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High Energy Density Science

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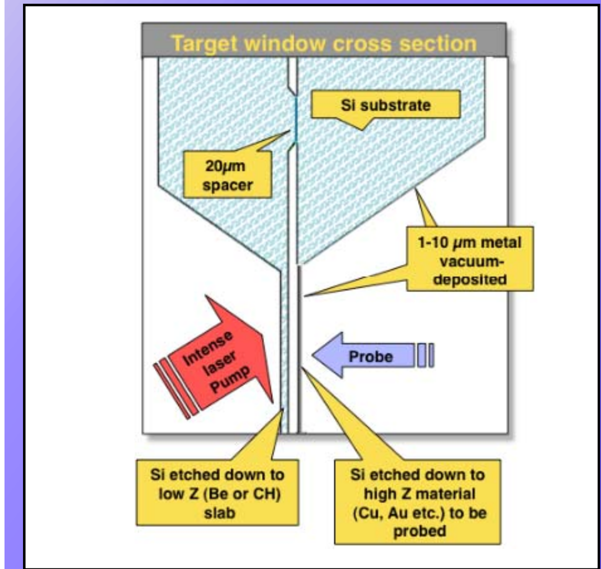

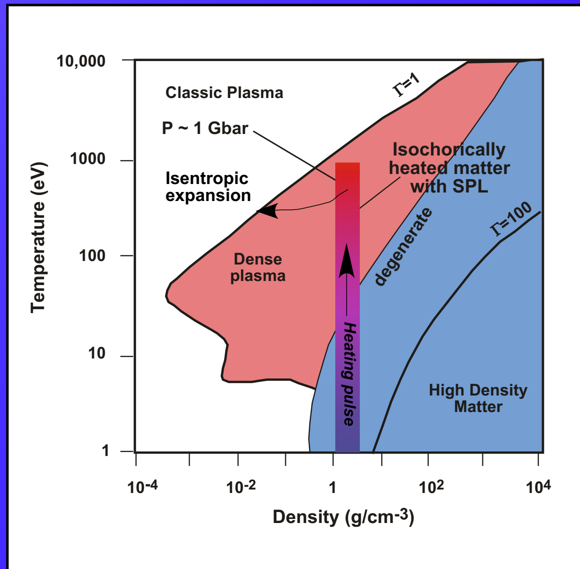

Presented by:

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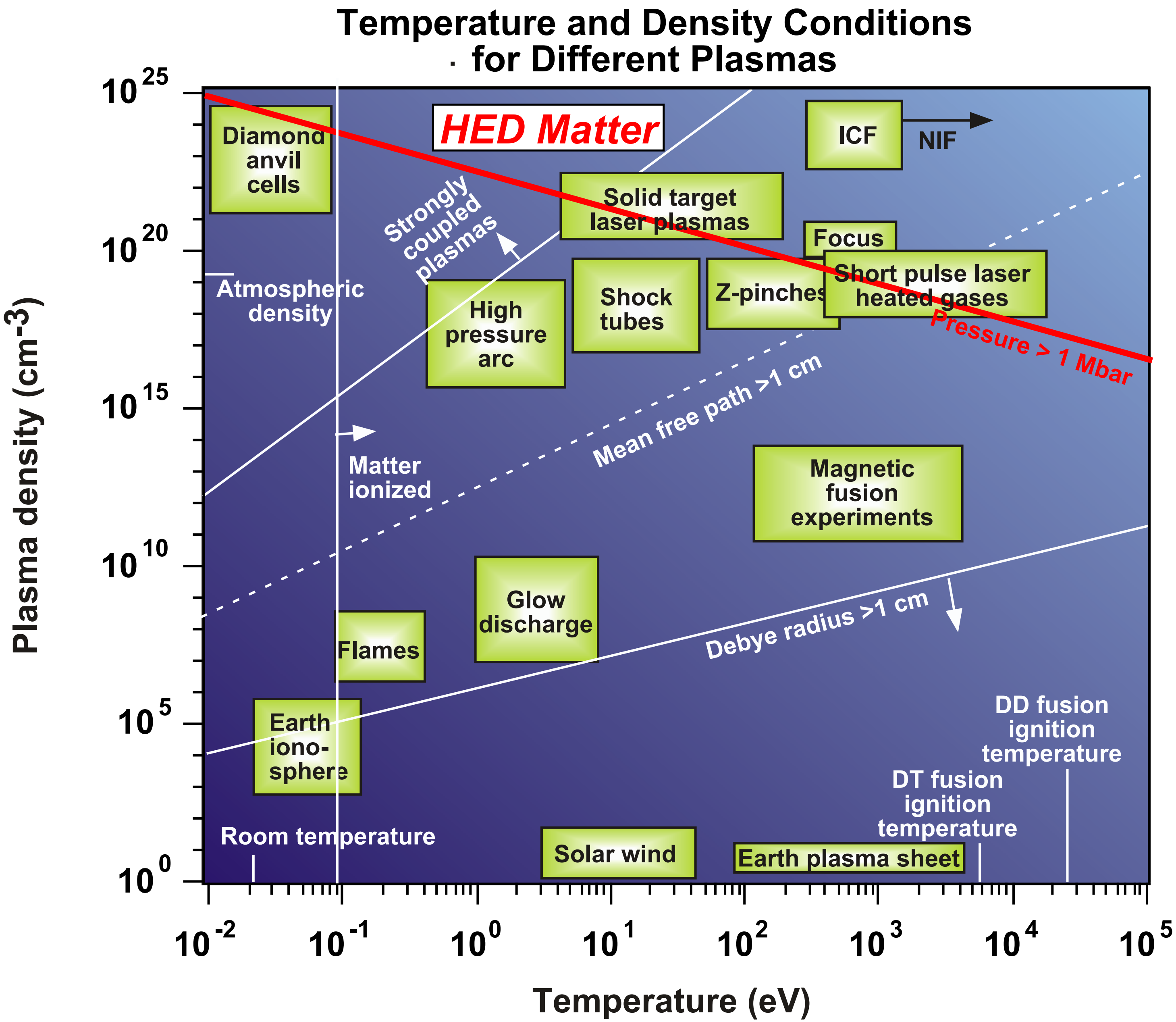
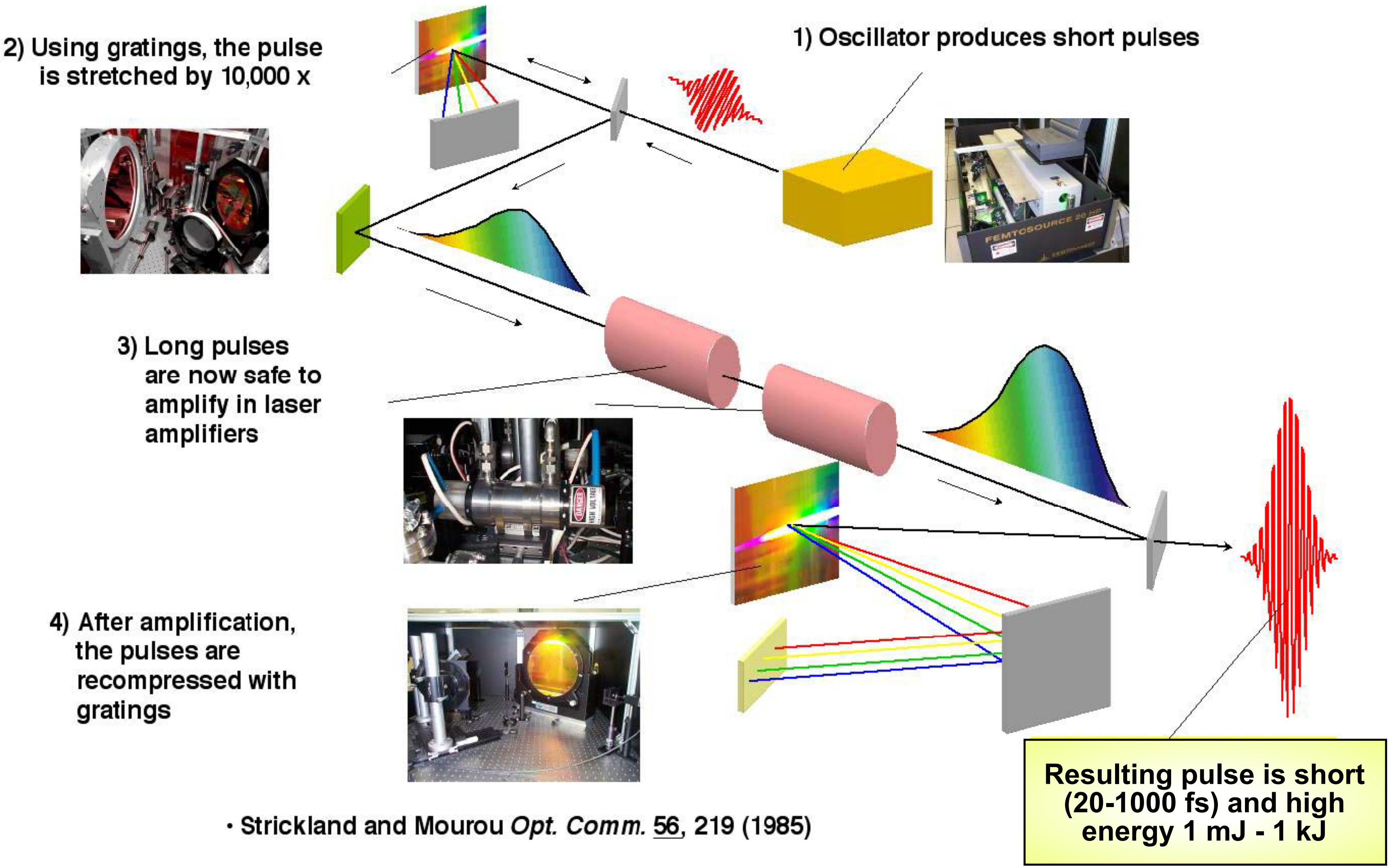
"High Energy Density Physics" can be roughly defined as study of matter at energy density 10^{11} J/m^3

High Energy Density Parameter	Value yielding equivalent to 1 Mbar – Energy density of 10^{11} J/m^3
Plasma density with T = 1 keV (10^7 K)	6×10^{20} cm^{-3}
Plasma temp at solid density ($n \approx 10^{23}$ cm^{-3})	6 eV
Electromagnetic wave intensity	3×10^{15} W/cm^2
Electric field strength	1.5×10^{11} V/m
Magnetic field strength	500 T
Blackbody radiation temperature	400 eV
Current density for 100 MeV electrons	30 MA/cm^2
Laser intensity to yield 1 Mbar ablation pressure	4×10^{12} W/cm^2

High energy density matter is created by heating dense plasma to very high temperature

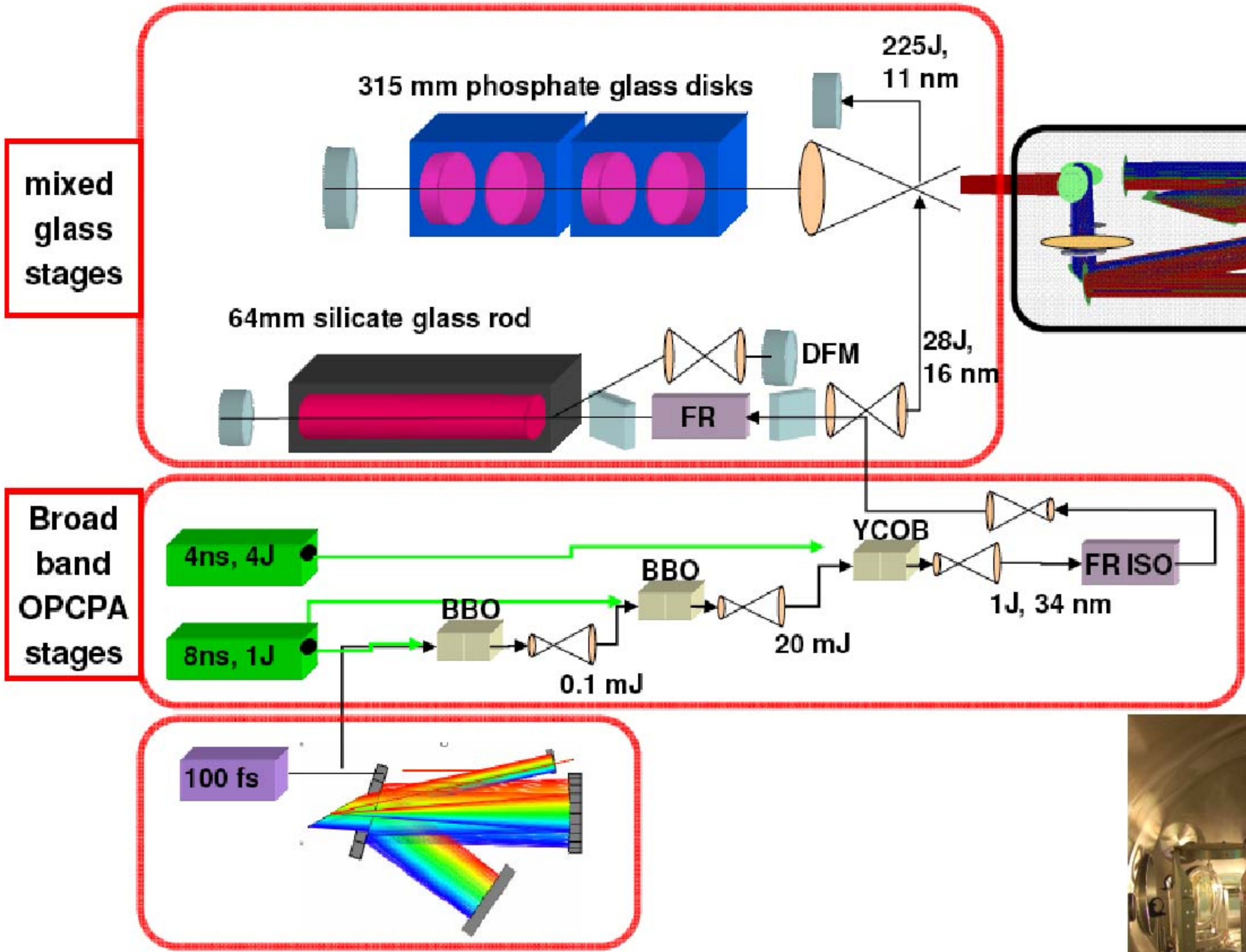


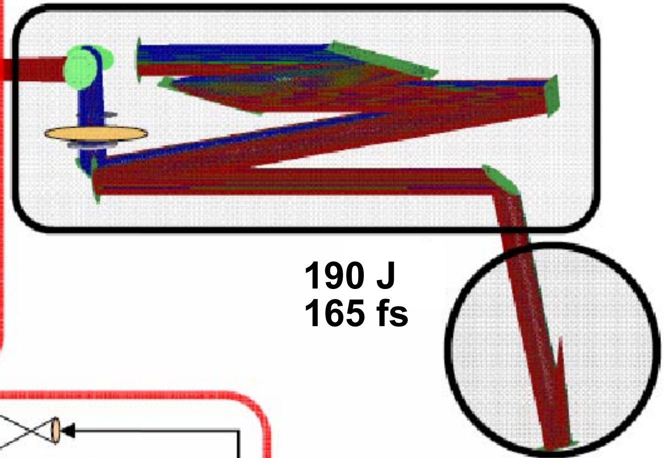
Most modern ultraintense lasers are based on Chirped Pulse Amplification



• Strickland and Mourou *Opt. Comm.* 56, 219 (1985)

The Texas Petawatt design is based on a 3-stage OPCPA amp and a mixed glass chain

