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Engineering Challenges of the Target Station Solenoid System:

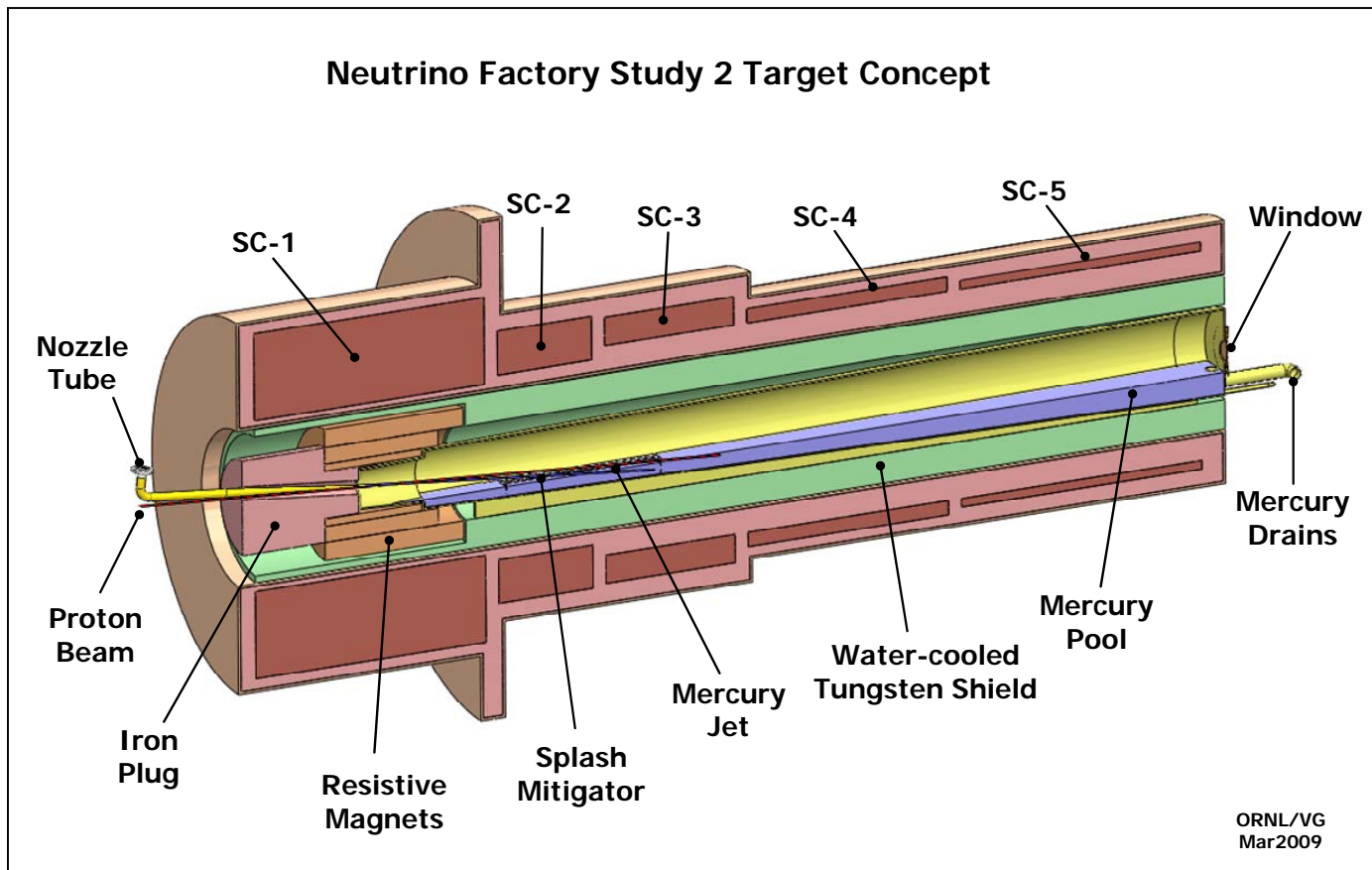
Thermal and Mechanical Loads

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Rutherford Appleton Laboratory

IDS NF Plenary Meeting
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NF Target Station Overview

- Objective is a 20 Tesla solenoid field in the target region:
 - 14 Tesla to be generated by a superconducting magnet
 - 6 Tesla to be generated using a resistive insert magnet



*Neutrino factory study-2 target concept
courtesy: Van Graves, ORNL*



Engineering Challenges

Two factors that lead to some significant engineering challenges:

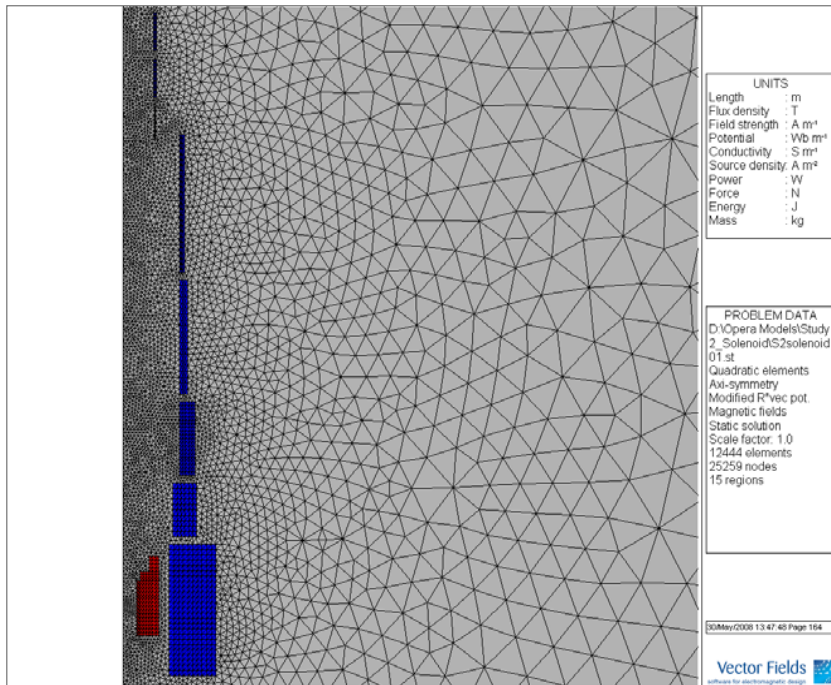
1. Ambitious physics requirements - High field in a large bore
 - Huge magnetic forces
 - Large stored energy
 - Pushing limits of present superconductor technology (14 Tesla in a 1.3 m bore)

2. Harsh radiation environment
 - Heat loads from 4 MW pulsed proton beam
 - Time averaged heating
 - Power Density
 - Instantaneous pulsed heating effects
 - Radiation damage to materials

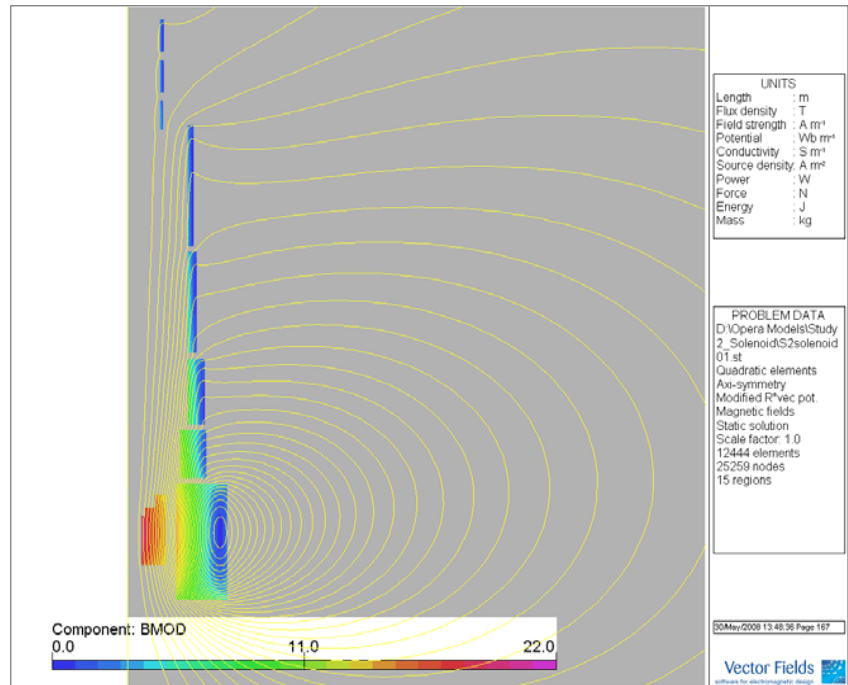


Magnetic Forces: FE Analysis

- Analysis of Study-2 geometry performed using Vector-Fields software
 - The Lorentz body force F comes from the cross product of the current density J and magnetic field B
$$F = J \times B$$
 - Calculated the net force acting on each coil
 - Results on next slide...



