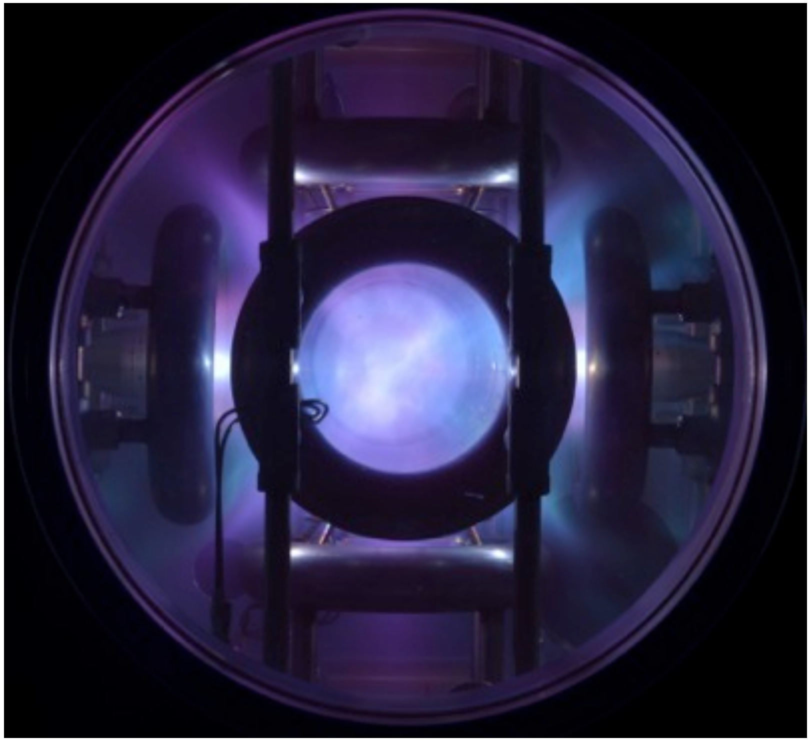
Polywell Fusion
Electric Fusion in a Magnetic Cusp



Jaeyoung Park
Energy Matter Conversion Corporation (EMC2)
Niels Bohr Institutet, Københavns Universitet (SolarCast)

Scientists whose work led to Polywell Fusion

Edward Teller: Plasma instability
Pioneer in fission and fusion

Philo Farnsworth
Electrostatic fusion & inventor of television

Harold Grad: Plasma theory (MHD) and Cusp confinement

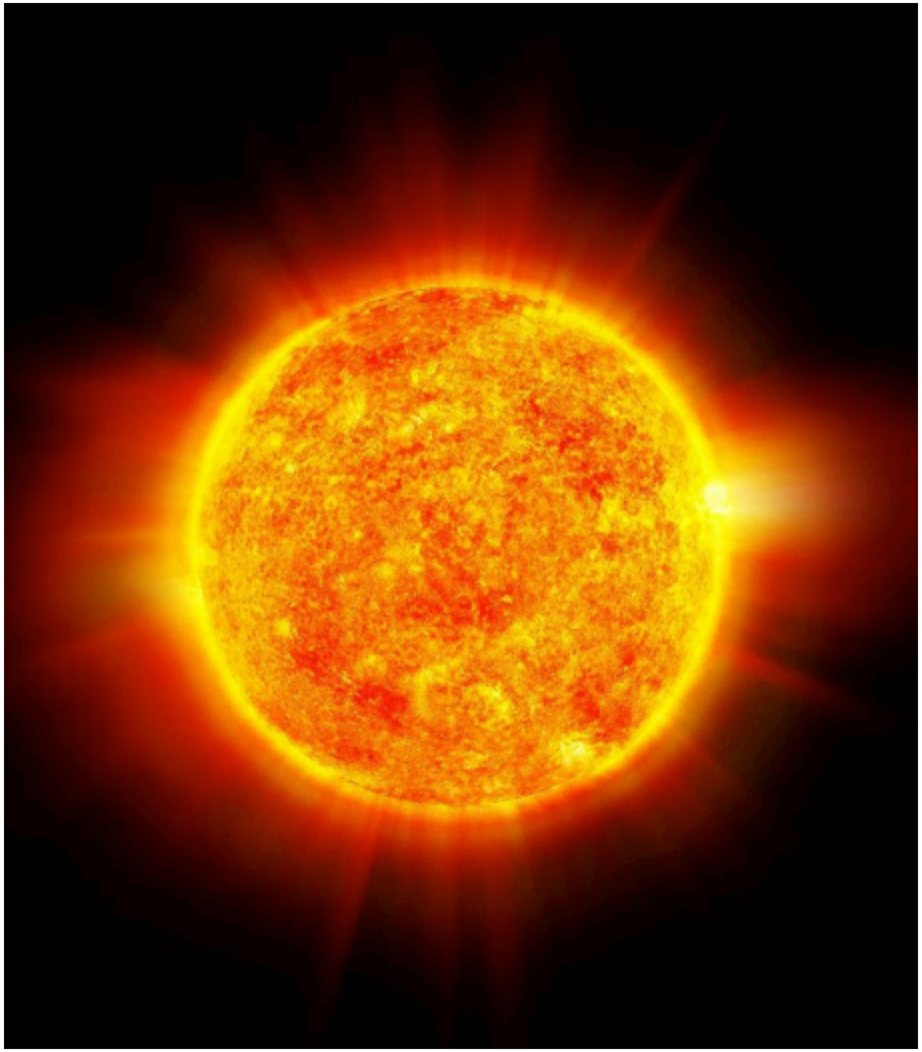
James Tuck: Picket Fence, Electrostatic fusion, & Explosive focus for A-bomb

Robert Bussard: **<u>Polywell Fusion</u>**, Nuclear Rocket & Bussard Ramjet

Outline

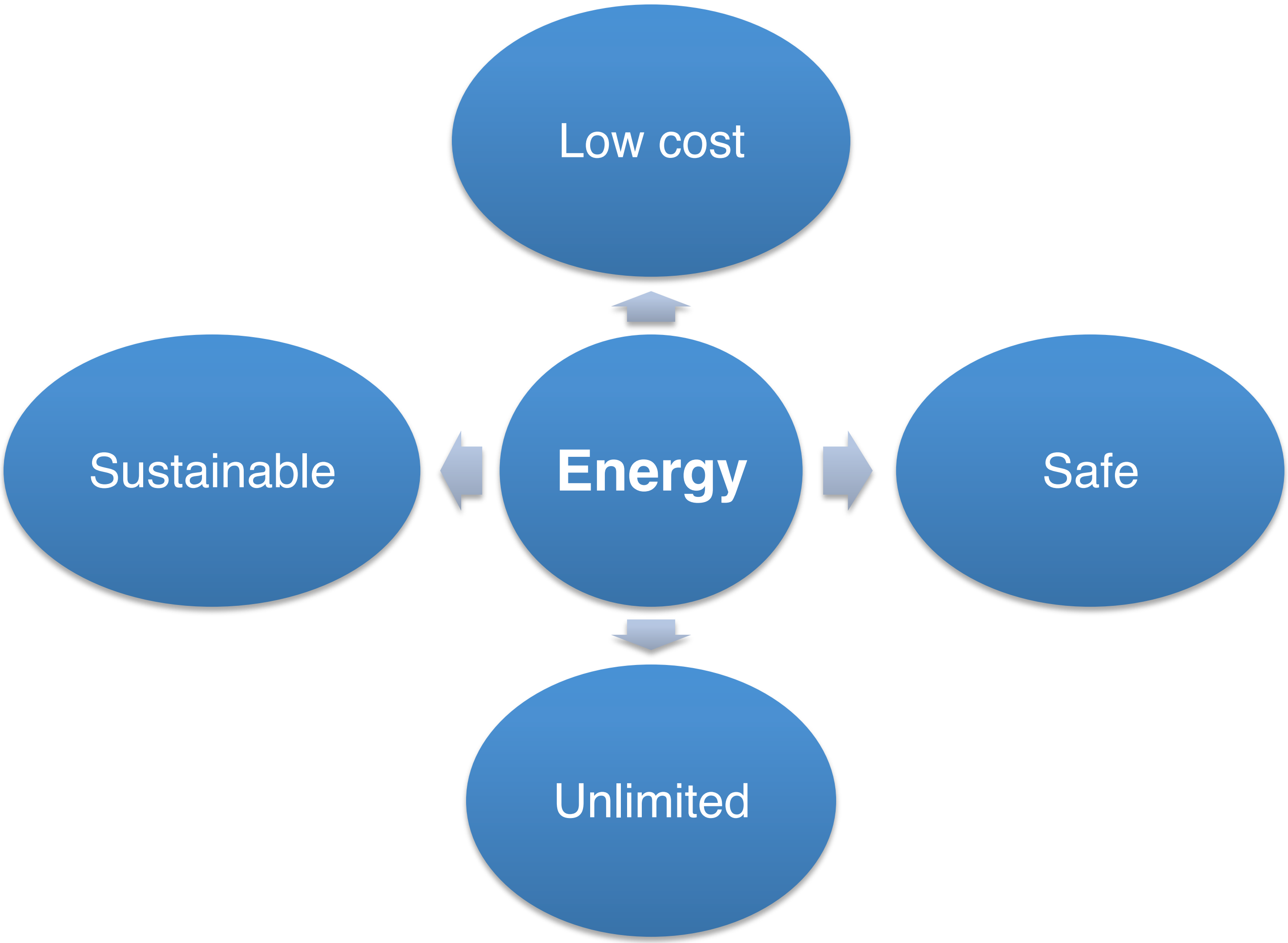
- Fusion Power
- Polywell Fusion:
  - Electric Fusion + Magnetic Confinement
- How does it work?
  - heating, confinement and keeping it small
- Recent Breakthrough and Polywell Fusion Reactor Properties
- Plan and Summary

WHAT IF?



We could capture the sun and put it in a box?

What would we have?



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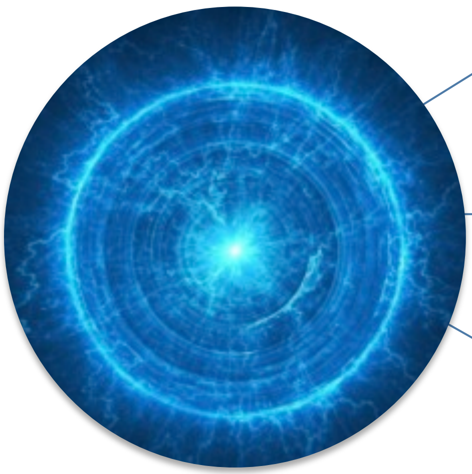
What would be its benefits?



No nuclear proliferation

can't be weaponised

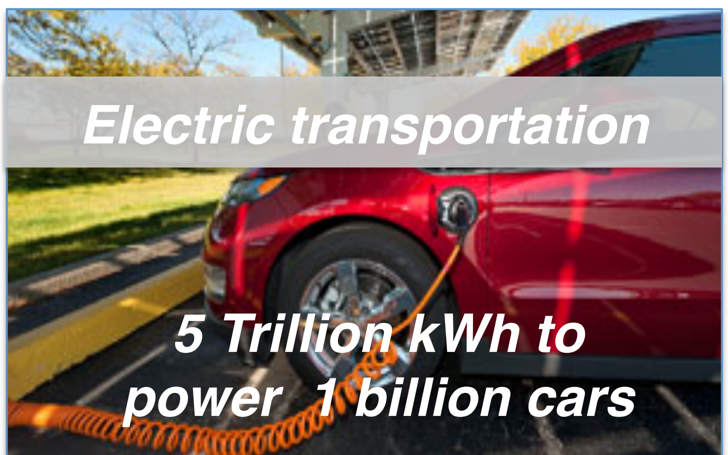
No nuclear meltdown

no Fukushima

Environmentally safe

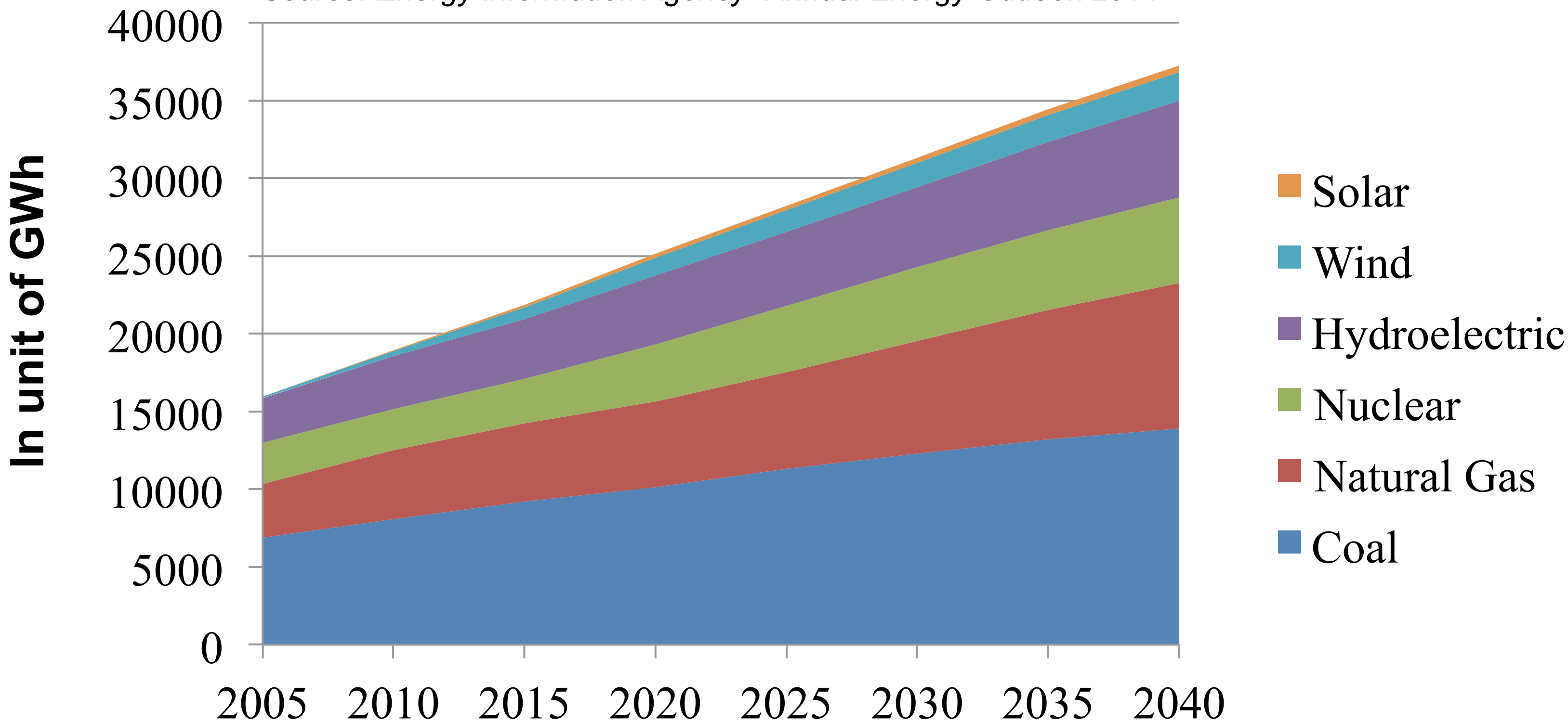
no greenhouse gas emissions

What could be used for?



