Fusion Power and the Engineering Challenge

Steve Cowley
UK Atomic Energy Authority and Imperial College

Talk

Delivering fusion at a cost and scale that will ensure commercial success.

1. ITER, what will it do?
2. Challenge of going further.
3. Engineering challenges of a Demonstration reactor.
4. Technology

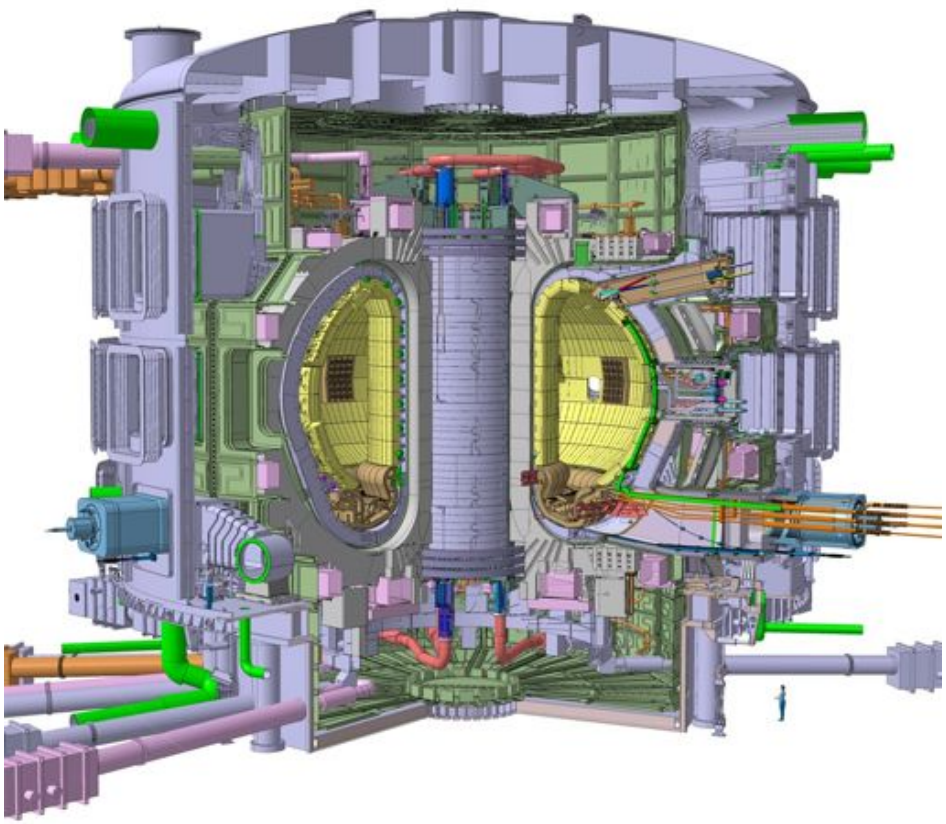
ITER

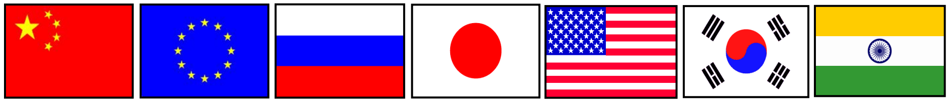
First sustained burning plasma.

Starts in 2020.

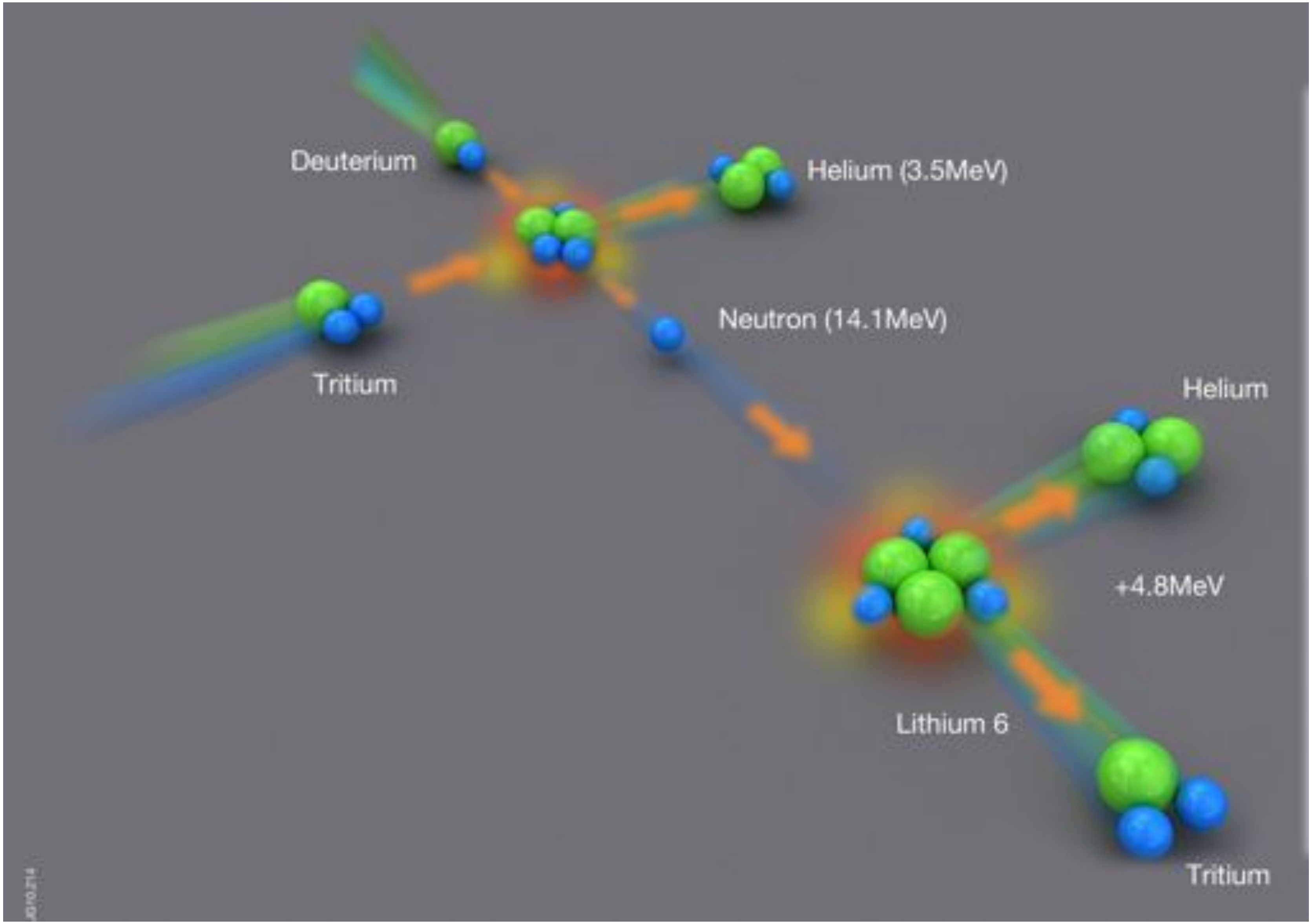
BASIC PARAMETERS:

- 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 > 10 Billion Euro.

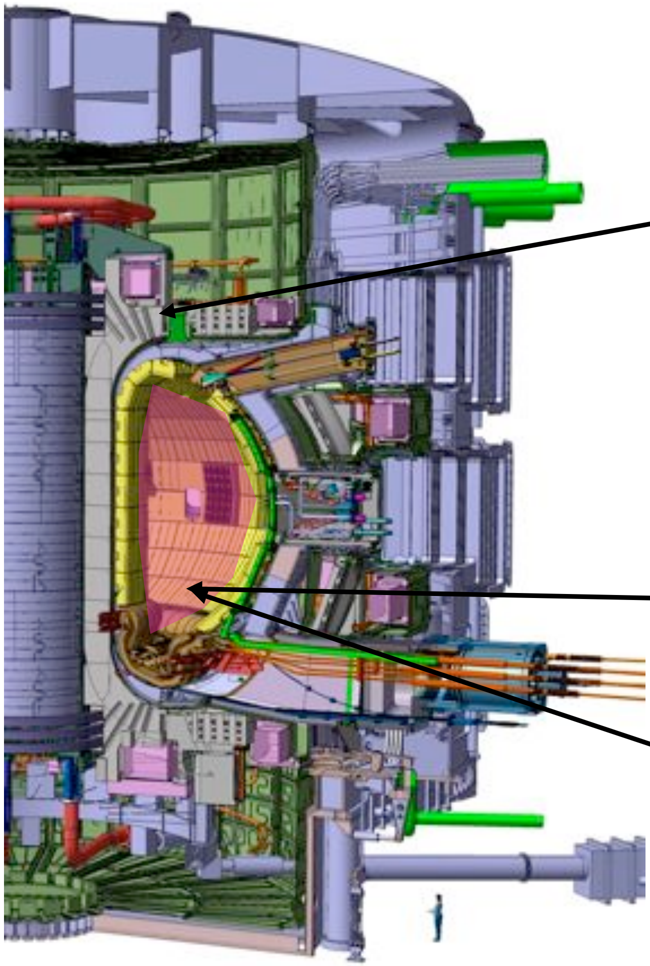




Which fusion?



