3D Plasma Detachment Simulations Using the LSP Particle-In-Cell Code

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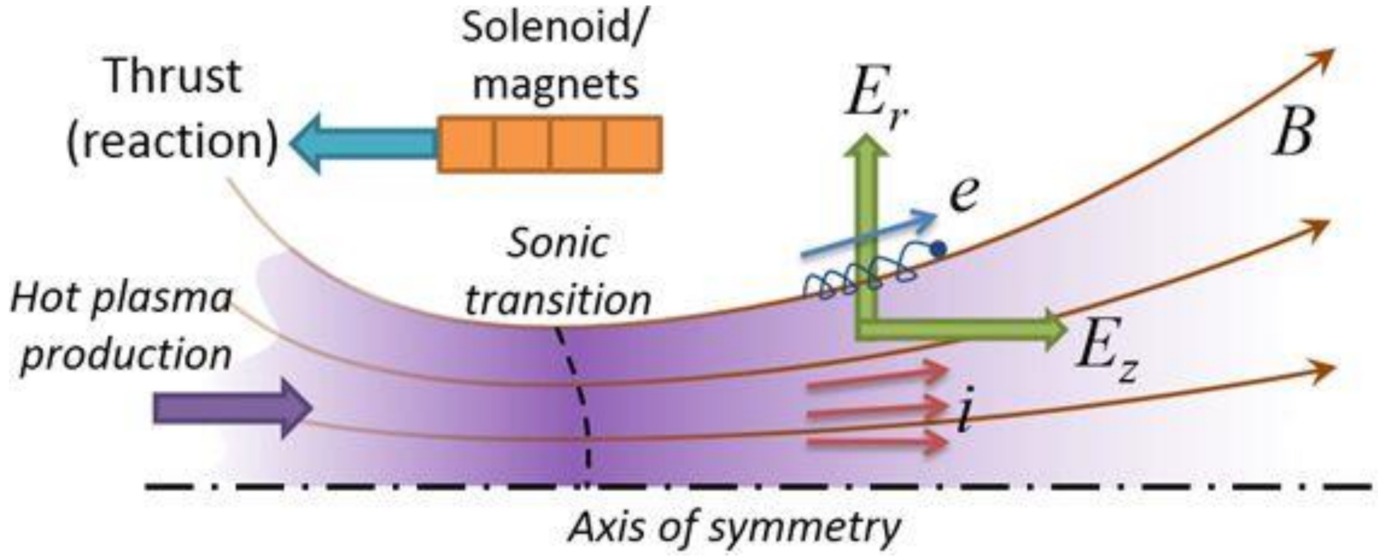
Outline

- Overview of Plasma Detachment
- Applications to Space Propulsion and Inertial Fusion
- The Particle-In-Cell Method and the LSP Code
- Previous Simulation Results in 2D
- Current Progress in 3D Simulations

Plasma Detachment

- Plasma detachment is when plasma flowing out of a magnetic nozzle detaches from the expanding magnetic field lines and flows in a direction more parallel with the axis
- This is predicted to occur due to turbulence and particle collisions [1]

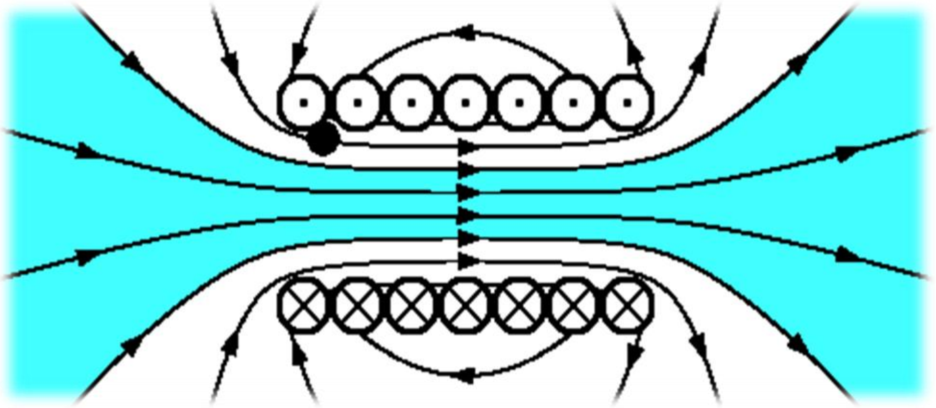


Expected Detachment Mechanism

- Due to the constancy of the magnetic moment $\mu = \frac{m}{2B} v_{\perp}^{2}$ and the decreasing magnetic field strength particles will gain axial momentum moving away from the nozzle
- The resulting increase in kinetic energy will lead to a higher $\beta = \frac{8\pi n_i (KE_e + KE_i)}{B^2}$ ratio in the expansion region
- Plasma detachment predicted at β=1 [2]

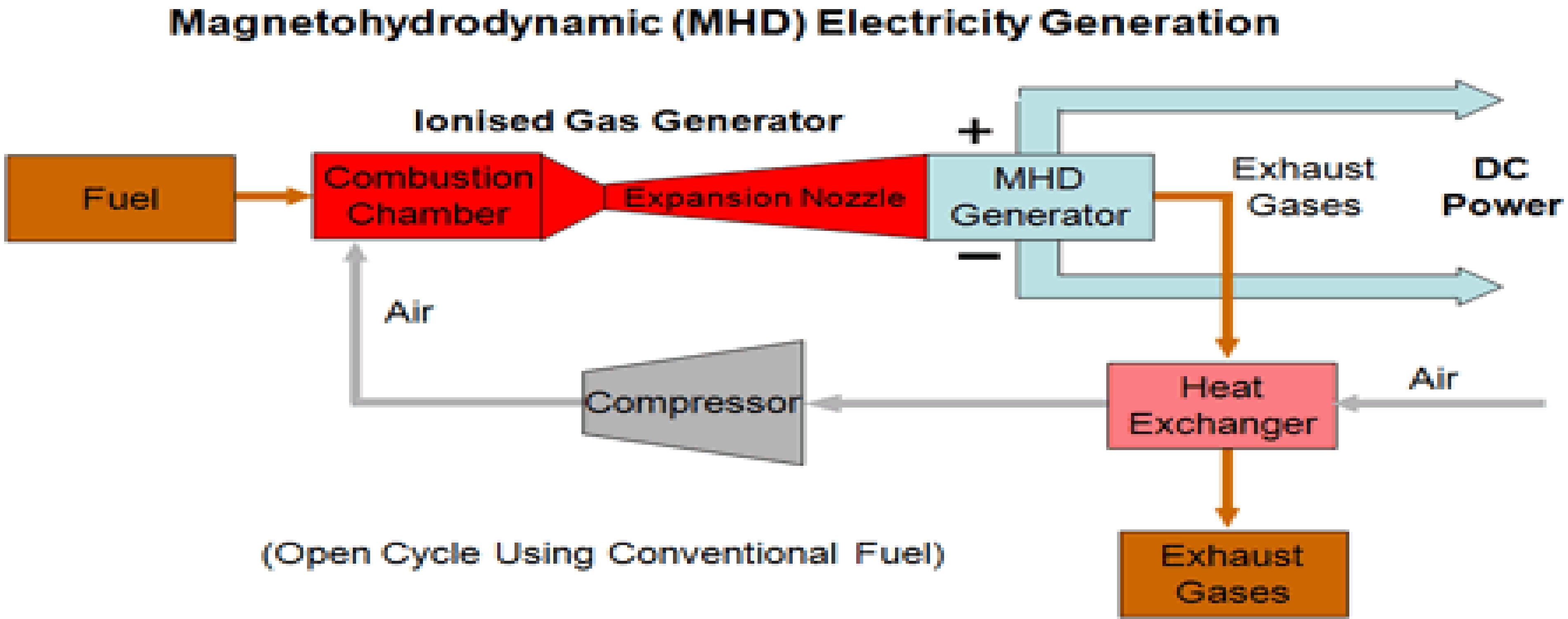
Expected Particle Movement

- Ions should detach first due to their larger gyroradii and greater momentum
- Electrons should initially remain tied to field lines due to their smaller gyroradii, but should then be coupled to the inertia of the ions and proceed to detach with them [3]



