Fast Ions from Laser Produced Plasma

Y. -G. Kang, K. Nishihara, M. Murakami, A. Sunahara,
S. Fujioka, A. Sasaki, H. Nishimura

Institute of Laser Engineering, Osaka University

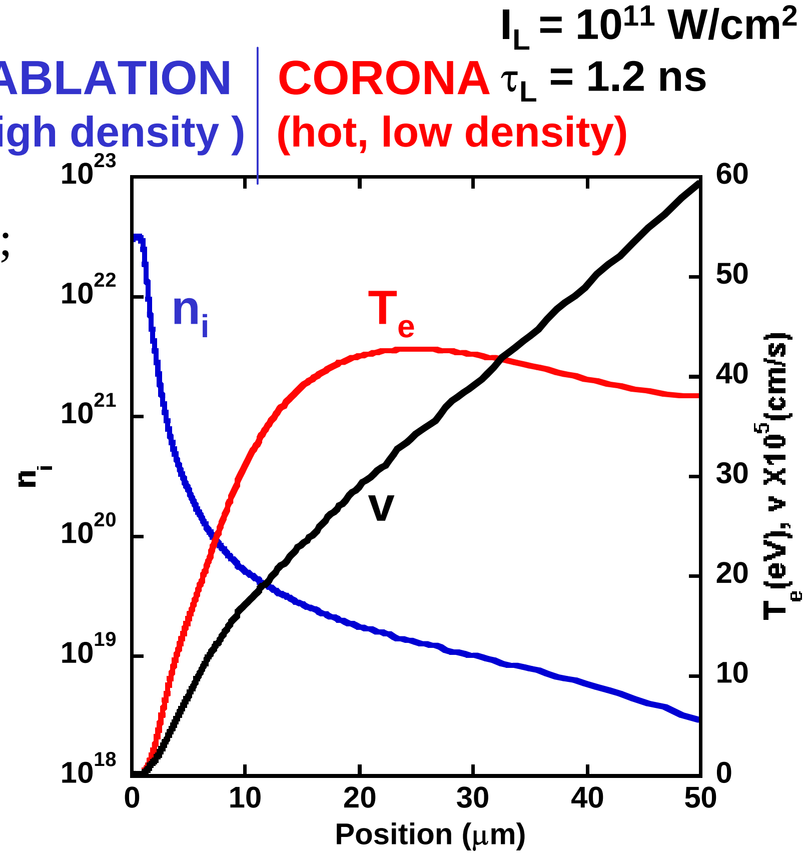
Two velocity component of ions in laser produced plasma

There may exist two velocity components of ions;

<u>from high density ablation layer</u>:
relatively low energy (peaked at a few keV),
but many particles.

<u>from hot corona region</u>:
fast ions (up to several tens of keV)
relatively small numbers.

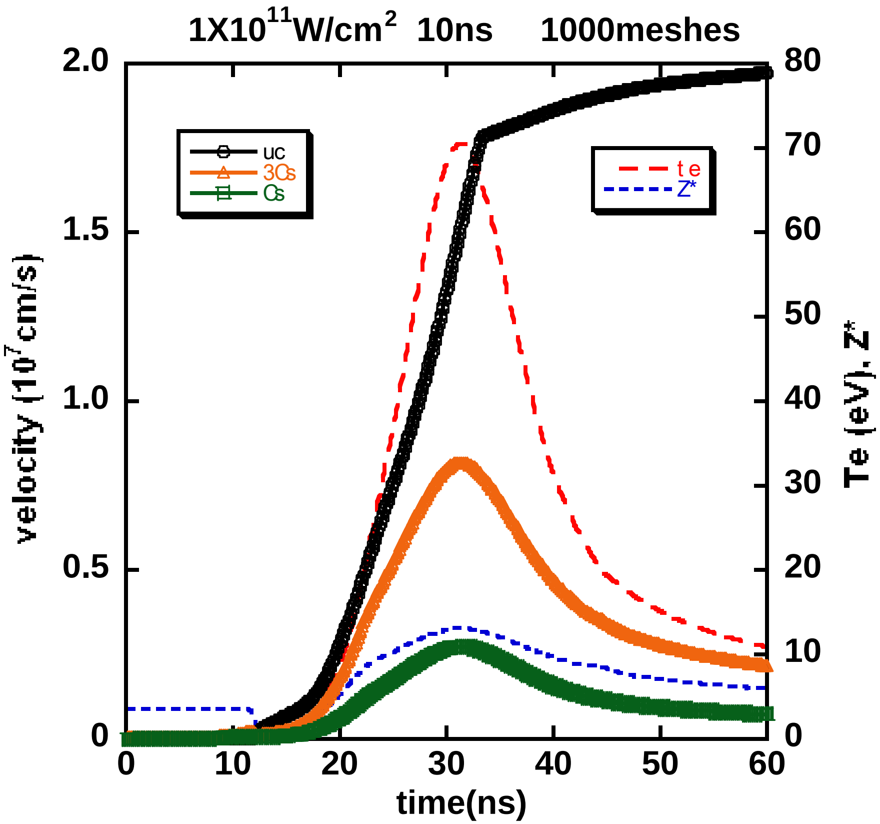
<u>Adiabatic expansion of high density plasma in ablation layer follows isothermal expansion of hot and low density plasma in corona</u>