Fusion force balance in ITER



Superconducting Coils

central B field 5.2 Tesla

$P_{magnetic}$ ~ 100 atmospheres

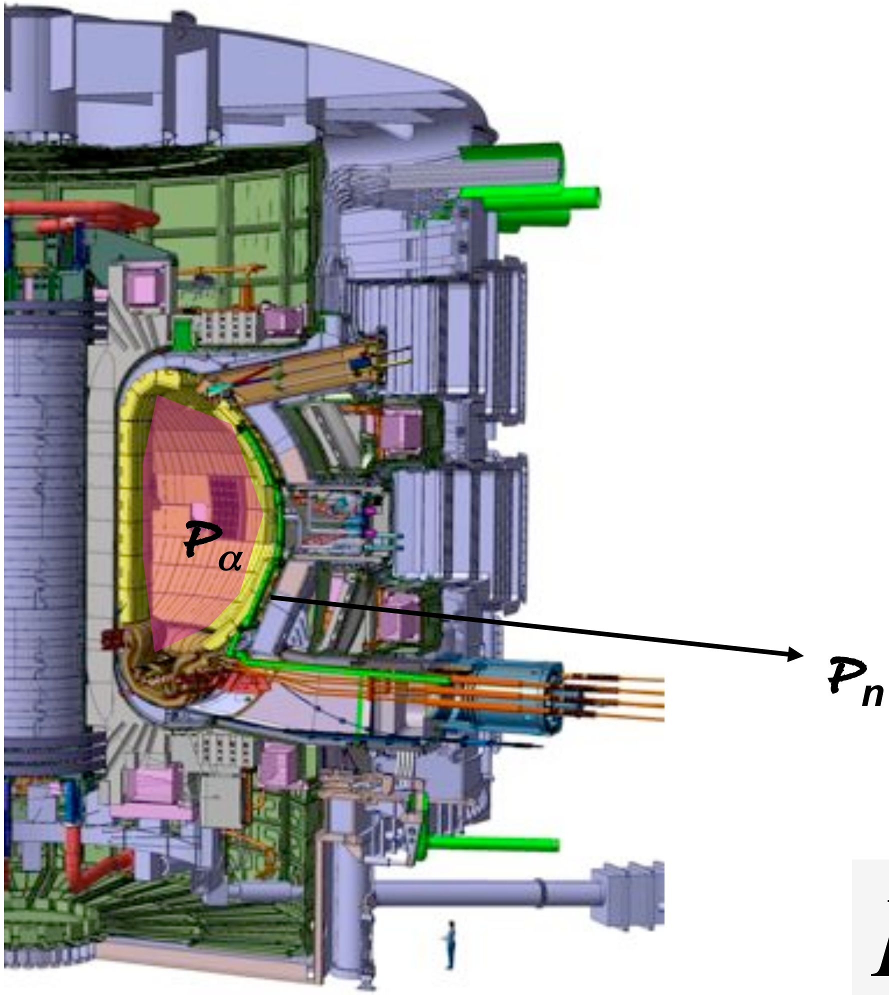
Central Temperature >20keV

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 $\mathcal{P}_\alpha$ *~ 100MW.*

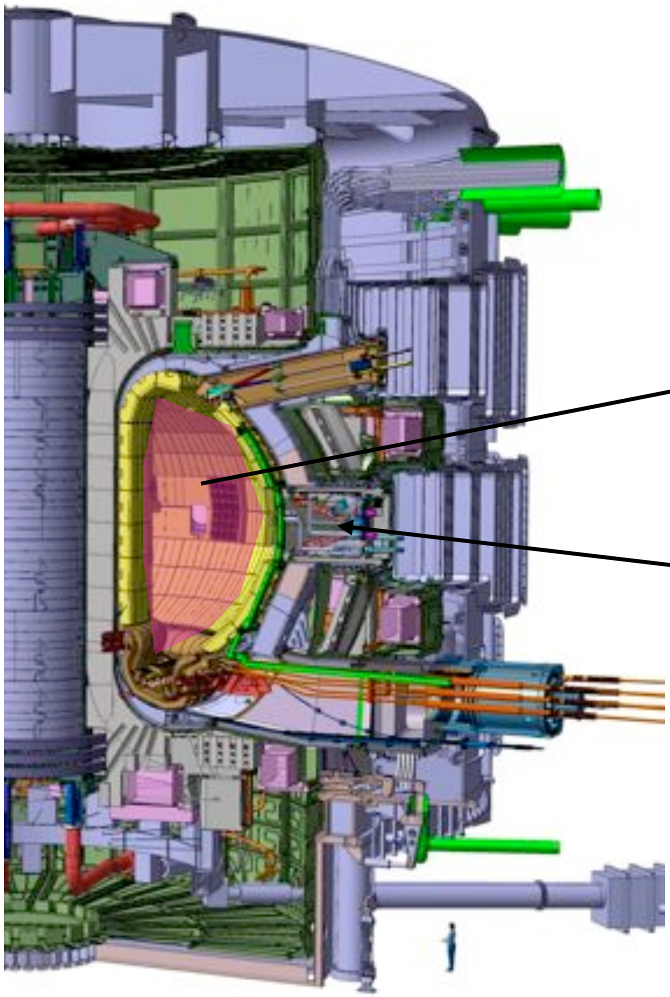
Power in neutrons escaping Plasma $\mathcal{P}_n$ *~ 400MW.*

