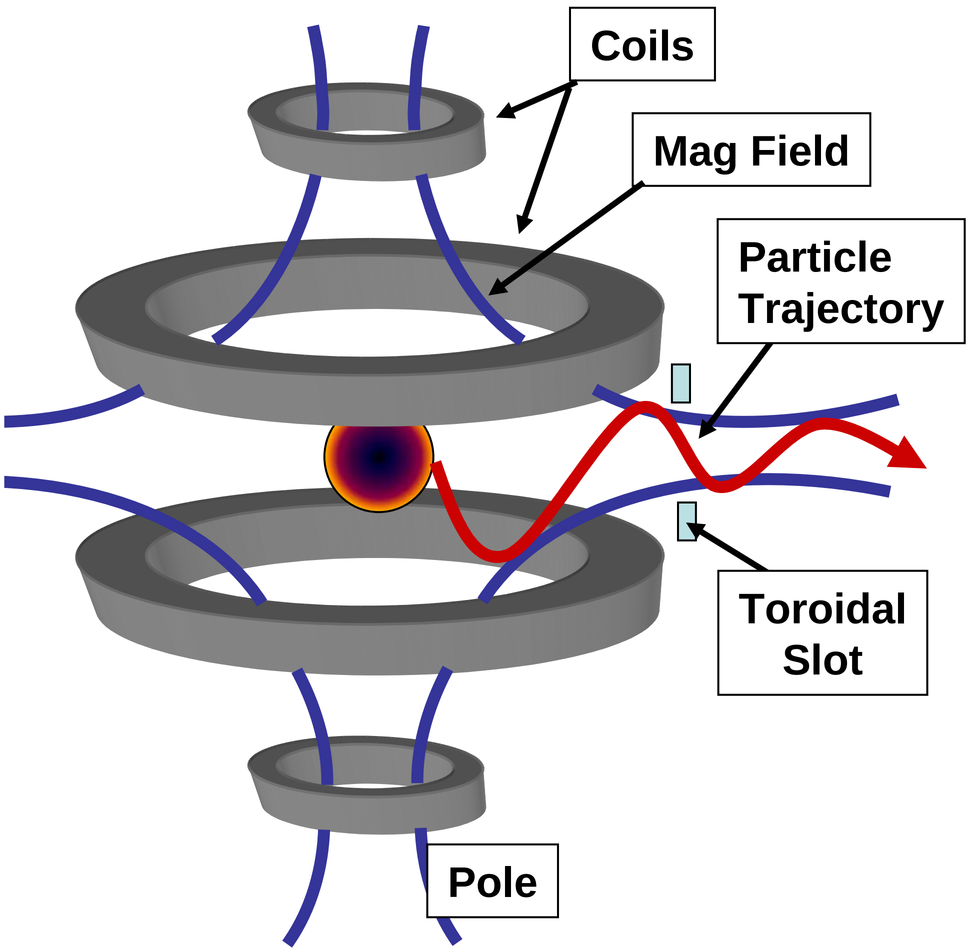
Magnetic Deflection of Ionized Target Ions

D. V. Rose, A. E. Robson,
J. D. Sethian, D. R. Welch,
and R. E. Clark

March 3, 2005
HAPL Meeting, NRL

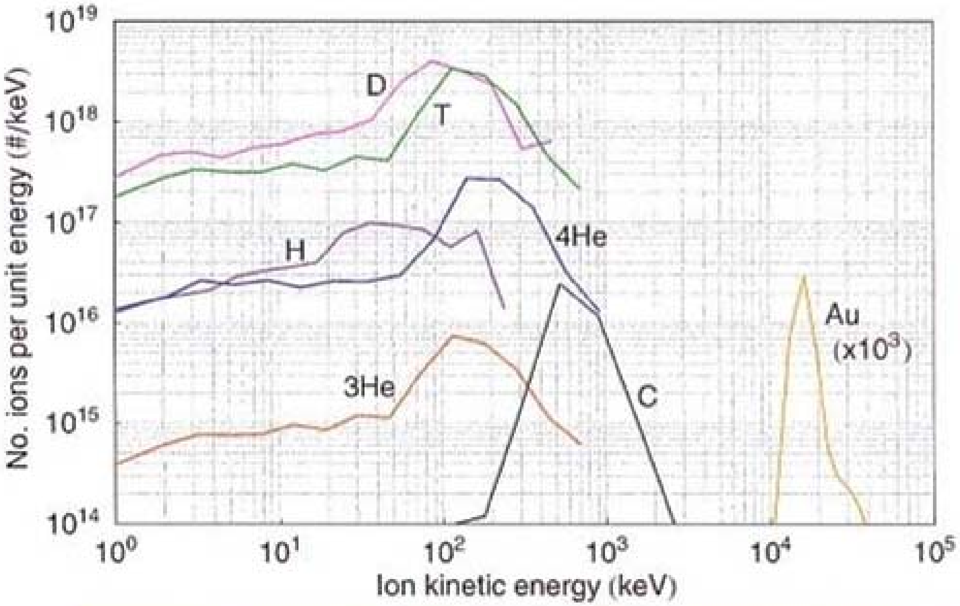
Solid wall, magnetic deflection

1. Cusp magnetic field imposed on to the chamber (external coils)
2. Ions compress field against the chamber wall: (chamber wall conserves flux)
3. Because these are energetic particles, that conserve canonical angular momentum (in the absence of collisions), *Ions never get to the wall!!*
4. Ions leak out of cusp (5 μsec), exit chamber through toroidal slot and holes at poles
5. Magnetic field directs ions to large area collectors
6. Energy in the collectors is harnessed as high grade heat



J. Perkins calculated target ion spectra
(9th HAPL, UCLA, June 2-3, 2004)

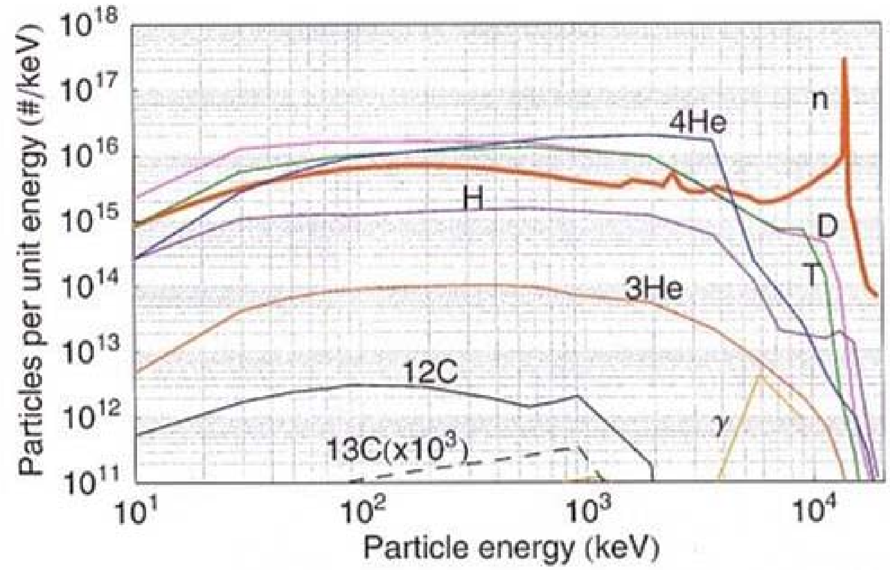
"Debris kinetic energy spectra"



