*Polywell Physics Modeling Considerations**

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Presented at US-Japan Workshop
Madison, Wisconsin
October 1, 2014

* Research funded by Energy Matter Conversion Corporation (EMC2)

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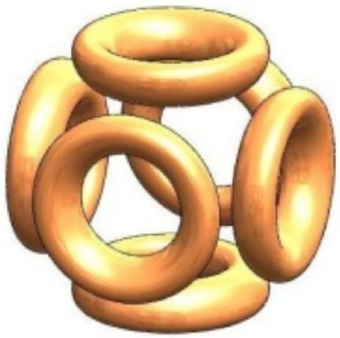
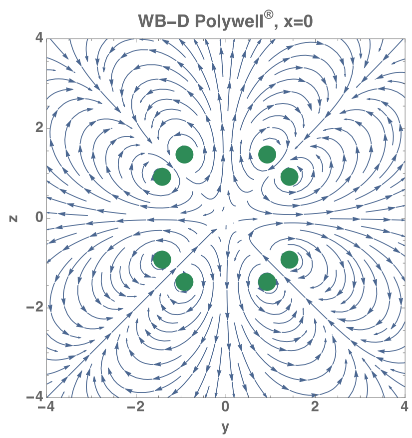
The Polywell Concept: Fast Electrons Create a Potential Well that Accelerates Ions

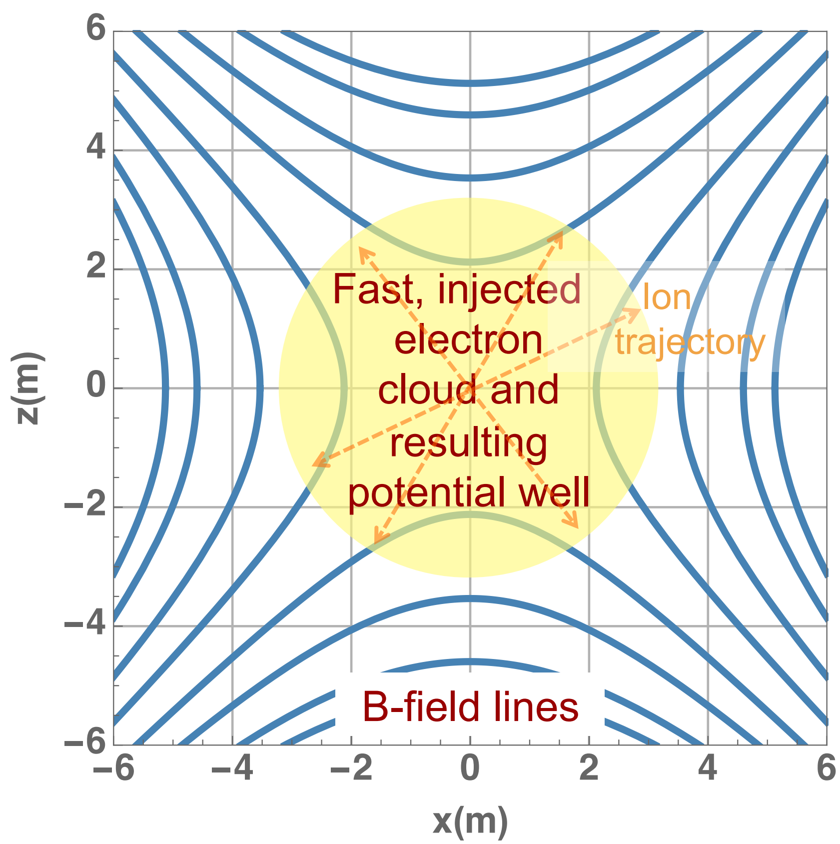
Six magnets create
point, corner, and line cusps.



Magnetic field at midplane has
a low-field region in its core.