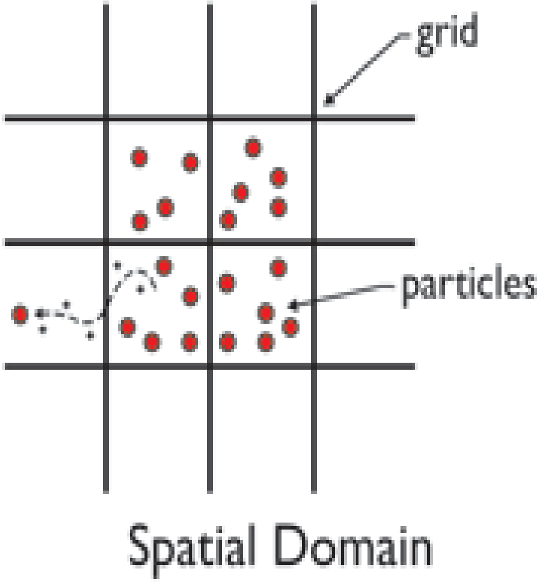
Applications of Plasma Detachment

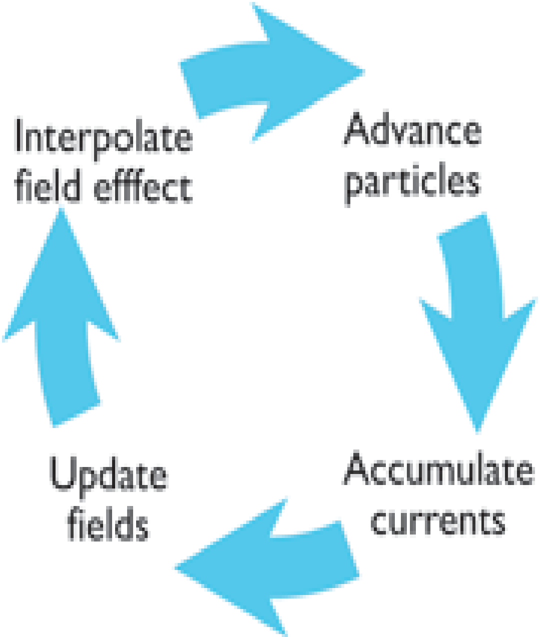
- Removing fusion plasma from the FRC reactor
- Converting thermal energy to directed kinetic energy for electromagnetic propulsion



The Particle-In-Cell (PIC) Method

- Iterative method for solving the evolution of a system of particles, in our case for charged particles in a magnetic field
- Uses macro-particles to represent many real-particles
- Two-step time iteration[4]:
  - Particle Push-solves for the motion of macro-particles in the field
  - Field Solve-updates the fields using the new particles by solving Maxwell's equations on the grid