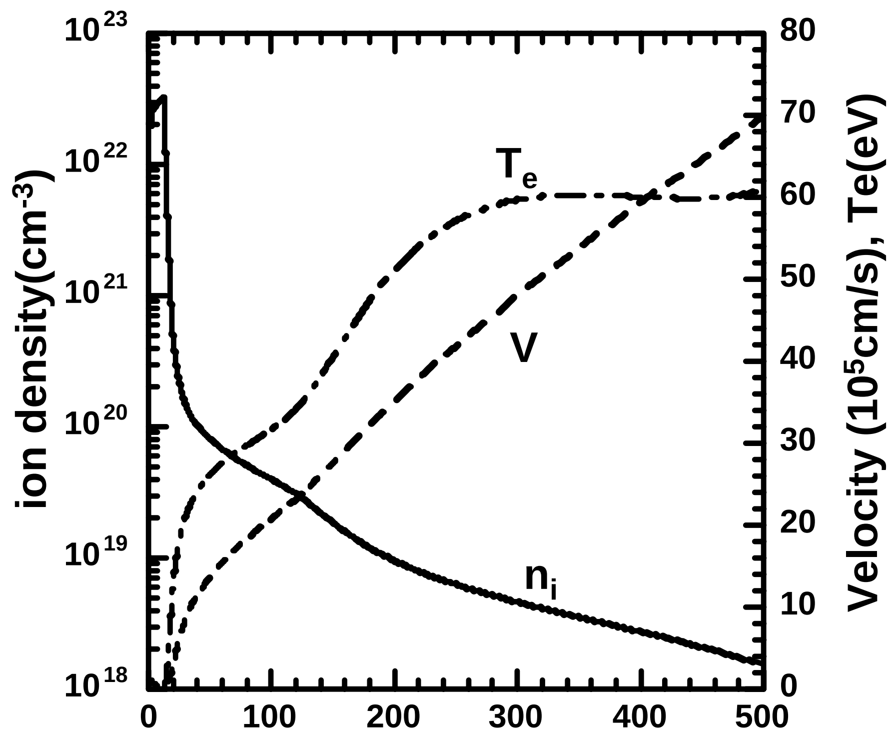


isothermal expansion in corona

$$n = n_o \exp(- x/c_s t),$$
$$v = c_s + x/t$$

Radiation Hydro Simulation : 1X10^{11}W/cm^2 10ns gaussian pulse centered at 30ns.





cf. $|u|_{\max} = \frac{2}{\gamma - 1} c_s = 3c_s$

Fast ions from Radiation Hydro simulation → $7c_s \sim (20keV)$

simulation by A. Sunahara

Isothermal expansion of plasma

At t = 0, a plasma occupies the half space x < 0, and begins to expand into vacuum.