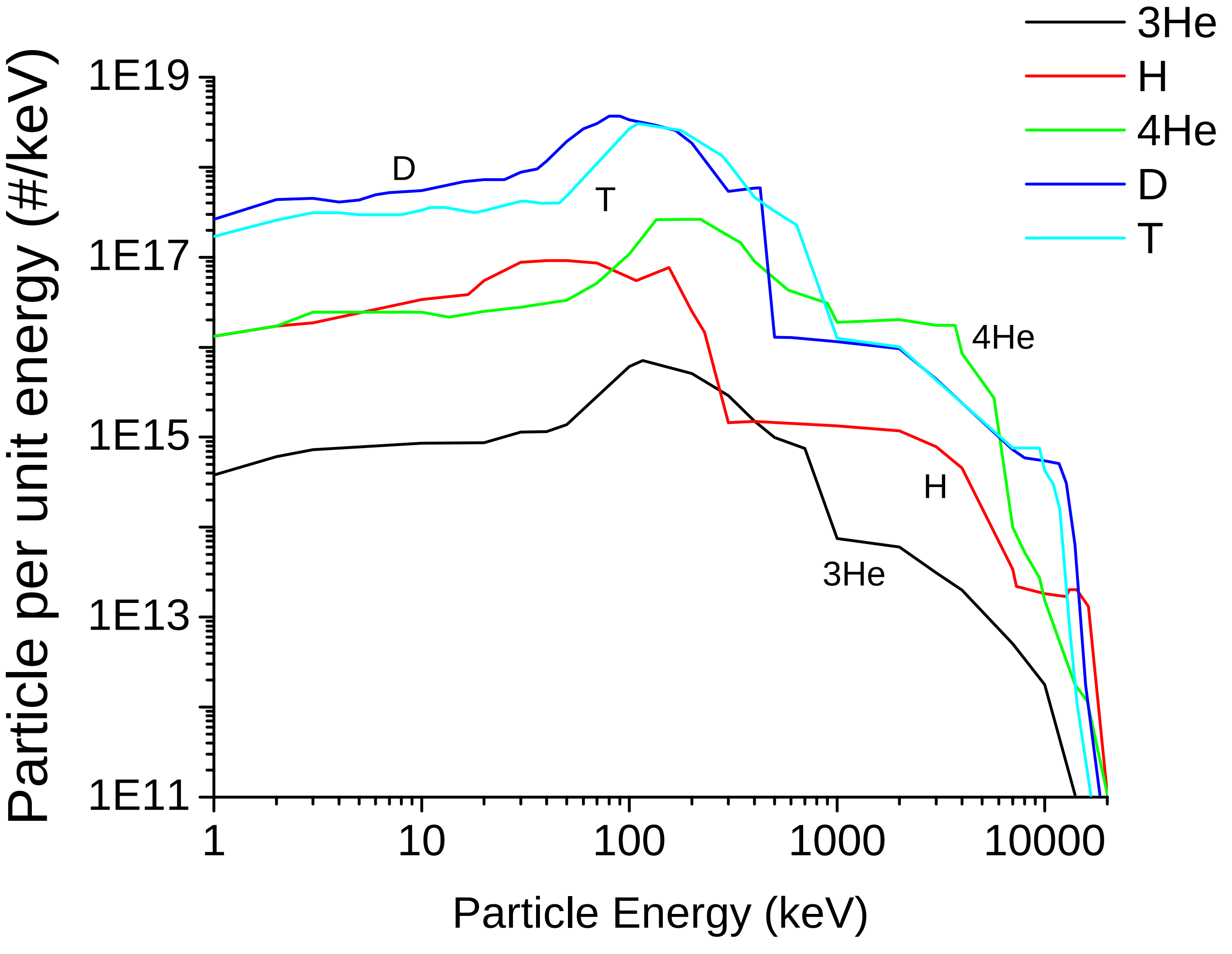
Original Target

- 400MJ
- C fraction = 9.3$^{w}/_{o}$
- DT burn fract, fuel/total = 0.399/0.147

"Fast burn product escape spectra"



Perkins “combined” ion spectra:



These energy spectra are sampled directly by LSP for creating PIC particles.

EMHD algorithm for LSP under development

- Quasi-neutrality assumed
- Displacement current ignored
- PIC ions (can undergo dE/dx collisions)
- Massless electron fluid (cold) with finite scalar conductivity
- Only ion time-scales, rather than electron time-scales, need to be resolved.
- Model is based on previous work, e.g., Omelchenko & Sudan, JCP **133**, 146 (1997), and references therein.
- Model used extensively for intense ion beam transport in preformed plasmas, ion rings, and field-reversed configurations.

EMHD model equations:

Currents are source terms for curl equations:

$$\vec{\nabla} \times \vec{B} = \frac{4\pi}{c}\left(\vec{j}_e + \vec{j}_i\right)$$

$$\frac{\partial \vec{B}}{\partial t} = -c\vec{\nabla} \times \vec{E}$$

Ohm's Law for electron fluid:

$$\vec{E} = \frac{1}{\sigma}\vec{j}_e + \frac{\vec{j}_e \times \vec{B}}{\rho_e c}$$

Scalar conductivity can be calculated from neutral collision frequencies:

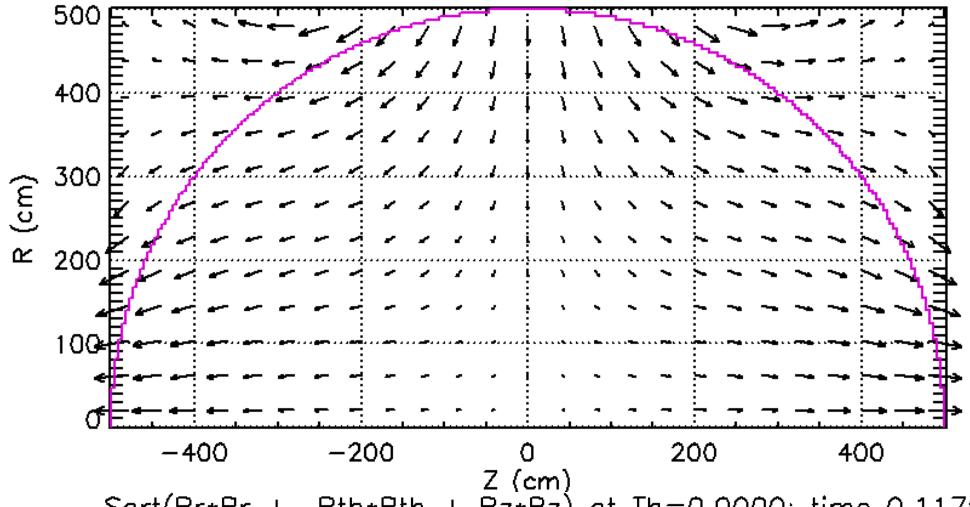
$$\sigma = \frac{\omega_{pe}^2}{4\pi\left(\nu_{ei} + \nu_{en}\right)}$$

"Full-scale" chamber simulations (PRELIMINARY RESULTS)

- 5-meter radius chamber, 2D (r,z) simulation
- 4 coil system for cusp B-field shape
- 10-cm initial radius plasma
  - Perkins "combined" energy spectra for light ion species only (H^+, D^+, T^+, $^3He^{++}$, $^4He^{++}$)
  - 10^{17} cm^{-3} combined initial ion density (uniform)*

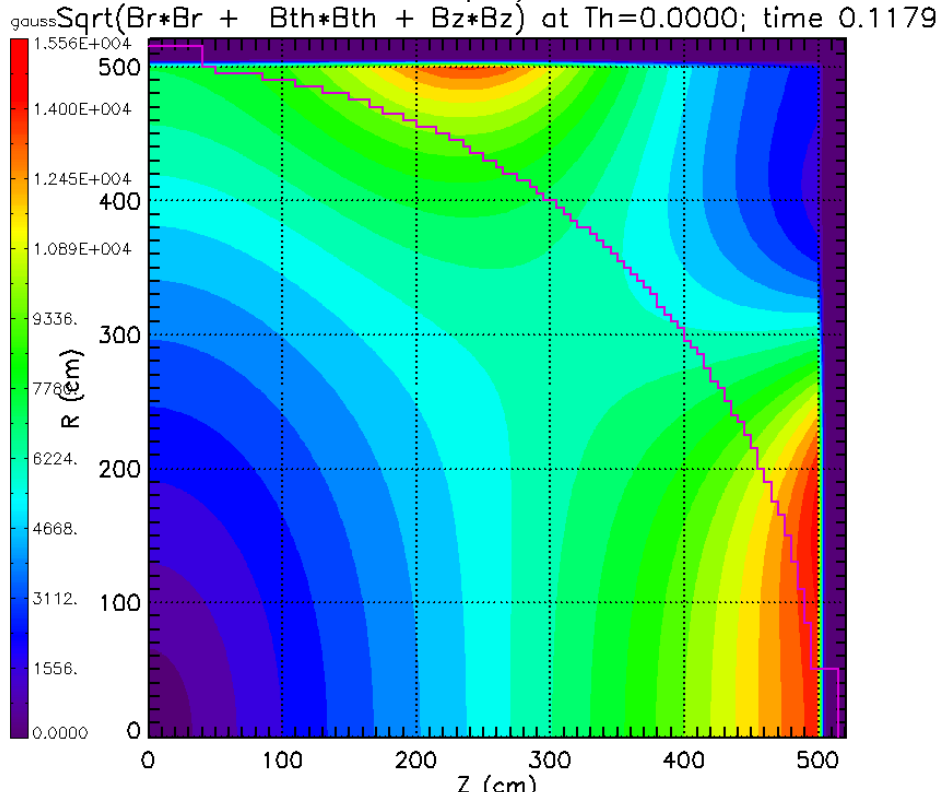
* ~4.2×10^{20} ions represented by 5×10^5 macro-particles

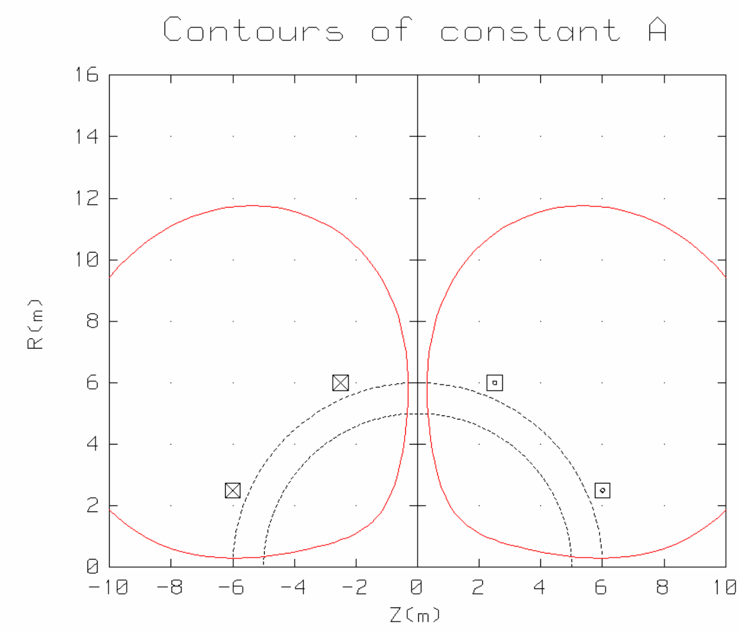
Magnetic field maps:



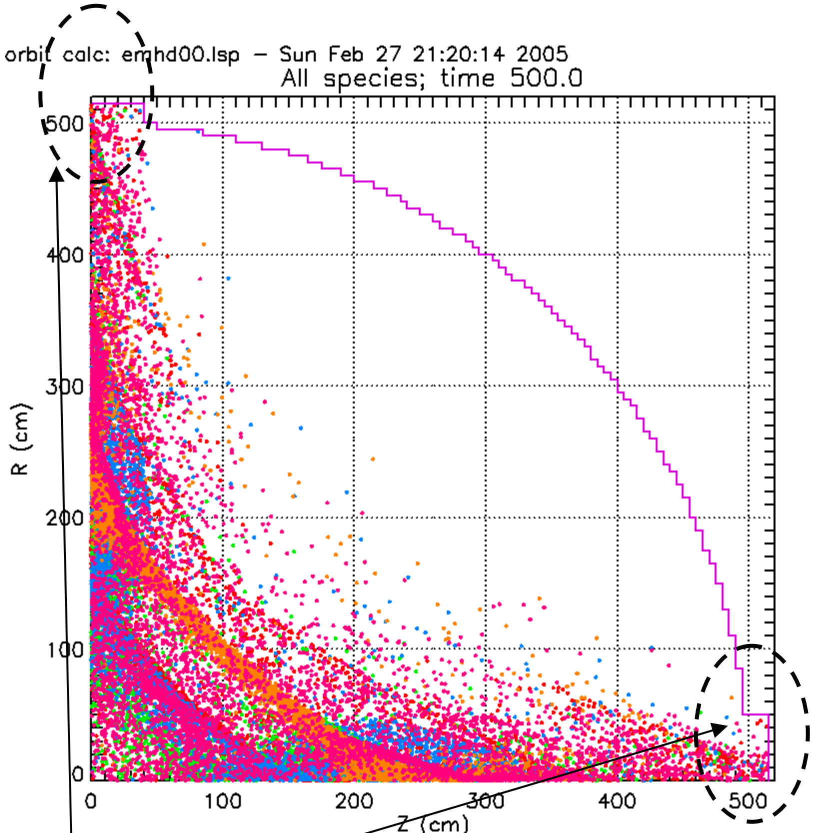
Coil configuration:

r(cm)	z(cm)	I(MA)
250	600	6.05
600	250	6.05
250	-600	-6.05
600	-250	-6.05



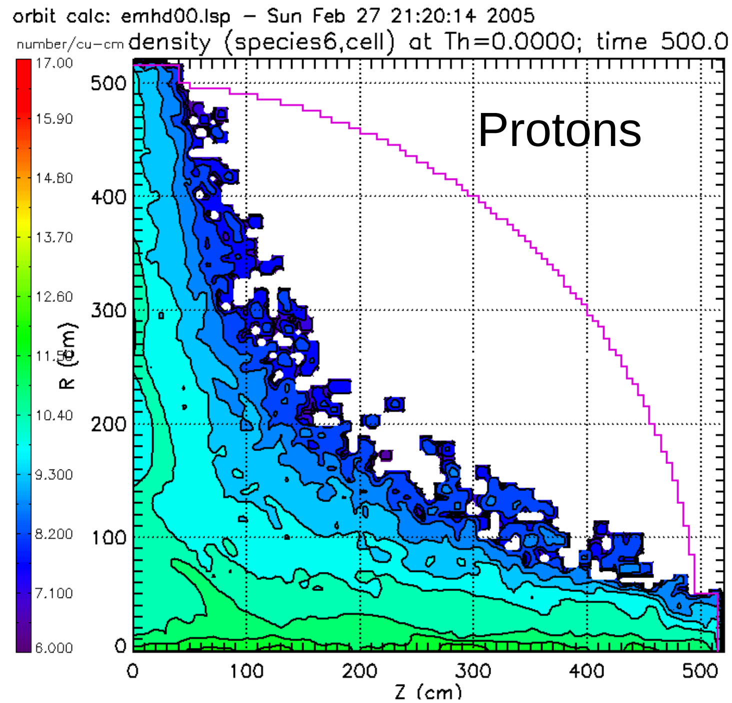


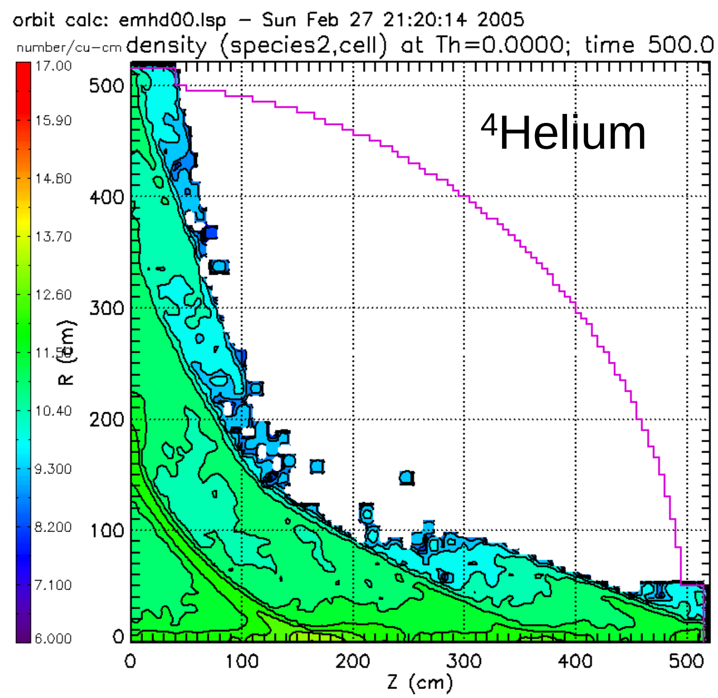
Orbit Calculation – ion positions at 500 ns



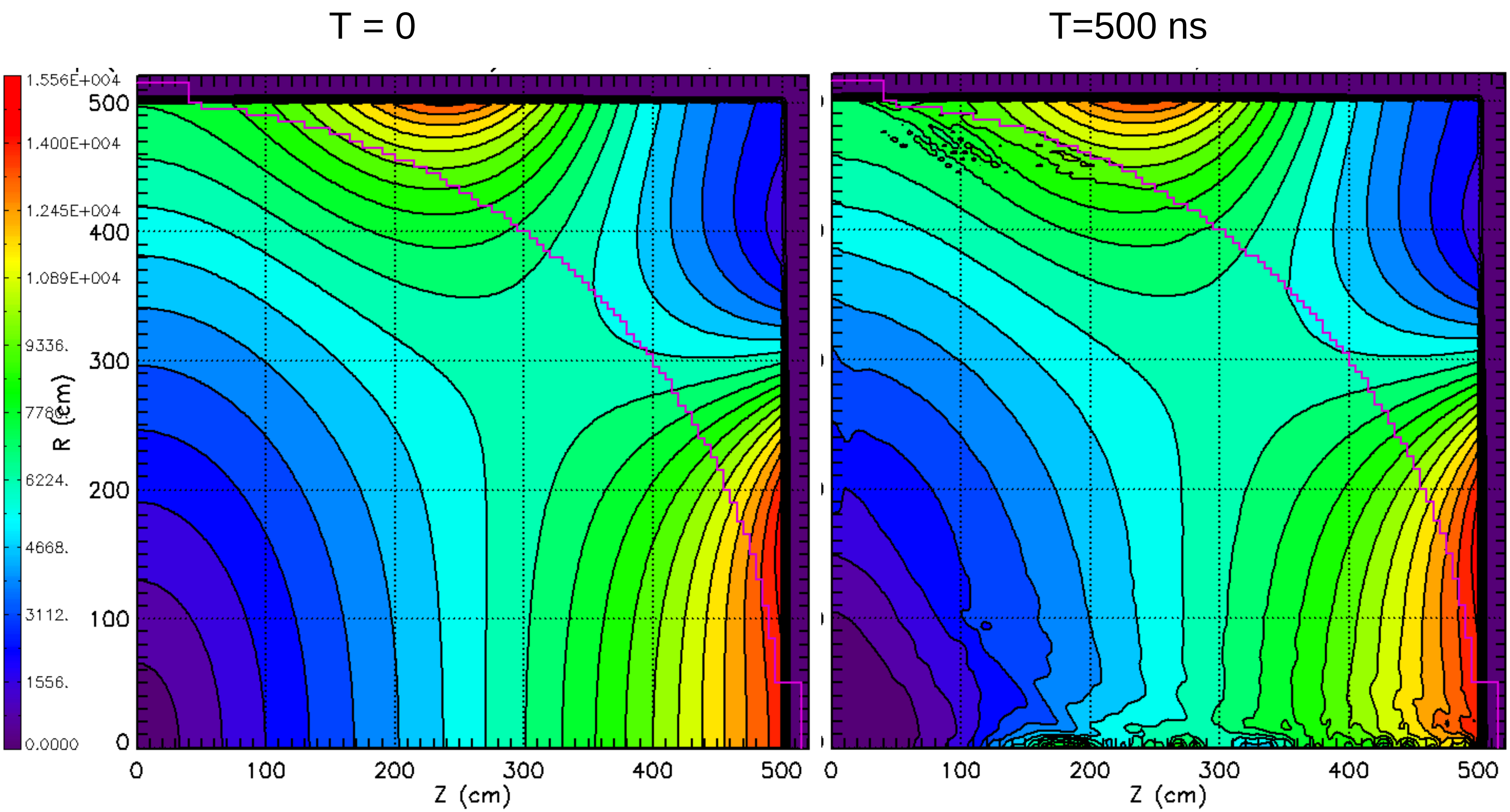
“Ports” at escape points in chamber added to estimate loss currents

dz ~ 80 cm (width of slot)
dr ~ 50 cm (radius of hole)

