Polywell Fusion

Electrostatic Fusion in a Magnetic Cusp

Jaeyoung Park
Energy Matter Conversion Corporation (EMC2)
Fusion Power Associates Meeting (December 17, 2014)
Support from US Navy Contract: N68936-09-C-0125
Contributions from EMC2 Personnel

4 Scientists, 5 Engineers/Technicians, 2 Support

Mike Skillicorn: Design, construction and maintenance of WB-8 device
Paul Sieck: WB-8 operation, control and safety system, and DAQ
Dustin Offermann: Plasma diagnostics – Spectroscopy, lasers and x-ray
Eric Alderson: Plasma diagnostics – Probes and particle diagnostics
Mike Wray: Vacuum and gas handling system and lab Management
Noli Casama: Electrical power system
Kevin Davis: Microwave system and HV pulse power operation
Andy Sanchez: Operation Support and Numerical Simulation
Grace Samodal: Business/Operations Management
Yoko Corniff: Accounting and HR
Jaeyoung Park: Lead the WB-8 project

EMC2 works closely with Dr. Nicholas A. Krall on Polywell theory
Contributors to the Polywell Fusion Concept

Philo Farnsworth: Electric fusion & inventor of television

Harold Grad: MHD theory and Cusp confinement

Robert Bussard: Polywell Fusion, Nuclear Rocket, Bussard Ramjet

James Tuck: Picket Fence, Elmore-Tuck-Watson virtual cathode, & Explosive focus for A-bomb
Combines two good ideas in fusion research: Bussard (1985)

a) **Electrostatic fusion**: High energy electron beams form a potential well, which accelerates and confines ions.

b) **High $\beta$ magnetic cusp**: High energy electron confinement in high $\beta$ cusp: Bussard termed this as “wiffle-ball” (WB).

**Electrostatic fusion provides**
- Ion heating
- Ion confinement

**High $\beta$ cusp provides**
- High energy electron confinement

*for high $\beta$ cusp*  
*for electrostatic fusion*
Polywell Cusp Magnetic Fields

- 6 coil Polywell cusp magnetic field lines

- Electron beam injection along the cusp openings
However, the potential well decayed away with increase in plasma density above $1 \times 10^9 \text{ cm}^{-3}$, which was contributed to the insufficient confinement of fast electrons inside the Polywell cusp field (Krall et al, Physics of Plasmas, 1995)
Since 1994, EMC2 had built and operated successive test devices from Wiffle-Ball-1 (WB-1) to WB-8 to demonstrate confinement of high energy electrons in a magnetic cusp.
Motivation of Magnetic Cusp

From “Project Sherwood: The U. S. Program in Controlled Fusion” by Amasa Bishop (1958).

Magnetic cusp was introduced to magnetic fusion program for plasma stability and high beta (β=1) operation.
Grad’s High Beta Cusp Conjecture

- Between 1955-1958, NYU group led by Grad investigated the case of plasma confinement in a high $\beta$ magnetic cusp.
- In Grad’s view, a boundary between plasma and magnetic fields are very different for low $\beta$ and high $\beta$ case.
- For high $\beta$ cusp, he envisioned “a sharp transition layer to exist between plasma and B-fields, while diamagnetic effect results in a field free central region”
- Plasma particles will undergo specular reflection at the boundary except for the particle moving almost exactly in the direction of the cusp $\rightarrow$ the plasma loss rate will be greatly reduced and have gyro-radius scaling.

**Low $\beta$**

Finite B-field (center)
Weak diamagnetism
Poor confinement

**High $\beta$**

Zero B-field (center)
Strong diamagnetism
Sufficient confinement for net power reactor
Plasma Confinement in Cusp at High $\beta$

In high $\beta$ cusp, **a sharp transition layer exists between plasma and B-fields**. Plasma particles will undergo specular reflection at the boundary except for the particle moving almost exactly in the direction of the cusp. The loss rate will have gyro-radius scaling.

Theoretically conjectured

Loss current per cusp by Grad and NYU team

$$\frac{I_{e,i}}{e} = \frac{\pi}{9} n_{e,i} v_{e,i} \times \pi (r_{e,i}^{gyro})^2$$

0.5s confinement time for 100 keV electron with 7 T, 1m radius, 6 coil cusp → favorable for a net power device.
History of Cusp Confinement Efforts

• Grad’s confinement enhancement conjecture made the cusp approach to be promising for a net power fusion reactor.