Equations of continuity and motion,
Boltzmann distribution, and Poisson equation;

$$E_{front} = \sqrt{\frac{2}{e}} E_0$$

$$E_0 = \left(\frac{n_{e0} k_B T_e}{\varepsilon_0} \right)^{1/2} = \frac{k_B T_e}{e \lambda_{D0}}$$

$$\left(\frac{\partial}{\partial t} + v \frac{\partial}{\partial x}\right) n_i = -n_i \frac{\partial v}{\partial x}$$

$$\left(\frac{\partial}{\partial t} + v \frac{\partial}{\partial x}\right) v = -\frac{Ze}{m_i} \frac{\partial \Phi}{\partial x}$$

$$n_e = n_{e0} \exp(e\Phi / kT_e)$$

$$\varepsilon_0 \frac{\partial^2 \Phi}{\partial x^2} = e(n_e - Zn_i)$$

Self-similar solution

$$v = c_s + x/t \qquad c_s = \sqrt{\frac{Z^* T_e}{m_i}}$$

$$n_e = Zn_i = n_{e0} \exp(-x / c_s t - 1)$$

$$E_{ss} = \frac{k_B T_e}{e c_s t} = \frac{E_0}{\omega_{pi} t}$$

Maximum Ion Energy

$$E_{\max} \approx \frac{1}{2} ZkT_e [2 \ln(\omega_{pi} t) + \ln 2 - 1]^2$$

Ion Energy Spectrum

$$\frac{dN}{dE} = \frac{S n_{io} c_s t}{\sqrt{2EZkT_e}} \exp\left[-\sqrt{\frac{2E}{ZkT_e}}\right]$$

P. Mora, Phys. Rev. Lett. **90**, 185002 (2003)

Self-similar solution for isothermal explantion (1)

1. Fluid equations for ions:

$$\frac{\partial n_i}{\partial t} + \nabla \cdot n_i \mathbf{v} = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{Ze}{m_i} \nabla \phi$$

2. Boltzmann statistics for electrons:

$$n_e(\mathbf{r}, t) = Zn_i(\mathbf{r}, t) = n_{ec}(t)\ \exp\left(\frac{e\phi(\mathbf{r})}{T_e}\right)$$

3. Reduced partially differential equation system:

$$\begin{cases} \dfrac{\partial n}{\partial t} + \dfrac{1}{r^{\nu-1}} \dfrac{\partial}{\partial r}\left(r^{\nu-1} n v\right) = 0 \\ \dfrac{\partial v}{\partial t} + v \dfrac{\partial v}{\partial r} = -\dfrac{c_s^2}{n} \dfrac{\partial n}{\partial r} \end{cases} \qquad \nu = \begin{cases} 1: \text{planar} \\ 2: \text{cylinder} \\ 3: \text{spherical} \end{cases}$$

where $c_s \equiv \sqrt{\dfrac{ZT_e}{m_i}}$ is the sound speed.

M.Murakami, et al., J. X-ray Sci. Technol. 2 127(1990)

Self-similar solution for isothermal expansion(2)

4. Similarity ansatz:

$$\xi = \frac{r}{R(t)}, \quad v = R'\xi, \quad n = n_0 (\frac{R_0}{R})^{\nu} N(\xi)$$

