Progress in Computational Modeling in Support of the Magnetic Intervention Concept

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Outline

1. Description of “new” EMHD model in cylindrical coordinates (based on model of D. Hewett)
2. Preliminary application of model to R. E. Pechacek magnetic intervention experiment
3. Preliminary shell calculation for HAPL magnetic intervention chamber parameters
4. Next steps…

1. 2D EMHD model implementation based on work of D. Hewett*

- We have implemented a version of D. Hewett's 2D cylindrical (r,z) field solver (advancing A_θ)
- Model includes "correct" evolution of vacuum magnetic fields
- Field solver implemented within Lsp code framework

*D. W. Hewett, J. Comp. Phys. **38**, 378 (1980)

Equation for A_θ

$$\frac{\partial A_\theta}{\partial t} - \frac{c^2}{4\pi}\frac{1}{\sigma}\nabla^2 \vec{A}\Big|_\theta + u_{er}\frac{1}{r}\frac{\partial(rA_\theta)}{\partial r} + u_{ez}\frac{\partial A_\theta}{\partial z} = 0$$

Conductivity is assumed to be a scalar to avoid carrying extra terms

B_θ can be obtained between ADI passes, but we have not implemented this yet.

In vacuum, this equation reduces to:

$$\nabla^2 \vec{A}\Big|_\theta = 0$$

Model Constraints:

- Most of the computational constraints associated with our previous EMHD solvers also apply here.
- In addition, T. Hughes and T. Genoni have identified “grid-Reynolds” constraints that can be expressed by the following inequality:

$$\left(\frac{c^2}{4\pi}\right)\frac{2\Delta t}{(\Delta x)^2} < \sigma\left(\mathrm{s}^{-1}\right) < \frac{2}{v\,\Delta x}\left(\frac{c^2}{4\pi}\right)$$

2: Pechacek Experiment Description

- A two-stage laser system drives a 1-mm scale, solid D2 pellet forming a plasma.
- The plasma is created inside the void of a cusp magnetic field.
- The adiabatically expanding plasma compresses the cusp field lines.
- Plasma ions escape from the “point” and “ring” cusps in the field geometry.
- Plasma ions are “deflected” away from the chamber walls

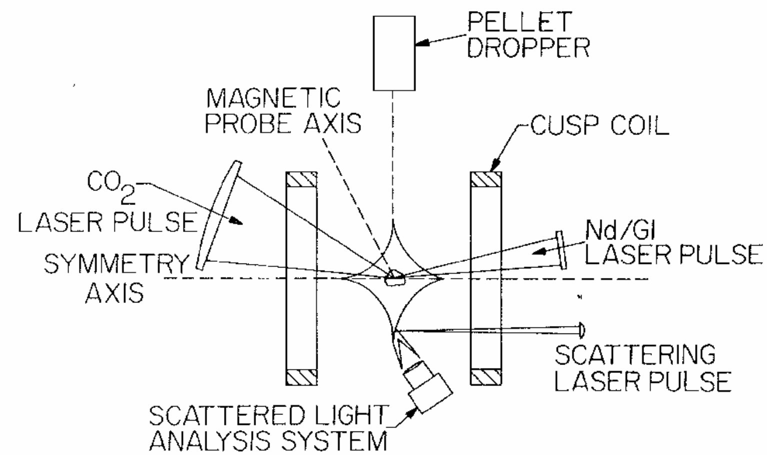


FIG. 1. Schematic diagram of the cusp experiment. The coil diameter is 70 cm. The scattered-light analyzing system and the incident-scattering laser pulse are actually in the same horizontal plane.

*R. E. Pechacek, *et al.*, Phys. Rev. Lett. **45**, 256 (1980).

Experimental Parameters

- Chamber wall radius is 30 cm (not shown)
- External field coils, 67 or 70 cm diam, 70 cm separation.
- $|B| = 2.0$ kG at ring cusp.
- 2×10^{19} "D_2" ions produced from cylindrical target of 1-mm diam., 1-mm length.
- Modeling assumes initial plasma is a thermal (51.1 eV), D^+ neutral plasma with intial radius of 2 cm.

