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Engineering Challenges of the Target Station Solenoid System:

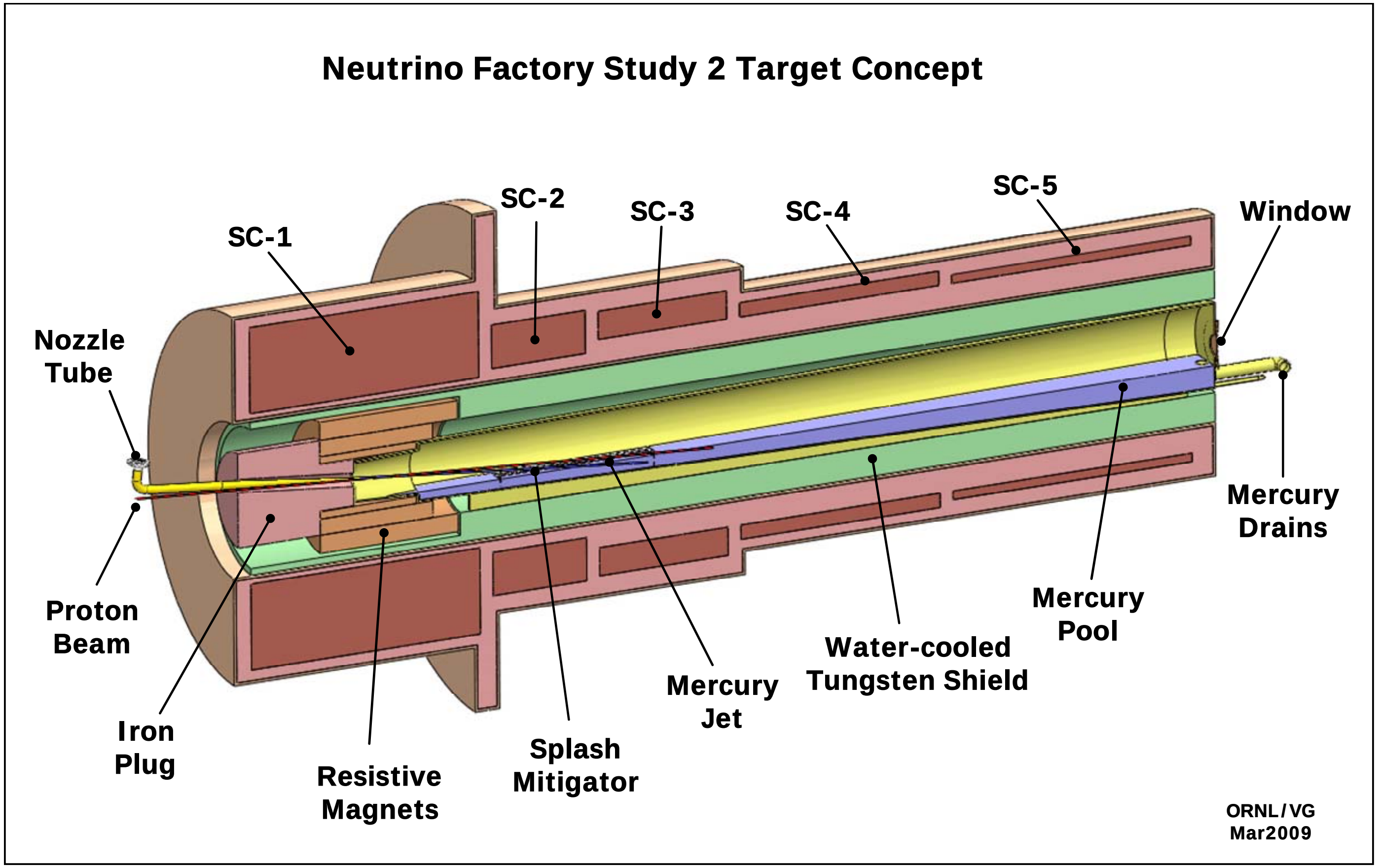
Thermal and Mechanical Loads

Peter Loveridge
Rutherford Appleton Laboratory

IDS NF Plenary Meeting
Sept. 22, 2010

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

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Engineering Challenges

Two factors that lead to some significant engineering challenges:

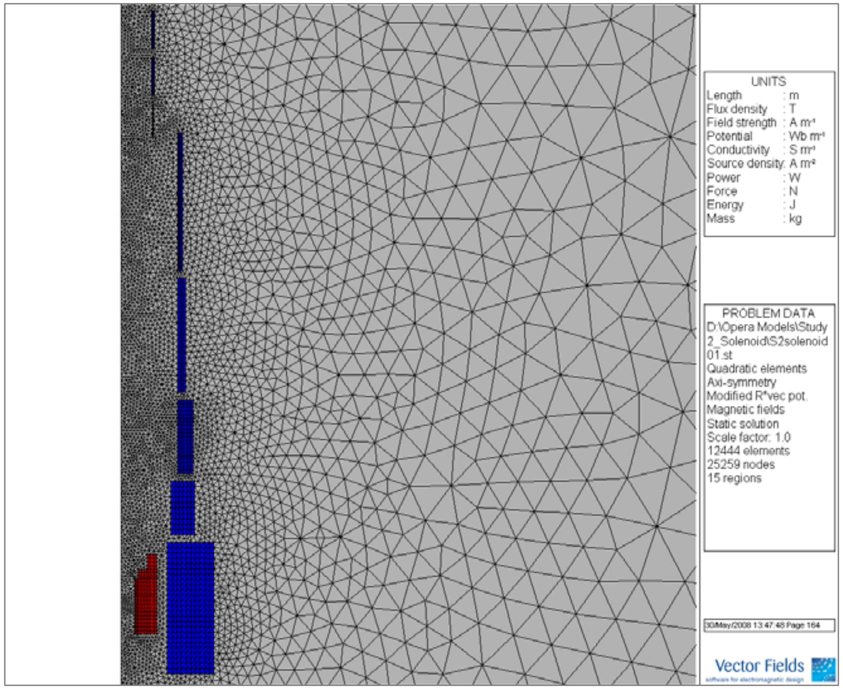
1. Ambitious physics requirements - High field in a large bore
    - Huge magnetic forces
    - Large stored energy
    - Pushing limits of present superconductor technology (14 Tesla in a 1.3 m bore)

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…



UNITS

Length	: m
Flux density	: T
Field strength	: A m^{-1}
Potential	: Wb m^{-1}
Conductivity	: S m^{-1}
Source density	: A m^{-2}
Power	: W
Force	: N
Energy	: J
Mass	: kg

PROBLEM DATA
D:\Opera Models\Study 2_Solenoid\S2solenoid 01.st
Quadratic elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
Static solution
Scale factor: 1.0
12444 elements
25259 nodes
15 regions

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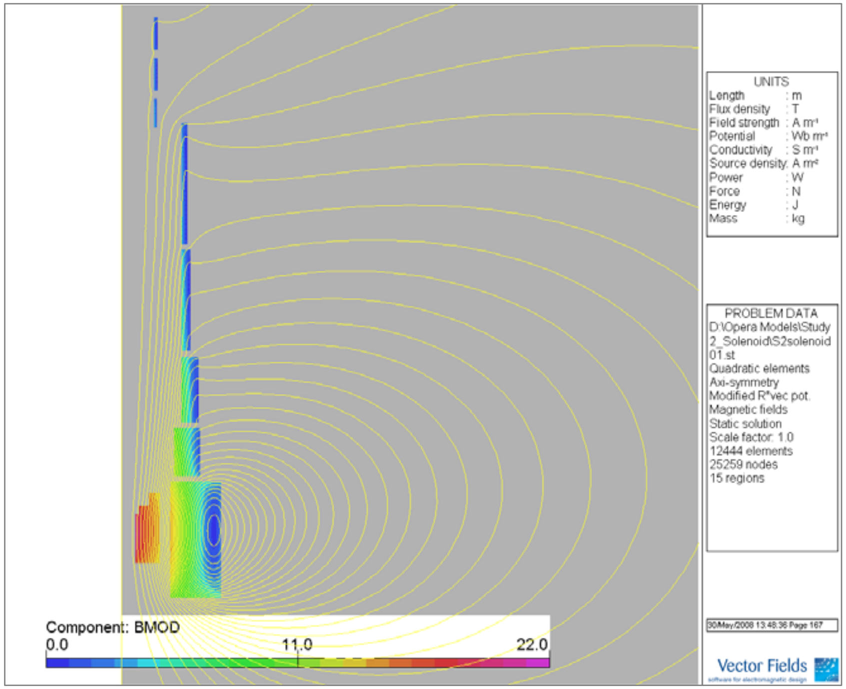
Study-2 geometry



