Getting to a Fusion Pilot Plant.

Steve Cowley, Princeton

January, 2022

<u>100 years of fusion</u>. August 24th 1920 The British Association

- Arthur Stanley Eddington -- delivered the presidential address:

"The Internal Constitution of Stars"

"This reservoir can scarcely be other than the sub-atomic energy which, it is known, exists abundantly in all matter; we sometimes dream that man (!) will one day learn how to release it and use it for his service. The store is well-nigh inexhaustible, if only it could be tapped".

Arthur Stanley Eddington 1920.

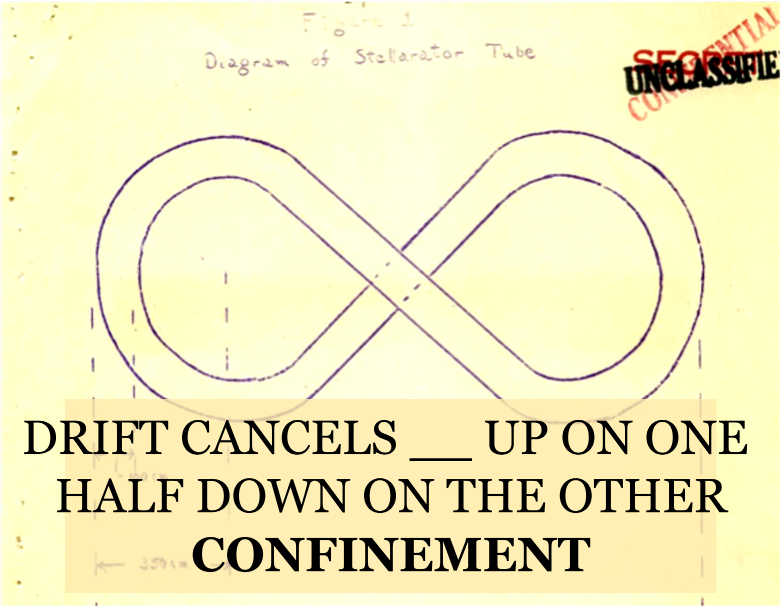
Wh

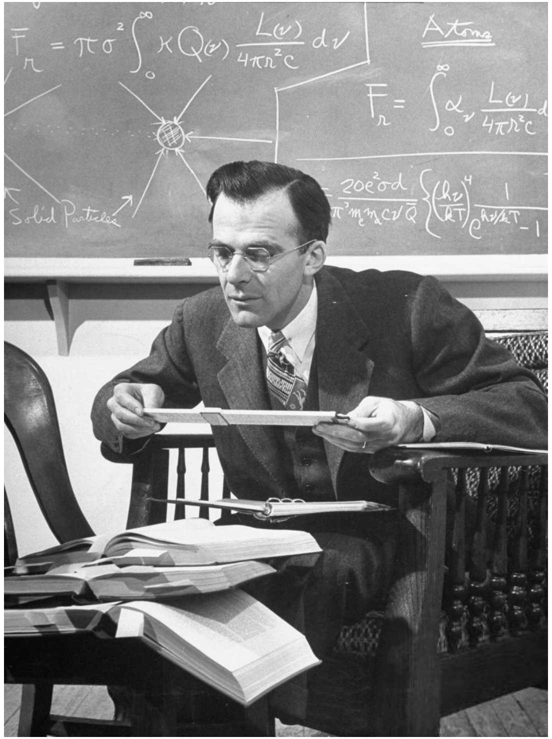
- Eddington proposed that the sun is transforming hydrogen into helium – thereby liberating "fusion energy". It is. He went on to estimate the sun's lifetime – surprisingly accurately (15 Billion years).

Lyman Spitzer – Invention of the Stellarator 1951

1951 Lyman Spitzer starts project Matterhorn with John Wheeler at Princeton.

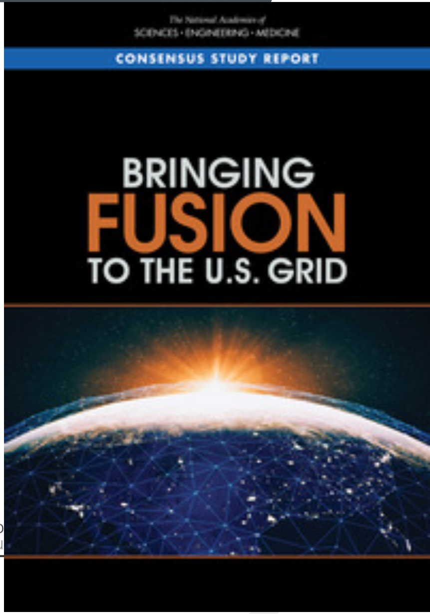
Spitzer's **Figure 8 Stellarator** from July 23rd 1951 proposal to Atomic Energy Commission.

