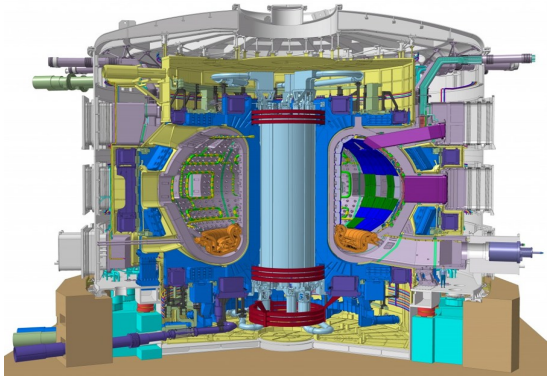
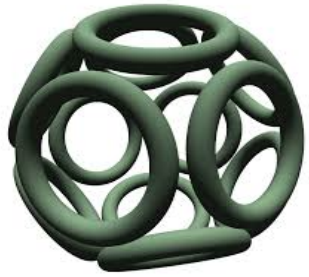


Tokamak Fusion
&
IEC



Robert L. Hirsch
Senior Technical Advisor
MISI

16th US/Japan Workshop on Fusion Neutron Sources for
Nuclear Assay and Alternate Applications
Madison, Wisconsin
September 30-October 2, 2014.

Tokamak Fusion Power

- **"Criteria for Practical Fusion Power Systems"**
  1994 U.S. Electric Power Research Institute (EPRI) report

  -- Economics

  -- Public Acceptance

  -- Regulatory Simplicity

- **Good News:** A recent review of tokamak demo & reactor studies indicates many investigators recognize some of these criteria.

- **Bad News:** No one in fusion research seems to explicitly consider regulator & utility interests.

Regulator Interests

- **Public safety**

Utility Interests

- **Reliable, low cost, environmentally & publically acceptable power**

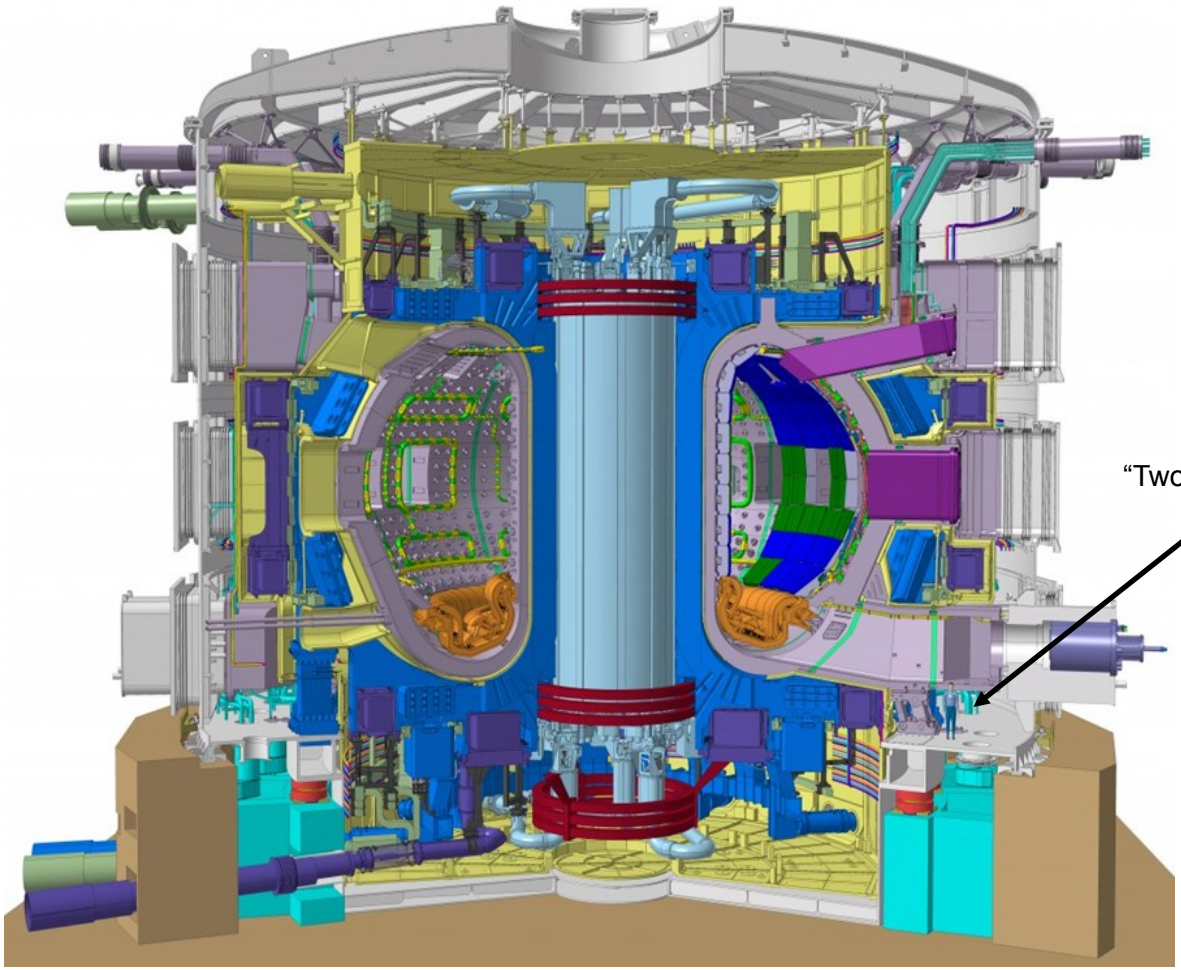
Regulator Interests

- **Public safety**
- What can go wrong / How wrong?
- Are the risks adequately mitigated?