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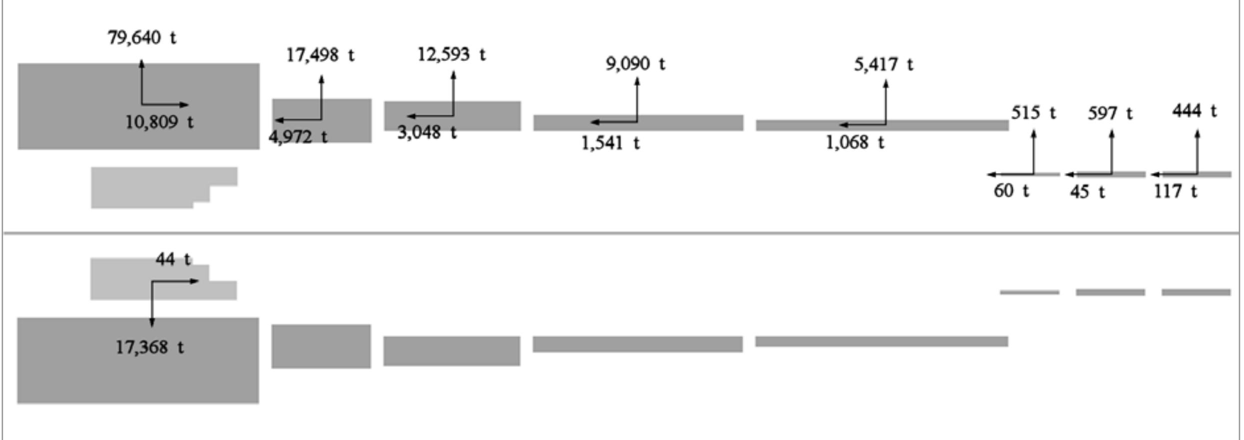
Magnetic field (Tesla) in the conductor regions

Magnetic Forces: Results

Coil	JDEN (A/mm2)	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



radial and axial force components acting on each solenoid (tonnes)
note: radial forces are on a full 360 degree basis

Equivalent Internal Pressure:

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

Max Compressive Radial Stress (@r = R_1):

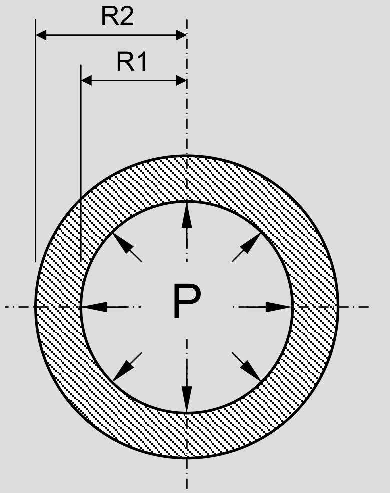
$$\sigma_{R\,\mathrm{MAX}} = P$$

Max Tensile Hoop Stress (@r = R_1):

$$\sigma_{\theta\,\mathrm{MAX}} = P\frac{(R_2^2 + R_1^2)}{(R_2^2 - R_1^2)}$$

Average Compressive Axial Stress:

$$\sigma_{Z\,\mathrm{MEAN}} = \frac{F_Z}{\pi(R_2^2 - R_1^2)}$$



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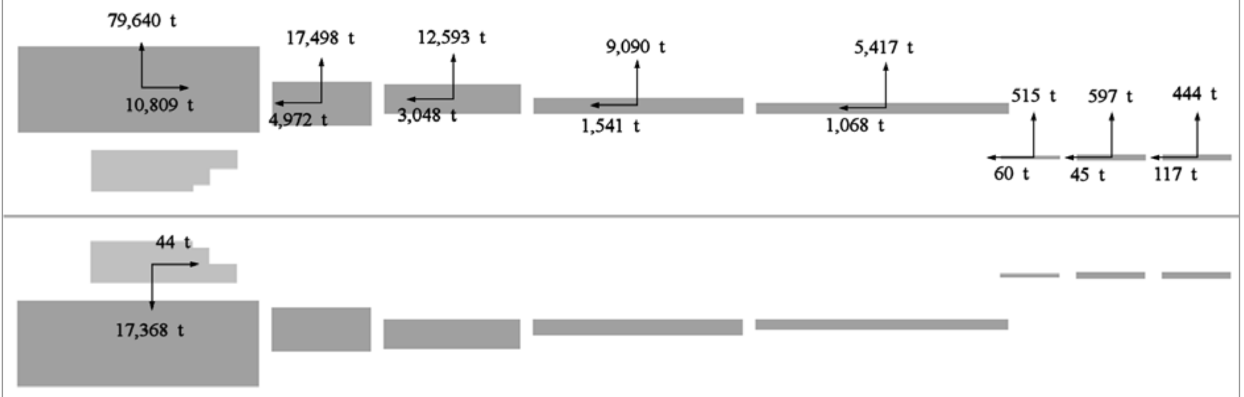