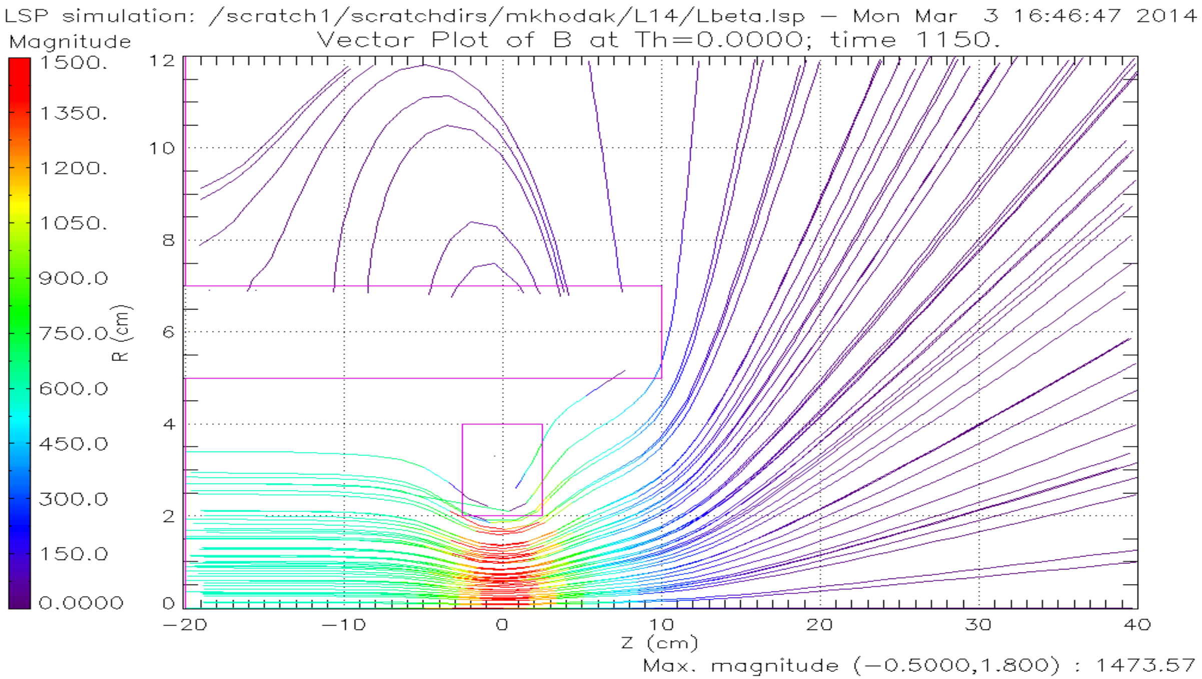


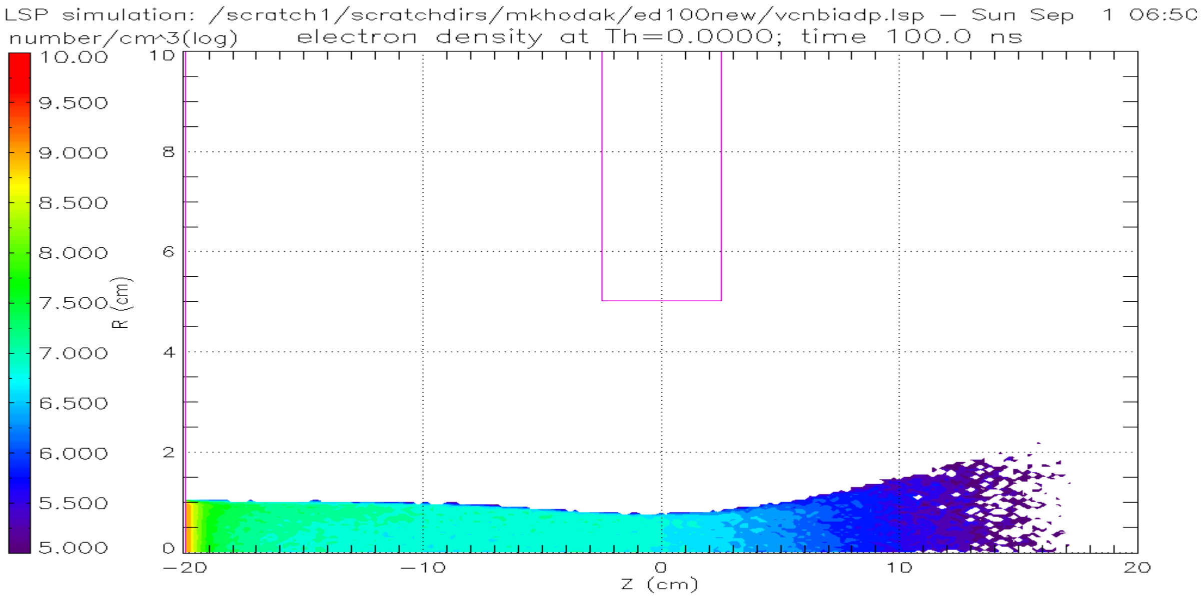
The PIC Method for Plasma Simulations

- Strengths:
  - Can examine particle movements without enforcing macroscopic properties (as in multi-fluid model)
  - Particle motion is found by solving the kinetic equations particles follow
  - Model can handle complex field geometries
- Weaknesses:
  - Still requires a large number of macro-particles for statistical accuracy of results
  - Large memory requirements to store particles
  - Elimination of low frequency events
- LSP
  - Parallel commercial PIC code written in C
  - Allows custom distribution of processor workload for a given problem
  - Code scales linearly, at least for fewer than 128 processors
  - Features
    - Particle collapse algorithm-removes nearby macro-particles with similar momenta
    - Implicit particle push-solves for particle motion with updated fields, allowing larger timesteps and coarser grids

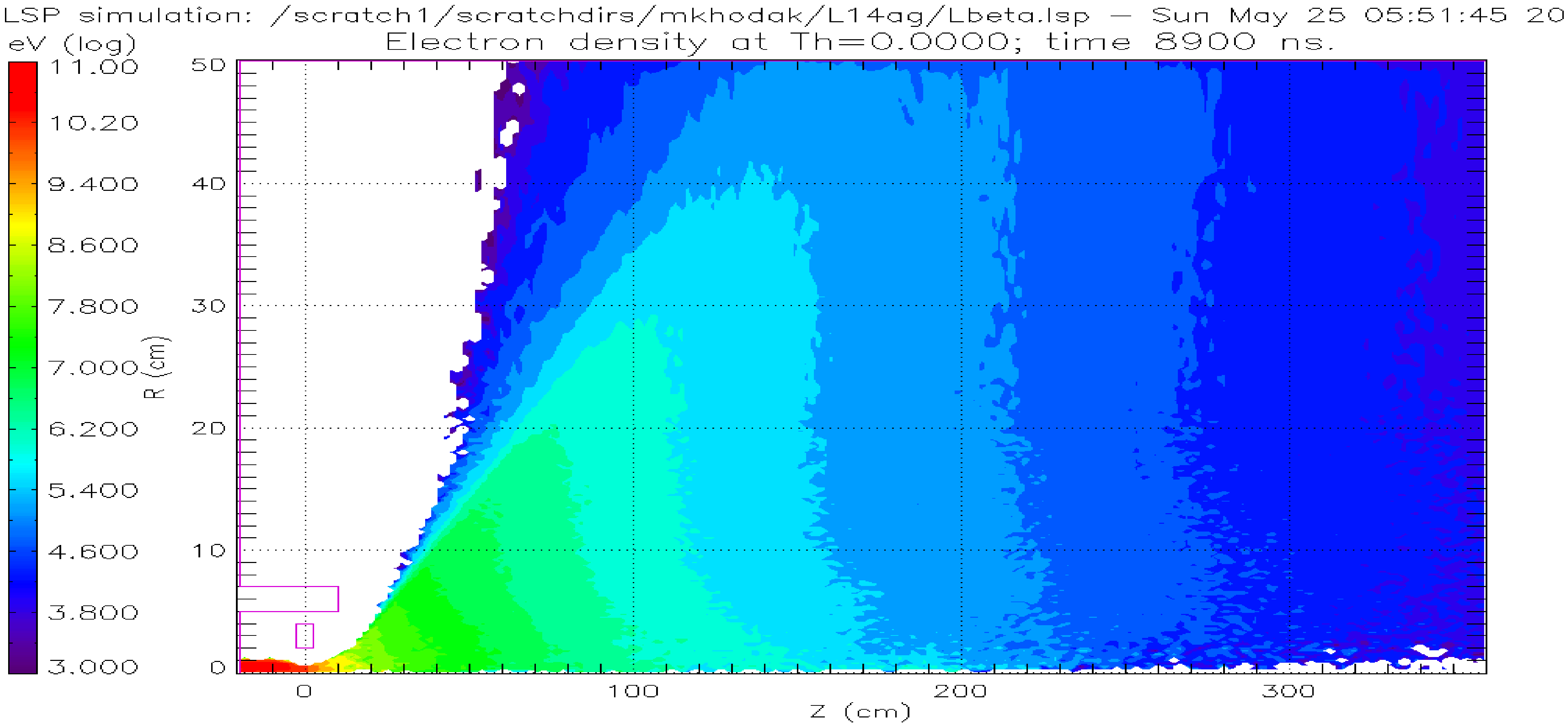
2D Simulation - Setup

- Grid
  - Cylindrical r-z coordinates, z = 0 at the nozzle
  - Simulation region stretches 520cm axially and 50cm radially
- Δt= .005 ns
- Magnetic Field
  - Created by two short thick solenoids, one around the plasma source region and one at the nozzle
  - Maximum field strength of 1400G at the nozzle, dropping off at $O(z^{2.5})$ in expansion region
- Particle Injection
  - H+ ions were injected at a density of 10^{10} cm^{-3} from the left end of the grid, with initial momentum in the axial direction
  - Electrons created using LSP's Child-Langmuir emission model in a region between z = -20 cm to -19.9 cm with initial energy 100 eV