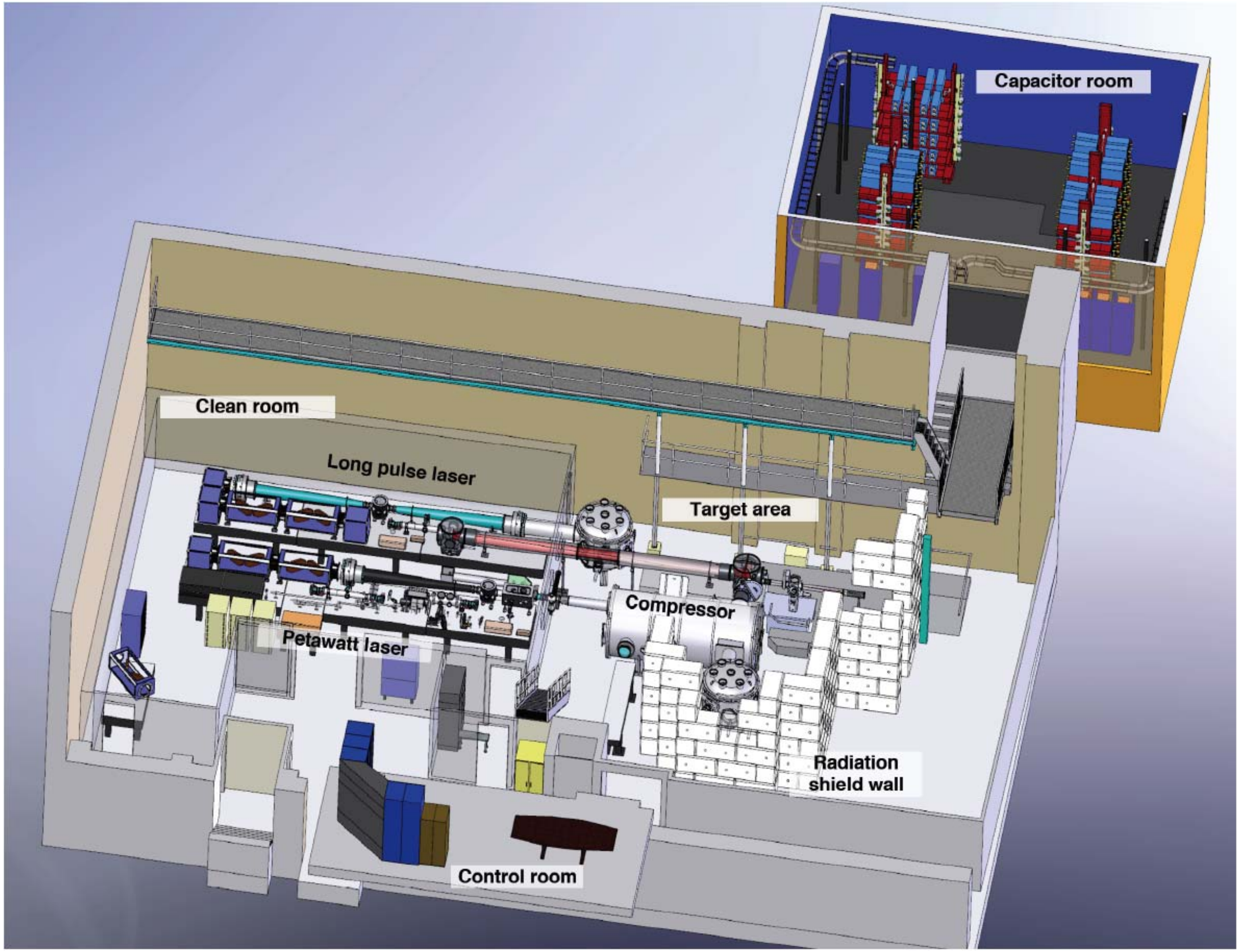




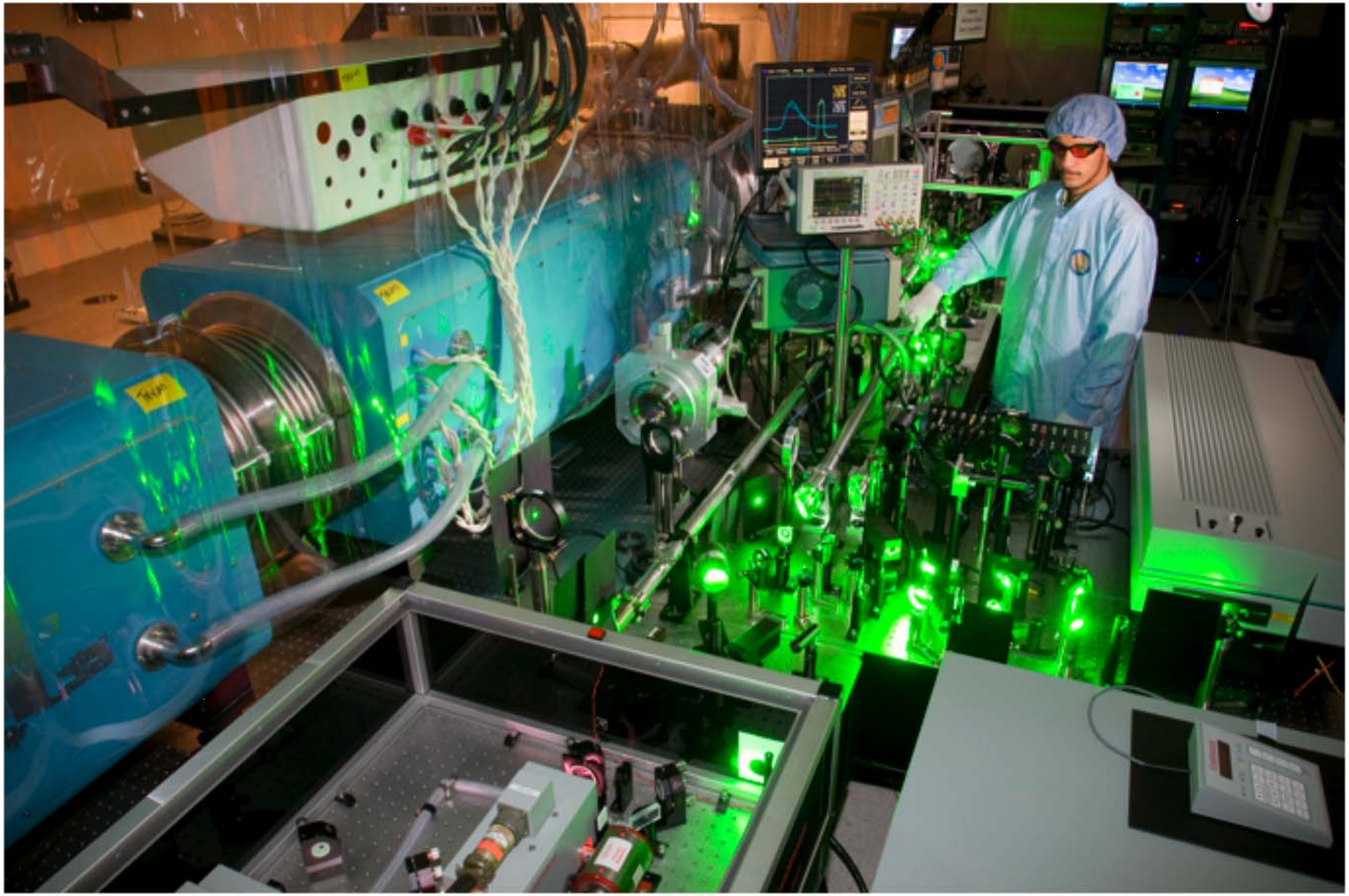
Large dielectric gratings in compressor

The Texas Petawatt Laser is housed in the RLM High Bay

Layout of the Texas Petawatt Facility in the Robert Lee Moore Basement



The Texas PW is a compact CPA laser operating with compressed energy of 190 J



The Titan laser at LLNL is a 250 TW Nd:glass laser devoted to HED research

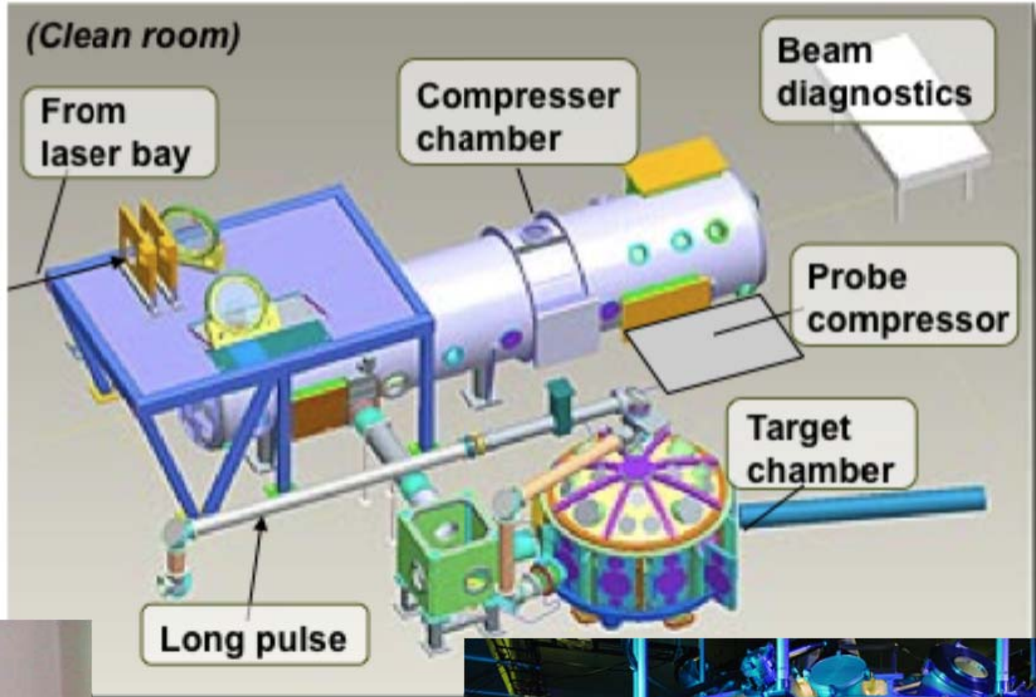
<u>Titan parameters</u>

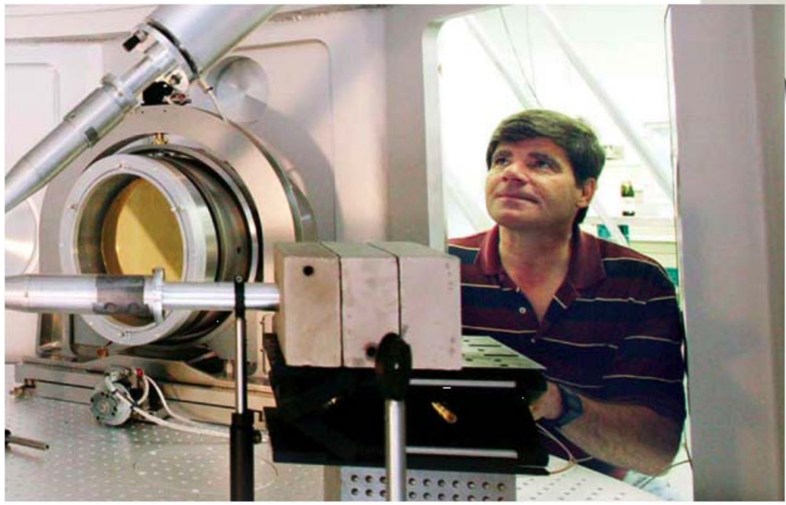
OPCPA glass 1054 nm

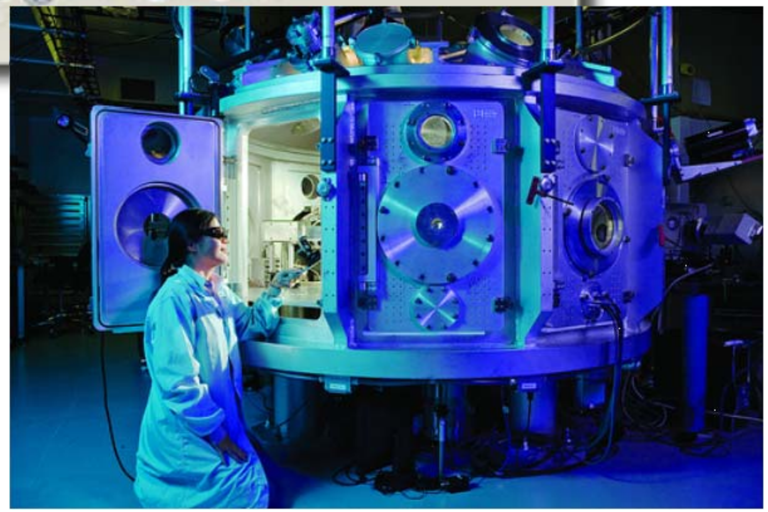
- 150 J (future: 400 J)
- 600 fs (future: 400 fs)
- Up to 5 shots per day (future: 3)

(contingent on rad. safety)

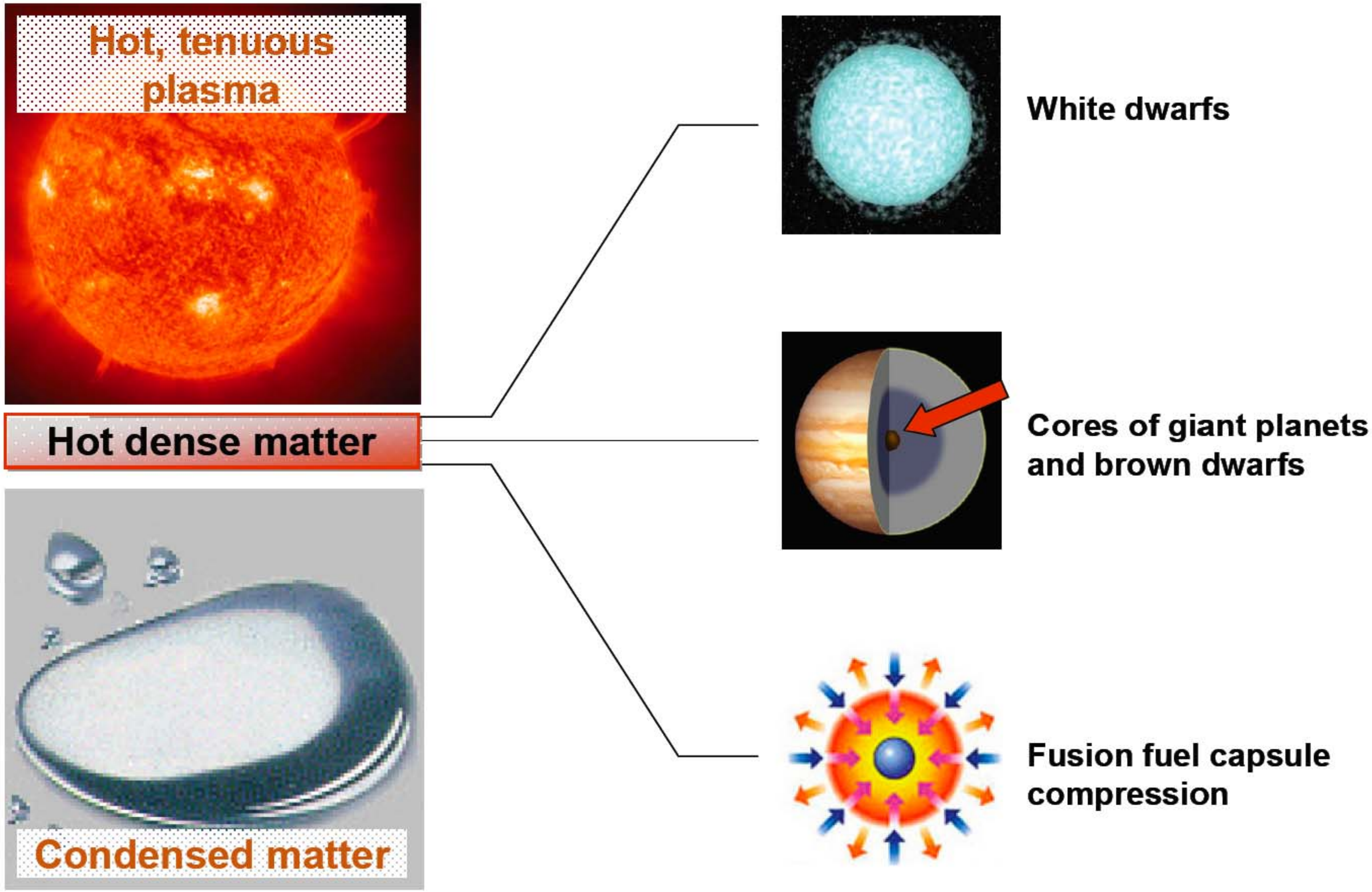
- kJ long pulse beam







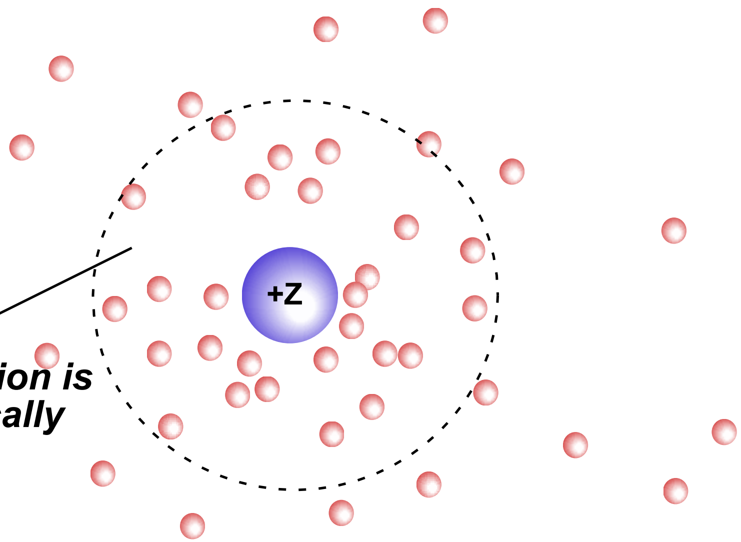
A quantitative understanding of these HED plasma physics issues is of considerable practical importance



HED plasmas exhibit significant differences to classic, tenuous plasmas

Debye length

$$\lambda_D = \sqrt{\frac{kT_e + kT_i}{4\pi e^2 Z n_o}}$$



Distance over which an ion is a plasma is electrostatically shielded by electrons

Plasma Parameter

$$\Lambda_p = \frac{1}{\sqrt{Zn_o}}\left(\frac{kT_e}{4\pi e^2}\right)^{3/2}$$

Number of electrons within a sphere with radius of the Debye length - determines if shielding picture is appropriate concept

Tokamak plasma	***HED plasma***
$kT_e = 10\ keV$	$kT_e = 100\ eV$
$n_e = 10^{14}\ cm^{-3}$	$n_e = 10^{22}\ cm^{-3}$
$\Lambda_p = 4 \times 10^7$	$\Lambda_p = 4$

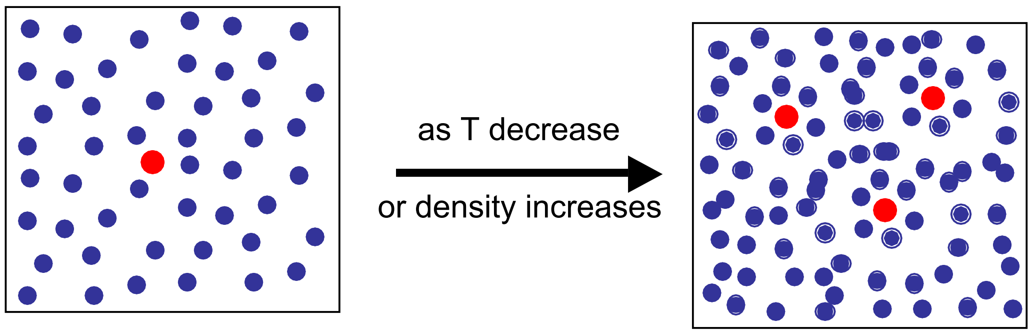
From a "plasma point-of-view", HED matter can not be described by classical, two-body interactions

- **In "classic" plasmas; $\Gamma < 1$**
  - **Particles treated as point charges**
  - **Two body interactions dominate kinetics**
- **At high density and temperature**; $\Gamma > 1$:
  - **Particle correlations become important**
  - **Ionization potentials are depressed**
  - **Energy levels shift**

Classic Cluster expansion (BBGKY hierarchy) leading to usual kinetic equations (Vlasov; Fokker-Planck) is not valid

- Γ *is the strong coupling parameter:* ratio of the interaction energy between the particles, V_{ii}, to the kinetic energy, T
- $$\Gamma = \frac{V_{ii}}{k_B T} = \frac{Z^2 e^2}{r_o k_B T}$$

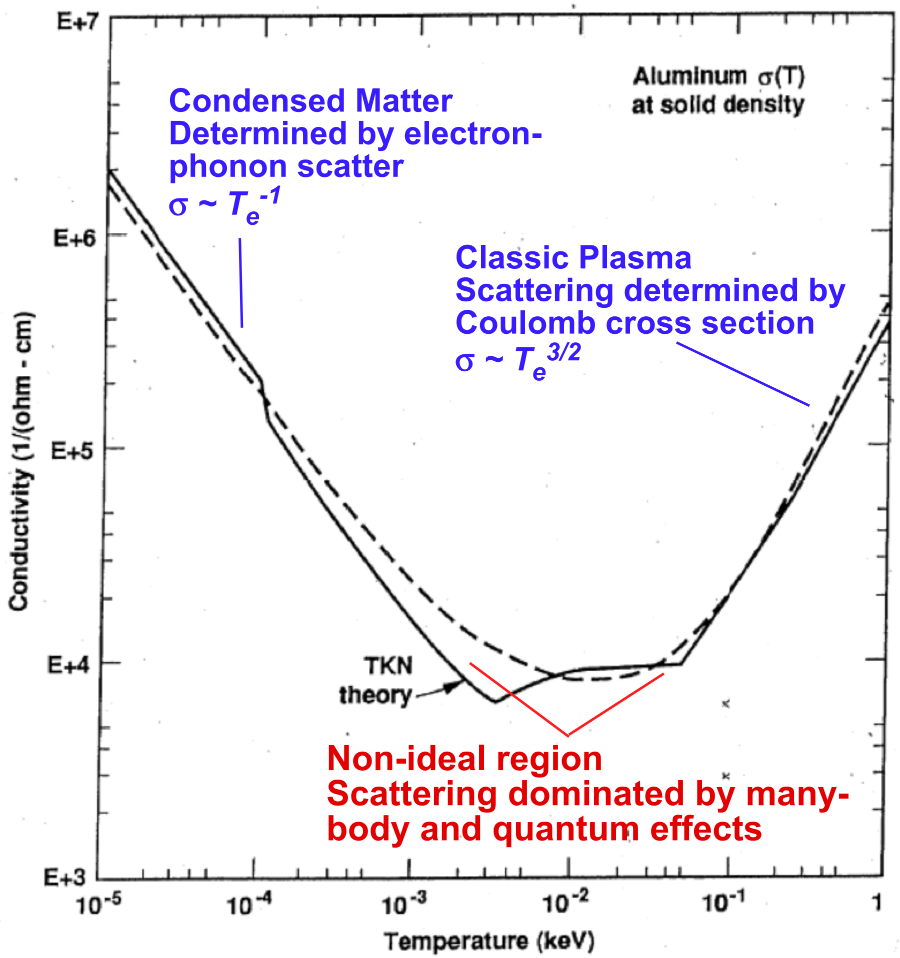
where $r_o \propto \frac{1}{\rho^{1/3}}$



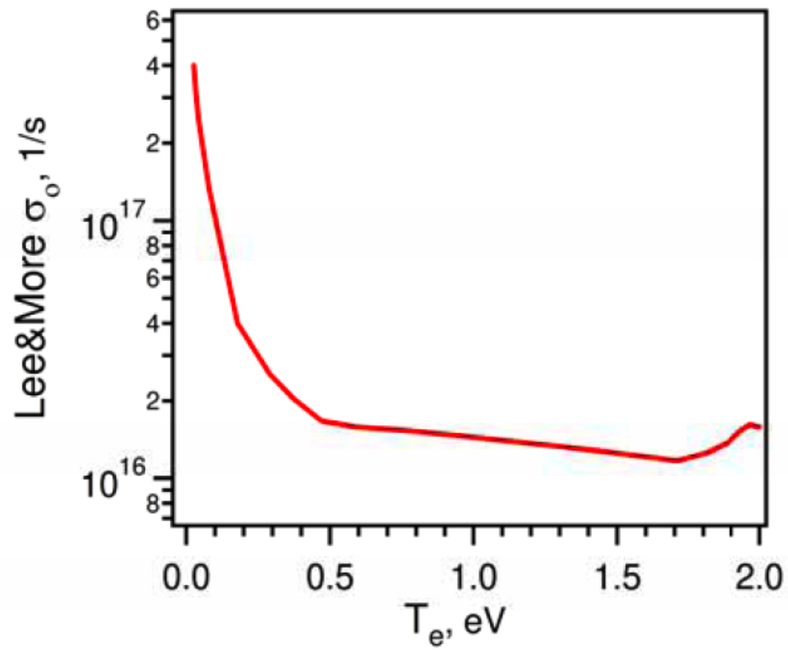
Solid aluminum is strongly coupled to temperature of >500 eV

The conductivity of a warm-dense strongly coupled plasma differs significantly from an ideal plasma

Calculated conductivity of solid Al vs. Temperature



Commonly used model for the conductivity of solid Al



Having a precise equation of state is critical for modeling many phenomena

Pure hydrodynamics can be described accurately by the Euler equations

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho v) = 0$$

Conservation of momentum:

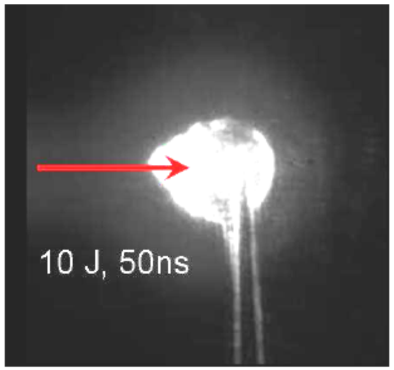
$$\frac{\partial v}{\partial t} + (v \bullet \nabla) v = -\frac{\nabla p}{\rho}$$

EOS

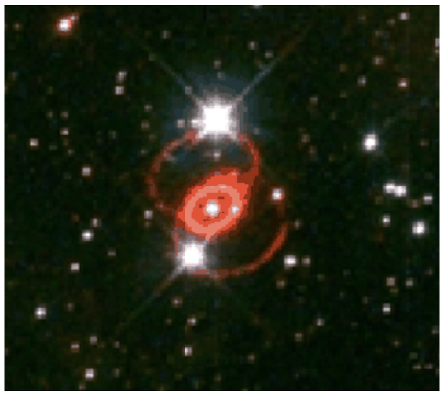
Conservation of entropy:

$$\frac{\partial p}{\partial t} - \gamma \frac{p}{\rho}\frac{\partial \rho}{\partial t} + v \bullet \nabla p - \gamma \frac{p}{\rho} v \bullet \nabla \rho = 0$$

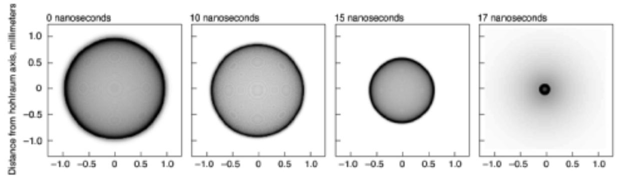
Laser heated plasma expansion



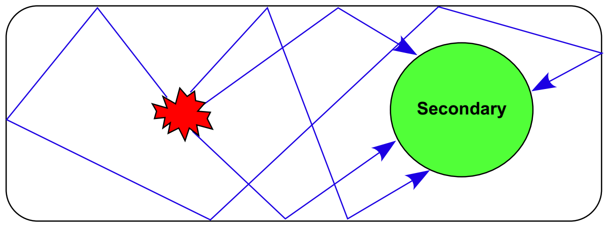
Super novae explosion



Inertial fusion implosions



Nuclear Weapons



The equations of state of dense plasmas have many complications

$$U = U_{elec} + U_{ion} + U_{rad}$$

Plasma internal energy

$$P = P_{elec} + P_{ion} + P_{rad}$$

Plasma pressure

$$P_e = \begin{cases} \bar{Z} n_i k T_e & \text{Ideal plasma} \\ \text{or} & \\ \dfrac{\hbar^2}{5 m_e}(3\pi^2)^{2/3} n_e^{5/3} & \text{Quantum degenerate plasma} \end{cases}$$

Ideal plasma

Quantum degenerate plasma

+ Coulomb effects

$$U_e = {}^{3}\!/_{2}\, \bar{Z} n_i k T_e + \sum_k n_k \left[\sum_{j=0}^{k} I_p^{(j)} \right]$$

ideal gas term

Energy in ionization

$$P_{ion} = n_i k T_i - \frac{2\pi}{3} n_i^2 \int_0^\infty \frac{\partial V(r)}{\partial r} g(r) r^3 dr$$

ideal gas term

Non-ideal correction where $g(r)$= ion radial distribution function

$$P_{rad} = \frac{\pi^2}{45} \frac{(kT_{rad})^4}{(\hbar c)^3}$$

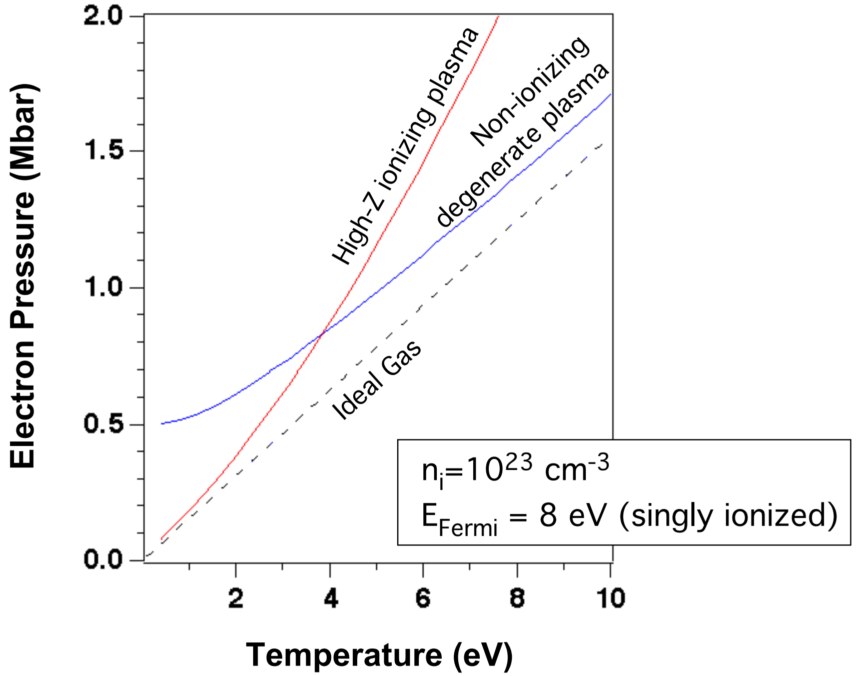
Only important if optically thick: ie $\lambda_{h\nu}$ Δx_{plasma}