Why should we do it?

Source: Energy Information Agency "Annual Energy Outlook 2014"



- Despite increased deployment of solar & wind, market prediction indicates coal and natural gas will account for 60% of electricity generation in 2040
- *Reflective of continuing technical challenges for renewable energy*

<u>**Great opportunity for Fusion Power**</u>

What makes fusion so challenging?

High Temperature

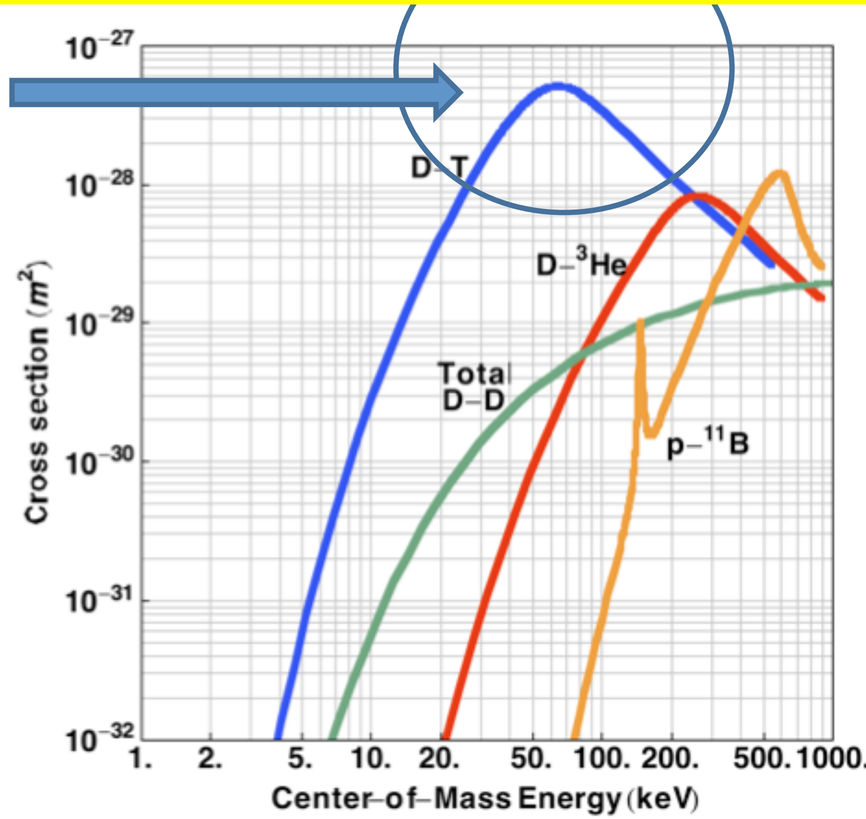
100 million degrees or hotter in order to overcome strong Coulomb force

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.

Conditions Required for Fusion

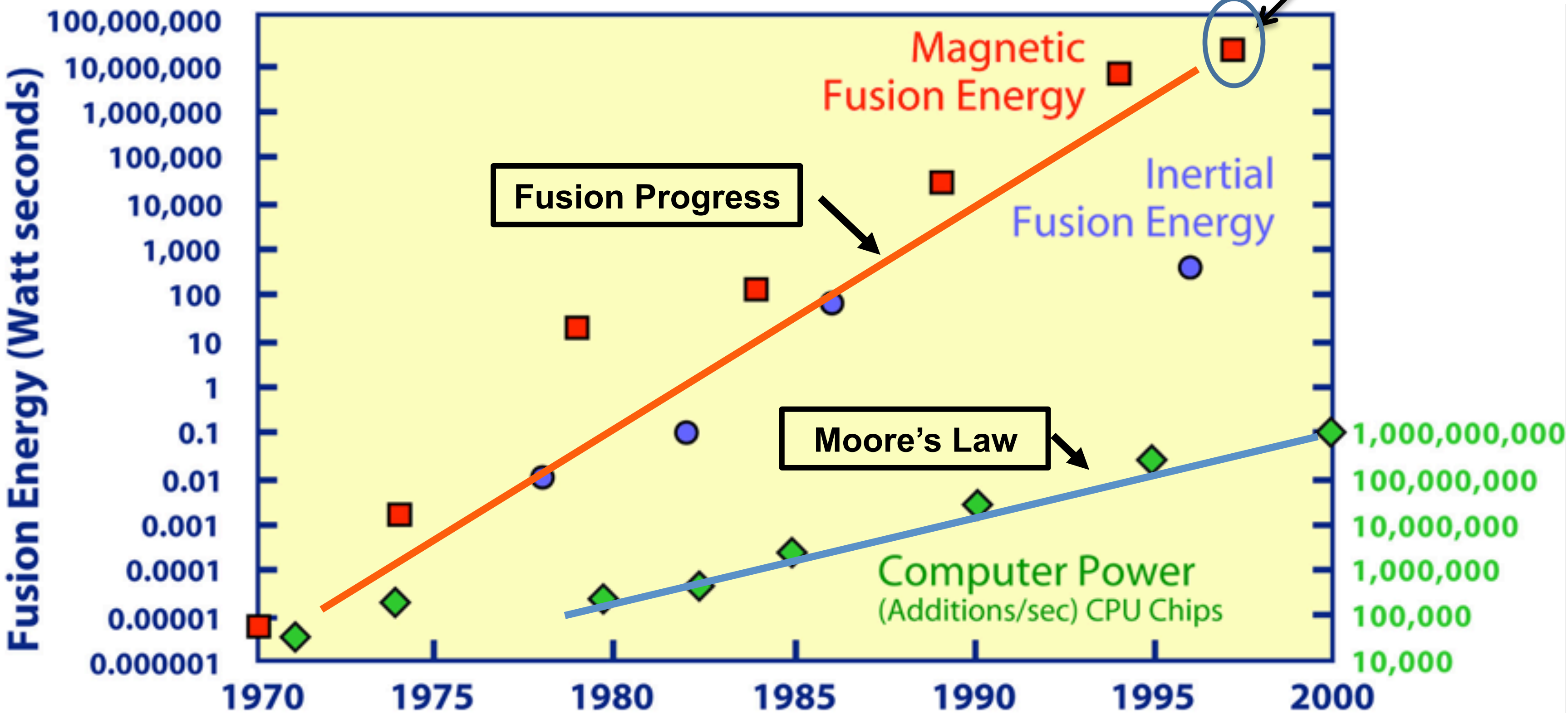


Fusion cross sections versus center-of-mass energy

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"

Fusion will work sooner or later
So, where is my fusion reactor?

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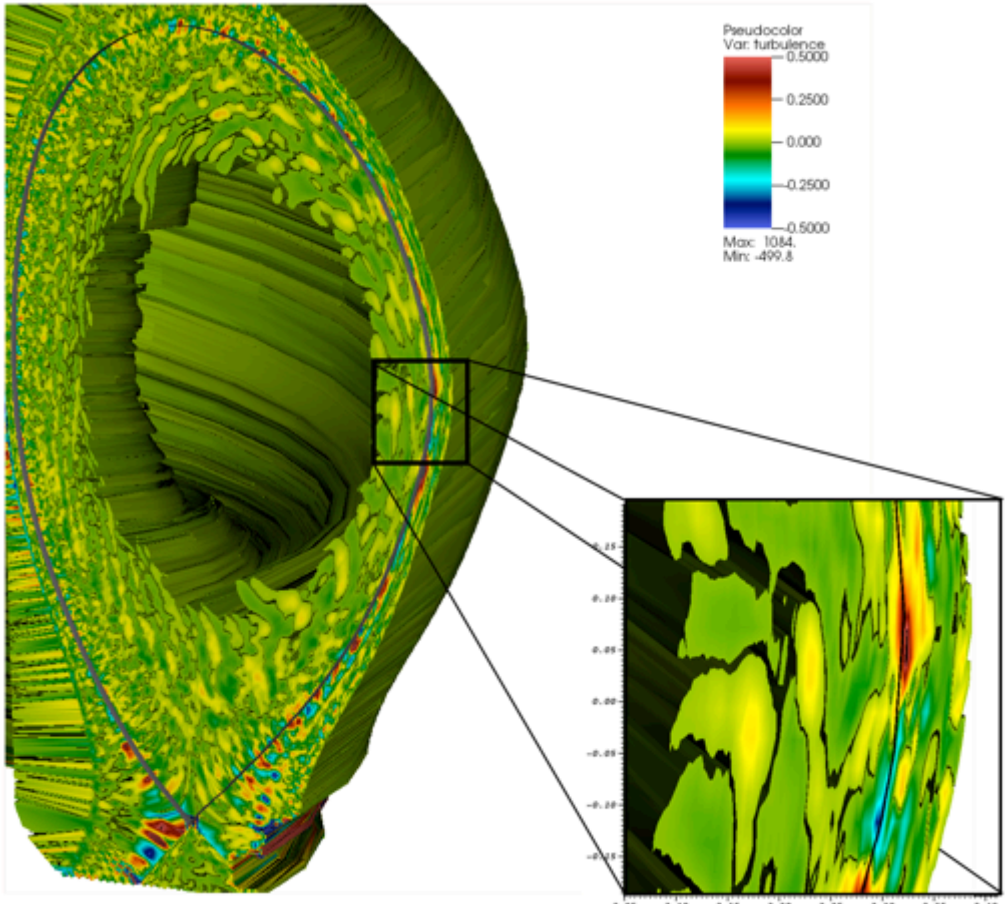
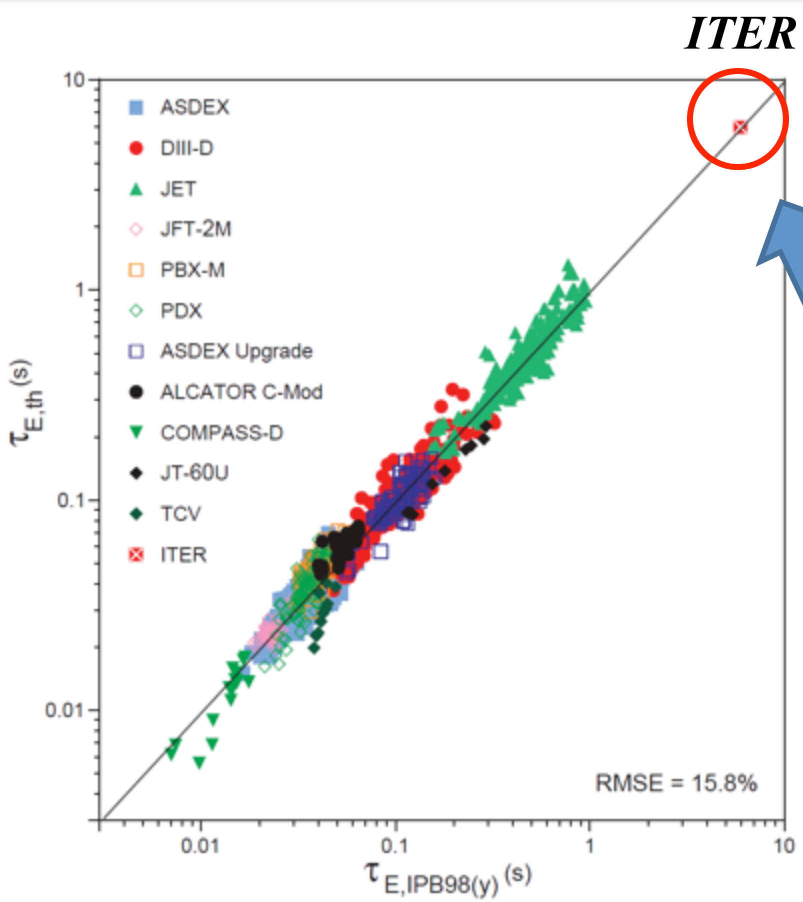
High Performance Computing is Aiding Fusion Research



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)

Path to Net Fusion Power



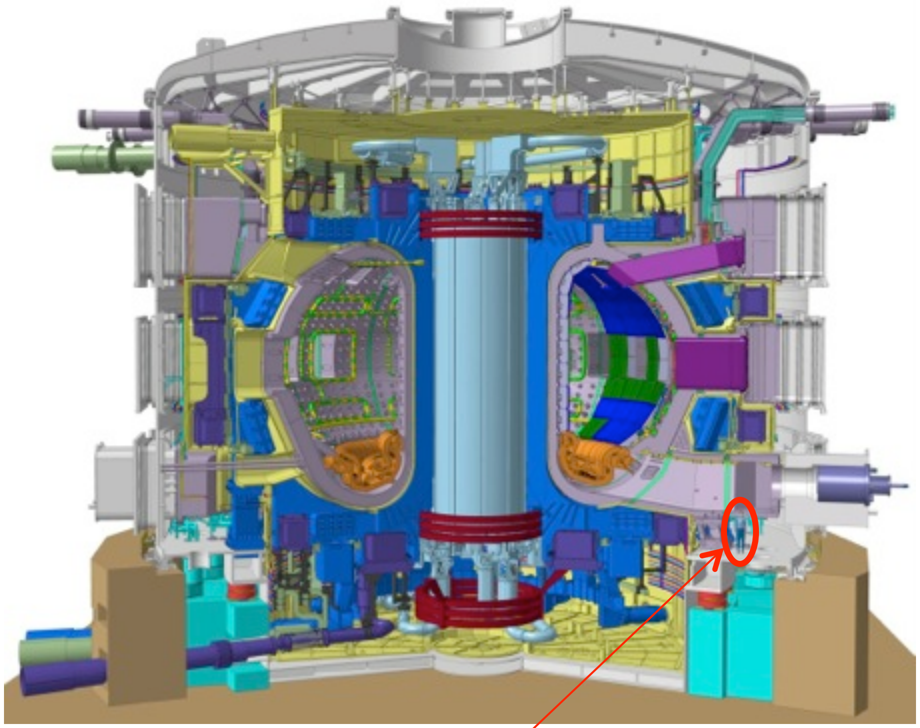
Confinement time (Exp. vs. model)

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)