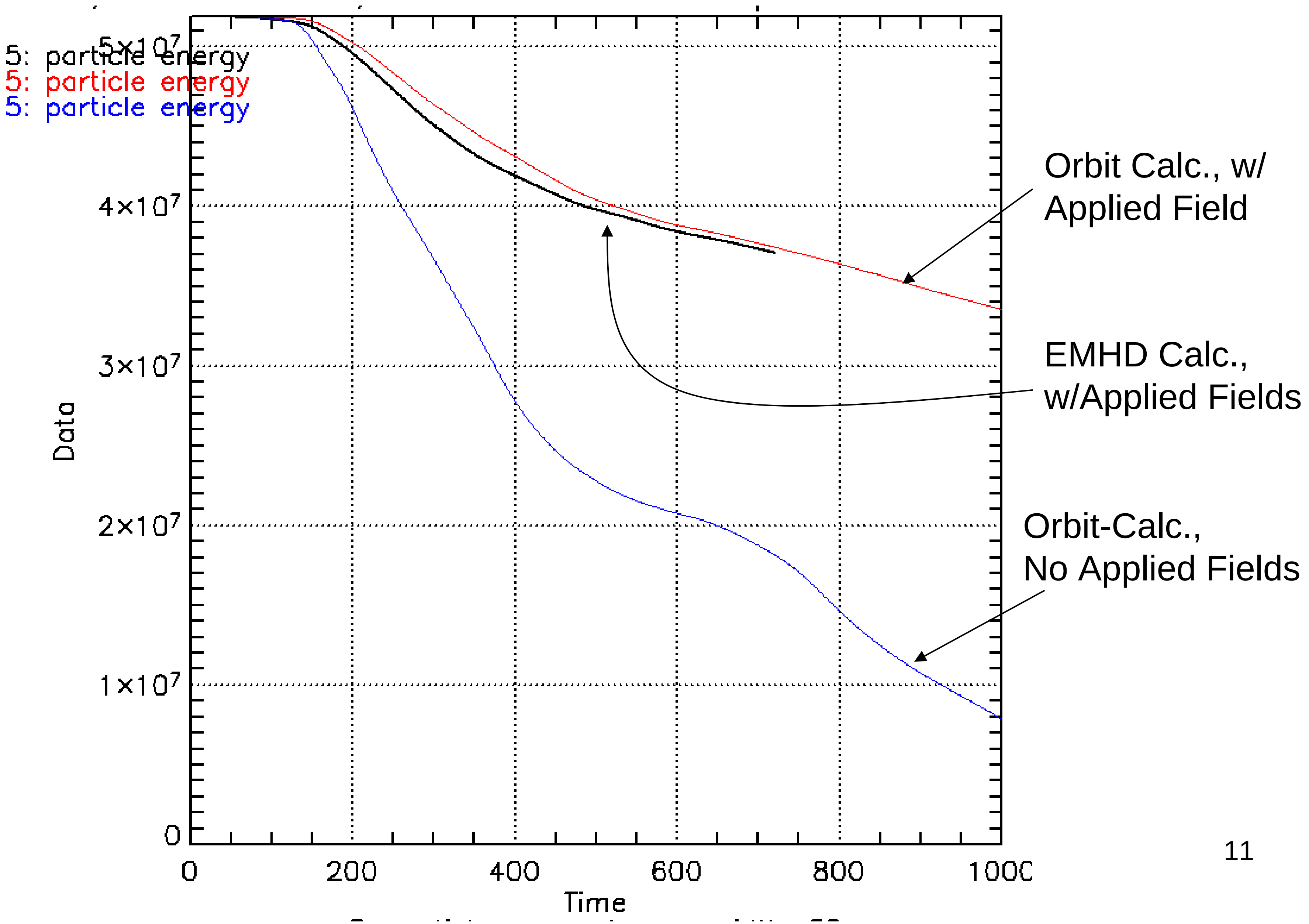




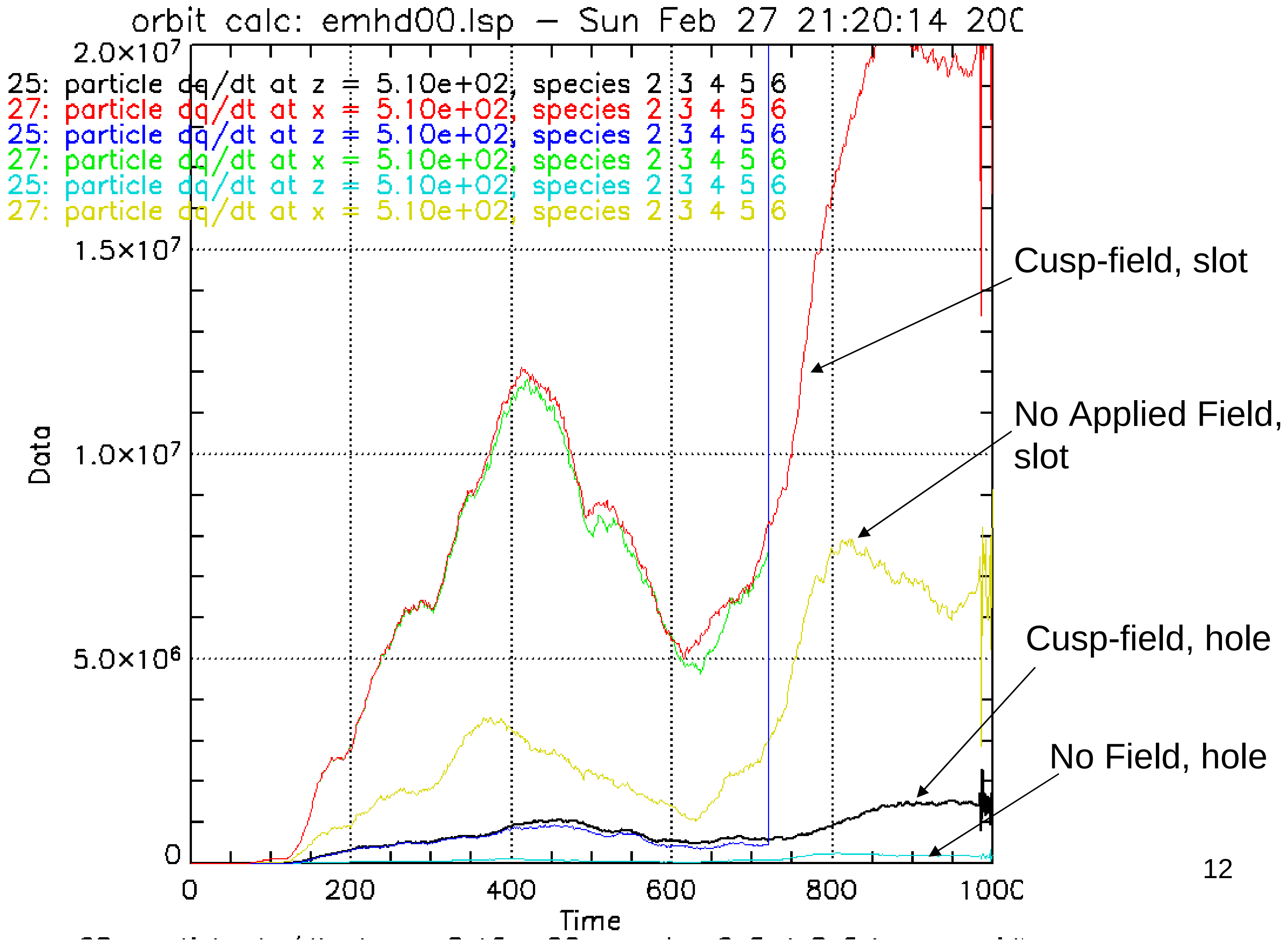
Preliminary EMHD simulations track magnetic field "push" during early phases of ion expansion.



Ion Energy In Chamber vs. Time



Escape Currents

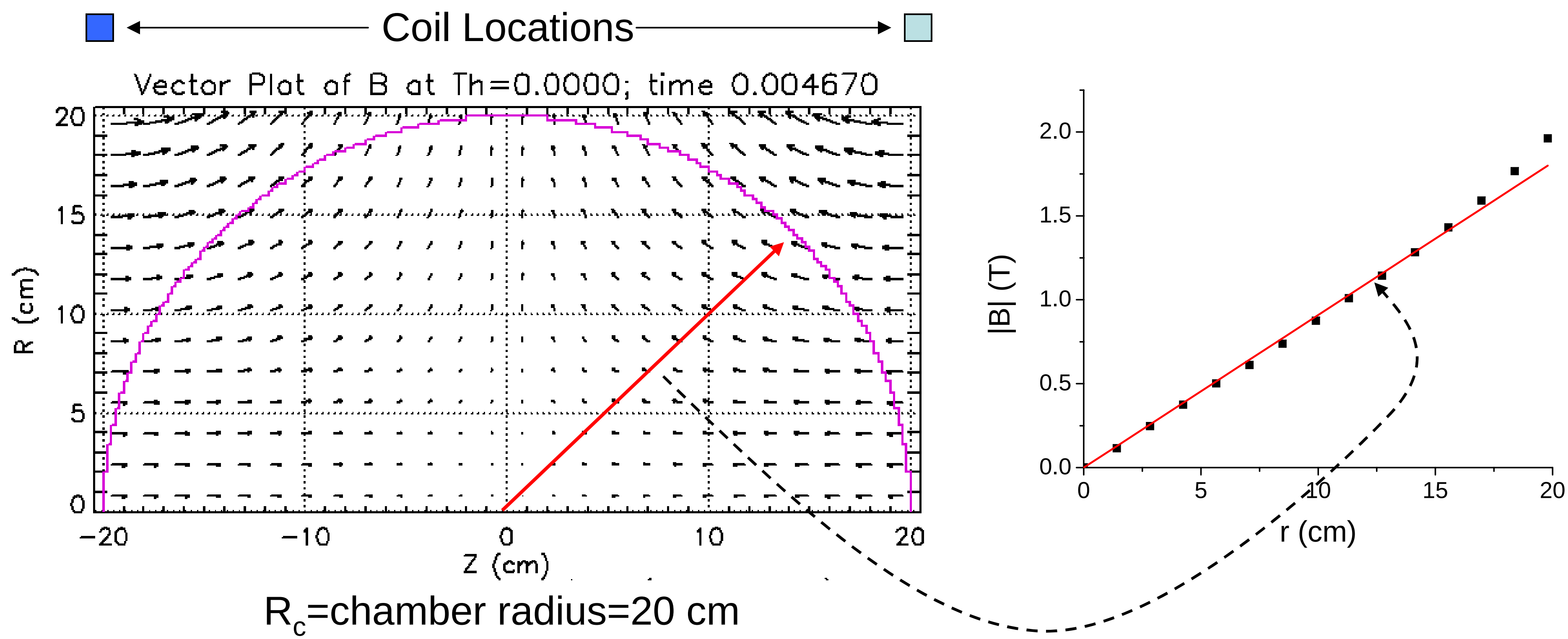


Status:

- Simulations using the Perkins' target ion spectra:
  - We have added a capability to LSP that loads ion energy spectra from tables
- EMHD model
  - EMHD model has been added to LSP.
  - Testing/benchmarking against simple models underway
- Results
  - Preliminary EMHD simulations with 10 cm initial radius plasma volumes suggest that ions DO NOT STRIKE THE WALL during the first shock.
  - Preliminary estimates for escape zone sizes determined.

