2-d Particle-in-Cell Simulations of the Energetic-Ion Slowing Down in Cool Plasma

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Summary

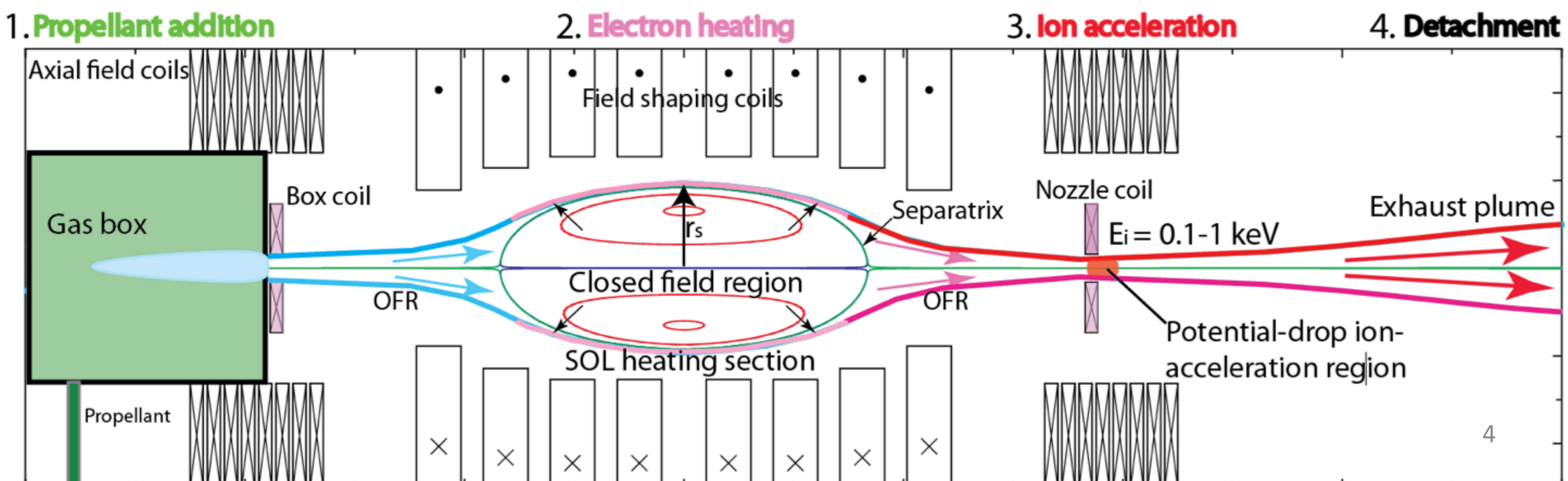
- LSP simulations of 14.7 MeV pulsed narrow proton beam propagation through a cool plasma features a slowing down time, t_s, much shorter than that expected from classical predictions
- Streaming instabilities near $\omega_{p,e}$ observed in beam-plasma interactions
- Instabilities likely to enhance beam ion slowing down
- **Enhanced slowing down of energetic fusion products in the SOL is beneficial for the PFRC**

Motivation

- Basic physics of particle energy transfer well known for certain regimes
- The regime of interest (PFRC) has a wealth of new physics
  - Non-monoenergetic beam
  - $v_b >> v_{th,e}$
  - $r_{c,e} > \lambda_D$ $(v_b \perp B)$
  - Beam-plasma modes and instabilities
- Applications for:
  - Astrophysics (cosmic rays)
  - Solid state physics
  - Especially for a small, clean FRC

Slowing Down in PFRC SOL

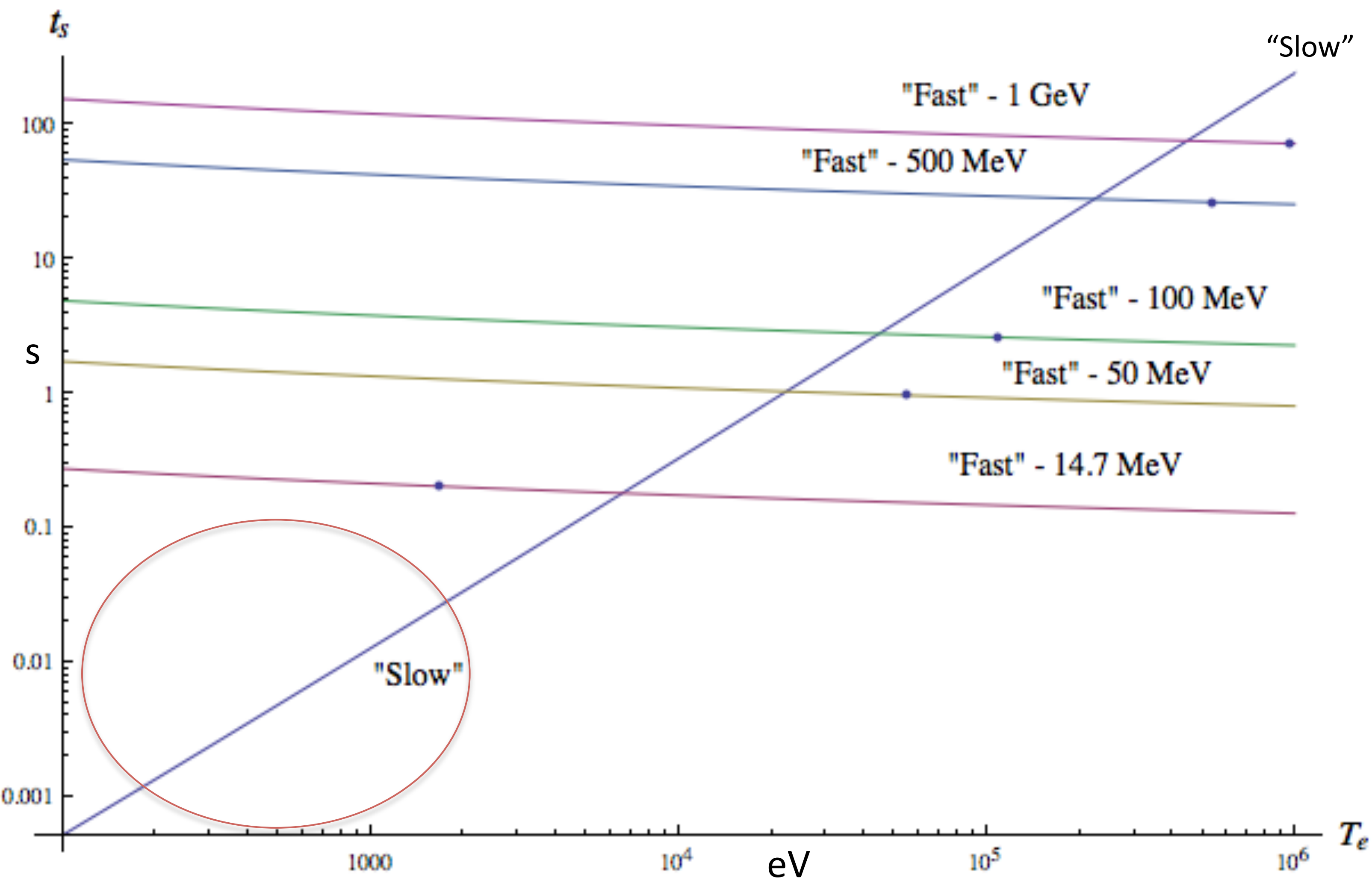
- Energy deposition from energetic proton to SOL electrons required for extracting energy
  - Want fusion products to slow down quickly
  - Hope to find that fast ions transfer energy to SOL plasma electrons
  - Knowledge of predicted fast-ion slowing down time, t_s for P_{fusion}, $T_{e,SOL}$ and $n_{e,SOL}$