$$\mathcal{P}_n + \mathcal{P}_\alpha = \mathcal{P}_{Fusion}$$

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

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

$\mathcal{P}_{Heat}$~50MW

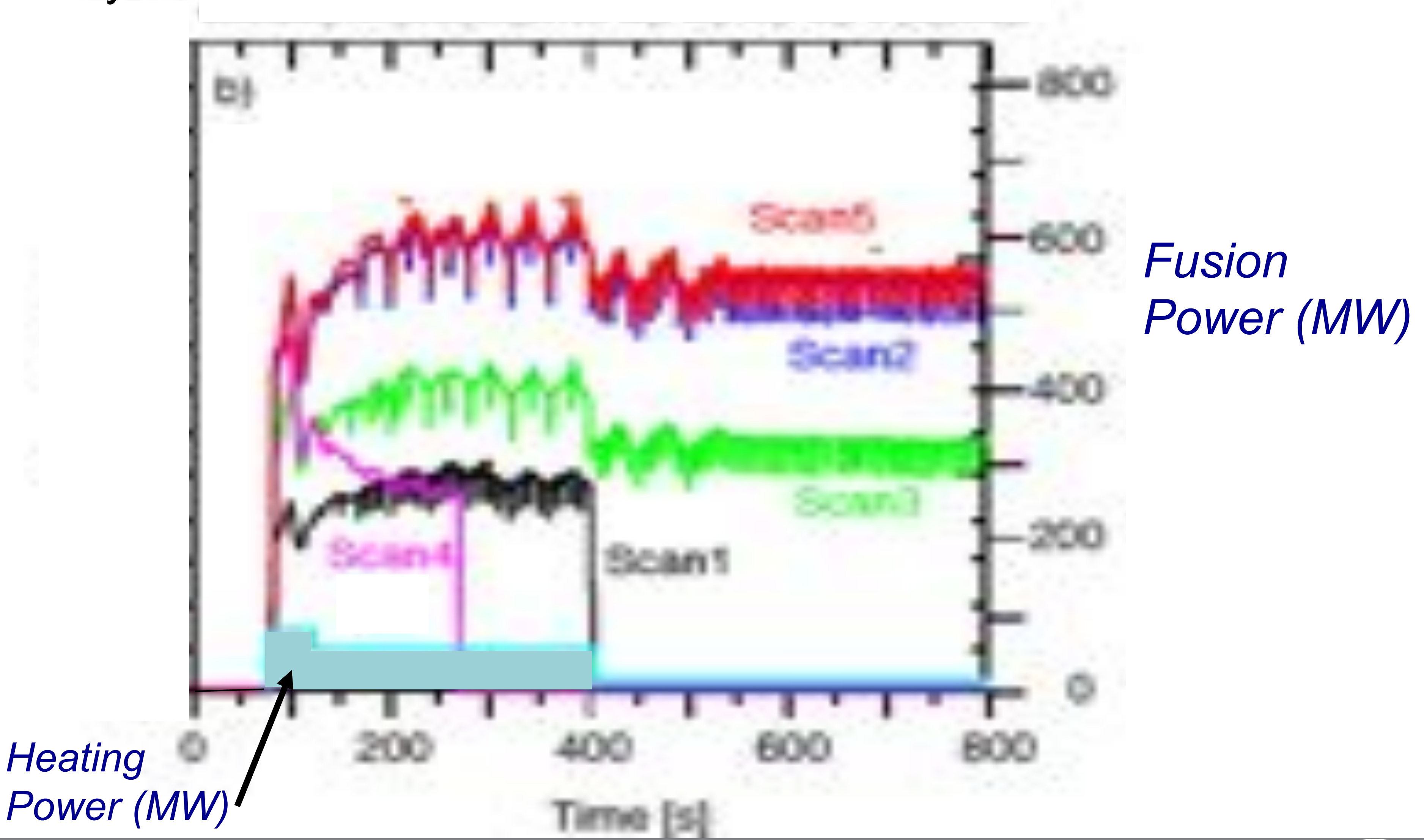
Energy Balance

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

Energy Gain > 10

ITER Detailed Modeling e.g.

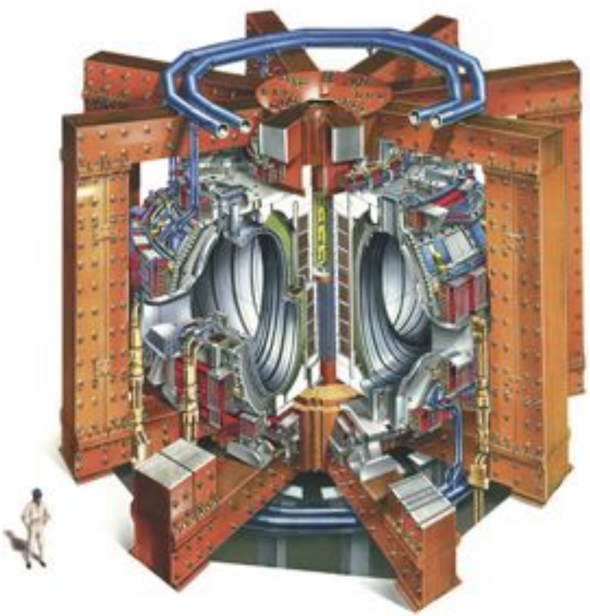
Budny 2009

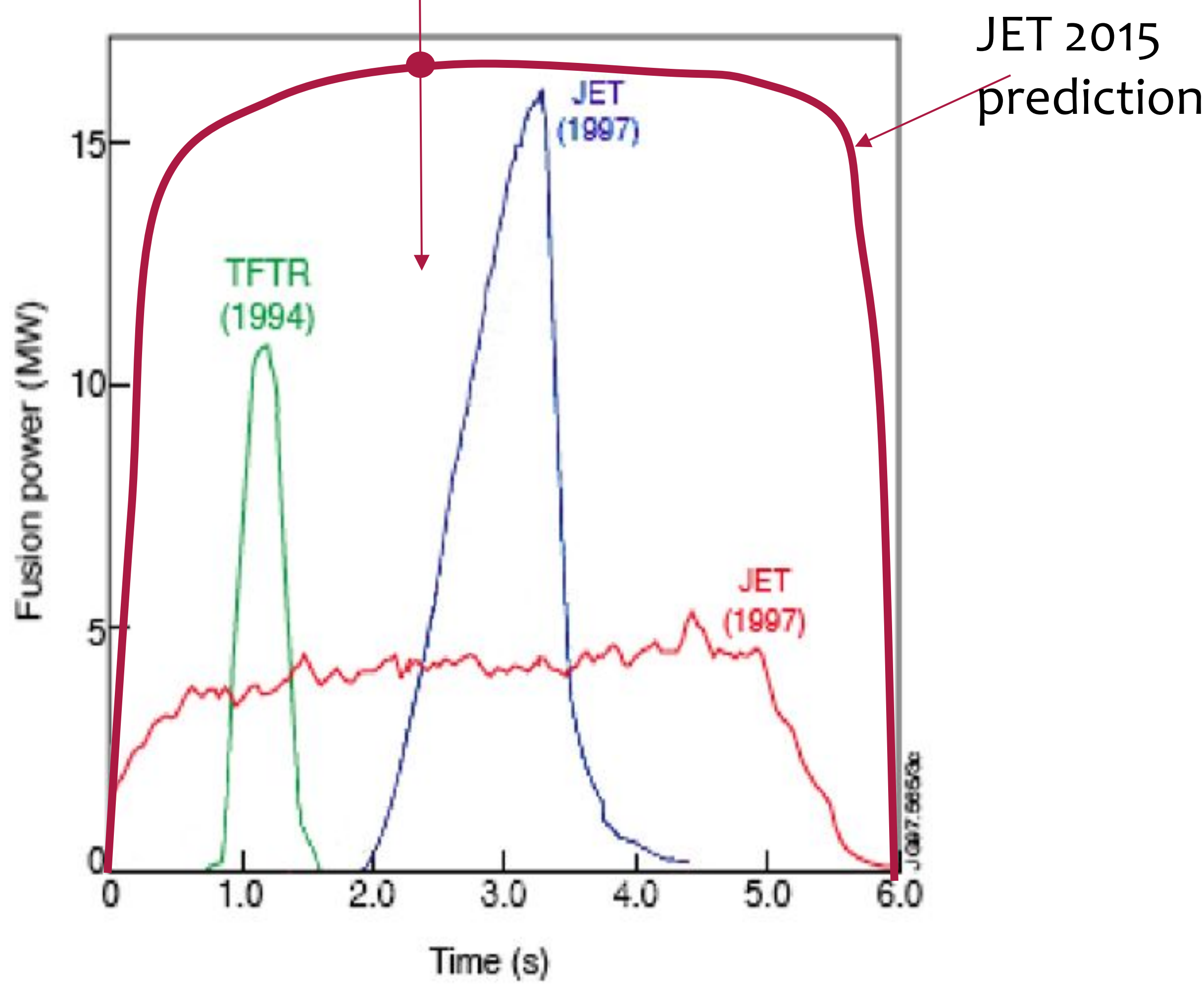


How do we know this will happen?

ITER Like Wall Installation

SUCCESS!!