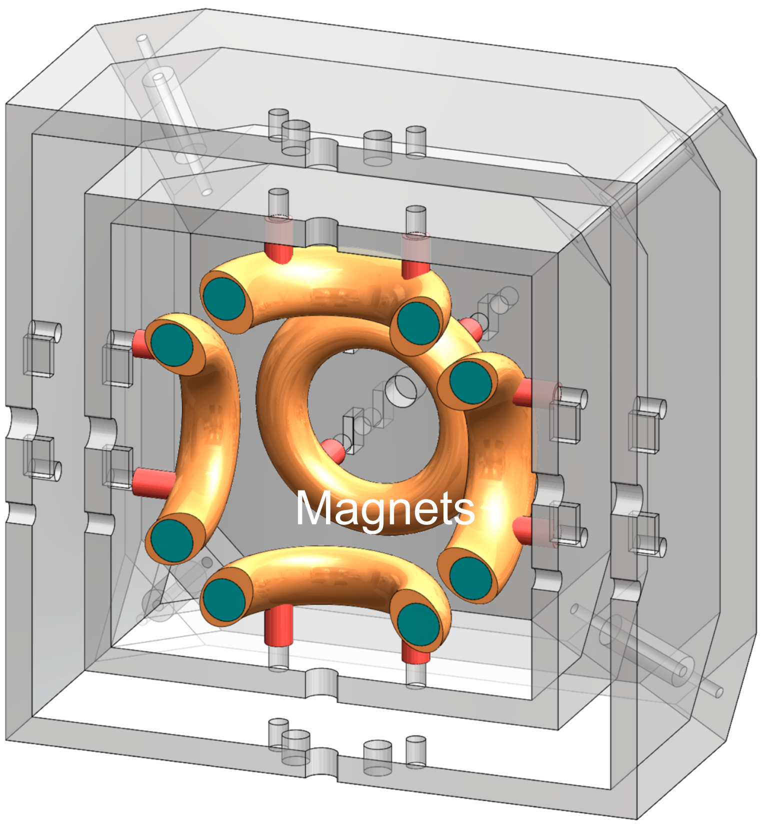


Schematic of Polywell Concept

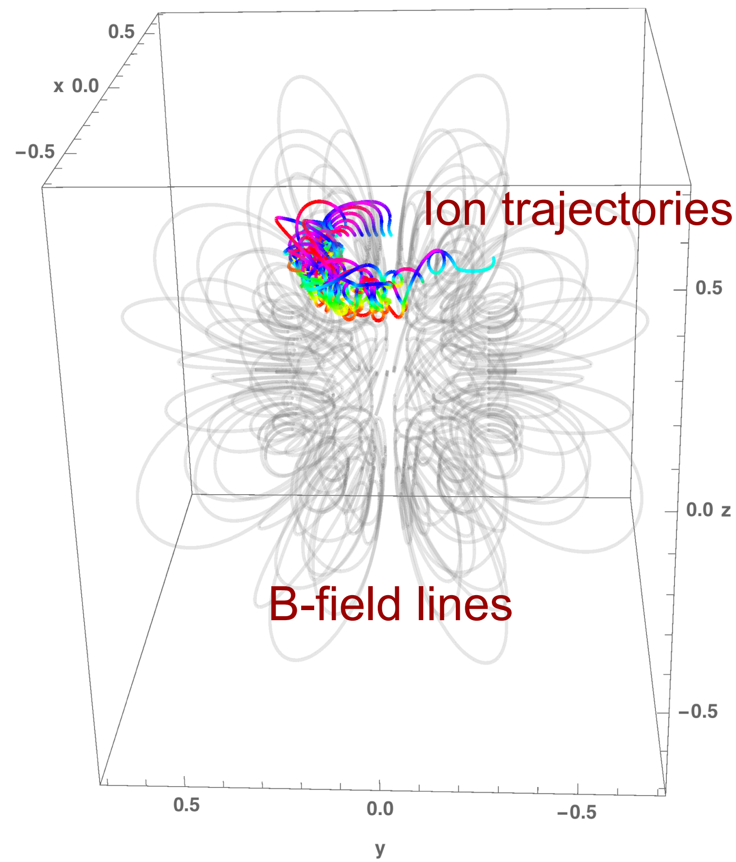


The Context: Polywell Engineering & Physics

Moderate engineering challenges in an accessible environment



Challenging physics modeling, not necessarily indicating lower reactor feasibility



