Suppression of Debris with punch-out target and Debris Mitigation by Magnetic Field

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Conclusion

- **An analytical solution for mass-limited target has been developed, which reproduces experimental ion spectra with different conditions.**

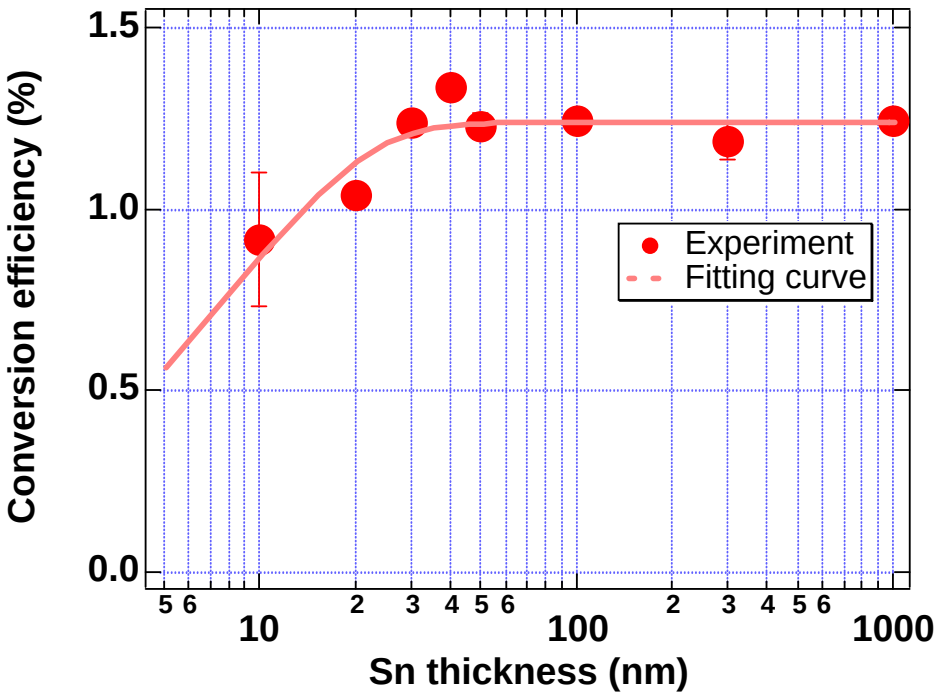
- **The theory shows that the maximum ion energy can be strongly suppressed in the punched-out target.**

- **Mitigation of energetic ions has been shown with the use of hybrid code, however, more detail study is required.**

punch-out target

Punch-out Target (mass-limited target for high repetition)
No reduction of the conversion efficiency for thin tin (>40nm)

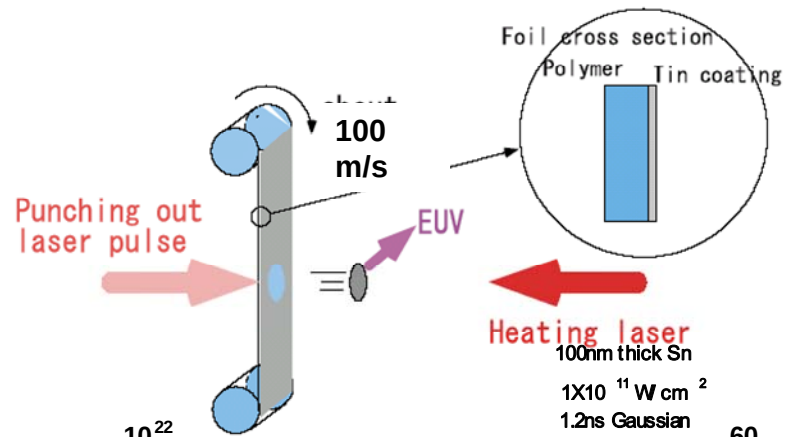
Foil thickness dependence of CE

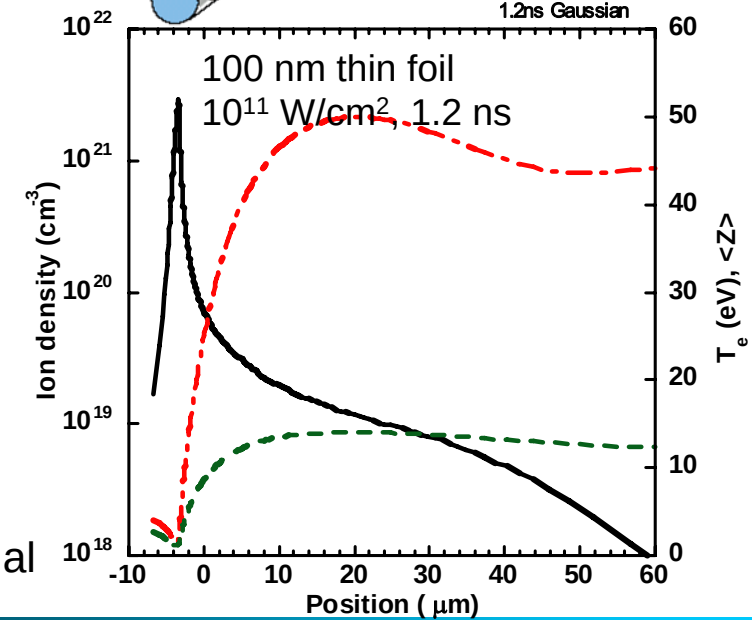


I_L = 1.0 x 10^{11} W/cm^2, 10ns

after S. Fujioka et al

Concept of the punch-out target





after Sunahara et al

Governing equations: hydro-equations and Poisson equation are coupled

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

mass conservation

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

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

momentum conservation

$$\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial r} = -\frac{Z e}{m_i} \frac{\partial \Phi}{\partial r} \qquad (3)$$

