Proton energy loss measurements in high-density, low temperature plasma

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WCI WEAPONS AND COMPLEX INTEGRATION

Physical and Life SCIENCES

Lawrence Livermore National Laboratory
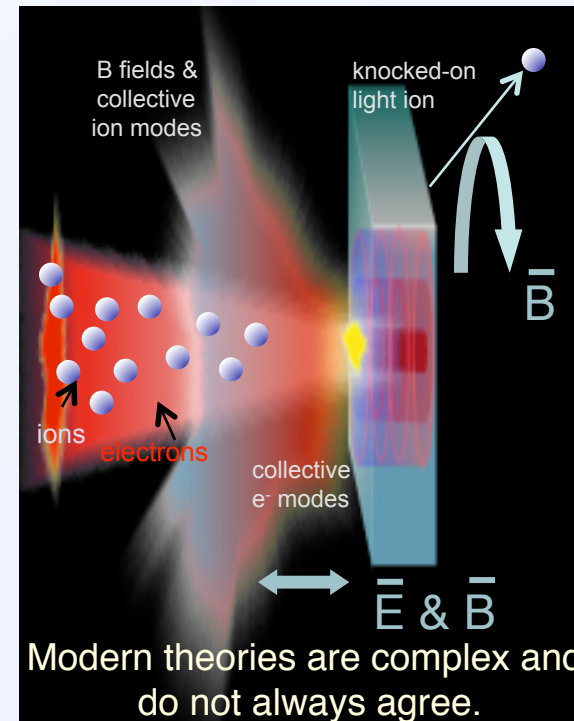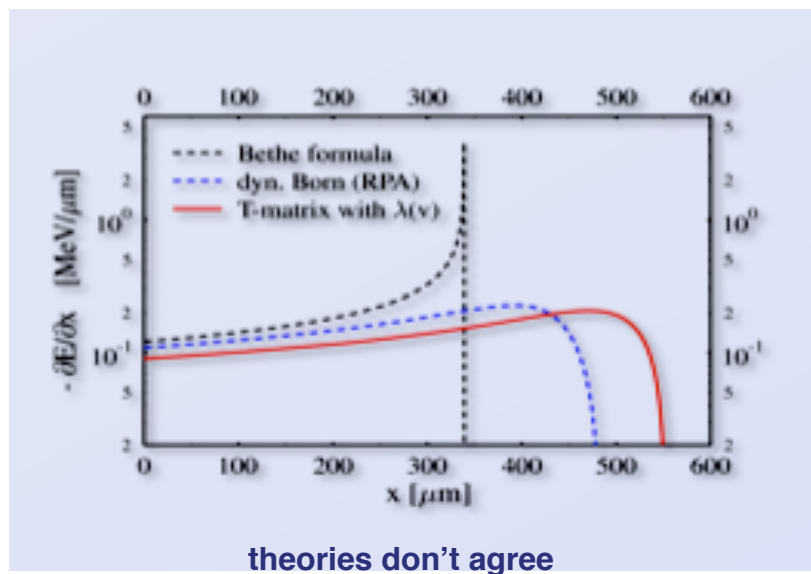
Outline

- Goal and motivation

- Description of experiment

- Pre –experiment simulations

- Data and analysis
  - Heated targets:

- Conclusion
  - What's next (?)

Motivation: Even today, modeling and understanding stopping is challenging

There are many considerations when calculating charged particle energy loss in dense plasmas

B fields & collective ion modes

knocked-on light ion

$\bar{B}$

ions

electrons

collective e⁻ modes

$\bar{E}$ & $\bar{B}$

Modern theories are complex and do not always agree.

- - - - Bethe formula
- - - - dyn. Born (RPA)
——— T-matrix with λ(v)

theories don't agree

$$\frac{dE}{dx} = \frac{Z_b^2 e^2}{\pi v^2} \int_0^\infty \frac{dk}{k} \int_{\hbar k^2/2m_b - kv}^{\hbar k^2/2m_b + kv} d\omega \left[\omega - \frac{\hbar^2 k^2}{2m_b} \right] \Im \varepsilon^{-1}(k,\omega)\, n_B(\omega)$$

(dynamic Born)

Basic idea: For a given proton energy, determine energy loss as a function of target thickness

- Idea is simple;
  - Measure the relative change in energy as a function of target thickness
    - Characterize proton beam before entering target and after passing through target

  - Measure plasma temperature and density
    - Ideally as a function of space and time

  - Determine time dependent ionization balance

  Execution is very hard

Plan: Use short pulse laser generated protons to heat sample and short pulse laser generated protons to measure energy loss

- **Basic concept of experiment:**

  - Short pulse laser generated protons have a short pulse duration. They also have a long mean free path. Thus they are a good candidate for volumetric heating of material.

    - This minimizes hydrodynamic expansion and spatial gradients during the stopping measurement

    - The short proton pulse duration allows one to probe during a snap-shot of the plasma characteristics
    - TITAN
    - LULI

Heating protons

Probe protons
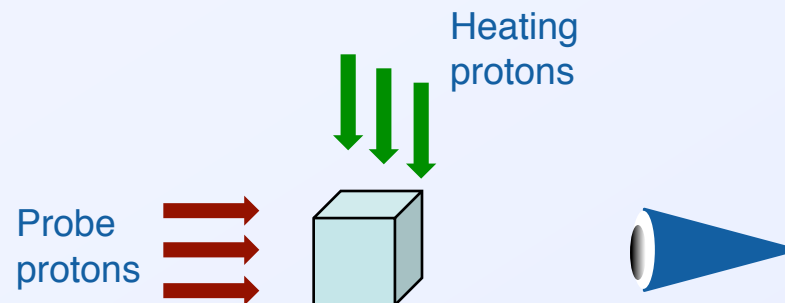
To look at proton heating of material, we have used the simulation code HYDRA

The physical assumptions for proton energy loss in solid material using HYDRA:
From Tom Kaiser, Gary Kerbel, Manoj Prasad, HYDRA uses the following assumptions:

Classical Ion Beam Energy Loss

$$-\frac{dE}{dx} = \left[\frac{4\pi e^4}{m_e c^2}\right]\left[\frac{N_c \rho_T}{A_T}\right]\left[\frac{Z_T^2}{\beta^2}\right]\left\{(Z_T - \bar{Z})\,\text{Log}\,\Lambda_B + \bar{Z}\,G(\beta/\beta_e)\,\text{Log}\,\Lambda_F\right\}$$

ρ_T = target density in g/cm^3, A_T = target atomic weight

Z_T = target atomic number, $\bar{Z}$ = target ionization state

$\Lambda_B = \dfrac{2m_e c^2 \beta^2}{\bar{I}}$, $\Lambda_F = \dfrac{m_e c^2 \beta^2}{\hbar \omega_p}$, $G(x) = erf(x) - x\,erf''(x) \approx 1$ for $x \gg 1$

$\bar{I}$ = average ionization potential $\approx .01 Z_T$ keV (Bloch's rule)

ω_p = plasma frequency $= \sqrt{4\pi e^2 n_e / m_e} = 56416\sqrt{n_e}$ / sec

$\hbar \omega_p = (3.7e-14)\sqrt{n_e}$ keV, n_e = electron density in $1/cm^3 = \bar{Z} N_0 \rho_T / A_T$

Ion Beam : $\beta = v/c$, $\gamma = \dfrac{1}{\sqrt{1-\beta^2}} = 1 + \dfrac{E}{Mc^2}$

E = Kinetic Energy of Ion Beam in keV,

Mc^2 = Ion Beam Rest Energy = $A_{IonBeam}$ (9.3e5) keV

$m_e c^2$ = Electron Rest Energy = 511 keV

Betz Empirical $Z_{eff} \approx Z_{IonBeam}\left[1 - \exp(-137\beta_{eff}/Z_{IonBeam}^{.69})\right]$

$\beta_{eff}^2 \equiv \beta^2 + \beta_r^2$, with $\gamma_r = \dfrac{1}{\sqrt{1-\beta_r^2}} = 1 + \dfrac{kT_e}{m_e c^2}$

Relativistic Correction : $\text{Log}\,\Lambda_B \rightarrow \text{Log}\,\Lambda_B + R$, $\text{Log}\,\Lambda_F \rightarrow \text{Log}\,\Lambda_F + R/2$

where $R = 2\,\text{Log}\,\gamma - \beta^2$

Ion Beam Power Deposition Algorithm

- Rectilinear Ion Beam trajectory (No Refraction!): $\dfrac{d^2\bar{x}}{dt^2} = 0$
- Get path length s traversed in cell
- Compute absorbed power in cell
- Neglect Energy Straggling

For each cell traversed by Ion Beam :

Energy Change : $E^{new} = MAX\left(0, E^{old} - \int_0^s |dE/dx|^{old}\,dx\right)$

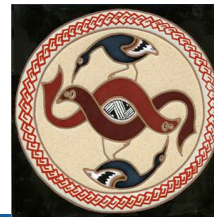$dx = MIN(s,.1*E/|dE/dx|)$

Power Change : $P^{new} = P^{old}\dfrac{E^{new}}{E^{old}}$

Absorbed Power : $P^{abs} = P^{old} - P^{new}$

Various Floors for "dump all" ion beam absorption :

$If (P^{new} < MAX(.01*P^{old}, 1.e-4*P^{original}))\,P^{new} = 0;$

$If (E^{new} < A_{IonBeam}*MAX(eflr, xflr*kT_e))\,E^{new} = 0;\ eflr \approx 30, xflr \approx 3$
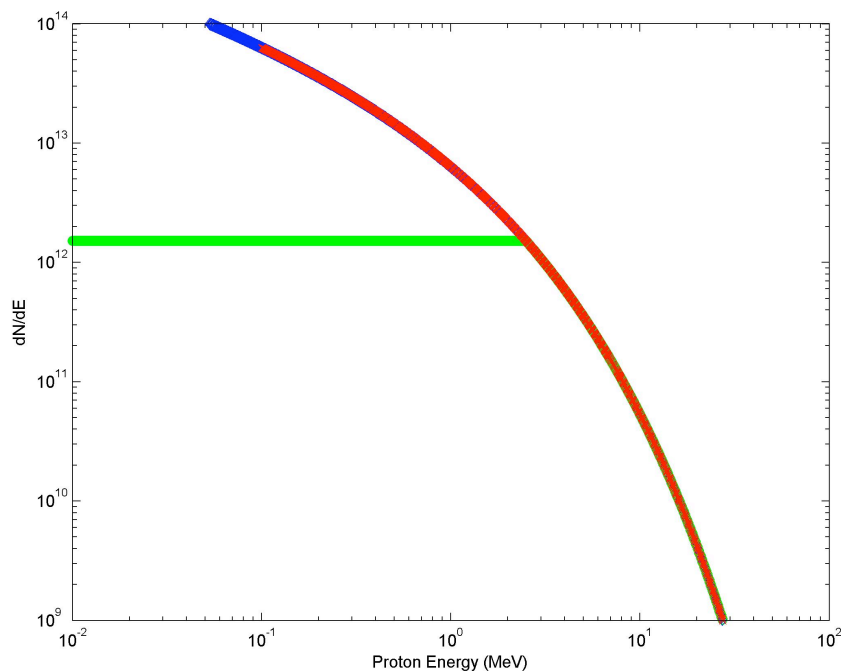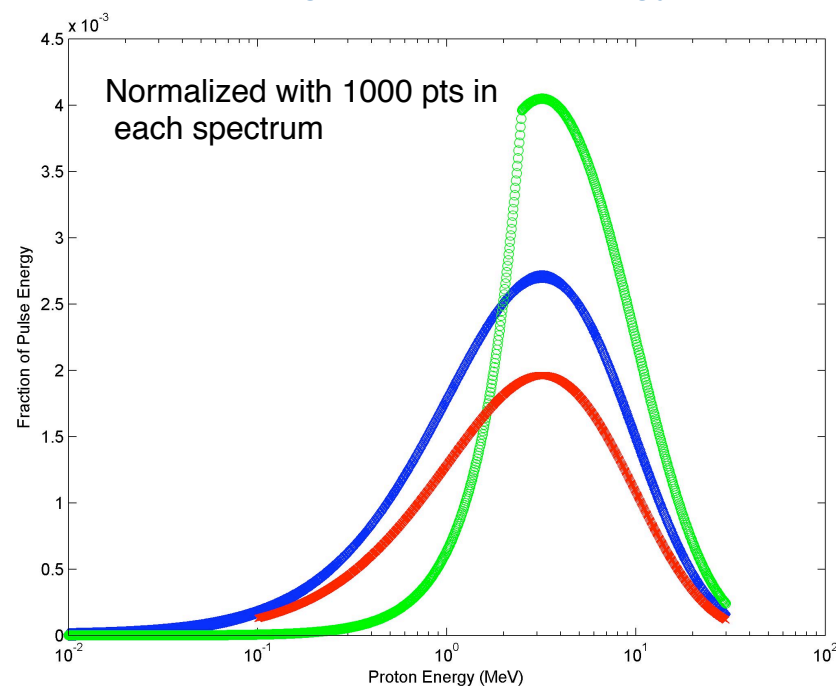
Comparison of 3 spectrums