Polywell Electrostatic Potential Well, If Sufficiently Deep, Allows Burning of Advanced Fuels

Key Fusion Fuels

$D + T \rightarrow n$ (14.07 MeV) + ^4He (3.52 MeV)

$D + D \rightarrow n$ (2.45 MeV) + ^3He (0.82 MeV)

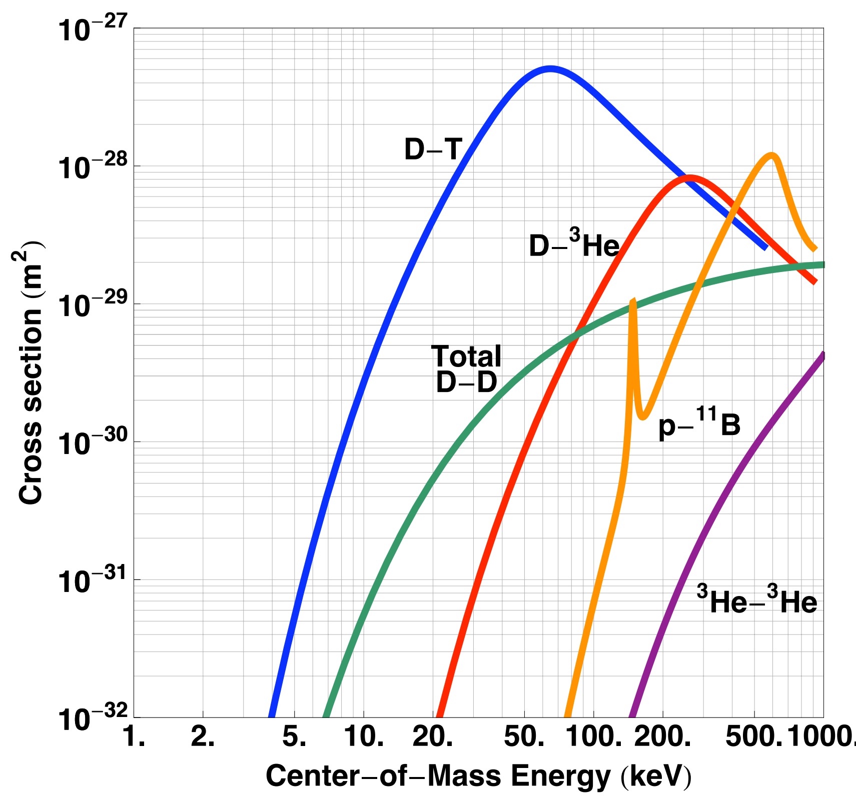
$\rightarrow p$ (3.02 MeV) + T (1.01 MeV)

{50% each channel}

$D + {}^3He \rightarrow p$ (14.68 MeV) + ^4He (3.67 MeV)

$p + {}^{11}B \rightarrow 3\ {}^4He$ (8.68 MeV)

$^3He + {}^3He \rightarrow 2\ p + {}^4He$ (12.86 MeV)



What Makes Polywell Physics Hard?

