 10^{18} W/cm^2

Target : Aluminium

Probe:
λ = 400 nm

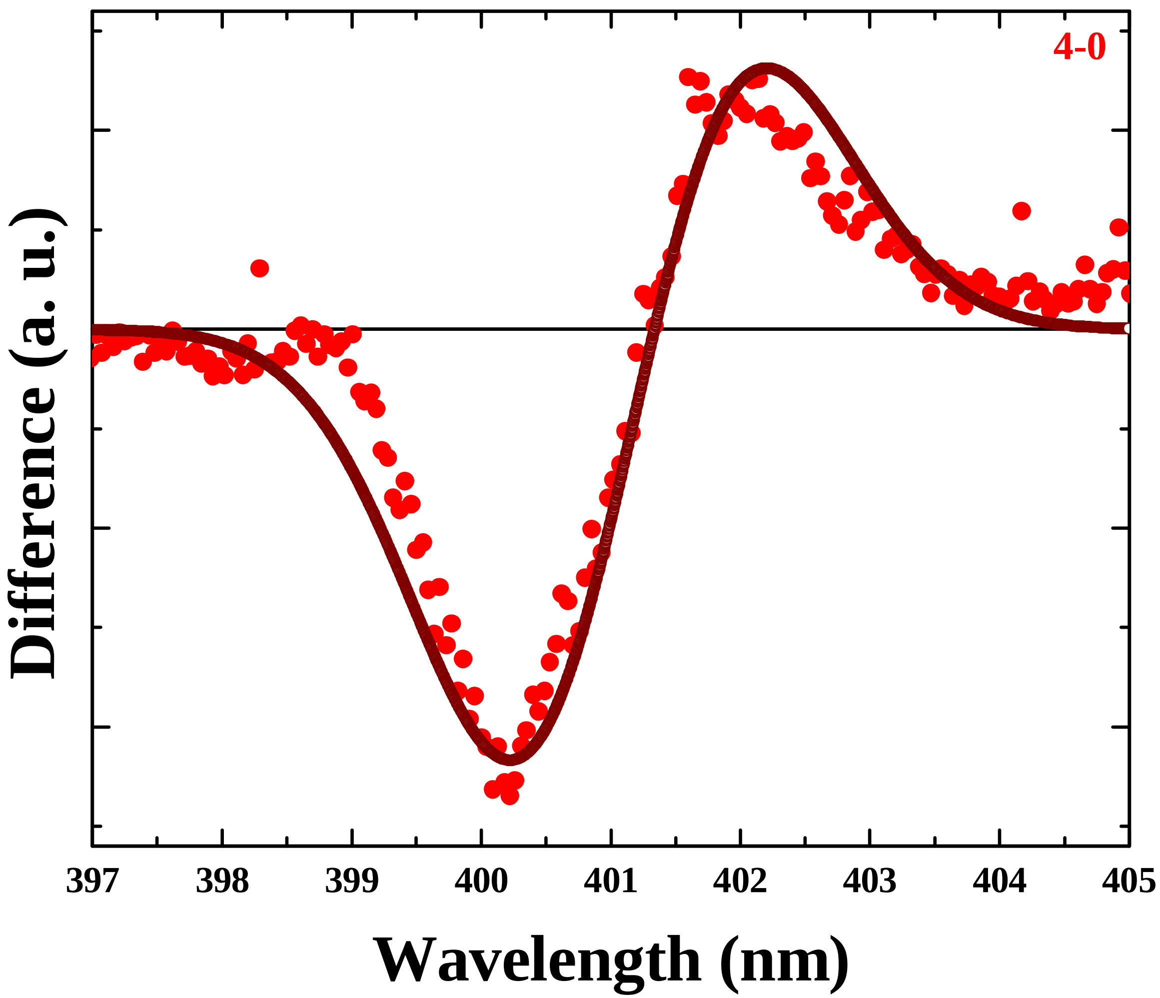


To Observe Small Shifts it is Better to Observe Differences

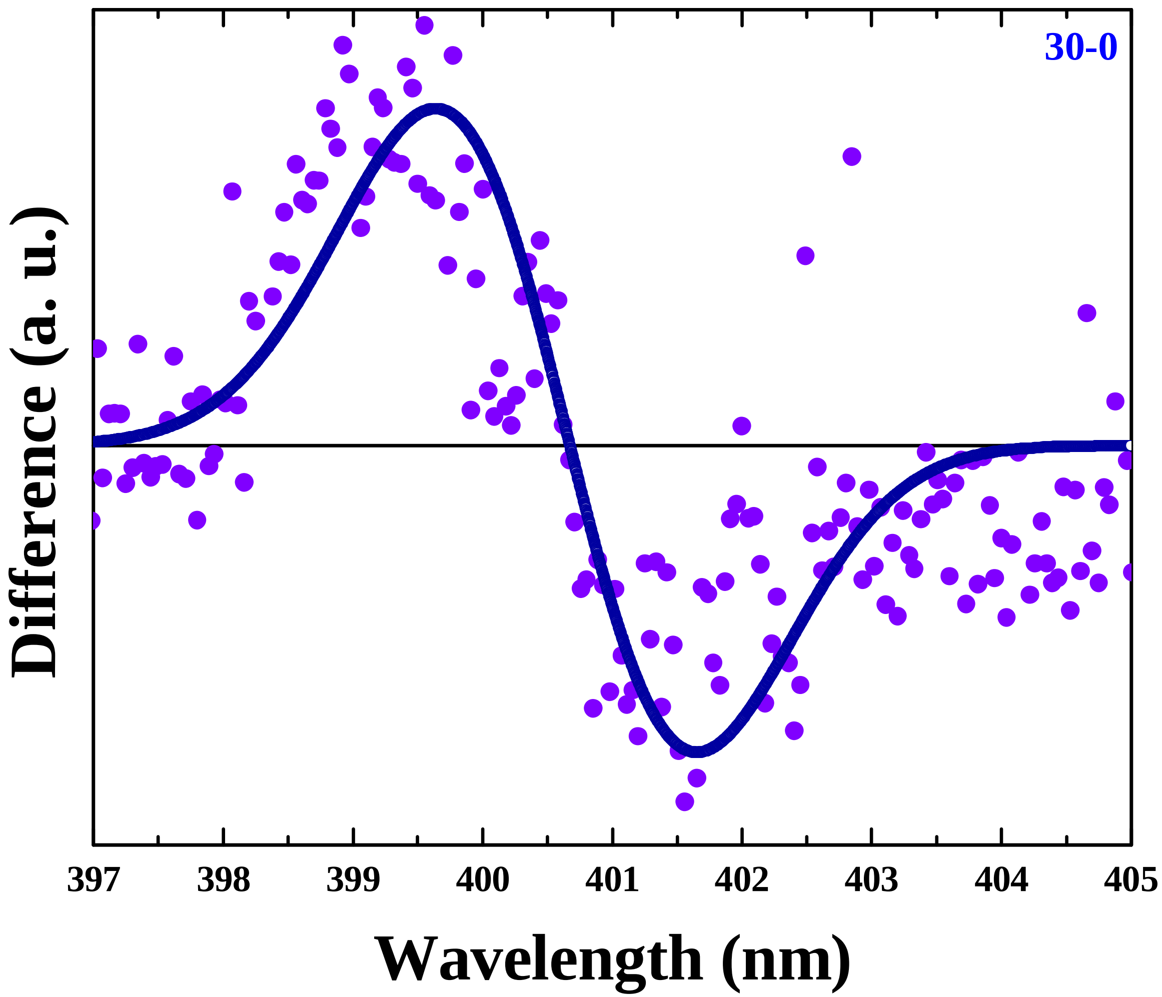
i.e.

Time Delayed Probe Spectrum – Reference Probe Spectrum