Supplemental/poster slides

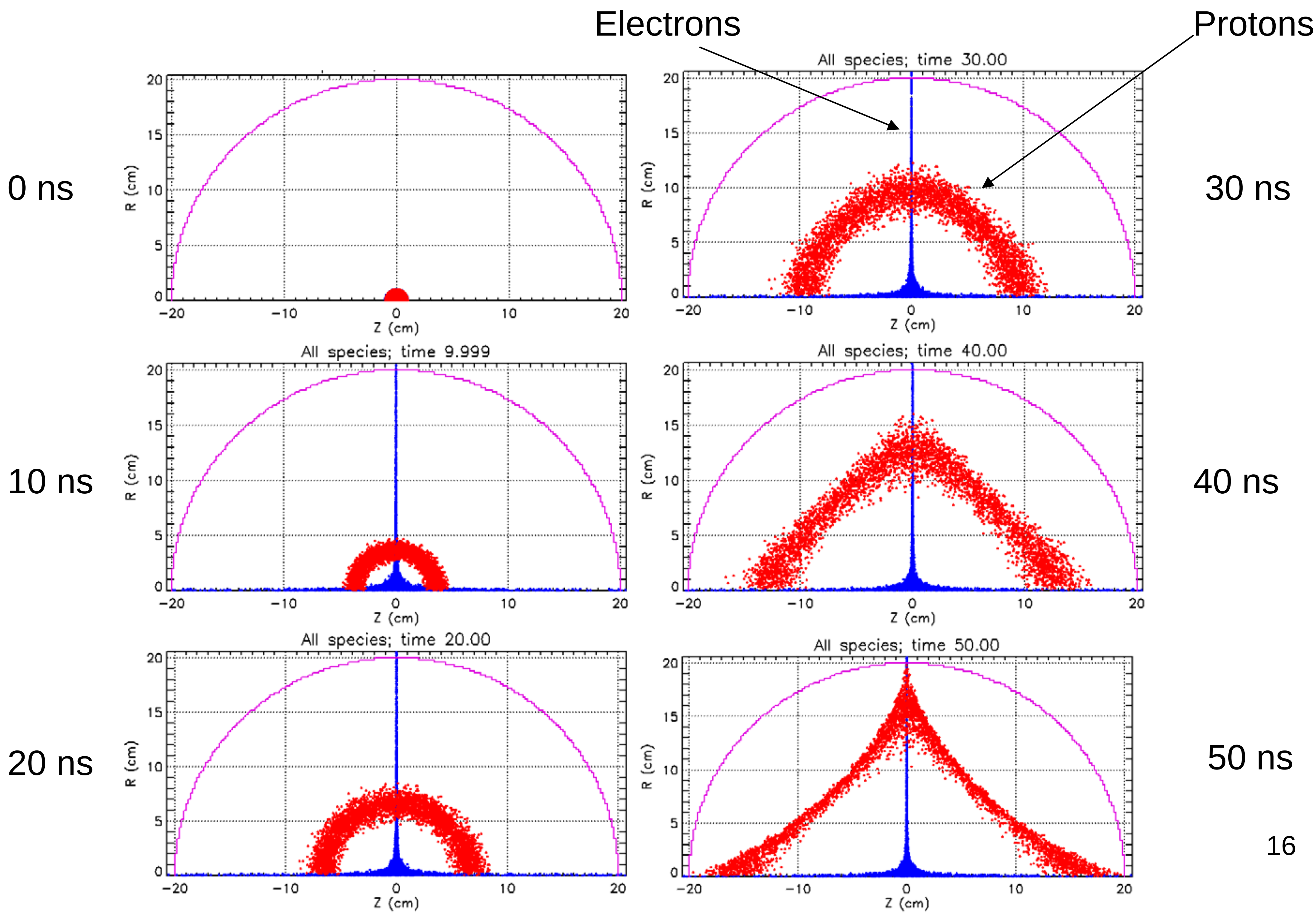
Test simulation: cusp field, small chamber, reduced energy ions:



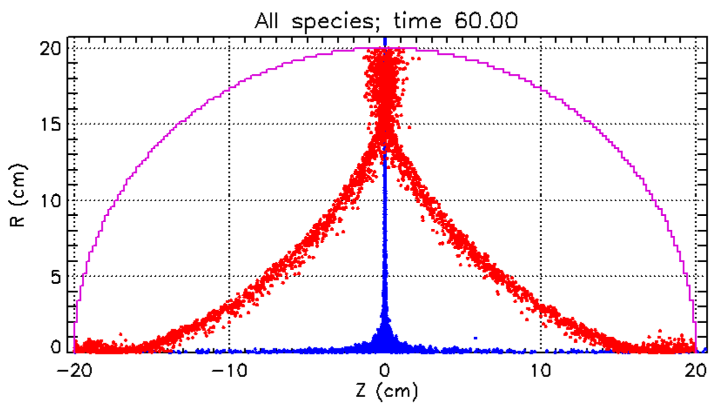
R_c=chamber radius=20 cm

Particle energy scaling estimate: For R_c=20 cm, assume maximum ion gyro-radius of (1/2)*R_c (use average |B|=0.5 T), then v_{ion} ~ 0.03c for protons, or ~120 keV. Here I use 45 keV protons (directed energy) with a 1 keV thermal spread.

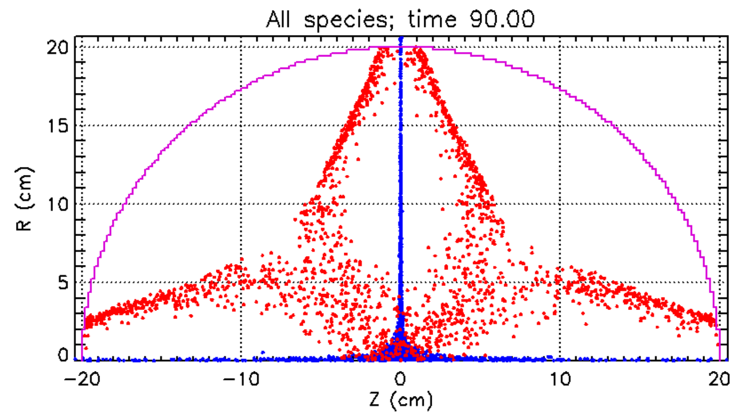
Simple cusp field for a 20-cm chamber, 45 keV protons: No self-field generation (Particle orbit calculations ONLY)



