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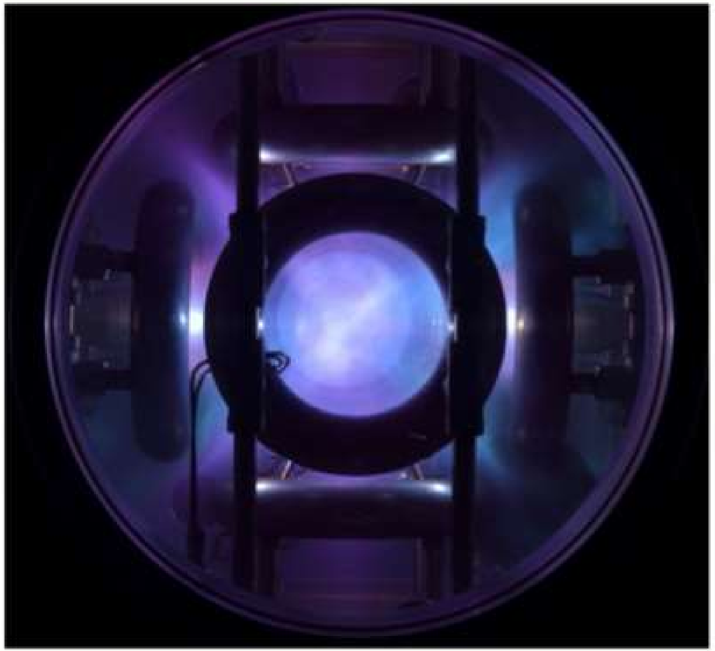
POLYWELL
Electric Fusion in a Magnetic Cusp



Jaeyoung Park
Energy Matter Conversion Corporation (EMC2)
Microsoft, January 22, 2015
Support from US Navy Contract: N68936-09-C-0125

Quotable Quotes on Fusion

"Fusion is the Ultimate Energy Source"

"Fusion is 20 years away *and will always be*"

My goal is to share my hope of a future with fusion powering the world

Scientists whose work led to Polywell Fusion

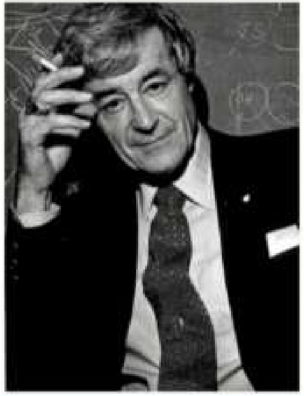
Edward Teller: Plasma instability, Pioneer in fission and fusion
Herbert York: 1st Director of Livermore Lab, Comment on high beta fusion (asked R.F Post to start Magnetic Mirror fusion)

Harold Grad: Plasma theory (MHD) and Cusp confinement

Philo Farnsworth
Electrostatic fusion & inventor of television

James Tuck: Picket Fence, Electrostatic fusion, & Explosive focus for A-bomb

Robert Bussard: **Polywell Fusion**, Nuclear Rocket & Bussard Ramjet



Outline

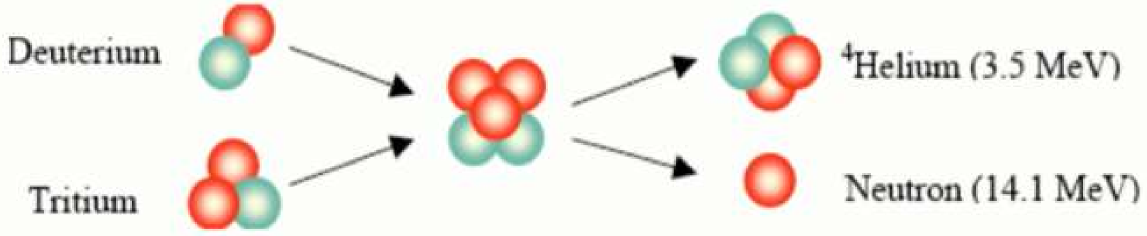
- Fusion Primer
- Polywell Fusion Story:

  Magnetic Cusp + Electric Fusion
- Recent Experiments at EMC2
- Future Work

What is Fusion?

Fusion generates net usable power from merging of lightweight nuclei such as deuterium and tritium and releases a large amount of energy based on Einstein's equation

$$E = mc^2$$



By fusing ~2 grams of Deuterium and ~ 3 grams of Tritium, fusion generates 1.7×10^{12} J of energy (Equivalent to the combustion of 276 barrels of Oil)

Advantages of fusion

Fusion has been pursued for over 60 years because it offers several advantages over alternate energy sources:

- **Abundant supply of low cost fuel**
  - ➢ Deuterium is abundant in seawater and can be extracted at low cost
  - ➢ Tritium can be generated at a reasonable cost from breeding using Lithium, which is also abundant in seawater
- **No danger of a nuclear fission type melt-down**
- **No Greenhouse gas emissions**
- **No or minimal danger of nuclear proliferation**
- **Fuel residue is not radioactive**
  - ➢ *Long term waste depository is not required*

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What makes fusion so challenging?

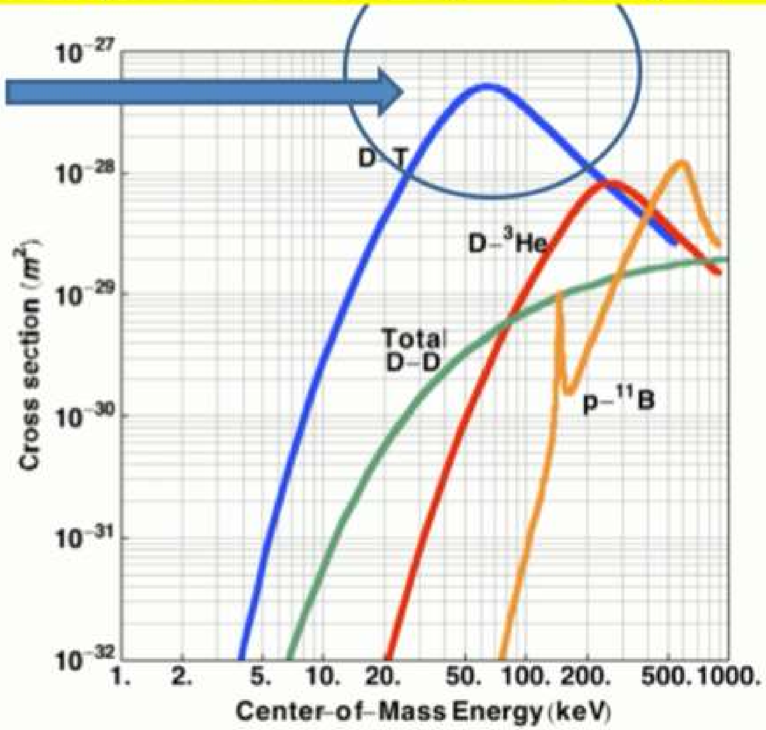
Conditions Required for Fusion (D-T example)

High Temperature

100 million degrees or hotter in order to overcome strong Coulomb force

Good confinement

- To produce fusion, two nuclei need to be brought together within 0.1-1x10^{-14} m
- Typically (in Polywell or conventional magnetic fusion), a nucleus will go through one fusion for every 10,000 km travelled.

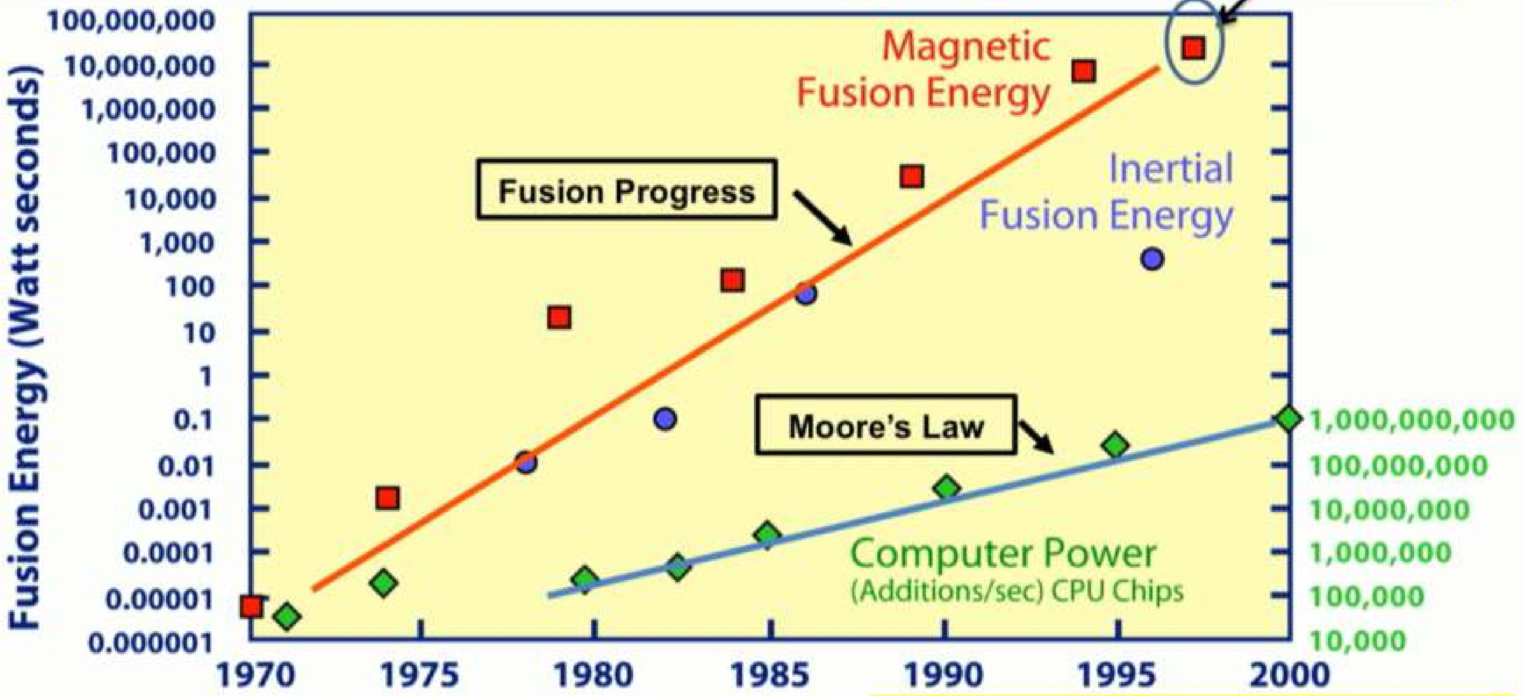


Fusion cross sections versus center-of-mass energy

Note: 1 keV ~ 10 million degrees

How much progress has fusion research accomplished?

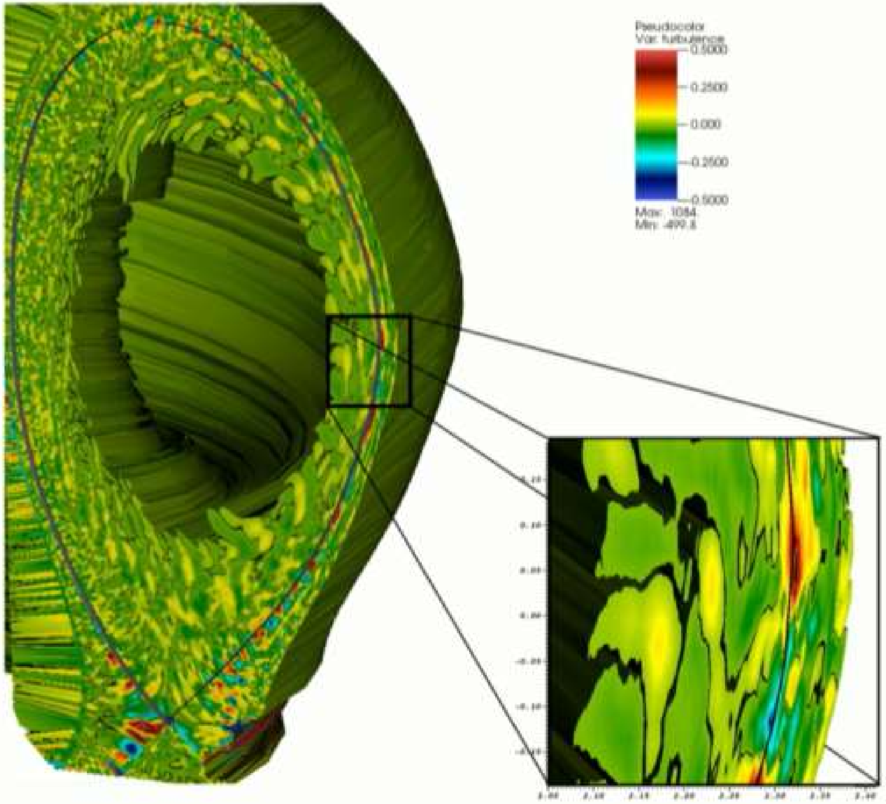
Progress in fusion (led by Tokamak and laser system) has been impressive
Fusion output of 16 MW with 24MW input: Q=0.65, JET (1998)



From talk by Prof. Greg Hammett at PPPL (2013): "Spitzer's Pioneering Fusion Work and the Search for Improved Confinement"

<u>Fusion will work sooner or later</u>
<u>So, where is my fusion reactor?</u>

High Performance Computing is Aiding Fusion Research



Courtesy of S. Ku (PPPL)
XGC1 simulation for plasma turbulence

- 40 Billion particles
- Titan (Cray-XK7) at ORNL
- 131,168 processor cores with 8,198 GPUs, 2 days of simulation (6M processor hours)
- ~1 ms physical time for DIII-D tokamak
- Fully nonlinear & 6D simulation (3D for space & 3D for velocity space)

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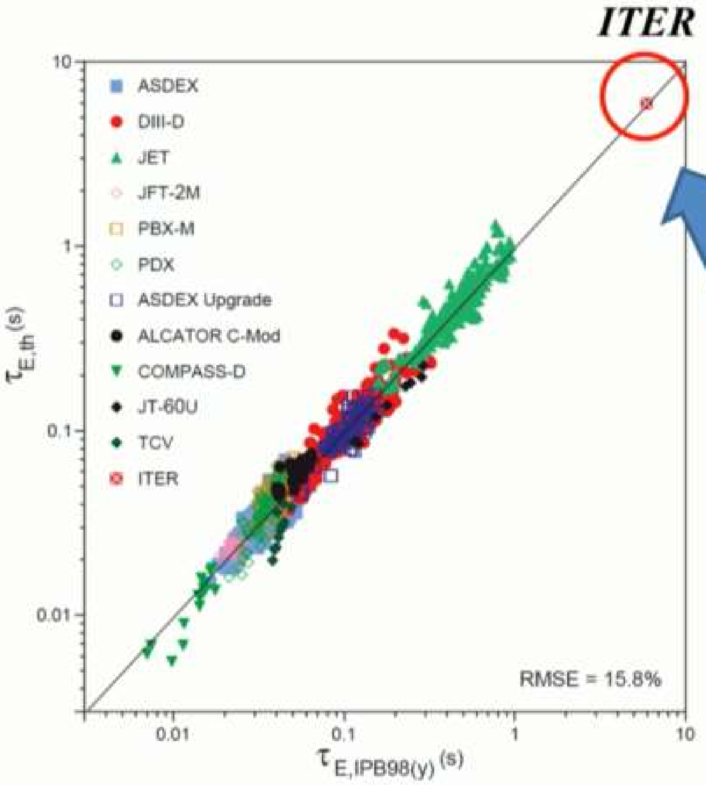
Path to Net Fusion Power

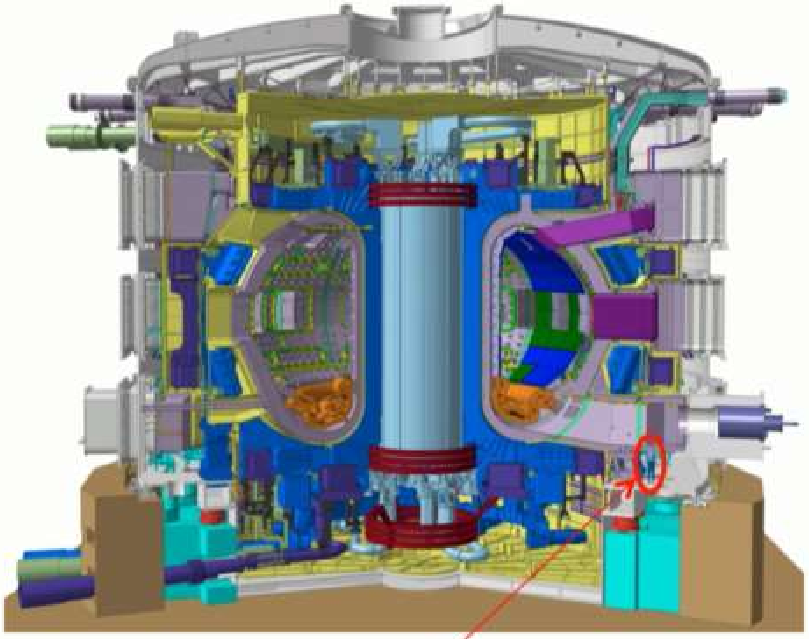


Confinement time (Exp. vs. model)
ITER Physics Expert Group (1999)

<u>ITER begins</u>
Geneva, *1985*
from ITER webpage

~ 20 years of worldwide research effort went into designing the next generation fusion device for net power production → ITER

Case Study of ITER: Big Machine



6 ft tall person

- There is no doubt Tokamak is a great scientific machine

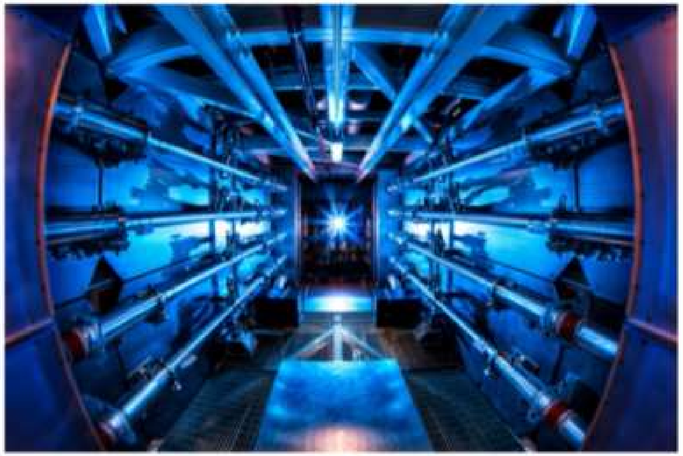
- A critical question: Can tokamak be a practical fusion reactor?

