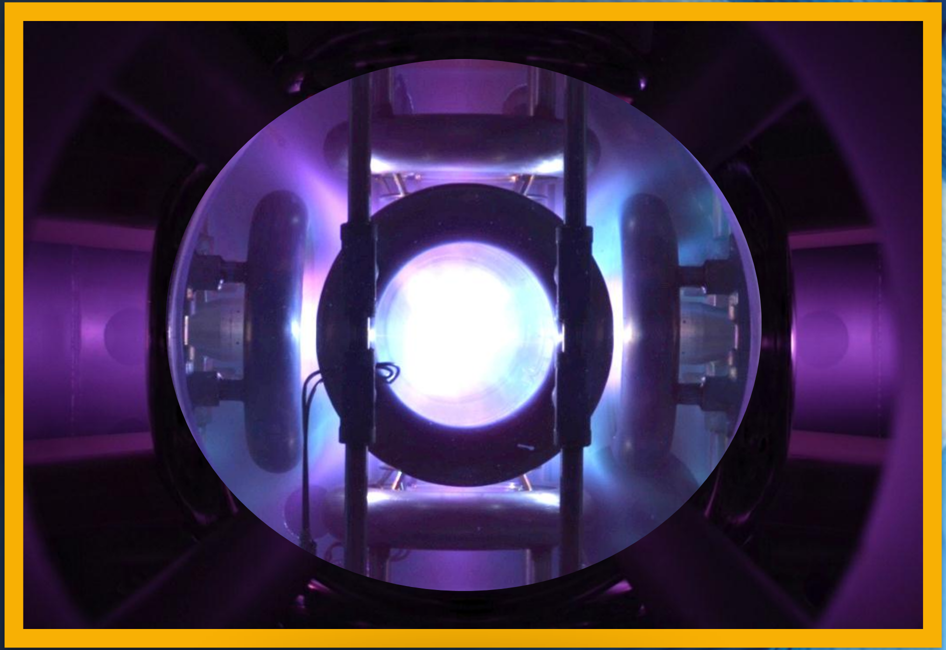
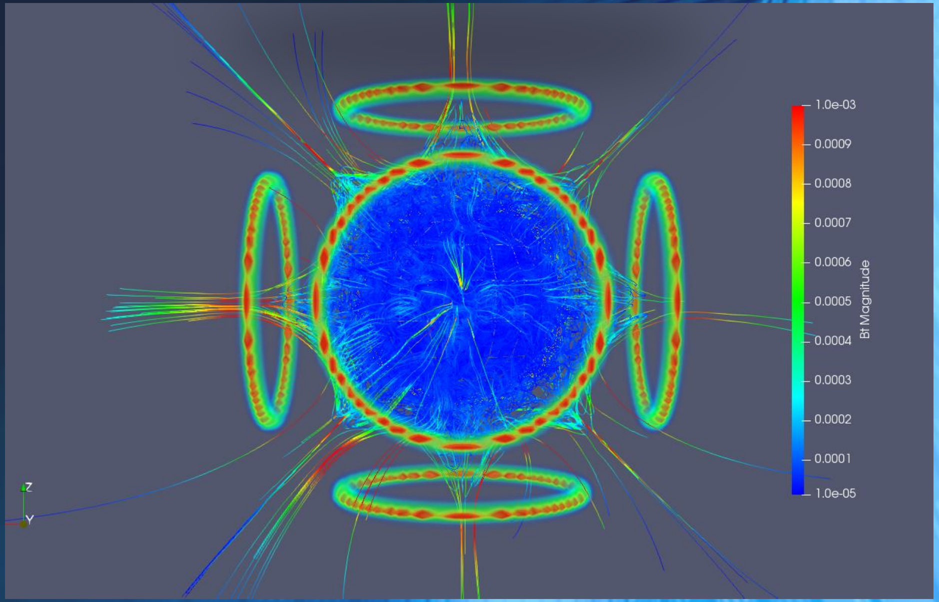
Polywell Fusion





JAEYOUNG PARK

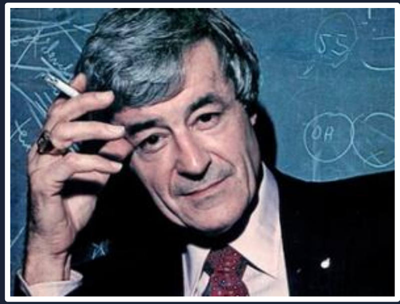
ENERGY MATTER CONVERSION CORPORATION

ENN FUSION SYMPOSIUM, APRIL 20 2018

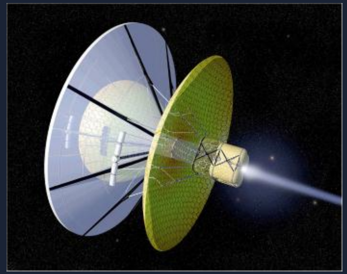
History of EMC2

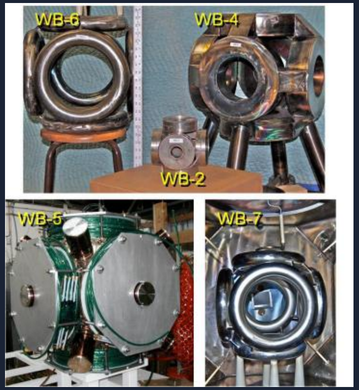
Energy Matter Conversion Corporation is a US-incorporated, San Diego-based company developing nuclear fusion

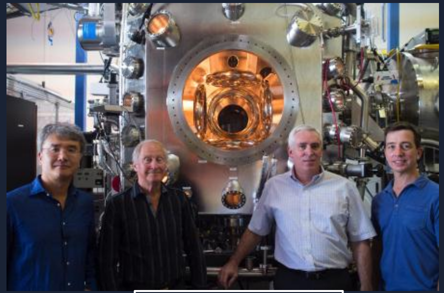
- 1985: EMC2 founded by the late Dr. Robert Bussard
- Polywell technology is based on high pressure magnetic confinement of plasma called the "Wiffle-Ball" and plasma heating with an electrostatic potential well by e-beams
- 1992 – 1995: First Polywell device was built with DARPA funding. Successfully demonstrated electrostatic potential well using electron beams.