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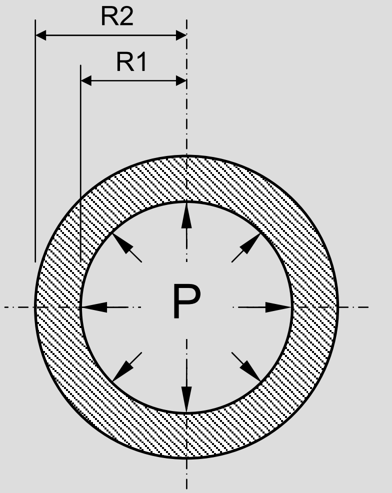


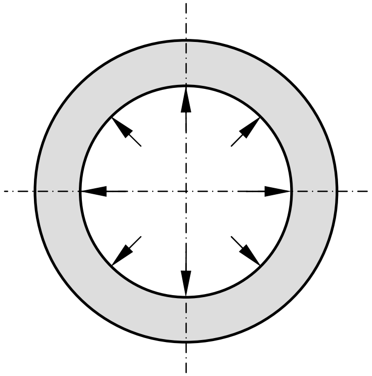
Magnetic Forces: Implications

- 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

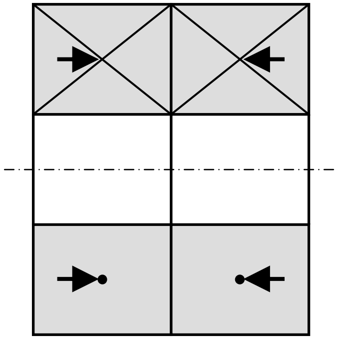
  ~10,000 tonnes in SC1!

  – 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



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Peter Loveridge, September 2010

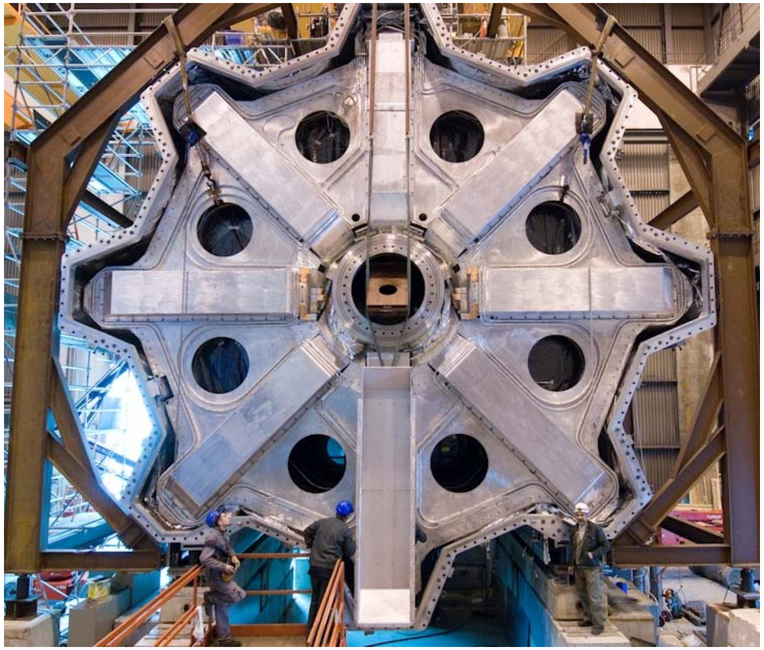
Stored Energy

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

$$E_m = \frac{1}{2} L I^2$$

  - 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



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)

- 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

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
SC Coils	62.7	1.6
Iron Plug	15.2	0.4
Hg Pool	12.5	0.3
Be Window (at 6m)	1.7	-

