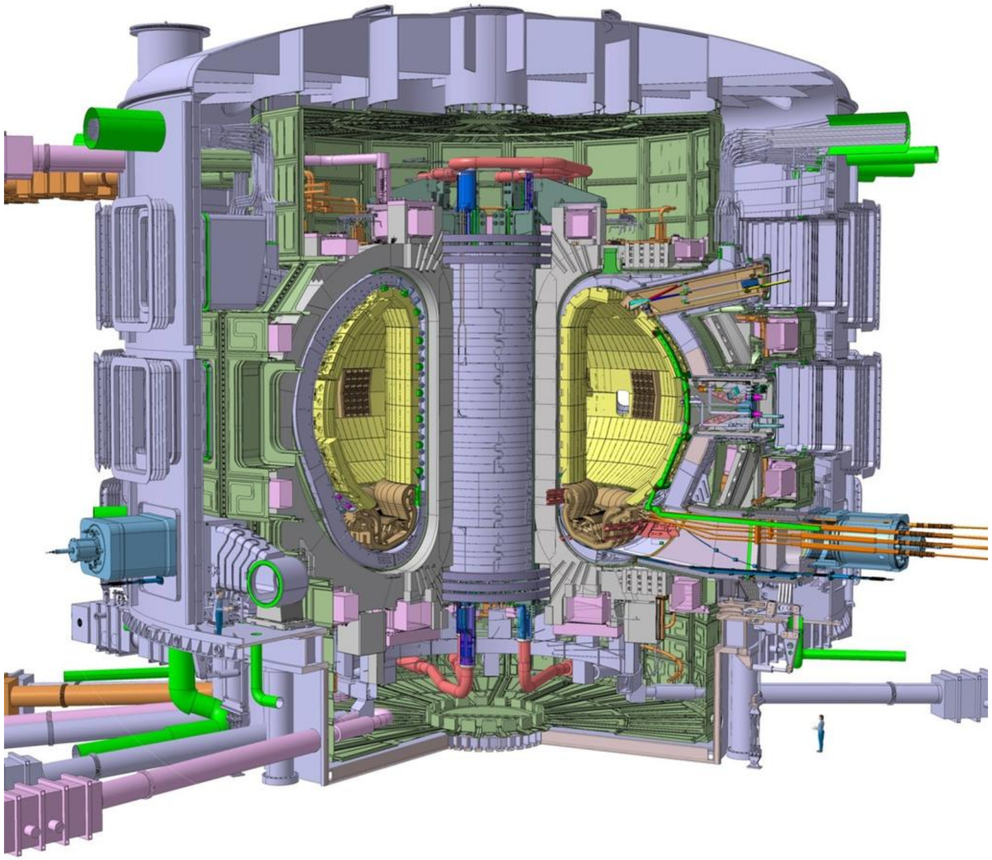
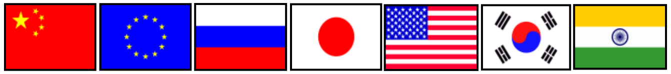
ITER

First Sustained Burning Plasma. Starts in 2018 - 2020.

BASIC PARAMETERS.
Plasma Major Radius 6.2m
Plasma Minor Radius 2.0m
Plasma Current 15.0MA
Toroidal Field on Axis 5.3T
Fusion Power 500MW
Burn Flat Top >400s
Power Amplification Q>10

Cost is > 12 Billion Euro.





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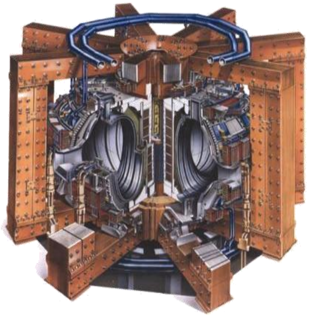
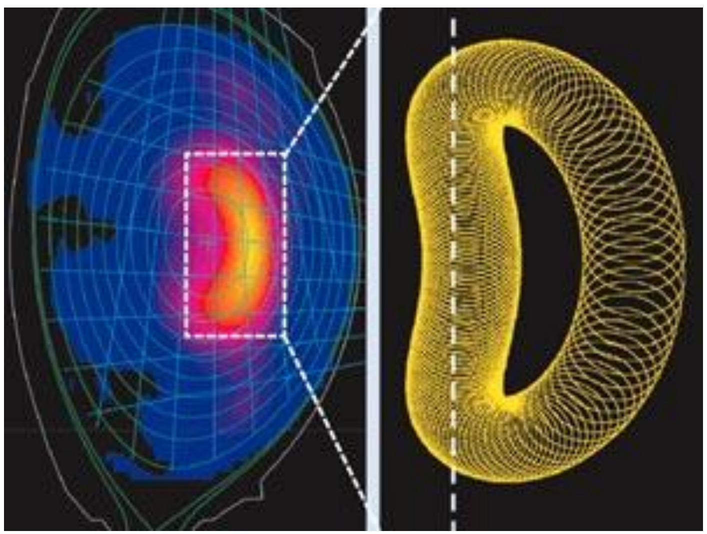
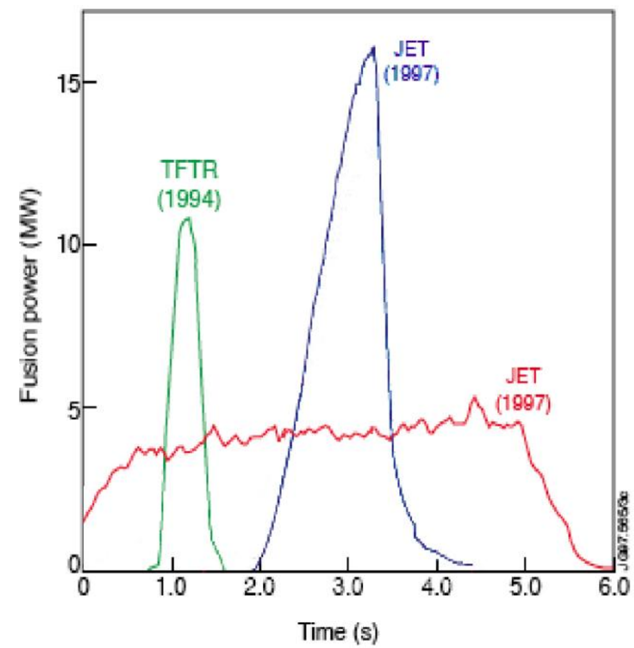
JET



Science and Engineering Challenges for Fusion: When and How

Professor Steve Cowley -- United Kingdom Atomic Energy Authority and Imperial College.





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This Lecture

- Which fusion reaction?
- Why bother?
- How does a reactor work -- ignition etc.
- Will ITER work?
- What next? Materials and technology
- When will fusion be a reliable cheap source of baseload electricity?