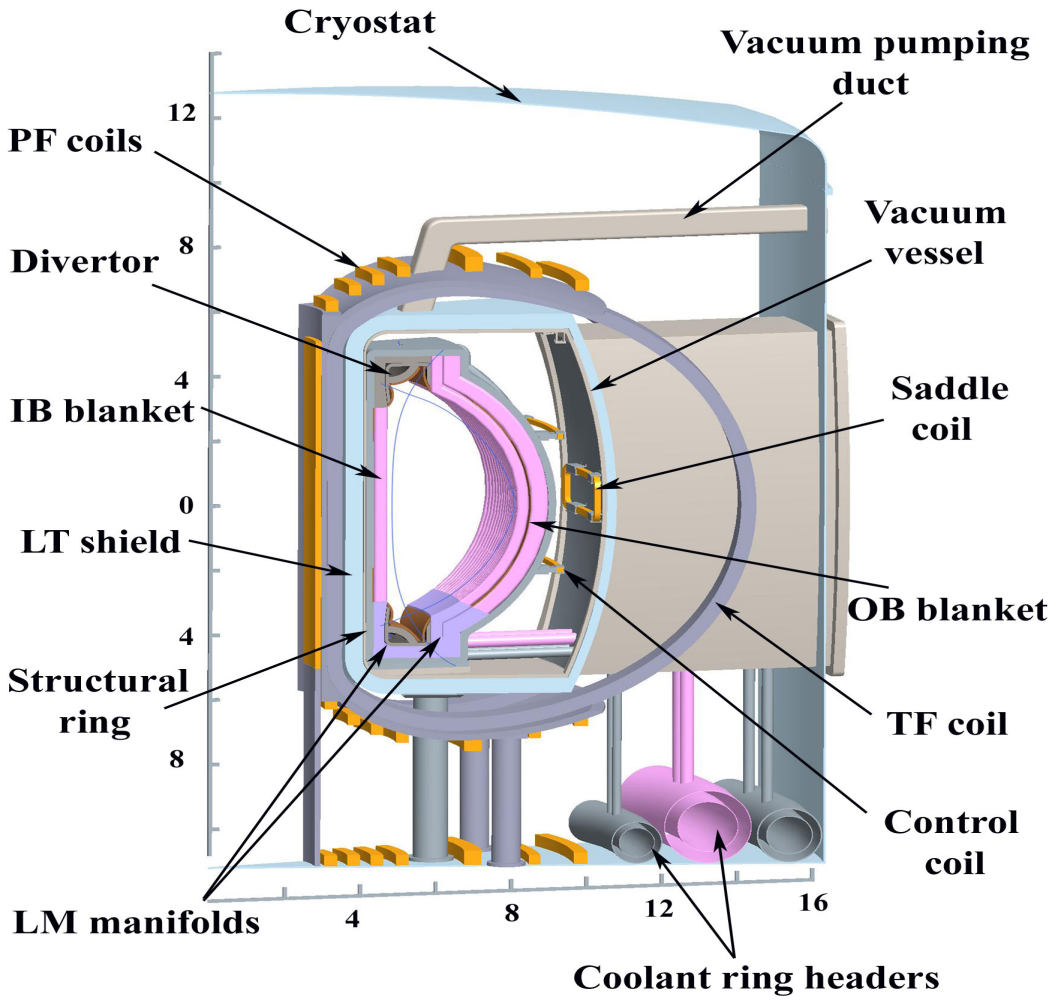
Utility Interests

- **Reliable, low cost, environmentally & publically acceptable power**
- What can go wrong / How wrong?
- Are the risks adequately mitigated?

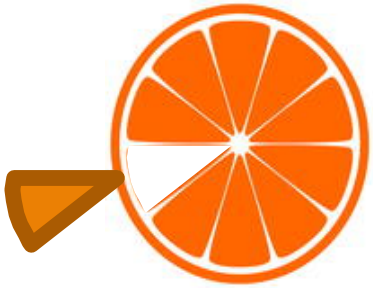
ITER – A Prototype Tokamak Fusion Reactor