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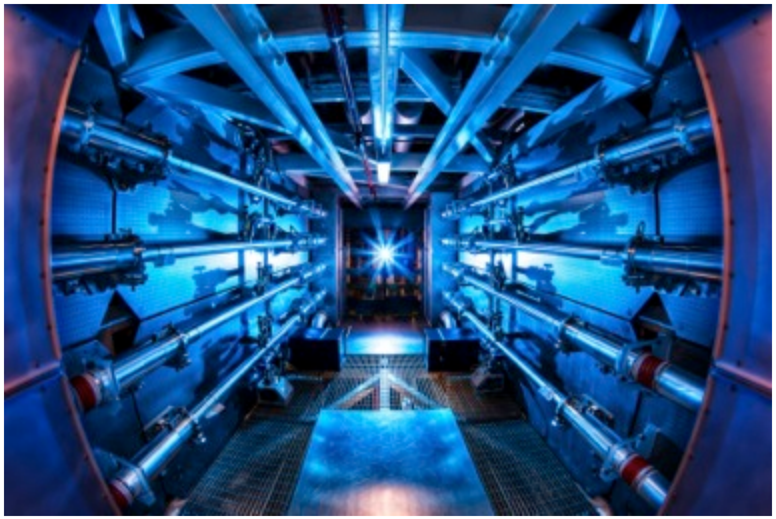
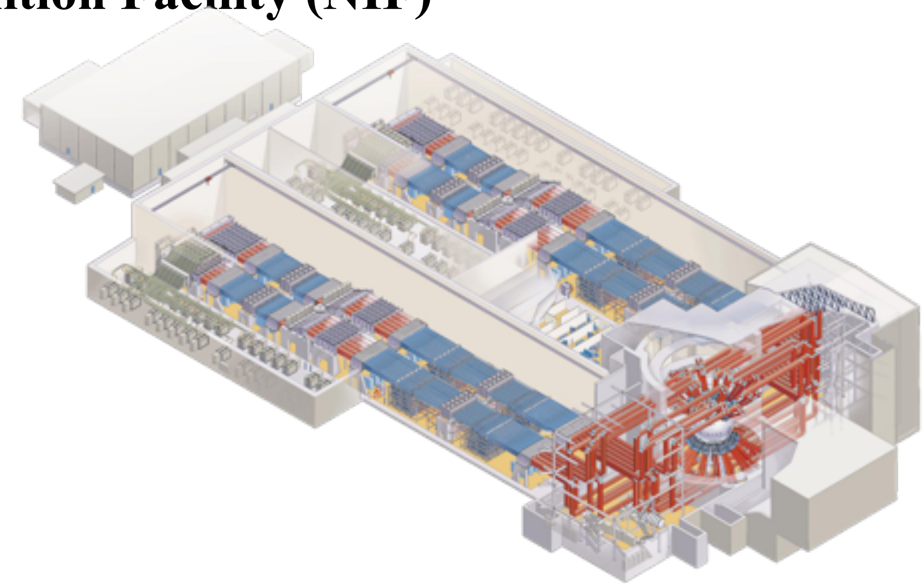
Case Study of NIF: Another Big Machine

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

Motivation for Polywell Fusion

Can a fusion reactor be small and efficient?

Three key ingredients for fusion power

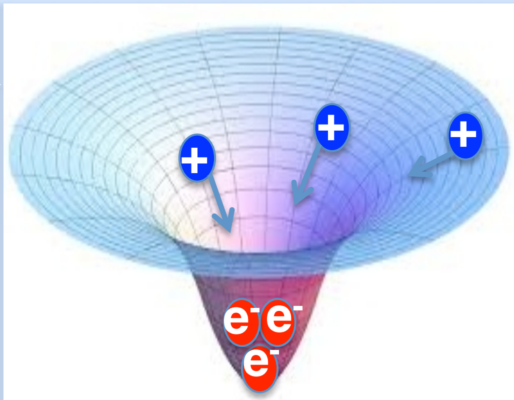
- Ion heating over 100 million degrees (or 10 keV)
- Confinement: ~1s
- High pressure operation (~ 100 atmospheric pressure)

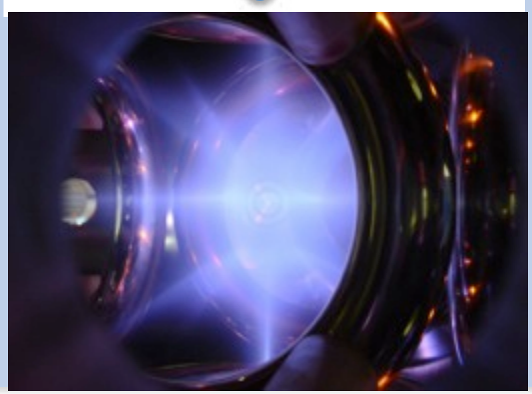
What is Polywell?

Polywell Fusion: Combines Magnetic and Electrostatic fusion concepts

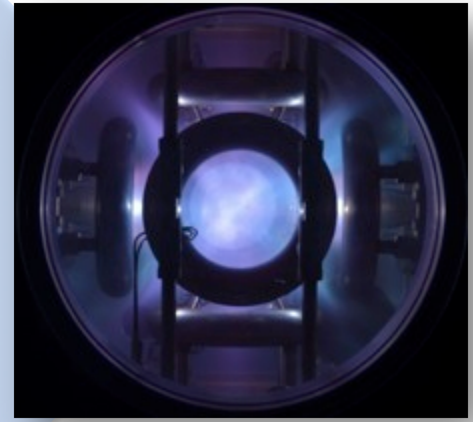
Electrostatic fusion: uses electron beams to generate a deep potential well to **heat and confine ions for fusion**

Cusp confinement: uses cusp magnetic fields to **confine energetic electrons at high plasma pressure stably**





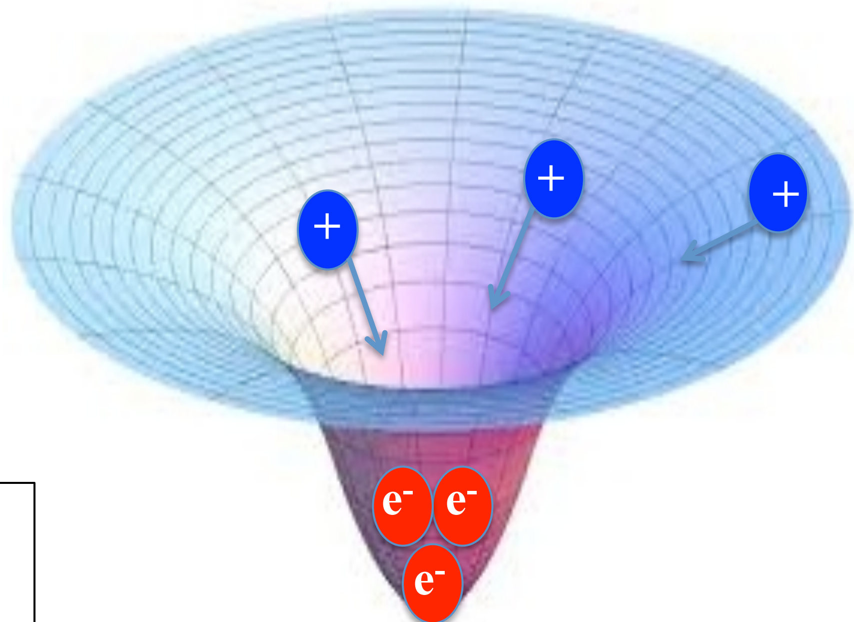
Polywell Fusion



Polywell fusion:
*Poly*hedral magnets and Electrostatic potential *well* for fusion power reactor

How Does Polywell Work?

Let's start with
Ion heating
(& confinement)
by electrostatic fields
from excess electrons



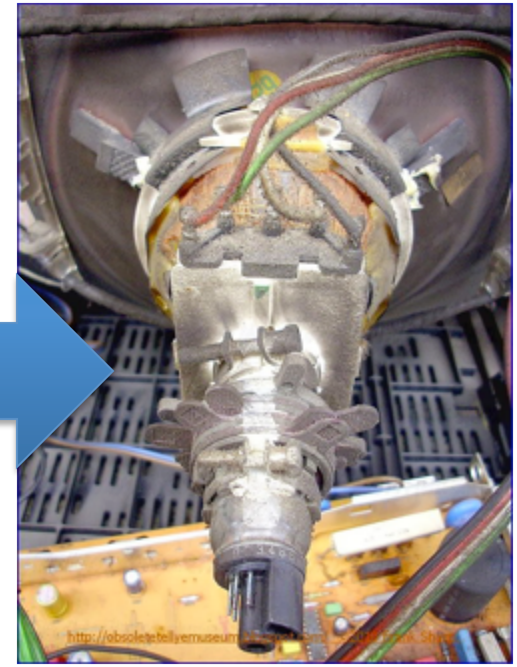
Ideas from Elmore, Tuck, Watson, Farnsworth, Hirsch and others

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

$N_e = N_i + \delta$
$\delta \sim 2x10^6$ cm^{-3}
over 1 m → 40 kV Well

Key merits of using electron beams

30 inch TV would operate with ~75 keV electron beam (or 750 million degrees)



Electron gun for TV

Electron beam is a well established, highly efficient technology

What is challenging about electric heating?

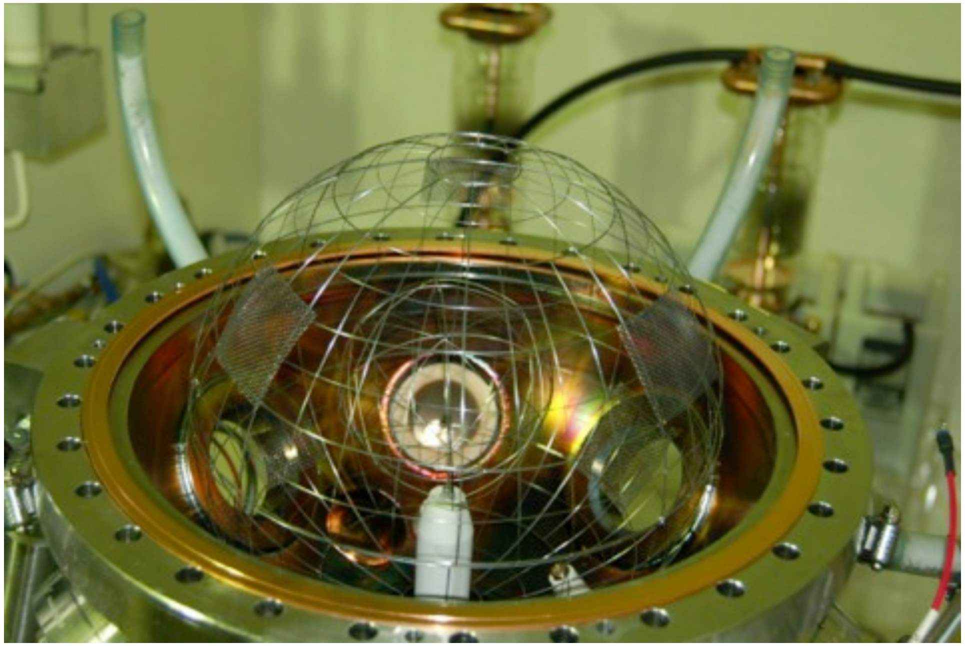
Plasma has an incredible ability to neutralize electric fields → needs more electrons than ions

$$I_{beam}(A) \times \tau^{beam}_{confinement}(s) = 67(A * s)$$

1 s beam confinement → necessary beam current is only 67 A (3 MW at 50 kV)
1 μs beam confinement → necessary beam current is 67 MA (3,000 GW at 50 kV)

For a 1 meter radius fusion reactor operating at ion density ~ ***1 x10^{14} cm^{-3}***

Use of Electrical Grid



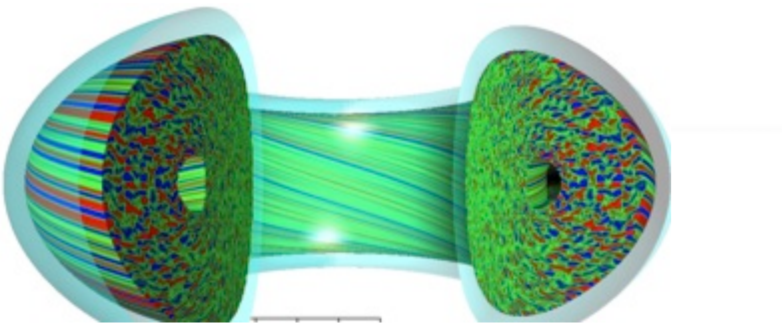
- Geometrical Transparency is about 95%

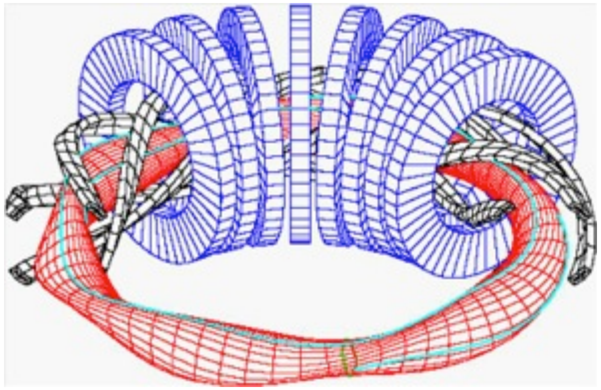
- Electrons will hit the grid after about 10-20 bounces

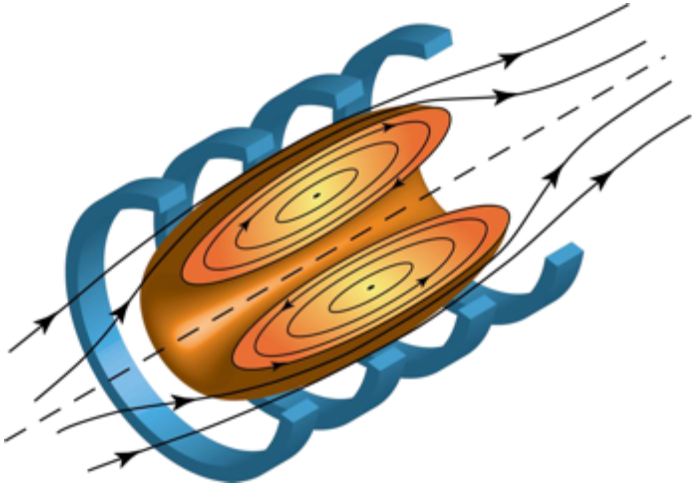
Transit time of 50 keV electron across a 1 m radius sphere ~ 20 ns → Corresponding to confinement time of ~0.4 μs

Can Magnetic Fields Help Electron Confinement?

