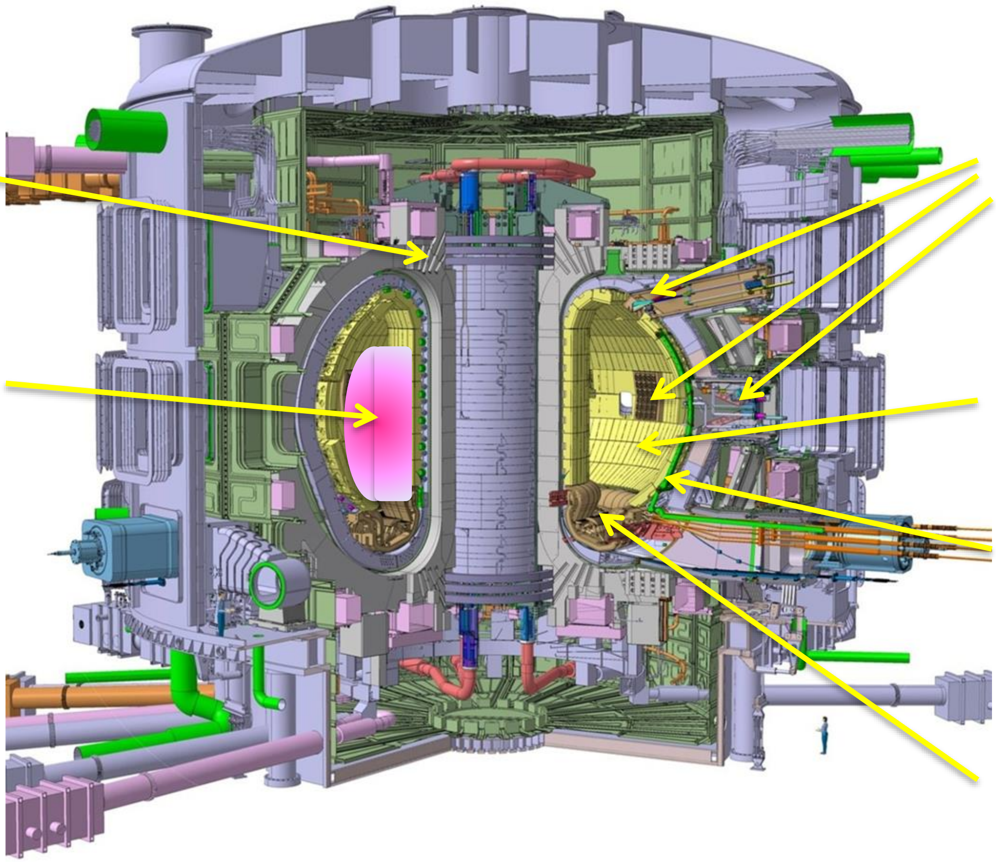
The Challenges of Small Fusion Reactors

Elizabeth Surrey, UKAEA Culham

The anatomy of a tokamak is complex



Fuelling – D/T pellets and gas

Plasma - D/T at temperatures of 10^8C

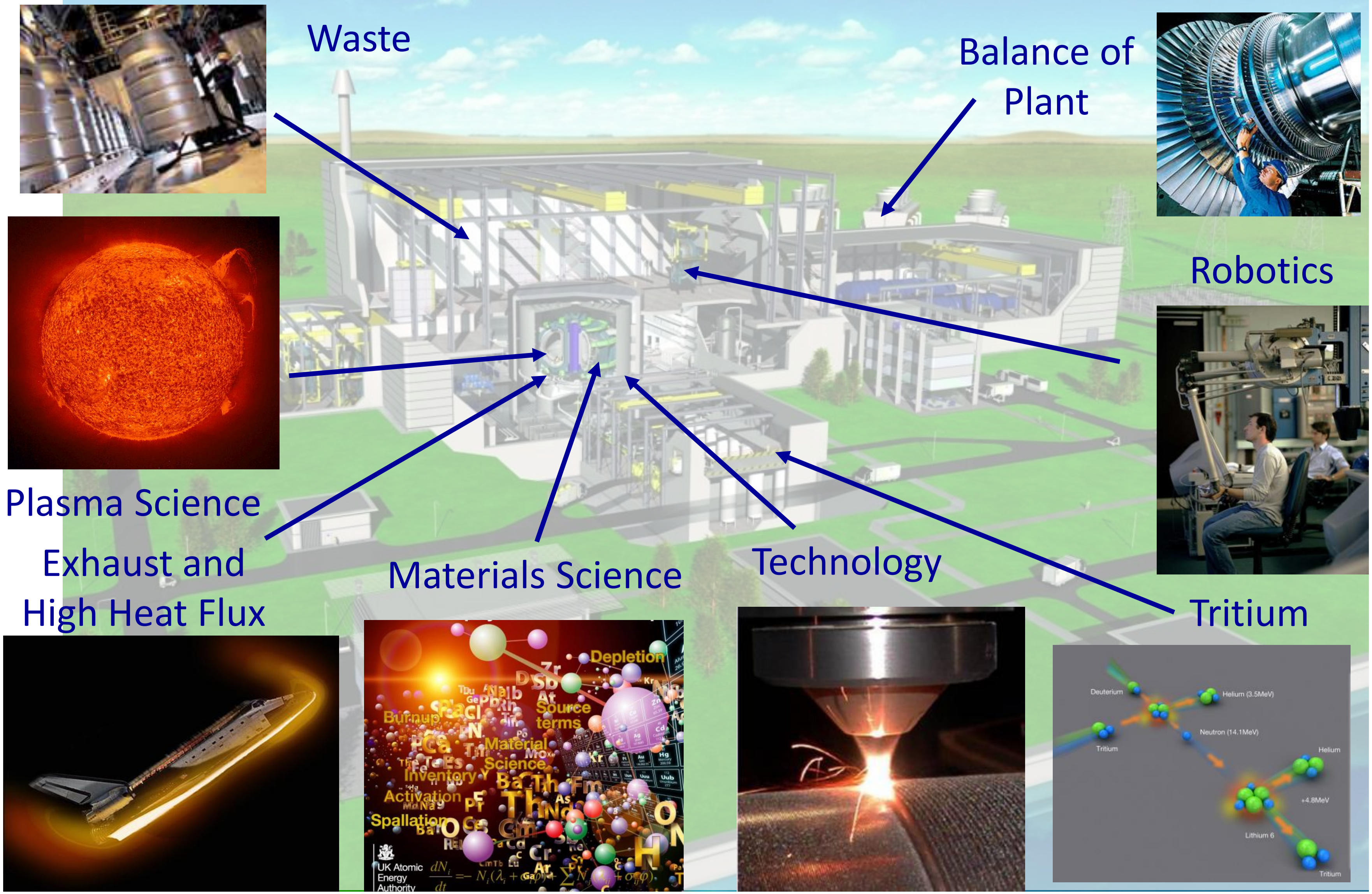
Heating & current drive systems – sustain and control plasma

Blanket – breeds tritium, converts neutrons to heat, shields vacuum vessel, coolant is first loop of thermodynamic cycle

Divertor – allows removal of He from fusion reaction & other impurities

But a fusion reactor is much more than the tokamak…..