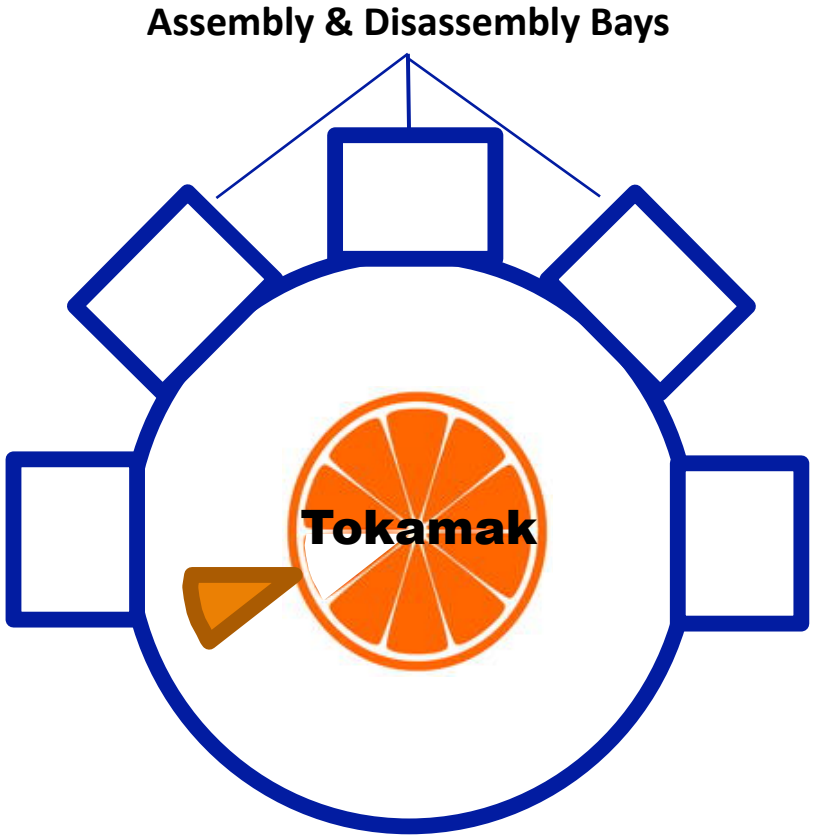
Radial Segment Assembly of a Conceptual DT Tokamak Power Plant



The assembly & disassembly of a DT tokamak power plant requires a huge building to accommodate radial segment assembly removal.



Top view of an orange with one radial segment removed.



The huge reactor building must be able to withstand major energy releases……

A Tokamak Reactor -- What can go wrong / How wrong?

1. Superconducting magnets can go normal with catastrophic consequences

-- **"An uncontrolled quench poses a number of threats to a superconducting magnet and its surroundings."** Safeguarding the superconducting magnets. CERN COURIER. Aug 19, 2013.

-- **"…quenches have occurred on at least 17 occasions in (S/C) tokamaks."**

Ivanov, D.P. et al. Necessity of Reliability Enhancement for Forced Cooled Superconducting magnet Systems. 2012.

2. Tokamak plasmas can disrupt, causing damage.

-- **"Disruption in a Tokamak reactor is a sudden loss of confinement that can cause damage to the machine walls and support structures."**

Fuzzy time series approach for disruption prediction in Tokamak reactors. Versaci, M. et al. IEEE Transactions. May 2003.

-- **"Tokamaks operate within a limited parameter range. Outside this range sudden losses of energy confinement can occur. These, known as disruptions, cause major thermal and mechanical stresses to the structure and walls."**

Research on Tokamaks. http://www.fusion-eur.org/fusion_cd/tokamak.htm

Earlier Question:
Are the risks adequately mitigated?

- **The reactor building will have to withstand the maximum credible accidental energy release – Likely the stored magnetic energy.**

- **Accordingly, the reactor building will be very expensive because of the large tokamak size and the large energy releases that must be contained.**

DT Tokamak Fusion Cost

Old Rule of Thumb:
Relative cost is roughly proportional to the mass ratio

DT Tokamak Fusion Cost

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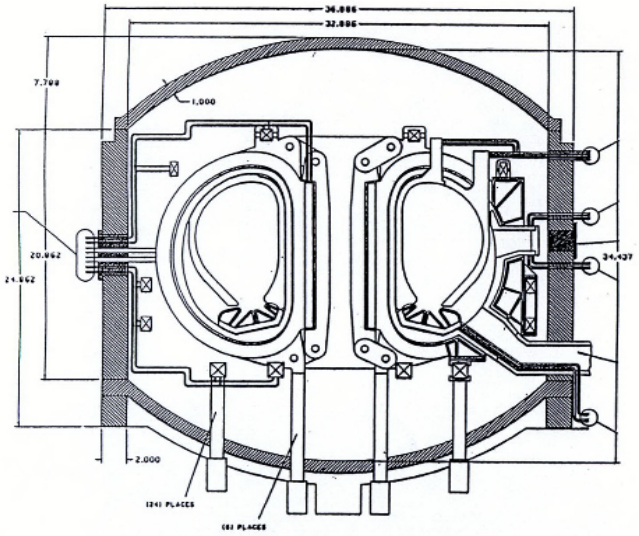
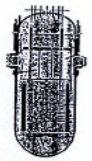


International Thermonuclear Experimental Reactor (ITER):
A Prototype Fusion Reactor Core

Volume:	25,600m^3	-v-	167m^3	(factor of 154)
Mass:	40,560tn	-v-	630tn	(factor of 64)
Cost:	$3137M	-v-	$53M w/o fuel $108M, w/ fuel	(factor of 59) (factor of 29)

Factor of 64!