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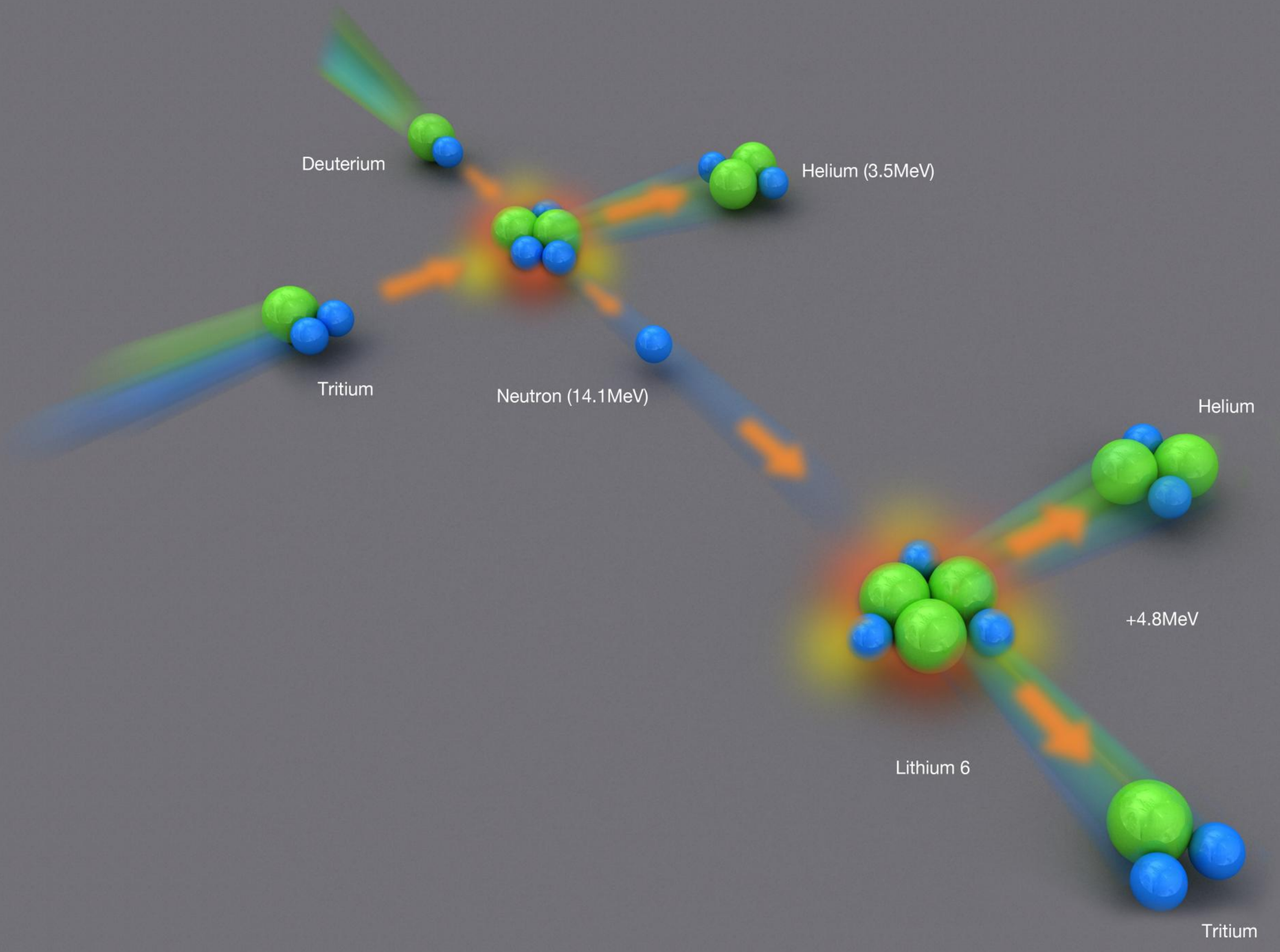
Deuterium
Helium (3.5MeV)
Tritium
Neutron (14.1MeV)
Helium
+4.8MeV
Lithium 6
Tritium

Why bother?

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Advantages

- In units of current world energy consumption we have:
  - ~ 60 Billion years of deuterium in sea water.
  - ~ 800 years of cheap lithium in Andean salty brines
  - ~ 30 million years of lithium in sea water (at a cost of about 0.2C kWh)
- No need for long term rad. waste storage.
- No CO_2
- Minimal land use.
- Worst case accident needs no evacuation of surrounding population.

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How?

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Is Fusion Possible?

For plasma at 10-20Kev temperatures (100-200MºC) D-T fusion power density is approximated by:

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

Plasma pressure in atmospheres

We need >1MWm^{-3} for a economic system -- need a few Atmospheres of plasma pressure. Can we hold it with a magnetic field?

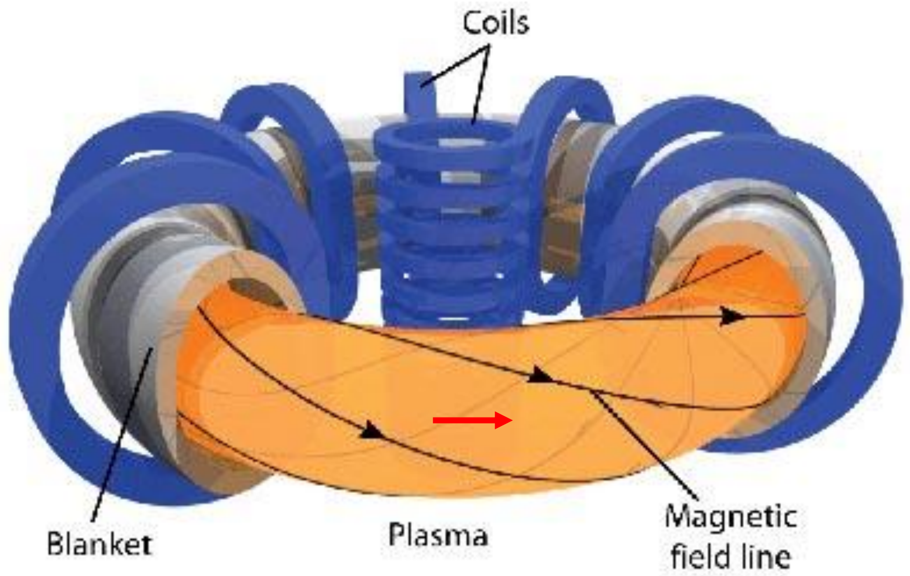
Magnetic pressure = $P_{Magnetic} \sim 4B^2$ (atmospheres)

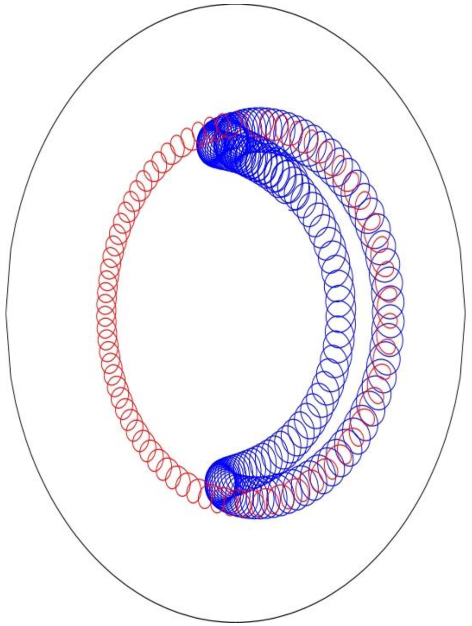
Figure of merit $\beta = P/P_{Magnetic}$

Magnetic Field in Tesla

How do you hold something at 100 million degrees? The Magnetic Bottle.

At these temperatures gas ➔ plasma
electrons and ions move independently





Projected particle orbits
Charged Particles stay inside plasma

Current

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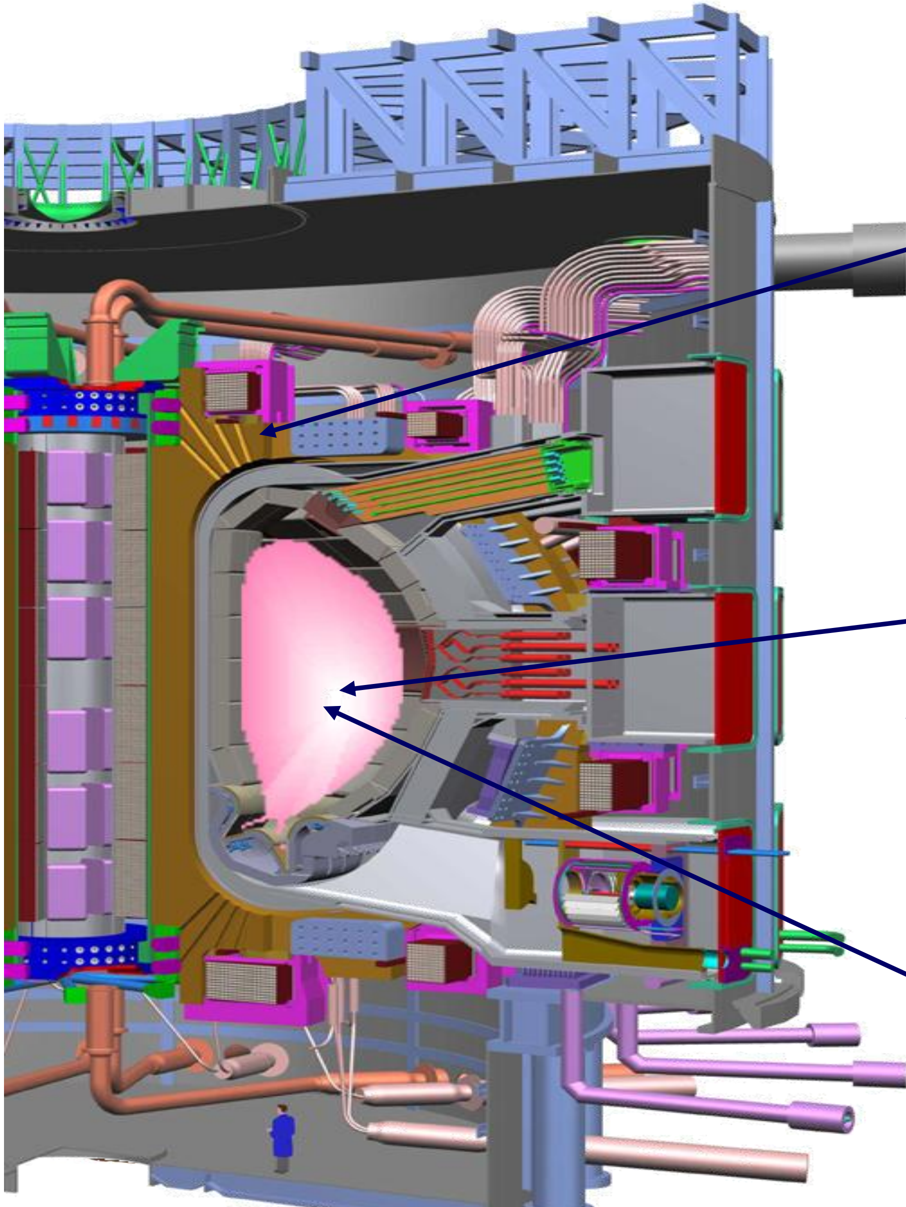
Fusion Force Balance in ITER



