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Hybrid and Kinetic Simulations of Particle Dynamics in Coaxial Plasma Jet Accelerators*

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Topics

1. Motivation: Application of plasma jets to Magnetized Target Fusion

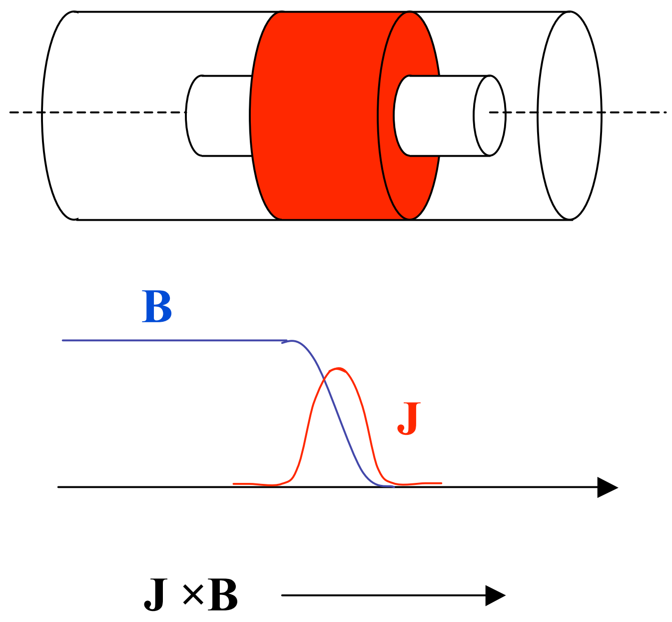
2. EMHD and Collisional PIC Algorithms for Plasma Jet Simulations

3. Multi-species acceleration in 1D

4. 2D coaxial simulations

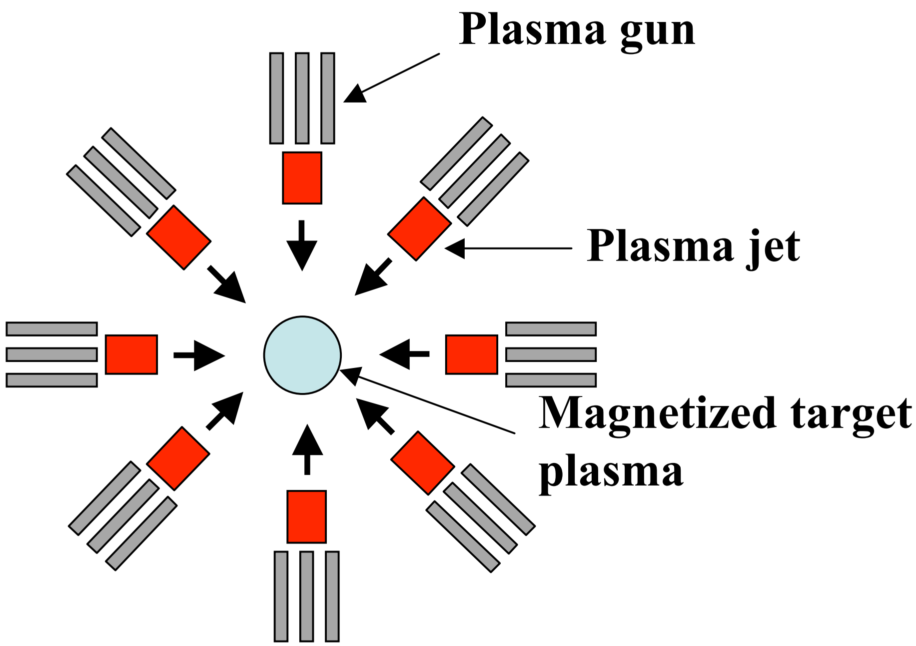
5. Conclusions and Future Work

Coaxial plasma jets: Drivers for Magnetized Target Fusion (MTF)



Coax length ~ 1 m

Deuterium plasma "slug" (~10^{17} /cm^{-3}) accelerated to velocities ~200 km/s in a few μs.



MTF: Plasma jets merge to form an imploding liner. *

*Y.C.F. Thio *et al*, Journal of Fusion Energy **20** 1 (2002)

EMHD and Kinetic PIC Algorithms in LSP

EMHD:

Drop electron inertia: **Do not have to resolve fast electron time-scales**

Ion species treated kinetically (including ion-ion collisions);

Electric field obtained from generalized Ohm's law.

EMHD algorithm uses constant σ calculated from initial values of T_e and n_e

$$\sigma = \frac{n_e e^2}{m_e \nu_{ei}} \propto T_e^{3/2}$$

Implicit Kinetic PIC:

At somewhat lower densities can run fully kinetic simulations using Direct Implicit model in LSP*.