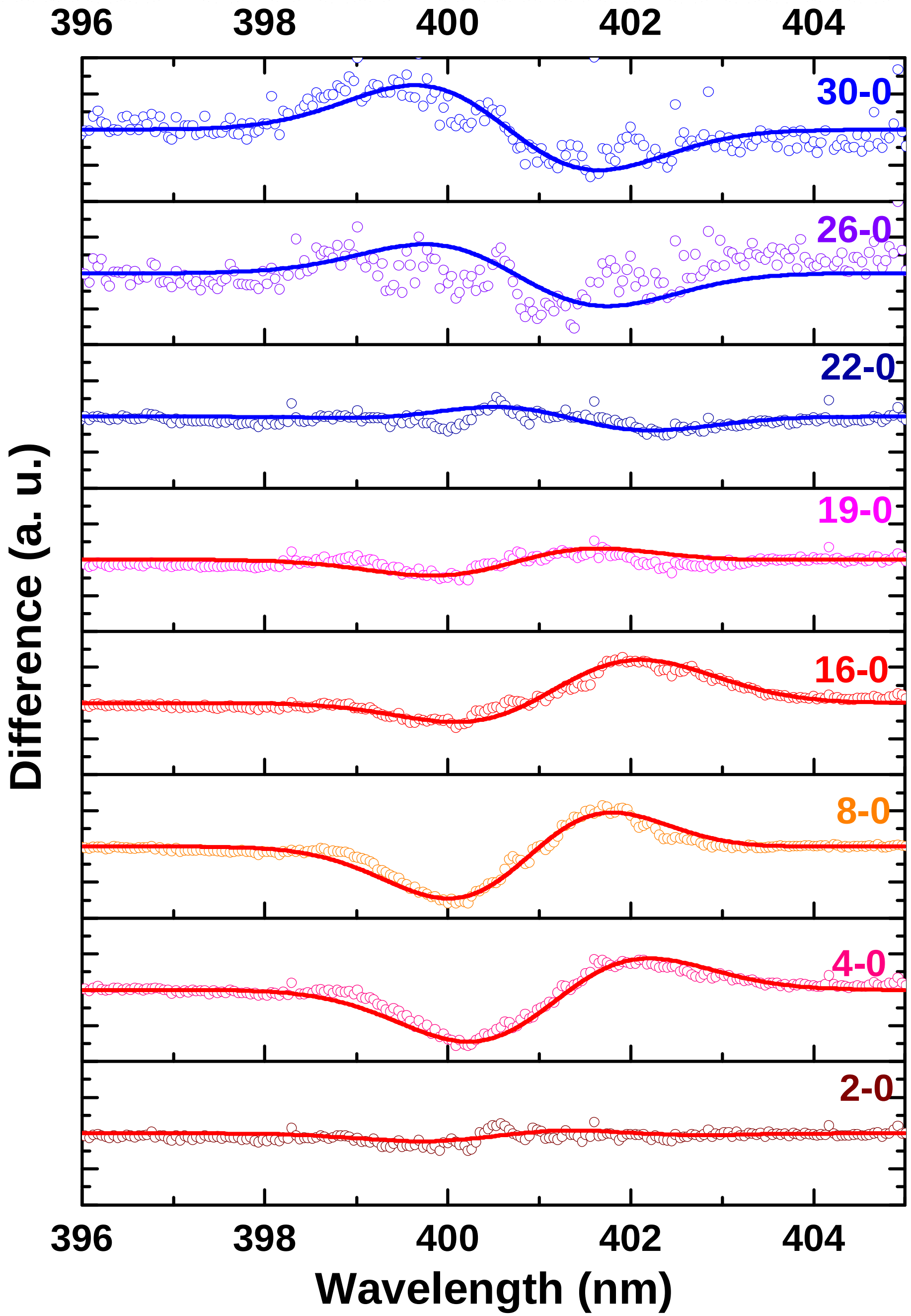
If the time delayed spectrum is red-shifted with respect to zero time delayed spectrum :
subtracted spectrum (later spectrum - zero time delay spectrum) will show minima followed by maxima