• For the next 20 years, detailed experiments were conducted on ~20 different devices and ~200 papers were published related to the cusp confinement as a result. Two excellent review articles by Spalding (1971) and Haines (1977).

• However, most efforts on cusp confinement stopped by 1980 due to a lack of progress.
## High Beta Cusp Experiments in 1960s using plasma injection

### Table I

<table>
<thead>
<tr>
<th>References</th>
<th>Plasma source; confinement geometry</th>
<th>Diameter $D$ (cm)</th>
<th>Length $L$ (cm)</th>
<th>$B$ (max) (kG)</th>
<th>$n_e$ cm$^{-3}$</th>
<th>$W^*$ keV</th>
<th>$T_e$ eV</th>
<th>Quoted $\beta$ near axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>67</td>
<td>Single-pulse coaxial gun; axisymmetric quadrupole and octupole</td>
<td>90</td>
<td>120</td>
<td>4.5</td>
<td>$10^{13}$-$10^{14}$</td>
<td>$5 \times 10^{-2}$</td>
<td>15</td>
<td>?</td>
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<tr>
<td>68</td>
<td>12 conical Z-pinch guns; axisymmetric triple cusp (radial injection)</td>
<td>20</td>
<td>45</td>
<td>1.9</td>
<td>$7.5 \times 10^{14}$</td>
<td>$&gt;5 \times 10^{-3}$</td>
<td>4.5</td>
<td>&lt;1</td>
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<tr>
<td>69</td>
<td>Coaxial gun; spindle-cusp</td>
<td>53</td>
<td>53</td>
<td>12</td>
<td>$\sim 3 \times 10^{13}$</td>
<td>13</td>
<td>Nonthermal</td>
<td>&lt;1/2</td>
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<tr>
<td>70, 71</td>
<td>2 $\theta$-Pinch (single pulse) guns; spindle cusp</td>
<td>25</td>
<td>230</td>
<td>3.2</td>
<td>$\sim 10^{15}$</td>
<td>$2.4 \times 10^{-1}$</td>
<td>20</td>
<td>$&gt;0.90$ in core</td>
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<tr>
<td>72</td>
<td>Conical Z-pinch; spindle cusp</td>
<td>40</td>
<td>40</td>
<td>4</td>
<td>$(3-10) \times 10^{15}$</td>
<td>$\sim 1$</td>
<td>?</td>
<td>$\sim 1$</td>
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<tr>
<td>73</td>
<td>Titanium guns; spindle cusp (radial injection)</td>
<td>12</td>
<td>12</td>
<td>3.9</td>
<td>$\sim 8 \times 10^{15}$</td>
<td>$5 \times 10^{-2}$</td>
<td>$&gt;5$</td>
<td>$\sim 1$</td>
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<tr>
<td>74</td>
<td>2 multiple-pulse coaxial guns; spindle cusp</td>
<td>17</td>
<td>15</td>
<td>3.9</td>
<td>$10^{13}$</td>
<td>$2 \times 10^{-2}$</td>
<td>6</td>
<td>$\sim 1$</td>
</tr>
</tbody>
</table>

* Axial injection unless radial injection at ring cusps is specifically noted. $W^*$ is the injected energy in keV.
Cont. High Beta Cusp Experiments in 1960s using plasma compression