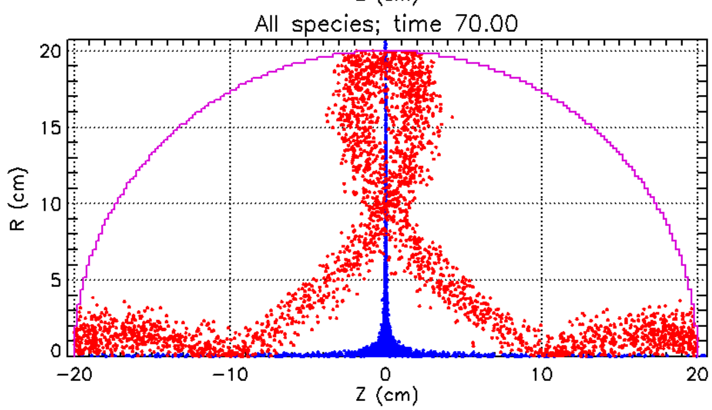
60 ns



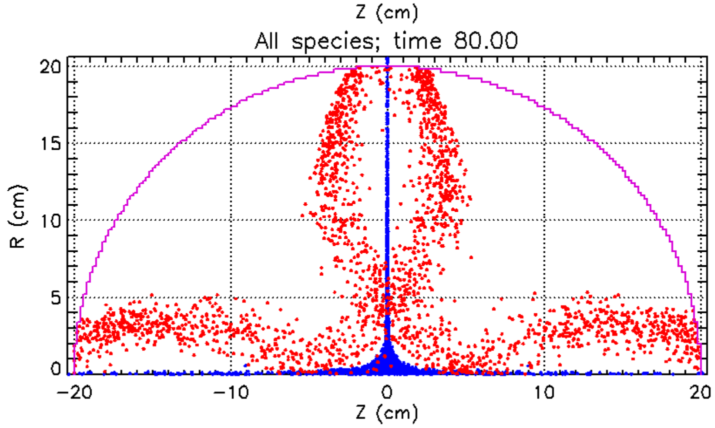
90 ns



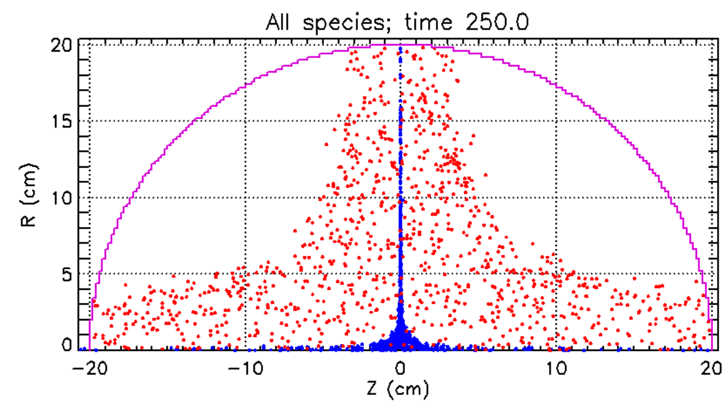
70 ns



80 ns

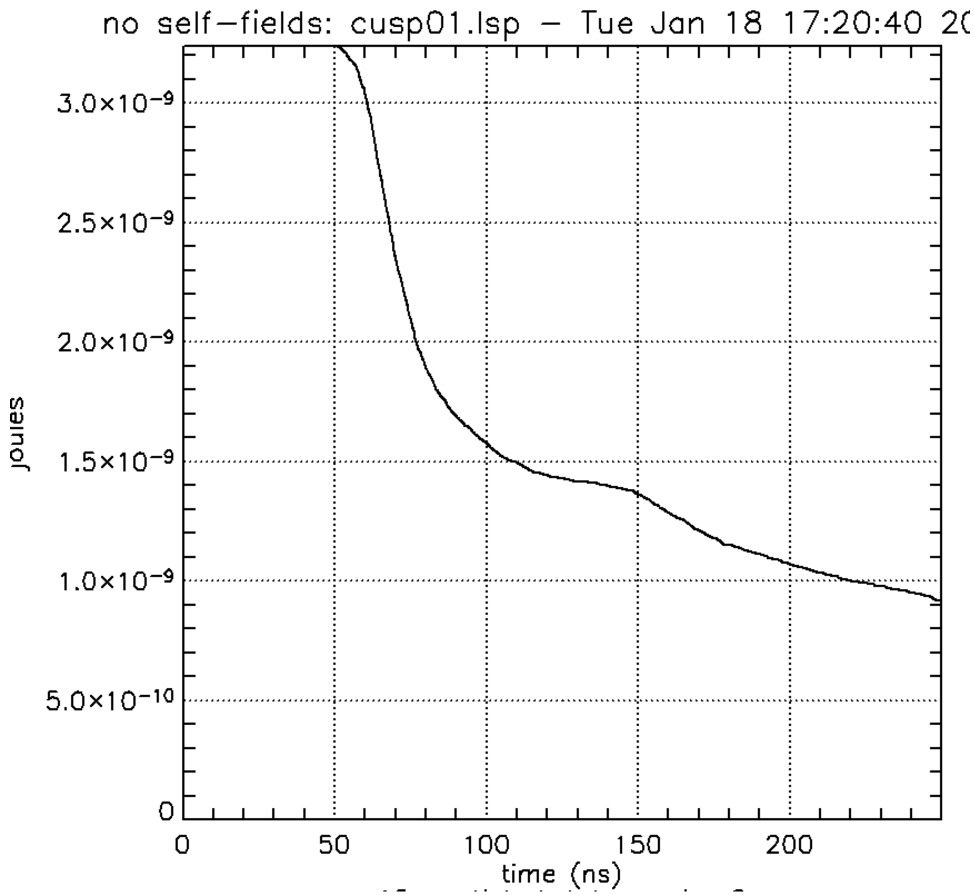


250 ns

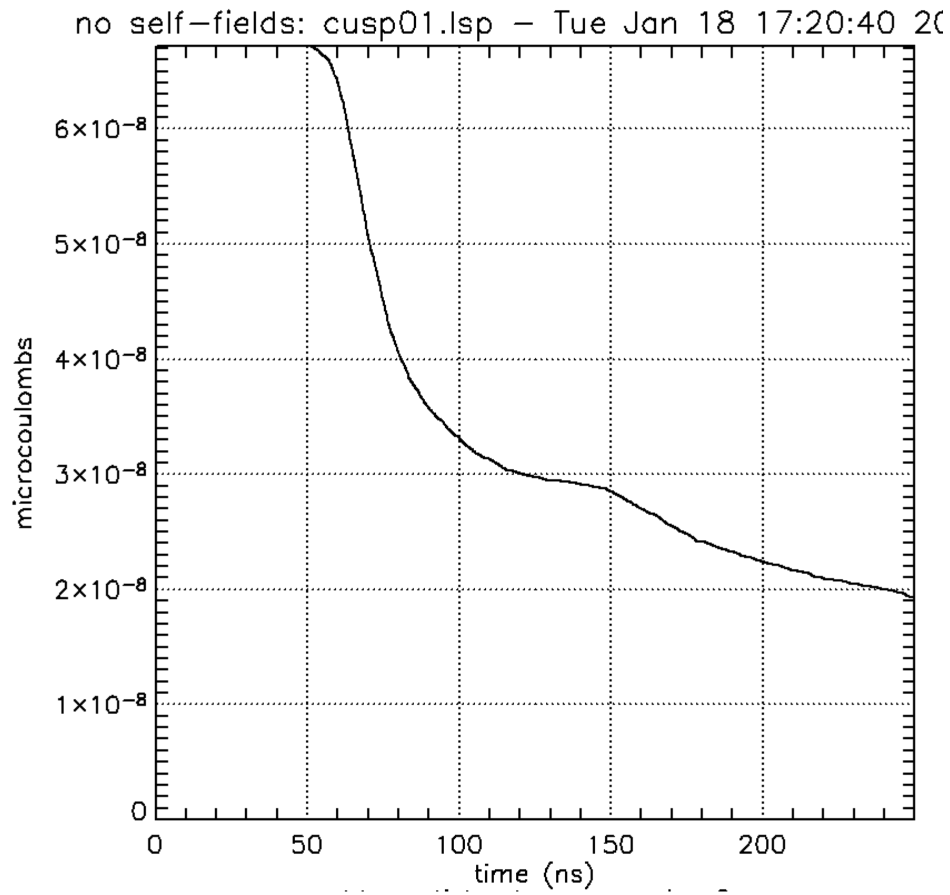


~30% of the ion energy and charge remains after 250 ns.