5. Reduced ordinary deferential equation :

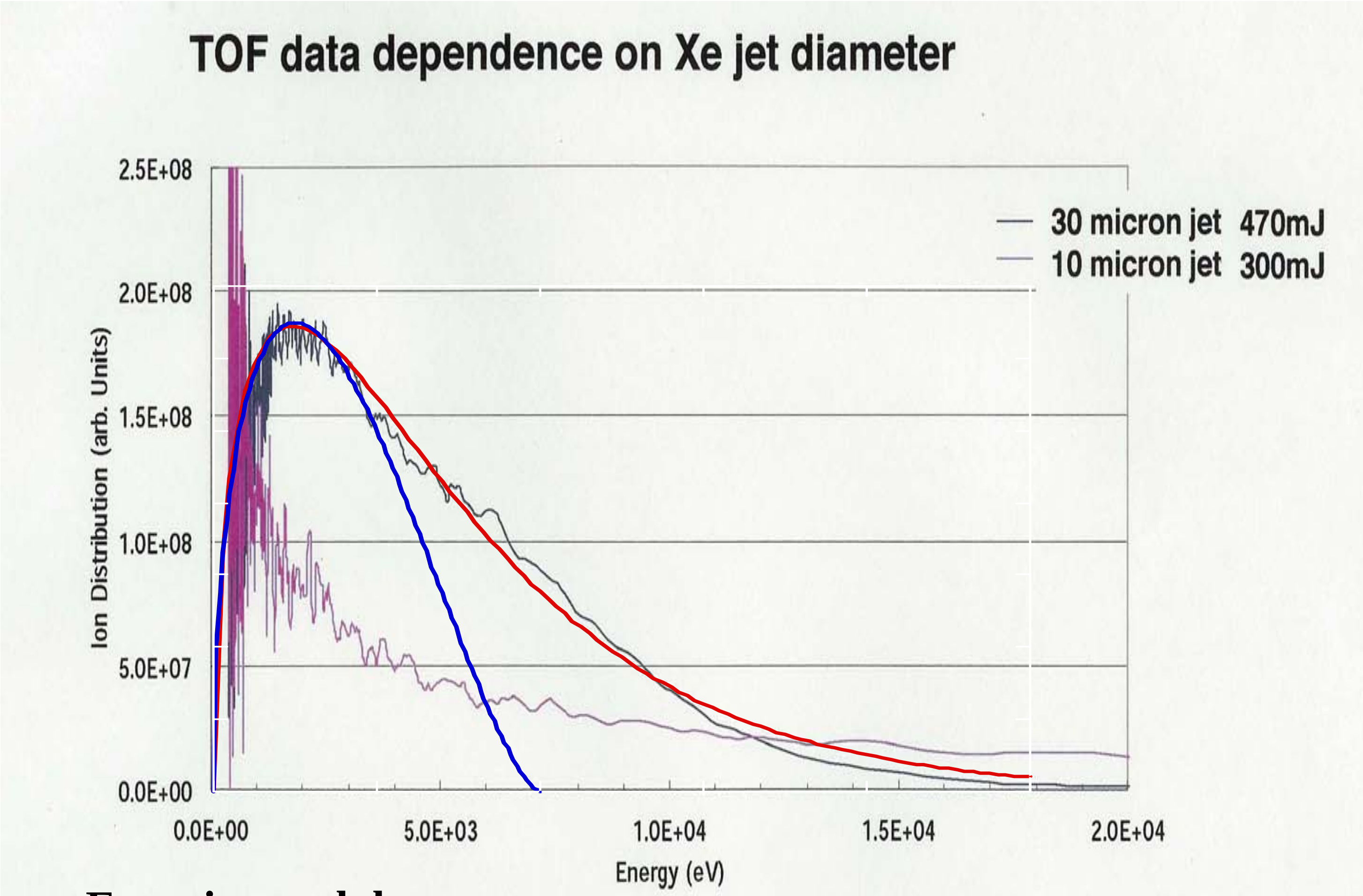
$$\frac{RR''}{c_s^{\ 2}} = -\frac{N'}{\xi N} = \lambda_\nu$$