Study-2 geometry

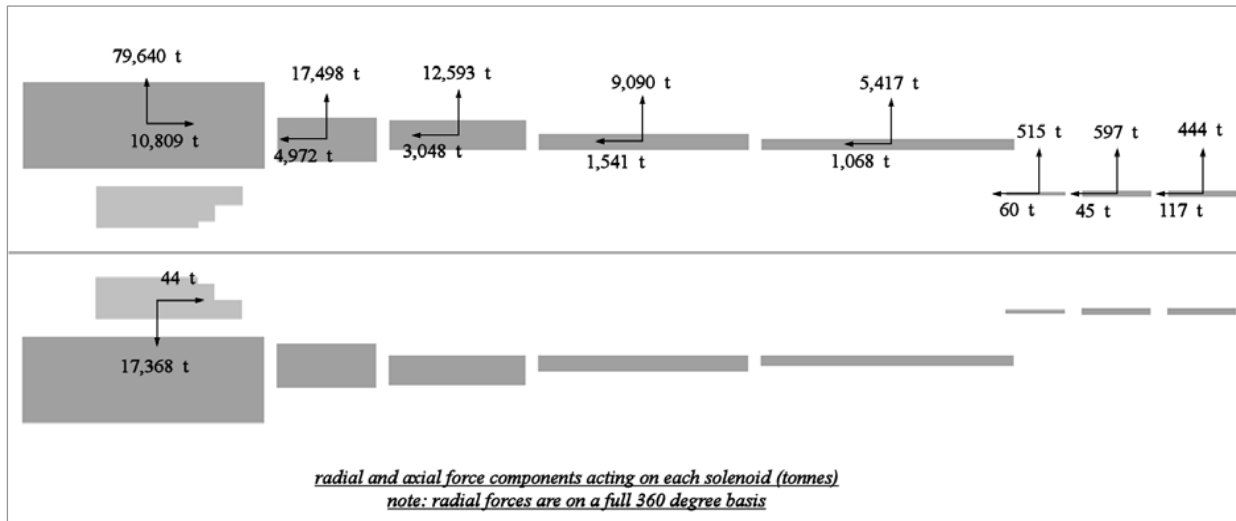


Magnetic field (Tesla) in the conductor regions



Magnetic Forces: Results

Coil	JDEN (A/mm ²)	BMAX (T)	FZ (Tonnes)	FR (Tonnes)	PINT (bar)	σR max (MPa)	σθ max (MPa)	σZ mean (MPa)
NC01	24.4	20.1	42	2,409	282	28	109	6
NC02	19.1	18.6	68	6,340	486	49	123	3
NC03	14.9	16.1	-67	8,620	355	36	112	2
SC01	23.4	14.5	10,809	79,640	1097	110	182	27
SC02	25.5	11.3	-4,972	17,498	546	55	148	28
SC03	29.7	7.9	-3,048	12,593	254	25	107	25
SC04	38.3	5.8	-1,541	9,090	118	12	92	27
SC05	48.4	4.1	-1,068	5,417	59	6	73	32
SC06	67.9	3.8	-60	515	44	4	72	8
SC07	70.5	3.3	-45	597	45	4	53	4
SC08	70.5	2.9	-117	444	33	3	40	11



Equivalent Internal Pressure :

$$P = \frac{F_R}{2\pi R_1(Z_2 - Z_1)}$$

Max Compressive Radial Stress (@r = R₁) :

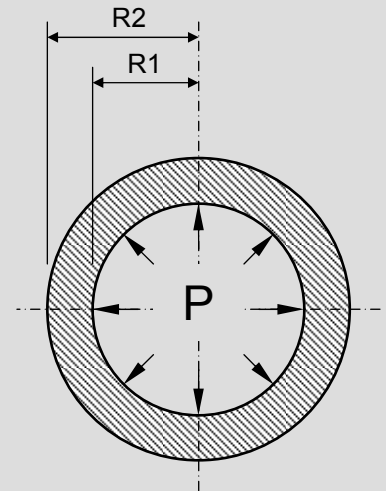
$$\sigma_{R\text{MAX}} = P$$

Max Tensile Hoop Stress (@r = R₁) :

$$\sigma_{\theta\text{MAX}} = P \left(\frac{R_2^2 + R_1^2}{R_2^2 - R_1^2} \right)$$