Comparison of Theoretically Predicted Relaxation Times

$$t_s(fast) = (\nu_s^{i|e})^{-1} = \frac{5882\epsilon^{3/2}}{\mu^{1/2} n_e Z^2 ln\Lambda}$$

(Slow) $$t_s = 6{\cdot}27 \times 10^8 \frac{A(kT_e)^{3/2}}{Z^2 n_e \ln \Lambda} \text{ sec,}$$



μ = 1

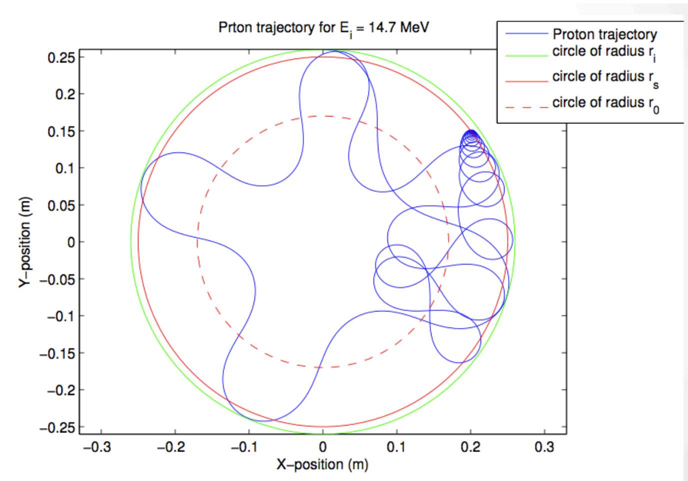
$Z_b = 1$

$n_e = 10^{14}$

Deviation from classical predictions for fusion products in FRC SOL

Slowing down energy loss

- Background magnetic field
  - $r_{c,e} > \lambda_D \quad (v_b \perp B)$
- $v_b > v_{th,e}$
  - $v_b \sim 5 \times 10^9$ cm/s
  - $v_{th,e} \sim 3 \times 10^8$ cm/s
- Betatron orbit through SOL



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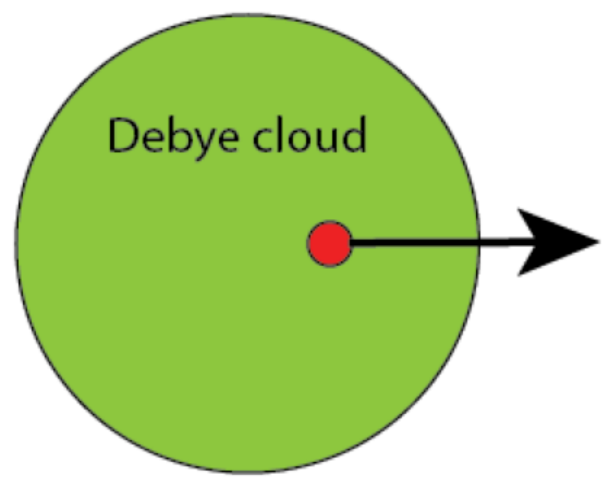
Possibly speeding up energy loss

- Current-driven instabilities and excitation of plasma modes
  - 2-stream
  - Segmentation instability
  - Instability in presence of B filed



Particle-in-cell Simulations with LSP

- Doing a dimensionally correct simulation is very difficult
  - CPU time (24-48 hrs. for 25 ns simulation)
  - Required numerical accuracy
    - Resolution of λ_D, $\omega_{p,e}$
    - Long t_s timescale (~ 0.1 ms)
  - Balance between decreasing t_s and increasing λ_D
    - Lsp n_e and Z far from experimental value

$$t_s = 6{\cdot}27 \times 10^8 \frac{A(kT_e)^{3/2}}{Z^2 n_e \ln \Lambda} \text{ sec,}$$