Superconducting Coils

central B field 5.2 Tesla

$P_{magnetic}$ ~ 100 atmospheres

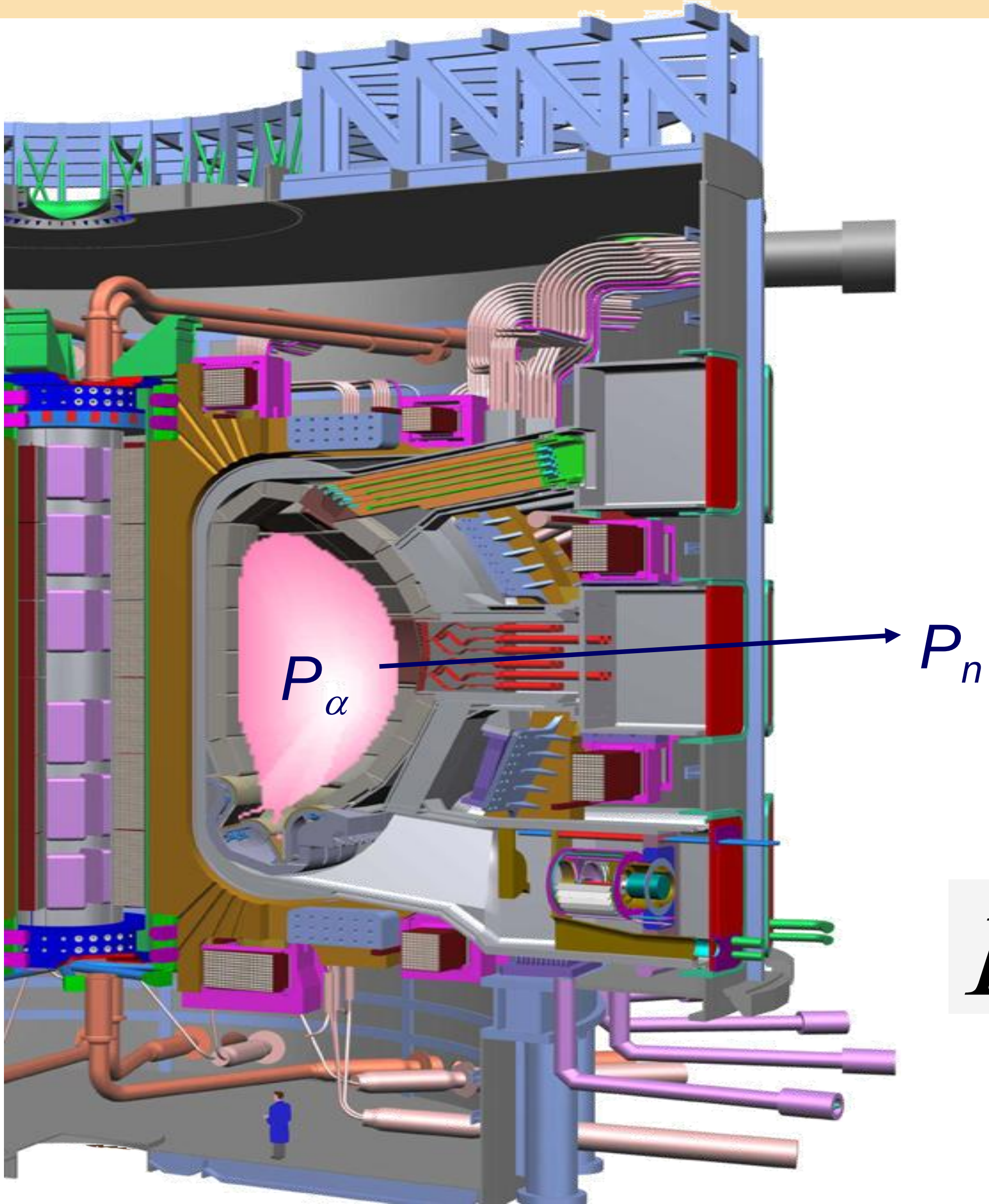
Central Temperature >20keV

P =Plasma Pressure ~7 atmospheres

$$D + T \rightarrow He^4 + n$$

3.5MeV 14MeV

Fusion Energy Balance in ITER



'Baseline Performance'

Power in alphas captured by Plasma $P_\alpha \sim 100MW$.

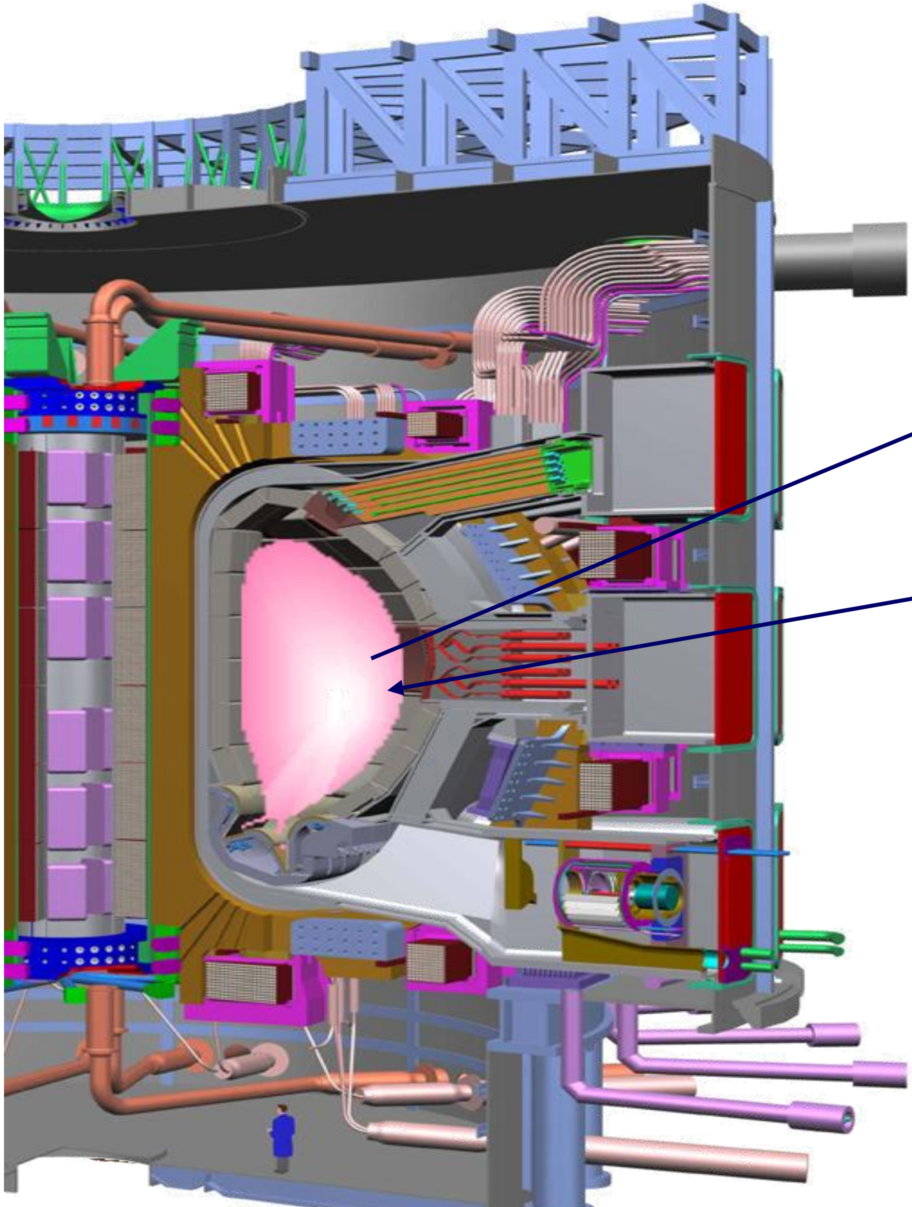
Power in neutrons escaping Plasma $P_n \sim 400MW$.