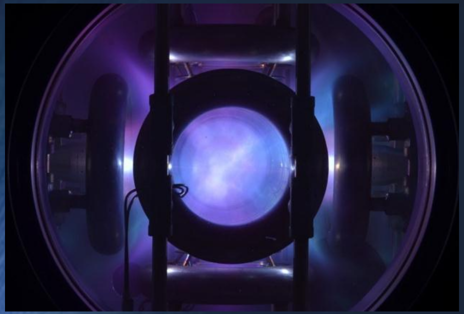
1985



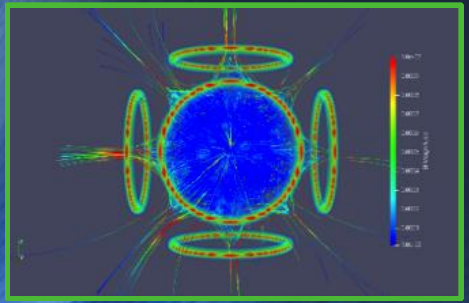




1995-2013



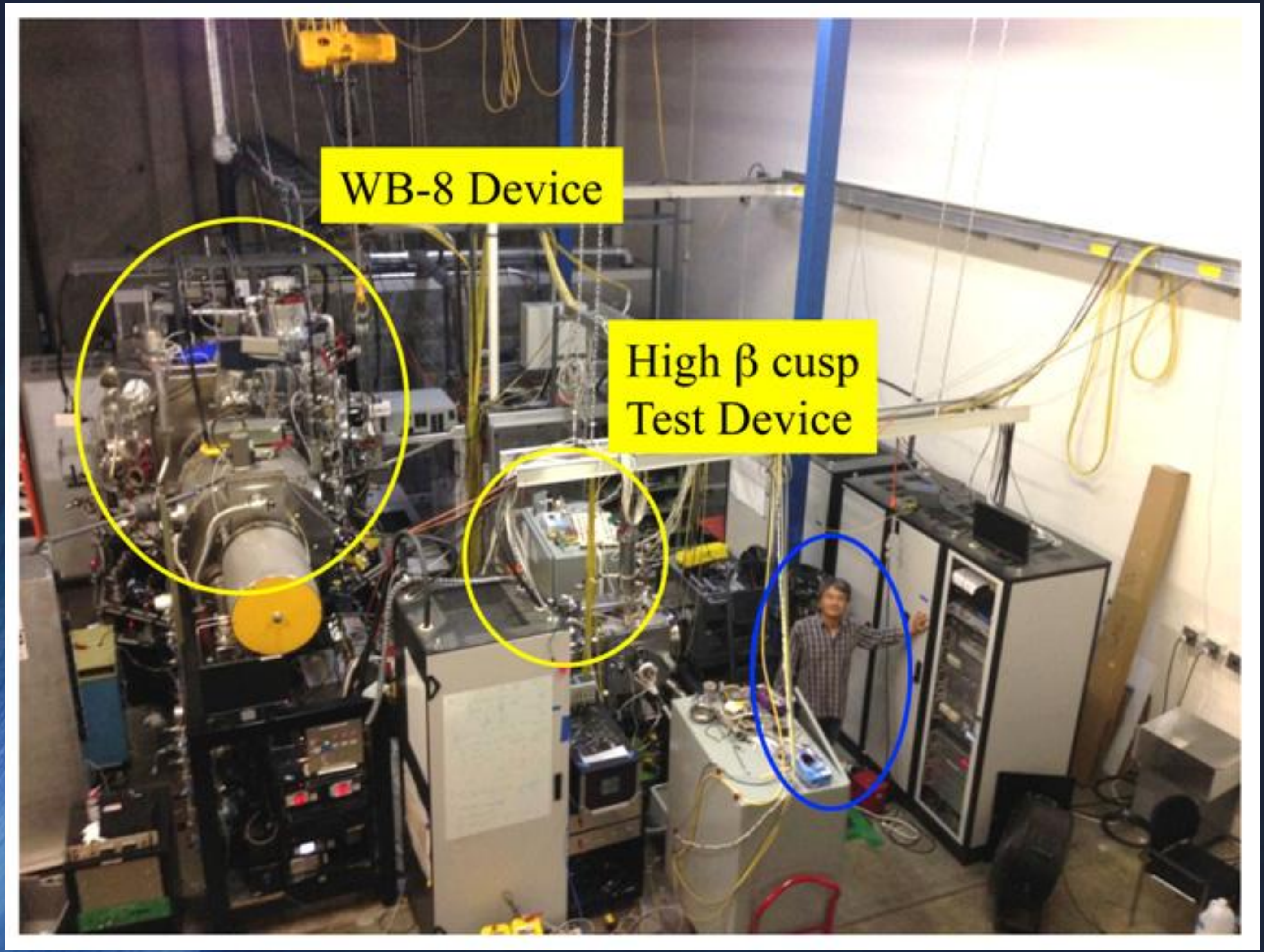
2013

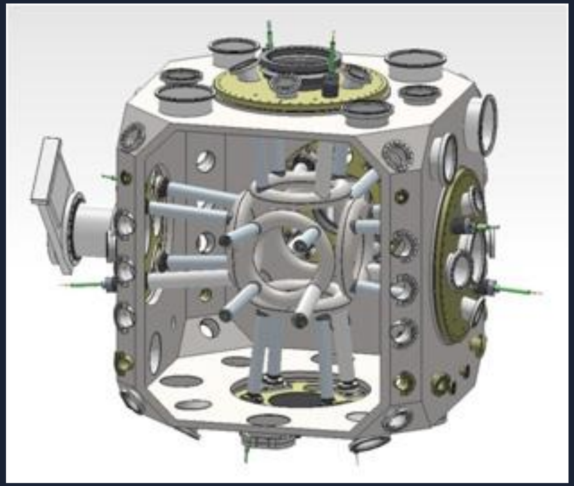


2017

- 1995 -2013: EMC2 continued R&D efforts utilizing a series of 19 test Polywell devices to demonstrate and examine Wiffle-Ball (WB) plasma confinement backed by the US Navy.
- 2013: Successful formation of WB and demonstration of enhanced confinement.
- 2014-2017: EMC2 filed two patents, published a peer-reviewed paper, and provided public disclosures of the Polywell technology.
- 2017: EMC2 developed computer code to validate and began optimizing the Polywell technology.

