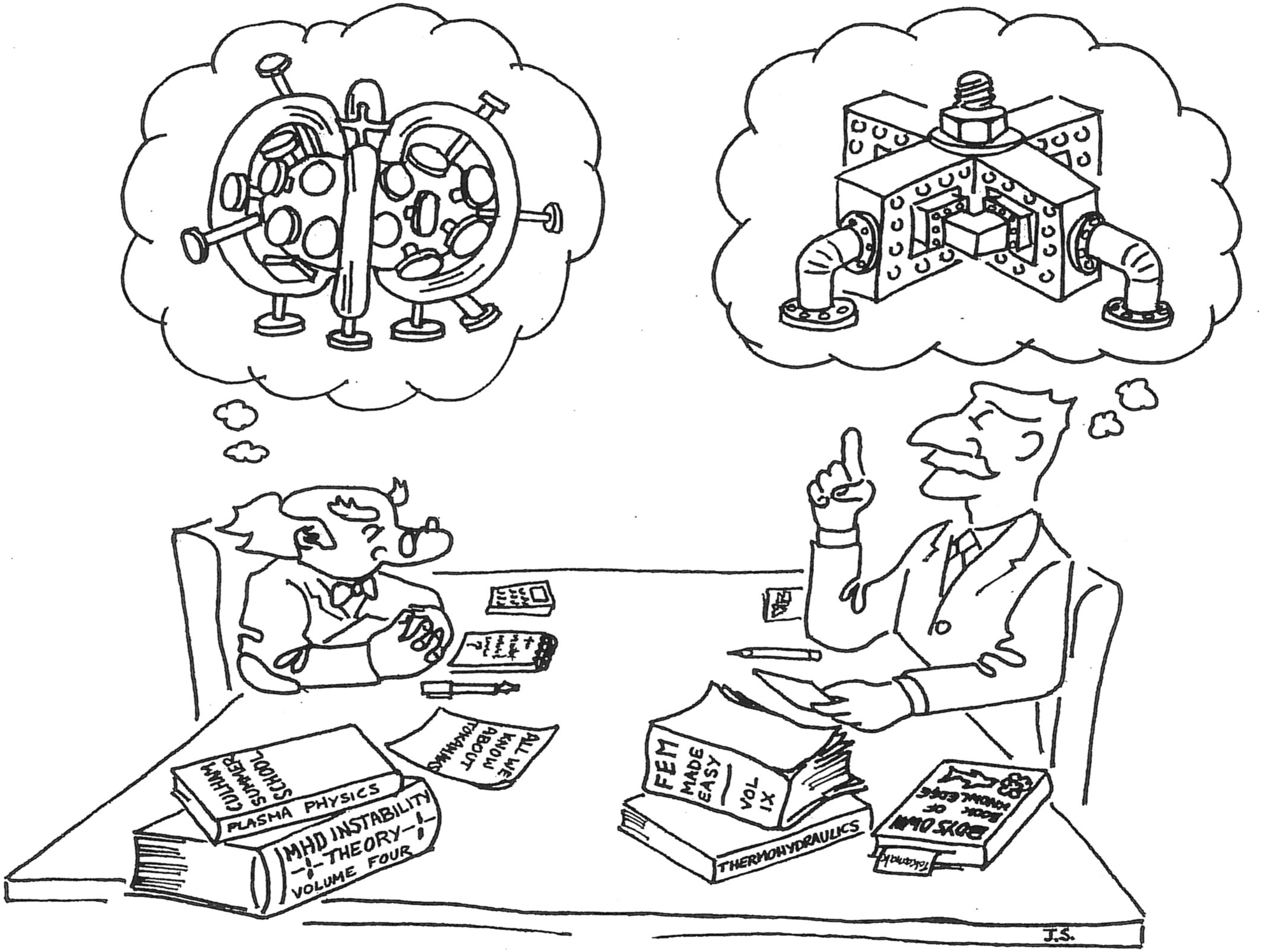
How to Build a Tokamak

or “Engineering Issues for Physicists”

- **Topology**
- **Toroidal Field System**
- **Design Tools**
- **Poloidal Field System**
- **Power Supplies**
- **Support Structure**
- **Vacuum Vessel**
- **Limiters and Armour**
- **Machine Assembly**

This talk is based (increasingly loosely) upon Chapter 17 of the Culham Summer School book ‘Plasma Physics, An Introductory Course’. Ed RO Dendy CUP 1993

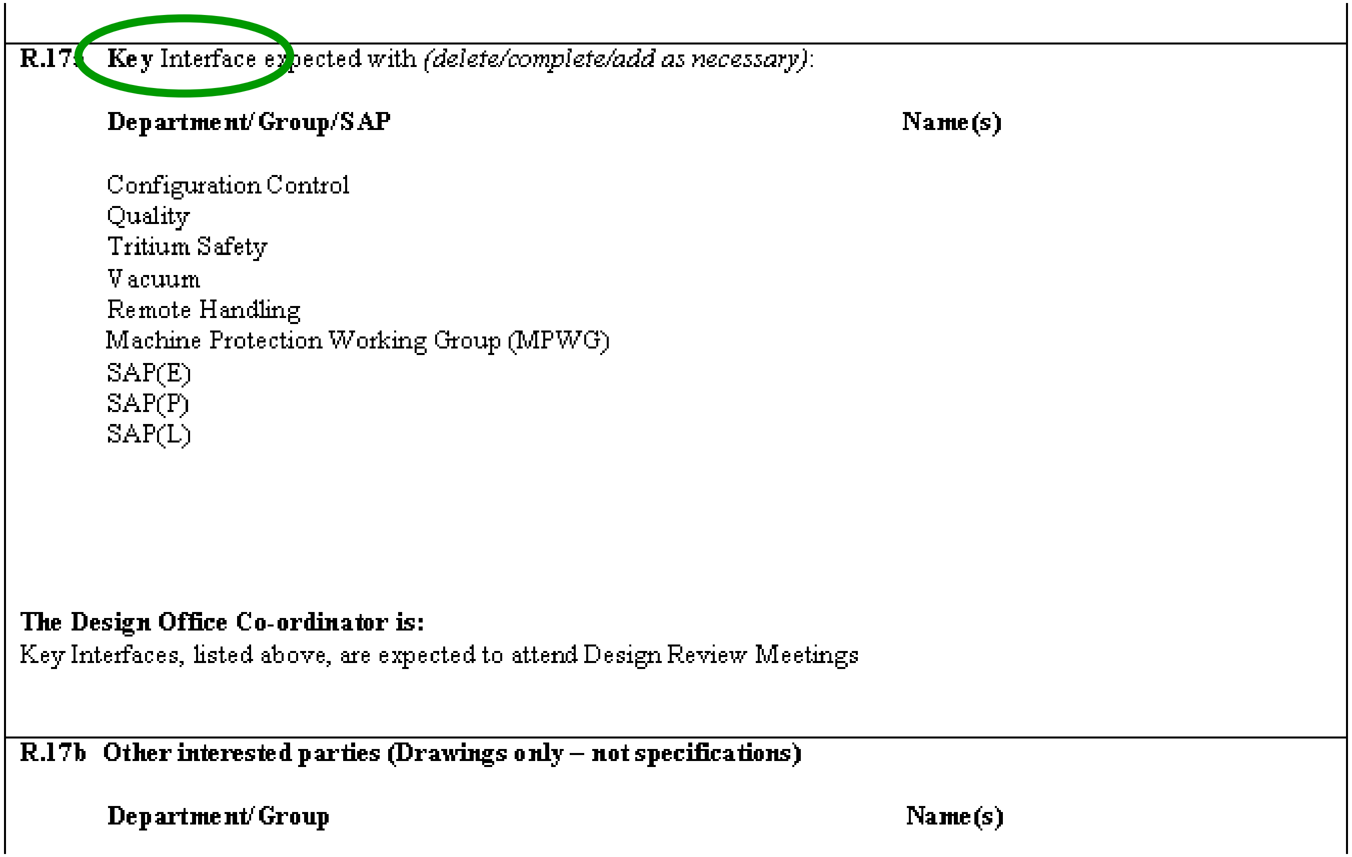
TOKAMAK DESIGN PROCESS:- STAGE 1



New design studies start with a “TCD-R” or PERF

The Design & Assembly Coordination Committee agrees:

- Safety classifications
- Drawing Office allocations
- Key “Interfaces”



R.17 **Key** Interface expected with *(delete/complete/add as necessary)*:

Department/Group/SAP **Name(s)**

Configuration Control
Quality
Tritium Safety
Vacuum
Remote Handling
Machine Protection Working Group (MPWG)
SAP(E)
SAP(P)
SAP(L)

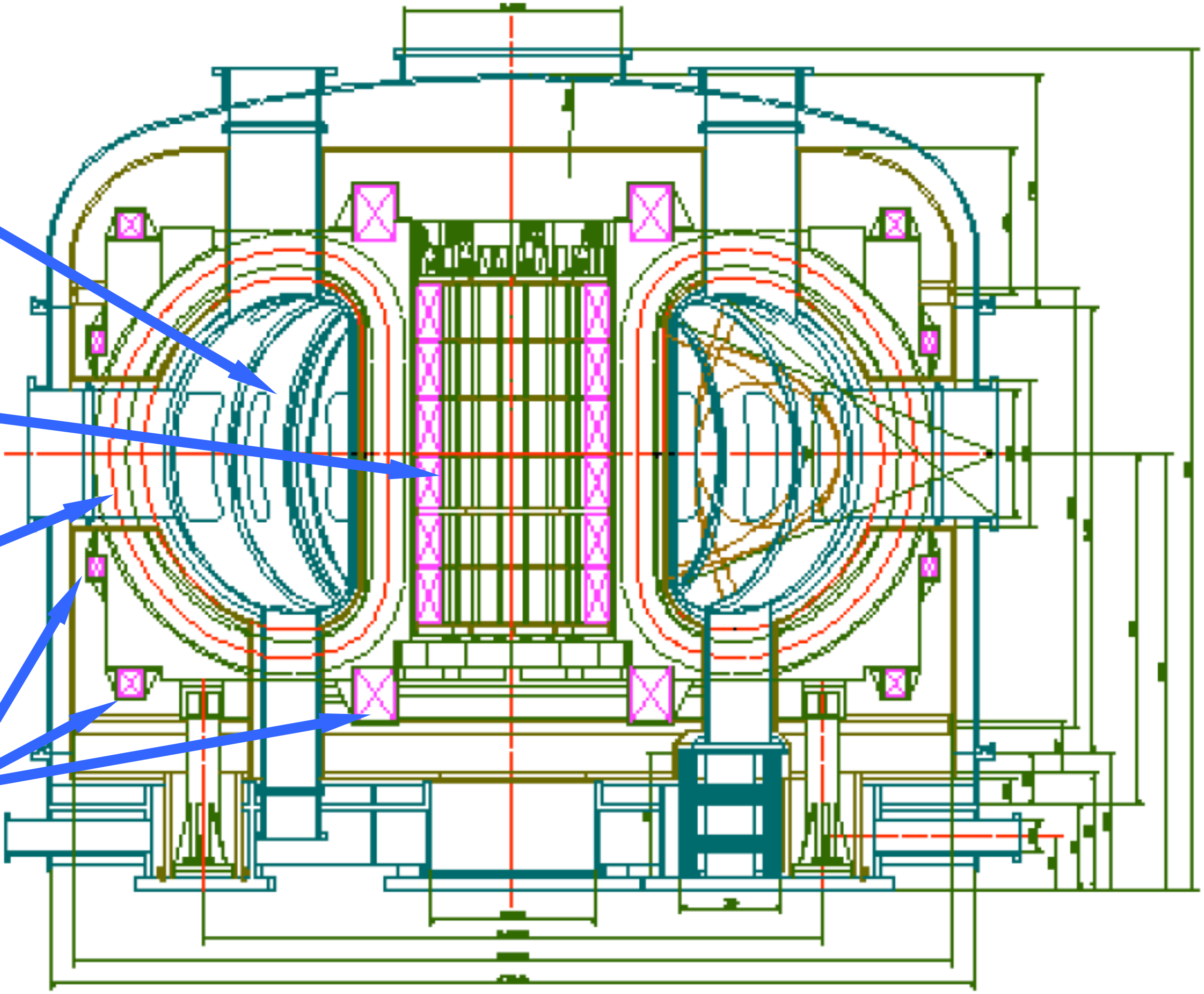
The Design Office Co-ordinator is:
Key Interfaces, listed above, are expected to attend Design Review Meetings

R.17b Other interested parties (Drawings only – not specifications)

Department/Group **Name(s)**

Topology - Example: **EAST** (née HT-7U) Full Superconducting Tokamak

I_p = 1 MA, t=1000s, DN, B_T = 3.5T, R= 1.75m, a/b = 40/80 cm



Plasma chamber

Solenoid

Toroidal field coils

Poloidal field coils

Topology

An early design option is to choose which coils are nearest to the plasma – toroidal or poloidal

Coils near plasma:	Advantages	Disadvantages
Toroidal Field		
Poloidal Field, including Solenoid		

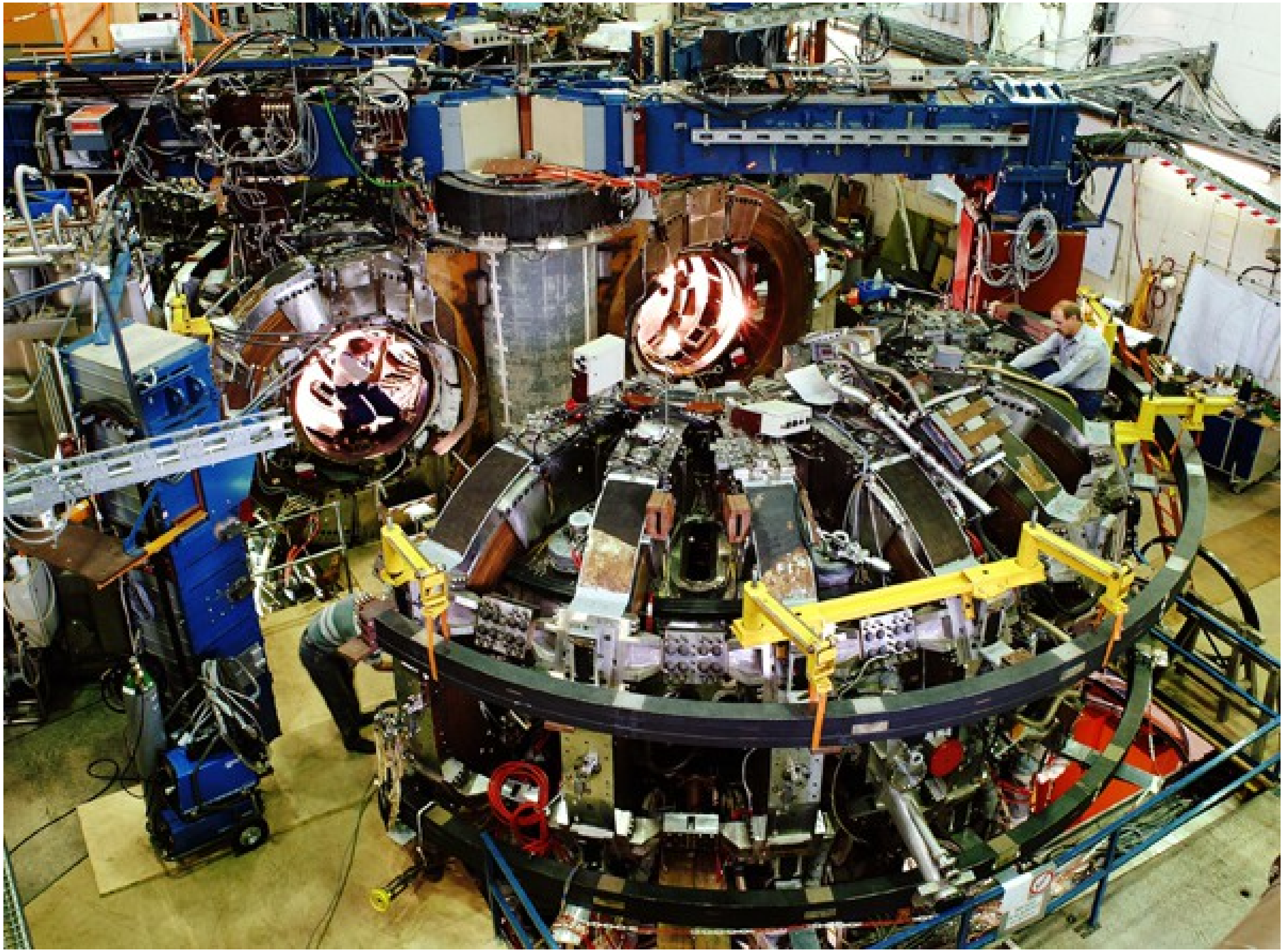
Topology

An early design option is to choose which coils are nearest to the plasma – toroidal or poloidal

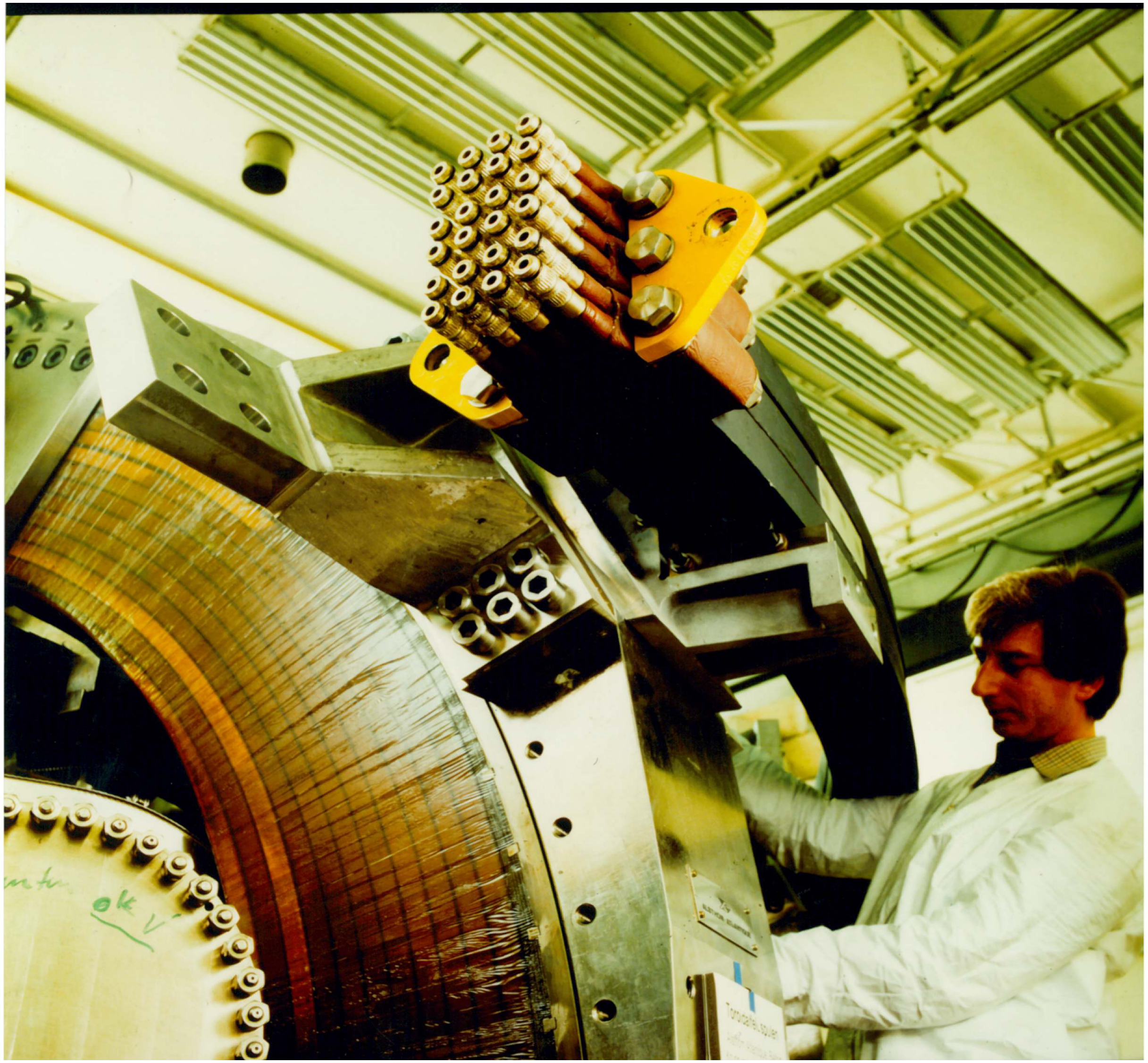
Coils near plasma:	Advantages	Disadvantages
Toroidal Field	Smallest possible stored magnetic energy. No interlinking of coils.	Many coils needed to avoid severe ripple. Restricted OH solenoid diameter if air-cored. Difficult to get strong plasma shaping.
Poloidal Field, including Solenoid	Easy to shape plasma. Possible gain in plasma vertical stability. Largest possible (air-cored) OH solenoid diameter. Can use fewer TF coils. Good access for (small) diagnostics.	Interlinked coils, therefore joints somewhere. Larger TF stored energy.

These considerations lead to a variety of design solutions …

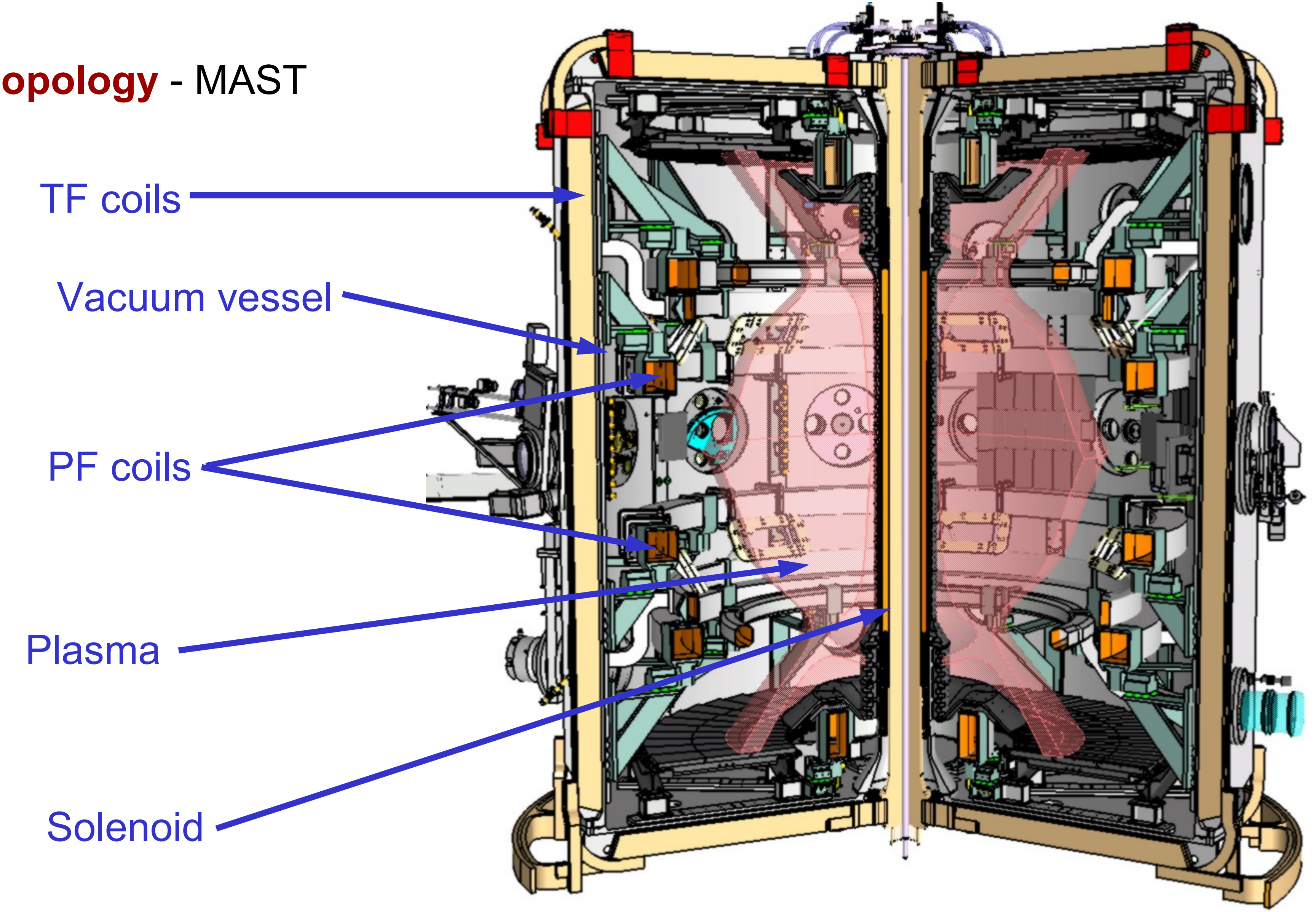
Topology - TEXTOR: Split Vacuum Vessel <u>and</u> PF Coils



Topology - Detail of TEXTOR Split Poloidal Field Coils



Topology - MAST



TF coils

Vacuum vessel

PF coils

Plasma

Solenoid

Toroidal Field Coils

Stray Fields

i. **Average perpendicular fields** which inhibit plasma breakdown and require feedback control to avoid plasma motion during the shot.

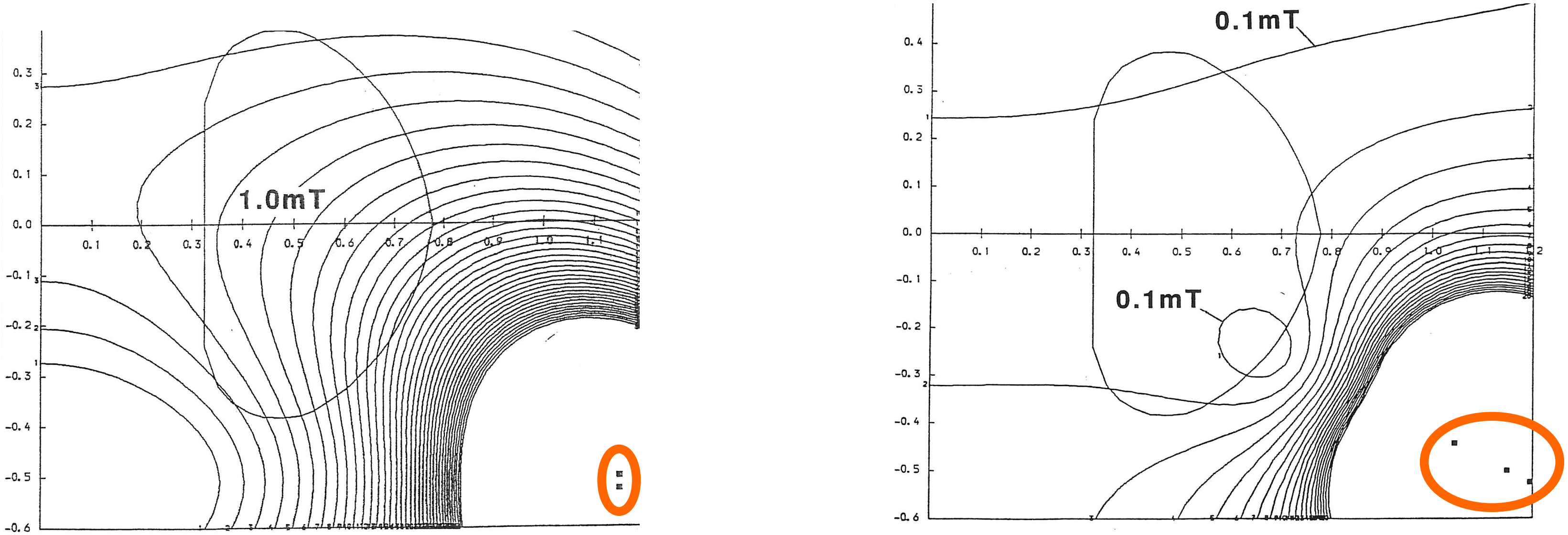
The perpendicular fields usually originate from systematic (or net) tilt errors in the placement of the coils, and/or from the coil interconnection scheme if this is not well thought out.

Conventionally one tries to achieve $B_\perp / B_\varphi << 10^{-3}$, directly mapped to tilt-angles in radians.

COMPASS-D Toroidal field coil inter-connection bars (1.75T at R_o):

- unoptimised dipole

- optimised quadrupole

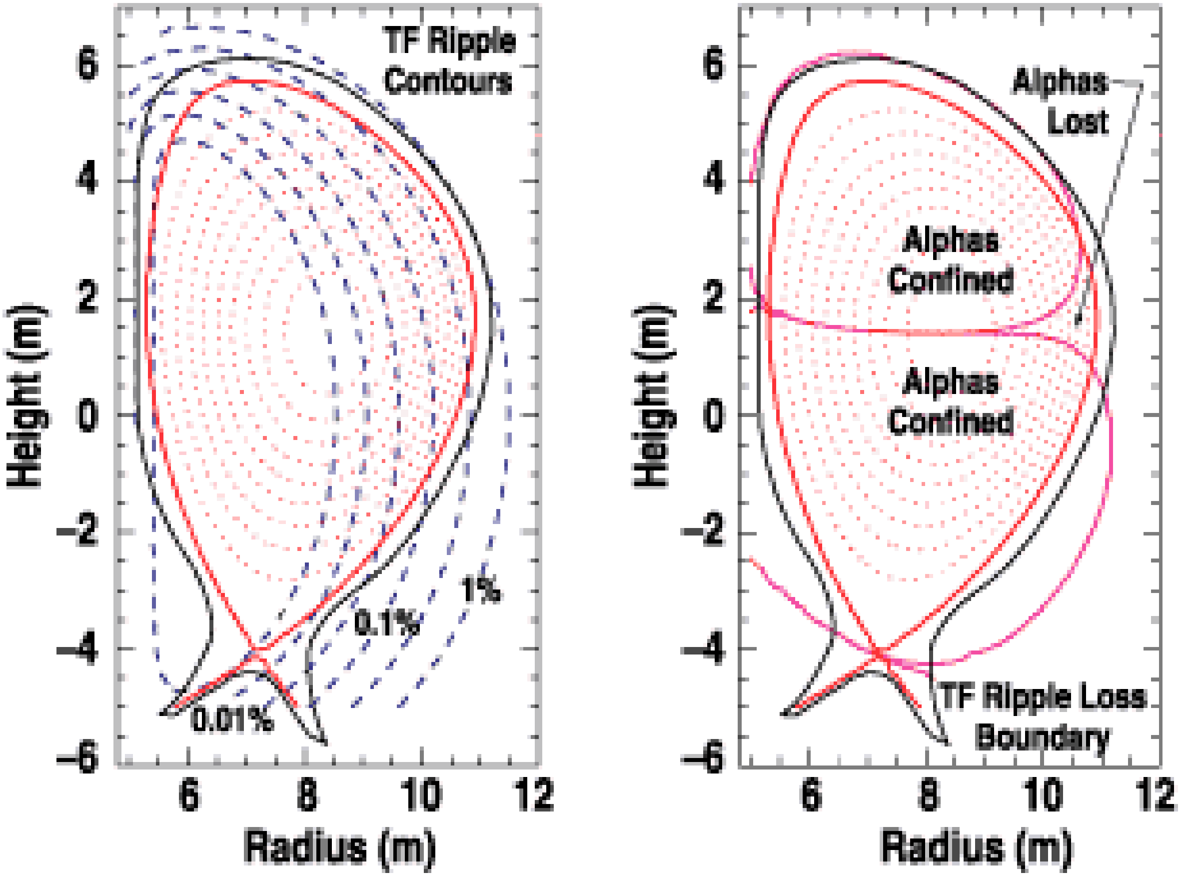


Toroidal Field Coils

Stray Fields

2 Ripple

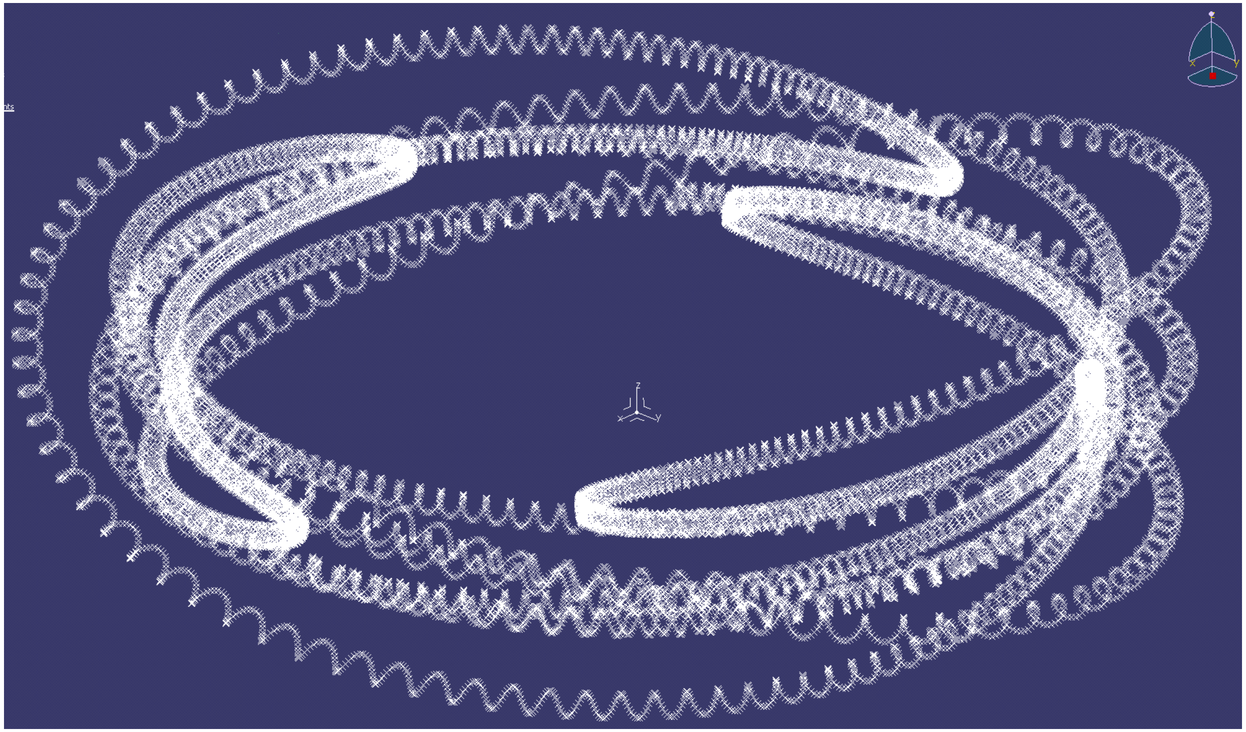
This is due to the discretisation of the return limbs of the TF coil set, which makes the TF “lumpy”, randomising the turning points of the trapped ions (banana orbits – see next slide) and hence creating an additional diffusive loss term for the plasma ions.



