Generation of quasi-monoenergetic ions with nanocluster targets

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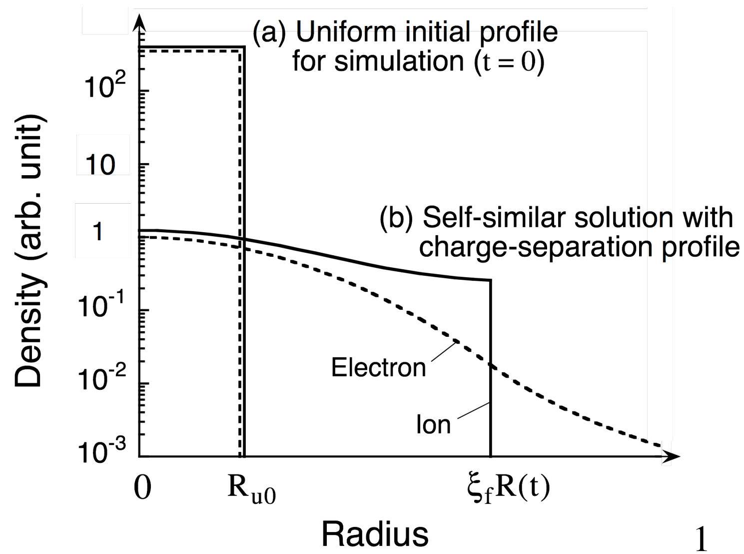
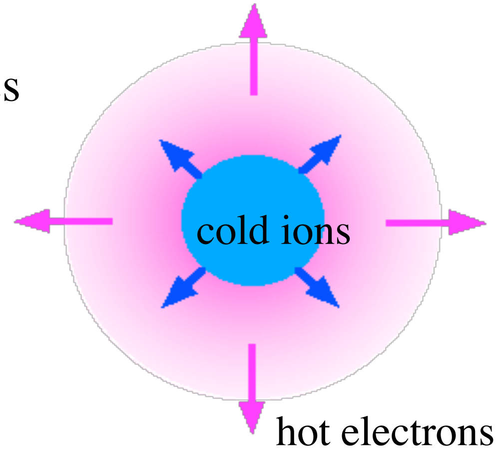
- Quasi-monoenergetic spectrum



Formulation of the problem

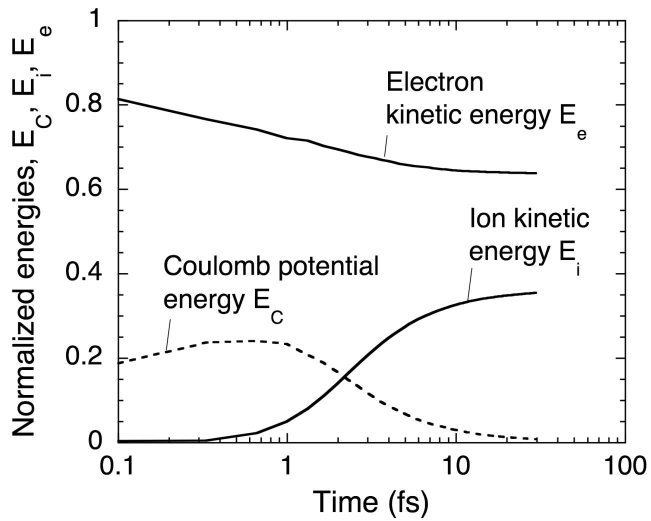
At $t = 0$ the electron component of a finite plasma mass is heated to a uniform temperature $T_e(r, 0) = T_{e0}$.
Hot electrons expand and create an ambipolar electric field $E(r, t)$, which drags the cold ions.



Assumptions

(1)There are no collisions between electrons and ions.

(2)At all times, the electron temperature is very quickly leveled off across the plasma volume: $T_e(r, t) = T_e(t)$.