EMC2 San Diego Laboratory





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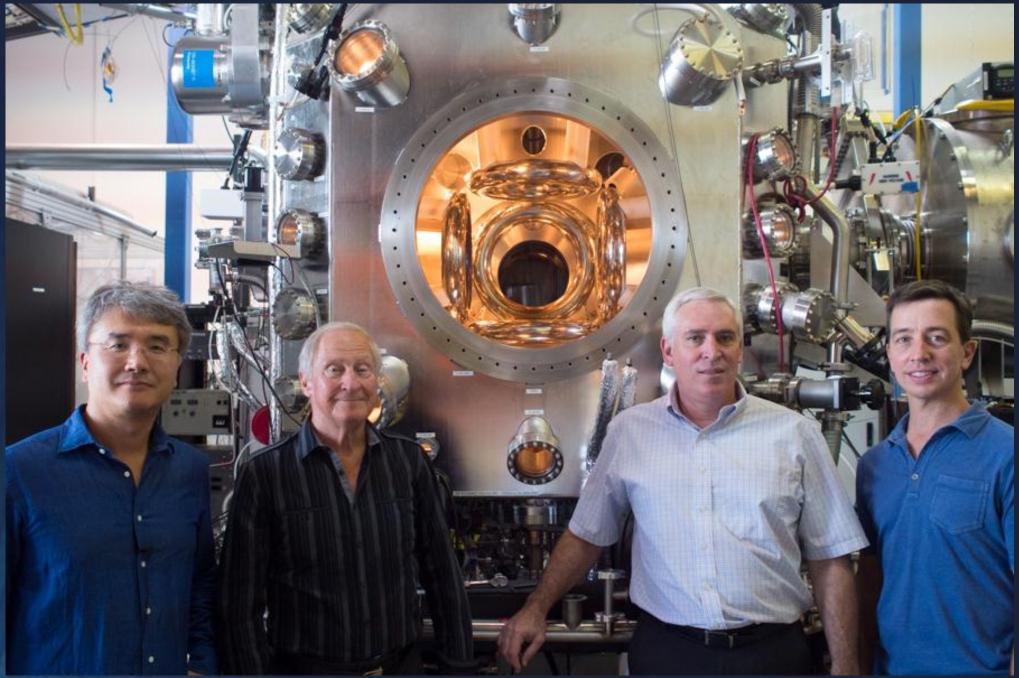
EMC2 Teams and Collaborations



KU Leuven
Plasma Simulation

Los Alamos National Laboratory EST. 1943

Power Systems, Magnets
Particle Diagnostics

The University of Wisconsin Madison

Reactor Engineering,
Neutronics & Modeling

Budker Institute of Nuclear Physics

Neutral beam injector
plasma sources

The University of New Mexico

μ-wave & laser
diagnostics

Why EMC2 Pursues Polywell Fusion?

Lawson Criteria for Polywell
$n * \tau * T$

- High density using stable magnetic cusp trap: **10n** compared to tokamak (5×10^{20} m^{-3})
- Sufficient confinement using Wiffle-Ball (i.e. high beta cusp): **0.1 τ** compared to tokamak (0.1-1s)
- High temperature using electron beam heating: **1.5-2T** compared to tokamak (30-50 keV)

Additional Metrics Critical to Fusion Energy

- Plasma stability: uncontrolled plasma behaviors degrade reactor performance and damage reactor
- Efficient fuel heating allows 2nd generation fuels (D – ^{3}He and p-^{11}B)
- Needs to address engineering and materials limitations
- Size and cost of reactor matters to compete against other power plants

An important Question: how to make a better fusion reactor than tokamak or stellarator?
Bonus question: Can we use a fusion engine to travel within and outside the solar system?

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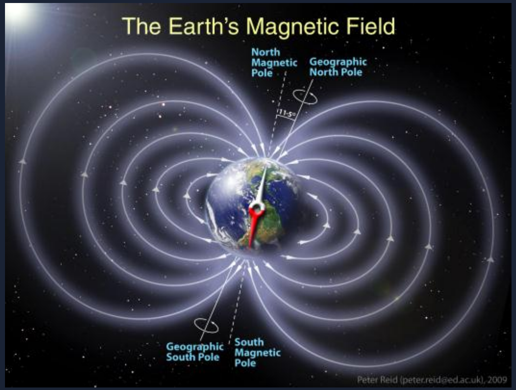
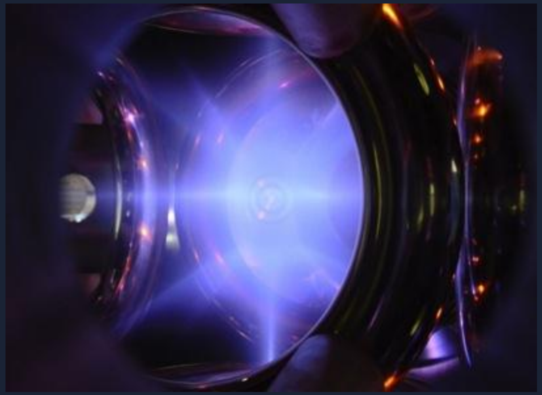
What is Polywell Fusion?

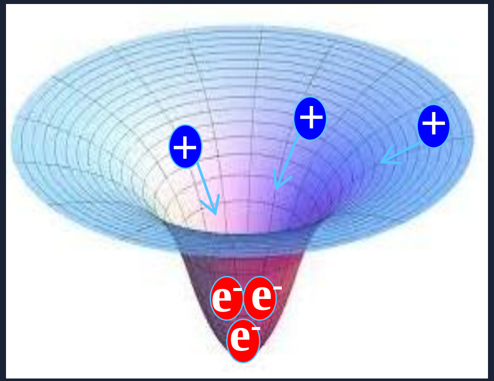
1. Magnetic cusp
- Cusp has the best stability property
- Key to achieve high density and compact reactor size



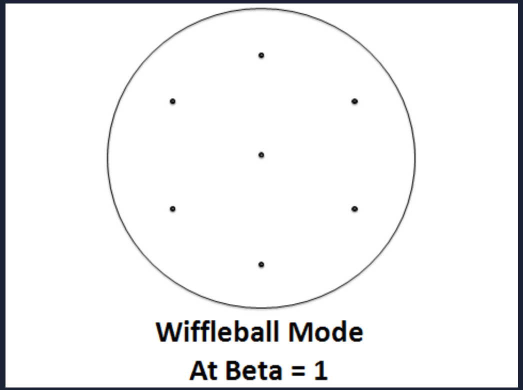


2. Electrostatic heating
- Potential well to heat & confine ions
- Cusp is compatible with electron beams

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

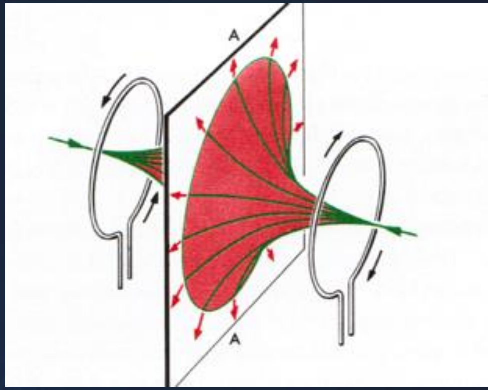


3. Wiffle-Ball (WB) Confinement
- High pressure plasma in the cusp generates a unique equilibrium
- WB can greatly enhance energetic electron confinement