Both quantum and Coulomb effects play an important role in the electron EOS

Quantum degeneracy effects:

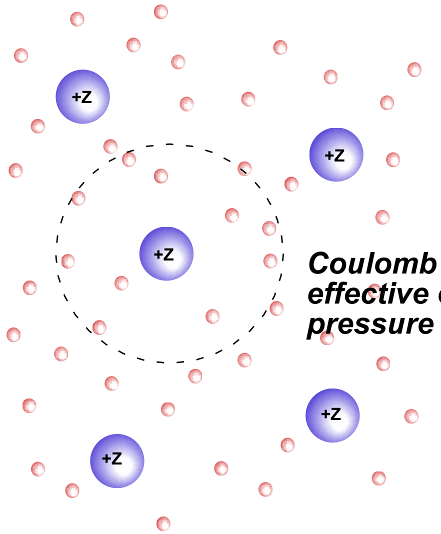
$kT_e \sim E_{Fermi}$

E_{Fermi} 11 eV in singly ionized Al



Degeneracy effects ~ 20% when $kT_e \sim E_{Fermi}$

Coulomb effects:



Coulomb interactions lower effective energy density and pressure

$$P_e = \bar{Z} n_i k T_e - \frac{3}{10} \bar{Z}^2 e^2 n_i^{4/3}$$

Coulomb correction in the "ion sphere" model

Coulomb effects are a 50% correction with $n_i \sim 10^{23}$ cm^{-3}, Z 3, and kT = 50 eV

At solid density, Fermi energy is ~ 10 eV. Many HED plasmas have temperature in this vicinity, mandating a quantum mechanical treatment of the plasma

Ionization models do not converge in the HED plasma regime

Saha equilibrium equations for ion charge states

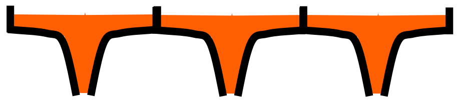
- Low to moderate density
- High temperature

$$\frac{n_e n_Z}{n_{Z-1}} = 2\frac{W_Z(T)}{W_{Z-1}(T)}\left(\frac{m_e k T_e}{2\pi\hbar^2}\right)^{3/2}\exp\left[-\frac{I_p^{(Z-1)} - \Delta I_p^{(CL)}}{kT_e}\right] \qquad n_e = \sum_{j=1}^{Z_{nuc}} n_j$$

"Average Atom" picture based on Thomas Fermi Model

- High density
- Low to moderate temperature

$$\frac{d^2\chi}{dr^2} = \frac{4}{3\pi\hbar^3}(2m_e e^2)^{3/2}\frac{Z^{1/2}}{r^{1/2}}\chi^{3/2}$$

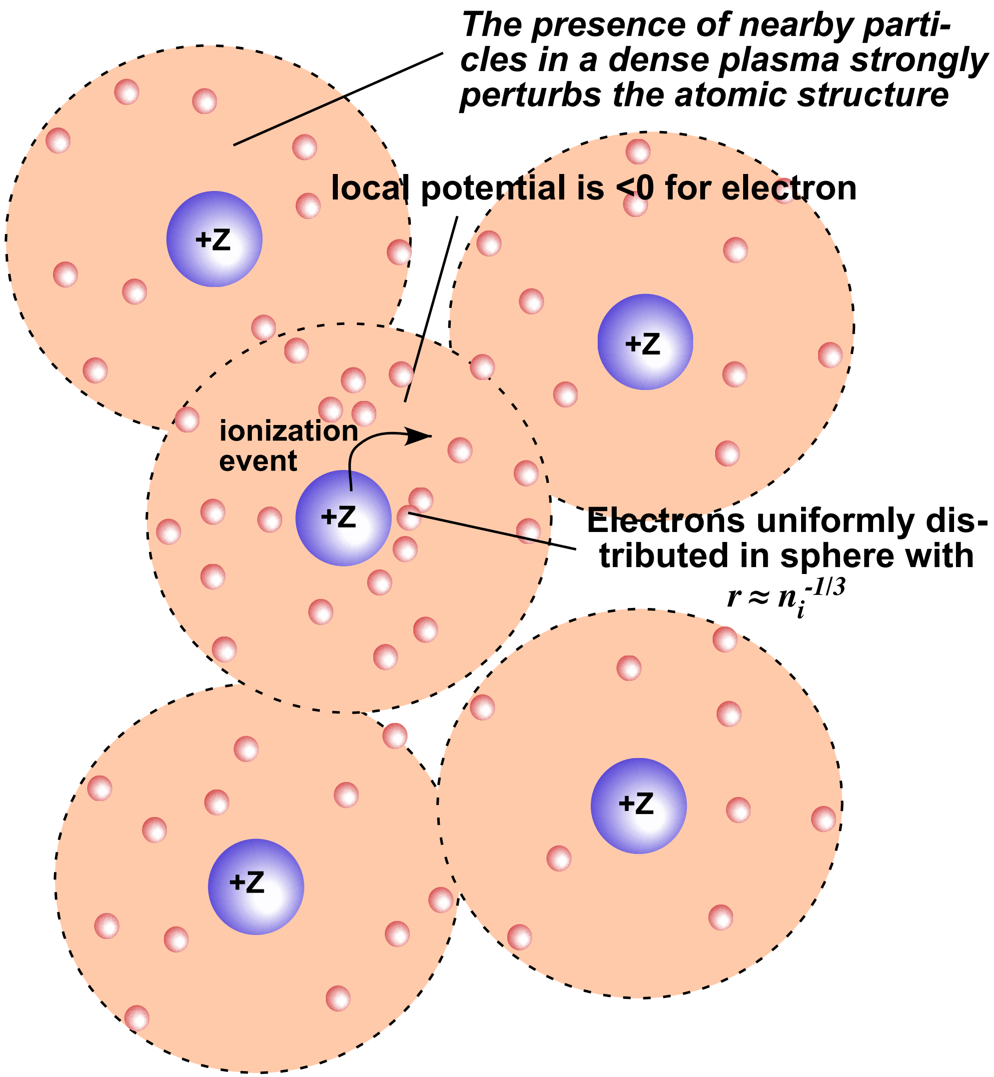


These models are complicated by many other factors

Co-existing constituents in a dense plasma:

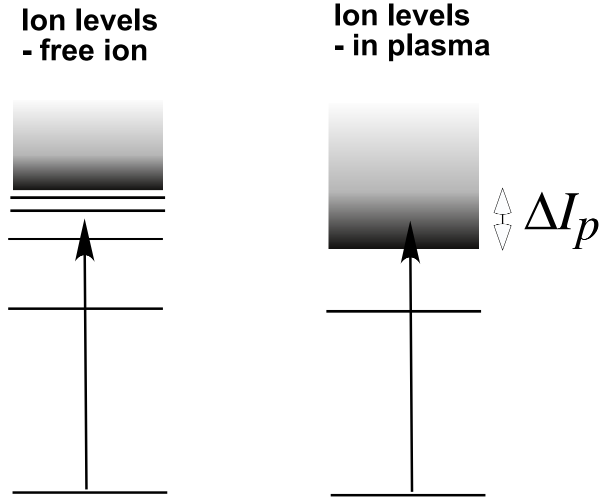
- Ions
- Neutrals
- Negative ions — Electron affinity of Au: 2.3 eV
- Dimers — Bond strength of Al_2: ~ 5 eV
- Negatively charged dimers

A significant question in dense plasmas is the extent to which the ionization potential of the plasma ions is altered

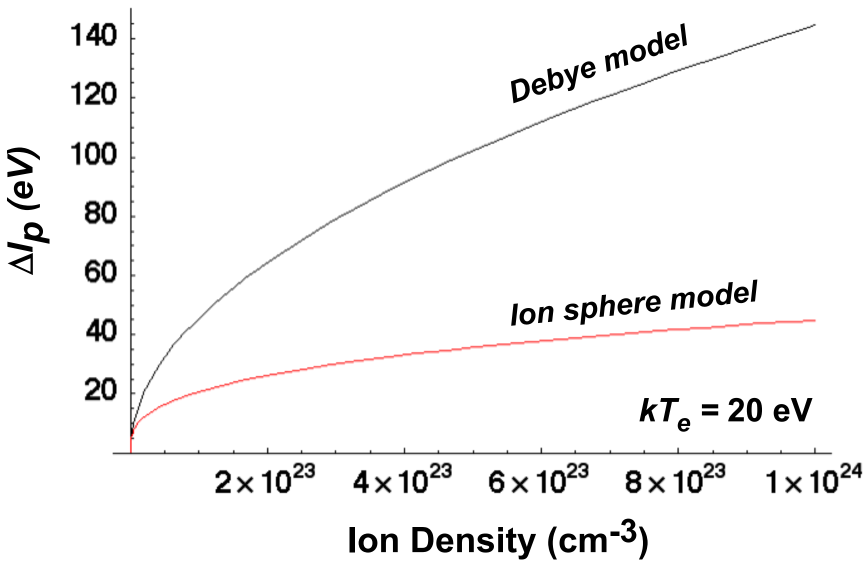


effective energy needed for ionization is lowered

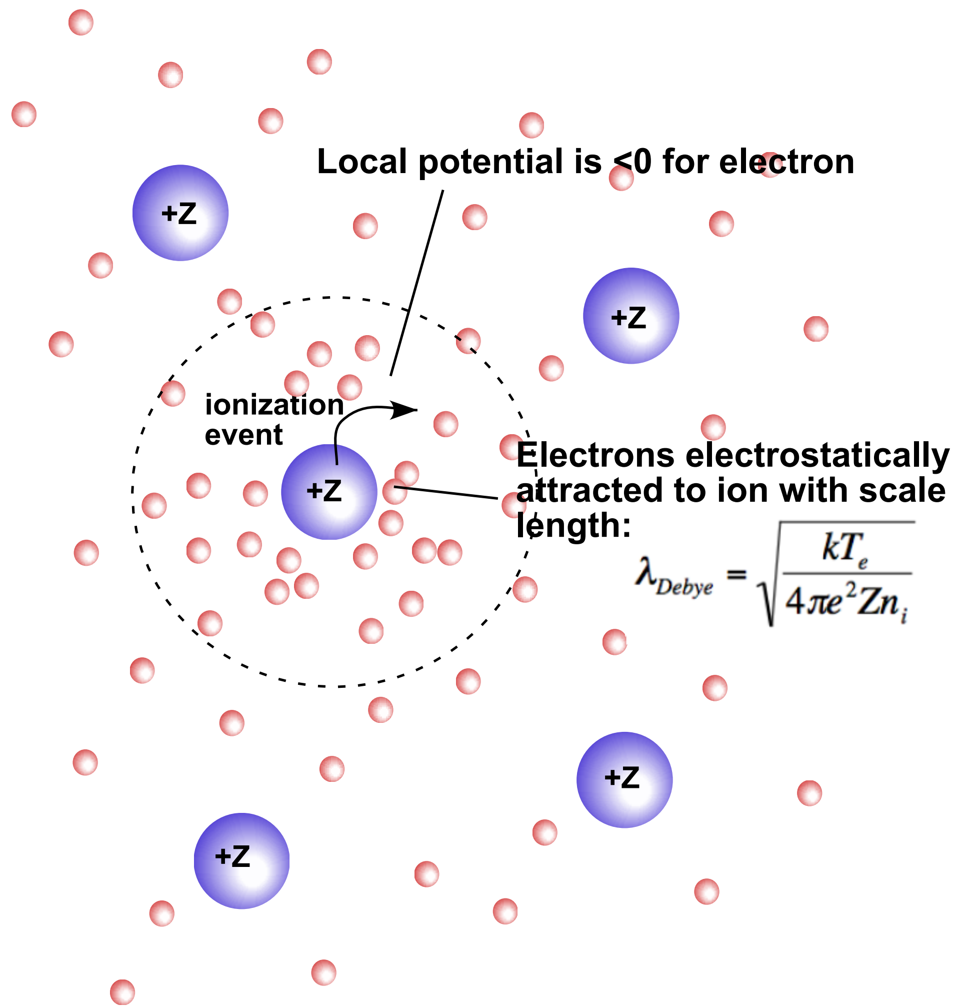
One significant effect is the lowering of the ionization potential: "Continuum lowering"



Continuum lowering predictions with a Saha model for ionization



The traditional method of calculating continuum lowering is to assume Debye shielding by the plasma electrons



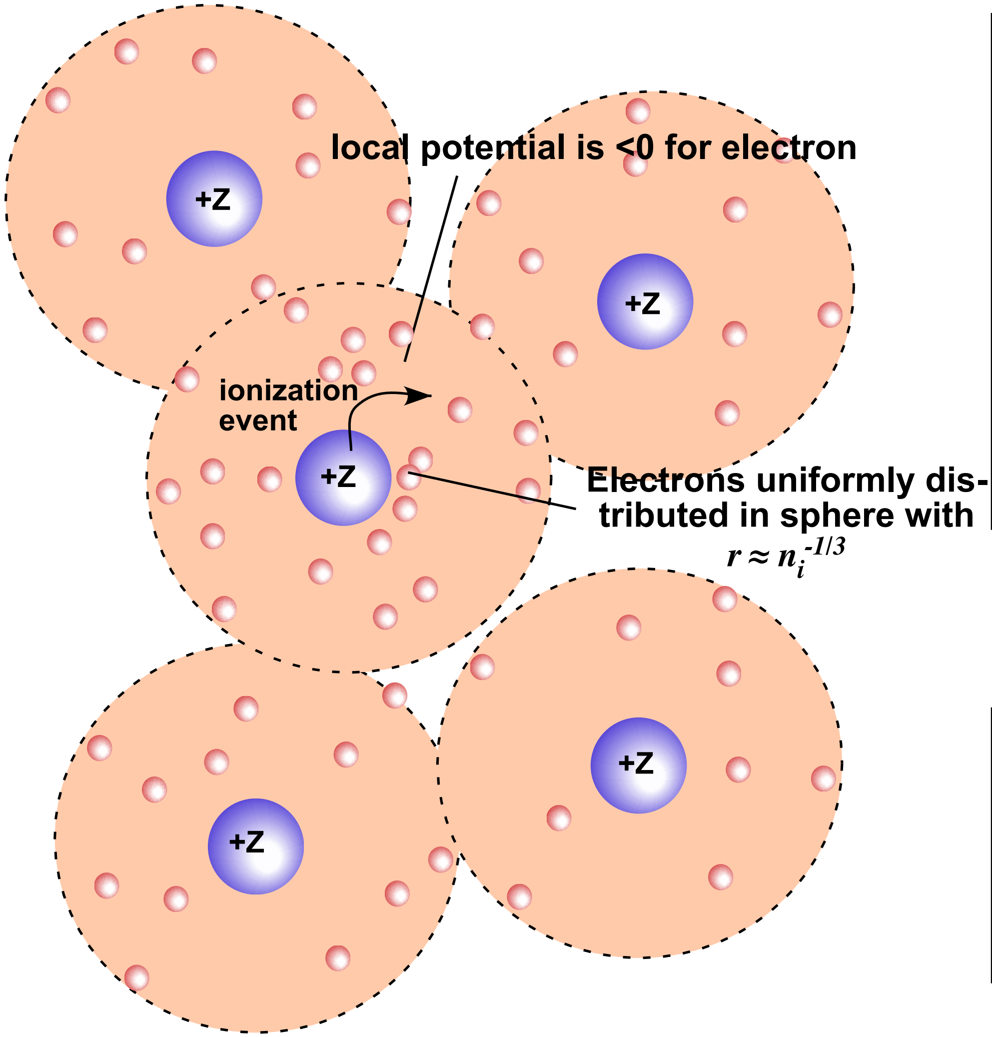
Effective energy needed for ionization is lowered

Debye model assumes WEAK coupling between electrons

- **Linearizes Poisson's equation**
- **Calculate electrostatic energy of liberated electron to determine ionization potential lowering**

$$\Delta I_p^{(Debye)} = 2Z^{3/2} e^3 \sqrt{\frac{\pi n_i}{kT_e}}$$

In strongly coupled plasma, the electrostatic continuum lowering can be estimated using the "Ion sphere" model



effective energy needed for ionization is lowered

In strongly coupled plasma Debye model does not work: use a simple "Ion sphere model"

- **Assume electrons are uniformly distributed within a sphere of radius $n_i^{-1/3}$**
- **Calculate electrostatic energy of liberated electron to determine ionization potential lowering**

$$\Delta I_p^{(Z)} = \frac{9}{10}(2Z-1)e^2 n_i^{1/3}$$

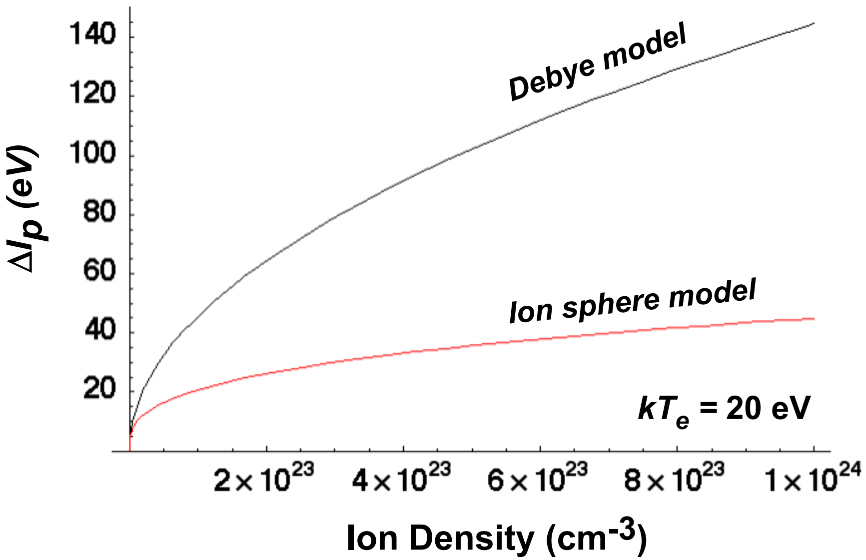
Different continuum lowering models yield very different predictions in the strongly coupled regime

Continuum lowering model predictions:

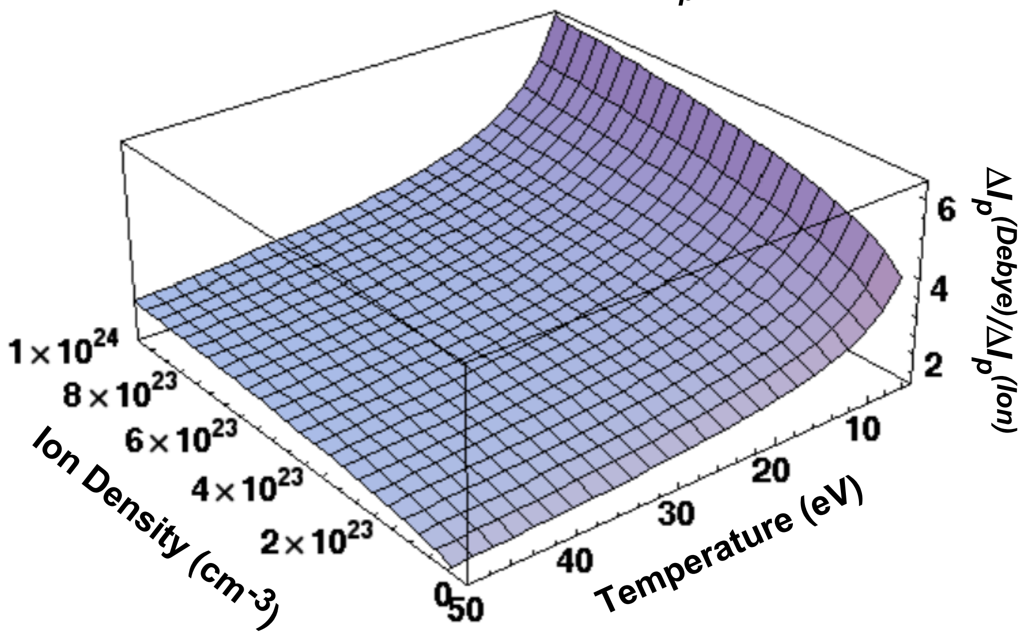
$n_i = 2 \times 10^{23}$ cm^{-3}
$kT_e = 10$ eV
Z 3

Quantum model	1.2 eV
Ion Sphere model	38 eV
Debye Model	140 eV

Continuum lowering predictions with a Saha model for ionization



Ratio of Debye and Ion Sphere predictions for ΔI_p



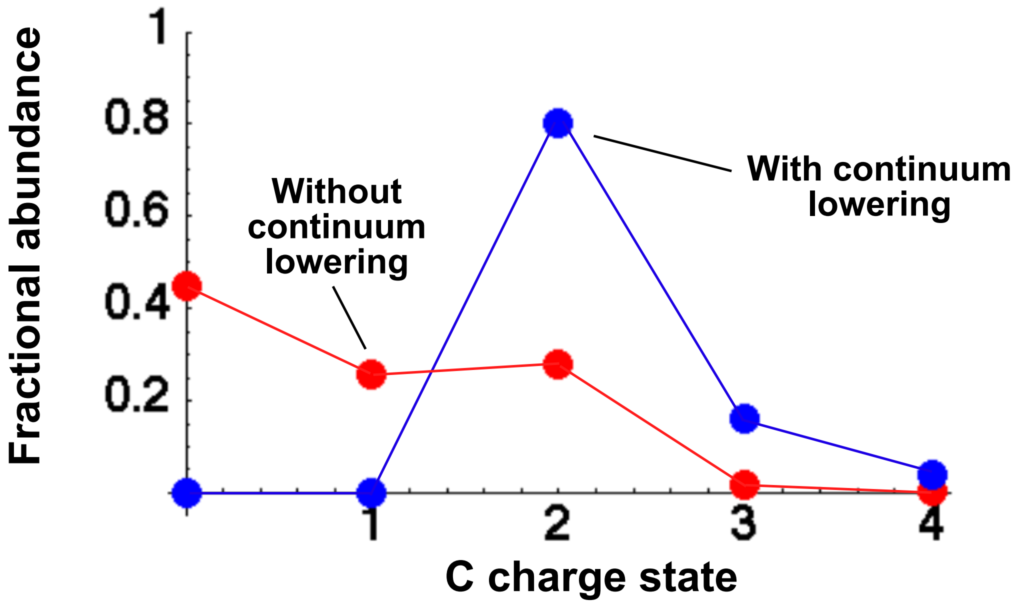
We believe that the ion sphere model is most appropriate for the cold dense plasmas produced by XUV irradiation of clusters