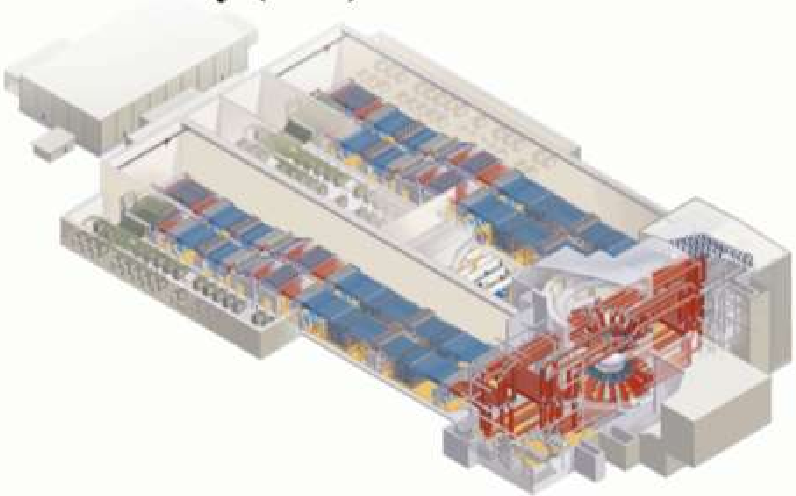
ITER: culmination of 200+ tokamaks

- 30 m tall & 23,000 tons
- Big & Complex
- Becoming very expensive with ongoing cost overruns ($5B in 2001 to more than $20B in 2013)

Case Study of NIF: Another Big Machine

National Ignition Facility (NIF)



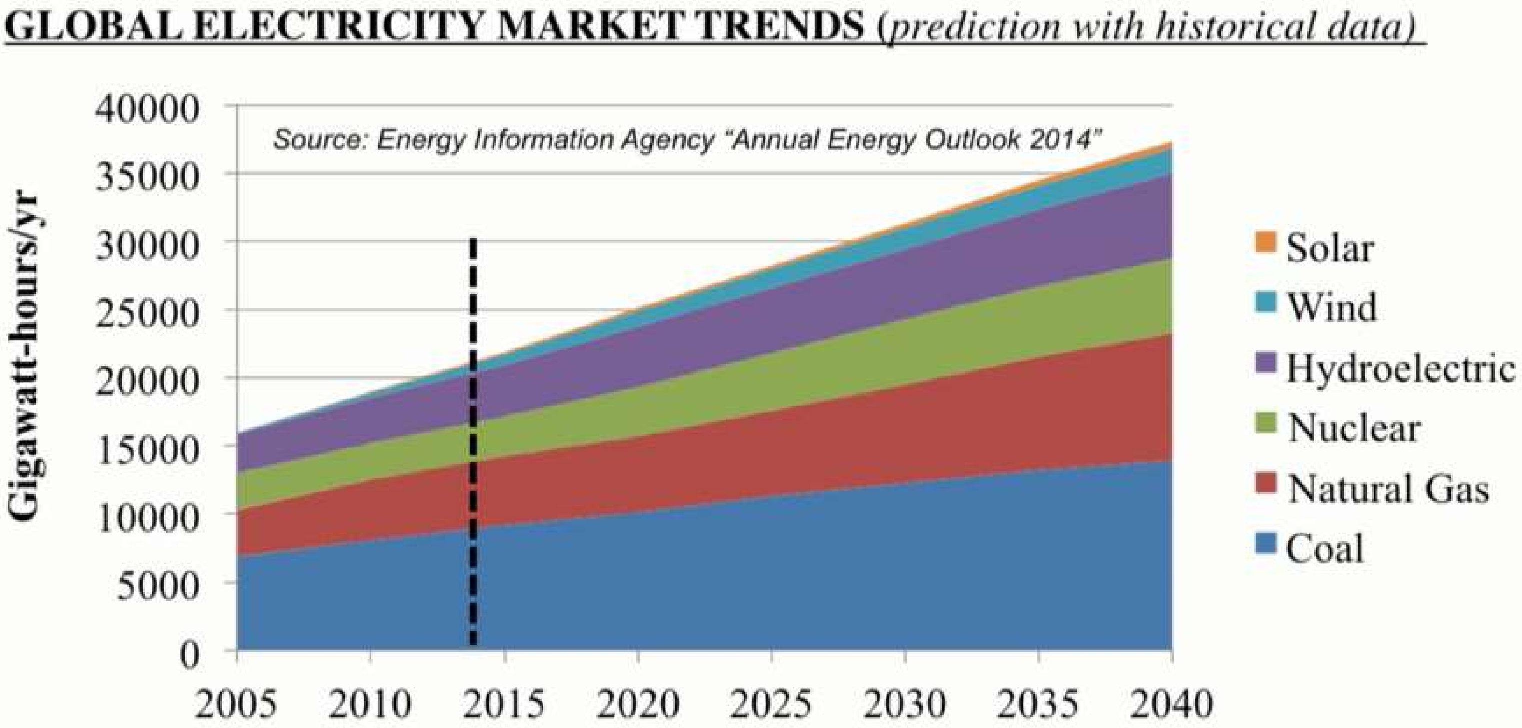


Laser Driven Inertial Confinement Fusion in which pellets of fuel are to be compressed, heated and ignited by lasers to release bursts of energy.

Uses192 high power lasers and 3 football fields fit inside the facility

No net power yet despite 15 year, $3.5B investment

Future without fusion power

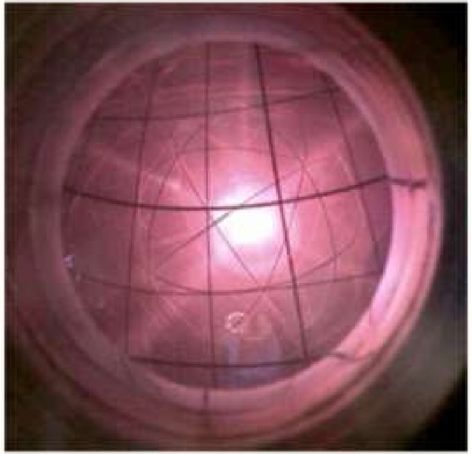


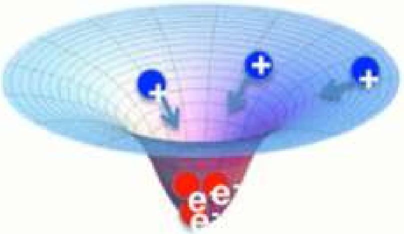
- Despite increased deployment of wind & solar, current prediction indicates **coal and natural gas will account for 60% of electricity generation in 2040 (nuclear at 14%)**
- *Reflective of continuing technical challenges for renewable energy sources*

Story of Polywell Fusion

Can a fusion reactor be small and efficient?

Electrostatic Fusion – no Magnetic Field





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

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

Operating principles

(virtual cathode type)

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

(Gridded) Electrostatic Fusion (cont.)

Courtesy of Fusion Technology Institute
Univ. of Wisconsin

Great for generating energetic ions with good confinement in a small system.

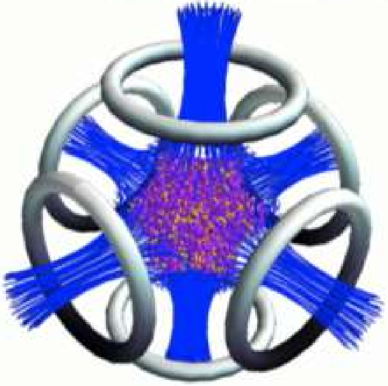
But loss of high energy electrons to the grid is too large.

Net power generation is unlikely
(present efficiency: 10^{-6} to 10^{-5})

Initial Idea behind Polywell Magnetic Insulation of Grid

Coil winding inside Polywell device

<u>Poly</u>hedral coils: electron confinement

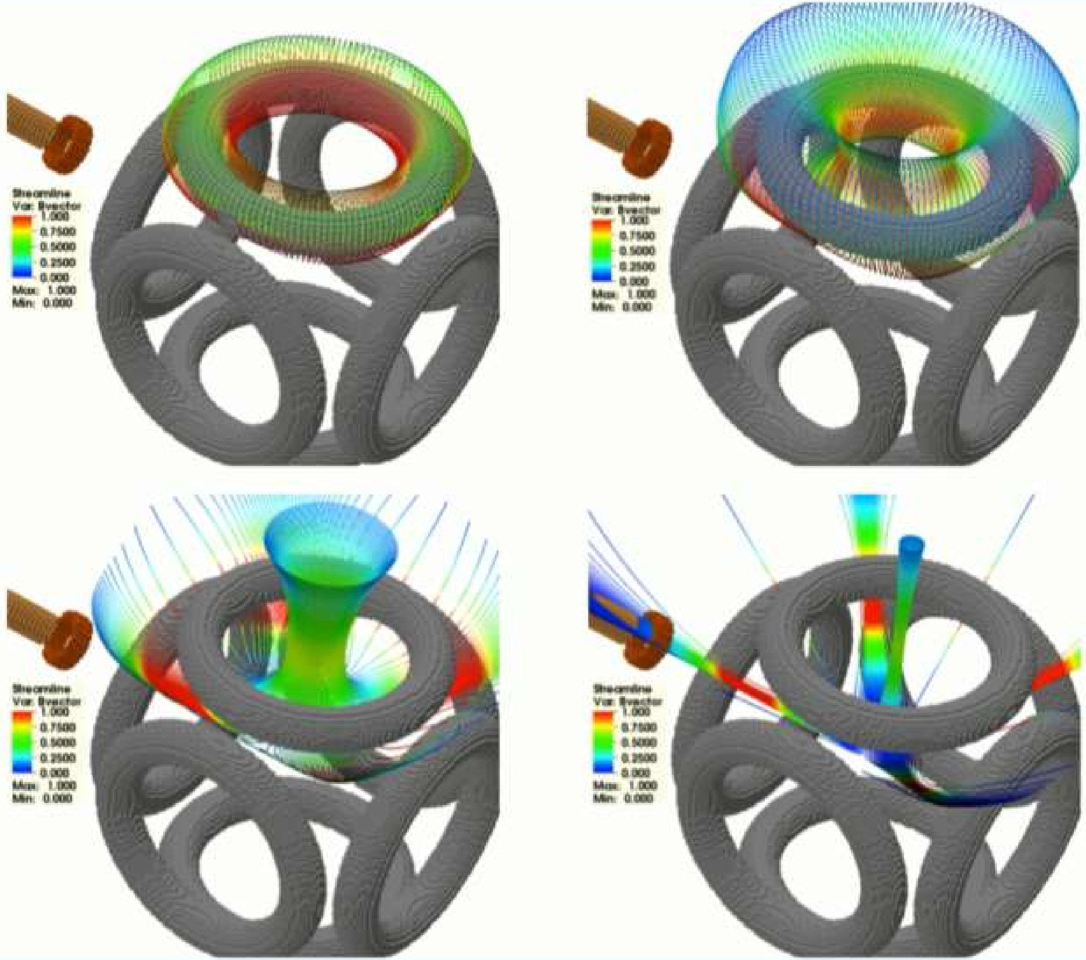


Magnetic field can greatly reduce the plasma loss to the grid

Potential **<u>Well</u>**: ion heating &confinement

Conceived by Bussard, 1985

Polywell Magnetic Fields

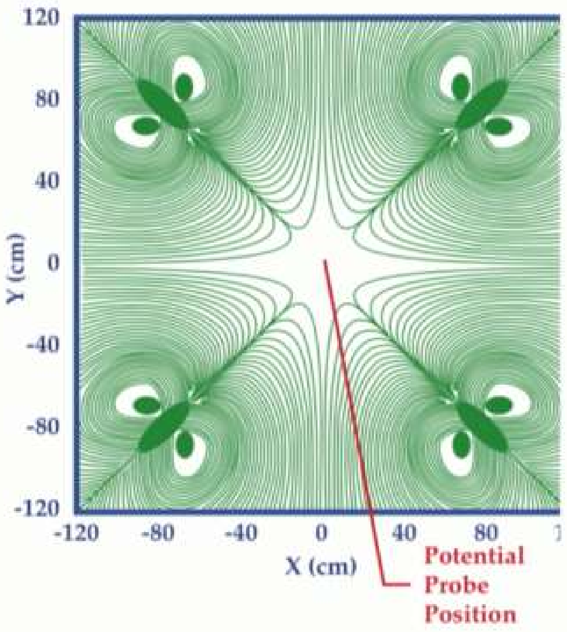


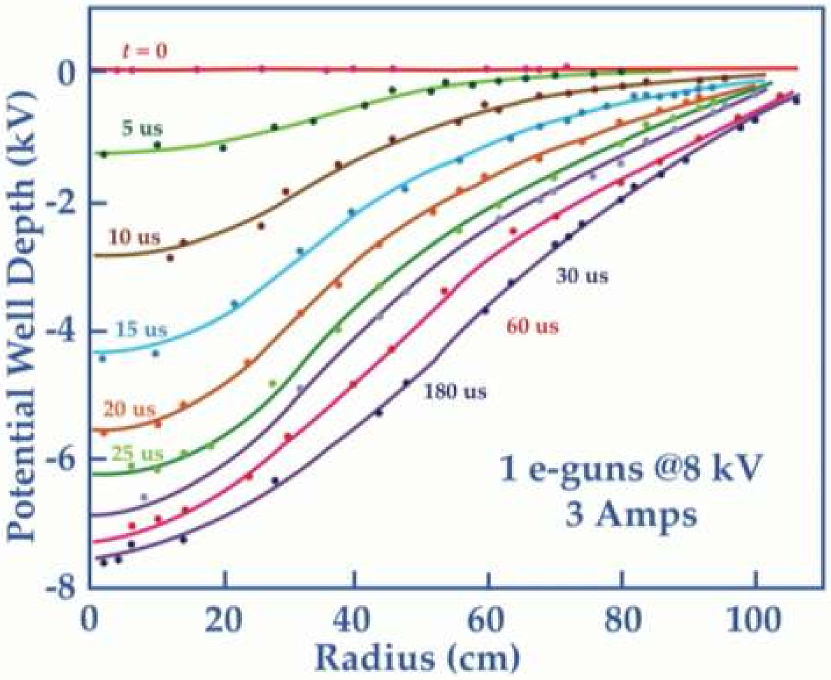
6 coil Polywell

magnetic field lines

Early Success, ~1995
Potential well formation by e-beam injection

at low plasma density





However, the potential well decayed away with increase in plasma density, **which was attributed to the insufficient confinement of high energy electrons inside the Polywell cusp field** (*Krall et al, Physics of Plasmas,1995*)

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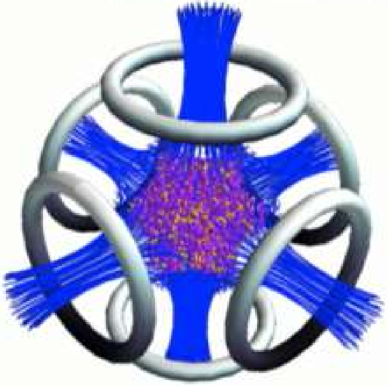

