Superconducting Solenoid: Thermal Issues

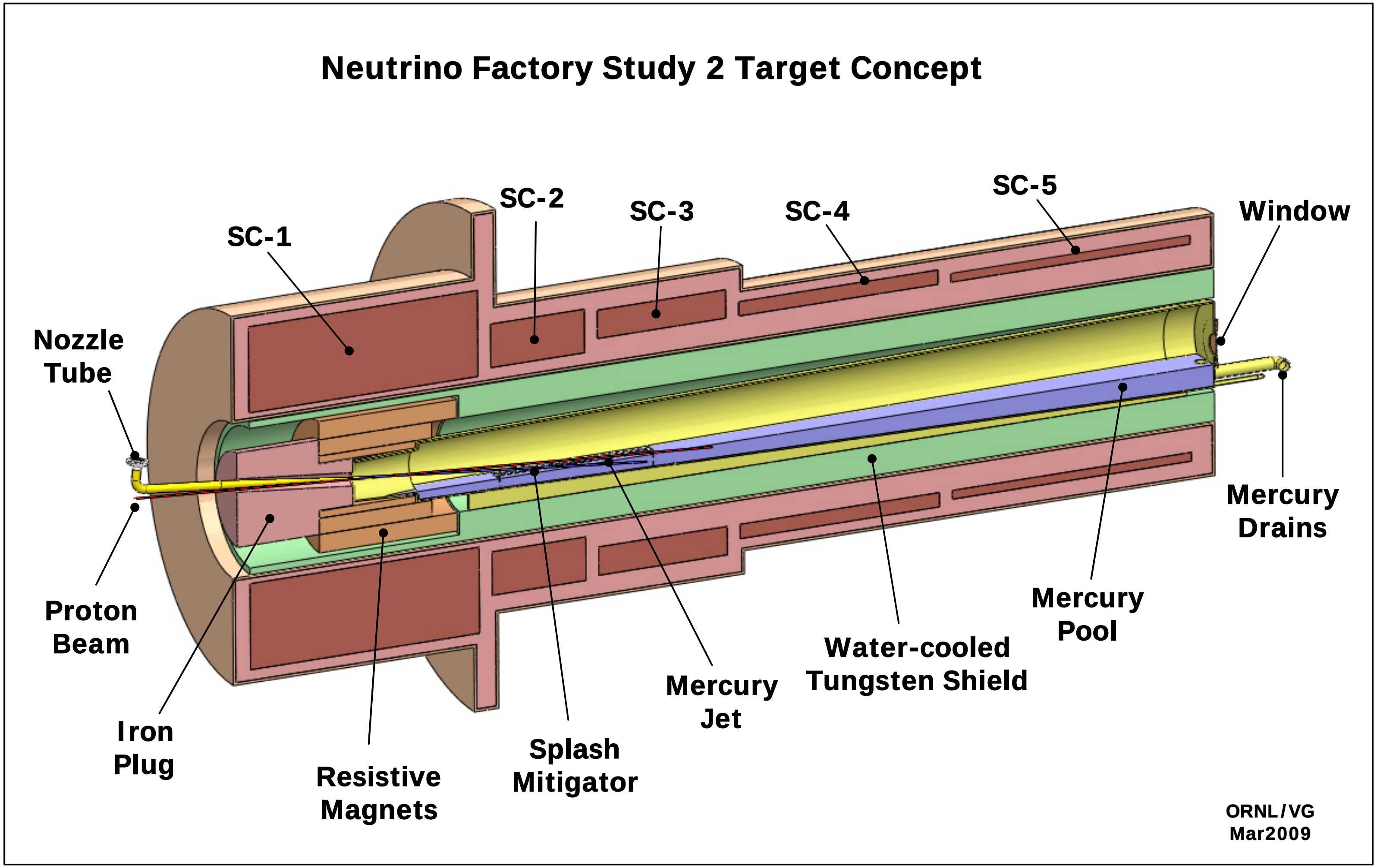
Peter Loveridge

P.Loveridge@rl.ac.uk

STFC Rutherford Appleton Laboratory, UK

January 2010

Context



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

Superconducting Solenoid: Technical Challenges

- Combination of high field (~14T) and large bore (~1.3 m)
  - Huge inter-coil forces (~10,000 metric tons axial compression)
  - Huge stored energy (600 MJ)
- Nb3Sn superconductor
  - Brittle
  - Strain sensitivity
- Harsh radiation environment
  - Radiation damage to materials
  - Heat load on coils