Governing equations

In the framework of two fluid approximation, expansion of the considered plasma is governed by the following system of equations,

mass conservation

$$\frac{\partial n_i}{\partial t} + \frac{1}{\partial r^{\nu-1}} \frac{\partial}{\partial r}\left(r^{\nu-1} n_i v_i\right) = 0 \quad (1)$$

$$\frac{\partial n_e}{\partial t} + \frac{1}{\partial r^{\nu-1}} \frac{\partial}{\partial r}\left(r^{\nu-1} n_e v_e\right) = 0 \quad (2)$$

momentum conservation

$$\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial r} = -\frac{Ze}{m_i} \frac{\partial \Phi}{\partial r} \quad (3)$$

$$\frac{\partial v_e}{\partial t} + v_e \frac{\partial v_e}{\partial r} = \frac{e}{m_e} \frac{\partial \Phi}{\partial r} - \frac{T_e}{m_e n_e} \frac{\partial n_e}{\partial r} \quad (4)$$

Poisson equation

$$\frac{1}{r^{\nu-1}} \frac{\partial}{\partial r}\left(r^{\nu-1} \frac{\partial \Phi}{\partial r}\right) = 4\pi e\left(n_e - Z n_i\right) \quad (5)$$

where n stands for the geometrical index:

$$\begin{cases} \nu = 1, & \text{planar} \\ \nu = 2, & \text{cylindrical} \\ \nu = 3, & \text{spherical} \end{cases}$$

Similarity ansatz

The key assumption is that the velocity, $v(r, t)$, is linear in radius. This is always correct for the asymptotic stage of free expansion of a finite mass.

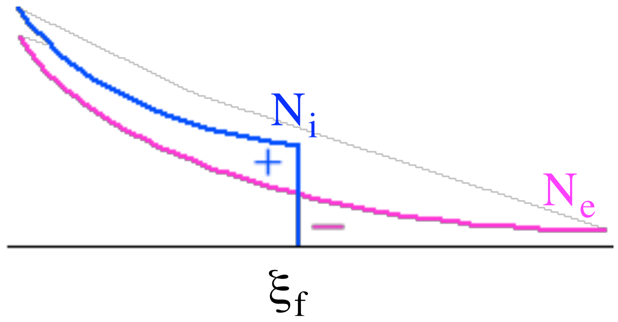
$$\xi = \frac{r}{R(t)}, \qquad \dot{R} \equiv \frac{dR}{dt} \tag{6}$$

$$v_e(r,t) = v_i(r,t) = \dot{R}\,\xi \tag{7}$$

$$n_e(r,t) = n_{e0}\left(\frac{R_0}{R(t)}\right)^{\nu} N_e(\xi), \qquad N_e(0) = 1 \tag{8}$$

$$Z n_i(r,t) = n_{i0}\left(\frac{R_0}{R(t)}\right)^{\nu} N_i(\xi), \qquad N_i(0) \neq 1 \tag{9}$$

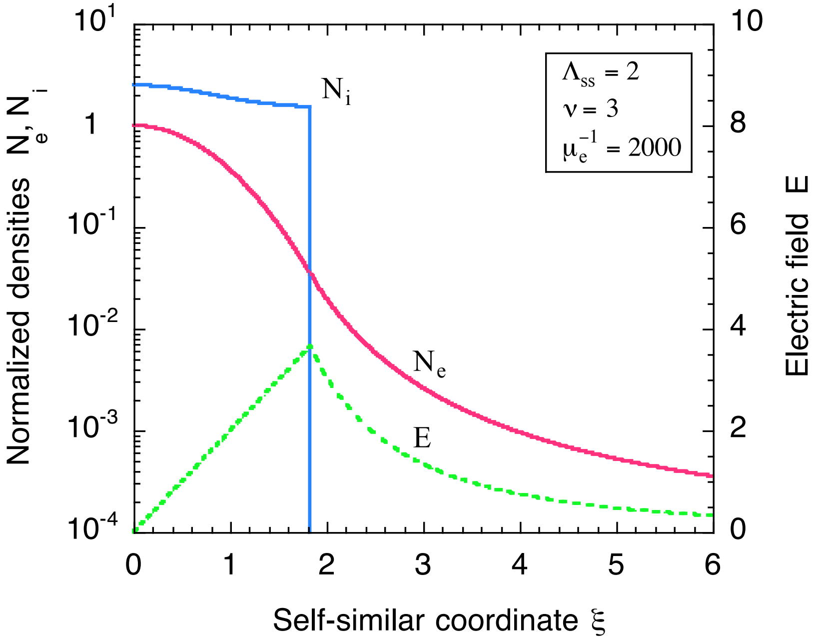
- Cold ions preserve a sharp edge at $x = x_f$ (still unknown).
- Functions, v_i and N_i, are then defined only for $0 \leq \xi \leq \xi_f$



