Technical Challenges of the Neutrino-Factory / Muon-Collider Capture System

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Background

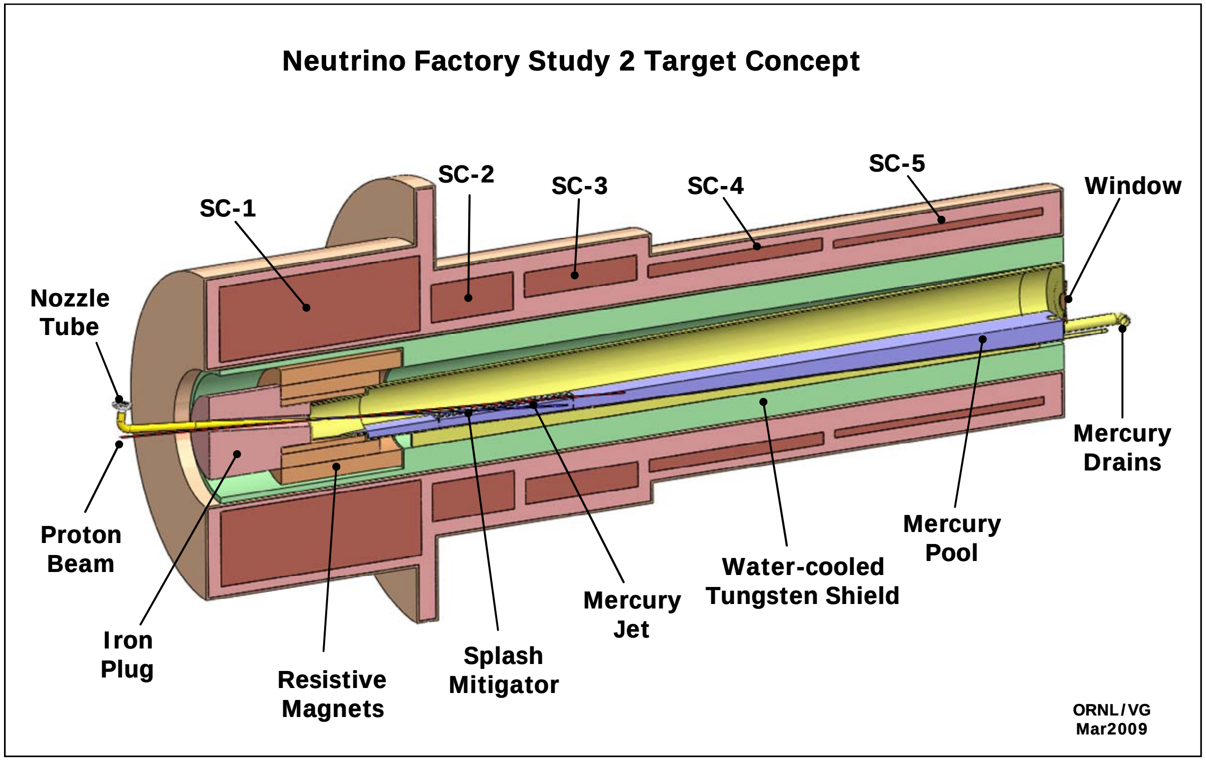
- NF/MC Target station concept emerged ~10 years ago in “Study-II” document
- Since that time:
  - Much effort devoted to target development
  - But little development on issues of target integration with solenoid capture system…

In this Presentation

- Will set out some of the technical issues
- Will present some “Order of magnitude” calculations
- Will draw comparisons with “state-of-the-art” technology

NF/MC Target Station Concept

- A 20 Tesla hybrid Nb3Sn / Cu solenoid is proposed
  - 14 Tesla to be generated by a superconducting magnet
  - 6 Tesla to be generated using a resistive insert magnet
- 4 MW proton beam interacting with a high Z target material
  - Pions captured in the clear bore of the magnet and transported downstream