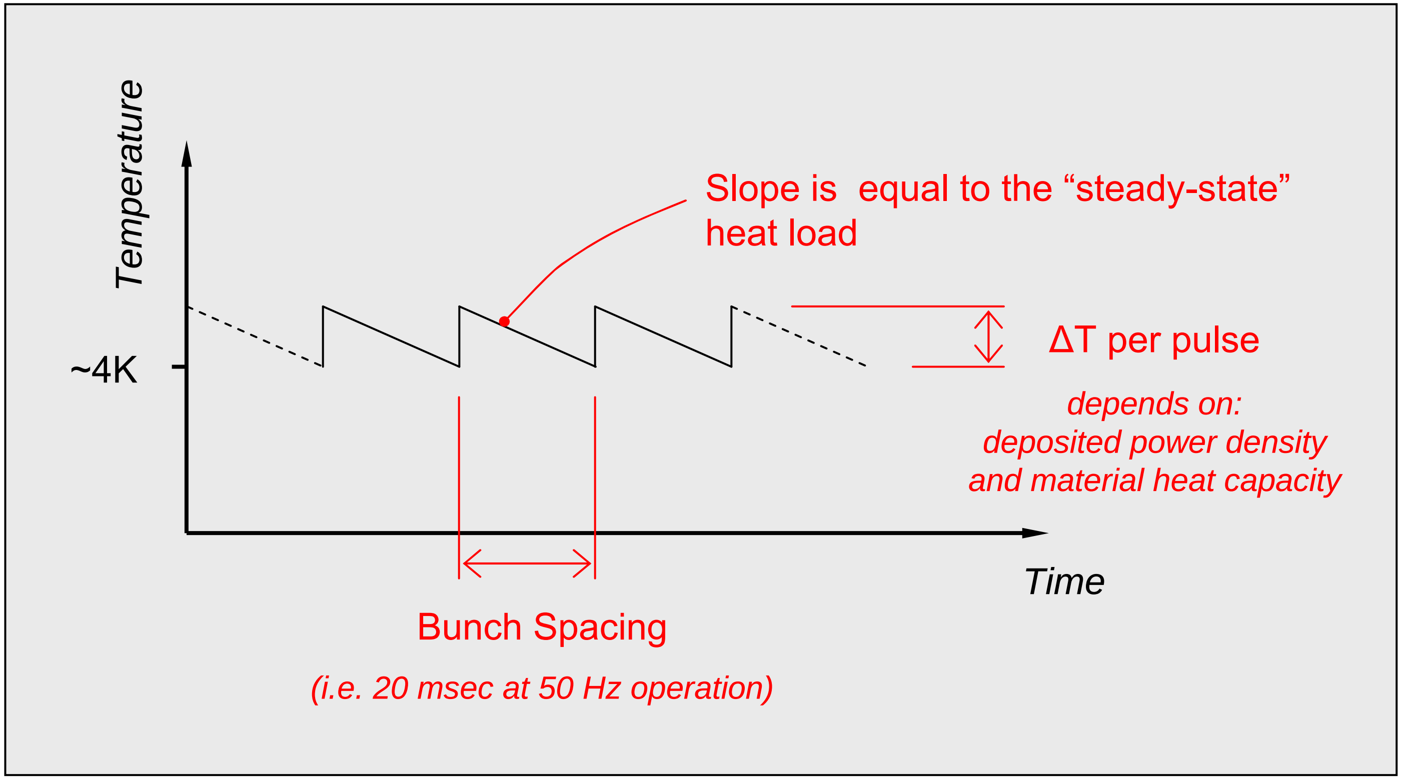
Of particular concern:

1. Time averaged heat load on cold mass
2. Instantaneous pulsed beam heating of superconductor

Theory

- Consider steady-state thermal operation of SC coils:

Energy In	=	Energy Out
(secondary beam heating rate)		(cooling rate)



Temperature history in cold mass

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	$\boxed{62.7}$	1.6
Iron Plug	15.2	0.4
Hg Pool	12.5	0.3
Be Window (at 6m)	1.7	-

~63 kW heat load on the cold mass at 4K is very large

What does this mean practically?