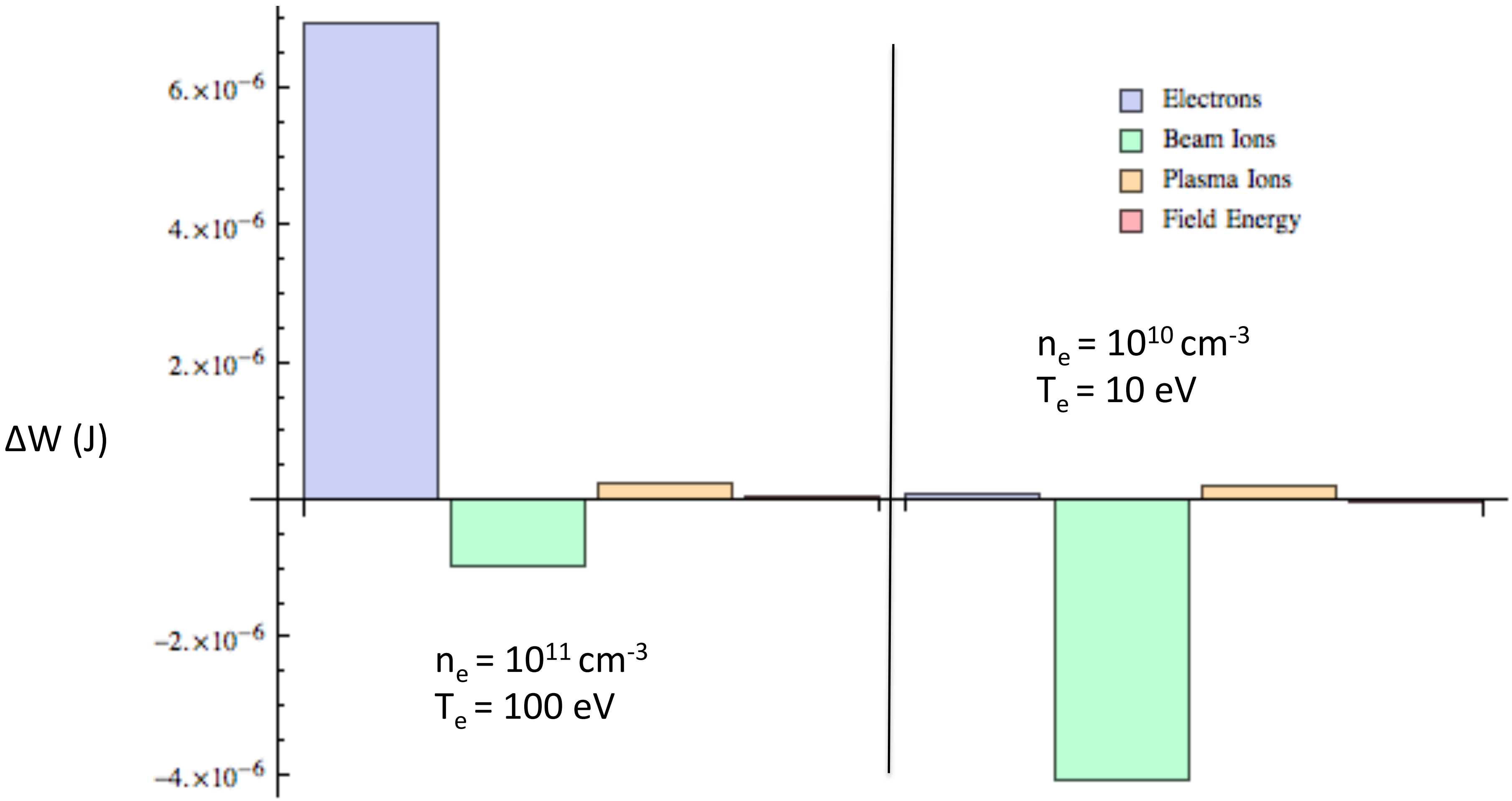
Slowing Down Simulations

- Adjustments to decrease computation time
  - Runtime of 25 ns simulation ~ 24-48 hrs. w/ 48 CPUs
  - $dx = dy \sim \lambda_d/5 - \lambda_d/4$
  - 0.5 x 0.5 cm ($50\ \lambda_d \times 50\ \lambda_d$) system
  - 2-D
  - $n_e = 10^{10} - 10^{11}\ cm^{-3}$ (increases grid-space requirements)

$$C_o = \left|\frac{\Delta t * v}{\Delta x}\right| \leq 1$$

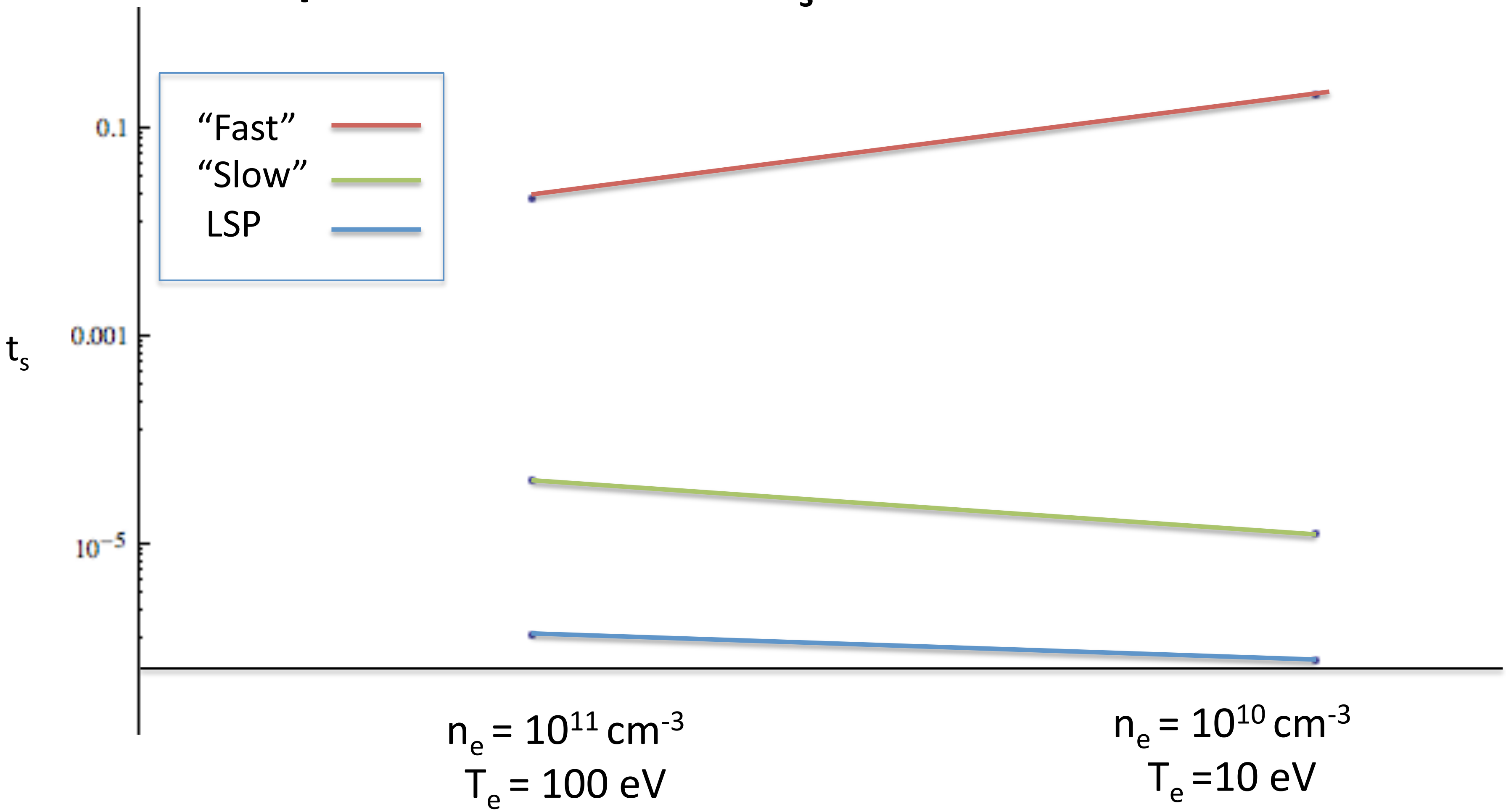
- Adjustments to decrease theoretical t_s
  - T_e = 10 eV – 100 eV
  - Z_b = 100 esu