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

Technical Challenges

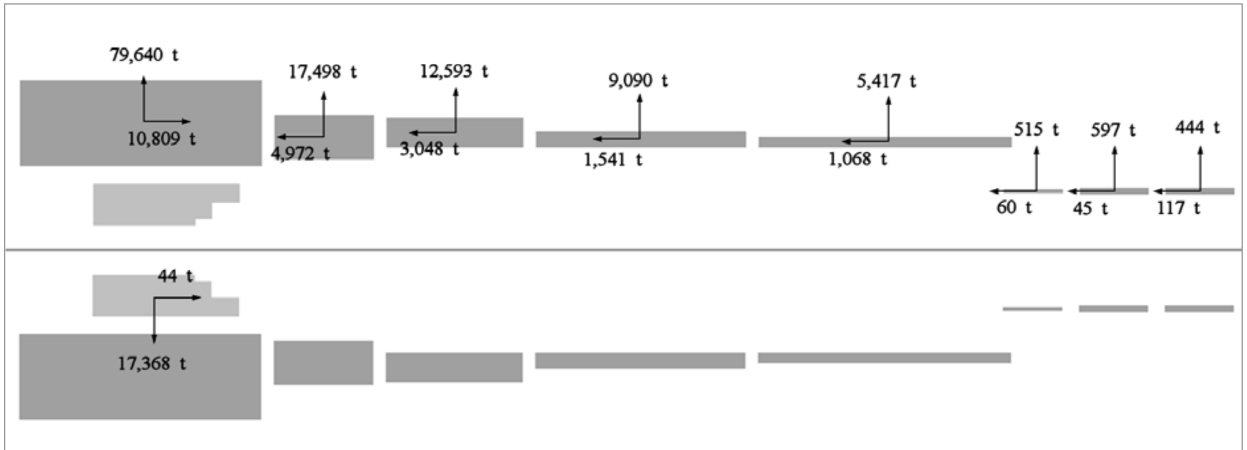
Two factors that lead to some significant technical challenges:

1. Demanding Magnet Parameters - *High field (14 Tesla) in a large bore (1.3 m)*
   - Huge magnetic forces (10,000 Ton)
   - Large stored energy (~600 MJ)
   - Pushing at the limits of present superconductor technology

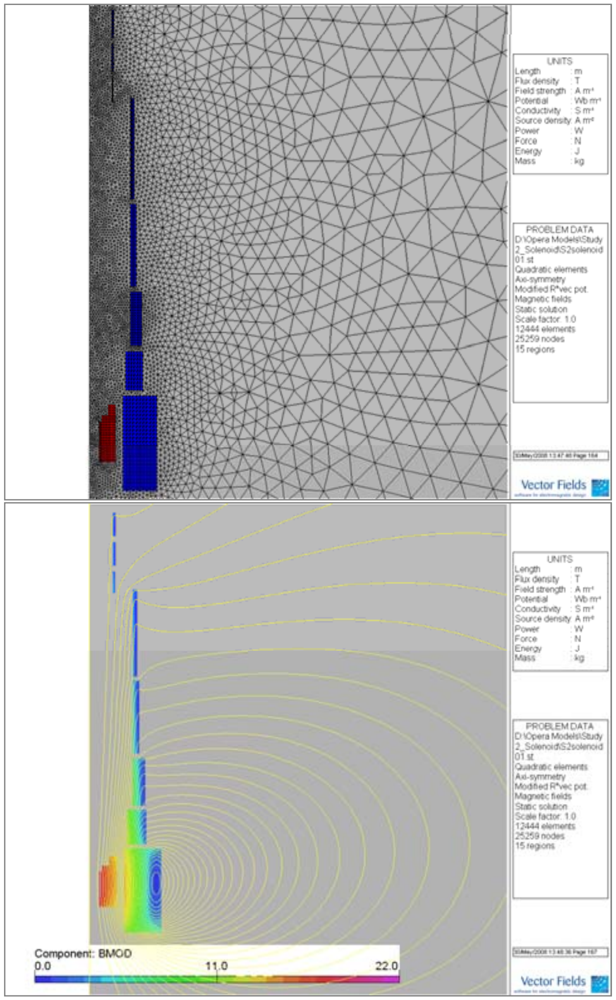
2. Harsh Radiation Environment – *Heating and material damage Issues*
   - Heat load from 4 MW pulsed proton beam
     - Total Heat load into the cold mass
     - Local Power Density
     - Instantaneous pulsed heating effects
   - Radiation damage to materials
     - Superconductor
     - Stabiliser
     - Turn-to-turn insulation
     - Load Bearing Elements

Magnetic Forces

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



Finite Element Analysis
Top: Element Mesh
Bottom: B Field plot

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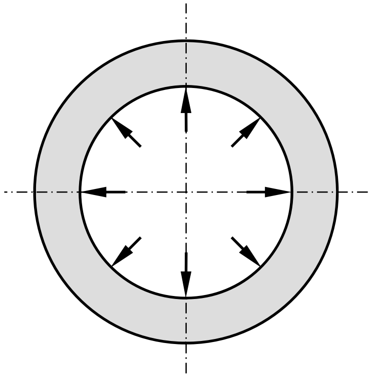
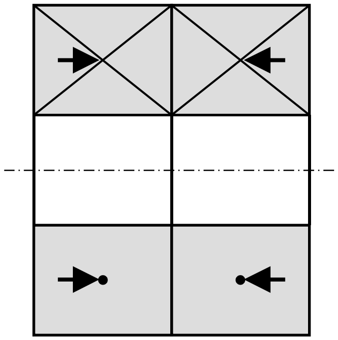
Magnetic Forces: Implications