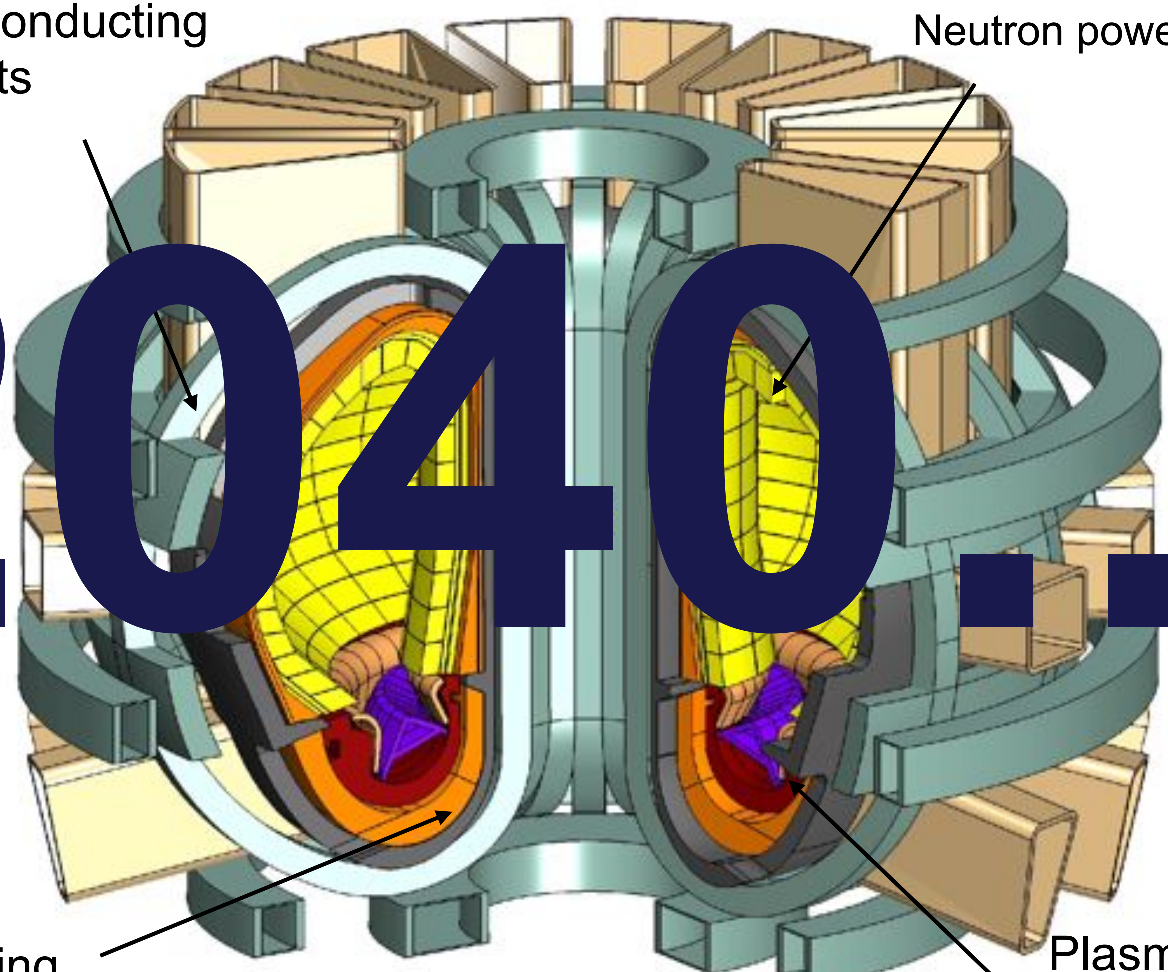




JET Currently the only machine capable of fusion

First Electricity When?

EU Demonstration Reactor.

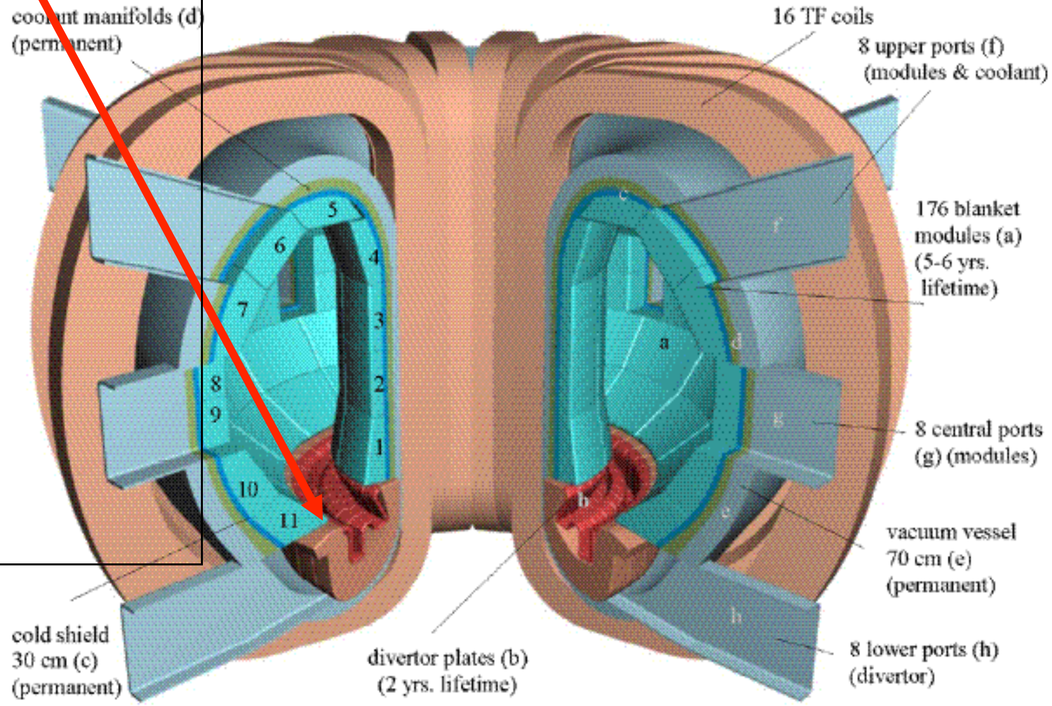


Technology challenge.

Handling the exhaust heat

DEMO power exhaust handling

- **Mission of a Tokamak Divertor:**
  - exhaust of heat and particles (including Helium 'ash');
  - keep sputtered impurities out of the plasma;
  - provide ~20% of the heat to the 'steam circuits'.

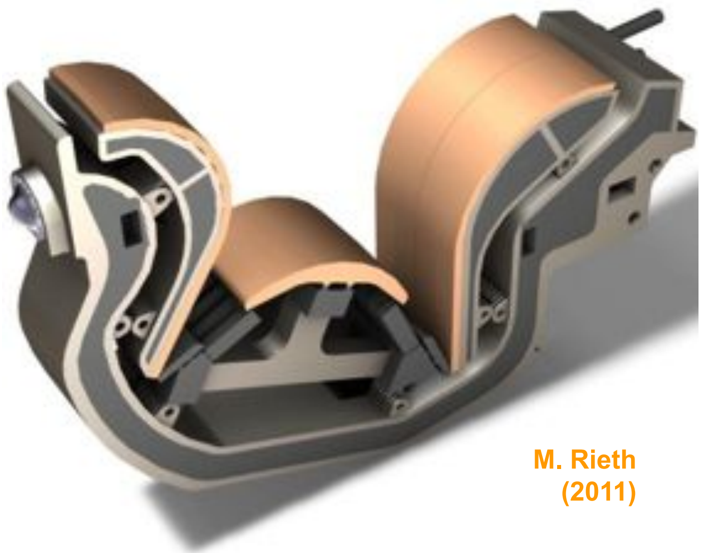


- very high power loading in the Divertor region > 50 $MW.m^{-2}$ possible in a DEMO/reactor with no mitigation.

High Heat Flux Components

- There is currently no viable solution to the divertor problem. We believe that the heat flux will have to be limited to < 10MWm^{-2}

➢ **There is a need to develop technologies which enhance high heat flux capability**
  - **coolants, composite layers**



M. Rieth (2011)

- DEMO is expected to operate at **>500MW recirculating power**, so there is a great need to **reduce pumping power** by increasing heat transfer efficiency

➢ **There is a need for more efficient heat exchangers**

➢ Helium cooling of a reactor will be very challenging, and there is renewed interest in **water cooling** for critical systems such as the blankets and divertor.