Total ΔKE Comparison



Note that energy is not conserved!

Comparison of Predicted t_s with LSP Results



Many more simulations needed to quantify t_s

- T_e
- n_e
- Z_b
- I_b

$n_e = 10^{11}\ cm^{-3}$
$T_e = 100$ eV

Formation of electron cloud behind beam ions and holes develop in system corners

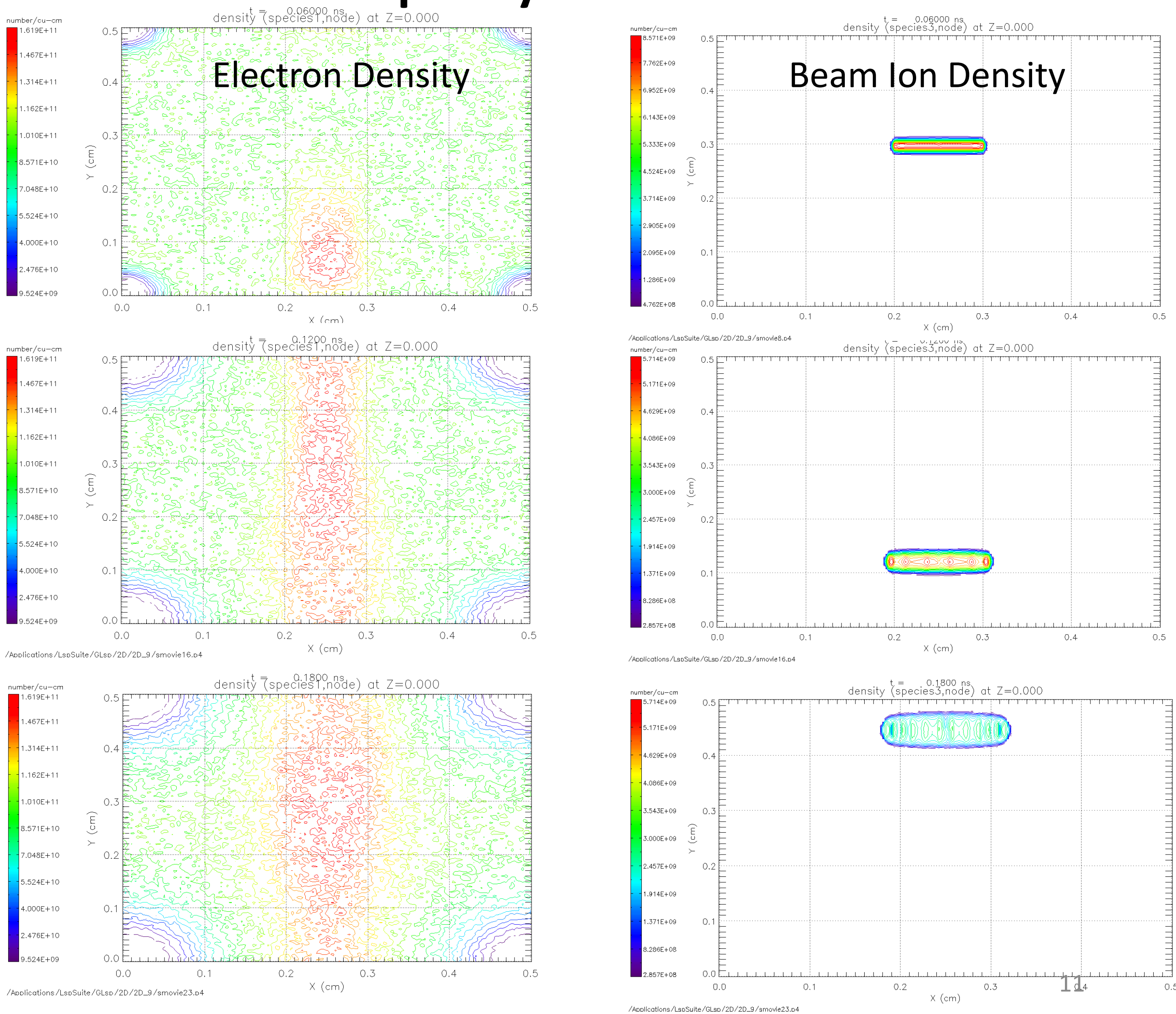
t = 0.06 ns

Possible Limitations:

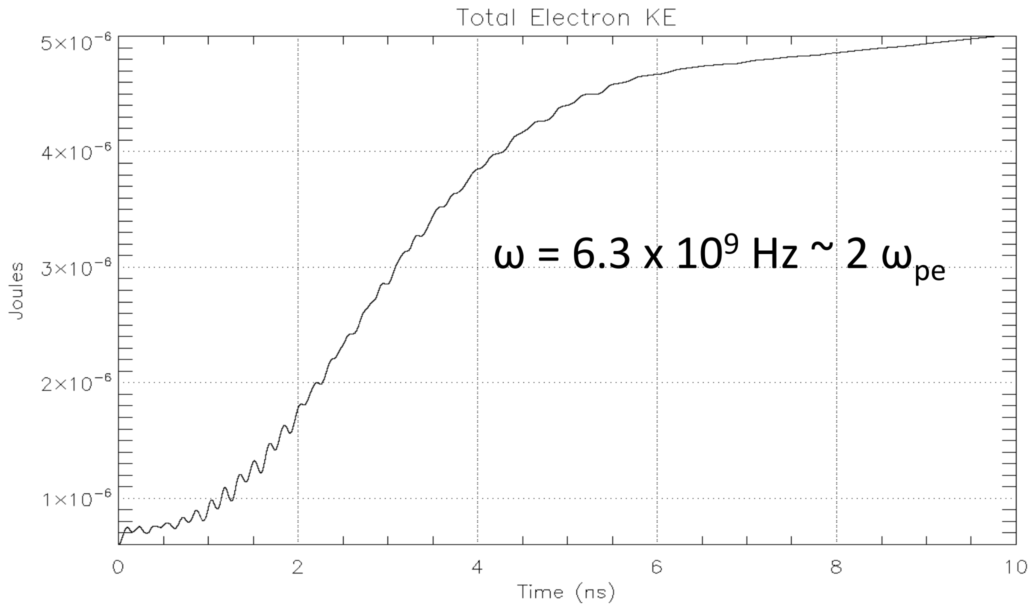
- Simulation volume
- Periodic boundaries
- Pulsed beam effect