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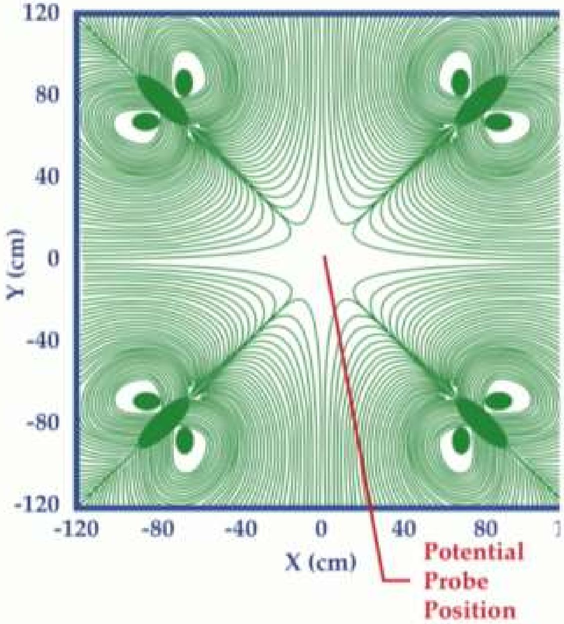
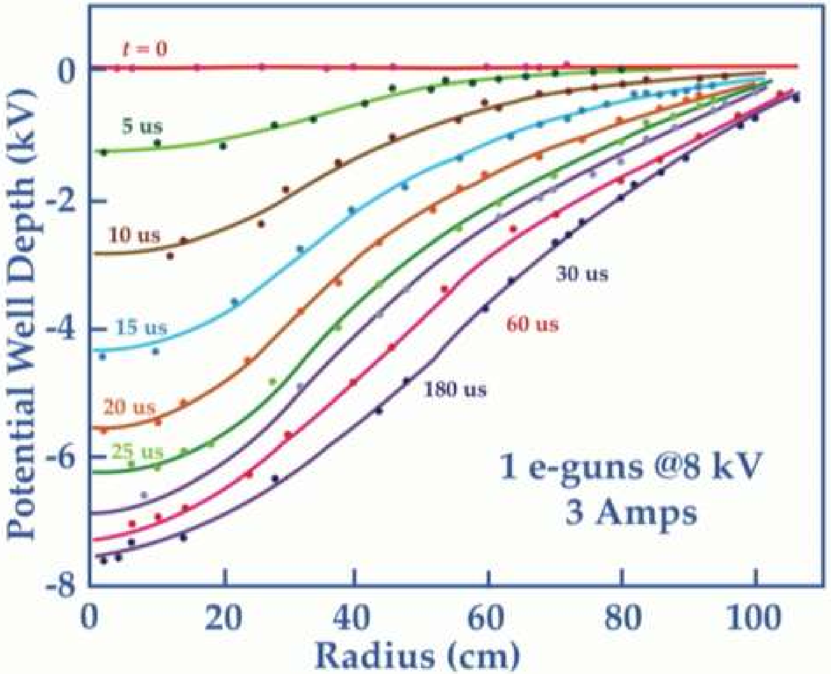


at low plasma density



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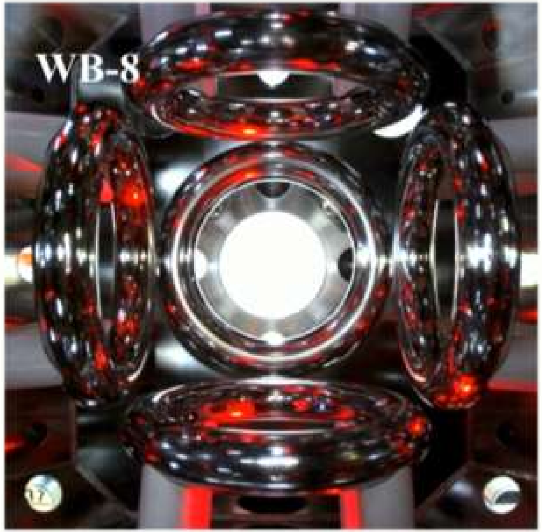
EMC2 Efforts in Electron Confinement

WB-6 **WB-4**

WB-2



WB-5

WB-7

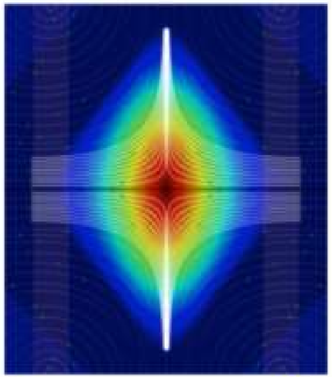
Since 1994, EMC2 had built and operated successive test devices from Wiffle-Ball-1 (WB-1) to WB-8 to demonstrate confinement of high energy electrons in Polywell devices

2nd Look into Polywell
Diamagnetism in Plasma and more

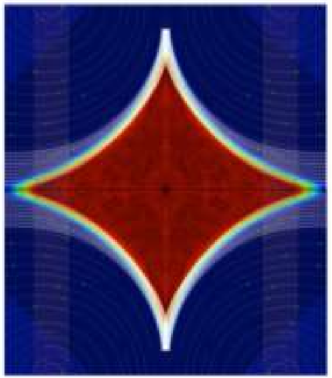
- Current produced by plasma can cancel out magnetic fields. This effect is called diamagnetism and is proportional to plasma pressure
- With increasing plasma pressure, dynamics of Polywell changes due to diamagnetic effects
- Similar to the cause of magnetic levitation in superconductor (Meissner effect)

β= plasma pressure/ magnetic pressure

Note: fusion power ~ $\beta^2 R^3$



Low β



High β

History: Fusion Research in 1958

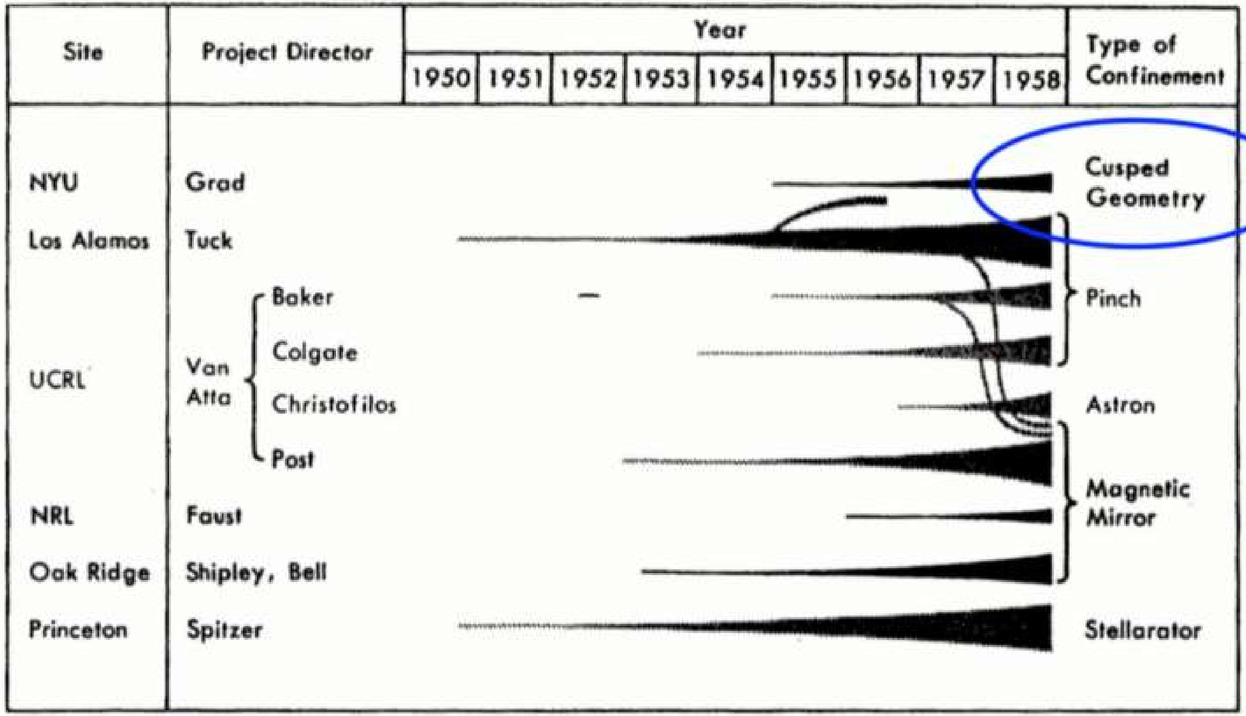


FIG. 19–2. CHRONOLOGY OF THE SHERWOOD PROGRAM, showing methods of plasma confinement in experiments to date.

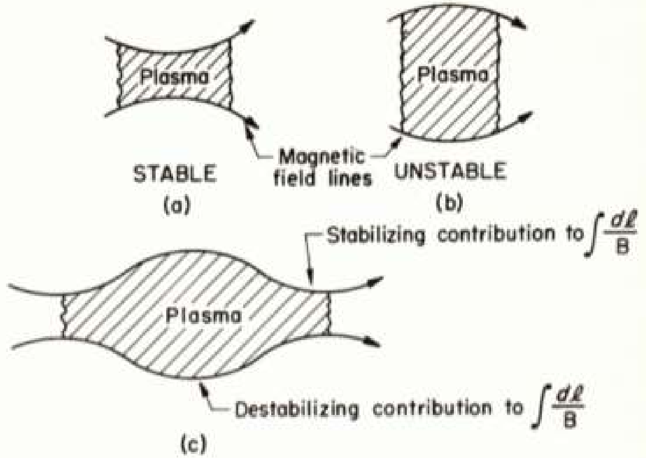
From "Project Sherwood: The U. S. Program in Controlled Fusion" by Amasa Bishop (1958).

Question on Plasma Stability

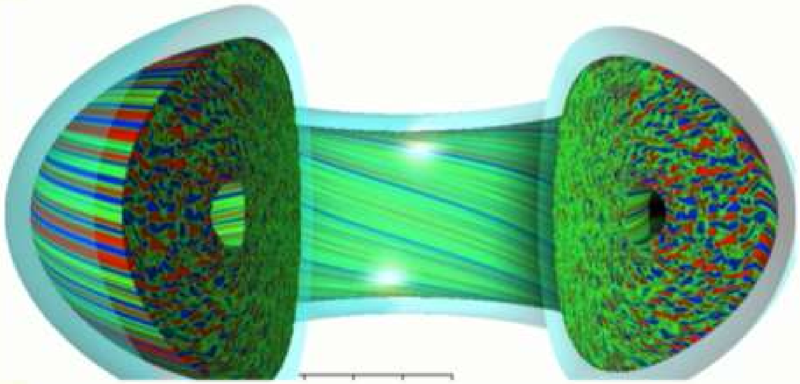
Reference: "Project Sherwood: The U. S. Program in Controlled Fusion" by Bishop (1958).

• Question on Plasma Stability by Teller in 1954

- Attempts to contain a plasma are somewhat similar to containing jello using rubber bands
- Basis of interchange instability (plasma version of Rayleigh Taylor instability) and idea of "good curvature" vs. "bad curvature"



From Principles of Plasma Physics
Krall & Trivelpiece (1973)



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

Legacy of Plasma Stability Constraints

ITER design calls for β to be 0.03

while the fusion power output ~ $\beta^2 R^3$

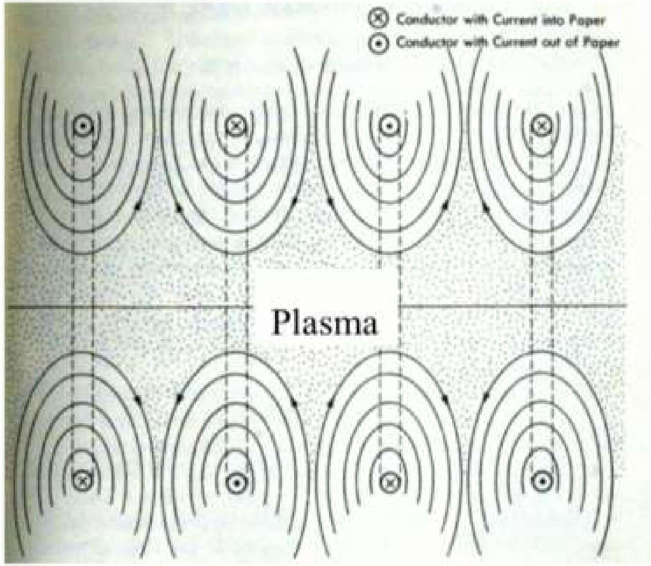
In 1950s, H. York at Livermore was concerned that "the limitation on β might so reduce the net power output that this device (stellarator) could never be of economic interest" and started magnetic mirror fusion (later found to be unstable at high beta) program at Lawrence Livermore National Laboratory.

Also, laser fusion approach at National Ignition Facility continues to battle with hydrodynamic instability.

Plasma stability is key to economical fusion

Cusp Confinement Configuration

Picket Fence



Conceived by Tuck in 1954

(from Bishop's book)

- Picket-Fence (cusp confinement) concept by Tuck is the first stable magnetic confinement scheme against interchange instability.
- The entire region of confined plasma faces magnetic fields with good curvature. As such, good plasma stability has been observed in many cusp experiments.
- However, original picket fence approach was quickly abandoned due to rapid plasma loss along the open magnetic field lines.

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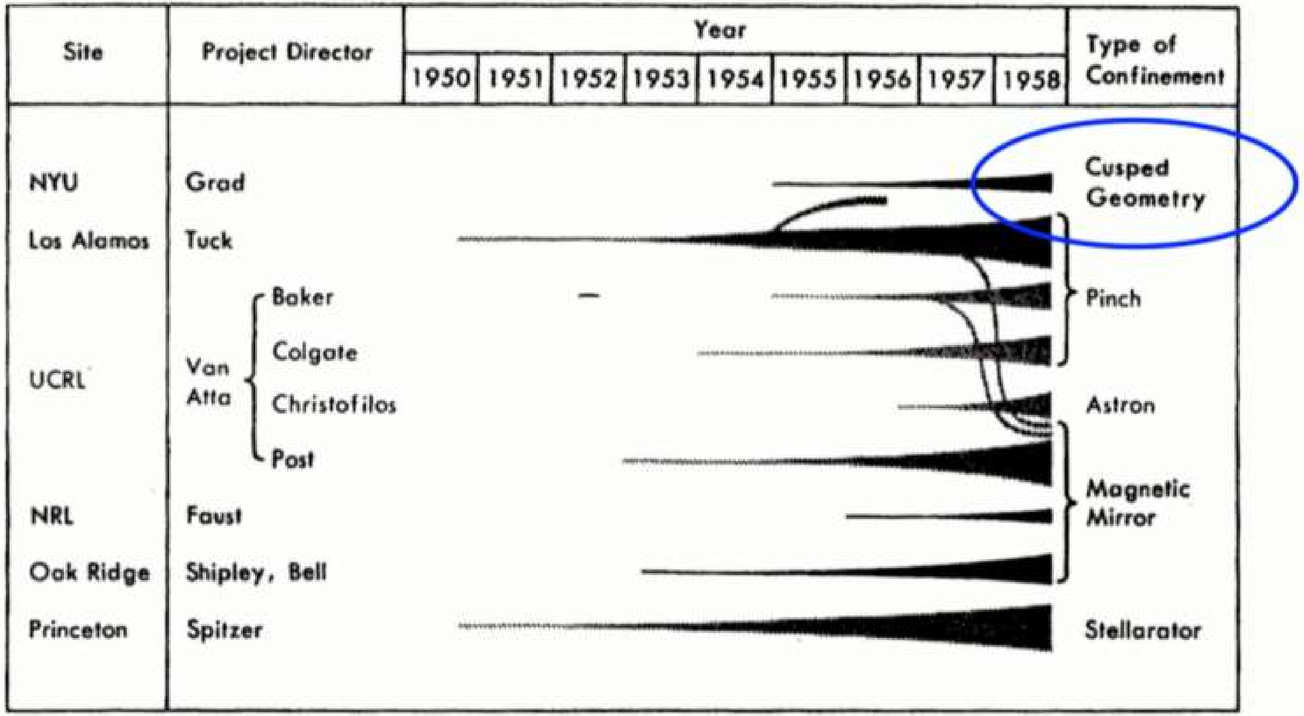

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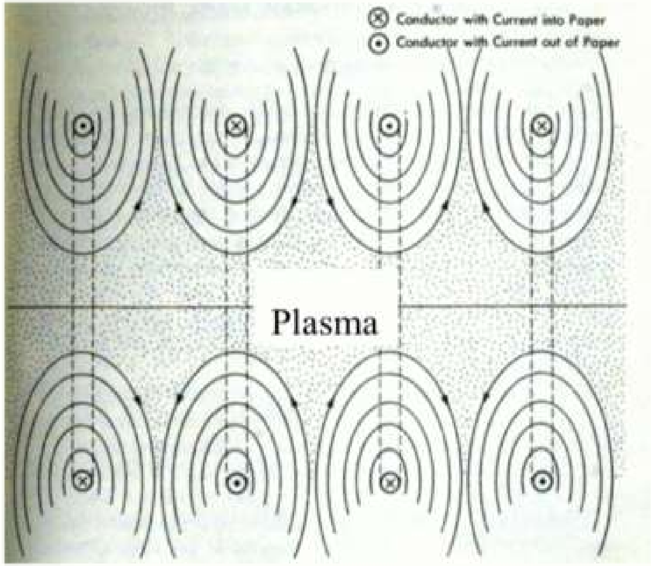