A fusion reactor is a challenge of integration



Waste

Balance of Plant

Robotics

Plasma Science

Exhaust and High Heat Flux

Materials Science

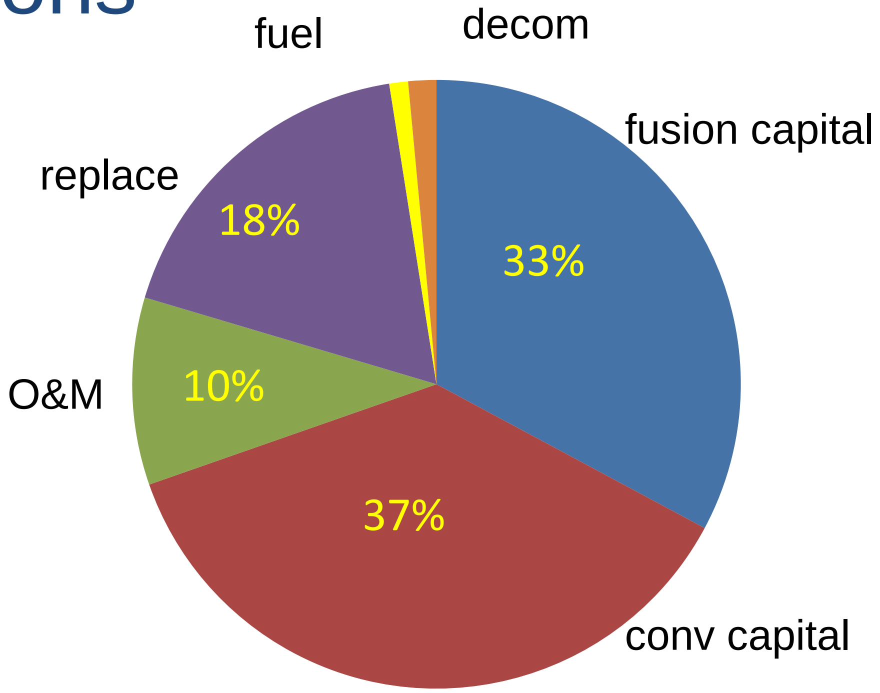
Technology

Tritium

The cost of electricity is one driver for design decisions

CoE depends on

- Capital
- Operation & Maintenance
- Fuel
- Component Replacement
- Decommissioning & Waste
- Annual electricity output
- Discount rate



10th of a kind
D Ward, IAEA
Workshop, 2005

Studies show that smaller size reduces capital cost but requires higher performance plasmas for same output power

The perception of size

Increase in size is largely due to the engineering infrastructure arising from the need for remote maintenance – the “industrialisation” of fusion

JET

ITER

DEMO

System codes provide scaling laws for CoE

PROCESS code

$$CoE \propto \left(\frac{1}{A}\right)^{0.6} \frac{1}{\eta^{0.5} P_e^{0.4} \beta_N^{0.4} N^{0.3}}$$

plant availability

thermodynamic efficiency

net electric output

ratio plasma pressure to magnetic pressure

ratio plasma density to Greenwald limit

For commercial power aim for: A>70%, η>40%, P_e depends on grid

Engineering factors dominate – particularly availability

High β_N and high N imply advanced plasma scenarios

All of these factors have practical limits that arise from physical constraints

Availability is influenced by maintenance

$$A = \frac{\sum Mean\ Time\ Between\ Failures}{\sum Mean\ Time\ to\ Replace/Repair} + \frac{Time\ Between\ Maintenance}{Maintenance\ Time}$$