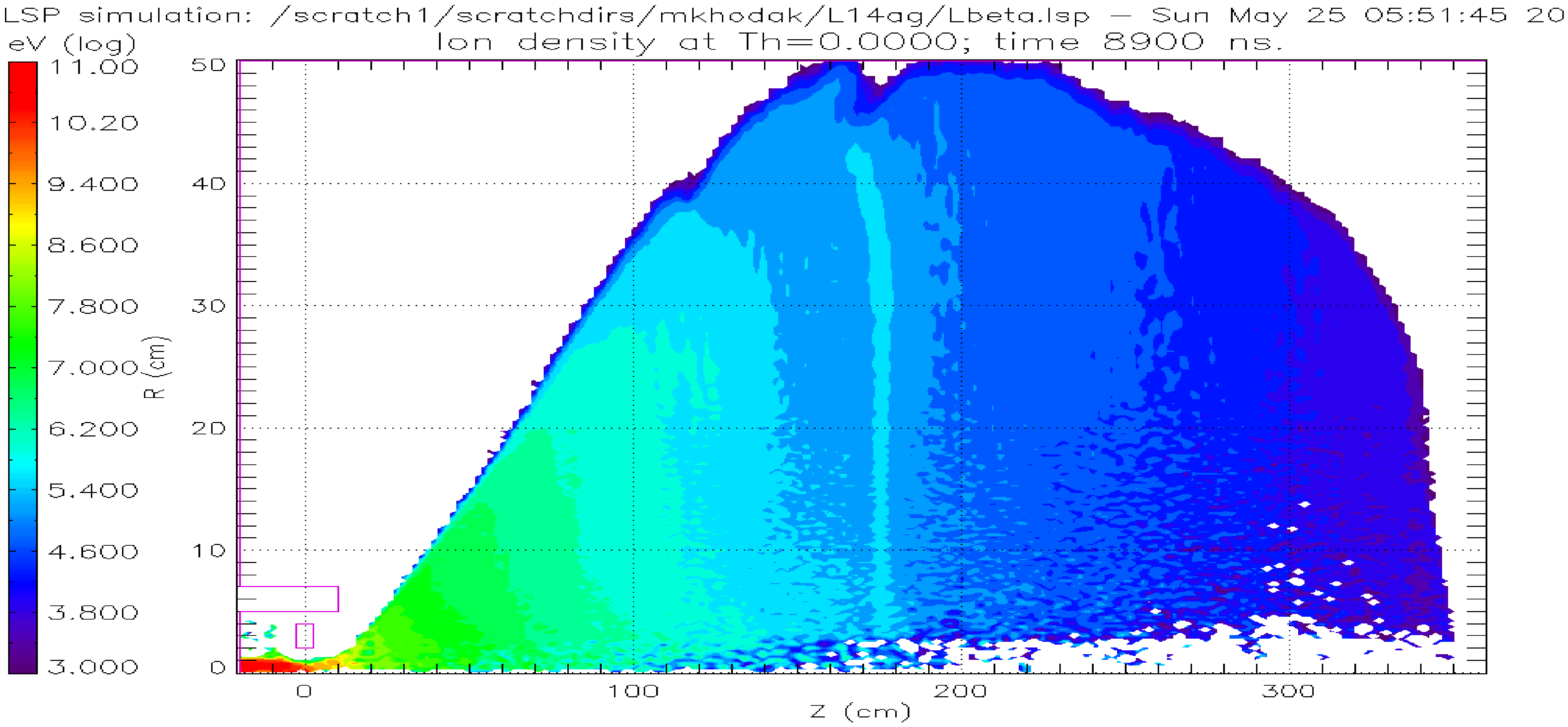




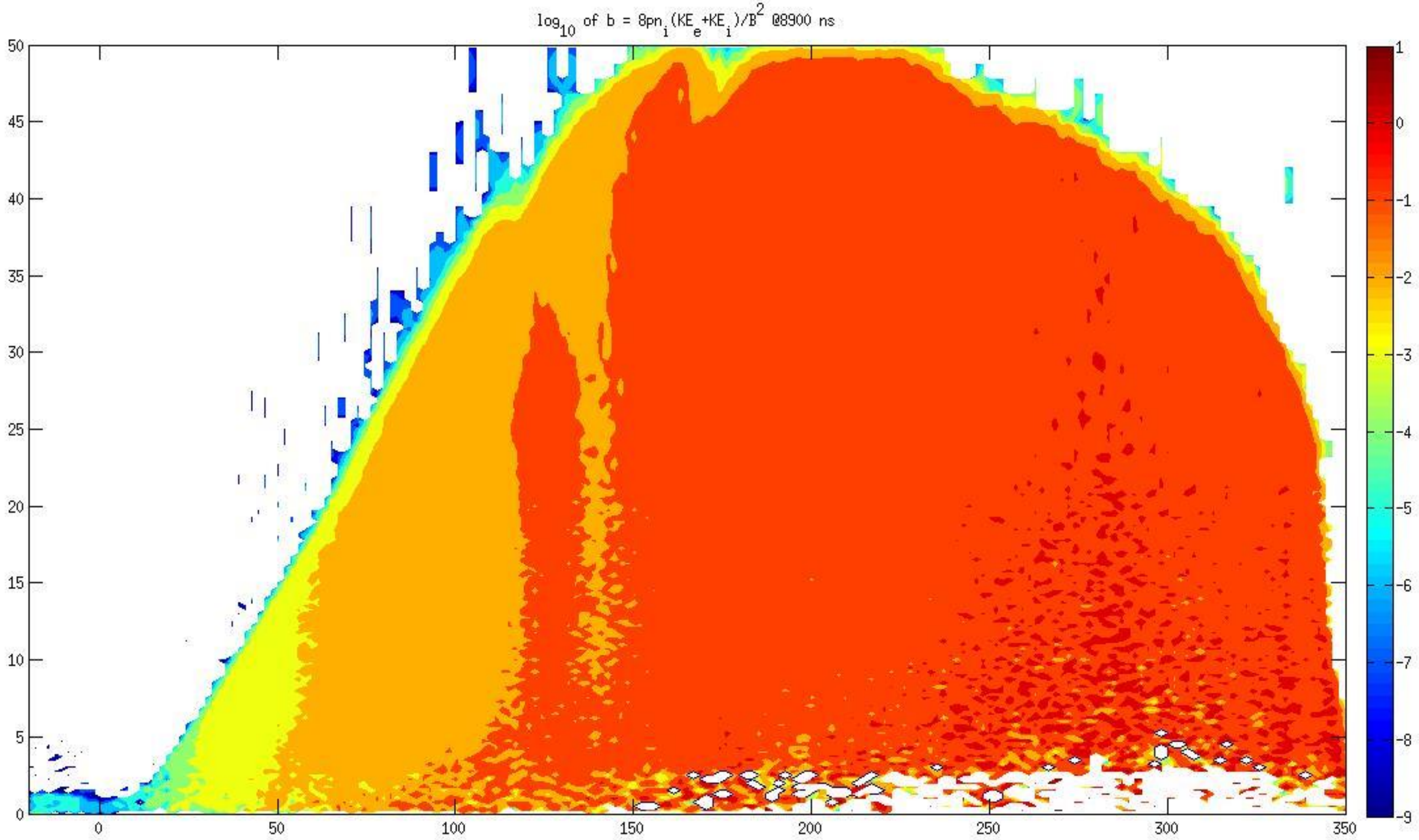
2D Simulation e- density at 8900ns



2D Simulation H+ density at 8900ns



2D Simulation log(β) at 8900ns



1

-1

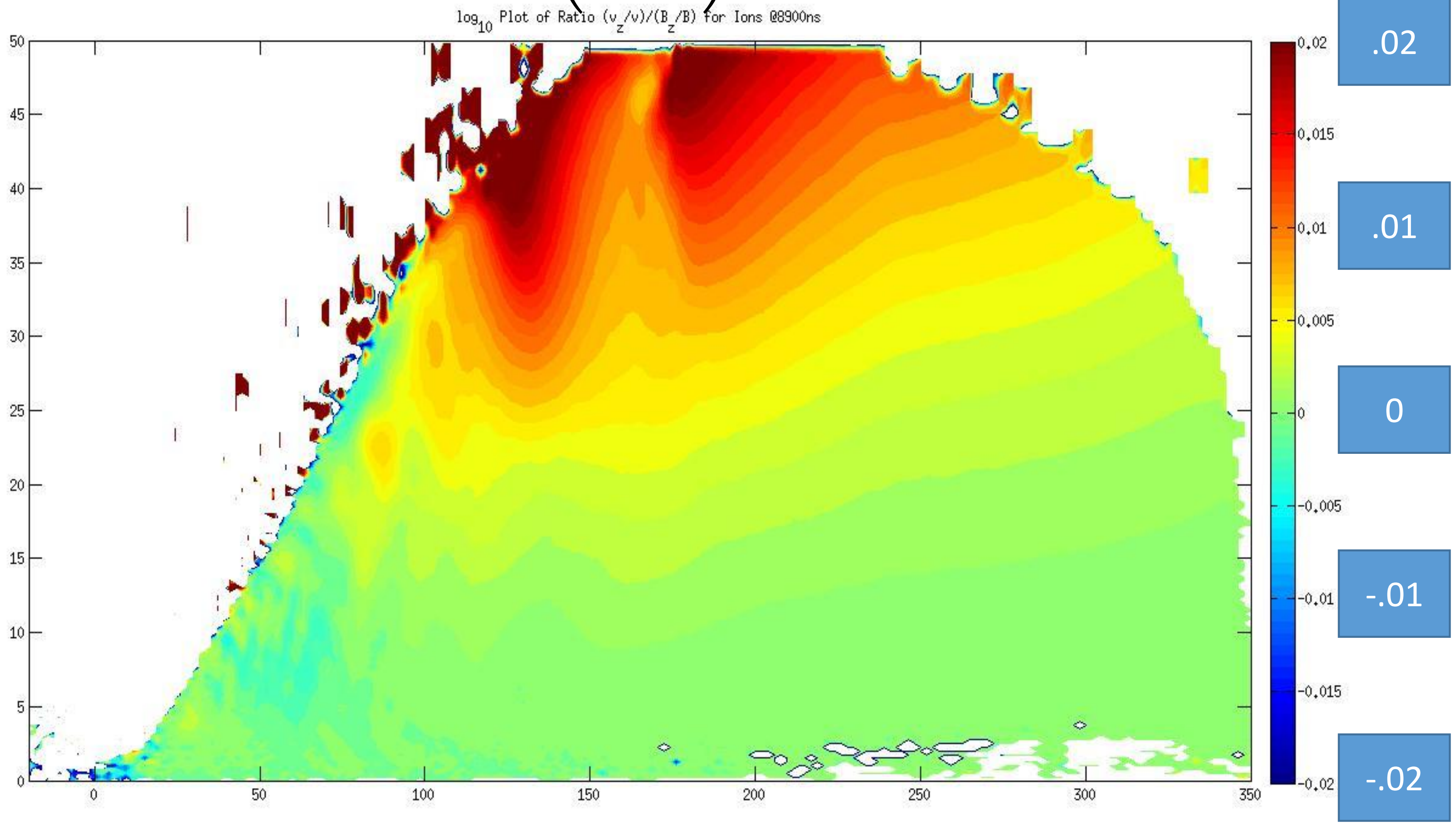