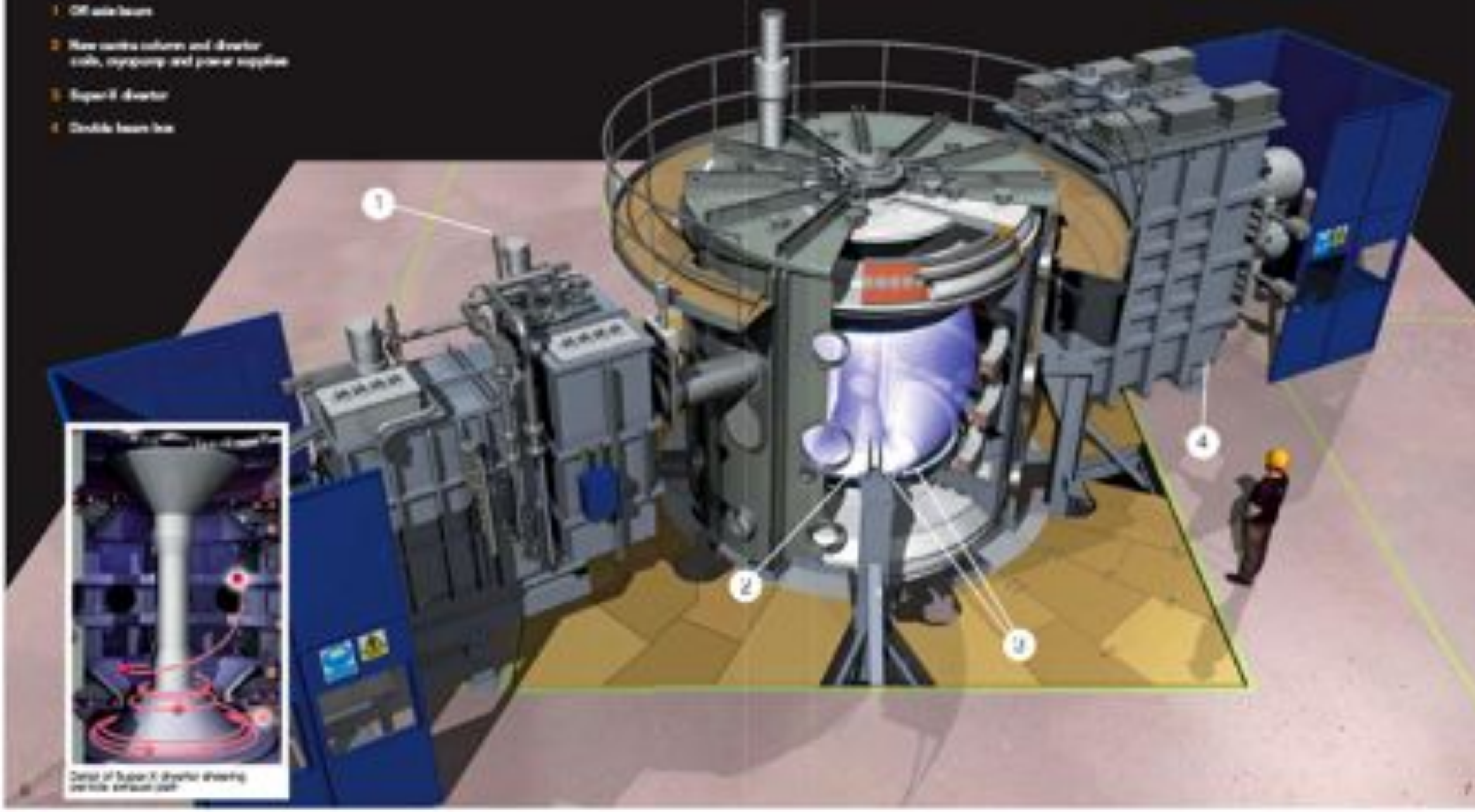
- Water cooling could allow simpler plant design and use of established **PWR** generating technology – but thermodynamic efficiency compromised by need to work at lower temperatures

➢ **There is a need to develop and enhance solutions based on water-cooling**

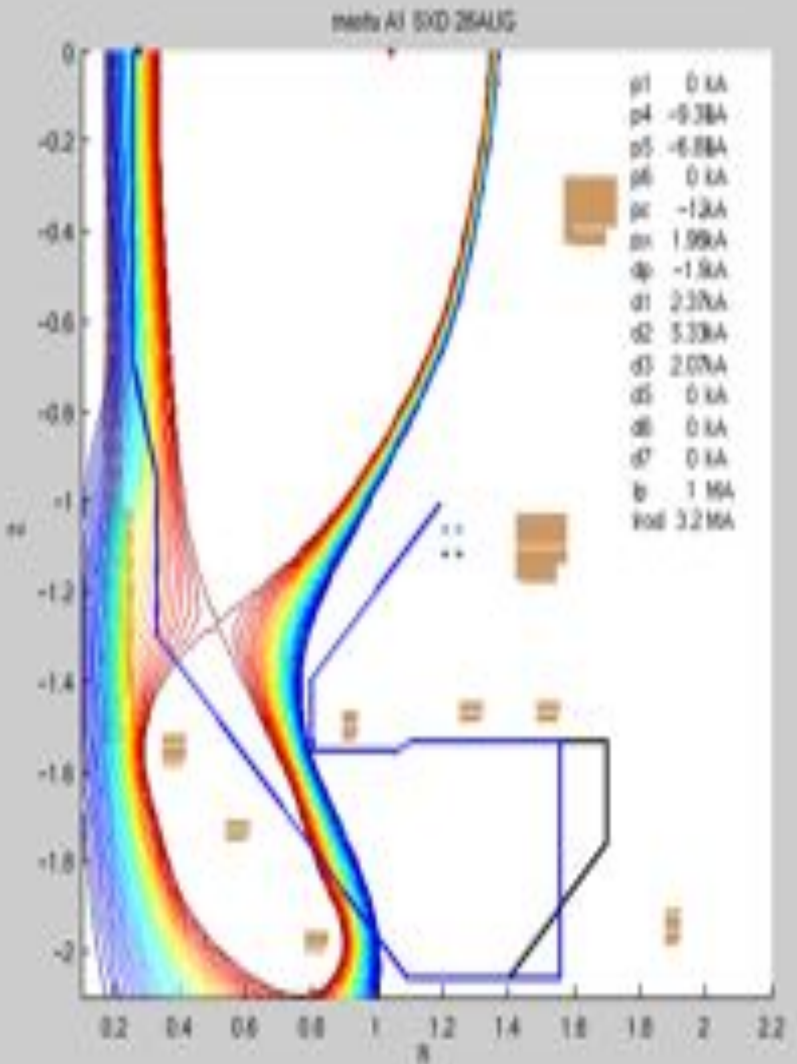
The new MAST

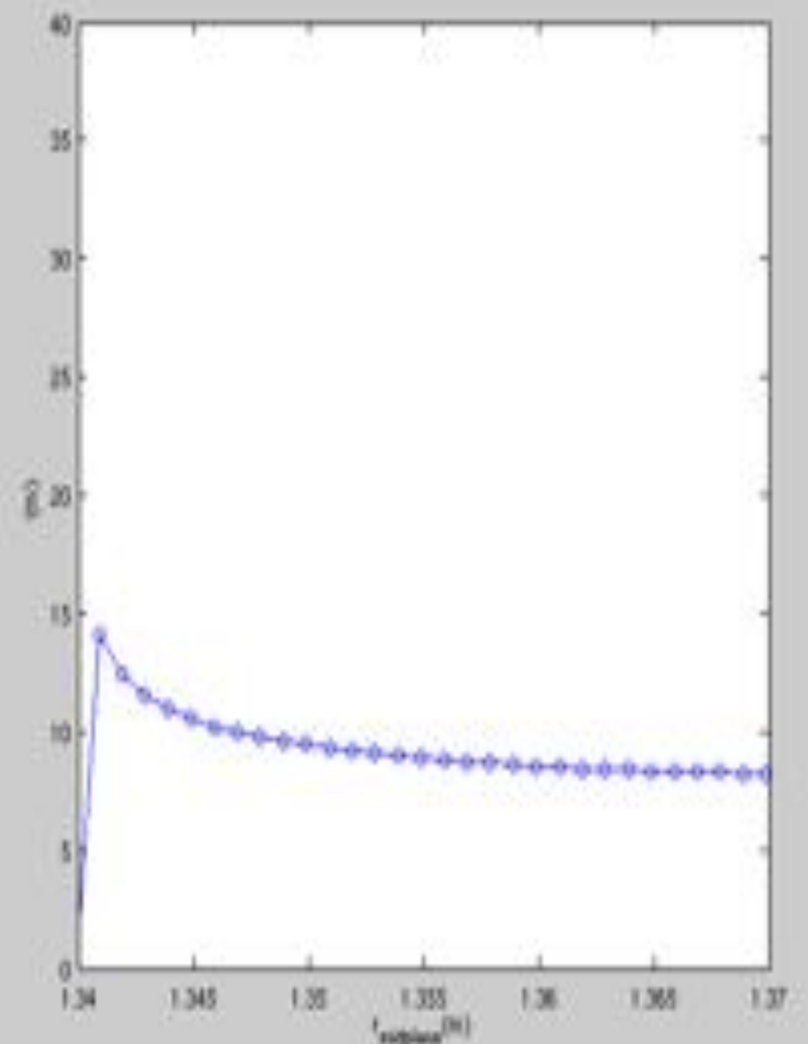
Key features of MAST Upgrade

1. Off axis beam
2. New centre column and divertor coils, cryopump and power supplies
3. Super-X divertor
4. Double beam box