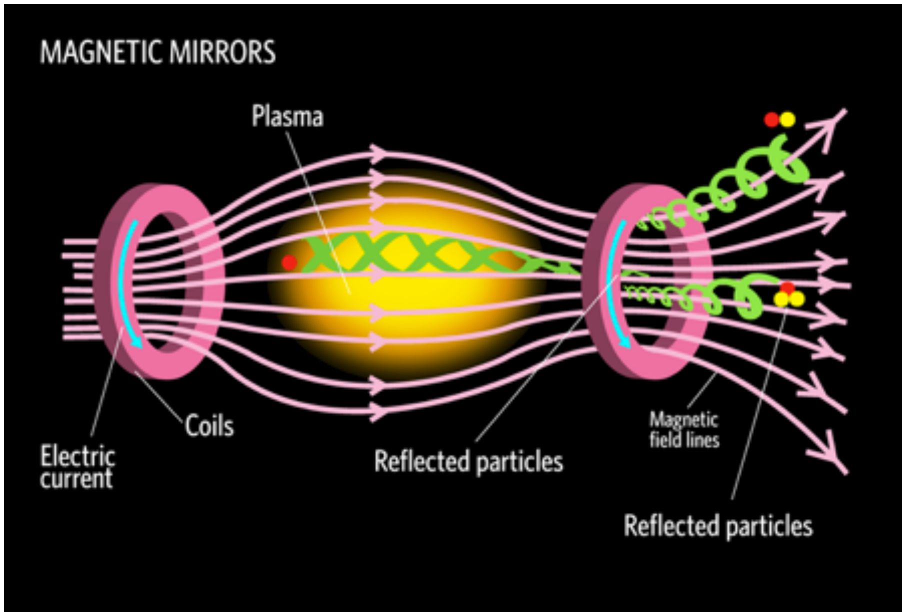
Closed Field Systems: Tokamak, Stellarator, FRC won't work

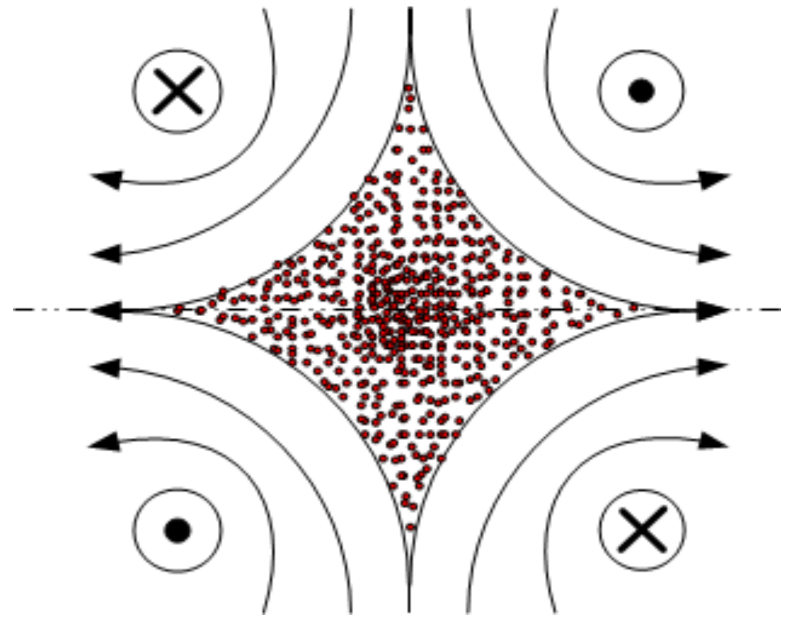






Can Magnetic Field Help?



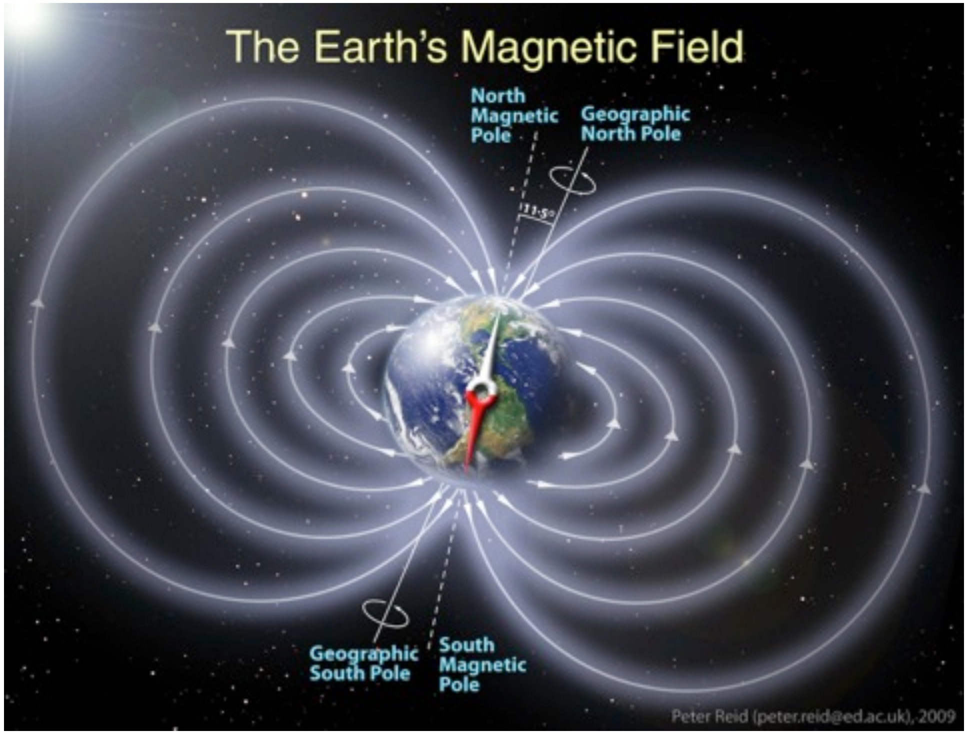


Magnetic mirror: Two coils in the same direction of current
(Credit: Anton Banulski)

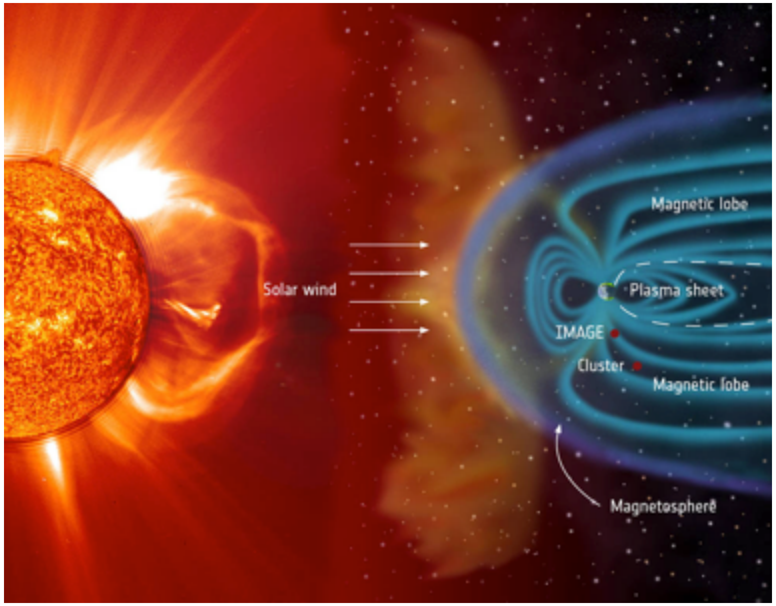
Magnetic cusp: Two coils in the opposite direction of current

Answer: Cusp Magnetic Field

It turns out magnetic cusp is the only magnetic system that can work with electron beams.



Images from NASA

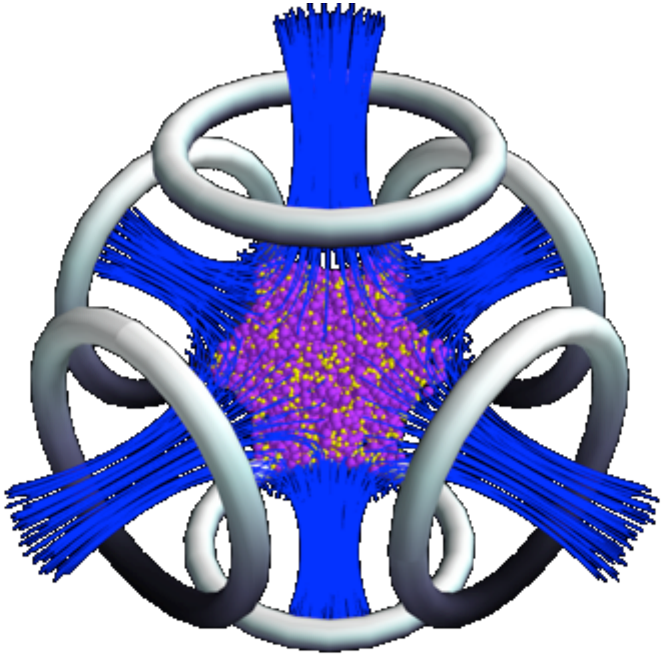


Earth magnetic fields showing polar cusp → Magnetic field is essential for protecting Earth from Solar storm

3D Magnetic Cusp in Polywell

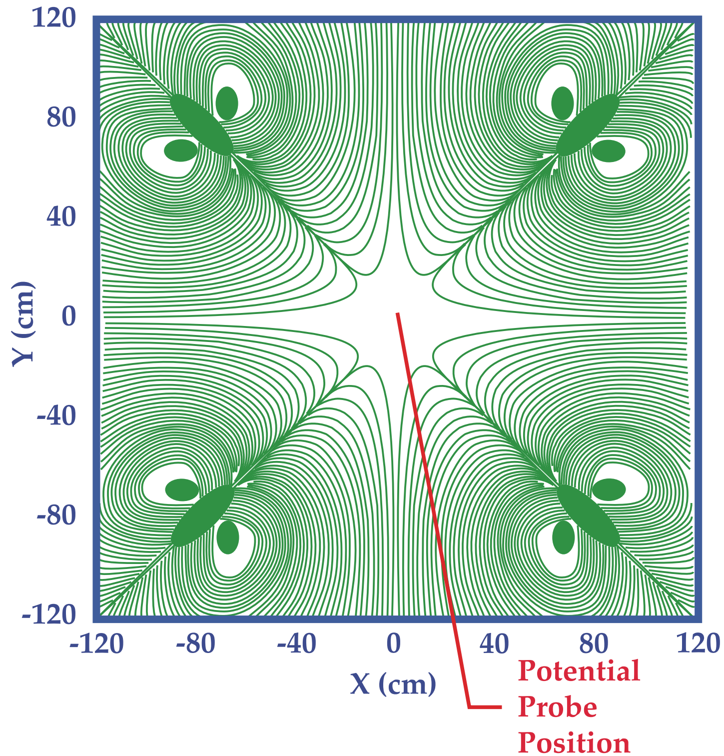
Coil winding inside Polywell device

Magnetic field lines

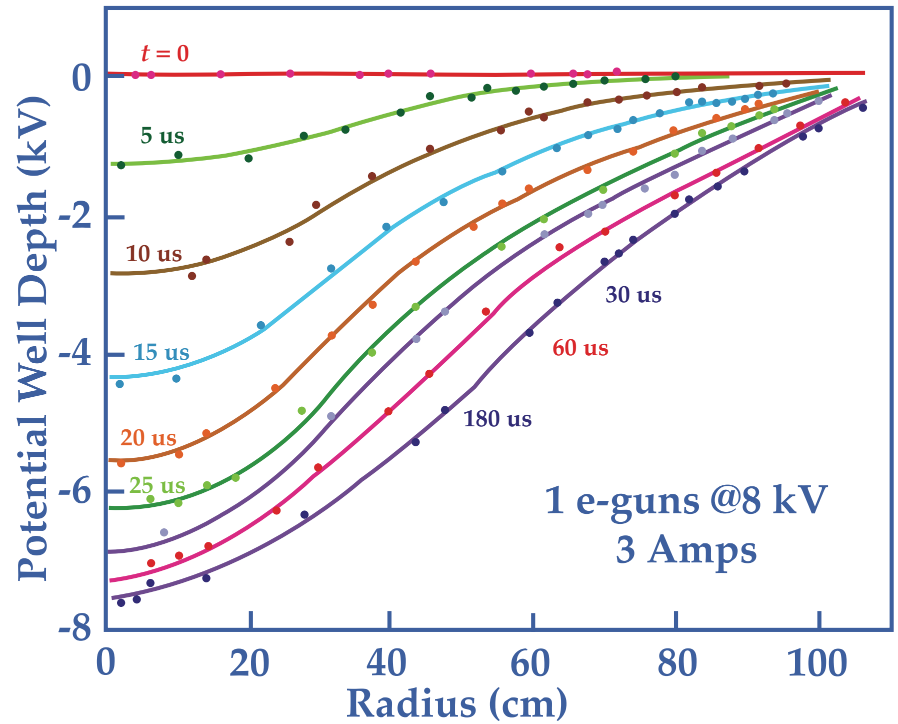


Unique feature of Cusp allows electron injection but prevents immediate exit of injected electron beams (due to zero field in the center)

Potential well formation by e-beam injection



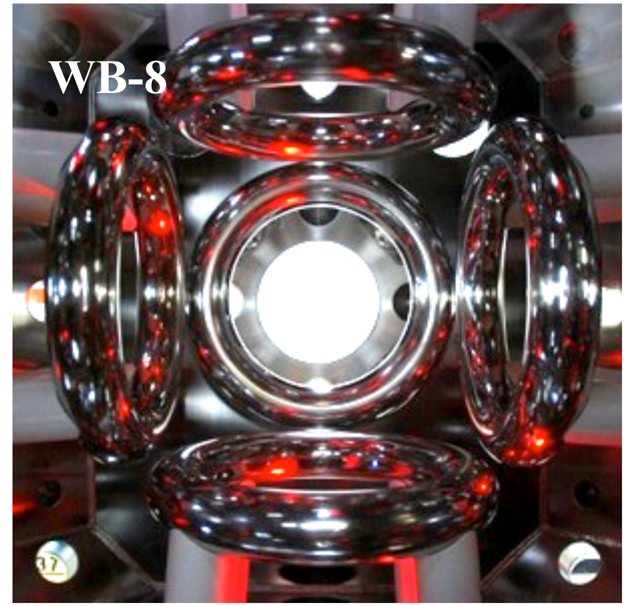
Only at low plasma density



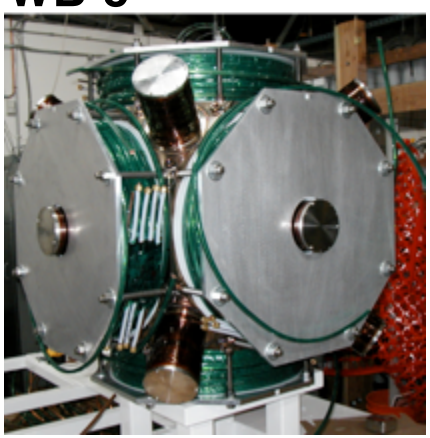
The low density limit attributed to the insufficient confinement of high energy electrons inside Polywell cusp (*Krall et al, Phys. of Plasmas,1995)*