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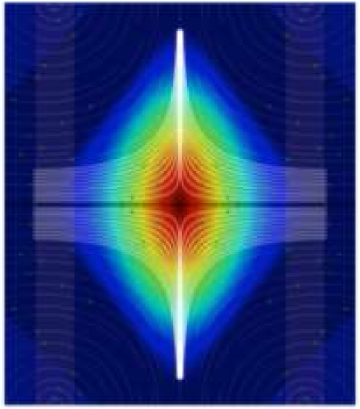
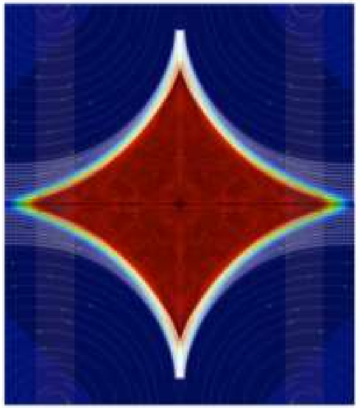
Grad's High Beta Cusp Conjecture

Low β

Weak diamagnetism (plasma penetrated by magnetic field)





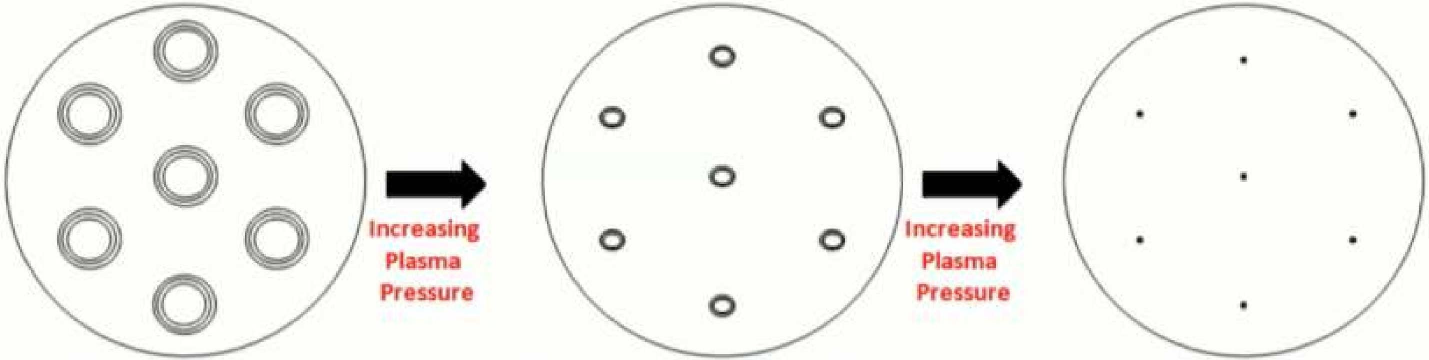
High β

Strong diamagnetism (plasma excludes magnetic field)

- Between 1955-1958, NYU group led by Grad investigated the case of plasma confinement in high β magnetic cusp.
- In Grad's view, the boundary between plasma and magnetic fields changes dramatically if there is sufficiently high plasma pressure in a cusp → **this leads to greatly enhanced plasma confinement at high β (for example at β =1)**
- Theoretically estimated confinement time: 1 μs at low β and 0.5 s at high β for 100 keV electrons confined by a 6 coil cusp system with 7 T magnetic field and 1 m coil radius

WiffleBall: Bussard's take on Grad's prediction

"The enormous flux of electrons at the center exhibits "diamagnetic" properties (it excludes magnetic fields). This pushes back the magnetic field and constricts the cusp holes."



Magnetic Cusps- No Plasma

Diamagnetism from Plasma Pressure Reduces Cusp Losses

Wiffleball Mode At Beta = 1

Brief History of Cusp Confinement

- Grad's confinement enhancement conjecture made the cusp approach promising for a net power fusion reactor.

- As a result, experiments were conducted for the next 20 years on ~20 different devices and ~200 papers were published related to the cusp confinement. There are 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 and experimental data which casted a shadow to the cusp confinement prediction.

Polywell Addresses Critical Challenging Issues of Cusp System

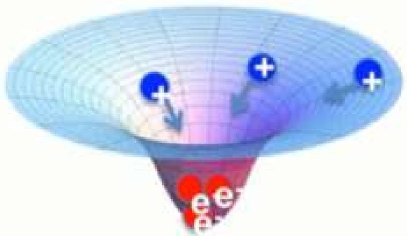
Two major challenges of conventional cusp

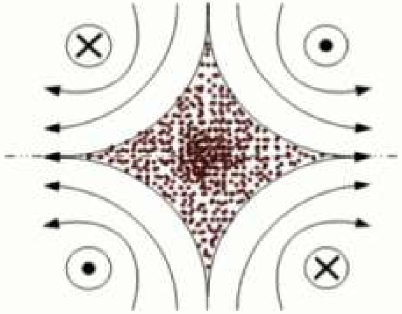
a) How to heat ions to fusion temperature?

- Electron beams generate electric fields, which accelerates ions efficiently to fusion temperature

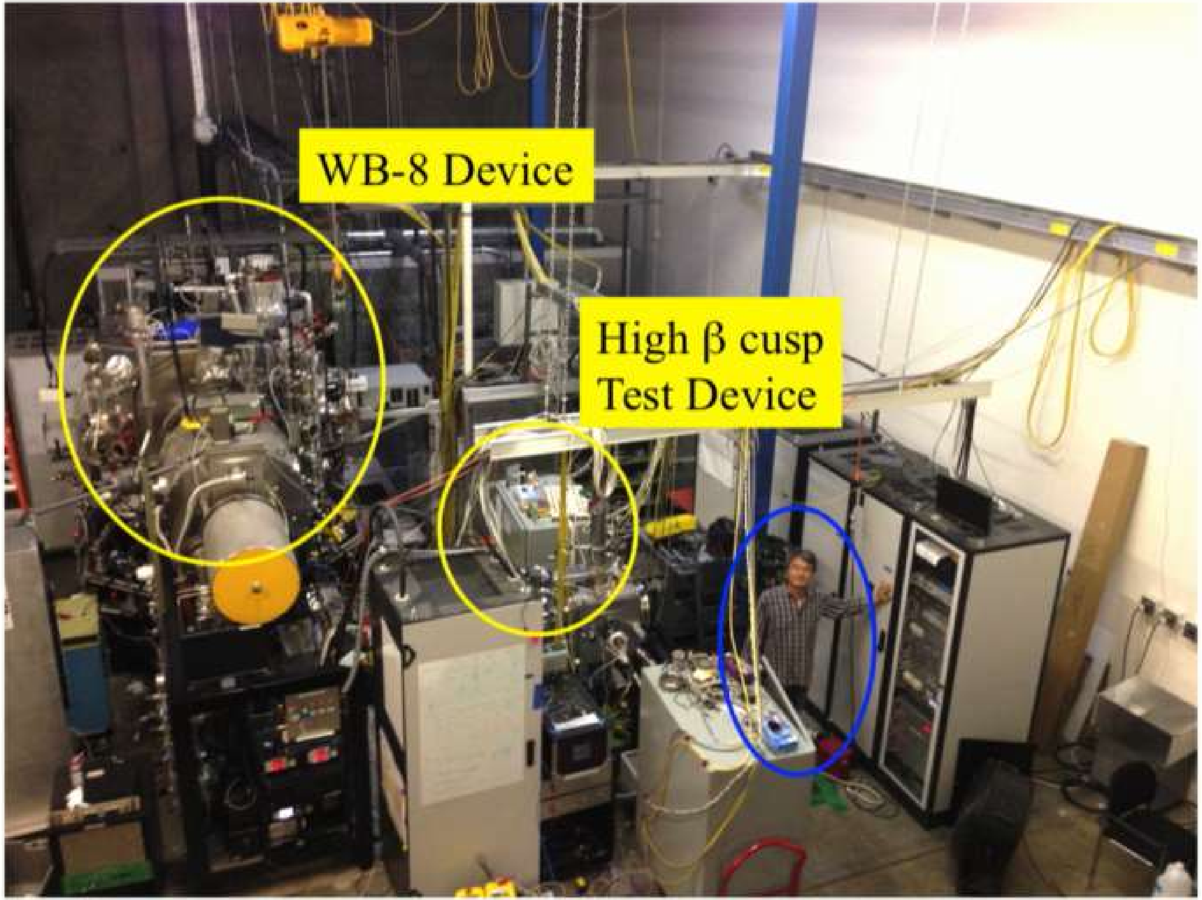
b) Is loss rate determined by electrons, ions or both?

- In Polywell, only electron loss matters because ions are cold at the boundary where the loss occurs

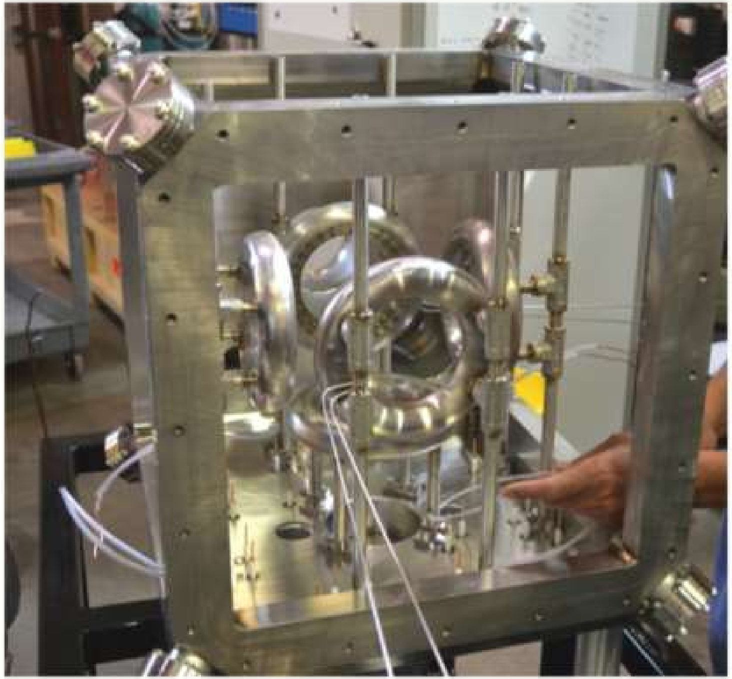




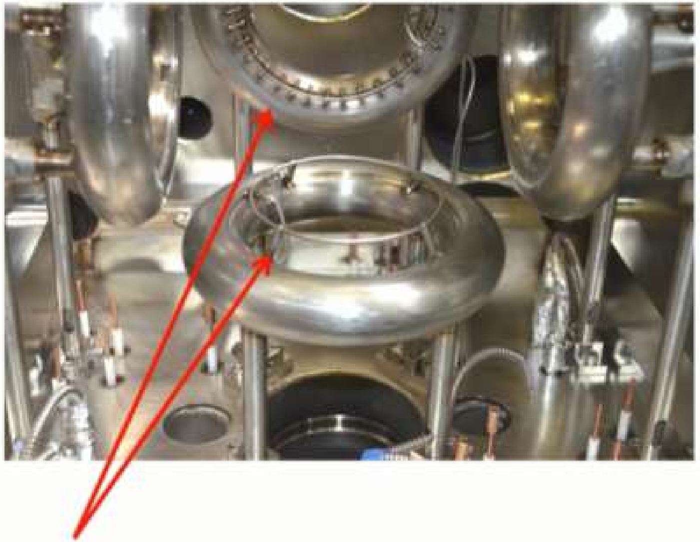
Recent Experiments at EMC2
(EMC2 San Diego Facility)



High β cusp test device installation

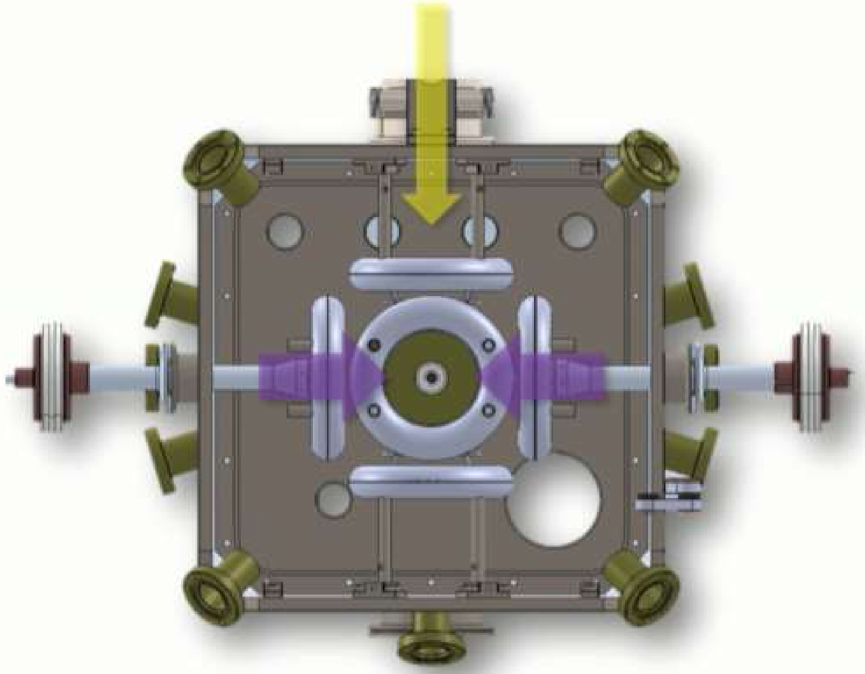


6 coil cusp installation



Locations of flux loop
to measure diamagnetic effect

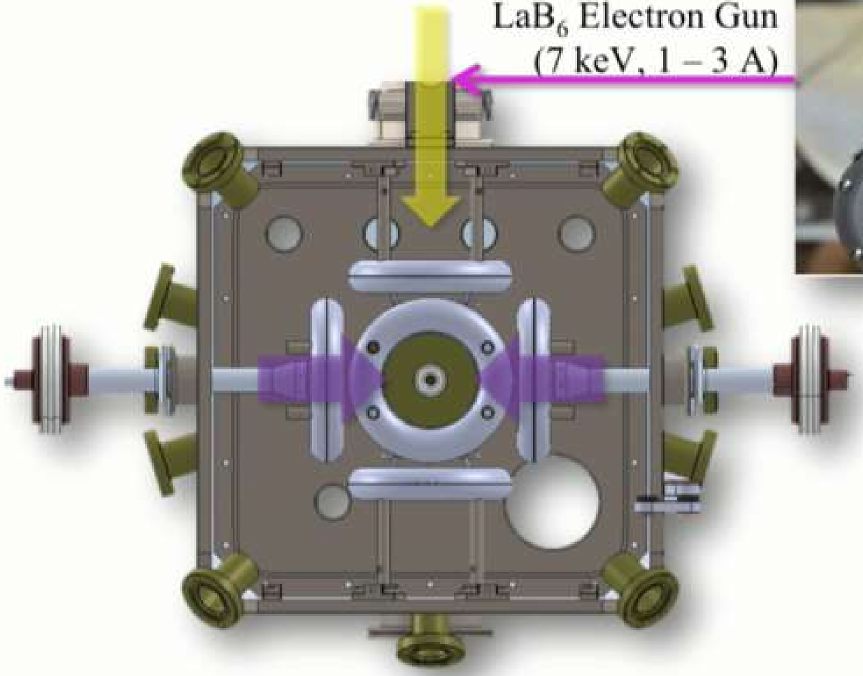
Experimental Setup
for high β cusp confinement