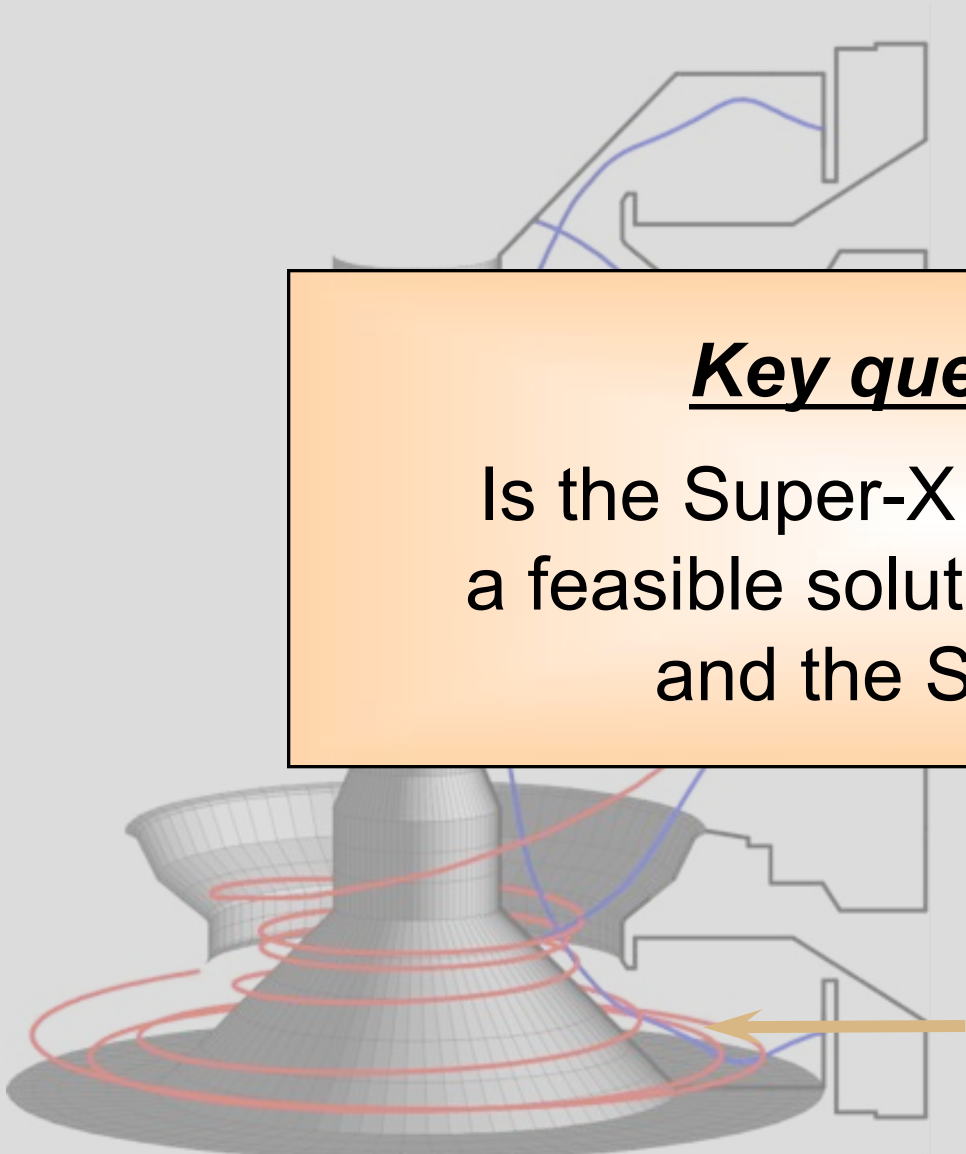


Flexible coil function





Key component: Closed, pumped divertor



- Closure provides low neutral density in the tank
  - High performance edge
  - Low plasma density
- ... article
- ... s:
- ... point
- ... expansion
  - Operation in the unique SXD configuration
- Region of low poloidal field helps heat load mitigation

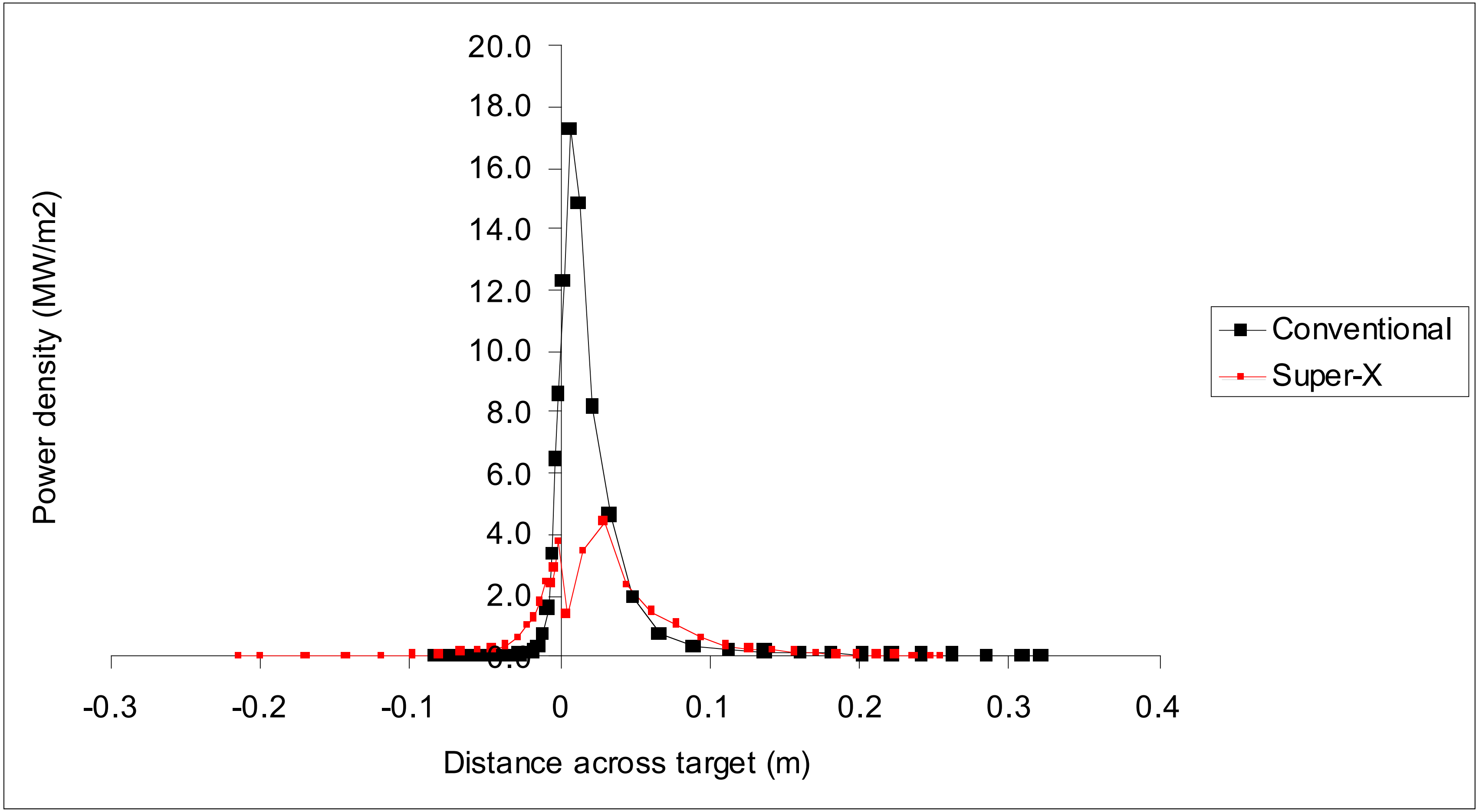
Key question:

Is the Super-X configuration a feasible solution for DEMO and the ST-CTF?