If the time delayed spectrum is blue-shifted with respect to zero time delayed spectrum :
subtracted spectrum (later spectrum-zero time delay spectrum) will show maxima followed by minima



Dynamics Over Time Scale of 30 ps



Doppler Shift

Why Red Shift ???

The pump laser launches a compression wave into front surface plasma

At early times compression wave forces the critical surface into the target

Doppler Shift

Why Blue Shift ???

At later times a compression wave has propagated into

a region of overdense plasma

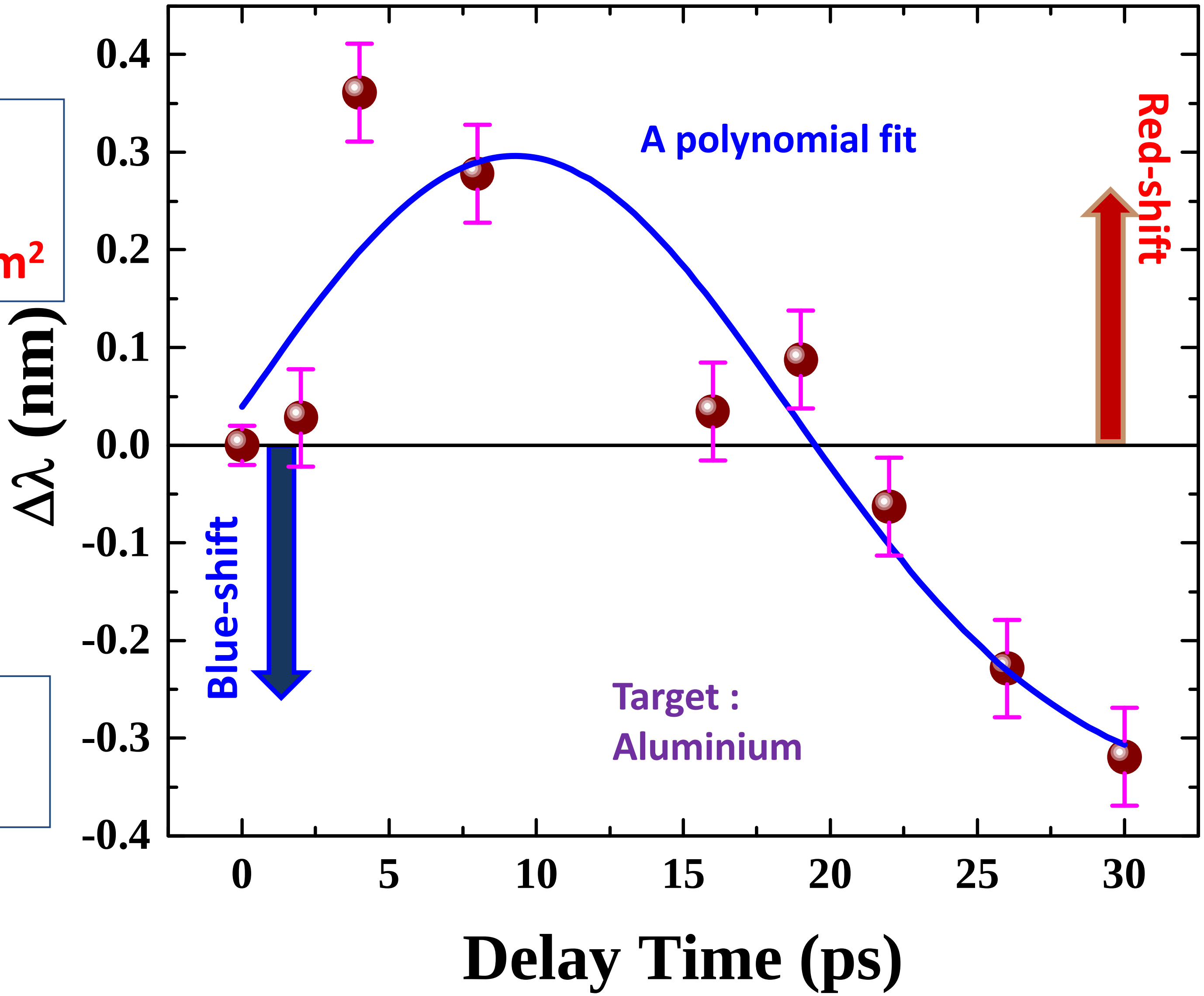
Critical surface of the probe sits in the region that is undergoing rarefaction,