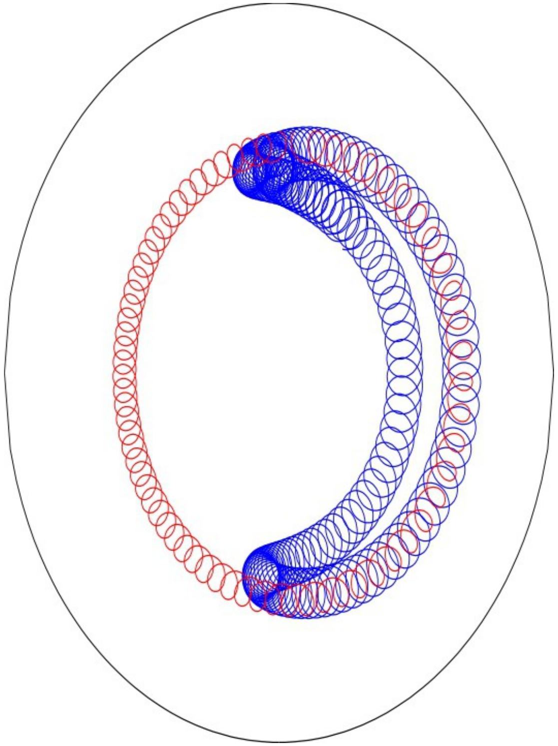
TF Ripple in ITER

Toroidal Field Coils

Stray Fields: ripple in the toroidal field muddles the turning points of the fast ion banana orbits, which basically look like this:



Isometric 3D view of a full banana orbit



2D projection into the poloidal plane of one banana orbit and one "passing particle".

Toroidal Field Coils

Stray Fields

iii. **Resonant magnetic perturbations** which tend to create **magnetic islands** in the plasma region, affecting plasma confinement and stability (eg via “mode lock” phenomena).

- The resonant magnetic perturbations primarily originate from random asymmetries in placement of the coils, and from non-axisymmetric stray fields generated by the feeder bars.

Toroidal Field Coils

Stray Fields - **magnetic islands**

The island width formula can be expressed as:

$$\frac{W}{a} = \sqrt{\frac{16}{n}\left(\frac{\tilde{b}_r}{B_{\varphi 0}}\right)\left(\frac{R}{a}\right)\left(\frac{r_q}{q}\right)}$$

where W is the full width, n is the toroidal mode number, $\tilde{b}_r$ is the perturbation field, $B_{\phi 0}$ is the toroidal field and $r_q = q / \nabla q$.

Hence for $W / a \leq 0.1$ (ignoring any plasma amplification or attenuation) typically

$$\frac{\tilde{b}_r}{B} \leq 0.1^2 \, x \, \frac{1}{16} \, x \, \frac{1}{3} \, x \, 1 \approx 2 \, x \, 10^{-4}$$

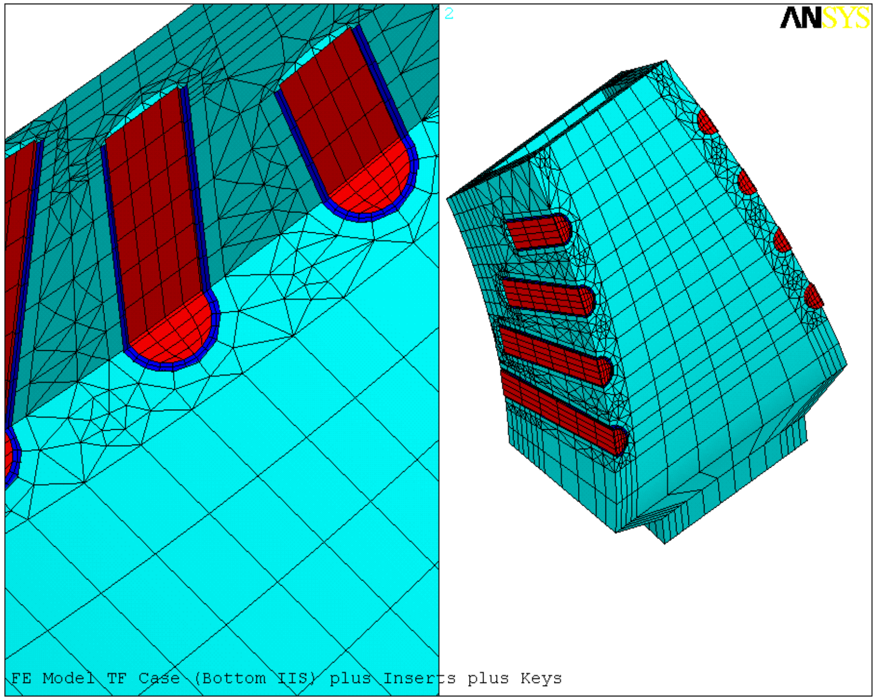
which is quite demanding (unless mode-locking and island formation are inhibited by rapid plasma rotation, as is usually true for small machines).

Toroidal Field Coils

- The TF coil system has to be heavy enough to tolerate the forces upon it, which are primarily the self (i.e. bursting) force and the toppling force immediately following a plasma disruption (due to the vertical field remaining after the plasma current has disappeared).
- The integral of these forces around the coil gives rise to tensile and bending stresses (pure tension for the self-force on an appropriately D-shaped coil) which have to be kept below ~120MPa for conventional OFHC copper, 200MPa or more for special copper alloys.
- Usually a significant shear stress arises in the insulators separating the segments of the TFC vault (ie. twisting the vault), due to the TFC current crossing the radial component of the end-field of the Ohmic heating solenoid.
- The “pinch force” on the vault conductors helps the insulator to survive the shear stresses by putting it into compression.

The original early 1990’s talk featured many approximate stress equations, but these days almost all stress analyses are done by FEA.

Finite Element Analysis in tokamak design – meshes



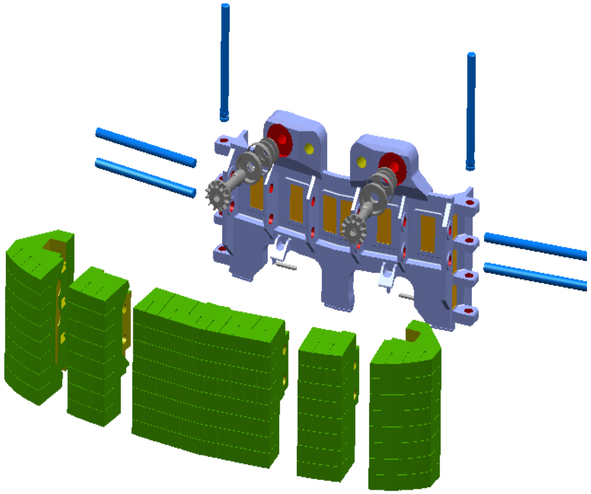
- ITER TF Coil Case FE mesh detail, near anti-shear keys

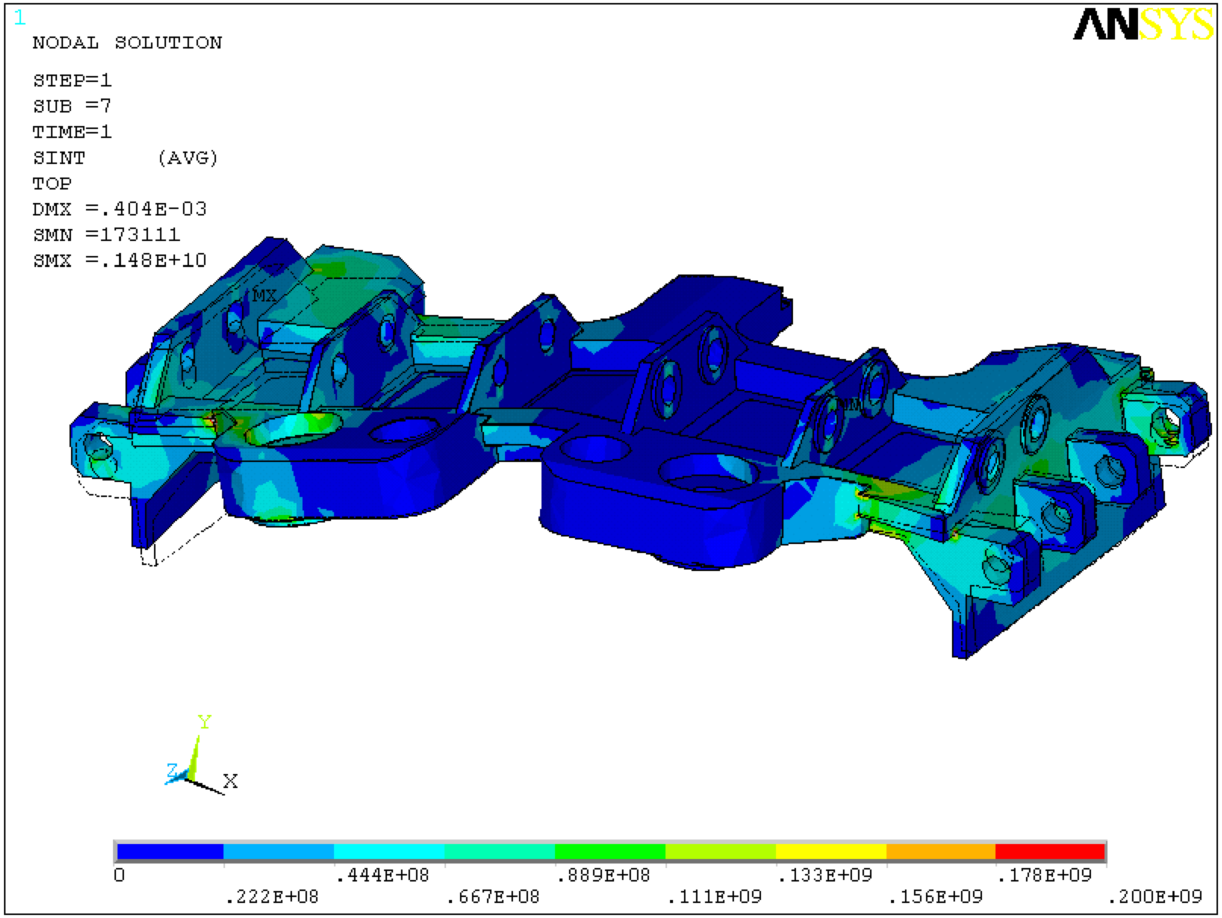
Typical questions / checks for FEA:

- Is it an elastic (linear) or plastic analysis?
- What material properties were used?
- Are there any singularities?
- Did you do a mesh convergence study?
- What were the boundary conditions?
- Where were planes of symmetry or reflection used?
- Were any “slip planes” used at component junctions?
- Where was high (or low) friction needed, and what was assumed?
- What special physics effects were used (e.g. CFD)?
- Did you make a rough hand calculation?