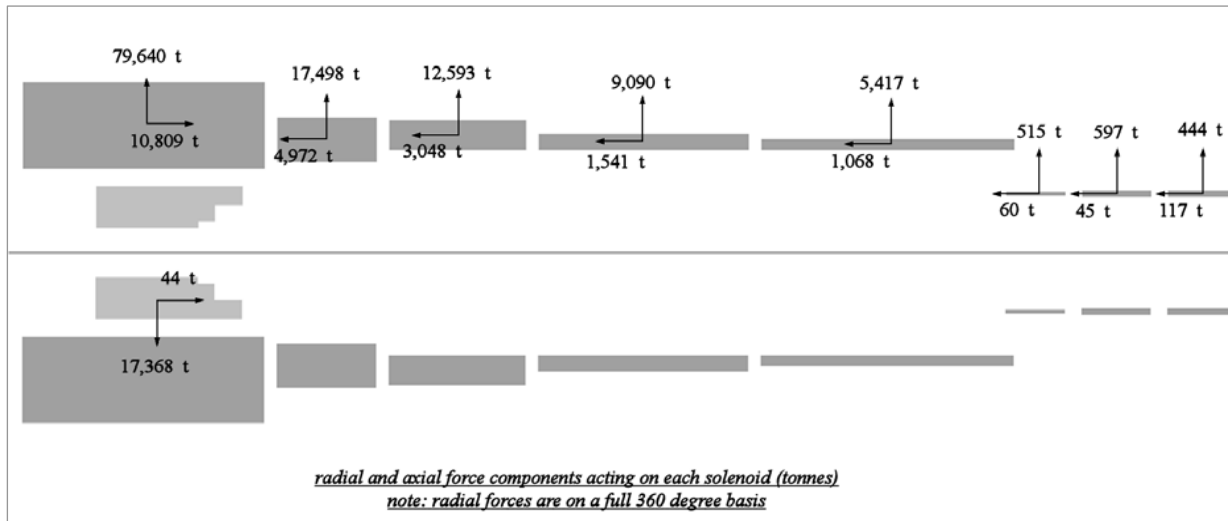
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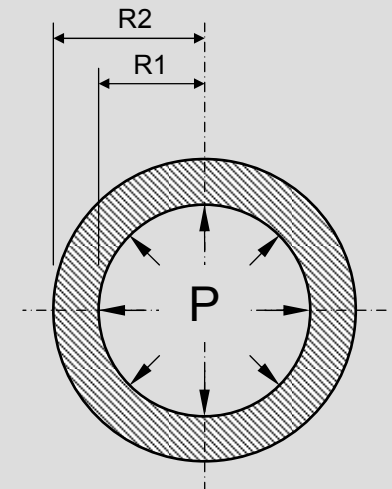
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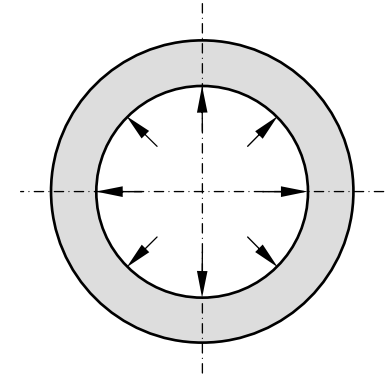


Magnetic Forces: Implications

- Radial “magnetic pressure” Forces

~1000 bar in SC1!

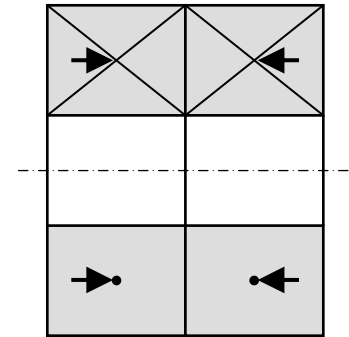
- “magnetic pressure” realised as a tensile hoop stress in the winding and support structure
- Much of the coil cross-section to be taken up by load bearing elements



- Axial “inter-coil” Forces

~10,000 tonnes in SC1!

- Equal and opposite attractive forces balanced between the first five SC coils
 - House these coils in a single cryostat and let them react against one-another
 - Must avoid transmitting the inter-coil loads up to room temperature (generates large cross-section heat leak path)
- Axial spaces between coils to be filled with load bearing material in order to support the axial compressive load
 - Difficult to generate axial spaces between coils for potential target system integration