- 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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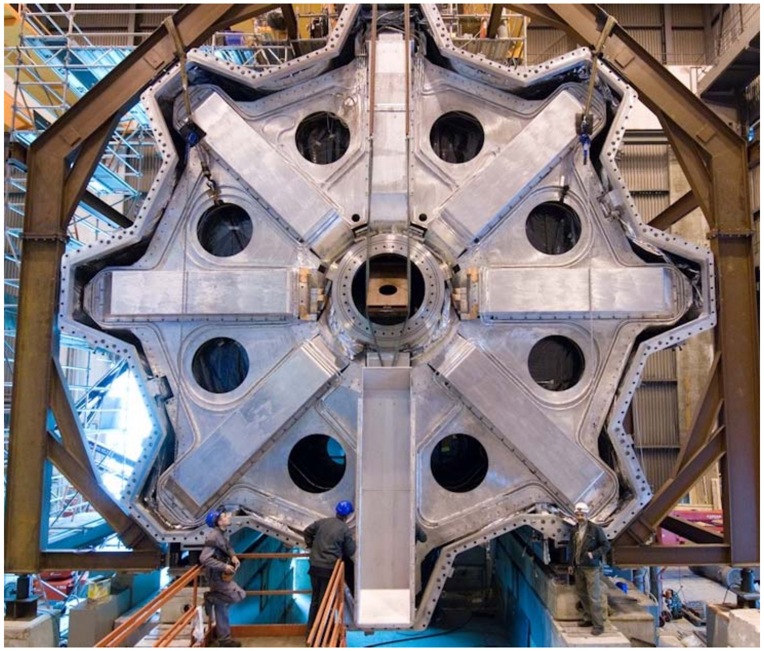
Stored Energy

- 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 “engineering” current density



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)

What are the Operating Limits of Present SC Solenoids?

- Recall: NF/MC capture system relies on a combination of ***large bore*** and ***high field***

Operating Parameters of the NF MC Capture solenoid in Context

Magnet	**Central Field Contribution from SC coils (Tesla)**	**Bore Diameter (m)**	**Stored Energy (MJoule)**	**Operating Temperature (Kelvin)**	**Cable Technology**
NF/MC Capture Solenoid	14	1.3	600	?	Proposed Nb_3Sn CICC
Delphi (LEP) (1989)	1.2	5.6	100	4.5 K	NbTi cable coextruded with Al stabiliser
NHFML 45-T Hybrid Magnet (2000)	14	0.7	100	1.8 K	CICC, 3 nested coils 2xNb_3Sn, 1xNbTi
ITER CSMC (2000)	13	1.6	640	4.5 K	Nb_3Sn CICC
CMS (LHC) (2006)	4	6	2600	4.5 K	NbTi cable coextruded with Al stabiliser

- The desired operating parameters are similar to those of the ITER CSMC

Notes on Bore Shielding

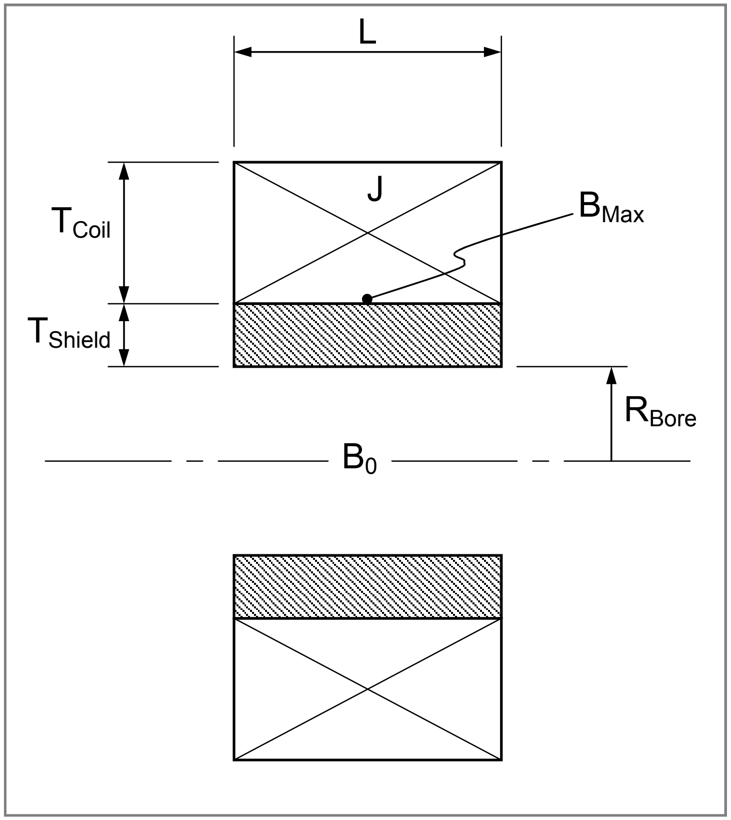
- Shielding in the Solenoid bore must be sufficient to:
  - Limit the heat load on the cold mass to a "reasonable" level
  - Prevent excessive radiation damage to the coil materials