Westinghouse AP-600:
Advanced, Passively-Safe, LWR

ITER IS A START. IS IT THE BEST THAT FUSION CAN OFFER?

L.J. Perkins, D.E. Baldwin, J.H. Hammer, Lawrence Livermore National Laboratory, March 1994

1994!

Proponents claim comparable costs !!!!

Why talk so much about tokamak?

To learn lessons for successful fusion power.

- A viable fusion concept should be as simple as possible; fusion will always be more complicated than fission.
- Small size is desirable & low unit cost is essential.
- Plasma configurations with disruptions are undesirable.
- S/C magnet quenching must be avoided and / or minimized.
- Materials problems must be minimized.
- Neutrons should be avoided or minimized.
- Inherent safety should be maximized.
- Regulator & utilities concerns must be addressed early.

Other Lurking Tokamak Reactor Issues

- **Univ. Of Wisconsin divertor materials research**

  -- **No material performed favorably** when tested under the test irradiation conditions.

  -- Mass loss on the order observed … would create an **unacceptable amount of radioactive dust.**

  -- Material eroded from plasma facing materials could **quench the fusion plasma.**

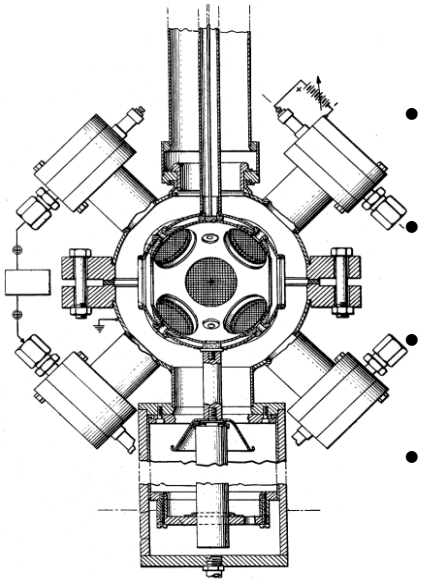
- **Congressional Subcommittee recommends defunding ITER**

  -- On July 24, the Senate Appropriations, "…directs the Department of Energy to work with the Department of State to **withdraw from the ITER project**."

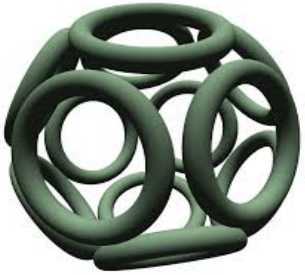
  -- Still open to the full committee & the full Congress.

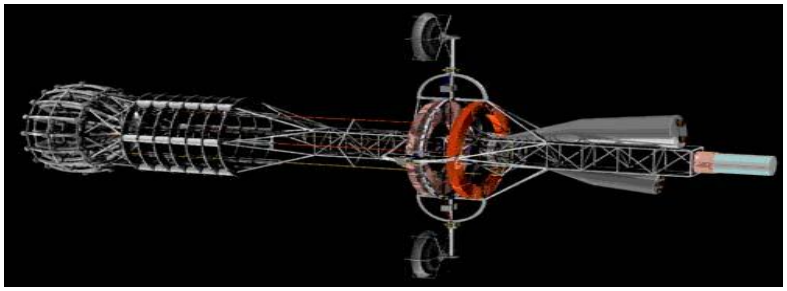
My conclusion:
Tokamak fusion power will die sooner or later.

Inertial Electrostatic Confinement



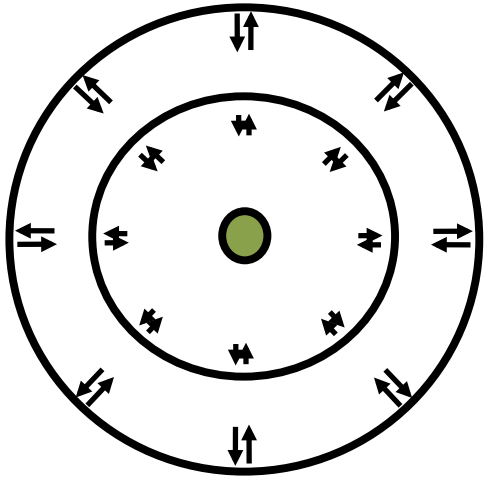
- Most concepts are inherently small – A big positive.
- IEC is a family of concepts.
- IEC has potential near-term, non-power applications.
- A form of IEC could lead to fusion power.



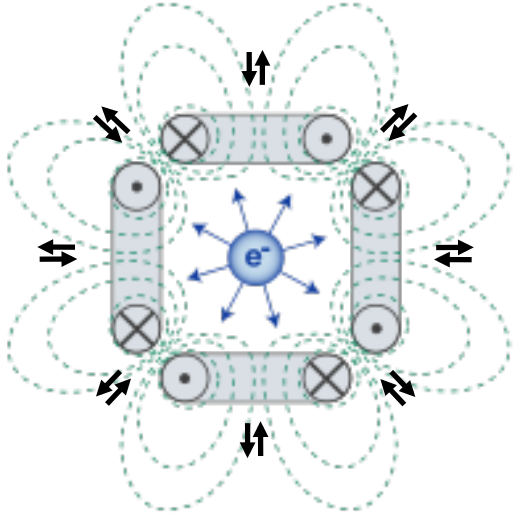


Some Basic Aspects of IEC

- Forced non-Maxwellian particle distributions
- Non-neutral charge in many / most regions
- Convergent flows
- Small, high-density central region
- Low-density, non-plasma regions