Proximity to operating limits

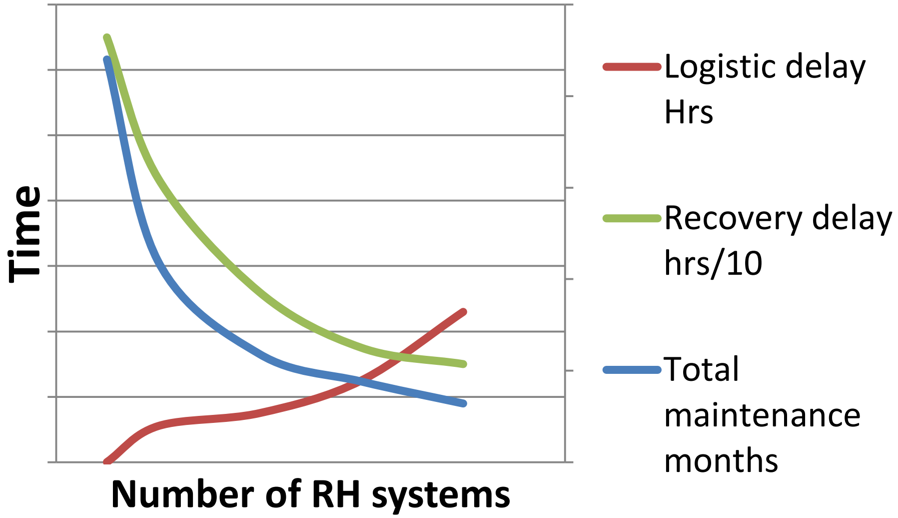
Number of redundant systems

In service component lifetime

Number of maintenance systems

Access

Complexity of process



Number and speed of maintenance systems

Equipment failure - environment

Complex procedures – lifting, turning, cutting, welding, inspection

Remote maintenance may throw up challenges

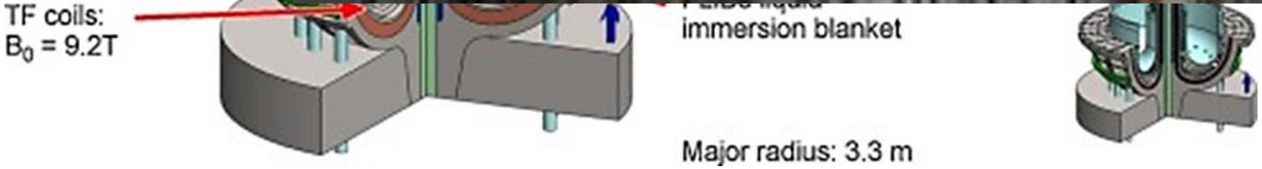
Expect lifting and movement to be easier (lowe

Providing access is not

60% of ma
time is cutt
and inspec
pipes

n

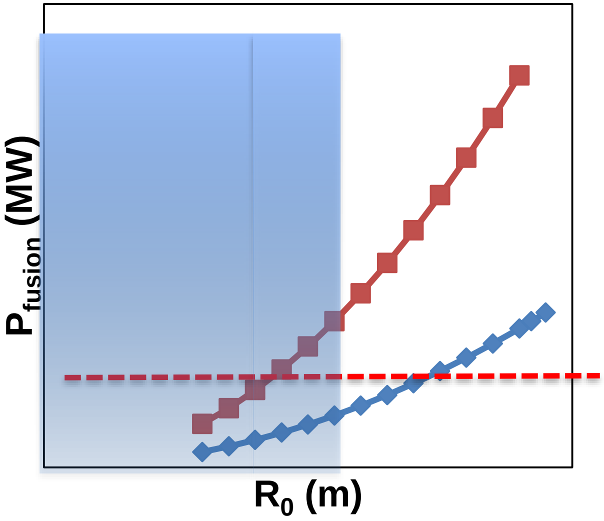
https://youtu.be/La9cc6XS2Gs



BN Sorbom, et al, Fus Eng Des, 100 (2015) 378–405

First wall and structural materials pose limits

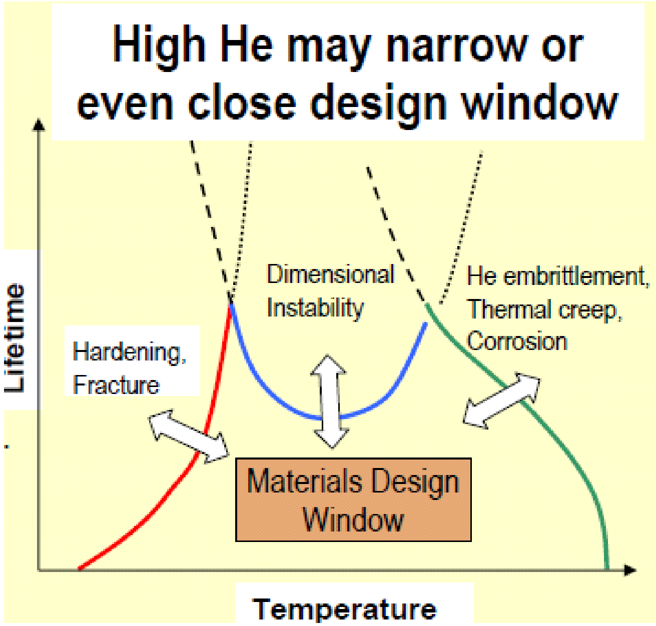
Max fusion power for given neutron wall power limit – favours lower aspect ratio (R_0/a)



Inner radial build (blanket, shield, central solenoid) reduces available R space

One solution for small reactors - remove inboard Tritium Breeding Blanket
BUT central solenoid requires shielding (~60cm)

Practical limit depends on component in service lifetime e.g. 2MWm^{-2} corresponds to ~20dpa/FPY in Fe @ FW
70% availability ~10y for tentative 150dpa limit



S. Zinkle & N. Ghoniem, J Nucl Mat **417** (2011) 2

Maintenance frequency determined by lifetime of FW, divertor and other components

