Particle-in-cell investigation of diamagnetic field-reversal in expanding plasmas

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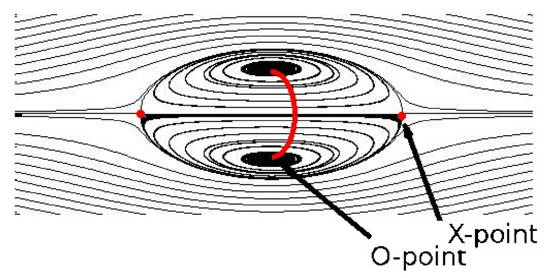
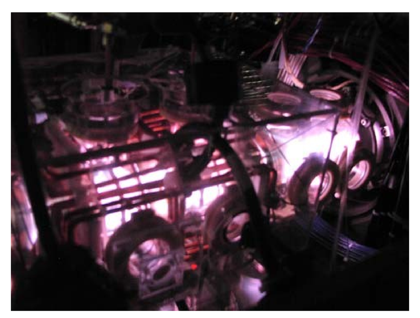
Goal to study basic field-reversed configuration (FRC) physics

FRC topology

- Type of compact toroid
- Closed magnetic field lines inside an ovaloid separatrix region
- Similar to tokamak without center body or toroidal field component
- Magnetic nulls located at ends and around current loop





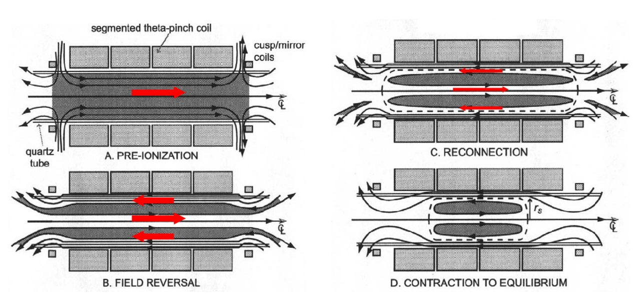
PFRC1 experiment at PPPL

Relevance to fusion research

- FRC-based confinement concepts complement tokamak and ICF research
- Potential for smaller reactor, advanced fuels, and space propulsion
- Understanding FRC physics is complicated; not explained by MHD
- Relatively inexpensive experiments; research in USA and Japan
- Overcoming instabilities rotational, tearing, and tilt modes) major challenge

Interest in FRC formation

- Theta-pinch – standard method (LANL, AFRL, Nihon)
- Spheromak merging (MRX, SSX, Colorado)
- Rotating magnetic fields (PFRC, TCS-U)
- Interesting to find new ways to form FRCs

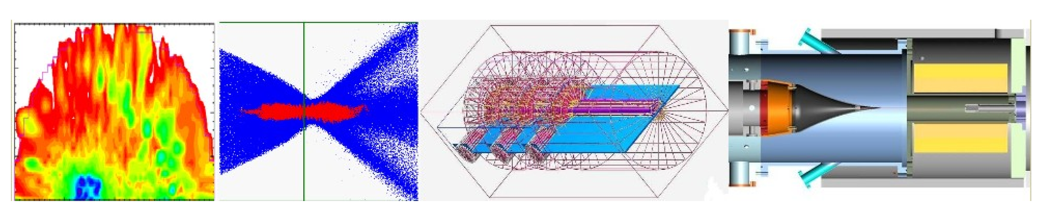


Theta-pinch FRC formation (Source: Ref. [1])

The Large-Scale Plasma (Lsp) particle-in-cell code

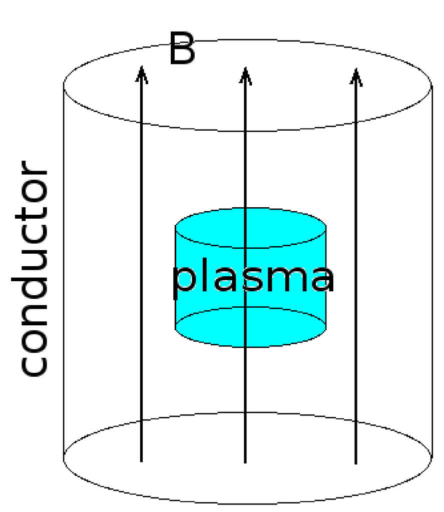
Code description

- Fully electromagnetic, particle-in-cell (PIC) description of plasma
- Serial or parallel with standard MPI for communication
- Multiprocessor jobs subdivide structured grids into regions and domains
- Extensible C code with many physics packages added over time (scattering, fusion, circuits, ionization etc.)
- Energy conserving explicit (ECE), Direct Implicit (DI), and new Magnetic Implicit (MI) algorithms for time-advance
- Lsp is commercial software developed my Mission Research Corporation, ATK, and Voss Scientific [2]

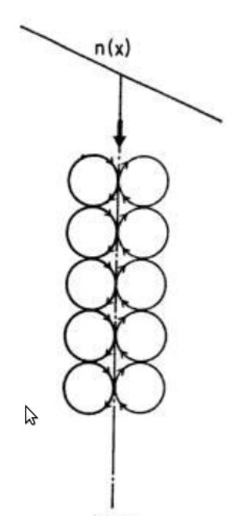


Can an expanding plasma cloud spontaneously form an FRC?