-3

-5

-7

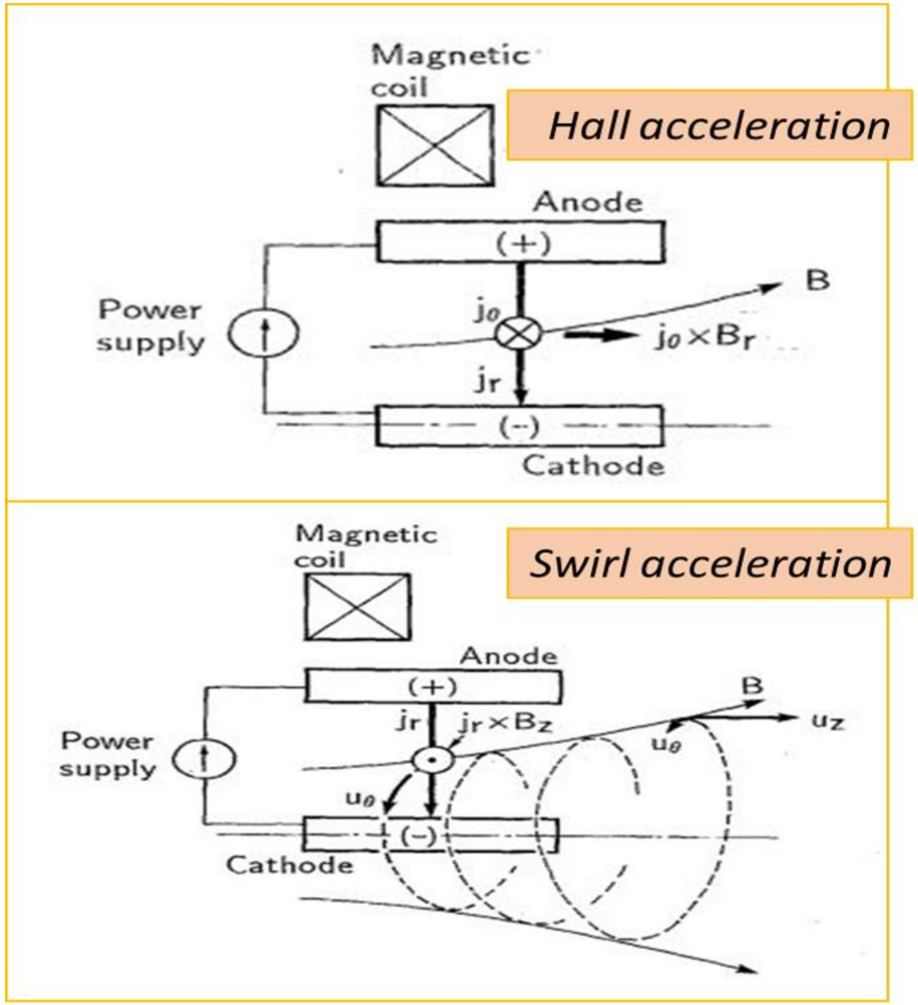
-9

2D Simulation $\log_{10}\left(\frac{v_{zi}/|v_i|}{B_z/|B|}\right)$ at 8900ns



2D Simulation Problems

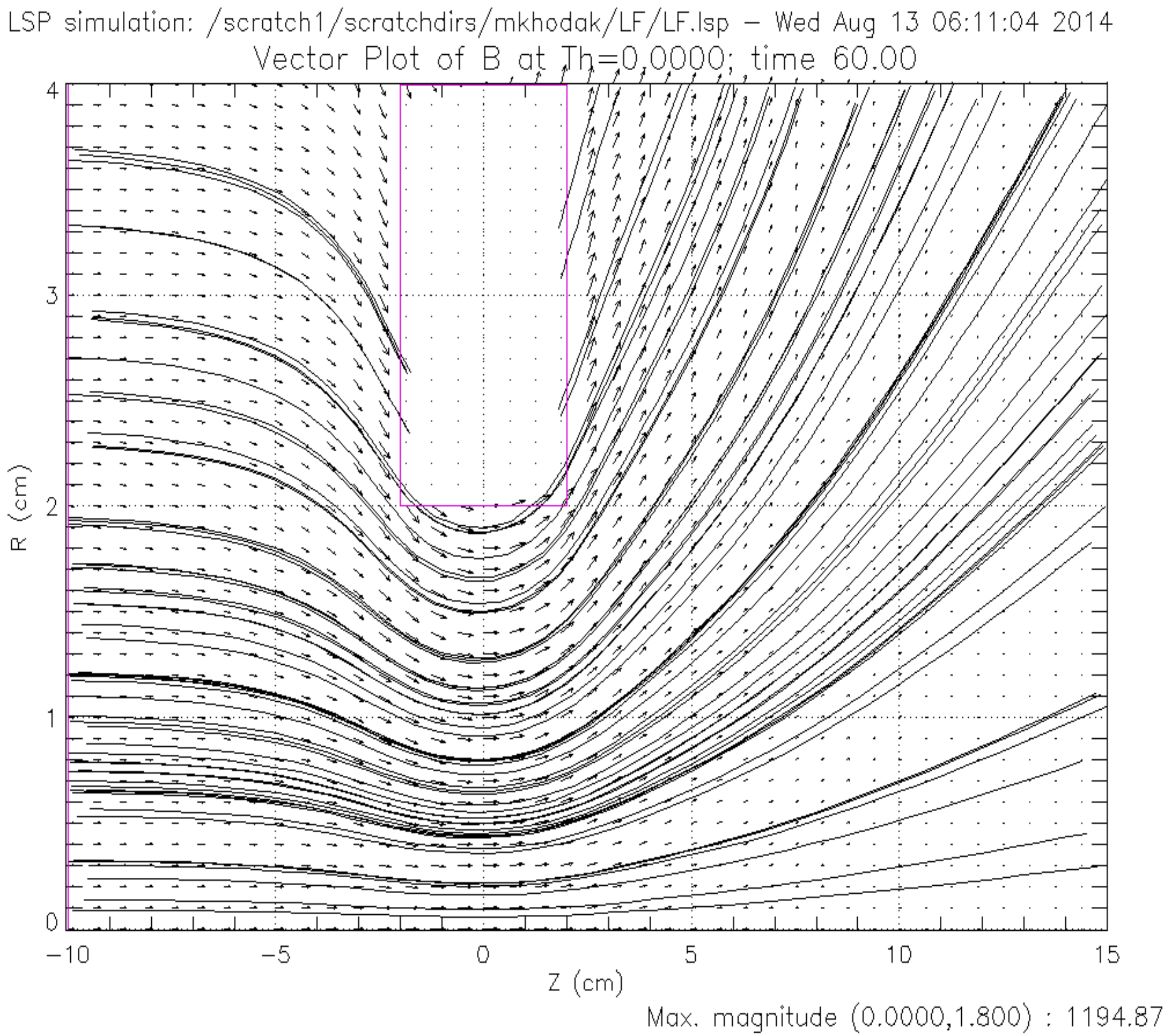