— 0.1MeV-30MeV analytical

— 0.01MeV-30MeV analytical

— 0.01MeV-2.5MeV Flat with2.5MeV-30MeV analytical

Reproduction of Andy Hazi's figure

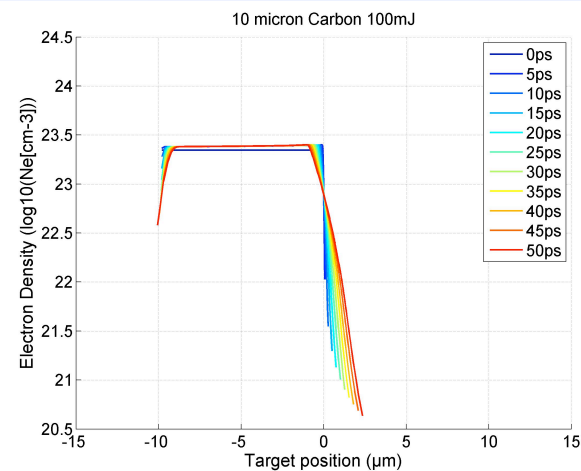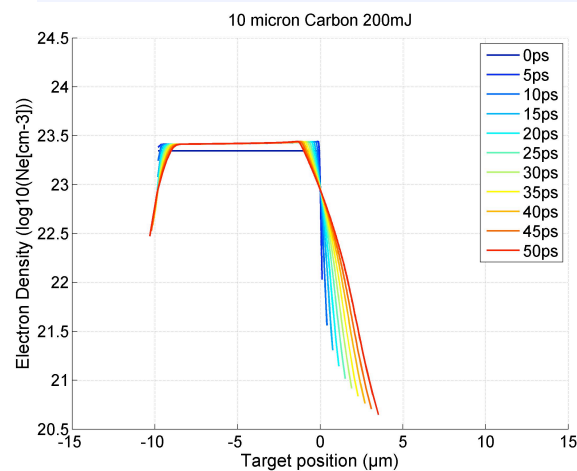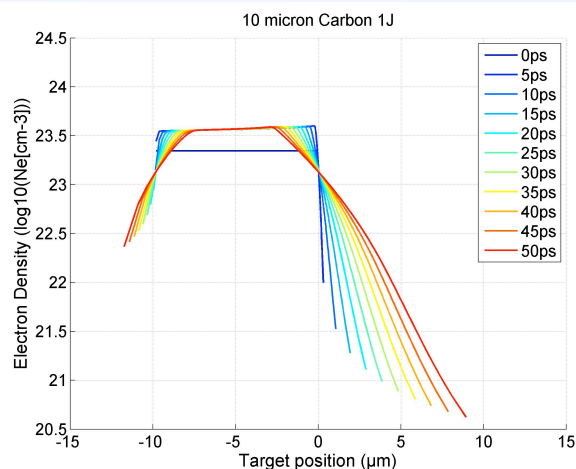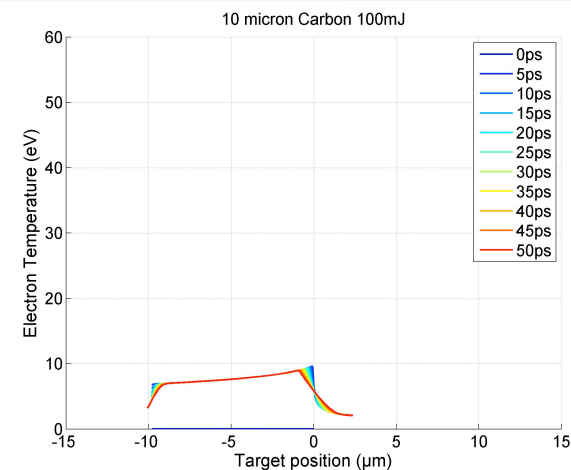### Fraction of the total pulse energy for a given proton energy.

Normalized with 1000 pts in each spectrum
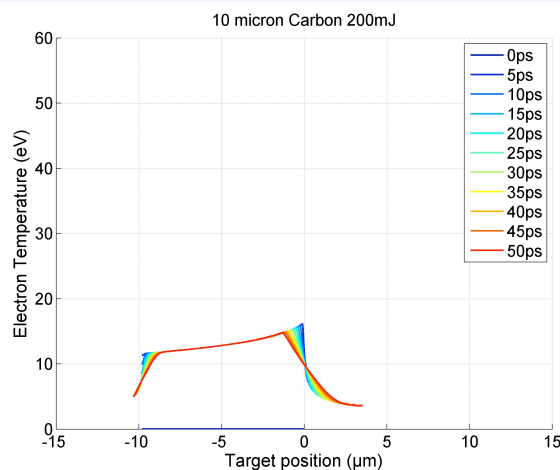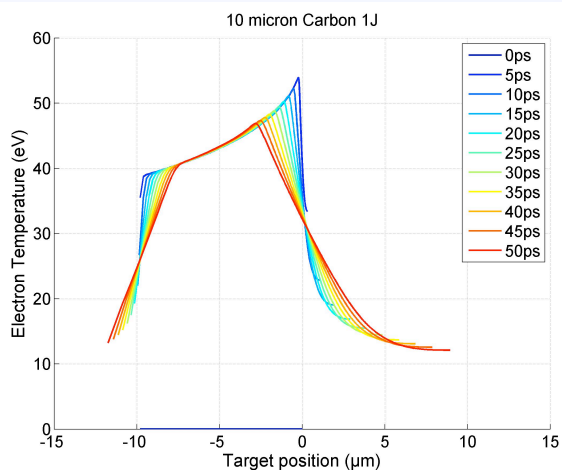
A HYDRA input