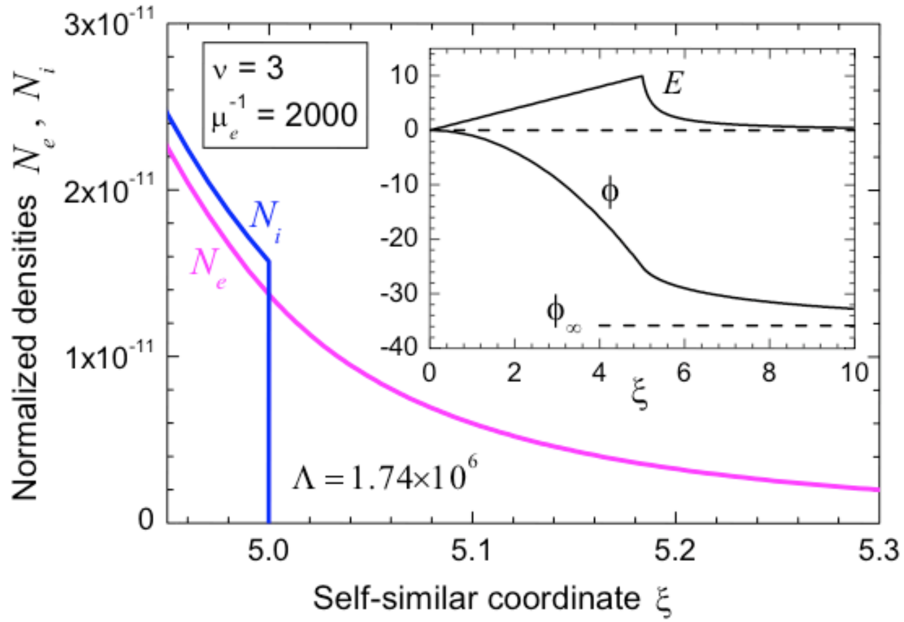
The self-similar solution produces various plasma profiles

as a function of the dimensionless plasma size $\Lambda = \frac{R}{\lambda_D}$

$\Lambda \sim 1$



$\Lambda \sim 10^6$



The analytical model excellently reproduces the experimental results on ion kinetic energy spectrum (planar geometry)

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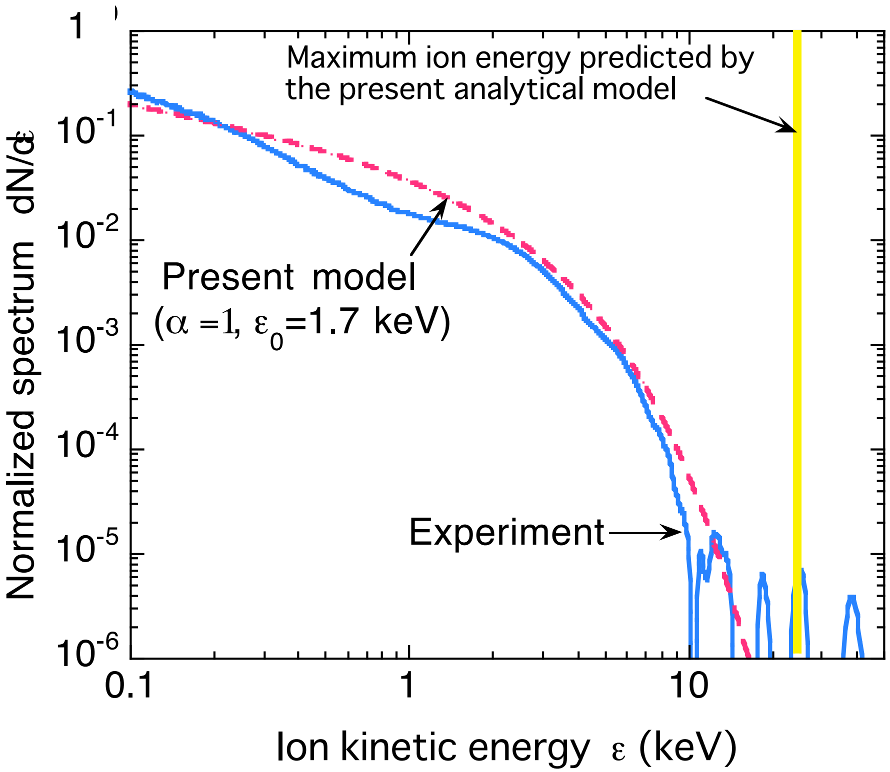