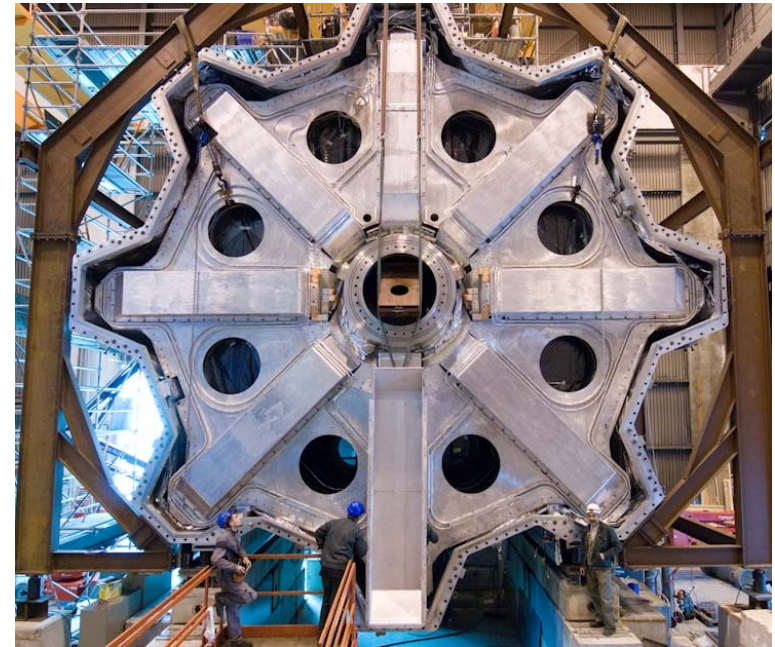


Stored Energy

- Stored Energy in NF target solenoids ~600 MJ
 - Stored magnetic energy comes from

$$E_m = \frac{1}{2} LI^2$$

- Inductance of a solenoid depends on coil geometry and increases as the bore radius is enlarged
 - i.e. enlarging the magnet bore size increases the stored energy
- This energy needs to be managed safely in the event of a quench
 - Means that much of the coil cross-section taken up by stabilising copper or aluminium, reducing the net current density in SC mode
- Radiation damage issue:
 - From recent discussions it seems that there is a critical DPA in the stabiliser at which the rise in resistance could lead to damage during a quench
 - Further investigation needed



*Context:
The stored energy in each ATLAS end-cap magnet is ~200 MJ
(Equivalent to the energy of an inter-city train at full speed)*



Heat Loads: Where does the 4 MW Beam Power go?

*Regional deposition of 4MW beam power
(From FLUKA simulation by John Back, Warwick)*

Region	Power [kW]	% of 4 MW Beam Power
WC Shield	2,694	67.3
Other (mostly particles inside bore)	577	14.4
Hg Jet	401	10.0
Cu Coils	232	5.9
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Iron Plug	15.2	0.4
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Designing a cooling system capable of removing ~2.7 MW from the shielding is a challenge in its own right



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Beam induced heating adds to the resistive heat load in the copper coils.

Radiation material damage could be an issue here (mechanical strength, electrical resistivity).



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Enormous heat load on the cold mass, looks unfeasible...



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Surprisingly little heating in the mercury “dump”

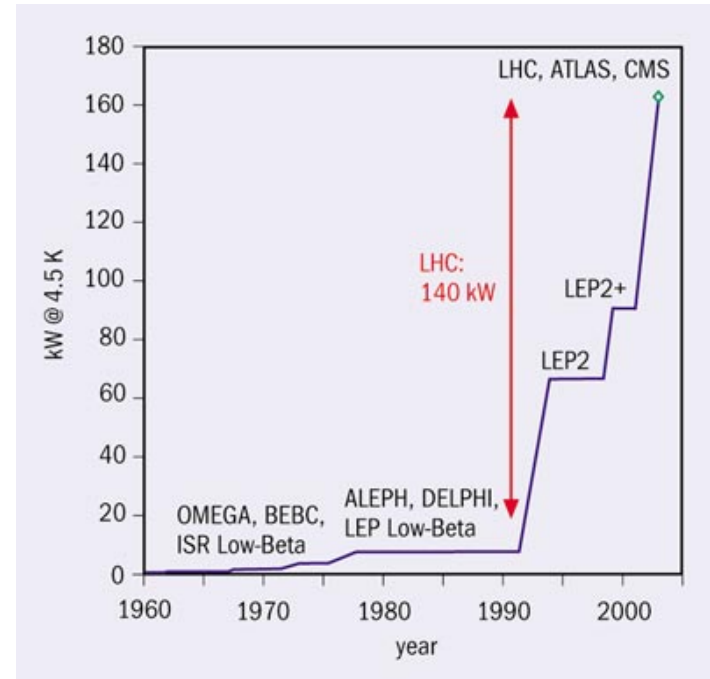


Heat Loads: Time Averaged Heating

- 63 kW heat load on the NF target station cold mass is enormous...
- To put it into perspective:
 - Total capacity of ITER cryoplant is 65 kW @ 4.5 K
 - LHC uses eight 4.5K refrigerators – one for each sector – each with a capacity of 18kW at 4.5K. Each one requires an electrical input power of 4 MW.