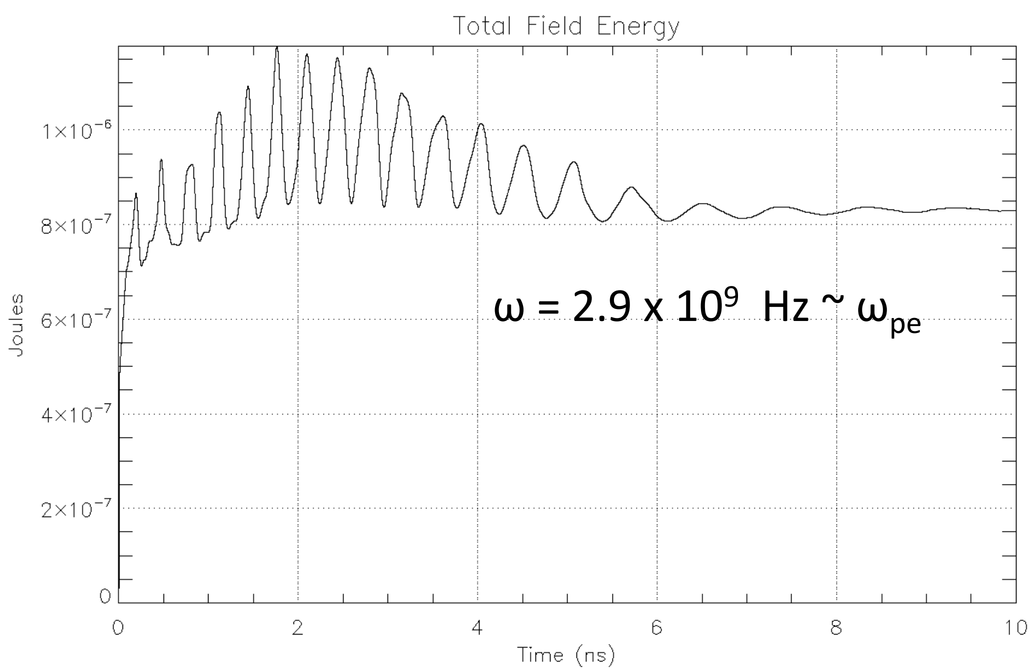
t = 0.12 ns

t = 0.18 ns



Plasma Wave Excitation: Electron KE and Field Energy Oscillations



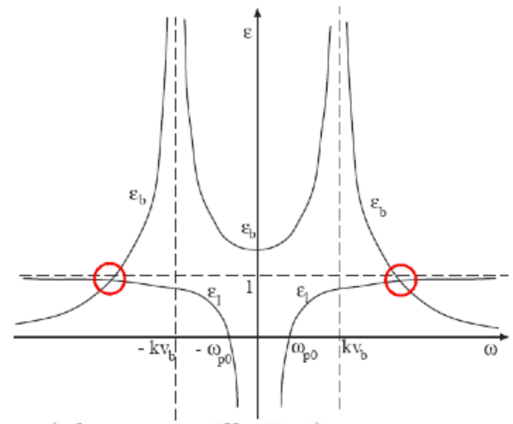


$\omega_{pe} = 2.8 \times 10^9$ Hz

$n_e = 10^{11}$ cm^{-3}
T_e = 100 eV
10 A, 0.01 ns beam

Streaming Instabilities

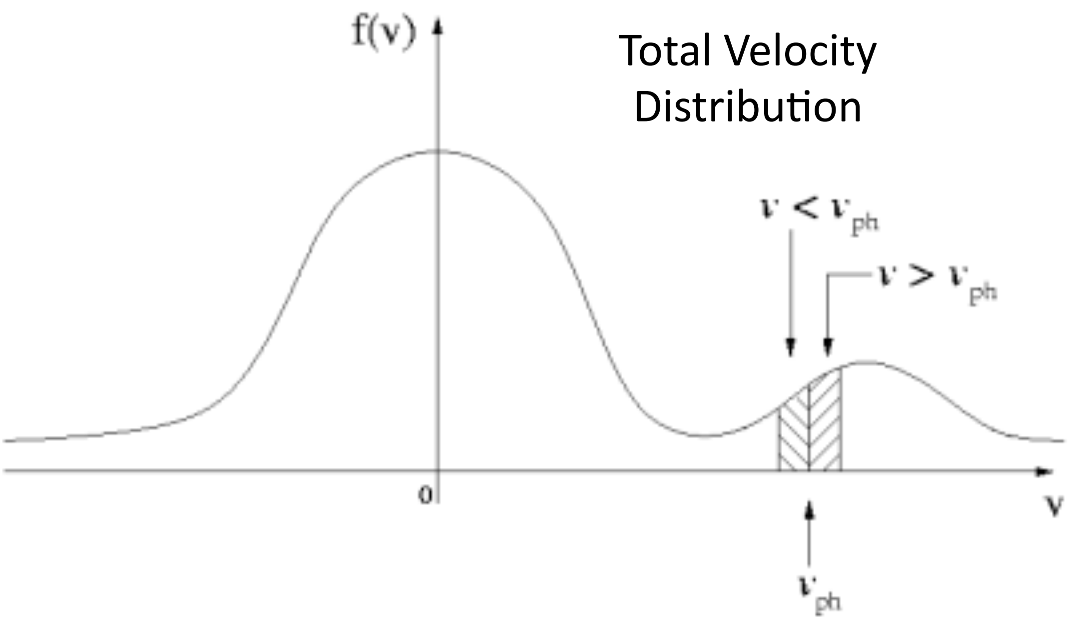
- Occur when two or more species have relative velocity
- Fundamental frequencies (e.g. plasma ion and elec.) can coincide b/c of Doppler shift between fluids