Spitzer collision model for electrons and ions

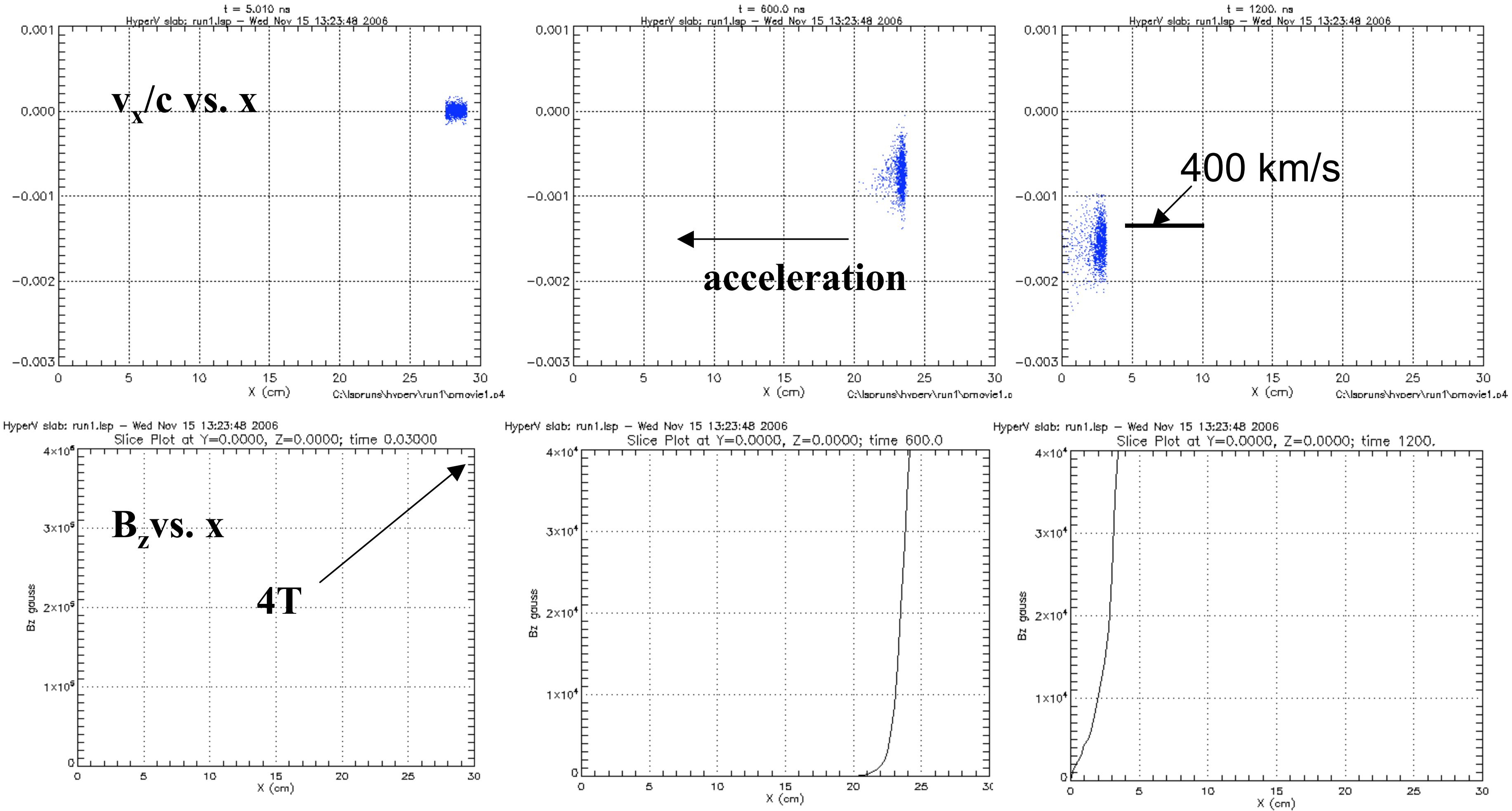
*** D.R. Welch, D.V. Rose, M.E. Cuneo, R.B. Campbell, and T.A. Mehlhorn, Phys. Plasmas 11, 751 (2004)**

EMHD simulation of plasma jet acceleration in 1.2μs

$n_i = 3\times10^{17}\,\mathrm{cm}^{-3}$ ($\rho=10^{-6}\,\mathrm{g/cm}^{-3}$) Deuterium

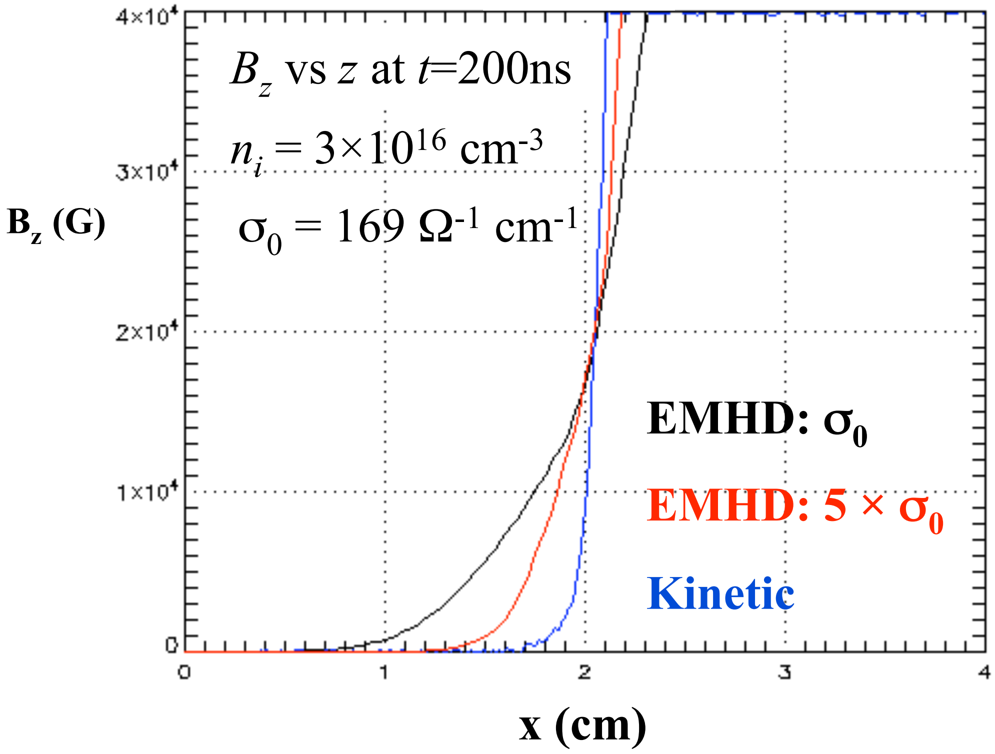
$T_i = 5\ \mathrm{eV} = T_e$

t ~ 0 **t = 600 ns** **t = 1200 ns**



Propagates 30 cm in 1.2 μs, in agreement with slug model.
Some axial heating of ions is seen