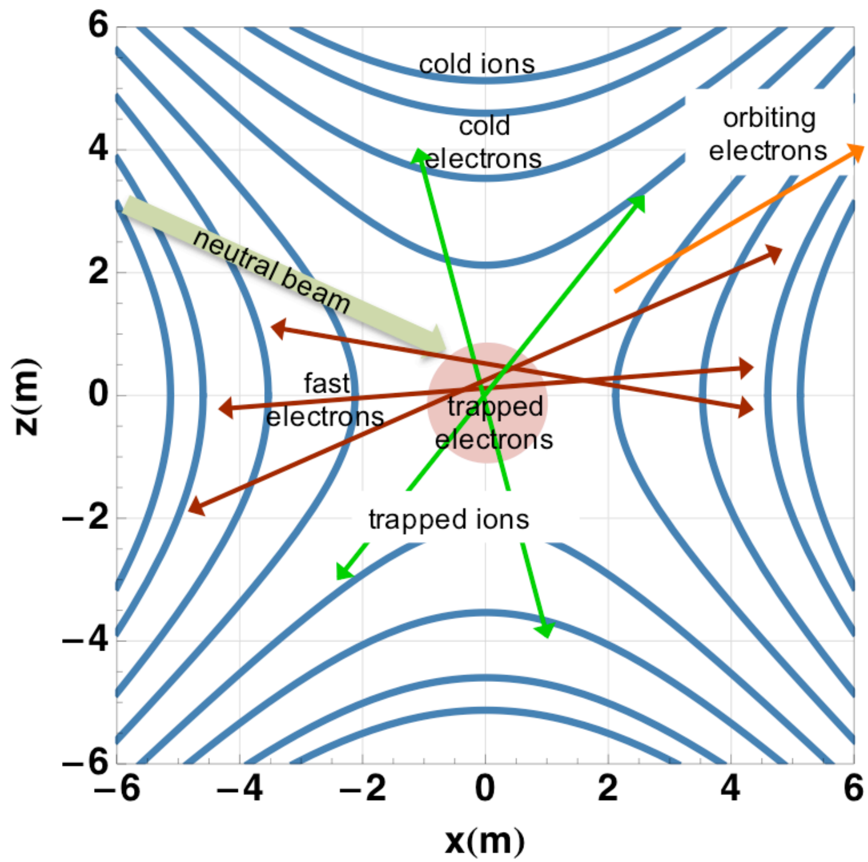
- Intrinsically 3D geometry
- BCs vary with $\{r, \theta, \phi\}$
- Plasma pressure/B-field pressure (β) ~ 1
- Space charge
- Electric fields
- Steep gradients
- Flows

Multiple Physics Effects Play Major Polywell Roles

- Nonadiabaticity
- Collisions
- Sheath physics
- Particle drifts
- Microinstabilities and related plasma transport
- Plasma particle and power balance
- Fuel and power input details
- Plasma-surface interactions

Particle and Power Balance Modeling for Polywells Requires Including Many Species

- Electrons
  - Fast electrons traversing core and confined by Polywell B-field
  - Cold electrons magnetically confined near coils
  - Orbiting electrons transiting along B-field into region between coils and wall
  - Trapped electrons electrostatically confined near origin by converging ion space charge well
- Ions
  - Trapped ions electrostatically confined and oscillating through the core
  - Cold ions magnetically confined near coils
- Neutrals
  - Neutral beams ionized while passing through the plasma
  - Neutral gas