$$P_n + P_\alpha = P_{Fusion}$$

$$D + T \rightarrow He^4 + n$$

3.5MeV 14MeV

Fusion Energy Balance in ITER



Turbulent Plasma Energy Loss

$$\mathcal{P}_{loss} = \frac{0.15P}{\tau_E}(MWm^{-3})$$

Confinement Time

External Plasma heating

P_{Heat}~50MW

Energy Balance

$$\frac{\mathcal{P}_{Fusion}}{5} + \mathcal{P}_{Heat} = \mathcal{P}_{loss} \sim 0.15\frac{P}{\tau_E}$$

Energy Gain > 10

Why so Big?

Will ITER work?

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Gyro-kinetic simulation.

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

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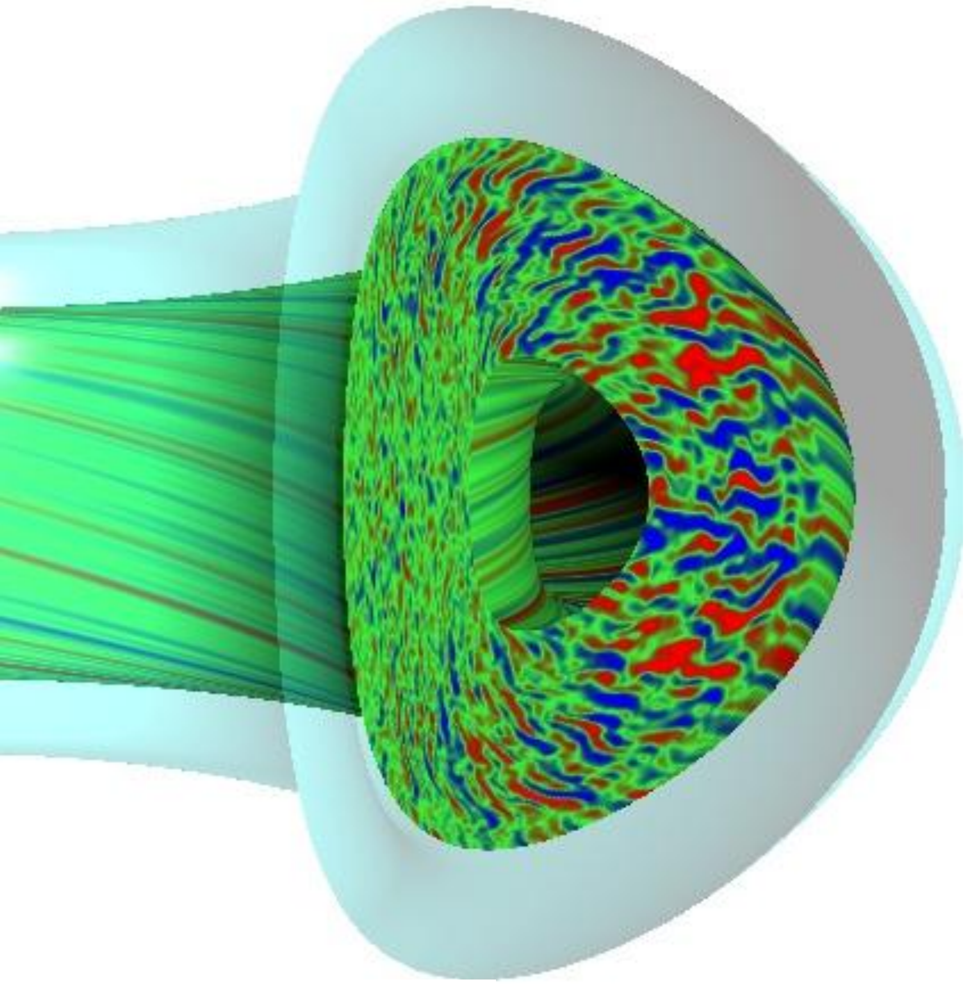
GYRO code simulations by Jeff Candy and Ron Waltz GA

Energy Confinement -- Random walk of heat/particles.



L = typical machine size

Δ= radial eddy size ∝ Ion larmor Radius ρ_i = random step.

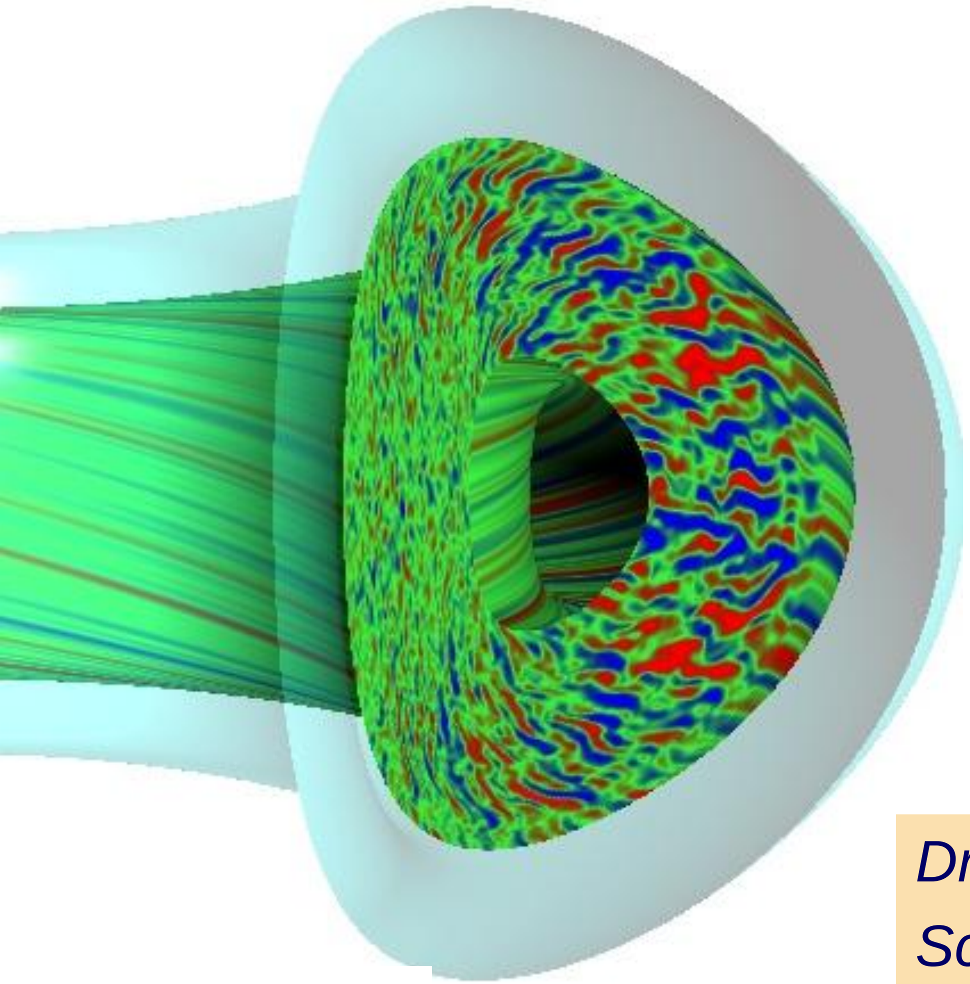
N = number of steps to random walk out of plasma

$$L \sim \sqrt{N}\rho_i$$

$$\rightarrow N = (\frac{L}{\rho_i})^2$$

For ITER N ~ 10^6.