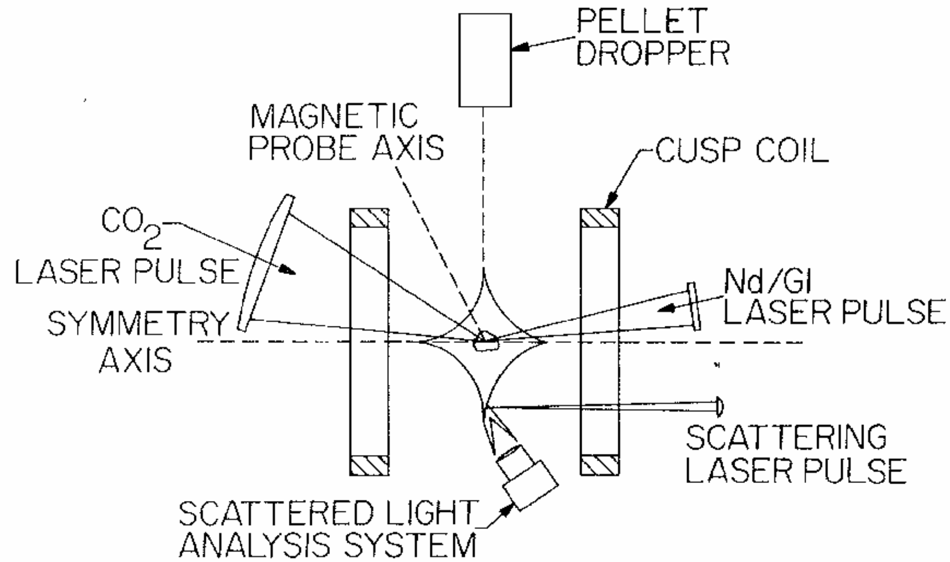
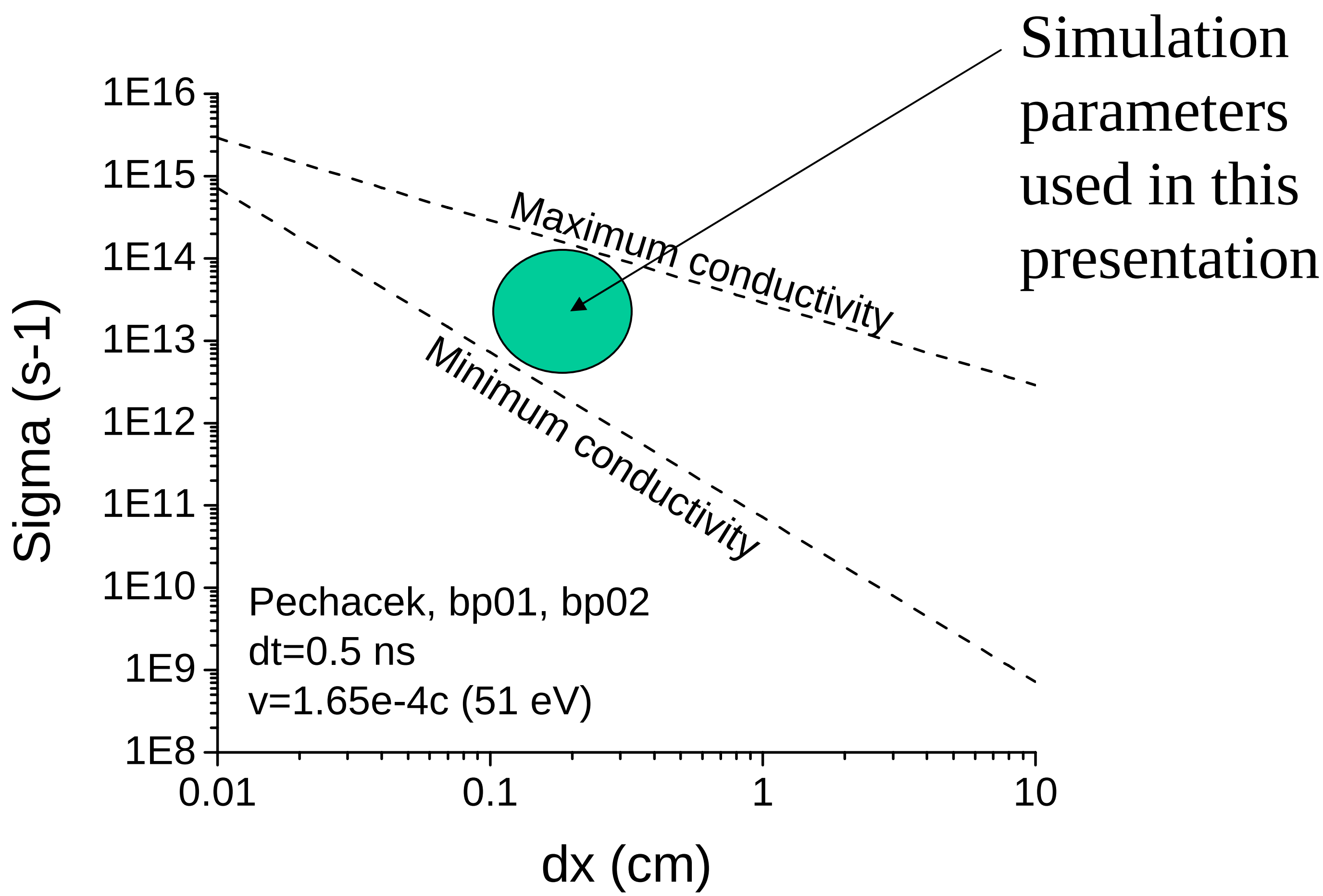
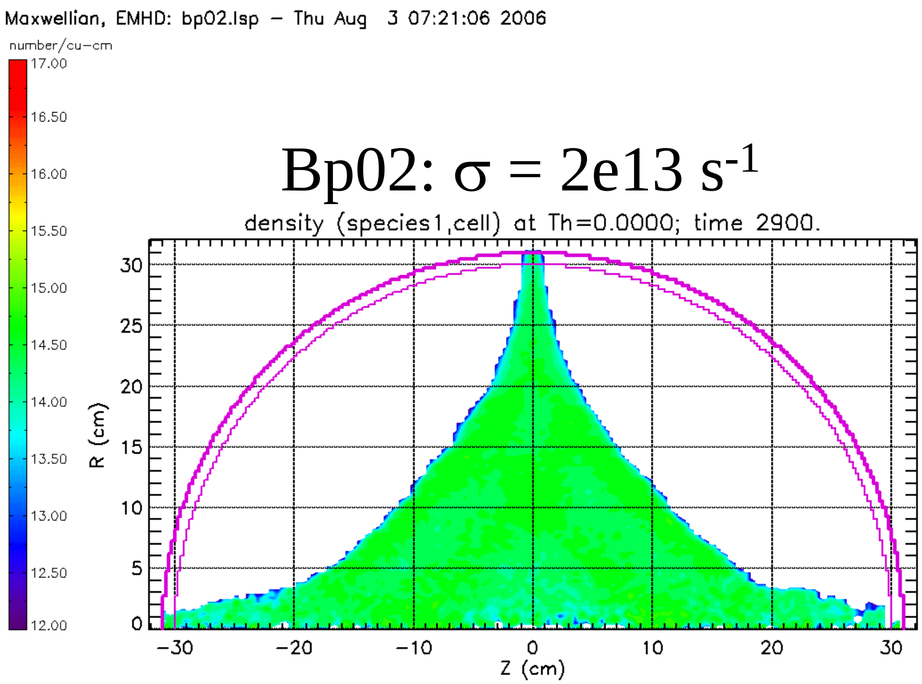


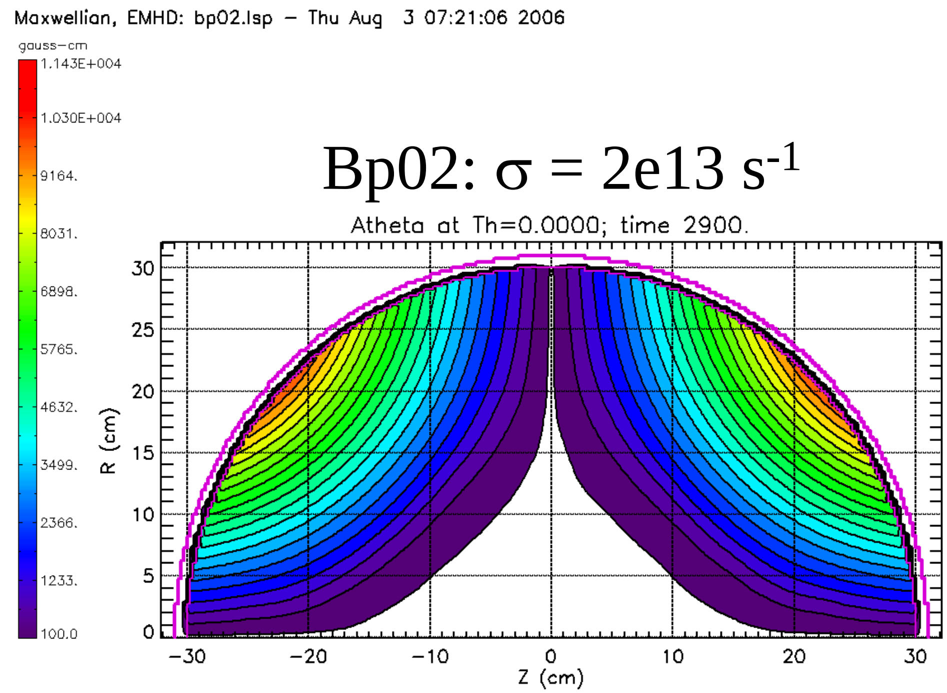
FIG. 1. Schematic diagram of the cusp experiment. The coil diameter is 70 cm. The scattered-light analyzing system and the incident-scattering laser pulse are actually in the same horizontal plane.