Magnetic Cusp: Stable but leaky magnetic trap

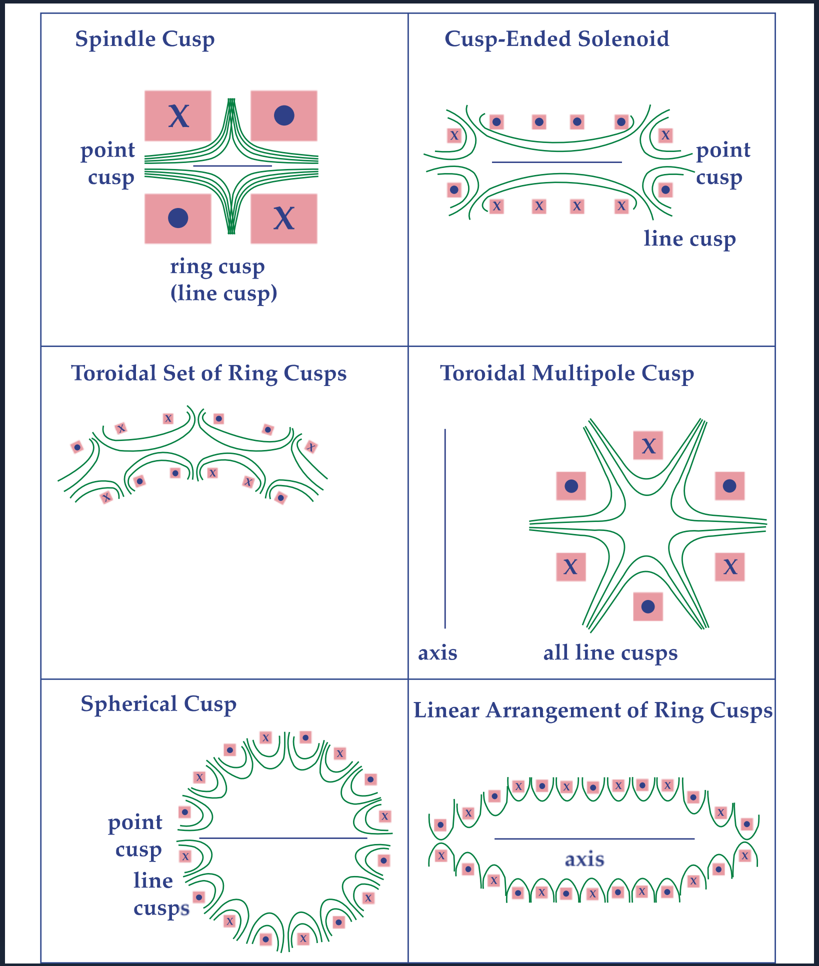
Simple magnetic cusp can be produced by 2 coils with opposite currents



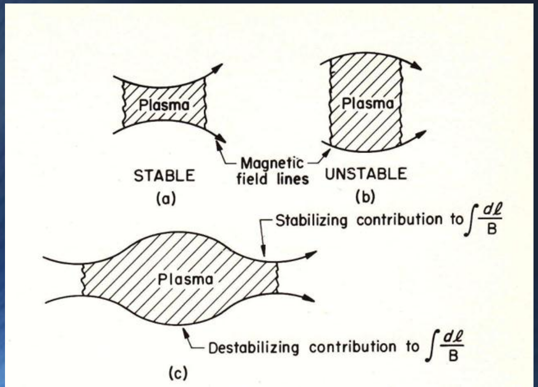
From "Project Sherwood: The U. S. Program in Controlled Fusion" by Amasa Bishop (1958).

Magnetic cusp was proposed as a fusion concept in 1954 due to its favorable stability

~ 20 cusp devices were built for fusion



Various types of cusp systems from Dolan's review article (1994)



From Principles of Plasma Physics Krall & Trivelpiece (1973)

Cusp is stable due to its curvature – note that B-field increase from center to boundary

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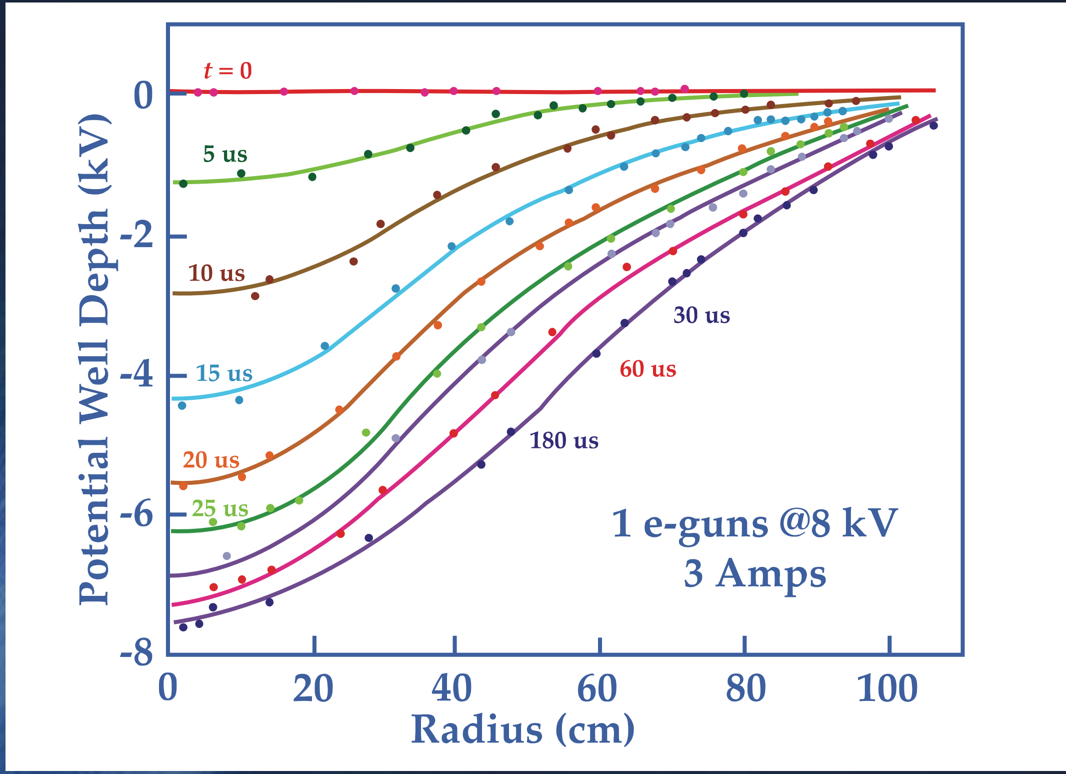
Electrostatic Heating of Ions: A Potential Game Changer

- The simplest known method of heating ions to fusion temperature (100M degree or more)
- Pioneered by Farnsworth and Hirsch in 1960s for Inertial Electrostatic Confinement (IEC) fusion system
- Electron beam approach compatible with magnetic cusp system
- Potential well formation inside magnetic cusp demonstrated in 1995



"Forming and Maintaining a Potential Well in a Quasispherical Magnetic Trap", Krall et al, Physics of Plasma (1995)

- 8 kV electron beam injection yielded 7kV potential well – **very high efficiency**
- Due to poor confinement of energetic electrons, the potential well failed with increasing plasma density
- That's why EMC2 started focusing on improving confinement of energetic electrons

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WB: A critical missing piece for Polywell Fusion

How is WB formed and what does it do?