ϵ_l (plasma oscillation)

$1 - \epsilon_b$ (1 – beam modes)

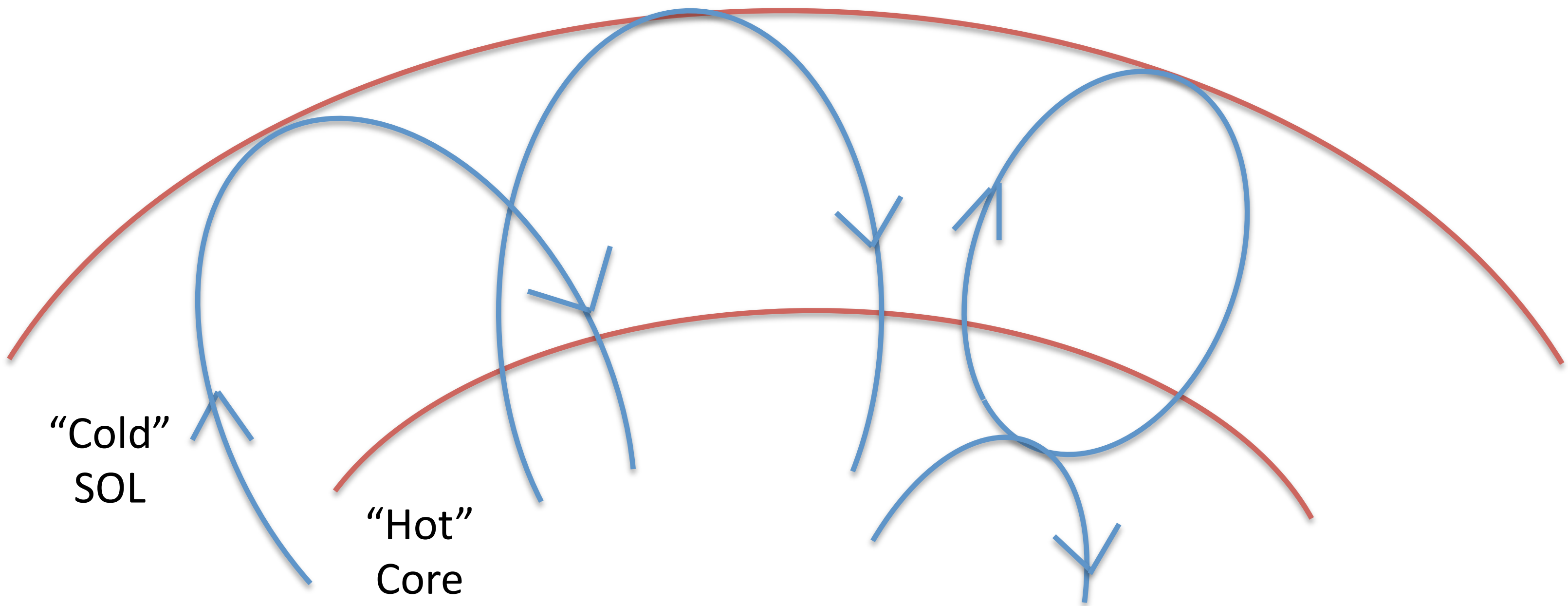
$$1 - \frac{\omega_{p0}^2}{\omega^2} = \frac{\omega_{pb}^2}{(\omega - \mathbf{k} \cdot \mathbf{V}_b)^2}$$



Total Velocity Distribution

- If greater number of particles with v > v_{ph}
  - More energy transferred to the wave
  - Exponential growth of instability

Instabilities in the PFRC SOL



PFRC regime differs from typical beam-plasma instabilities

- Counter-streaming
- B field
- Short distance (~ 10 cm)
- Large transverse extent of beam
- Beam not of uniform energy density (200 keV – 14.7 MeV)

