

On the use of a hyperconducting centre solenoid for spherical tokamaks

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Outline

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Magnetic cage in a Tokamak

Different set of coils:

- Toroidal (“frame”) coils, rather constant current (and losses)
- Poloidal (“O”) coils, plasma initialisation, shaping, and control

Central solenoid for plasma burnthrough and initialisation:

- Trafo role, where the secondary is the plasma loop
- Constrained space
- Higher levels of radiation
- Relieved of topping-up role

Most coils HTS at 20 K

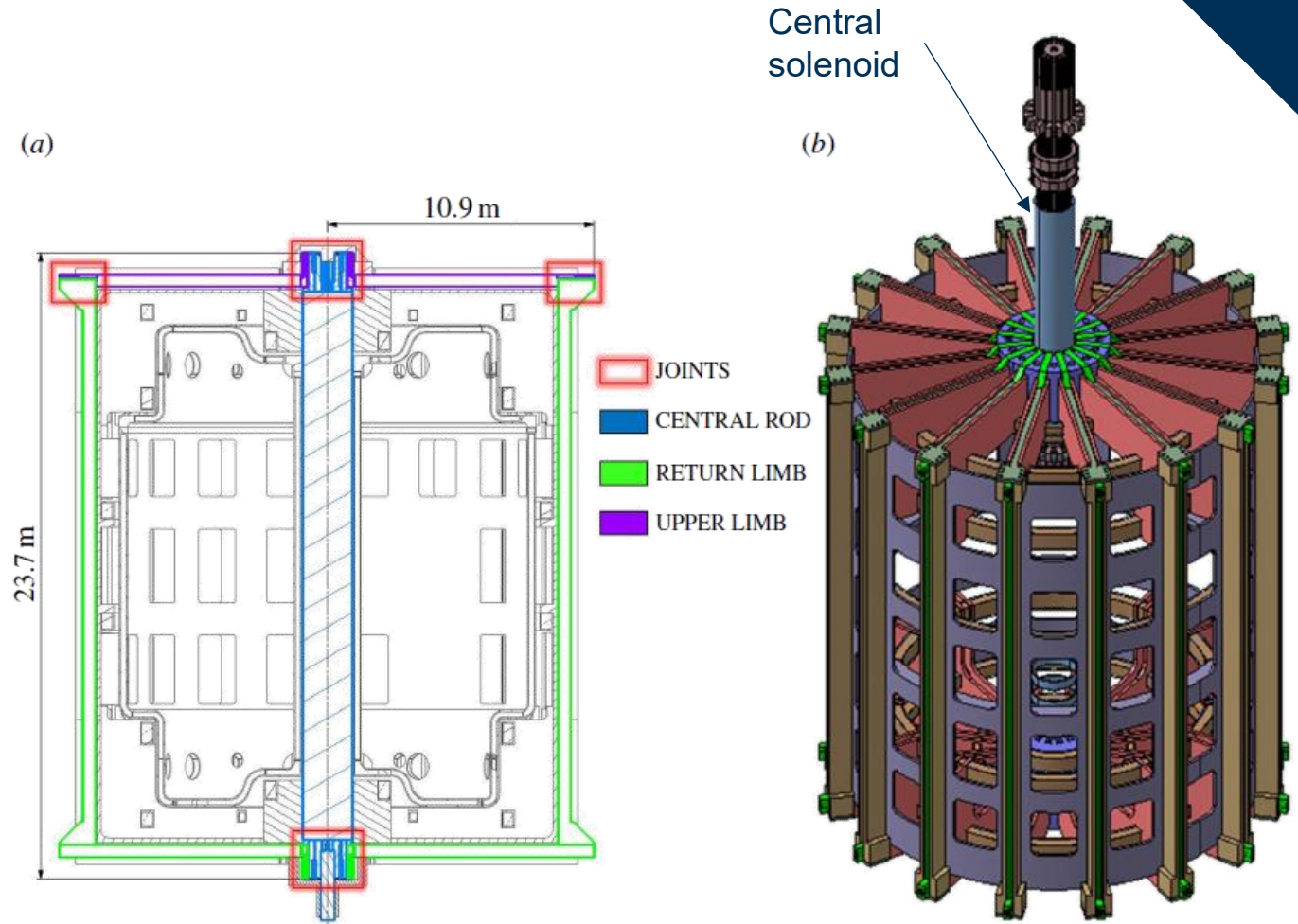


Figure 1. Cross section of the TF cage indicating segmentation of TF coil (a) and representation of the centre rod being retrieved (b). The CS (in light blue) can be seen wrapped around the inboard TF limbs.