EMC2 Efforts in Electron Confinement

WB-6 WB-4



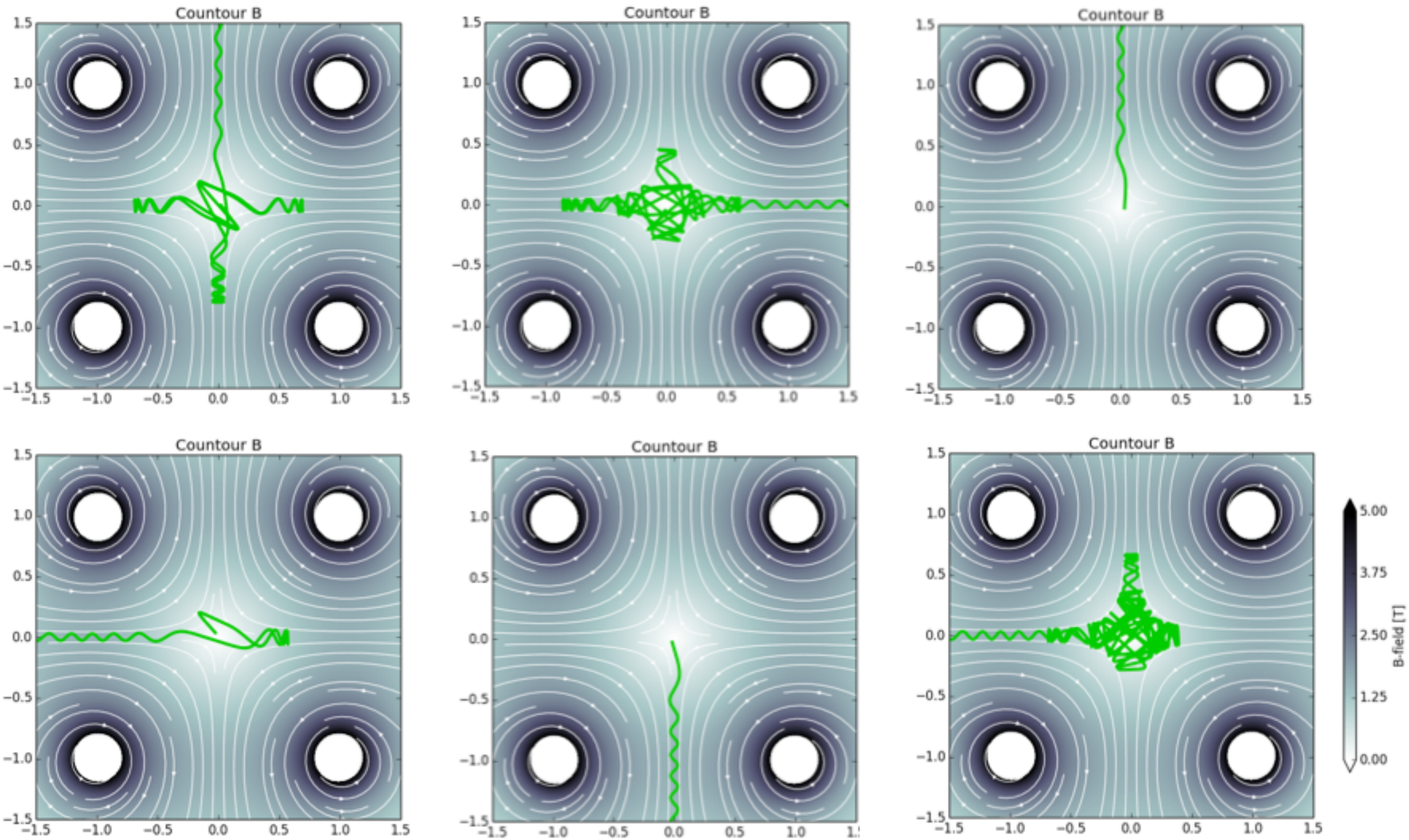
WB-5



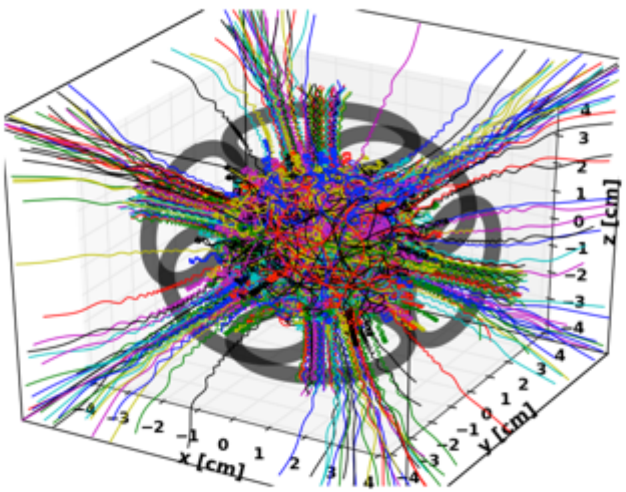
WB-7

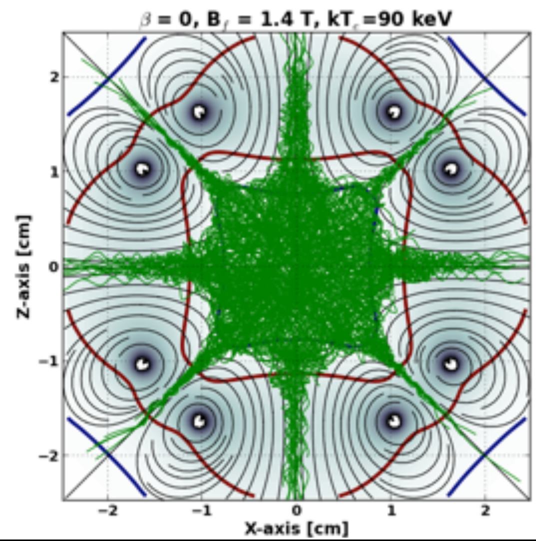
Since 1994, EMC2 had built and operated successive test devices from Wiffle-Ball-1 (WB-1) to WB-8 to demonstrate confinement of high energy electrons in Polywell devices

Charged Particle Motion in a 2D Cusp



Plasma Confinement in Cusp at Low β





Low β cusp confinement can be modeled as **"magnetic mirror"** with particle transit time as a scattering time to a phase space loss cone: from non-conserved magnetic moment near r=0

$$\tau_e(r_{coil}, E_e, B_{\max}) \approx (2r_{coil}/\upsilon_e) \times M^* \text{ or } \propto (r_{coil})^{1.75} \times E_e^{-7/8} \times B_{\max}^{3/4}$$

where υ_e is a electron velocity at E_e, M^* is an effective mirror ratio, $\mathrm{B}_{\max}/\mathrm{B}^*_{\min}$

and $\mathrm{B}^*_{\min}$ is given as $\frac{1}{B} \times \frac{dB}{dr}(r = r_{adibatic}) = \frac{1}{A \times r_{Lamor}(E_e, \mathrm{B}^*_{\min}(r = r_{adibatic}))}$

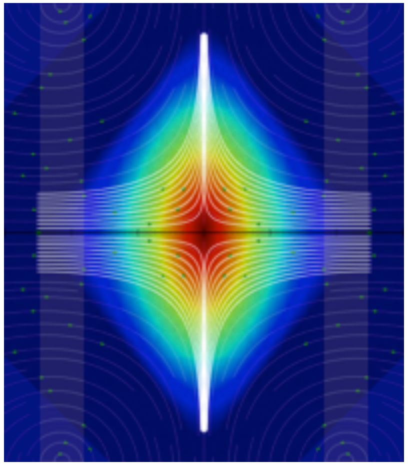
and A is a constant between 3 - 5 for a given magnetic field profile

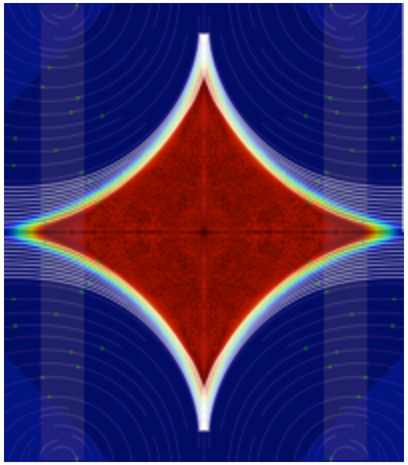
1 μs confinement time for 100 keV electron with 7 T, 1 m, 6 coil cusp

Grad's High Beta Cusp Conjecture

Low β

Weak diamagnetism (plasma penetrated by magnetic field)





High β

Strong diamagnetism (plasma excludes magnetic field)

In Plasma Physics, Beta is defined as the ratio of plasma pressure and magnetic field pressure (*beta=0, no plasma, beta=1 maximum pressure*)

- Between 1955-1958, NYU group led by Harold Grad investigated the case of plasma confinement in high β magnetic cusp.
- In Grad's view, the boundary between plasma and magnetic fields changes if there is sufficiently high plasma pressure in a cusp

This leads to greatly enhanced confinement at high β (e.g. at β =1)

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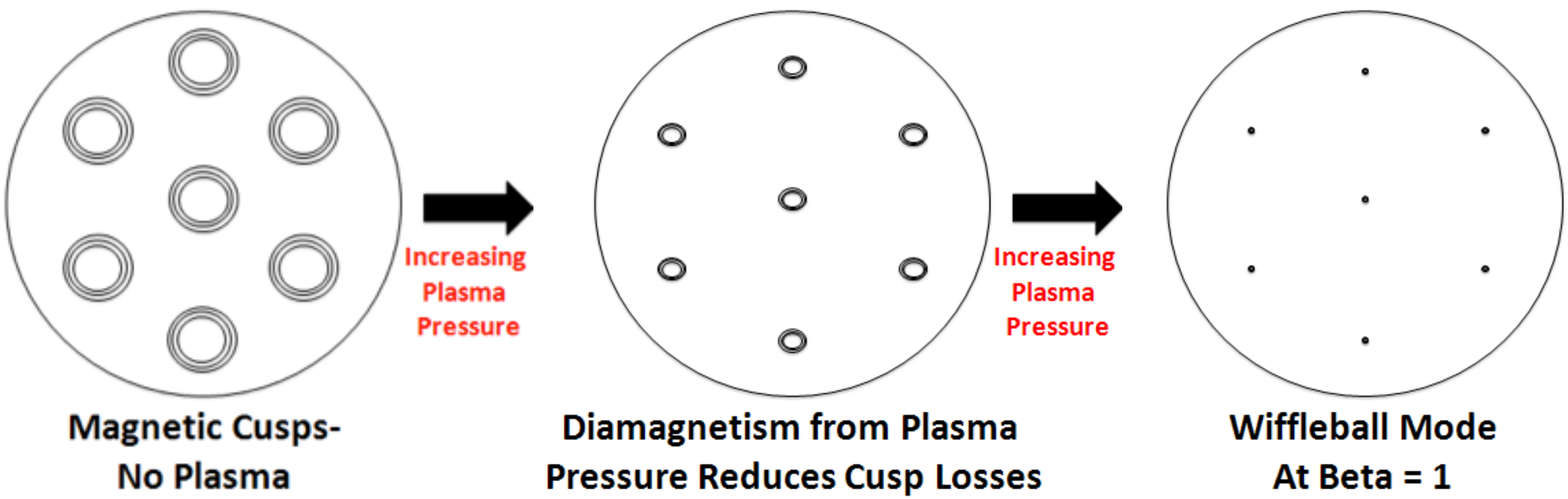
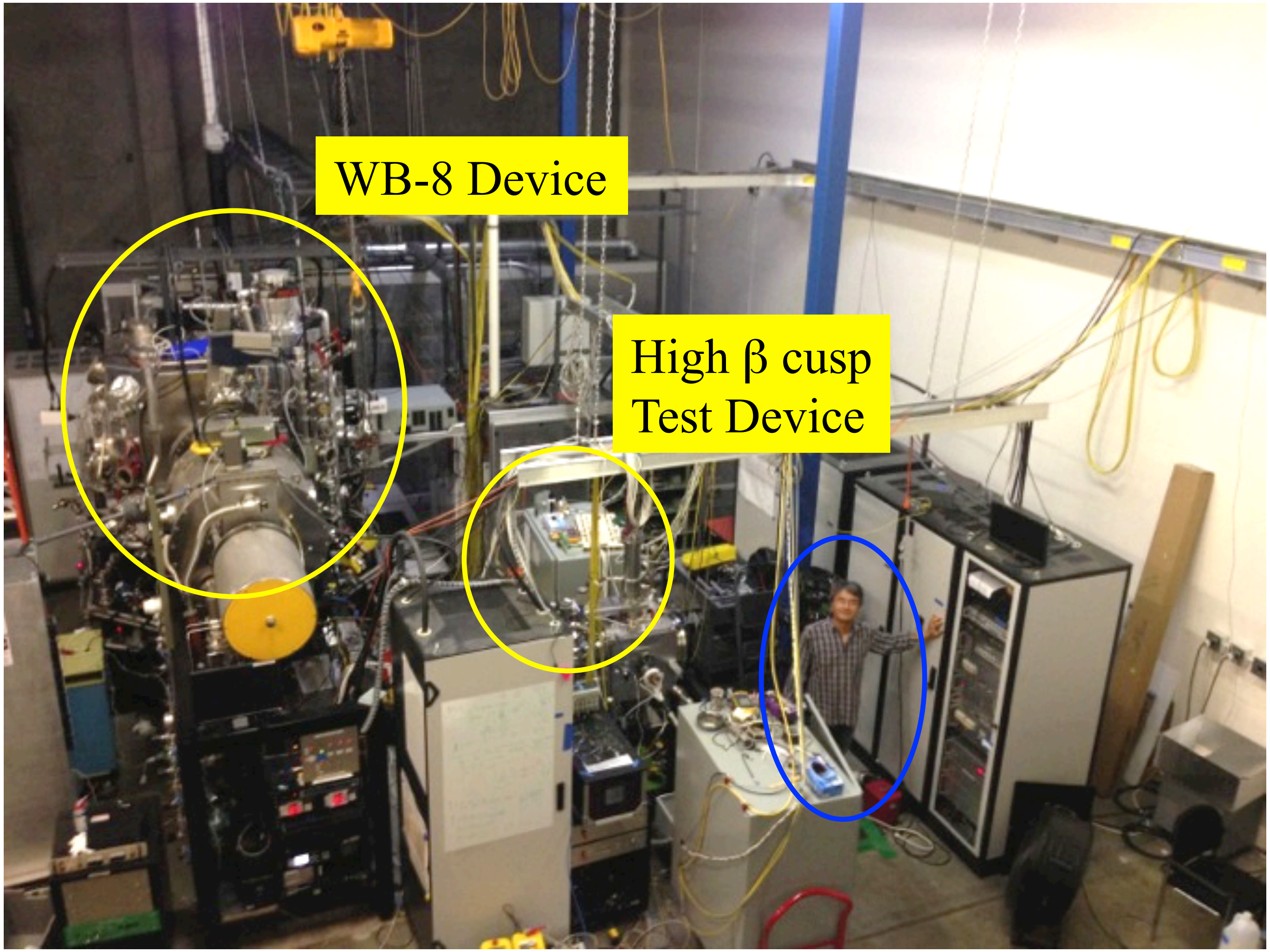
WiffleBall:
Bussard's take on Grad's prediction

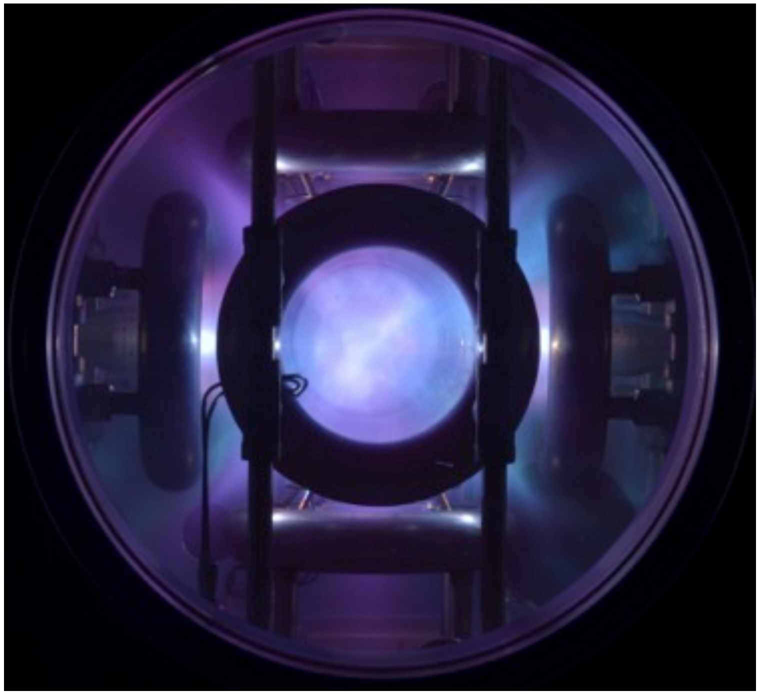
"The enormous flux of electrons at the center exhibits "diamagnetic" properties (it excludes magnetic fields). This pushes back the magnetic field and constricts the cusp holes."