*Large Scale Helium Refrigerator by Linde:
18 kW for CERN - LHC*



*The cryogenic cooling power at 4.5K at the
CERN accelerator complex*



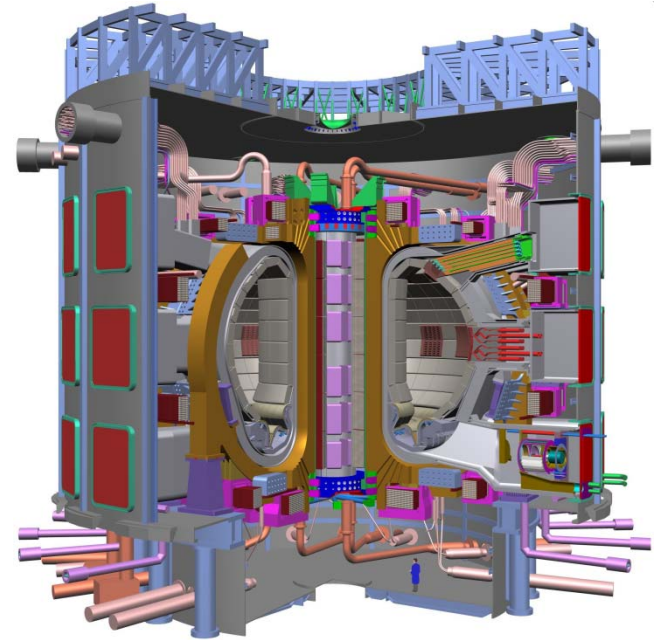
Heat Loads: Power Density

- Total heat load [W] is only part of the story...
- Power *density* [W/m³] is also critical in the thermal design, where feasibility depends on
 - Proximity of cooling channels
 - Helium flow-rate and pressure drop
 - Heat transfer surface area
 - Thermal diffusion time
- The FLUKA simulation suggested a peak power density in SC1 of the order

$$0.2 \text{ [J/kg/pulse]} \times 50 \text{ [Hz]} = 10 \text{ [mW/g]}$$

and an average power density in SC1 of

$$\frac{50 \text{ [kW]}}{50 \text{ [Tonnes]}} = 1 \text{ [mW/g]}$$



Context:

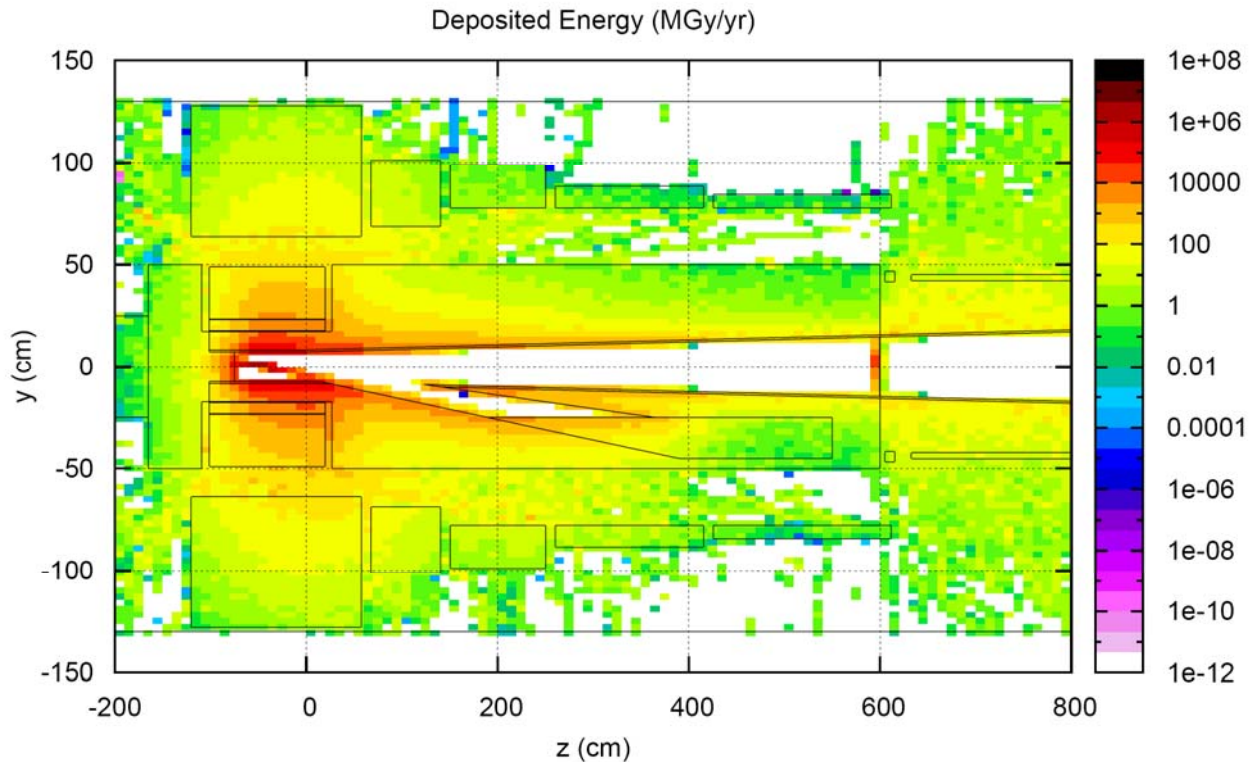
The superconducting magnets of ITER weigh ~10,000 Tonnes