Diamagnetic currents on plasma edge may reduce/reverse field in core



- Consider blob of plasma in center of conducting cavity
- Axial magnetic field present (e.g. from mirror coils)
- Density gradient at edges will produce diamagnetic current
- How will plasma respond?

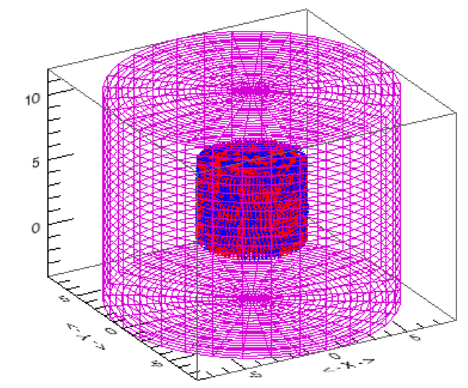


3D cylindrical simulations

A typical case:

Conducting cylindrical cavity; R=8 cm, Z=16 cm
Cylindrical column of hydrogen plasma; R_p=3 cm, Z_p= 8 cm
Initial plasma conditions:

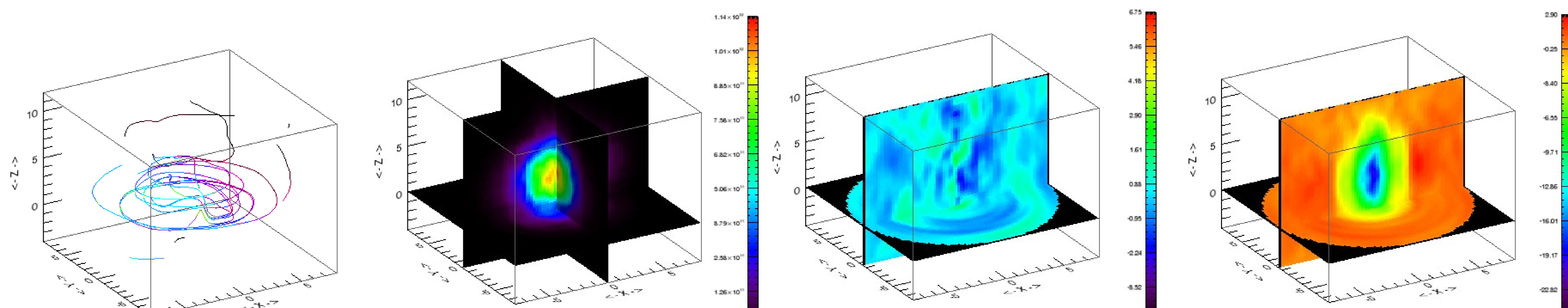
- Plasma density, n=1.0E+12 cm^{-3}
- Ion temperature, T_i=1 eV
- Electron temperature, T_e=100 eV
- Initial B_z field varied parametrically (e.g. 0G, 200G, 300G, and 500G)



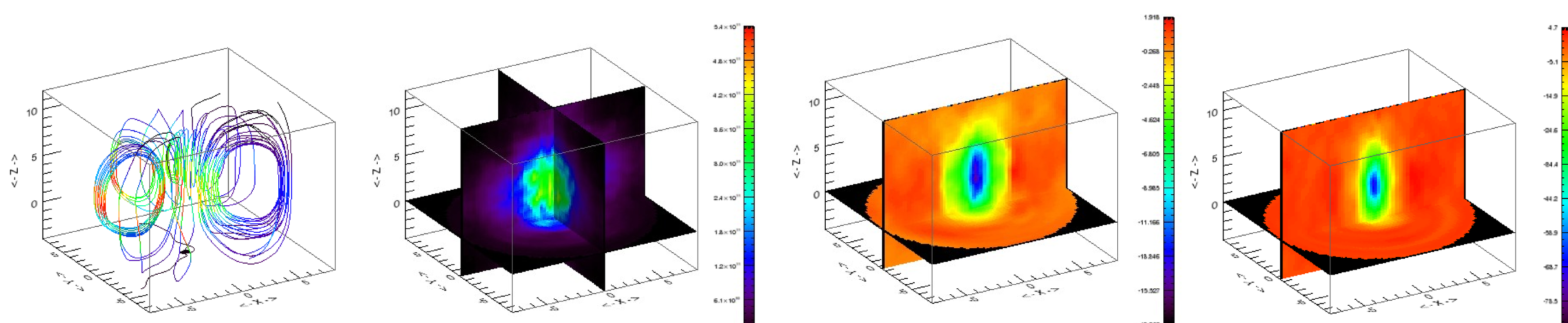
Typical coarse discretization – 24x16x24 structured mesh, 324,000 particles, dt=1.8 ps, Direct Implicit (all parameters varied)