<table>
<thead>
<tr>
<th>Refs.</th>
<th>Description</th>
<th>$D$ (cm)</th>
<th>$L$ (cm)</th>
<th>$B$ kg</th>
<th>Rise time ($\mu$sec)</th>
<th>$\hat{n}$ (cm$^{-3}$)</th>
<th>$T_e$ eV</th>
<th>$\beta_A$</th>
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<tr>
<td>75</td>
<td>Adiabatic spindle cusp</td>
<td>11</td>
<td>8</td>
<td>25</td>
<td>4.5</td>
<td>?</td>
<td>?</td>
<td>?</td>
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<tr>
<td>76-78</td>
<td>Ditto (shock preheat)</td>
<td>20</td>
<td>20</td>
<td>24</td>
<td>15</td>
<td>$2.5 \times 10^{16}$</td>
<td>15</td>
<td>0.98</td>
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<tr>
<td>79</td>
<td>Ditto (gun preheat)</td>
<td>20</td>
<td>20</td>
<td>34</td>
<td>15</td>
<td>$10^{16}$</td>
<td>70</td>
<td>$\sim 1.0$</td>
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<td>80</td>
<td>Shock-heated spindle cusp</td>
<td>10.5</td>
<td>13</td>
<td>70</td>
<td>1.1</td>
<td>$10^{17}$</td>
<td>120</td>
<td>?</td>
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<tr>
<td>81</td>
<td>Linear $\theta$-cusp-\theta pinch</td>
<td>5</td>
<td>2.5</td>
<td>27</td>
<td>1</td>
<td>$\sim 3 \times 10^{16}$</td>
<td>100-180</td>
<td>?</td>
</tr>
<tr>
<td>82-84</td>
<td>Shock-heated linear cusp-\theta-cusp pinch</td>
<td>19</td>
<td>50</td>
<td>60</td>
<td>2.1</td>
<td>$1.5 \times 10^{16}$</td>
<td>150</td>
<td>0.99 ± 0.01</td>
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<td>85</td>
<td>Shock-heated toroidal hexapole</td>
<td>6</td>
<td>163</td>
<td>10</td>
<td>3.0</td>
<td>$3 \times 10^{16}$</td>
<td>50</td>
<td>0.8</td>
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<tr>
<td>86</td>
<td>Shock-heated toroidal hexapole</td>
<td>6</td>
<td>163</td>
<td>21</td>
<td>3.0</td>
<td>$3.5 \times 10^{16}$</td>
<td>93</td>
<td>0.4</td>
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<tr>
<td></td>
<td></td>
<td>6</td>
<td>163</td>
<td>10.5</td>
<td>3.0</td>
<td>$1.4 \times 10^{16}$</td>
<td>62</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Recent Experiments at EMC2  
(EMC2 San Diego Facility)
EMC2 Experimental Plan

1. Plasma injection to the cusp
   - Use high power arc (solid target) plasma injectors

2. Verify high $\beta$ plasma formation in the cusp
   - Measurements on plasma density, magnetic flux and electron temperature

3. High energy electron injection to high $\beta$ cusp
   - LaB$_6$ based electron beam injector, used as fast test particles.

4. Confinement measurement of high energy electrons in the cusp
   - Time resolved hard x-ray intensity from bremsstrahlung

Bulk (cold & dense) plasma from arc injectors provides plasma pressure (high $\beta$) to modify cusp B-fields, while the confinement property is measured for high energy electrons in the cusp.
First ever confirmation of high $\beta$ cusp confinement enhancement (October 23, 2013)

High $\beta$ shot 15610

X-ray intensity (a.u.)
Face and corner cusp chord

$n_e$ bulk

X-ray face
X-ray corner

$\Delta B$

Flux exclusion (%)

$\frac{n_{e \text{ bulk}}}{10^{15} \text{ cm}^{-3}}$

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Cusp confinement vs. Injection input power

Cusp confinement enhancement requires sufficiently high $\beta$ plasma condition.
Cusp confinement vs. initial B-fields

No confinement enhancement at B=0 but we need to do more to understand B-field effects
Our Findings on High $\beta$ Cusp Confinement

Increase in X-ray signal

- Coincides with high $\beta$ plasma state in the cusp
- Only observed when there is sufficient flux exclusion or plasma injection reaches a threshold
- Peak increase is 10-20x or more compared to low $\beta$ state
- Exhibits asymmetrical time behavior: gradual increase followed by rapid decrease
- Clearly separated from W impurities injection in time domain

We believe our x-ray measurements unambiguously validate the enhanced electron confinement in a high $\beta$ cusp compared to a low $\beta$ cusp

A Path to Polywell Fusion

- **High β cusp**
  - (Confinement of energetic electrons)
  - Proven in 2013

- **Electrostatic fusion**
  - (Potential well for energetic ions)
  - Proven in 1995

**Polywell**

- High β cusp + Electrostatic fusion at the same time
Merits of Polywell Fusion Reactor

Scientific merits
- MHD stability
- High $\beta$ operation
- Electrostatic heating of ions
- No helium ash issue

Engineering merits
- Compact size
- Heating by electron beam injection
- Natural divertor
- Modular, non-interlocking coils
- Remote first wall

Polywell fusion may offer a low cost and rapid development path
Movie of Polywell Fusion Reactor Assembly
Next Phase: Last Part of Proof-of-Principle