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

Poisson equation

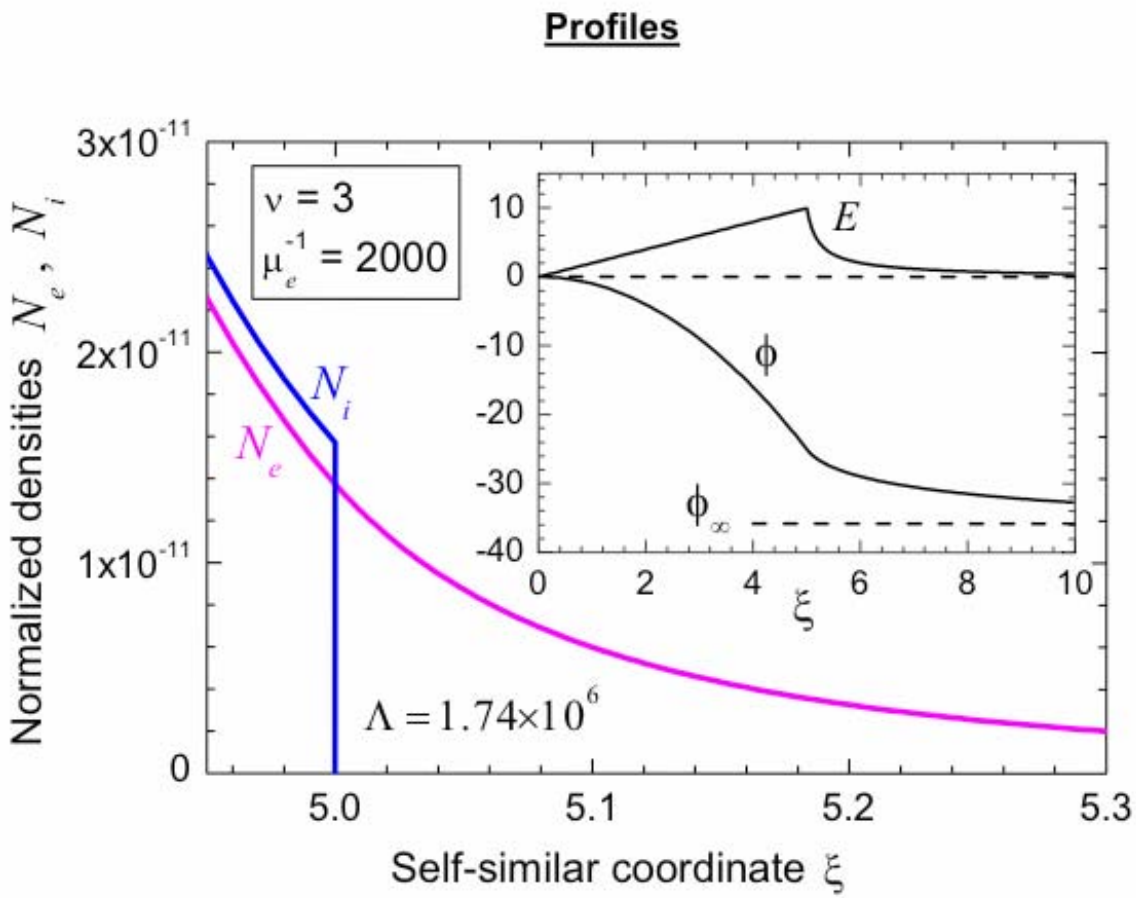
$$\frac{1}{r^{\nu-1}} \frac{\partial}{\partial r}\left(r^{\nu-1} \frac{\partial \Phi}{\partial r}\right) = 4\pi e\left(n_e - Z n_i\right) \qquad (5)$$

where ν stands for the geometrical index:

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

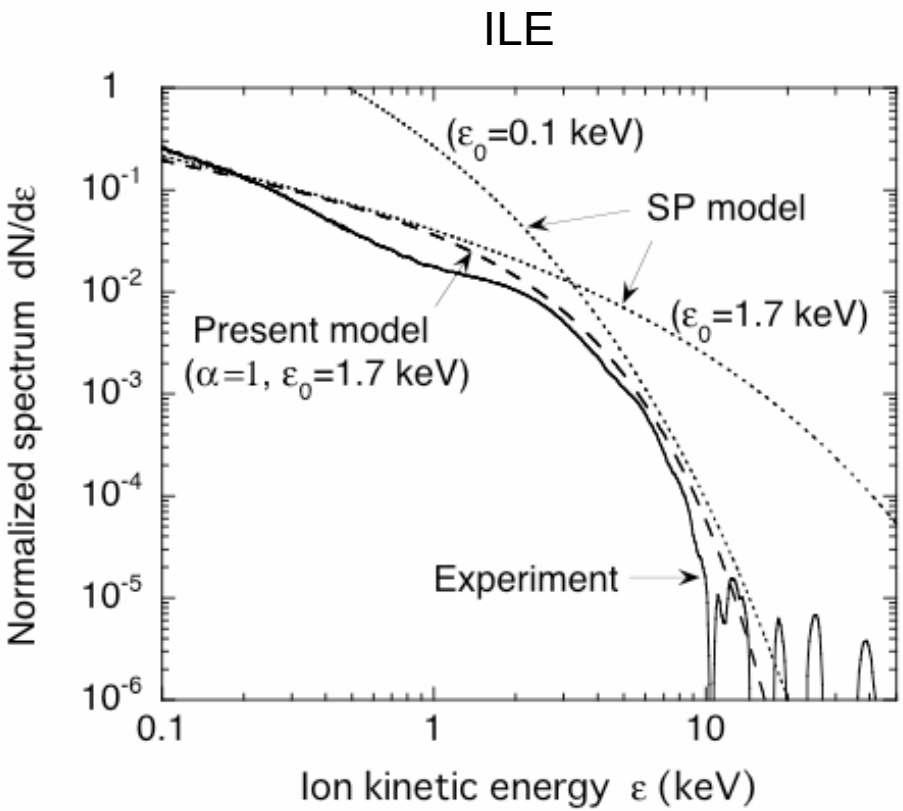
Ion energy

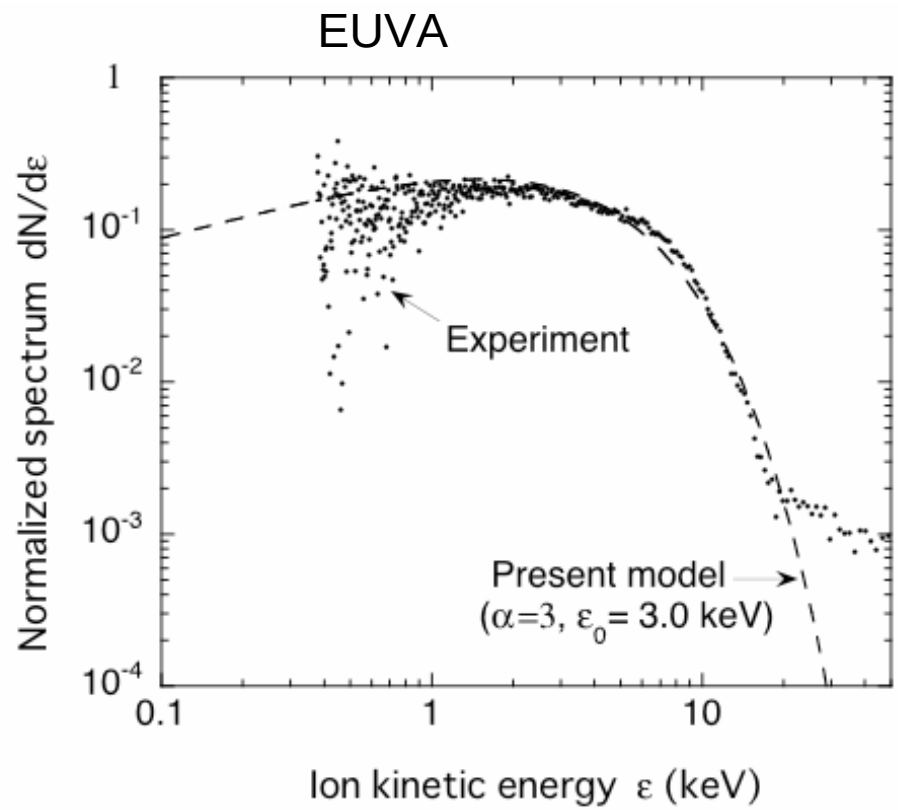
Spatial profiles of ion and electron densities with electric field (electric potential)



Ion energy

The analytical model reproduces experimental results on ion energy spectra.