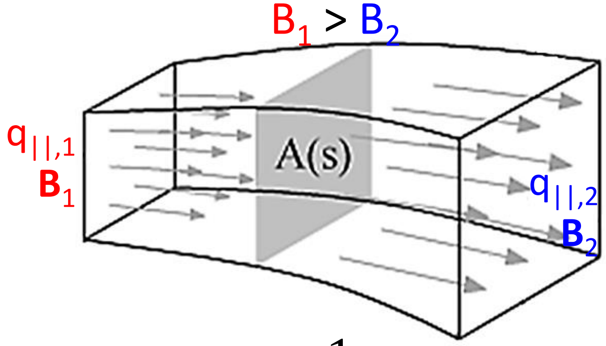
Divertor imposes limits

Heat flux to the divertor surface $q \propto \frac{P}{R} B \propto \frac{P}{R^2}$

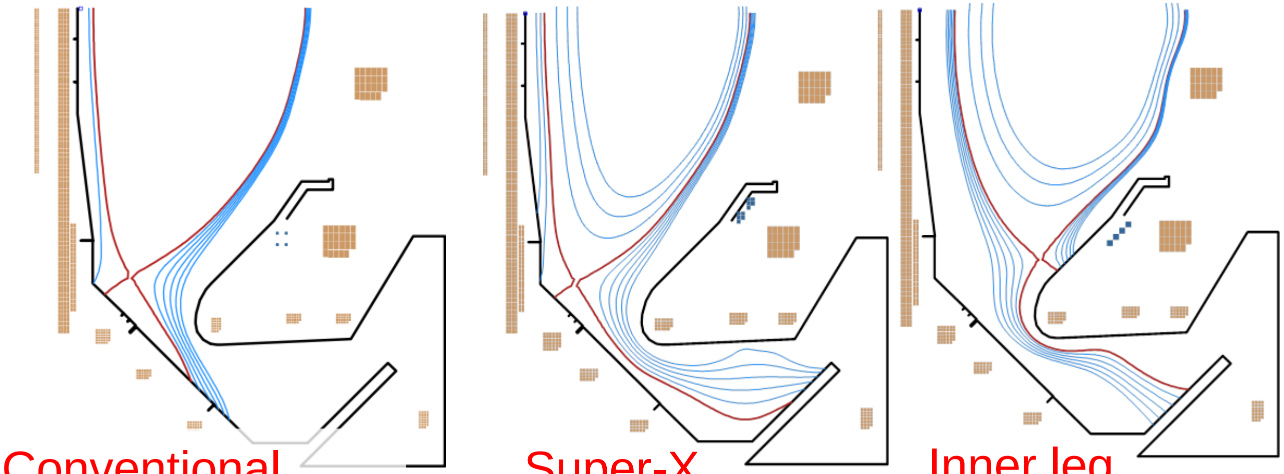
Present materials ~10-20MWm^{-2} tolerable?

ITER test bed but low availability acceptable

Alternative architectures needed



$$q_\parallel \propto B \sim \frac{1}{R}$$



Conventional

Super-X

Inner leg
Super-X

J. R. Harrison, IoP
Plasma Physics Meeting
(2017)

MAST-U will investigate. Coils will need ~ 60cm shielding in reactor

Magnet stresses impose limits on B field

Small reactors favour high B field to improve confinement $\frac{P_{fus}}{V} \propto \beta_T B_0^4$