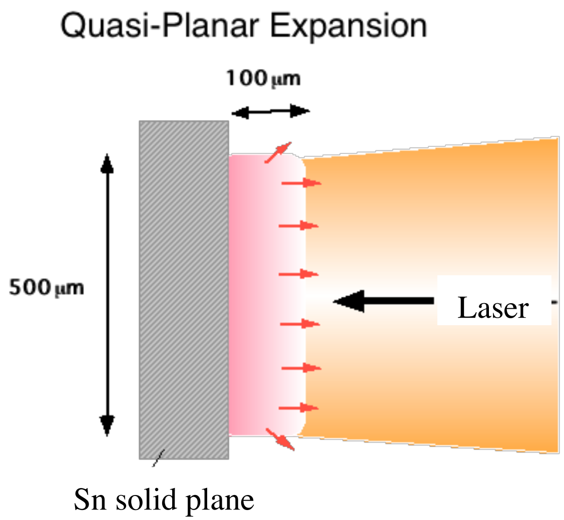

The analytical model excellently reproduces the experimental results on ion kinetic energy spectrum (spherical geometry)

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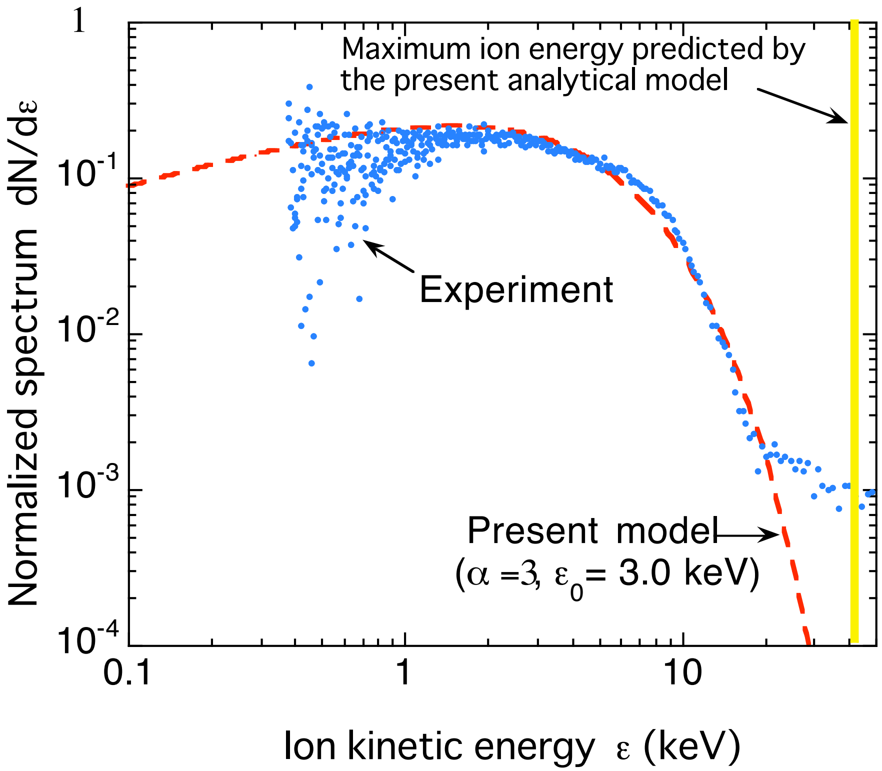
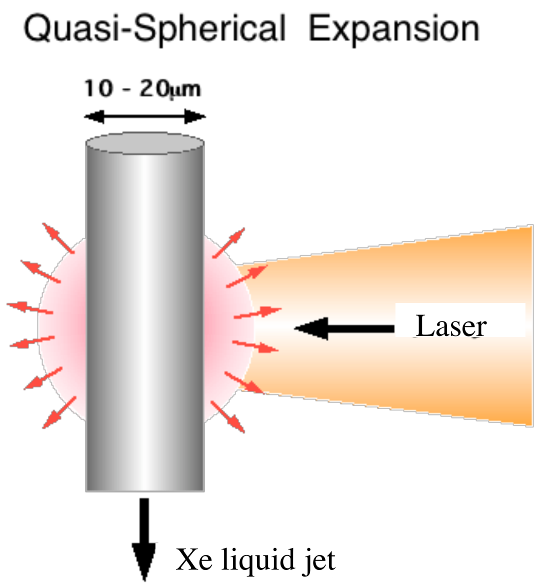
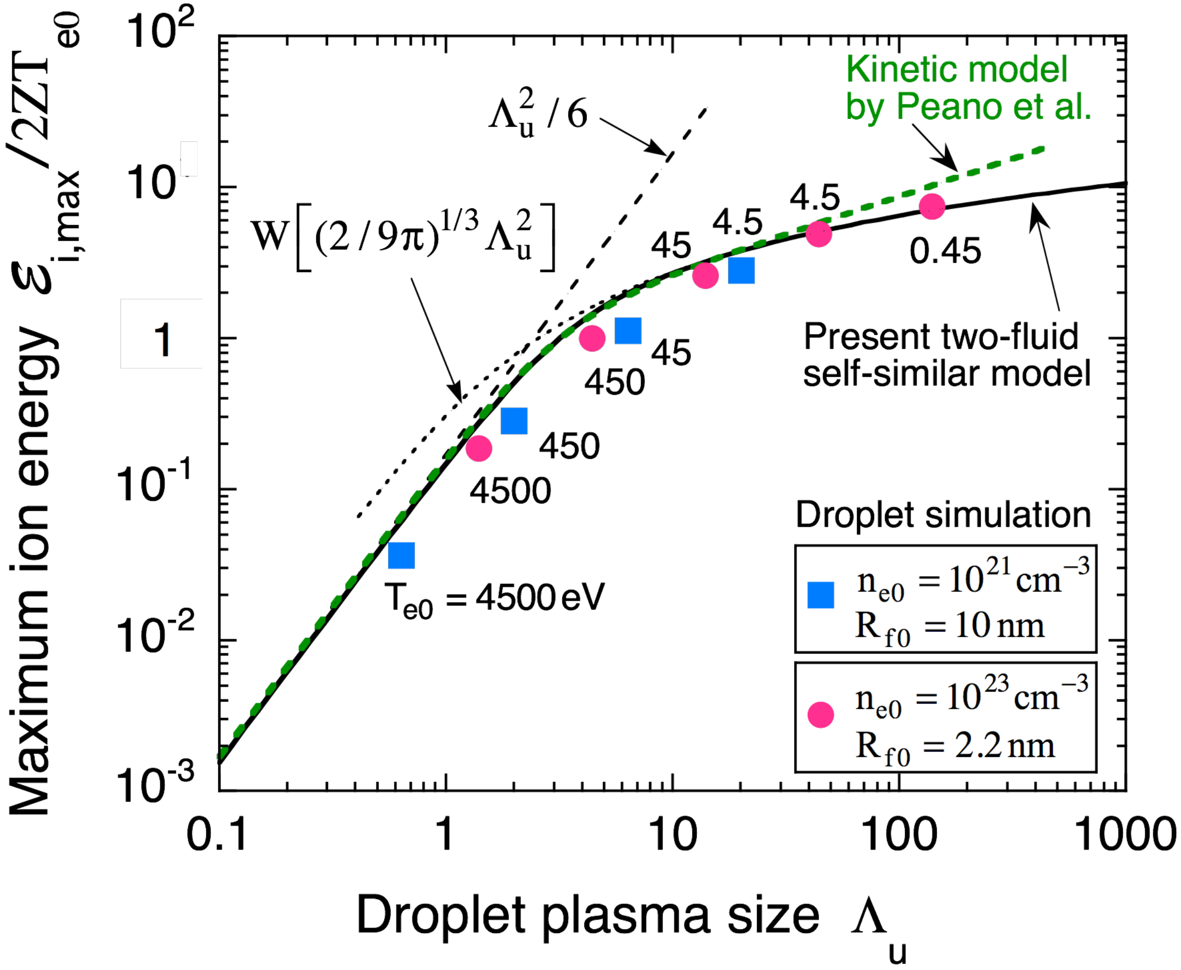




Maximum ion kinetic energy



Generation of quasimonoenergetic spectra

- with homogeneously distributed impurity ions -

It is well known that quasimonoenergetic ions can be produced using planar targets coated with a thin foil made of light ions on the rear side.

In spherical case, however, quasimonoenergetic ions can be produced by doping impurity ions homogeneously in the spherical target.

We here demonstrate the generation of the quasimonoenergetic spectrum and explain it by using the self-similar solution.