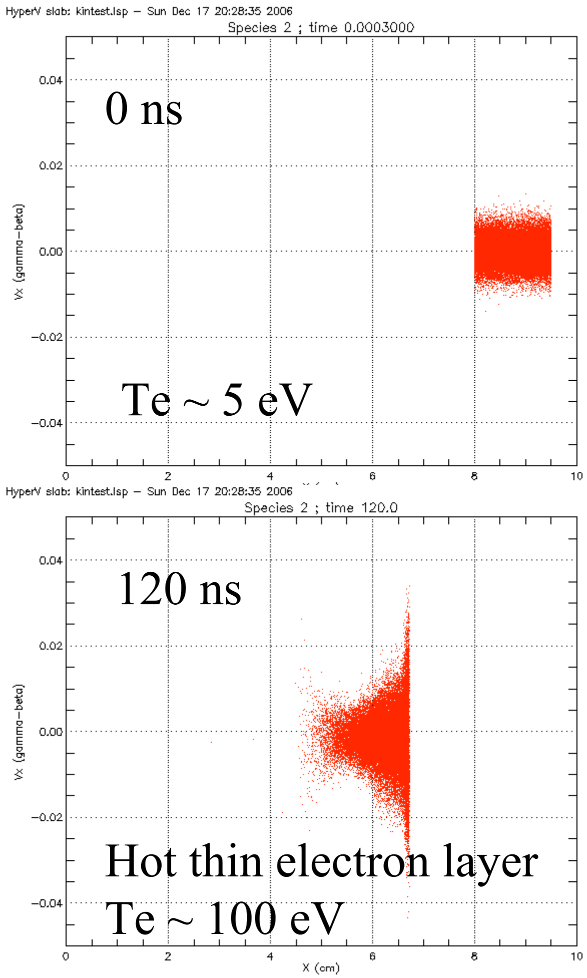
Kinetic diffusion layer thinner than EMHD layer due to large electron heating