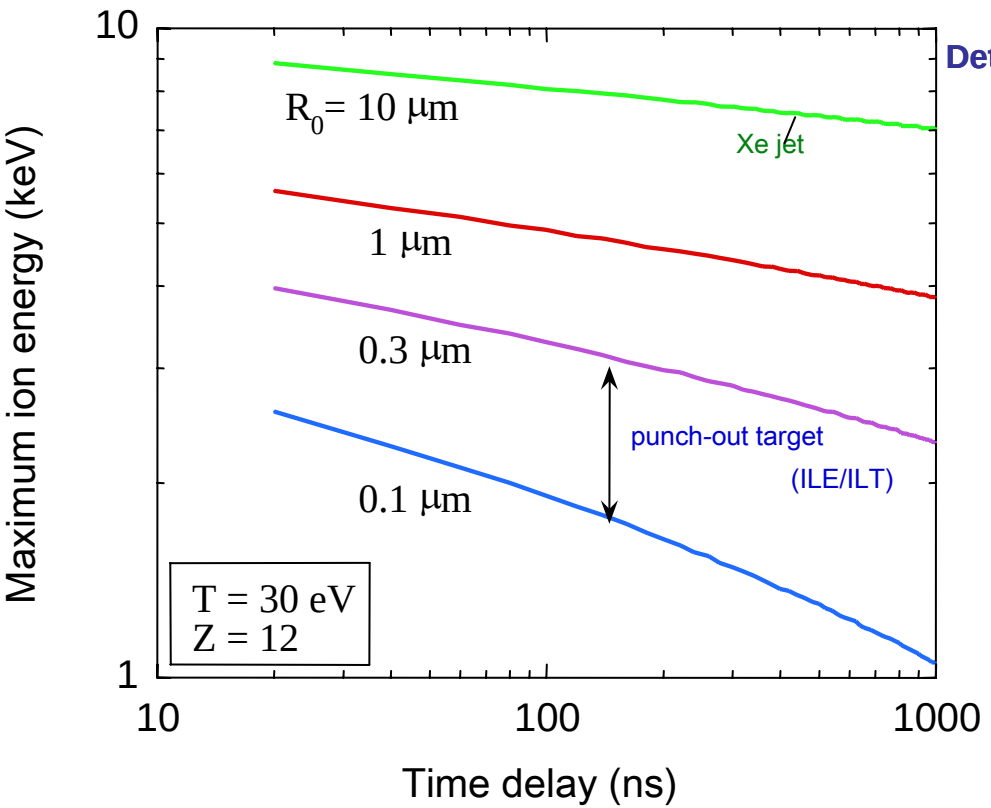


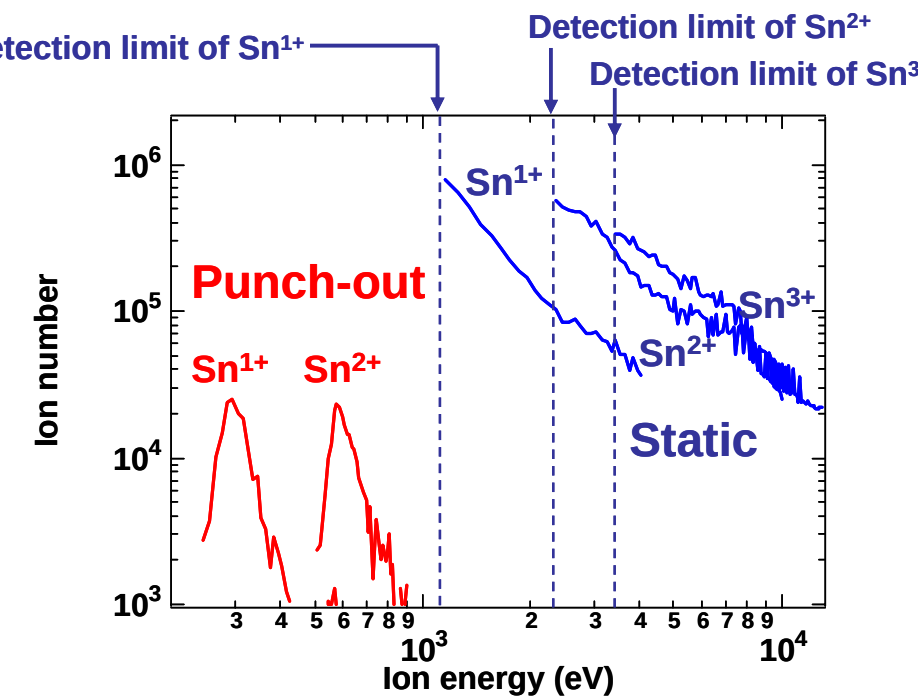


punch-out target

Maximum ion energy can be strongly suppressed in the punch-out target.

Comparison of ion energy between punch-out target and plane





after Murakami et al

after Fujioka et al

Numerical model of a hybrid code

$$0 \leftarrow m_e n_e (dv_e / dt) = -e n_e (E + v_e \times B) - \nabla P_e$$

Electron is treated as massless fluid

$$P_e = n_e T_e \qquad J_e = -e n_e v_e$$

$$\nabla \times B = \mu_0 (J_e + J_i)$$

$$Z n_i = n_e$$ Quasi-neutrality

$$E = \frac{1}{Z e n_i} \{ \frac{1}{\mu_0} (\nabla \times B_p) \times B - J_i \times B - Z T_e \nabla (n_e) \}$$

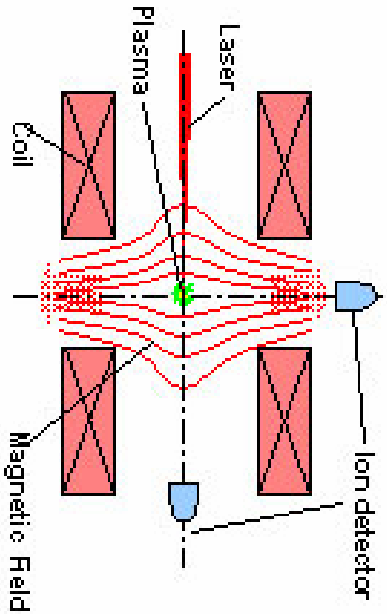
$$\frac{\partial B}{\partial t} = -\nabla \times E$$ Faraday's law