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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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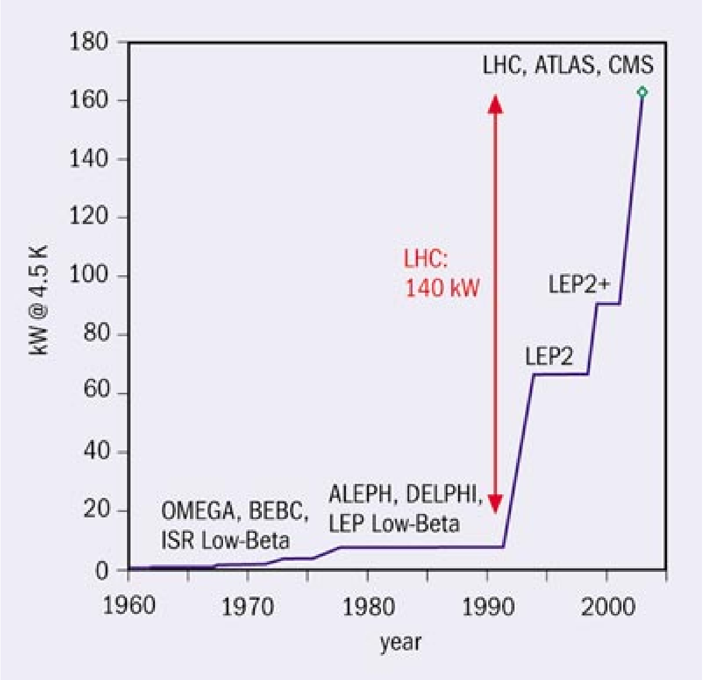
Surprisingly little heating in the mercury “dump”

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

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Heat Loads: Power Density

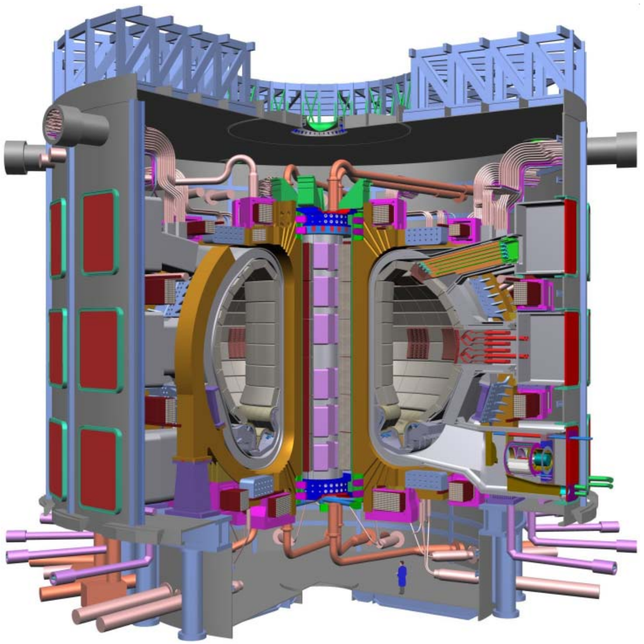
- Total heat load [W] is only part of the story…
- Power *density* [W/m^3] is also critical in the thermal design, where feasibility depends on
  - Proximity of cooling channels
  - Helium flow-rate and pressure drop
  - Heat transfer surface area
  - Thermal diffusion time