Recent Experiments at EMC2



A Breakthrough Finally!



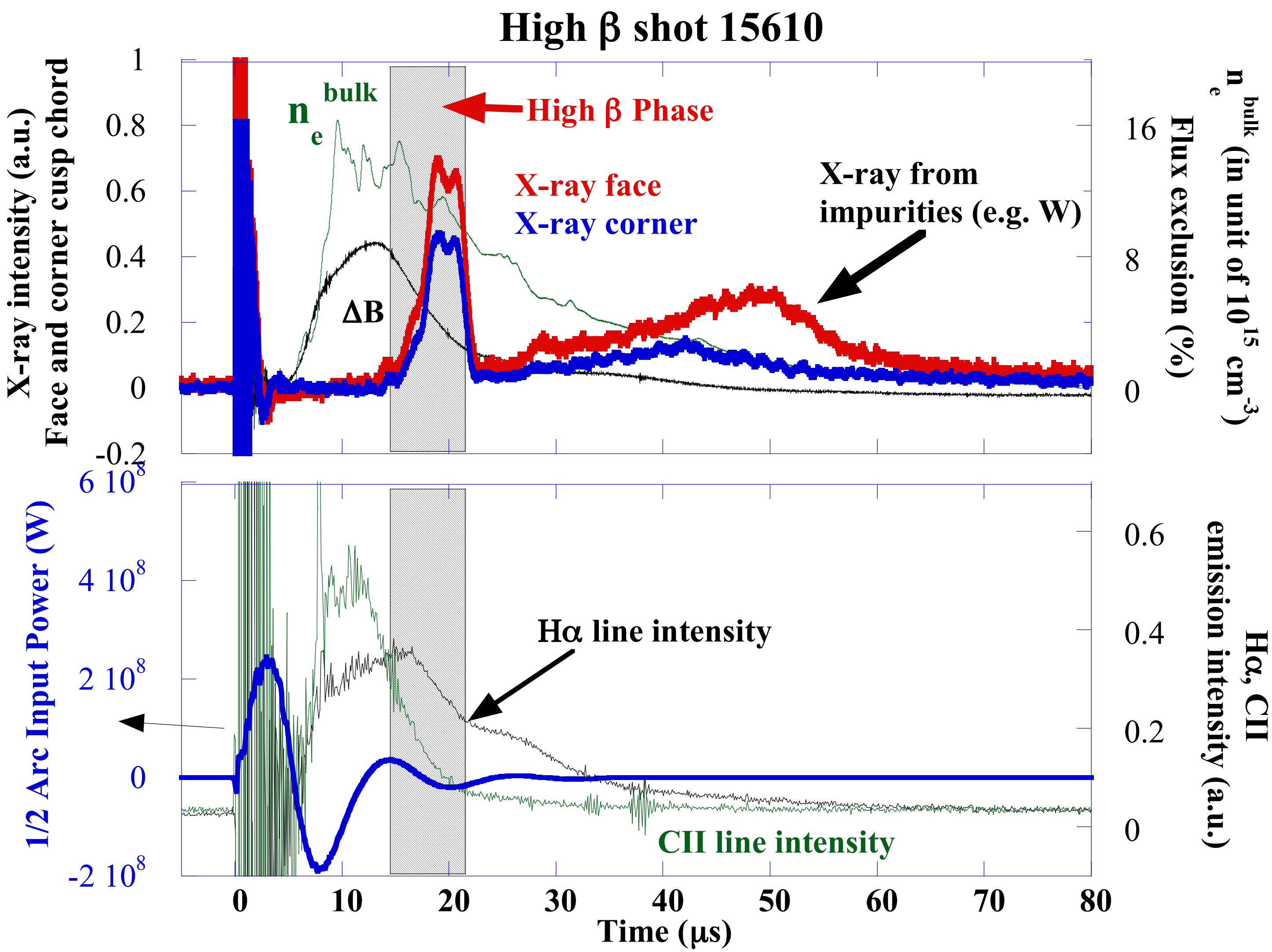
Shot # 15640

700 MW injection

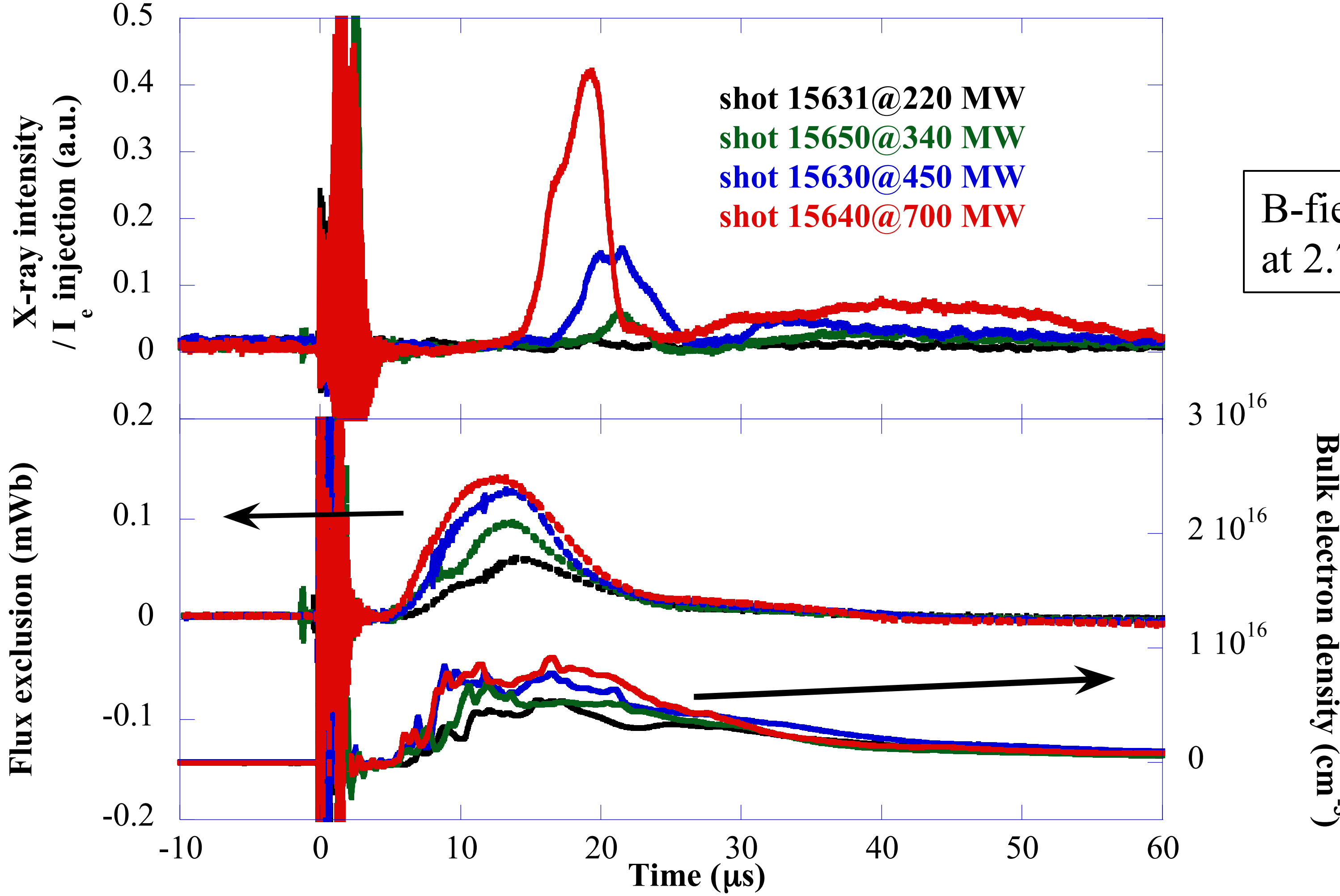
(Don't worry: you only have to do this once at the beginning)

"High-Energy Electron Confinement in a Magnetic Cusp Configuration" Jaeyoung Park, Nicholas A. Krall, Paul E. Sieck, Dustin T. Offermann, Michael Skillicorn, Andrew Sanchez, Kevin Davis, Eric Alderson, and Giovanni Lapenta, **Phys. Rev. X 5, 021024** – Published 11 June 2015

First ever confirmation of high energy electron confinement enhancement during high β cusp



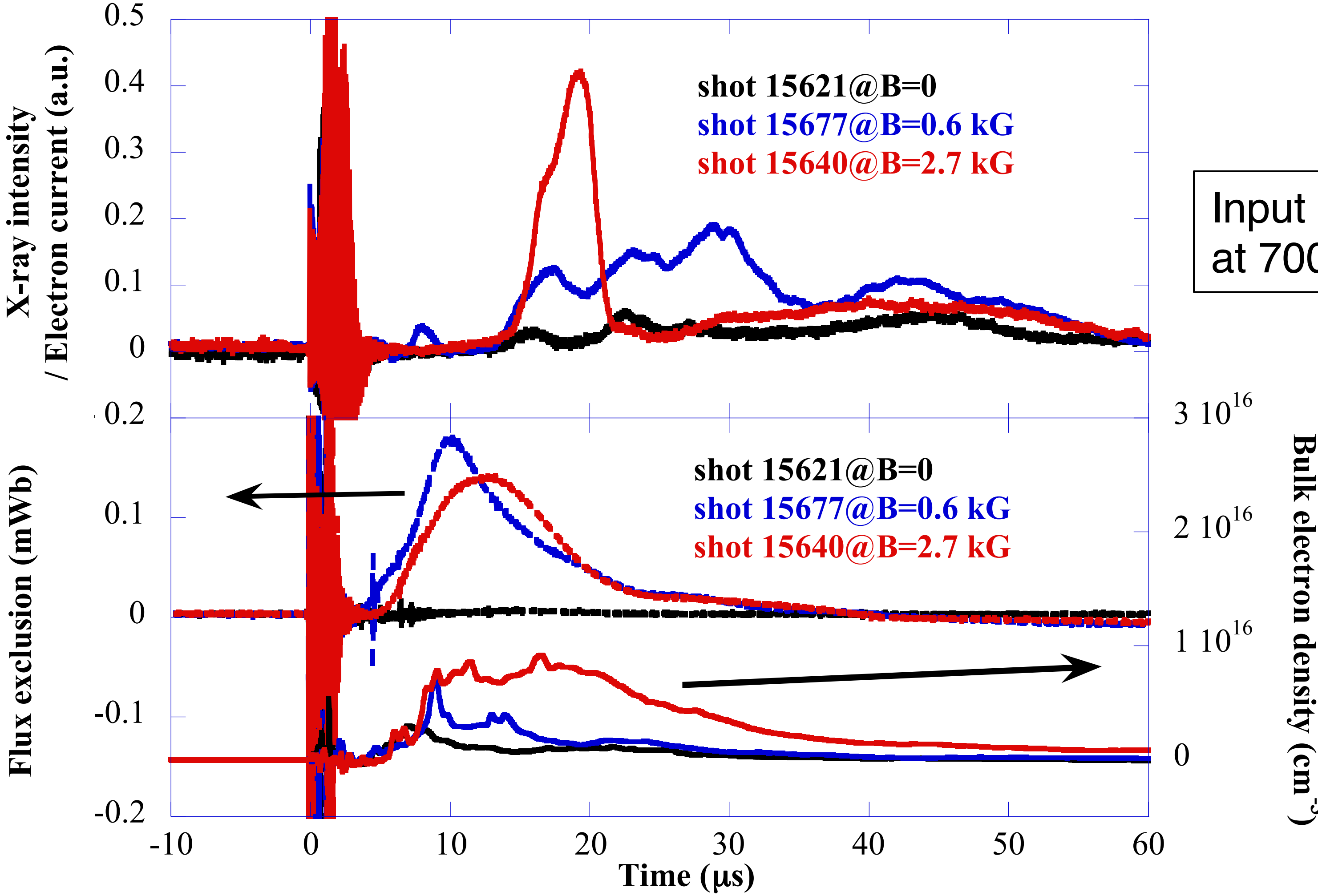
Confinement enhancement requires high β condition



B-field at 2.7 kG

Cusp confinement vs. Injection input power

Confinement enhancement related to pressure balance between plasma and magnetic field



Input power at 700 MW

Cusp confinement vs. initial B-fields

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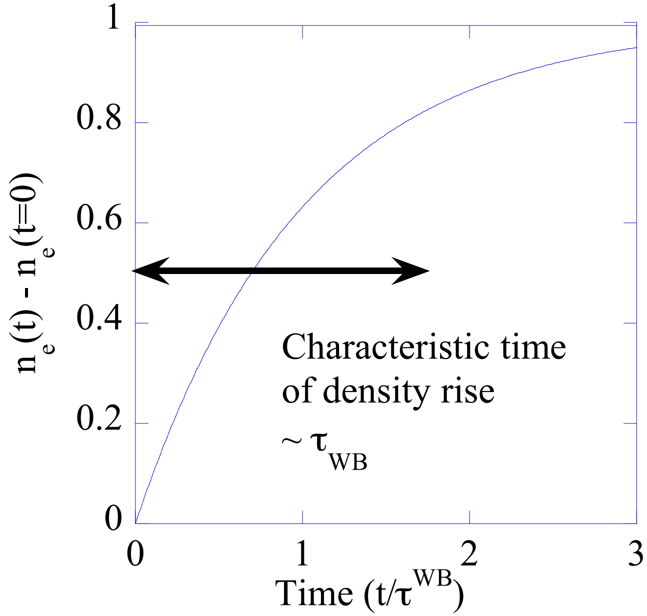
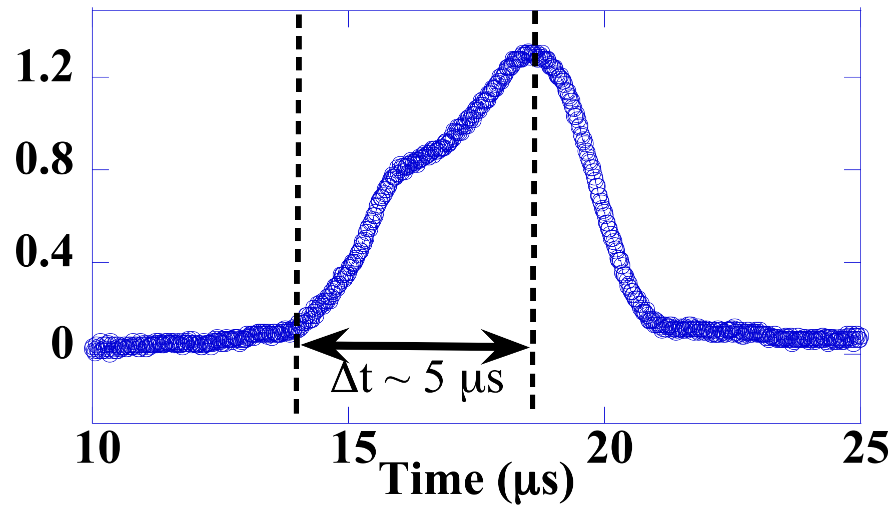
Estimate of High β Confinement Time