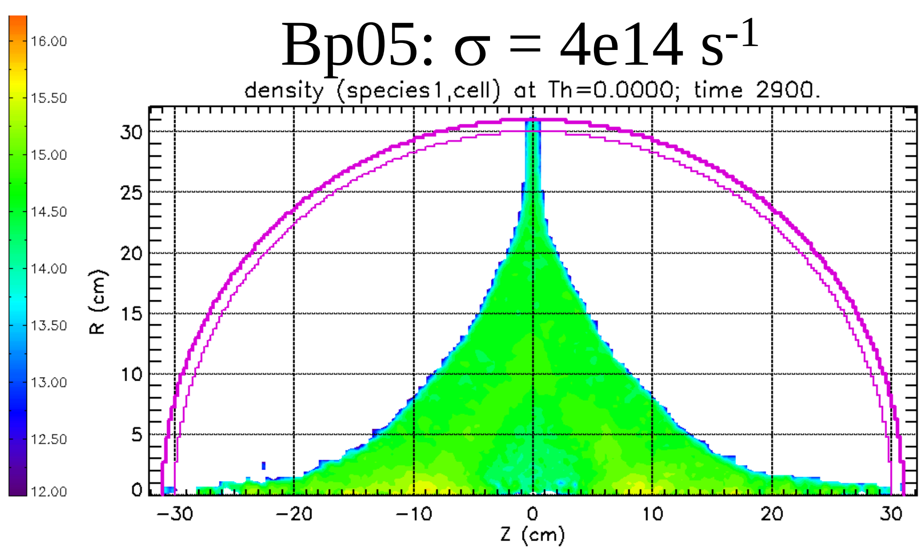
The grid-Reynolds constraints suggests a reasonably wide parameter space for the Pechacek experiment

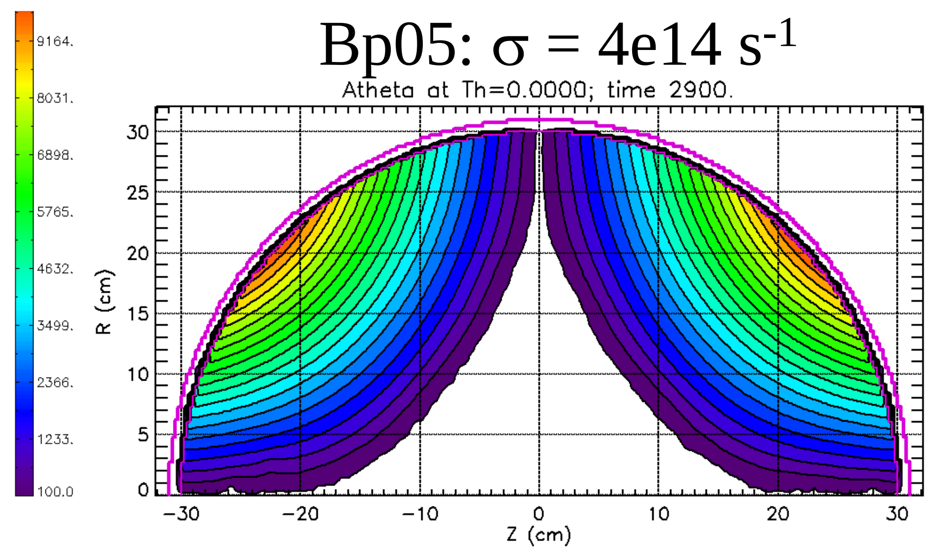


Effect of Different Conductivities (t=2.9 μs):









Plasma/Field boundary along 27 degree radial line from the cusp center (experimental result):

