Artificially Structured Boundary for Confinement of Effectively Unmagnetized Cryogenic Antimatter Plasmas

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Outline:

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- An ASB is a configuration of electrodes and magnets that creates a static electromagnetic field that is short in range, affecting only the trajectories of particles that are very close to the material wall

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- In the context of this presentation:
  - Spatially periodic arrangement of magnetic cusps
  - Cusps are electrostatically plugged to enhance confinement

Examples:

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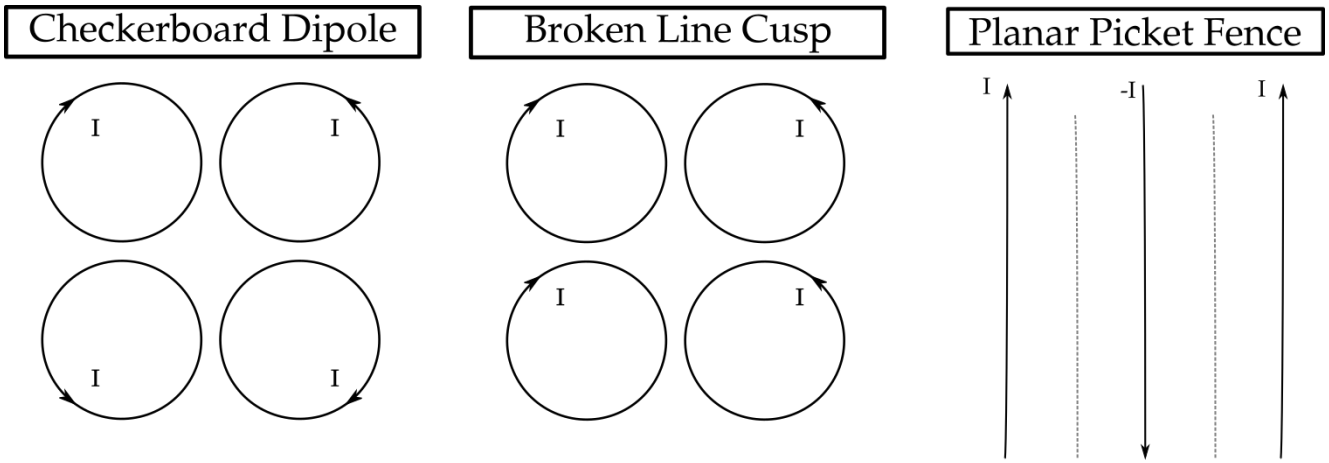

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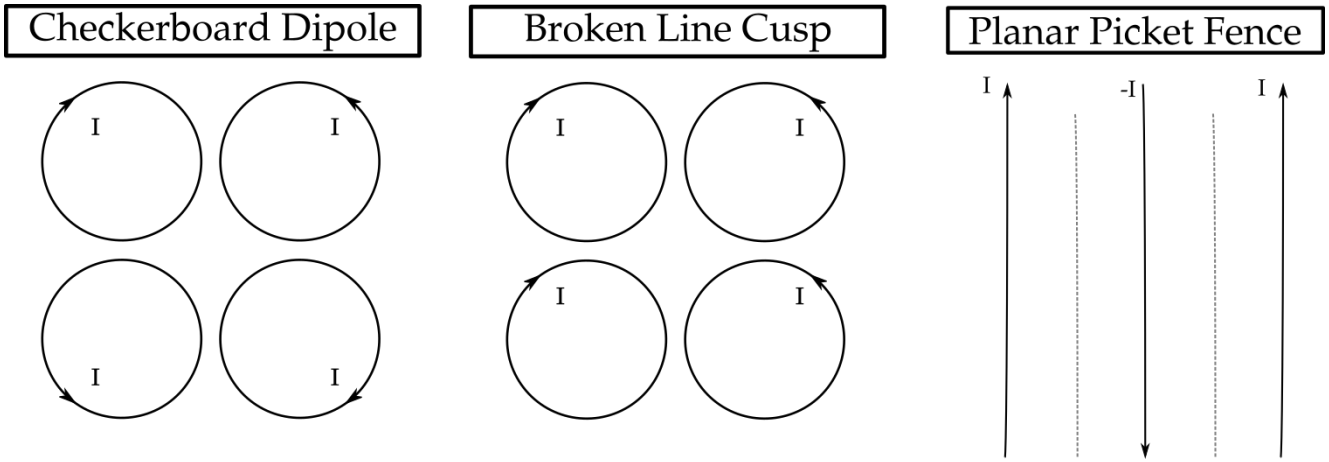

- Traps:
  - Spherical Multipole Trap
  - Cylindrical Multipole Trap
  - Cylindrical Multi-cusp (Picket Fence)

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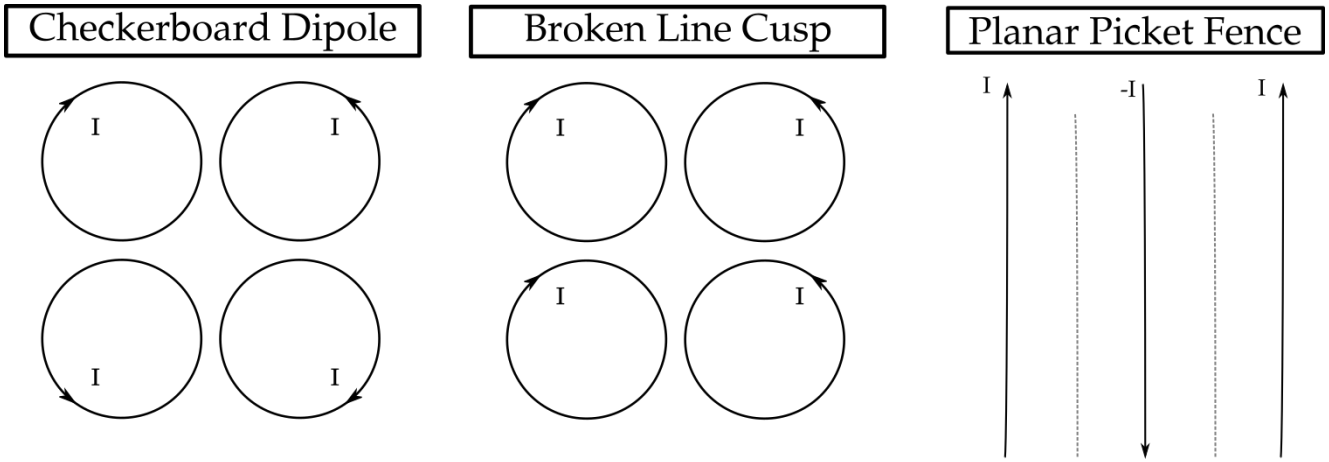

- Traps:
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  - Cylindrical Multipole Trap
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- Old idea, new application

Motivations:

- Confinement volume is effectively free of external electromagnetic fields:
  - $B \approx 0 \implies$ Increase in three-body recombination rate by approximately an order of magnitude

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- Challenges for the production of cold $\bar{H}$ in Penning traps:
  - Space-charge induced $\mathbf{E} \times \mathbf{B}$ drifts
  - Collisions between $\bar{p}$ during mixing process

Outline

Computational Challenges:

- Many possible geometries
- For dipole wall configurations, $\mathbf{B}$ is expensive to compute (2-3 elliptic integrals/dipole/particle/time step)
- $\Longrightarrow$ Need a way to efficiently evaluate many geometries over a wide parameter space

Classical Trajectory Monte Carlo (CTMC) Simulation:

- A CTMC simulation suite was developed in C++ to:
  - Quickly simulate planar geometries
  - Gain baseline understanding of system requirements
  - Determine whether system should be further investigated via PIC
- Parallelized using OpenMP
- Boost C++ Libraries (ODEINT, Math, Random)
- Intel MKL fast Poisson solver used for calculation of electrostatic potential $\phi(\mathbf{r})$
- Normalized units used: $K_{0n} = m_n = q_n = S_n = 1$
  - Simulation results theoretically valid for any particle mass, charge state, initial kinetic energy, or spatial scale
  - Reality limits the applicability of the results (i.e., breakdown voltage, maximum current possible in wire, etc.)

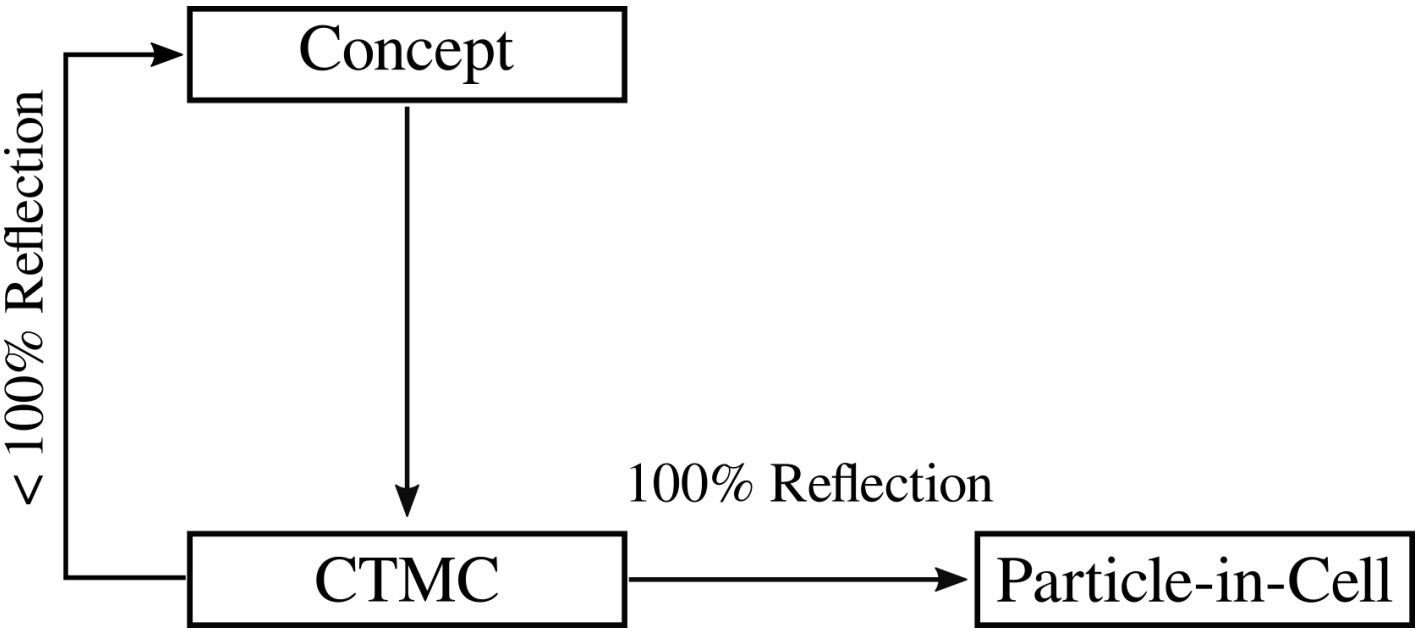
CTMC: Limitations

- Space-charge not included
- No collisional effects
- Poisson solver limited to 3D Cartesian or Spherical Geometry