Theoretical model
to estimate high β confinement time



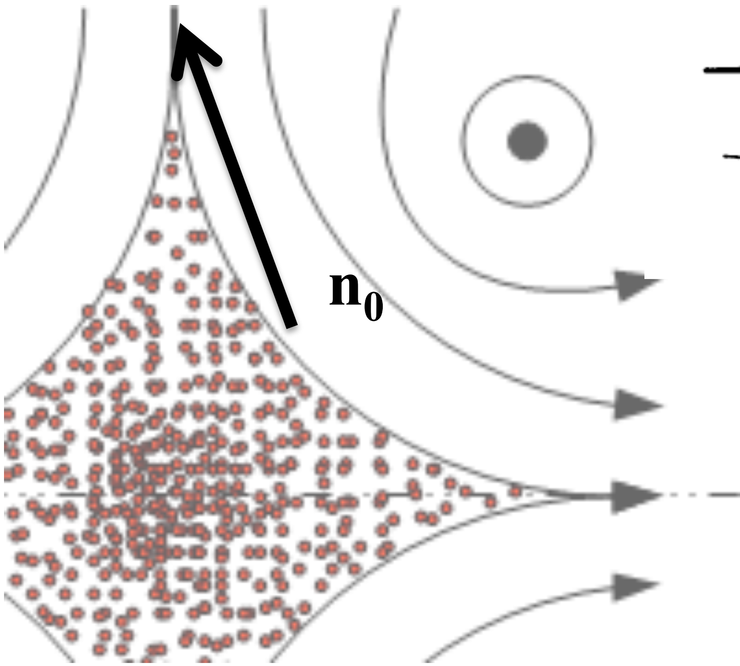
Experimental results
Shot 15640



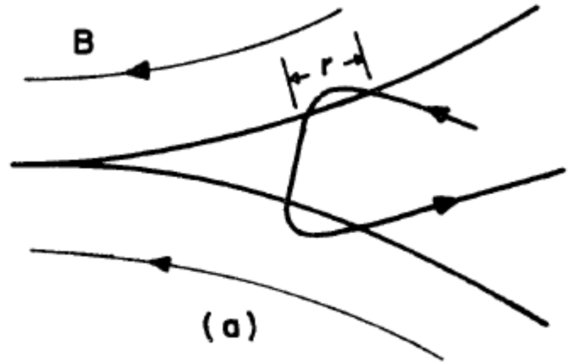
- Estimated confinement time τ >2.5 μs
- 2.5 μs is about ~ 50 times better than estimated low β cusp confinement time

Cusp Loss as Diffusion Process?
a la Grad and Krall

Loss boundary
n = 0



Plasma flow
from ∇n



Electrons will make random yet outward excursion every time they encounter field boundary

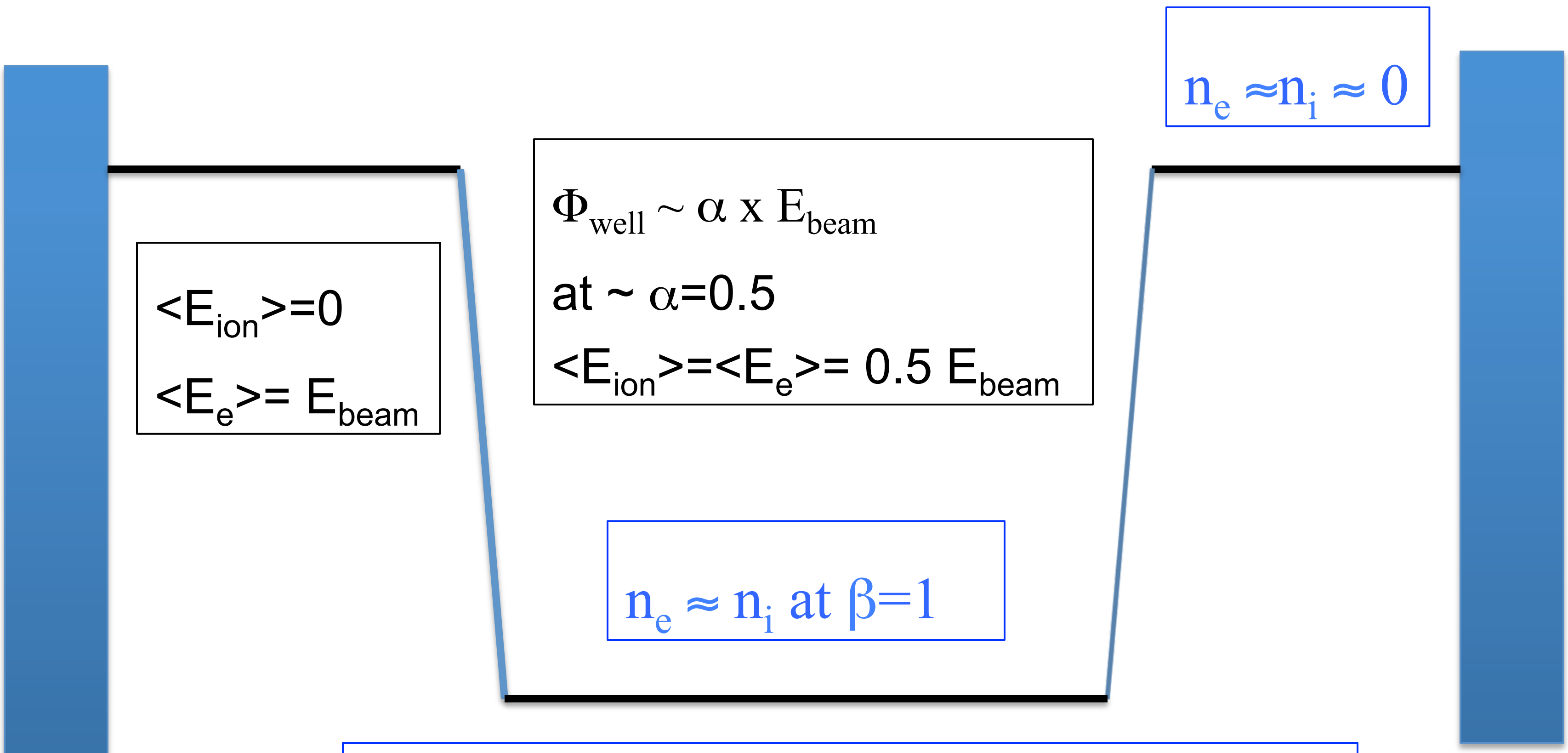
$$\text{Loss rate} \sim D\frac{\partial n}{\partial L} \quad \text{with } D \sim \frac{(\Delta x)^2}{\Delta t}$$

$$\text{If we set } \Delta x = \rho_e \text{ and } \Delta t = \frac{R}{\upsilon_e}$$

$$\text{Loss rate} \sim n\upsilon_e(\rho_e)^2$$

Confinement time ~ $R^3/\upsilon_e(\rho_e)^2$
7 keV, 0.27 Tesla, 0.1 m → 52 μs
100 keV, 7 Tesla, 1m → 0.65 s

Estimated Potential Well Depth



Chamber
Wall at ground

Good confinement likely leads to efficient energy transfer between electrons and ions in the cusp → 50% seems very achievable

Where Are We Now?

1. Finally found a path to solve the confinement of high energy electron beams in the cusp
2. Diffusion theory of high beta cusp looks promising
3. Efficient ion heating via electric potential looks reasonable
4. Cusp system forms the basis of stability & high beta operation.

Unresolved Physics Issues on High β Cusp

1. Decay of good confinement phase

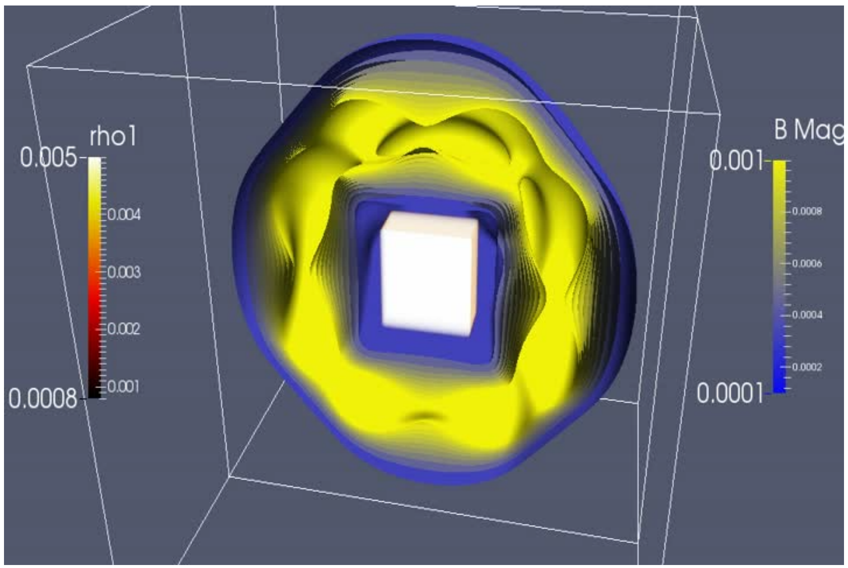
- Decay mechanism: plasma loss/plasma cooling or magnetic field diffusion or something else
- How to extend high β state and prevent the decay

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

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

3. Better theoretical foundation of high β plasma dynamics including confinement scaling

Particle Simulation of Polywell



IPIC 3D simulation of
High Beta Plasma Injection into Polywell
Collaboration with Prof. Lapenta
at KU Leuven

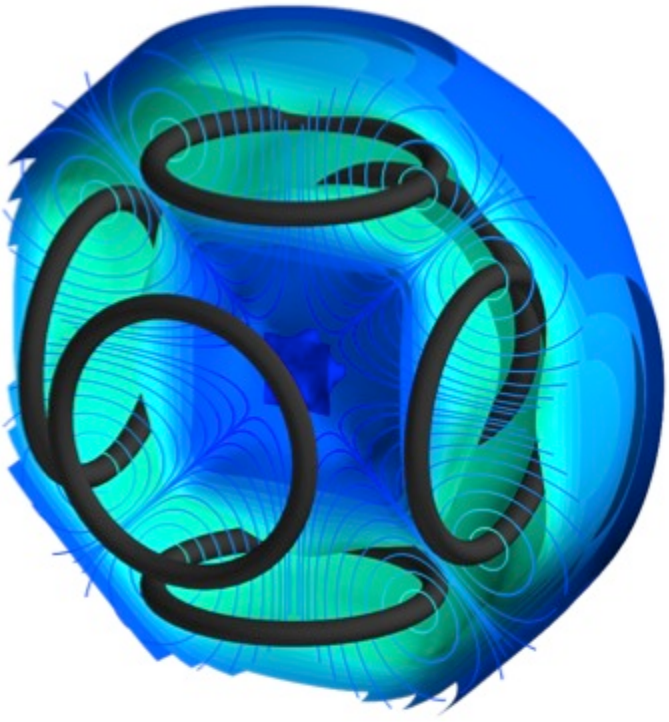
- EMC2 has been working on a numerical tool to investigate the physics of high β cusp plasma using a three dimensional particle-in-cell code, IPIC3D.

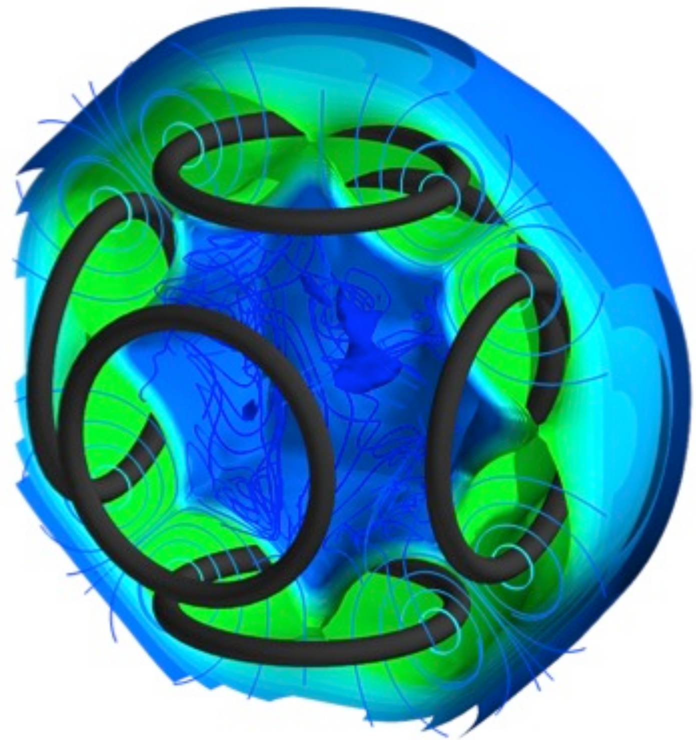
- IPIC3D is a massively parallel code that has been used extensively in simulating space weather.

- As seen on the left, high β plasma injection produce significant change in magnetic field in a Polywell system.

- We are in the process of validating the observed confinement enhancement at high β.