- 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

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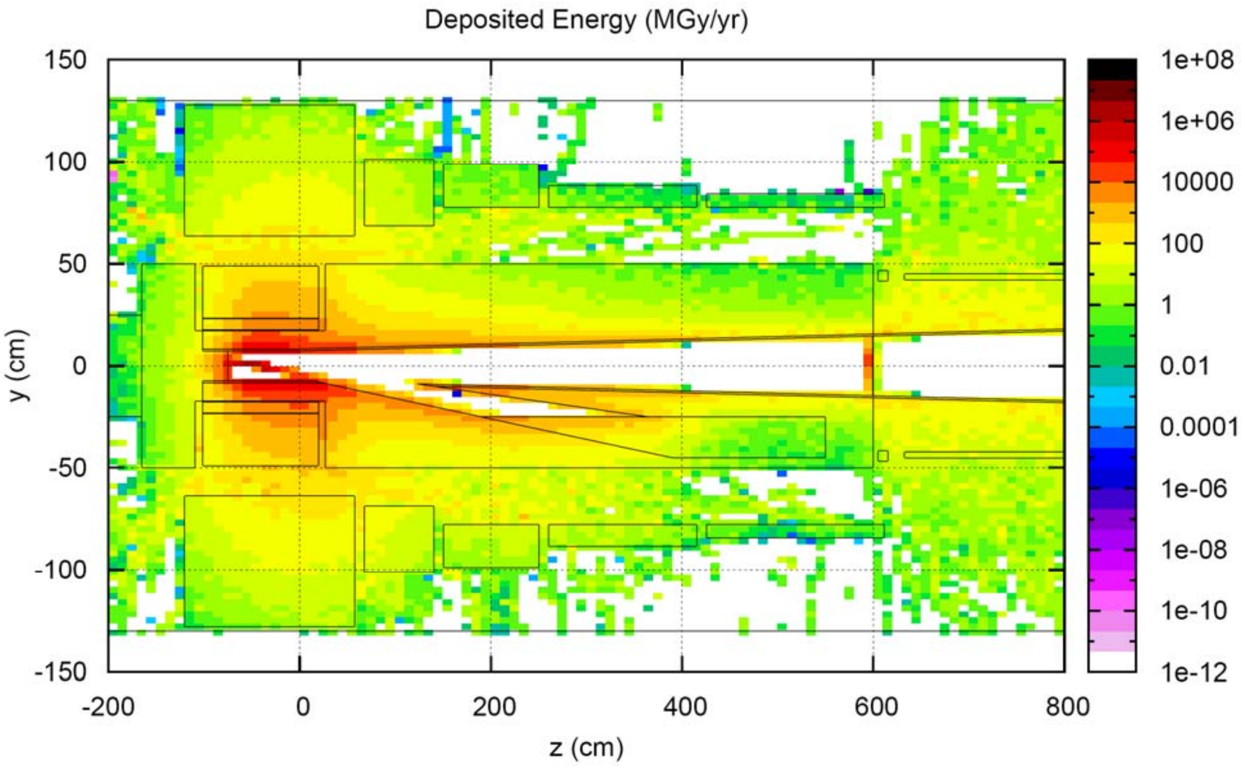
Heat Loads: Pulsed Beam Heating



FLUKA energy deposition simulation
courtesy: John Back, Warwick

- Peak energy deposition in superconducting coil: $\dfrac{200\ [\mathrm{MGy/yr}]}{2\mathrm{e}7\ [\mathrm{sec}] \times 50\ [\mathrm{Hz}]}$ = 0.2 [J/kg per pulse]
- Note: no DPA output from FLUKA

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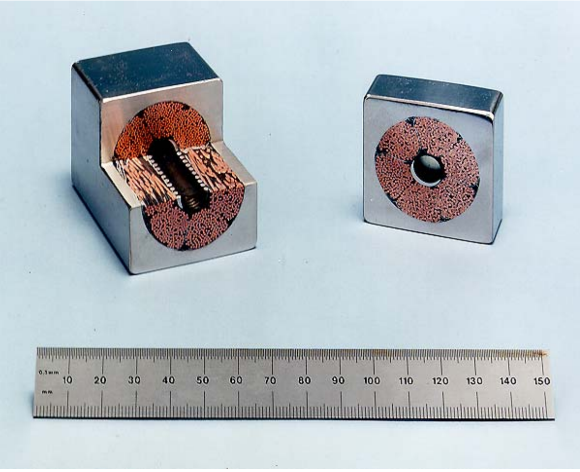
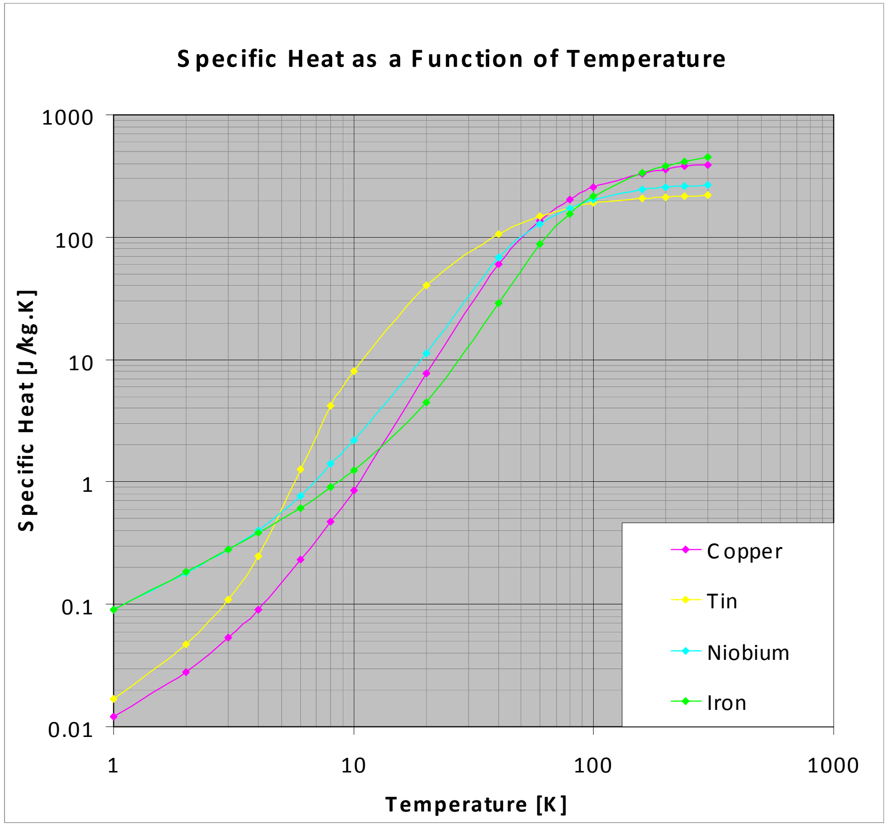
Heat Loads: Pulsed Beam Heating