Diffusion layer gets thinner for EMHD simulation with increased conductivity

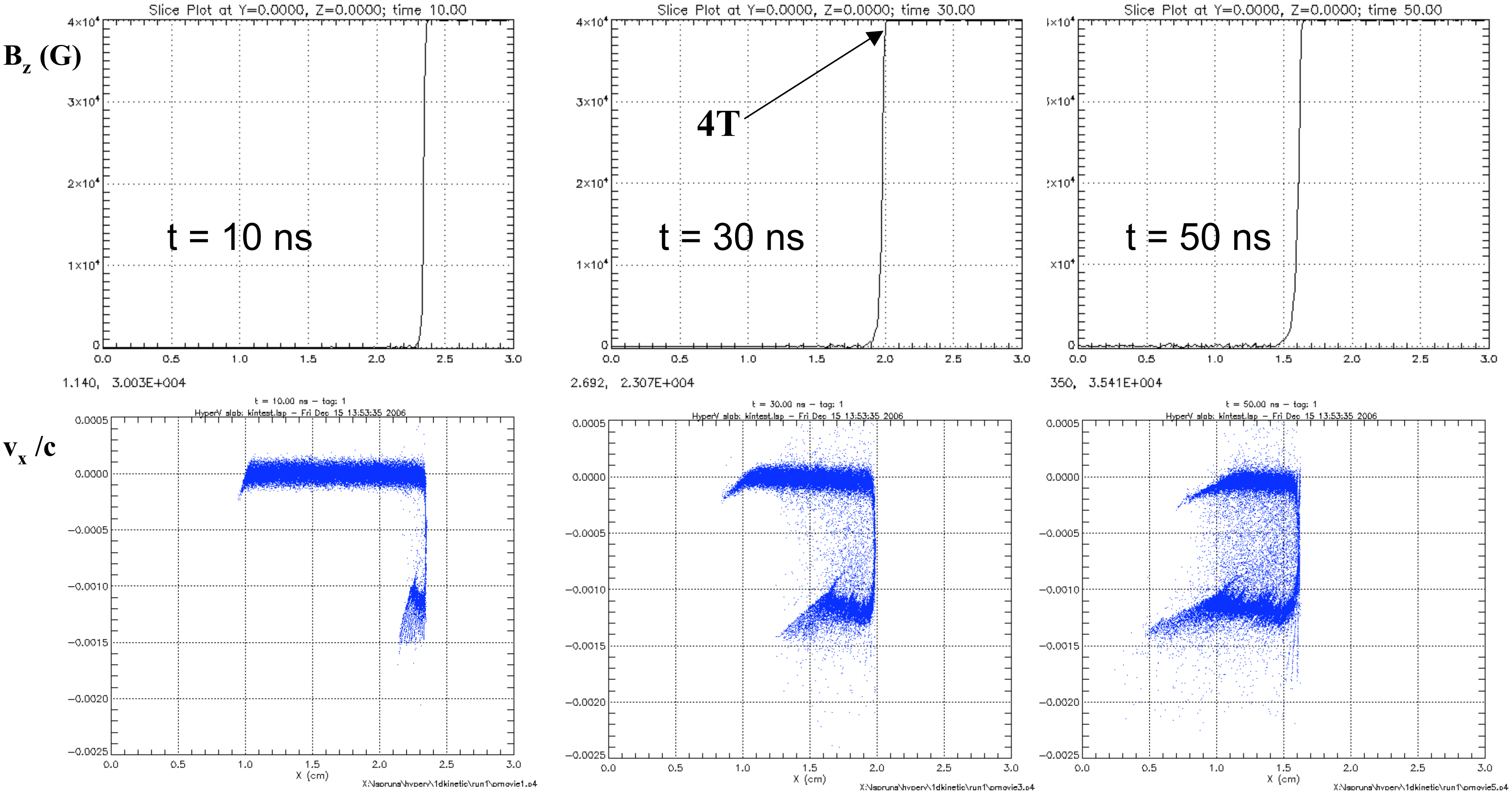
$$\sigma \propto T_e^{3/2}$$

Electron phase-space



Increased local conductivity

For large fields ions accelerated ballistically in thin diffusion layer



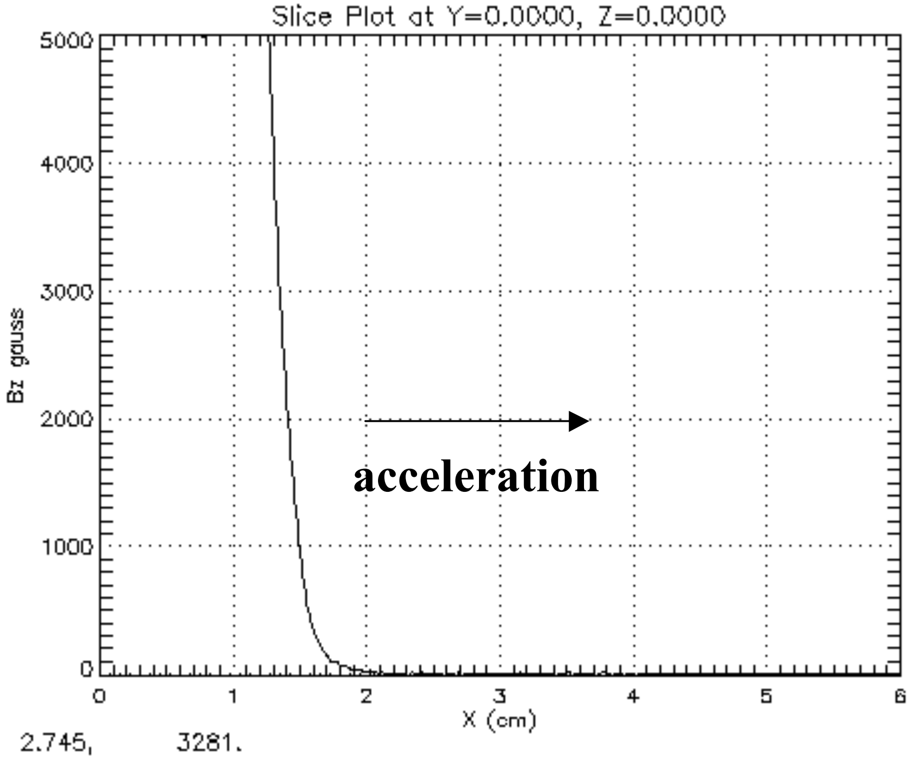
Accelerated ions have much increased mean-free-path
Ion-ion collisions "fill-in" the phase-space

Different ion dynamics at lower field values

$B_z = 0.5$ Tesla

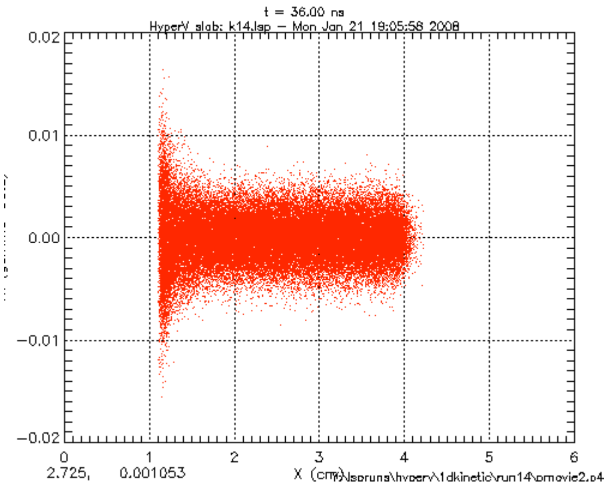
$n_i = 10^{16}\,\text{cm}^{-3}$ Deuterium