Finite Element Analysis in tokamak design – often detailed

JET ITER-Like Wall – Inner Wall Guard Limiter carrier





```
1
NODAL SOLUTION

STEP=1
SUB =7
TIME=1
SINT      (AVG)
TOP
DMX =.404E-03
SMN =173111
SMX =.148E+10
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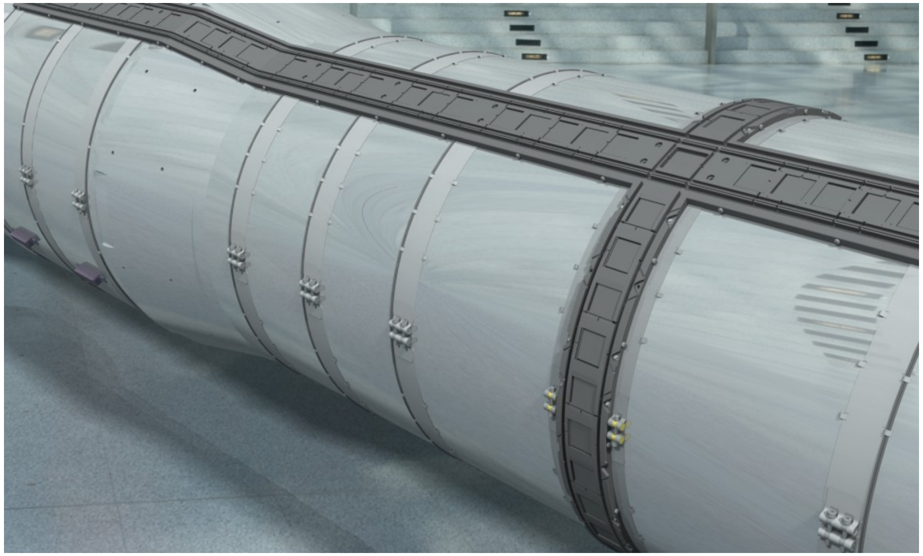
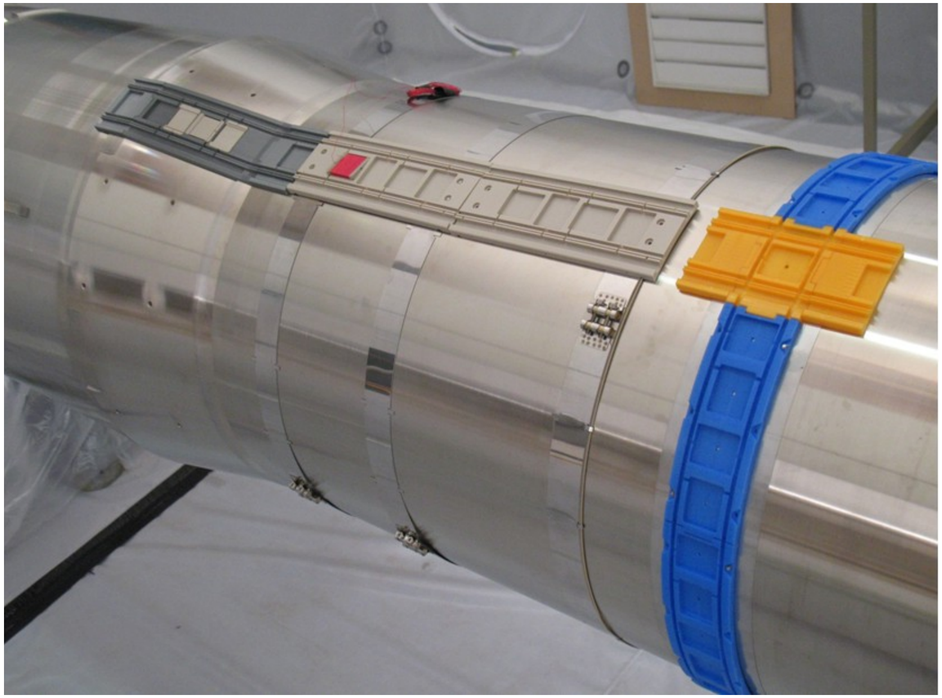
MAST-U Centre Column magnetic diagnostic (cuboid) coil holder blocks

Reality trial by 3D printing (by Gyrobot Ltd).

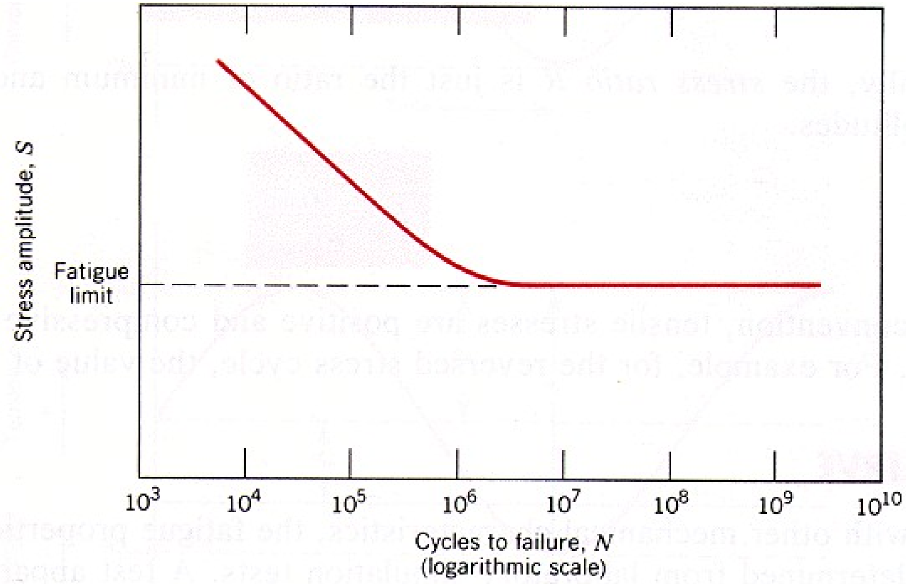


CAD Virtual Reality render

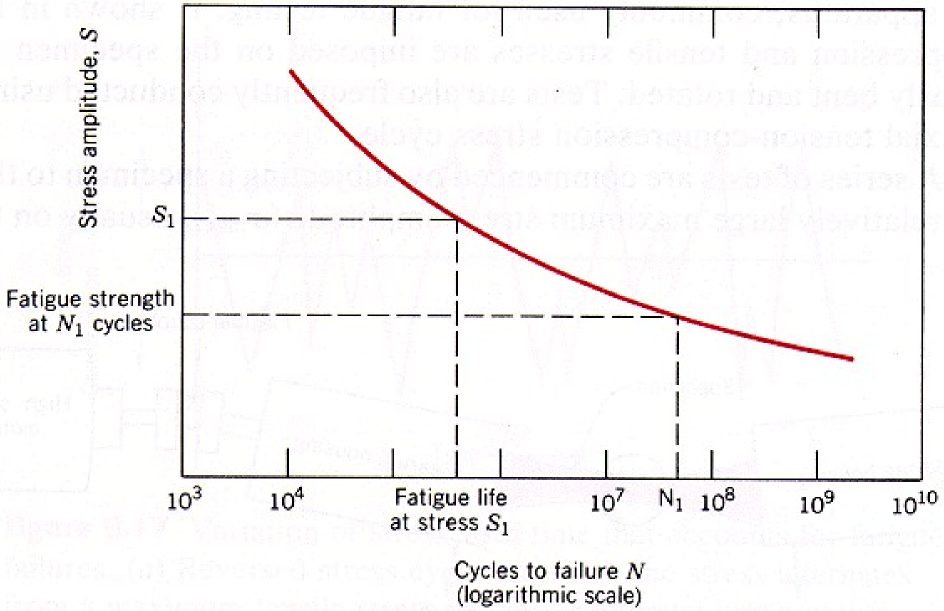


Fatigue – the S-N (Wohler) curve

- If the curve becomes horizontal, the material has a *fatigue (endurance) limit*, eg ferrous and titanium alloys.
  - The fatigue limit for steel is typically 35 to 60% of the ultimate tensile strength of the material.



  - In many cases, the S-N curve does not flatten out, eg copper, aluminium, magnesium alloys.
  - The *Fatigue Strength* is the stress level at which the material will fail after a specified number of cycles, the *Fatigue Life*.



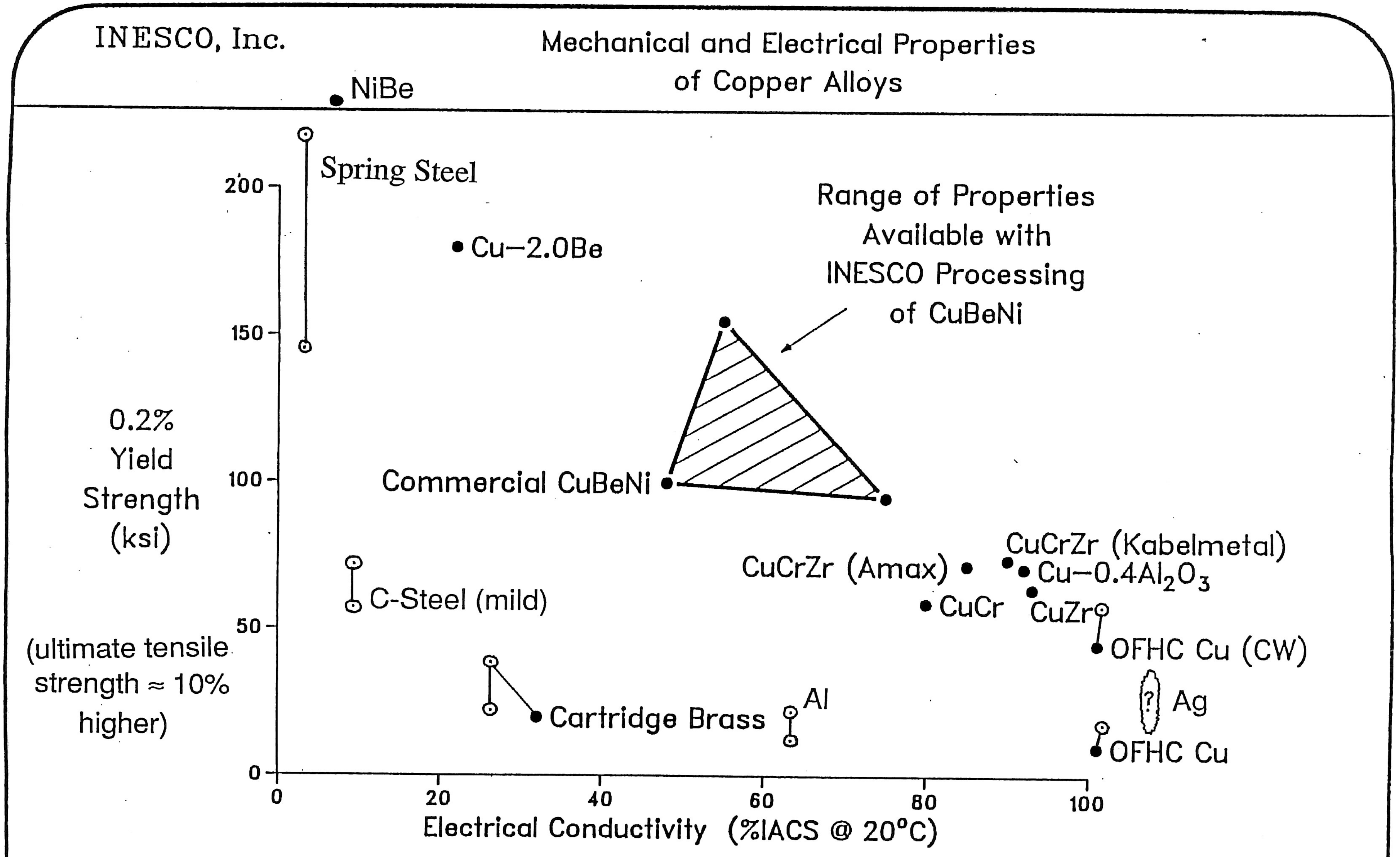
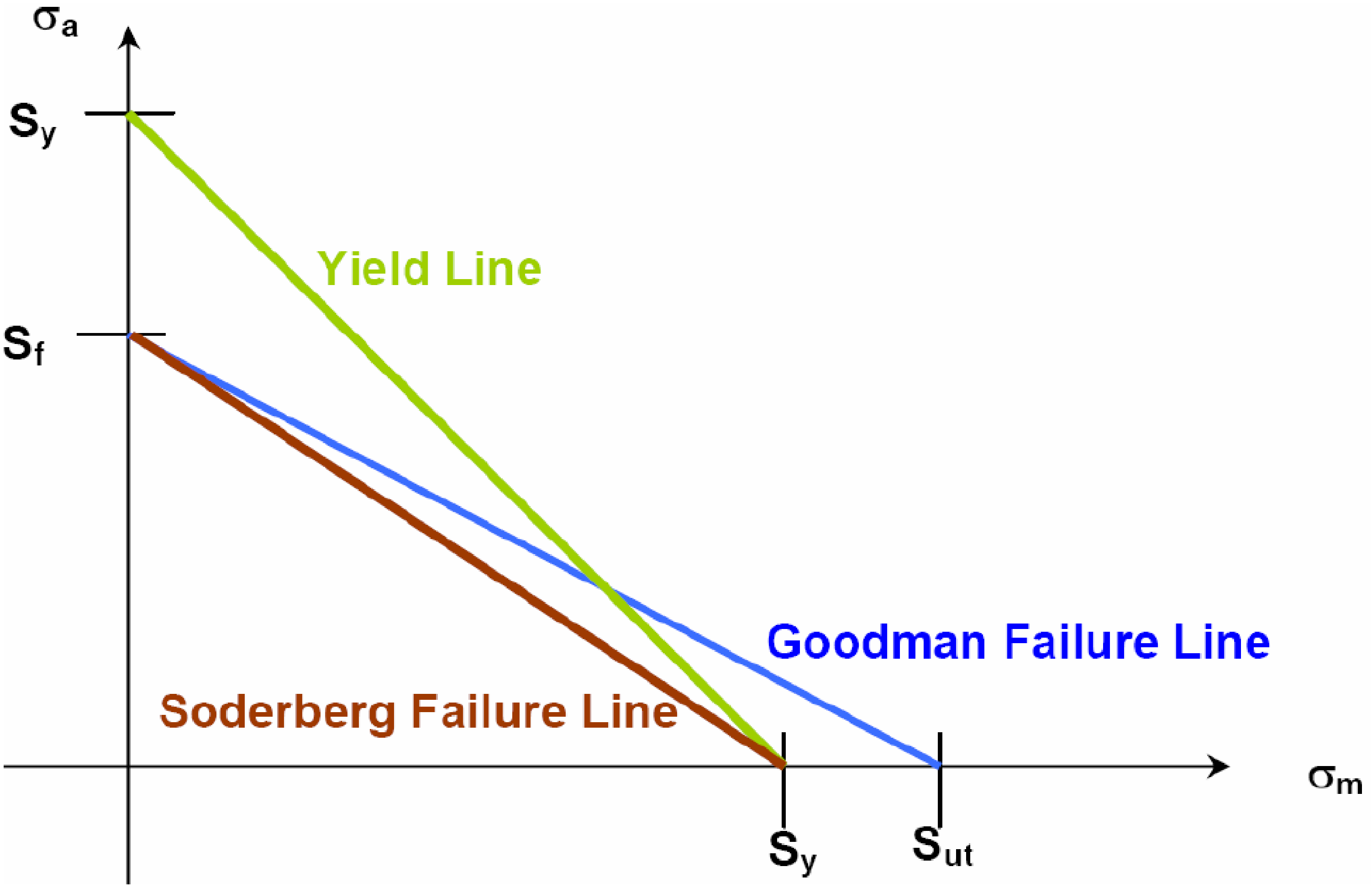
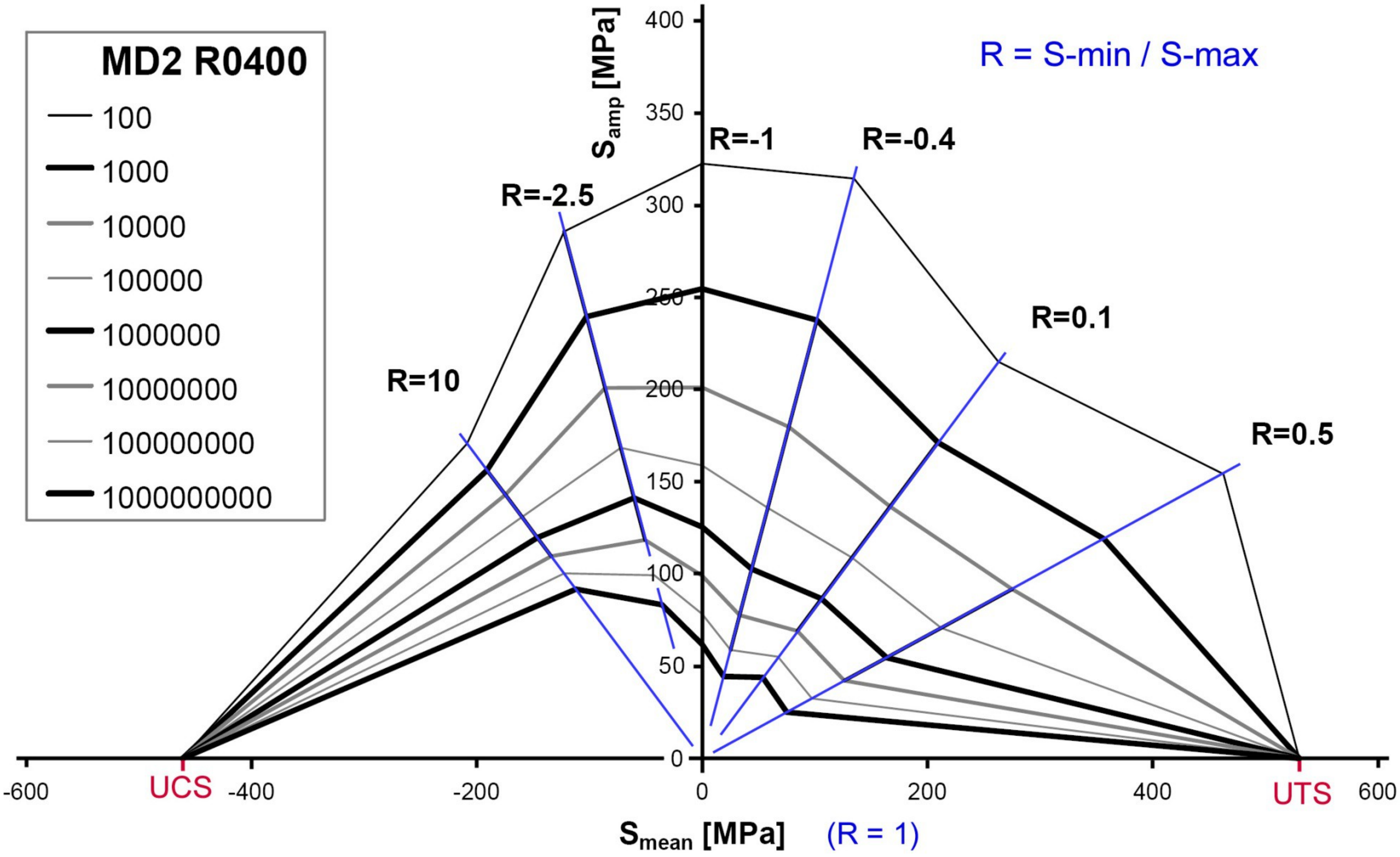


Fig 7 Properties of conducting materials: strength versus conductivity.
Inconel has a yield strength of ≈75ksi and conductivity of 1.3% IACS. (100% IACS = 1.7241 micro-Ω-cm)

Fatigue - Goodman diagram for offset stress cycling (theory)

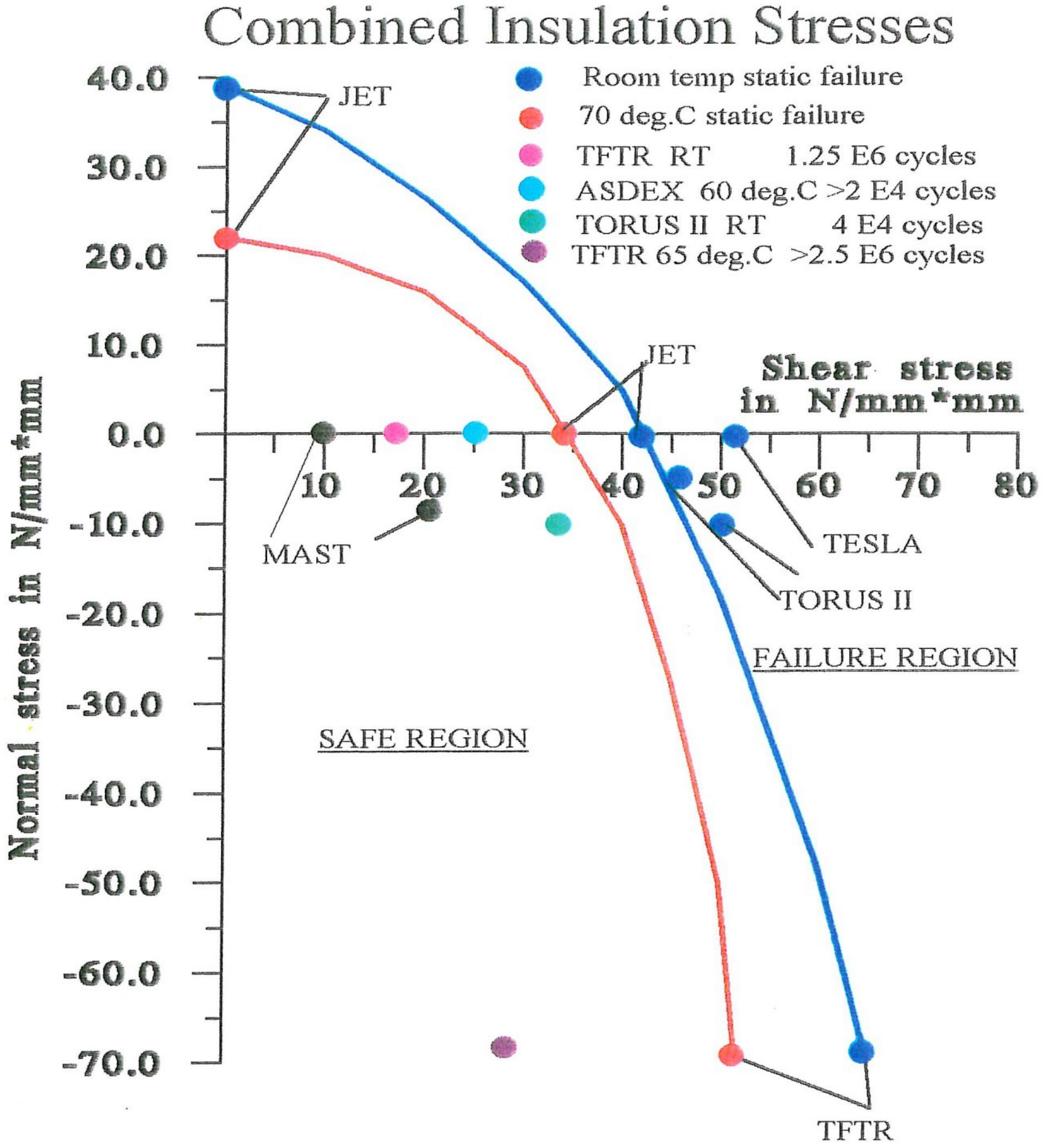


Fatigue - Goodman diagram for offset stress cycling (example)



Wind Turbine Epoxy GFRP

Fatigue - Mohr diagram for glass-reinforced epoxy resin



Toroidal Field Coils

- However heating in the coils is often more of a problem than the mechanical stresses imposed and frequently a compromise between strength and conductivity is required.
- The Ohmic heating rate in a conductor is given by

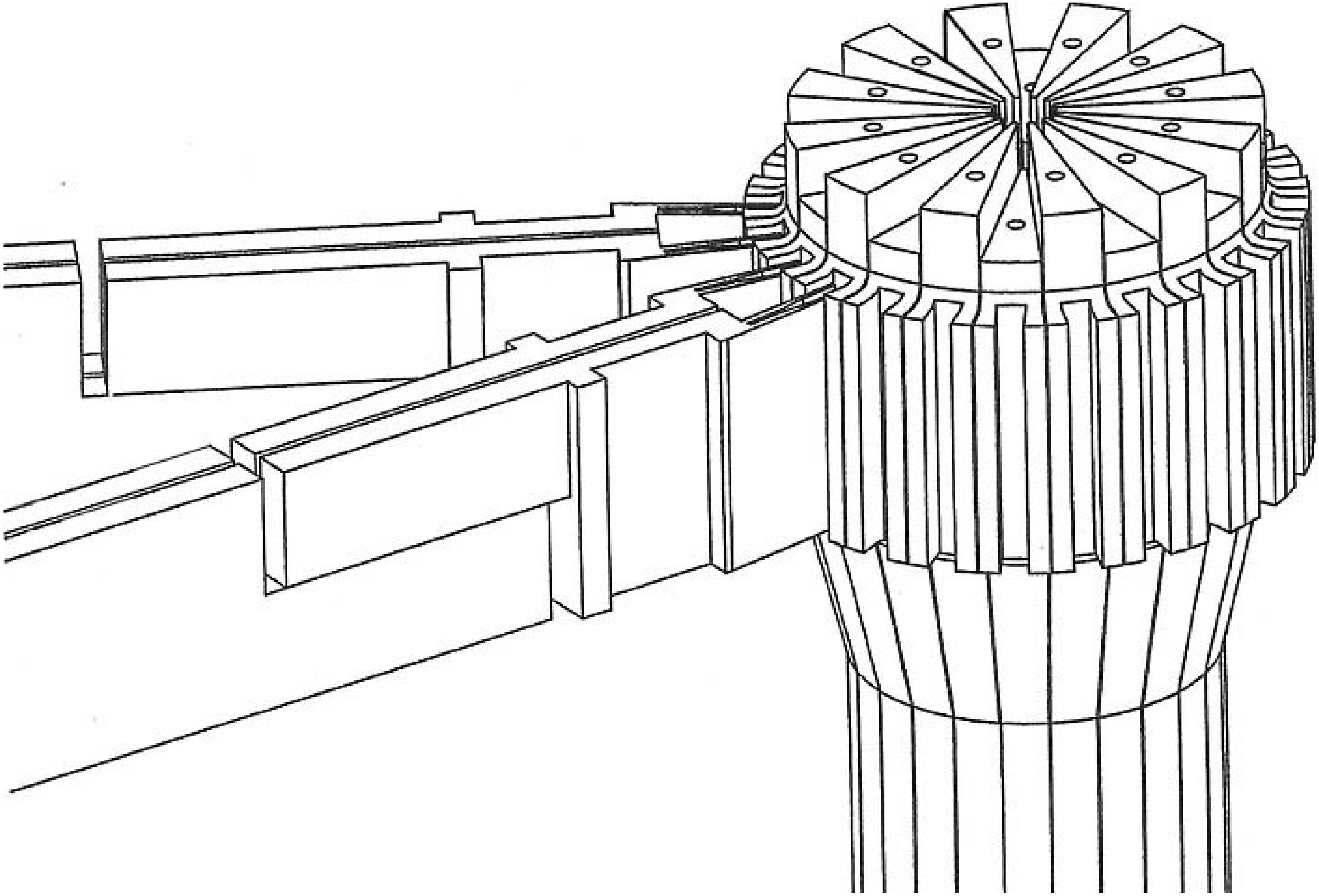
$$\dot{\Theta} = \eta\, j^2 / \rho S$$

which for warm copper becomes

$$\dot{\Theta} \approx 0.6\, j^2 \qquad (\mathrm{kA/cm^2, Kelvin/sec})$$

- When $j \lesssim 2 \rightarrow 3$ kA/cm² it is possible to run copper coils steady-state using water cooling, otherwise inter-shot cooling is usually required.
- Differential expansion often requires special design features...

MAST - TF Coil Sliding Joints



Poloidal Field Coils

General

- The functions of the poloidal field coils are to produce the magnetising flux, main equilibrium field, shaping fields and position feedback.
- Some or all of these functions can be combined (so fewer coils are required) using appropriate feedback control techniques.
- Many old machines used an iron core to reduce power supply demand, but the B(H) non-linearities introduce many operational problems.
- Some significant operational advantages (and engineering disadvantages) accrue if a poloidal divertor is included in the design to improve impurity control or energy confinement times.
- Shaping fields (including those for a divertor configuration) are of the same magnitude as, indeed are part of, the main equilibrium fields and have comparable power requirements.
- Feedback systems are usually relatively low power but fast, based on eg thyristor choppers or linear amplifiers.

Poloidal Field Coils

Forces

Truly circular and aligned poloidal field coils do not “feel” the main toroidal field, only its small ripple. The principle forces are self (hoop) and vertical and radial forces arising from other PF coils and the plasma current. Often the most highly stressed PF coil is the OH solenoid, because experimentalists always seek the largest possible volt-seconds swing.

Magnetising Winding

The magnetising winding produces the flux swing necessary to produce and sustain the plasma current. The volt-second consumption can be approximated for small machines by

$$\Delta\phi \approx 1.5\,\mathrm{IL} + \mathrm{T}_{\mathrm{pulse}}\,\mathrm{V}_{\mathrm{loop}} \quad (\mathrm{MA},\ \mu\mathrm{H},\ \mathrm{secs},\ \mathrm{Wb})$$

Poloidal Field Coils

… or for large machines

$$\Delta\phi \approx 2 + IL + T_{pulse} V_{loop},$$

where $1 \lesssim V_{loop} \lesssim 2$ Volts/turn. Here L is the total inductance of the plasma loop,

$$L = L_{int} + L_{ext}$$

$$\approx \mu_0 R(l_i / 2 + ln(1.3R / a\sqrt{\kappa}))$$

$$(m, H)$$

Where l_i is the normalised internal inductance (typically ~0.8 - 1.6, but as low as 0.4 - 0.6 for reversed-shear plasmas)

$$ie. L \approx\approx 2R$$

$$(m, \mu H)$$

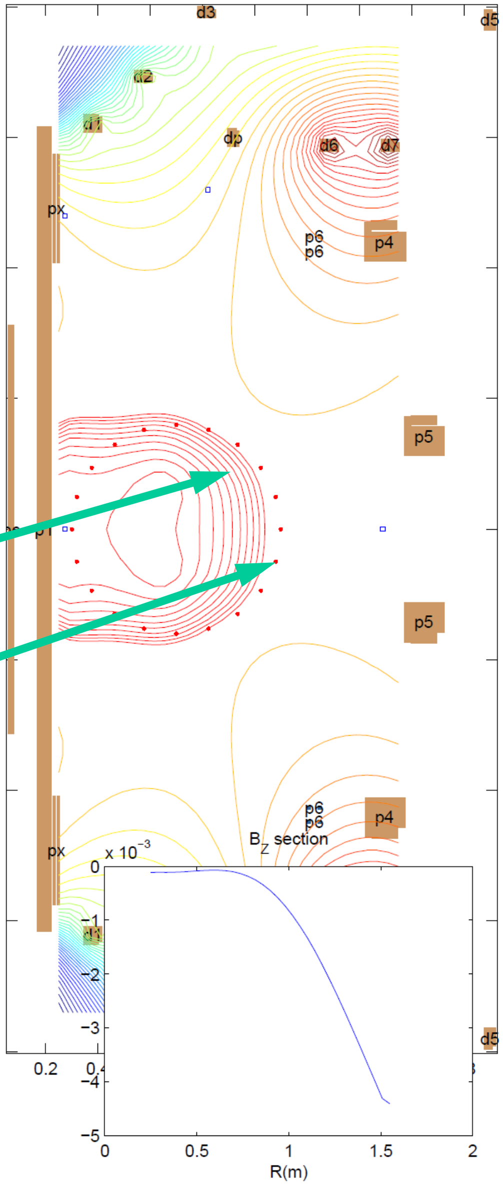
Poloidal Field Coils

It is important to add extra coils to compensate the return field of the solenoid, ideally to null it throughout the plasma region.

Example of good poloidal field null projected for MAST-U

|B| contours (Gauss or 10^{-4}T)

Boundary of target zone for optimisation



MAST-U load assembly

Poloidal Field Coils

Magnetising Winding

- The volt-seconds produced by a simple long solenoid are of course (for a bidirectional swing B_{max} , radius r_{sol} , thickness δr_{sol} , packing fraction f_{sol}),

$$\Delta\Phi = 2B_{max} \cdot \pi r^2_{sol}$$

$$(T, m, Wb)$$

$$or\ \Delta\Phi = 8\pi^2\, j\, r^2_{sol}\, \delta r_{sol}\, f_{sol}$$

$$(kA/cm^2, m, m, Wb)$$

The average hoop stress in the solenoid winding is

$$\sigma = 20\pi\, j^2\, r_{sol}\, \delta r_{sol}\, f_{sol}$$

$$(kA/cm^2, m, m, MPa)$$

Poloidal Field Coils

- The radial component of the end-field of the solenoid generates an axial compressive force and hence an additional stress on the conductor and insulation:

$$\sigma_{compr,axial} \approx \Phi^2 / (4\pi^2 \mu_o r_{sol}^3 \delta r_{sol})$$

$$(Wb, m, m, Pa)$$

- Designers have to balance the r_{sol} and δr_{sol} to obtain the desired volt-seconds swing without breaking or overheating the magnetising solenoid.

Poloidal Field Coils

Vertical Field

- The vertical field requirement is approximated by:

$$B_V \approx \frac{I}{10\,R_0}(\ln(8R_0/a)+\beta_p+l_i/2-3/2)$$

where I is the plasma current,

$$ie.\ B_V \approx \frac{I}{10\,R_0}\ln(6R_0/a)$$

$$(MA, m, T)$$

Shaping (Elongation) Field

- High plasma elongation and poloidal divertor “x-points” require poloidal field coils above and below the plasma, with amp-turns of the same order as the plasma current, since at the x-point the poloidal field is nulled.

Poloidal Field Coils

Power Supply Requirements

- In an air-cored system the power supply has to drive the current swing in the magnetising winding, which typically has an inductance ~50% greater than the central solenoid alone. Thus

$$L_{TOT} \approx 1.5 \, x \, 3.9 \, N^2_{sol} \, r^2_{sol} / l_{sol}$$

$$(m, m, \mu H)$$

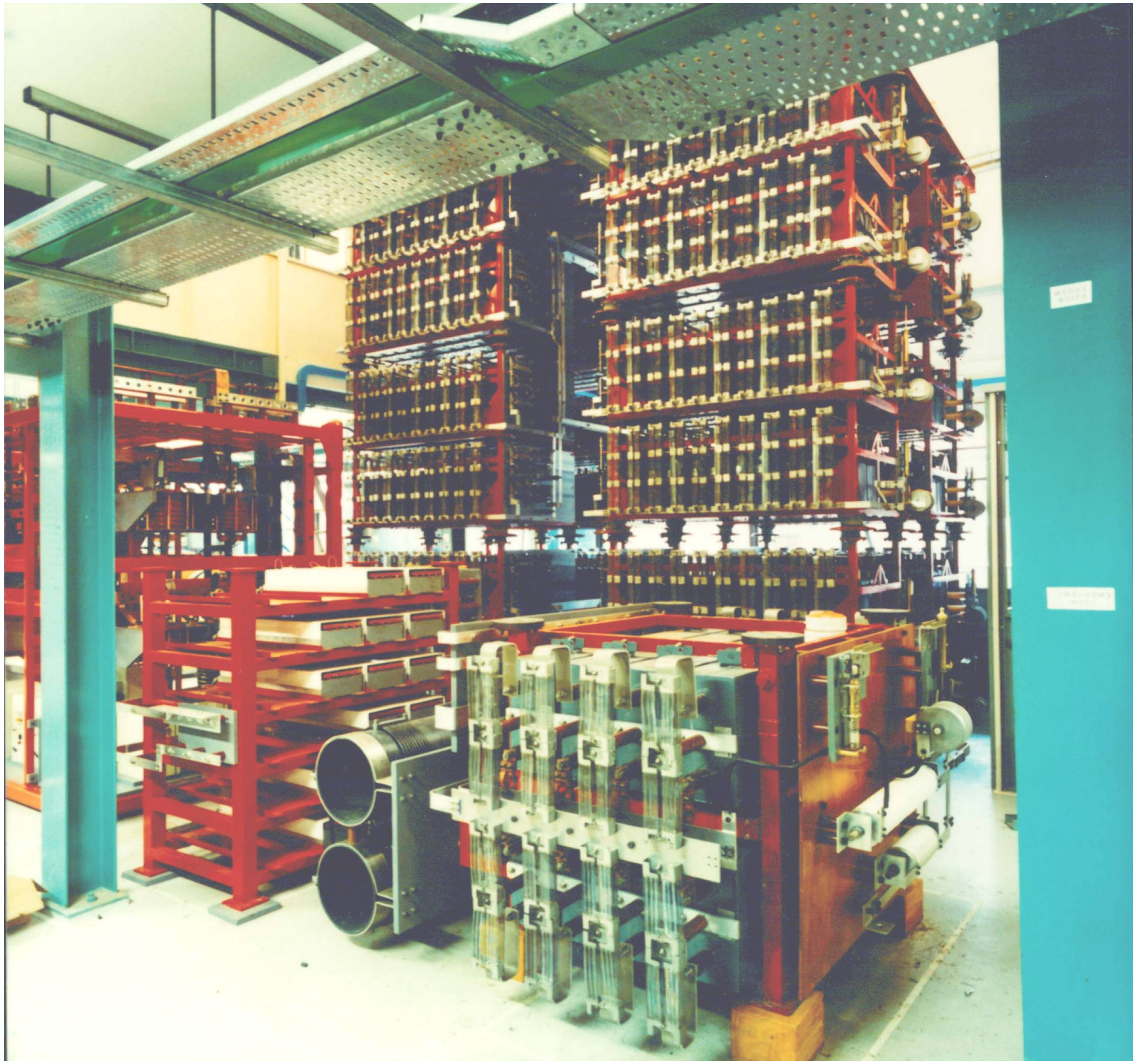
where N_{sol} and l_{sol} are the number of turns and length of the solenoid respectively. The reactive voltage is dominated by $I_{pri} L_{TOT}$ since coupling to the plasma is usually very poor.

Power Supply Options

Type	Advantages	Disadvantages
Capacitor banks	Very low mains power demand. Simple & very cheap.	Very poor control of current waveform.
Inductive Storage	Cheaper than capacitor bank systems at very large energies.	Switching problems.
Flywheel motor generators	Low (pony motor) mains demand. Optional stator field control. Very large powers & energies readily available.	Output frequency falls during pulse.
Steady-state motor-generators	Some flywheel effect to accommodate transients. Clean DC output with optional feedback control by stator field.	Severe mains demand. Feedback response time can be slow.

Power Supply Options

Type	Advantages	Disadvantages
Thyristor Rectifier	Fairly fast if multiphase (eg 12 or 24 phases). Natural inversion available.	Ripple & noise in load current. Worst possible option for mains demand. Large signal BW poor, particularly for turn-off. Four quadrant versions “messy”.
Thyristor Chopper	Very fast. Can run from capacitor bank(s). Readily made multiple-quadrant.	Ripple & noise in load current (and/or complexity if multi-rail).
Transistor Amplifier	Linear, clean output, very fast, four-quadrant feedback control.	A few hundred kW max per unit. Expensive.
Resonant Switched-Mode Convertor	Very high efficiency (low loss). Very fast. Readily modularised.	Complicated. Expensive.

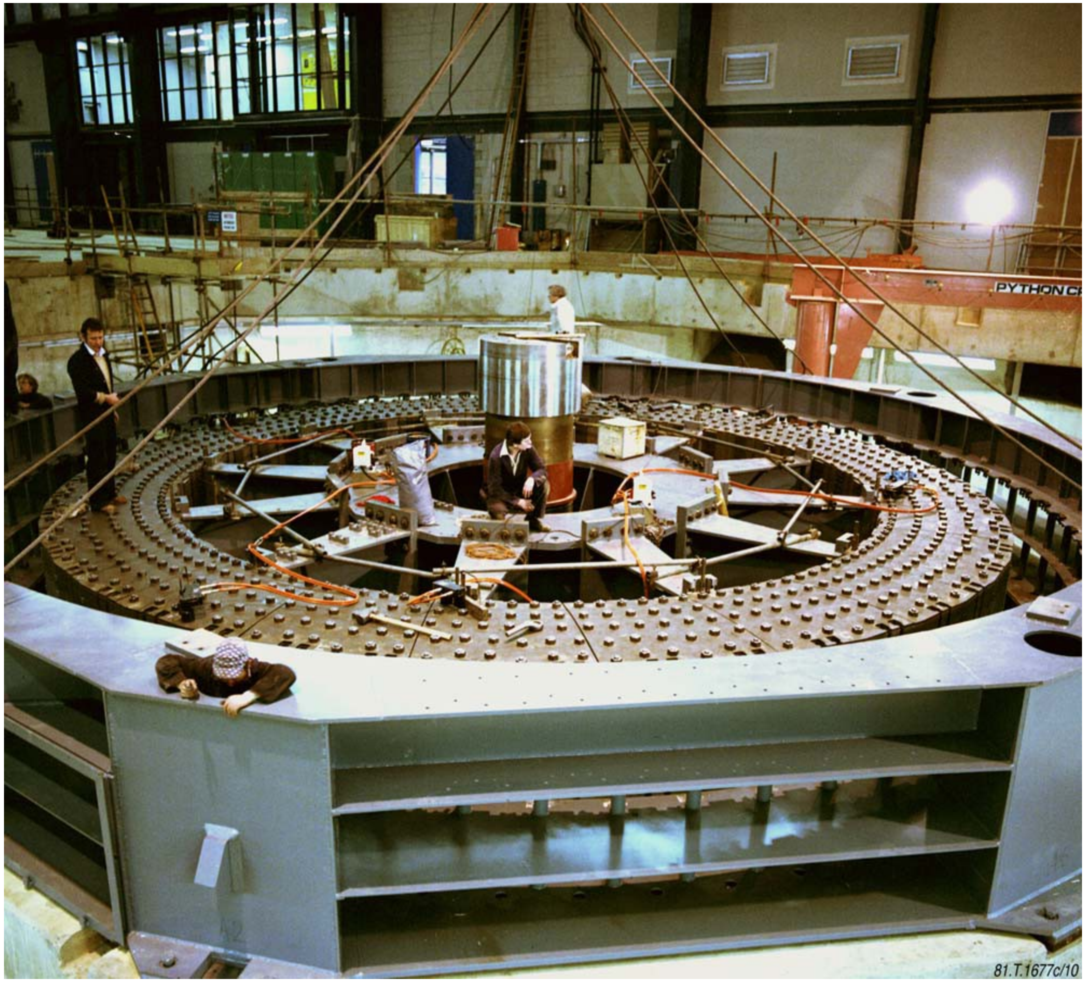


Power Supplies - COMPASS 1MJ OH Capacitor Bank

Power Supplies - JET Flywheel Generator Convertors

Two units (PF & TF), each:

- 800 tonnes
- 112 - 225 rpm
- 8MW pony motor
- 410MVA
- 2.6GJ extractable energy



Poloidal Field Coils

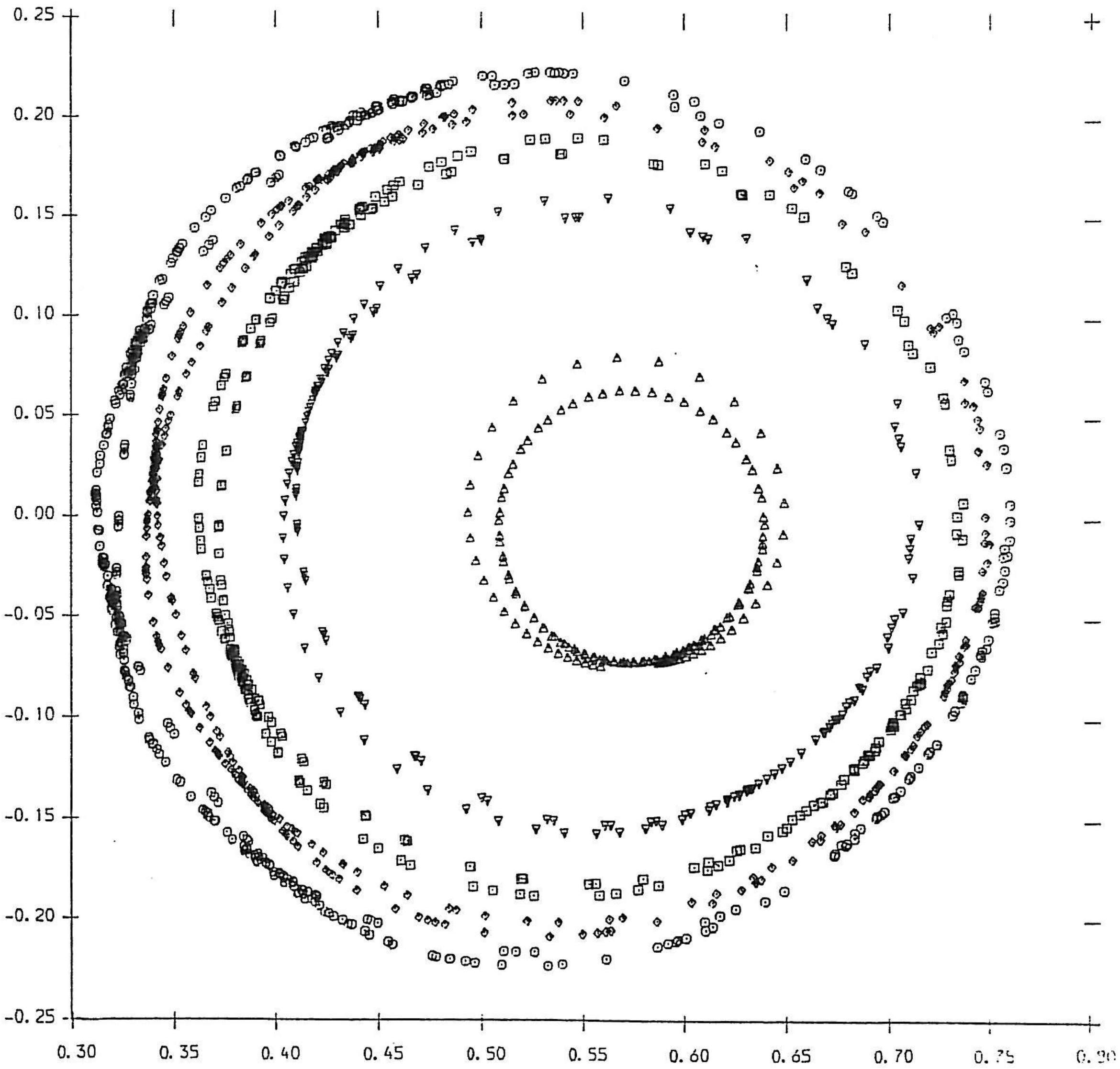
Alignment Errors

- The PF coils have to be circular and well aligned to the TFC to avoid producing resonant magnetic perturbations. They also have to be positioned in radius and height so as to minimise stray perpendicular fields (particularly important for the magnetising winding if it is carrying current at the time of plasma initiation).
- Each of these requirements results in a positional tolerance ~10^{-3} of the major radius of the machine.
- Coils with small numbers of turns are troublesome because of the effective dipole errors associated with the feeder bars (unless the feeders are coaxial etc), and the turn-to-turn joggles in the winding.

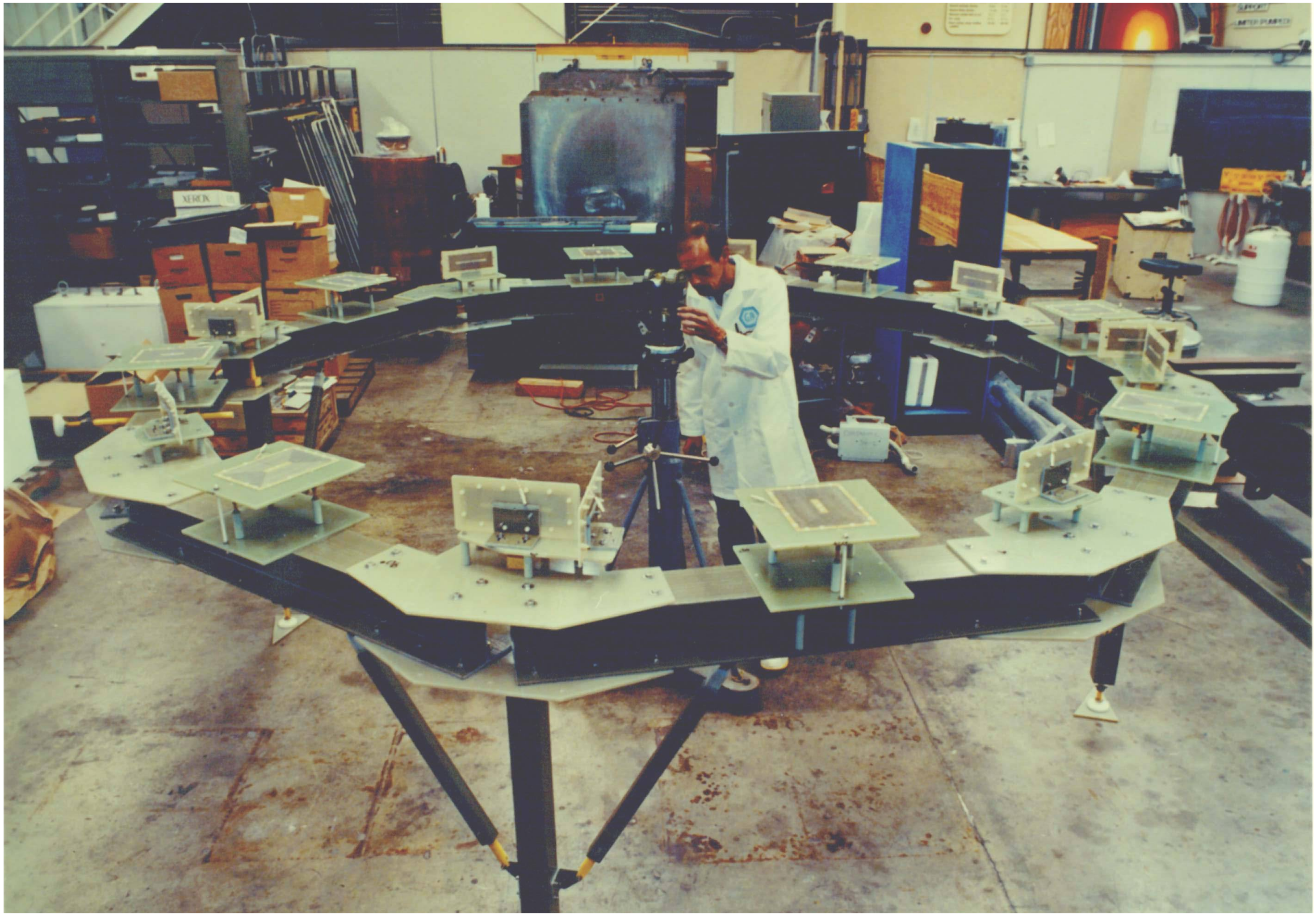
Poloidal Field Coils
- alignment errors

COMPASS -C

Magnetic islands due to hypothetical 10mm lateral shift of one B_v coil, creating resonant magnetic perturbation fields



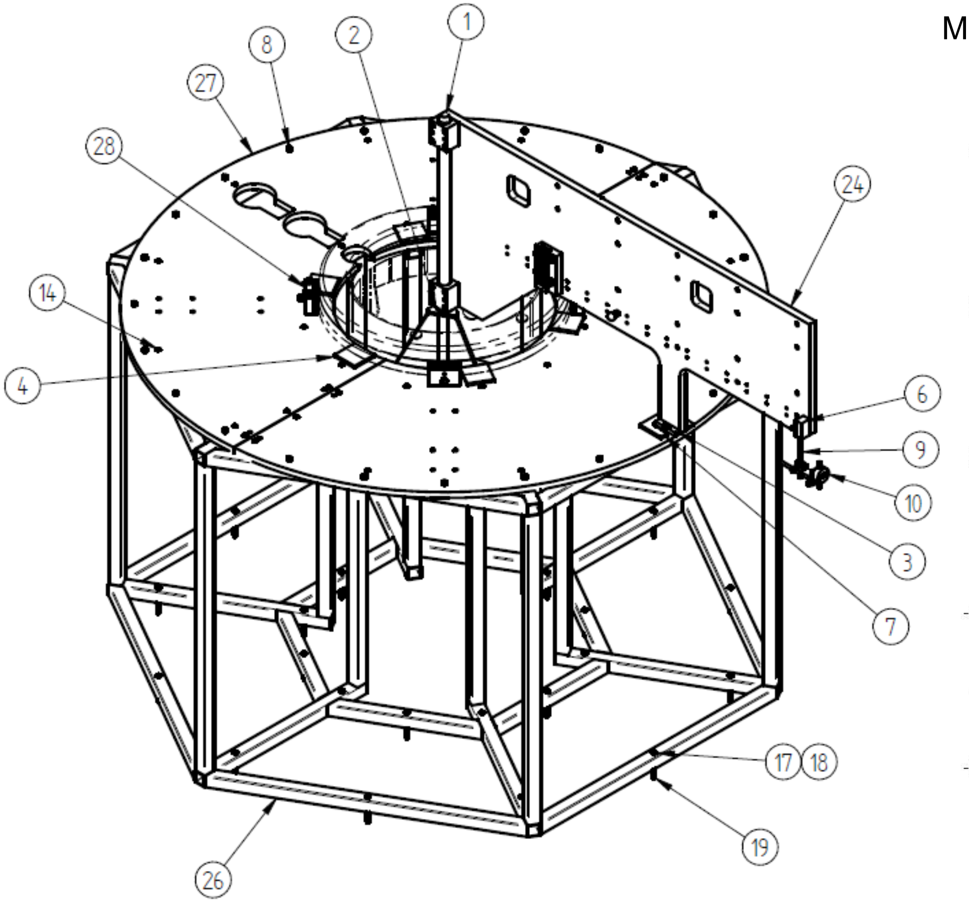
Poloidal Field Coils – avoiding alignment errors

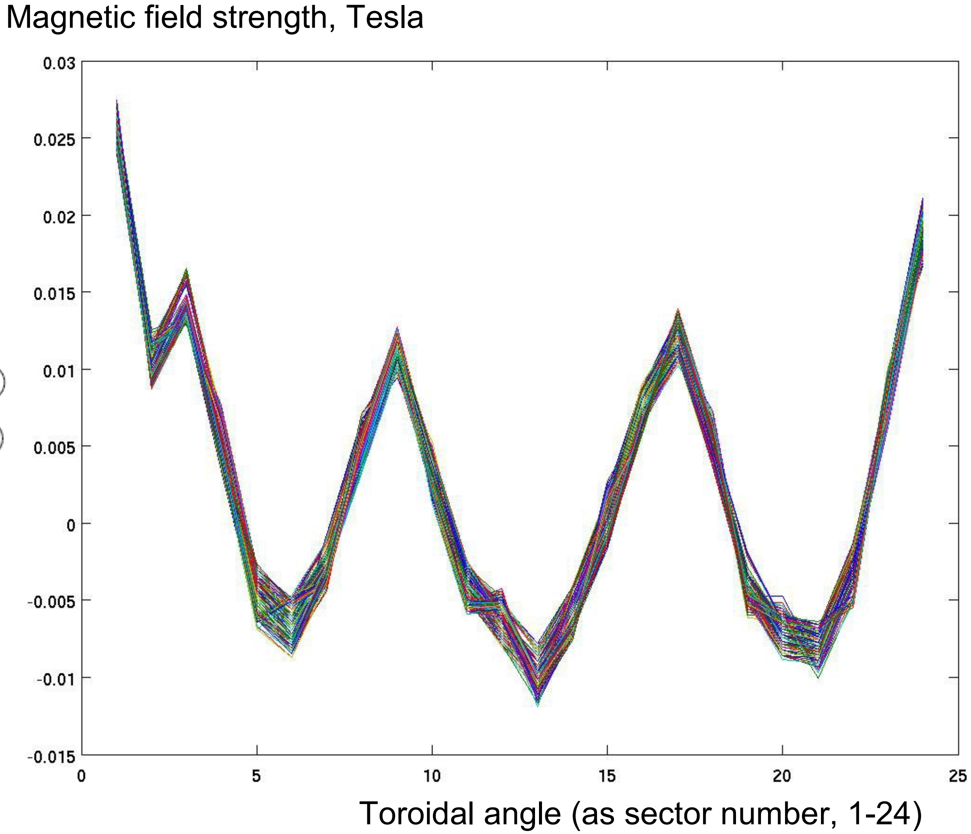


DIIID Coil Alignment Array

Poloidal Field Coils – avoiding alignment errors

MAST-U: PF Coil magnetic characterisation rig (at the Tesla coil fabrication works)

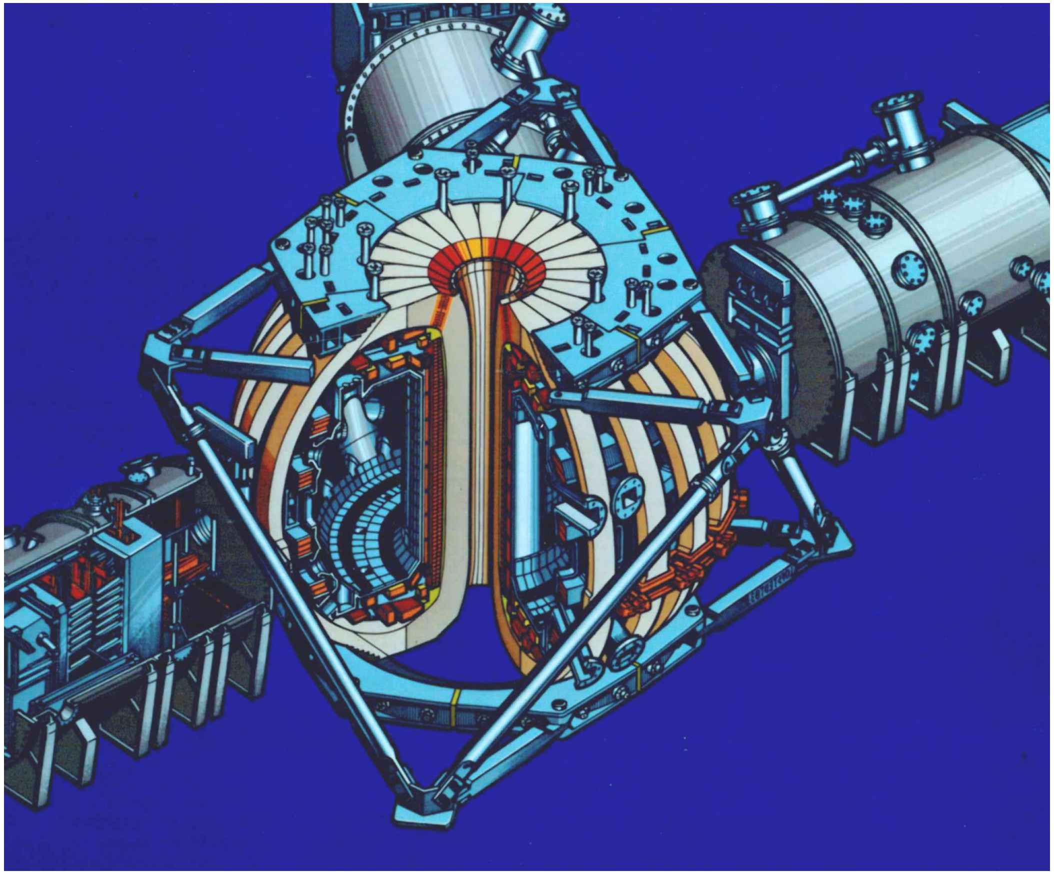




Example of data from test rig, showing an n=3 component of ~20mG pk-pk

Support Structure

- Some structure has to accommodate the toppling forces on the TF coils and the vertical forces on the PF coils. There are many geometrical options. This might be the lightest and simplest:



DIIID Geodesic structure

Support Structure

- Since the support structure has to be strong, stainless steel is commonly used in order to obtain high strength with low magnetic permeability. However stainless steels increase in permeability where worked, cut or welded and so (sometimes even after heat treatment) it is easy to generate non-axisymmetric and potentially resonant perturbation fields.

- Any volume of unsaturated magnetic material "sucks in" the ambient magnetic field creating a disturbance in the field similar to a dipole source. This dipole source produces a field back in the plasma region which will usually be non-axisymmetric and is therefore likely to generate islands.

Outside the TFC the ambient field is dipole-like and the critical volume to generate 10^{-4} of the poloidal field at the plasma edge is given by