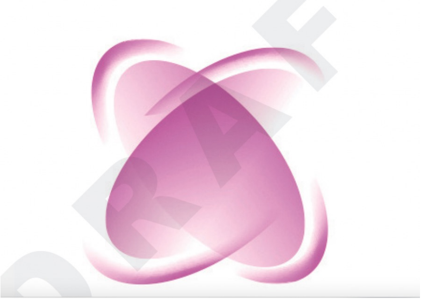




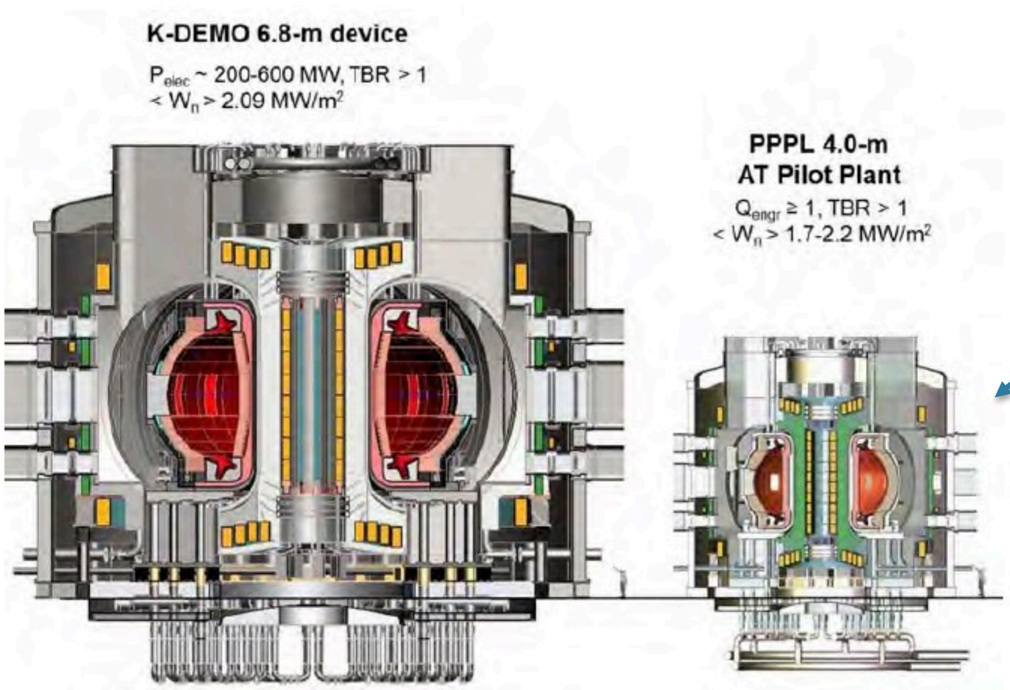
Lyman Spitzer 1948

- Fusion Research in transition
  - Planning now for an electricity producing Pilot Plant
  - Are we ready? What innovation is needed?
- What sets the cost?
  - Don't make the mistakes of fission.
- Will high magnetic fields help us?
  - Smaller cheaper faster?
  - Problems?
- Radical simplification.
  - Science is just maturing for 3D approach.





What Kind of Pilot Plant? High Field Compact?



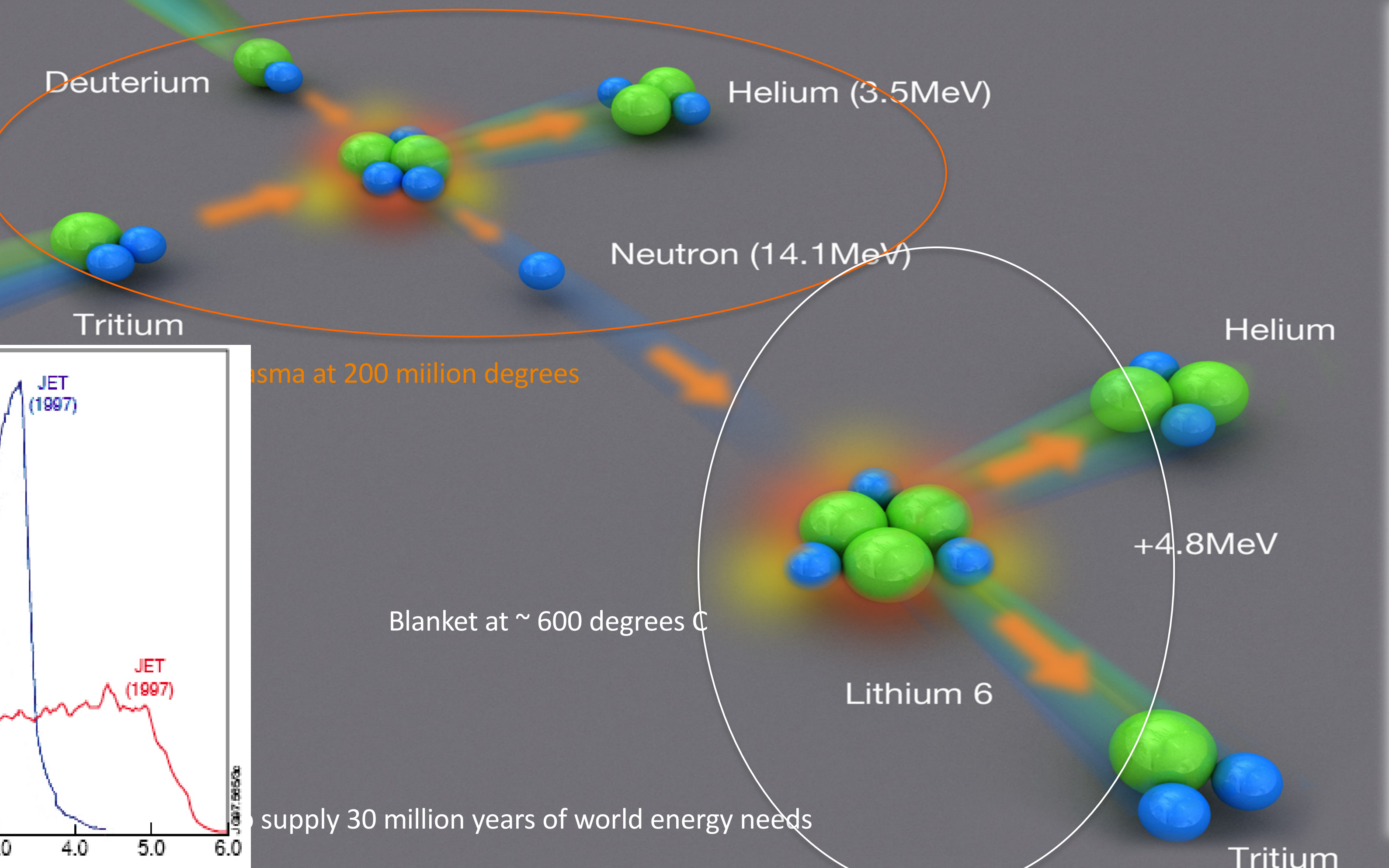
High field compact Designs from **MIT** "ARC"

And this **Princeton** one shown in NAS report.