Nanocluster Expansion into Vacuum

N-body Relativisitc Molecular Dynamics

4500 eV, 10^{23} cm^{-3}

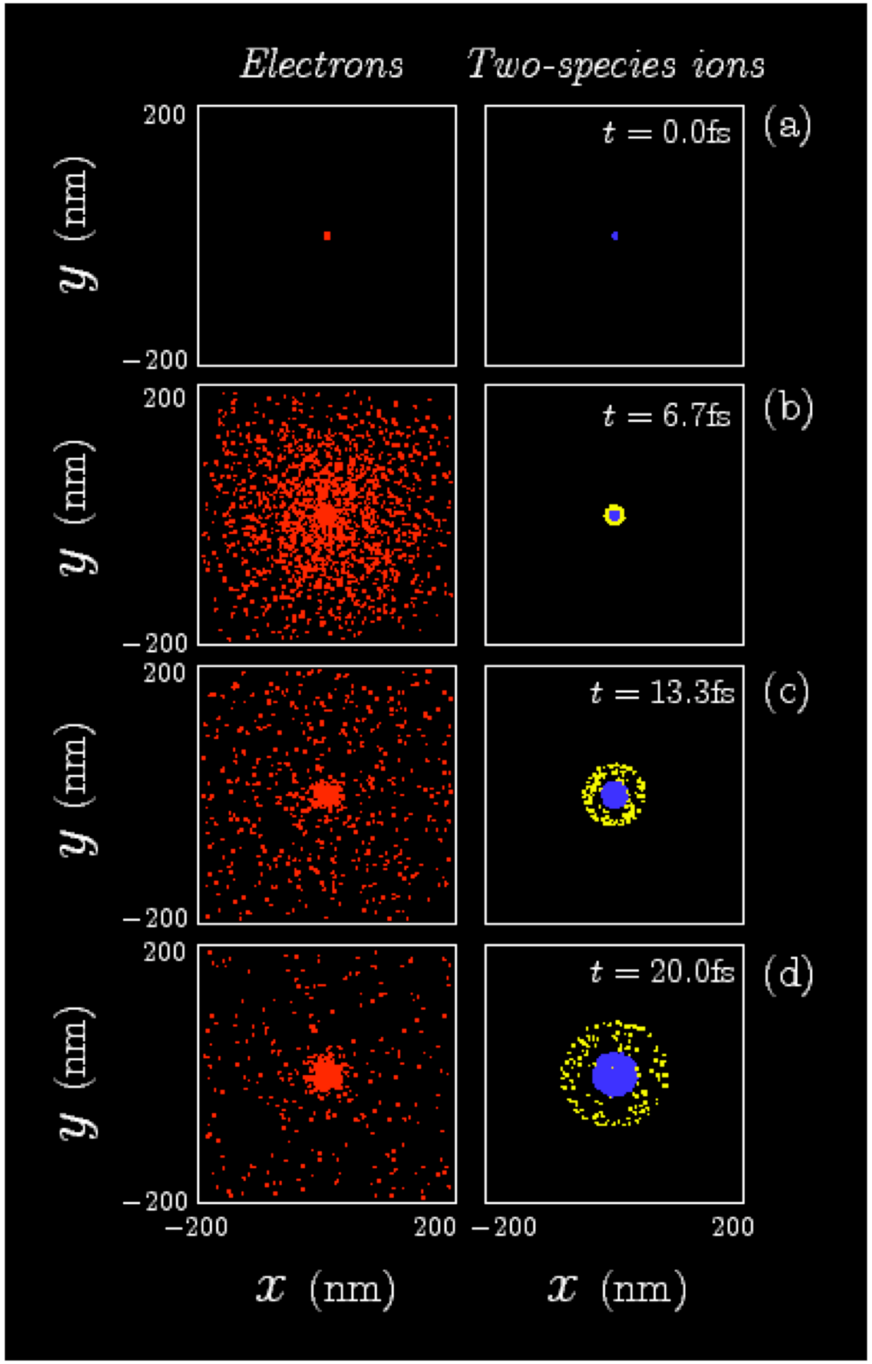
Pellet: radius 2.1 nm
Electrons: q/e= -1, ca. 4200
Impurity ions: q/e= 4, 150, cold
Base ions: q/e= 1, ca. 3600, cold