$$V_c \lesssim 300\,\Re^6 / R_0^2\, a(\mu_R - 1) \qquad (\mathrm{m, m, m, cm^3})$$

for $\mu_R \approx 1$, where $\Re$ is the range of the offending lump from the machine centre.

Support Structure

Inside the TFC the ambient field is essentially $B_{\phi 0} R_0 / R$ and the same criterion (at the machine centre) yields

$$V_c \lesssim 250\, I\, R\, R_0^2 / a B_0 (\mu_R - 1)$$

$$(MA, m, m, m, T, cm^3)$$

where R is the major radius of the offending piece of material.

- Clearly the support structure is responsible for maintaining the alignment of all the TF and PF coils, with the accuracy requirements discussed earlier.

Vacuum Vessel

Forces

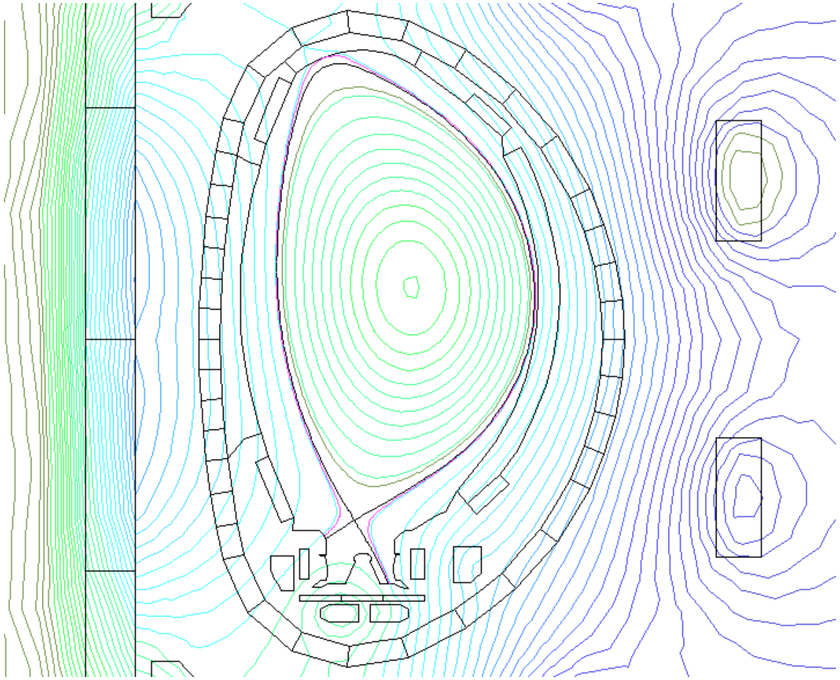
Forces on the vessel arise from the following sources, in decreasing order of importance:-

- disruption-induced currents
- thermal gradients
- air pressure
- human malpractice
- diagnostic loads
- currents induced during plasma start-up
- diagnostic flange bolting

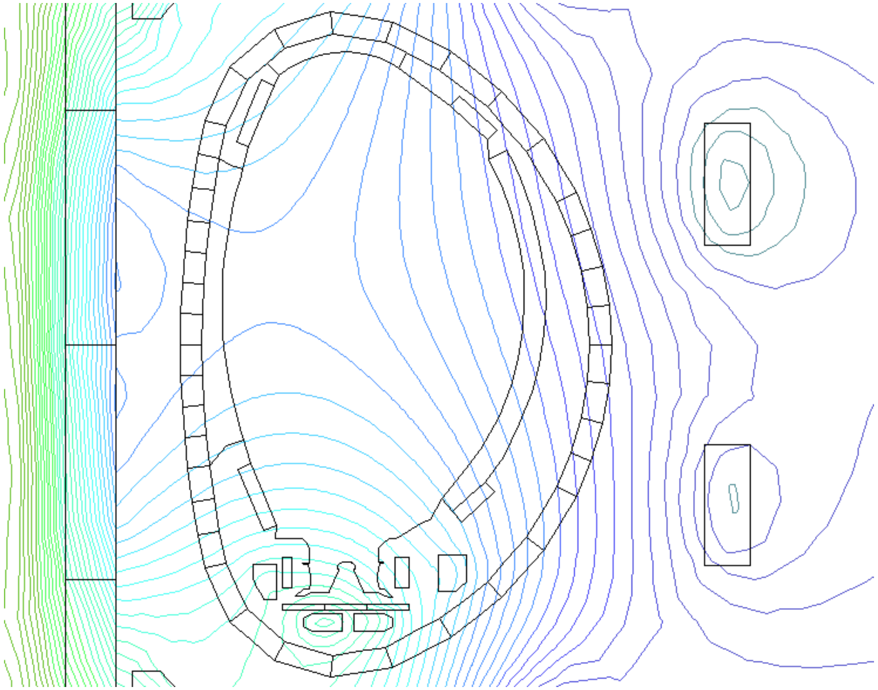
- Disruption induced currents arise when the plasma terminates rapidly, commutating its current into the vessel. This current then “stands off” the external vertical field giving rise to inward pressures on the vessel which can easily attain ~1bar (as well the atmospheric loading).

Disruption dynamics

In a disruption, the plasma “goes away” at up to 1MA/msec:



Before…



...after →large, rapid poloidal field changes

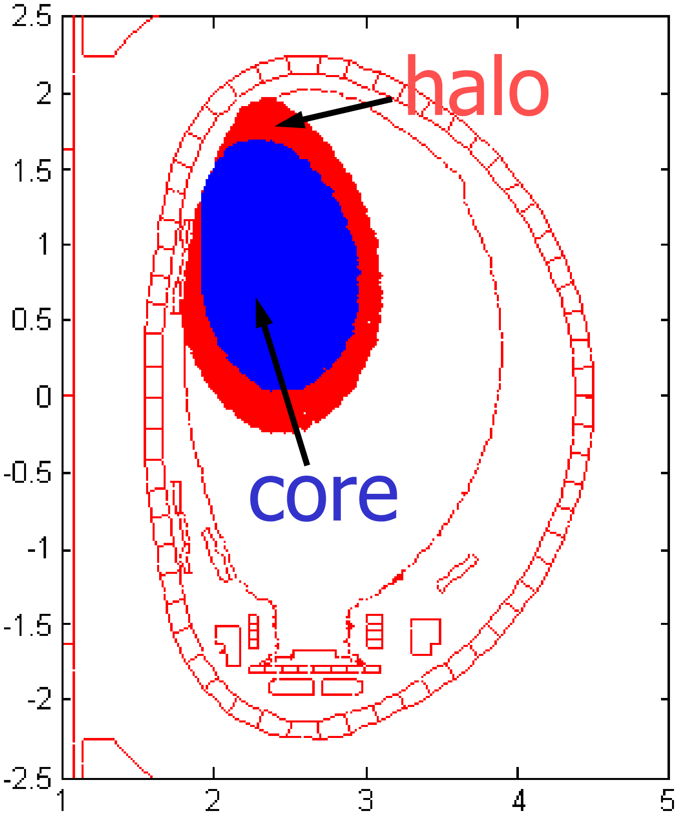
The rapid change in poloidal field induces currents in the surrounding metal structures.

Vacuum Vessel

- Worse than this, the commutated current has to get around port-holes, causing regions of high current density and crossing of the toroidal field, producing very large local stresses.
- Rapid plasma displacement events (during vertical instability) have been shown to “scrape off” up to ~40% or more of the toroidal plasma current, which can also flow very asymmetrically due to helical distortion of the plasma This results in large “halo” currents crossing the toroidal field within components mounted inside the vessel, severely stressing the mountings.

Disruption dynamics

The “Halo Current”; partly flows along the edge of the plasma and partly in the plasma facing components.



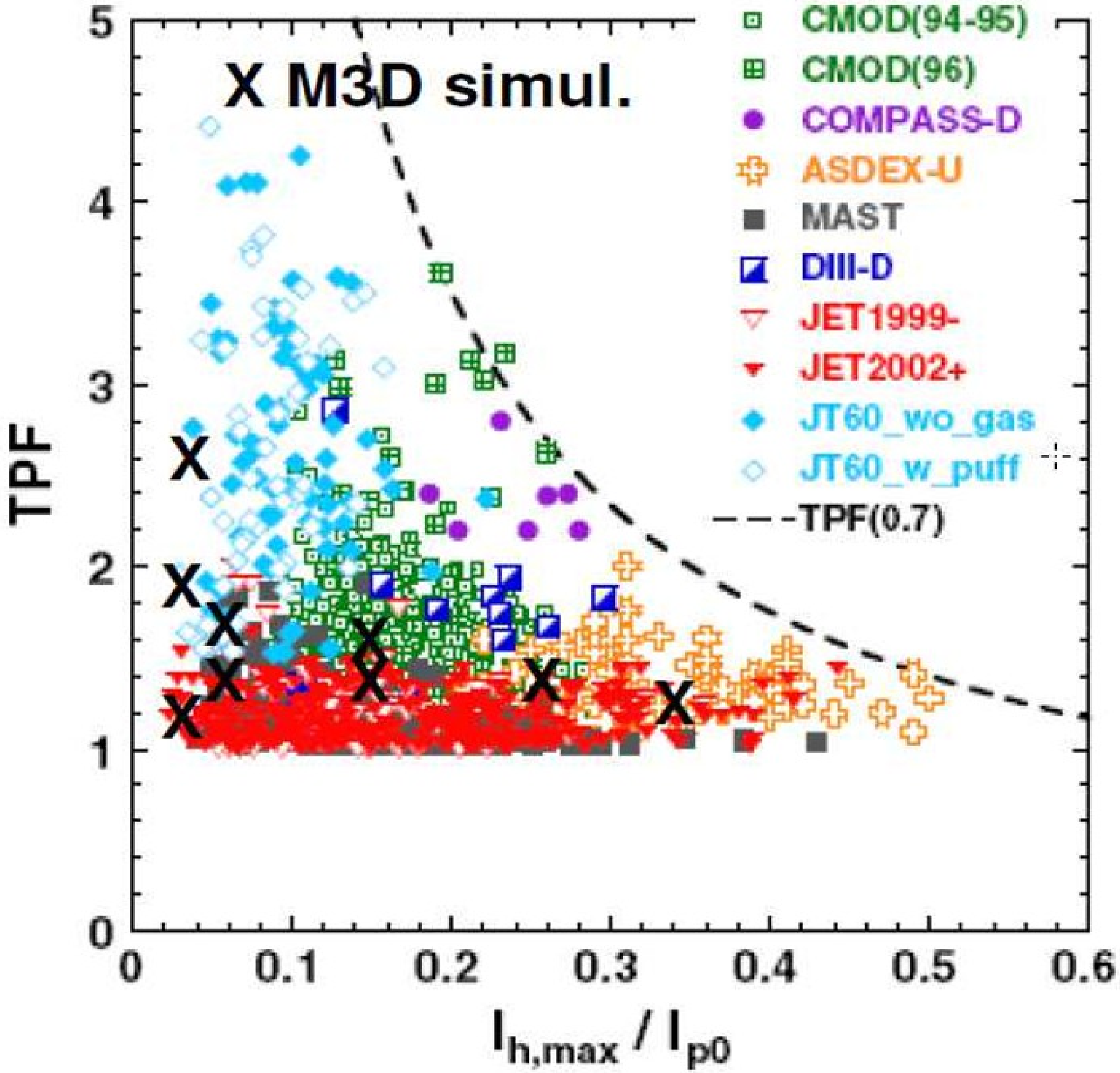
The core plasma is ~ force free, but each part of the halo current path is not ⇒ loads on plasma facing components and their supports, and the vessel.

halo fraction ($f = I_{halo}/I_{plasma}$)

ratio of poloidal halo current to pre-disruption plasma current (up to ~50%)

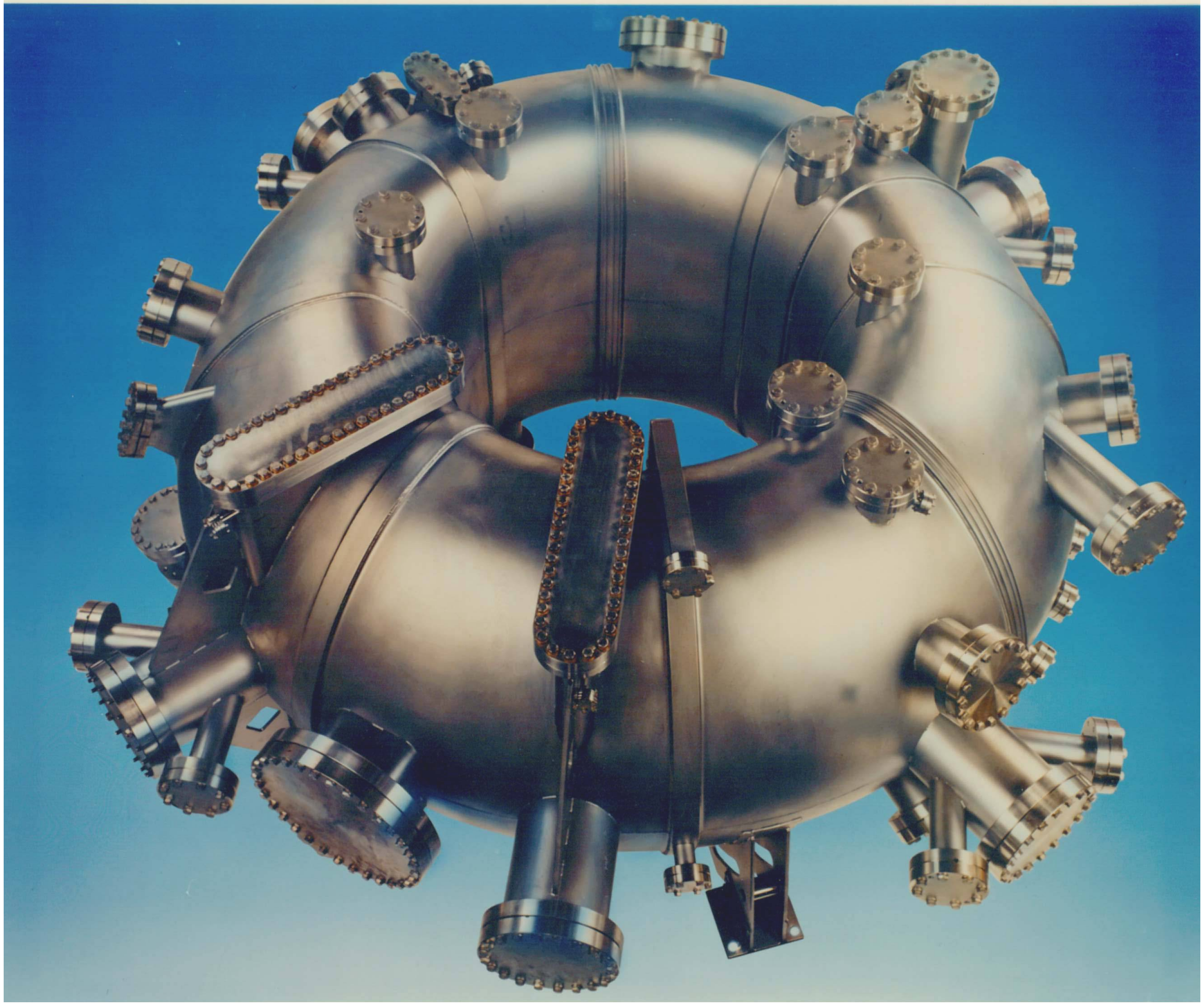
toroidal peaking factor (TPF)

degree of halo current asymmetry: ratio of the maximum to the average halo current (up to ~4)



Tokamak Rotation and Halo Current caused by Disruptions

H.Strauss et al, a PPPL talk (2013)



COMPASS-D Vacuum Vessel

Vacuum Vessel

Vacuum Quality

- Tokamaks do not work properly if the vacuum base pressure is $>2\times10^{-7}$torr
- Some routes to a high vacuum standard include the following:-
  - try to achieve an all-metal set of vacuum seals, welded wherever reasonable
  - avoid materials with high vapour pressures (eg brass, plastics …)
  - avoid unstable materials
  - avoid trapped volumes (eg in screw threads, between mating surfaces)
  - don't let marking pens or crack-detecting dye penetrants be used inside the vessel
  - avoid the use of cleaning fluids with tightly binding high *Z* elements (eg the ubiquitous chlorine)

Vacuum Vessel

Vacuum Quality (cont'd)

- don't directly touch anything destined to go in a vacuum system
- do vacuum-bake components of the vessel itself during manufacture (eg to 400ºC)
- do bake everything that goes inside the vessel to whatever temperature it will tolerate (eg to 200ºC)
- specify and preserve mirror-bright interior surfaces
- consider electropolishing the vessel interior surfaces
- avoid, or plate over, plastics to which the plasma has a line of sight

Vacuum Vessel

Pumps

- Today, turbomolecular pumps are the standard choice: they produce excellent base pressure, down to the 10^{-10} torr region if the system is clean and leak-free. Bearings can be oil, gas or magnetic; some have been known to break up, allowing oil vapour back into the system. The high rotational speed vanes suffer strong eddy currents (ie drag) if the TMP is exposed to magnetic fields above ~300G however, so siting needs consideration.

- Cryopumps are increasingly used and are best where enormous pumping speeds are required (such as in divertors and ion beam neutraliser cells). Also available are small automatically regenerating modular cryopumps, compact, helium-sealed and easy to use.

Limiters

Purpose

Limiters and armour are required in tokamaks to:-

- Define the place and material of the principle plasma edge interaction
- Stop runaway electrons from damaging the vacuum vessel
- Protect the vessel from neutral beam shine through
- Shadow in-vessel components from the plasma edge

Geometry

Historically, poloidal ring (even “diaphragm”) limiters were popular, but as power input and pulse duration have risen these have become much less favoured, giving way to various toroidal ring options.

Some old machines used horizontal rails and/or out-board rail limiters, generally with sophisticated front surface profiles to optimise the power handling capability.

Limiters

Power Handling

- Some of the plasma input power is lost as radiation, charge exchanged energetic atoms etc, but a substantial fraction flows to the limiters or divertor target plates.
- At the plasma edge the charged particles flow rapidly along the field lines and diffuse slowly across them. This gives rise to a “fuzzy” edge region characterised by an exponential fall-off of power flux, density etc

$$P_{\|} = P_{\|0}\, e^{-(r-r_{lim})/\lambda}$$

with

$$\lambda \approx \sqrt{\chi_{\perp}\tau_{\|}}$$

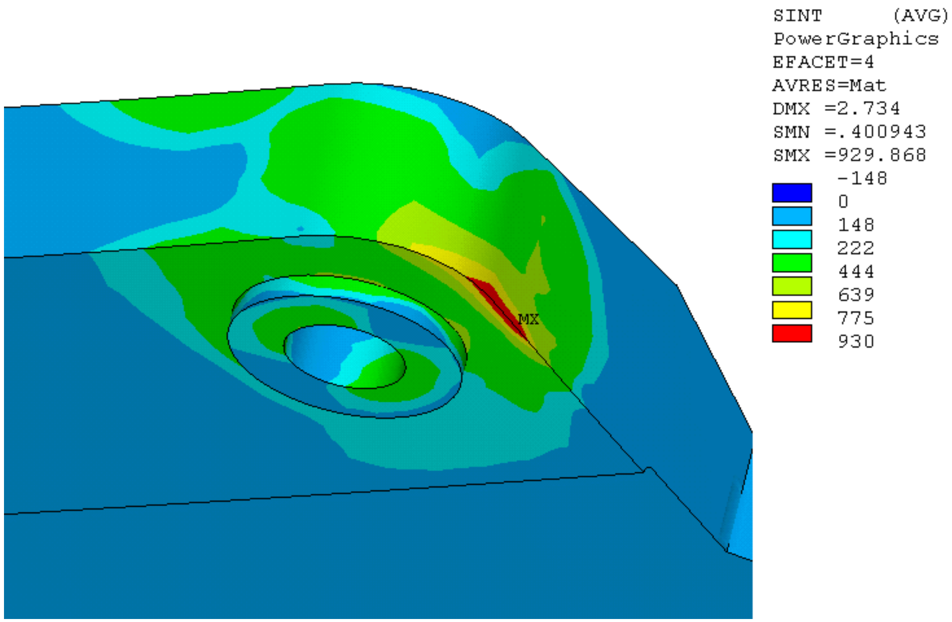
Where $\chi_{\perp}$ is the cross field diffusion coefficient ($\gtrsim$1m^2/sec), and $\tau_{\|}$ is the time the ions take to explore the field lines between limiter intersections, $\lesssim 2\pi Rq\, f / v_{th(i)}$. For typical tokamaks this gives rise to λ ~0.5 - 2cm, while P $_{\|0}$ is $\gtrsim 10\mathrm{kW/cm^2}$.

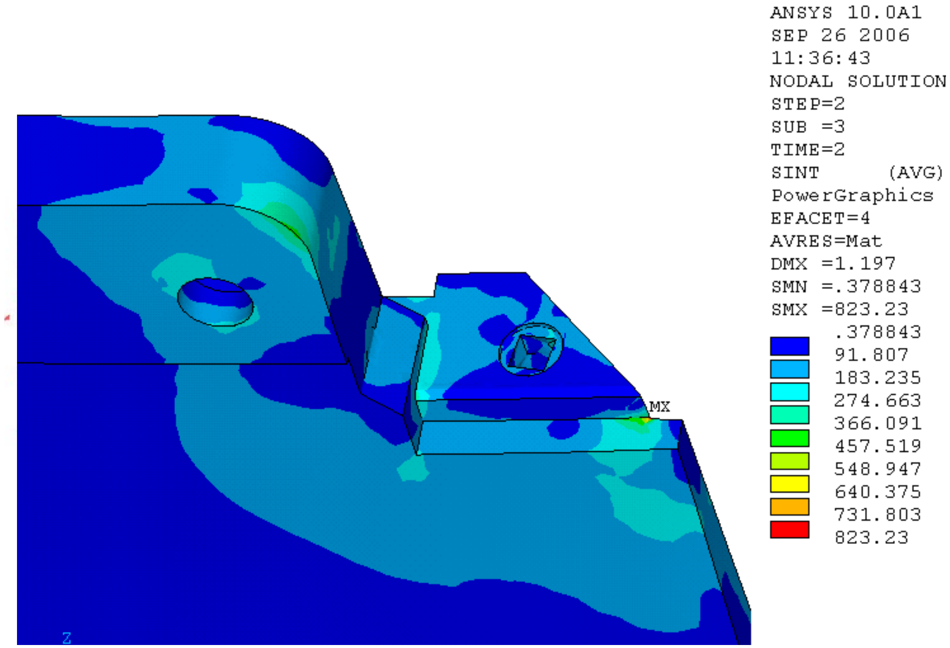
The tiles and tile carriers benefit from design evolution guided by FEA

The induced currents create torques and forces on the tiles and carriers

Designers aim to have peak stresses no more than say ~50% of the allowable stress for the selected material at the required temperature

Scheme design ⇨ analysis ⇨ detailed design





Limiters

Power Handling

- A high heat flux for a short duration causes a temperature gradient in the limiter material, leading to differential expansion resisted by the elasticity of the material but limited by the yield point. The figure of merit for the thermal shock capability of materials is thus

$$\frac{\text{yield stress}}{\text{elastic modulus}} \text{ x } \frac{\text{thermal conductivity}}{\text{expansion coefficient}} \text{ x (density x heat capacity)}$$

Limiters

Material Selection

- Good thermal shock behaviour combined with a requirement for high melting point allows a small range of suitable limiter materials to be identified, eg
  - refractory metals – tungsten, tantalum, molybdenum, titanium etc
  - carbon (graphite, CFC)
  - certain carbides – eg titanium, silicon, boron (usually as coatings)
  - beryllium
- The early machines mostly used refractory metals but graphite or CFC is now very popular, particularly as it sublimes rather than melting and allows runaway electrons to penetrate (and thus dissipate their energy) deeply. *And now tungsten is back!*
- Graphite can be improved by densification using chemical vapour deposition techniques (which also seal off the porosity) and by incorporating carbon fibres to raise the strength and conductivity, optionally with 2D, 2 ½ D or 3D geometry of the fibres.

Limiters

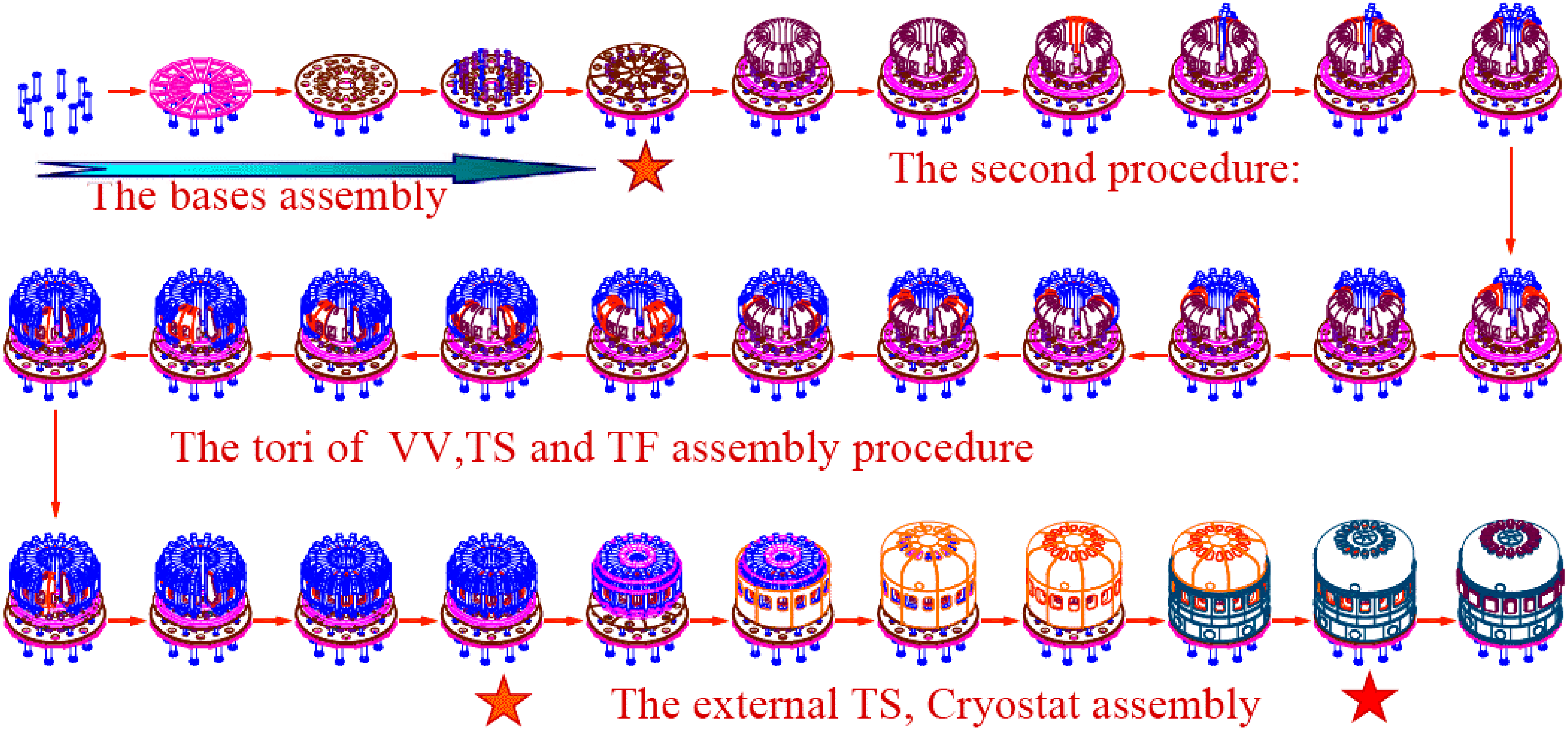
Material Selection

- Large quantities of graphite can result in gas absorption/desorption problems, and at very high thermal loads (ie surface temperature) a type of "cluster sputtering" arises which rapidly contaminates the plasma. In addition it is hard to match the expansion coefficient of graphite to metals so active steady state cooling is tricky/expensive.
- Few carbides are available in block form and thin coatings are rapidly eroded.
- Beryllium has considerable toxicity and therefore handling problems, particularly in finely particulate beryllia forms (such as arise during machining or when venting a torus where beryllium has been plasma-eroded).

Machine Assembly

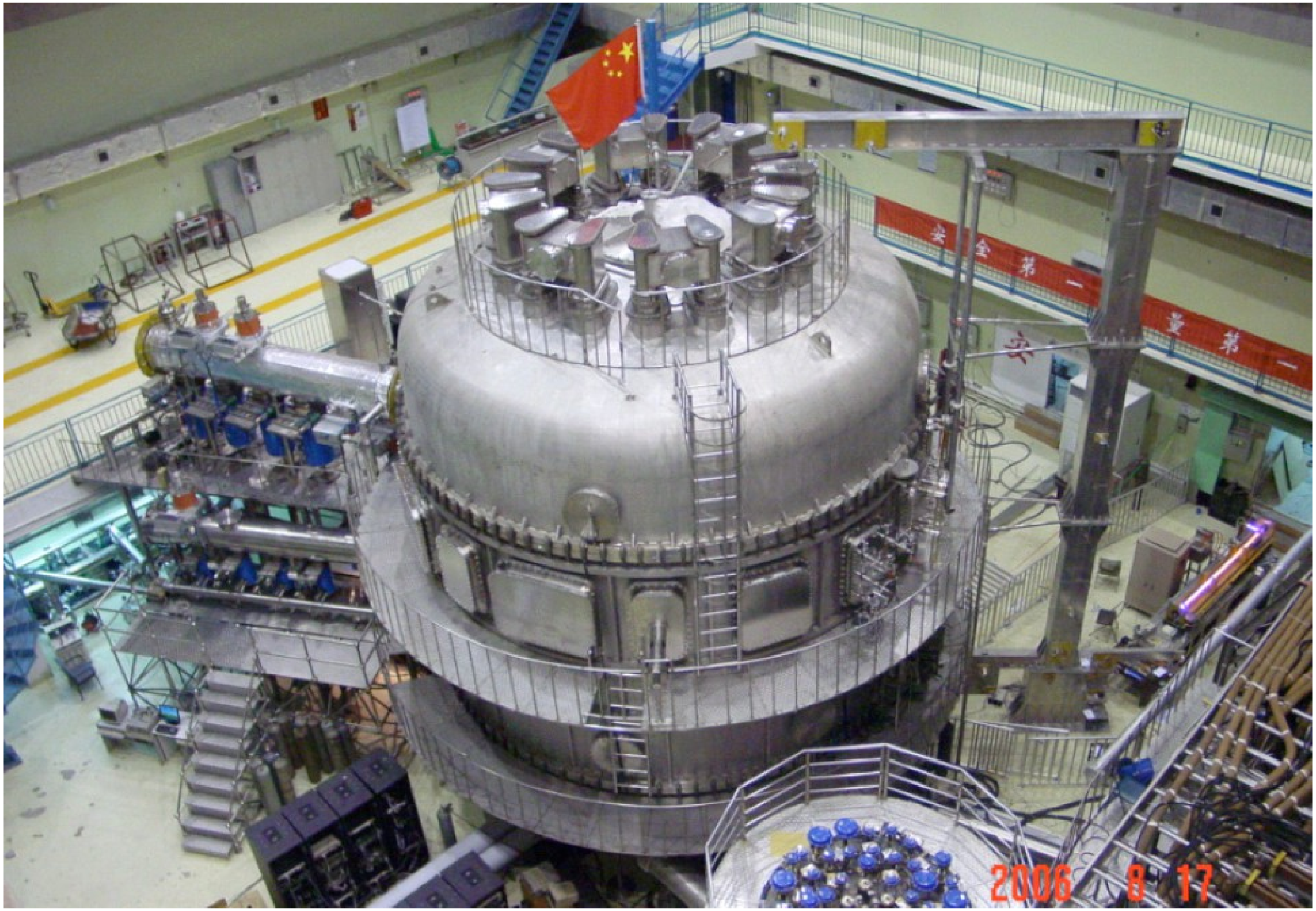
Once the design and procurement are done, you have to put it together...

EAST (née HT-7U) Full Superconducting Tokamak



EAST - Fully Superconducting Tokamak

Ip = 1 MA, t=1000s, Double Null Divertor, B_T = 3.5T, R= 1.75m, a/b = 40/80 cm



Machine Assembly

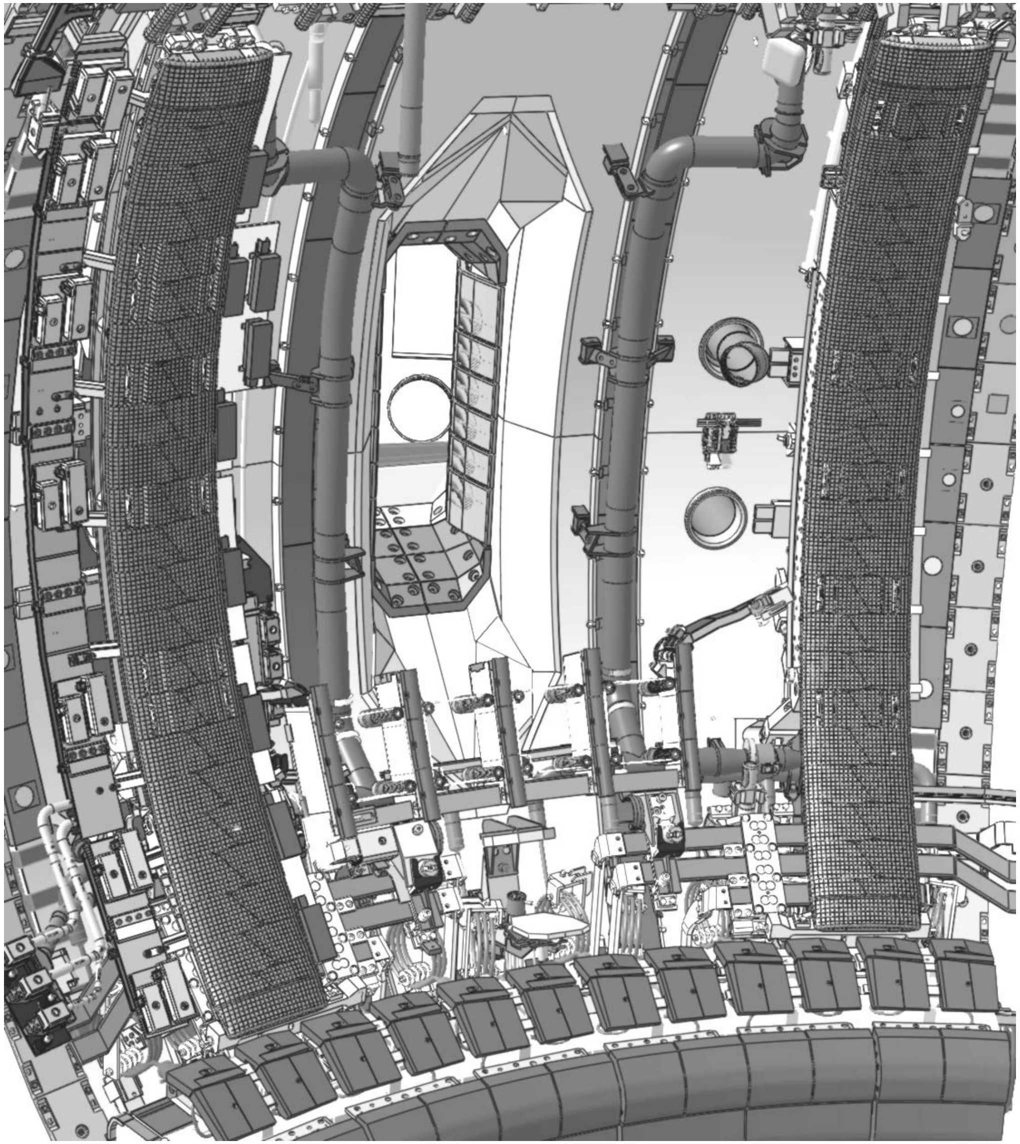
Dimensional inspection

“Low density” virtual target scan in mock-up of JET vessel

Machine Assembly

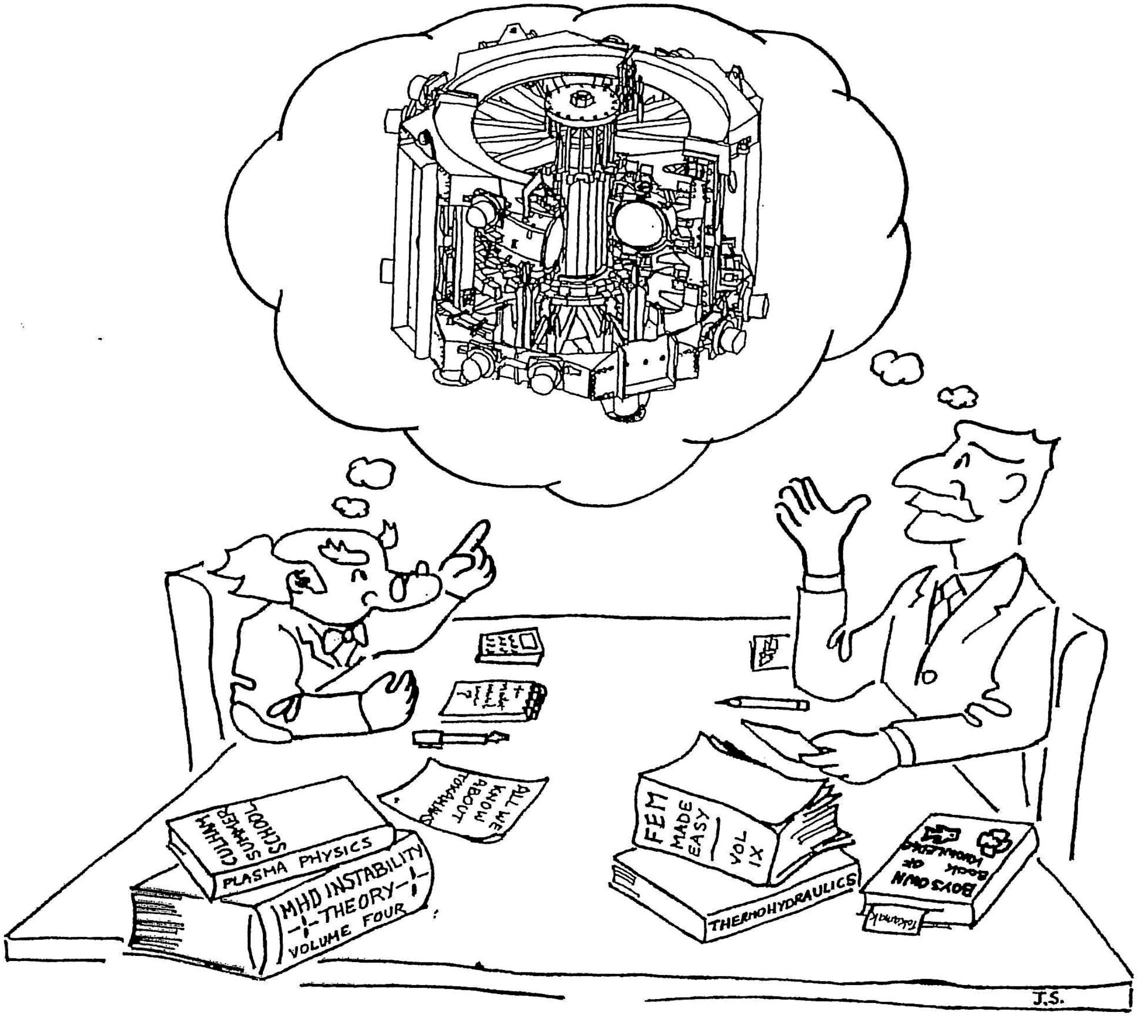
The metrology results are then used to modify the 3D CAD files in ever-increasing complexity, to facilitate Configuration Control

This avoids clashes between components and unintended vignetting of diagnostic viewing lines



Part of the interior of the JET torus: note the fine detail

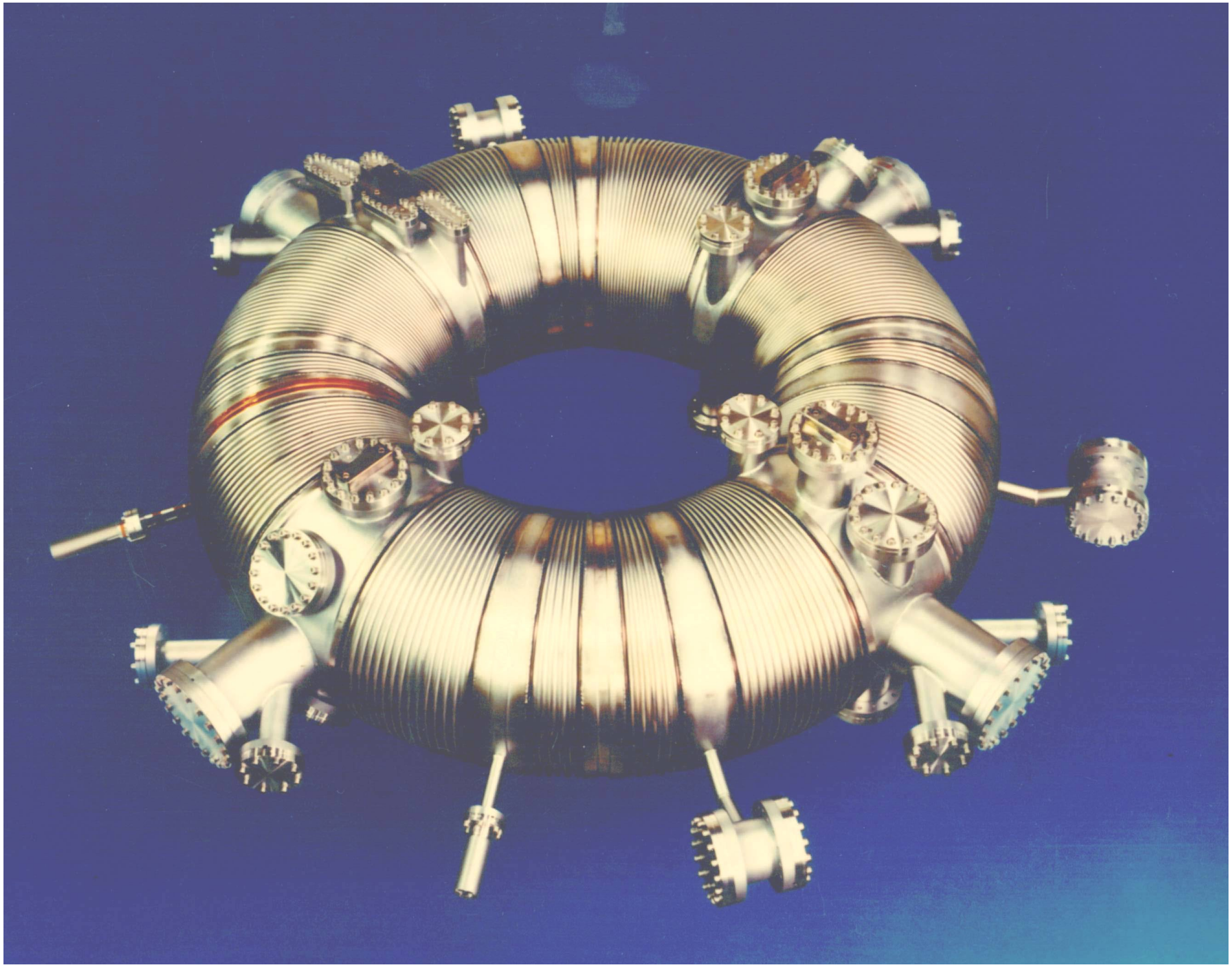
TOKAMAK DESIGN PROCESS:- STAGE 37



Summary

- This talk has attempted to outline the broad-brush thinking underlying the design and assembly of a generic tokamak.
- Many topologies are possible, with the options narrowed by considering any special engineering features required in the machine.
- A great deal of FEA underlies modern machine design, with due consideration to fatigue life for the duty cycles in mind.
- In tokamaks with strongly elongated plasmas, Vertical Displacement Events and associated halo currents are amongst the most demanding effects to accommodate in the design.
- Coil accuracy, magnetic permeability, vacuum system cleanliness and conditioning are all important to the eventual physics operations.
- Limiter design, including material selection, strongly affects achievable pulse length in high power density and/or long-pulse systems.
- Machine assembly requires precision metrology of delivered parts to generate accurate configuration files
- So how do you ***operate*** a tokamak? Wait for the companion talk!

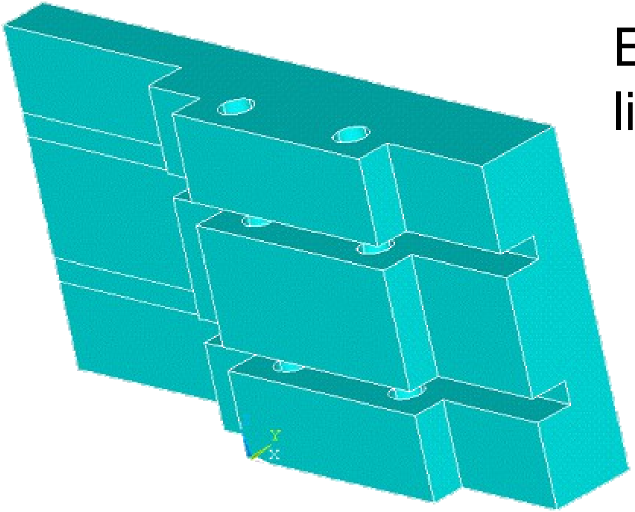
End



COMPASS-C Vacuum Vessel

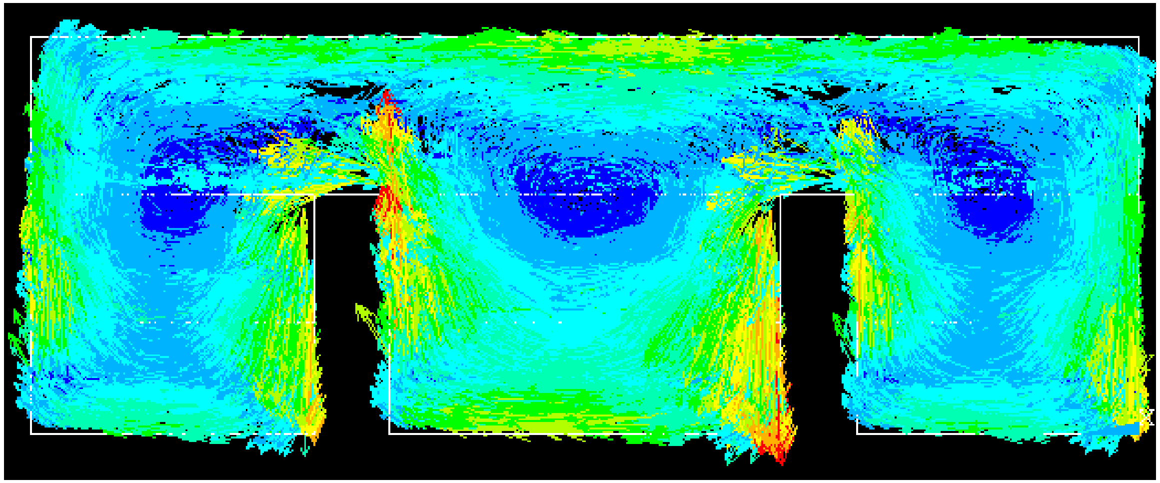
Plasma-facing components - stresses due to disruption-induced currents

Use of metal (eg Be or W) exacerbates the induced currents and associated forces