  i.e. Shielding must not be too thin!

- But… to increase T_{Shield} while keeping B_0, R_{Bore}, and J the same means:
  - Increased SC volume (expense)
  - Greater magnetic forces (mechanical design)
  - Increased inductance (stored energy)
  - Ratio B_{Max}/B_0 less favourable (magnetic design)

  i.e. Shielding must not be too thick!

- Getting the shield design right is critical
  - See talk by Nicholas Souchlas



Schematic showing a "short-fat" solenoid with shielding in the bore

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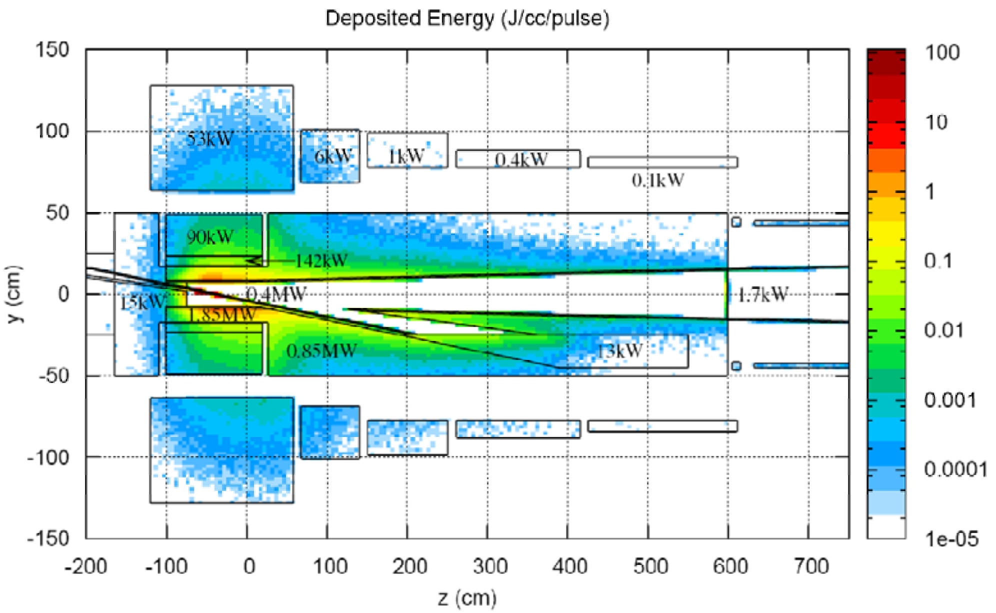
Notes on Bore Shielding

Q: Where does the 4 MW Beam Power go?

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	-



Regional deposition of 4MW beam power

(From FLUKA simulation by John Back, Warwick, Nov 2009)