6. Self-similar solution :

$$\mathrm{N} = \exp(-\xi^2), \qquad \frac{\mathrm{e}\phi}{\mathrm{T}} = -\xi^2$$

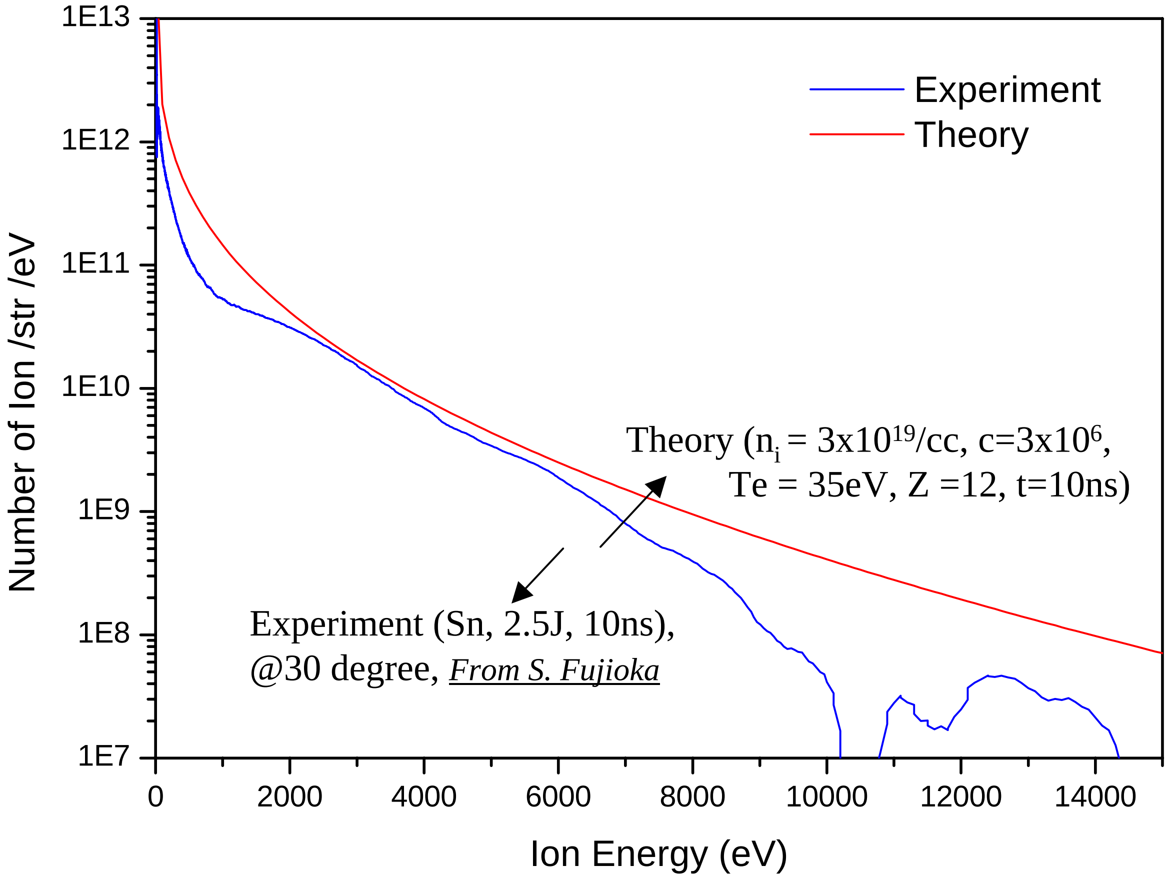
$$R' = 2c_s\sqrt{\ln(R/R_0)}, \quad \int_0^{R'} \frac{dR}{\sqrt{\ln R}} = \frac{2c_s t}{R_0}$$

Analytical model agrees fairly well with EUVA experiment



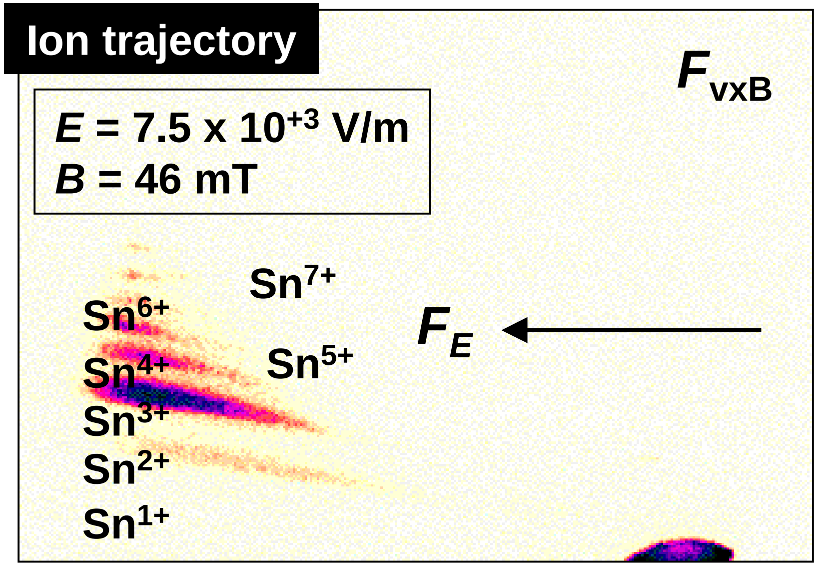
Experimental data from EUVA

Analytical model agrees fairly well with ILE experiment



E_{max} (theory) = ~ 100 keV for Z=12(Sn), Te=35eV, n=2x10^{19}, at t=10ns
50 keV for Z=10(Sn), Te=30eV, n=2x10^{19}, at t= 2ns
60 keV for Z=10(Sn), Te=30eV, n=2x10^{19}, at t= 5ns

Ion trajectory (Thompson parabola)



7 ions are measured.
Recombination/charge exchange processes need to be studied.