Comparison of proton energy: 1J, 200mJ, 100mJ

10µm C target with a FLAT/Analytical proton beam focused to 50 µm diam

Option:UCRL#

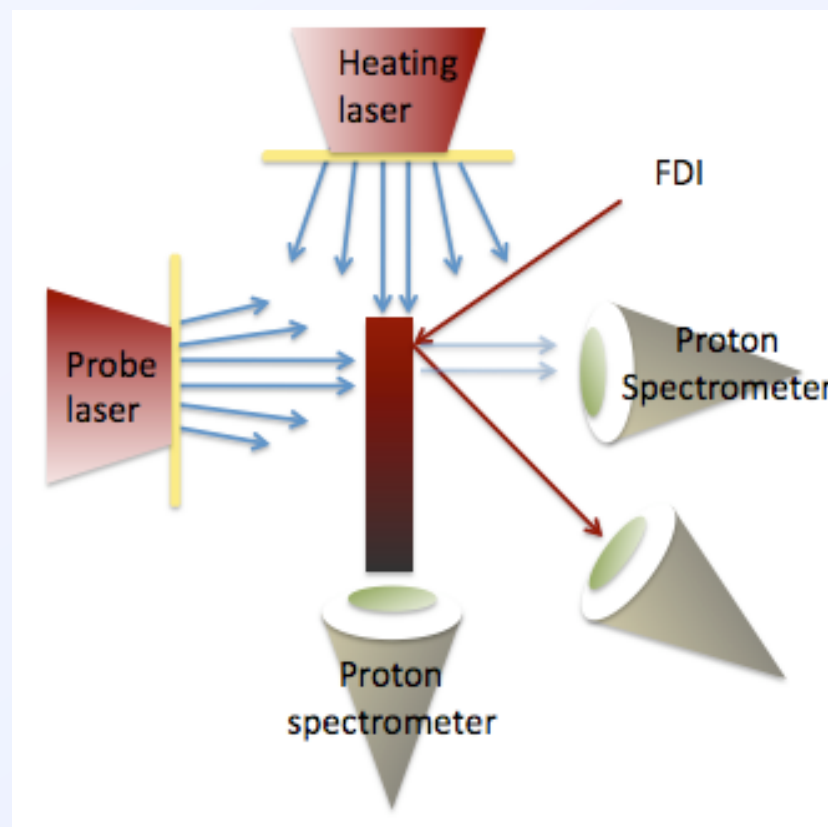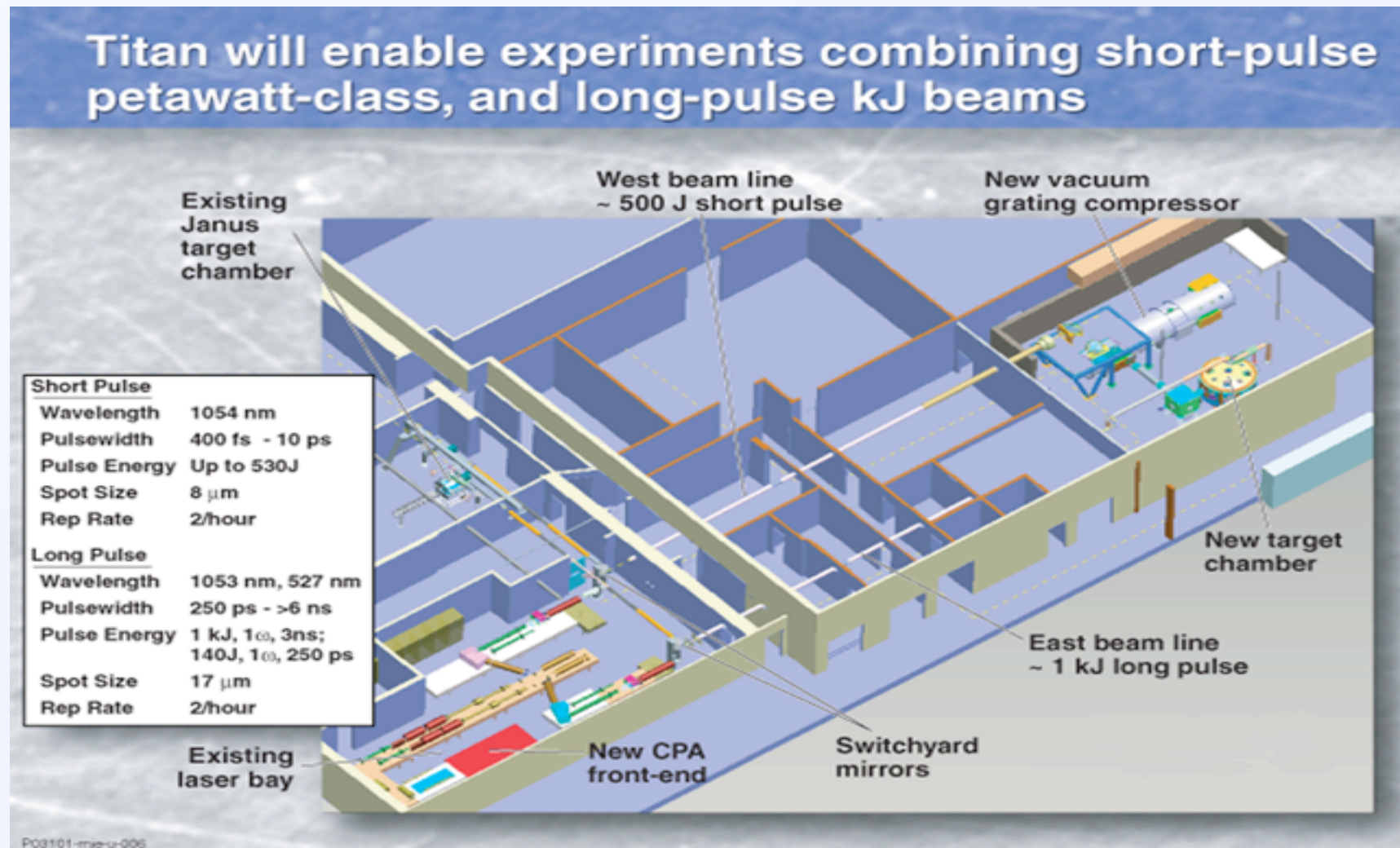Option:Directorate/Department Additional Information