Impact of PFRC Parameters

- $0.5 < k < 100$ cm^{-1}
- $v_{ph} < v_{beam} \sim 5 \times 10^9$ cm/s

-> $n_{e,\ SOL} \sim 3 \times 10^{13}$ cm^{-3}

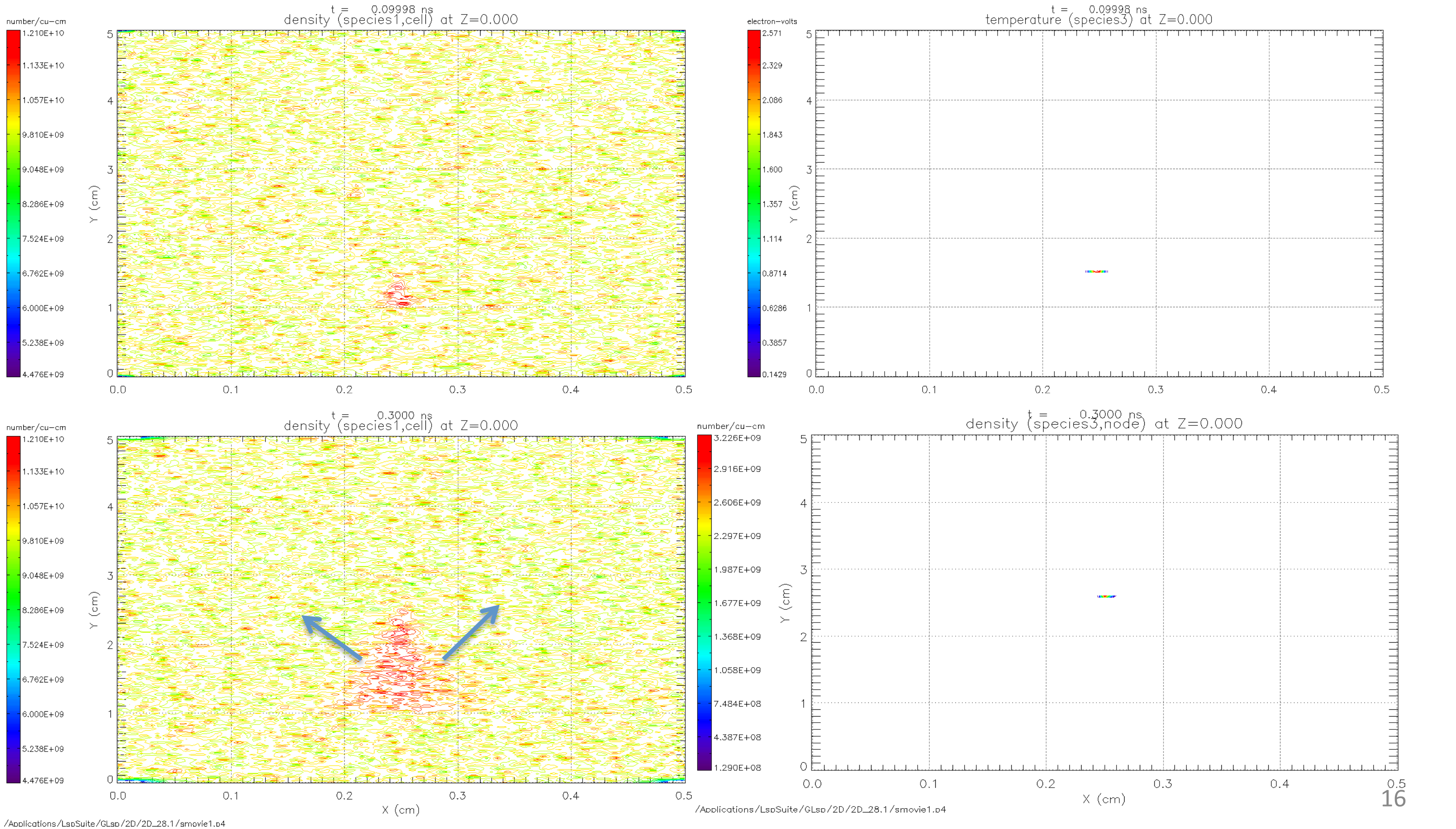
-> increased $T_{e,\ SOL}$

0.5 ns Simulations – Current-dependent Plasma Wave Excitation

- Current-dependent oscillations in electron kinetic energy and relation to plasma frequency
- Development of 'wake' in electron density in response to beam
- Segmentation of wide beam

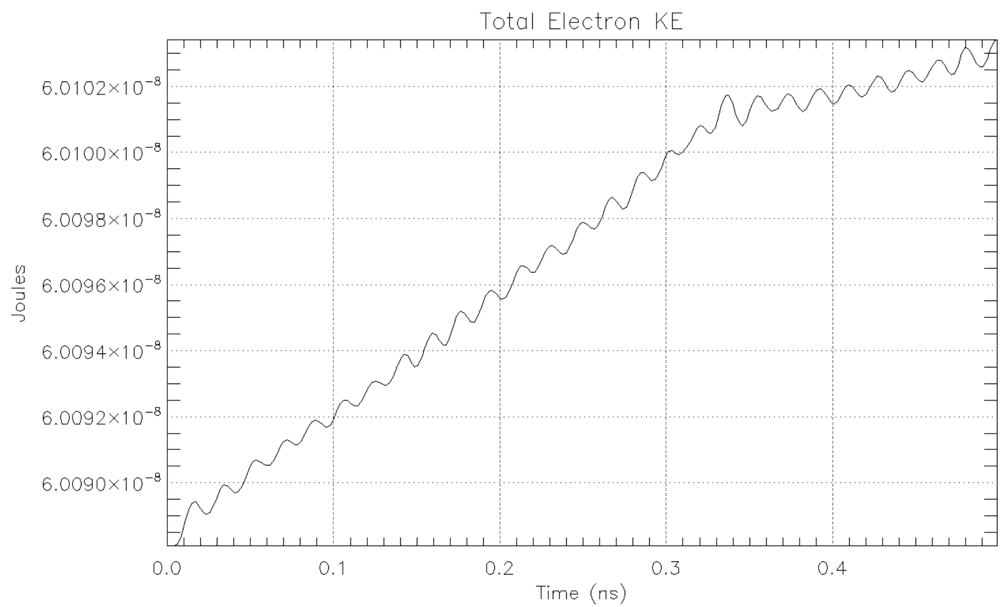
Wake Formation with Narrow Beam

10 A beam
Beam width = 0.005 cm
0.5 x 5 cm plasma $n_e = 10^{10}\ cm^{-3}$, T_e 10 eV



0.5 ns Simulations – Addition of B field

- $n_e = 10^{10}\ cm^{-3}$, T_e 10 eV
- 10 A beam, 0.005 cm width
- 20 kG uniform field (Z)
- Beam orbits at $\omega_{ci} = 3.04\times10^{9}$ Hz and $r_i = 0.28$ cm
- Effect of E x B drift and beam motion
  - For electron within 0.01 cm of beam, $v_d \sim v_b$
- Fluctuation of electron KE at $\omega_{ce} = 5.6\times10^{10}$ Hz