High β tends to introduce plasma instability – increases HCD requirements

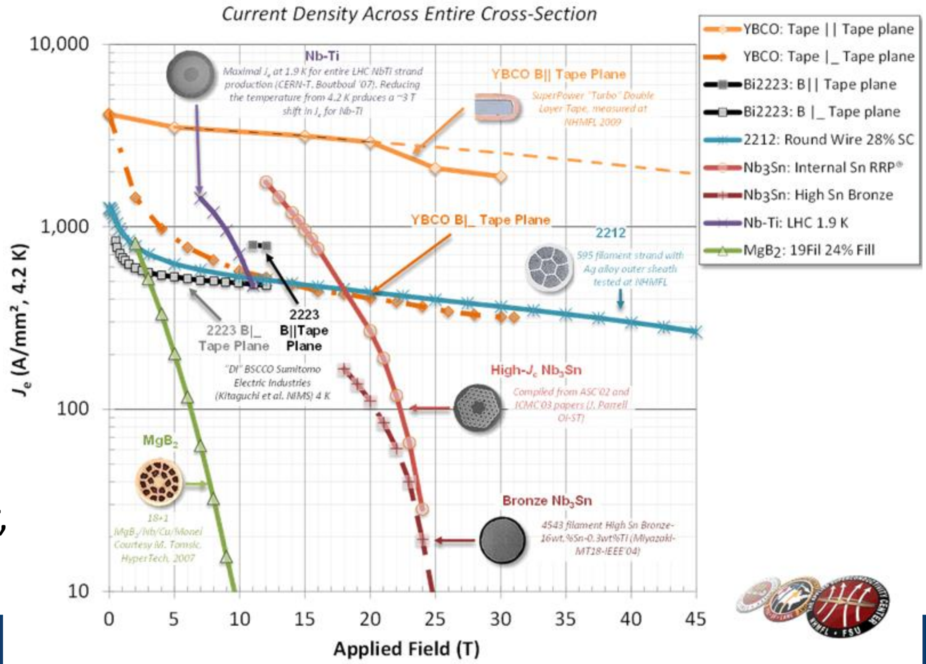
B is limited by maximum coil current density due to stress on coils

$$\langle j_{TF} \rangle \propto \frac{f\sigma - B_{TF}^2}{\sigma/_{j_{sc}} + {B_0 R_0}/_{4} \ln {R_{outer}}/_{R_{inner}}}$$

σ<UTS/3

For small tokamaks $<j_{TF}>$~15MAm^{-2}

B_{TF} limited by max j_{SC} for field at superconductor



P. J. Lee and D. C. Larbalestier, www.magnet.fsu.edu

Plasma scenarios need developing……

Operation at high β_N and high N require high energy confinement, H

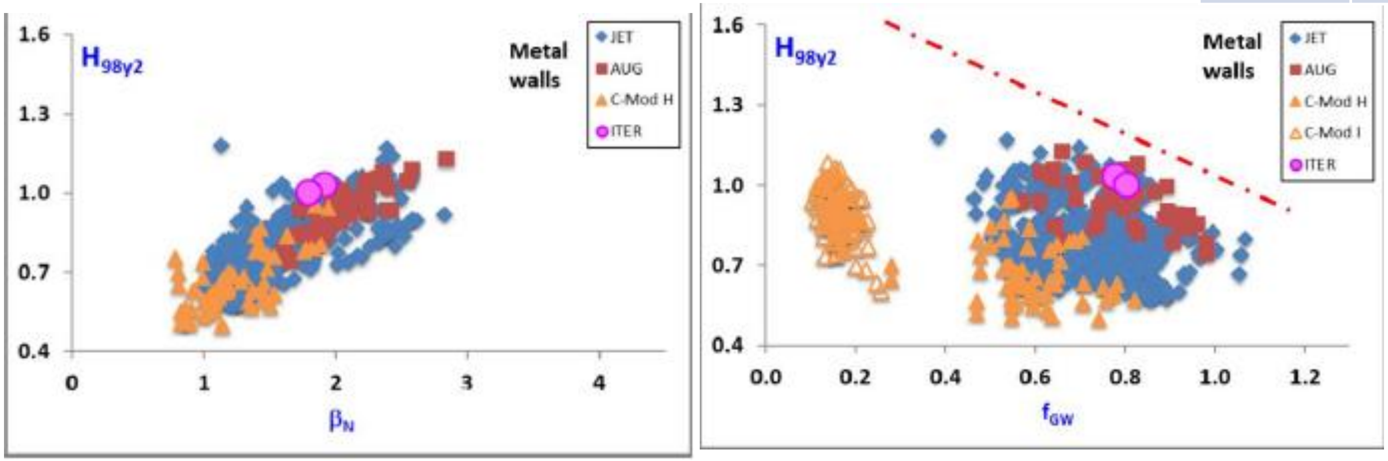
Most small tokamak power plant schemes have