E.g. central block of Be poloidal limiter on RF antenna in JET:

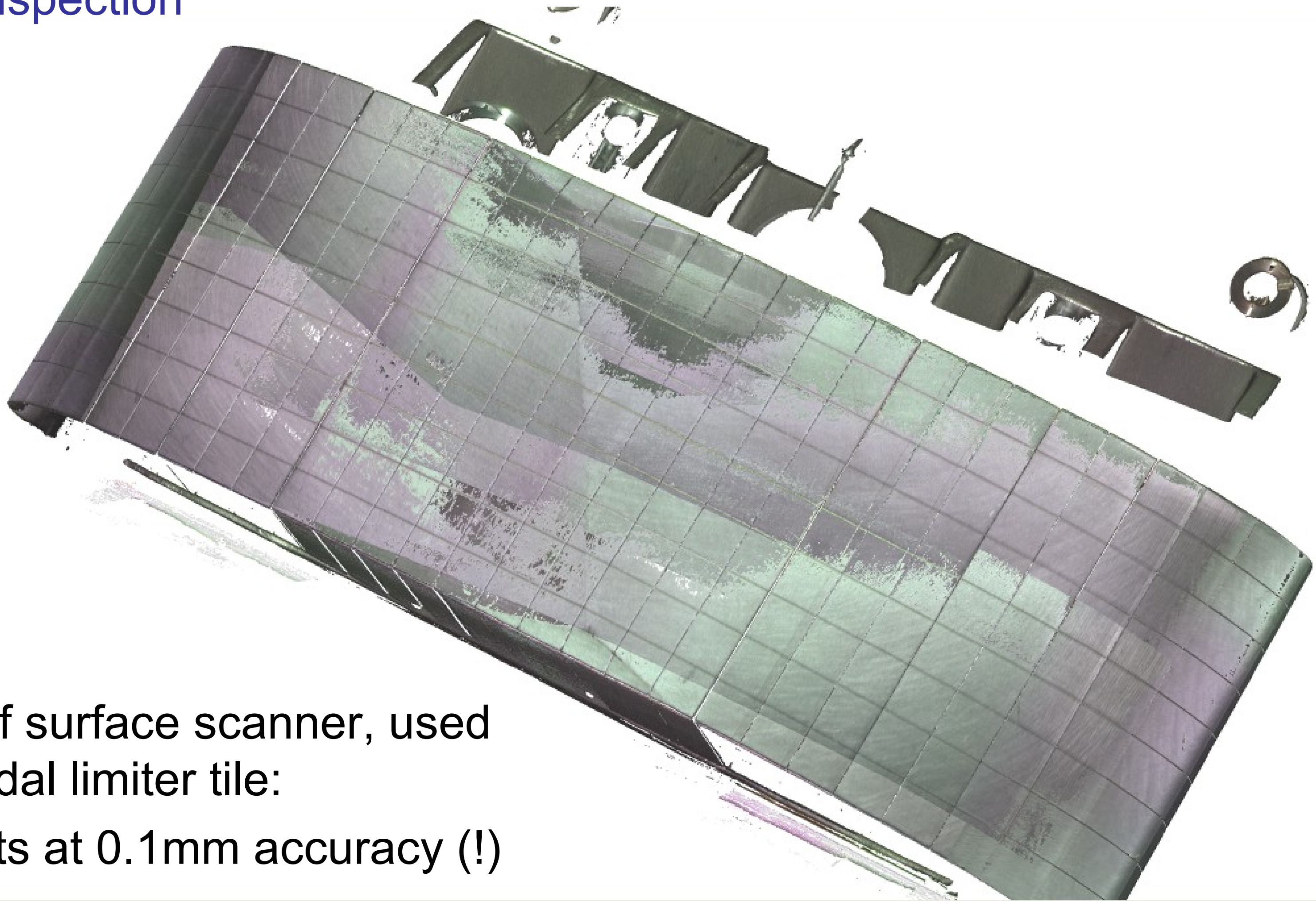
…suffers eddy currents as modeled in ANSYS:



… creating torques on the tile carrier and its supports.

Machine Assembly

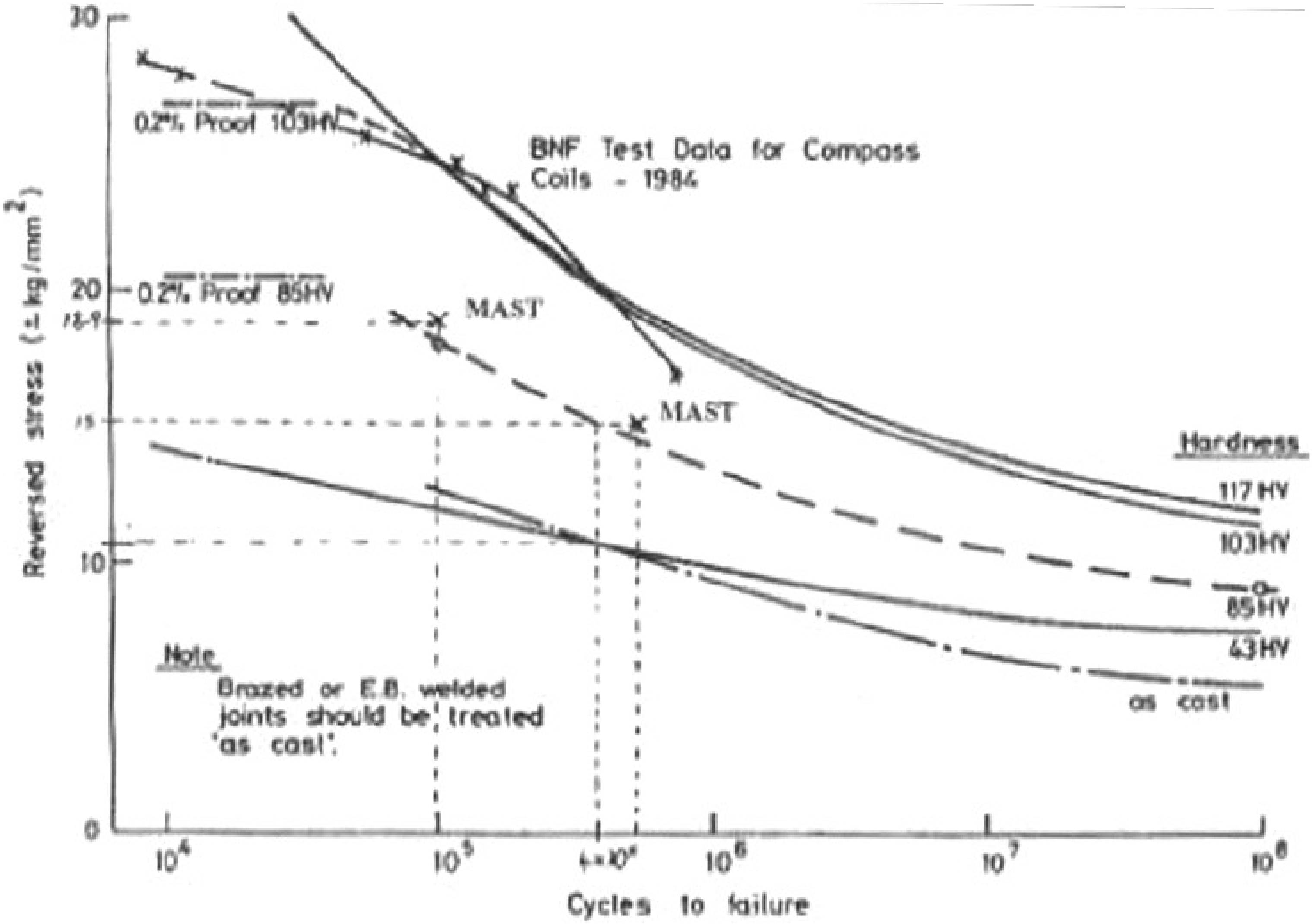
Dimensional inspection

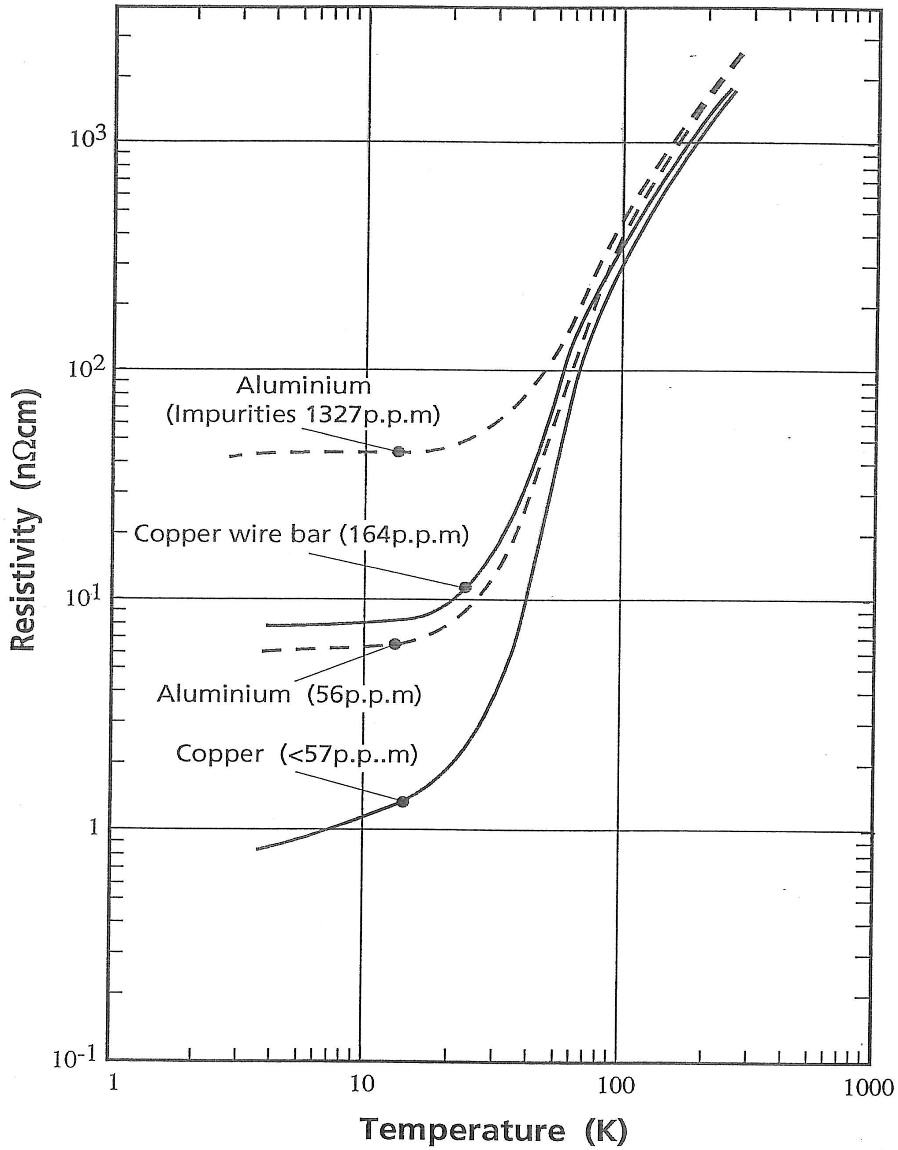


Another type of surface scanner, used on a JET poloidal limiter tile:

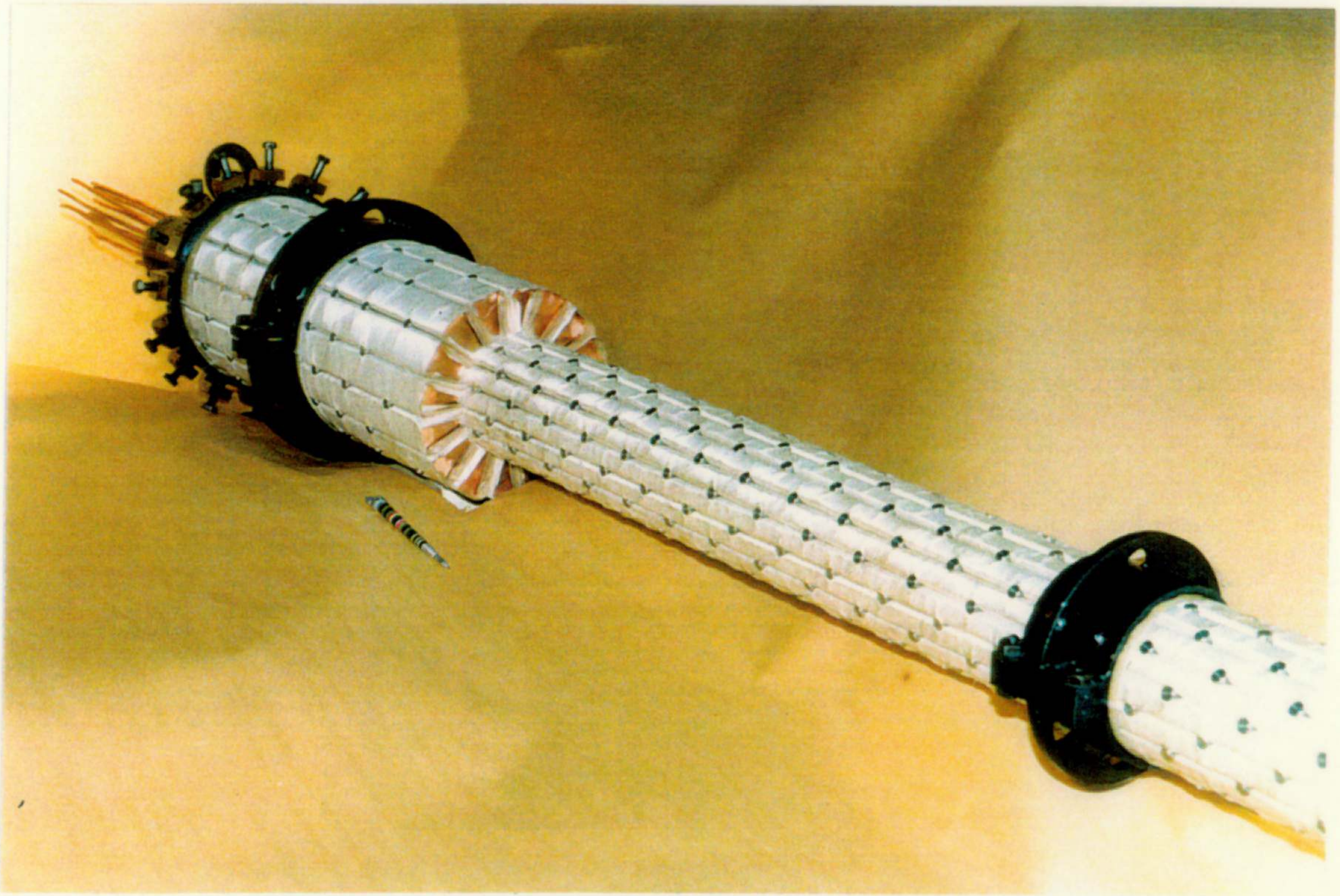
13 million points at 0.1mm accuracy (!)

Fatigue life of copper

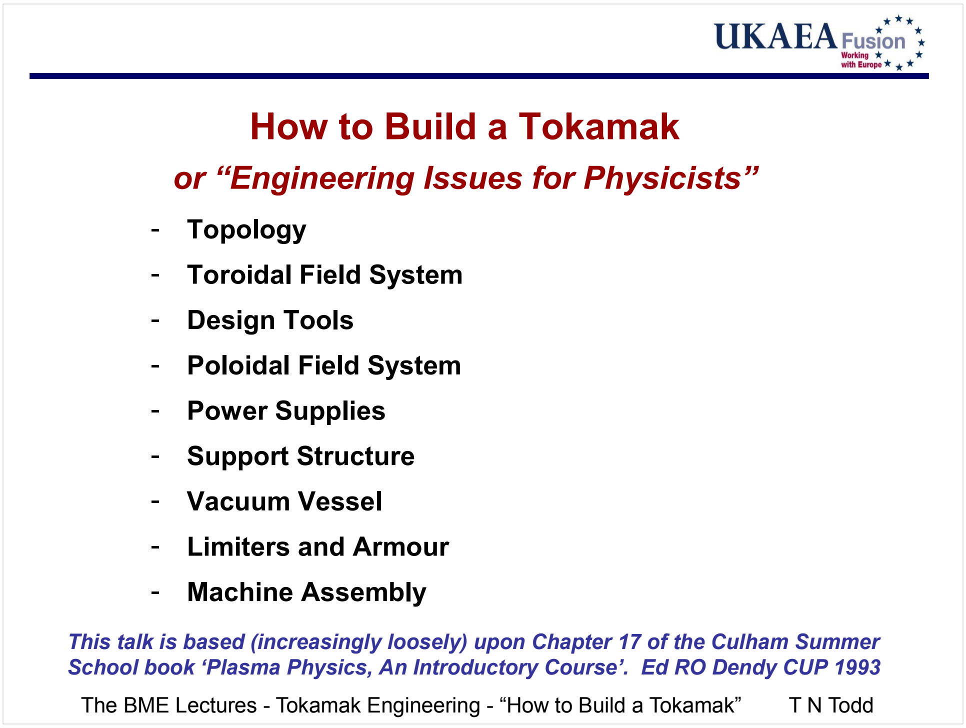



Resistivity (nΩcm)
10^3
10^2
10^1
1
10^{-1}
1
10
100
1000
Temperature (K)
Aluminium
(Impurities 1327p.p.m)
Copper wire bar (164p.p.m)
Aluminium (56p.p.m)
Copper (<57p.p..m)

Globus-M, showing dowel inserts in central vault



Central rod (16 assembled TF coil legs)
before vacuum impregnation



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How to Build a Tokamak

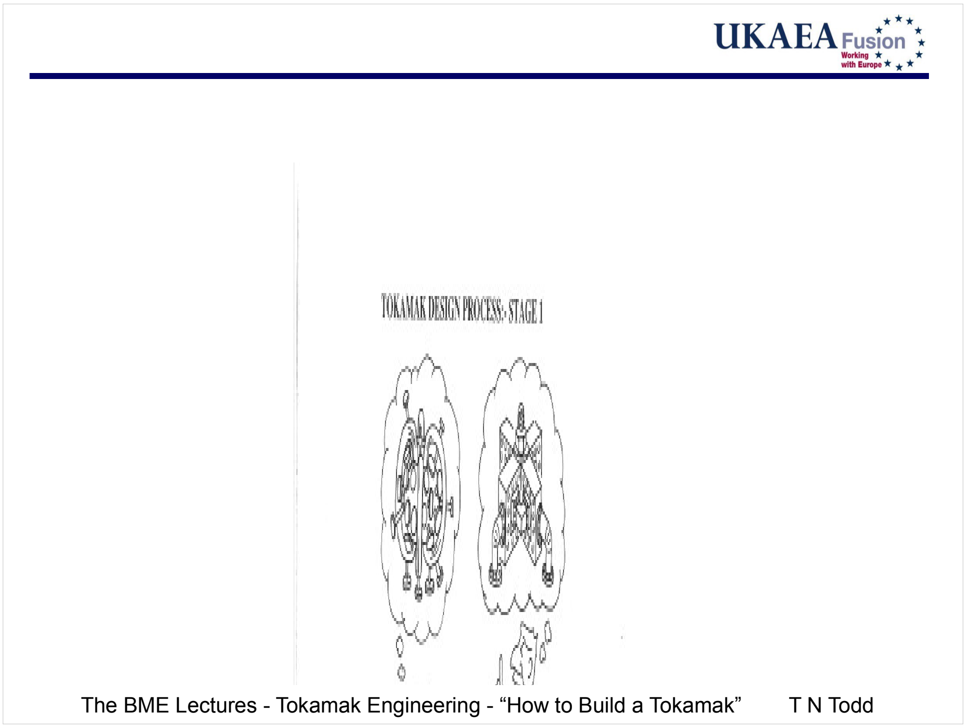
or "Engineering Issues for Physicists"

- **Topology**
- **Toroidal Field System**
- **Design Tools**
- **Poloidal Field System**
- **Power Supplies**
- **Support Structure**
- **Vacuum Vessel**
- **Limiters and Armour**
- **Machine Assembly**

This talk is based (increasingly loosely) upon Chapter 17 of the Culham Summer School book 'Plasma Physics, An Introductory Course'. Ed RO Dendy CUP 1993

The BME Lectures - Tokamak Engineering - "How to Build a Tokamak" T N Todd

The original version of this talk was created when I was an experimental physicist asked to liaise with an engineering team designing and building the COMPASS tokamak, which began operation in Culham ~1989 but is now reincarnated in Prague. In the intervening years I have become a design engineer with a somewhat different view of my physics colleagues!



TOKAMAK DESIGN PROCESS: STAGE 1

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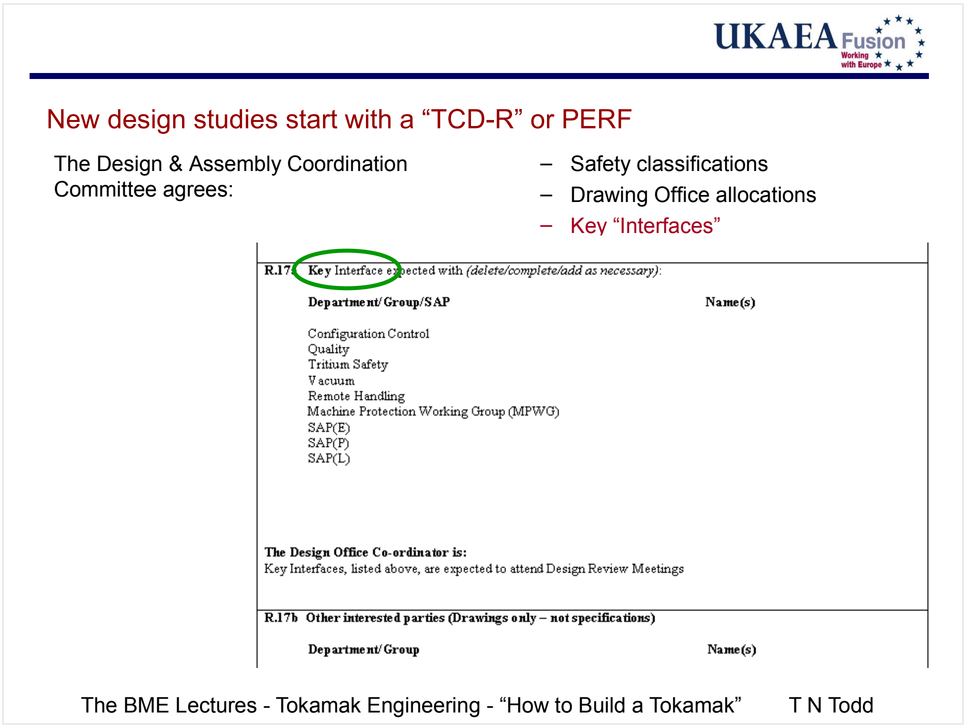
Physicists traditionally want maximum diagnostic access to any research machine and care little about the engineering details, while engineers stereotypically care little about the details of the physics but most certainly want the machine to meet its required lifetime.


UKAEA Fusion

Working with Europe

New design studies start with a “TCD-R” or PERF

The Design & Assembly Coordination Committee agrees:

- Safety classifications
- Drawing Office allocations
- Key “Interfaces”

R.17a **Key** Interface expected with *(delete/complete/add as necessary)*:

Department/Group/SAP	**Name(s)**
Configuration Control	
Quality	
Tritium Safety	
Vacuum	
Remote Handling	
Machine Protection Working Group (MPWG)	
SAP(E)	
SAP(F)	
SAP(L)	

The Design Office Co-ordinator is:

Key Interfaces, listed above, are expected to attend Design Review Meetings

R.17b Other interested parties (Drawings only – not specifications)

Department/Group	**Name(s)**

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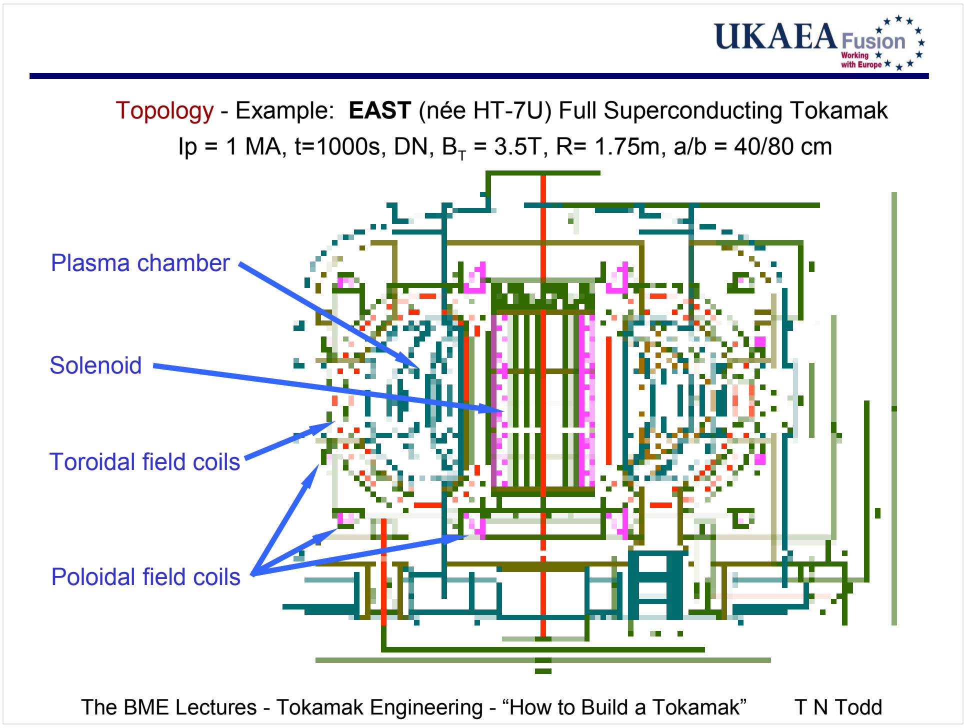
This form has been used on JET to guide new modifications of that machine.

When a modification or new sub-system is proposed, a design coordination committee first has to consider what all the possible interfaces are, and nominate the individuals who will provide the necessary design input for each interface.

Similar forms are used for the MAST tokamak, now shut down to make way for MAST-Upgrade (due on line in 2015)..



Topology - Example: **EAST** (née HT-7U) Full Superconducting Tokamak

Ip = 1 MA, t=1000s, DN, B_T = 3.5T, R= 1.75m, a/b = 40/80 cm

Plasma chamber

Solenoid

Toroidal field coils

Poloidal field coils

The principle components of a tokamak. The word comes from Russian and means “toroidal'naya kamera s aksial'nym magnitnym polem” (toroidal chamber with axial magnetic field). Earlier toroidal devices had no axial magnetic field, and were found to be very unstable to kink modes.

Topology

An early design option is to choose which coils are nearest to the plasma – toroidal or poloidal

Coils near plasma:	Advantages	Disadvantages
Toroidal Field		
Poloidal Field, including Solenoid		

Topology

An early design option is to choose which coils are nearest to the plasma – toroidal or poloidal

Coils near plasma:	Advantages	Disadvantages
Toroidal Field	Smallest possible stored magnetic energy. No interlinking of coils.	Many coils needed to avoid severe ripple. Restricted OH solenoid diameter if air-cored. Difficult to get strong plasma shaping.
Poloidal Field, including Solenoid	Easy to shape plasma. Possible gain in plasma vertical stability. Largest possible (air-cored) OH solenoid diameter. Can use fewer TF coils. Good access for (small) diagnostics.	Interlinked coils, therefore joints somewhere. Larger TF stored energy.

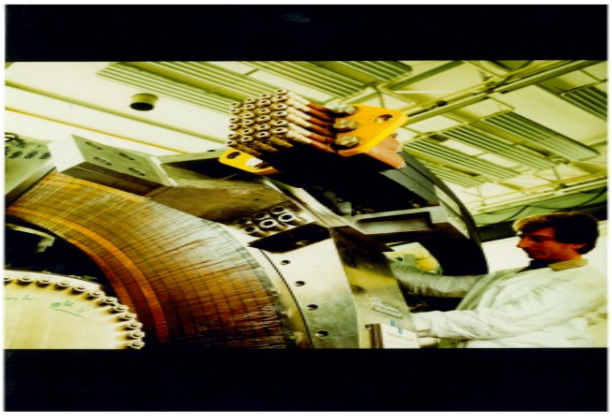
These considerations lead to a variety of design solutions …

Topology - TEXTOR: Split Vacuum Vessel and PF Coils

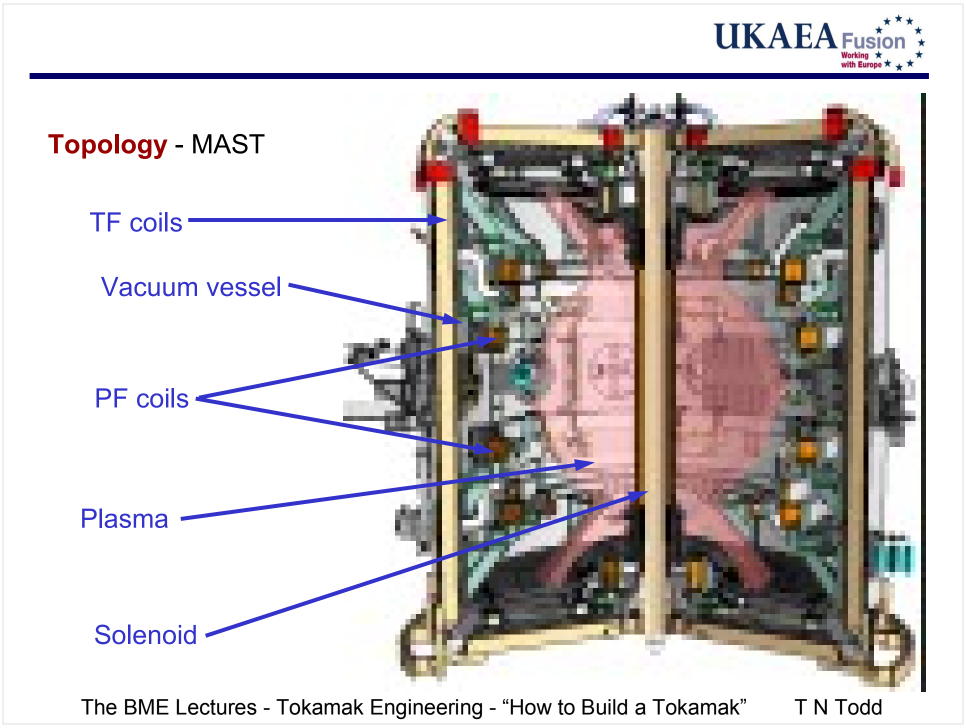
This is an extremely unusual design option!

TEXTOR was closed down in 2013, after many decades of productive operation.

Topology - Detail of TEXTOR Split Poloidal Field Coils



Each individual turn of each poloidal field coil (basically the vertical field coils that control the plasma major radius) has to be jointed for both electrical current and cooling water – with no leaks.



Topology - MAST

TF coils

Vacuum vessel

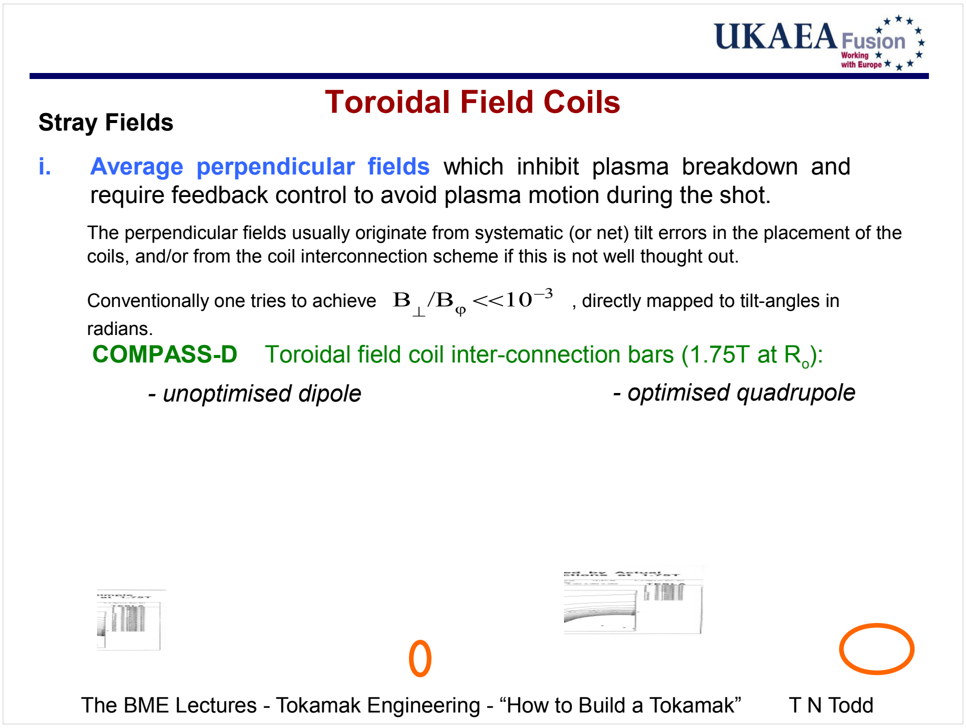
PF coils

Plasma

Solenoid

Another unusual design. Many tokamaks have jointed toroidal field coils but few have poloidal field coils inside the vacuum vessel, where they must be reliably canned to suit the ultra-high vacuum requirements.

In addition, this is a “spherical tokamak”, meaning one with the ratio of major radius ‘R’ to minor radius ‘a’ below 2.0, here ~1.4.



Toroidal Field Coils

Stray Fields

i. **Average perpendicular fields** which inhibit plasma breakdown and require feedback control to avoid plasma motion during the shot.

The perpendicular fields usually originate from systematic (or net) tilt errors in the placement of the coils, and/or from the coil interconnection scheme if this is not well thought out.

Conventionally one tries to achieve $B_\perp / B_\varphi << 10^{-3}$, directly mapped to tilt-angles in radians.

COMPASS-D Toroidal field coil inter-connection bars (1.75T at R_o):

- unoptimised dipole *- optimised quadrupole*

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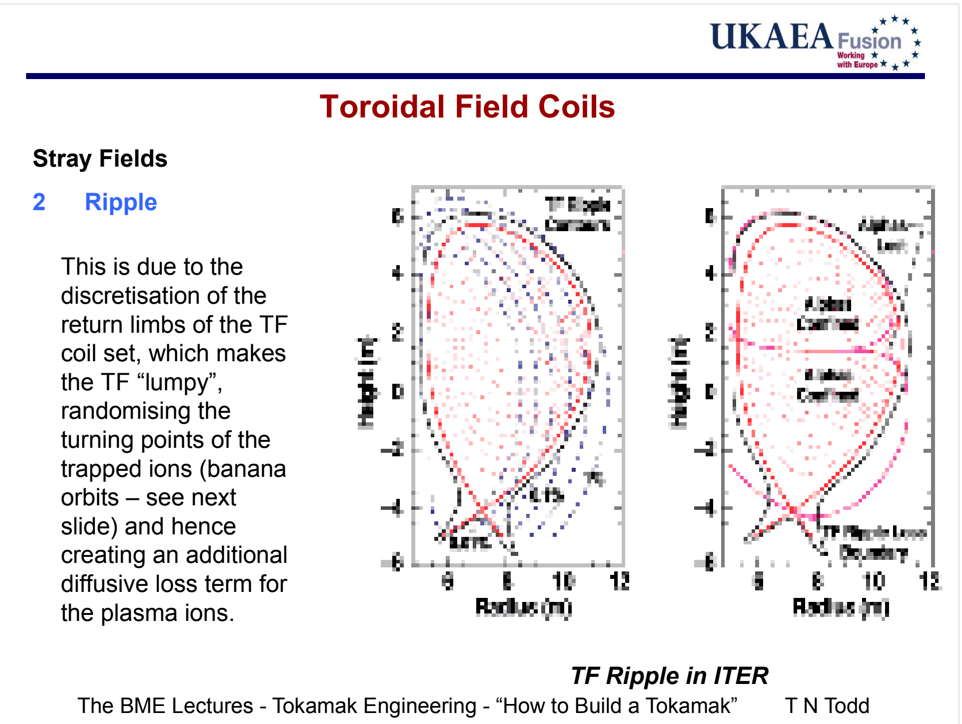
In the right-hand figure, the three dots represent the locations of the feeder bar currents. The central one is constant in location between all the TF coils, while the return bar alternates between the other two positions, from one TF coil to the next. Thus when averaged toroidally, the stray field is cancelled out in the region of interest.



Toroidal Field Coils

Stray Fields

2 Ripple

This is due to the discretisation of the return limbs of the TF coil set, which makes the TF “lumpy”, randomising the turning points of the trapped ions (banana orbits – see next slide) and hence creating an additional diffusive loss term for the plasma ions.

TF Ripple in ITER

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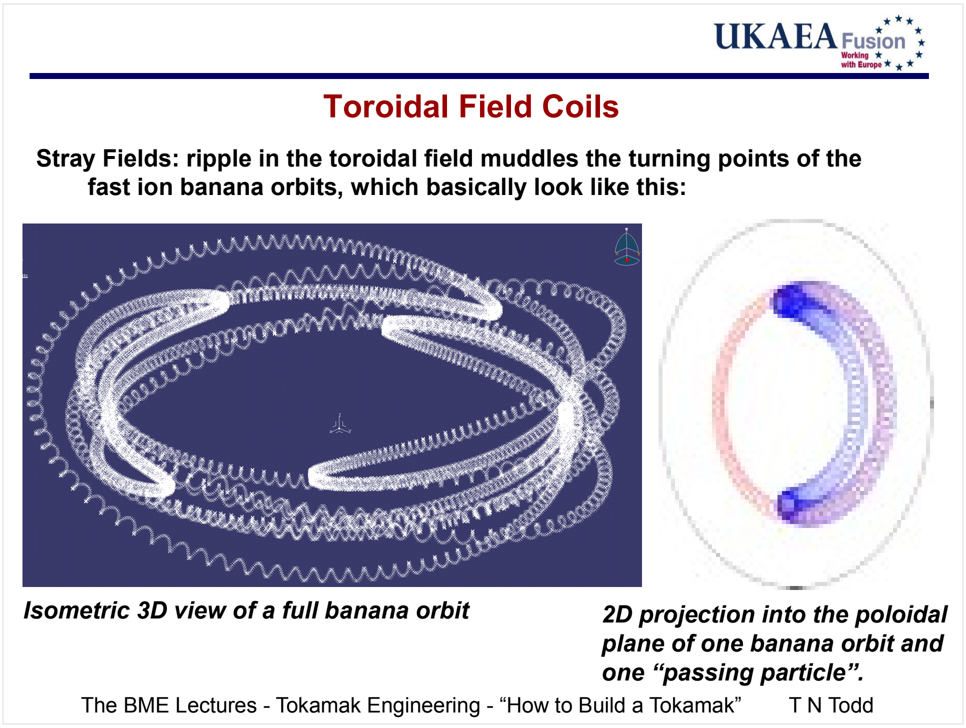
Fast ions in tokamaks can be mirrored in the magnetic field since it rises in strength towards the major axis of the machine. This causes the fast ions to execute banana-shaped orbits (as projected into the poloidal plane), which in a perfectly axisymmetric machine would overlay each-other precisely.



Toroidal Field Coils

Stray Fields: ripple in the toroidal field muddles the turning points of the fast ion banana orbits, which basically look like this:

Isometric 3D view of a full banana orbit

2D projection into the poloidal plane of one banana orbit and one "passing particle".

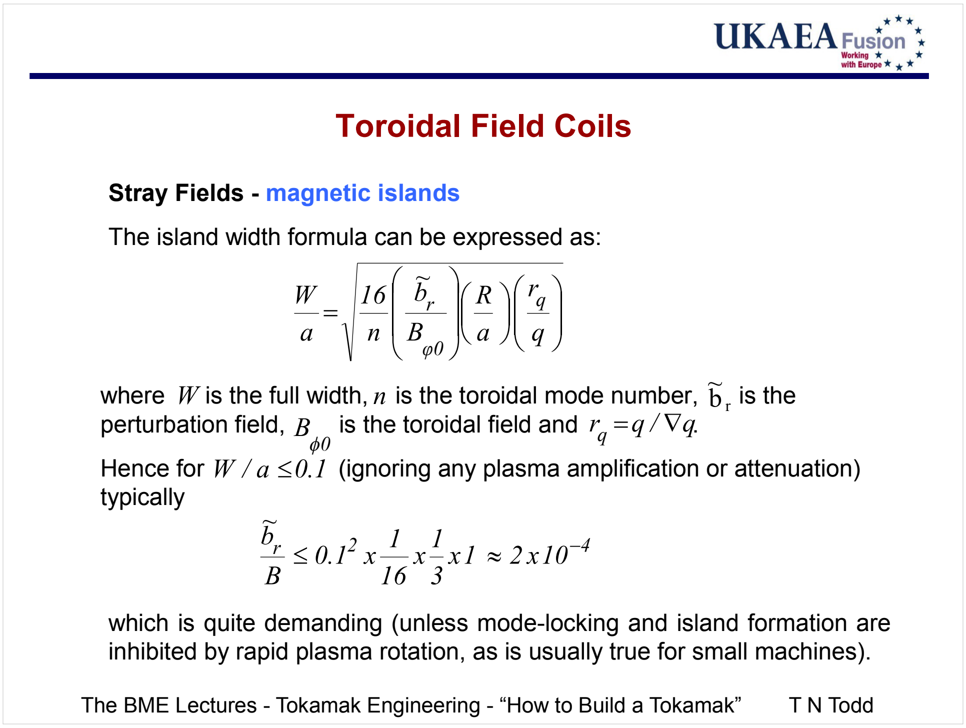
Fast ions in tokamaks can be mirrored in the magnetic field since it rises in strength towards the major axis of the machine. This causes the fast ions to execute banana-shaped orbits (as projected into the poloidal plane), which in a perfectly axisymmetric machine would overlay each-other precisely.

Toroidal Field Coils

Stray Fields

iii. **Resonant magnetic perturbations** which tend to create **magnetic islands** in the plasma region, affecting plasma confinement and stability (eg via “mode lock” phenomena).

- The resonant magnetic perturbations primarily originate from random asymmetries in placement of the coils, and from non-axisymmetric stray fields generated by the feeder bars.



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Toroidal Field Coils

Stray Fields - **magnetic islands**

The island width formula can be expressed as:

$$\frac{W}{a} = \sqrt{\frac{16}{n}\left(\frac{\tilde{b}_r}{B_{\varphi 0}}\right)\left(\frac{R}{a}\right)\left(\frac{r_q}{q}\right)}$$

where W is the full width, n is the toroidal mode number, $\tilde{b}_r$ is the perturbation field, $B_{\phi 0}$ is the toroidal field and $r_q = q / \nabla q$.

Hence for $W / a \le 0.1$ (ignoring any plasma amplification or attenuation) typically

$$\frac{\tilde{b}_r}{B} \le 0.1^2 \, x \, \frac{1}{16} \, x \, \frac{1}{3} \, x \, 1 \approx 2 \, x \, 10^{-4}$$

which is quite demanding (unless mode-locking and island formation are inhibited by rapid plasma rotation, as is usually true for small machines).

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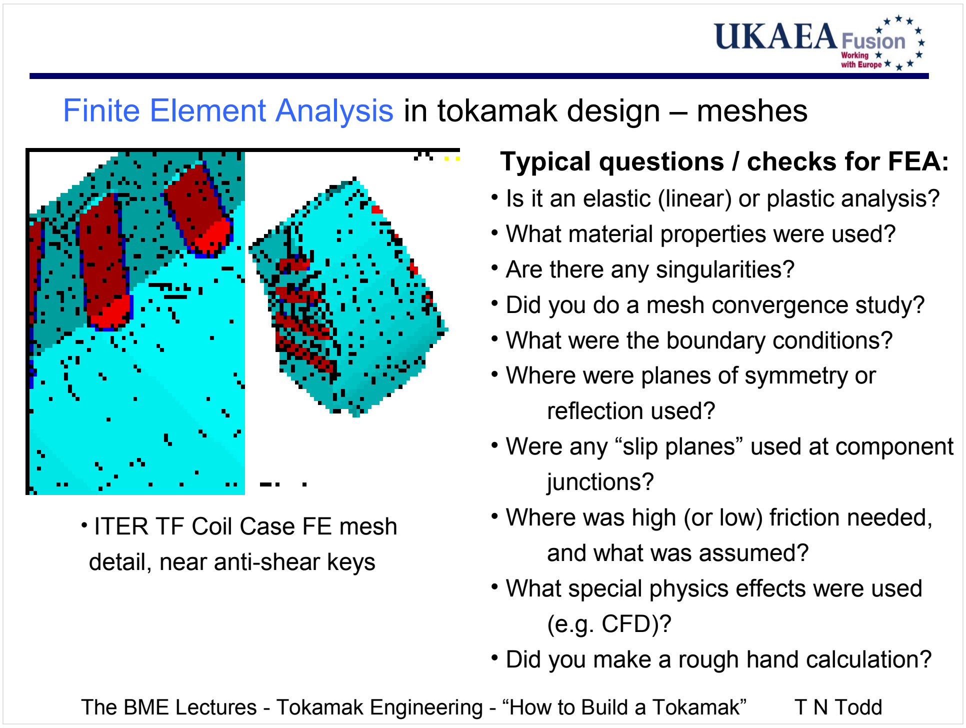
The toroidal mode ‘n’ number is how many oscillations in the perturbation field strength there are in one toroidal revolution. As can be seen from the formula, the most dangerous number in a tokamak (i.e. the one which generates the largest islands for a given field strength) is 1, the next most dangerous 2.

n=3 or 4 is often used to drive magnetic islands in the edge region of tokamaks to alter the edge topology (and therefore the edge physics) but is rarely dangerous for the machine operation like n=1 or n=2, which tend to trigger large-scale plasma instabilities.

Toroidal Field Coils

- The TF coil system has to be heavy enough to tolerate the forces upon it, which are primarily the self (i.e. bursting) force and the toppling force immediately following a plasma disruption (due to the vertical field remaining after the plasma current has disappeared).
- The integral of these forces around the coil gives rise to tensile and bending stresses (pure tension for the self-force on an appropriately D-shaped coil) which have to be kept below ~120MPa for conventional OFHC copper, 200MPa or more for special copper alloys.
- Usually a significant shear stress arises in the insulators separating the segments of the TFC vault (ie. twisting the vault), due to the TFC current crossing the radial component of the end-field of the Ohmic heating solenoid.