A Saha model of ionization in solid density carbon plasma illustrates the dramatic impact of continuum lowering

Saha equilibrium equations

$$\frac{n_e n_Z}{n_{Z-1}} = 2\frac{W_Z(T)}{W_{Z-1}(T)}\left(\frac{m_e k T_e}{2\pi\hbar^2}\right)^{3/2} \exp\left[-\frac{I_p^{(Z-1)} - \Delta I_p^{(CL)}}{kT_e}\right] \qquad n_e = \sum_{j=1}^{Z_{nuc}} n_j$$

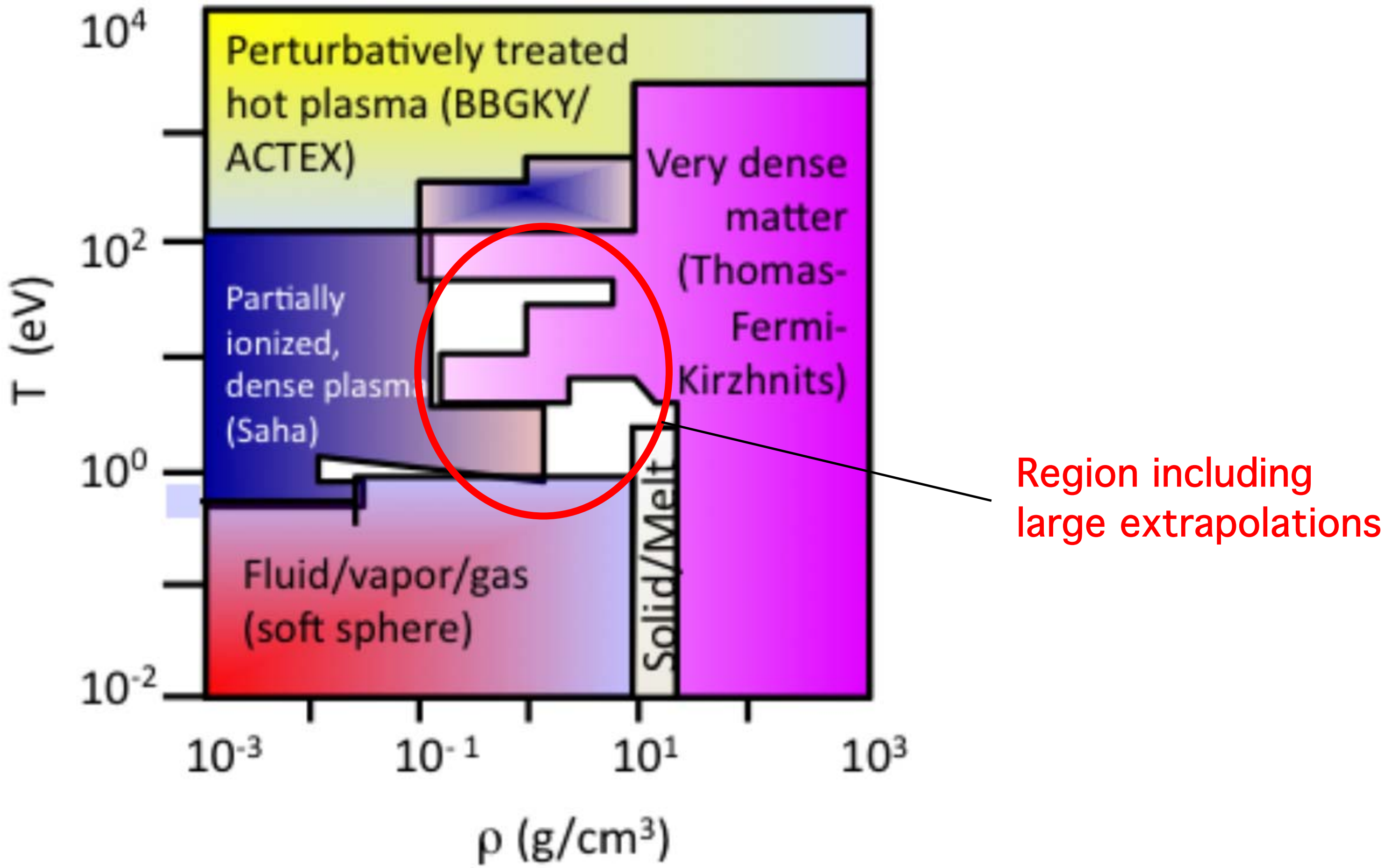
Charge distribution in a solid density Carbon plasma with 15 eV electron temperature



Saha collisional equilibrium implies about twice the electron density in a carbon plasma with continuum lowering

The common theoretical practice is to piece together many different models in the WDM regime

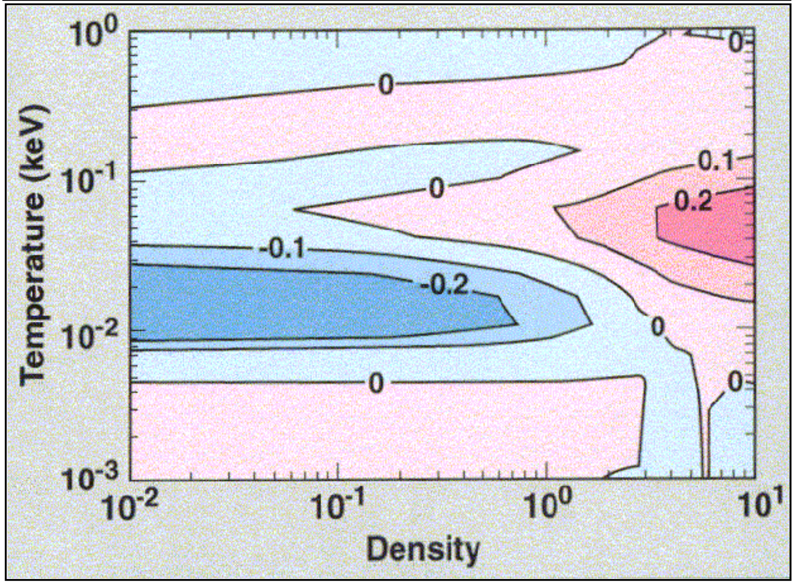
ρ-t diagram (copper): the range of applicability for the best theories in each region, including intricate corrections



In the warm/hot dense matter regime sizeable errors exist in the equation of state

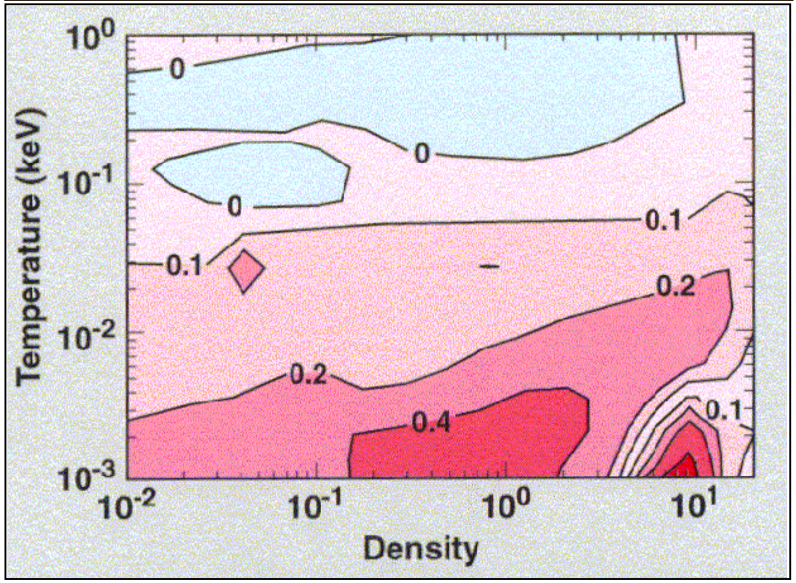
Contours of fractional difference in pressure predicted by different models

Model uncertainty for Al pressure



- Simple atomic physics
- Although most studied, differences of more than 20% in calculated pressure values can be found in the regime for hot expanded states;

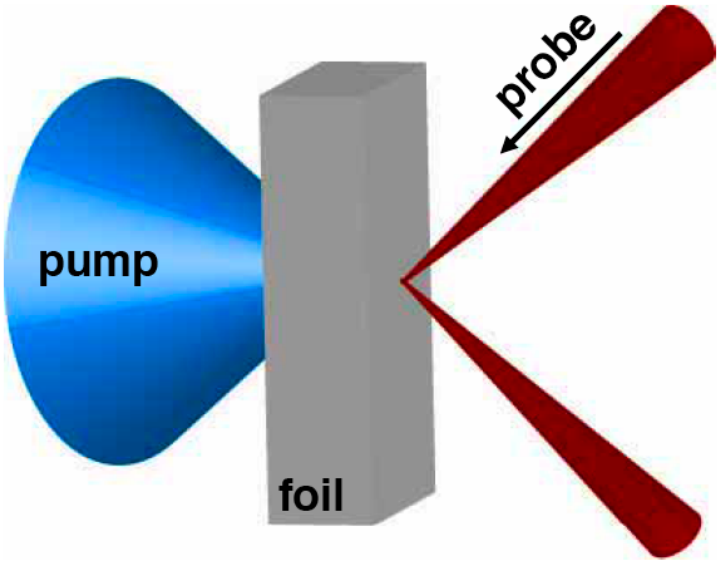
Model uncertainty for Cu pressure



- Complex atomic physics - d-shell electrons
- Large model differences in the WDM region
- Measurements required for guidance

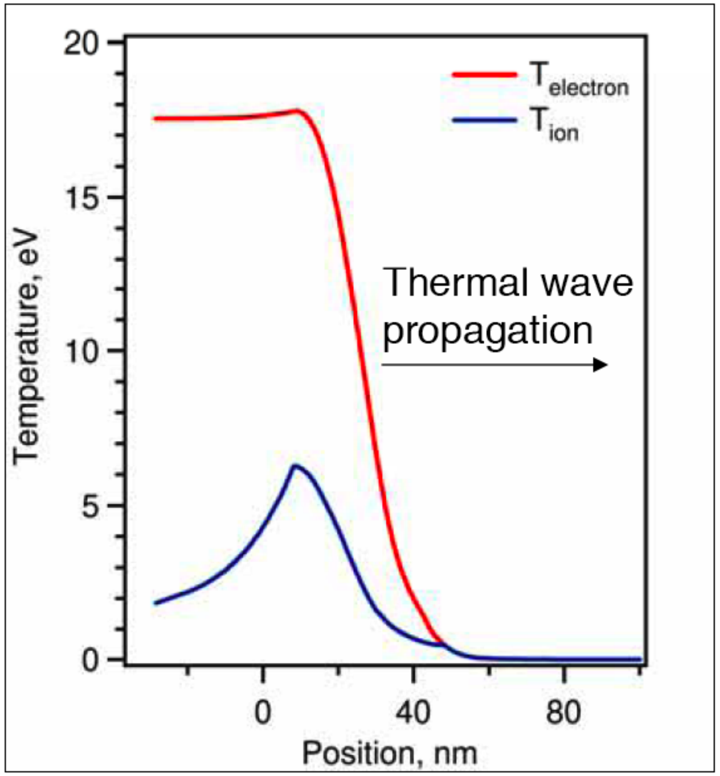
Implementation of atomic physics in this (ρ, T) regime is very challenging

We use direct laser heating of thin foils to study plasmas with temperatures of 1-10 eV



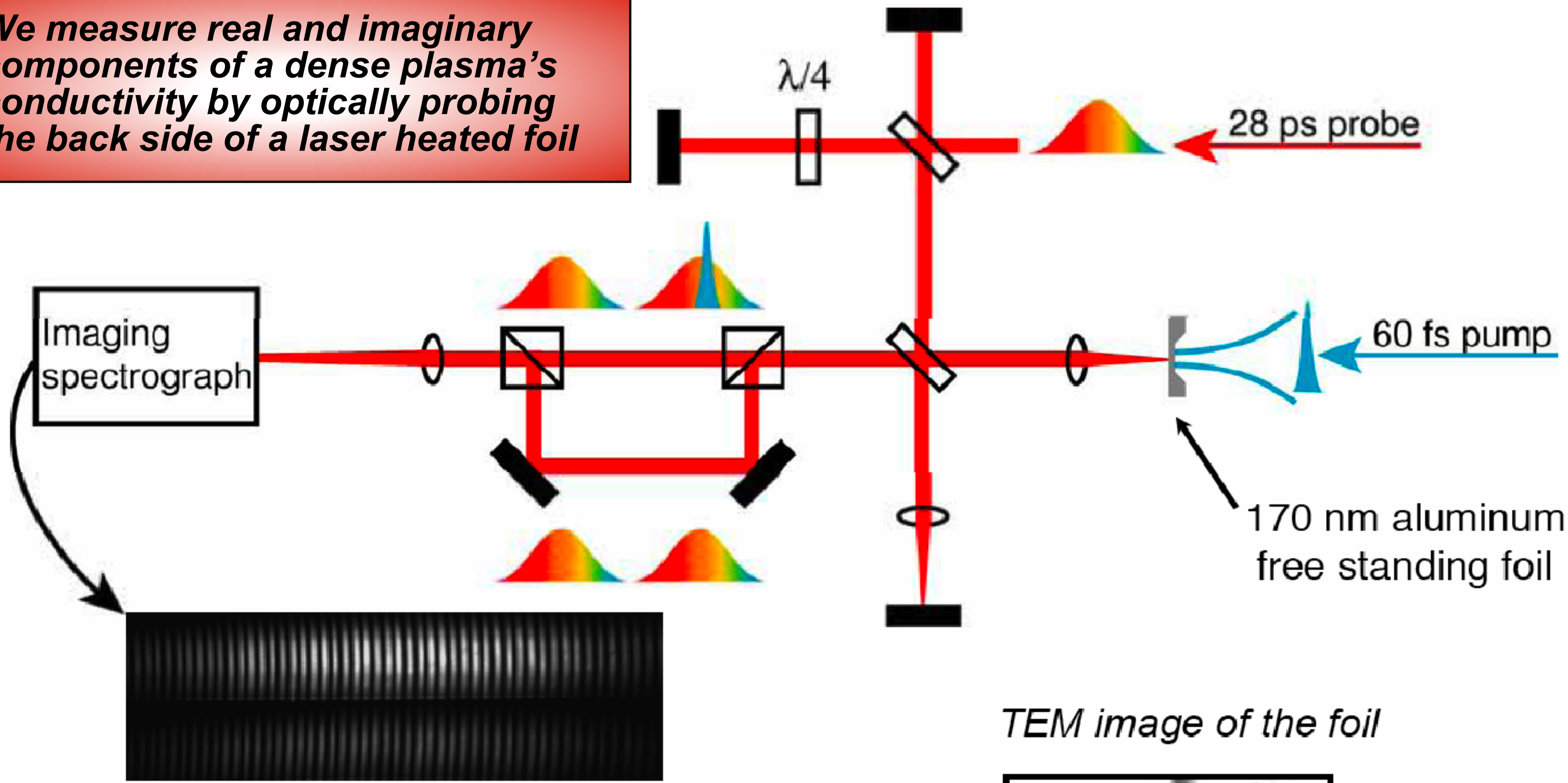
Electron (red) and ion (blue) temperature distributions in Al foil 500fs after it was heated with 60 fs pulse at 2.*10^{14} W/cm^{2}.

Optically probing the back surface of the foil will allow us to investigate non-equilibrium phenomena due to direct femtosecond laser heating.



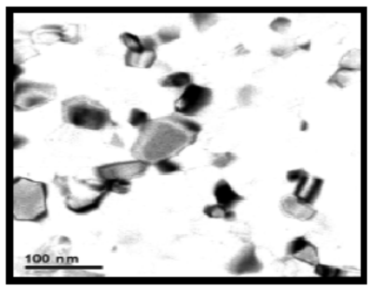
Using chirped probe pulses, we can measure the time evolution of the optical properties of a laser-heated plasma

We measure real and imaginary components of a dense plasma's conductivity by optically probing the back side of a laser heated foil



Two sets of probe pulses were split from the pump pulse to perform the entire experiment with a single shot.

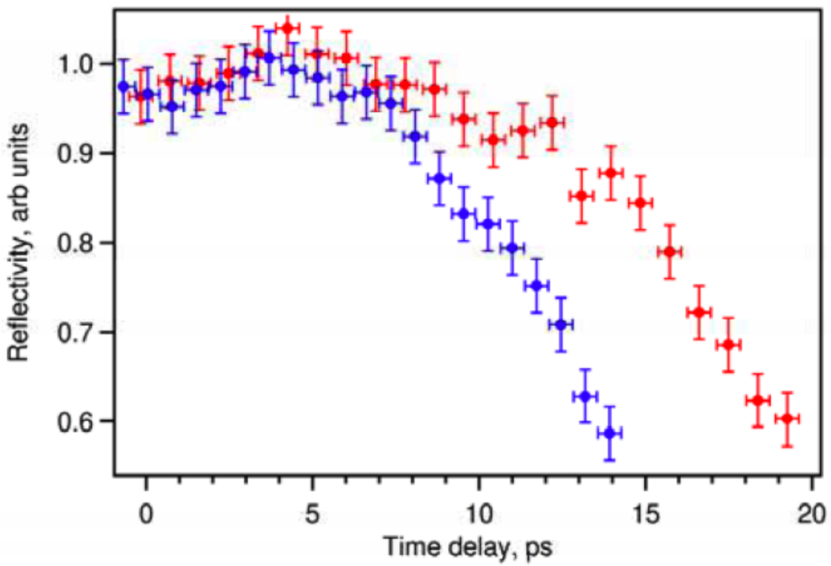
TEM image of the foil

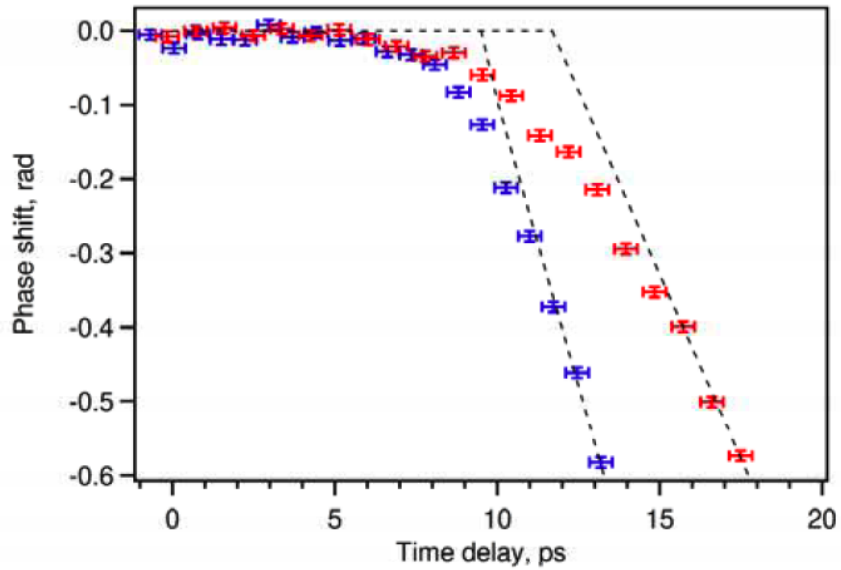


- *FCC structure*
- *Polycrystalline*
- *grain size ~40nm*

We have measured the optical properties of dense Al plasma heated with a 40 fs pulse

Back surface reflectivity and phase shift of 170 nm foil irradiated with $2.2*10^{14}W/cm^2$(blue) and $1.6*10^{14}W/cm^2$(red) intensities.