Particle-in-Cell (PIC) Simulations: Warp

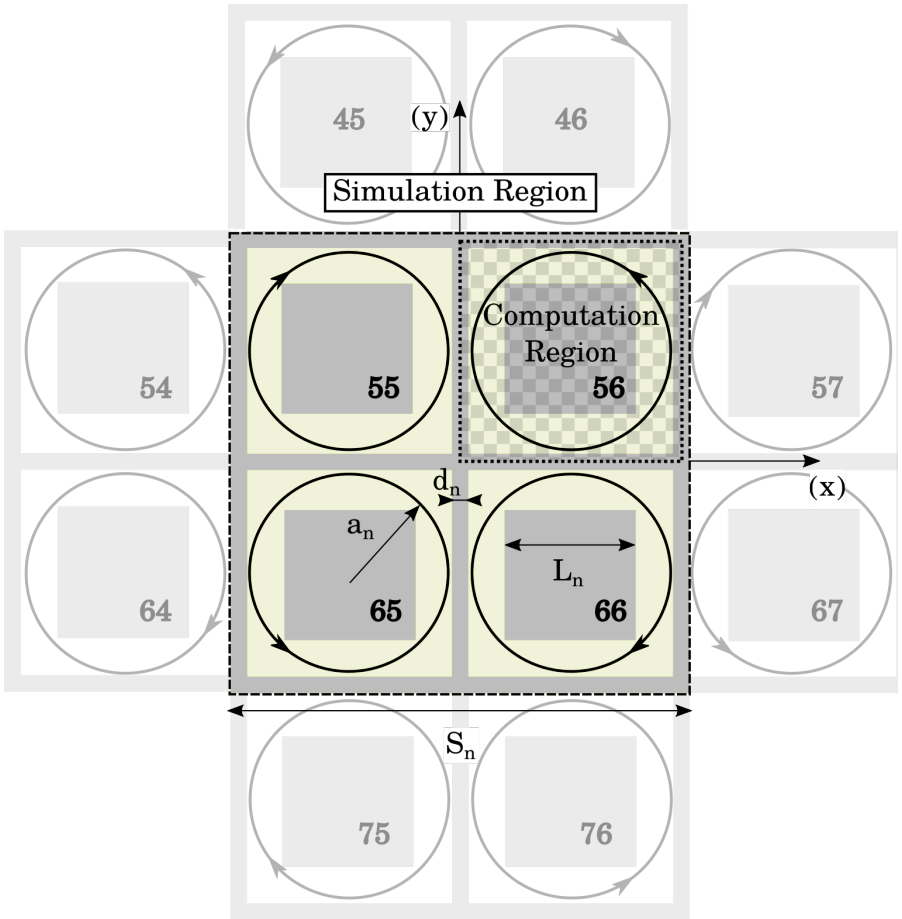
- Benefits:
  - Far more complete picture of plasma dynamics
- Challenges: All good things in life come at a cost...
  - **B** has high gradient near boundary $\Longrightarrow$ Fine grid
  - Plasma has sharp boundary near ASB $\Longrightarrow$ Fine grid
  - Fine grid + Large number of macro particles $\Longrightarrow$ Computation time is extensive
- Warp:
  - Multi-grid solvers
    - Static mesh refinement
    - Adaptive mesh refinement
    - Conductors easily implemented on mesh
  - Drift-Lorentz pusher

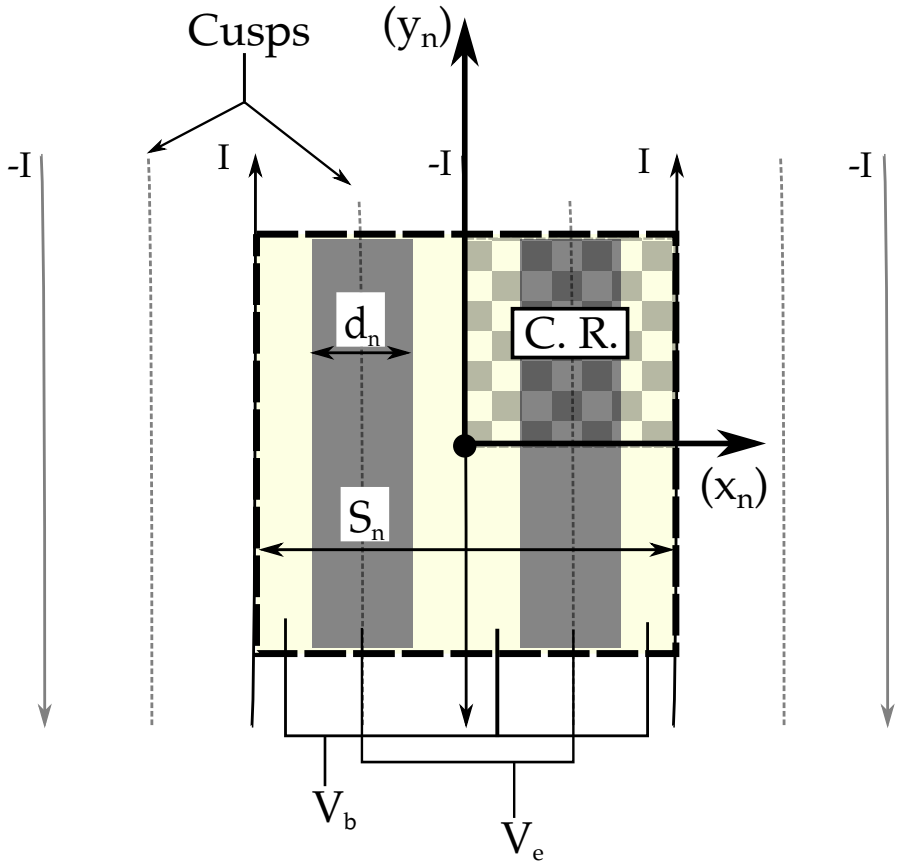
Method of Solution:



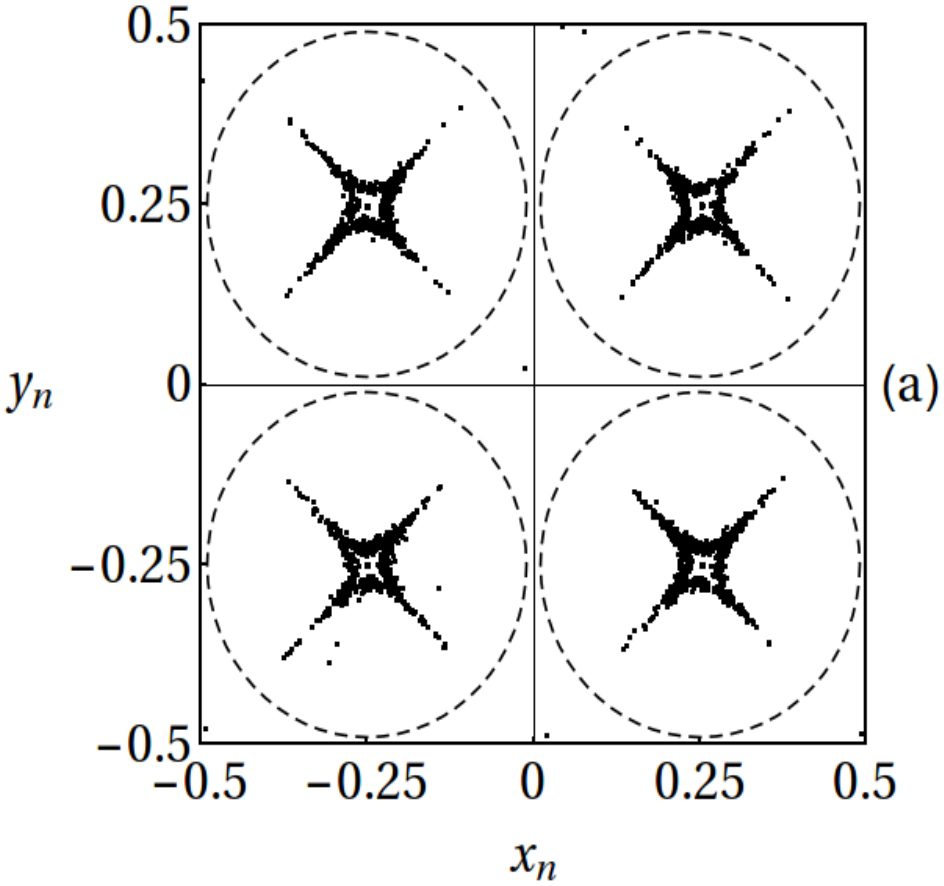
Outline

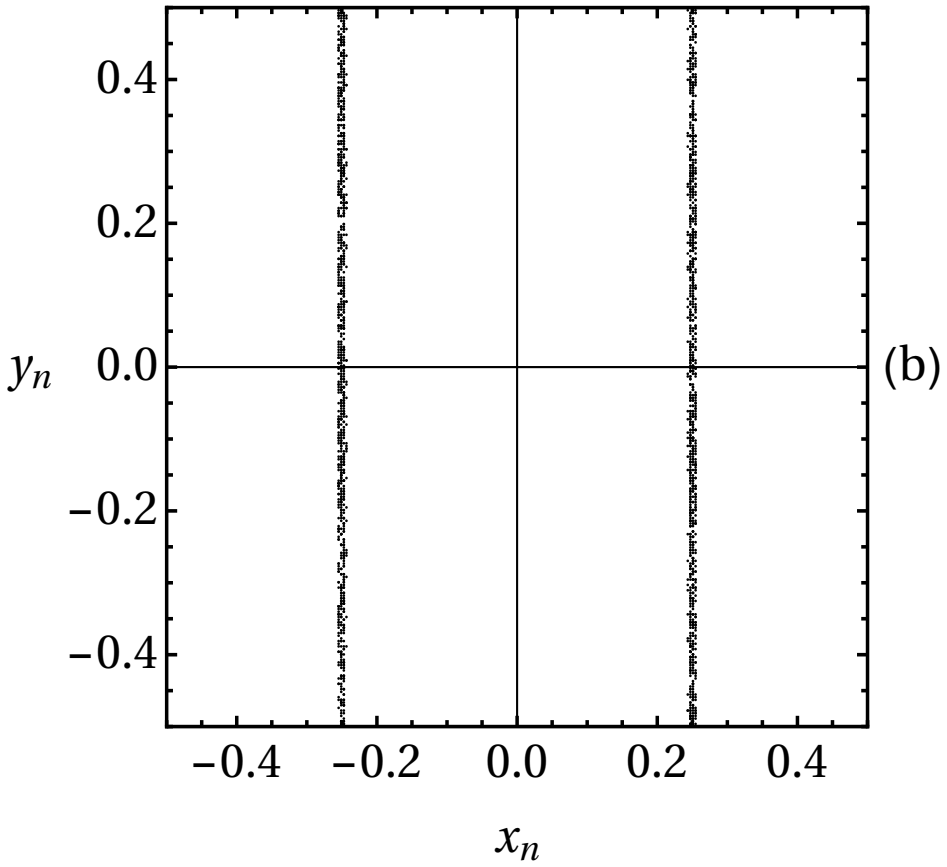
Systems studied via CTMC:



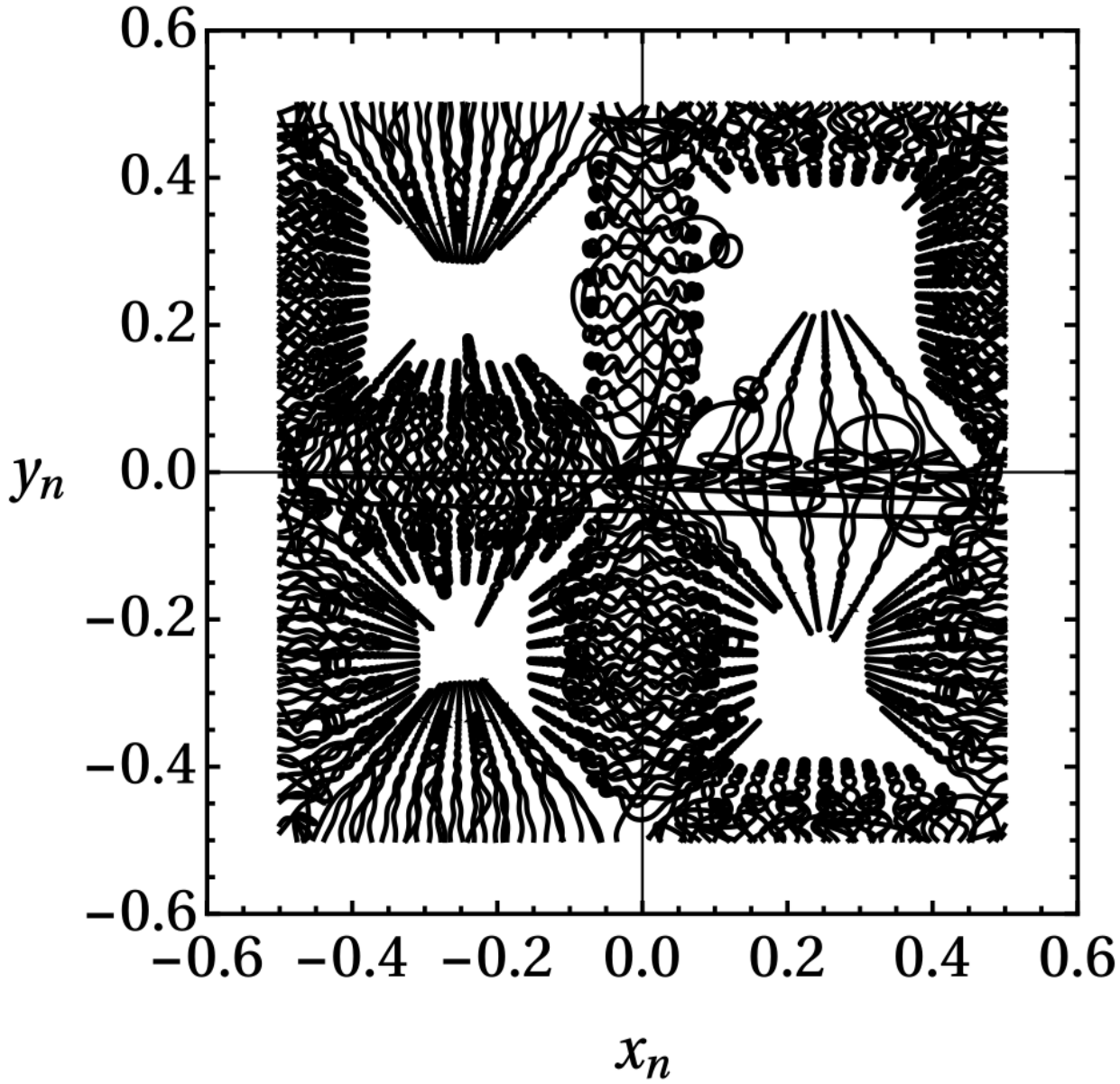


Spatial Distribution of Transmitted Particles:





Checkerboard Dipole: Problematic Trajectories



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  - Difficult to plug
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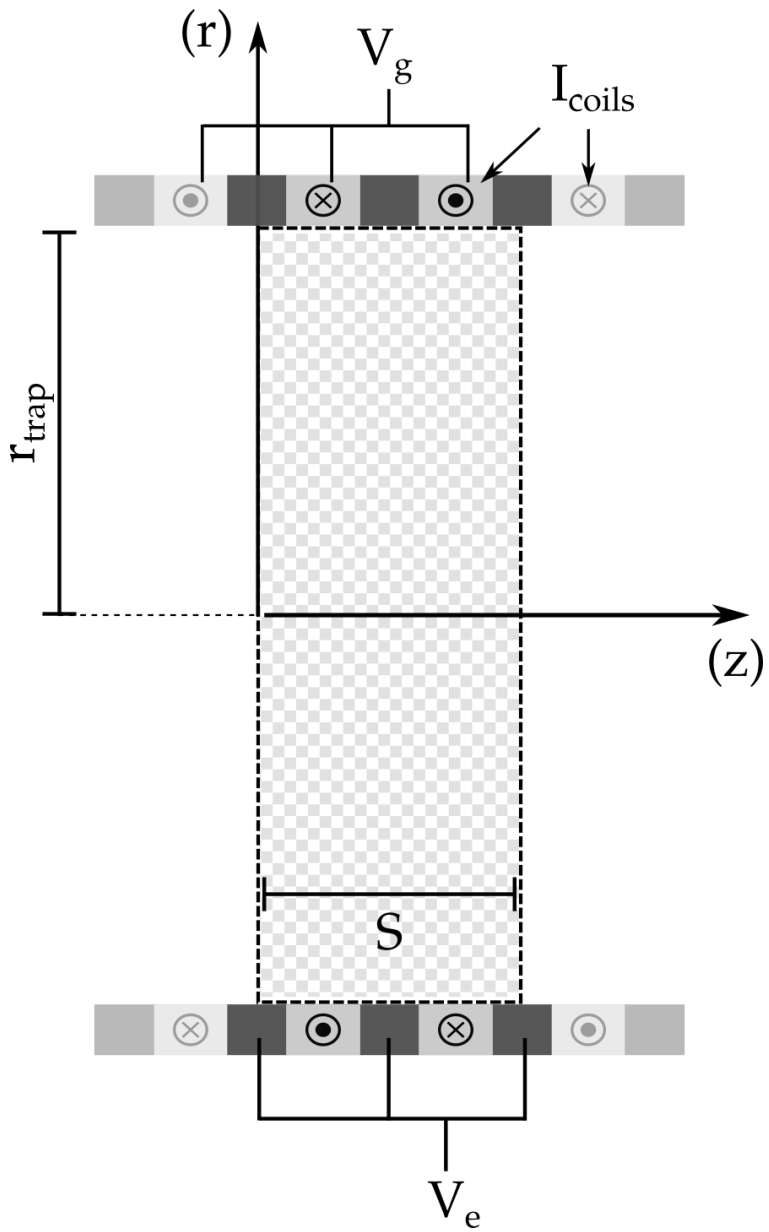
- Dipole wall geometries:
  - Difficult to plug
  - Simulation time is extensive
  - Likely to be difficult to build
- Picket fence:
  - Simple plugging electrode configuration
  - Easy generalization to a full trap design
  - $P_R = 100\%$ for a range of parameters
  - $\implies$ Picket fence should be further examined with PIC