- The “pinch force” on the vault conductors helps the insulator to survive the shear stresses by putting it into compression.

The original early 1990’s talk featured many approximate stress equations, but these days almost all stress analyses are done by FEA.



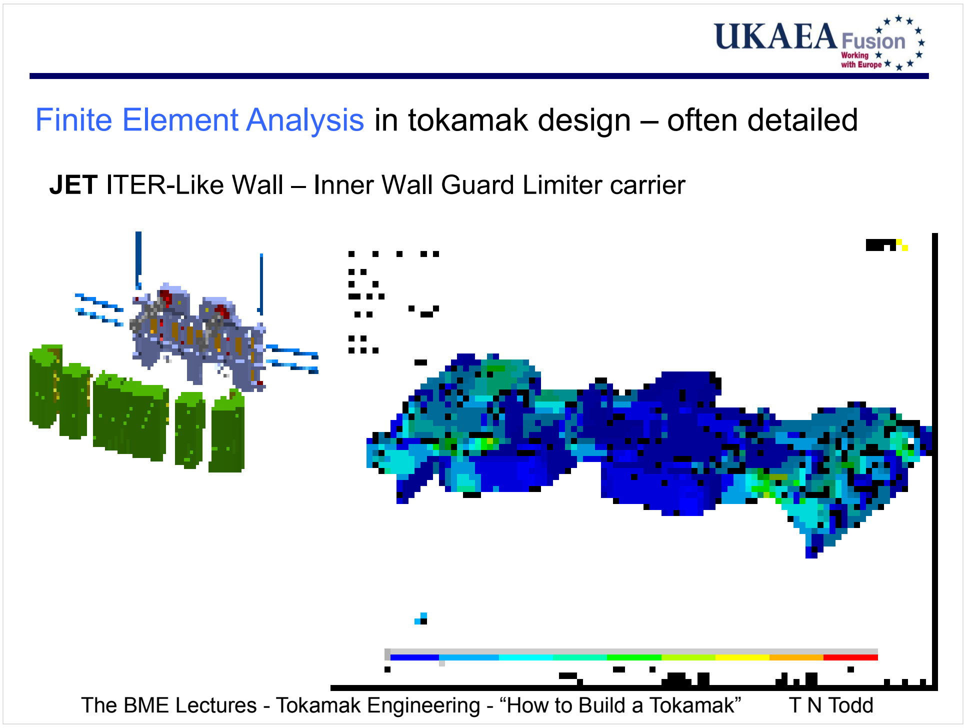
Finite Element Analysis in tokamak design – meshes

- ITER TF Coil Case FE mesh detail, near anti-shear keys

Typical questions / checks for FEA:

- Is it an elastic (linear) or plastic analysis?
- What material properties were used?
- Are there any singularities?
- Did you do a mesh convergence study?
- What were the boundary conditions?
- Where were planes of symmetry or reflection used?
- Were any “slip planes” used at component junctions?
- Where was high (or low) friction needed, and what was assumed?
- What special physics effects were used (e.g. CFD)?
- Did you make a rough hand calculation?

Modern Finite Element Analysis codes feature automatic mesh generation and automatic mesh size adjustment, aiming to avoid sparse distributions of mesh points in regions with strong gradients of stress.



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Finite Element Analysis in tokamak design – often detailed

JET ITER-Like Wall – Inner Wall Guard Limiter carrier

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Since FEA codes are now quite fast, there is a temptation amongst modern designers to analyse “everything”, when often an obvious design solution that obviates key stress-raising features can be used right from the earliest sketches.

Even so, many aspects of magnetic confinement fusion research machines such as tokamaks push materials and engineering design codes to the limits, and often extremely detailed analyses will be required, to refine a design and achieve an adequate component life.

MAST-U Centre Column magnetic diagnostic (cuboid) coil holder blocks

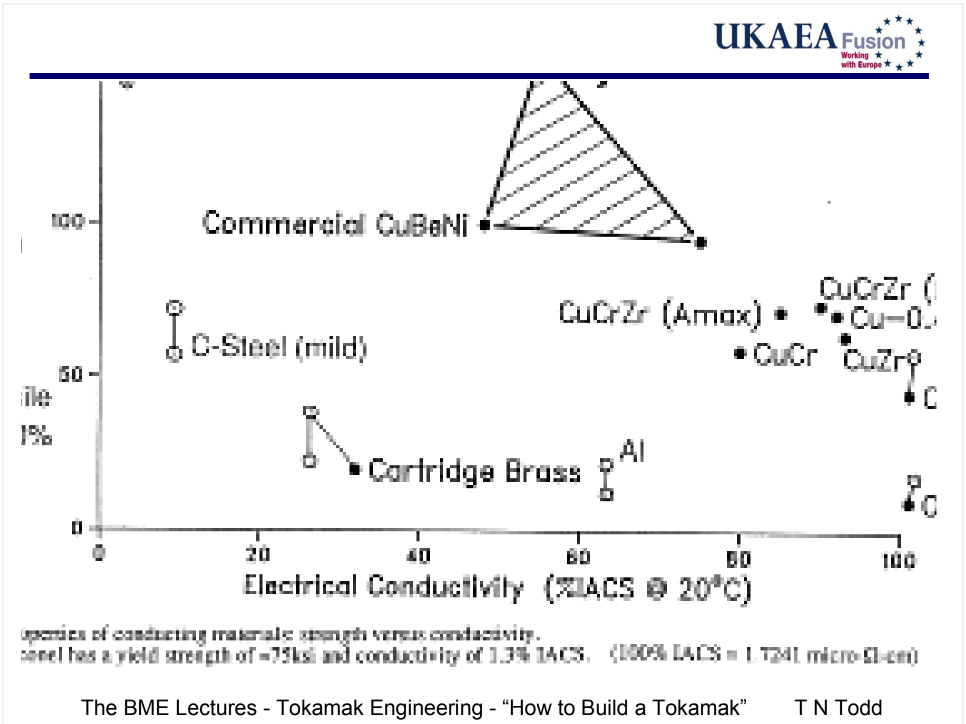
CAD Virtual Reality render

Reality trial by 3D printing (by Gyrobot Ltd).

Fatigue – the S-N (Wohler) curve

- If the curve becomes horizontal, the material has a *fatigue (endurance) limit*, eg ferrous and titanium alloys.
  - The fatigue limit for steel is typically 35 to 60% of the ultimate tensile strength of the material.

  - In many cases, the S-N curve does not flatten out, eg copper, aluminium, magnesium alloys.
  - The *Fatigue Strength* is the stress level at which the material will fail after a specified number of cycles, the *Fatigue Life*.



operties of conducting materials: strength versus conductivity.
onel has a yield strength of ≈75ksi and conductivity of 1.3% IACS. (100% IACS = 1.7241 micro Ω-cm)

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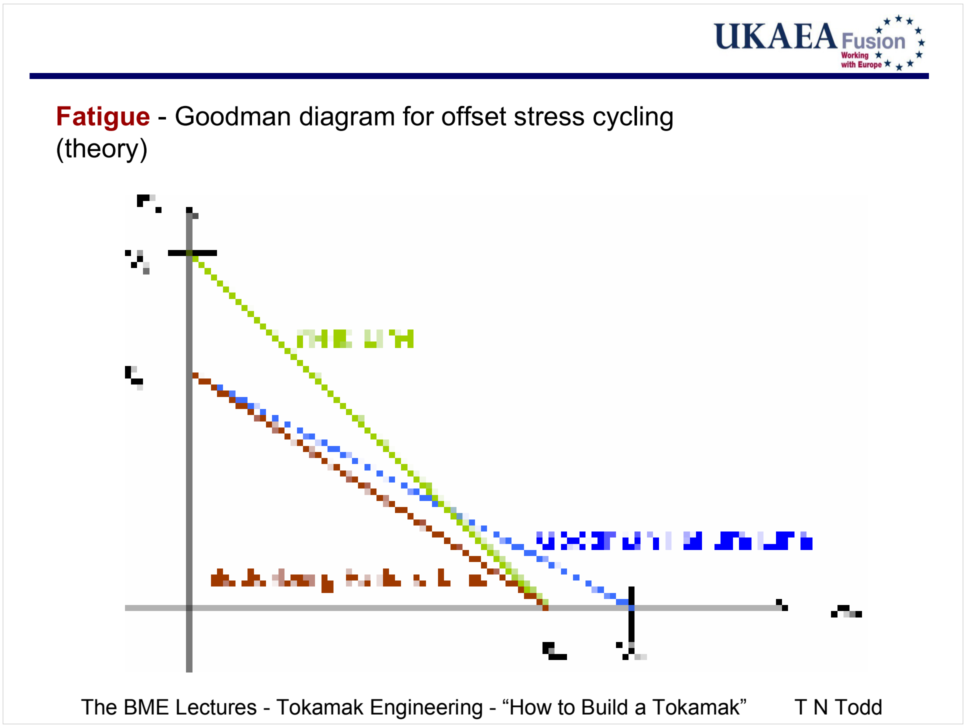
Sadly, there is no very high conductivity alloy that also has very high strength!

The alloying constituents can be considered as “impurities” in the elemental metal, as far as the electrons carrying the current are concerned.

To get to MPa from the American unit ‘ksi’ (kilo-pounds per square inch!), multiply by about 7.



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Fatigue - Goodman diagram for offset stress cycling (theory)

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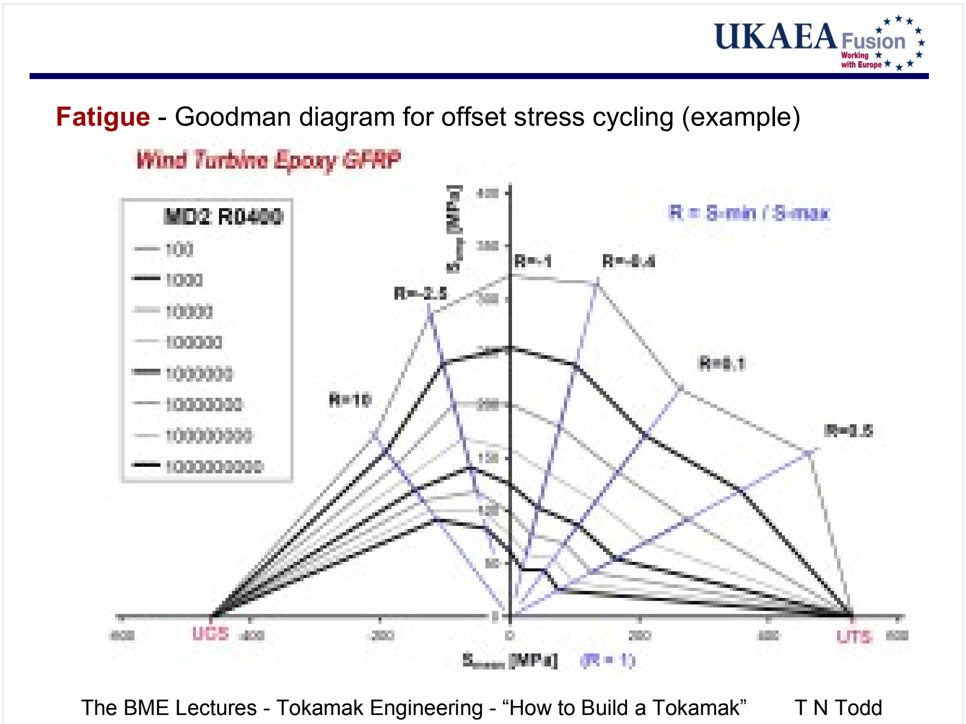
Intuitively you would not expect that a material stressed almost to breaking point continuously would be able to exhibit a good fatigue life when additionally subjected to cyclic stress.



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Fatigue - Goodman diagram for offset stress cycling (example)

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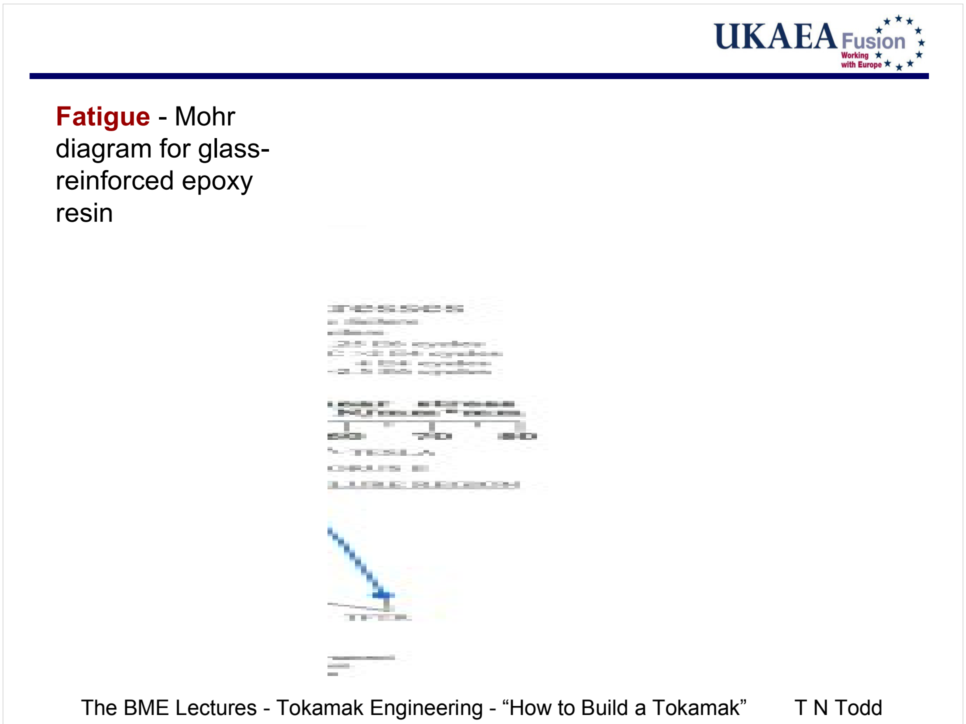
The shapes of the curves (one curve for each lifetime in number of cycles) vary considerably for different materials.



Fatigue - Mohr diagram for glass-reinforced epoxy resin

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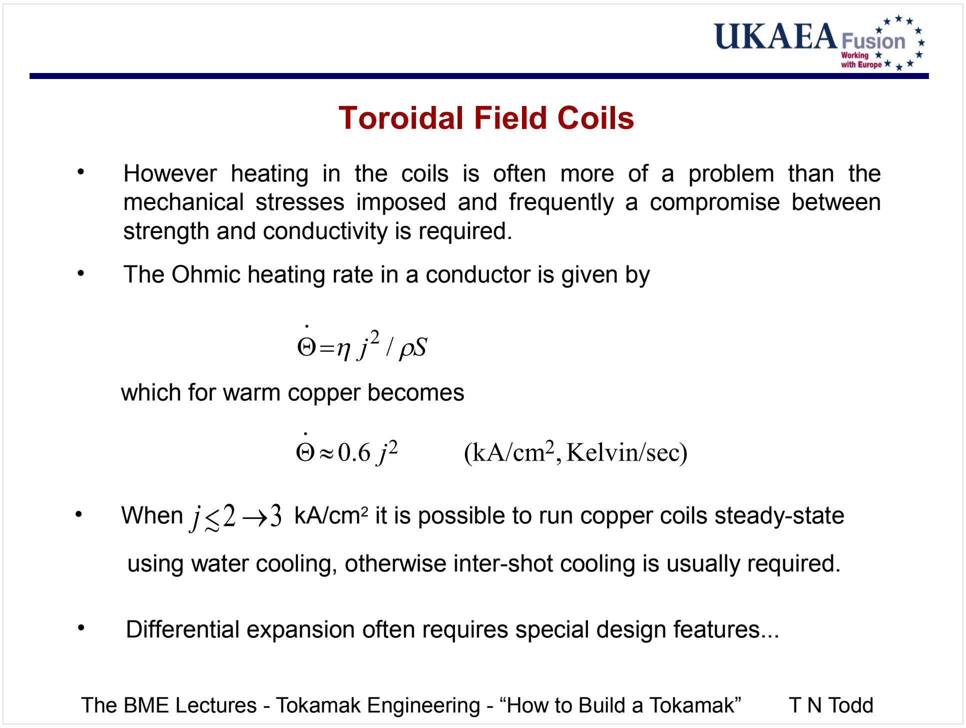
A simplified plot, betraying an engineer as the originator! In reality the plot has to be exactly symmetrical on the left and right of the y-axis, and must have zero gradient at the y-axis.

In addition, there will not be infinite strength in compression, and so this plot is often called the “Mohr circle” or the “Mohr ellipse”, when the points describing the compression limit at zero shear stress are added.



Toroidal Field Coils

- However heating in the coils is often more of a problem than the mechanical stresses imposed and frequently a compromise between strength and conductivity is required.
- The Ohmic heating rate in a conductor is given by

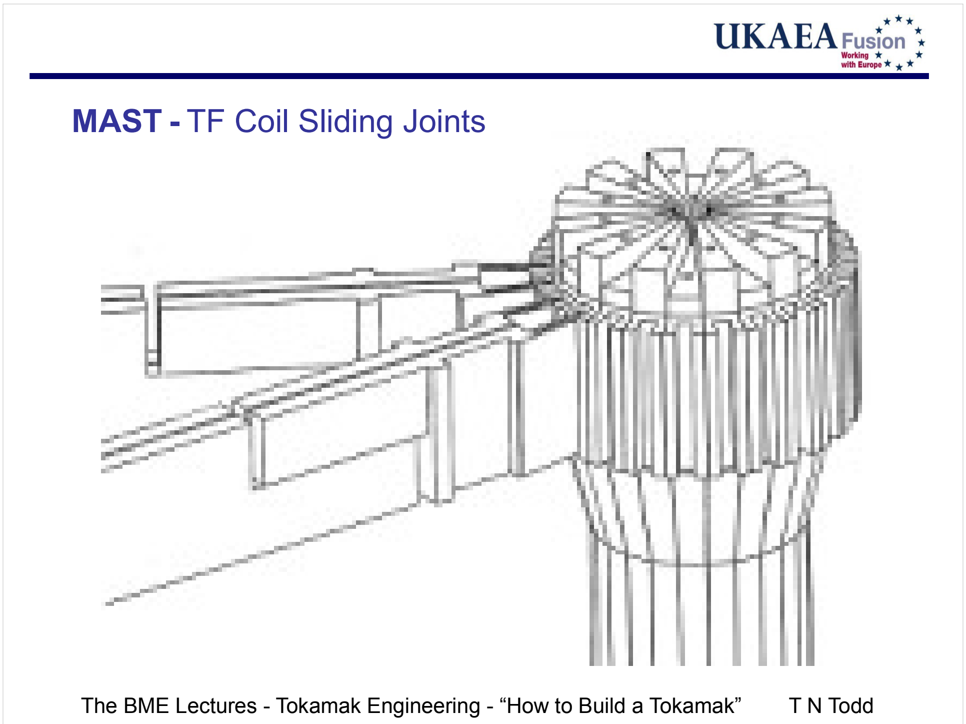
$$\dot{\Theta} = \eta\, j^2 / \rho S$$

which for warm copper becomes

$$\dot{\Theta} \approx 0.6\, j^2 \qquad (\mathrm{kA/cm^2, Kelvin/sec})$$

- When $j \lesssim 2 \rightarrow 3$ kA/cm² it is possible to run copper coils steady-state using water cooling, otherwise inter-shot cooling is usually required.
- Differential expansion often requires special design features...

Some extreme designs have featured current density in copper up to ~7kA/cm^2. Long coolant channels are then a particular problem, or else the insulator will overheat (or an unusual insulating material is required).



MAST - TF Coil Sliding Joints

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The TF horizontal limbs are attached to the top and bottom plates of the vacuum vessel and therefore slide towards the mid-plane of the machine when vacuum is applied.

Subsequently when the toroidal magnetic field is energised, the net force reverses and the horizontal limbs slide away from the mid-plane.

During the shot, the centre column of the TF coil set heats up and expands, producing yet a third differential motion at the sliding joints.

Poloidal Field Coils

General

- The functions of the poloidal field coils are to produce the magnetising flux, main equilibrium field, shaping fields and position feedback.
- Some or all of these functions can be combined (so fewer coils are required) using appropriate feedback control techniques.
- Many old machines used an iron core to reduce power supply demand, but the B(H) non-linearities introduce many operational problems.
- Some significant operational advantages (and engineering disadvantages) accrue if a poloidal divertor is included in the design to improve impurity control or energy confinement times.
- Shaping fields (including those for a divertor configuration) are of the same magnitude as, indeed are part of, the main equilibrium fields and have comparable power requirements.
- Feedback systems are usually relatively low power but fast, based on eg thyristor choppers or linear amplifiers.

Poloidal Field Coils

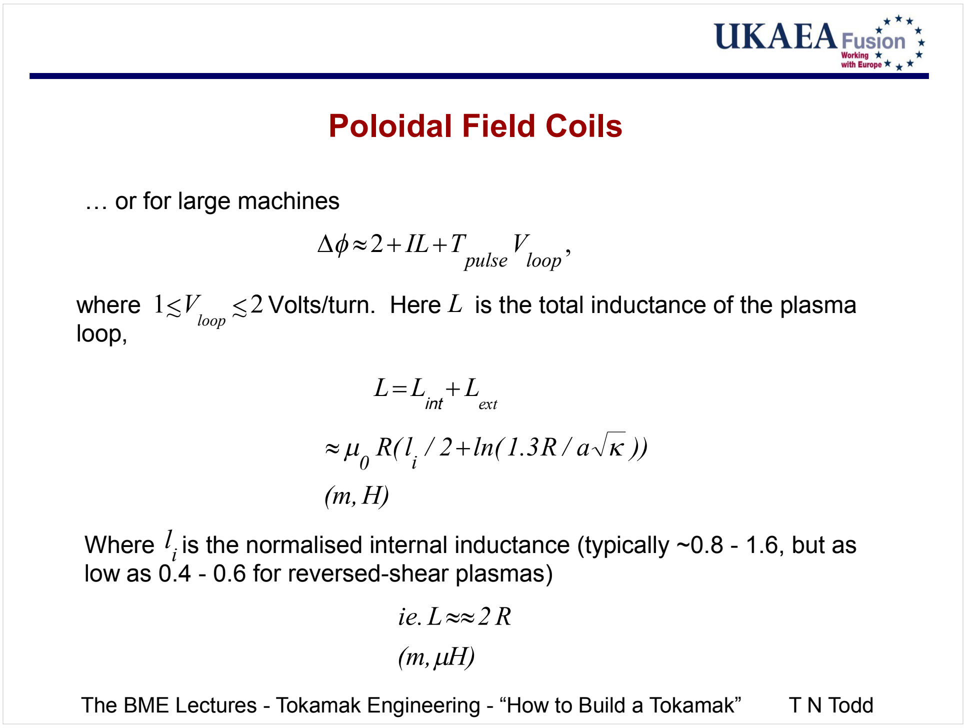
Forces

Truly circular and aligned poloidal field coils do not “feel” the main toroidal field, only its small ripple. The principle forces are self (hoop) and vertical and radial forces arising from other PF coils and the plasma current. Often the most highly stressed PF coil is the OH solenoid, because experimentalists always seek the largest possible volt-seconds swing.

Magnetising Winding

The magnetising winding produces the flux swing necessary to produce and sustain the plasma current. The volt-second consumption can be approximated for small machines by

$$\Delta\phi \approx 1.5\,\mathrm{IL} + \mathrm{T}_{\mathrm{pulse}}\,\mathrm{V}_{\mathrm{loop}} \quad (\mathrm{MA},\ \mu\mathrm{H},\ \mathrm{secs},\ \mathrm{Wb})$$



Poloidal Field Coils

… or for large machines

$$\Delta\phi \approx 2 + IL + T_{pulse} V_{loop},$$

where $1 \lesssim V_{loop} \lesssim 2$ Volts/turn. Here L is the total inductance of the plasma loop,

$$L = L_{int} + L_{ext}$$

$$\approx \mu_0 R(l_i / 2 + ln(1.3R / a\sqrt{\kappa}))$$

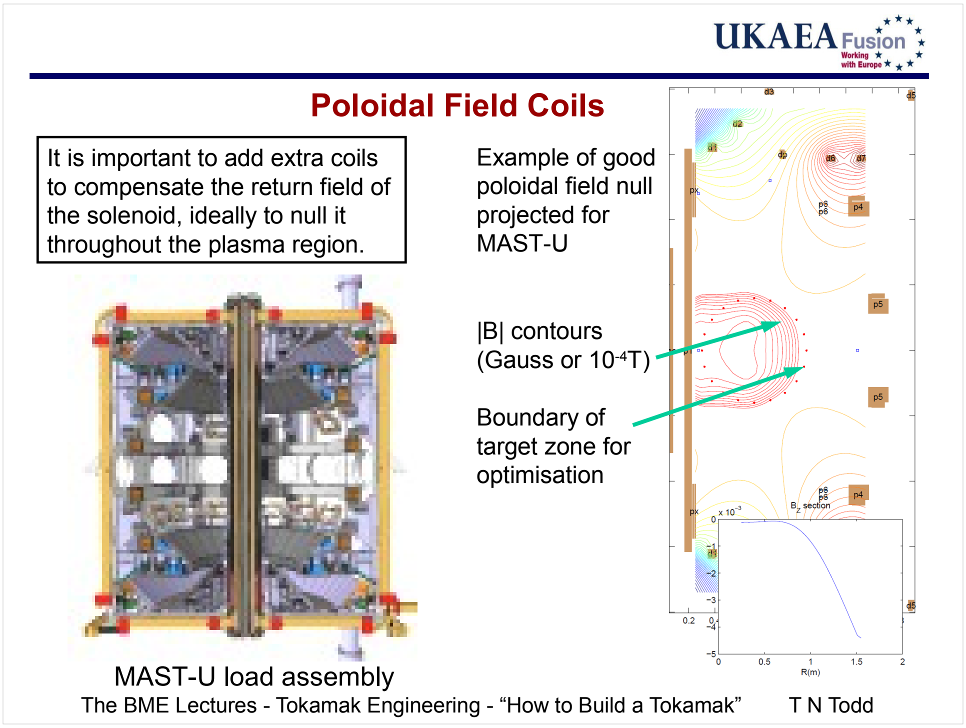
$$(m, H)$$

Where l_i is the normalised internal inductance (typically ~0.8 - 1.6, but as low as 0.4 - 0.6 for reversed-shear plasmas)

$$ie. \, L \approx\approx 2R$$

$$(m, \mu H)$$

“Reversed shear” means with the profile of magnetic field line pitch, ‘q’, which usually only rises monotonically from the minor axis of the tokamak towards the edge of the plasma, featuring a minimum so that the gradient of q is reversed near the minor axis of the machine. Experimentally this is found to increase the energy confinement time of the plasma.



Poloidal Field Coils

It is important to add extra coils to compensate the return field of the solenoid, ideally to null it throughout the plasma region.

Example of good poloidal field null projected for MAST-U

|B| contours (Gauss or 10^{-4}T)

Boundary of target zone for optimisation

MAST-U load assembly

It is important to remember that when the plasma is being initiated, there will be a toroidal loop voltage and therefore a current flowing in the vacuum vessel (unless this is toroidally gapped, which I believe is not true of any modern design). This toroidal current of course also creates a contribution to the poloidal field structure at the moment intended for plasma initiation (i.e. breaking down of the prefill gas).

Poloidal Field Coils

Magnetising Winding

- The volt-seconds produced by a simple long solenoid are of course (for a bidirectional swing B_{max} , radius r_{sol} , thickness δr_{sol} , packing fraction f_{sol}),

$$\Delta\Phi = 2B_{max} \cdot \pi r_{sol}^2$$

(T, m, Wb)

$$or\ \Delta\Phi = 8\pi^2 j r_{sol}^2 \delta r_{sol} f_{sol}$$

$(kA/cm^2, m, m, Wb)$

The average hoop stress in the solenoid winding is

$$\sigma = 20\pi j^2 r_{sol} \delta r_{sol} f_{sol}$$

$(kA/cm^2, m, m, MPa)$

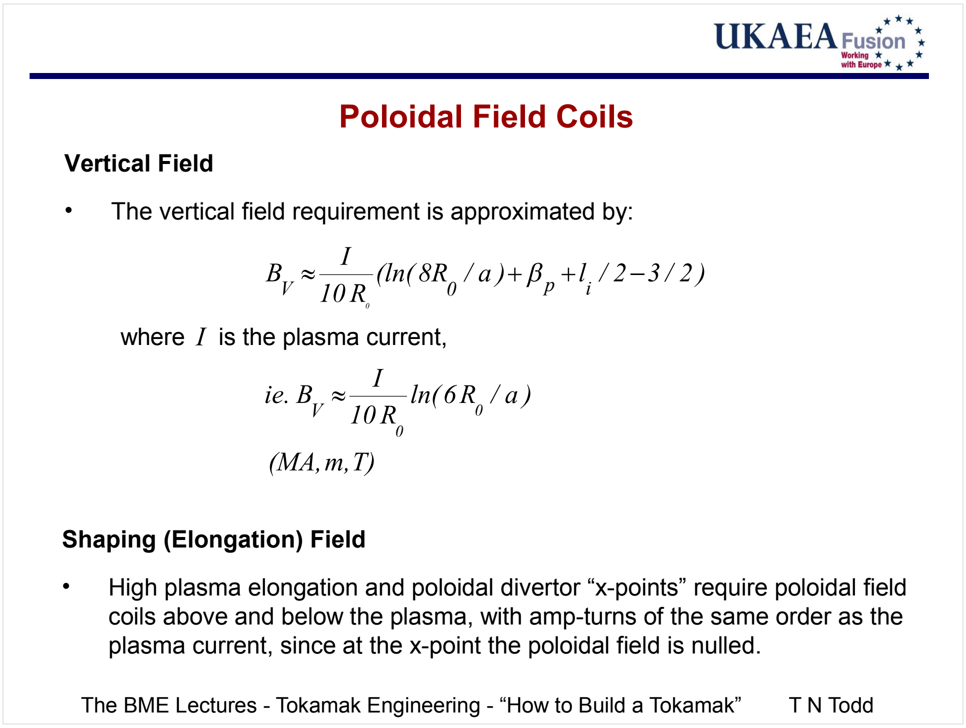
Poloidal Field Coils

- The radial component of the end-field of the solenoid generates an axial compressive force and hence an additional stress on the conductor and insulation:

$$\sigma_{compr,axial} \approx \Phi^2 / (4\pi^2 \mu_o r_{sol}^3 \delta r_{sol})$$

$$(Wb, m, m, Pa)$$

- Designers have to balance the r_{sol} and δr_{sol} to obtain the desired volt-seconds swing without breaking or overheating the magnetising solenoid.



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Poloidal Field Coils

Vertical Field

- The vertical field requirement is approximated by:

$$B_V \approx \frac{I}{10\,R_0}(\ln(8R_0/a)+\beta_p+l_i/2-3/2)$$

where I is the plasma current,

$$ie.\ B_V \approx \frac{I}{10\,R_0}\ln(6R_0/a)$$

(MA, m, T)

Shaping (Elongation) Field

- High plasma elongation and poloidal divertor “x-points” require poloidal field coils above and below the plasma, with amp-turns of the same order as the plasma current, since at the x-point the poloidal field is nulled.

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The formula is theoretical, due to Shafranov, and can be in error by up to ~15% for realistic magnetic configurations.