High T_c at ~ 20° Superconductors ~25T on coil

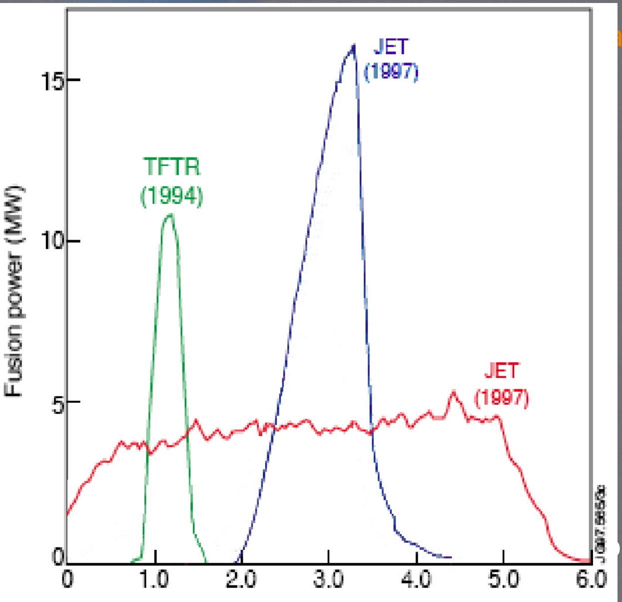
Tom Brown, Jon Menard PPPL

Power Density = $0.08(\text{Pressure in Atmospheres})^2 (\text{MWm}^{-3})$

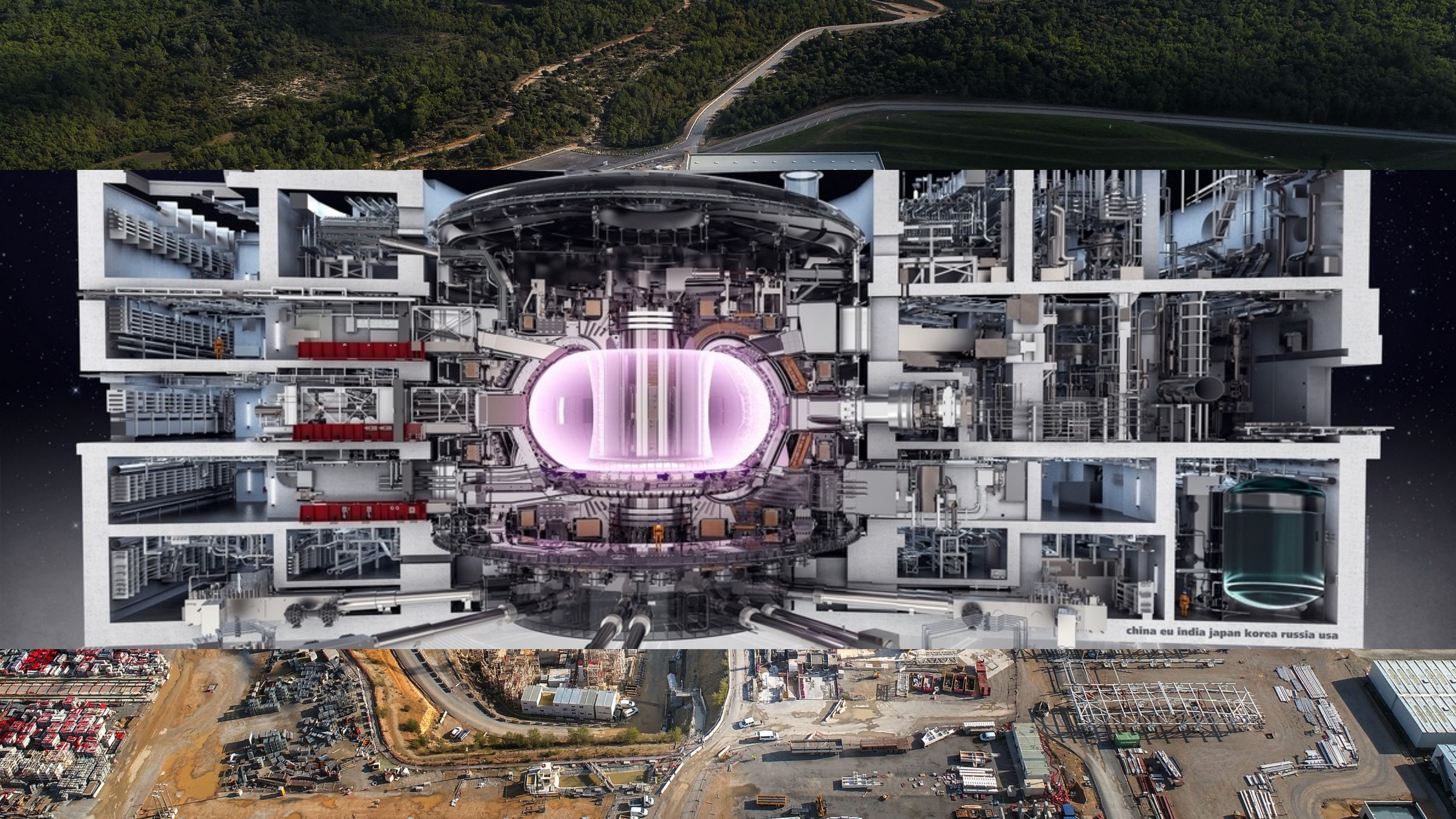


asma at 200 miilion degrees

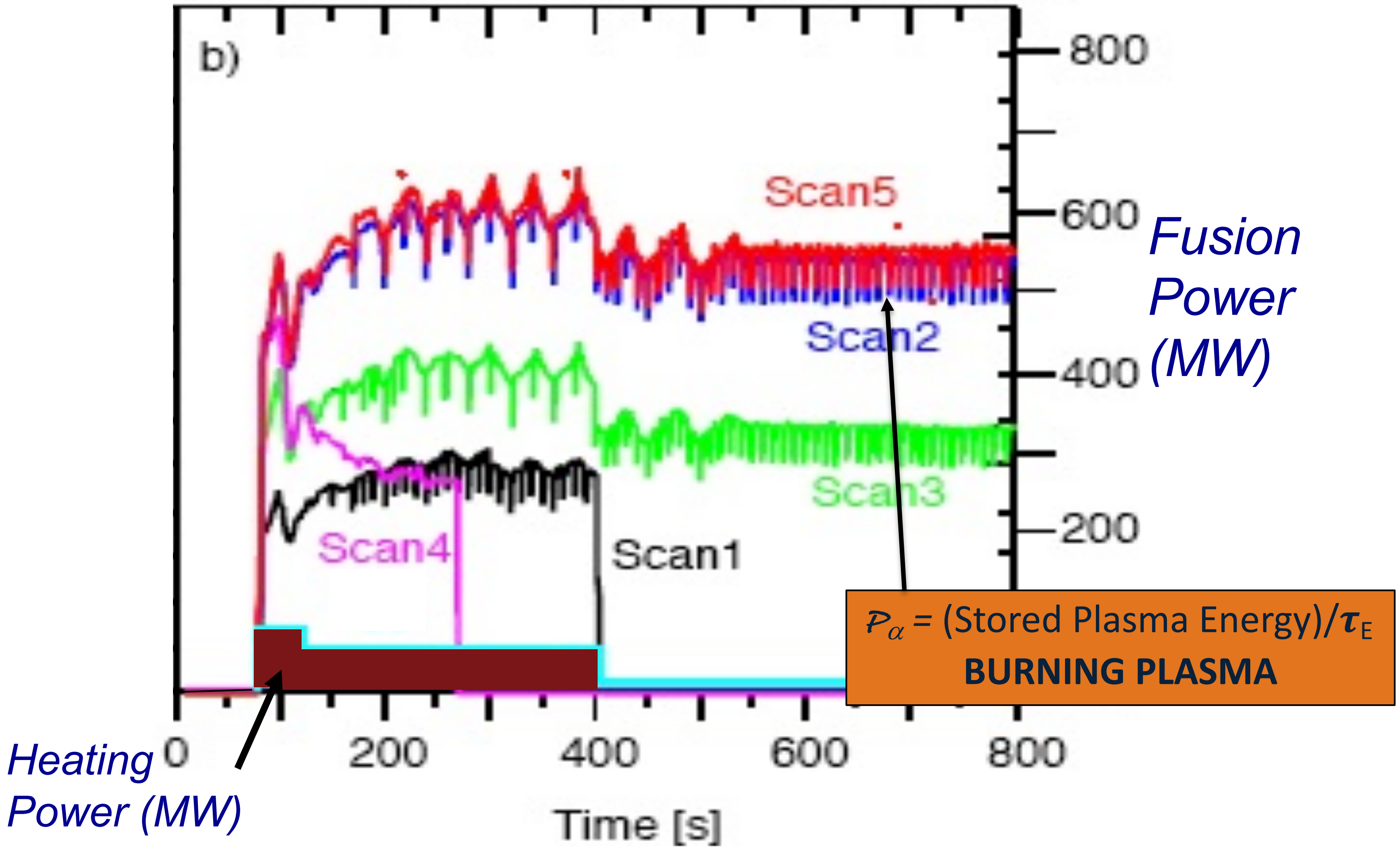
Blanket at ~ 600 degrees C



supply 30 million years of world energy needs


china eu india japan korea russia usa

Simulation by Bob Budny: Based on JET results from 2008-2013



Simple considerations – things we all know

For plasma at 7-20 Kev temperatures (70-200M° C) D-T fusion power density is approximated by:

$$\mathcal{P}_{Fusion} = 0.08P^2 \; (MWm^{-3})$$

Plasma pressure in atmospheres

Magnetic pressure: $P_{magnetic} = 4B^2 \quad (atmopsheres)$

Magnetic Field in Tesla

Figure of merit