$$m_i \frac{dv_i}{dt} = Ze(E + v_i \times B) \qquad \frac{dx_i}{dt} = v_i$$

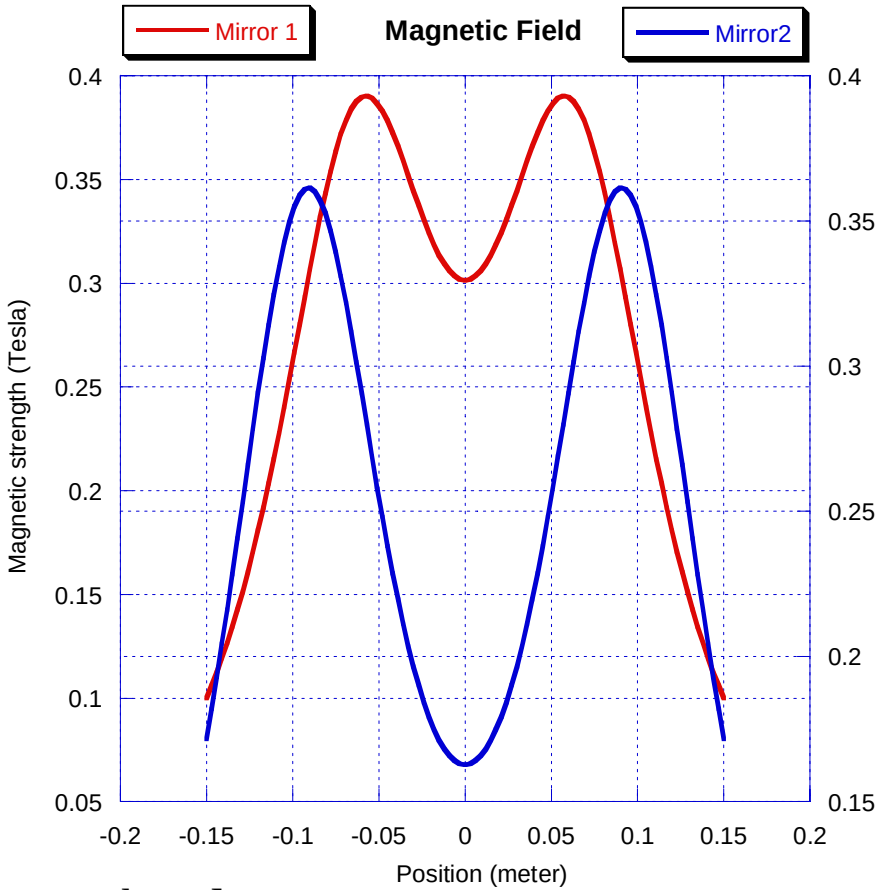
Equations of motion for ions

mitigation by B-field

Simulation condition for magnetic mirrors



Magnetic mirror, EUVA [H. Komori, et al., Proc. SPIE, **5374**, p.839 (2004)]



[Simulation condition]

Initial ablation mass: 0.3 μg, Initial radius: 3.1mm

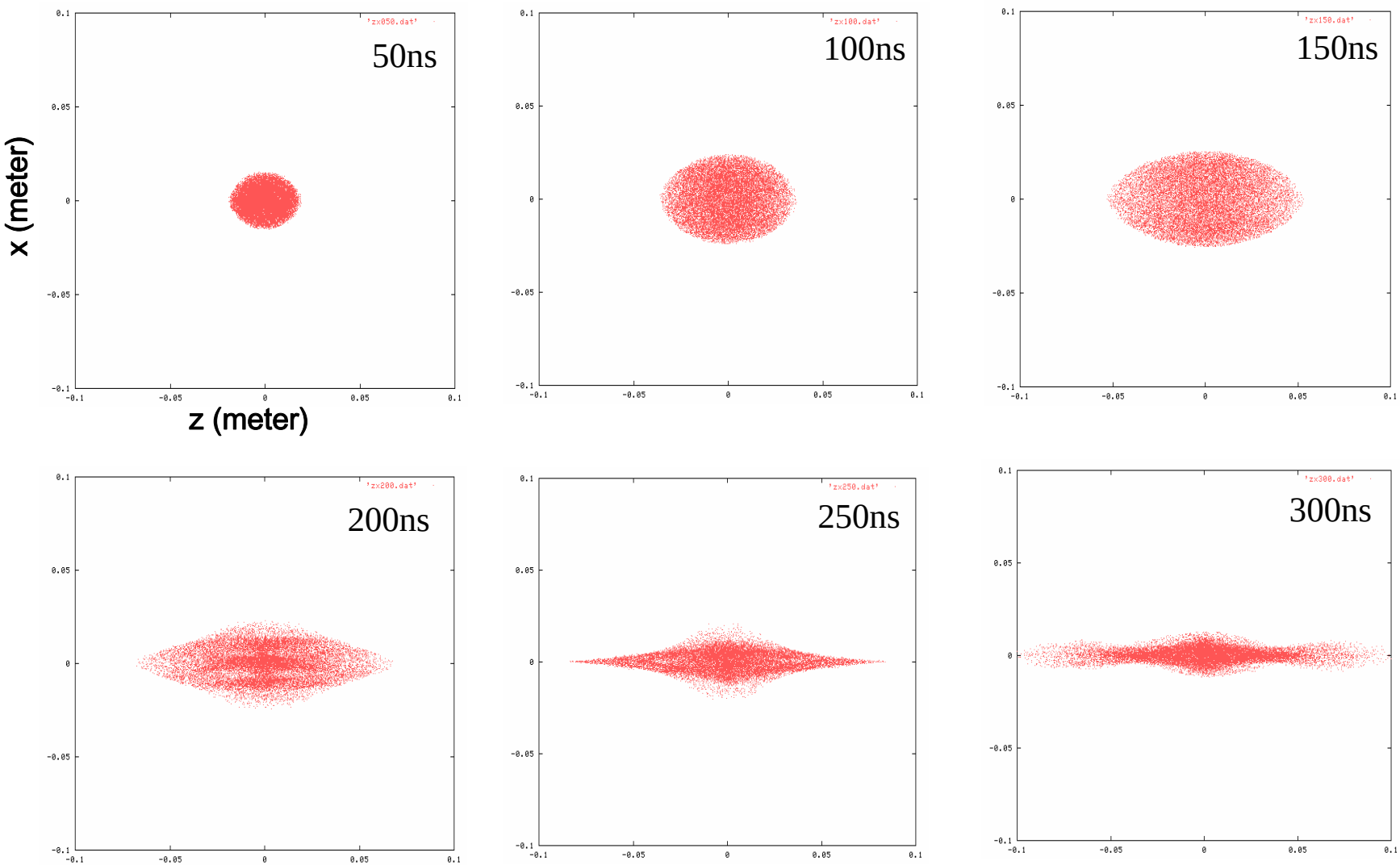
Maximum velocity: $3.3*10^6$ cm/s, Te: 30eV, Z = 10