$\beta_N > 3.5$, N>0.2 and H>1.3

Present data base for machines with high Z walls covers

$1<\beta_N<3$, 0.2<N<1, 0.4<H<1.2

	Aries ST	STPP	ARC
β_N	7.4	8.2	2.59
N	0.7	0.76	0.67
H	1.47	1.6	2.78



A.C.C. Sips et al, IAEA FEC 2016

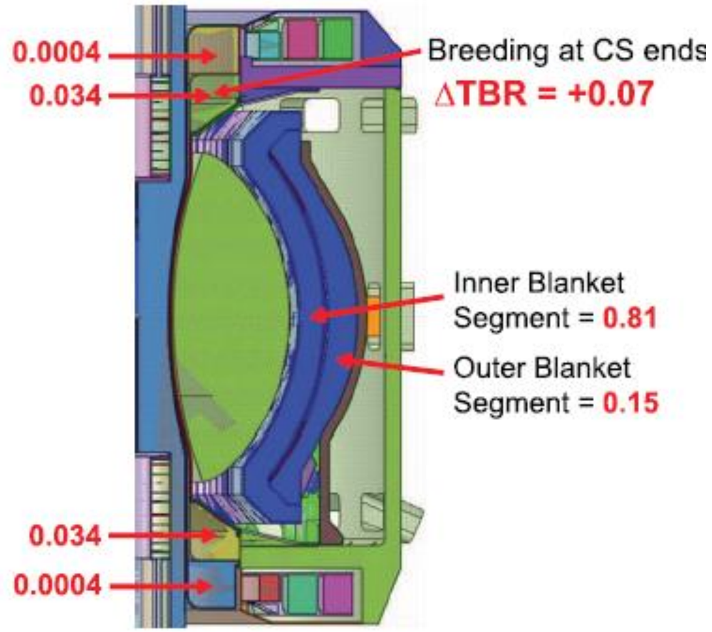
F. Najmabadi, et al Fus Eng Des 65 (2003) 143; H.R. Wilson, et al Nucl. Fusion **44** (2004) 917–929; B.N. Sorbom, et al, Fus Eng Des, 100 (2015) 378–405

Operation at high β_N and H probably require more plasma control actuators………

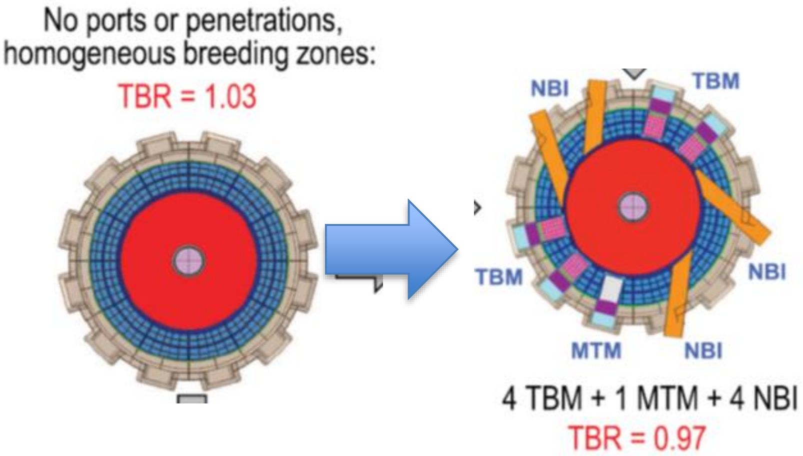
Tritium Breeding Ratio is sensitive to design

Required TBR>1.1? T retention, diffusion, 5% decay p.a.

Achieved TBR quickly eroded by heating/control/diagnostic systems



Total TBR ~ 1.03 with no penetrations or ports
(heterogenous outboard blanket)



4TBM+1MTM=-0.3TBR

NSFS R_0=1.7m

J. E. Meynard, et al, Nucl. Fus, 56, 106023, 2016

Maintaining TBR is more difficult for smaller reactors ….especially if actuators require penetrations