Limited by stability: $\beta = \dfrac{P}{P_{magnetic}}$

Self Heating

$$\mathcal{P}_{Fusion} = 1.28\beta^2 B^4$$

$$\mathcal{P}_{\alpha} = 0.2\mathcal{P}_{Fusion} = 0.25\beta^2 B^4 (MWm^{-3})$$

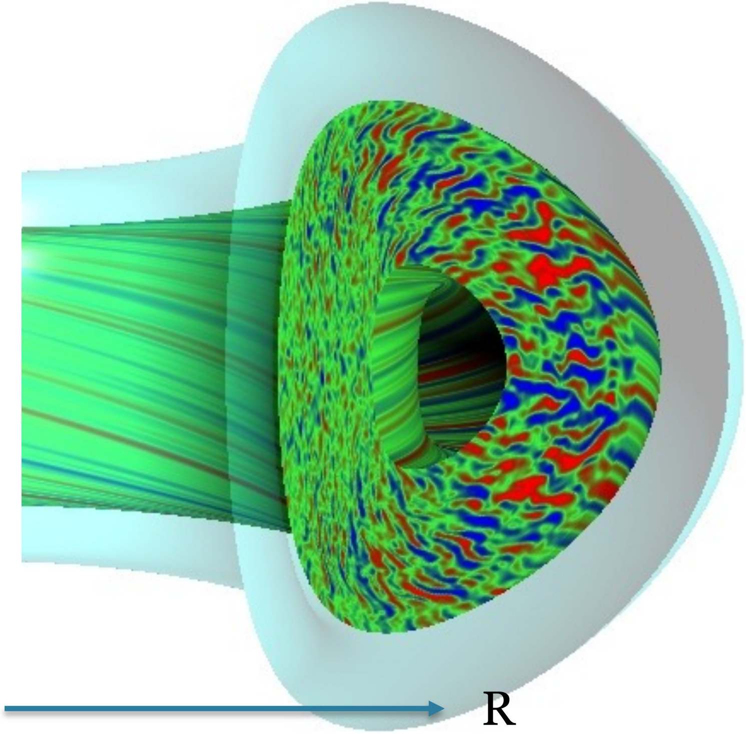
Energy Confinement -- Random walk of heat/particles.

N random turbulent steps to leave machine
Eddy size ρ_i – Larmor radius
V_{thi} = ion thermal velocity

$$R \sim \sqrt{N}\rho_i \rightarrow N \sim \left(\frac{R}{\rho_i}\right)^2$$

For ITER N ~ 10^6.

Eddy turnover time = $\tau_{eddy} \sim \dfrac{R}{v_{thi}}$



$$\tau_E = N\tau_{eddy} \propto B^2 R^3 T^{-3/2}$$

H^3

Burning

$$\mathcal{P}_\alpha = \frac{energy\ \ density}{\tau_E} = \frac{3P}{2\tau_E} \rightarrow self\ \ heated$$

$$\rightarrow H^3 B^4 R^3 \geq constant$$

Constant depends on shape profiles etc. Physics!