B=0.35-0.4 Tesla, E = 100mJ (initial kinetic energy)

Number of particles = $1.5*10^{15}$, Number of test particles = 10^5

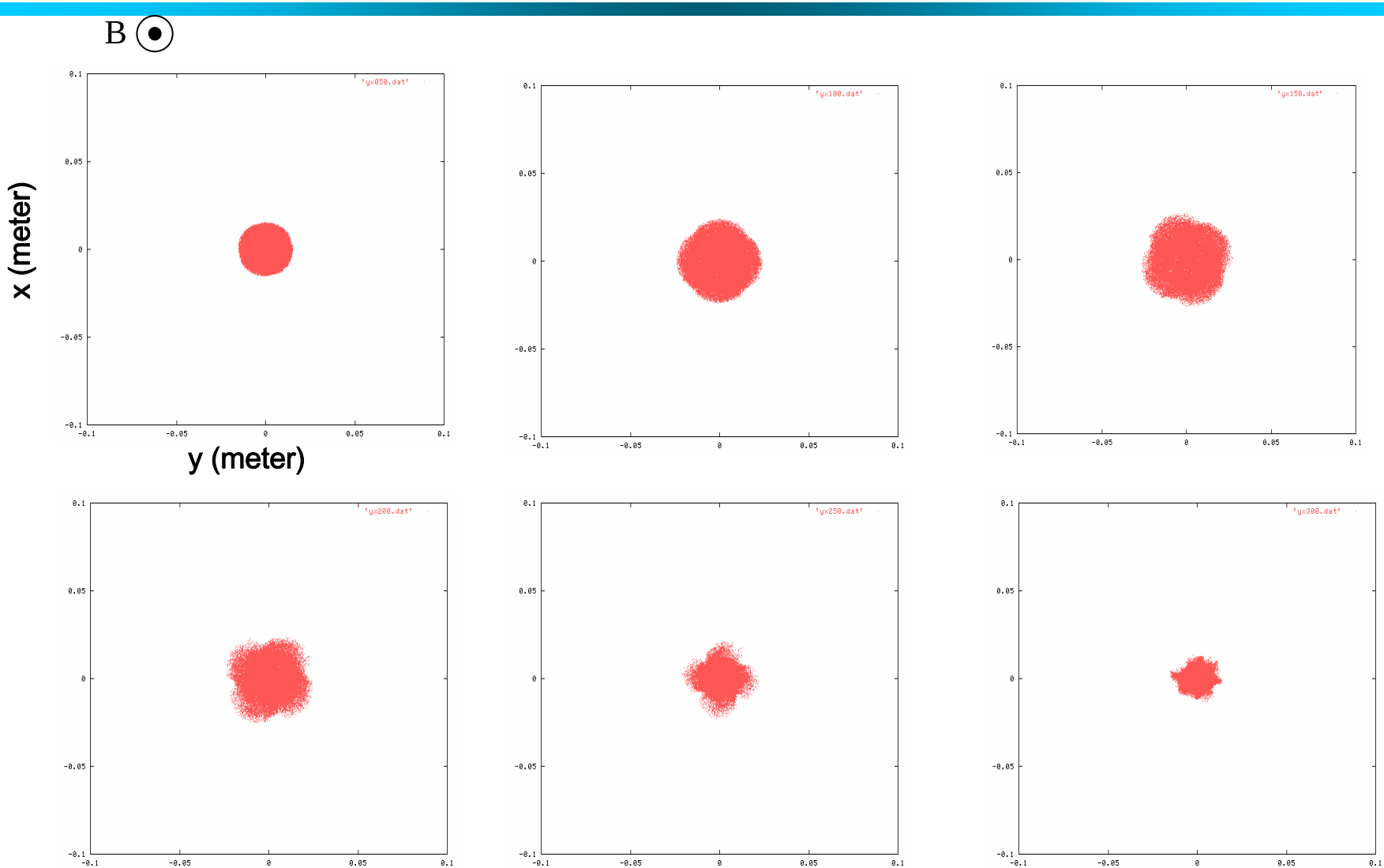
mitigation by B-field

Simulation results of particle positions (mirror1, zx-plane)