Plasma Physics Advantage (provisional)

Higher power simulations

- 10MW into SOLs



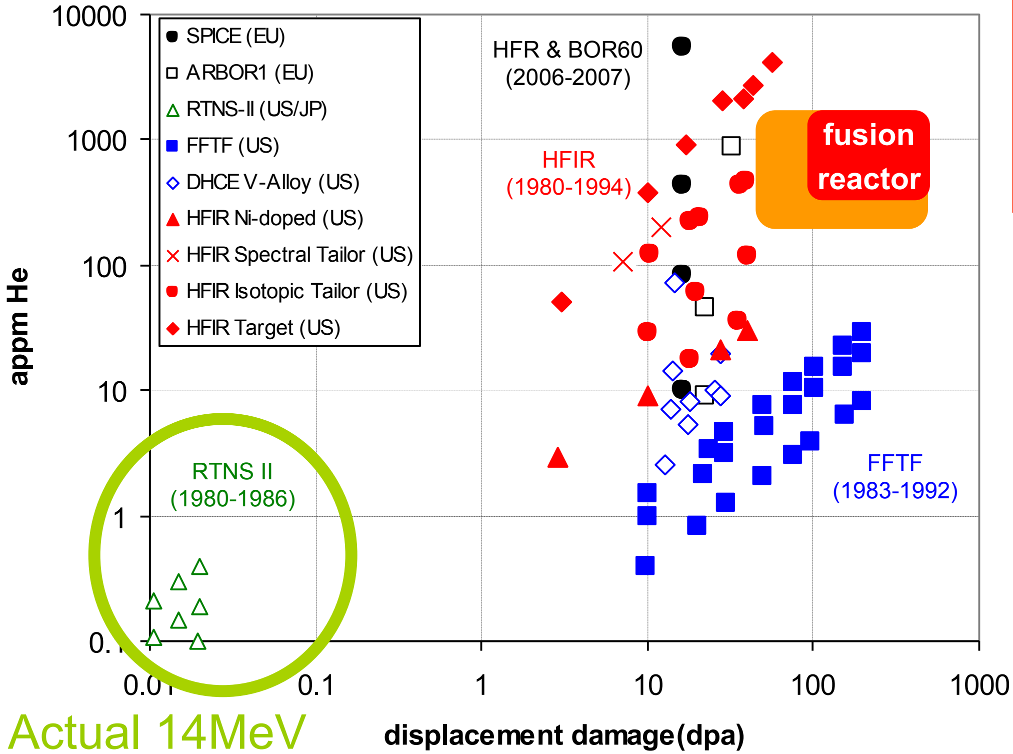
Technology challenge.
Materials that survive.

Fusion - advanced fission synergy

Kostia Trachenko

Materials – 14MeV Neutron Data Problem

- Highest damage in 14MeV spectrum < 0.1dpa at RTNS-II (1980-1986)
- Greater damage only achieved via fission spectrum
  → Unrepresentative as transmutation (He and H production) occurs above a few MeV and increases embrittlement
  - insight into helium effects via isotopic tailoring
  - differing transmutations and thus material response



Actual 14MeV irradiation data

rest is isotopic tailoring

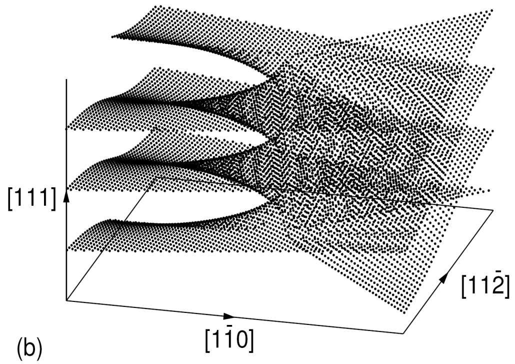
25 years with numerous available reactors to generate a reliable data base for fission core structural materials…

There is no 14MeV source operating or planned of sufficient intensity to generate >1dpa/FPY

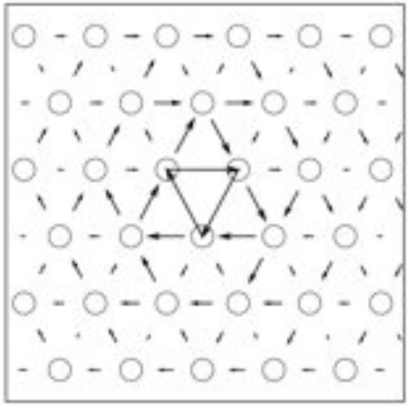
There is growing consensus in the materials community on the need for small, novel neutron sources to address this shortfall in 14MeV irradiation knowledge

e.g. Kurtz et al. Briefing for Synakowski (2009)

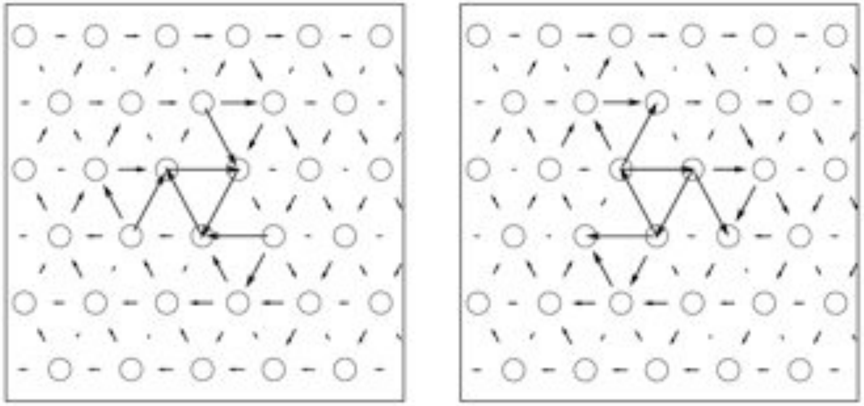
Brittle fracture of tungsten: modelling screw dislocations