Experimental layout

- **Protons heat edge-on**
  - **Typical heating energy~130 J**
  - **Typical probe energy~20 J**

- **Proton spectrometer measures heating spectrum**
  - **Spectrum is used to infer temperature**

- **FDI measures expansion of critical surface**
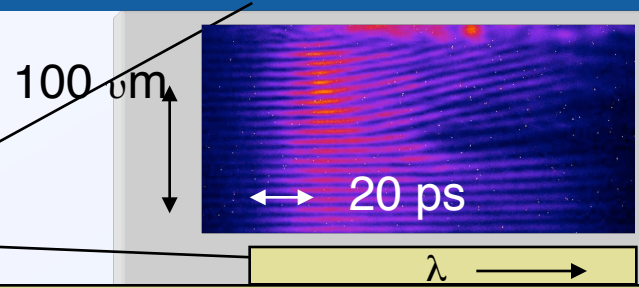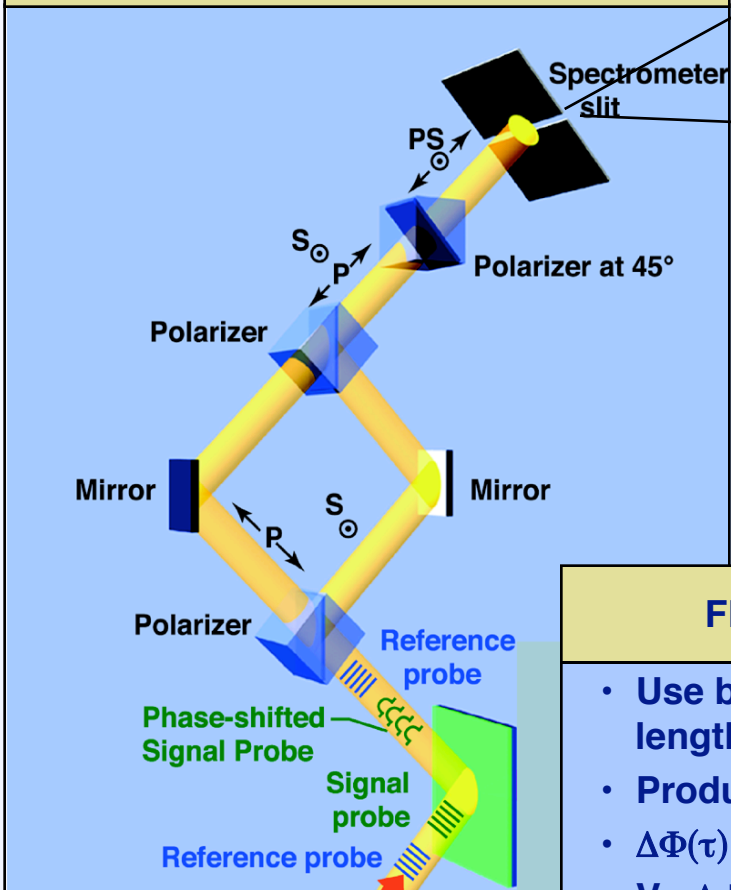 - **Expansion velocity is used to infer temperature**

Titan will enable experiments combining short-pulse petawatt-class, and long-pulse kJ beams

West beam line ~ 500 J short pulse

New vacuum grating compressor

Existing Janus target chamber

Short Pulse

Wavelength	1054 nm
Pulsewidth	400 fs - 10 ps
Pulse Energy	Up to 530J
Spot Size	8 μm
Rep Rate	2/hour

Long Pulse

Wavelength	1053 nm, 527 nm
Pulsewidth	250 ps - >6 ns
Pulse Energy	1 kJ, 1ω, 3ns; 140J, 1ω, 250 ps
Spot Size	17 μm
Rep Rate	2/hour

New target chamber

East beam line ~ 1 kJ long pulse

Existing laser bay

New CPA front-end

Switchyard mirrors

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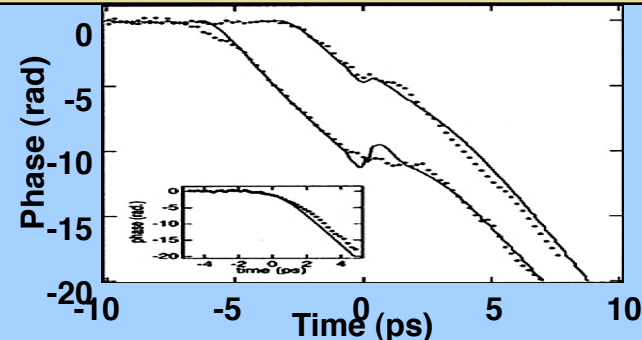
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Methodology: Use Fourier domain interferometry to determine the target characteristics

Fourier Domain Interferometry (FDI)

