Talk Outline

› The Polywell as a hybrid device
  - IEC embedded in a magnetic field

› Magnetic field structure
  - Electron motion and confinement.
  - Identify two classes of trajectories
  - Compare point and line cusps

› Principle finding
  - At small coil spacings, the Polywell field can be approximated as a system of point cusps.
  - This simplification allows the application of conventional point cusp theories to confinement time calculations

› Limitations → low beta VS high beta operation
The Polywell Concept – A hybrid device

› Uses large magnetic fields in addition to electrostatic grids to create a virtual cathode.

› Field created by pairs of opposing current loops, each creating a cusp about the origin.

› Magnetic fields vanish in centre due to symmetry creating a null point.

Magnetic Mirror Effect

Mirror Machines

Absolute Magnitude of B

Simple-mirror field configuration.

Single Electron Trajectory Simulation

- entering a point cusp in coil face
- magnetic null at origin
- magnetic moment is well defined
The electron gyroradius changes rapidly near the centre. Over a distance of $\frac{1}{2}R$ it can change from $\approx 1\text{cm}$ to $\infty$. Thus the magnetic moment $\mu$ is not conserved in this region.

Outside the dashed circle, the gyroradius changes very slowly and the magnetic moment is a constant of motion. In this region the motion is completely adiabatic and the mirror effect applies.

Reflection condition: $B_m > \frac{KE}{\mu}$
Adiabatic Condition

condition for adiabatic $\mu$

$$r_L \left| \frac{\nabla B}{B} \right| \ll 1$$

(the spatial change in magnetic field occurs slowly compared with the gyroradius)
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Critical Flux Tube

- adiabatic transition region
- critical flux surface
- magnetic fieldlines
Second Class of Trajectories

› A 3D isometric view of trajectory (b)
› This motion is completely adiabatic and the electron will be confined indefinitely.
› These trajectories are not suitable for IEC operation
Despite MHD stability – rapid plasma loss from the line cusp region. Plugging mechanisms such as RF power and repeller plates have failed to make it work.

Sadowski (1970) developed a spherical multipole configuration with 30 point cusps [3].

Central idea is that a system of point cusps will be much more efficient than any system with broad line cusps.

Observed a confinement time 2.5 times longer than a spindle cusp.

NOTE: Sadowski did not do IEC, only neutral plasma confinement.
At small spacings \((s/r \to 1)\) \(B\) face is extremely weak. But at large spacings \((s/r \to 2)\) \(B\) corner is very weak.

The ideal spacing is approx 1.2 where \(B_{\text{face}} = B_{\text{corner}}\) and \(B_{\text{edge}}\) is an order of magnitude larger than both, effectively plugging the line cusp.
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Comparison with Cusps

Polywell Field
Magnitude of B

Spindle Cusp Field
Magnitude of B

 › Point cusp escape trajectory:

 › Line cusp escape trajectory:
Fraction of electrons inside the loss cone of a point cusp is well known [2].

Bussard argued that if the loss cones are not overlapping, the conventional equation only needs to be modified by a factor $n$, where $n$ is the number of point cusps [4]. We have shown that $n = 14$ for a cubic polywell.

The loss fraction can be interpreted as the probability of escape after each successive random scattering event inside the magnetic null region.

\[
L = \frac{n}{2} \left(1 - \sqrt{1 - \frac{B_0}{B_m}}\right)
\]

**Loss Fraction**

\[
\tau_{\text{trans}} = \frac{2}{v_0} \int \sqrt{1 - \frac{B(z)}{B_0}} \sin^2 \theta_0 dz + 2 \frac{10r_0}{v_0}
\]

**Transit Time Estimate**

\[
\frac{dN(t)}{dt} = -\frac{LN}{\tau_{\text{trans}}}
\]

\[
\therefore N(t) = N_0 e^{-\frac{Lt}{\tau_{\text{trans}}}}
\]

**Loss Rate**
The distribution of confinement times for 10,000 electrons [5].

Simulation $\tau_0 = 0.129\mu s$ vs theory $\tau_0 = 0.163\mu s$
The distribution of confinement times for 10,000 electrons [5].

Simulation $\tau_0 = 0.129\mu s$ vs theory $\tau_0 = 0.163\mu s$

If $\tau_0 = 0.15\mu s$, then a litre of 100eV electrons at a density of $10^{19} \text{ m}^{-3}$ requires approximately 400kW of input power to replace energy lost by electrons.
Limitations and further questions

› Model only applies to low beta

› Other effects that need to be considered:
  - Need to establish how high beta changes the flux surfaces → effective loss area
  - Low beta confinement times appear too short for efficient IEC operation.
  - Electrostatic plugging of point cusps during high beta may improve confinement times.
  - Modification to include radial electric fields created by virtual cathode
  - Are completely adiabatic orbits unfavorable? How do they effect the potential well?


Cover image created by Torulf Greek, Gothenburg, Sweden