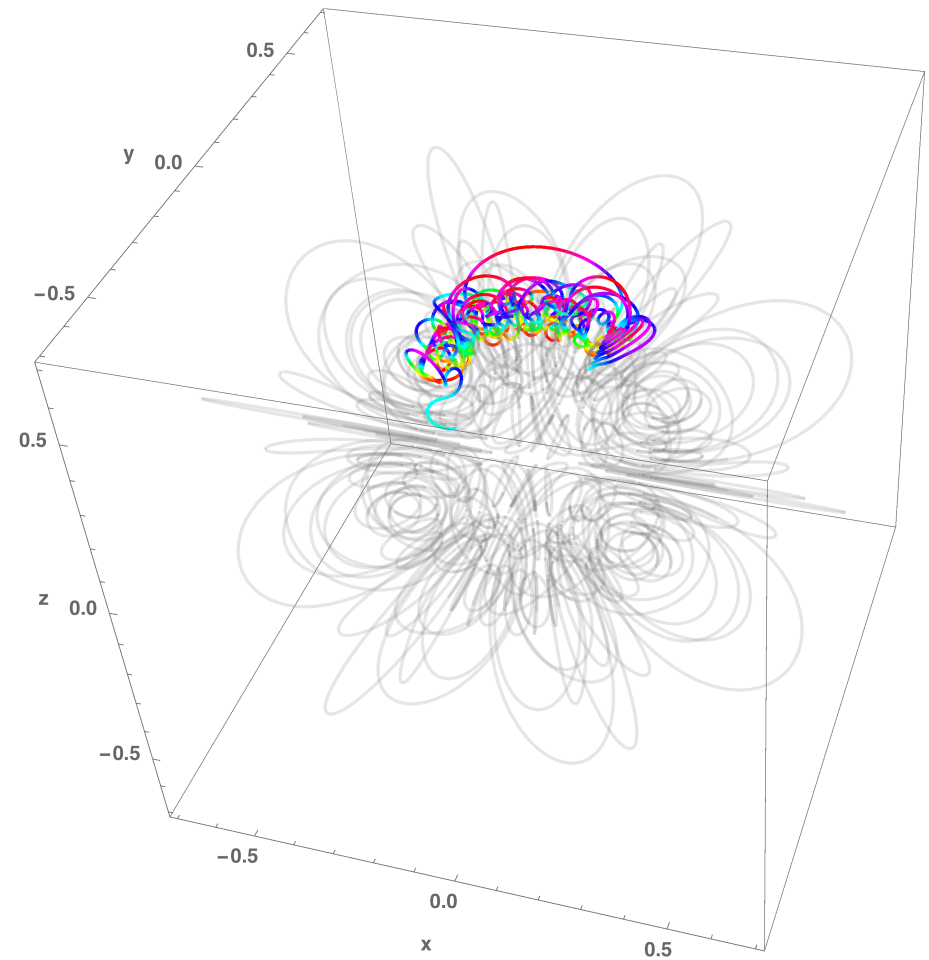


Nonadiabaticity

- The conservation of the magnetic moment, $\mu \equiv \frac{v_\perp^2}{2B}$, called "adiabaticity" applies when the magnetic field is not changing too quickly in space and time, such as near the β~1 surface's strong B-fields and in the cusps.
  - "Too quickly" in space is defined by the ratio of the magnetic field scale length, $L_B \equiv |B/\nabla B|$ to the gyroradius ρ of the charged particle of interest.
- In mirror machines, $L_B \approx 10\ \rho$ leads to *weak nonadiabaticity* (my term), which causes jumps in the pitch angle of the particle's velocity vector to the magnetic field and causes transport, and this can occur in Polywells.
- If $L_B \leq \varrho$, which occurs, the resulting *strong nonadiabaticity* (my term) can lead to extremely complicated trajectories.
  - Particles will sample many field lines within a single trajectory.
  - Even small collisional effects can transfer a particle into a dramatically different trajectory.

Charged Particle Trajectories in Polywells Are Often Complicated

- Charged particles in Polywells experience all of the classic drift motions:
  - **E** x **B**
  - Grad B
  - Curl **B**
- Electrostatic potential well and its associated electric field attract ions but repel electrons.
  - The force exerted by the well, $\mathbf{F} = q\,\mathbf{E}$, can add or subtract energy from particles through $W = \mathbf{F} \bullet \mathbf{v}_d$, where $\mathbf{v}_d$ is the grad B or curl **B** drift.
- All of the interacting particles, following their complicated trajectories, will combine to create sheaths at the β~1 surface.
  - Calculating the characteristics of such sheaths presents a major challenge to Polywell modelers.