thus critical surface is moving into the vacuum and towards the laser

Doppler Shift in Reflected Probe Spectra

Pump:
800 nm,
3 x 10^{18} W/cm^2

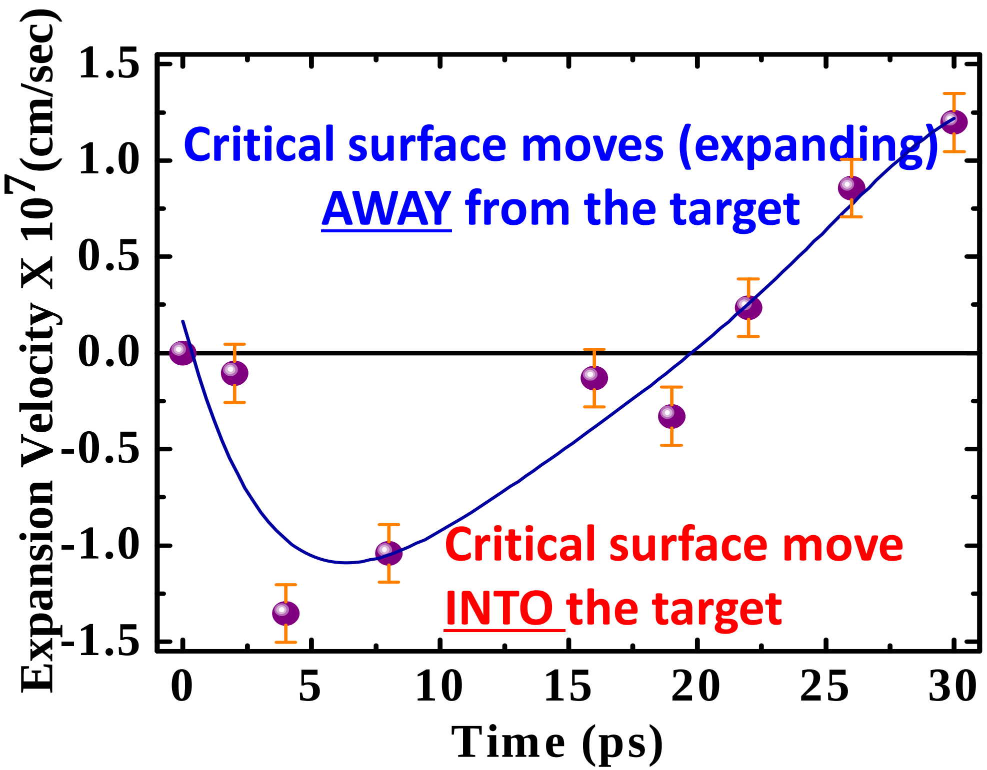
Probe:
400 nm



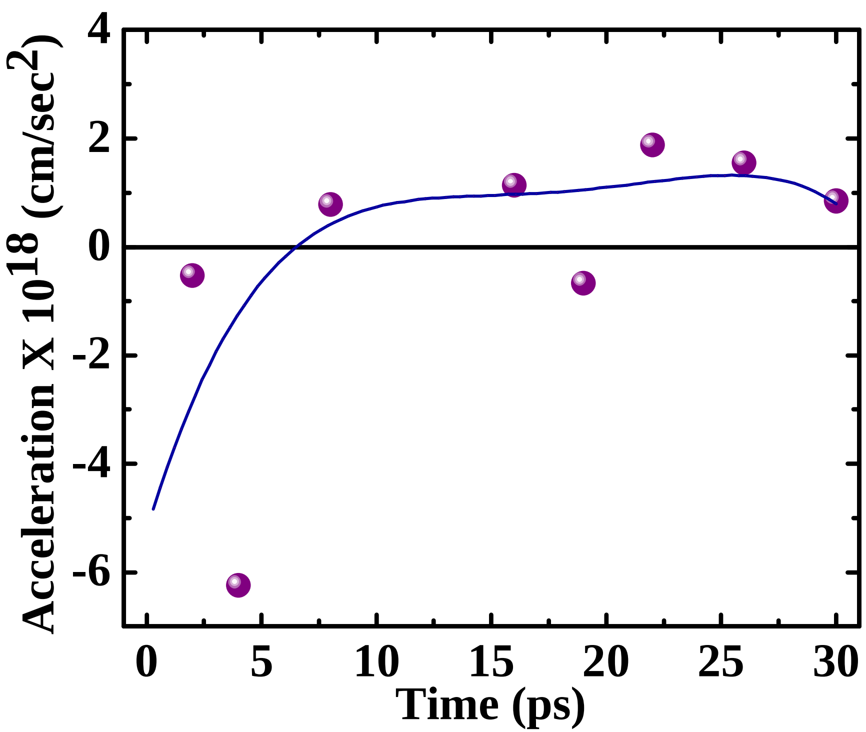
Velocity and Acceleration from Doppler Shift