Experiment by Fujioka, Nishimura

Multispecies ion plasma expansion

ne = 10^{20}/cm^3, Te = 40eV

<Z> = 12.224

Sn10+ = 0.023 (9+ = 0.001)

Sn11+ = 0.167

Sn12+ = 0.421

Sn13+ = 0.340

Sn14+ = 0.049 (15+=0.003)

(fraction using HULLAC atomic code by A. Sasaki)

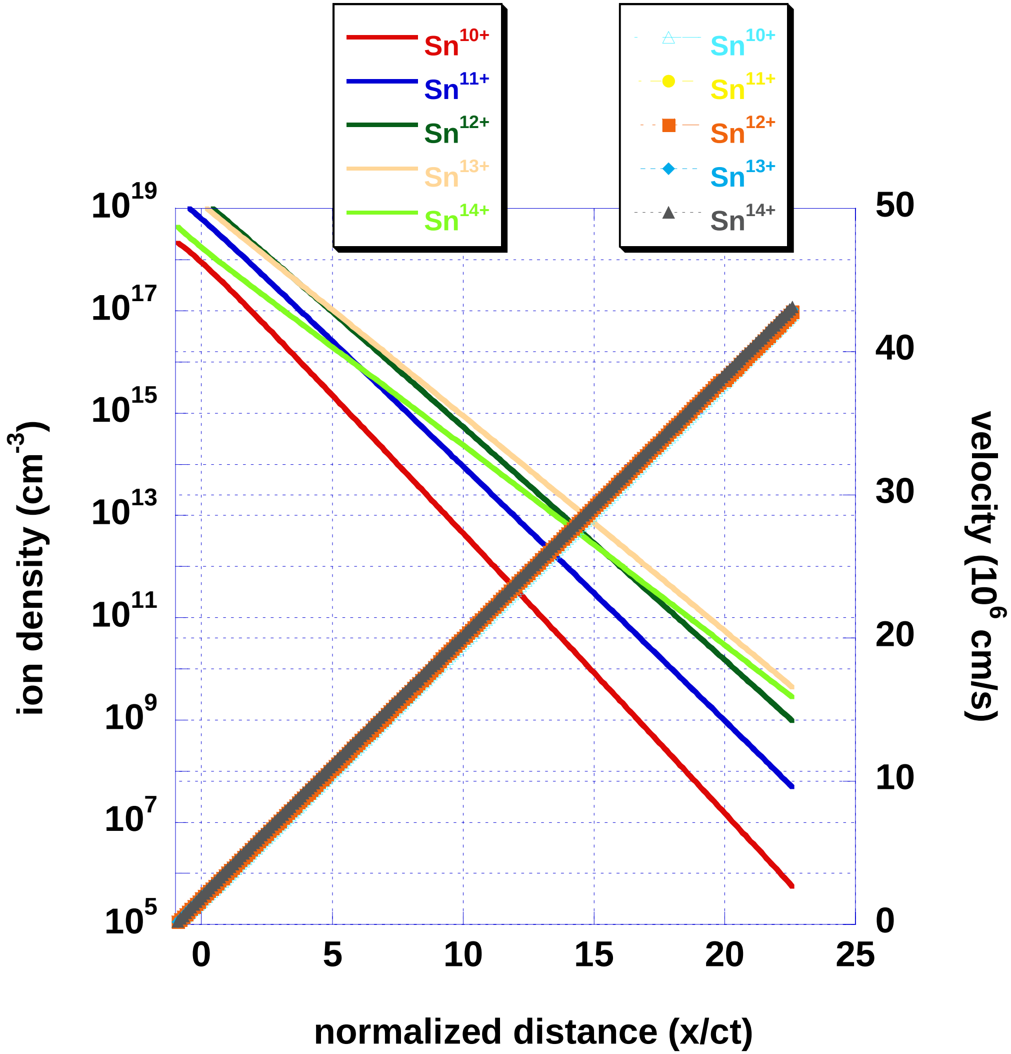
Plasma scale length $L = n_e \left(\frac{dn_e}{d\xi} \right)^{-1}$