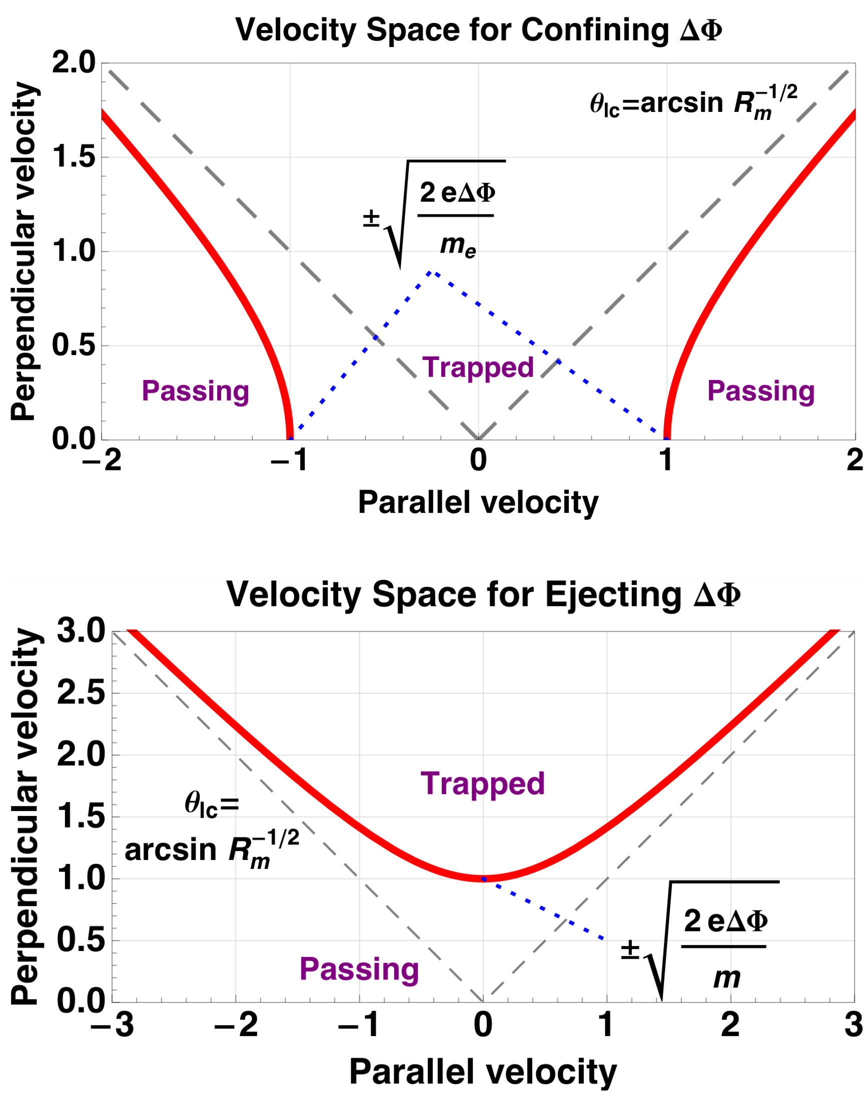


3D Polywell Sheath Physics is *Very* Difficult => Understand in 2D Spindle Cusp

- Sheath physics in 2D should be analogous to 3D sheath physics, although missing some drift physics.
- Particle-in-cell and other computer codes can handle 2D geometry with much less computational power and thus with much better turnaround time.
- Spindle cusp experiments require only a relatively simple magnet set, although the difficulty of many other aspects will be similar.
- Although an extensive spindle cusp literature exists, much of it is at low β, and modern diagnostics are much further developed than was true in the early days.