100 um

20 ps

λ

Spectrometer slit

PS

S P

Polarizer at 45°

Polarizer

Mirror

P   S

Mirror

Polarizer

Reference probe

Phase-shifted Signal Probe

Signal probe

Reference probe
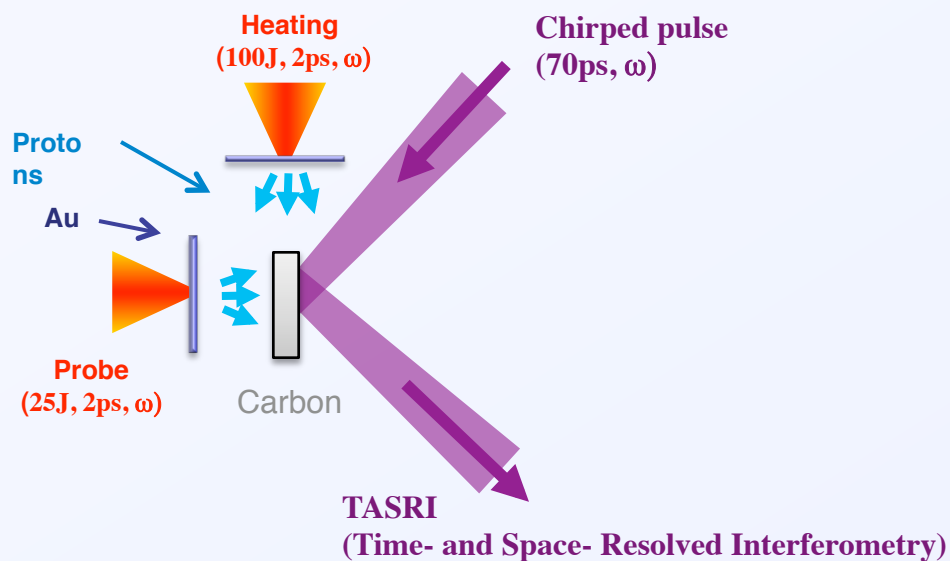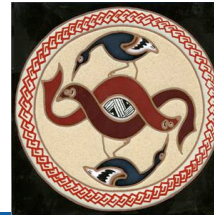
Audebert, *et. al.* PRE, 2001; 64: 056412

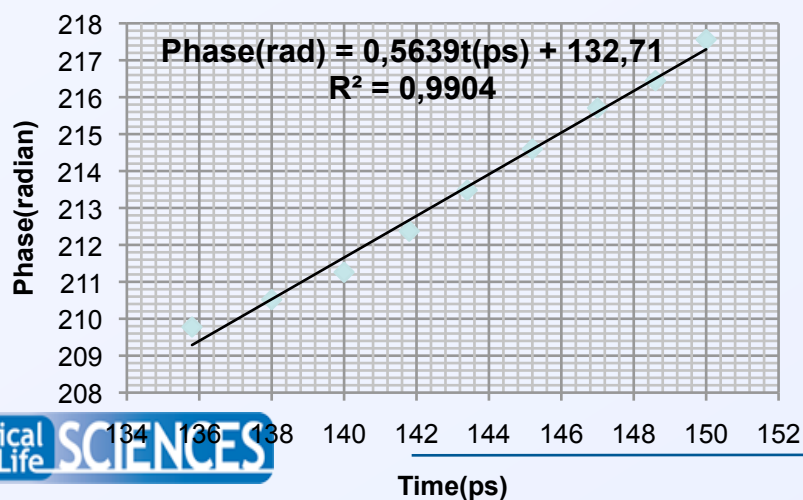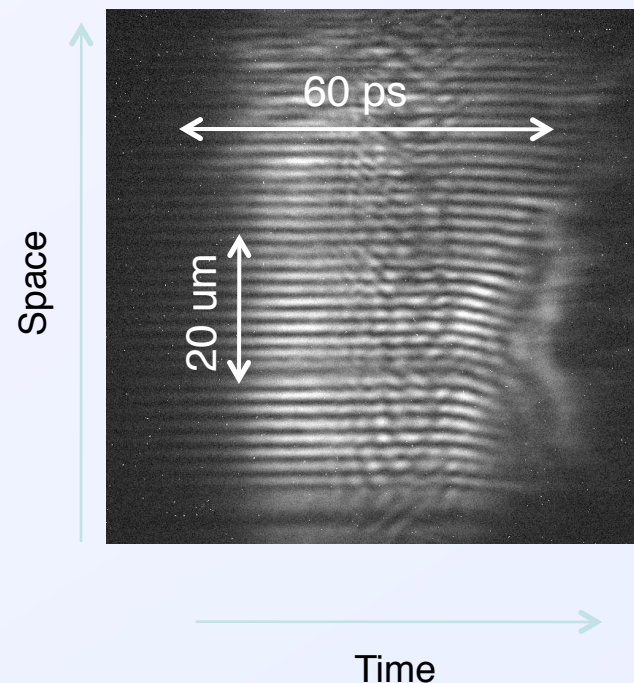### FDI is a well Established Technique

- Use beam splitter and delay line control scale length
- Produce phase as a function of time
- $\Delta\Phi(\tau) \approx$ expansion velocity
- $V \cdot \Delta t$ -> density
- Isothermal expansion ->temperature-> Z^{*}

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11.5 um thick Carbon foil probed at 50 um from the heated surface

Heating
(100J, 2ps, ω)

Protons

Au

Probe
(25J, 2ps, ω)

Carbon

Chirped pulse
(70ps, ω)

TASRI
(Time- and Space- Resolved Interferometry)

TASRI raw data

60 ps

20 um

Space

Time

Phase(rad) = 0,5639t(ps) + 132,71
R² = 0,9904

Phase(radian)

218
217
216
215
214
213
212
211
210
209
208

134 136 138 140 142 144 146 148 150 152

Time(ps)