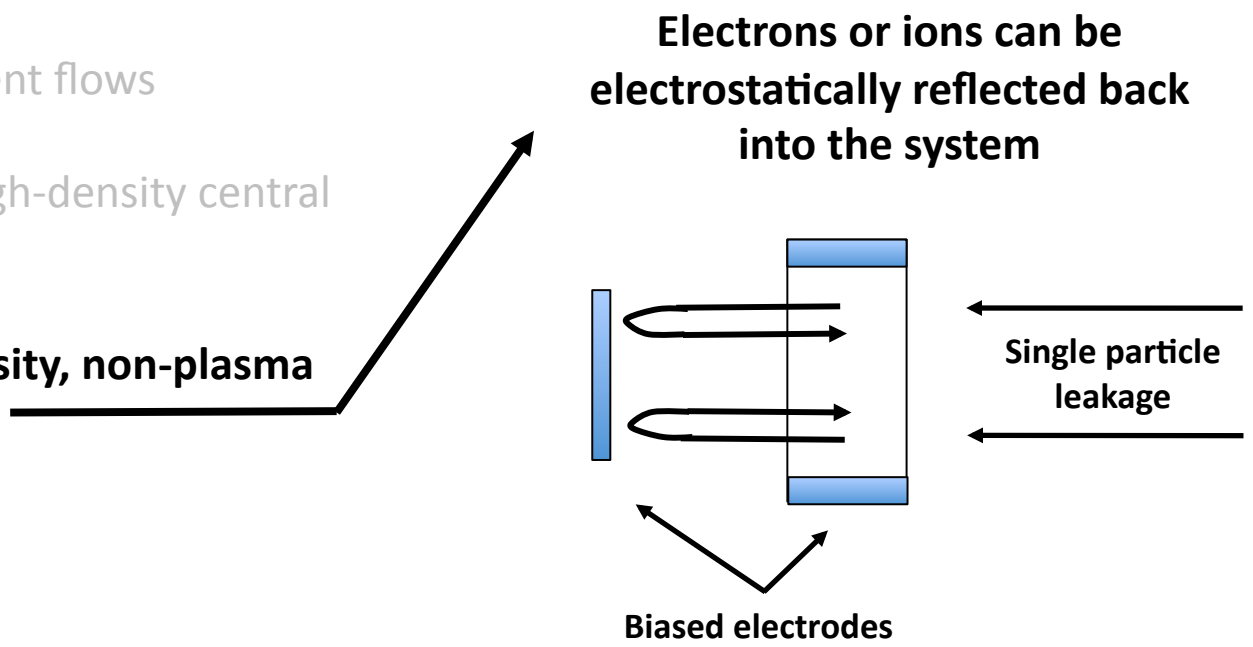
Non-Magnetic Configuration



Polywell Magnetic Configuration

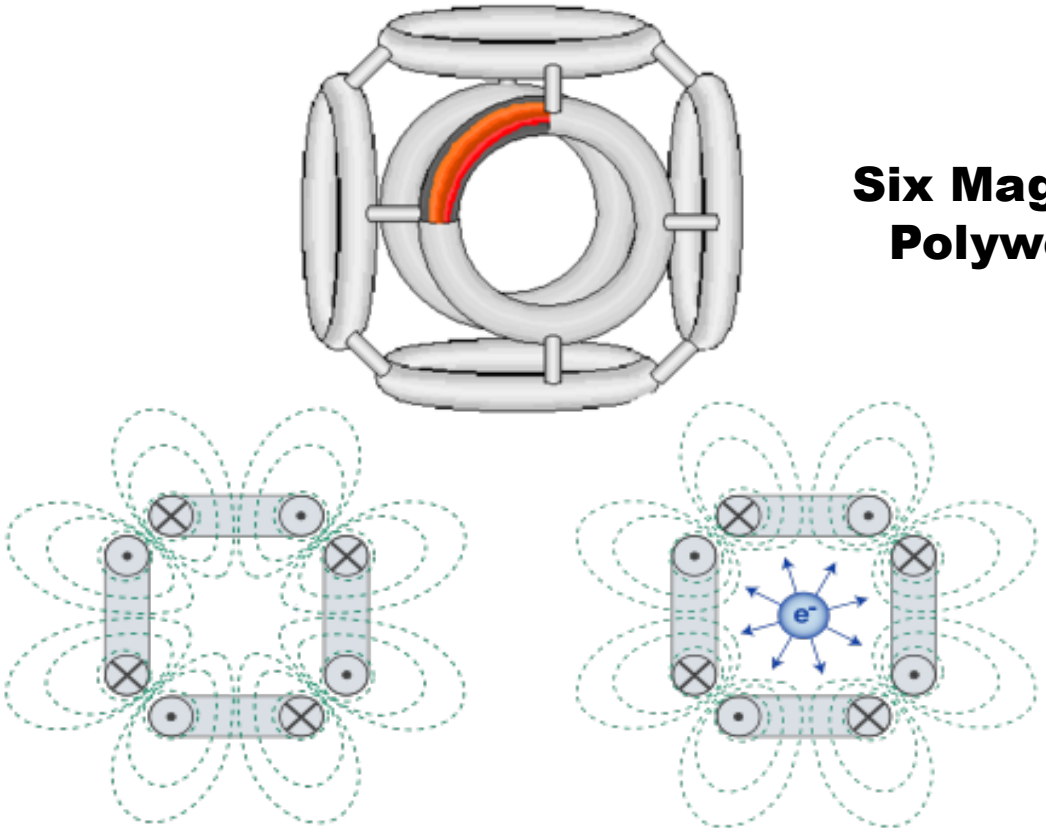
Some Basic Aspects of IEC

- Forced non-Maxwellian particle distributions
- Non-neutral charge in many / most regions
- Convergent flows
- Small, high-density central region
- **Low-density, non-plasma regions**



A Magnetic IEC - Polywell

From Wikipedia



Six Magnet Polywell

"WiffleBall confinement in a Polywell: magnetic field lines are expelled and cusps narrowed ….due to the high-beta diamagnetic cloud of electrons in the center."