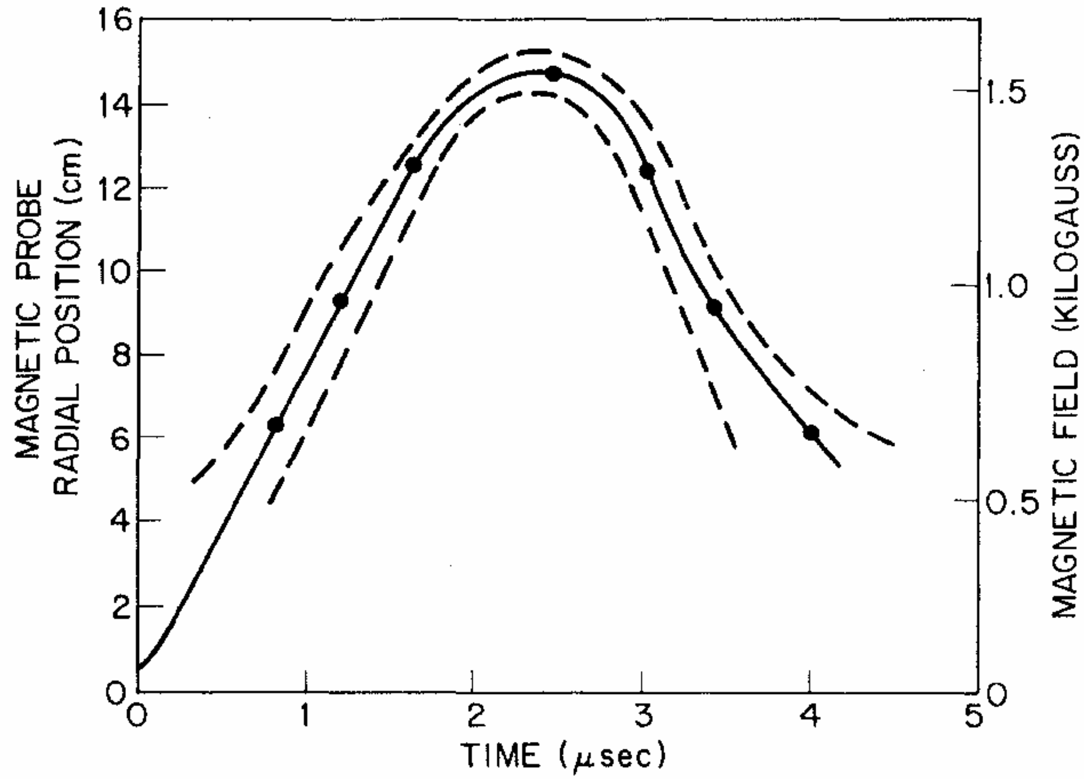
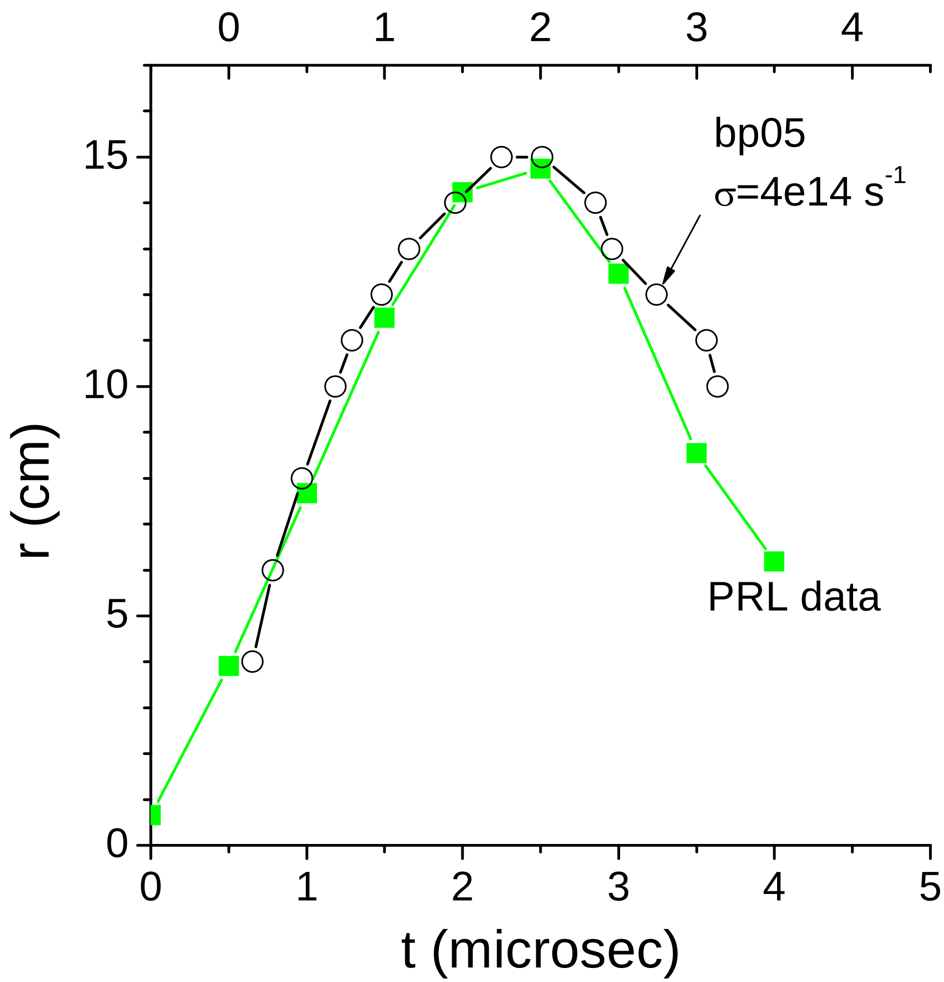


FIG. 3. Radial position of the plasma–magnetic-field interface vs time after the peak of the CO_2 laser pulse, derived from the time of arrival of the peak of the diamagnetic signal from a probe that is movable along a radial line inclined at 27° to the midplane. The dashed curves represent the half-peak points of the $\dot{B}$ signal.

Radial position of magnetic-field / plasma-interface (along 27 degree line) in good agreement with high σ simulation.



Simulation results shifted by 0.5 ms; accounts for time-of-flight for field-free plasma expansion to 2-cm radius.

At r=22 cm inside ring cusp, electron density was measured at 5 different times:

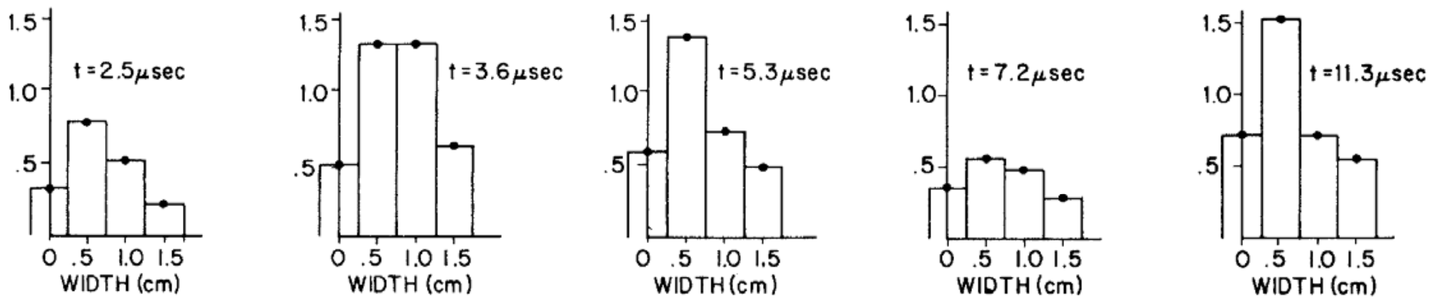
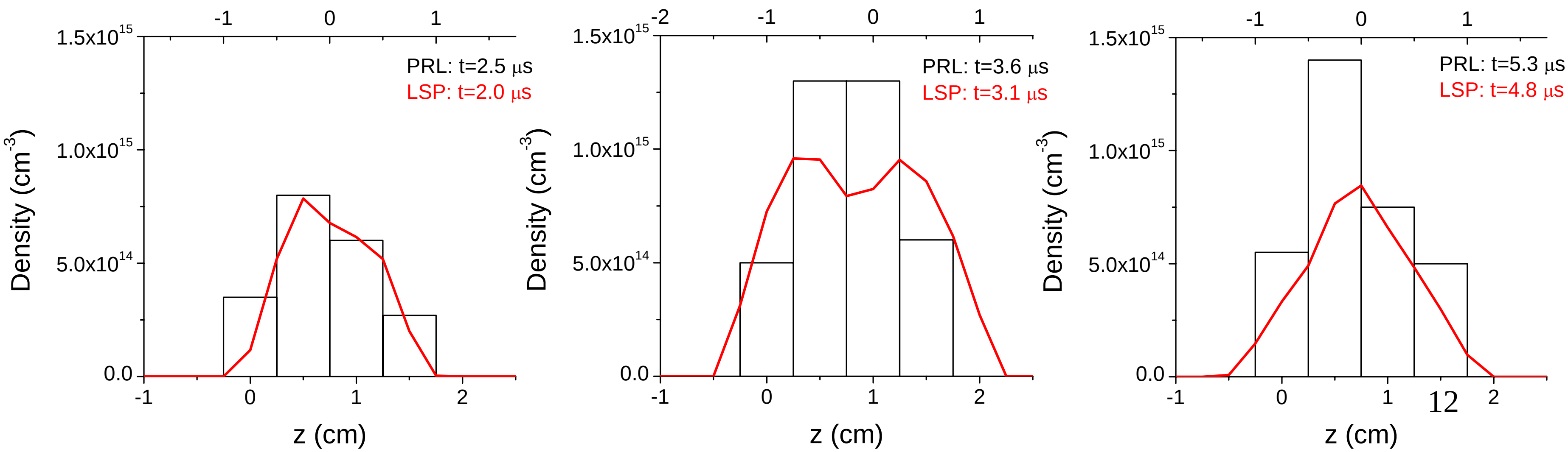
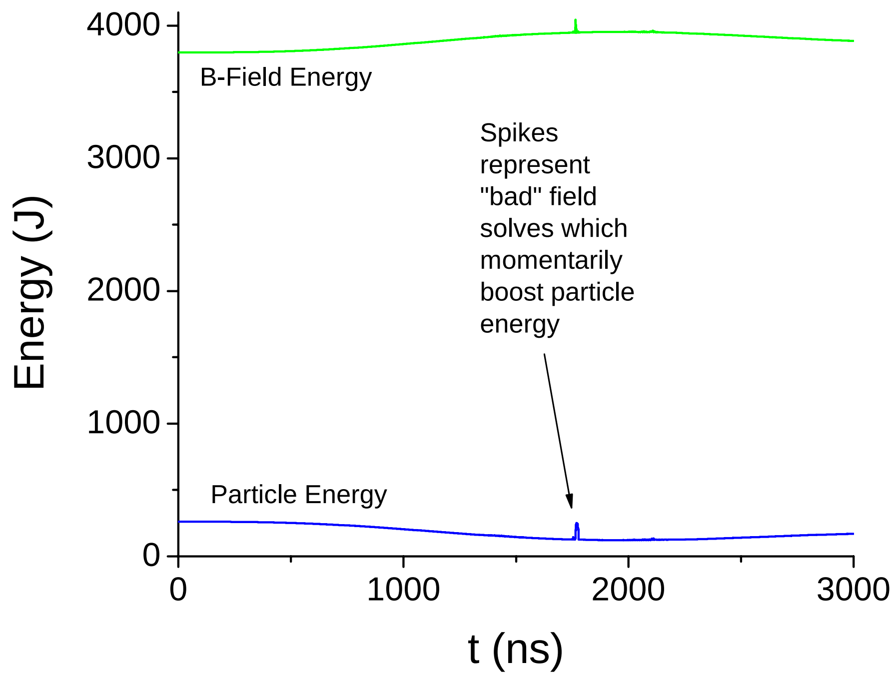


FIG. 4. Electron density as a function of position across the width of the ring cusp, at time t after the creation of the plasma. Each point is an average of two to four shots. The units of the vertical axes are 10^{15} cm^{-3}.

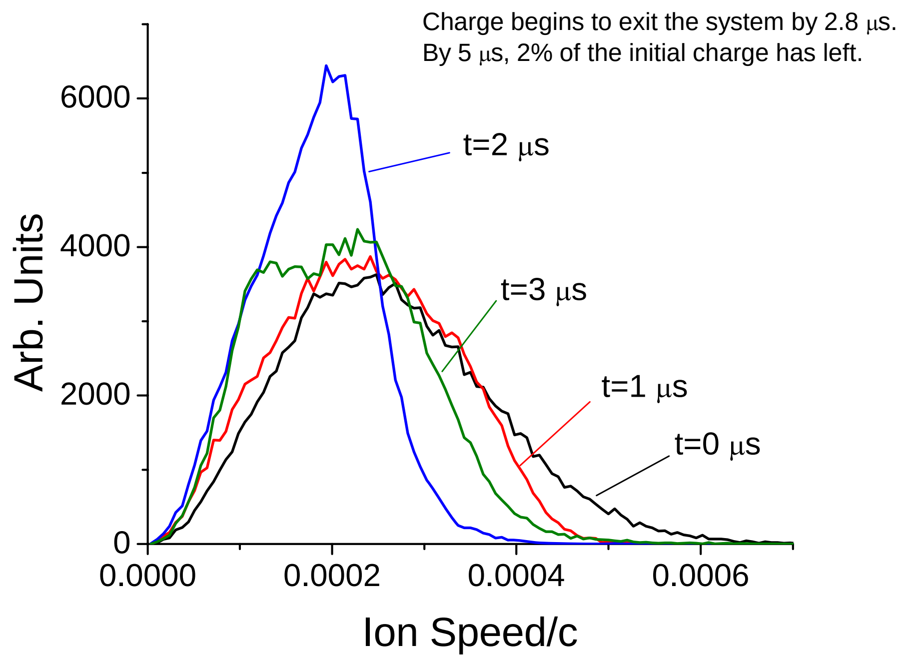
Simulations results in reasonable agreement with these measurements (at least for first 3 times):



Particle energy reaches first minimum at ~2 μs, consistent with experiment. Field solution problems still remain…



The velocity (speed) distribution is well resolved, and the dynamics can be tracked for the first time.