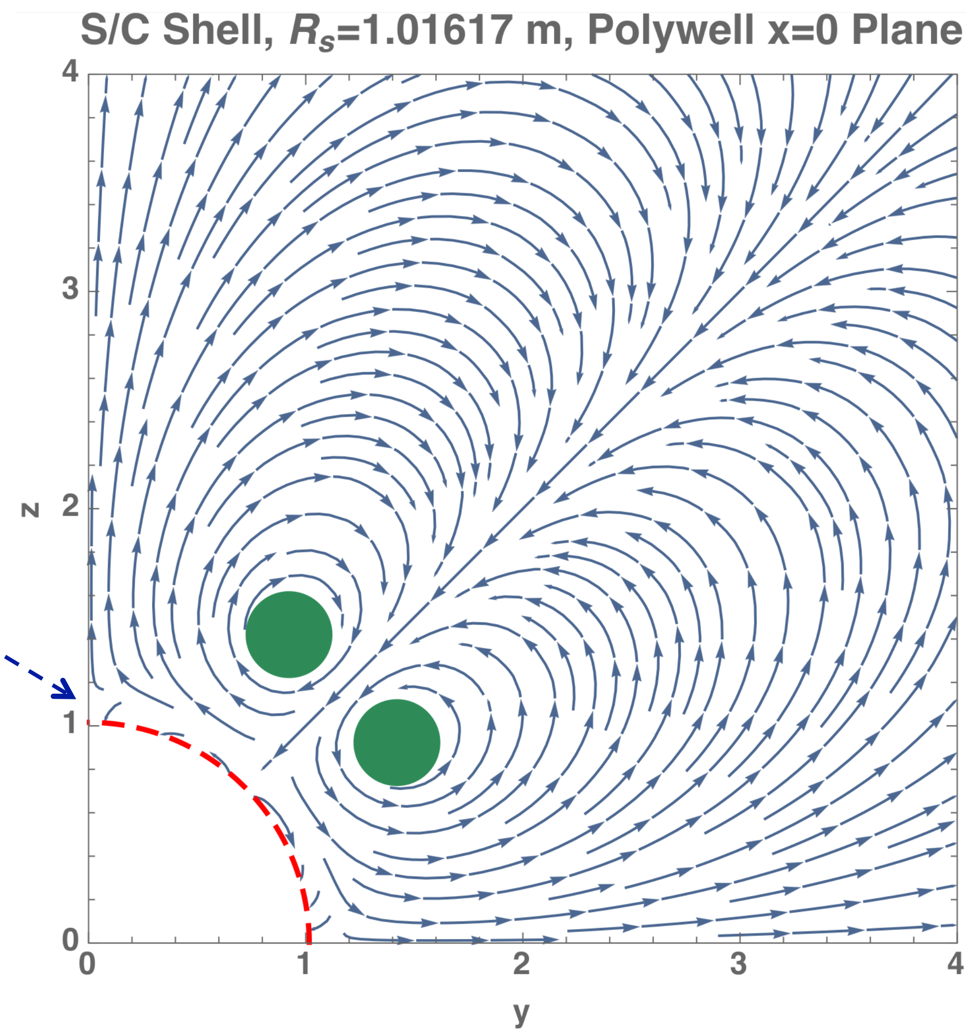
Polywells Will Most Likely Have Some Magnetically Trapped Ions and Electrons

- Some ions will be magnetically trapped in the strong B-fields near the coils. Collisions will eventually cause them to diffuse into the coil or fall into the potential well.
- "Cold," electrons will be magnetically trapped unless the electric field ejects them.
- The trapped ion and electron motion will be adiabatic and fairly smooth.
- The velocity space loss boundaries for both case appear at right.



Polywells May Have Room for Neutron Shielding of the Superconducting Magnets

- Midplane cross section of the WB-D Polywell with coils shown in green and magnetic field streamlines in blue.
- Computing a β~1 equilibrium is very difficult, but it can be approximated by inserting a superconducting shell (shown as a dashed red line).
  - The detailed B-field in the cusps will likely be different, however, for actual Polywell sheaths.
- The case shown has ~0.3-0.5 m available for shielding magnets from neutrons, which might suffice.



Summary

- Polywells contain many interacting species in populations with very different characteristics.
- Nonadiabaticity and the details of charged particle drift trajectories play a key role in Polywell transport and sheath physics.
- The EMC2 team's modeling of Polywell physics has begun, but much remains to be done.

Final Thoughts

The complexity of the required physics analysis should not be interpreted as indicating reduced feasibility for Polywell reactors.

The Polywell approach possesses excellent engineering features, and the physics design space is flexible.