IEC Issues

- **Incomplete understanding of non-neutral plasma physics**
- **Difficult diagnostics in spherical / semi-spherical geometries**
- **Physical grids are limiting**

  -- Likely best ~ 10 round trips before capture

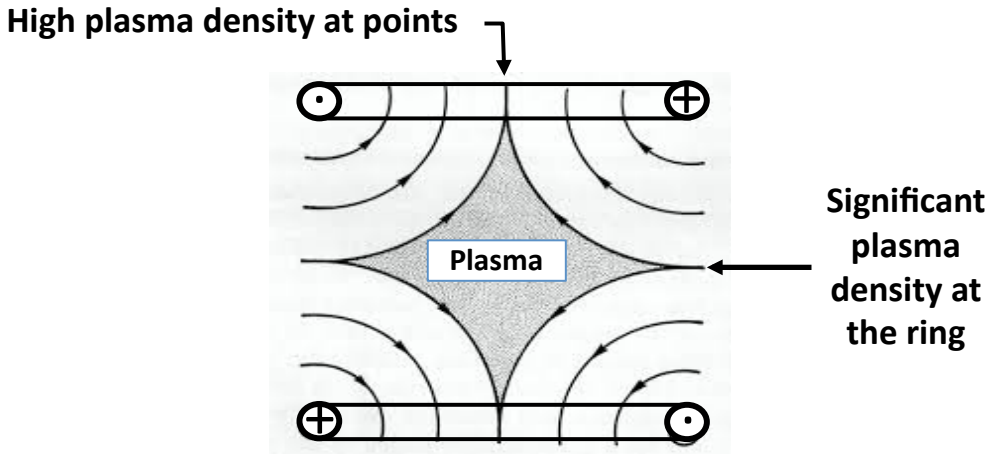
- **Magnetic fields may be a viable substitute for physical grids**

  -- Polywell is an option; recent EMC2 results indicate cusp losses might be dramatically reduced, but unhindered recirculation may still be necessary.

  -- What about other magnetic configurations?

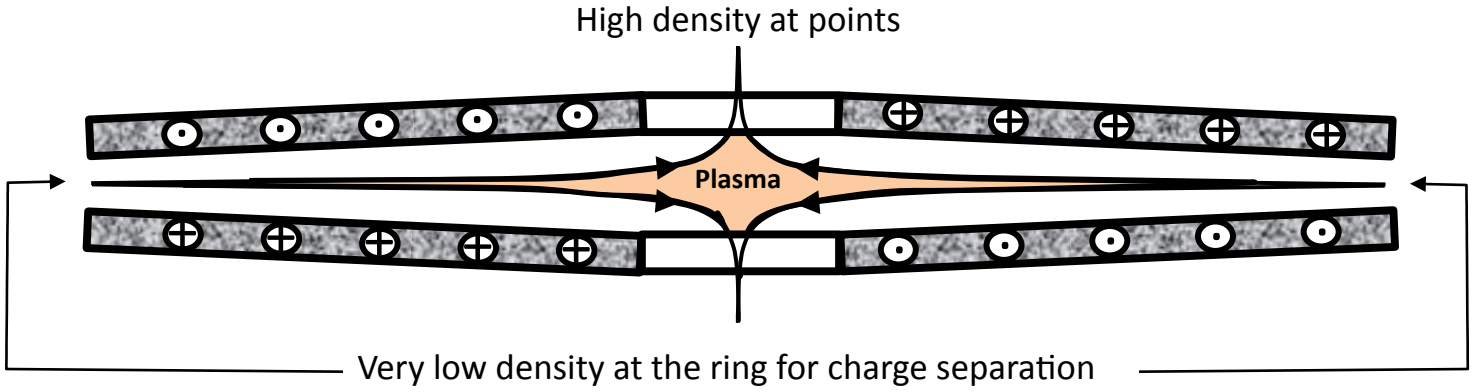
Brainstorming:

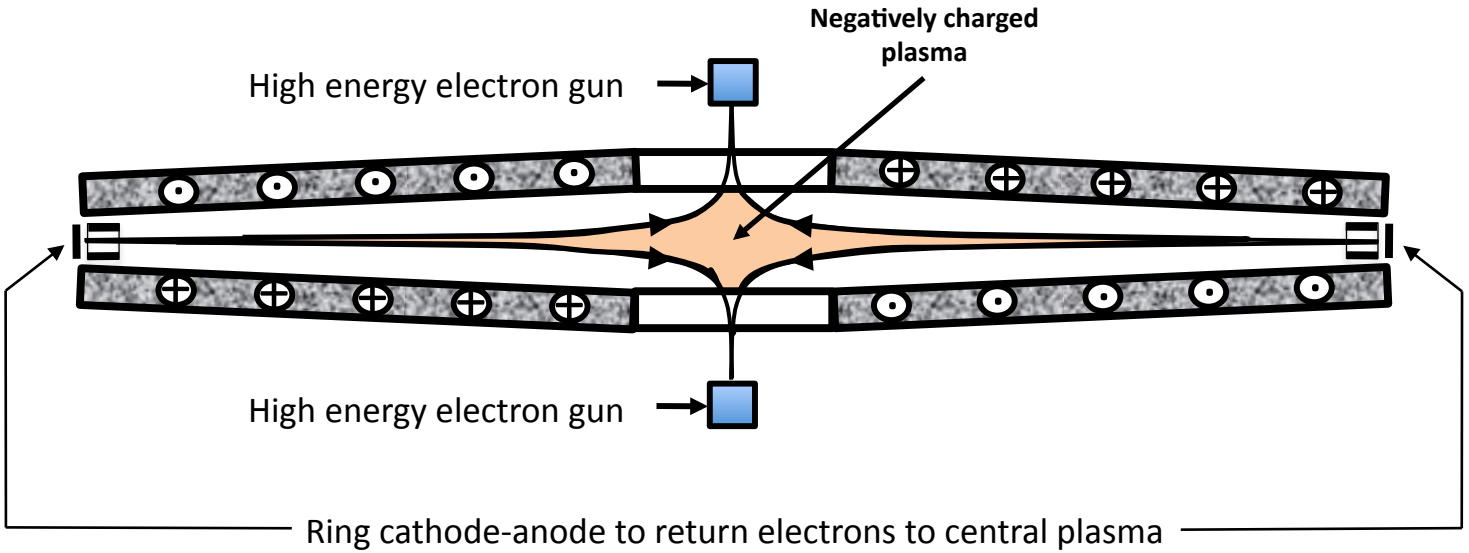
Rethink the spindle cusp for IEC?



- **Mechanically attractive**
- **Not viable for Maxwellian plasma confinement**

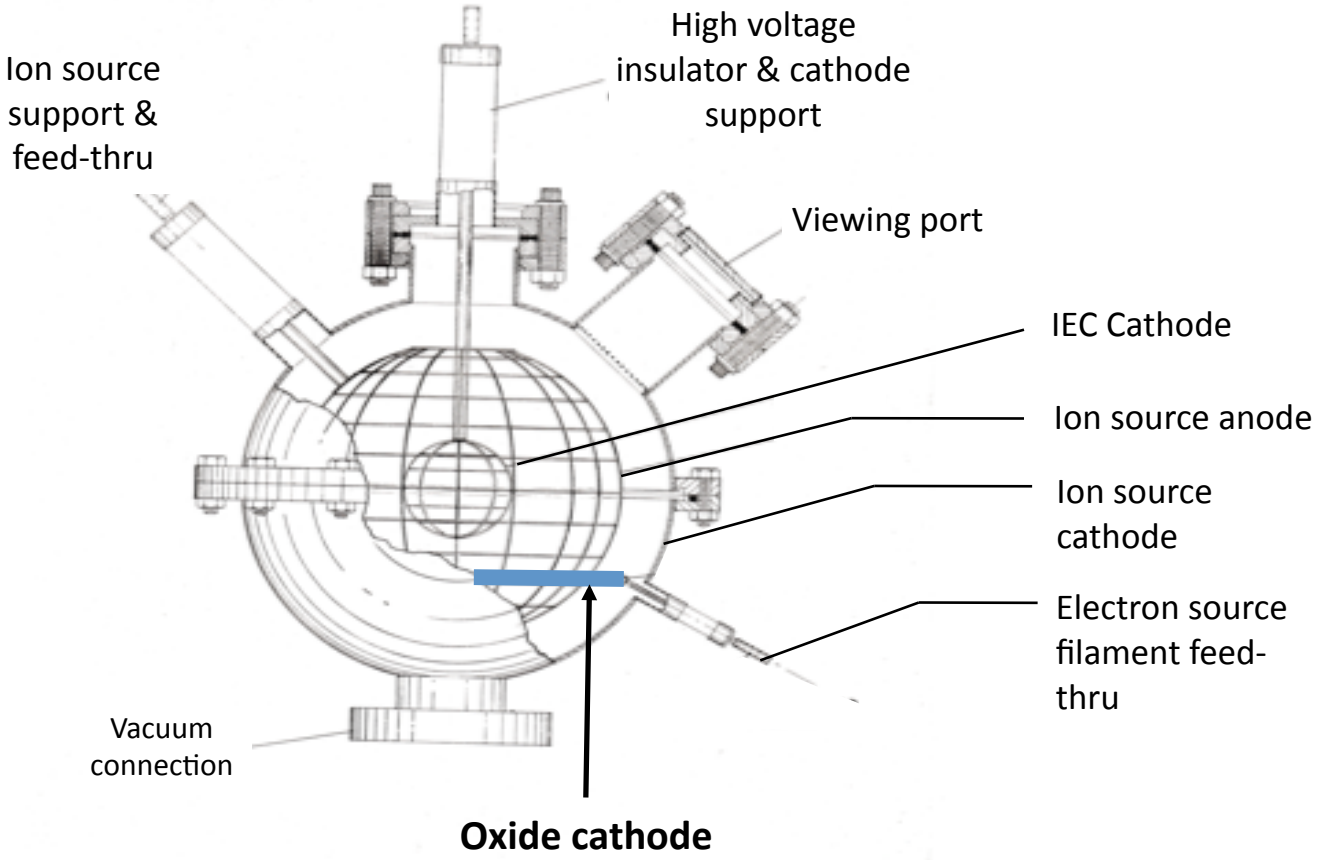
Instead of a standard spindle cusp, how about a large diameter slightly conical, pancake cusp?