Ratio of structure to breeder volumes may increase – design dependent

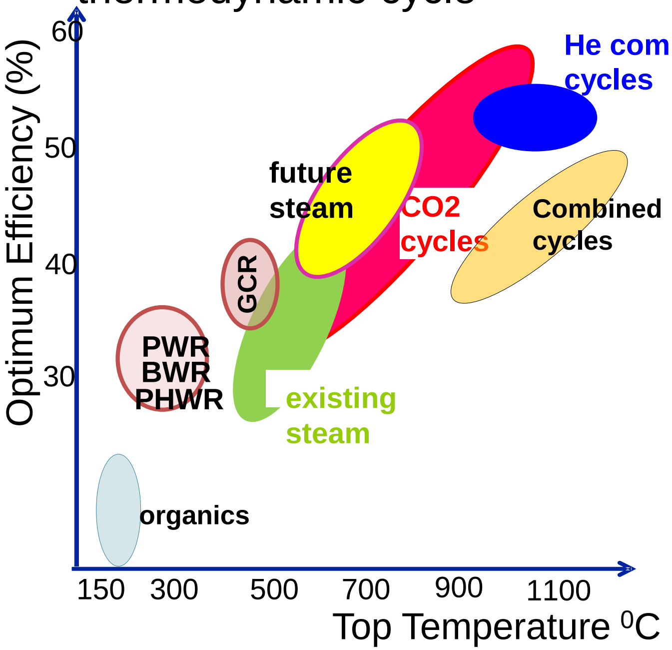
Auxilliary systems will impact on net electricity

$$P_e = \eta P_{th} - P_{aux} \qquad P_{aux} = P_{HCD} + P_{mag} + P_{BOP}$$

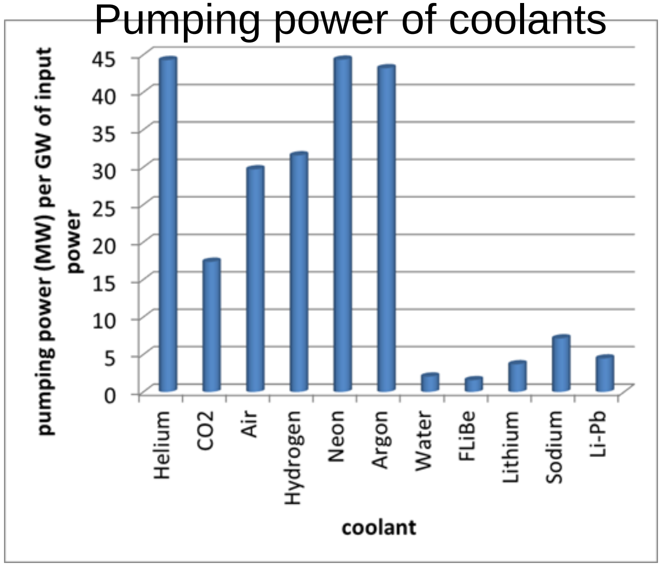
~ 50MW typical

present efficiencies 25-50% =>~150MW

Efficiency of thermodynamic cycle



Pumping power of coolants



Need to maximise efficiency of HCD, magnet cryo and BoP (includes coolant choice)

The grid imposes its own requirements

Varies with location

Western Europe, USA nodal grids – small number of large (>1GW$_e$) generating units

Developing world possibly distributed grids – large number of small generation units

The two are not easily compatible: voltage, frequency, waveform, voltage stability, harmonics, reliability, protection and control

Increasing number of units leads to “congestion” and requires new grid management methodologies (IEA Repowering Markets 2016)

Is it feasible to operate multiple small reactors as a node?

Not everything can be scaled or shared:

Scaled with fusion power	Scaled with size	Shared	Scaled with number	Other
Tritium consumption & fuelling systems	Structure to breeder ratio	Tritium storage Tritium breeding process plant	Tritium inventory, Tritium fuel plant	Blanket thickness independent
Balance of plant	Nuclear infrastructure and buildings	Balance of plant (some)	Nuclear infrastructure and buildings	Shielding thickness independent
			Safety systems	
Magnet coils	Magnet coils	Cryo plant	Cryo plant	
Divertor power	Divertor power	Coolant plant	Coolant plant	
Auxiliary power			Auxiliary power	

Summary on size effects…..

- Some aspects are made more difficult by small size – divertor power loading, coil stress, wall loading, maintenance access(?), TBR(?)
- Some aspects are improved – reduced capital cost, easier manufacture(?)
- General move towards higher performance plasmas for small machines – scenarios to be developed
- Possibly TBR more sensitive to penetrations

Challenges of small fusion reactors are…

- Basically the same as for large reactors – integrating several interdependent systems
- Ensuring….