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

EMC2®

Experimental Setup
for high β cusp confinement



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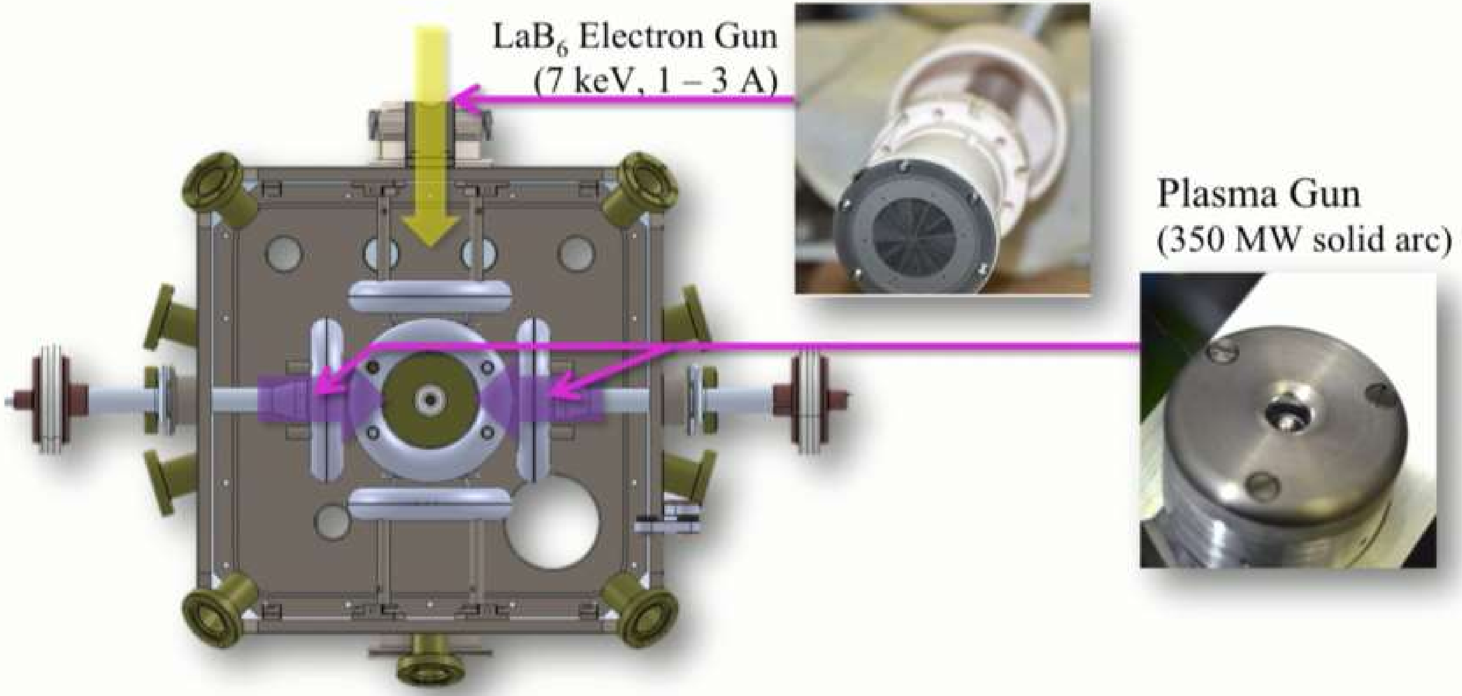

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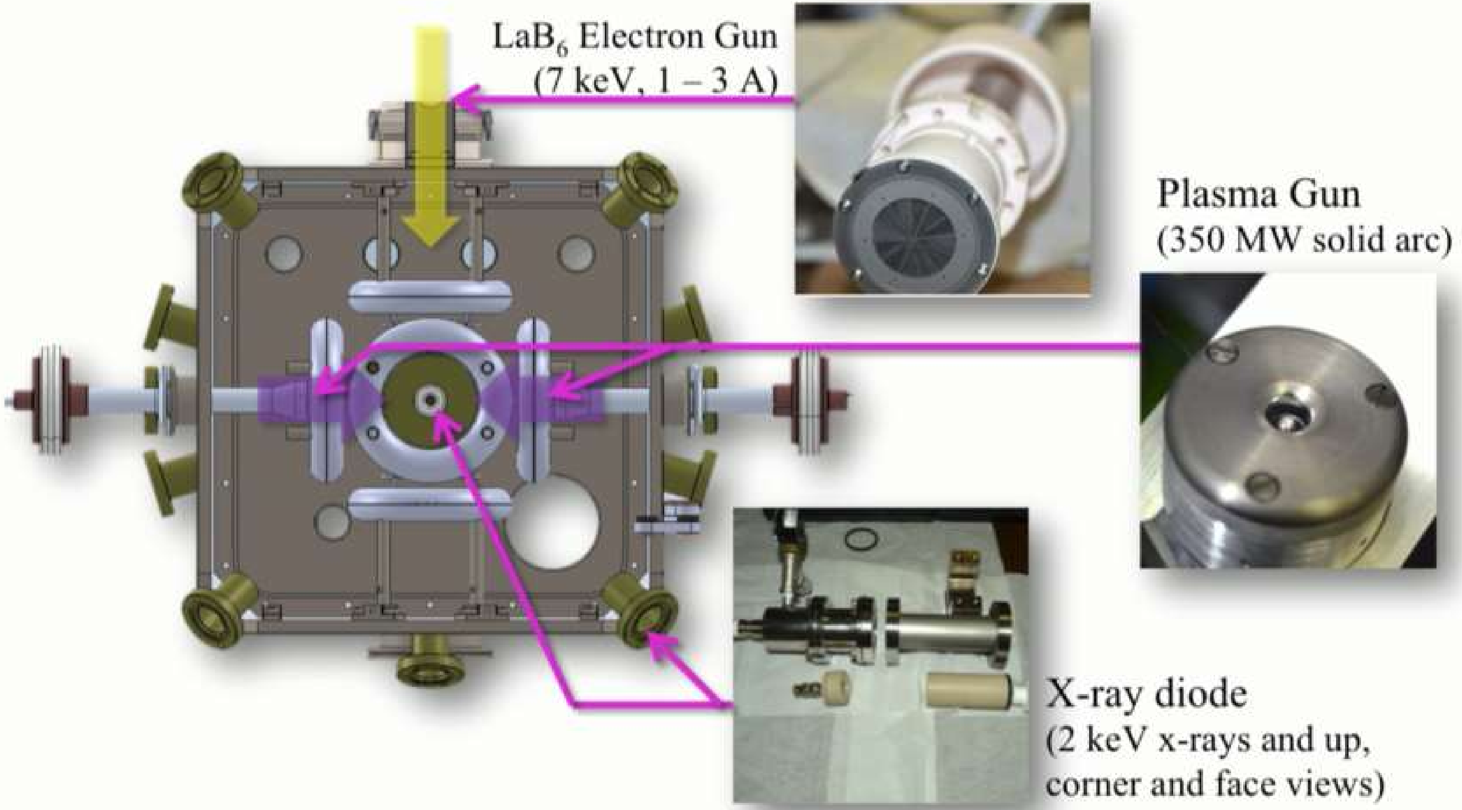

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Experimental Plan

1. Plasma injection to the cusp
   - Use high power arc (solid target) plasma injectors
2. Verify high β plasma formation in the cusp
   - Measurements of plasma density, magnetic flux and electron temperature
3. High energy electron injection to high β cusp
   - LaB_6 based electron beam injector, sufficient for diagnostics but not for potential well formation
4. Confinement measurement of high energy electrons in the cusp
   - Time resolved hard x-ray intensity from bremsstrahlung

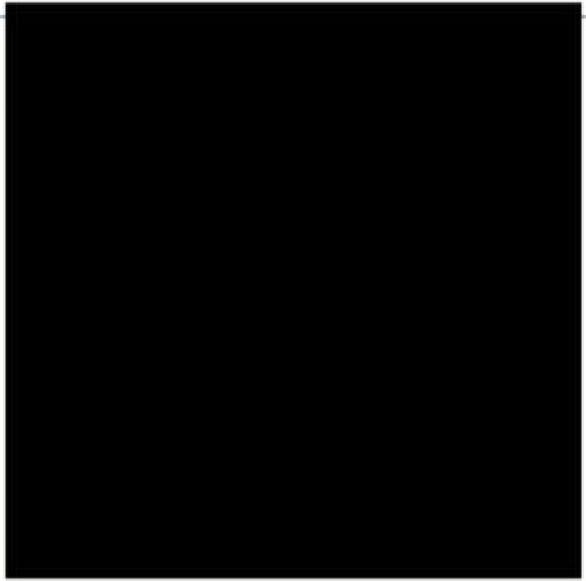
Bulk (cold & dense) plasma from arc injectors provides plasma pressure (high β) to modify cusp B-fields, while the confinement property is measured for high energy electrons in the cusp.

Initial Plasma Injection

Plasma injection using solid fuel

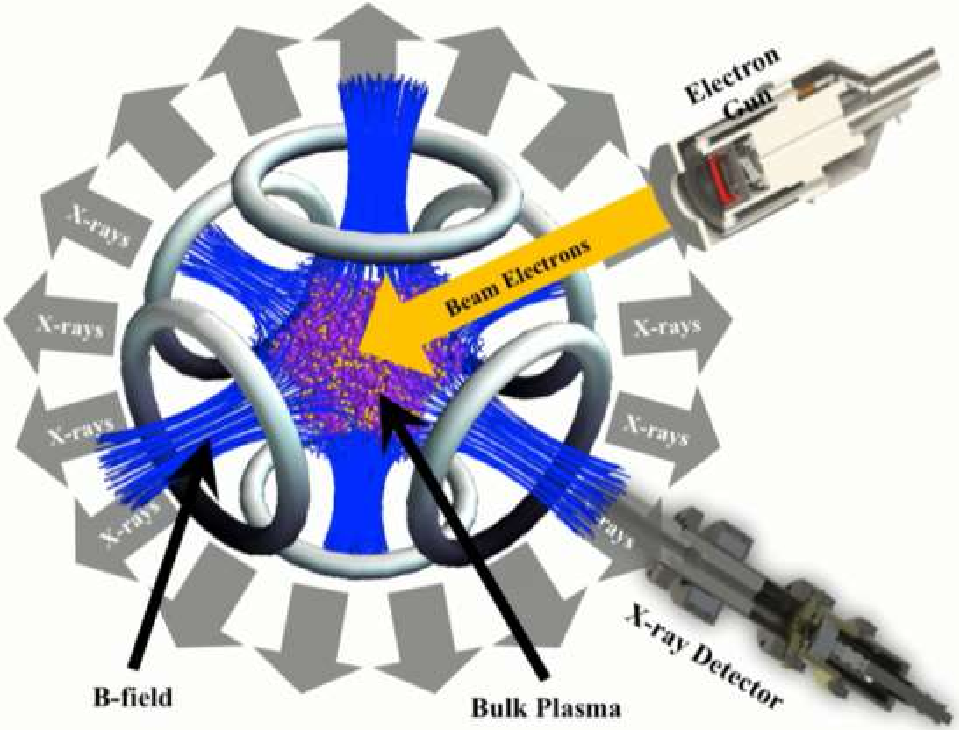
- ~100 kA arc current → ~350 MW peak power and ~7 μs pulse
- By using two high power injectors, we were able to pressurize the Polywell system to high beta condition.

Solid arc with 2 mm gap
using polypropylene film



Dual arc plasma injection movie

High energy electrons produce hard x-rays



E-gun injects
Beam Electrons (7 keV)

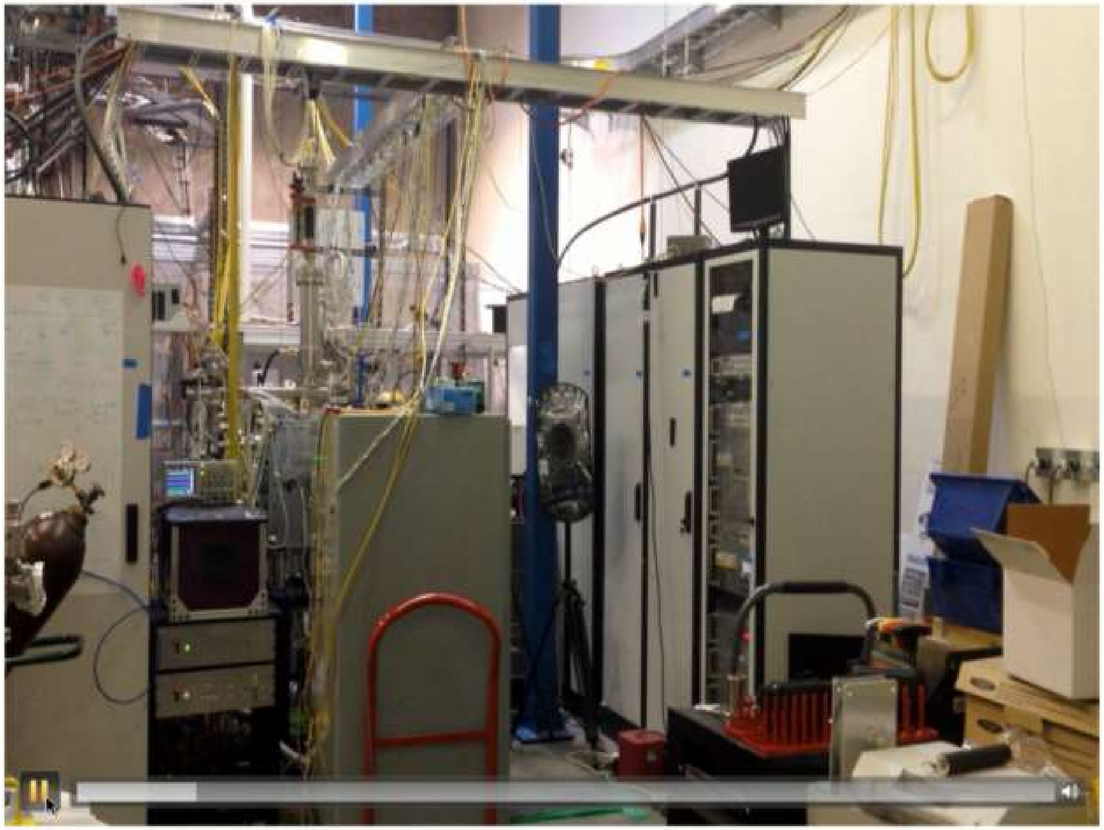
Beam electron confinement by Cusp magnetic fields

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

Transit time: ~7 ns for 7 keV electron for 22 cm transit

Expected confinement time: ~45 ns for low β and ~18 μs for high β (x400 increase)