$T_i = 5\text{ eV} = T_e$

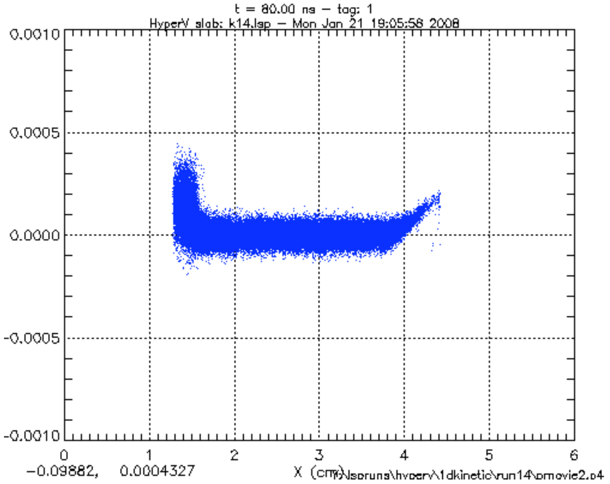


acceleration

Thicker diffusion layer



Less ohmic heating of electrons



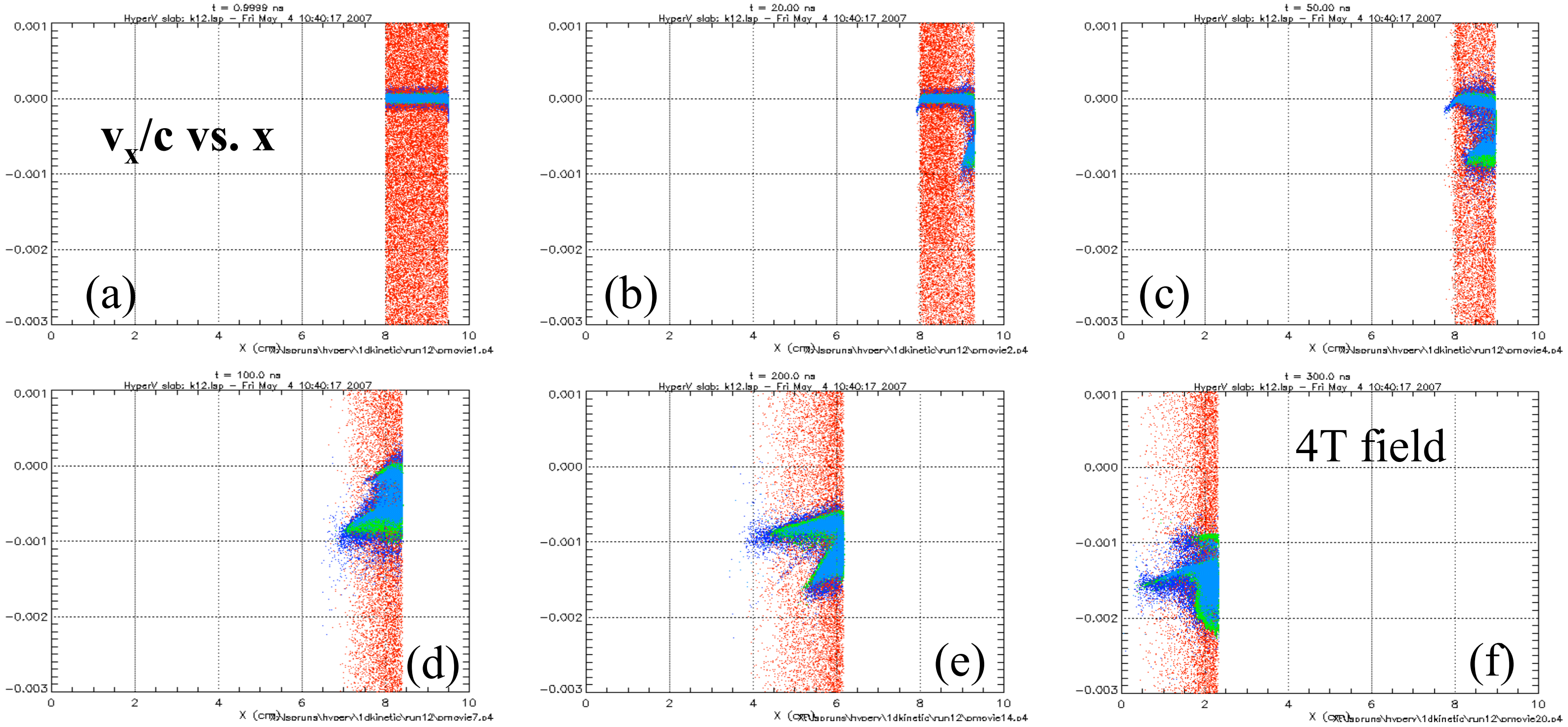
Ions collisional in sheath

Acceleration of mixed-species jet

HyperV jet is composed of 2 parts Hydrogen to 1 part Carbon

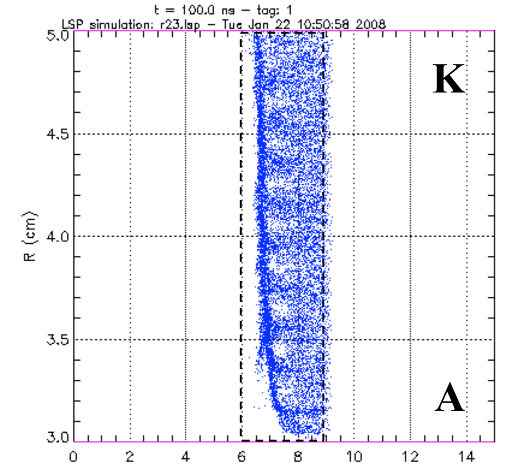
e : $n = 3.5\times10^{16}$ cm^{-3}
D^+ : $n = 2\times10^{16}$ cm^{-3}
C^+ : $n = 0.5\times10^{16}$ cm^{-3}
C^{2+} : $n = 0.5\times10^{16}$ cm^{-3}