~63 kW heat load on the cold mass at 4K

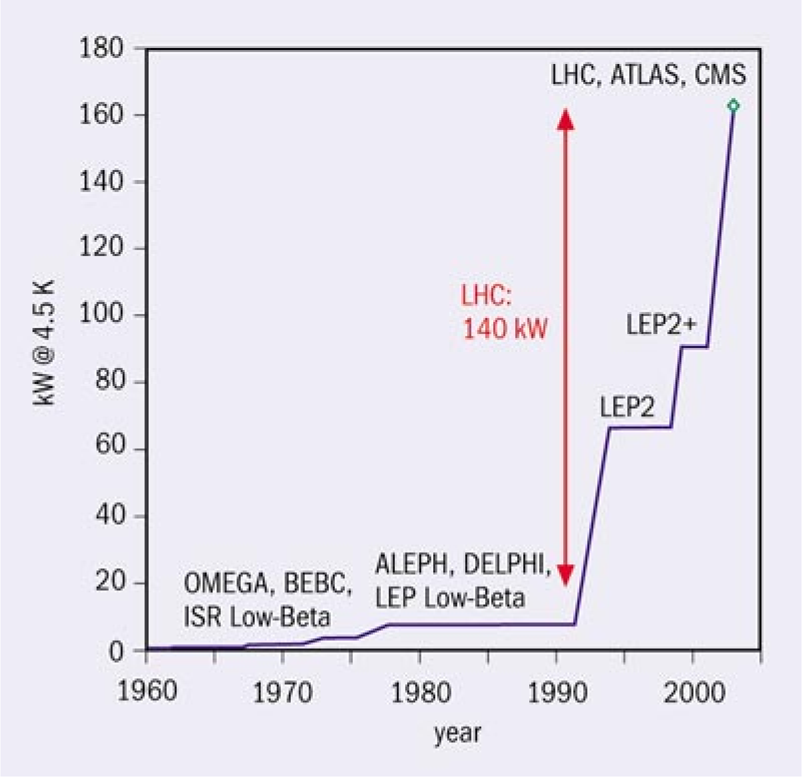
Some numbers…

- 1W boils off 1.4 litres of liquid helium in 1 hour (latent heat)
  - 63 kW would boil off 86 m^3 of liquid helium in 1 hour
- 1000 litres of liquid helium costs ~£3000
  - 86 m^3 of liquid helium equivalent to £258,000 per hour
- Need to recover helium
  - i.e. 63 kW re-condensing power would be required

Comparison with the LHC

- CERN - LHC uses eight 4.5K refrigerators – one for each sector – each with a capacity of 18kW at 4.5K

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



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

- i.e. 63 kW is equivalent to ~1/2 the total cooling power at the LHC!

Interpretation

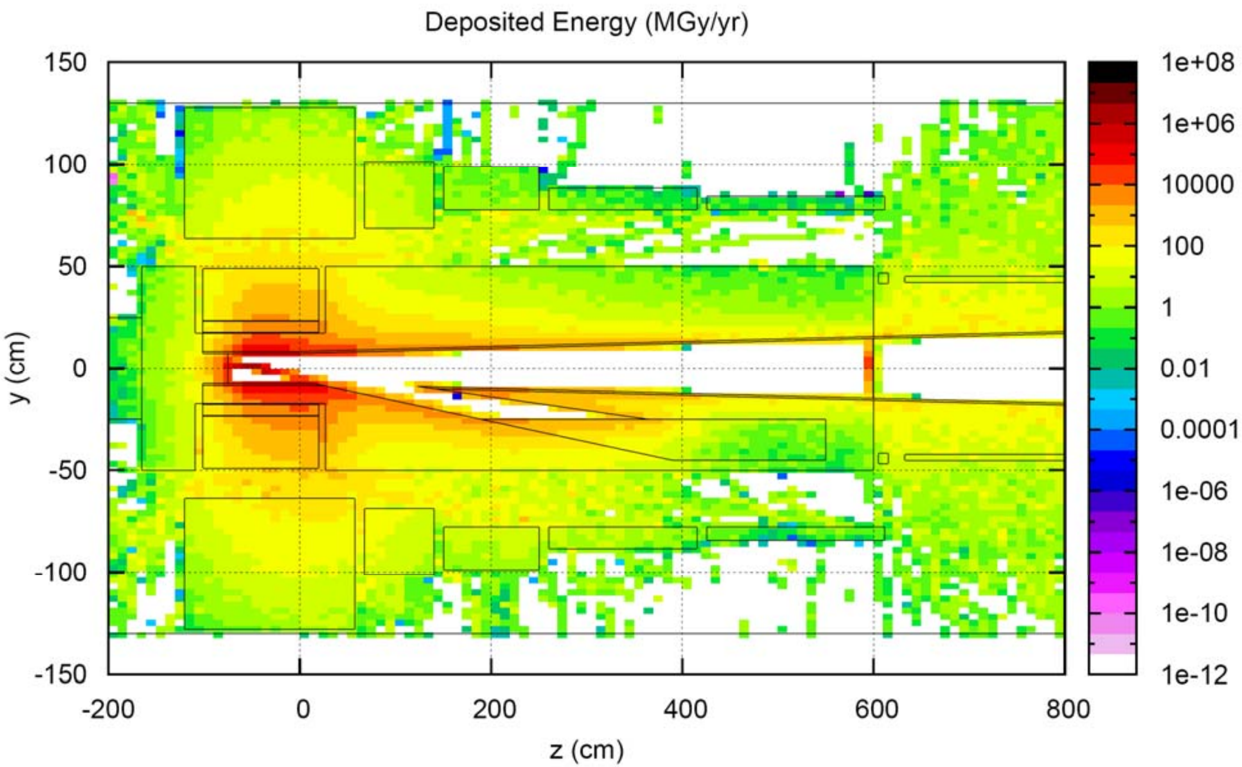
Steady-state heat load:

- 63 kW load on the cold mass is huge

- Technical feasibility issues
  - Heat transfer rates and thermal time constants
  - Is it possible to remove heat from the SC cable at that rate?

- Prohibitive cost
  - Refrigeration plant

Pulsed Beam Heating



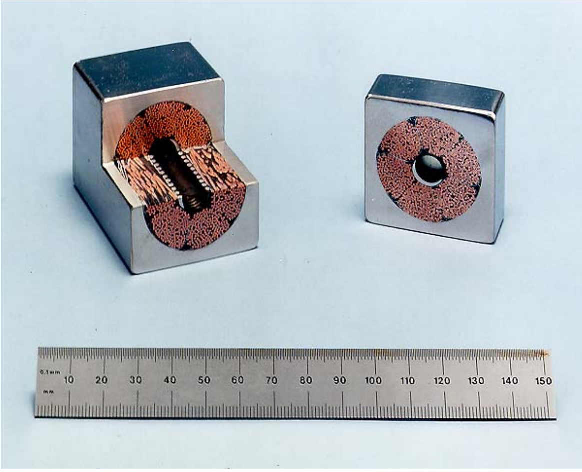
FLUKA energy deposition simulation
courtesy: John Back, Warwick

- Peak energy deposition in superconducting coil:

$$\frac{200\ [\mathrm{MGy/yr}]}{2e7\ [\mathrm{sec}] \times 50\ [\mathrm{Hz}]} = 0.2\ [\mathrm{J/kg\ per\ pulse}]$$