Movie of WB test experiments



WiffleBall in Operation

Shot # 15640, 700 MW injection, Oct. 25, 2013

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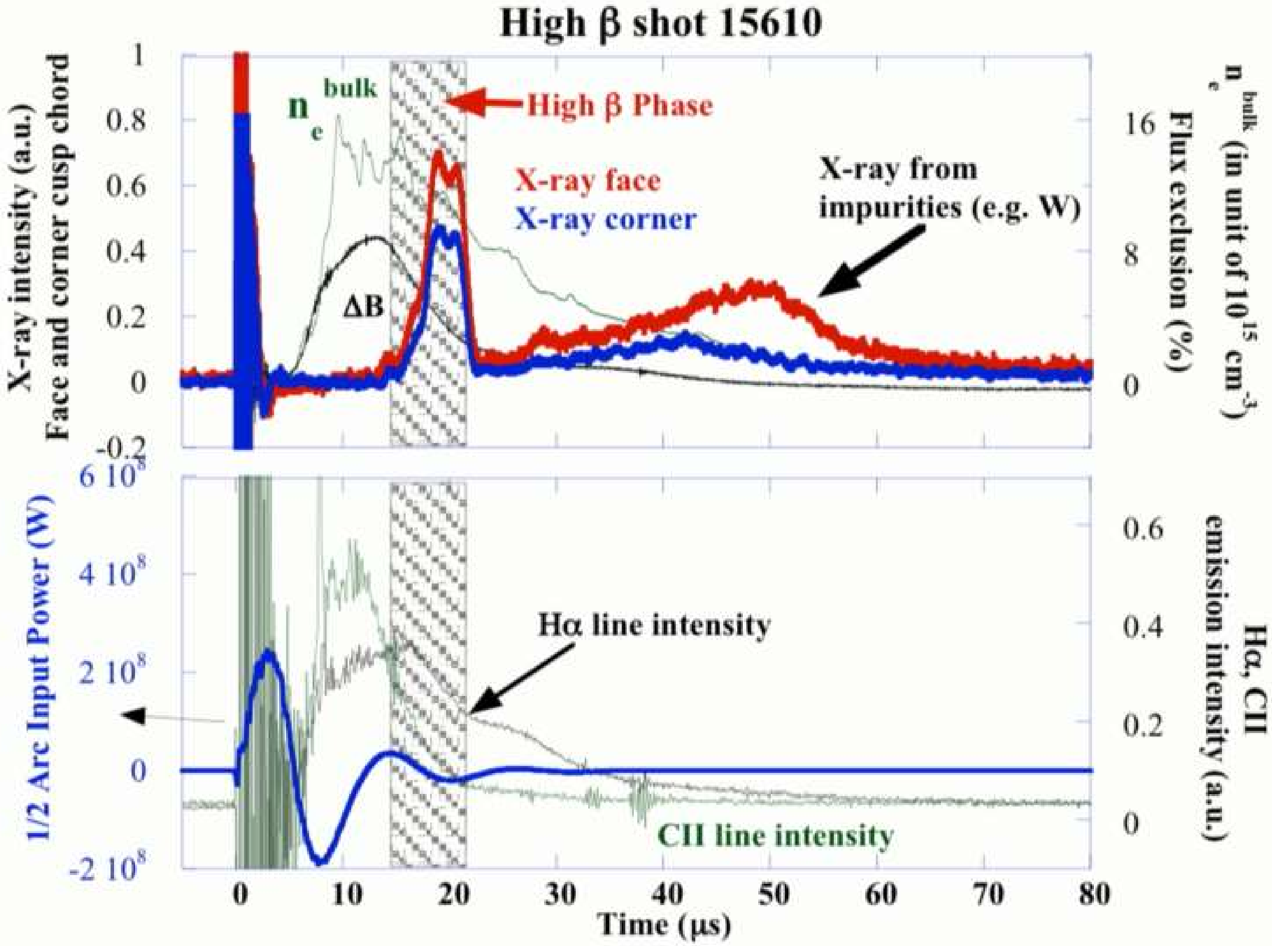
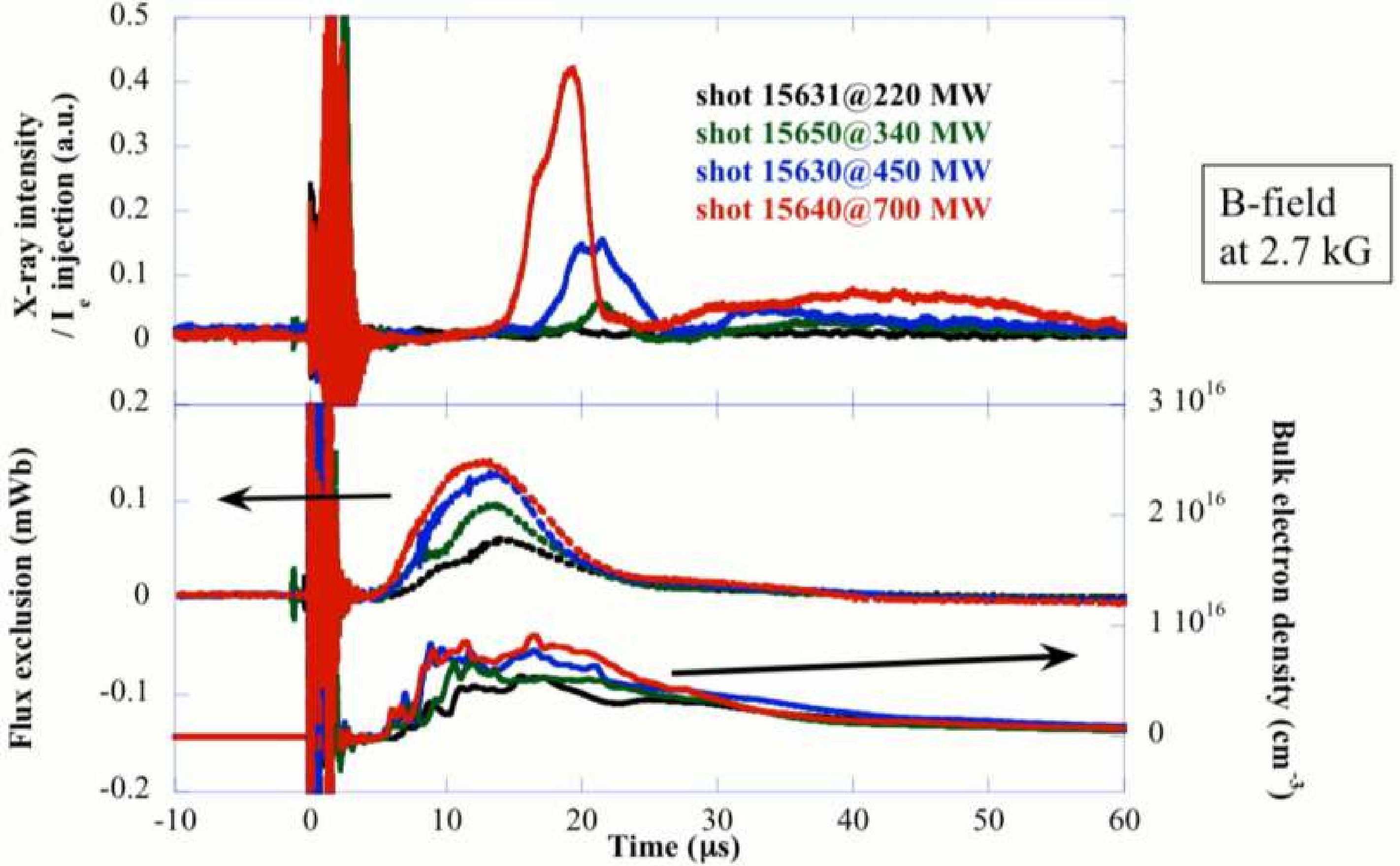
First ever confirmation of electron confinement enhancement during high β cusp (October 23, 2013)

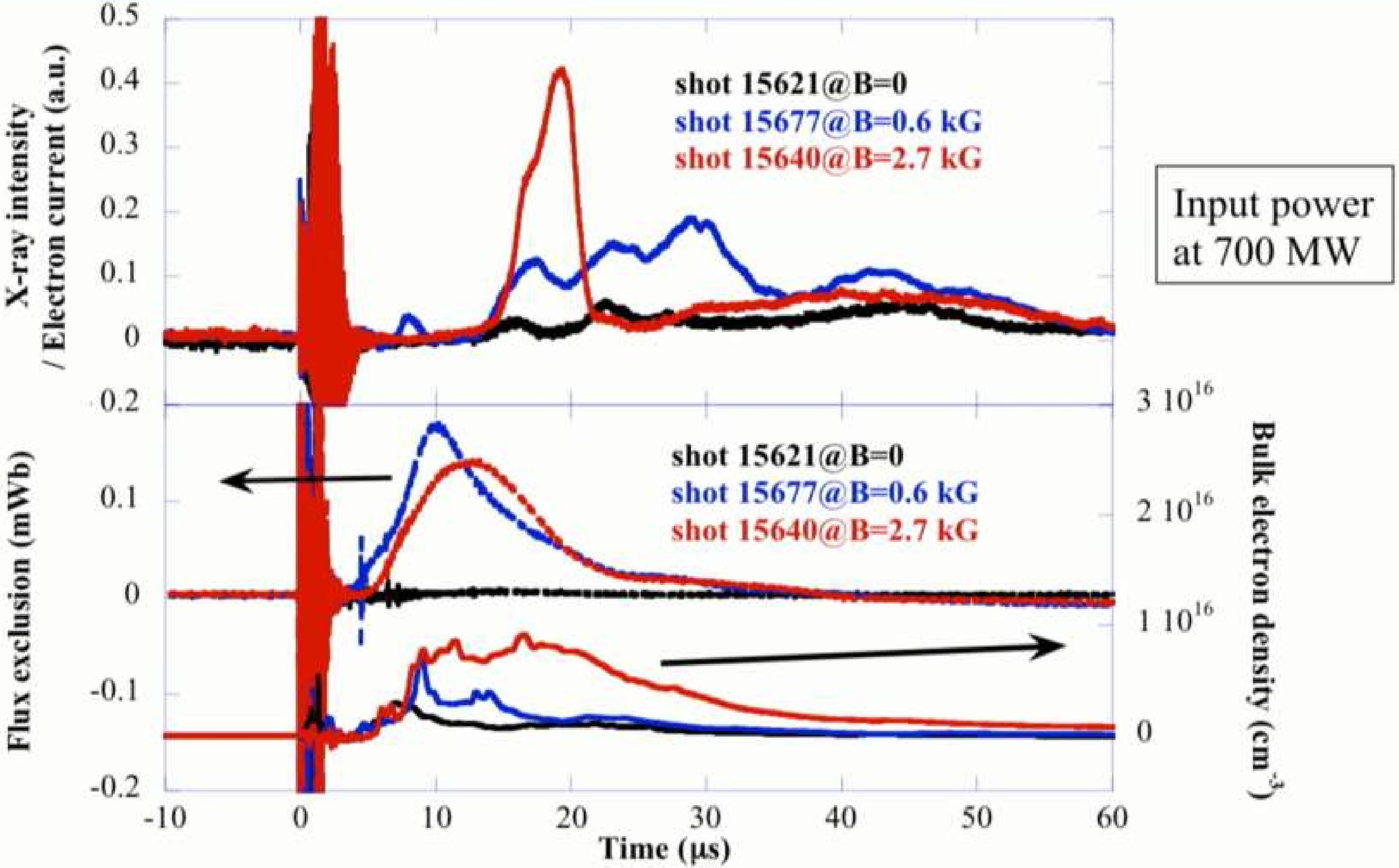


Confinement enhancement requires high β condition



Cusp confinement vs. Injection input power

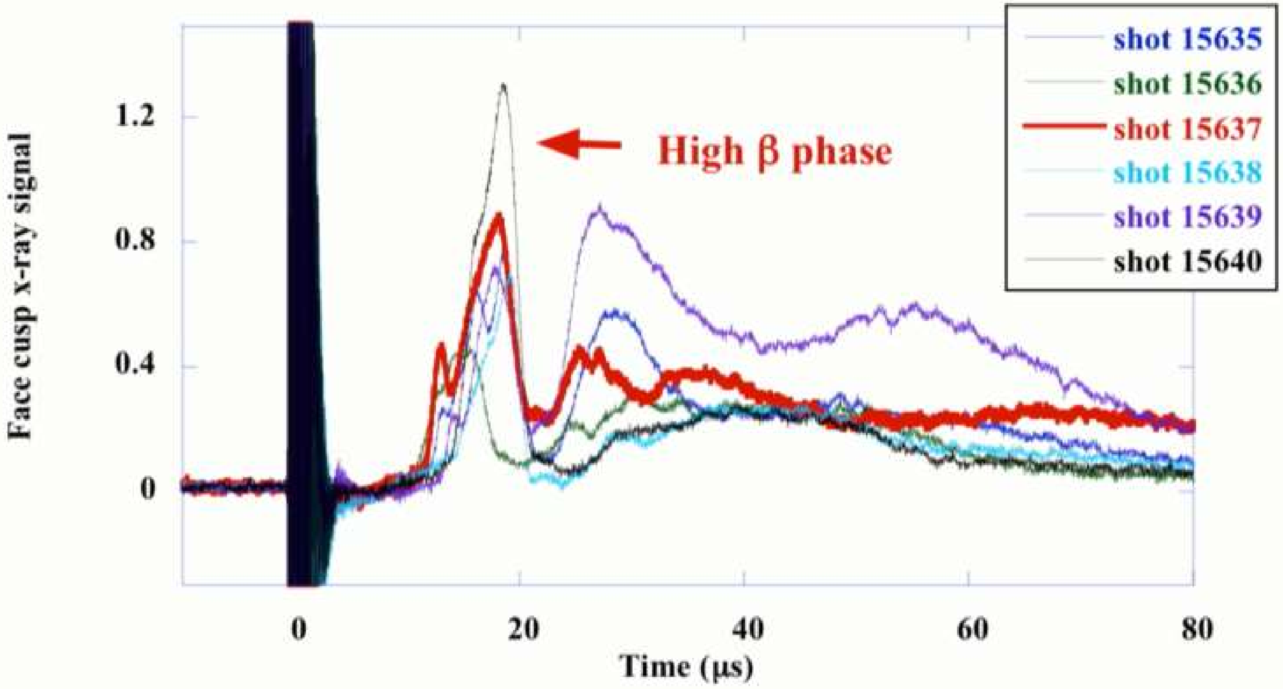
Confinement enhancement related to pressure balance between plasma and magnetic field



Cusp confinement vs. initial B-fields

Reproducibility of high β cusp confinement phase

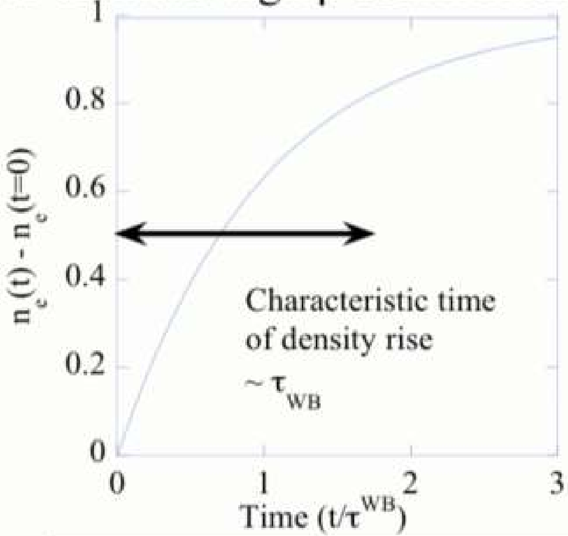
6 consecutive shots with ~ 200 J of injected plasma energy at 2.7 kG B-fields
→ estimated beta ~ 0.7 and 10% measured flux exclusion



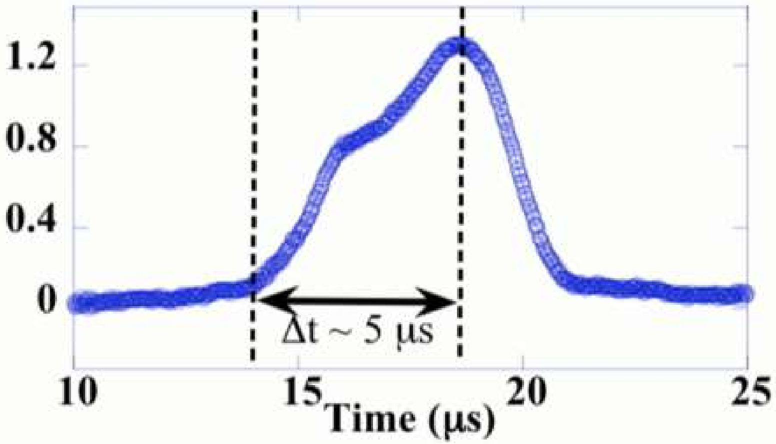
All six shots show distinctive high β phase → good reproducibility

Estimate of High β Confinement Time

Theoretical model
to estimate high β confinement time



Experimental results
Shot 15640



- Note the shape of x-ray intensity profile: a gradual rise and a rapid drop
- From time response of x-ray signal → τ >2.5 μs (2x τ ~ x-ray signal rise time)
- **2.5 μs is about ~ 50 times better than low β cusp confinement time**
- The observed confinement enhancement is very significant and compares well with the theoretically predicted high β cusp confinement time by Grad and his team

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Unresolved Physics Issues on High β Cusp

1. Decay of good confinement phase

- Decay mechanism: plasma loss/plasma cooling or magnetic field diffusion or something else
- How to extend high β state and prevent the decay

2. Topological information on cusp magnetic fields during high β state

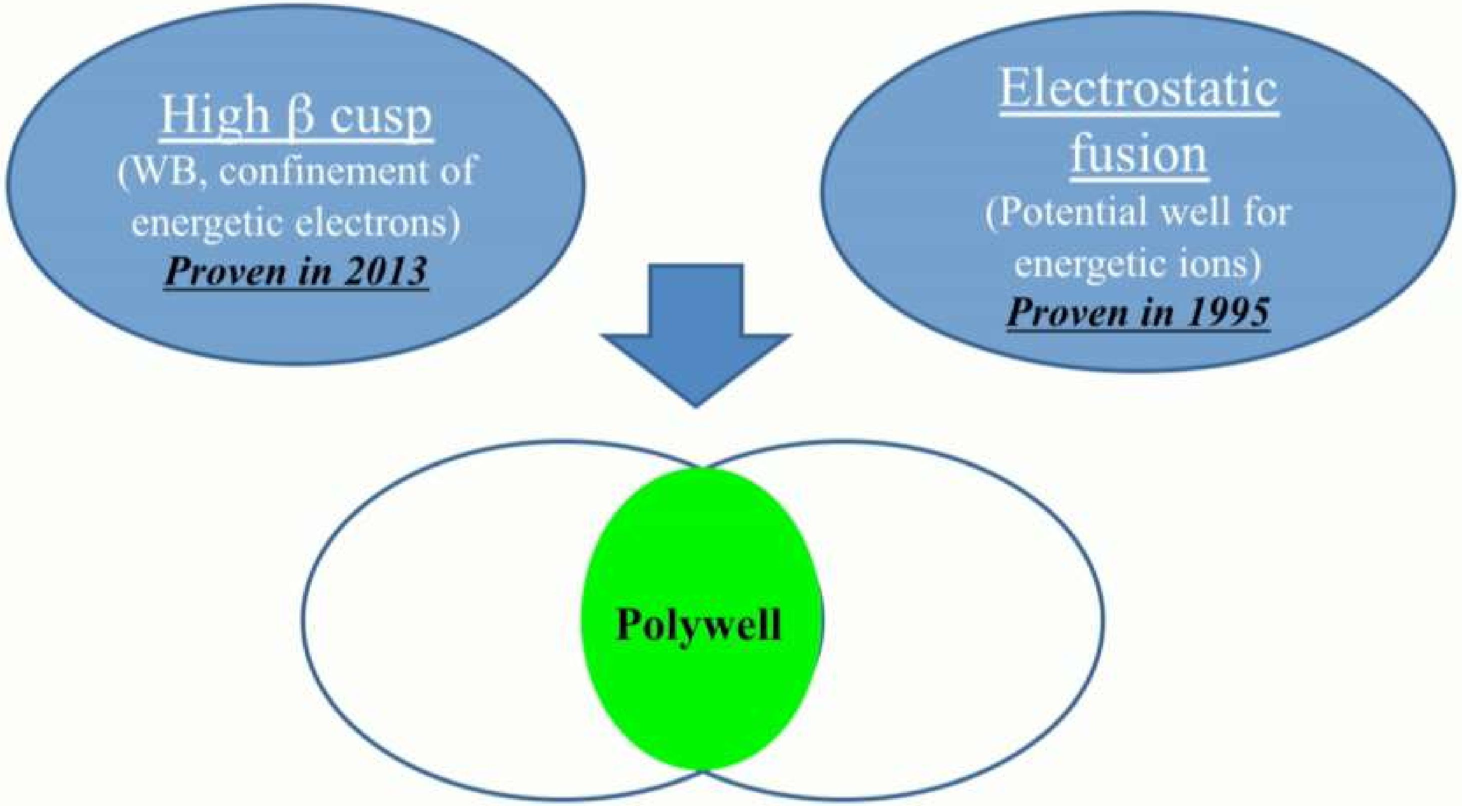
- Thickness of transition layer at β=1 surface
- Magnetic field lines near the cusp openings

Summary of Experiments

- X-ray measurements clearly showed enhanced electron confinement in high β cusp (WB effect).
- This result validates a key conjecture made by Grad and his team in 1950s.
- EMC2 can move forward to complete the proof-of-principle test of the Polywell fusion premise.