When considering the volt-seconds available for plasma initiation and current sustainment, it is as well to remember that there will be some volt-seconds (= poloidal Webers) contributed by the vertical field, as roughly $\pi R^2 B_V$ (m, Tesla, Wb). This is often ~ 0.4 of the total inductive volt-second requirement, $I_p L$.

Poloidal Field Coils

Power Supply Requirements

- In an air-cored system the power supply has to drive the current swing in the magnetising winding, which typically has an inductance ~50% greater than the central solenoid alone. Thus

$$L_{TOT} \approx 1.5 \, x \, 3.9 \, N^2_{sol} \, r^2_{sol} \, / \, l_{sol}$$

$$(m, m, \mu H)$$

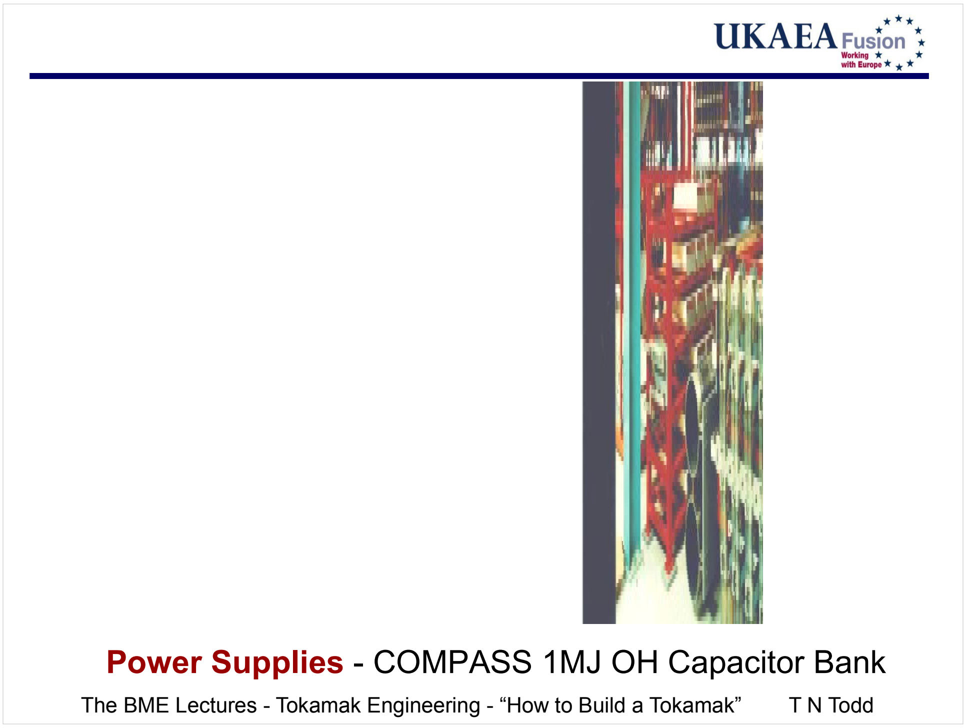
where N_{sol} and l_{sol} are the number of turns and length of the solenoid respectively. The reactive voltage is dominated by $I_{pri} \, L_{TOT}$ since coupling to the plasma is usually very poor.

Power Supply Options

Type	Advantages	Disadvantages
Capacitor banks	Very low mains power demand. Simple & very cheap.	Very poor control of current waveform.
Inductive Storage	Cheaper than capacitor bank systems at very large energies.	Switching problems.
Flywheel motor generators	Low (pony motor) mains demand. Optional stator field control. Very large powers & energies readily available.	Output frequency falls during pulse.
Steady-state motor-generators	Some flywheel effect to accommodate transients. Clean DC output with optional feedback control by stator field.	Severe mains demand. Feedback response time can be slow.

Power Supply Options

Type	Advantages	Disadvantages
Thyristor Rectifier	Fairly fast if multiphase (eg 12 or 24 phases). Natural inversion available.	Ripple & noise in load current. Worst possible option for mains demand. Large signal BW poor, particularly for turn-off. Four quadrant versions “messy”.
Thyristor Chopper	Very fast. Can run from capacitor bank(s). Readily made multiple-quadrant.	Ripple & noise in load current (and/or complexity if multi-rail).
Transistor Amplifier	Linear, clean output, very fast, four-quadrant feedback control.	A few hundred kW max per unit. Expensive.
Resonant Switched-Mode Convertor	Very high efficiency (low loss). Very fast. Readily modularised.	Complicated. Expensive.



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Power Supplies - COMPASS 1MJ OH Capacitor Bank

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These were 1960’s “paper” capacitors (from the infamous ZETA project), meaning oil-soaked paper wrapped tightly and encapsulated in steel cans. They were specified in terms of 100% fast reversal and very long cyclic life for the specified voltage, but the result was very low energy density (large volume per MJ) – although this allowed them to be useful for many different machines over many decades!

Power Supplies - JET Flywheel Generator Convertors

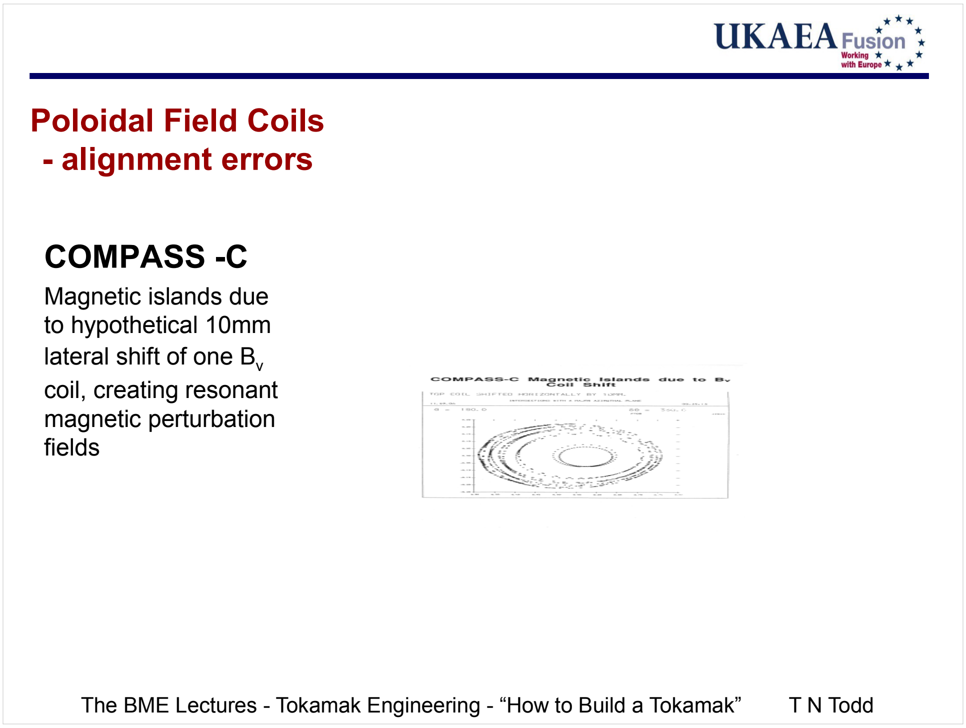
Two units (PF & TF), each:

- 800 tonnes
- 112 - 225 rpm
- 8MW pony motor
- 410MVA
- 2.6GJ extractable energy

Poloidal Field Coils

Alignment Errors

- The PF coils have to be circular and well aligned to the TFC to avoid producing resonant magnetic perturbations. They also have to be positioned in radius and height so as to minimise stray perpendicular fields (particularly important for the magnetising winding if it is carrying current at the time of plasma initiation).
- Each of these requirements results in a positional tolerance ~10^{-3} of the major radius of the machine.
- Coils with small numbers of turns are troublesome because of the effective dipole errors associated with the feeder bars (unless the feeders are coaxial etc), and the turn-to-turn joggles in the winding.



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Poloidal Field Coils
- alignment errors

COMPASS -C

Magnetic islands due to hypothetical 10mm lateral shift of one B_v coil, creating resonant magnetic perturbation fields

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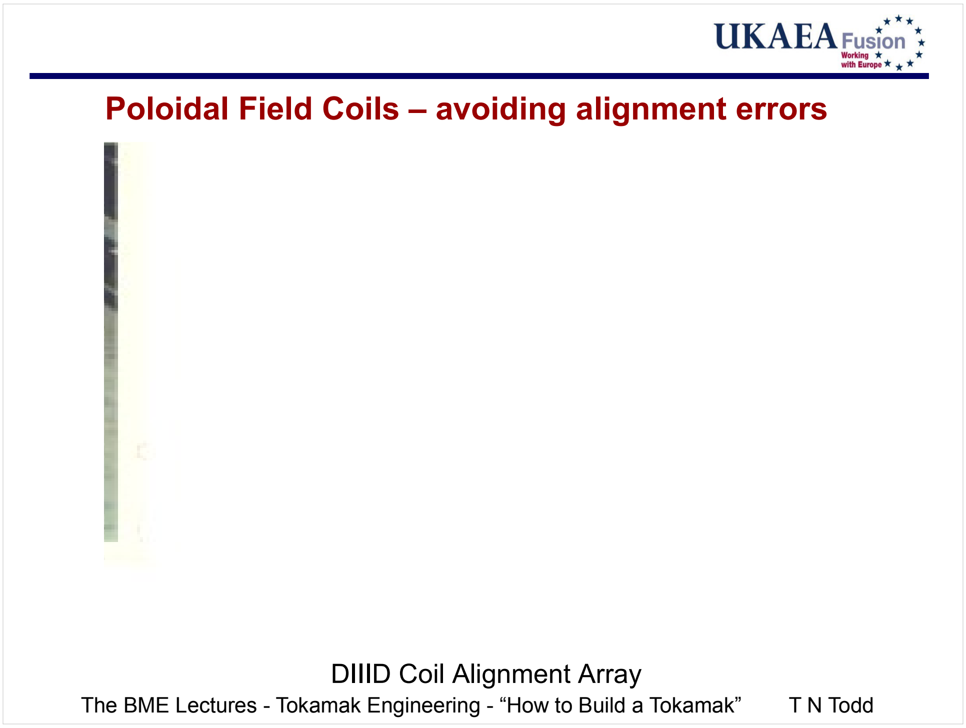
With no islands, tokamak magnetic field lines trace out nested toroidal surfaces, which would appear as nested circles in this projection. The circular surfaces which were not split into islands are not shown here, for clarity.



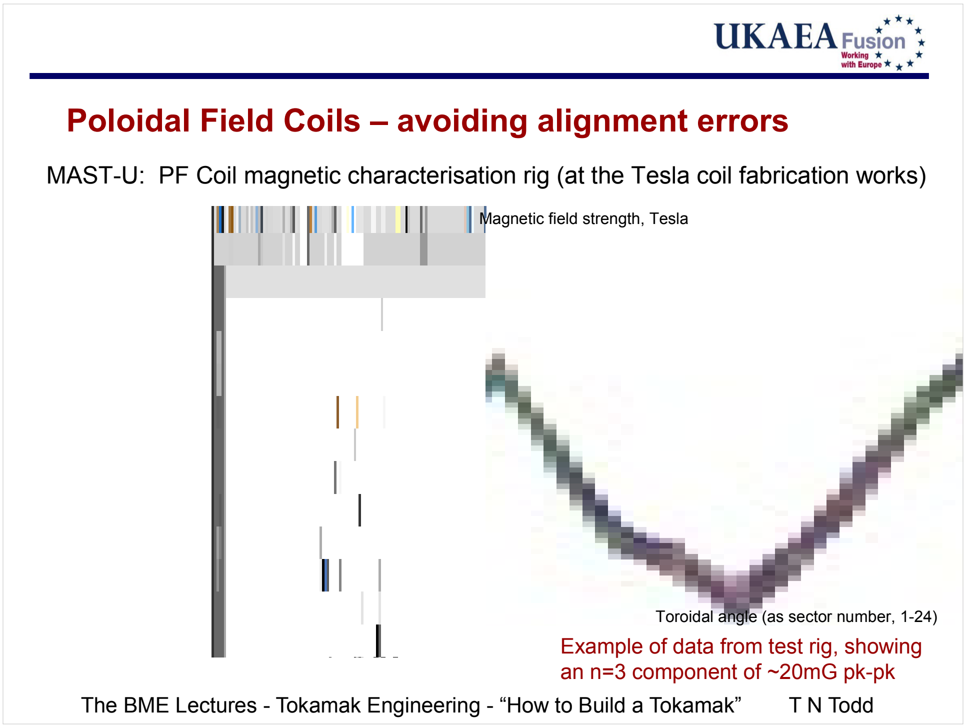
Poloidal Field Coils – avoiding alignment errors

DIIID Coil Alignment Array

As far as I know, only COMPASS and DIII-D have built high precision alignment coils to set up their poloidal field coils, magnetically accurately matched to the TF coil position and tilt.

The pick-up coils, manufactured to be accurately identical on opposite sides of the torus, are configured in sets (of n=1,2,3) with positive and negative polarity so that perfect alignment would produce zero output signal. You start by powering up the TF on its own to characterise its position and tilt, then each of the PF coils one at a time.

In the case of COMPASS, the PF coils were deformable and could be jacked into shape, position and tilt. In the case of DIII-D, the errors in shape and location were recorded and a separate set of coils was used to null the error fields of importance.



Poloidal Field Coils – avoiding alignment errors

MAST-U: PF Coil magnetic characterisation rig (at the Tesla coil fabrication works)

Example of data from test rig, showing an n=3 component of ~20mG pk-pk

As part of the magnetic alignment planned for the construction of MAST-U, the supplier (a company called Tesla) was asked to build a precision jig with a rotating arm carrying a Hall probe, to measure the x,y,z components of magnetic field around the coil at selected heights and radii.

The right-hand figure shows an overlay of several measurement runs, with the average magnetic field and residual axis misalignment corrected out. It clearly reveals the n=3 turn-t-turn joggles in the winding pack, and a small n=1 distortion that will be nullified in MAST-U by judicious placement of the coil.

Support Structure

- Some structure has to accommodate the toppling forces on the TF coils and the vertical forces on the PF coils. There are many geometrical options. This might be the lightest and simplest:

DIIID Geodesic structure

Support Structure

- Since the support structure has to be strong, stainless steel is commonly used in order to obtain high strength with low magnetic permeability. However stainless steels increase in permeability where worked, cut or welded and so (sometimes even after heat treatment) it is easy to generate non-axisymmetric and potentially resonant perturbation fields.
- Any volume of unsaturated magnetic material “sucks in” the ambient magnetic field creating a disturbance in the field similar to a dipole source. This dipole source produces a field back in the plasma region which will usually be non-axisymmetric and is therefore likely to generate islands.

  Outside the TFC the ambient field is dipole-like and the critical volume to generate 10^{-4} of the poloidal field at the plasma edge is given by

$$V_c \lesssim 300\,\Re^6 / R_0^2\, a(\mu_R - 1) \qquad (\mathrm{m, m, m, cm^3})$$

  for $\mu_R \approx 1,$ where $\Re$ is the range of the offending lump from the machine centre.

Support Structure

Inside the TFC the ambient field is essentially $B_{\phi 0} R_0 / R$ and the same criterion (at the machine centre) yields

$$V_c \lesssim 250\, I\, R\, R_0^2 / a B_0 (\mu_R - 1)$$

$$(MA, m, m, m, T, cm^3)$$

where R is the major radius of the offending piece of material.

- Clearly the support structure is responsible for maintaining the alignment of all the TF and PF coils, with the accuracy requirements discussed earlier.

Vacuum Vessel

Forces

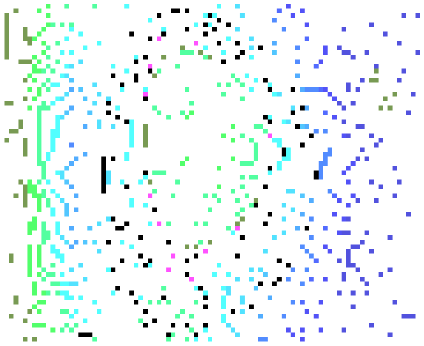
Forces on the vessel arise from the following sources, in decreasing order of importance:-

- disruption-induced currents
- thermal gradients
- air pressure
- human malpractice
- diagnostic loads
- currents induced during plasma start-up
- diagnostic flange bolting

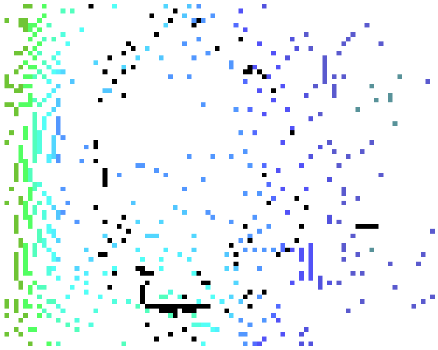
- Disruption induced currents arise when the plasma terminates rapidly, commutating its current into the vessel. This current then “stands off” the external vertical field giving rise to inward pressures on the vessel which can easily attain ~1bar (as well the atmospheric loading).

Disruption dynamics

In a disruption, the plasma “goes away” at up to 1MA/msec:



Before…



...after →large, rapid poloidal field changes

The rapid change in poloidal field induces currents in the surrounding metal structures.

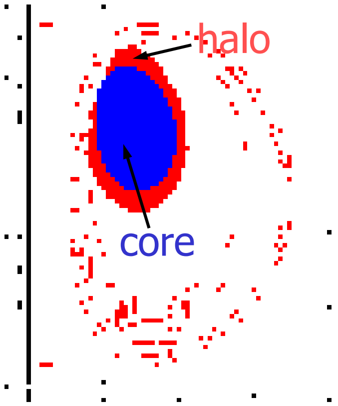
Vacuum Vessel

- Worse than this, the commutated current has to get around port-holes, causing regions of high current density and crossing of the toroidal field, producing very large local stresses.

- Rapid plasma displacement events (during vertical instability) have been shown to “scrape off” up to ~40% or more of the toroidal plasma current, which can also flow very asymmetrically due to helical distortion of the plasma This results in large “halo” currents crossing the toroidal field within components mounted inside the vessel, severely stressing the mountings.

Disruption dynamics

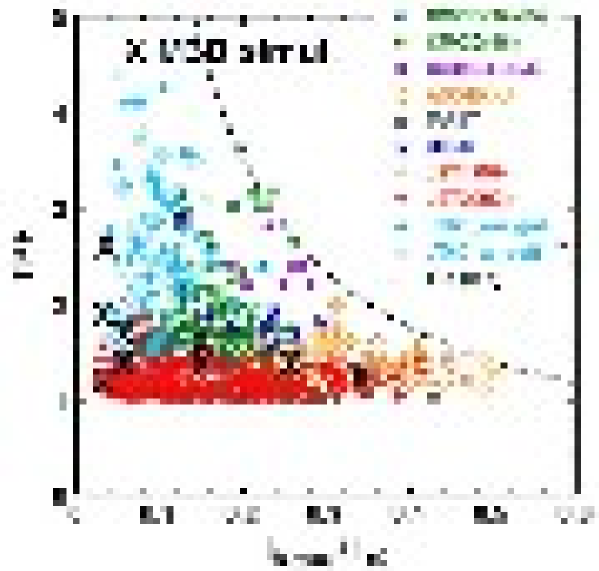
The “Halo Current”; partly flows along the edge of the plasma and partly in the plasma facing components.



The core plasma is ~ force free, but each part of the halo current path is not ⇒ loads on plasma facing components and their supports, and the vessel.

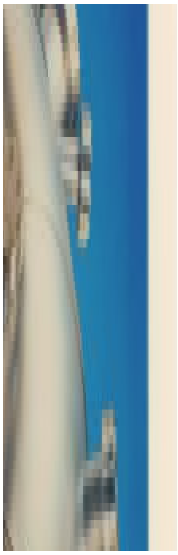
halo fraction (f = I_{halo}/I_{plasma})
ratio of poloidal halo current to pre-disruption plasma current (up to ~50%)

toroidal peaking factor (**TPF**)
degree of halo current asymmetry: ratio of the maximum to the average halo current (up to ~4)



Tokamak Rotation and Halo Current caused by Disruptions

H.Strauss et al, a PPPL talk (2013)



COMPASS-D Vacuum Vessel

Inconel 3mm thick. No gaps. Many dozens of magnetic diagnostics embedded into 7 of the 8 hollow ribs joining the 8 sectors of the torus together, and an inboard ECE antenna and waveguide built into the 8th.

Vacuum Vessel

Vacuum Quality

- Tokamaks do not work properly if the vacuum base pressure is $>2\times10^{-7}$torr
- Some routes to a high vacuum standard include the following:-
  - try to achieve an all-metal set of vacuum seals, welded wherever reasonable
  - avoid materials with high vapour pressures (eg brass, plastics …)
  - avoid unstable materials
  - avoid trapped volumes (eg in screw threads, between mating surfaces)
  - don't let marking pens or crack-detecting dye penetrants be used inside the vessel
  - avoid the use of cleaning fluids with tightly binding high *Z* elements (eg the ubiquitous chlorine)

Vacuum Vessel

Vacuum Quality (cont'd)

- don't directly touch anything destined to go in a vacuum system