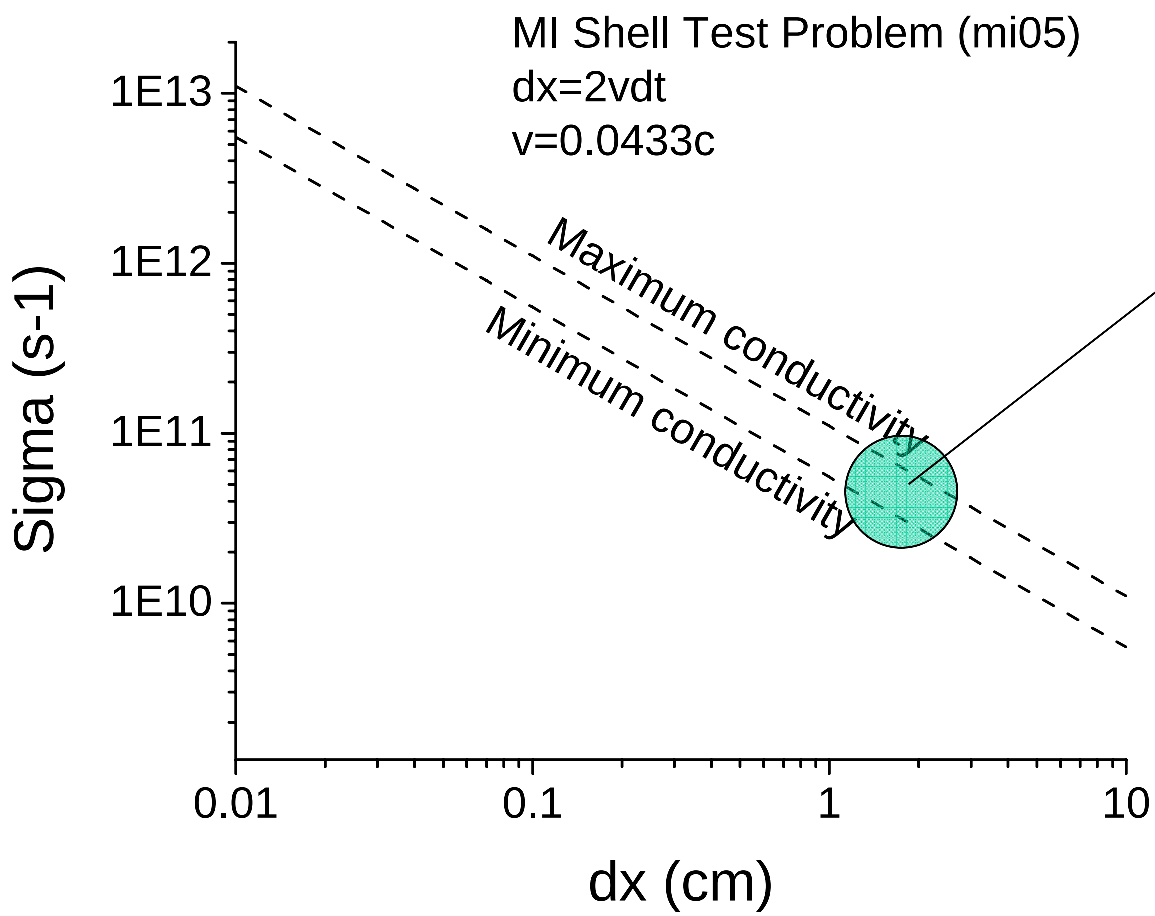
Status: Pechacek Experiment Modeling

- Present modeling is providing the best results to date, and detailed comparisons with the data are very compelling.
- Some problems with the new solver remain to be worked out.
- Additional developments such as convergence testing are expected to make the algorithm faster.

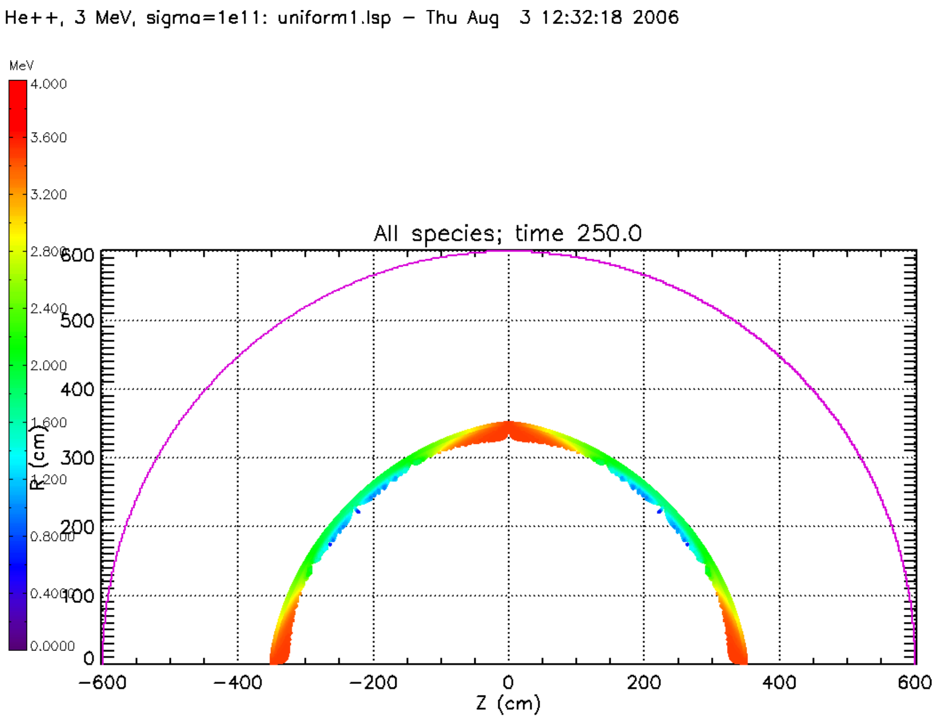
3. Expanding "shell" simulation for Magnetic Intervention parameters:

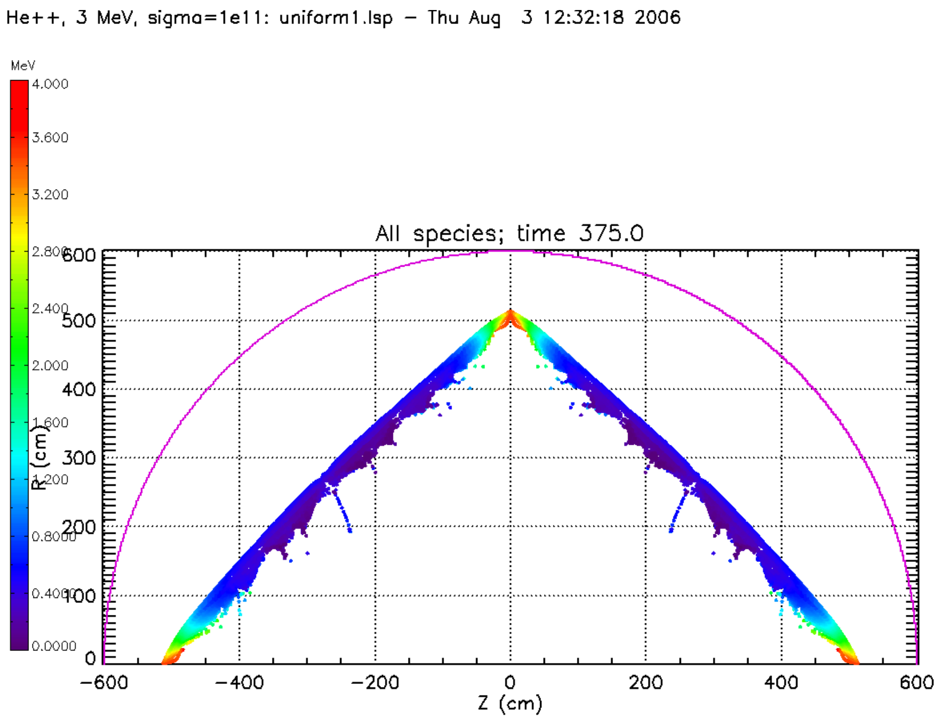
- A preliminary simulation result using the new solver is presented
- We model a mono-energetic, spherically expanding plasma "shell" in a 6-meter radius chamber (3.5 MeV, He++ ions)
- 4-coil magnetic field topology taken from previous "shell" model calculations of Robson and Genoni.