Details of EMC2's recent experiments can be found from [*http://arxiv.org/abs/1406.0133*](http://arxiv.org/abs/1406.0133)
Technical manuscript is currently being reviewed for scientific publication.

The Last Step to Validate Polywell Concept



High β cusp + Electrostatic fusion at the same time

Where do we go from here?

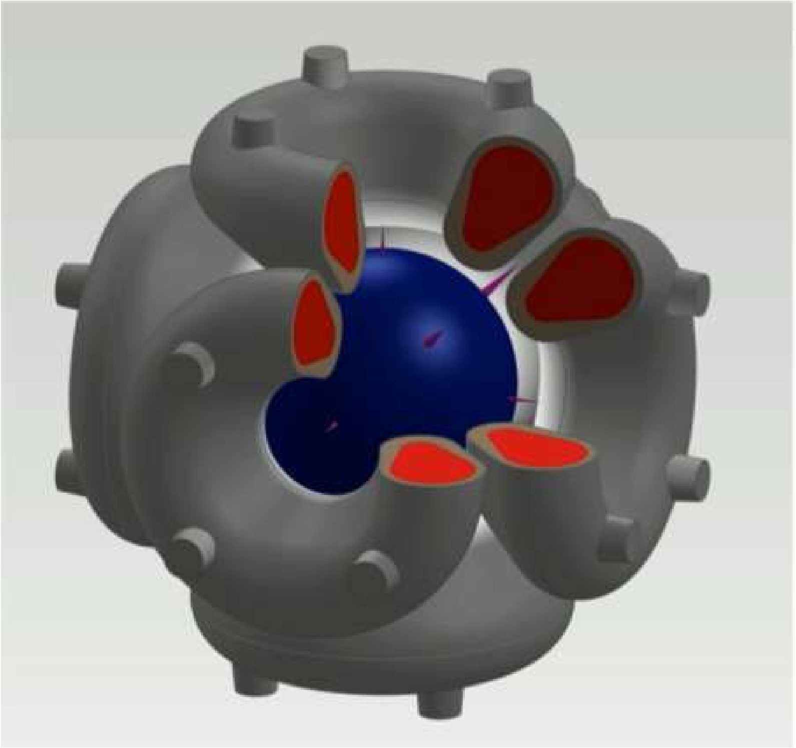
If Grad's loss rate is valid

&

If Bussard's idea of using electron beams to accelerate ions during WB works well (say 50% efficiency)

Can we make a net power producing Polywell fusion reactor?

Net Power Producing Polywell Reactor



We can build this in a few years

Reactor Parameters

Coil Radius: 2.0 m
B-field: 5 T
e-beam: 80 keV
Plasma pressure: 98 atm
Magnetic pressure: 98 atm

Fusion power: 1.1 GW (D-T fuel)
Heating power to plasma: 185 MW

Disclaimer: This design is for a scientific test fusion device (not for engineering demonstration)

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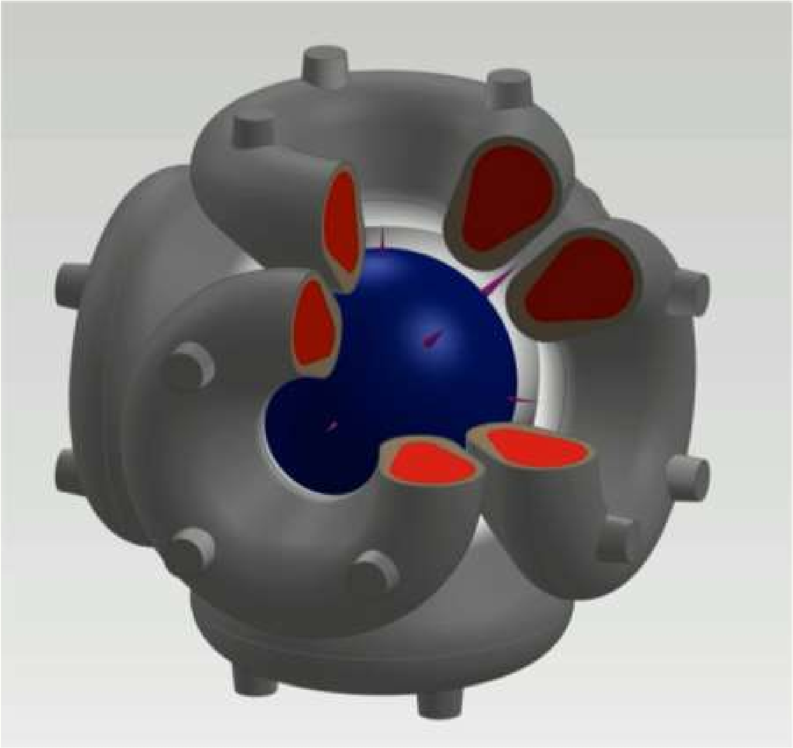

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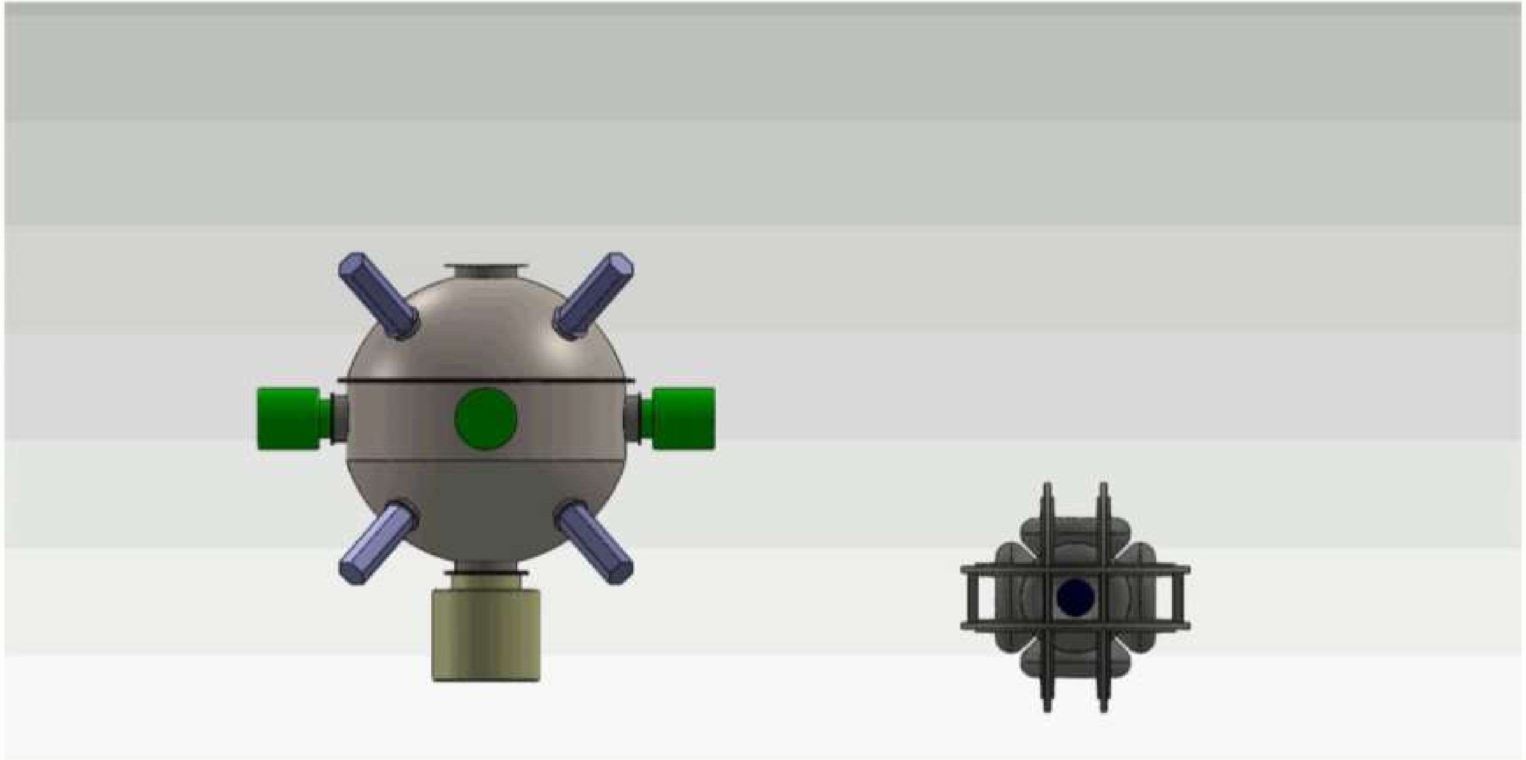
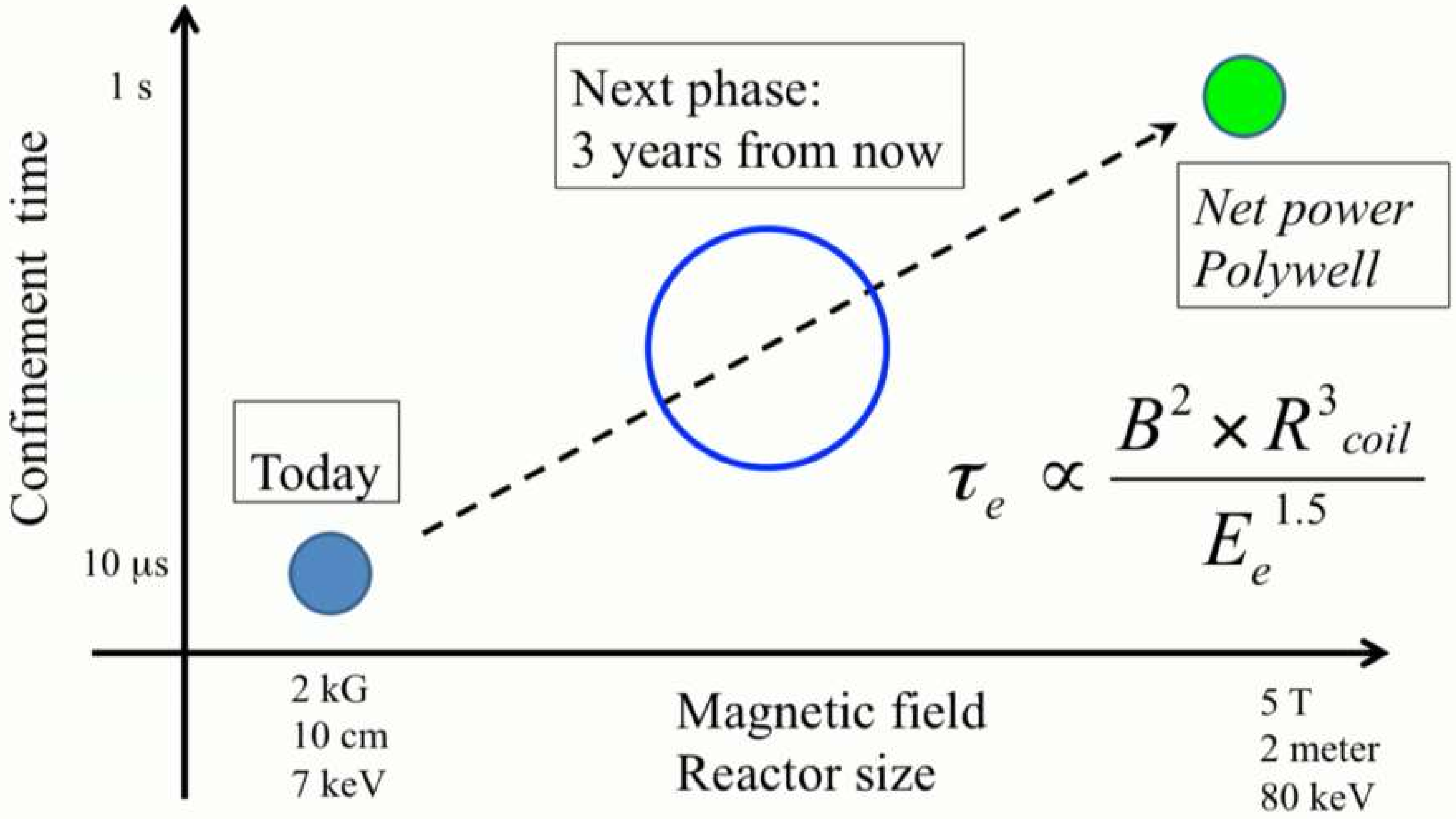
Polywell Reactor Assembly & Maintenance



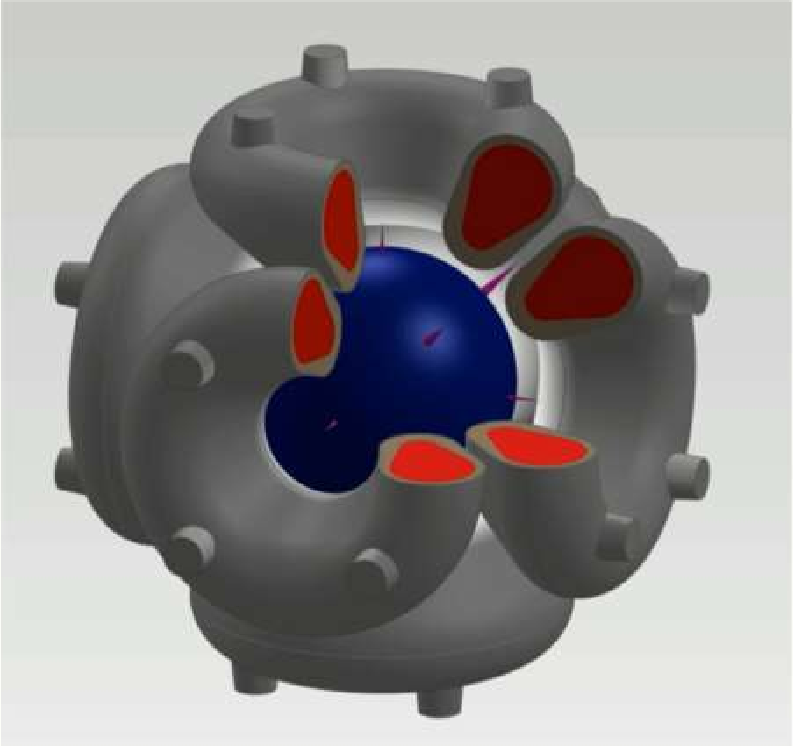
A Polywell reactor is simple to build and to maintain.

Path to Polywell Fusion



$$\tau_e \propto \frac{B^2 \times R^3{}_{coil}}{E_e^{1.5}}$$

Net Power Producing Polywell Reactor



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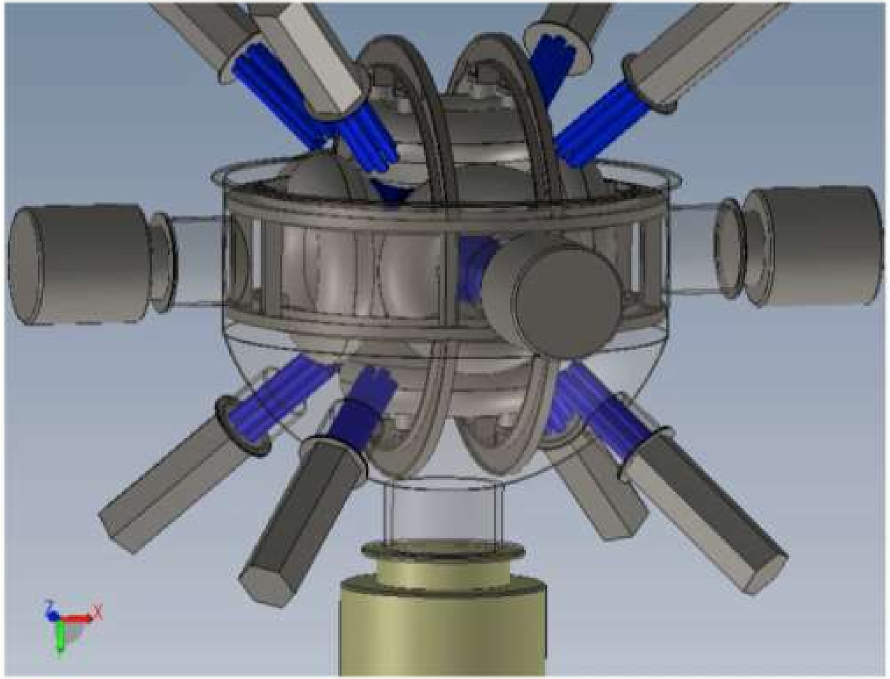
Next Phase: Last Part of Proof-of-Principle



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

<u>3 year R&D program to complete proof-of-principle</u>

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.