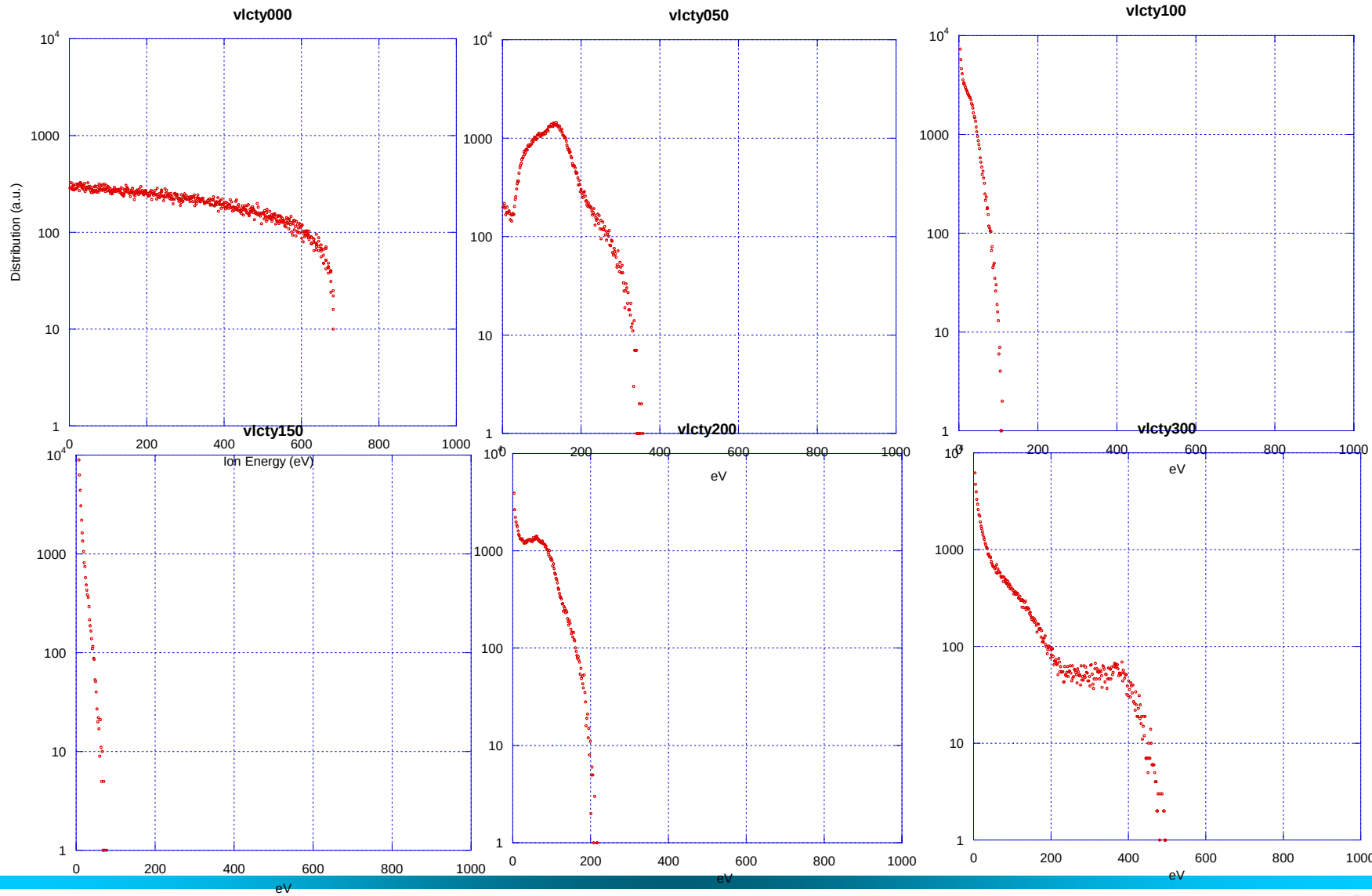
mitigation by B-field

Simulation results of particle positions (mirror1, yx-plane)