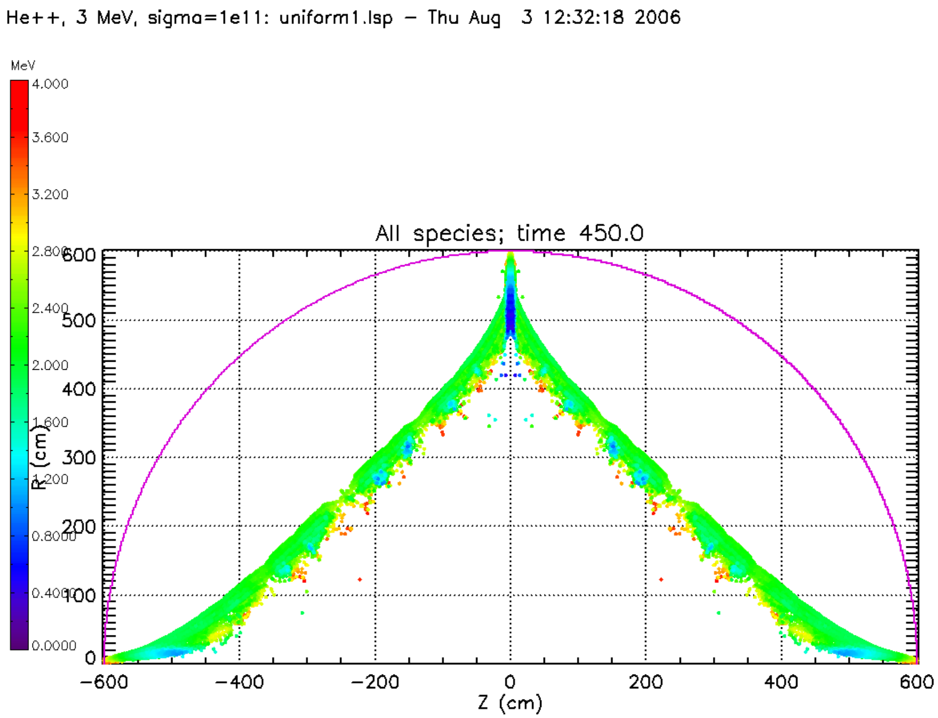
Computational constraints are <u>significant</u> for these ion speeds and scale lengths:



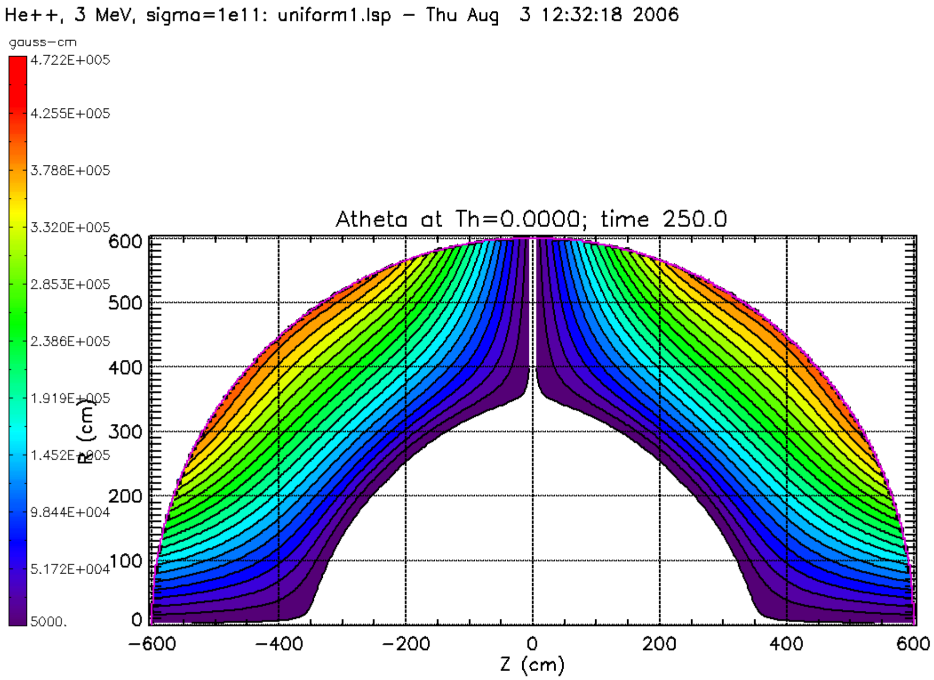
Parameter regime explored in this report.