- 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:

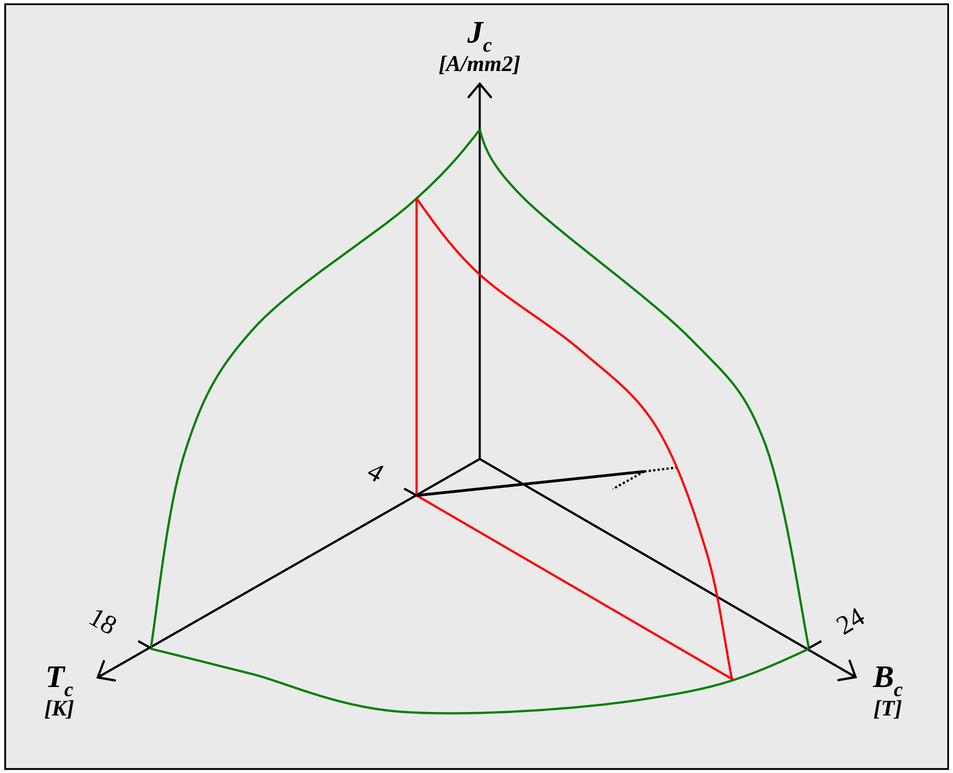
$$\Delta T = \frac{\text{Energy Density}}{\text{Heat Capacity}} = \frac{0.2\ [\text{J/kg}]}{0.1\ [\text{J/kg.K}]} = 2\ \text{K}$$

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:

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



Critical surface diagram for Nb_3Sn

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

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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