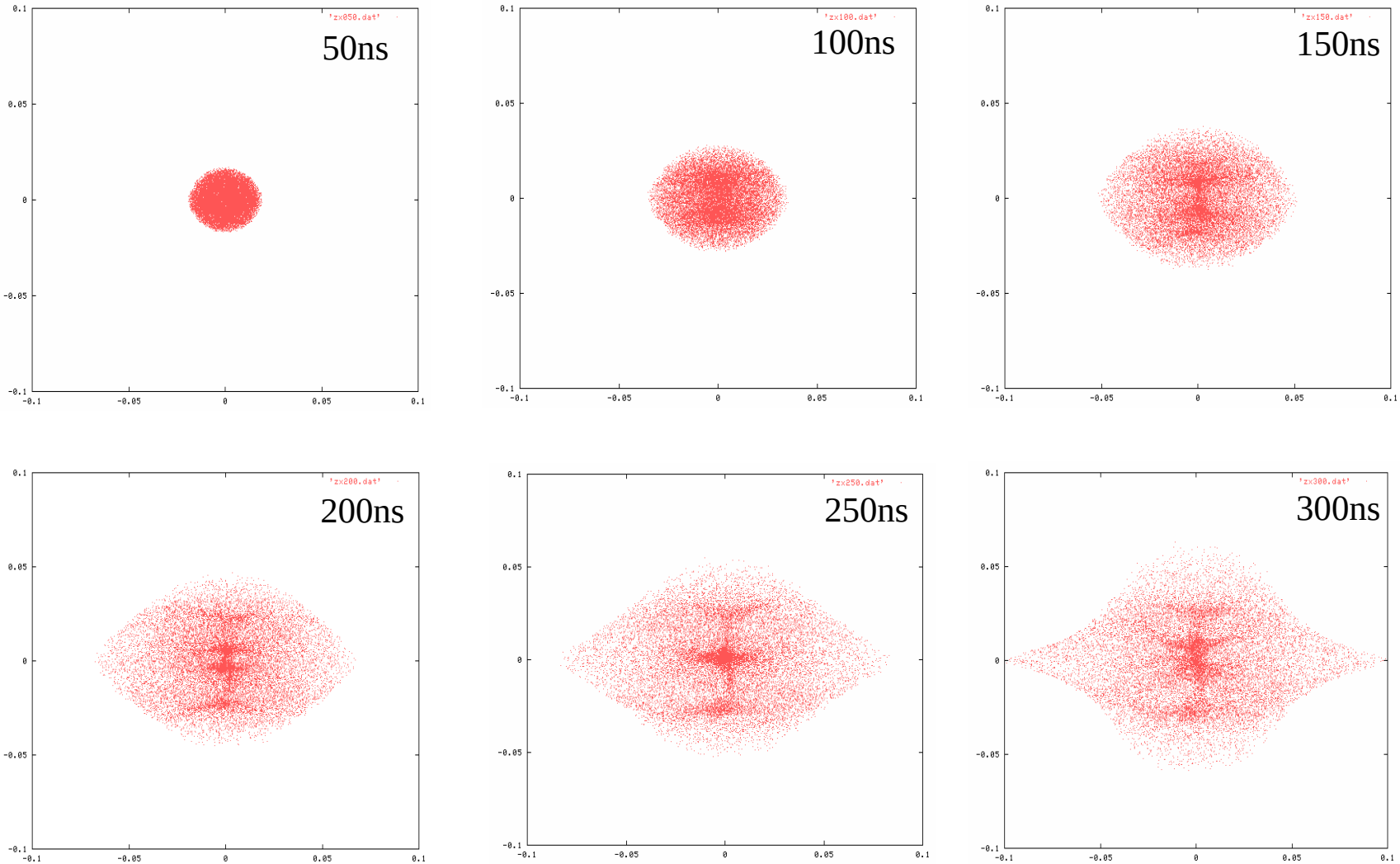
mitigation by B-field

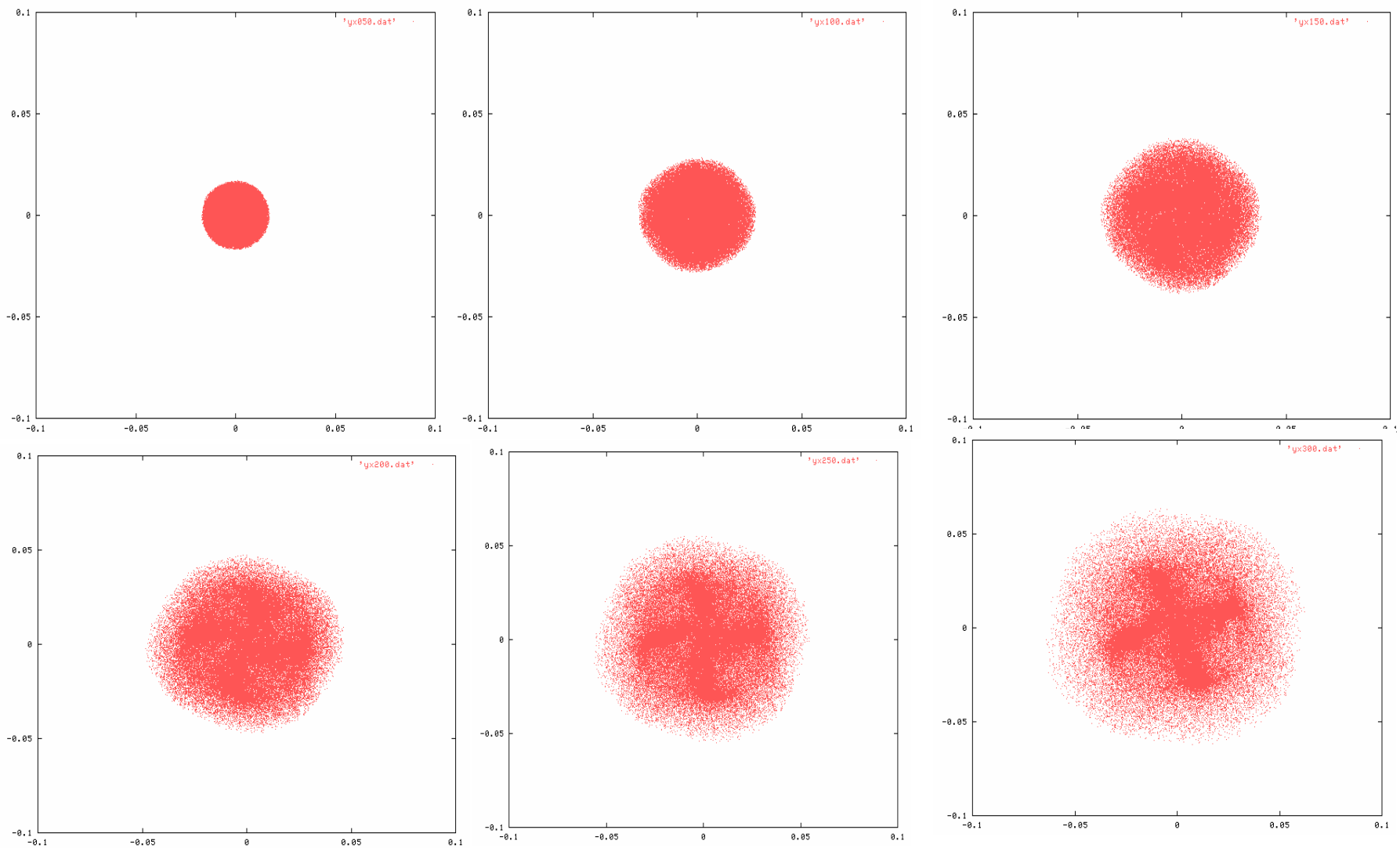
Simulation results of radial velocity (mirror1)



mitigation by B-field

Simulation results of particle positions (mirror2, zx-plane)



mitigation by B-field

Simulation results of particle positions (mirror2, yx-plane)