Instantaneous

Velocity



Acceleration



$$V_{expansion} = 0.5c\,(\Delta\lambda / \lambda)\,(1/\cos\theta)$$

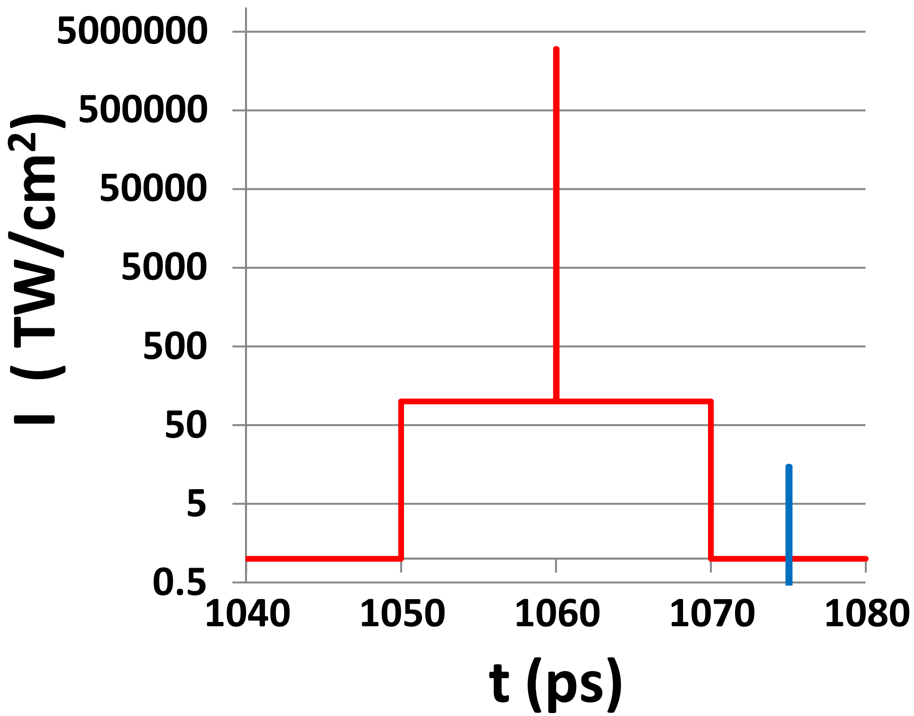
Doppler Shift : Simulations

1D PIC+1D Hydrodynamic Simulations : HYADES

Results of PIC simulation as input of HYADES

500 µm Al target : 100 Lagrangian cells

Two different Laser Sources : 800 nm and 400 nm



Red line is 800 nm pump profile

Blue line is 400 nm probe profile

Pump main pulse is 30 fs flat top

Probe is 80 fs flat top

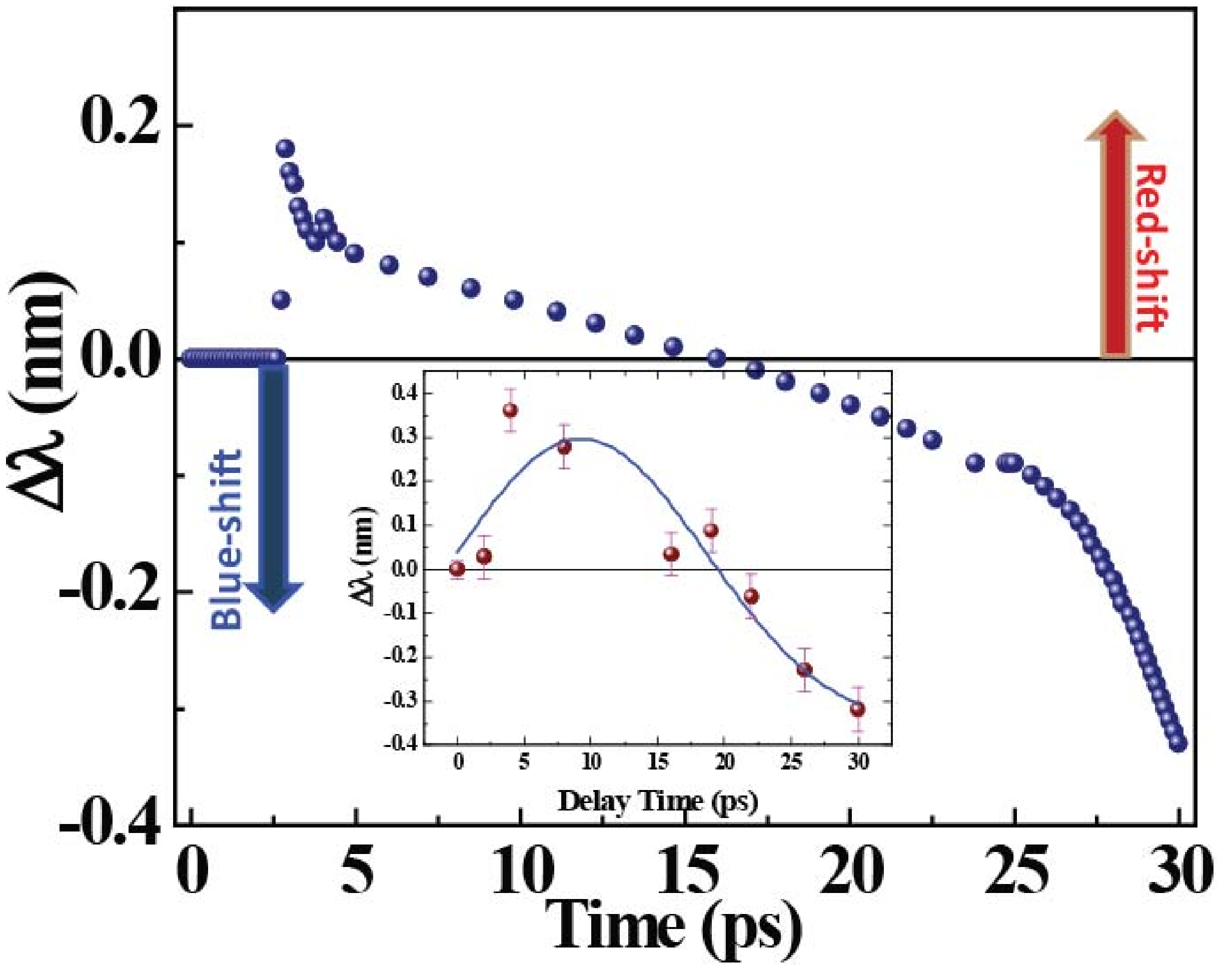
Simulations by : John Pasley

Doppler Shift in Reflected Probe Spectra

Pump:
λ = 800 nm

Probe:
λ = 400 nm

Target : Aluminium



$$\Delta\lambda = \frac{2\dot{x}_{crit}\lambda_{probe}}{c}$$

Doppler Spectrometry for Ultrafast Temporal Mapping of Density Dynamics in Laser-Induced Plasmas

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J. Pasley
Department of Physics, University of York, Heslington, York, United Kingdom
Central Laser Facility, Rutherford-Appleton Laboratory, Chilton, Oxfordshire, United Kingdom

P. P. Rajeev and A. P. L. Robinson
Central Laser Facility, Rutherford-Appleton Laboratory, Chilton, Oxfordshire, United Kingdom

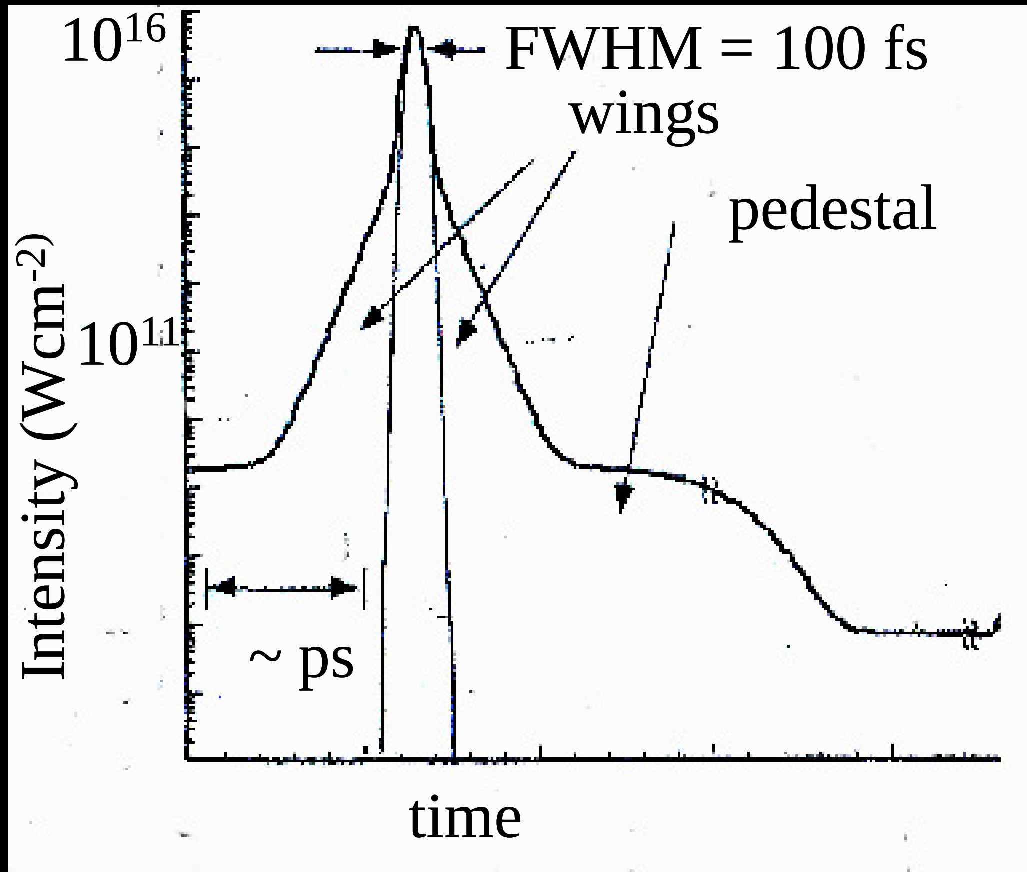
G. Ravindra Kumar*
Tata Institute of Fundamental Research, 1 Homi Bhabha Road, Colaba, Mumbai—400005, India
(Received 19 October 2009; revised manuscript received 25 May 2010; published 30 August 2010)

We present high resolution measurements of the ultrafast temporal dynamics of the critical surface in moderately overdense, hot plasma by using two-color, pump-probe Doppler spectrometry. Our measurements clearly capture the initial inward motion of the plasma inside the critical surface of the pump laser which is followed by outward expansion. The measured instantaneous velocity and acceleration profiles are very well reproduced by a hybrid simulation that uses a 1D electromagnetic particle-in-cell simulation for the initial evolution and a hydrodynamics simulation for the later times. The combination of high temporal resolution and dynamic range in our measurements clearly provides quantitative unraveling of the dynamics in this important region, enabling this as a powerful technique to obtain ultrafast snapshots of plasma density and temperature profiles for providing benchmarks for simulations.

DOI: 10.1103/PhysRevLett.105.105002 PACS numbers: 52.38.−r, 52.50.Jm, 52.65.−y

How short is a femtosecond pulse ?