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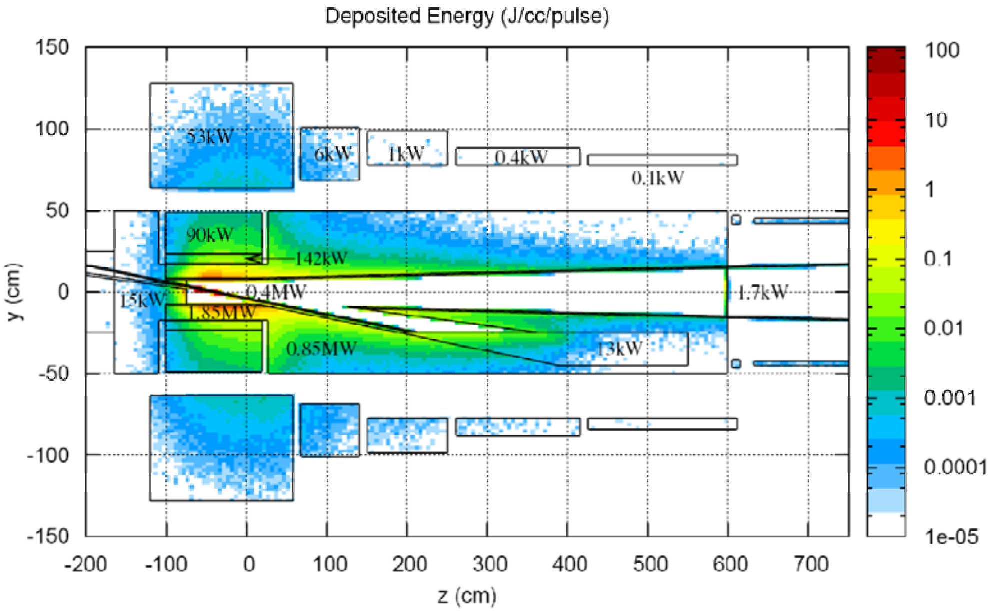
Designing a cooling system capable of removing ~2.7 MW from the shielding is a challenge in its own right



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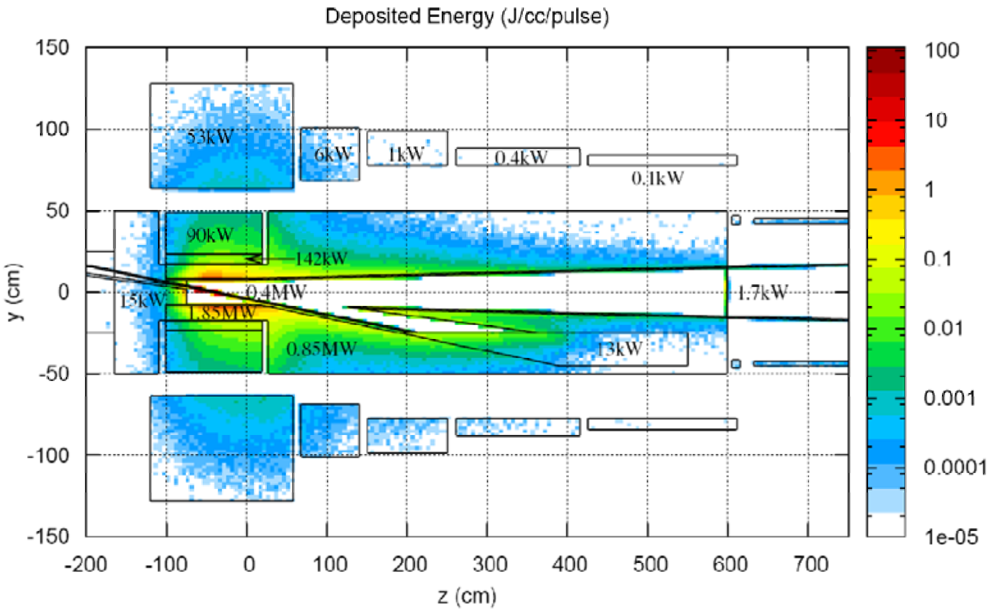
Enormous heat load on the cold mass, looks unfeasible…



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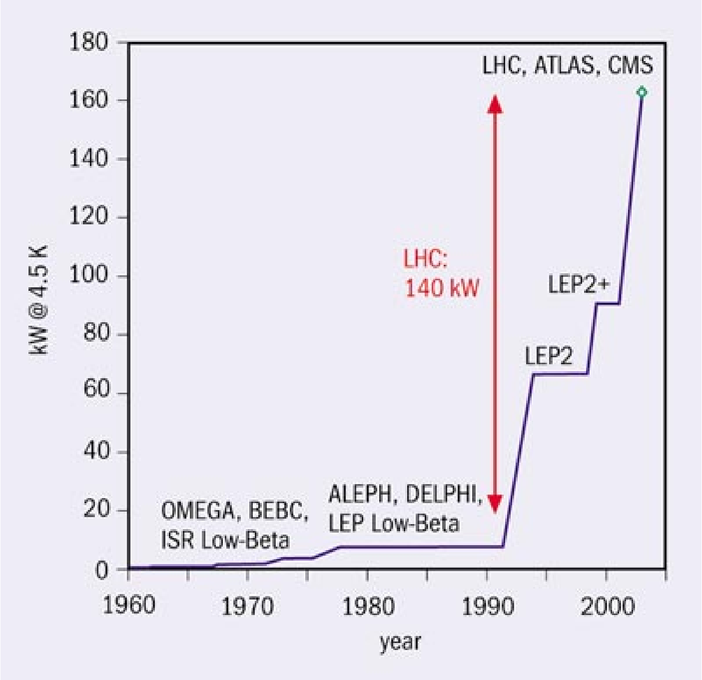
Total Heat Load into the Cold Mass