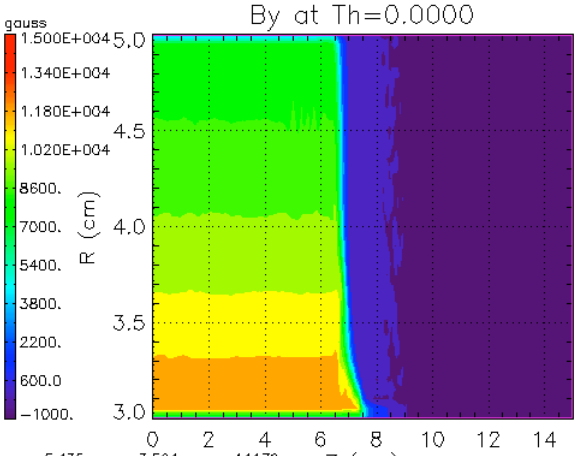
Simulations show mixture remains relatively homogeneous



t = (a) 1 (b) 20 (c) 50 (d) 100 (e) 200 (f) 300 ns

2D cylindrical coax simulations undertaken to investigate modifications to 1-D predictions

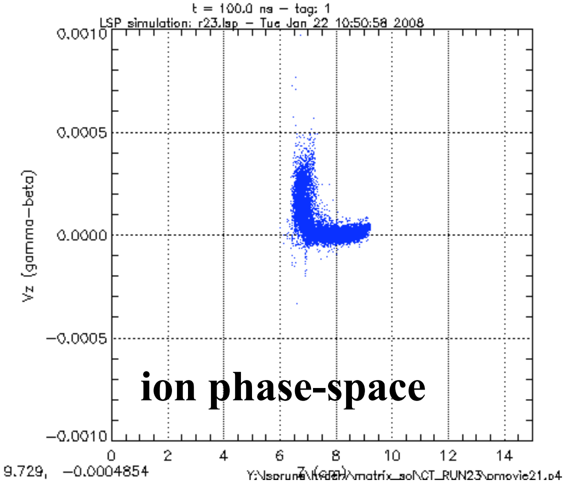




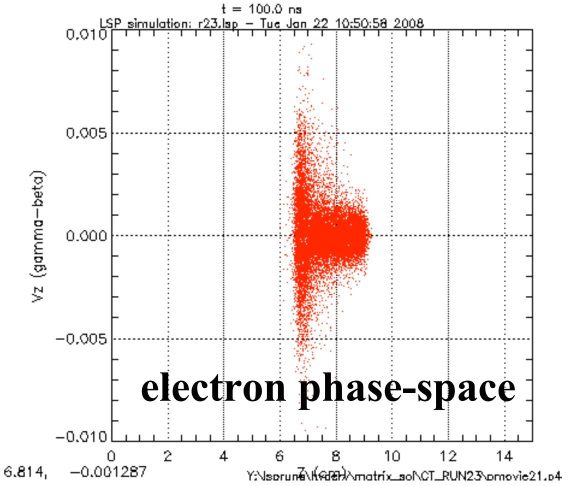
n_0 $= 3\times10^{16}$ cm^{-3}

T_0 =5 eV

$B_\theta \sim 1.2$ T



ion phase-space

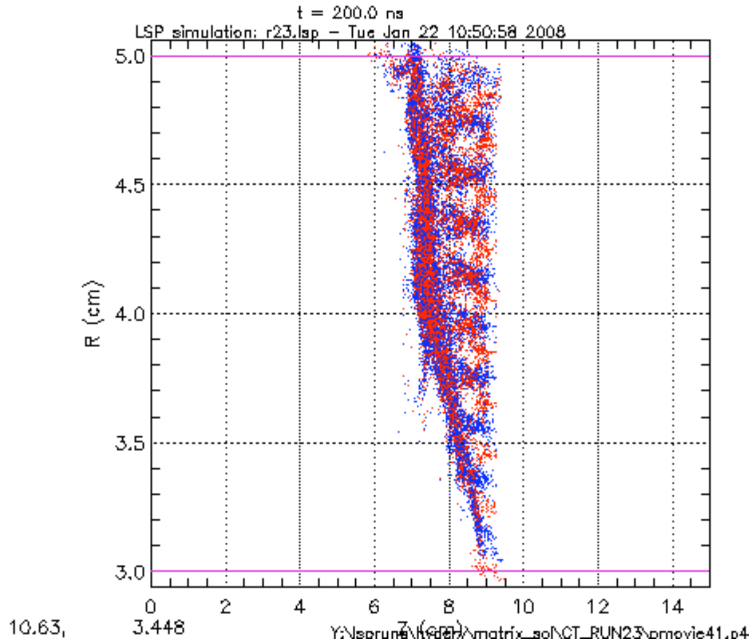


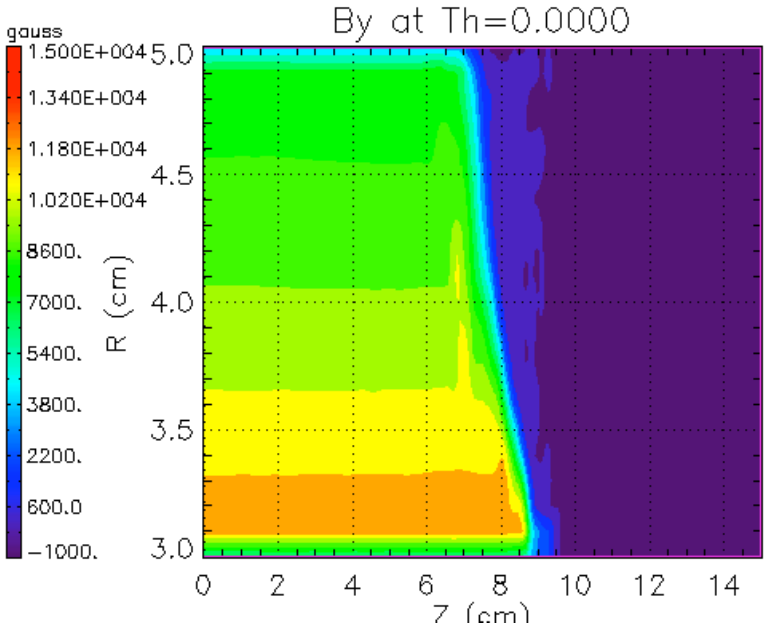
electron phase-space