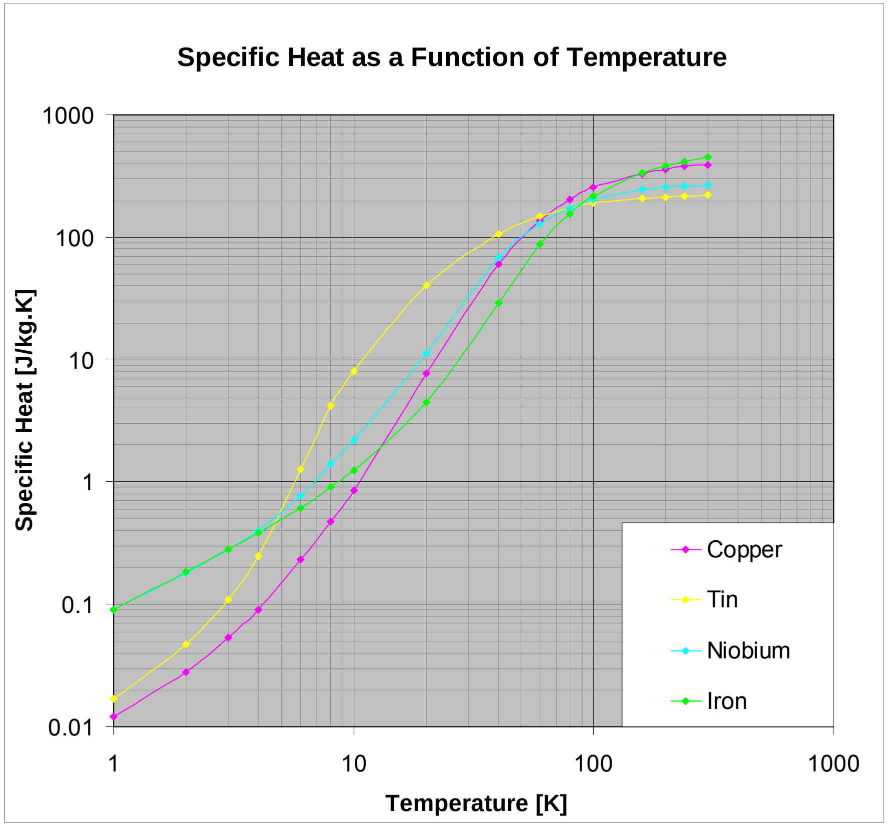
Temperature jump in Cold Mass Materials

- 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

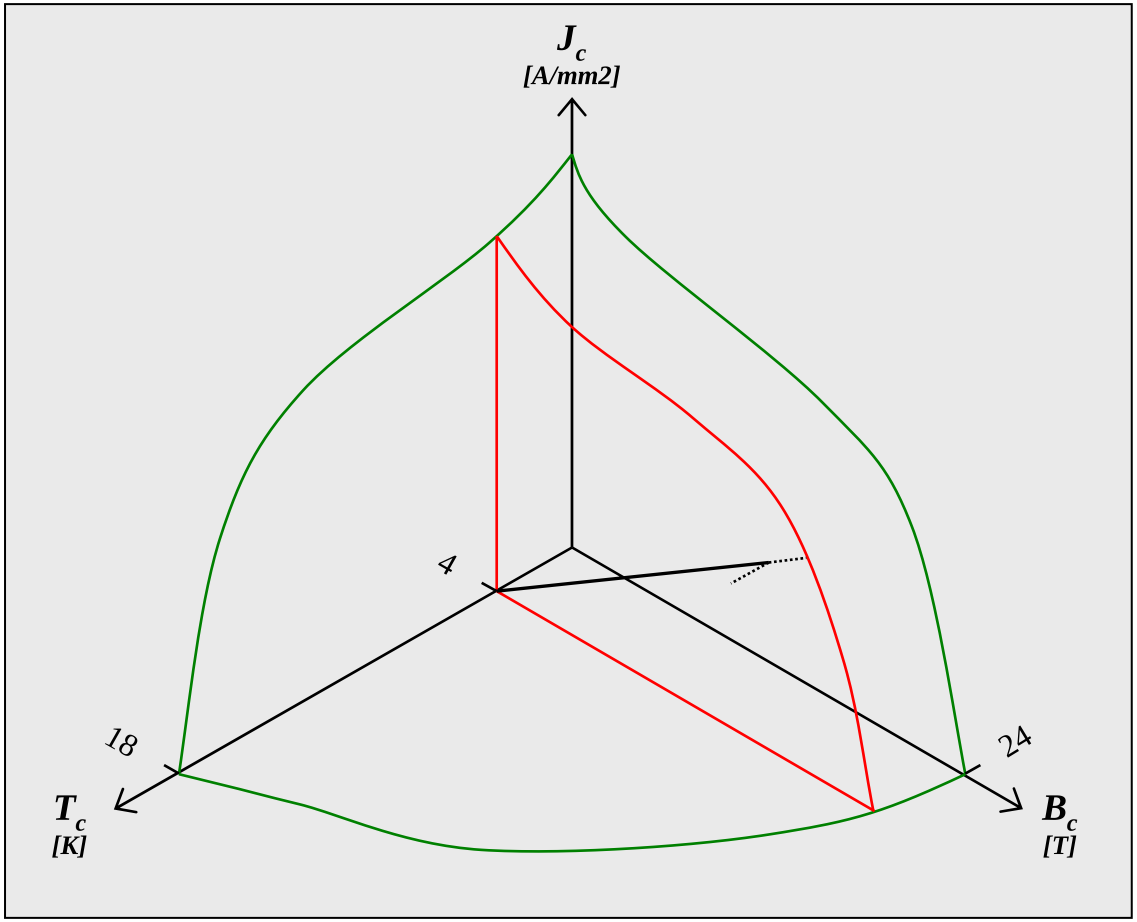
- e.g. each pulse gives a ΔT in Copper of the order:

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

Superconductor Temperature Margin

- 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 Nb_3Sn

- i.e. operating superconductor margin will typically be of the order 1 K

Interpretation

Pulsed Heating

- The temperature jump from a single beam pulse of the order ~ 2 K
- Operating temperature margin of the order ~ 1 K
- i.e. a single pulse could quench the magnet?!

Summary

The radiation heat load on the main superconducting coil is extremely high!

Identified two areas of concern:

1. The steady state heat load on the cold mass
2. The instantaneous ΔT from a single beam pulse

Need to revisit the conceptual thermal design