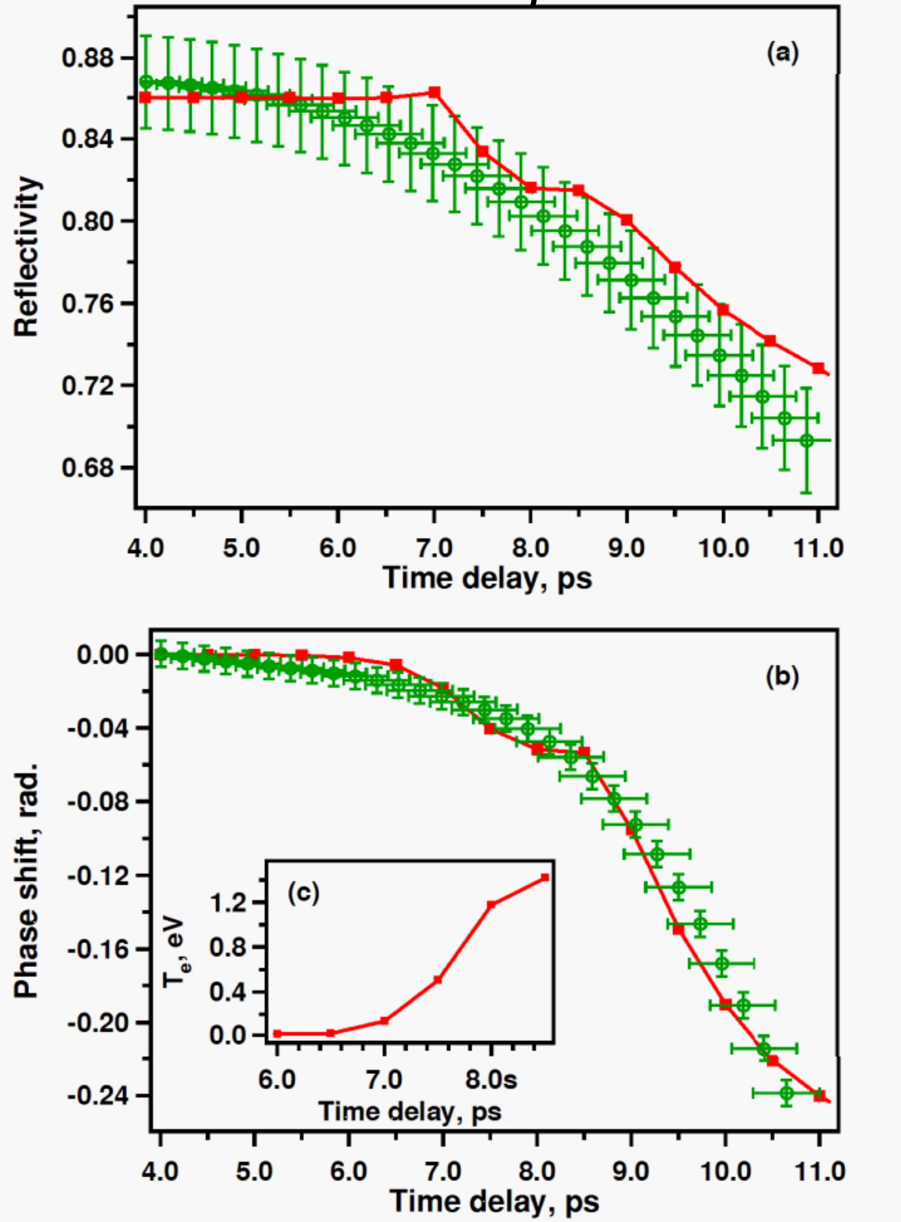


- For the first few ps the returned probe signal stays unchanged.
- 6ps later the heat wave reaches the back surface of target, electron temperature rises.
- >10 ps Shock wave reaches the back surface. Phase shift changes are dominated by the particle motion as material expands

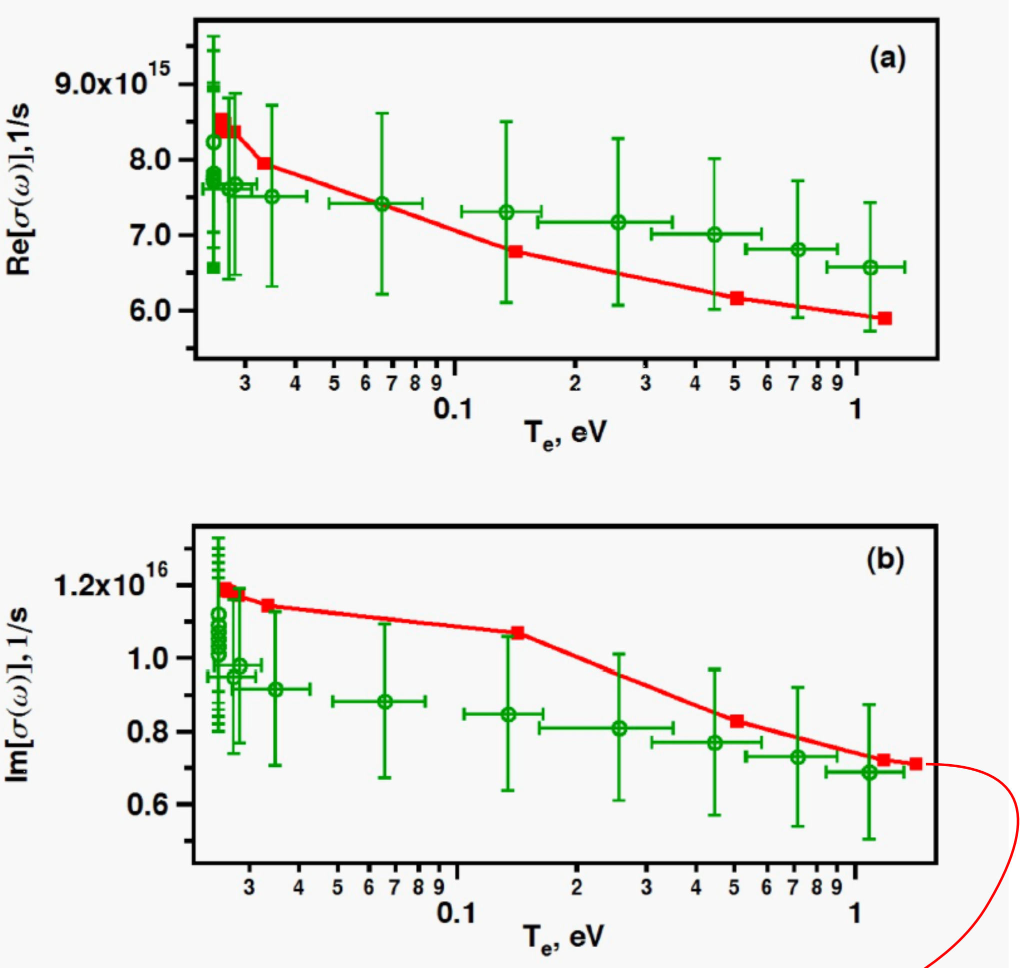
So, between 6 and 10 ps we have a heated back surface with a sharp interface to vacuum

Our measurements are roughly consistent with a well known dense plasma conductivity model

Measured time dependence of reflectivity and reflected phase shift

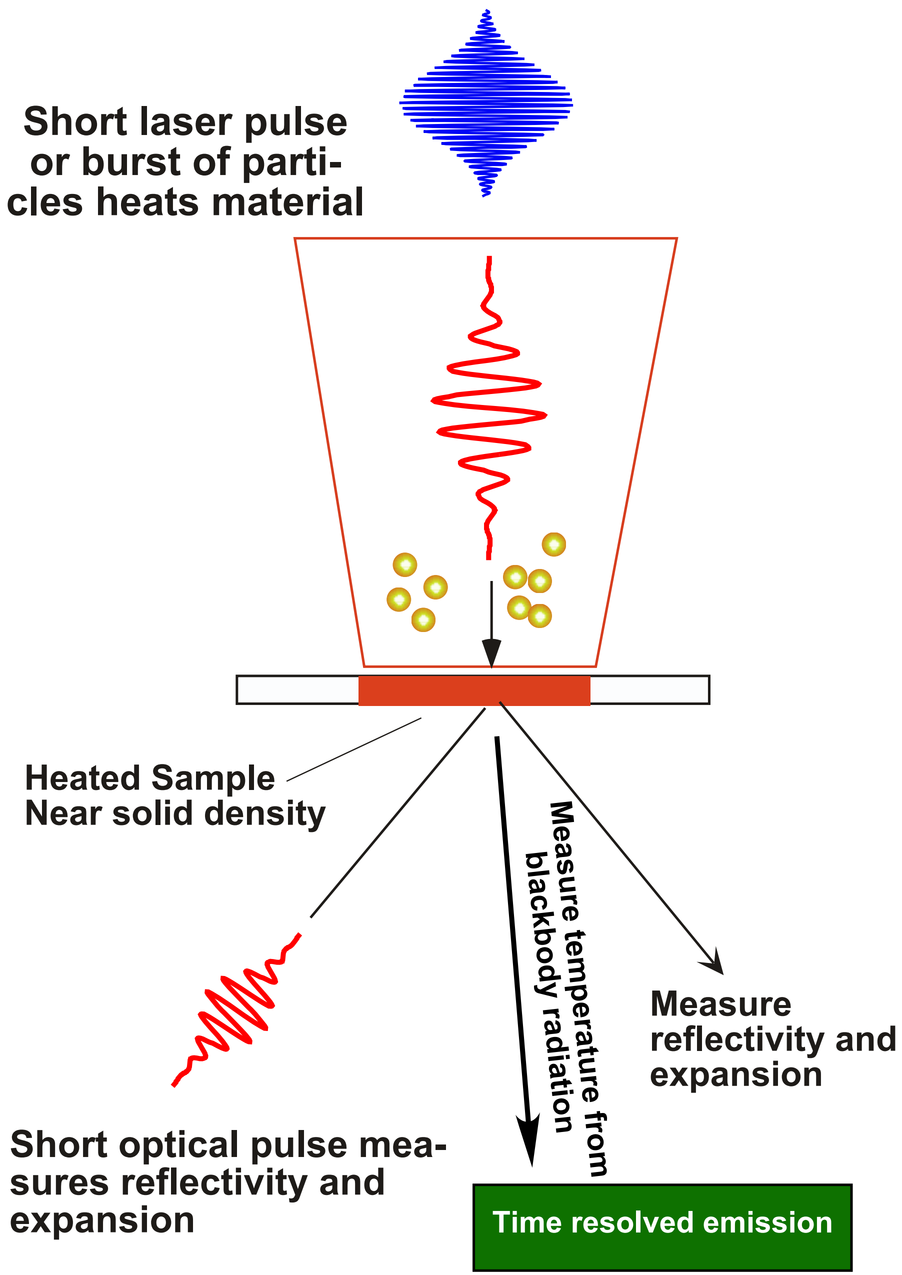


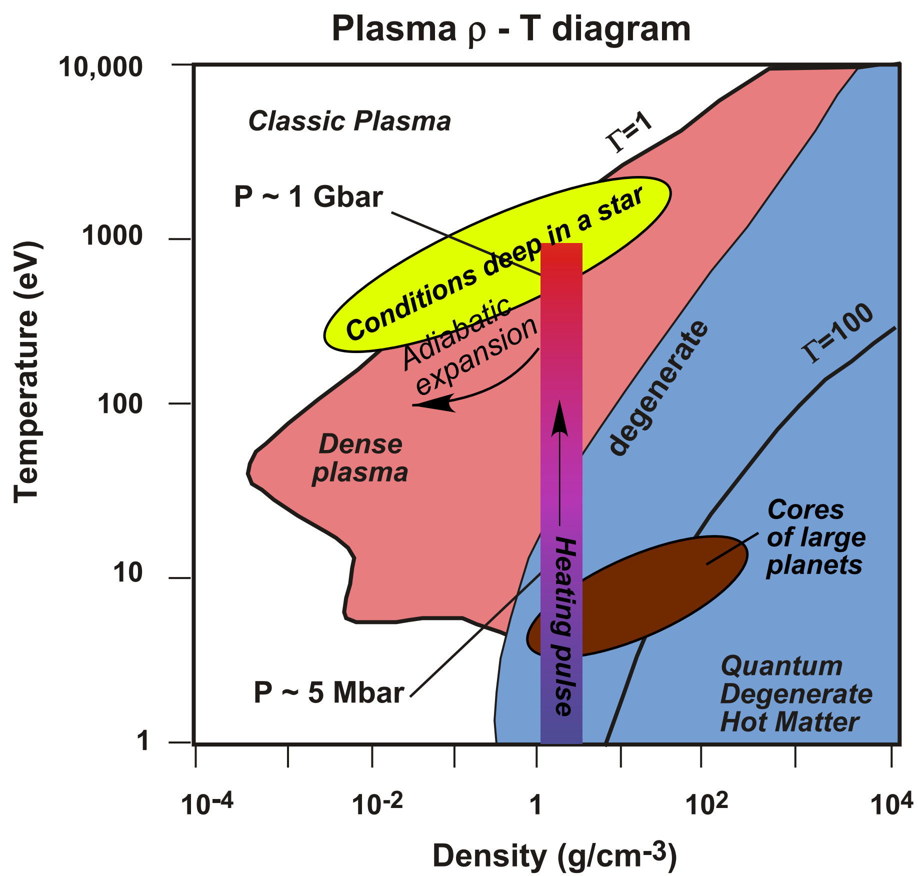
Derived real and imaginary conductivity



Predictions of the LEE & More model
Y. T. Lee and R. M. More, Phys. Fluids 27, 1273 (1984).

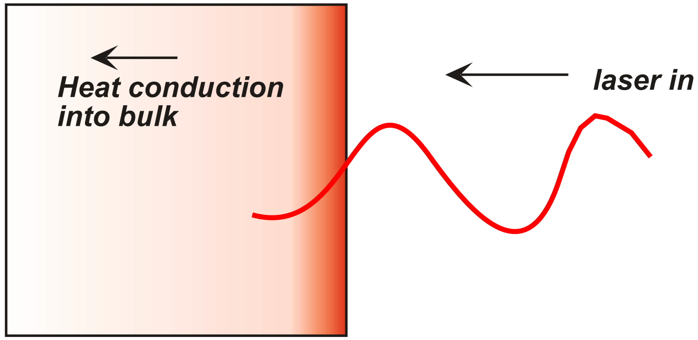
Isochoric heating can be combined with optical and x-ray probes to derive information about a hot dense plasma



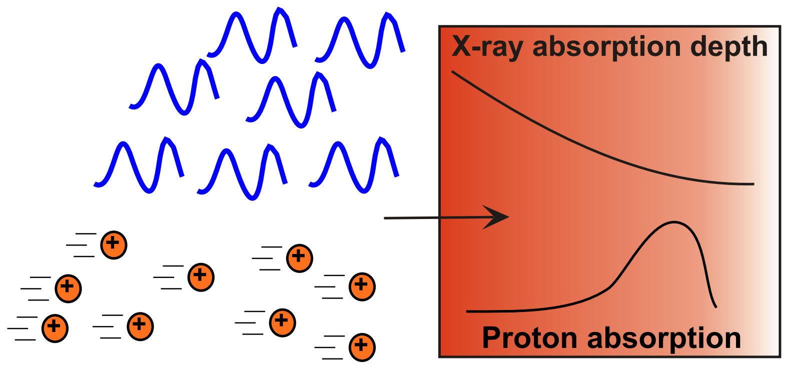


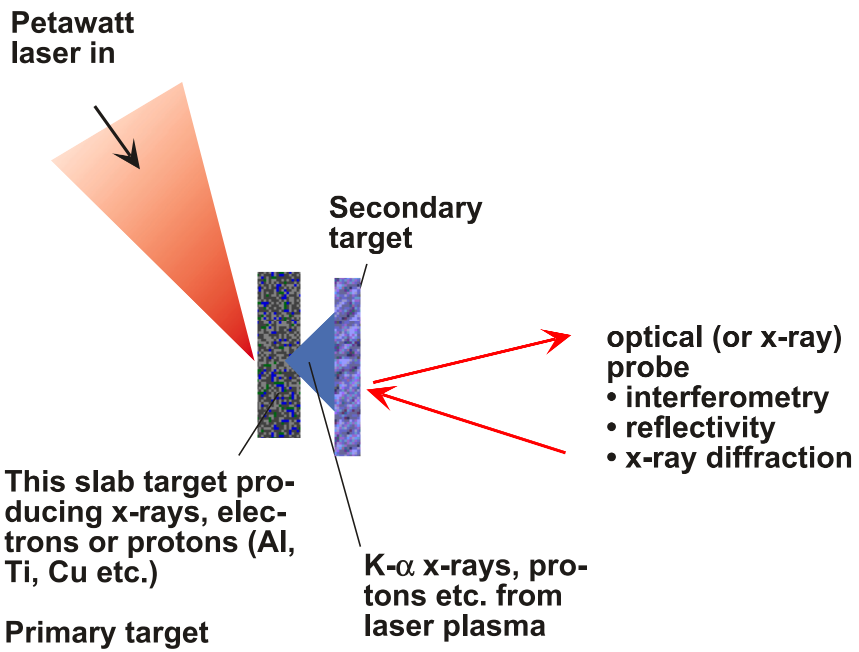
Short pulse laser produced radiation can be used to heat isochorically bulk matter

Optical radiation heats only over one skin depth ~10-100 nm

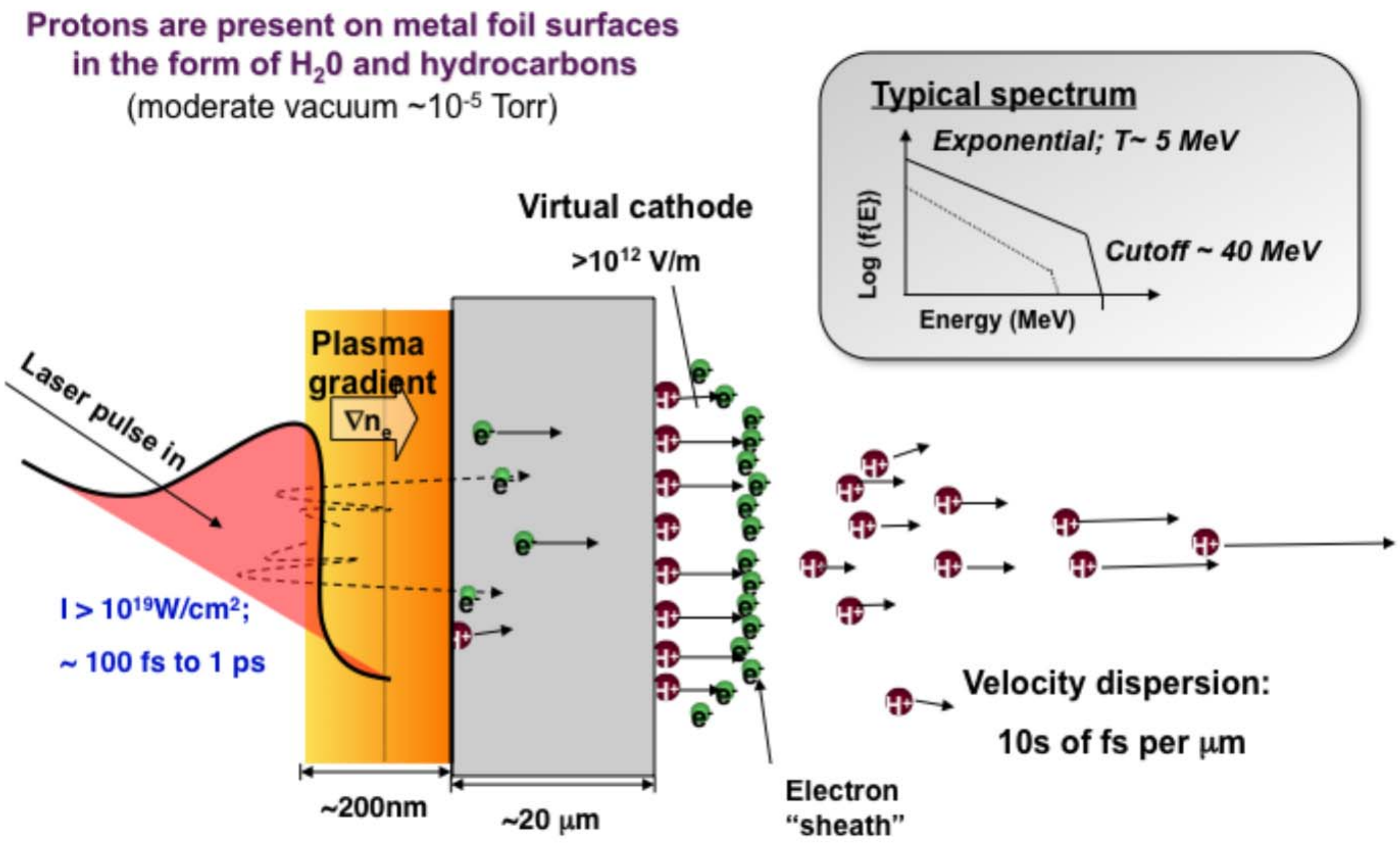


Protons (1 - 10 MeV) deposit energy within the bulk of a target (10-100 μm)



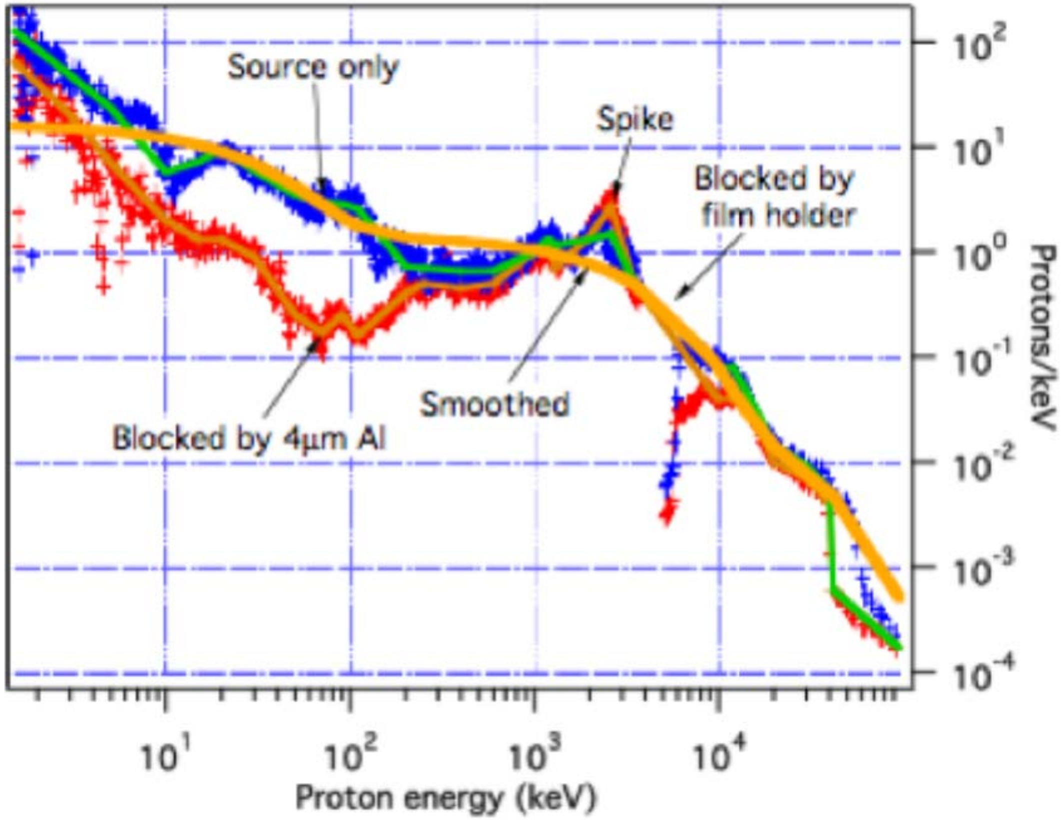


With a petawatt laser, very intense, energetic pulses of protons can be produced



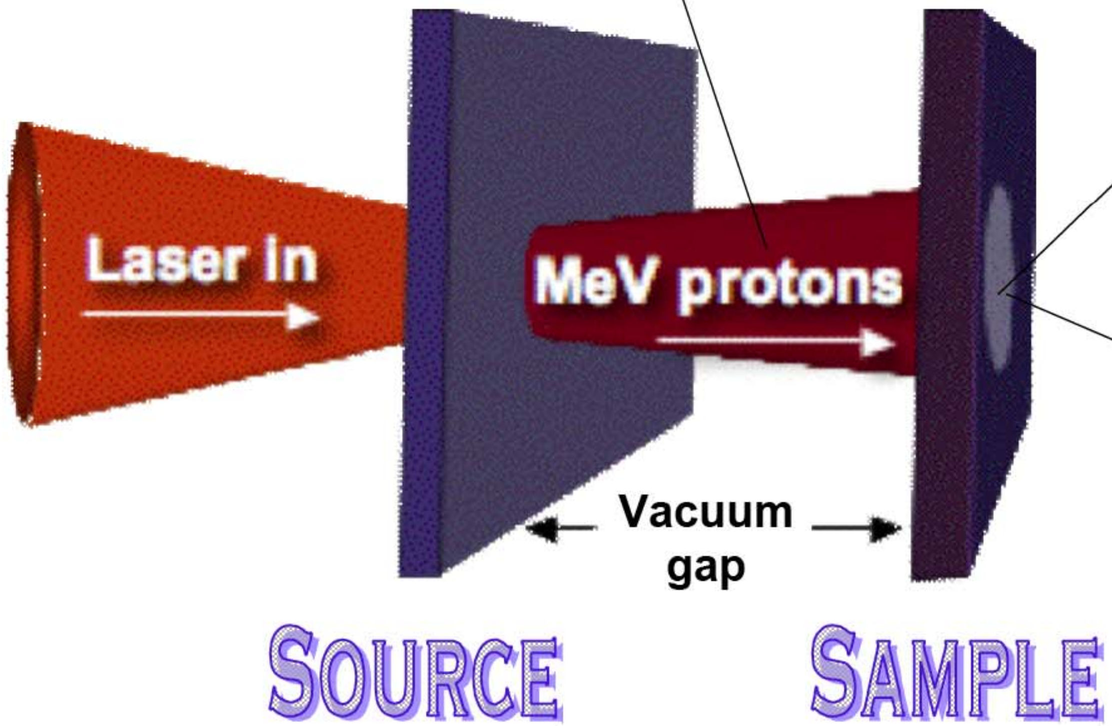
Proton spectra from PW irradiation of solids are typically broad, stretching to a cut-off of many MeV