Modified version of "Direct-Implicit" algorithm in Lsp run with large time-step

$\omega_{pe}\,\Delta t \sim 40$

Plasma Erosion at Anode





$n_0 = 3\times10^{16}$ cm^{-3}

T_0 =5 eV

$B_\theta \sim 1.2$ T

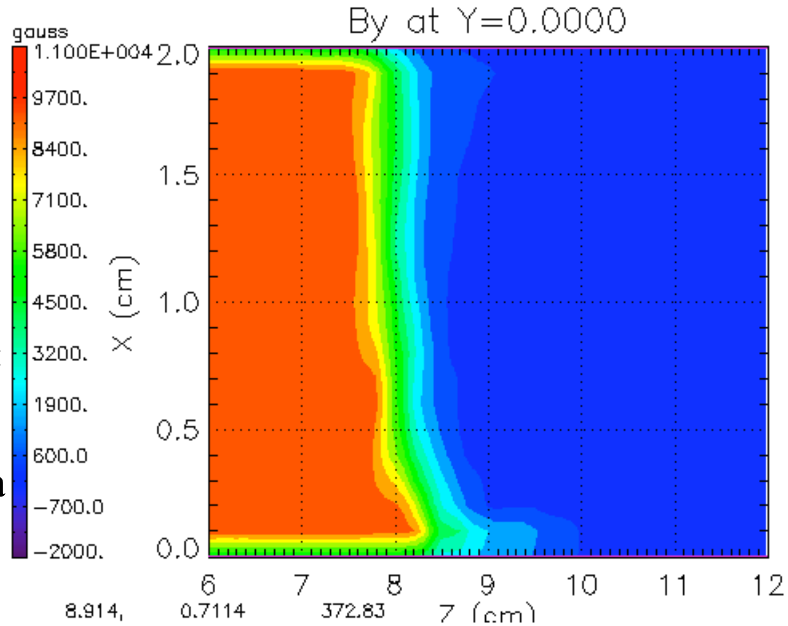
$B_\theta \approx 1.2$T

Thinning of plasma at anode: "snowplow" ion acceleration plus "blow-by" instability?

But similar effect seen in planar geometry.

Note: Impractical to resolve Debye sheath: 10^{-5} cm (Δr=1 mm!)

Large cell size may increase rate of plasma erosion at anode.