- WB (also known as high beta cusp) was proposed by Grad between 1954-1958.
- WB is formed when the plasma pressure becomes high and comparable to magnetic filed pressure in the cusp boundary
- For example, the critical density (beta=1) is $6\times10^{20}/m^3$ at 50 keV for 5T B-field
- Due to diamagnetic nature of plasma, the magnetic fields are pushed outward and forms a sharp boundary with strong plasma current on the surface
- This diamagnetic current is responsible to change the magnetic field topology to enhance plasma confinement in the center.

WB formation – Simulation Results

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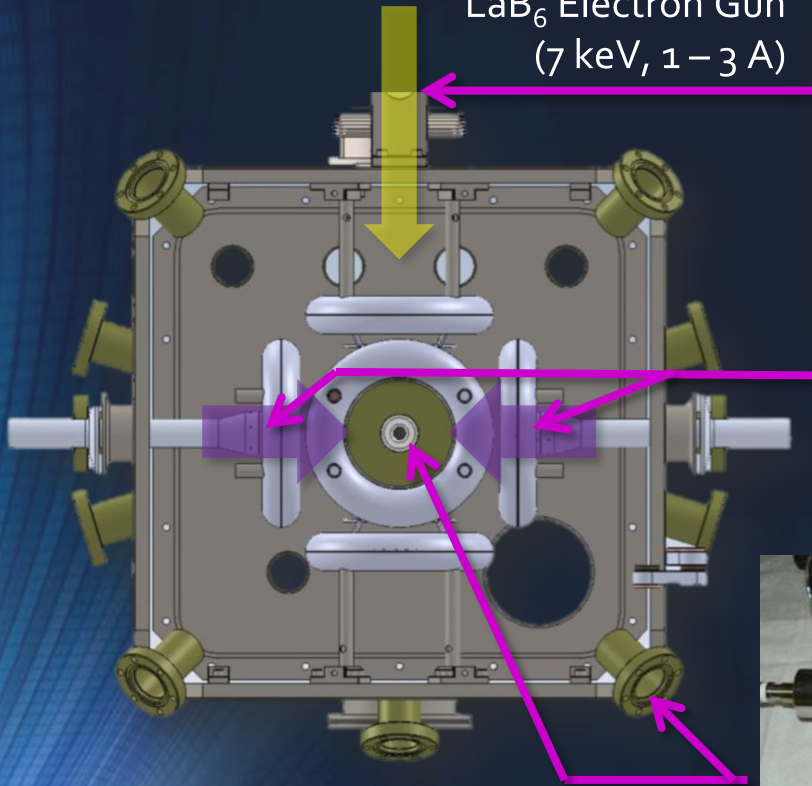
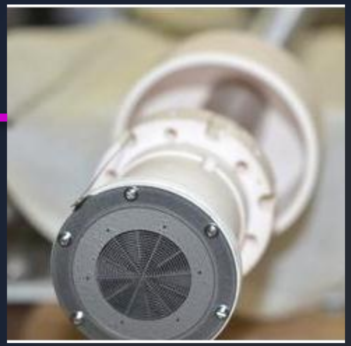
Experimental Validation of WB Formation and Confinement Property

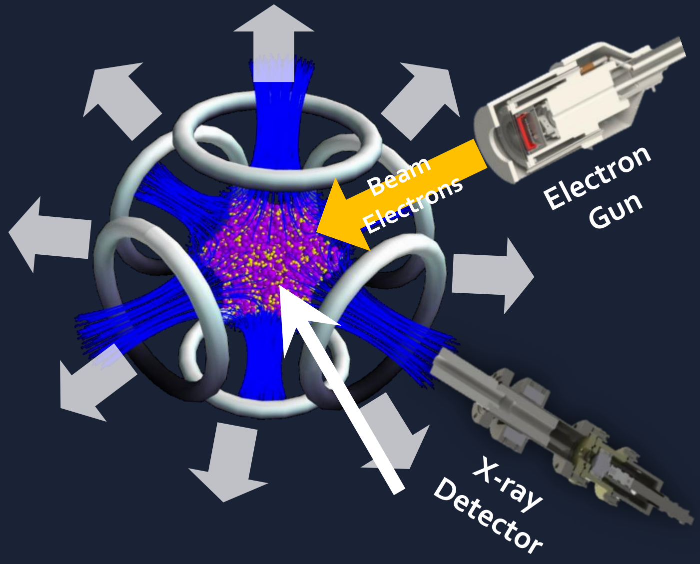


LaB_6 Electron Gun
(7 keV, 1 – 3 A)



Plasma Gun
(350 MW solid arc)