- Ion particle density gap along the z-axis, downstream from the nozzle
- 2D setup makes it difficult to account for theta-direction swirl currents



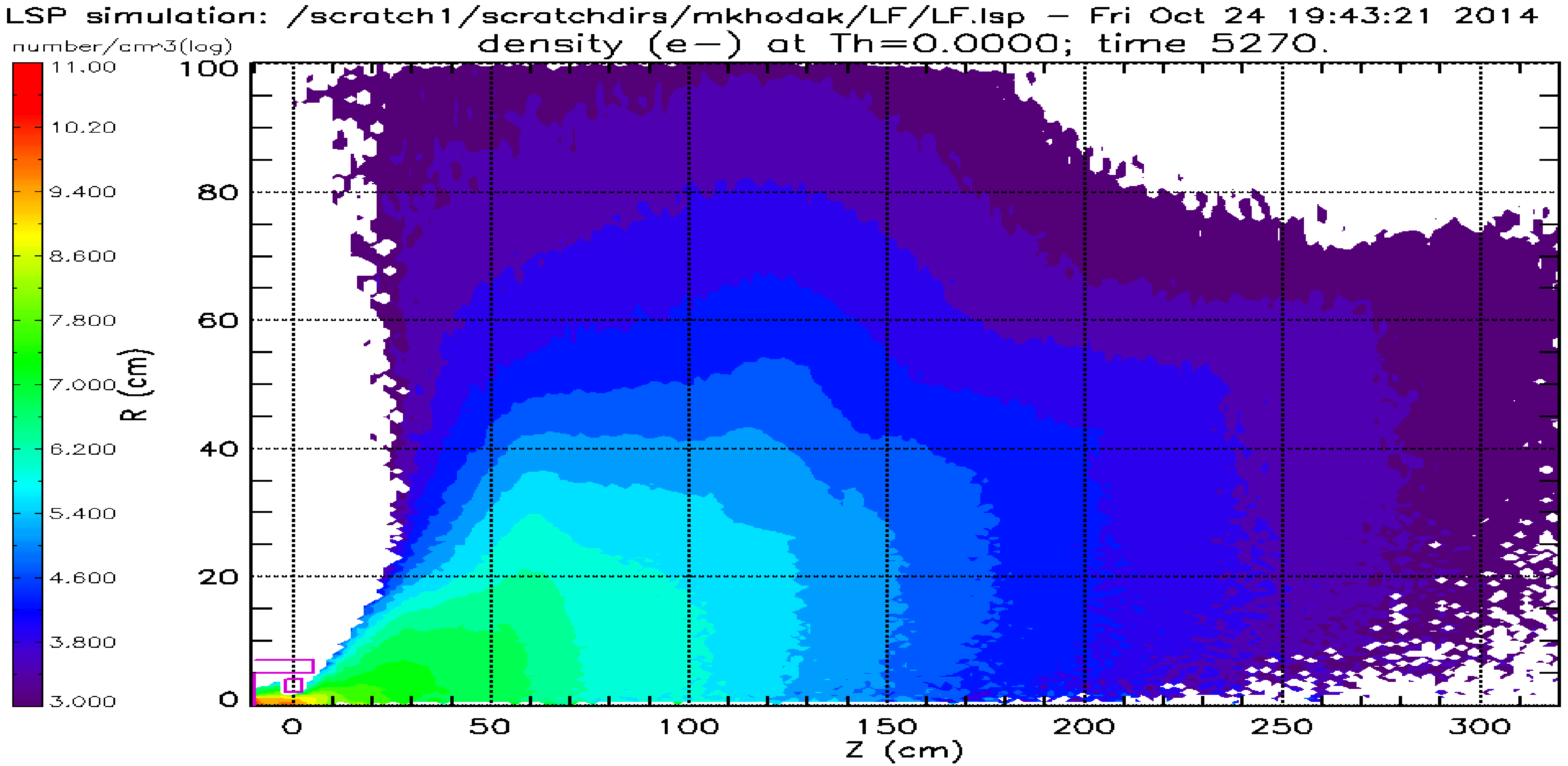
A. Sasoh: Phys. Plasmas 1, 464 (1994)