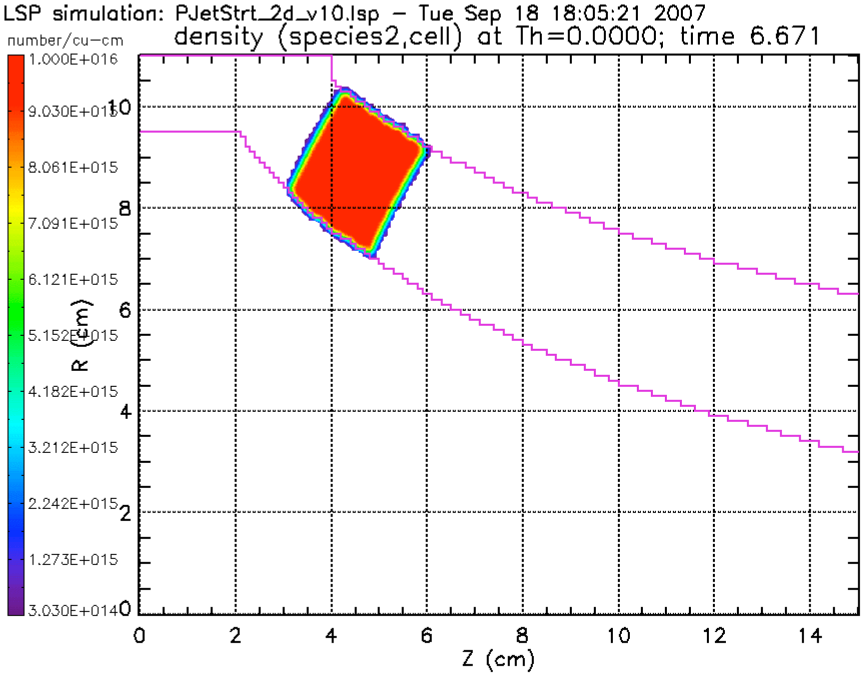
Planar

Geometry

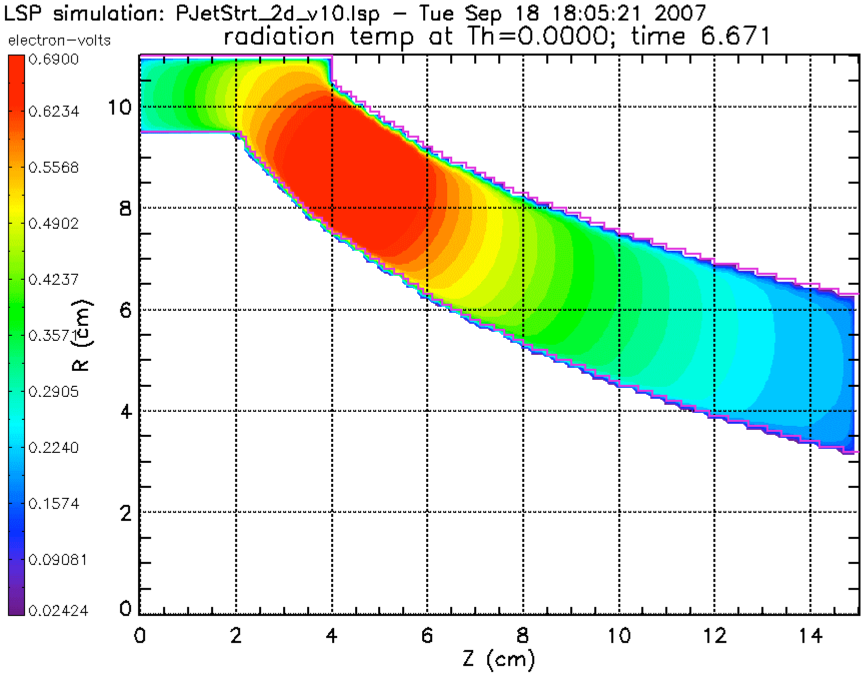
B_y =1T

Work in progress with PCS to access opacity, EOS tables

CH_2 plasma, 10^{16} cm^{-3}, 5 eV



Radiation output



Multi-group radiation diffusion model ported to LSP and parallelized

Summary of Results

Compared EMHD to kinetic-collisional PIC simulation in 1-D for plasma density of 3×10^{16} cm^{-3}.

Obtain similar ion dynamics from both algorithms.

Kinetic simulations show strong electron heating at vacuum interface

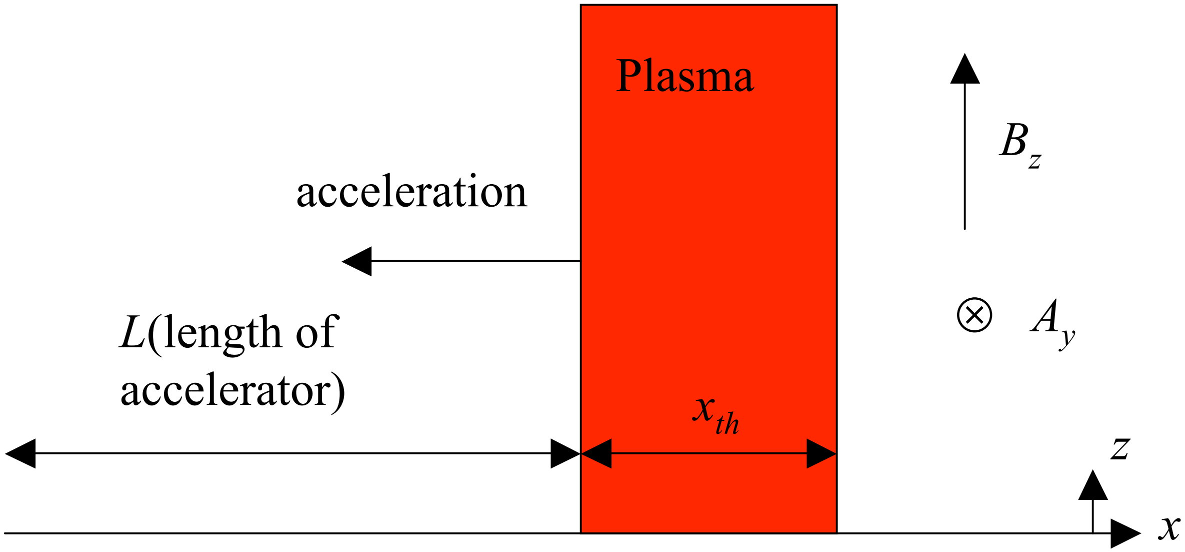
Significantly increases Hall parameter at interface

Multi-species jet simulations show mixture remains homogeneous

2D EM coaxial plasma jet simulations feasible but may require mitigation of plasma erosion at electrode surfaces.

In progress with PCS: EOS model to obtain ion charge-states from n_i, T_e

1-D plasma jet geometry



Ideal equation of motion:

$$\rho \Delta A x_{th} \frac{dv_x}{dt} = \frac{B_z^{\ 2}}{2\mu_o} \Delta A$$

Slug acceleration:

$$a = \frac{B_z^{\ 2}}{2\mu_o \rho x_{th}}$$

Final velocity:

$$v_f = \sqrt{2aL}$$

The time to reach the end of the accelerator:

$$t_f = 2L / v_f$$

Different q/m ions accelerated to same velocity

Estimate of impulse for plasma with (total) mass density ρ

$$\Delta v / c \approx 9.4\times10^{-12}\left[\Delta B / \mathrm{G}\right]\left[\frac{\rho}{\mathrm{g/cm^3}}\right]^{-1/2}$$

$$\Delta B \sim 4\times10^{4}\ \mathrm{G}$$

$$\rho \sim \left[2\cdot2\times10^{16} + 12\cdot2\cdot0.5\times10^{16}\right] m_p \cdot \mathrm{cm^{-3}} = 2.7\times10^{-7}\,\mathrm{g/cm^3}$$

$$\Delta v / c \sim 0.00073$$

More massive ions penetrate deeper into the diffusion layer, and experience a larger total force which compensates for their greater inertia.