Energy Confinement -- Random walk of heat/particles.



Eddy turnover time =

$$\tau_{eddy} = (\frac{L}{v_{thi}})$$

$$\tau_E \sim N\tau_{eddy} \sim (\frac{L^3}{\rho_i^2 v_{thi}})$$

$$\propto L^3 B^2 T^{-3/2}$$

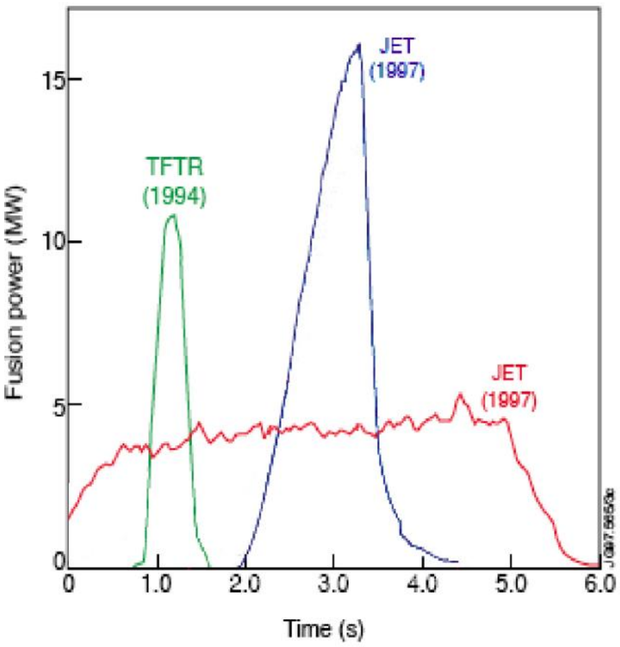
Dramatic scaling with size!

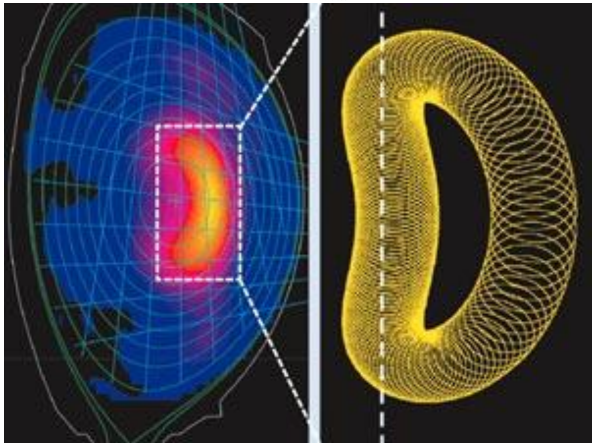
Scaling approximately agrees with data BUT geometry dependant.

JET the Worlds Biggest Fusion Experiment

QuickTime™ and a
decompressor
are needed to see this picture.

16MW fusion power 1997





Currently the only Tritium machine more fusion power records in 2014-15.

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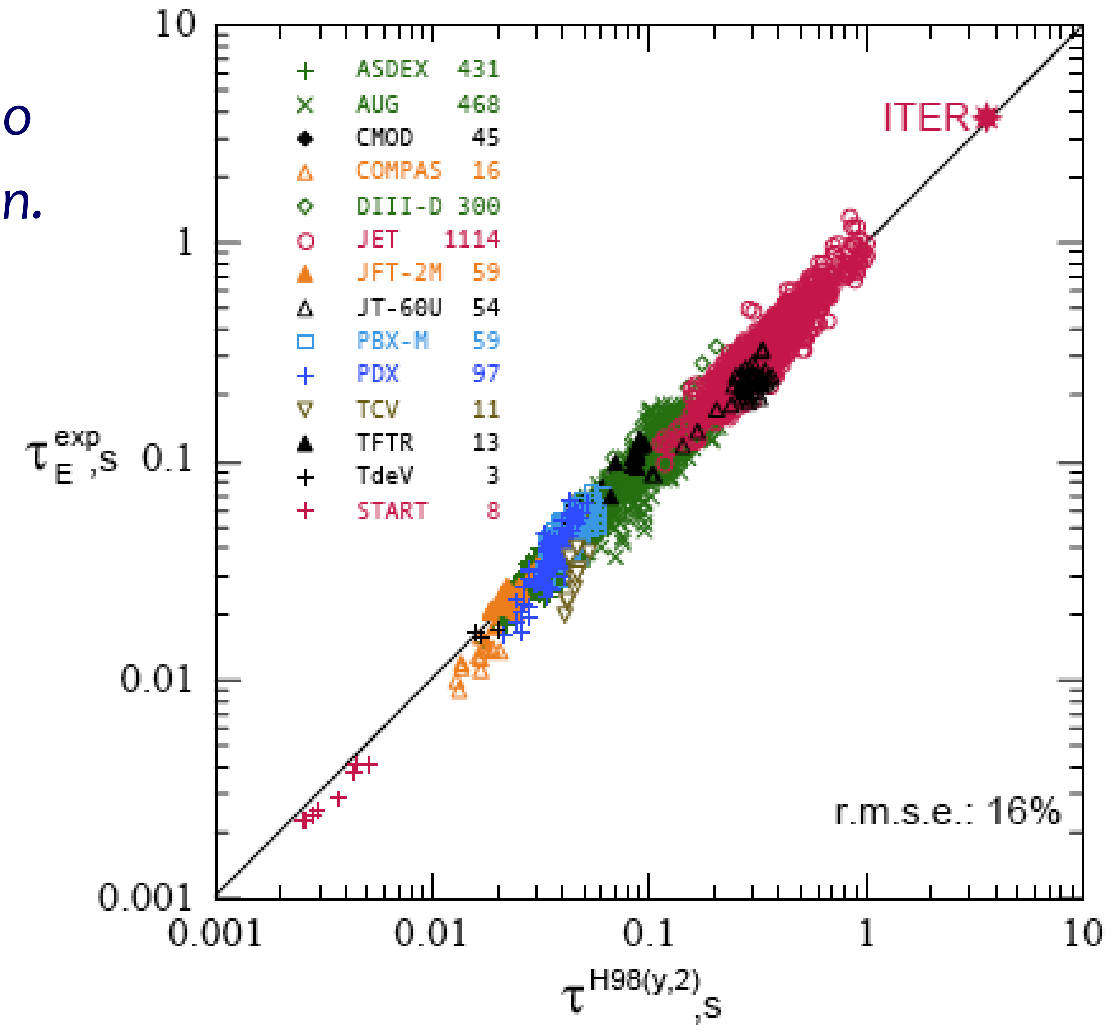
Empirical Scaling

Empirical scaling is very close to Back of envelop argument given.



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Detailed Modeling e.g.

Budny 2009

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are needed to see this picture.

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The reactor step -- when?