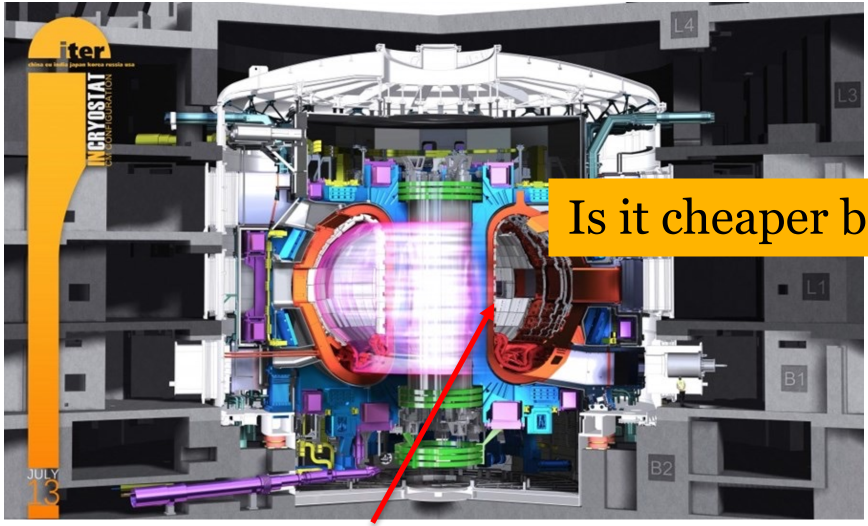
SCALING FOR SELF SIMILAR TOKAMAKS

$$H^{3/4} B R^{3/4} = constant$$

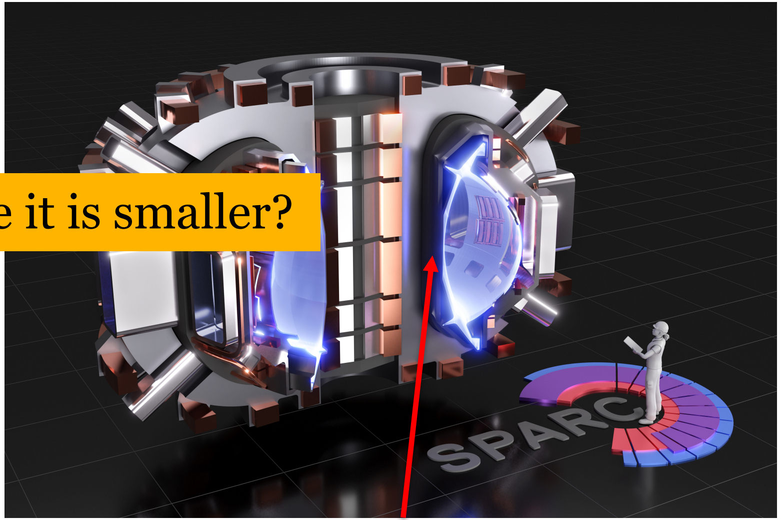
Note total power $P_{fusion} \propto \beta^2 B^4 R^3 \propto \beta^2 H^{-3}$

Smaller – faster - cheaper.

- SELF SIMILAR SCALING AT CONSTANT GAIN AND SHAPE
  - **ITER:** R= 6.2m, B = 5.3T $BR^{3/4} = 20.8$
  - **SPARC:** R = 1.78m B = 12.5T $BR^{3/4} = 19.2$



Is it cheaper because it is smaller?



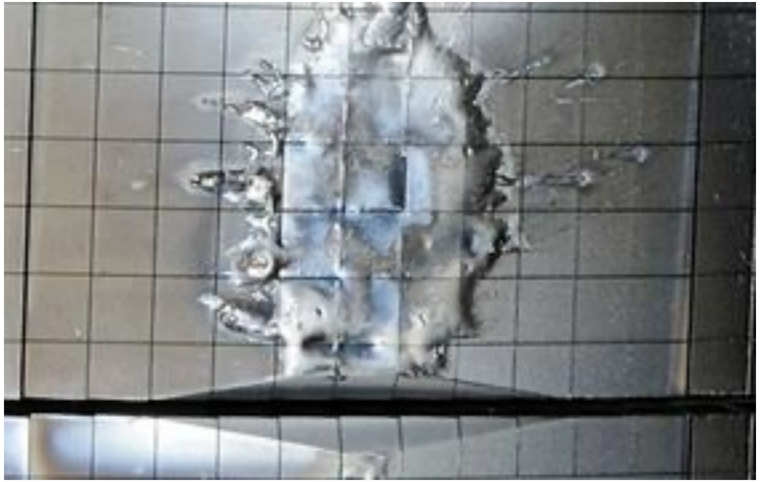
ITER 11.8T on coil
Ni Sn technology

SPARC 23T on coil
YBCO technology – in development

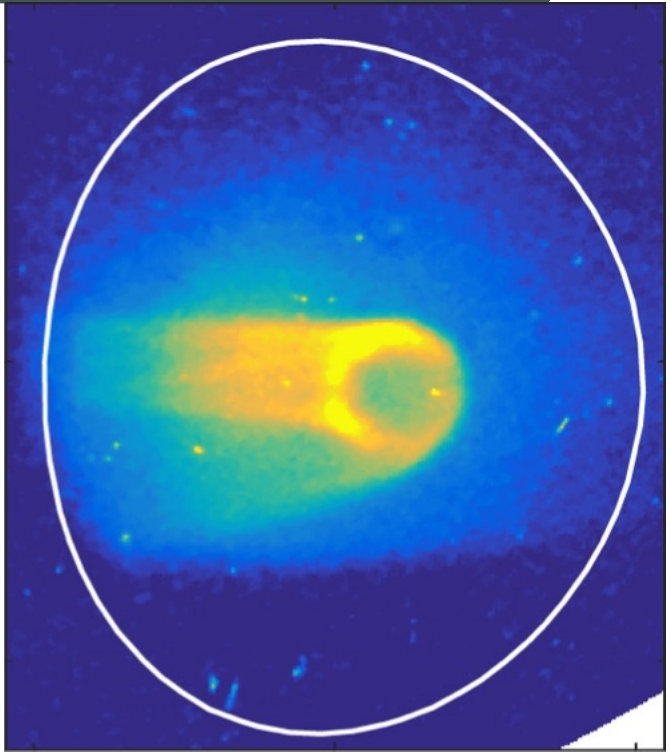
Problem? Not sure.