Murakami (ILE) and Tanaka (NIFS) (2008)
by Opteron 2.8GHz cluster machine

$R_{u0} = 2.15\text{nm}$

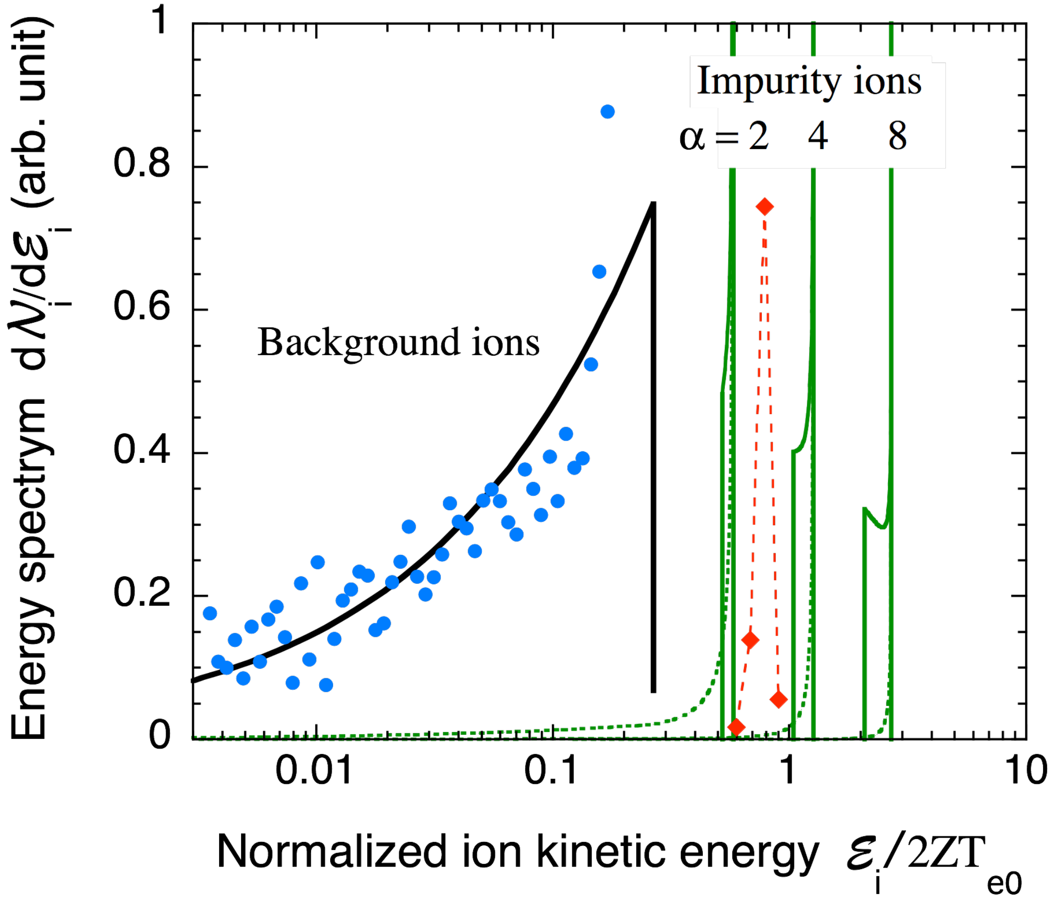
$n_{u0} = 10^{23}\text{cm}^{-3}$

$\alpha = 4$



Generation of quasi-monoenergetic ion spectrum

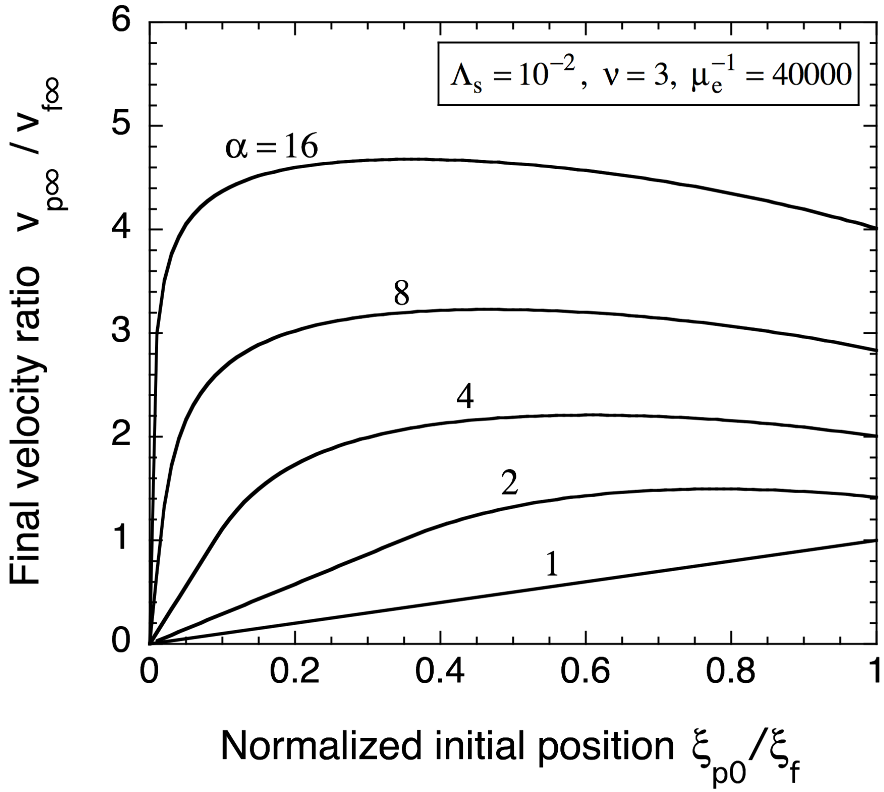
$$\frac{E_{p,max}}{E_{i,max}} = \frac{m_p v_{p,max}^2}{m_i v_{i,max}^2} = \frac{Z_p}{Z_i}$$



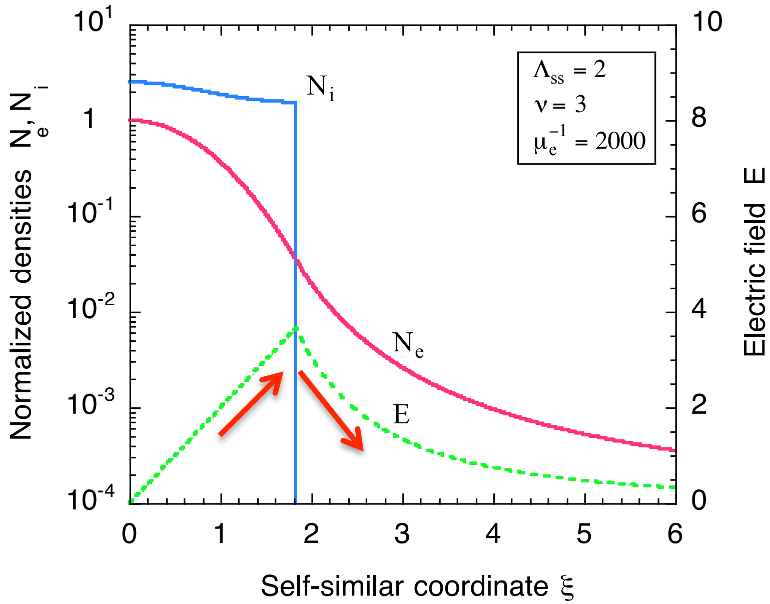
Generation of quasi-monoenergetic ion spectrum

$$\begin{cases} \dfrac{dr_p}{dR} = \dfrac{v_p}{2c_{s0}\sqrt{1-R_0/R}} \\ \dfrac{dv_p}{dR} = -\dfrac{\alpha c_{s0} R_0}{2R^2\sqrt{1-R_0/R}} \dfrac{d\Phi(\xi_p)}{d\xi} \end{cases}$$

$$\alpha = \frac{Z_p/m_p}{Z/m_i} \quad \Longrightarrow \quad \frac{v_{p,max}}{v_{i,max}} \to \sqrt{\alpha}$$



What matters is the work done on a particle: $W \propto \int F ds$



Conclusion

- The self-similar solution has been applied to expansion problem of a droplet or a nanocluster.
- Excellent agreement has been found between the theory and the simulation on such key physical quantities as the maximum ion energy and the energy spectrum.
- The self-similar solutions has predicted generation of quasi-monoenergetic spectrum by homogeneously doping impurity ions in a spherical droplet target.
- This prediction has been confirmed by N-body particle simulations.
- It is concluded that the origin of the monoenergetic spectrum is attributed to the spherical geometry.