- do vacuum-bake components of the vessel itself during manufacture (eg to 400ºC)
- do bake everything that goes inside the vessel to whatever temperature it will tolerate (eg to 200ºC)
- specify and preserve mirror-bright interior surfaces
- consider electropolishing the vessel interior surfaces
- avoid, or plate over, plastics to which the plasma has a line of sight

Vacuum Vessel

Pumps

- Today, turbomolecular pumps are the standard choice: they produce excellent base pressure, down to the 10^{-10} torr region if the system is clean and leak-free. Bearings can be oil, gas or magnetic; some have been known to break up, allowing oil vapour back into the system. The high rotational speed vanes suffer strong eddy currents (ie drag) if the TMP is exposed to magnetic fields above ~300G however, so siting needs consideration.

- Cryopumps are increasingly used and are best where enormous pumping speeds are required (such as in divertors and ion beam neutraliser cells). Also available are small automatically regenerating modular cryopumps, compact, helium-sealed and easy to use.

Limiters

Purpose

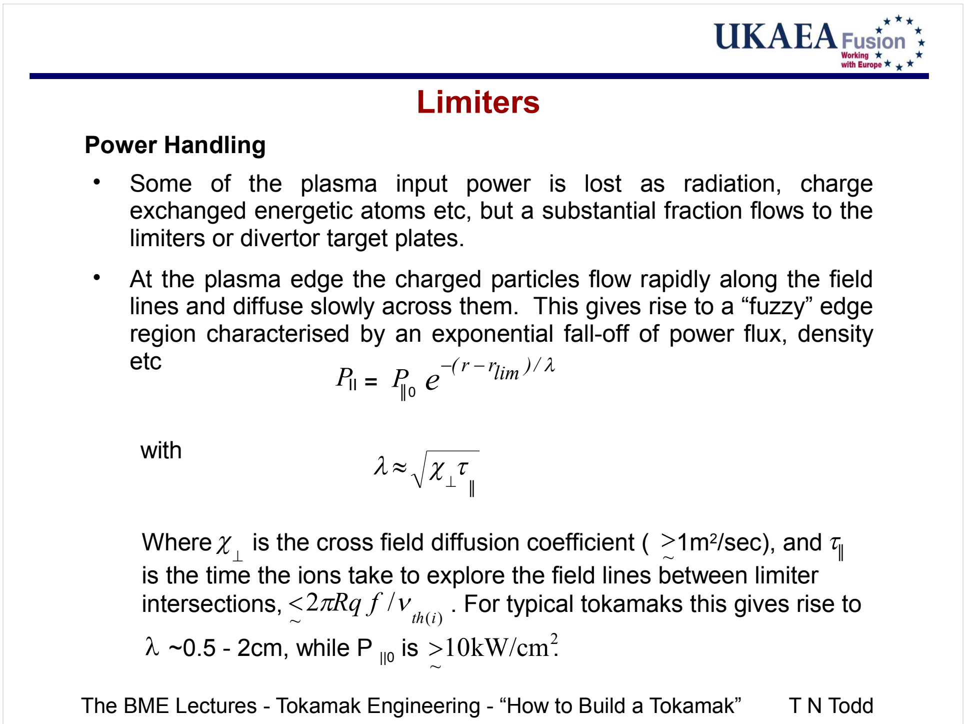
Limiters and armour are required in tokamaks to:-

- Define the place and material of the principle plasma edge interaction
- Stop runaway electrons from damaging the vacuum vessel
- Protect the vessel from neutral beam shine through
- Shadow in-vessel components from the plasma edge

Geometry

Historically, poloidal ring (even “diaphragm”) limiters were popular, but as power input and pulse duration have risen these have become much less favoured, giving way to various toroidal ring options.

Some old machines used horizontal rails and/or out-board rail limiters, generally with sophisticated front surface profiles to optimise the power handling capability.



Limiters

Power Handling

- Some of the plasma input power is lost as radiation, charge exchanged energetic atoms etc, but a substantial fraction flows to the limiters or divertor target plates.
- At the plasma edge the charged particles flow rapidly along the field lines and diffuse slowly across them. This gives rise to a “fuzzy” edge region characterised by an exponential fall-off of power flux, density etc

$$P_{\|} = P_{\|0}\, e^{-(r-r_{lim})/\lambda}$$

with

$$\lambda \approx \sqrt{\chi_{\perp}\tau_{\|}}$$

Where $\chi_{\perp}$ is the cross field diffusion coefficient ($\gtrsim$1m²/sec), and $\tau_{\|}$ is the time the ions take to explore the field lines between limiter intersections, $\lesssim 2\pi Rq\, f / v_{th(i)}$. For typical tokamaks this gives rise to λ ~0.5 - 2cm, while $P_{\|0}$ is $\gtrsim 10\mathrm{kW/cm^2}$.

Recent power scrape-off length scalings suggest that this length scales mainly with poloidal Larmor radius, unfortunately suggesting that in a high current machine like ITER or DEMO, it could be as small as 0.4mm (!).

This demands a considerable factor of flux expansion to reduce the power flux on the divertor target plates.

The tiles and tile carriers benefit from design evolution guided by FEA

The induced currents create torques and forces on the tiles and carriers

Designers aim to have peak stresses no more than say ~50% of the allowable stress for the selected material at the required temperature

Scheme design ⇨ analysis ⇨ detailed design

Limiters

Power Handling

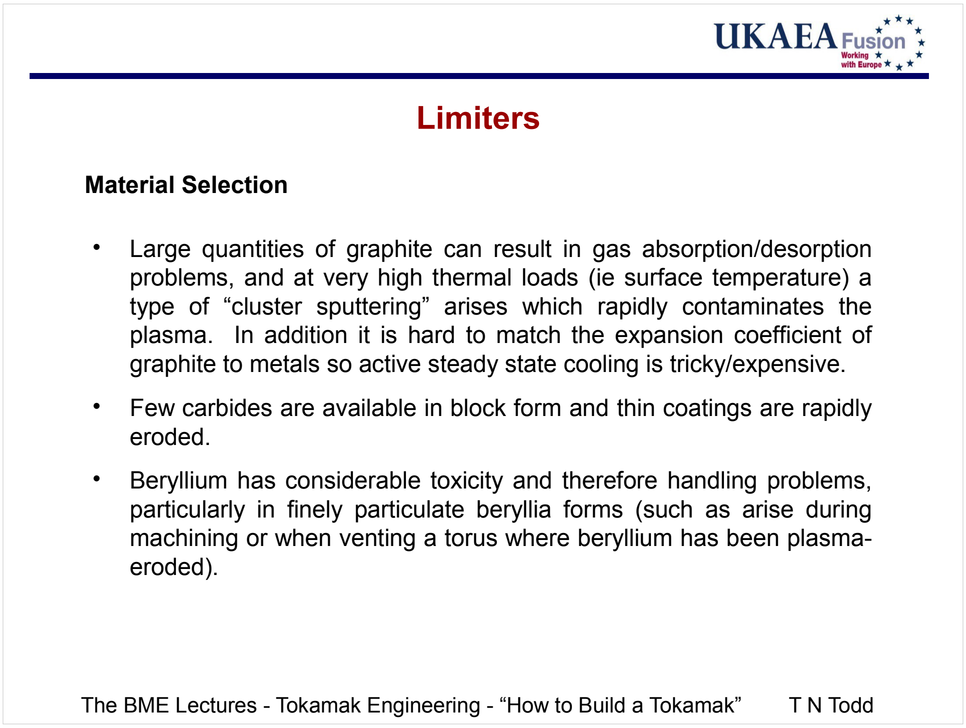
- A high heat flux for a short duration causes a temperature gradient in the limiter material, leading to differential expansion resisted by the elasticity of the material but limited by the yield point. The figure of merit for the thermal shock capability of materials is thus

$$\frac{\text{yield stress}}{\text{elastic modulus}} \text{ x } \frac{\text{thermal conductivity}}{\text{expansion coefficient}} \text{ x (density x heat capacity)}$$

Limiters

Material Selection

- Good thermal shock behaviour combined with a requirement for high melting point allows a small range of suitable limiter materials to be identified, eg
  - refractory metals – tungsten, tantalum, molybdenum, titanium etc
  - carbon (graphite, CFC)
  - certain carbides – eg titanium, silicon, boron (usually as coatings)
  - beryllium
- The early machines mostly used refractory metals but graphite or CFC is now very popular, particularly as it sublimes rather than melting and allows runaway electrons to penetrate (and thus dissipate their energy) deeply. *And now tungsten is back!*
- Graphite can be improved by densification using chemical vapour deposition techniques (which also seal off the porosity) and by incorporating carbon fibres to raise the strength and conductivity, optionally with 2D, 2 ½ D or 3D geometry of the fibres.



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Limiters

Material Selection

- Large quantities of graphite can result in gas absorption/desorption problems, and at very high thermal loads (ie surface temperature) a type of "cluster sputtering" arises which rapidly contaminates the plasma. In addition it is hard to match the expansion coefficient of graphite to metals so active steady state cooling is tricky/expensive.
- Few carbides are available in block form and thin coatings are rapidly eroded.
- Beryllium has considerable toxicity and therefore handling problems, particularly in finely particulate beryllia forms (such as arise during machining or when venting a torus where beryllium has been plasma-eroded).

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Beryllium is used in JET and will be used in ITER but is unsuitable for DEMO because it is too easily sputtered (excessive erosion rate), creates an explosion hazard from hydrogen production if exposed to water when heated (in a putative accident scenario), and reacts with the fast fusion neutrons to produce helium which does not diffuse out of the metal, which makes it swell, especially when heated.

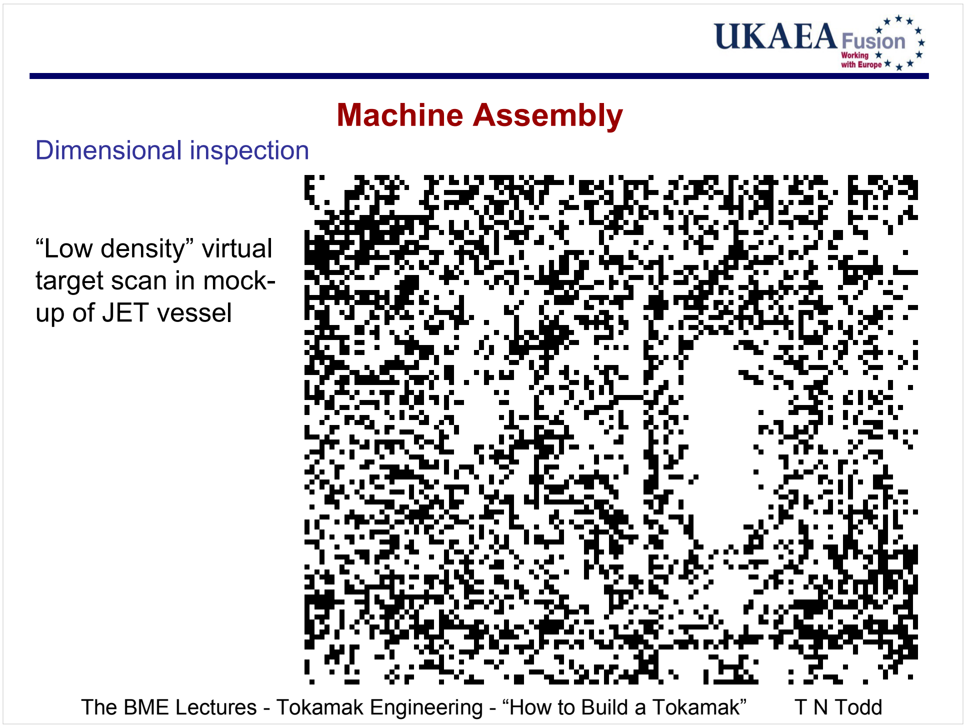
Machine Assembly

Once the design and procurement are done, you have to put it together...

EAST (née HT-7U) Full Superconducting Tokamak

EAST - Fully Superconducting Tokamak

Ip = 1 MA, t=1000s, Double Null Divertor, B_T = 3.5T, R= 1.75m, a/b = 40/80 cm



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Machine Assembly

Dimensional inspection

"Low density" virtual target scan in mock-up of JET vessel

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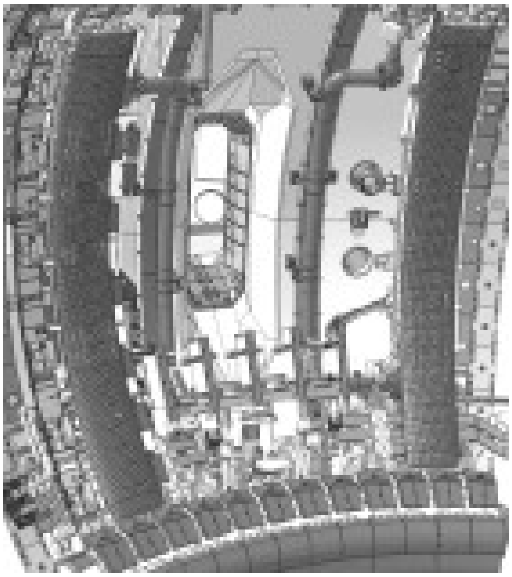
Today there are many different ways of scanning assemblies to produce data for input to CAD files. It is usually necessary to apply a data reduction scheme to smooth over noise and irrelevant surface details, to consider how to deal with weld features, and to average "clouds" of points representing unique actual points perceived from different viewing points.

Depending on the type of scan and the number of views achieved, it may also be necessary for a human reviewer to assert that the unscanned rear surfaces of pipes etc are simple cylinders or similar.

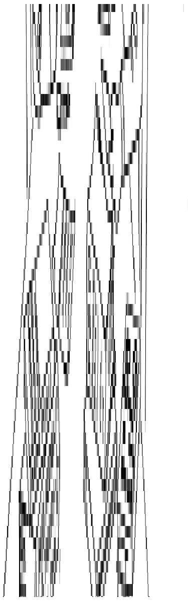
Machine Assembly

The metrology results are then used to modify the 3D CAD files in ever-increasing complexity, to facilitate Configuration Control

This avoids clashes between components and unintended vignetting of diagnostic viewing lines



Part of the interior of the JET torus: note the fine detail

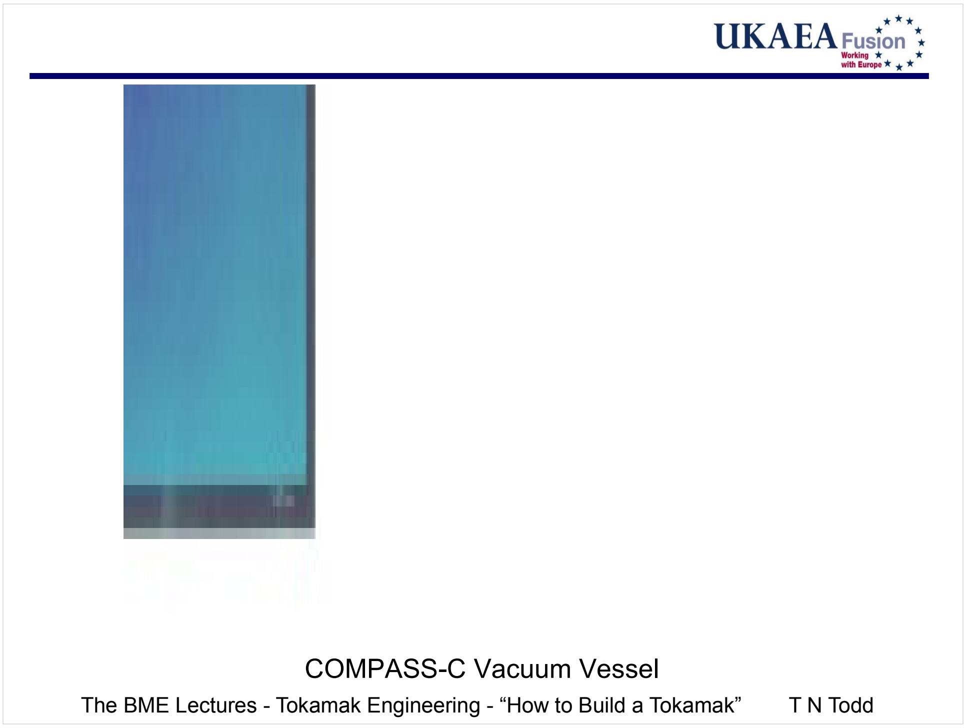


If the project is successful, there will have been a convergence of views between the physicists and the engineers!

Summary

- This talk has attempted to outline the broad-brush thinking underlying the design and assembly of a generic tokamak.
- Many topologies are possible, with the options narrowed by considering any special engineering features required in the machine.
- A great deal of FEA underlies modern machine design, with due consideration to fatigue life for the duty cycles in mind.
- In tokamaks with strongly elongated plasmas, Vertical Displacement Events and associated halo currents are amongst the most demanding effects to accommodate in the design.
- Coil accuracy, magnetic permeability, vacuum system cleanliness and conditioning are all important to the eventual physics operations.
- Limiter design, including material selection, strongly affects achievable pulse length in high power density and/or long-pulse systems.
- Machine assembly requires precision metrology of delivered parts to generate accurate configuration files
- So how do you ***operate*** a tokamak? Wait for the companion talk!

End



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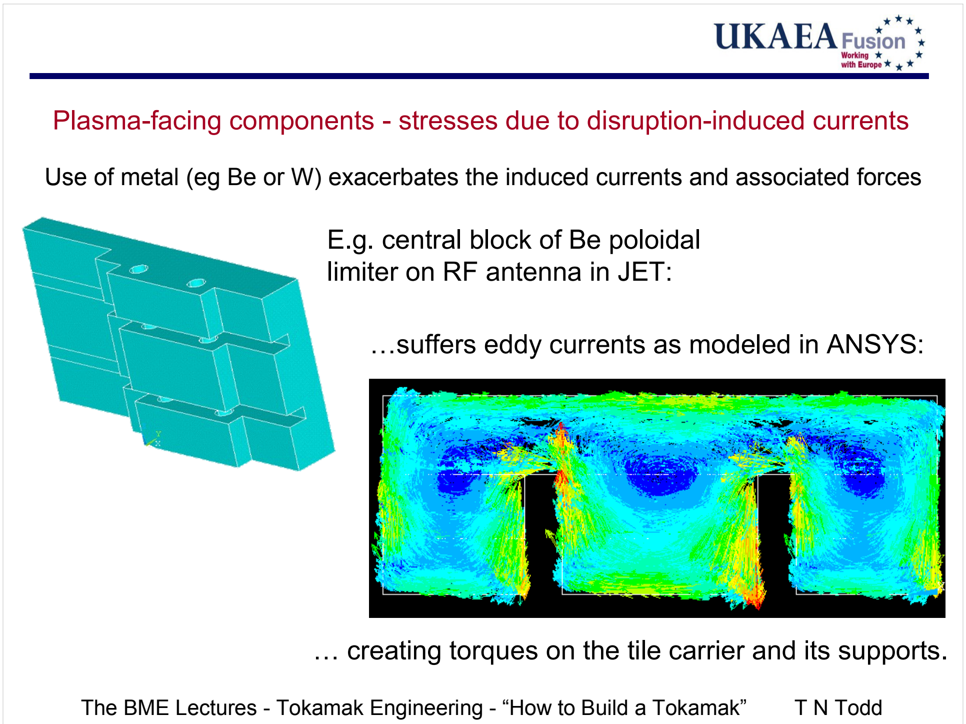
COMPASS-C Vacuum Vessel

0.7mm of stainless steel, in a bellows design to raise the toroidal loop resistance. No gaps. Ports only at the four forged sectors (of ~2mm thickness) joining the bellows sectors.

Embedded magnetic diagnostics at several toroidal angles, each array with its own feed-through port.



Plasma-facing components - stresses due to disruption-induced currents

Use of metal (eg Be or W) exacerbates the induced currents and associated forces

E.g. central block of Be poloidal limiter on RF antenna in JET:

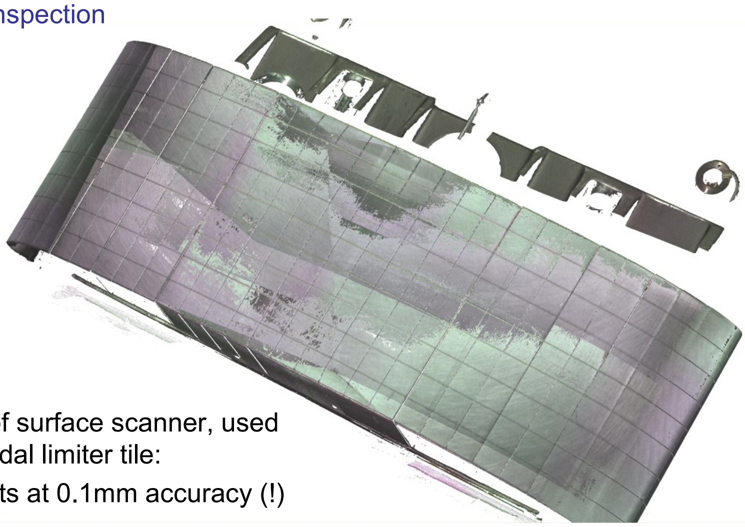
…suffers eddy currents as modeled in ANSYS:

… creating torques on the tile carrier and its supports.

“Exacerbates” here means with respect to the graphite previously used, which had a much higher resistivity.

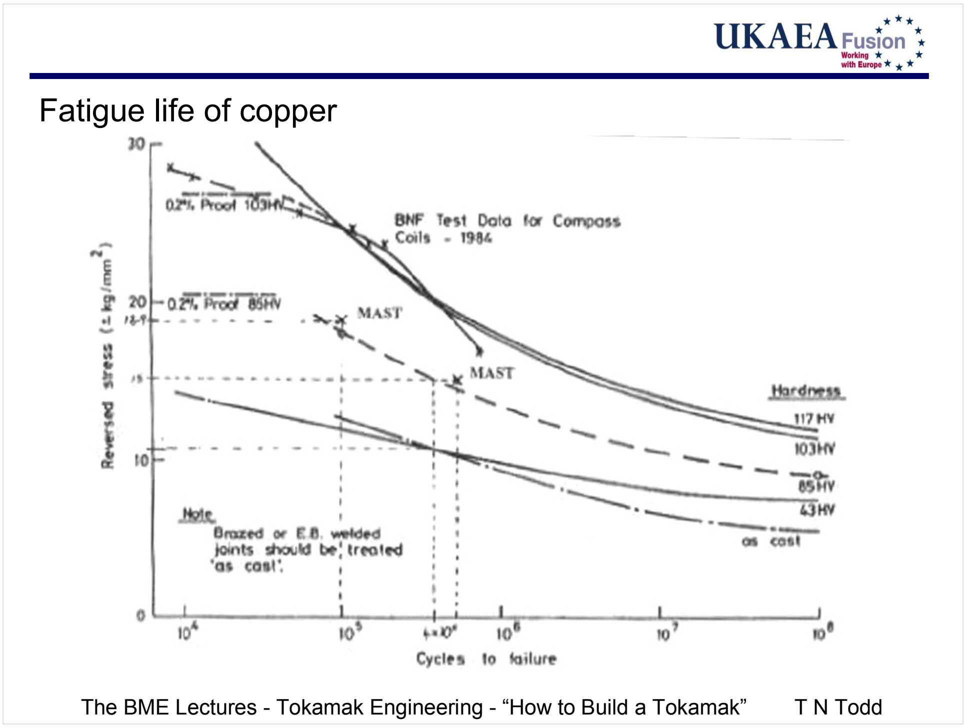
Machine Assembly

Dimensional inspection



Another type of surface scanner, used on a JET poloidal limiter tile:

13 million points at 0.1mm accuracy (!)



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Fatigue life of copper

Note

Brazed or E.B. welded joints should be treated 'as cast'.

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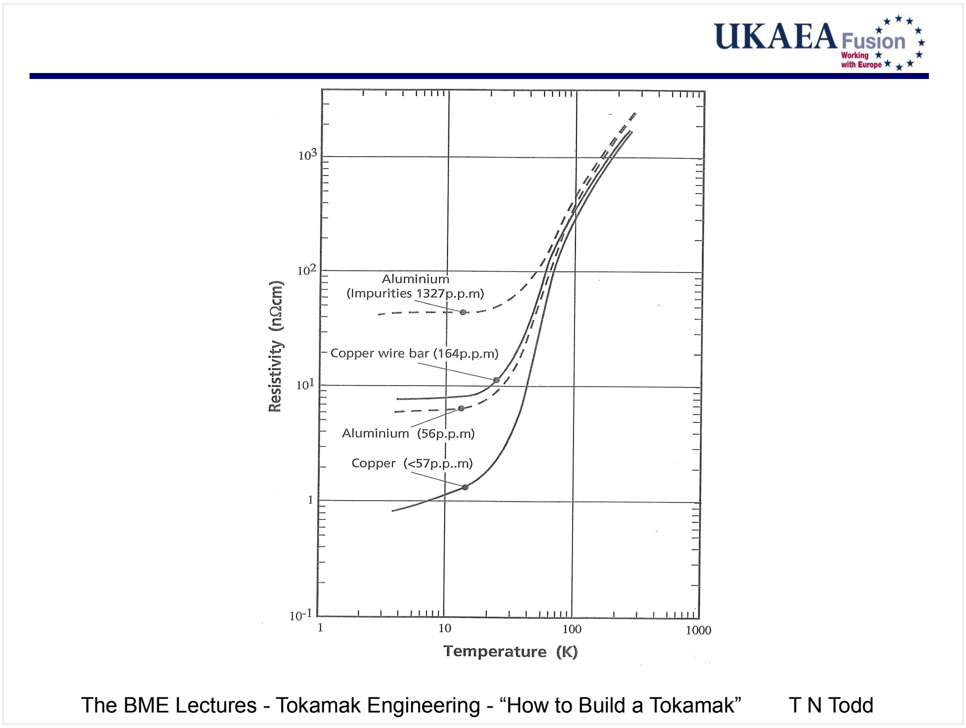

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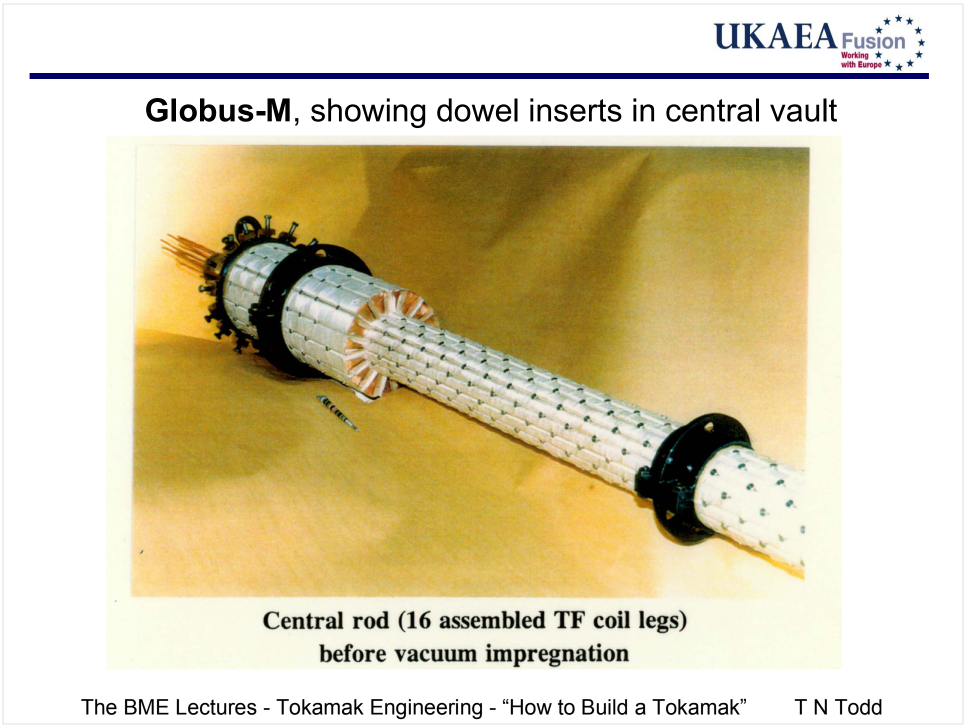
Cryogenically cooling the coils can considerably reduce their electrical resistance and hence the power needed to drive them – but there will be a power required for the cryorefrigeration, of course.



Globus-M, showing dowel inserts in central vault

Central rod (16 assembled TF coil legs)
before vacuum impregnation

When Globus-M was designed, the Russians told us, they did not like to rely upon the bond strength that could be achieved between the copper conductors and the epoxy-glass resin insulation system around them.

Accordingly, the central TF vault assembly of Globus-M (another spherical tokamak) featured a great many insulating dowels placed in holes at the interfaces between the conductors, to prevent them sliding with respect to each-other when the assembly was stressed by torque created by the poloidal field created by the solenoid etc.