Recall the cryogenic cooling capacity of 65 kW @ 4.5 K

i.e. Similar heat load to NF, but in ~100 times volume



Heat Loads: Pulsed Beam Heating



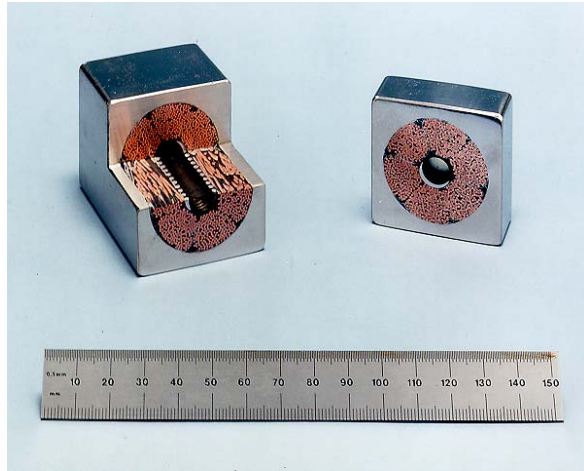
*FLUKA energy deposition simulation
courtesy: John Back, Warwick*

- Peak energy deposition in superconducting coil: $\frac{200 \text{ [MGy/yr]}}{2e7 \text{ [sec]} \times 50 \text{ [Hz]}} = 0.2 \text{ [J/kg per pulse]}$
- Note: no DPA output from FLUKA



Heat Loads: Pulsed Beam Heating

- Recall: ΔT per pulse depends on deposited power density and material heat capacity