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

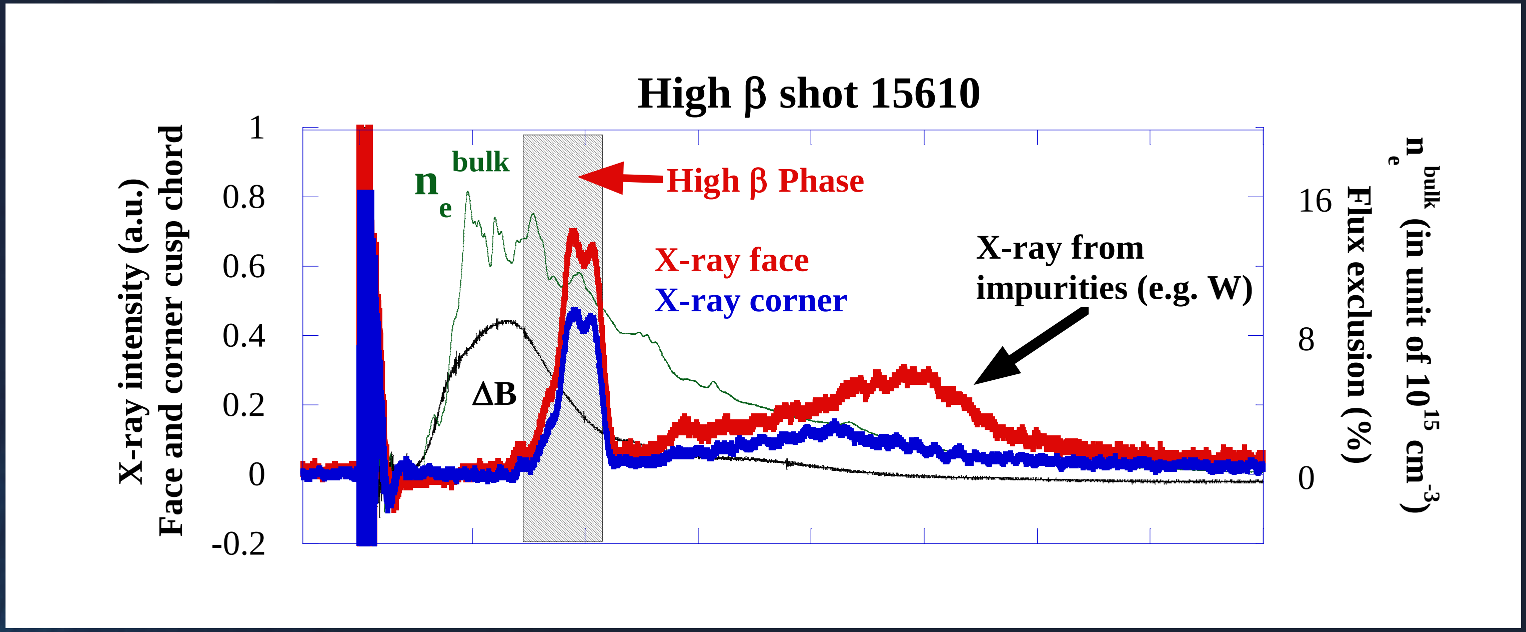


I(t): x-ray intensity

- dI(t)/dt ~ I(t)/τ

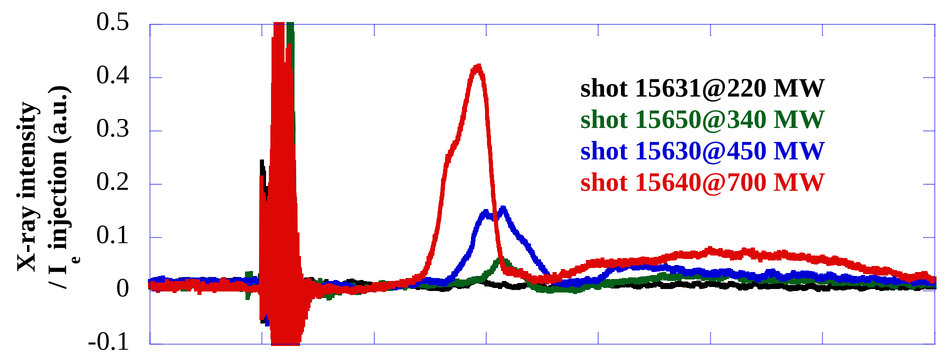
Chamber size: 45 cm cube, Coil major radius; 6.9 cm
Distance between two coils: 21.6 cm, B-field at cusp (near coil center) 0.6 – 2.7 kG

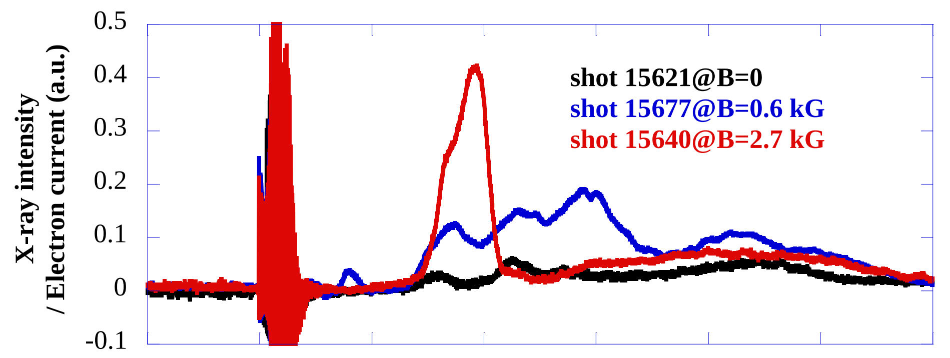
WB confirmation: enhanced confinement of 7 keV electrons



"High-Energy Electron Confinement in a Magnetic Cusp Configuration", Park et al, Physical Review X **5**, 021024, 2015

Quote from Navy Review Committee - "EMC2 has made a major breakthrough in its development of the Polywell … It has clearly and repeatedly demonstrated so-called wiffle ball plasma formation with dramatically enhanced plasma confinement, a major achievement and a prerequisite to concept success."





WB requires high β condition

WB requires balance between plasma and B-field pressure

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Plasma Simulation

A tool to understand how Polywell works & how we can optimize it

ECsim: **Energy Conserving semi-implicit method**

- Latest version of the implicit particle code developed over 35 years
- First-Principles code: solves Newton Eq. and Maxwell Eqs.
- EMC2 now uses ECsim for Polywell as well as other magnetic geometry like mirror and pinch

- 1980's
- Early development
- Simple solvers

J.U. Brackbill, D. Forslund, JCP, 46, 271, (1982).

Venus

- 1992-2005
- Vector computers (Crays)
- Advanced solvers

G. Lapenta, J.U. Brackbill, P. Ricci, PoP, 13, 055904, (2006).

Celeste

- 2005-2008
- First Massively parallel implementation

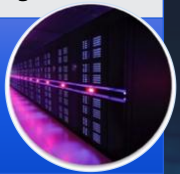
S. Markidis et al, Astronomical Society of Conference Series, vol 406, page. 237, (2009).

Parsek

- 08-Now
- Massively Parallel
- Vectorized operations
- 3D production

Review in Lapenta, JCP, 231, 795 (2011) & Lapenta et al, Nature Physics **11**, 690–695 (2015)

iPic3D



- 2015-Now
- Solves 3rd order matrix equation to conserve energy within machine accuracy
- Optimized for high beta fusion reactor simulation