Outline

Cylindrically Symmetric Picket Fence Trap:



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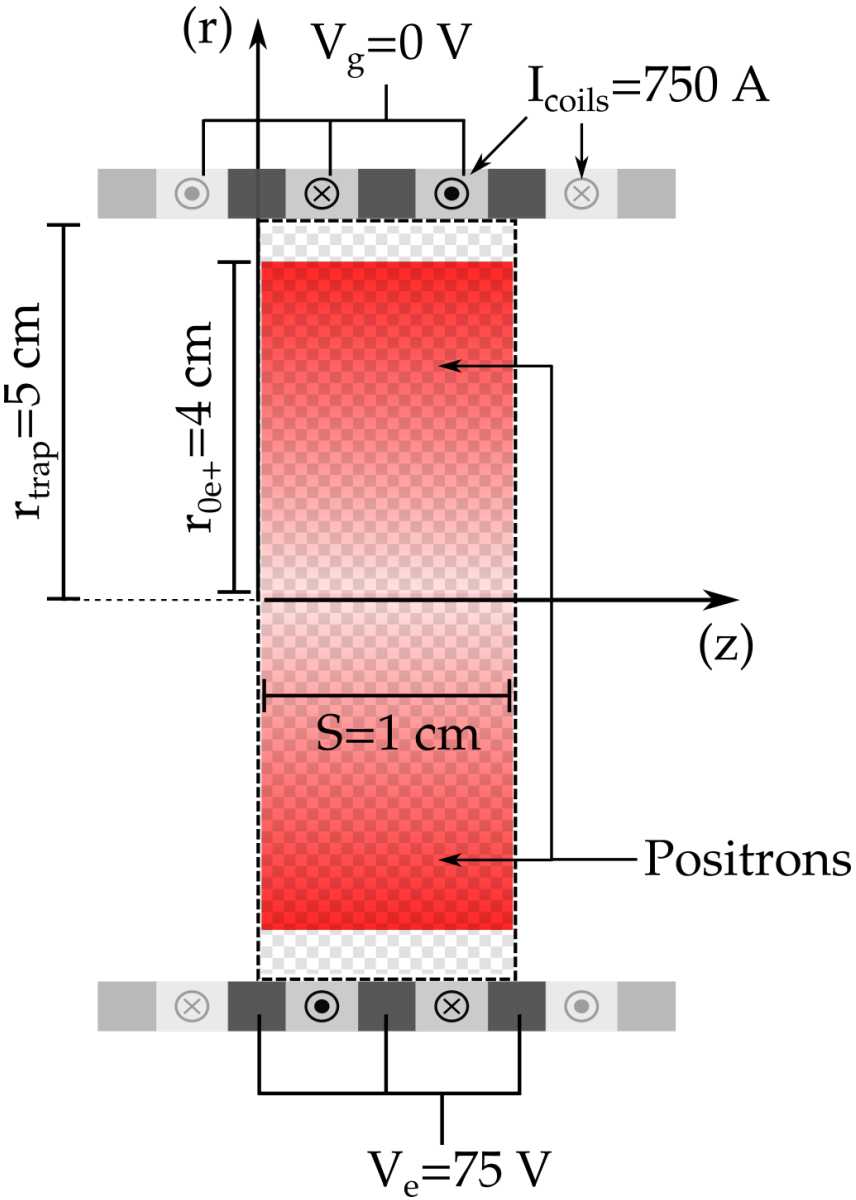
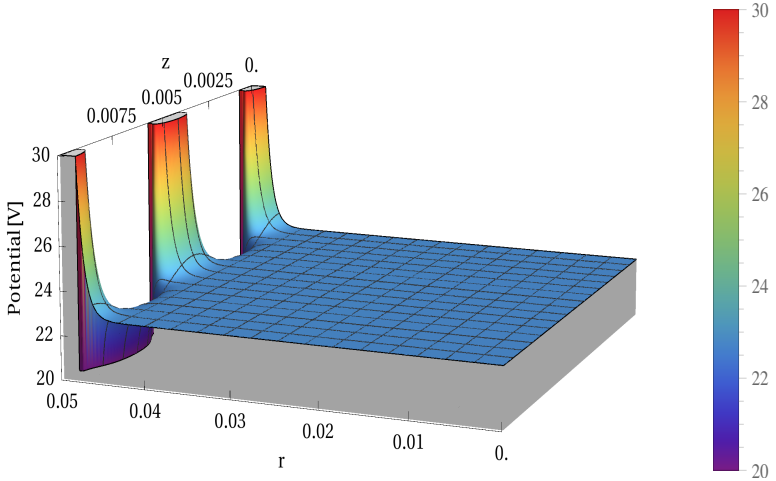
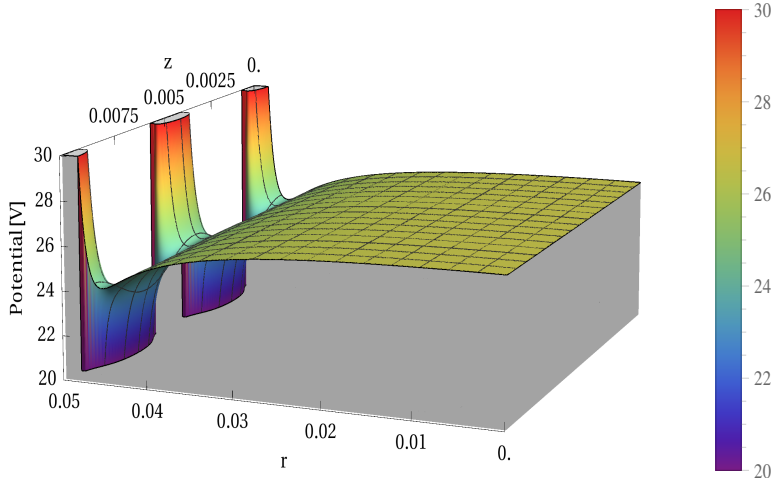
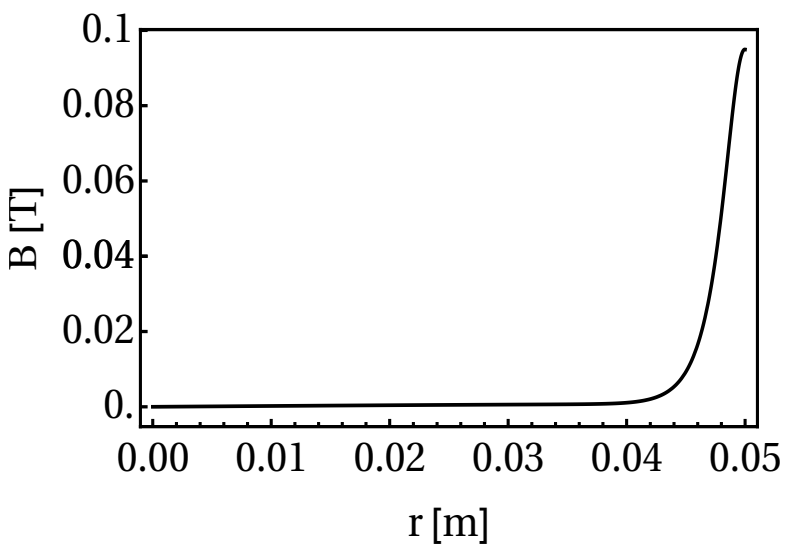
Non-neutral e^+ Plasma Confinement:

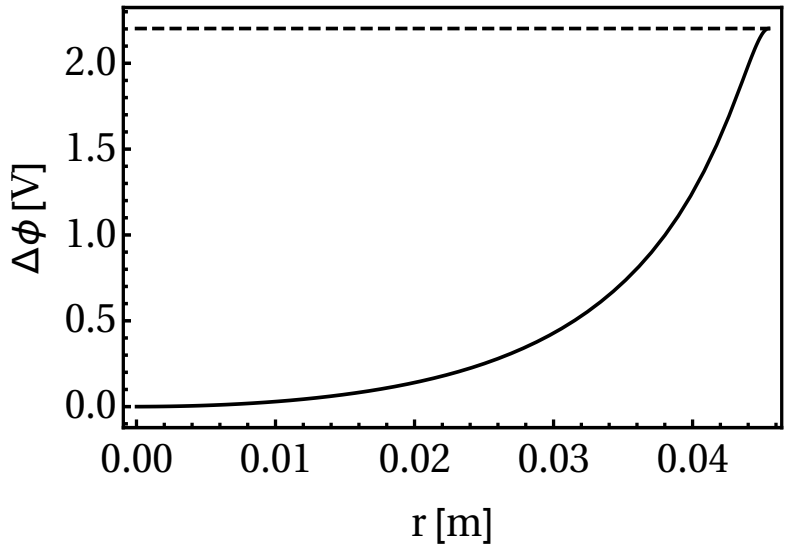


Potential Well and Magnetic Field:

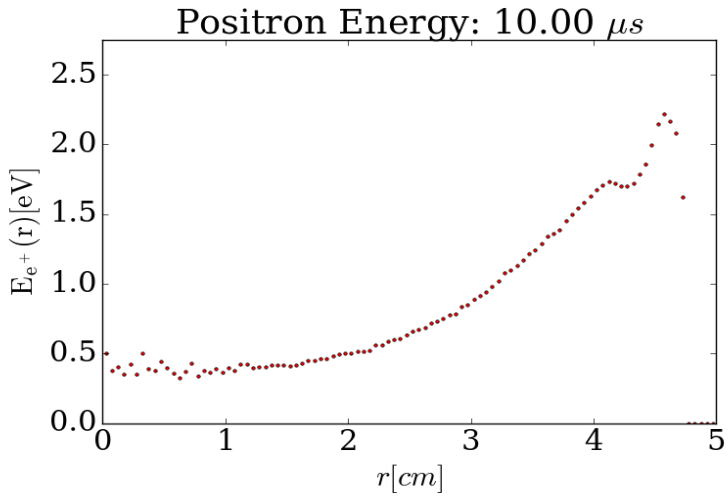


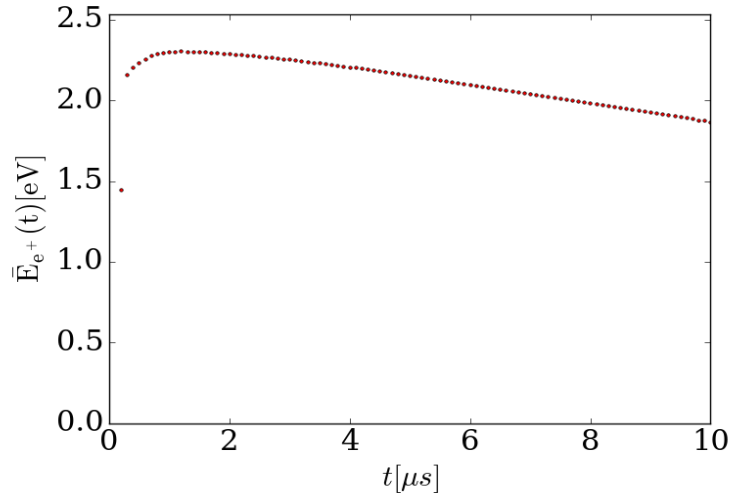


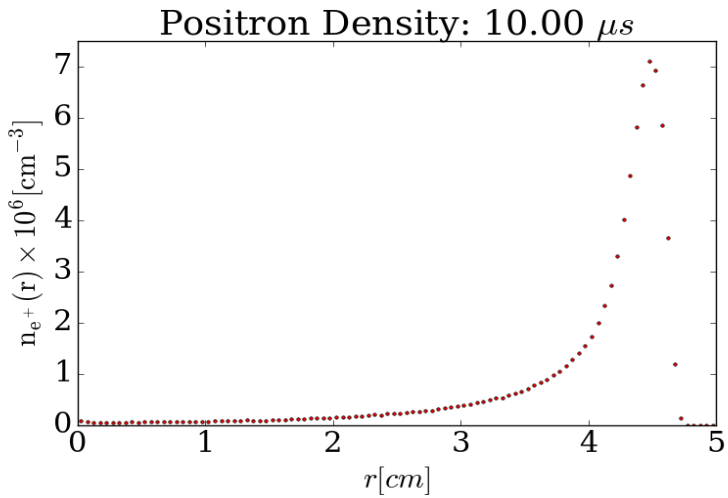


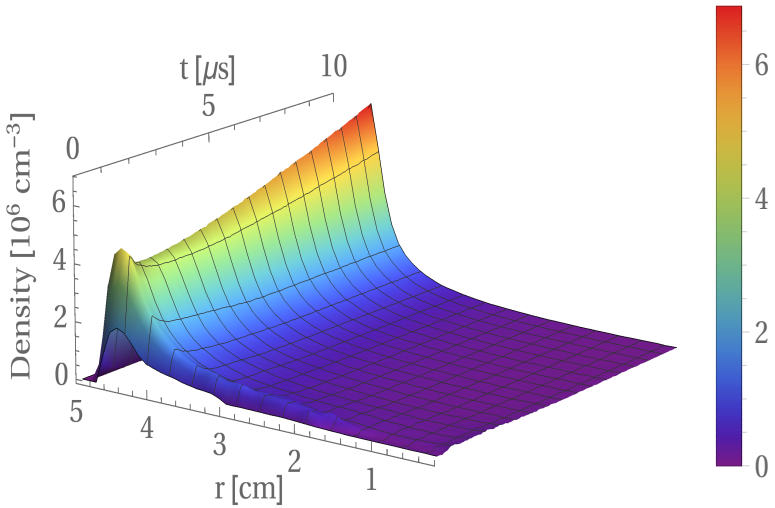


Energy and Density Profiles:









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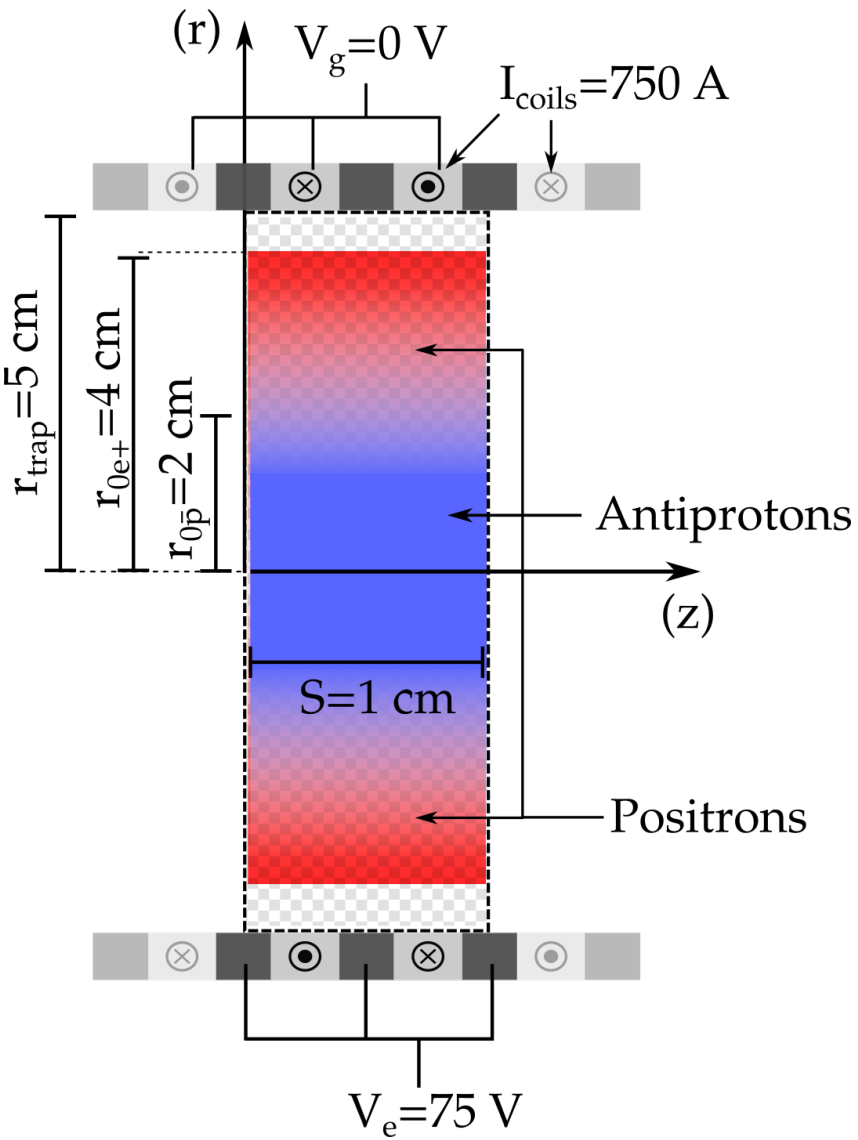
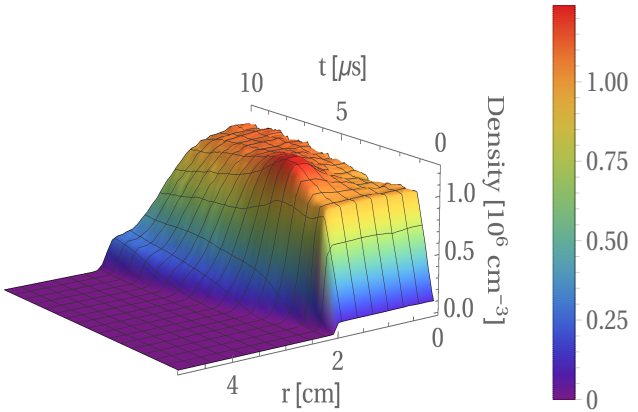
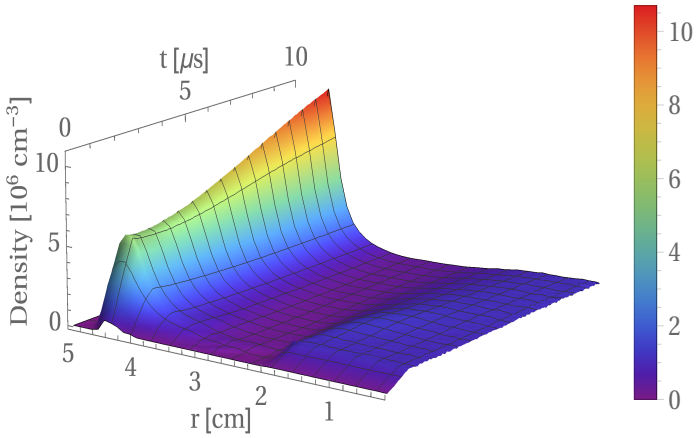
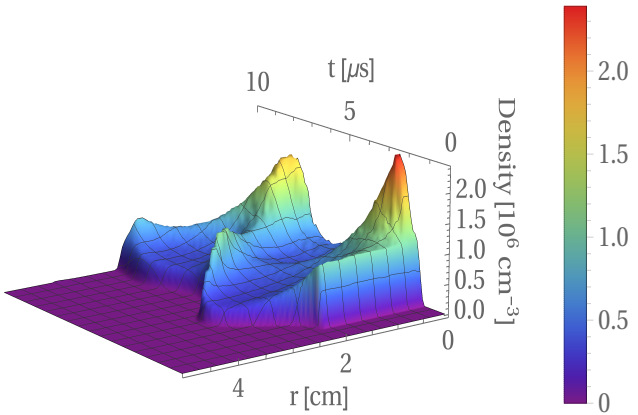
Space-Charge Confinement of Antiprotons:

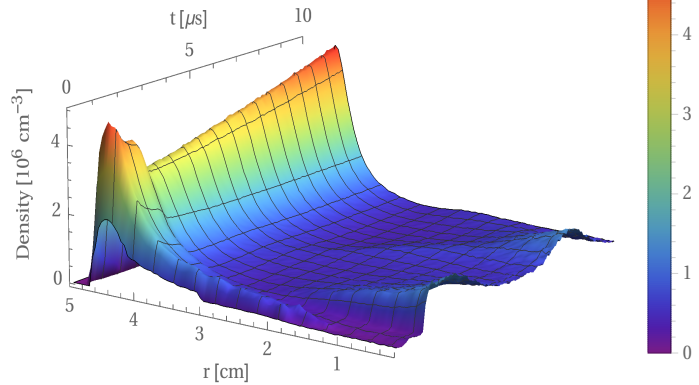


Stepped vs. Simultaneous Injection: Density Profiles









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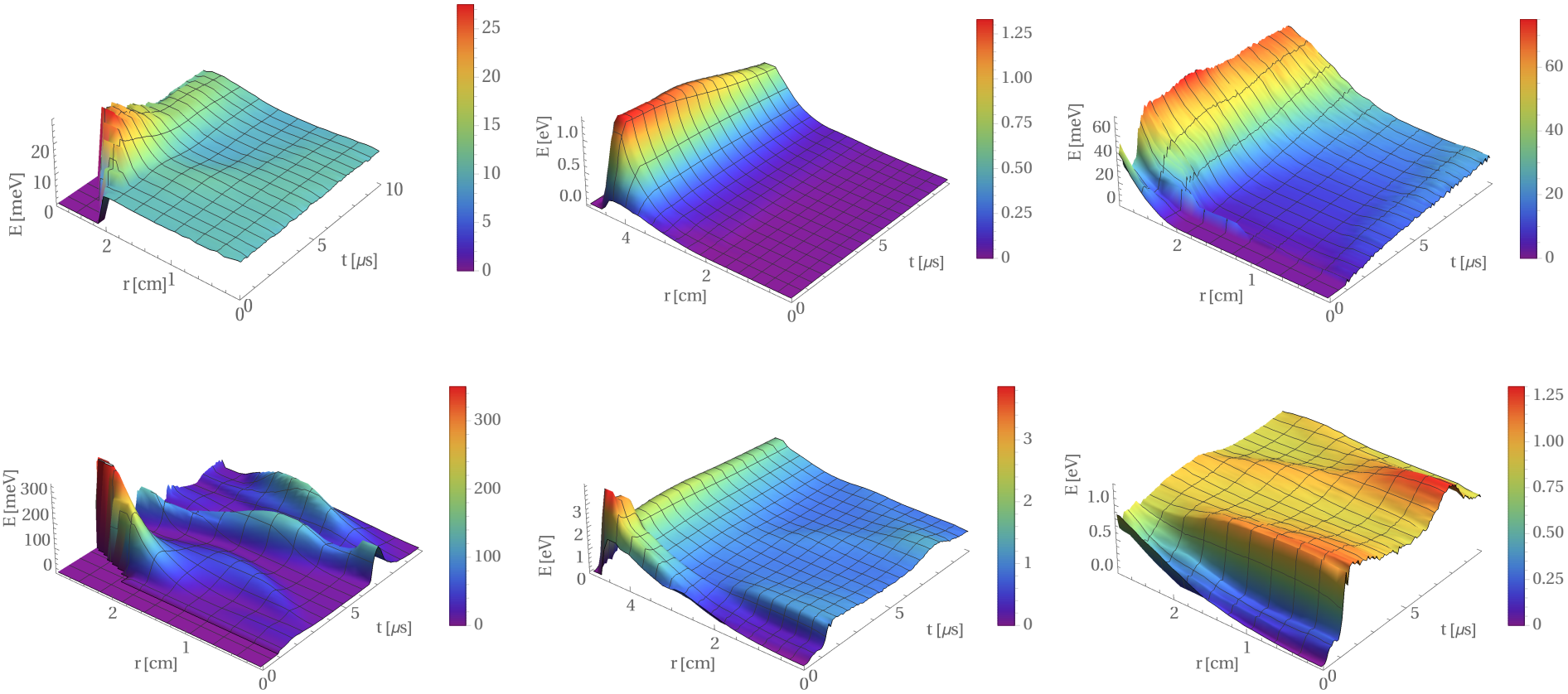

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  - A radial potential well is created
  - $\Longrightarrow$ It may be possible to confine $\bar{p}$ in the potential well formed by the space-charge of the e^+ plasma
- PIC: Space-charge confinement of antiprotons
  - Injection method for the two species is very important
    - Stepped injection $\Longrightarrow$ Large amount of heating in both species
    - Simultaneous injection $\Longrightarrow$ Significant reduction in heating
  - If the injection of cryogenic e^+ and $\bar{p}$ can be realized, space-charge based $\bar{p}$ confinement may result in a larger number of cold $\bar{H}$

Future Work:

- Simulate the full ASB trap:
  - What is the depth of the axial space-charge potential well?
  - How should the ends of the trap be constructed?
  - How should the plasmas be injected so as to maintain cryogenic plasma temperatures?

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- Simulate the full ASB trap:
  - What is the depth of the axial space-charge potential well?
  - How should the ends of the trap be constructed?
  - How should the plasmas be injected so as to maintain cryogenic plasma temperatures?
- What are the density and temperature limits of space-charge confined antiprotons?

Questions and Comments?

- Thank you for your attention

Properties:

Electrostatic Potential:

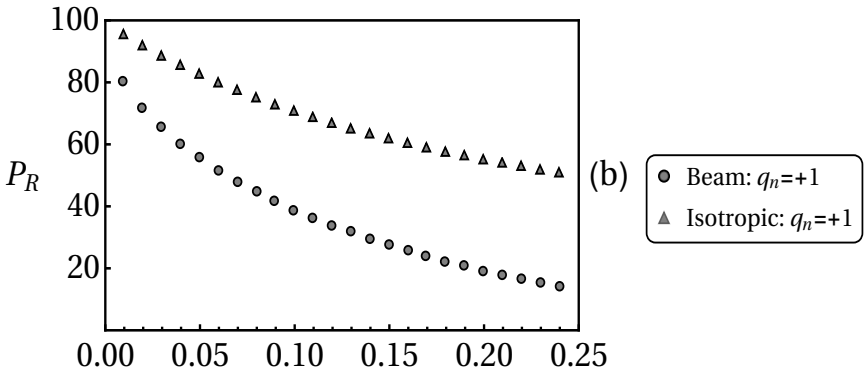
- Checkerboard: $\Longrightarrow$ Must be computed numerically
- Picket Fence: $\Longrightarrow$ Can be computed analytically

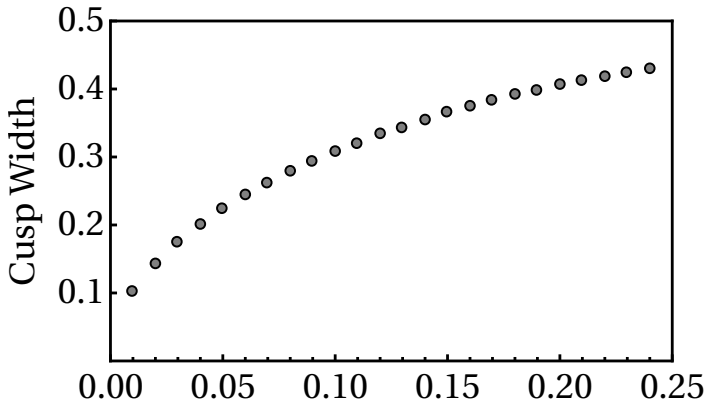
Magnetic Field:

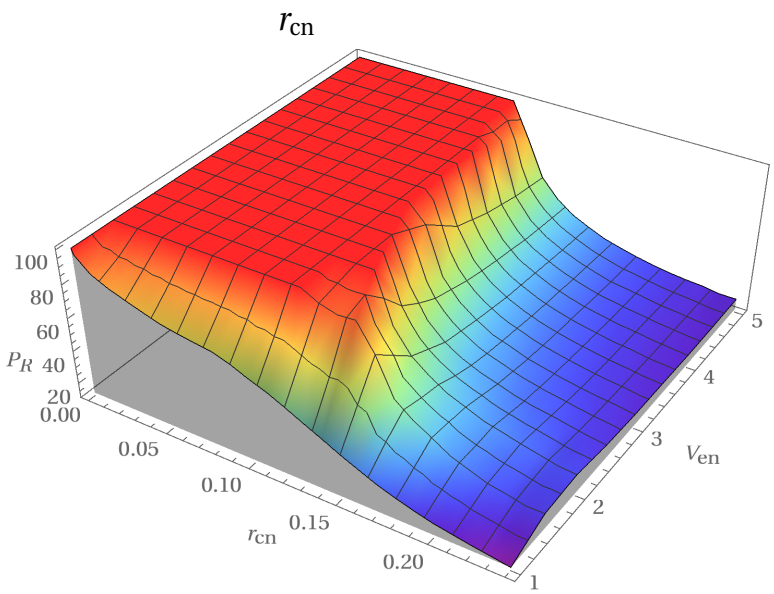
- Checkerboard: $\Longrightarrow$ Two elliptic integrals per timestep, per current loop, per particle
- Picket Fence: $\Longrightarrow$ Simple functions:

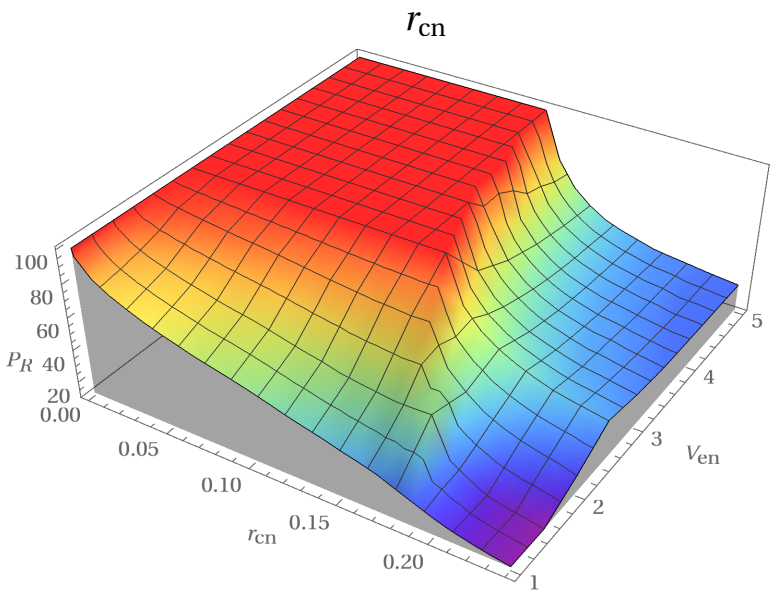
$$
\begin{aligned}
r_{cn} &= \frac{\sqrt{2mK_0}}{|q|B_m S}, \qquad B_m = 2\mu_0 I/S \\
\mathbf{B}_n &= \frac{\sqrt{2}\,\mathrm{sgn}(q)}{r_{cn}}(\beta_x(x_n, z_n)\hat{\mathbf{i}} + \beta_y(x_n, y_n)\hat{\mathbf{k}}) \\
\beta_x(x_n, z_n) &= -\frac{\cos(2\pi x_n)\sinh(2\pi z_n)}{\cos(4\pi x_n) - \cosh(4\pi z_n)} \\
\beta_y(x_n, z_n) &= \frac{\sin(2\pi x_n)\cosh(2\pi z_n)}{\cos(4\pi x_n) - \cosh(4\pi z_n)}
\end{aligned} \tag{1}
$$

Results: Picket Fence









Checkerboard Dipole:

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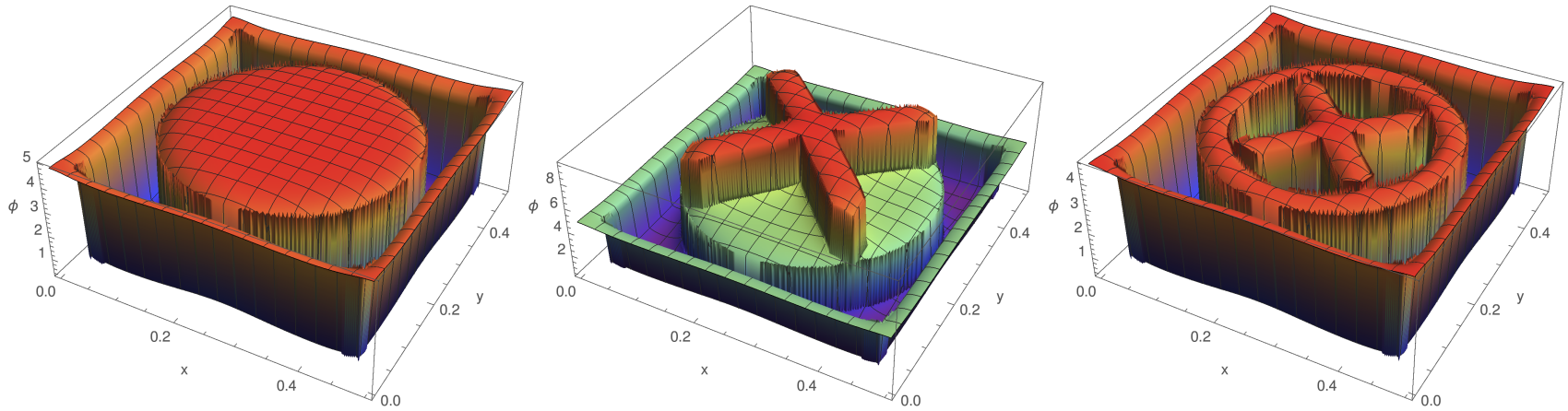

- Magnetic field is expensive to compute at each step:

$$B_{sn,r} = \frac{\sqrt{2}}{\pi}\frac{\mathrm{sgn}(q)}{r_{cn}}\eta_{1n}(r_n, z_n)[\kappa_{1n}(r_n, z_n)E(m_a) - K(m_a)],$$

$$B_{sn,z} = \frac{\sqrt{2}}{\pi}\frac{\mathrm{sgn}(q)}{r_{cn}}\eta_{2n}(r_n, z_n)[\kappa_{2n}(r_n, z_n)E(m_a) + K(m_a)], \quad (2)$$

Picket Fence:

- Electrostatic potential can be calculated analytically by separation of variables
- Magneteic field is in terms of simple functions:

$$\mathbf{B}_n = \frac{\sqrt{2}\,\mathrm{sgn}(q)}{r_{cn}}(\beta_x(x_n, z_n)\hat{\mathbf{i}} + \beta_y(x_n, y_n)\hat{\mathbf{k}})$$
$$\beta_x(x_n, z_n) = -\frac{\cos(2\pi x_n)\sinh(2\pi z_n)}{\cos(4\pi x_n) - \cosh(4\pi z_n)}$$
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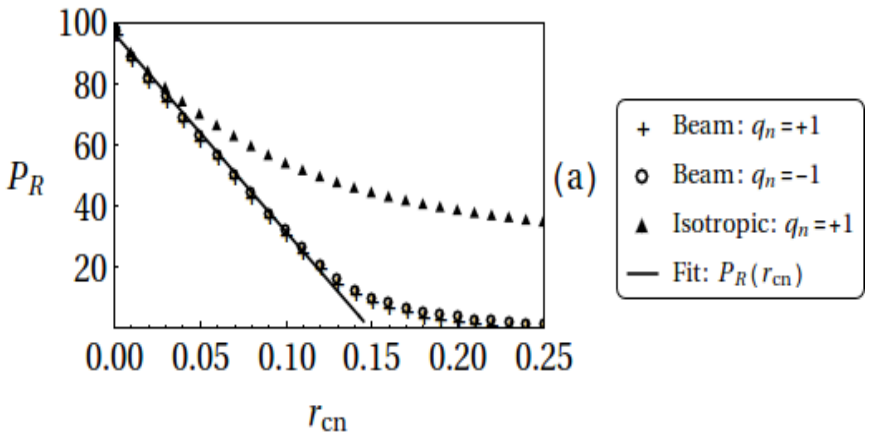
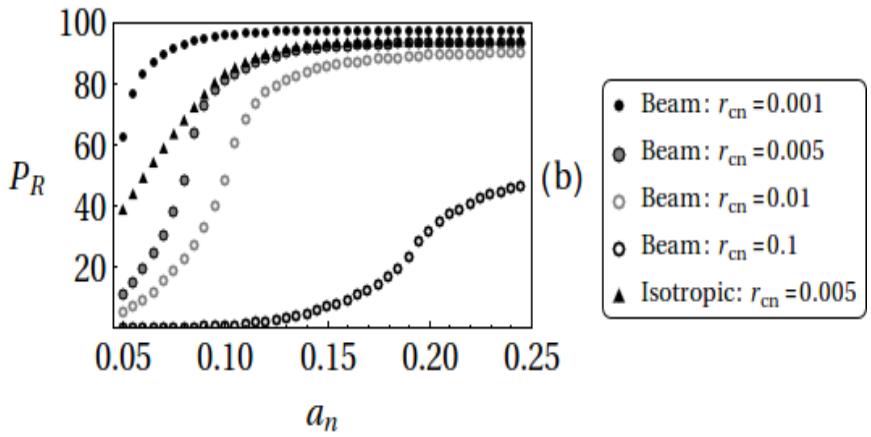
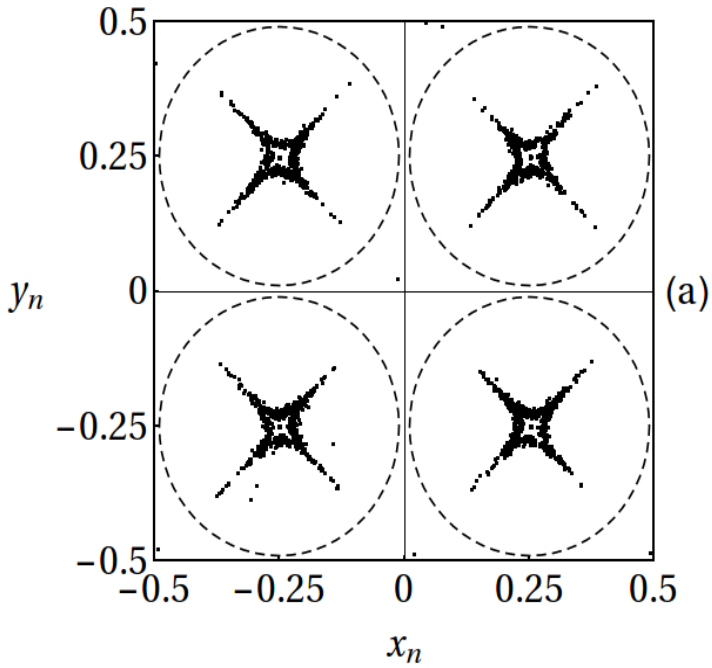
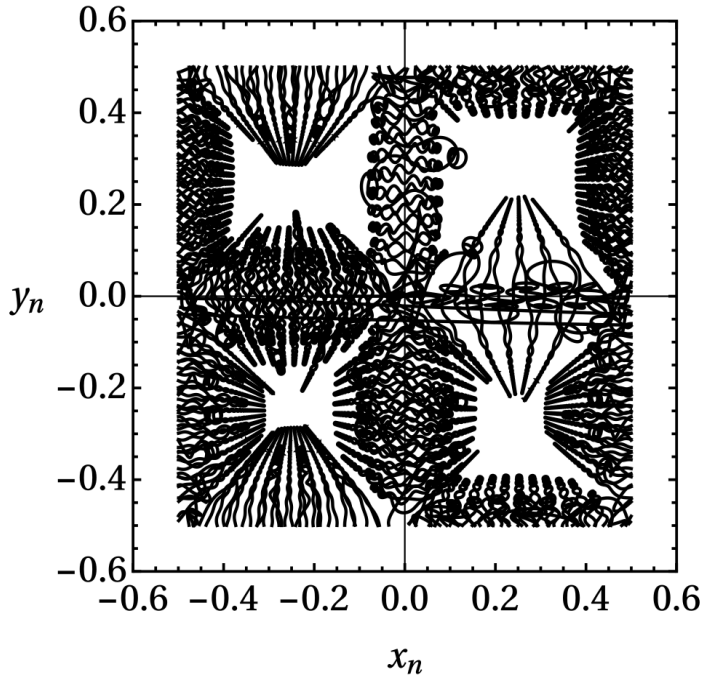
- $r_{cn} = \frac{\sqrt{2mK_0}}{|q|B_m S}$
- $B_m = 2\mu_0 I/S$