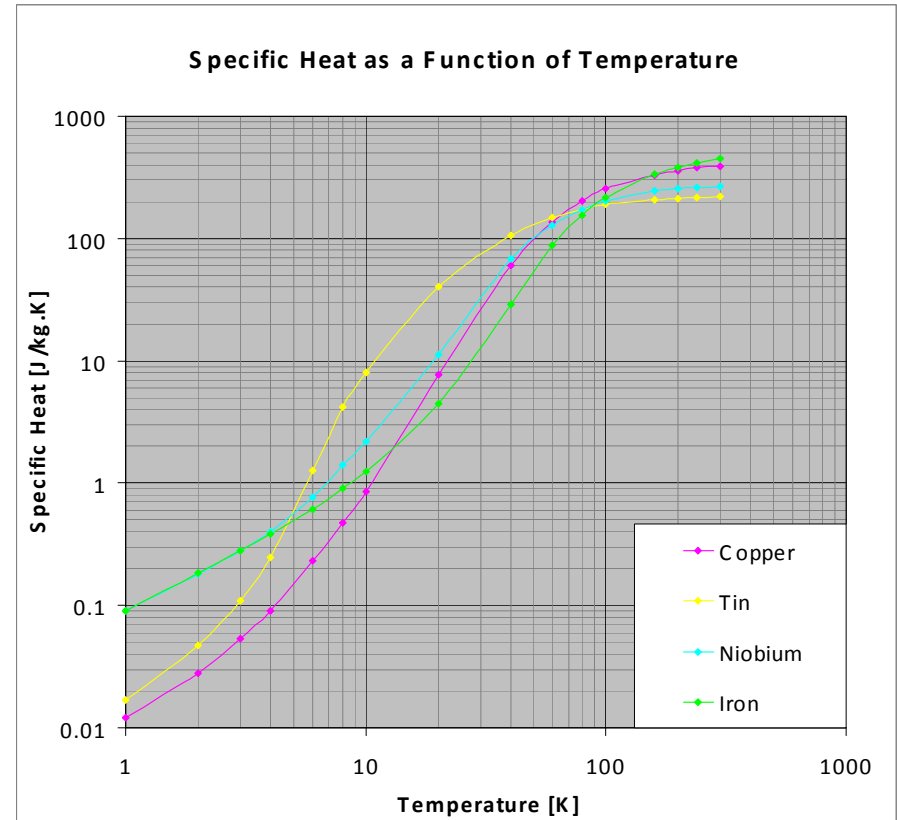


Example: ITER Cable cross-section

Stainless-steel area ~ 45%

Copper area ~ 13%

Nb3Sn area ~ 9%



Specific heat of coil materials

- e.g. each pulse gives a ΔT in Copper of the order:

$$\Delta T = \frac{\text{Energy Density}}{\text{Heat Capacity}} = \frac{0.2 \text{ [J/kg]}}{0.1 \text{ [J/kg.K]}} = 2 \text{ K}$$



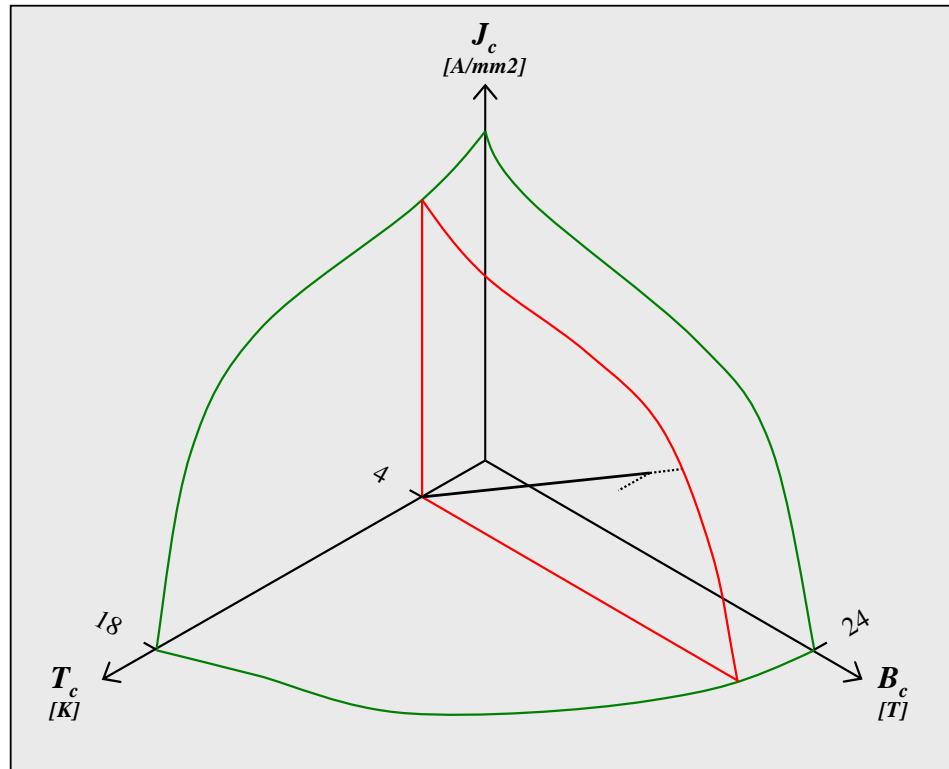
Heat Loads: Superconductor Temperature Margin

- What temperature rise can be tolerated by the superconductor?
 - Answer depends on how hard we are pushing in terms of J vs B...

- Example:

- Operating at 4K, with say, 10% margin on the load line
- Temperature margin is then of the order:

$$\frac{10}{100} \times (18 - 4) = 1.4 \text{ K}$$



Critical surface diagram for Nb₃Sn

- i.e. operating superconductor margin will typically be of the order 1K
 - Requires temperature stability < 1K in the superconductor



Summary

- Huge Magnetic Forces
 - Supporting the magnetic loads is a challenge in itself
 - Implications on target system integration
- 4 MW beam power is almost all realised as heat loads in target station components
 - ~3 MW in shielding
- Heat Load on Cold Mass
 - Total heat load is very high
 - Power **density**: critical in the thermal design
 - Pulsed heating: critical impact on SC temperature stability

Conclusion

- The target station solenoid system presents some serious engineering challenges
- Further work required to develop a viable thermo-mechanical design