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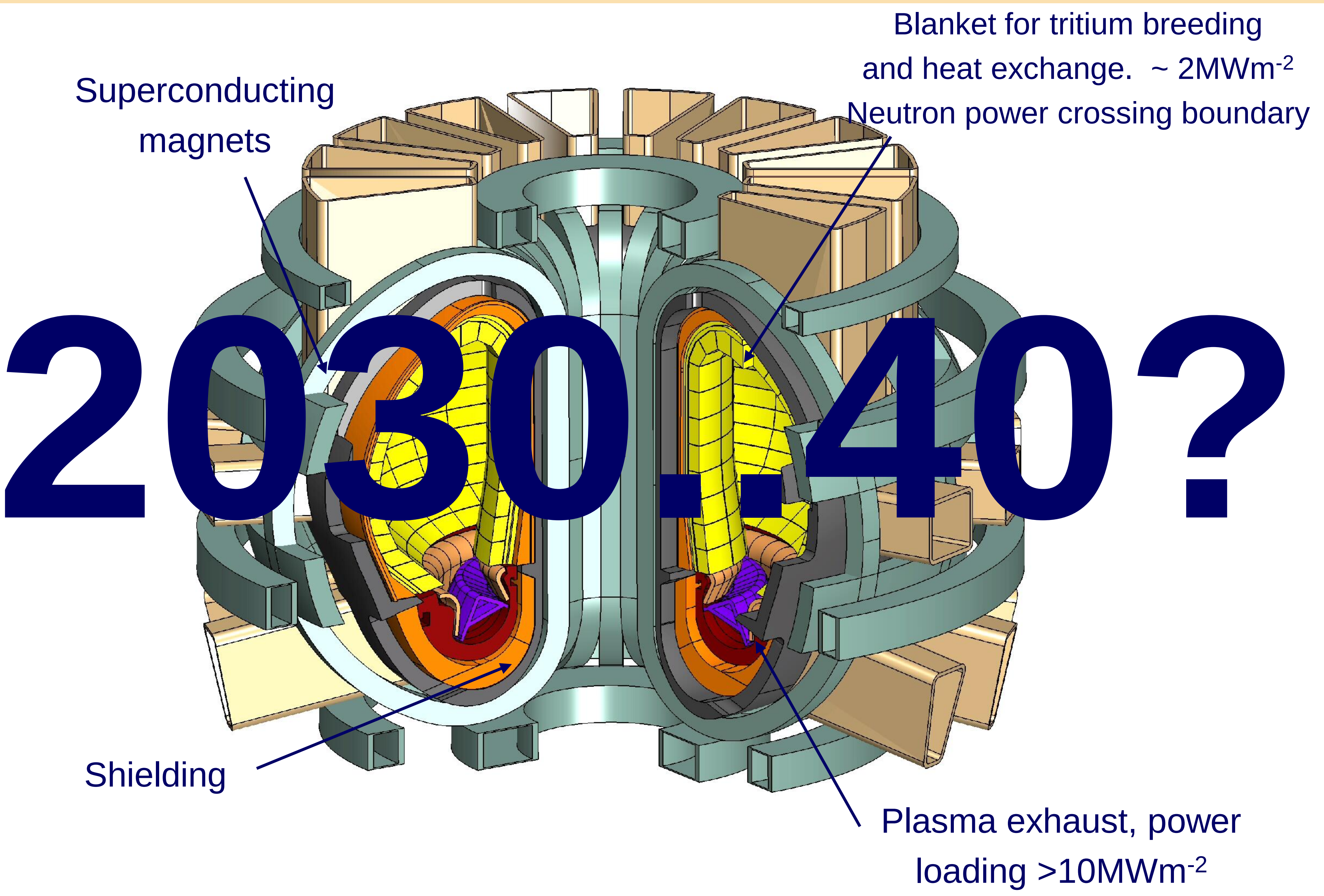
Demo Reactor -- some electricity.



Cost -- is it competitive?

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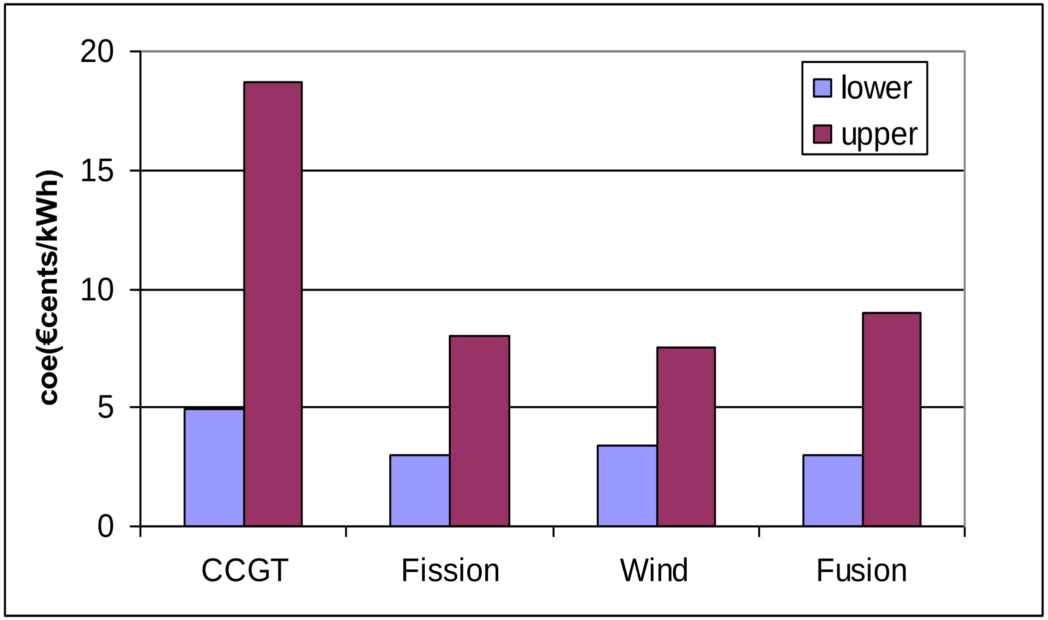
Direct Cost Comparison with Other Future Projections



Large uncertainty inherent in projections. Include projected fuel price increases but no carbon tax. Wind is near term technology but no standby or storage costs.

Source: “Projected Costs of Generating Electricity” IEA, 1998 Update, PPCS

Waste

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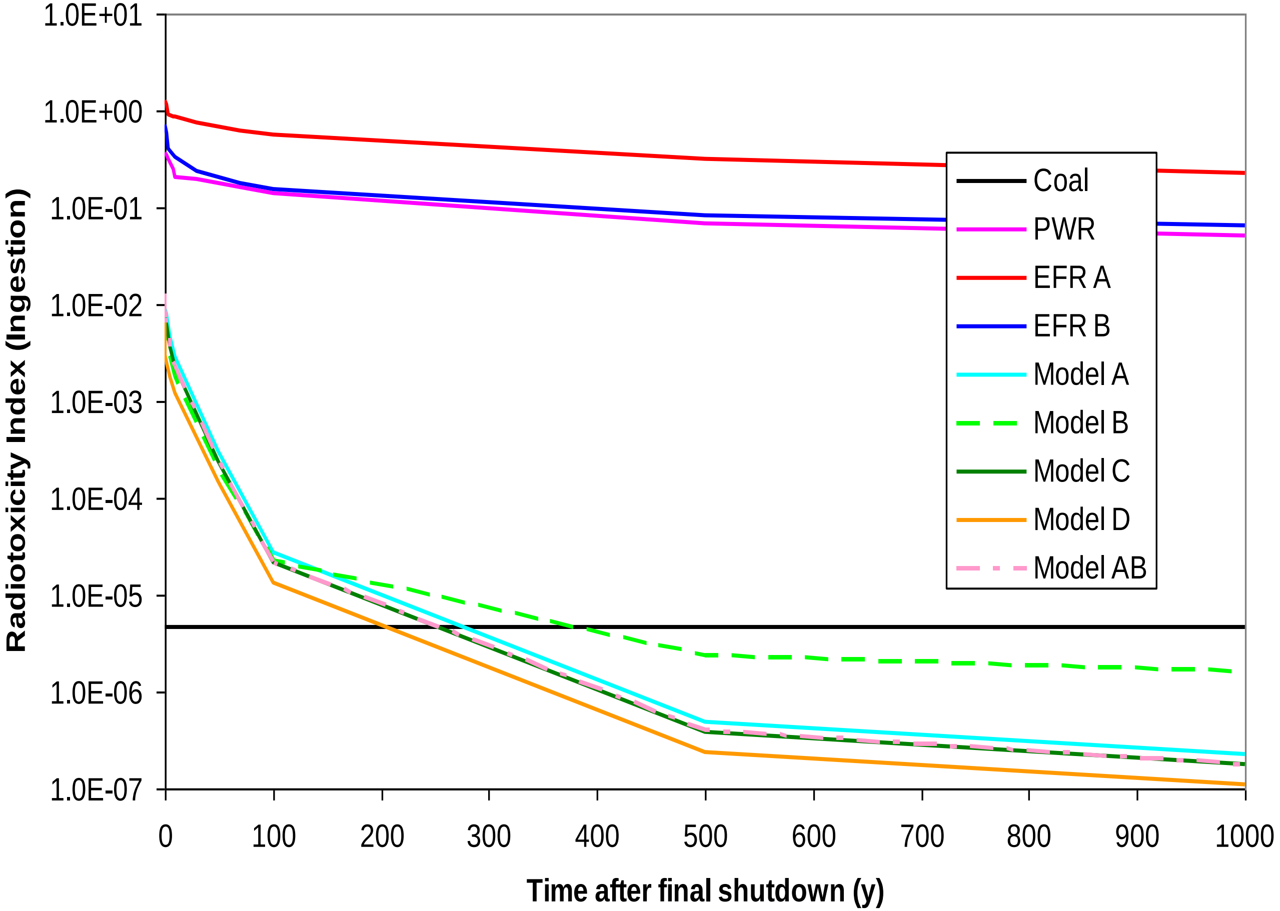
Potential Harm from Waste Materials



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Radiological hazard from fusion materials decays rapidly, with half life of around 10 years.