G. Lapenta, D. Gonzelez-Herrero, E. Boella, J. of Plasma Physics, **83**, 705830205 (2017).

ECsim

Magnetic Mirror Simulation

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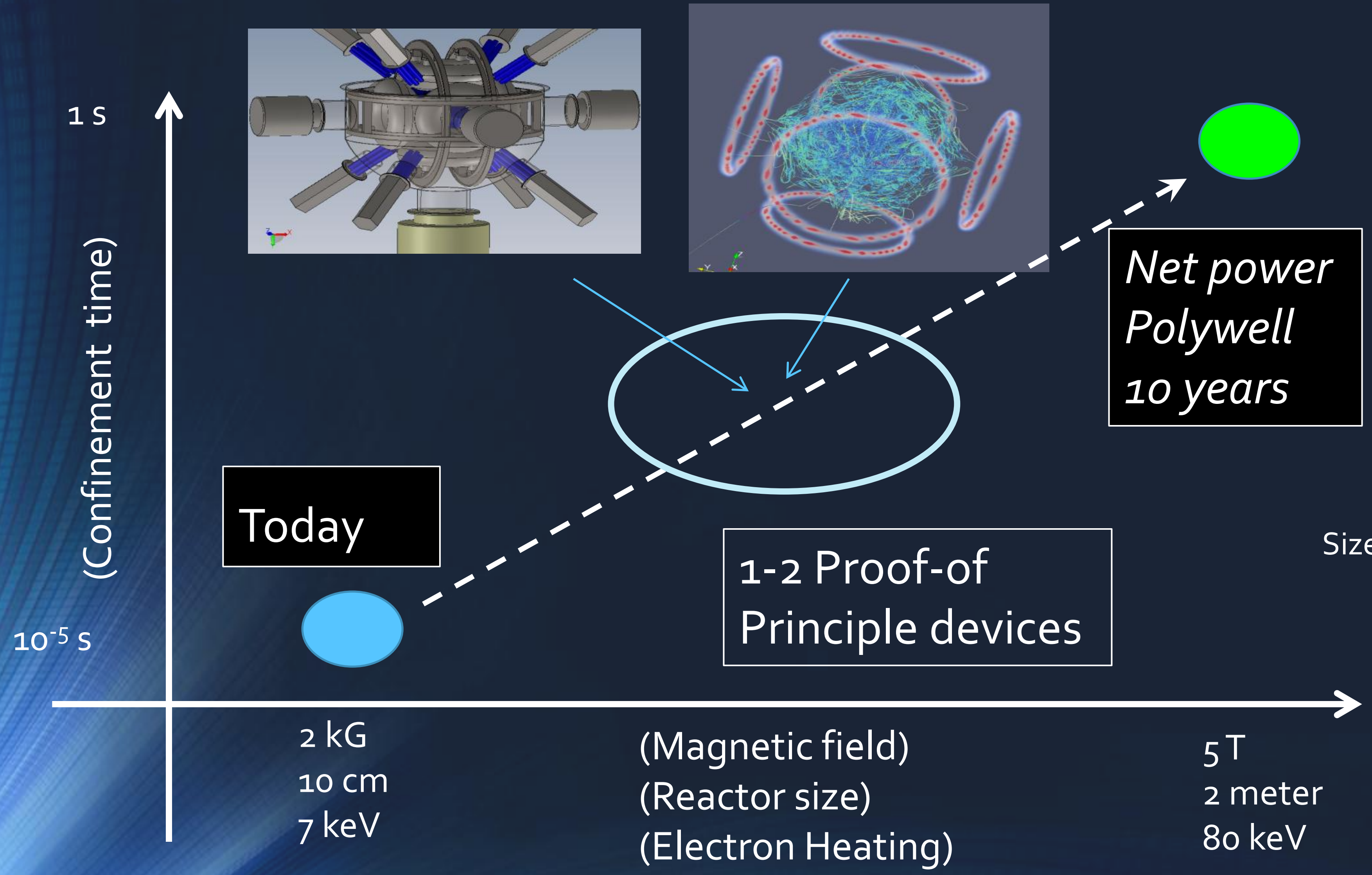
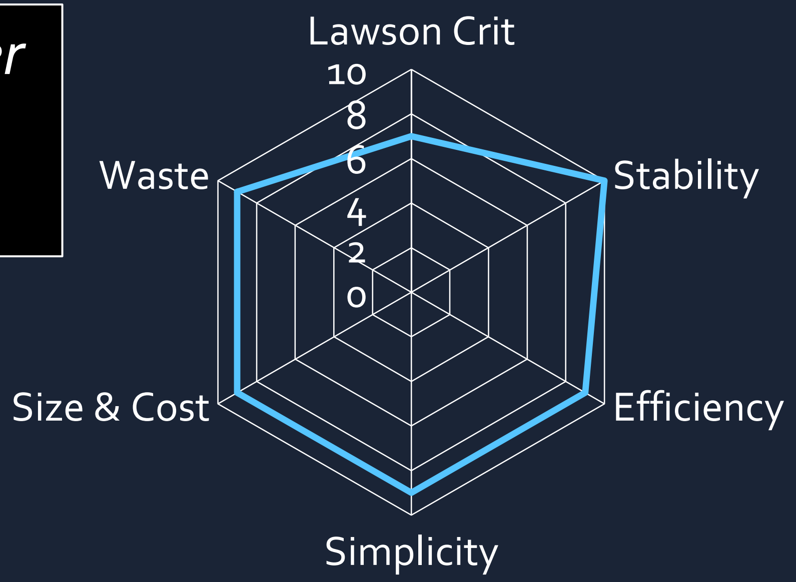
Path to Polywell Fusion Power