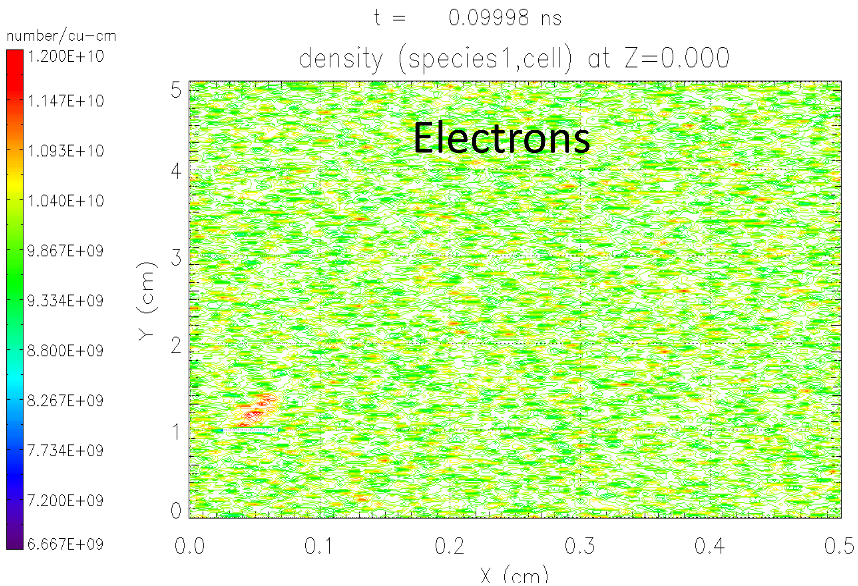


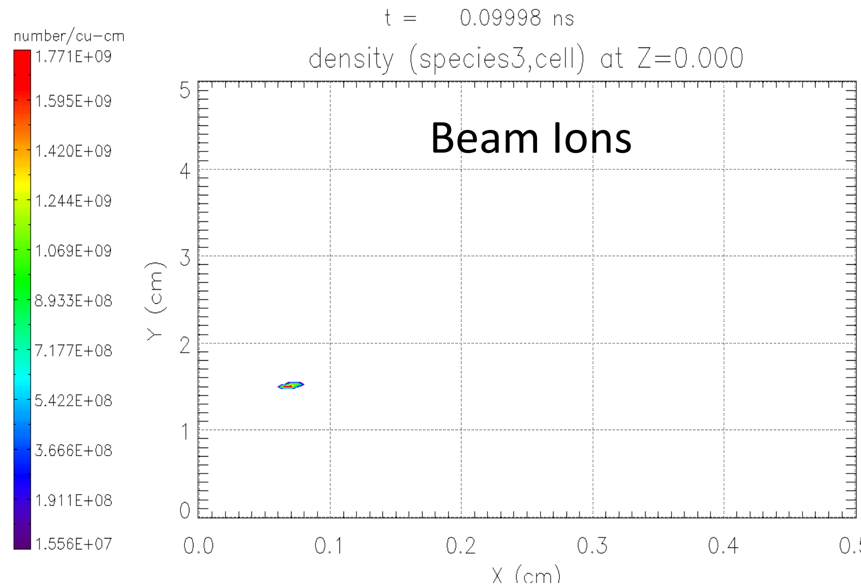
Wake Formation in Presence of Weak (<= 1 kG) Magnetic Field

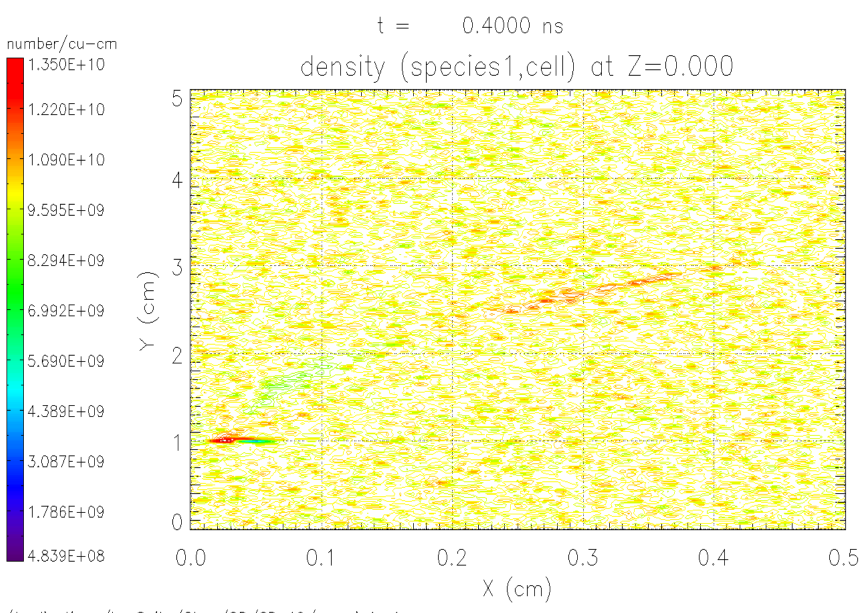
1 kG B- field, Z = 100

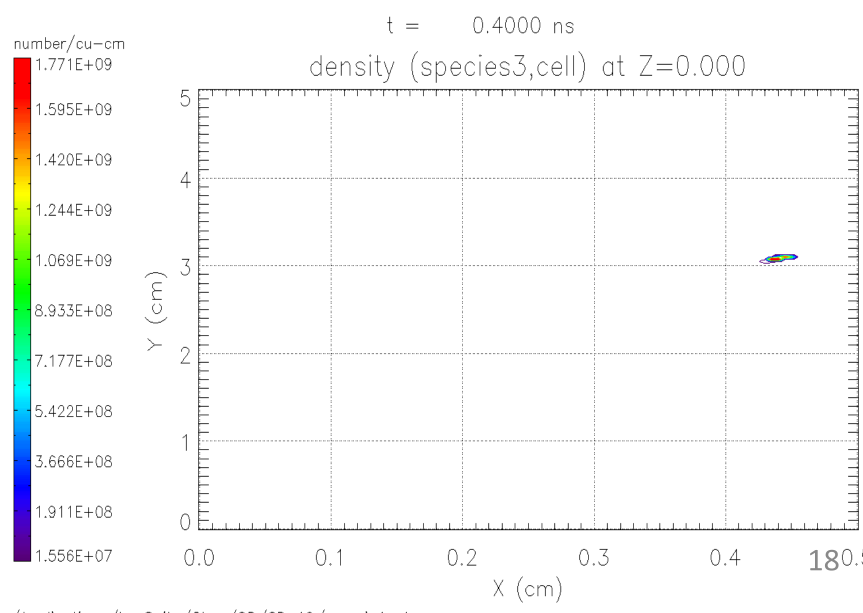
$\omega_{ce} = 2.8 \times 10^9$ Hz $\quad r_e = 0.0075$ cm

$\omega_{ci} = 1.5 \times 10^8$ Hz $\quad r_i = 5.63$ cm









Summary

- Using long (> 25 ns) Lsp simulations of energetic ion injection into cold unmagnetized plasmas, we have observed beam ion slowing times much faster than predicted by classical theory based on Coulomb collisions
- Using short (0.5-2 ns) Lsp simulations of beam injection in the absence of a magnetic field, oscillations of electron kinetic energy and field energy have been observed near $\omega_{p,e}$
  - Formation of electron wake in response to beam ions
  - Indicative of beam-plasma streaming instabilities
- Further simulations in the presence of a magnetic field have featured oscillations near ω_{ce} and have been shown to alter the formation of an electron wake
- Filamentation of wide fast ion beams in an unmagnetized plasma has been observed
  - Indicative of current-driven instabilities
- These instabilities may be contributing to the enhanced slowing down in this regime, which is beneficial for the PFRC.