- Integrated heat load determines the required cryo-plant capacity

  63 kW integrated heat load on the NF target station cold mass is enormous!
- To put it into perspective:
  - Total capacity of ITER cryo-plant 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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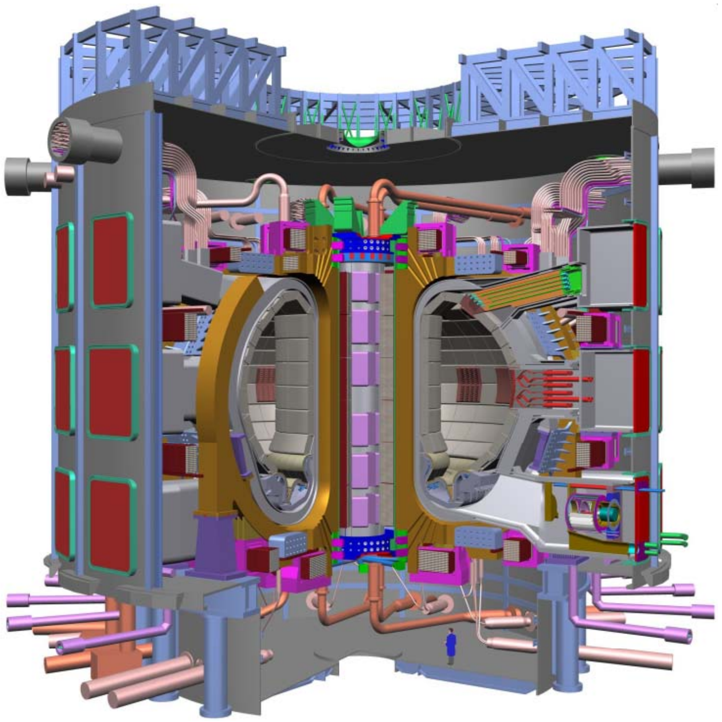
Local Power Density

- But 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 [J/kg/pulse] × 50 [Hz] = 10 [mW/g]

- This is extremely high
  - E.g. ITER design guidelines suggest a limit for "local nuclear heat in the conductor" of 1 mW/cc



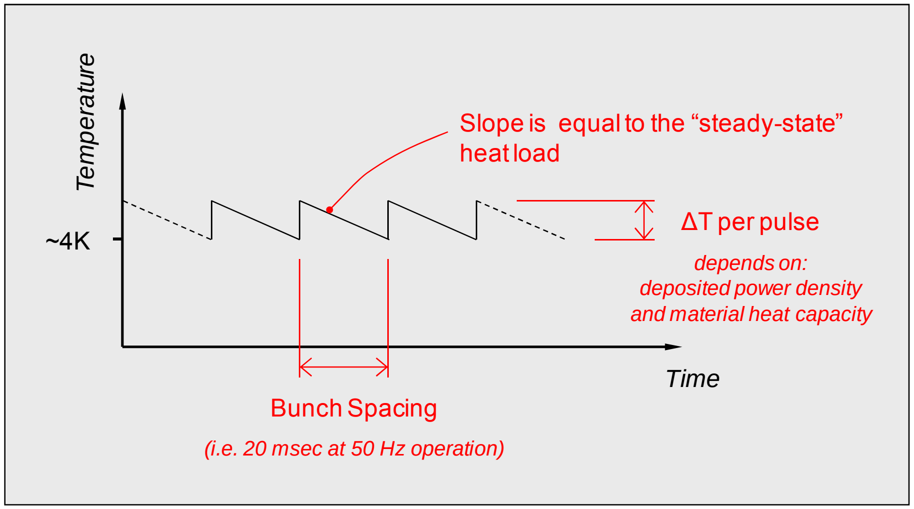
Context:

The superconducting magnets of ITER weigh ~10,000 Tonnes

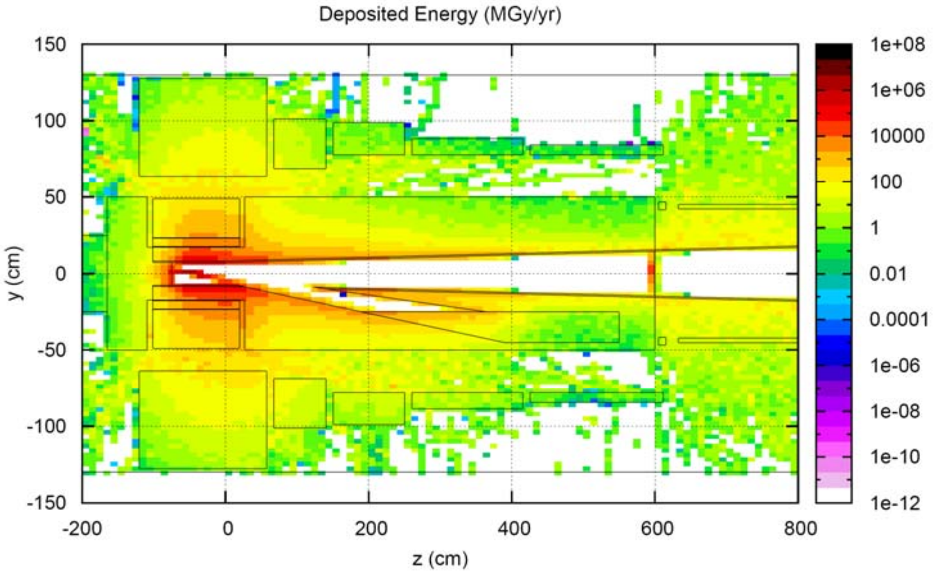
Recall the cryogenic cooling capacity of 65 kW @ 4.5 K
i.e. Similar heat load to NF, but in ~100 times volume

Instantaneous Pulsed Heating Effects

- Recall: beam repetition rate = 50 Hz
- Each beam/target interaction generates an “instantaneous” ΔT in surrounding components
  - ΔT Depends on ***Energy Density*** and material ***Heat Capacity***



Schematic: steady-state thermal operation

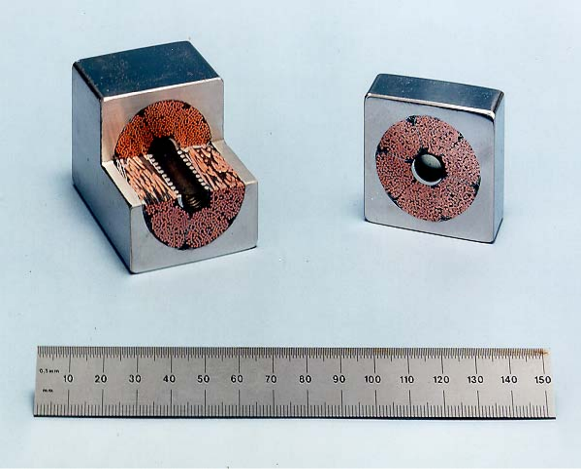


Energy Density Contour Plot
courtesy: John Back, Warwick, Nov 2009

- Peak ***Energy Density*** in superconducting coil: $\frac{200\ [\mathrm{MGy/yr}]}{2e7\ [\mathrm{sec}] \times 50\ [\mathrm{Hz}]}$ = 0.2 [J/kg per pulse]