Polywell Reactor Performance Matrix



Polywell Fusion Power Plant: how it will look

EMC2 Vision: Compatible with existing power conversion technology

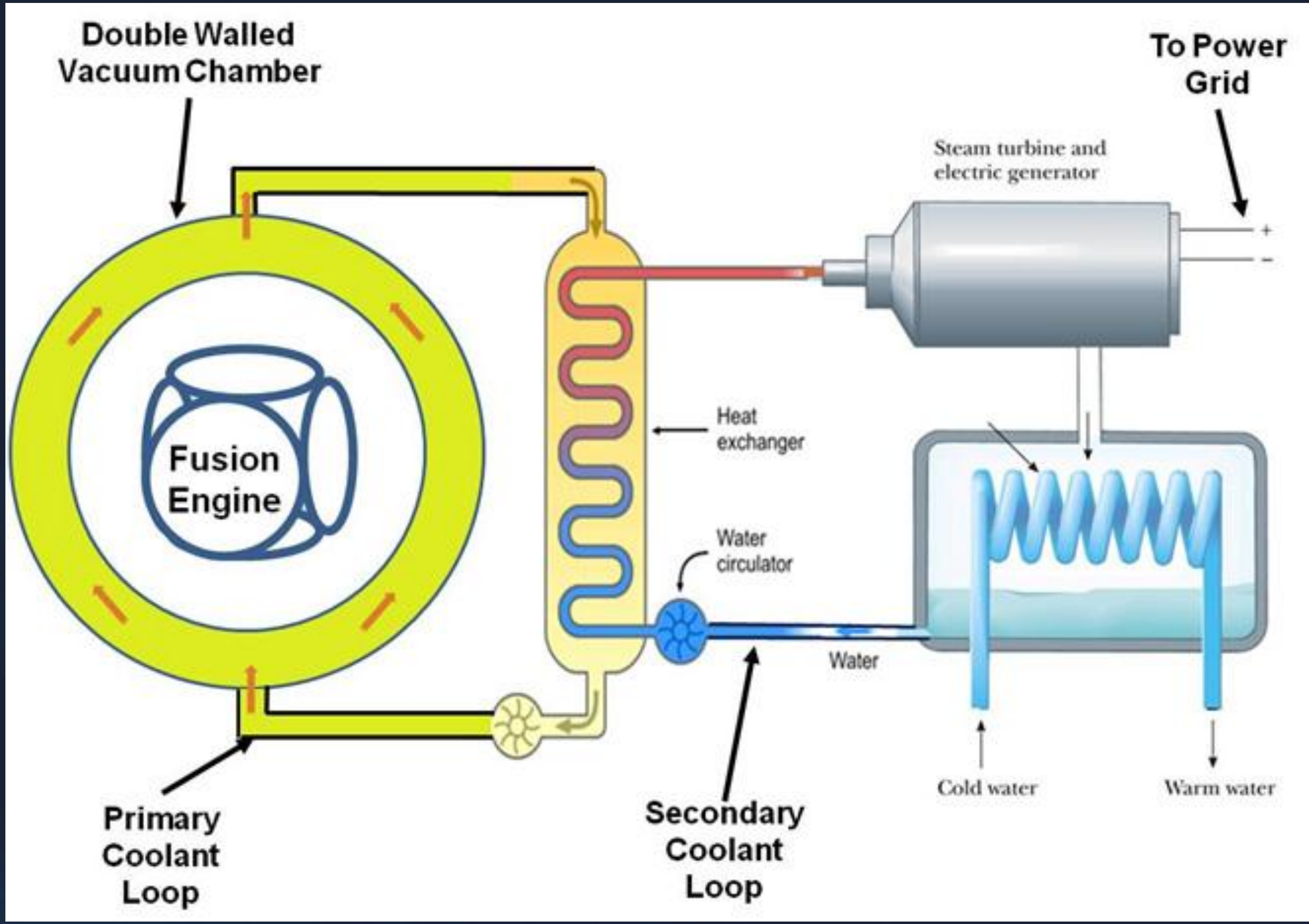
1st generation Polywell Power Plant will utilize existing HTGR technology

(high temperature gas cooled reactor): ~40% efficiency at 725 C Helium cooling

Initial cost breakdown for 500 MWe plant

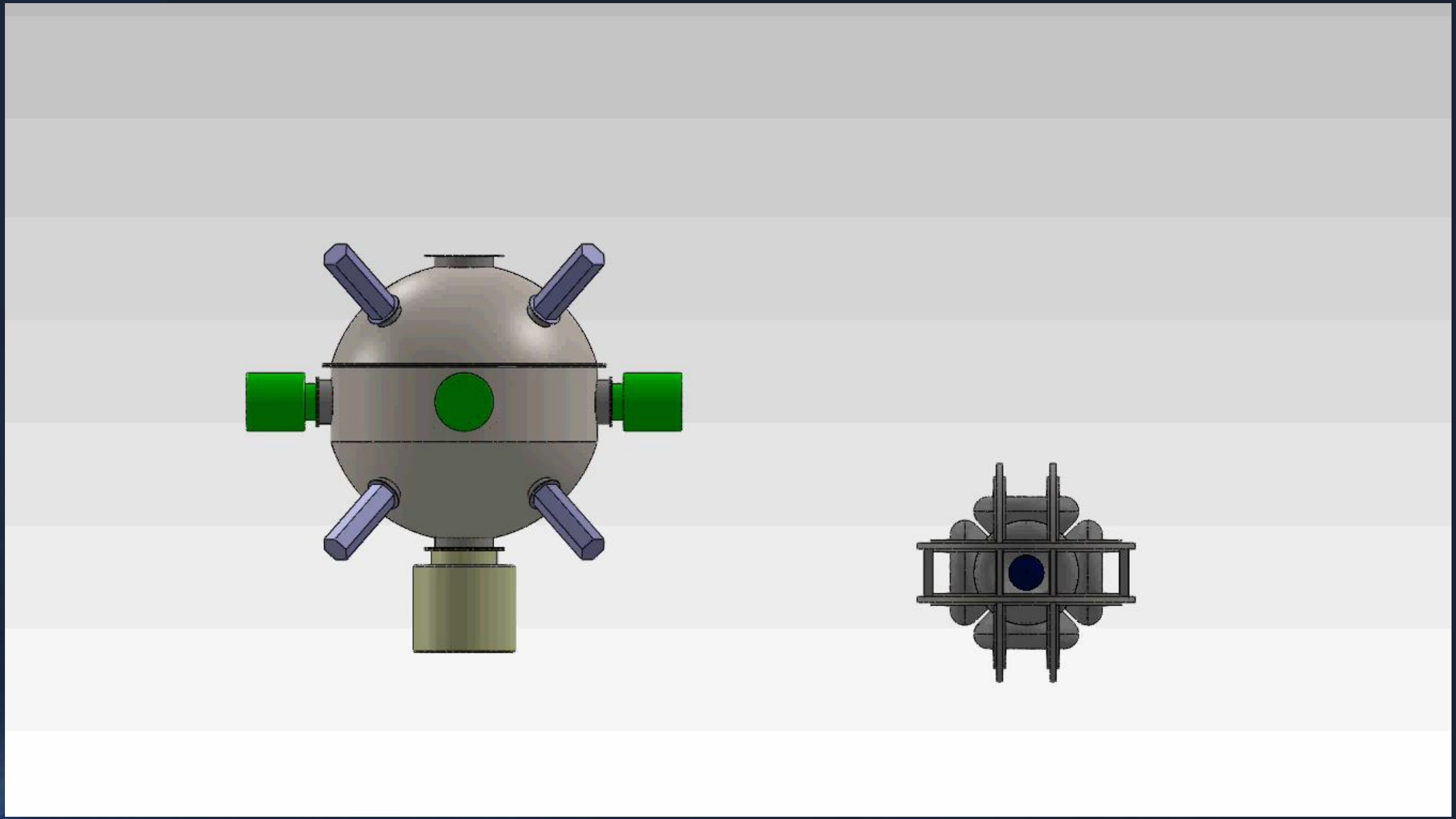
- $150M for Polywell Fusion Engine
- $400M for secondary loop/generator
- $150M for tritium breeding system

→ To achieve 7-9 cents per kWh electricity cost



Proposed Maintenance of Polywell Fusion Core

Use of D-T requires routine replacement of Polywell Fusion core



Simulation almost ready for e-beam driven potential well and dynamics equilibrium for advanced fuels

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Summary

- EMC2 has been working on a compact fusion reactor based on Polywell approach combining electrostatic fusion with magnetic cusp system.
- Recent breakthrough in confinement and simulation will catalyze our efforts toward the demonstration of net power generation in a compact Polywell fusion test device
- 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*