Ion Kinetic Energy

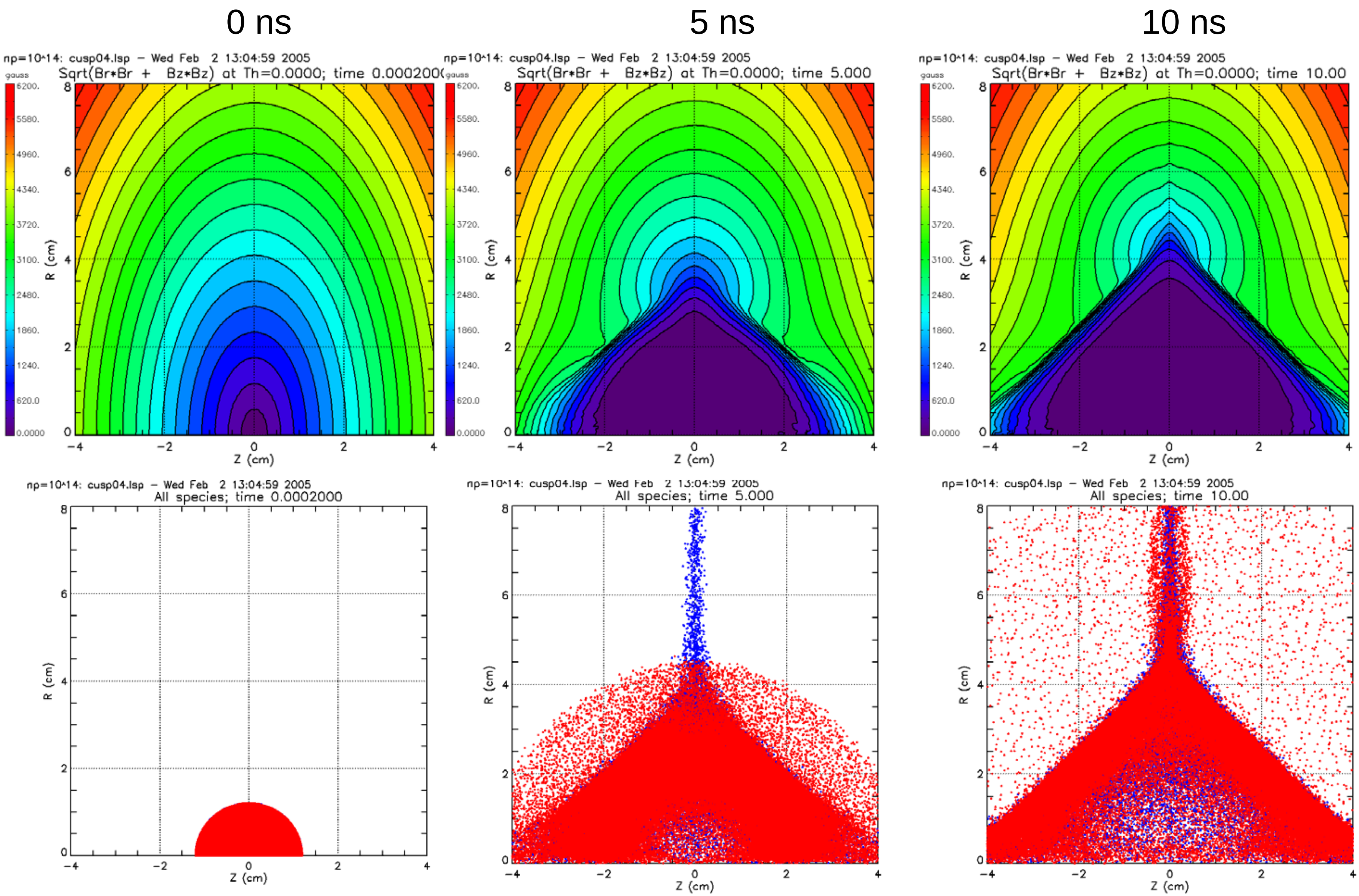


Ion Charge

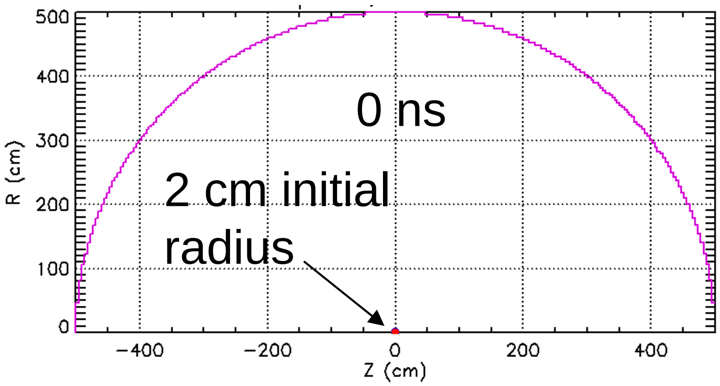


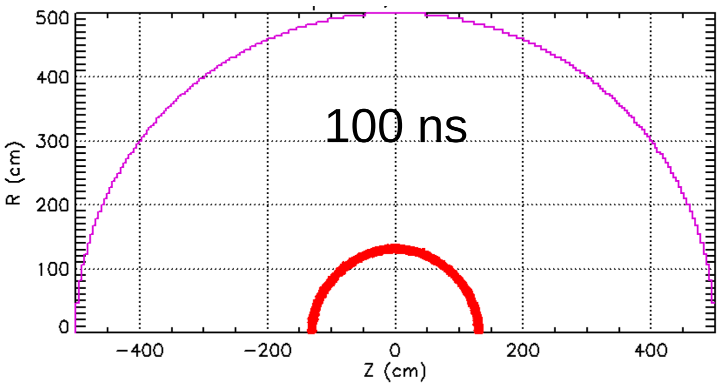
10^{14} cm^{-3} plasma:

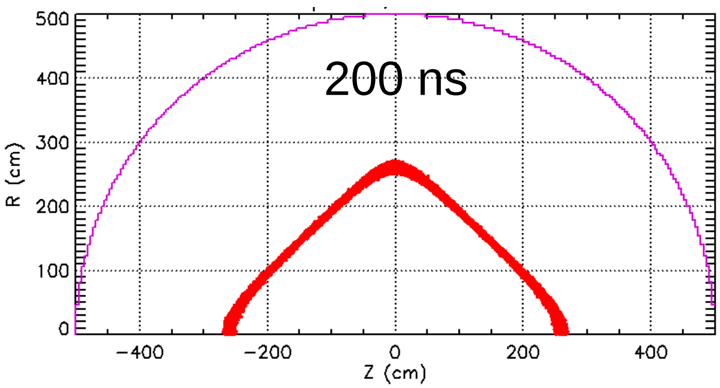
(Detail of |B| and particles near center of chamber)



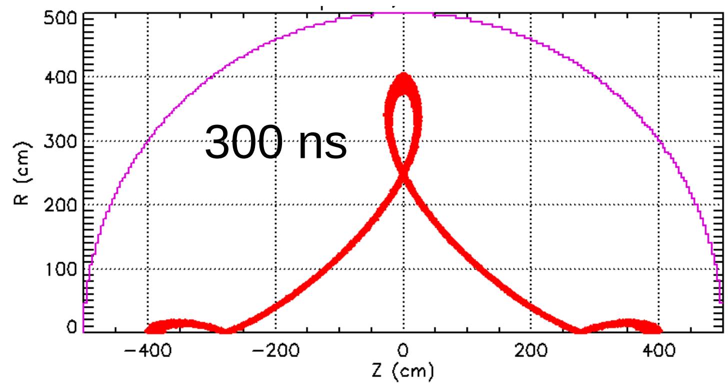
Ion orbit calculation (no self-fields)

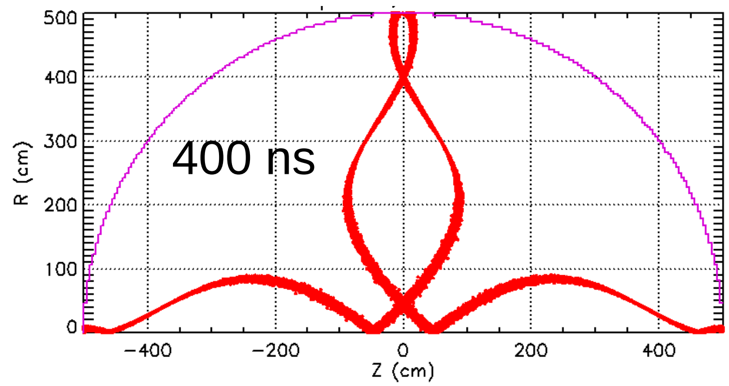


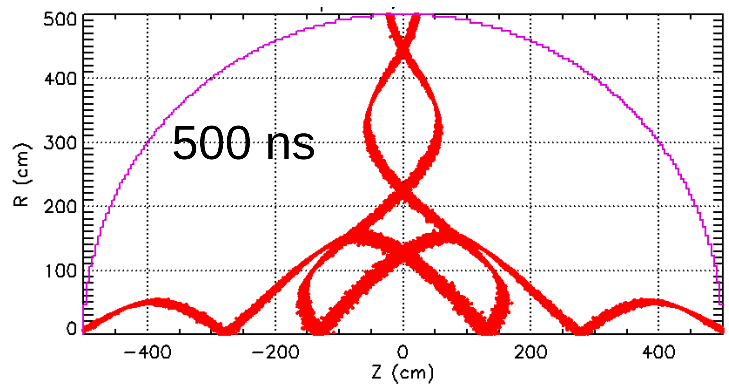




~30% of the ions leave system after 600 ns.

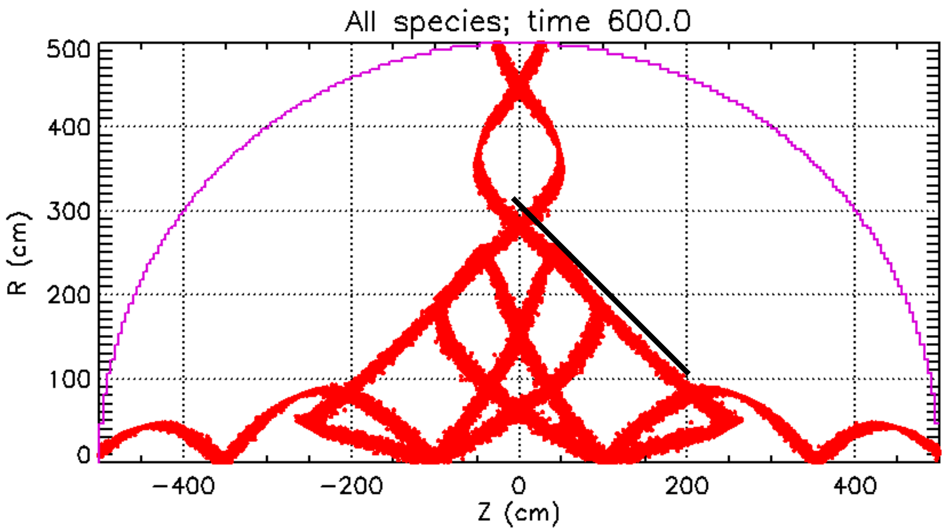


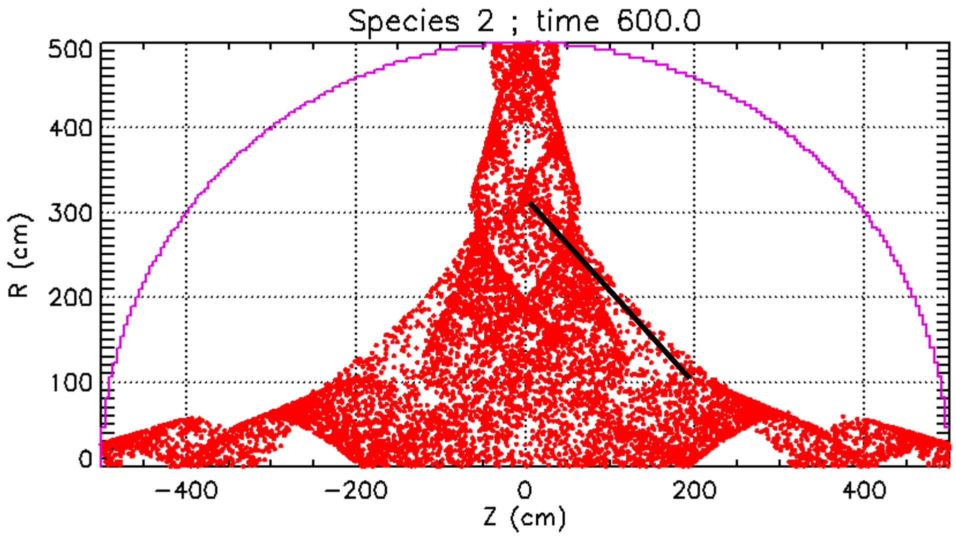




Full EM simulation with low initial plasma density:

For an initial plasma density of 10^{12} cm^{-3}, ion orbit patterns begin to fill in from self-consistent E-fields.
Small ion diamagnetic effects allow slightly deeper penetration into magnetic field.