3D Simulation - Setup

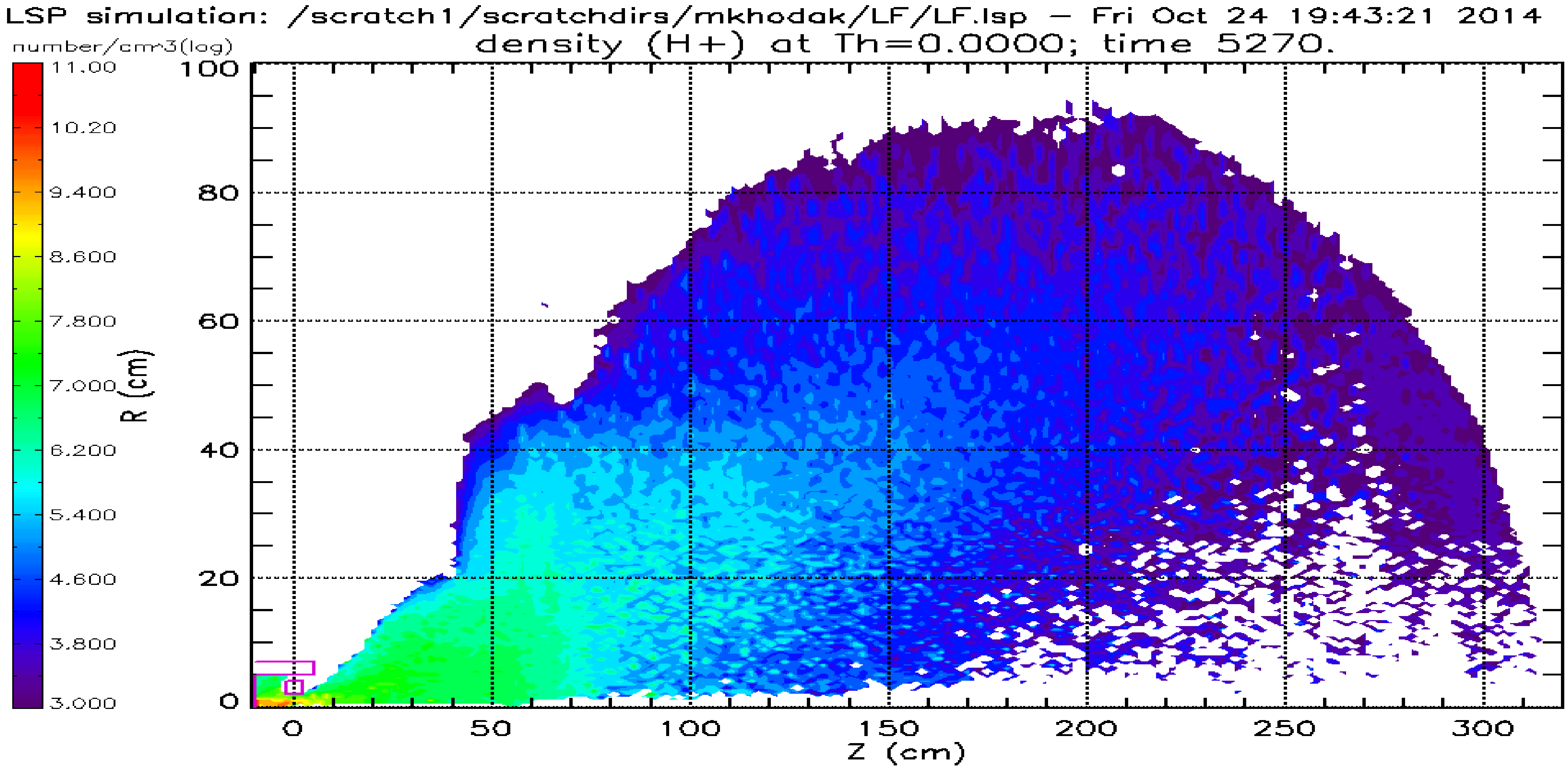
- Grid
  - Cylindrical r-z-theta coordinates, z = 0 at the nozzle
  - Simulation region stretches 1010cm axially and 100cm radially
- Δt= .005 ns
- Magnetic Field
  - Same setup as 2D, but more accurate field
  - Maximum field strength of 1100G at the nozzle