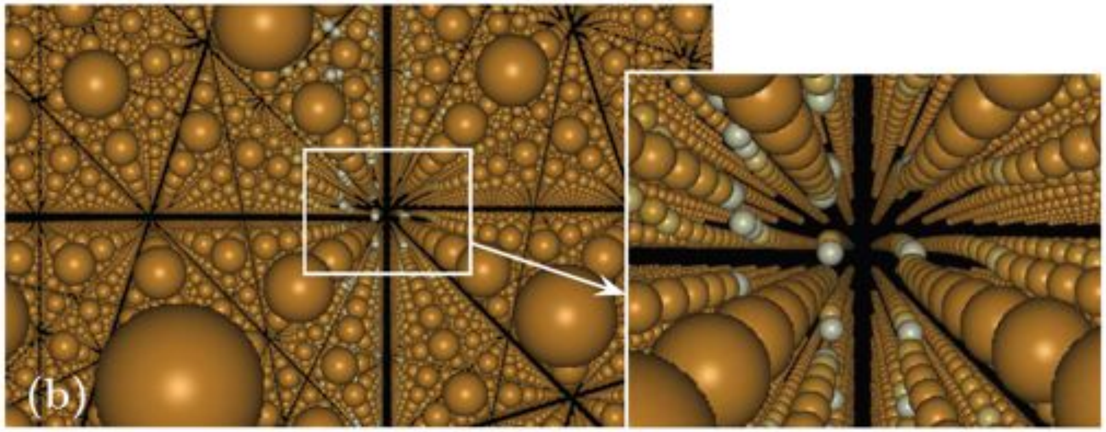


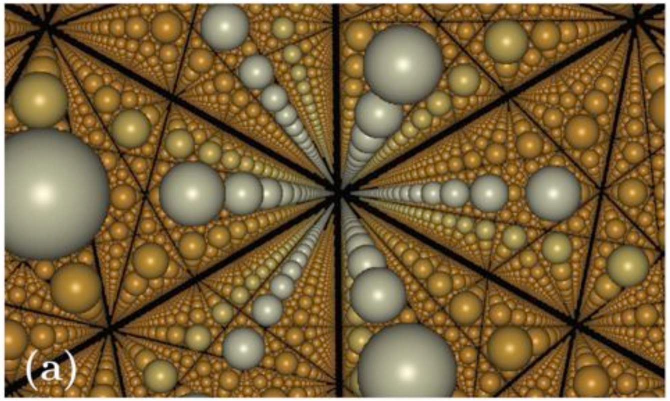
non-degenerate



degenerate



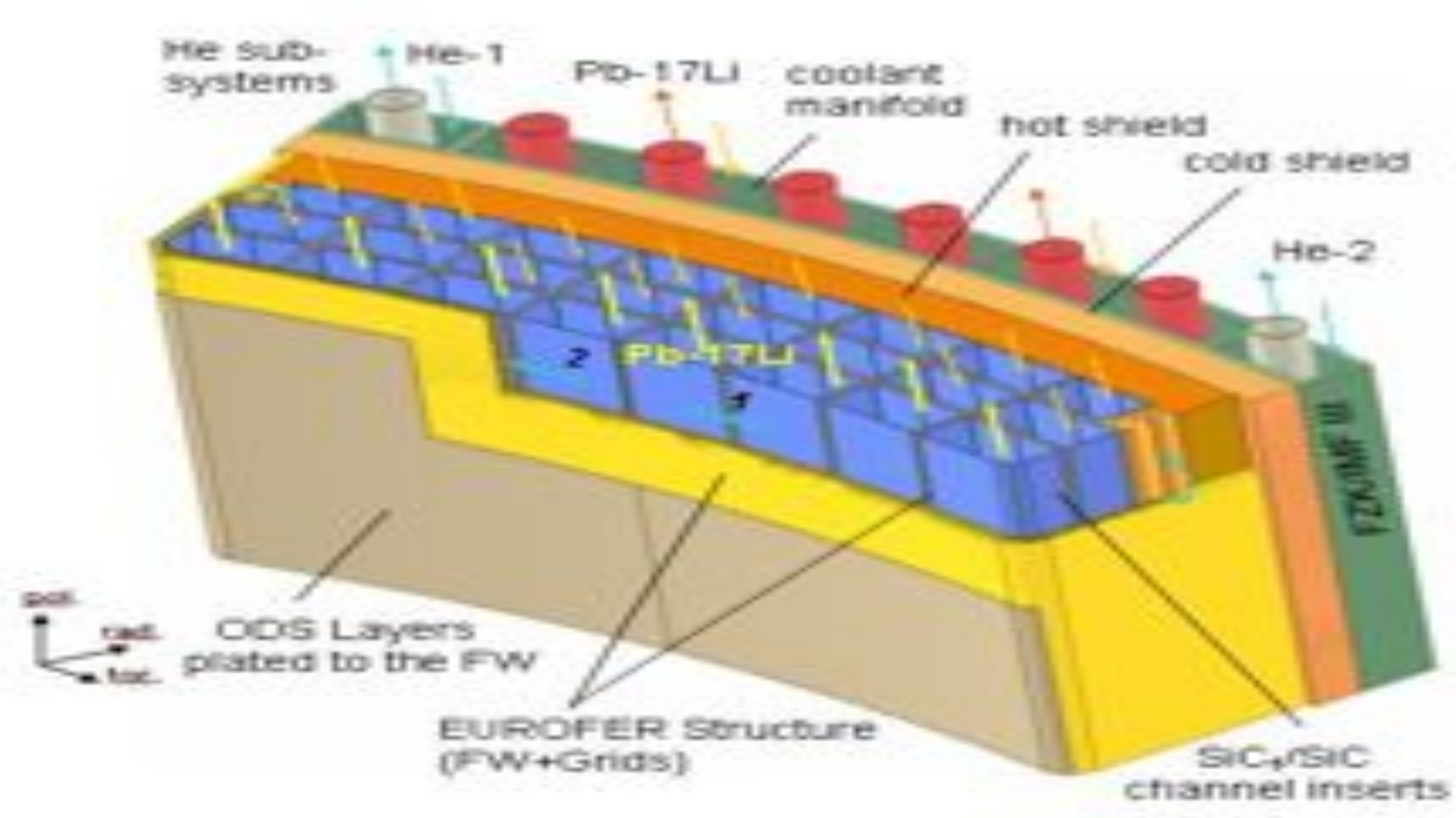




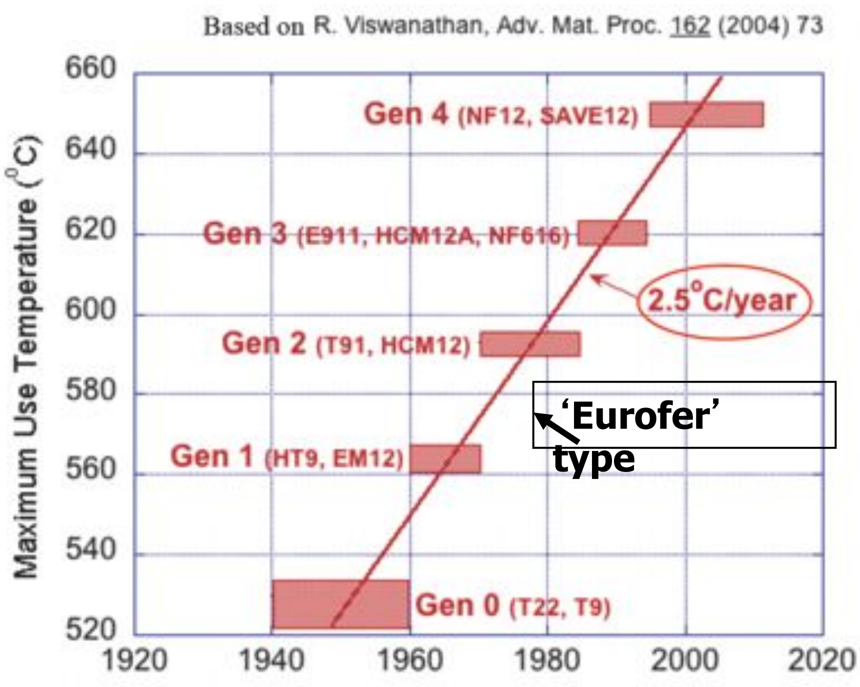
- It is vitally important to have an accurate model for screw dislocations at the atomistic level
- Accuracy is largely determined by inter-atomic potentials
- This new development opens a way of “designing” inter-atomic potentials

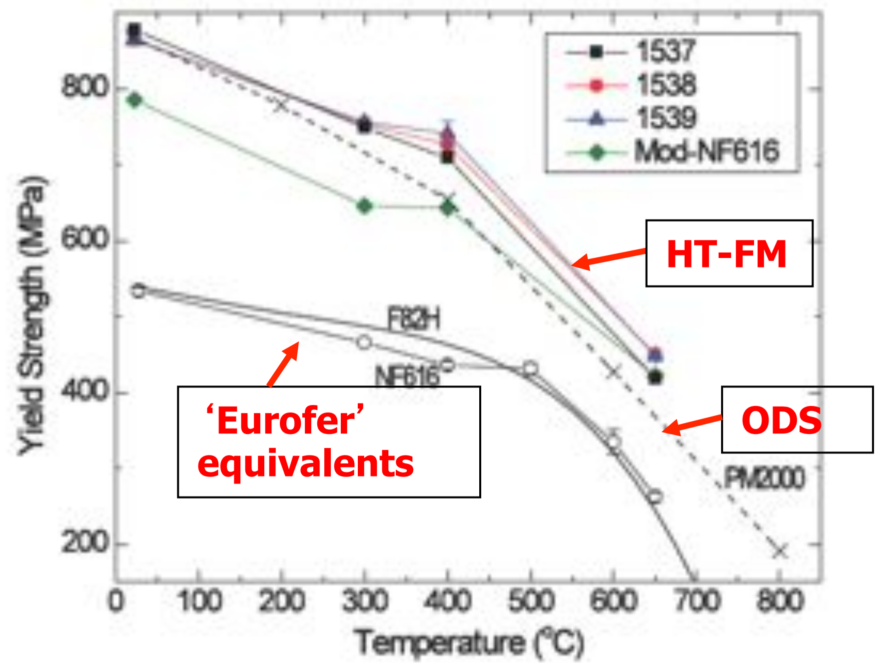
Fusion First Wall and Blanket integrate many technologies

Breeder Blankets + Materials Development are stongly coupled.



Development of HT FM steels outside Fusion…





High temperature Ferritic Martensitic steel development marches on:

- Driven mainly by needs of high temperature ultra-super critical fossil fuel steam generation

'Fourth generation' FM steels with much higher strength and creep rupture resistance - similar to ODS **but…**

… they are ductile…

… you can weld them.. they have 'mainstream manufacturing processes

Conclusion

Delivering fusion at a cost and scale that will ensure commercial success. Culham's plan is to become the design centre for first electricity producing power plant after closure of JET in 2020.

- There is much to do – mostly engineering.
- Nothing looks impossible – it does look challenging.
- We need help.