An example of "thinking outside the box" / Not yet fully thought through.

Of note…….
Missed by Some – An Independent Electron Source



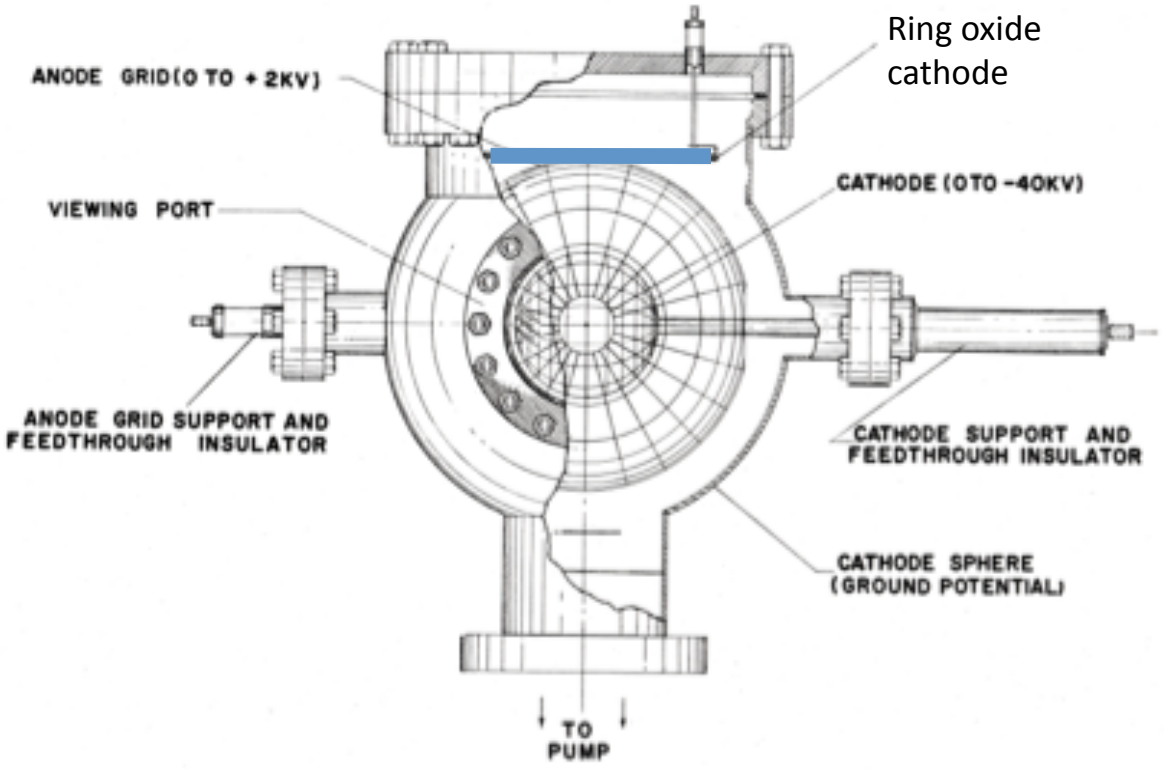
- An independent electron source allows lower pressure operation & greater control.
- Without an independent electron source, one is dealing with a complex discharge.

Of note…….

An opportunity for further research?

High Vacuum, Virtual Cathode Studies

The apparatus used decades ago to begin to study an electron-only spherical configuration.



Reference: Hirsch, Robert L. Experimental Studies of a Deep, Negative Electrostatic Potential Well in Spherical Geometry. Physics of Fluids. Nov. 1968.

In Conclusion:

- **Tokamak fusion power will die sooner or later.**
- **IEC likely has near-term applications, involves interesting physics, & may hold keys to practical fusion power.**

I wish you well.