Results: Checkerboard Dipole

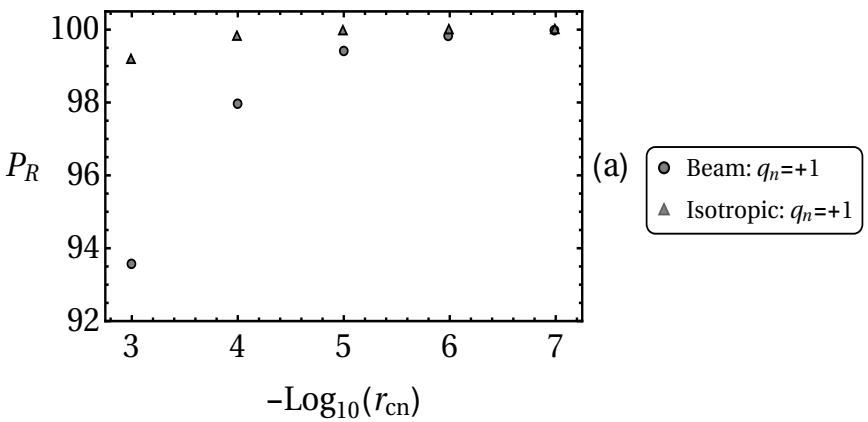


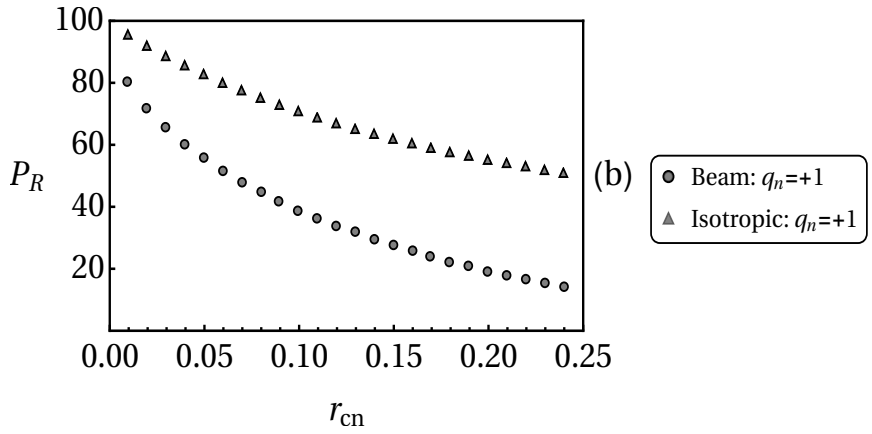


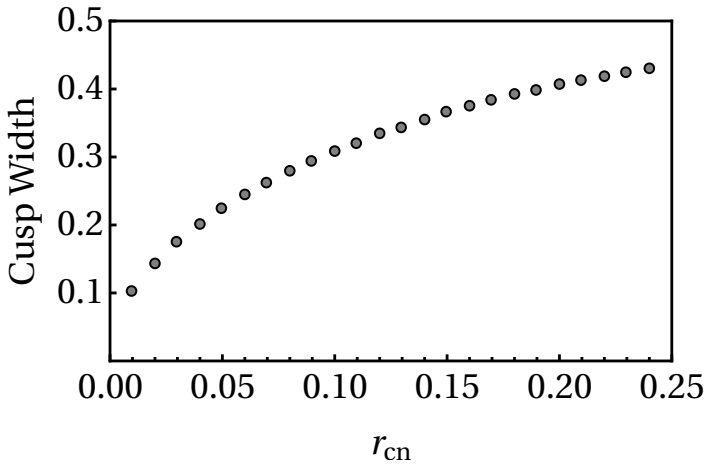


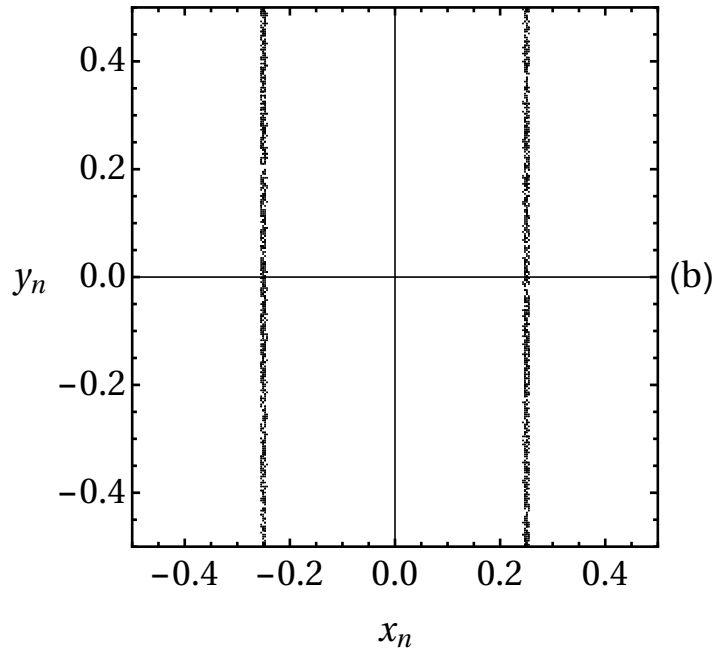


Results: Picket Fence ($\mathbf{E}_n = 0$)

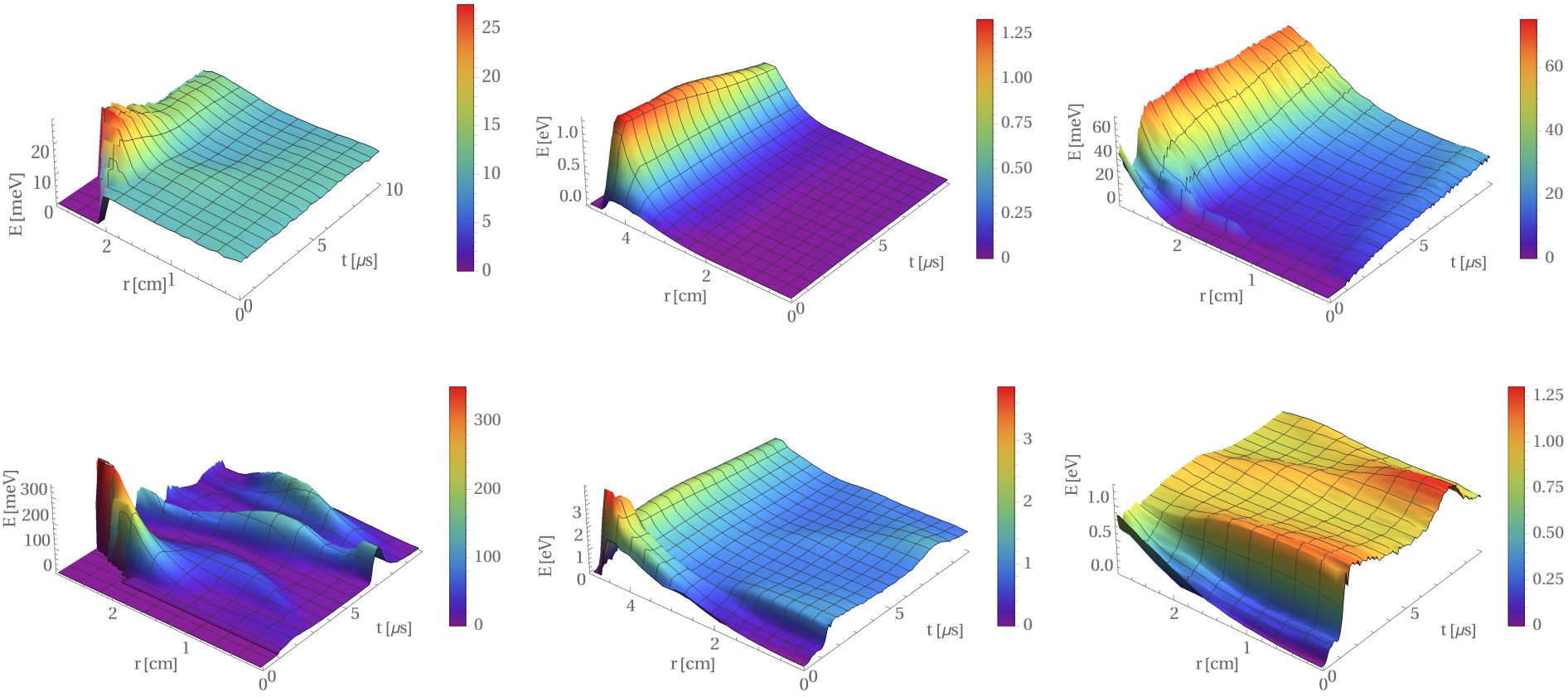








Stepped vs. Simultaneous Injection: Energy Profiles



Stepped vs. Simultaneous Injection: Density Profiles