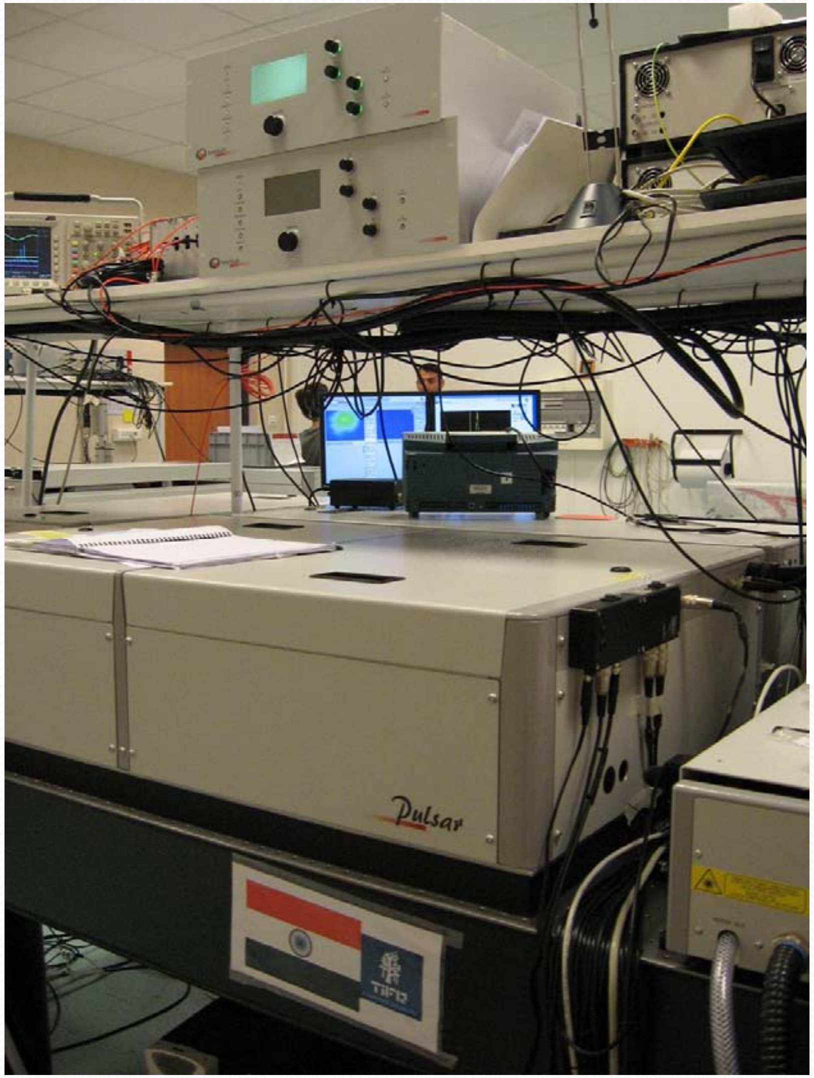
Uncompressed parts – pedestal

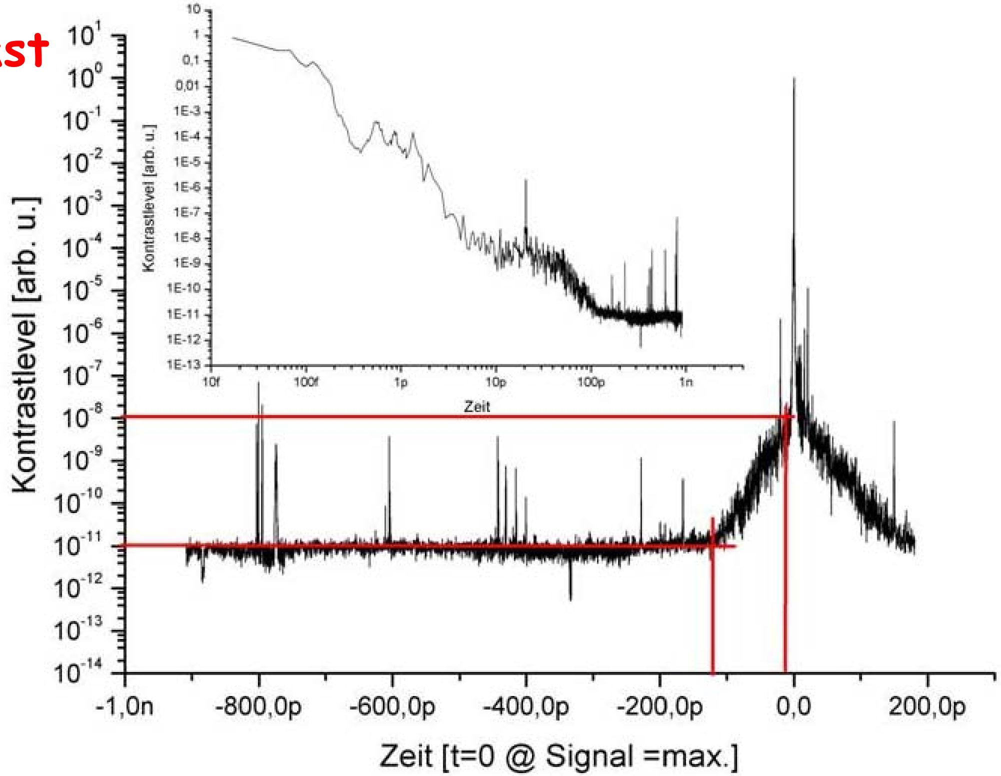


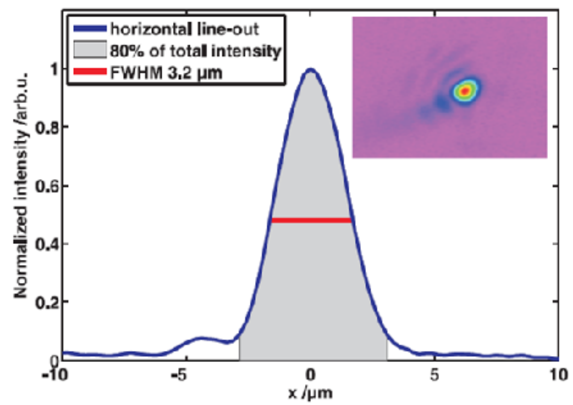
Picosecond pedestal : 10^{-5} times weaker

Can they form plasma before the main pulse arrives ?

100TW, 25 fs, high contrast laser at TIFR (2011)

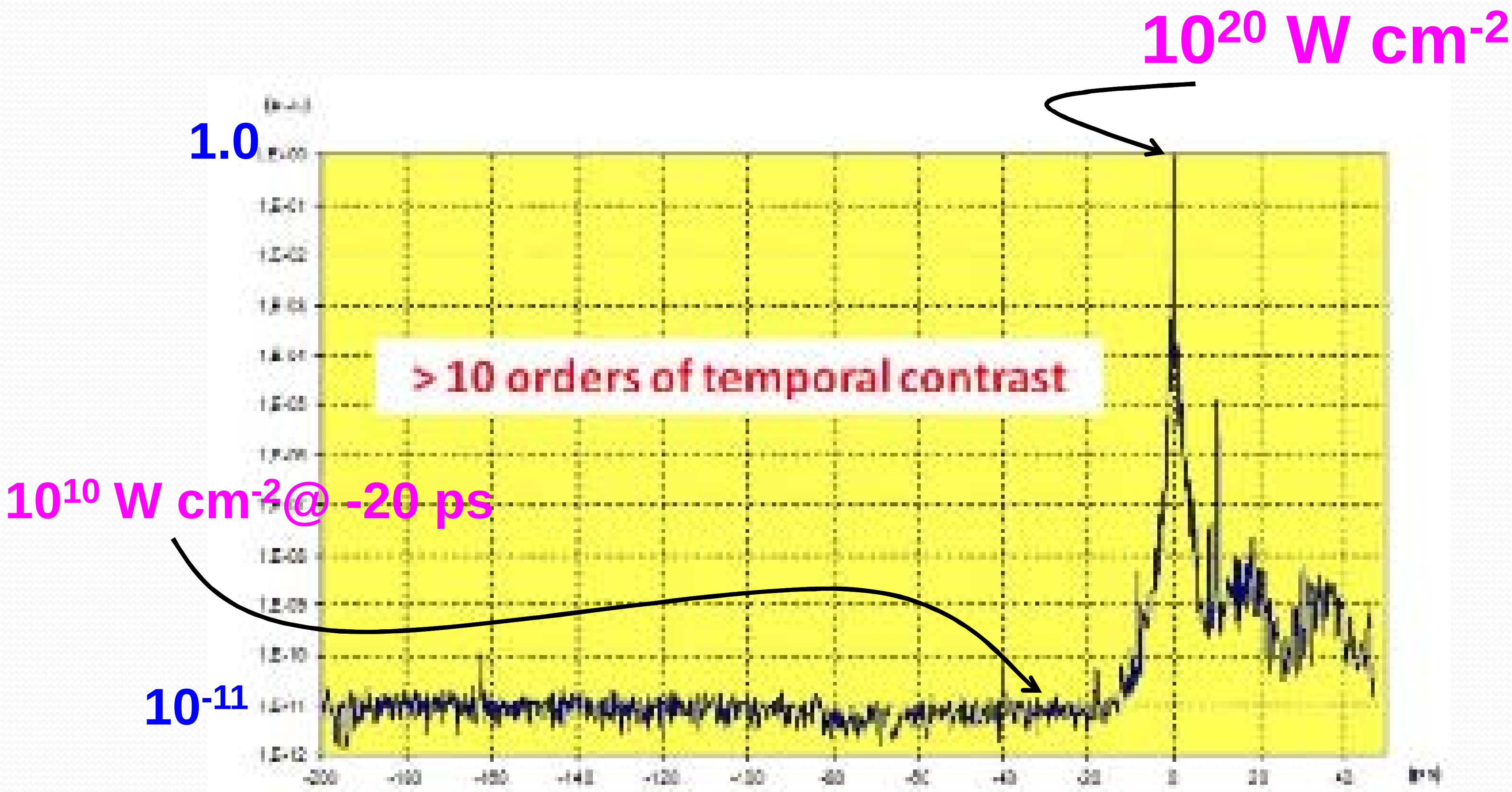






New experiments planned

- Establishing basic physics with ultrasteep pulses with solids, clusters and mesoscopic matter



Invitation!

- Please ask more questions about the experimental techniques in the Discussion Session in the afternoon today

ICTP-IAEA College on Plasma Physics October 2012
Lectures by G. Ravindra Kumar, TIFR Mumbai

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2. High energy density science (HEDS) experiments with table top terawatt lasers: the why and how –

3. Physics issues and challenges in HEDS with table top lasers: some examples- *TOMORROW!*