We expect particles to escape on time-scale inversely proportional to ion acoustic speed: L/C_S = (4 cm)/(1.4e7 cm/s) ~ 300 ns

Diamagnetic currents and magnetic fields produced



Diamagnetic Current B_{z0}=500G case; Density profile at 160 ns B_{z0}=0G case; B_z at 160 ns B_{z0}=0 case; Diamagnetic B_z at 160 ns B_{z0}=200G case (13% reversal)



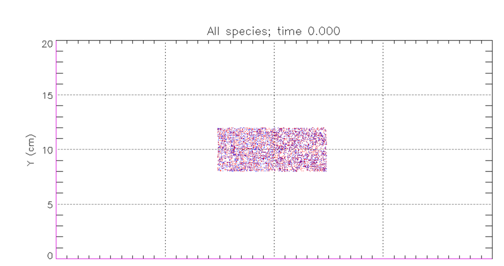
Diamagnetic B-field B_{z0}=500G case; Density profile at 160 ns B_{z0}=0G case; Diamagnetic B_z at 160 ns B_{z0}=300G case (6% reversal); Diamagnetic B_z at 160 ns B_{z0}=500G case (16% reversal)

2D Cartesian simulations

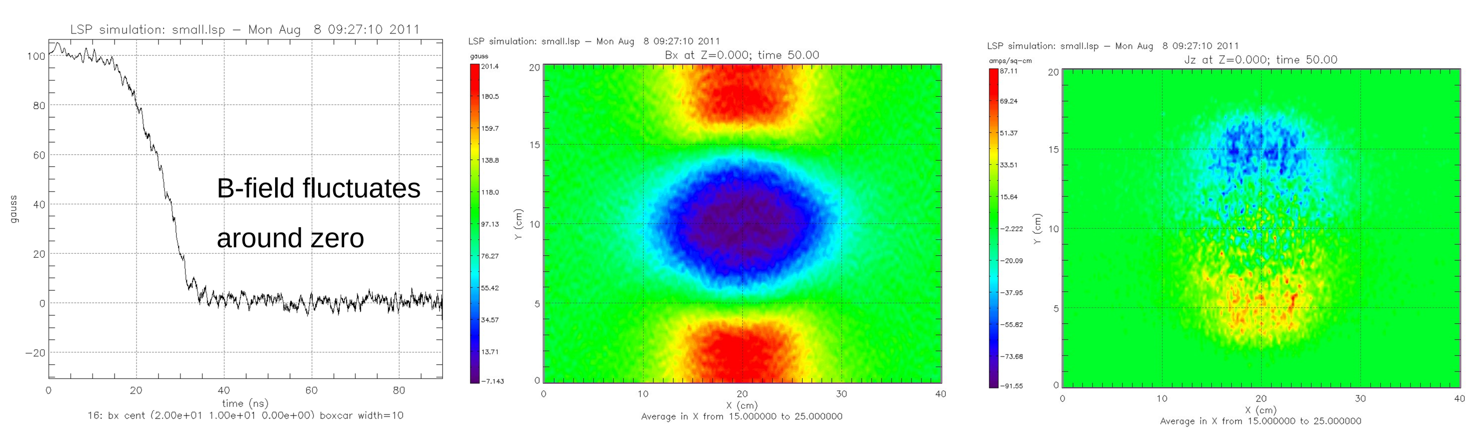
A Typical Case:

Conducting rectangular cavity; H=20 cm, W=40 cm
Rectangular plasma in center; H_p=4 cm, W_p=10 cm
Initial plasma conditions:

- Plasma density, n=2.0E+12 cm^{-3}
- Ion temperature, T_i=1 eV
- Electron temperature, T_e=100 eV
- Initial B_z field 100 G



Typical discretization – 200x100 Cartesian mesh, 400,000 particles, dt=10 ps, Energy Conserving Explicit