Post processed data showing phase
change due to heated carbon expansion

Code hydro 1D ESTHER

Temperature Vs TASRI Phasing

10eV : 0.44 ps⁻1
12eV : 0.53 ps⁻1
13eV : 0.56 ps⁻1
14eV : 0.60 ps⁻1
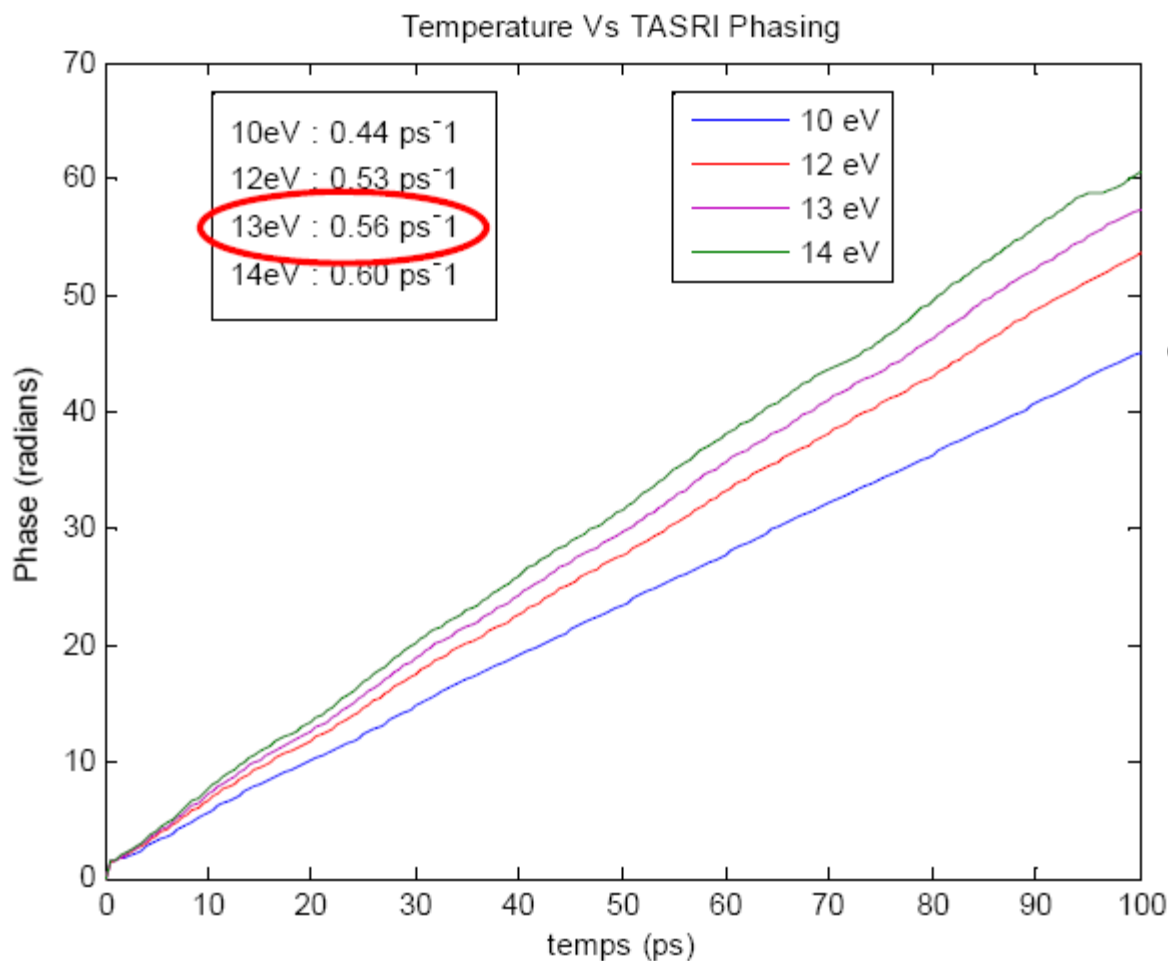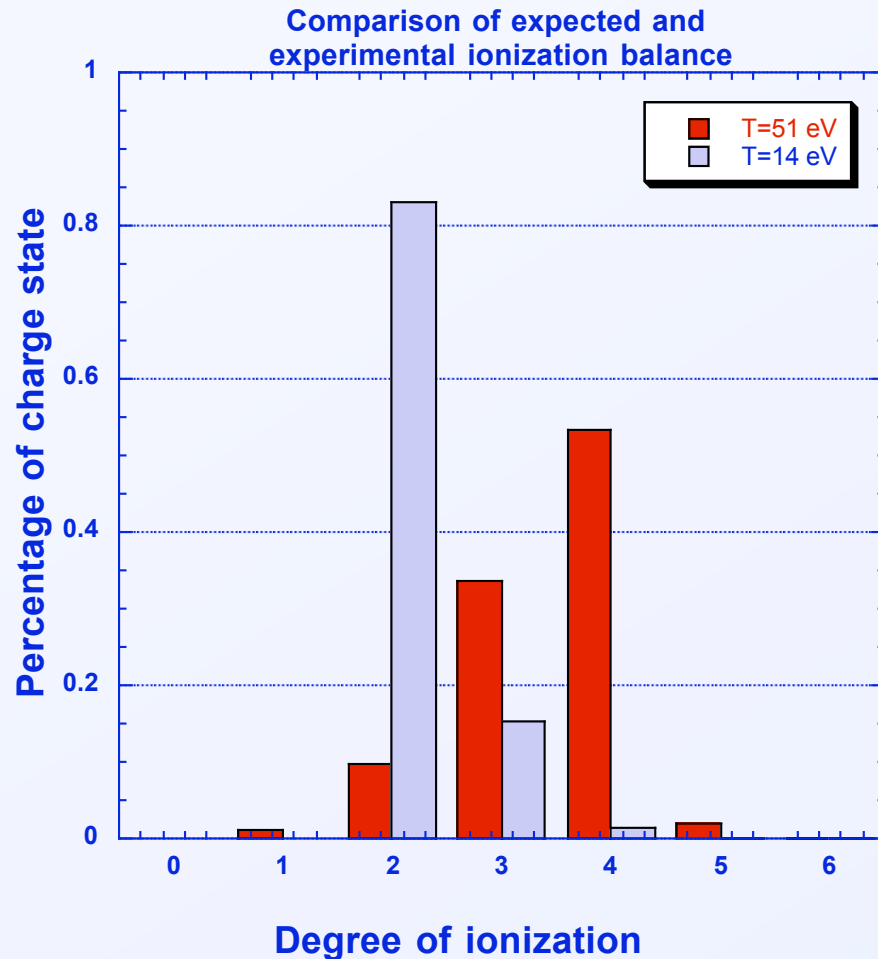
Code hydro 1D ESTHER showing the calculated phase change in case of carbon put at different temperatures (not proton heated).