What can Polywell fusion do? *Electricity Generation*

Source: EIA, IAEA and UN reports. Electric transportation market projection based on US DOT data, desalination projection based on membrane technology with an efficiency of 3 kWh/m^3.

Summary

- Fusion is the ultimate energy source.
- But fusion research has been, and still is, a very challenging endeavor.
- At present, there are reasons to be optimistic, especially with all the progress in fusion research and other technology advances during the past decades.
- Recent breakthrough in high beta cusp confinement will catalyze our efforts to complete the validation of the Polywell fusion in the next 3 years.
- If proven, Polywell technology would offer a low cost and rapid development path to power the world economically and sustainably.

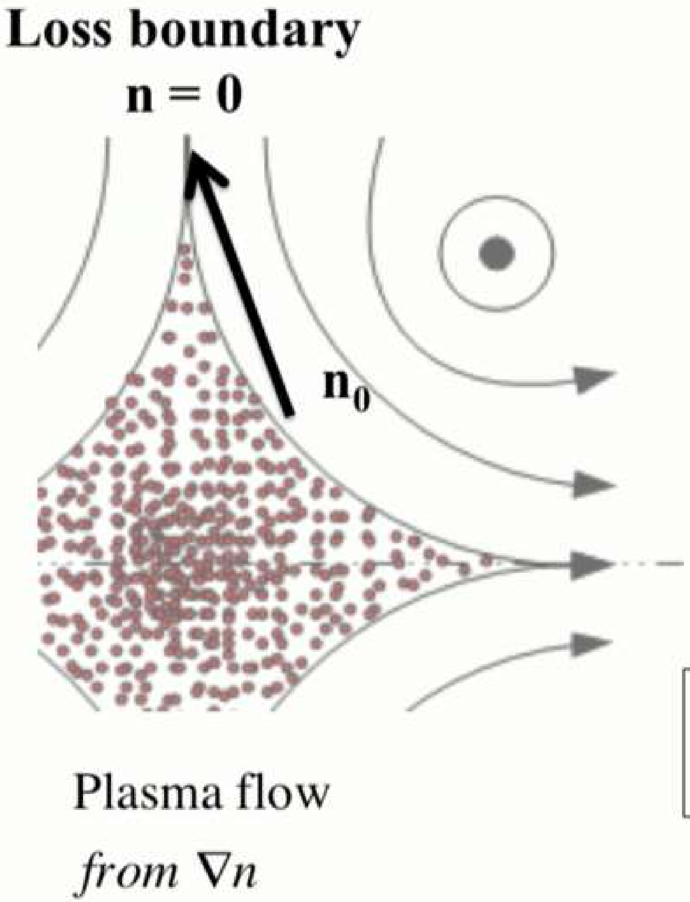
Unique Advantages of Polywell

Plasma stability: *economical and reliable reactor*

High beta cusp (WB) confinement: *confinement and compact size*

Use of electron beam driver: *efficient heating*

Cusp Loss as Diffusion Process?



$$\text{Loss rate} \sim D\frac{\partial n}{\partial L} \quad \text{with } D \sim \frac{(\Delta x)^2}{\Delta t}$$

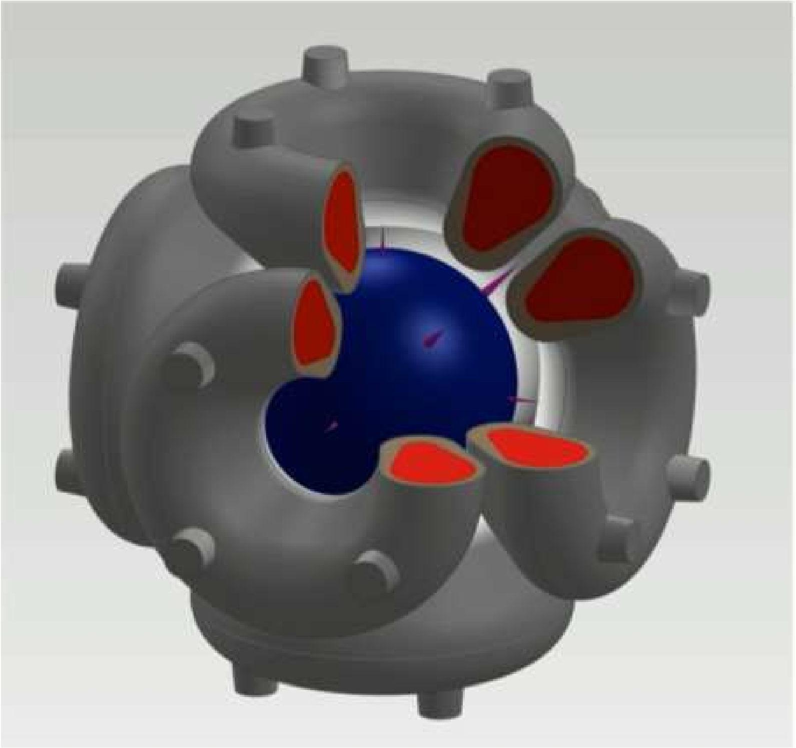
$$\text{If we set } \Delta x = \rho_{plasma} \text{ and } \Delta t = \frac{R}{\upsilon_{plasma}}$$

$$\text{Loss rate} \sim n\upsilon_{plasma}(\rho_{plasma})^2$$

$$\text{Grad's result: } \frac{I_{e,i}}{e} = \frac{\pi}{9} n_{e,i}\upsilon_{e,i} \times \pi(r_{e,i}^{gyro})^2$$

As of now, we are not completely sure how to interpret Grad's conjecture.

Net Power Producing Polywell Reactor



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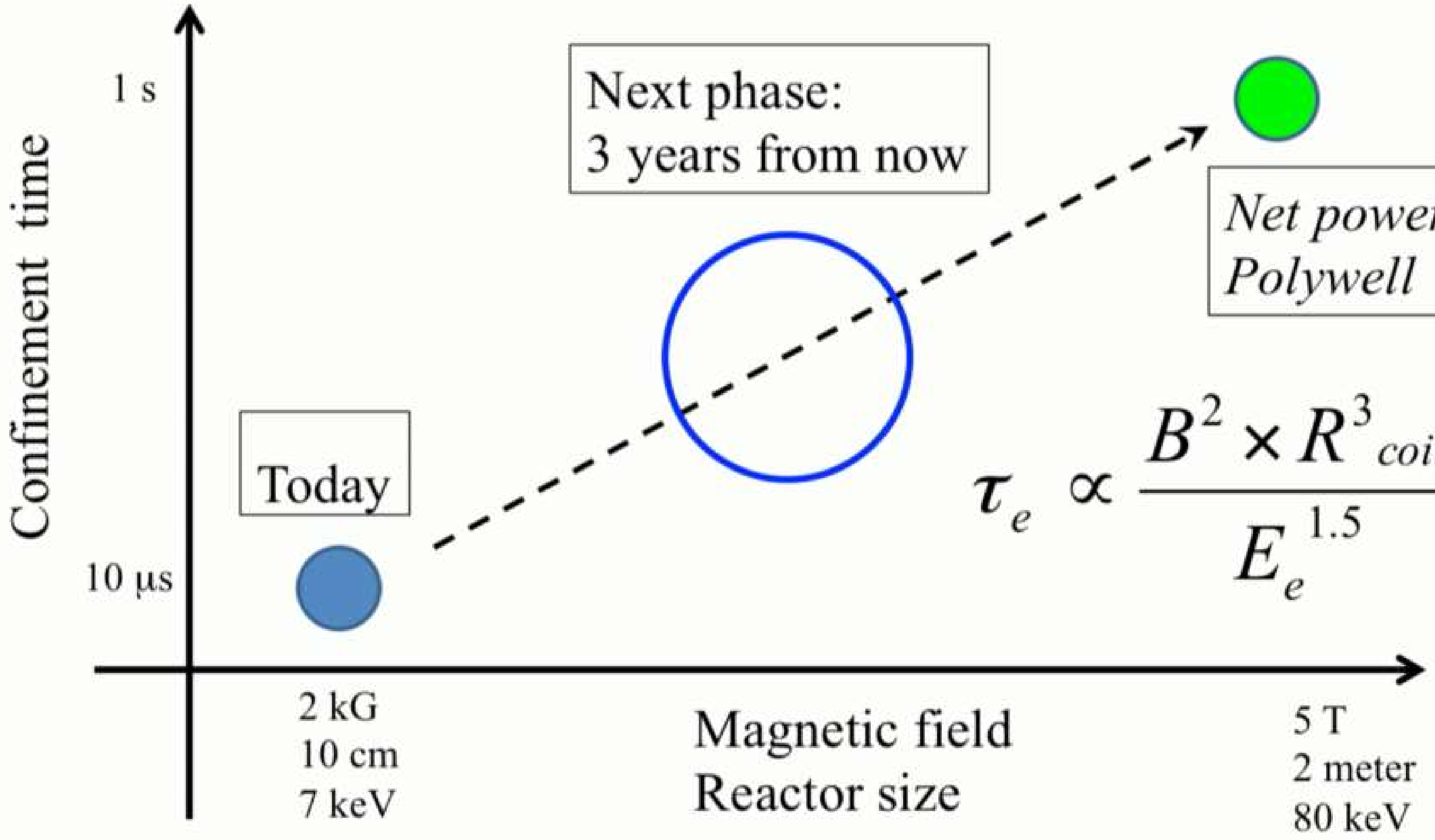

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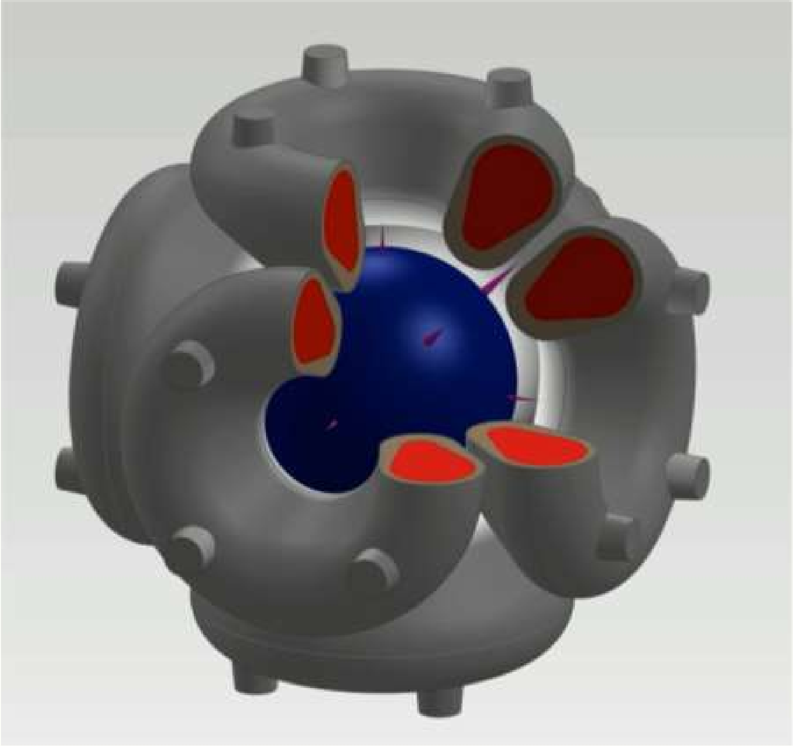

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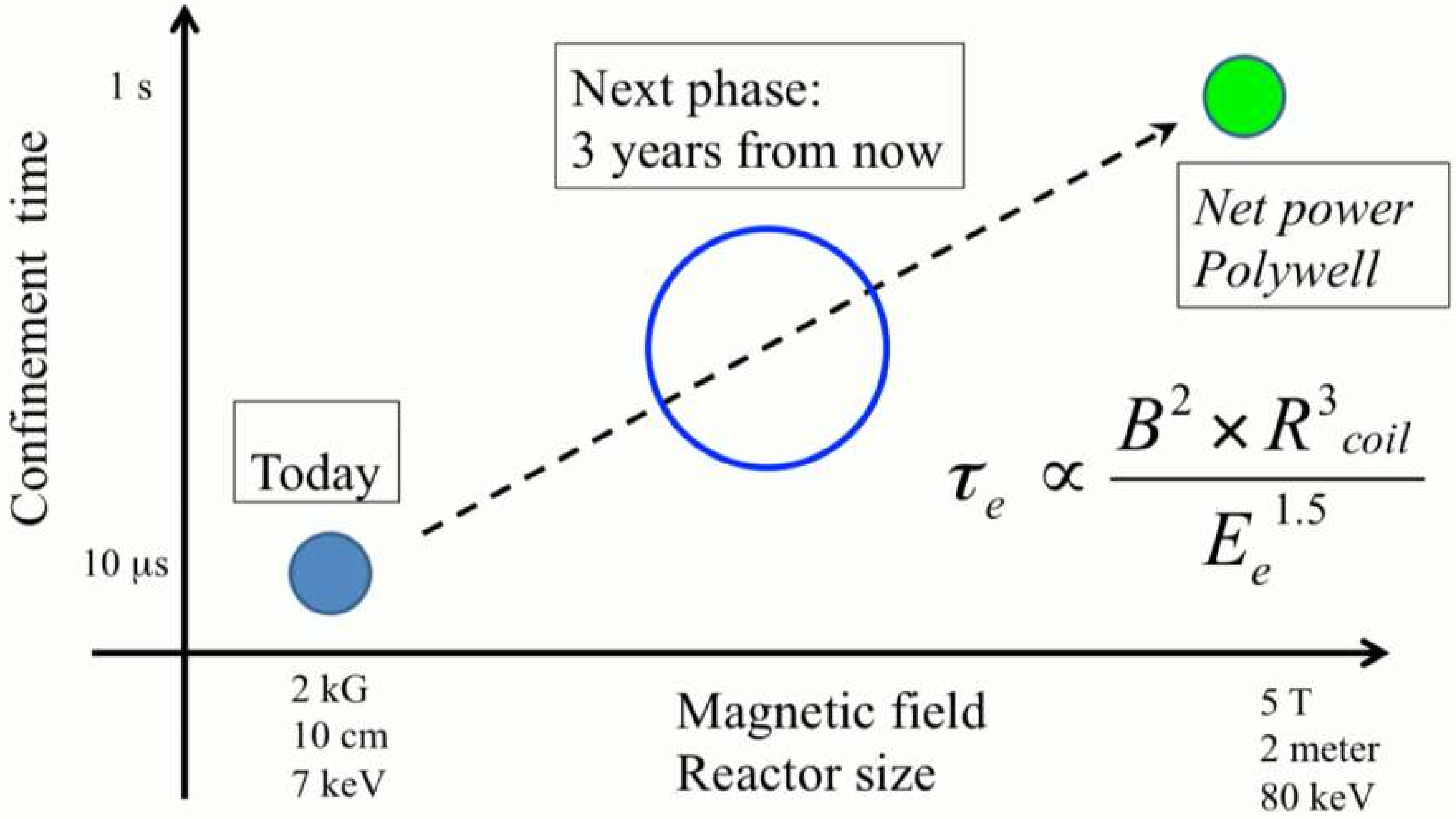


Polywell Addresses Critical Challenging Issues of Cusp System

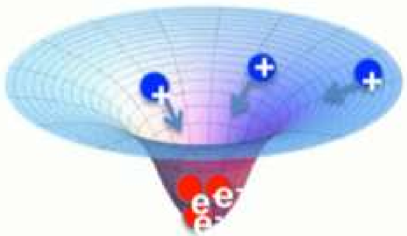
<u>Two major challenges of conventional cusp</u>

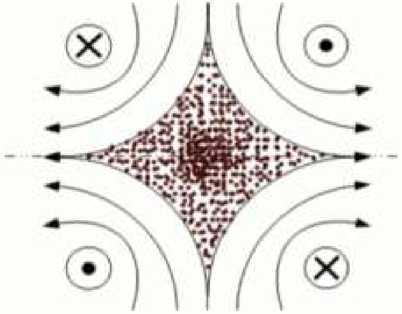
a) How to heat ions to fusion temperature?

- **Electron beams generate electric fields, which accelerates ions efficiently to fusion temperature**

b) Is loss rate determined by electrons, ions or both?

- **In Polywell, only electron loss matters because ions are cold at the boundary where the loss occurs**





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