Proton spectrum from Titan irradiation of a slab target



A petawatt-class laser can generate multi-joule pulses of protons to heat a secondary solid target

- Directional
- Efficiency ~1% from laser energy
- Heats sample several μm deep
- Not mon-oenergetic → velocity dispersion



P > 4 Mbar

⇒ Rapid expansion into vacuum

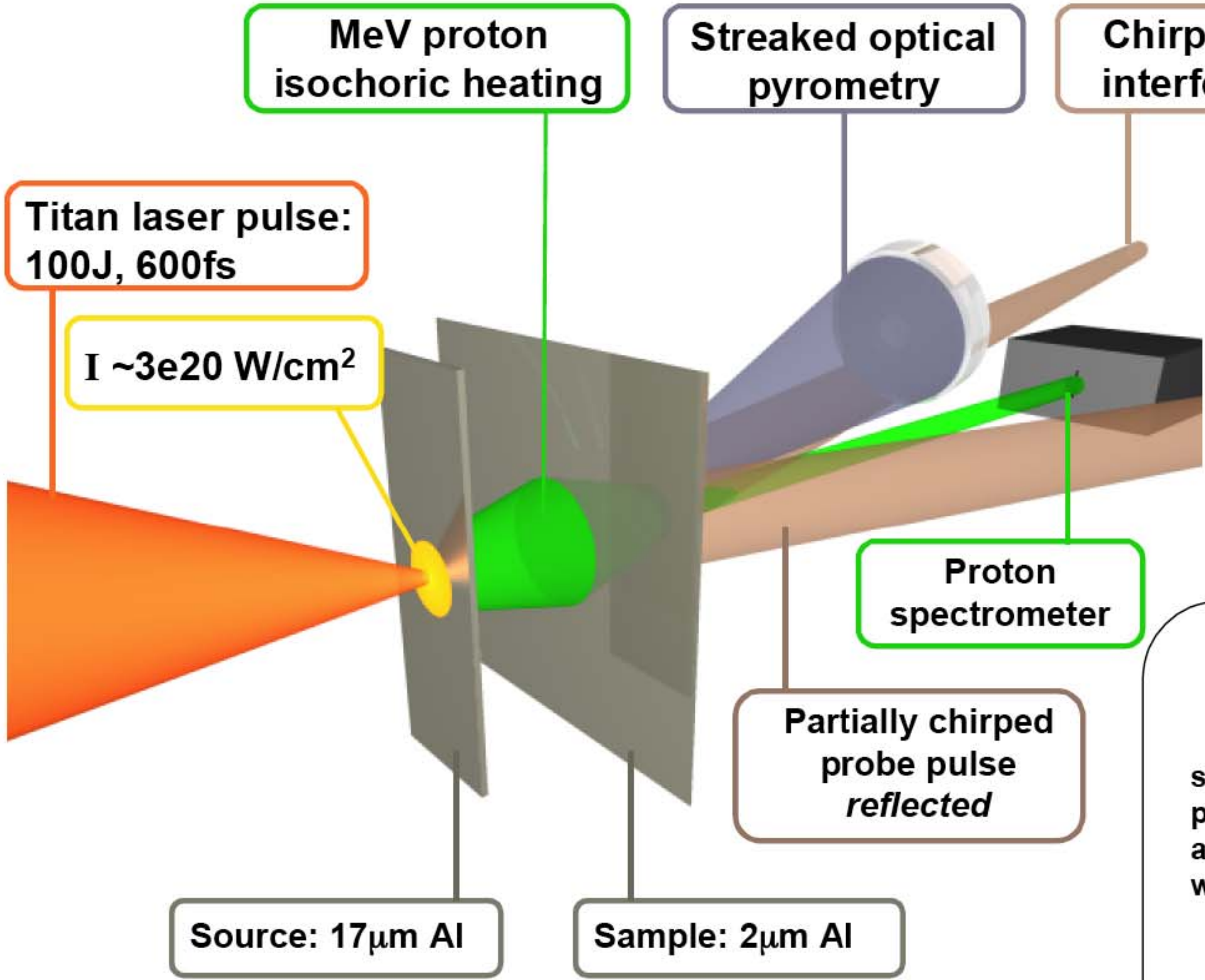
⇒v > 10^6 cm/s

T > 10eV

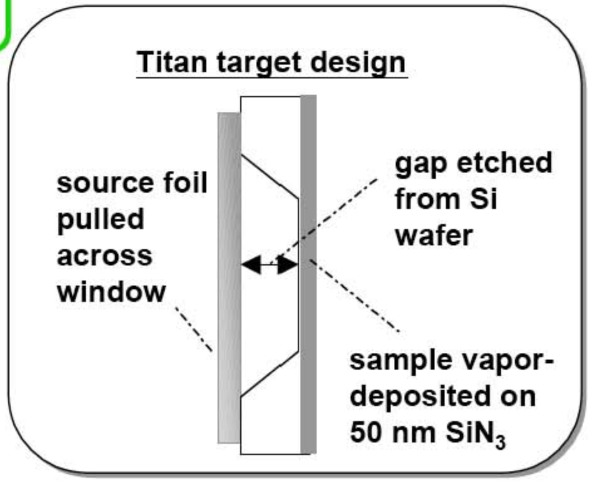
⇒ Blackbody emission through visible and UV

⇒Few-ps timescale

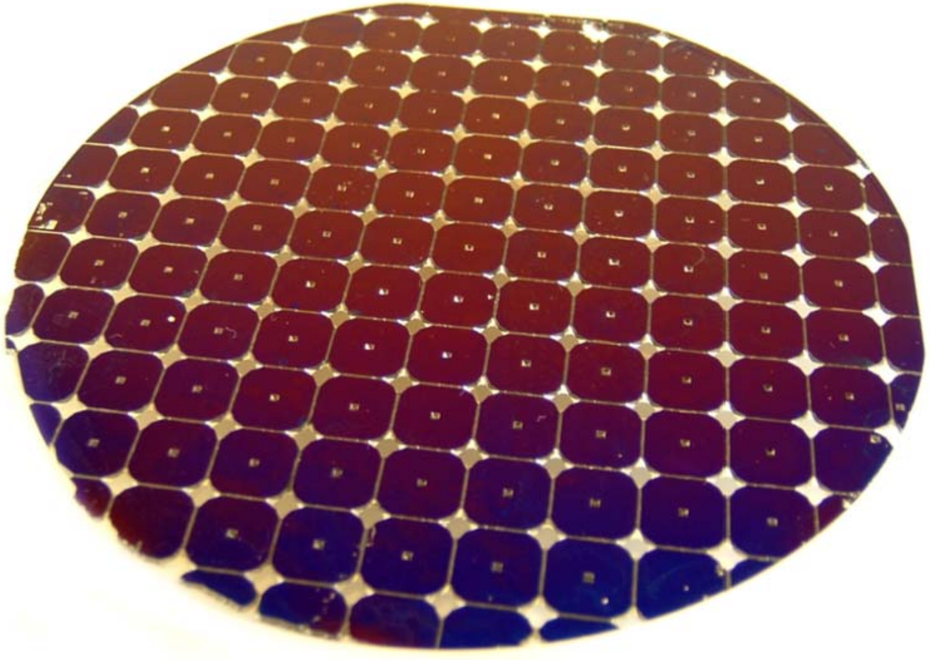
We have demonstrated proton heating using the LLNL 200 TW Titan laser

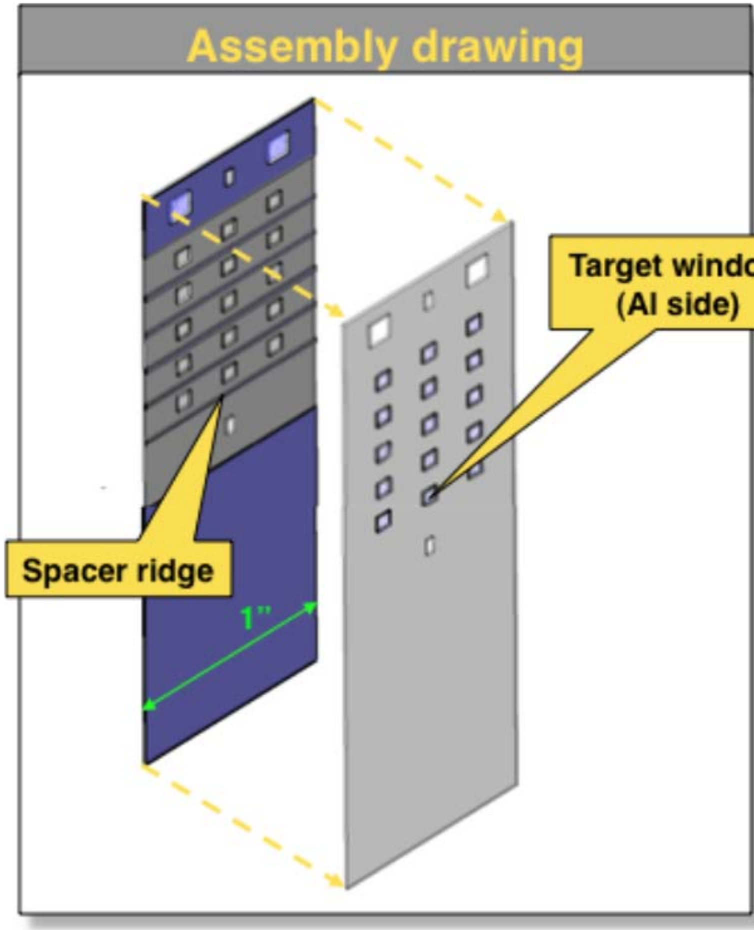


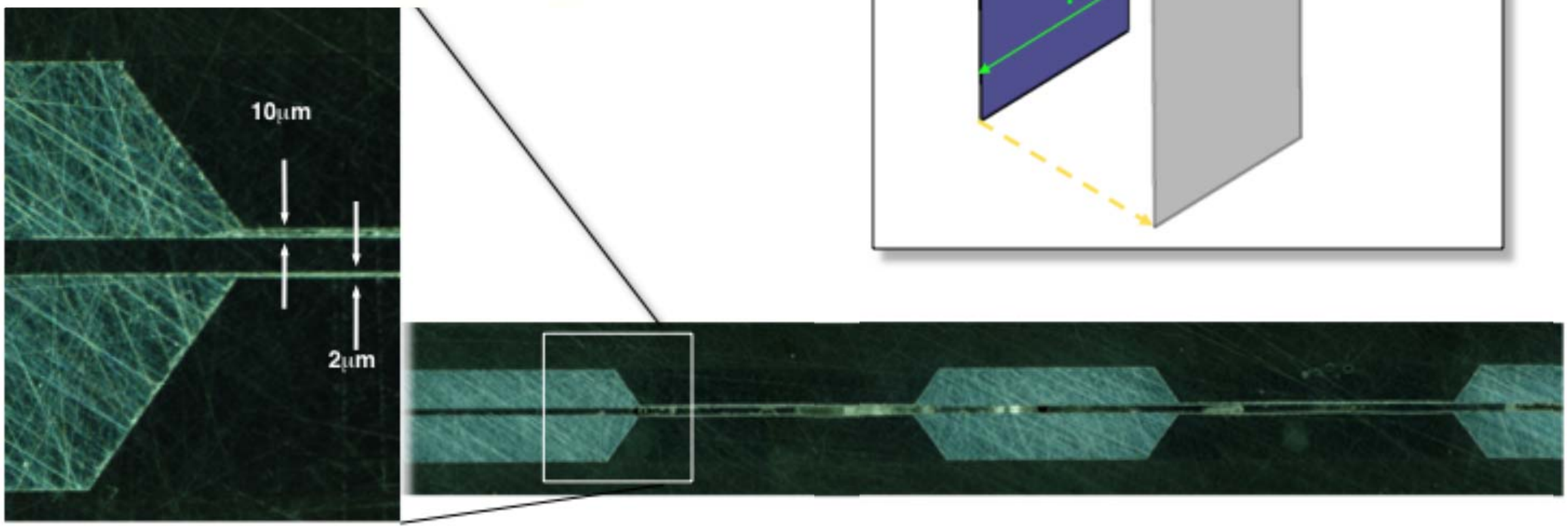
- Single shot time resolved thermal measurement (SOP)
- Single shot time-resolved expansion measurement (CPI)



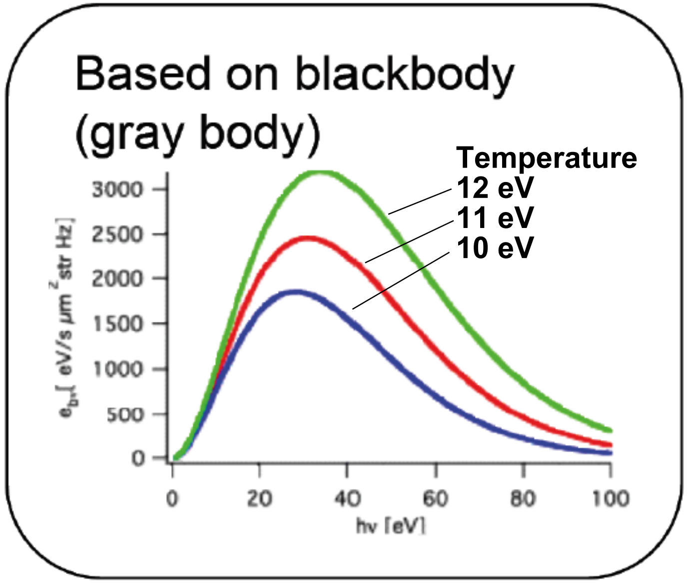
Multi-layer targets for proton isochoric heating experiments can be fabricated in silicon wafers

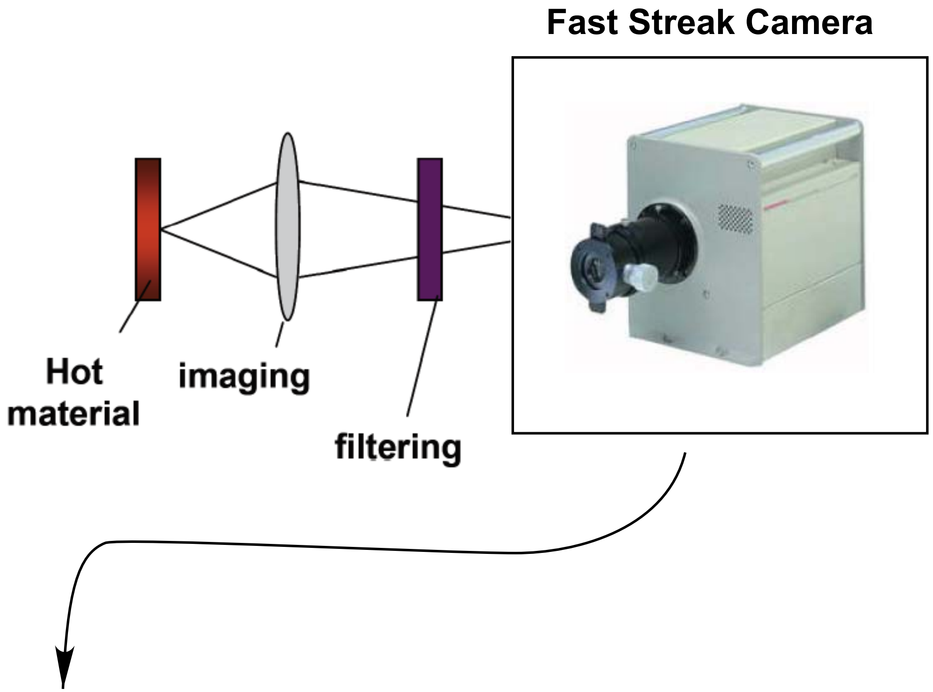


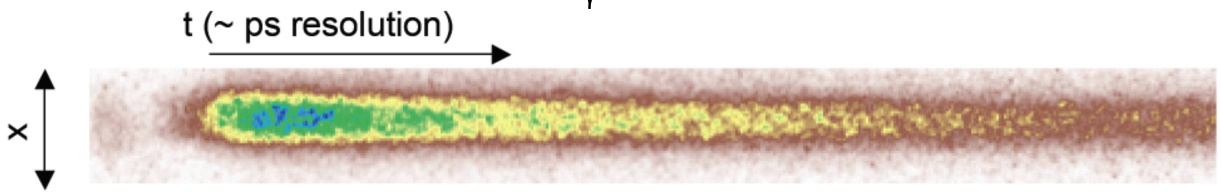




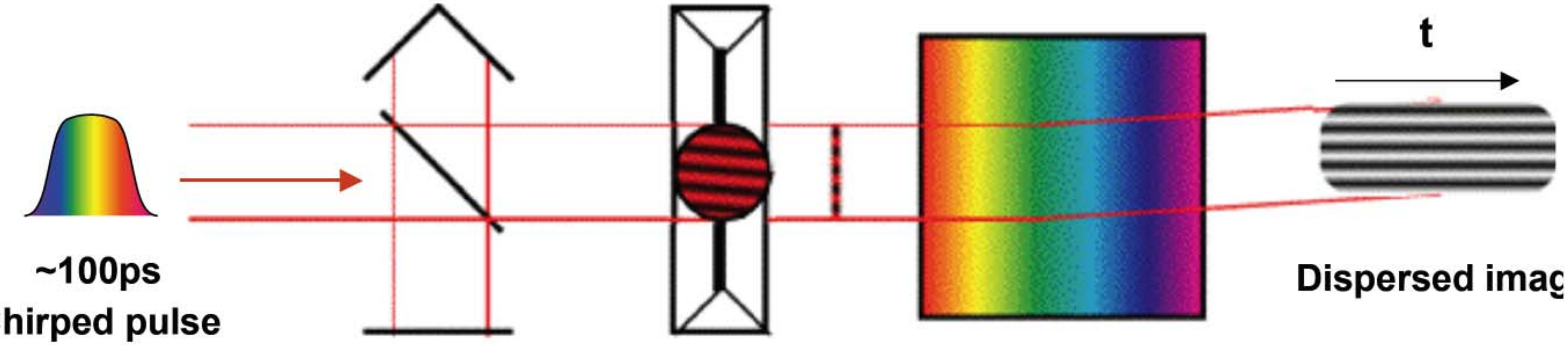
The plasma’s temperature is independently measured with a streaked optical pyrometer

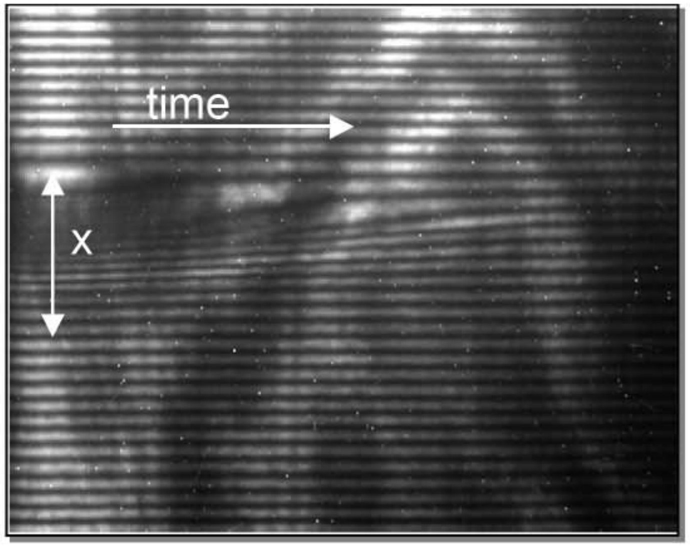






We measure the expansion rate of the heated plasma with chirped pulse interferometry



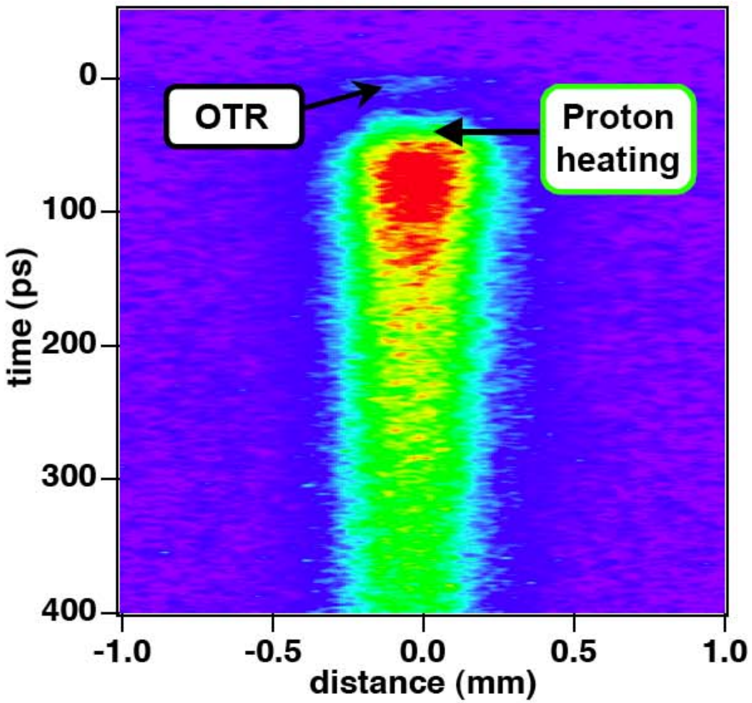


- Chirped: Spectrum → Time
- Bending of fringes →changing in time
- $\Delta t_{resolved}$ ~ $\Delta t_{unchirped}$ (post process)

J. P. Geindre, P. Audebert, S. Rebibo, and J. C. Gauthier. Single-shot spectral interferometry with chirped pulses. Optics Letters, 2001.