Preliminary MHD results on $B^2/2\mu_0$ Profiles



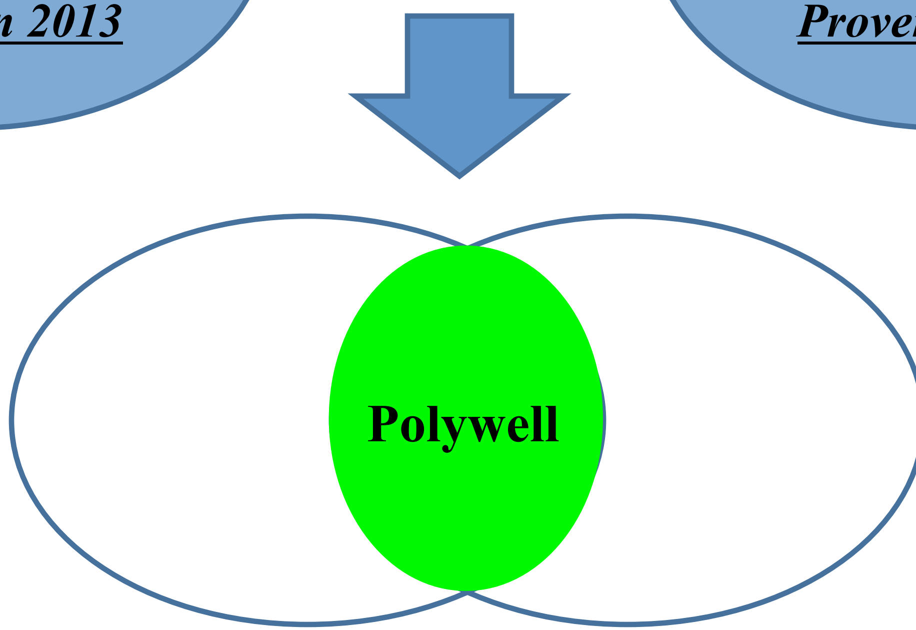


<u>Low β (β=0.1)</u> **<u>High β (β~1)</u>**

One Last Step to Validate Polywell Concept

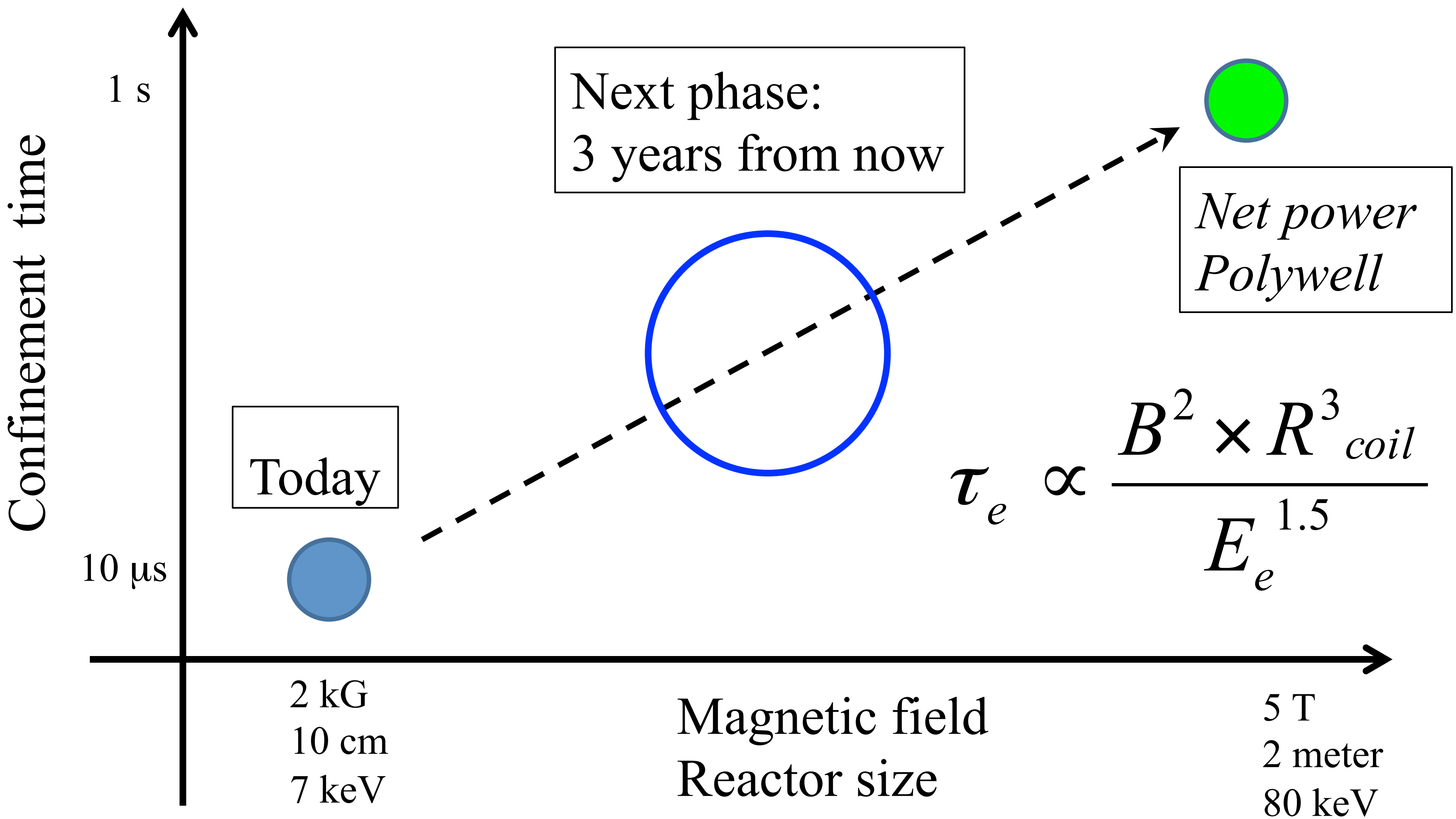
<u>High β cusp</u>
(Confinement of energetic electrons)
<u>Proven in 2013</u>

<u>Electric fusion</u>
(Potential well for energetic ions)
<u>Proven in 1995</u>



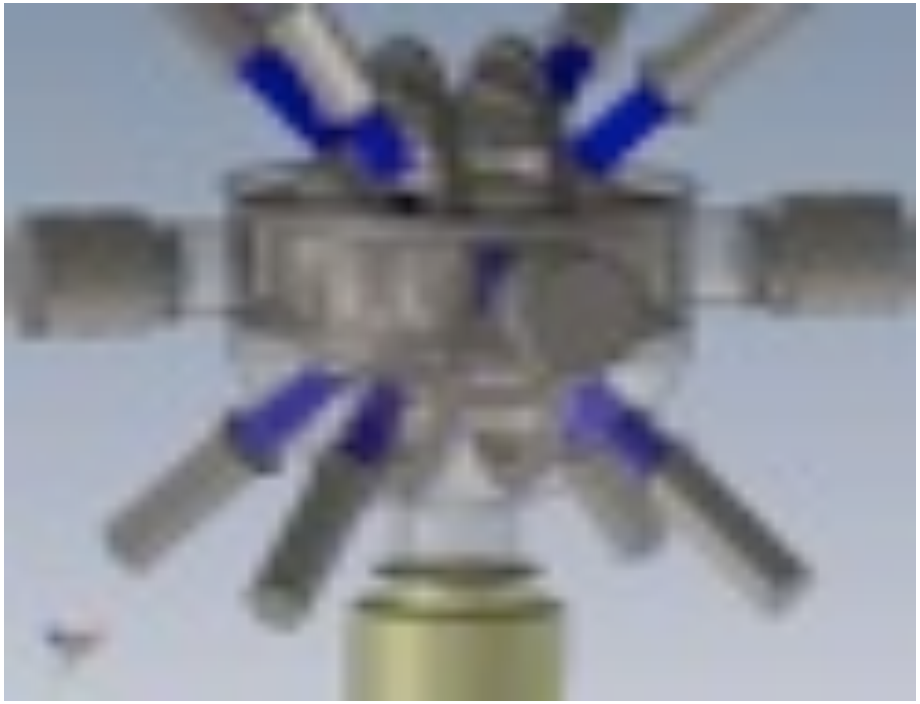
High β cusp + Deep potential well at the same time

Path to Polywell Fusion



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

Next Phase: Last Part of Proof-of-Principle



- Sustained high β operation (~ 5 ms)
- Verify cusp confinement scaling
- Demonstration of ion heating (>10 keV) by e-beam injection

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

Estimated budget of $8-10M/year for 3 years

Note: In FY 2015, US DOE Fusion budget to tokamak is ~$360M (budget for all non-tokamak programs is ~$10M combined)

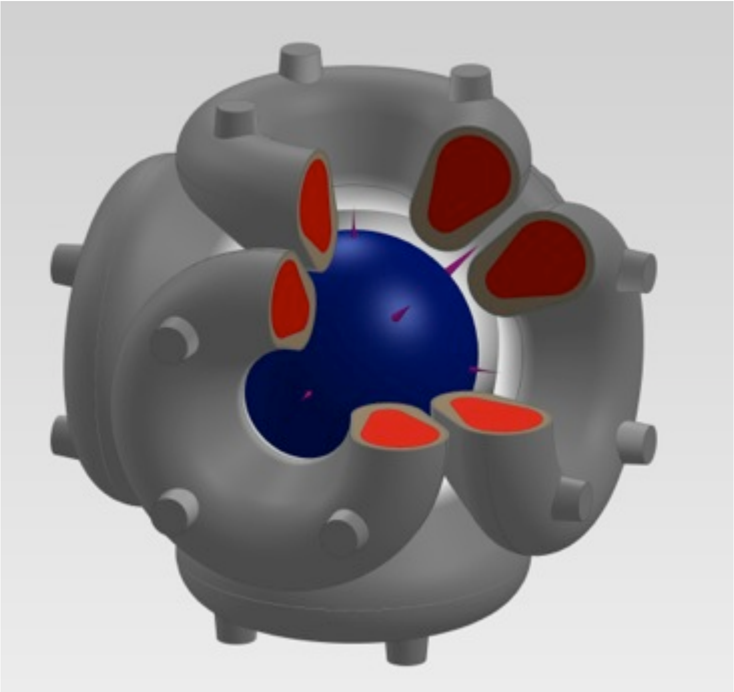
EMC2®

Where do we go from here?

If our next phase campaign is successful

Can we make a net power producing Polywell reactor?

Net Power Producing Polywell Reactor



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

Reactor Parameters

Coil Radius: 2.0 m

B-field: 5 T

e-beam: 80 keV

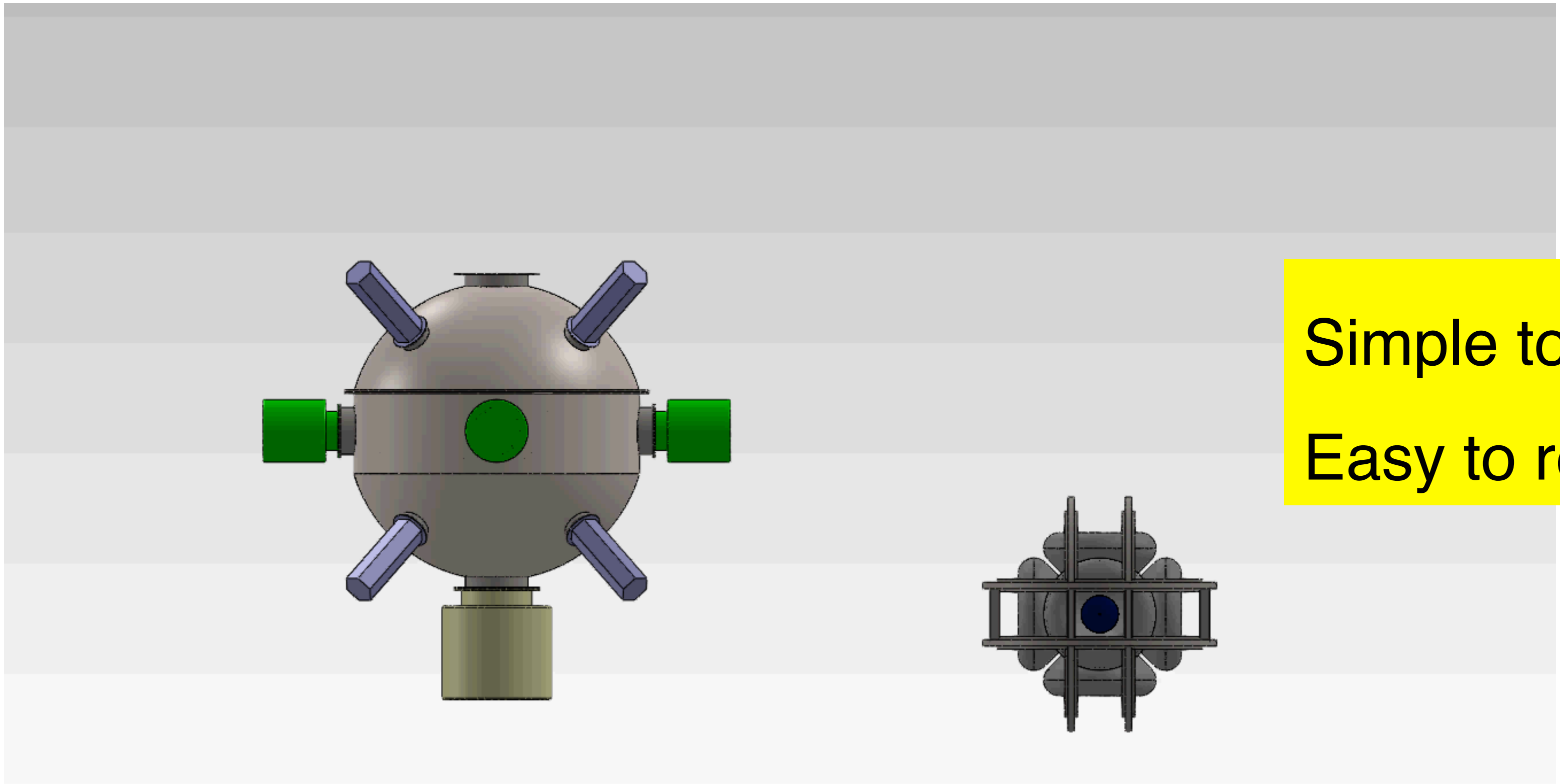
Plasma pressure: 98 atm

Magnetic pressure: 98 atm

Expected Fusion power: 1.1 GW (D-T fuel)

Heating power to plasma: 185 MW

Polywell Reactor
Assembly & Maintenance



Simple to build

Easy to replace

Polywell coils will not survive neutron damage without periodic replacement → Minimize reactor complexities for maintenance

Summary

- EMC2 has been working on a compact fusion reactor based on Polywell approach combining electric fusion with magnetic cusp system.
- Recent breakthrough in confinement will catalyze our efforts to complete the validation of the Polywell fusion in 3-4 years.
- If proven, Polywell technology would offer a low cost and rapid development path for practical fusion power.

<u>Unique Advantages of Polywell</u>

Plasma stability: *economical and reliable reactor*

High beta cusp: *confinement and compact size*

Use of electron beam driver: *efficient heating*

Supplemental Slides

More information can be found

1. Wikipedia article on Polywell Fusion (no inputs what so ever from EMC2) but surprisingly quite accurate (not perfect though)
2. I gave a lecture at Microsoft – online video is available. Also, it is great to watch Bussard's Polywell talk at Google (2006)
3. PRX is an open journal (anybody can read) and allows attachment including movies (and 10 pages)
4. Previous Polywell seminar materials are available online at various websites