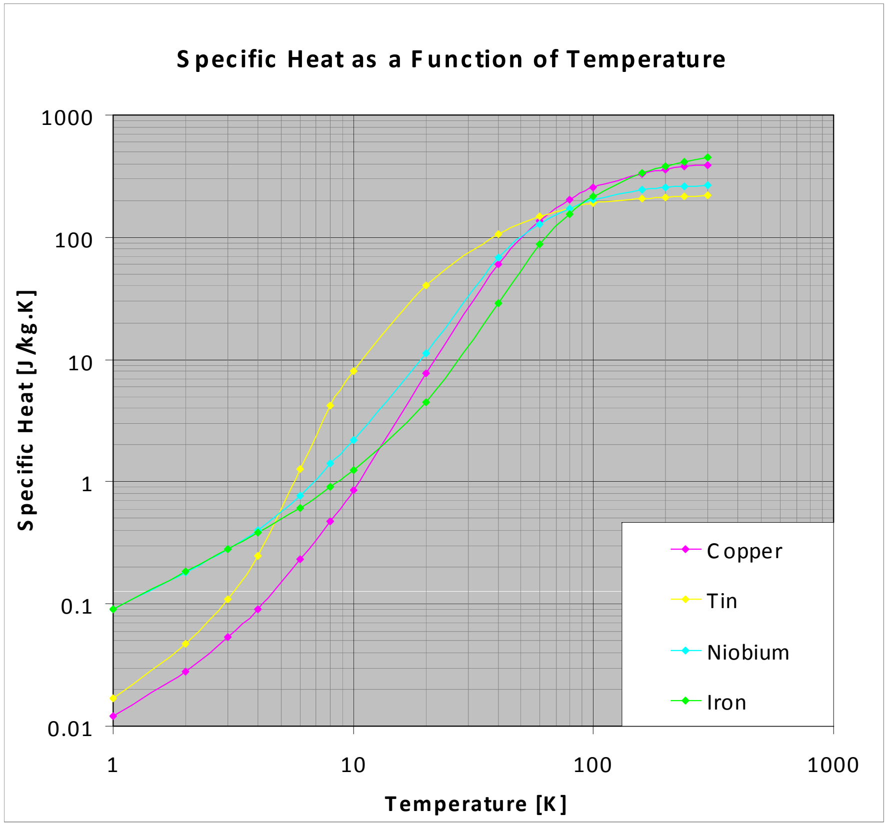
Instantaneous Pulsed Heating Effects

- Note: ***Heat Capacity*** of coil materials is markedly reduced at cryogenic temperatures



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 @ 4 Kelvin of the order:

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

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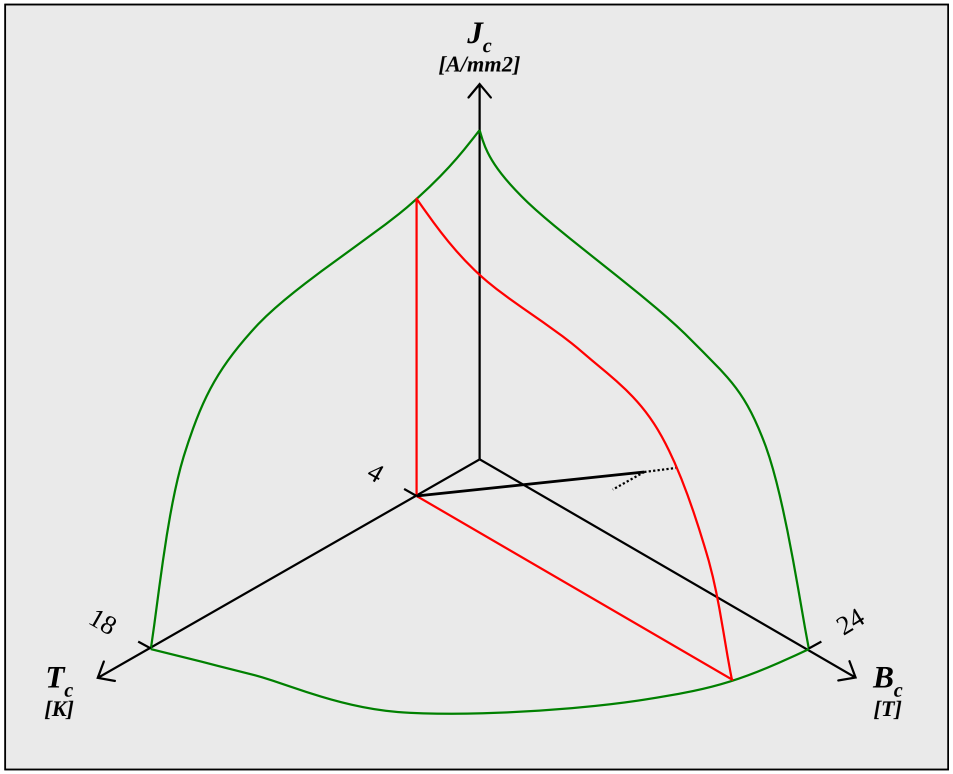
A Note on Superconductor Temperature Margin

- Q: What temperature rise can be tolerated by the superconductor?

  - Answer depends on how hard we are pushing in terms of J vs B…

- For 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

Summary

Demanding magnet parameters combined with a harsh radiation environment lead to a number of technical issues...

- Huge Magnetic Forces
  - Supporting the magnetic loads is a challenge in itself
  - Implications on target system integration
- Enormous Beam Heat Loads
  - Shielding in the solenoid bore is important!
  - Integrated heat load on cold mass affects plant capacity, cost
  - Power ***density***: critical in the thermal design
    - *1 mW/cc design limit?*
  - Superconductor temperature stability is key
    - Temperature margin ~1Kelvin

Conclusion

The target station solenoid system presents some serious technical challenges...

- Further work required to develop a viable thermo-mechanical design