- Sustained high $\beta$ operation (~ 5 ms)
- Demonstration of ion heating (>10 kV) by e-beam injection
- Verify Grad’s cusp scaling

3 year, $25-30M program to complete proof-of-principle
Success will be defined by 1) high energy electron confinement within a factor of 10 from Grad’s conjecture and 2) minimum 30% ion heating efficiency via e-beam.
“The qualitative properties of the plasma depend on the ratio of pressures in the plasma and the magnetic field. The former is the plasma pressure $p$, the latter $B^2/8\pi$. The ratio of the two quantities $8\pi p/B^2$ is known as $\beta$. In general, the plasma behavior is most simple for low-$\beta$ values and most interesting for high-$\beta$ values.”

Supplemental Slides
Electrostatic Fusion

Contributions from Farnsworth, Hirsch, Elmore, Tuck, Watson and others

Operating principles
(virtual cathode type)

- e-beam (or grid) accelerates electrons into center
- Injected electrons form potential well
- Potential well accelerates/confines ions
- Energetic ions generate fusion near the center

Attributes

- Excels in generating energetic ions with good confinement
- But loss of high energy electrons is too large

Deep negative potential well (1) accelerates and traps positive ions (2) until they generate fusion reactions

Net power generation is unlikely
(present efficiency: 1-10x10^-6)
Question on Plasma Stability


- Question on Plasma Stability by Teller in 1954
  - “Attempts to contain a plasma as somewhat similar to contain jello using rubber bands”
  - Basis of interchange instability (plasma version of Rayleigh Taylor instability) and idea of “good curvature” vs. “bad curvature”

- Stronger instability shown in an outer part of torus “Tokamak ballooning mode instability” from General Atomics Gyrokinetic simulation

From Principles of Plasma Physics
Krall & Trivelpiece (1973)
Experimental Setup
for high $\beta$ cusp confinement

LaB$_6$ Electron Gun
(7 keV, 1 – 3 A)

Plasma Gun
(300 MW solid arc)

X-ray diode
(2 keV x-rays and up, corner and face views)

Chamber size: 45 cm cube, Coil major radius; 6.9 cm
Distance between two coils: 21.6 cm, B-field at cusp (near coil center) 0.6 – 2.7 kG
Experimental Setup (continued)

Laser Interferometer
(532 nm, $10^{15} - 10^{17}$ per cc)

Magnetic Flux Loops

Photodiodes and Spectrometer
(Filtered for H$_\alpha$ and C$_{I-II}$,
High resolution spectrometer, fiber coupled)
Solid arc plasma injector

Plasma injection by co-axial guns \((j \times B)\) using solid fuel
- Ignitron based pulse power system (40 \(\mu\)F cap holds 3 kJ at 12kV)
- \(~100\) kA arc current \(\rightarrow\) \(~300\) MW peak power and \(~7\) \(\mu\)s pulse
- \(\beta=1@2.5\) kG: \(1.5 \times 10^{16}\) cm\(^{-3}\) at 10 eV or 100J in a 10 cm radius sphere

solid arc using polypropylene film
2 mm A-K gap

Animation of plasma injection
Dual arc plasma injection movie

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High $\beta$ plasma formation (two plasma guns)

- Plasma density on the order of $10^{16}$ cm$^{-3}$ from Stark broadening of H$\alpha$ line
- Laser interferometer provides single shot line integrated density variation in time

- Electron temperature is estimated $\sim 10$ eV from C II and CIII emission
- H$\alpha$, C II line by photodiode and visible spectra by gated CCD is used to monitor $T_e$ variation in time
High energy electron beam produces hard x-rays

E-gun injects
Beam Electrons (7 keV)

Beam electron confinement by Cusp magnetic fields

Collisions with bulk plasma create hard x-rays ($E > 2$ keV) via Bremsstrahlung

Transit time: $\sim 7$ ns for 7 keV electron for 22 cm transit
Expected confinement time: $\sim 45$ ns for low $\beta$ and $\sim 18$ $\mu$s for high $\beta$ (x400 increase)
Bremsstrahlung x-ray emission from interaction between beam electrons and plasma

Bremsstrahlung radiation from e-beam interaction with plasma ions

\[ e + \text{ion} \rightarrow e + \text{ion} + hv \]

\[ P^{Br} \propto n_e^{\text{beam}} E_{\text{beam}}^{1/2} n_{\text{ion}} Z_{\text{eff}}^2 \]

Bremsstrahlung x-ray intensity

\rightarrow \text{Direct measurement of beam e-density inside Cusp}

Careful measurement is required to eliminate spurious radiation from impurities, vacuum wall, coil surfaces, and characteristic line emission.