Disruptive event where mega-amp of current being carried by multi MeV “runaway” Electrons.

On ITER and SPARC this will be many Mega-amps of current.



Damage to JET wall from runaways



Hard X-ray image of bremsstrahlung On DIII_D Lvovskiy, A. *et al.* *Nuclear Fusion* **60**, 056008 (2020)

Smaller is worse

- Inductive Electric field accelerating electrons – magnetic field energy becomes relativistic electron energy.

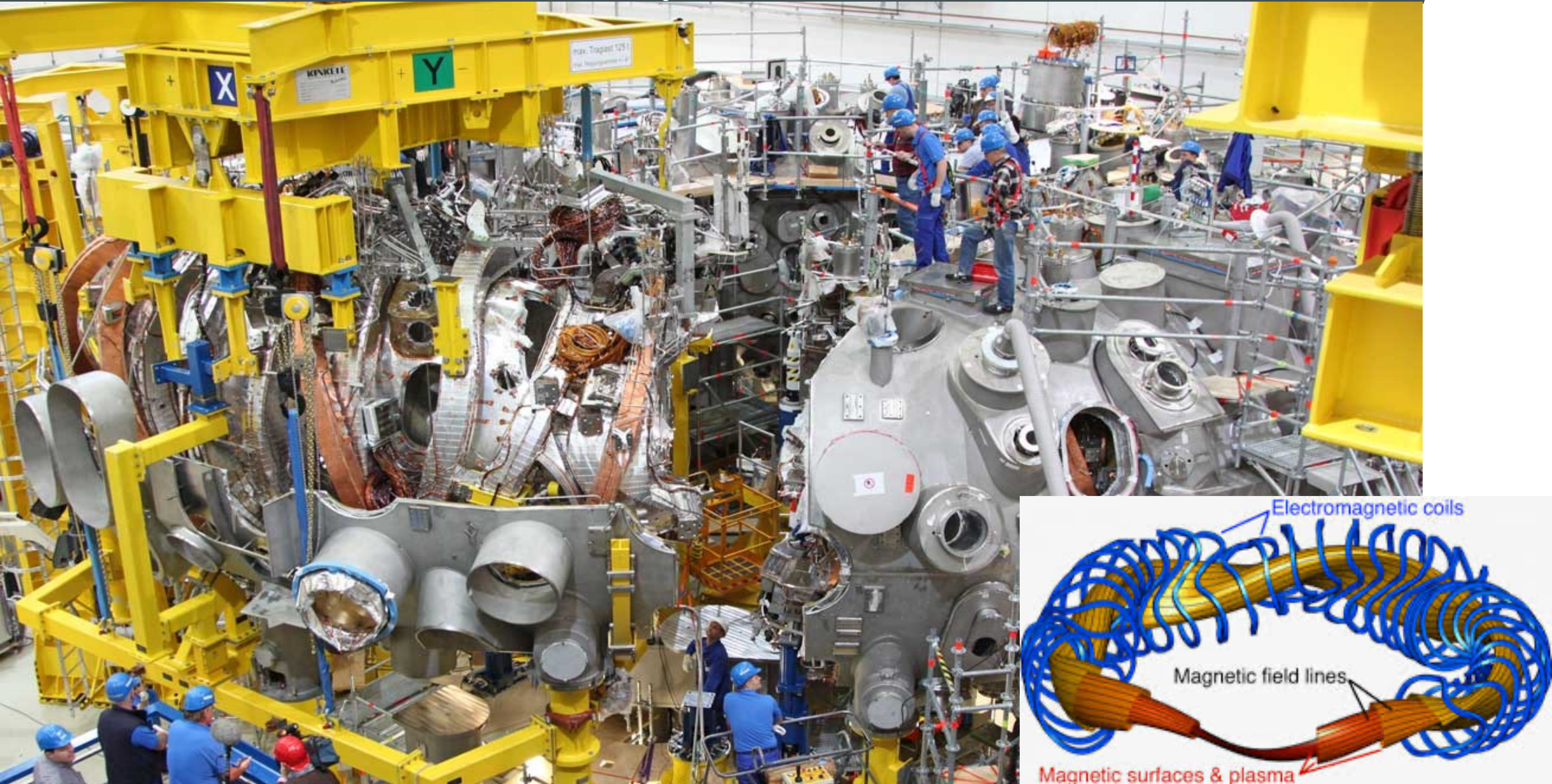
- Use the scaling $H^{3/4} B R^{3/4} = constant$