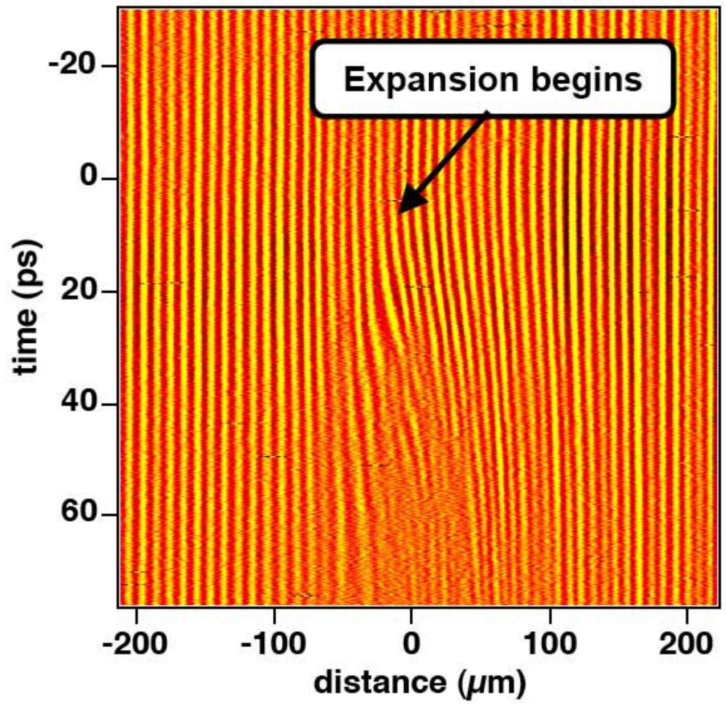
The time history of the temperature and expansion of the heated Al slab was measured on every shot

<u>SOP: Time-resolved temperature</u>



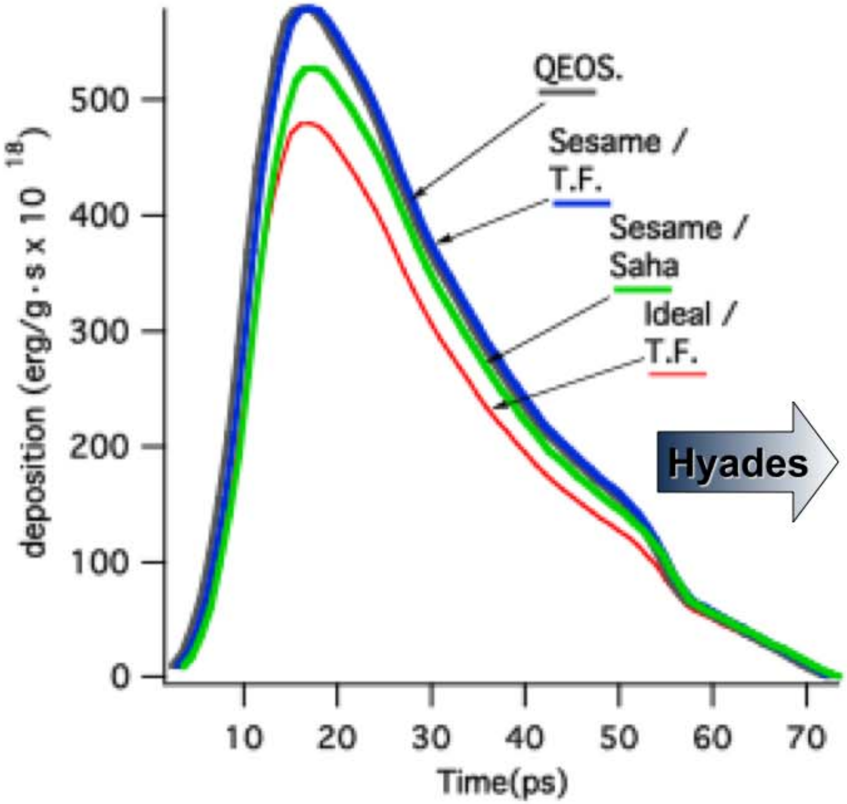
- Peak temperature ~ 25 eV
- Optical transition radiation signal at t_0

<u>CPI: Time-resolved expansion</u>

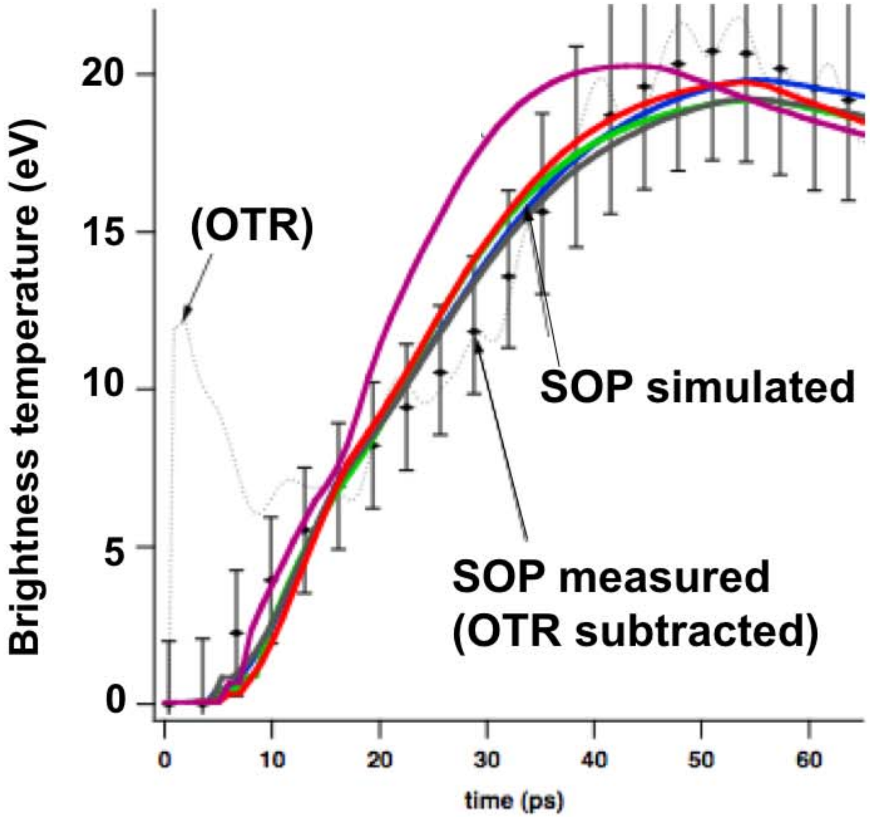


- Fourier analysis of bending fringes → phase shift → expansion in time

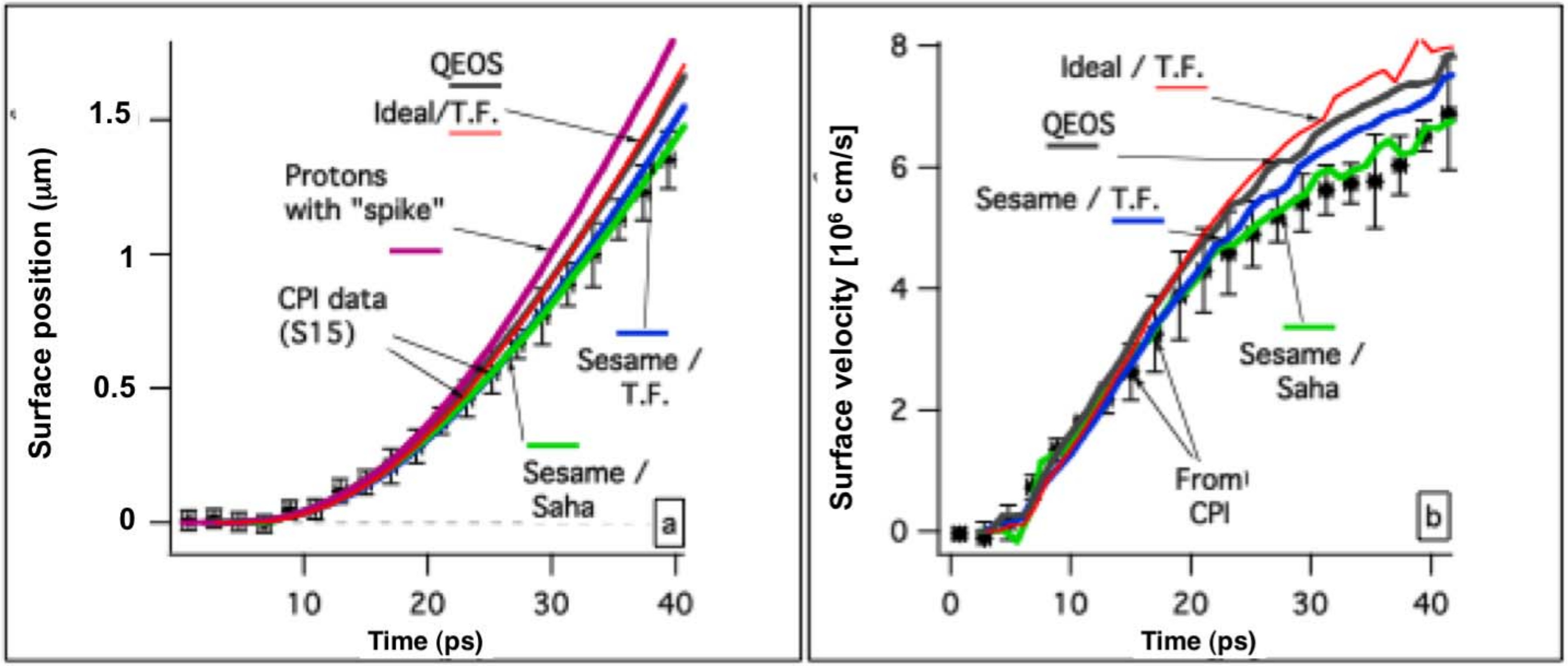
Time-resolved measurement of black-body emission indicated that we heated the solid Al to 20 eV



Hyades



Our proton-heated Al had an EOS which was consistent with the most commonly used SESAME table



Sesame / Saha fits expansion curve within 4%

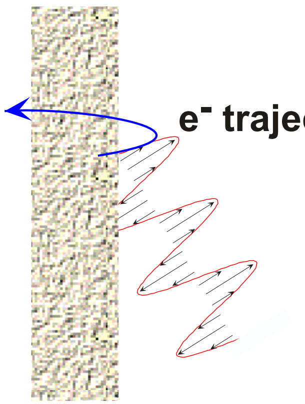
Sesame / Saha fits velocity curve within 10%

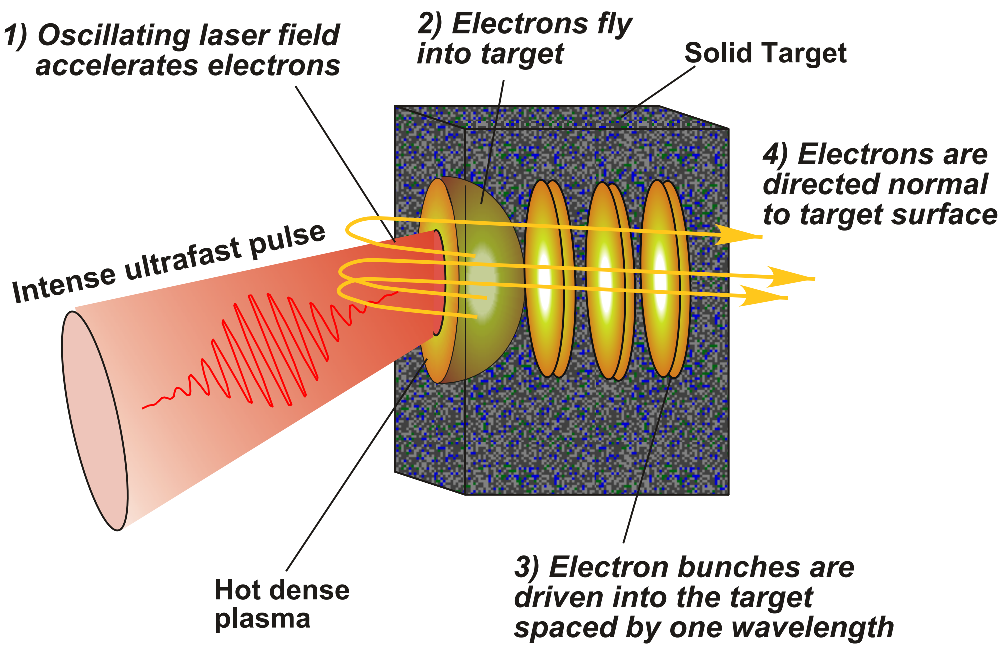
This measurement was in solid density aluminum at a maximum temperature of 20 eV

“Rescattering” of laser driven electrons at the surface of a sharp plasma gradient can produce pulses of fast electrons

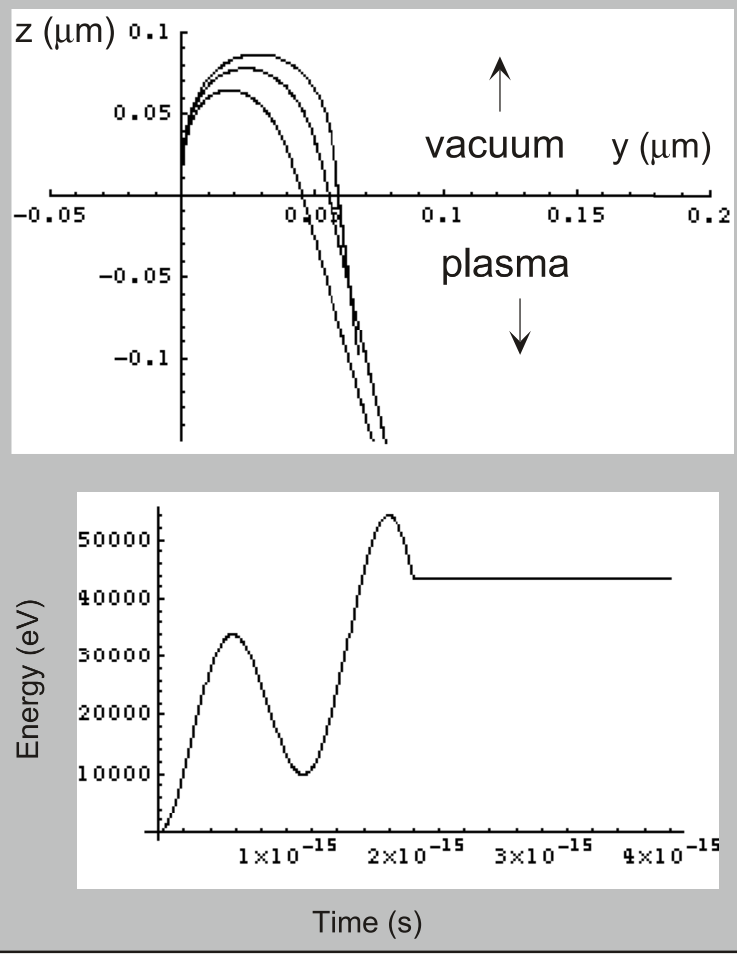
Scattering at the conducting surface breaks the adiabaticity of the laser oscillation

→ **"Brunel absorption"**



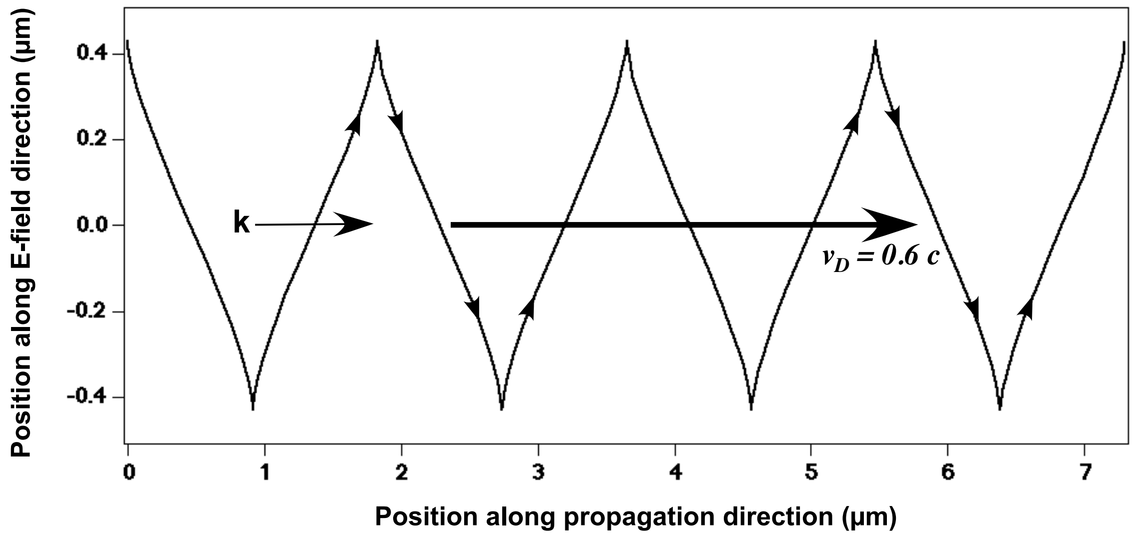


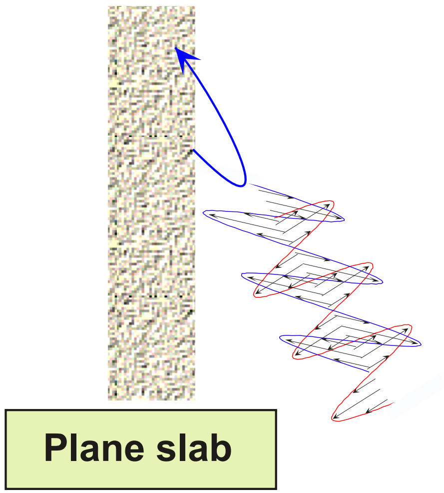
Simulated e⁻ trajectories and energy in relativistic field at plasma surface
U_p = 50 keV (5 x 10^{17} W/cm^2)

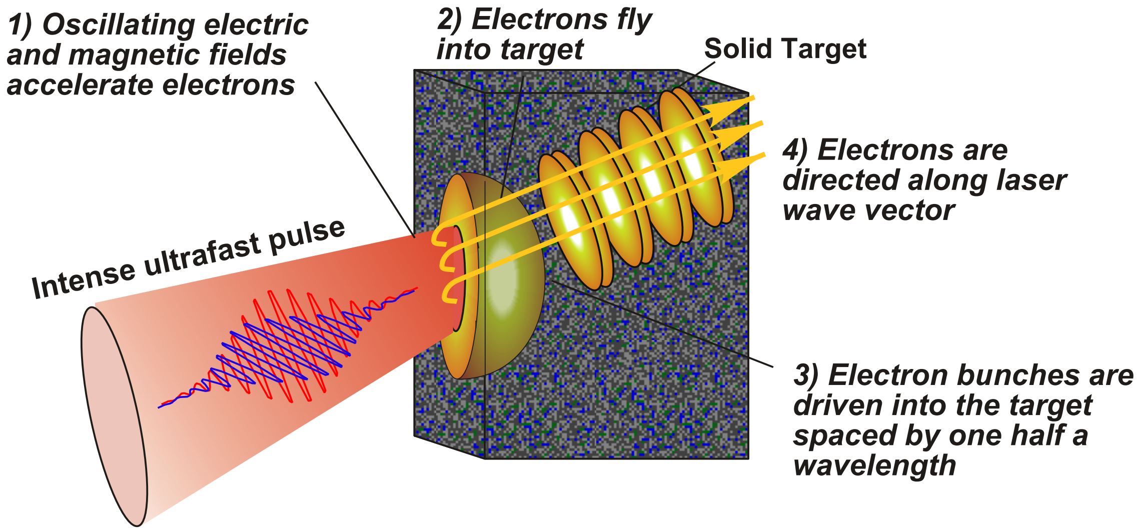


At relativistic intensity, the laser's magnetic field can also accelerate electrons at a sharp surface

Electron trajectory with λ =1 µm and I = 10^{19} W/cm^2, (a_0 = 2.7 and γ_{osc} = 2.1)







"*j* x *B* heating"

$$T_{hot} \approx U_p^{(rel)} = (\gamma_{osc}-1)\, m_e c^2$$

Transport of laser accelerated electrons on a solid target can be diagnosed by imaging their transition radiation

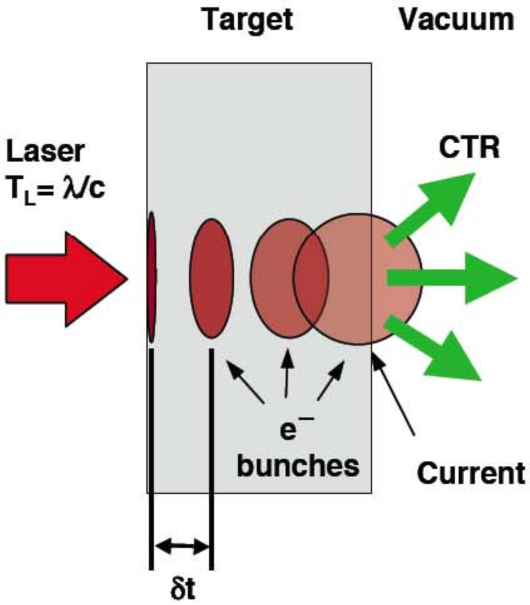
Ballistic transport model

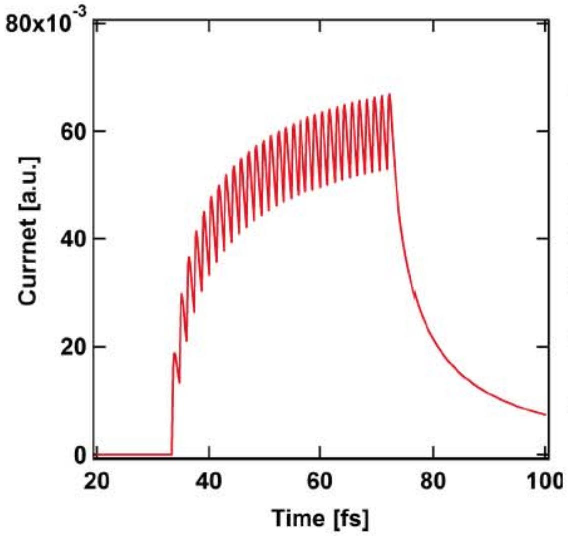
Electrons injected into the target have a relativistic Maxwellian velocity distribution

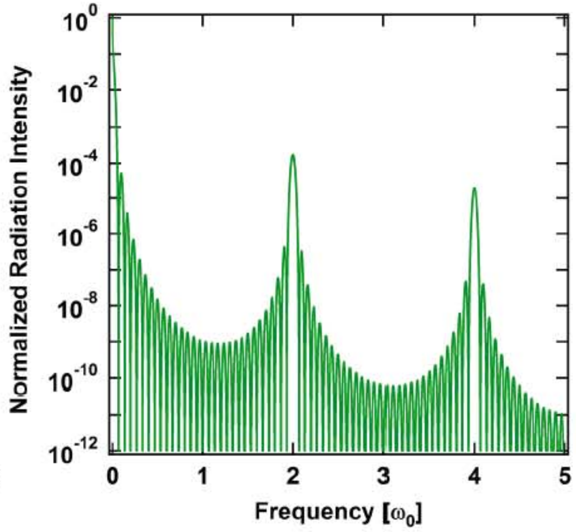
Current at target rear side generated by 30 e^- bunches in 40 fs

Radiation spectrum is given by Fourier transform of current

$$I_{CTR} = \eta(\omega) P^2 \left| j(\omega) \right|^2 \frac{\sin^2(M\omega\delta T/2)}{\sin^2(\omega\delta T/2)}$$