Source: PPCS

What next?

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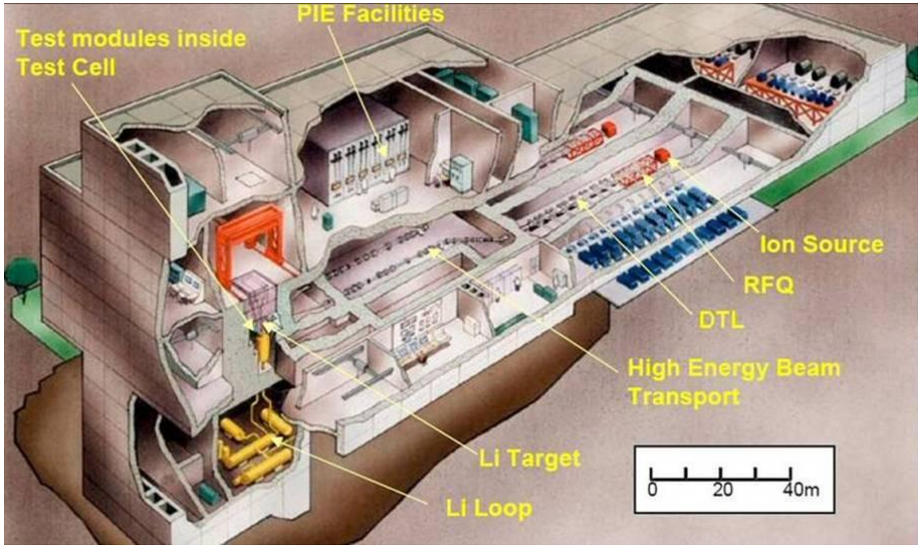
Materials Testing --The IFMIF/EVEDA Project

- EU-JA bilateral agreement. Its an addition to the ITER project

- IFMIF: International Fusion Materials Irradiation Facility -> intense flux of 14MeV neutrons for material characterization
  (2 CW linacs, 125mA deuterons, 40MeV, lithium target)



- EVEDA: Engineering Validation and Engineering Design Activities -> prototype for IFMIF (1 CW accelerator 125mA, 9MeV)

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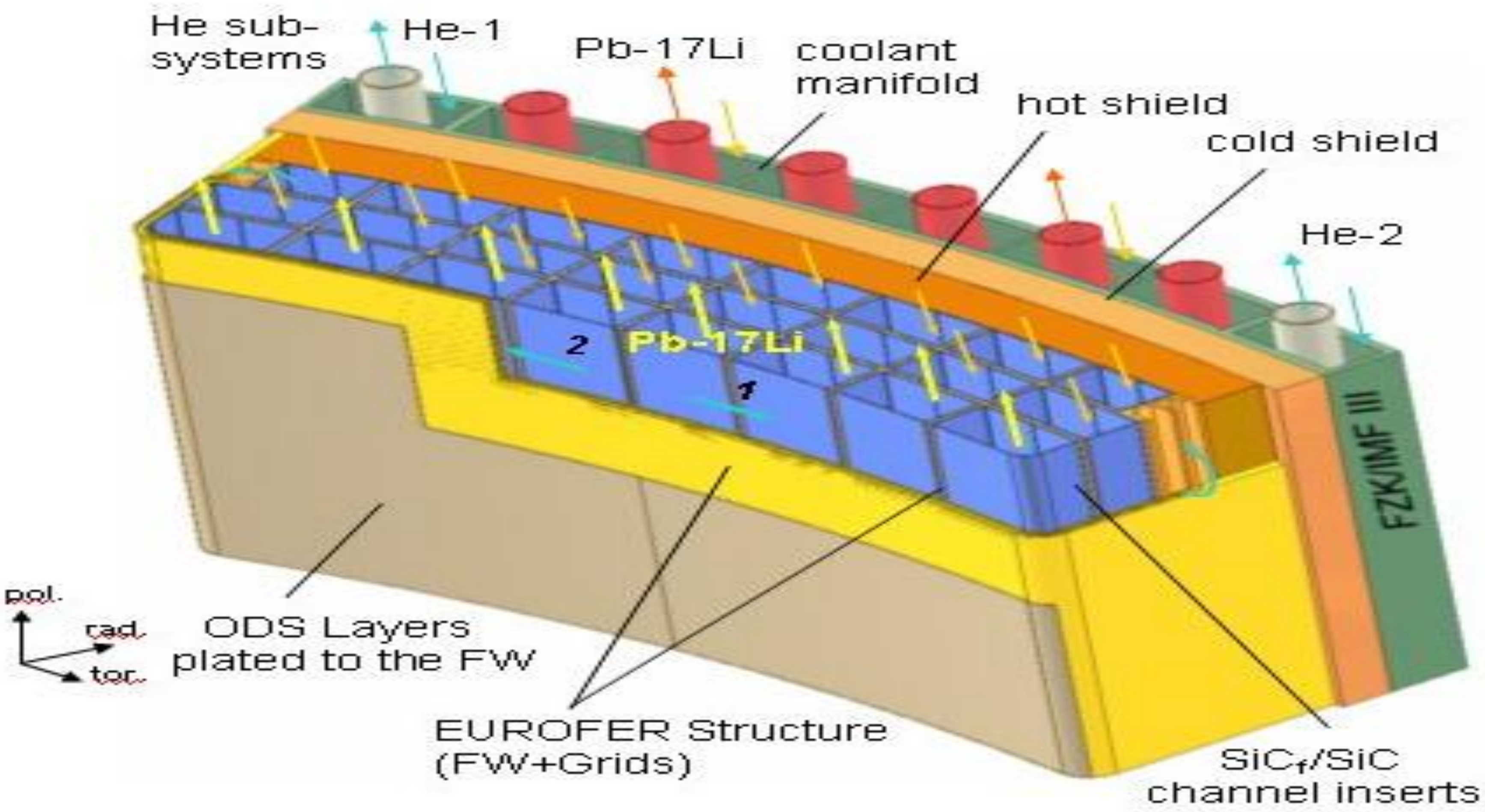
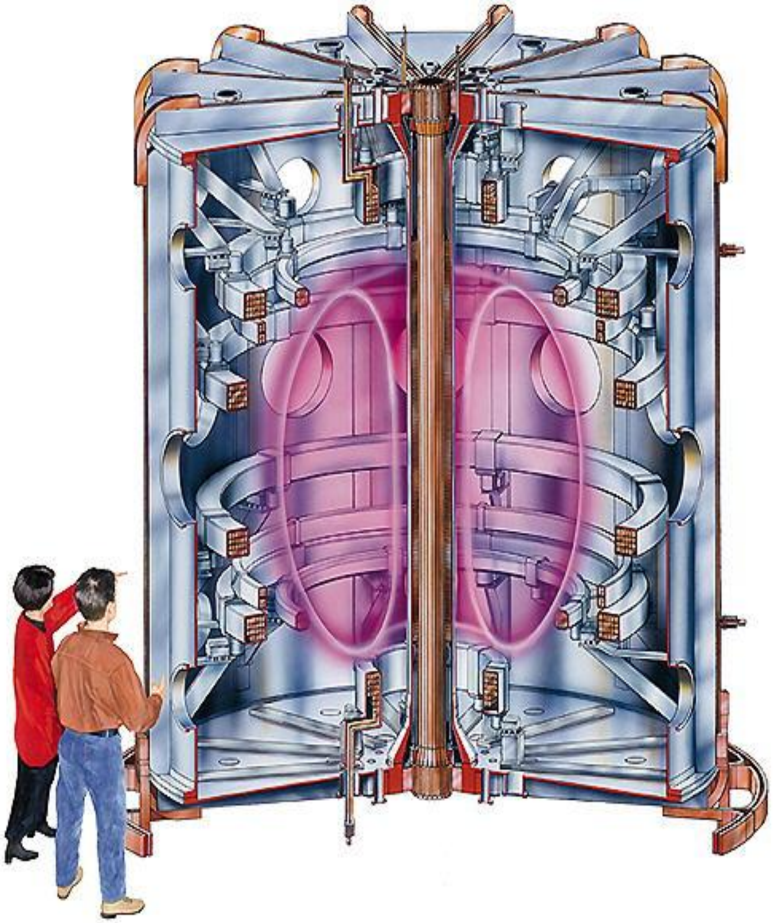
Fusion First Wall and Blanket integrate many technologies