Debye length $\lambda_{D0} = \left(\frac{\varepsilon_0 kT}{n_{e0} e^2} \right)^{-1/2}$

<u>Charge neutrality breaks at</u> $L \approx \lambda_D$

Position of ion front at $\xi = \frac{x}{c_s t} = 22.6$

$v_{\max} = 22 c_s, E_{\max} = 99 keV$



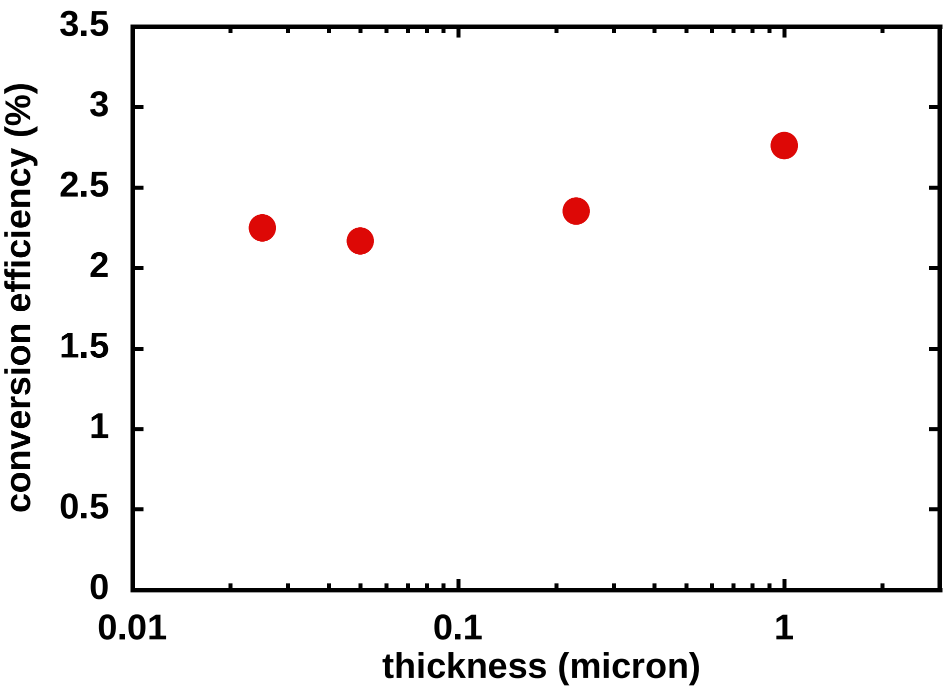
Higher charge state accelerates rapidly than lower charge state, thus yields higher energy. The maximum energy is about 100keV

High energy ions and debris

<u>Mass limited target for minimum debris</u>

$n_s v_a = n_0 c_s$, $l = v_a t_L$ = 20 nm
for $I_L = 10^{11}$ W/cm^2, t_L = 1.2 ns

(ex) Sn: 7.2 g/cm3
20nm x 4 (5ns) = 80nm
800 μm :
S = 3.14x(4e-2)**2 = 5e-3 cm2
7.2x(8e-6)x(5e-3) = 3e-7 = 0.3 μg



Summary

- Ion energy spectrum based on isothermal expansion modeling was compared to Faraday cup experiment. The qualitative feature compares favorably with experiment. However, maximum ion energy of 100keV may exist. *cf. maximum ion energy of ETS at Sandia is higher than 60keV.*

- Multispecies (five ions) plasma modeling was performed to compare with Thompson parabola experiment. The higher charge state accelerated more rapidly than lower charge state.

- Recombination and charge exchange dynamics will be investigated for better modeling of fast ion energy spectrum.
  cf. TP data shows <Z> = 2.5 at 1.78m.

- Based on the fast ion study, optimum magnetic field is being designed for debris mitigation. cf. $r_i = 102\sqrt{\mu T_i} / ZB$