Energy in distruption $\propto B^2 R^3$ in ITER about a Giga-joule

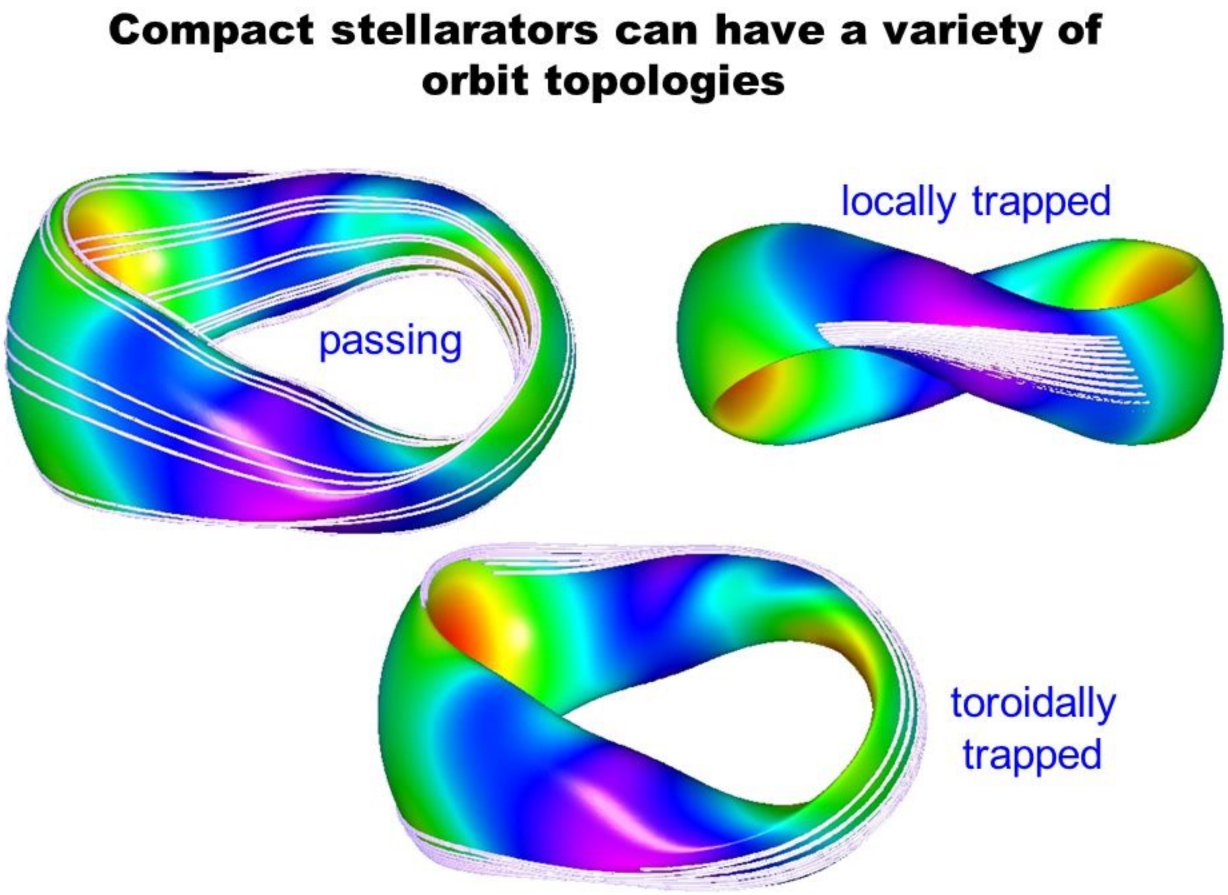
Per unit wall area $\propto B^2 R \propto R^{-1/2} H^{-3/2}$

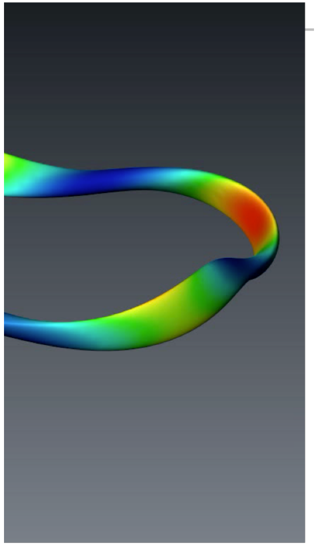
SPARC roughly 2 times worse than ITER.