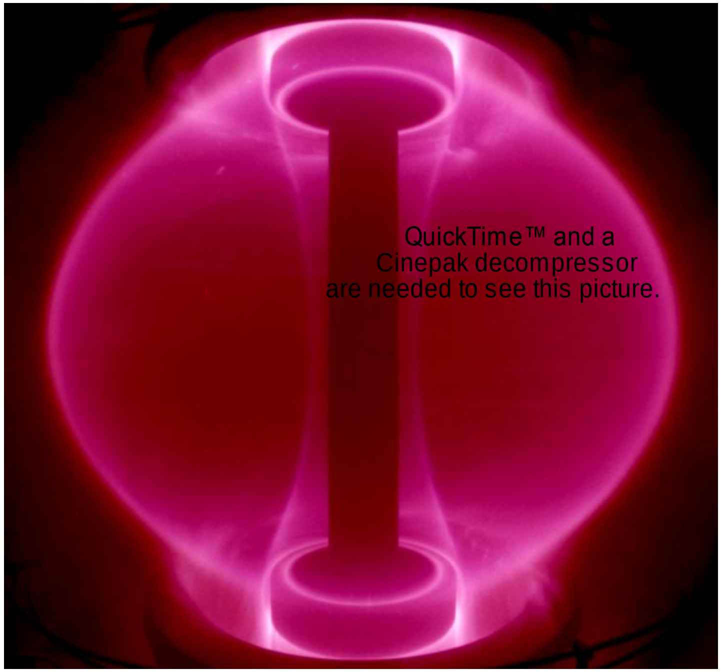
Breeder Blankets + Materials Development are stongly coupled.



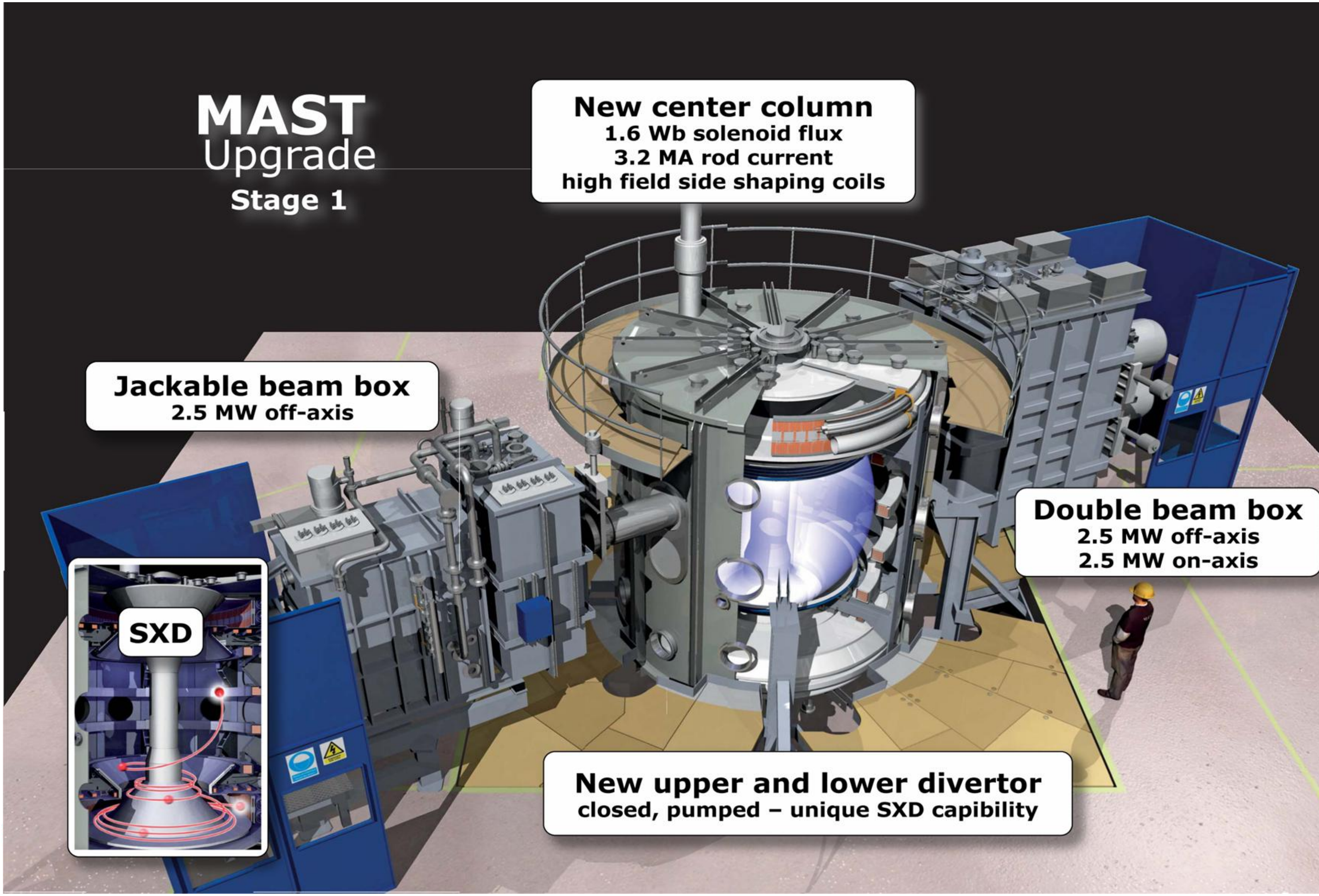
Can we make it compact, cheaper, faster …….?

MAST - Compact Fusion

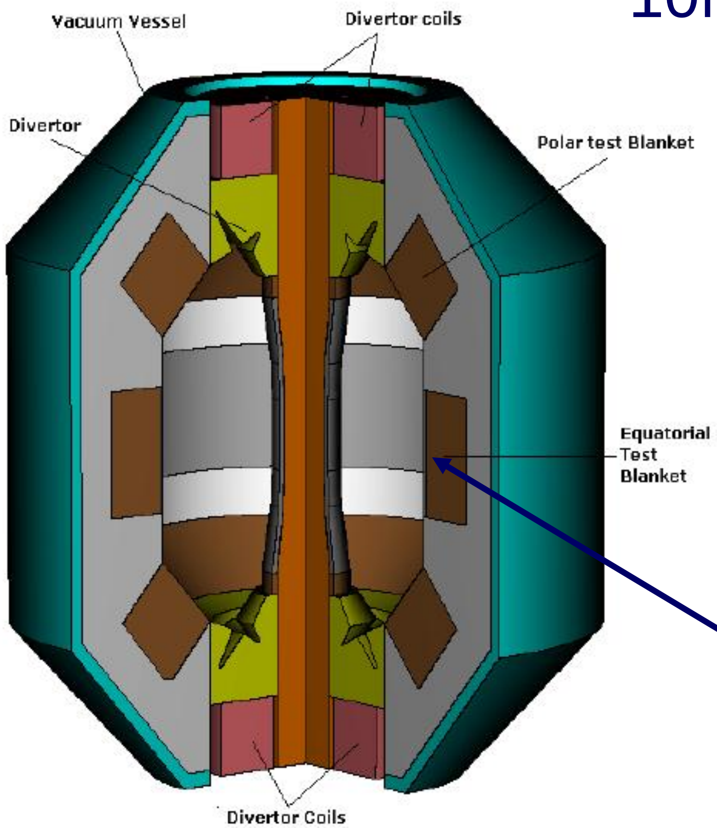




MAST Upgrade – Stage 1



A Hope -- Component Test Facility



10MWyear/m^2 fluence neutrons

12 years

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

*1.6*MW/m^2 neutron flux

<1kg tritium per year.

Based on MAST (Culham) and NSTX (Princeton).

Develop the IP of fusion.

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Fusion Soon.

- *With ITER we will do fusion at large scale. But commercial fusion needs technology developments.*

  We could get a first fusion reactor online by 2045.

- *It requires considerable investment -- political will is vital.*
- *Fusion at compact scale is more speculative -- but… …*
- *We need ideas, technical help and determination.*

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