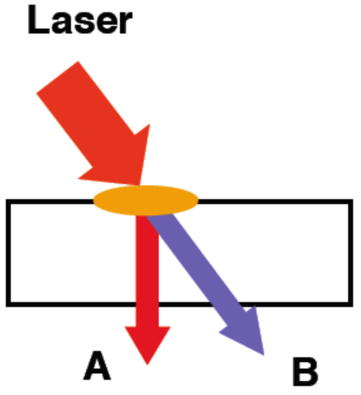




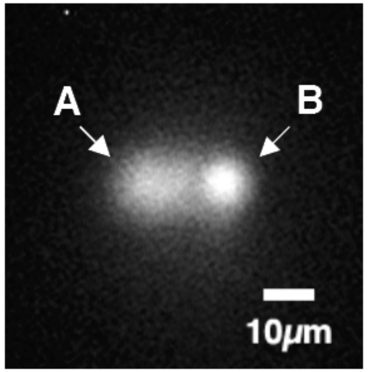


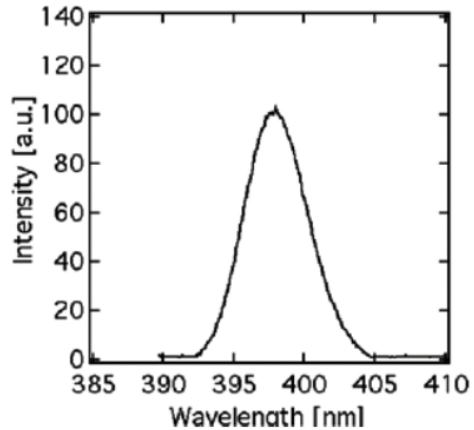
T_e= 1 MeV, δt = 1.33 fs, d = 10 μm

We have identified two hot electron generation mechanisms at work simultaneously on planar targets

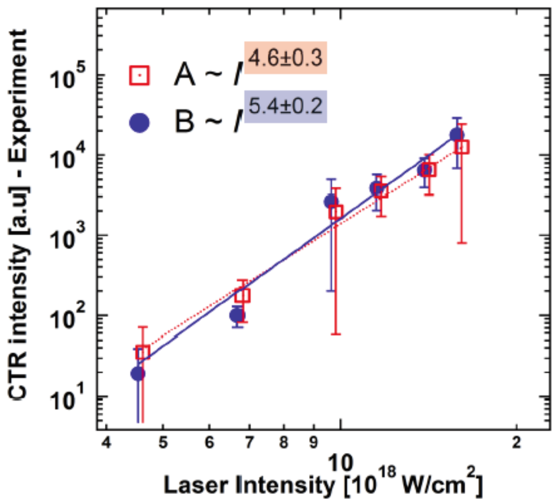


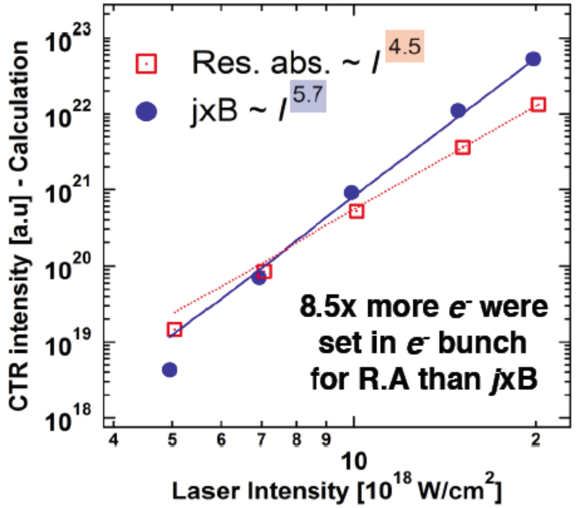
$2\omega_0$ CTR from 10 μm aluminum foil



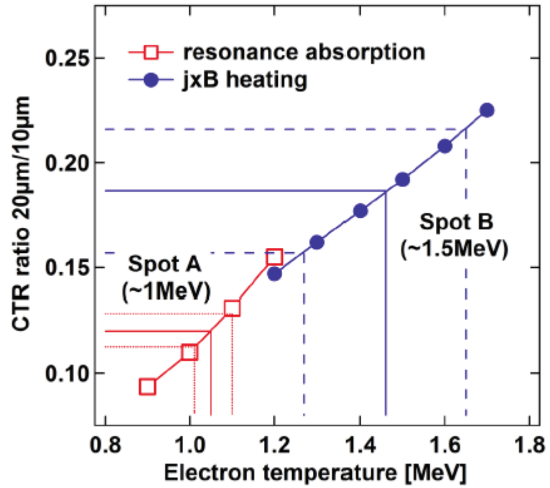


CTR vs *I*, measurement & calculation

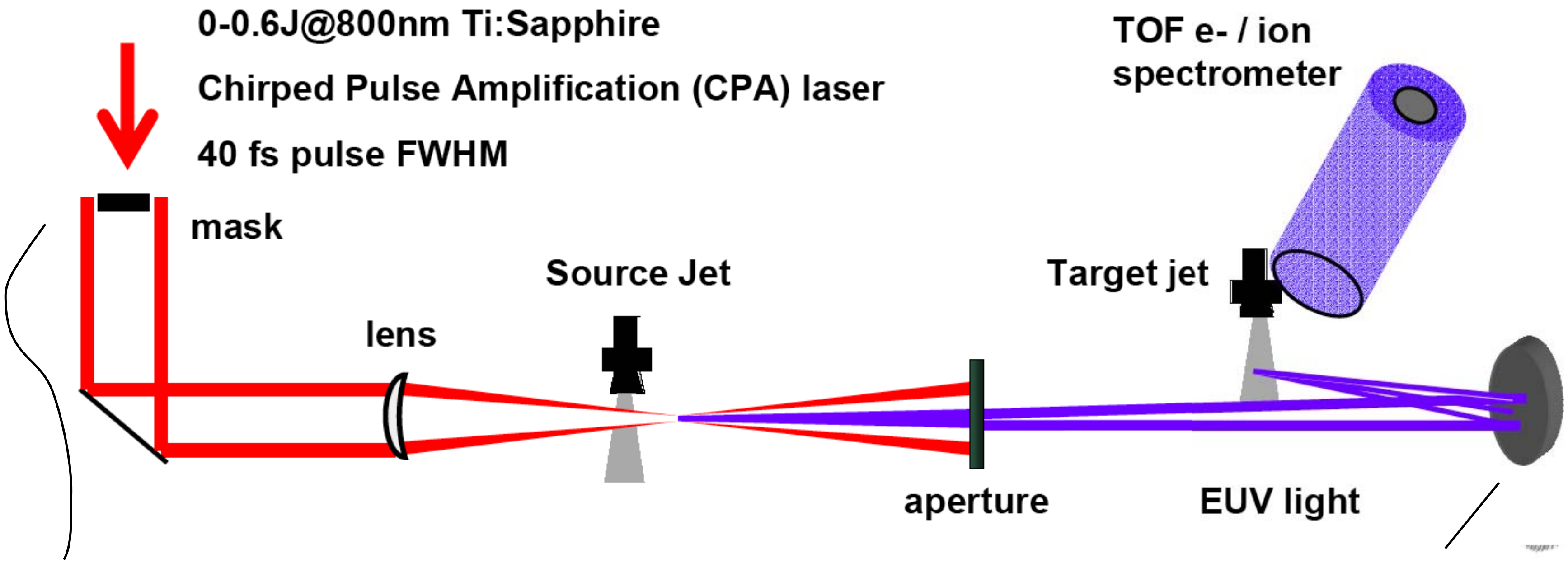




CTR ratios (20 / 10μm foils) & T_e

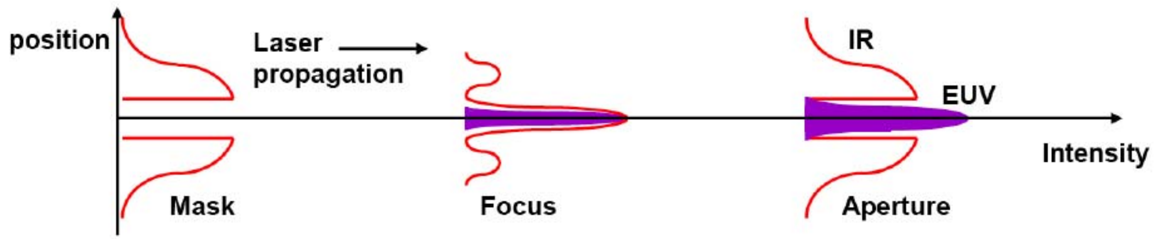


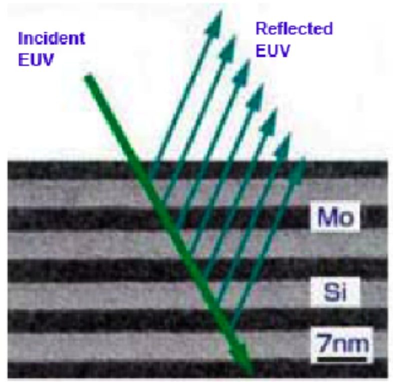
We use the THOR laser to generate harmonics in the ~30 nm region and refocus them into a cluster jet



Imaging a mask onto an aperture allows direct infrared light to be blocked.

Harmonics diverge less, so they pass through the aperture.





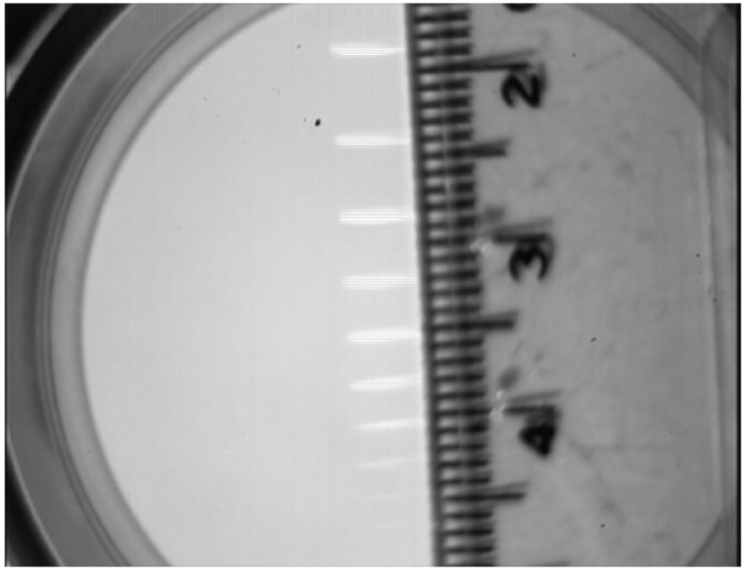
Cross sectional image of Mo/Si multilayer mirror and EUV reflection mechanism. (IOF Fraunhofer, Jena)

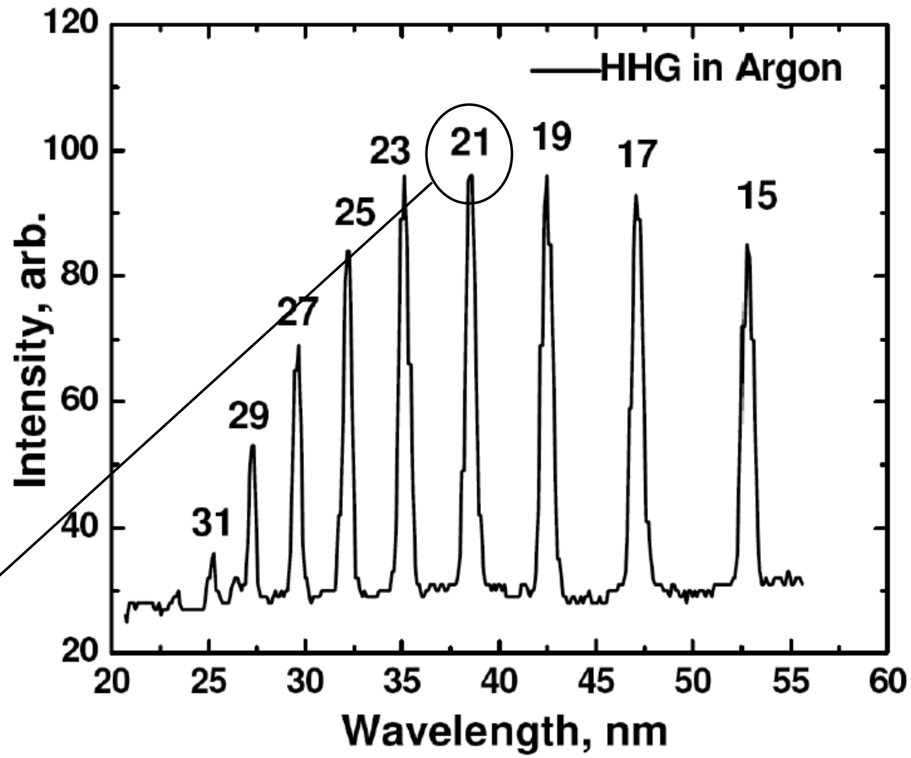
-Uspenskii, Vinogradov et. al., Optics Letters 20, 771 (1998)

Multilayer mirrors are $\lambda/4$ stacks, with periodicity ~10nm.

Sc/Si mirror reflectivity R ~ 0.3-0.5 in the 35-50nm region.

We generate 32.7 eV pulses by high harmonic generation in argon

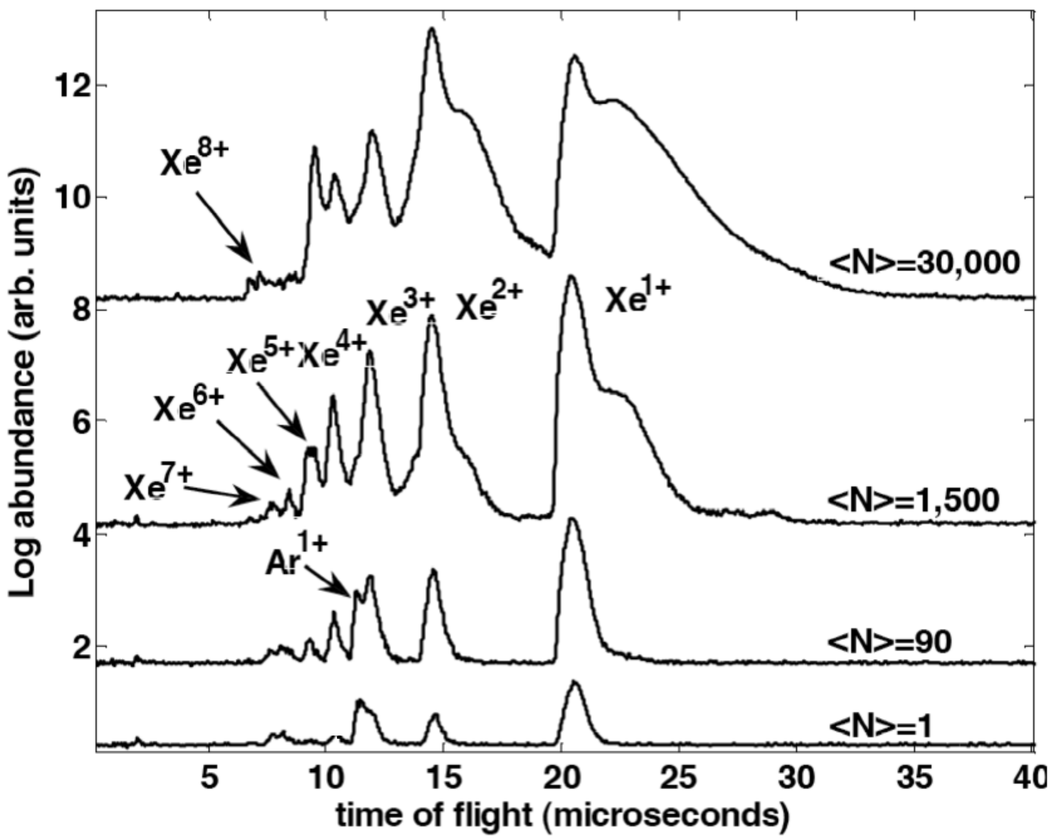




Harmonic selected for these experiments: $h\nu$ = 32.7 eV (λ =38 nm)

XUV photo diode measurements indicate that we focus ~ 1 nJ of 38 nm light into the Xe cluster jet

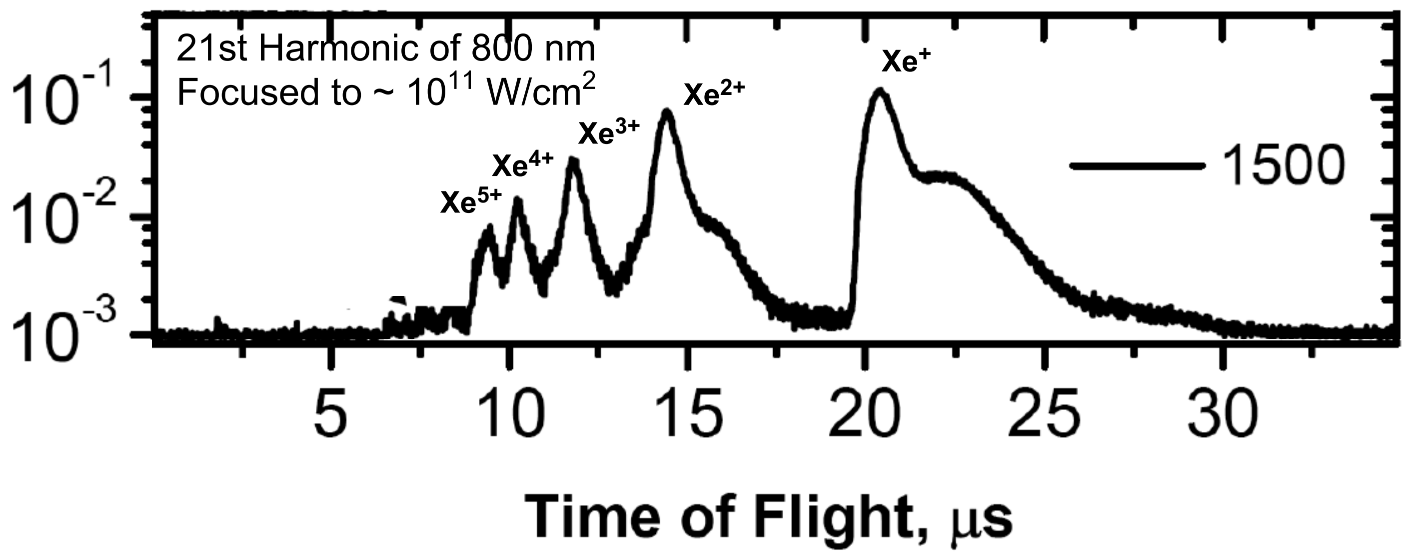
High charge states are produced when Xe clusters of > 1000 atoms are irradiated



Efficient production of charge states of up to 5+ are observed, with some evidence for charge states up to 8+

The high charge states observed in Xe clusters are anomalous

Exploding Xe cluster TOF spectrum

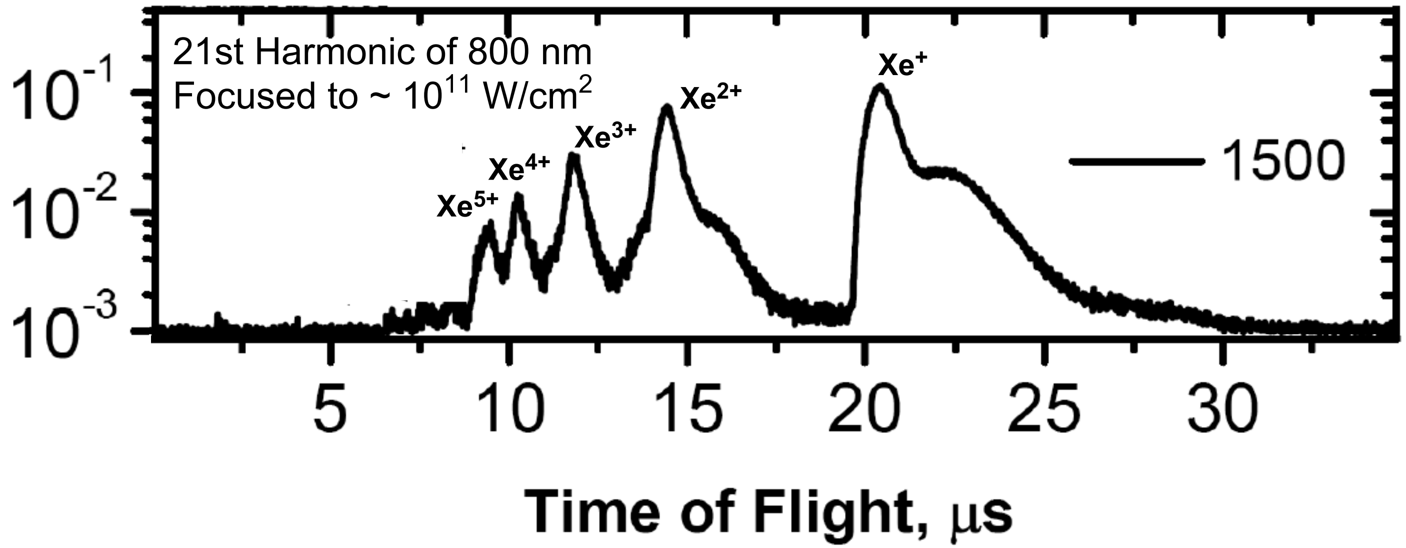


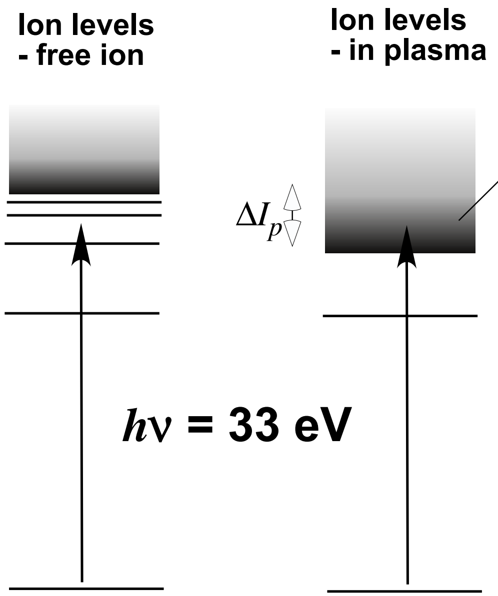
$h\nu_{q=21}$ = 32.6 eV

Charge state	Ionization Potential
Xe^0	12.1 eV
Xe^{+1}	21.2 eV
Xe^{+2}	32.1 eV
Xe^{+3}	46.7 eV
Xe^{+4}	59.7 eV
Xe^{+5}	71.8 eV
Xe^{+6}	92.1 eV
Xe^{+7}	105.9 eV

Continuum lowering coupled with photoionization may explain our observed charge states

Exploding Xe cluster TOF spectrum





Xe with $\langle Z \rangle$ 5 → ΔI_p 30 eV

Charge state	Ionization Potential
Xe^0	12.1 eV
Xe^{+1}	21.2 eV
Xe^{+2}	32.1 eV
Xe^{+3}	46.7 eV
Xe^{+4}	59.7 eV
Xe^{+5}	71.8 eV
Xe^{+6}	92.1 eV
Xe^{+7}	105.9 eV

Direct photoionization only possible in these charge states for free Xe (Xe^0 – Xe^{+2})

Photoionization possible up to here when continuum lowering included (Xe^{+3} – Xe^{+4})