Spitzer's return : W7-X 2013 – first plasma 2015 –NO CURRENT steady state



Optimization – Field and Particle Orbits

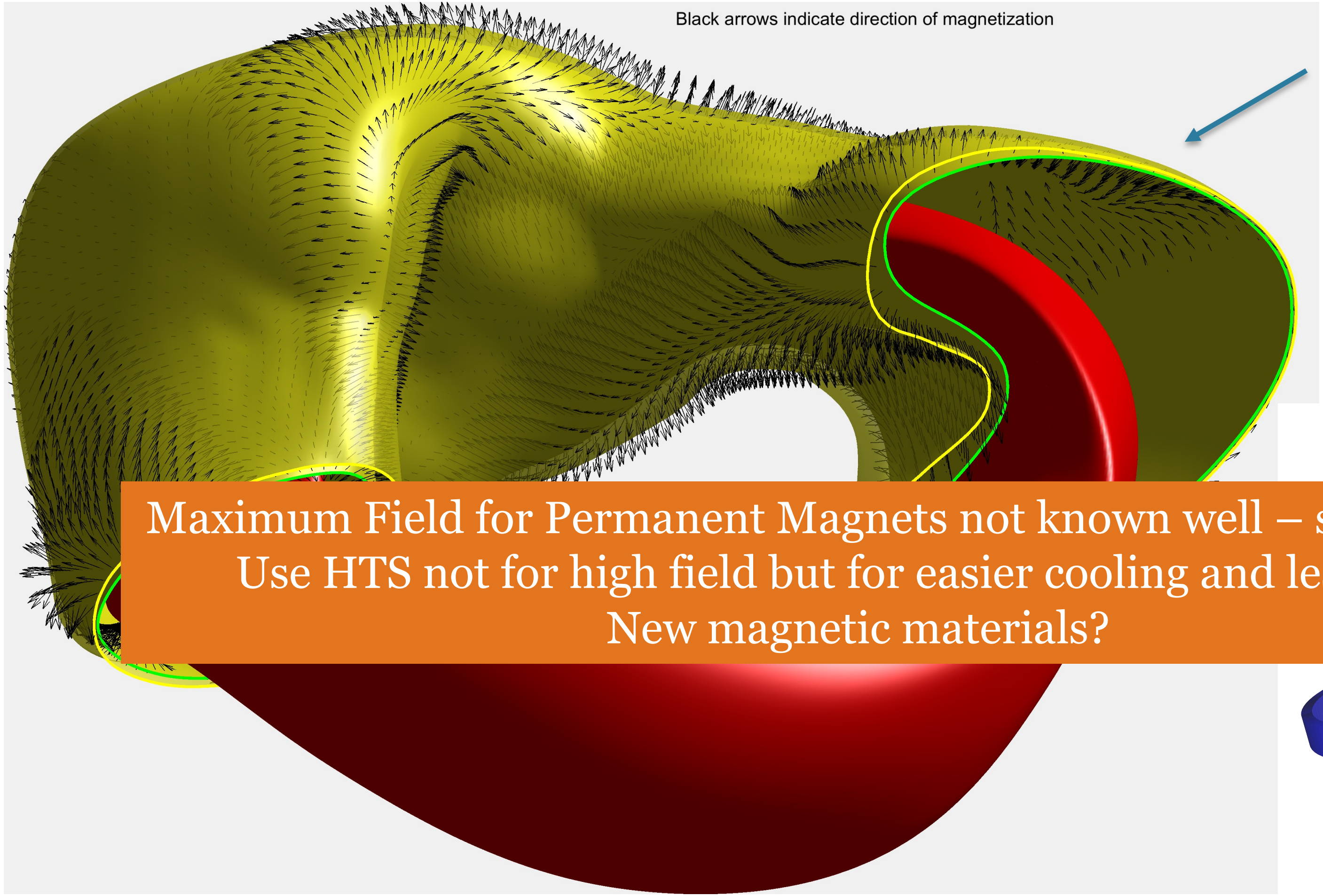




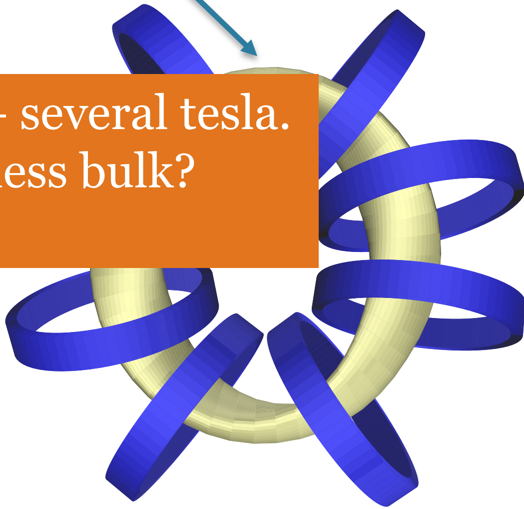
'endelstein 7-X

kamak: Obvious symmetry

Innovation – coils + permanent magnet (PM) stellarator

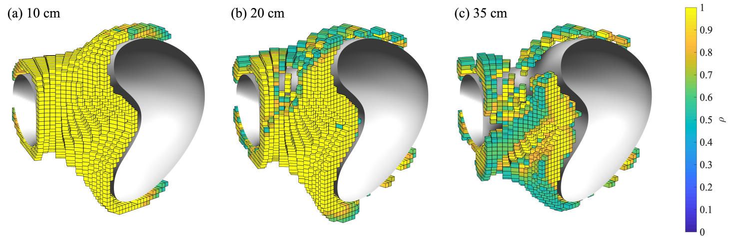


Matt Landreman
New improved QAS
Equilibria possible with
PMs.
Helander et. al.
(Physical review letters
124 (9), 095001

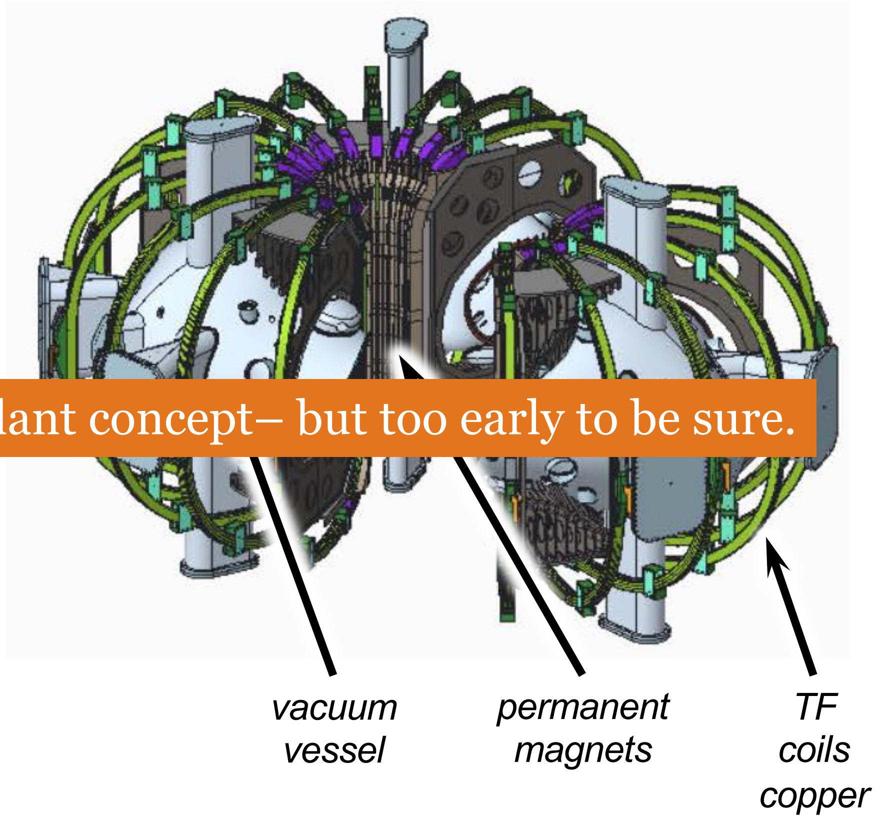


Maximum Field for Permanent Magnets not known well – several tesla.
Use HTS not for high field but for easier cooling and less bulk?
New magnetic materials?

SAS --- Quasi Symmetric Advanced Stellarator



K. C. Hammond et al. |
Geometric concepts for stellarator permanent magnet arrays



- ARPA-E + FES funded permanent magnet development
- Stellar Energy Foundation funding.
- Utilizes already constructed TF coils, vacuum vessel
- Target plasma configuration:
  - a_{min} = 0.32 m
- Research objectives
  - Short-term: design and construct magnet array for one half-period; test for accuracy
  - Long-term: finish magnet construction; study physics of new optimized configuration

In principle makes a very attractive Pilot Plant concept– but too early to be sure.

Conclusion

- 100 years from Eddington fusion is certainly possible but is it economic?
- We need "some" innovation.

We need a rigorous, modern, cost centered study of pilot plants. Industry partners are needed – real engineering partners.

- Economic Fusion power making a significant contribution by mid century should be the goal.