Slight transient pockets of reversed field found in above case (and many like it) but never full FRC formation

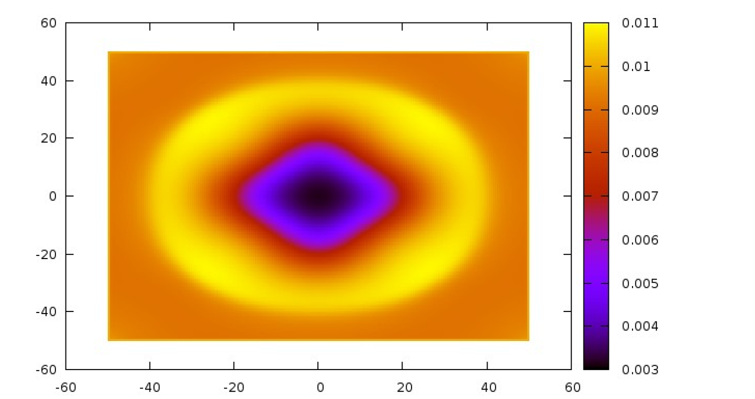
Comparison to ideal MHD

Solve similar problem with MHD2D solver[3]

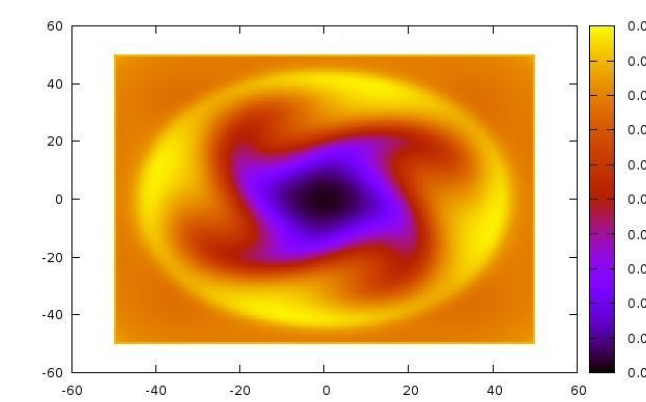
- Code solves for standard vector of conserved variables using Godunov finite-volume approach with HLL Riemann solver
- Periodic boundary conditions (as apposed to conducting used with PIC)
- Out-of-plane initial magnetic field set and watch reduction at center due to diamagnetic current
- Many cases tried but none show reversed field (for high Beta it nears zero)

Example: 100x100 domain, 200x200 grid, B_{OUT}=.01, P_0=1.0, Beta=$2P/B^2$=2.0E+4, CFL_{MAX}=.75

Plasma is 20x20 square. Cases below show out of plane B-field at T=100 for cases with and without rotation



Out of plane B-field (zero rotation)



Out of plane B-field (omega=.2)

Conclusions

FRC formation strictly due to diamagnetic currents in an expanding plasma cloud was not observed in our simulations

Diamagnetic currents *can reduce* the field to fluctuations around zero (PIC) or slightly above zero (MHD)

Continuing and future work

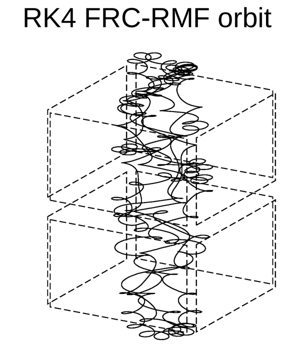
Expanding cloud case:

- Incorporate initial currents to aid the diamagnetic current
- Think harder about the physics. Could some conservation law be at play?

Apply Lsp code to understanding physics in new PFRC2 device

- Run larger simulations with more computing resources (e.g. 512 processors)
- Use new Magnetic Implicit algorithm
- Study heating and stability of the FRC in presence of rotating magnetic fields (RMF)
- Use Lsp circuit models to study plasma interaction with RMF antenna
- Study sensitivity to antenna geometry – could base ideas on single particle analysis as in Ref. [4]

RK4 FRC-RMF orbit



Acknowledgments:

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References:

[1] J. M. Tacetti et al., "FRX-L: FRC plasma injector for magnetized target fusion," RSI 74 (2003) 4314-4232.
[2] ATK Mission Systems: http://www.mrcwdc.com/LSP/index.html
[3] MHD2D is a program written by Peter Norgaard: http://www.princeton.edu/~norgaard/
[4] S.A. Cohen, A.H. Glasser, "Ion heating in the field-reversed configuration by rotating magnetic fields near the ion-cyclotron resonance", PRL, 85, (2000) 5114-5117.

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