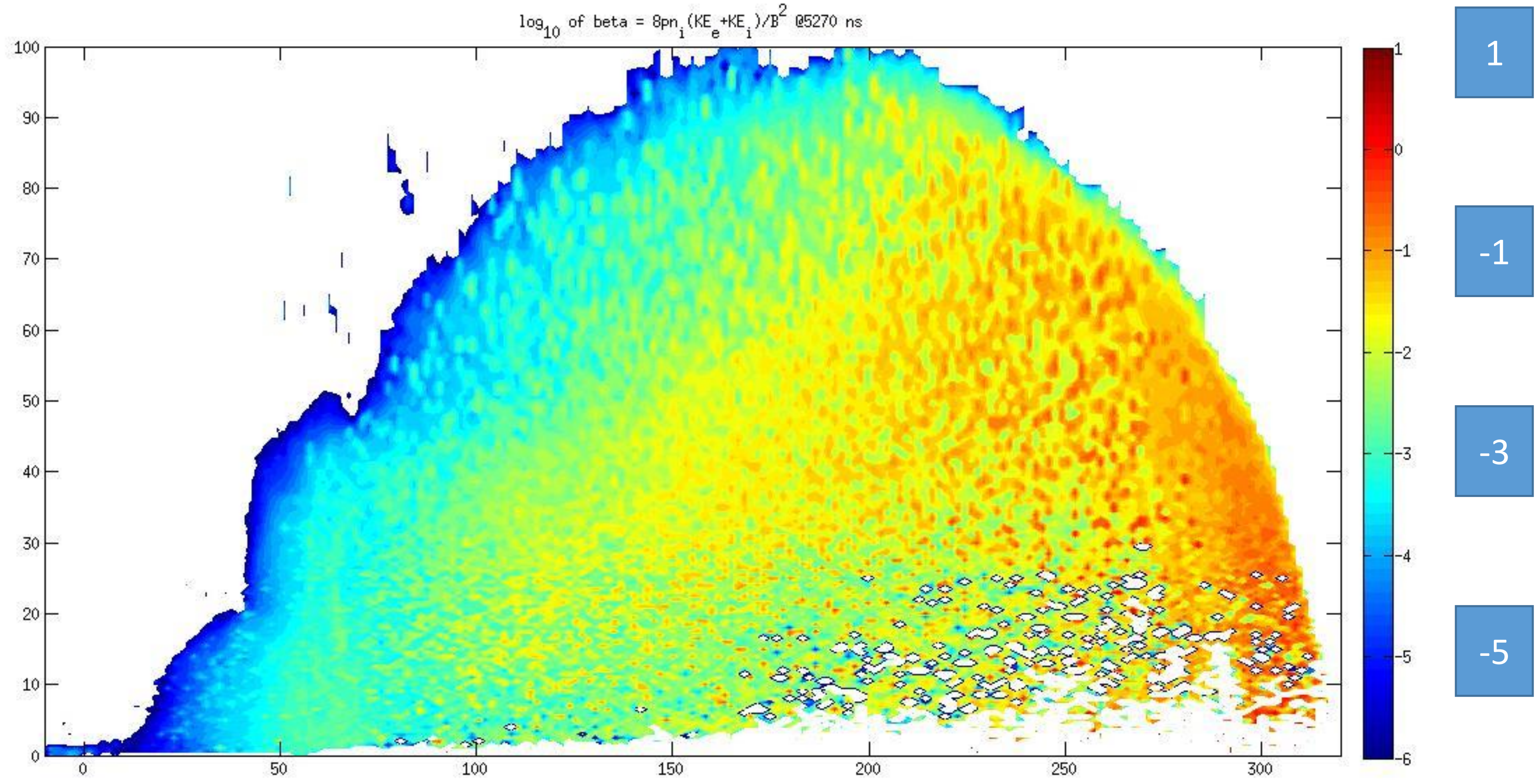
3D Simulation e- density at 5270ns



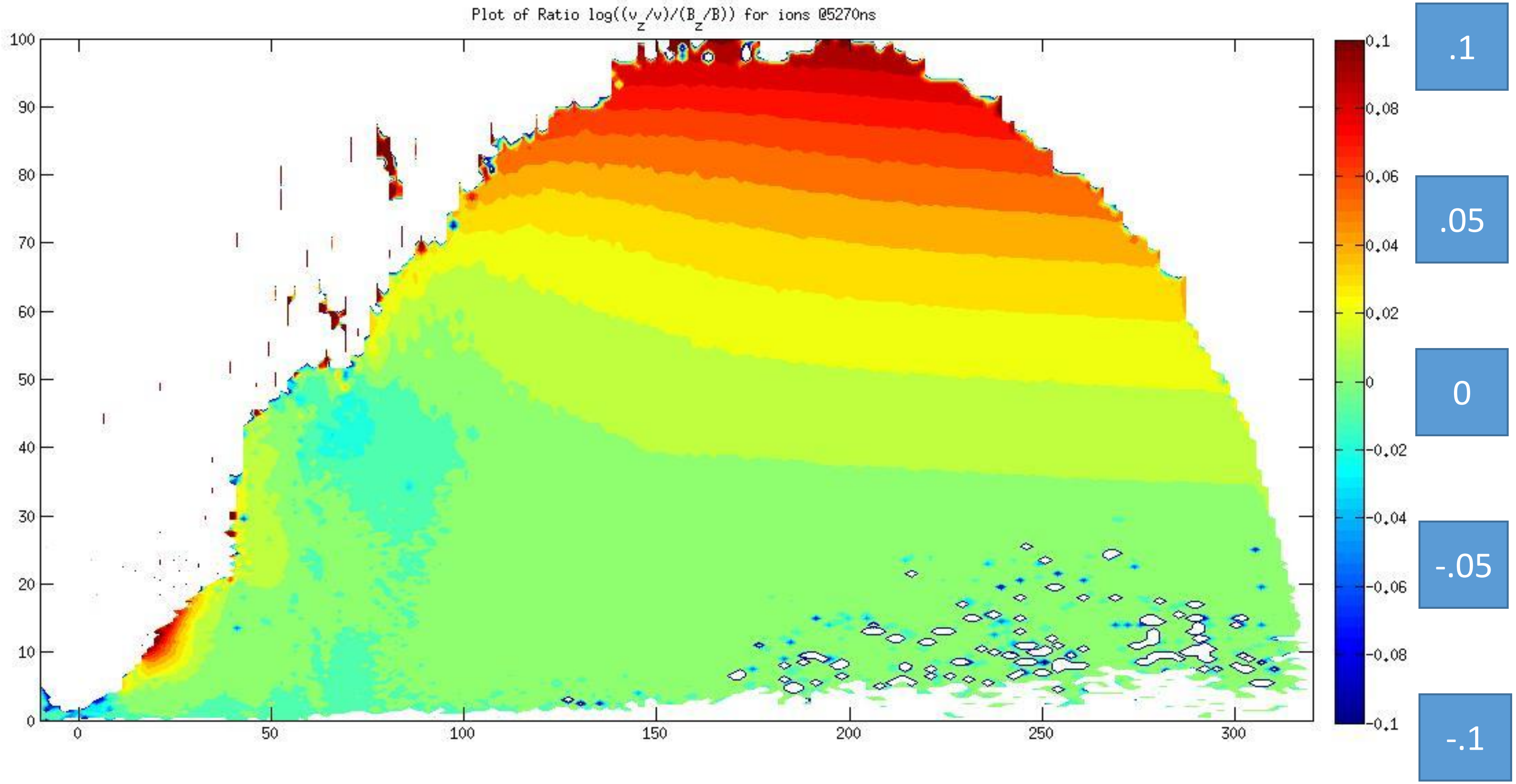
3D Simulation H+ density at 5270ns



3D Simulation log(β) at 5270ns



3D Simulation $\log_{10}\left(\frac{v_{zi}/|v_i|}{B_z/|B|}\right)$ at 5270ns



Performance Comparison

- 2D Simulation (after 8900ns):
    - 1224 processors
    - 2,375,000 cells
    - 20 ns simulated / hour
    - 31,286,470 macro-particles
- 3D Simulation (after 5270ns):
    - 4320 processors
    - 14,000,000 cells
    - 10 ns simulated / hour
    - 216,987,434 macro-particles

Current Work

- Results
  - Saw detachment in both 2D and 3D tests even with lower density plasma using PIC simulations
  - Developed feasible and computationally achievable setup for further investigation using 3D simulations
- Challenges
  - Explaining the on-axis ion density gap, either numerically or physically
  - Investigating the extent and effect of increasing particle anisotropy in the expansion region
  - Quantifying the extent to which detachment occurs in simulations
  - Increasing particle simulation densities to production levels (10^{13} cm^{-3})

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References

1. http://iopscience.iop.org/0963-0252/labtalk-article/57987
2. A.V. Arefiev and B.N. Breizman, Phys. Plasmas **12**, 043504 (2005)
3. Justin M. Little, Aaron S. Rubin, and Edgar Y. Choueiri, IEPC-2011-229 (2011)
4. http://www.lanl.gov/science/NSS/issue2_2010/story4.shtml