Typical beam target x-ray spectrum
X-ray collecting optics to eliminate unwanted signals

- **Silicon Diode Detector**
- **Kapton-Black Film**
  - Blocks plasma
  - Blocks soft x-rays
  - Blocks visible light
- **Magnetic Yoke**
  - Blocks beam electrons
- **Collimator Tube**
  - Limits view to plasma
  - Plastic material minimizes x-ray production inside tube

X-ray Diode and Collimator Assembly

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Hard x-ray filter

25 µm thick light tight Kapton filter (works as vacuum interface)

Filter has sharp cutoff at ~2 keV photon energy
→ blocks any characteristic x-ray emission from light elements up to $^{14}$Si and $^{15}$P
→ blocks UV-visible light from plasmas
→ blocks charged particles from reaching the detector
 Confirmation of X-ray filter vs. beam energy

- X-ray was generated by electron beam on Stainless Steel target
- 25 µm thick Kapton filter works well to eliminate X-ray photons below 2 keV
Spatial collimation of x-ray detectors

- Collimation is designed to eliminate direct line-of-sight view of metal surfaces
- In addition, opposite sides of the chamber wall are covered using Kapton film and quartz window
- Both chords allow good volume averaging of x-ray emission from core plasmas
Confirmation of X-ray collimation

- e-beam into vacuum magnetic field (no plasma) generates no x-ray response from the diode detector
- Indication of well collimated x-ray optics

- Uniform exposure
- No sign of spatial structure from coils & walls
- 10 mTorr N₂ gas target
- 20 ms exposure with 4A@7 kV e-beam
- B-field at 1.4 kG
Reproducibility of high $\beta$ cusp confinement

6 consecutive shots with $\sim 200$ J of injected plasma energy at 2.7 kG B-fields → Estimated cusp beta $\sim 0.7$ from line averaged density at $T_e \sim 10$ eV

All six shots show distinctive high $\beta$ phase → good reproducibility
Time averaged plasma images

High $\beta$ cusp formation: intense plasma in the core region
Time resolved spectroscopy on W-impurity

- Line emission intensities from main ion species (H and C) decay early
- Despite plasma density decay (& cooling of plasma), Tungsten line intensities peak later in time and decay slowly --> indicates gradual build up of Tungsten impurity.

--> x-ray peak late in the shot (40-50 µs) is from e-bam interaction with Tungsten

Tungsten cathode after 200 shots
Time resolved spectroscopy for impurity transport

During the high $\beta$ phase, plasma emission shows strong C$^+$ lines & presence of W$^+$ lines (Note that avg. $n_e \sim 1.5 \times 10^{16}$ cm$^{-3}$ and $T_e \sim 10$ eV during this period)
At later time, plasma emission is dominated by W neutral lines, while C\(^+\) and W\(^+\) lines disappear (Note that avg. \(n_e \sim 0.2 \times 10^{16} \text{ cm}^{-3}\) and \(T_e < 10 \text{ eV}\))
Estimate of High $\beta$ Confinement Time

Theoretical model to estimate high $\beta$ confinement time

Characteristic time of density rise $\sim \tau_{WB}$

- Note the shape of x-ray intensity profile: a gradual rise and a rapid drop
- From time response of x-ray signal $\Rightarrow \tau > 2.5 \mu s$ (2x $\tau \sim$ x-ray signal rise time)
- 2.5 $\mu s$ is about $\sim 50$ times better than low $\beta$ cusp confinement time
- The observed confinement enhancement is very significant and compares well with the theoretically predicted high $\beta$ cusp confinement time by Grad and his team

Experimental results
Shot 15640

$\Delta t \sim 5 \mu s$
Unresolved issues on high $\beta$ cusp

1. Decay of good confinement phase
   - Decay mechanism: plasma loss/plasma cooling or magnetic field diffusion or something else
   - How to extend high $\beta$ state and prevent the decay

2. Topological information on cusp magnetic fields during high $\beta$ state
   - Thickness of transition layer
   - Magnetic field lines near the cusp openings