The ionization dynamics of the carbon is critical to understanding the stopping power

Comparison of expected and experimental ionization balance

Legend:
- T=51 eV (red)
- T=14 eV (light purple)

Y-axis: **Percentage of charge state** (0 to 1)
X-axis: **Degree of ionization** (0 to 6)

$$S = \sum_n B\left[\left(1 - \overline{Z}/Z_a\right)\ln \Lambda_{bn}\right] + \left(\overline{Z}/Z_a\right)\ln \Lambda_f$$

$$B = 4\pi e^4 N Z_a / mV^2, \ \Lambda_{bn} = 2mV^2/I_{zn}, \ \Lambda_f = 2mV^2/I_f, \ Z_a = atomic\ number$$

$$N = plasma\ density, \ V = proton\ velocity, \ \overline{Z} = average\ ionization$$

$$I_{zn} = ionization\ potential, \ I_f = \overline{Z}e^2/\lambda_D$$

- Ionization balance calculated using FLYCHK
  - Solid density
  - Stewart-Pyatt continuum lowering

- **The bound electron stopping is dominated by the C^{2+} charge state.**
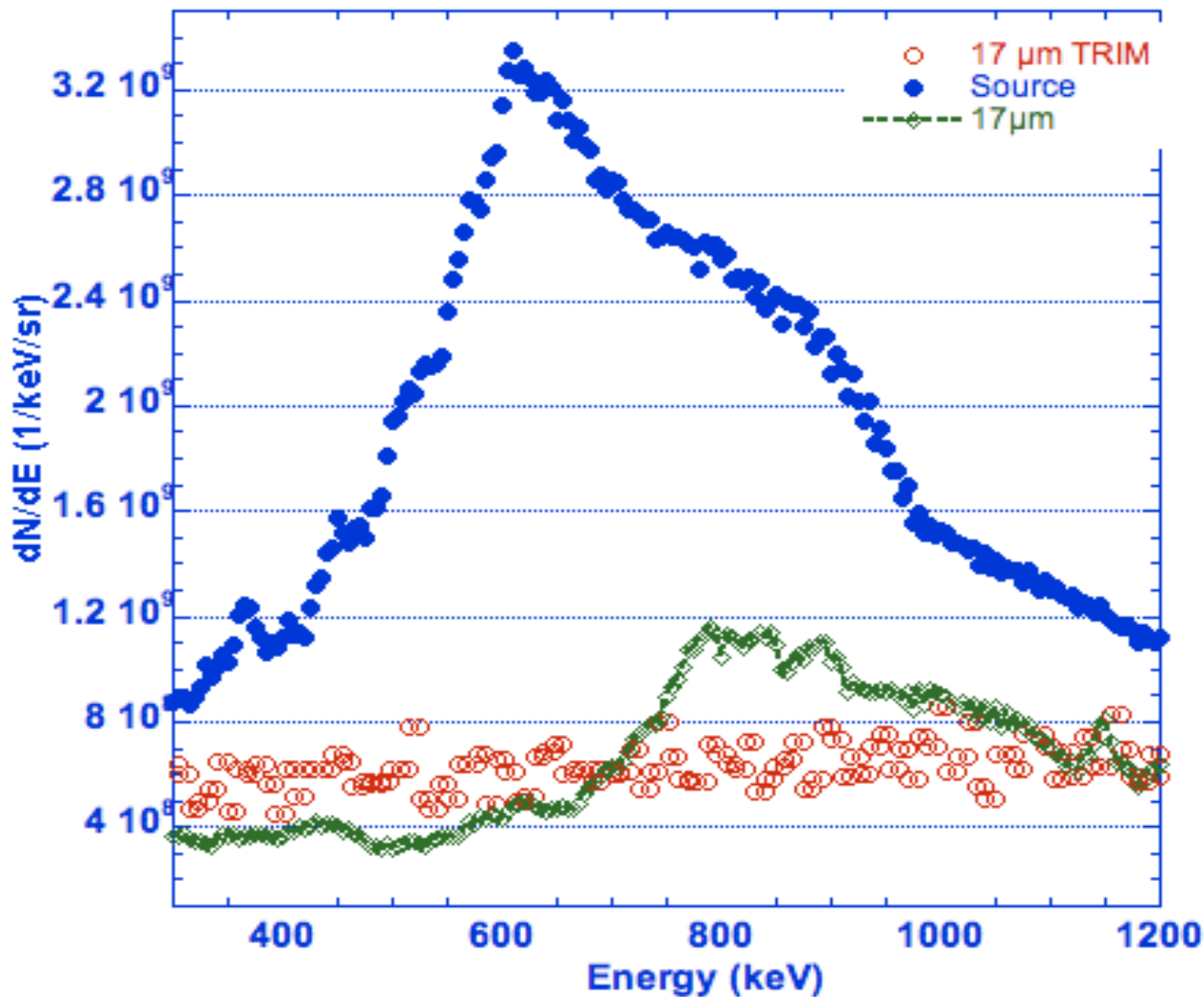
  - For our plasma we have:
  -

$$\Gamma_{ii} \approx 5, \ \Gamma_{ie} \approx 2, \ \vartheta_{Fermi} \approx 0.84$$
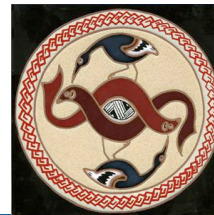
Free electron stopping is in a partially degenerate gas

Energy loss simulations have been performed using our proton spectrum as the source function

- Simulation performed with SRIM
- Uses Bethe-Bloch for *dE/dx*
- Effects are most significant below 0.7 MeV

Conclusion

- Data reduction is still on-going, however preliminary data reduction have resulted in some observations:

    1. Target charging makes wedge proton data difficult to unfold.

    2. "Cold" carbon data shows larger energy loss than anticipated.

    3. Rough comparison with heated target data suggest an enhanced dE/dx for heated versus cold cases (see next bullet).

    4. Temperature data suggest stopping is dominated by C^{+2} and partially degenerate free electrons

- We are continuing with data reduction. Our next experiment is in March 2011 (possibly something sooner at U. of Texas).