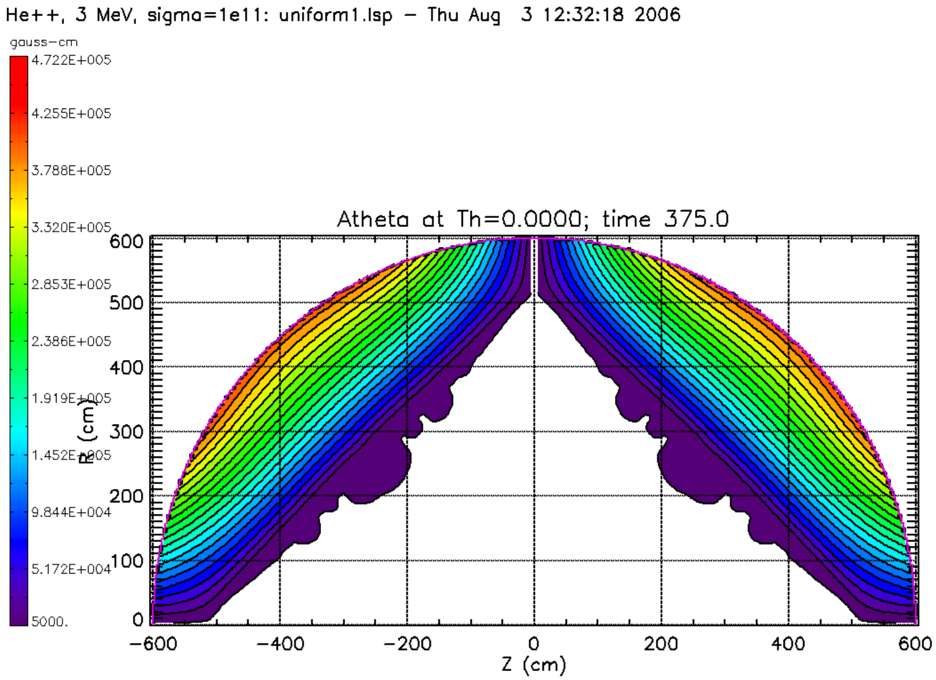




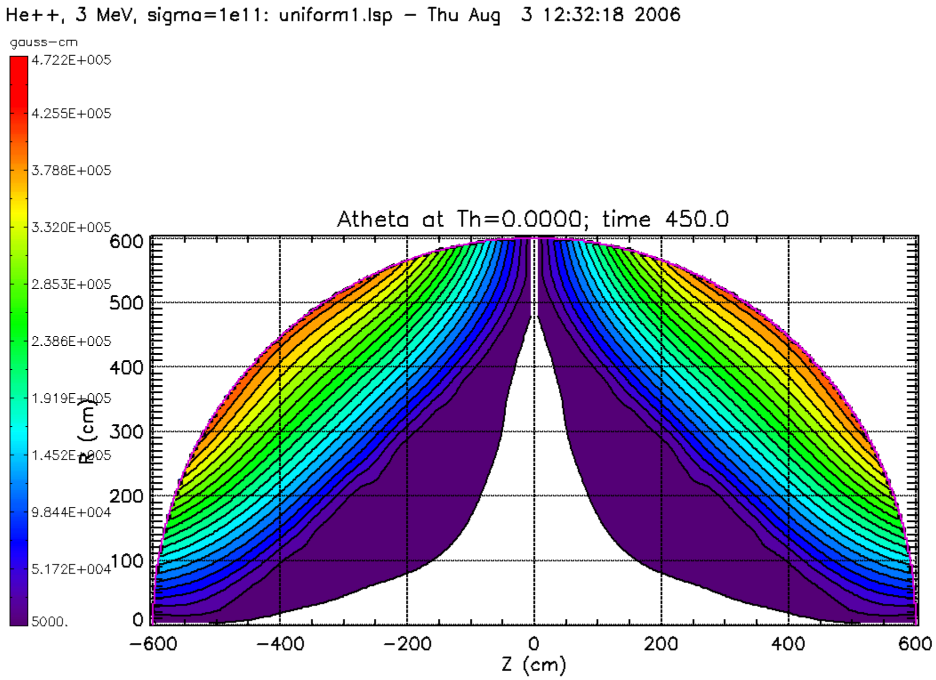


Particle positions and energies at 3 times: Particle slowing (250 ns), stopping (375 ns), and re-acceleration (450) can be seen away from the cusps.

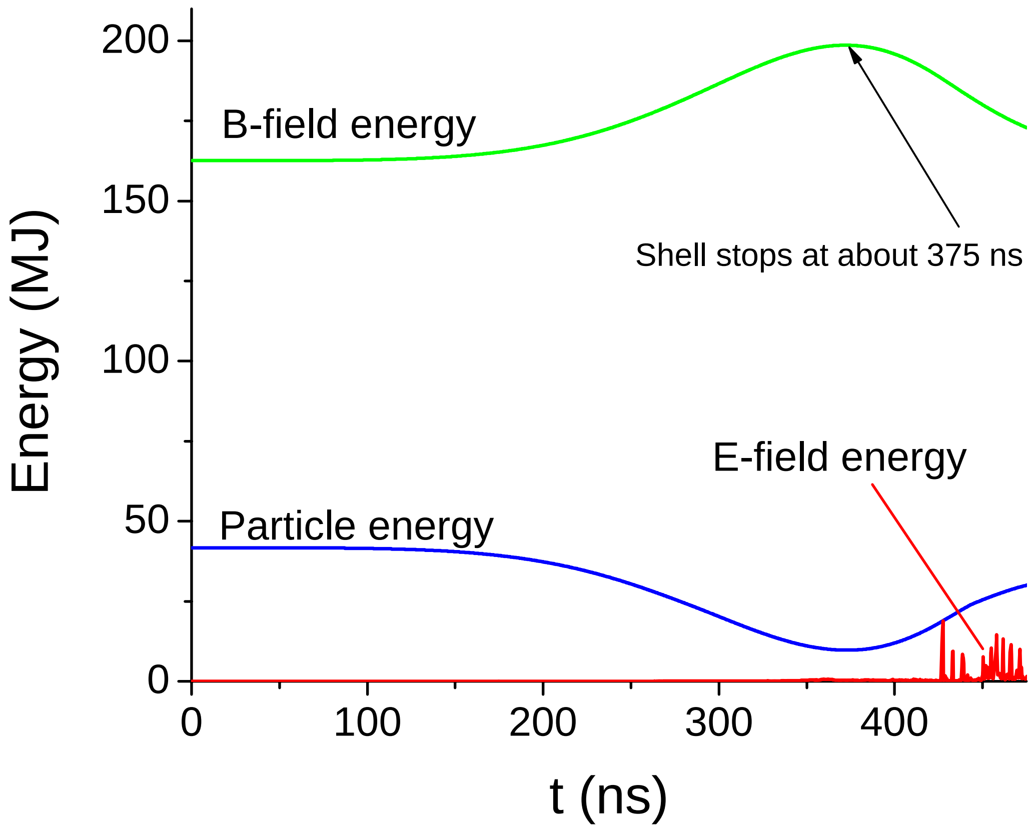




$|A_\theta|$ shows clear magnetic pushing at 250 ns, but by 375 ns, some magnetic field is leaking through the shell, as expected due to the relatively small conductivity. By 450 ns, significant magnetic field has penetrated the plasma shell.



Plasma "shell" stops at about 375 ns, consistent with minimum in the particle energy and maximum in the magnetic field energy.



E-field energy spikes are indicative of lack of convergence in ADI solve.

Status: Magnetic Intervention Chamber Modeling

- Overall, initial results are encouraging. A representative "shell" simulation is consistent with "shell" models of Robson and Genoni.
- Problems with the convergence of the solver (as seen in the Pechacek simulations) need to be resolved.
- Unlike the Pechacek experiment, the magnetic intervention parameter regime (ion speeds and scale lengths) will require *significant* computational resources. <u>A parallel implementation of this algorithm is essential.</u>

4: Next Steps…

- Resolve problem associated E-field spikes in solver
- Develop convergence criteria for solver
- Parallel implementation