Penning Traps as Neutron Sources

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Foreword

- Thanks to
  - Organizers
  - Tri Alpha Energy

- No neutrons were ever produced (detected) from this scheme

A Penning trap with uniform B, harmonic E can be tuned to make a spherical well for electrons (No grids)

Electrons are maintained IEC beam-like by appropriate boundary conditions

Spherical convergence produces a central virtual cathode

Ions confined in the central cathode can reach keV energies and produce neutrons
Penning Trap

- Electrons “dropped” off low radius part of cathode see 3D well (zero angular momentum – Brillouin flow)
- Tuning V with B can make well spherical and harmonic
- Geometry is such that electrons don’t hit anode
- Electrons are recollected at low energy at cathode

\[
\Phi = \frac{2V}{3} \left( \frac{r^2/2 - z^2}{a^2} + 1 \right)
\]
Cold-bore, spherical trap
PFX, LANL, 1997

Up to 30 kV w/o heater
PFX observations

- 30 times Brillouin
- 100:1 radial convergence
- Steady, IEC like electron distribution
- No ions
  - Liquid He system
- 30 kV w/o electrons, 8 kV with
- Poor pumping (geometry closed)
Theory

- This really is a “spherical cow”
- Theory can pretty much literally simulate system
- Solve Vlasov equation for steady state
- Solve Fokker-Planck equation for collisional effects
- Calculate stability with spherical harmonics
- Etc.
Electron-ion solution (1993)

\[ f = \frac{n_i}{n_e} = 0.5 \]

Stable to 2-stream
Scaling model

- Well region – neglect space charge, vacuum field
- Mantel – beam-like
- Core – 3 x density increase, thermal, constant density, 1 Debye length

\[ C = \frac{r_0}{c} \]
Scaling model

\[ \dot{N} \approx 2 \times 10^{14} \frac{f^2}{\left[ 3 \log C_{1000} + 20.7 + 1/(1 - f) \right]^{5/2} (1 - f)^{1/2}} \frac{V_{100kV}^{4.5} C_{1000}}{a_{cm}} \]

- Very strong voltage scaling
- Linear-ish scaling with convergence
- 1/size dependence
- \( f \sim \frac{1}{2} \) sufficient
- Neutron rates \( 10^9 - 10^{10} \) may be achievable
For example

- \( V = 100 \text{ kV}, a = 1 \text{ cm}, D-T, B = 0.15 \text{ T}, \bar{n} = 2.2 \times 10^{17} \text{ m}^{-3} \)
  - \( C = 3000, \quad \dot{N} = 6.2 \times 10^{10} \text{ s}^{-1} \)
  - \( C = 100, \quad \dot{N} = 7.2 \times 10^{9} \text{ s}^{-1} \)

- \( Q \sim 5 \times 10^{-3}, 5.6 \text{ W for } 10^{10} \text{ neutrons/s} \)

- \( V \uparrow 300 \text{ kV}, Q \uparrow 0.5 – 1! \)
Practical problems

- Arcs & sparks – lots of voltage in small system
  - Even the “air” side is challenging
  - Vacuum side requires lots of “black” art
- Quality of injected electron beam
- Need for excellent vacuum (working pressure is < order $10^{-5}$ Torr)
  - Electrostatic confinement is excellent
  - Charge exchange will kill $T_i$
Embellishments

- Induce POPS in confined ions
  - Increase effective reactivity
  - Increase effective heating rate
- Exotic scheme to fuel central cathode
  - Supersonic gas jet + cryopump?
- Heat engine (extensions of POPS)
- ...

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Future

- Currently no funding
  - “garage” scale experiment, hydrogen or deuterium?
- Technical features
  - Permanent magnets?
  - Room temperature bore
  - Use oil on “air” side
  - Make anode a mesh (probably slotted)
  - Use getters?
  - Magic cathode materials (Ti, Cr, Mo, Li?)
Summary

- PFX produced spherical focus, deep virtual cathode in miniature system
- Significant Q at mW fusion level
- Only need modest (but challenging) technology improvements to make Q ~ 1
- This speaker (and his past and present collaborators) welcomes your input
Published References