Simple estimate of "stopping distance" for expanding spherical plasma shell:

$$\beta(r) \approx \frac{n(r)\frac{1}{2}m_i v_i^2}{|B|^2 / 2\mu_0}$$

$$n(r) \propto n_0 \frac{1}{r^3}, \quad \text{for } r \geq 1 \text{ cm}$$

$$|B| \approx B_0 r$$

$$\beta(r) \approx \frac{n_0 (1/r^3) m_i v_i^2 \mu_0}{B_0^2 (r/R_c)^2} = \frac{n_0 m_i v_i^2 \mu_0 R_c^2}{B_o^2 r^5}$$

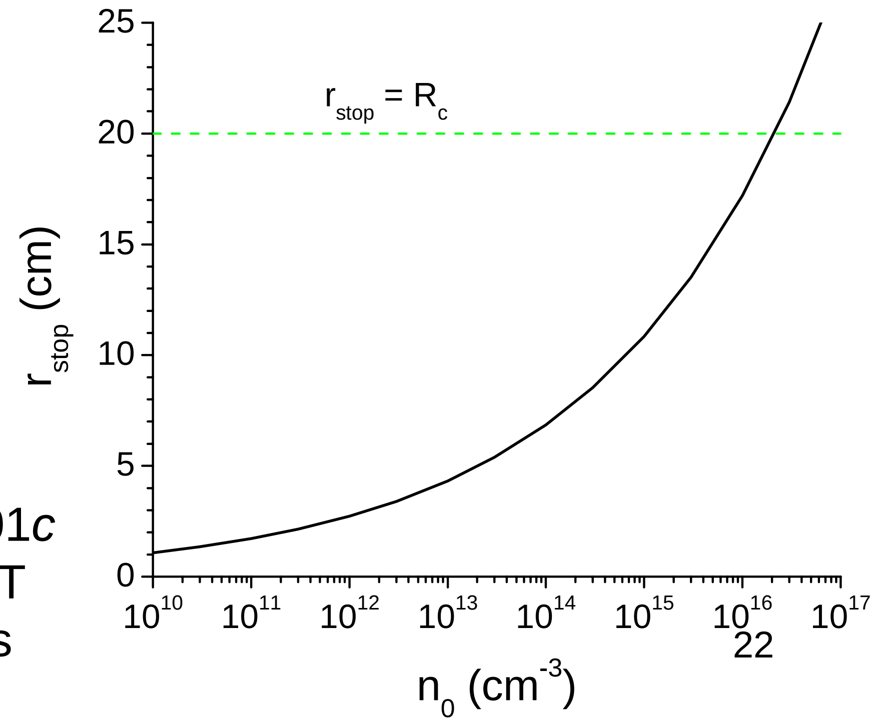
(in MKS units)

Assuming plasma expansion stops for β ~ 1, then:

$$r_{stop} \simeq \left(\frac{n_0 m_i v_i^2 \mu_0 R_c^2}{B_o^2} \right)^{1/5}$$

This results is consistent with simulation results for n_0 = 10^{11} – 10^{14} cm^{-3}.

v_i = 0.01c
B_o = 2 T
protons

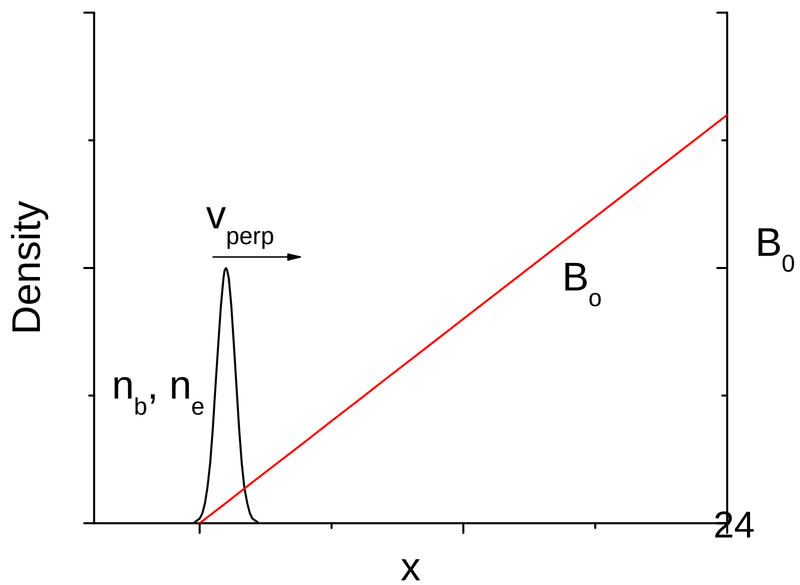


A Look at Diamagnetic Plasma Penetration in 1D

1D EMHD model*

- The model assumes local charge neutrality everywhere.
- Electrons are cold, massless, and with a local ExB drift velocity
- “Beam” ions are kinetic, with an analytic perpendicular distribution function.

Analysis is “local”, meaning that B_o is approximately uniform with in the ion blob.



*Adapted from K. Papadopoulos, *et al*., Phys. Fluids B **3**, 1075 (1991).

Model Equations: Ions Penetrating a Magnetized Vacuum

Quasi-neutrality: $n_b(x) = n_e(x)$

Electron velocity: $\vec{u}_e = \frac{c}{B_y}\left(-E_z\hat{i} + E_x\hat{k}\right)$

Continuity: $\vec{u}_e \bullet \nabla\left(\frac{n_e}{B_y}\right) = 0$

Ion Distribution: $F_b\left(\frac{H_\perp}{T_b}\right), \quad H_\perp = \frac{1}{2}M_b v_\perp^2 + e\phi\left(x\right)$

Ion Density: $n_b(x) = n_{b0}\int_0^\infty F_b\left(u + \frac{e\phi}{T_b}\right)du$

Ion Pressure $P_b(x) = n_{b0}T_b\int_0^\infty F_b\left(u + \frac{e\phi}{T_b}\right)u\,du$

Force Balance: $\vec{\nabla}P_b = n_b\left|e\right|\vec{E}, \quad \vec{E} = -\vec{\nabla}\phi$

Pressure Balance: $\nabla\left(\frac{B_y^2}{8\pi} + P_b\right) = 0$

Magnetic field exclusion:

Assume a perpendicular ion energy distribution given by:

$$F_b\left(\frac{H_\perp}{T_b}\right) = \exp\left(-\frac{M_b v_\perp^2}{2T_b} - \frac{e\phi}{T_b}\right)$$

Assume a 1D density profile: $n_e(x) = n_{e0}\exp\left(-\frac{x^2}{b^2}\right)$

The ion beam density and pressure are then given as:

$$n_b(x) = n_{b0}\exp\left(-\frac{e\phi}{T_b}\right), \quad P_b(x) = n_b(x)T_b$$

The potential and electric fields are then: $\phi(x) = \frac{T_b}{|e|}\frac{x^2}{b^2}, \quad E_x(x) = -\frac{2T_b}{|e|}\frac{x}{b^2}$

From pressure balance, this gives a magnetic field profile of:

$$B_y(x) = B_0\left[1 - \frac{8\pi n_{b0} e T_b}{B_0^2}\exp\left(-\frac{x^2}{b^2}\right)\right]^{1/2}$$

Sample Result:

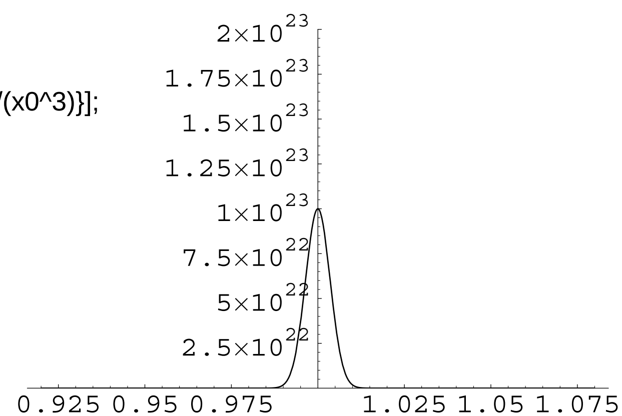
$$B_0(x) = \frac{2}{5}x \qquad B_y(x) = B_0(x)\left[1 - \frac{2\mu_0 n_{b0} e T_b}{B_0^2(x)} \exp\left(-\frac{(x-x_0)^2}{b^2}\right)\right]^{1/2}$$

(MKS units)

In the limit that the argument of the square root is > 0,
this gives a simple diamagnetic reduction to the applied field.
I assume that when the argument of the square root IS < 0,
then the applied field is too wimpy to impede the drifting cloud.

```
b = 0.005;
x0 = 1;
nb0 = 1.0*10^(17)*(10^6);

nb[x_] := nb0*Exp[-((x - x0)^2)/(b^2)]/(x0^3);

Plot[nb[x], {x, -0.02, 2*x0}, PlotRange -> {0, 2*nb0/(x0^3)}];

B0[x_] := (2/5)*x;


q = 1.6*10^(-19);
Tb = (0.5*4*1.67*10^(-27)*((0.043*3*10^8)^2))/q;
mu0 = Pi*4*10^(-7);

xmax = ((25/4)*2*mu0*nb0*q*Tb)^(1/5);
Print["Tb(eV) = ", Tb];
Print["xmax (m) = ", xmax];

By[x_] := B0[x]*(Max[1 - 2*mu0*nb[x]*q*Tb*(B0[x])^(-2), 0])^(0.5);

Plot[(By[x]), {x, 0, 2*x0}]
```

magdef01.nb



magdef01.nb 1