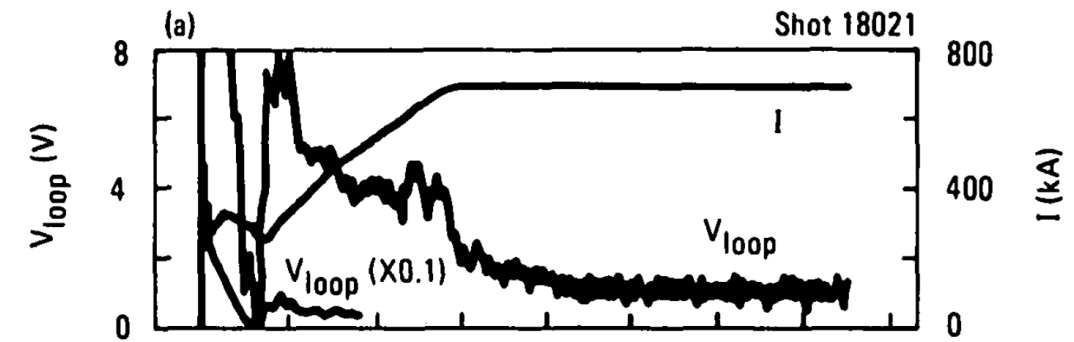
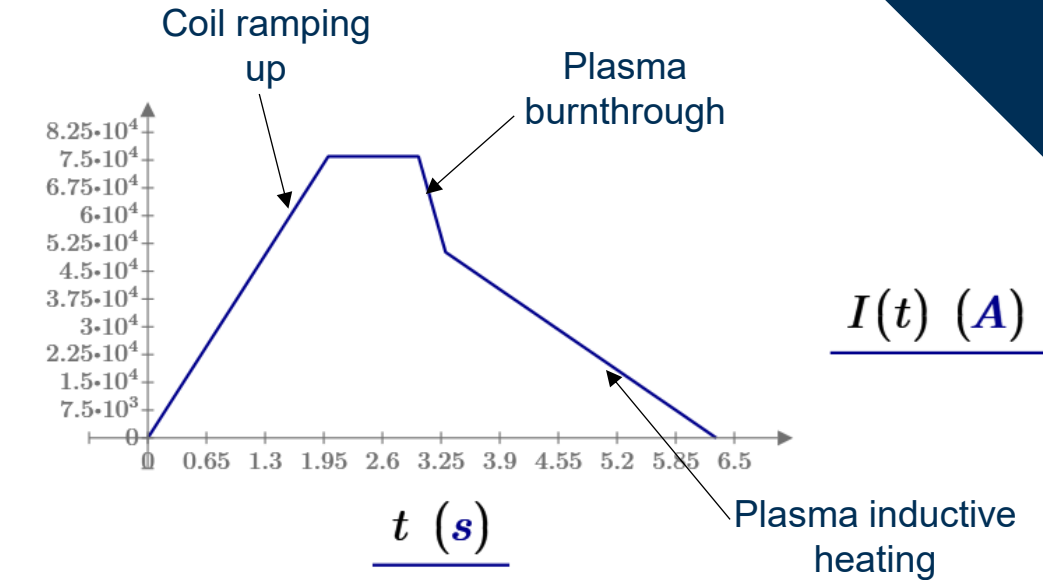
Load cycle in central solenoid

Plasma current level: a definitory figure of a tokamak

Translated into total flux and two flux drop rate requirements.

- Burnthrough: establishes coil nominal voltage
- Inductive heating: in conventional coils, limited by coil temperature
- The integration of both drops yields the total flux

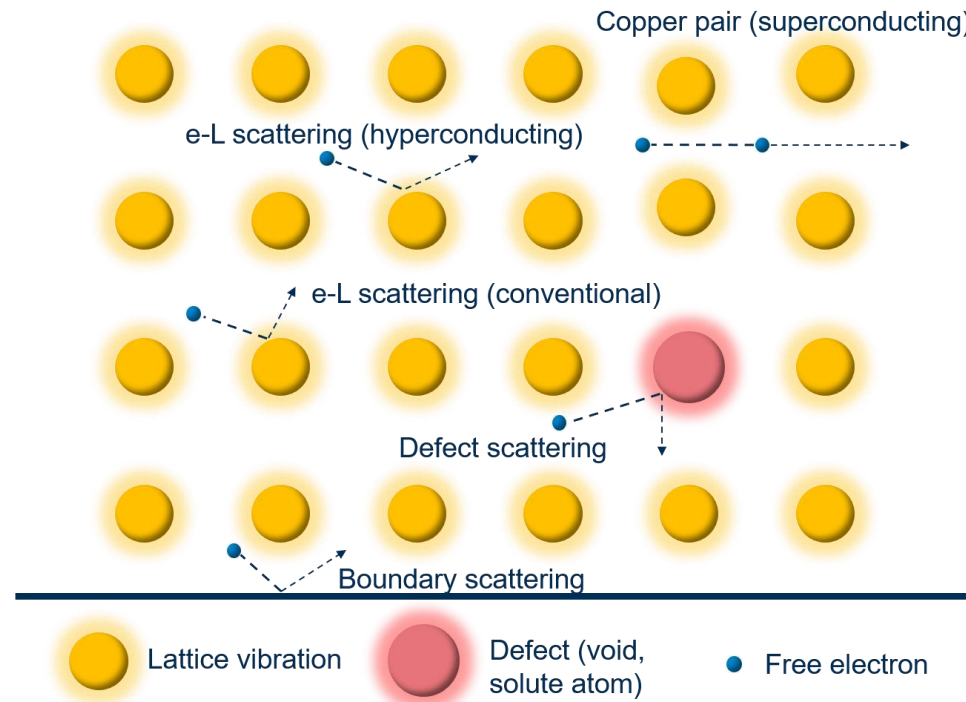
Also geometric requirements (coil diam 2 m)



(S. Ejima et al 1982 Nucl. Fusion 22 1313)

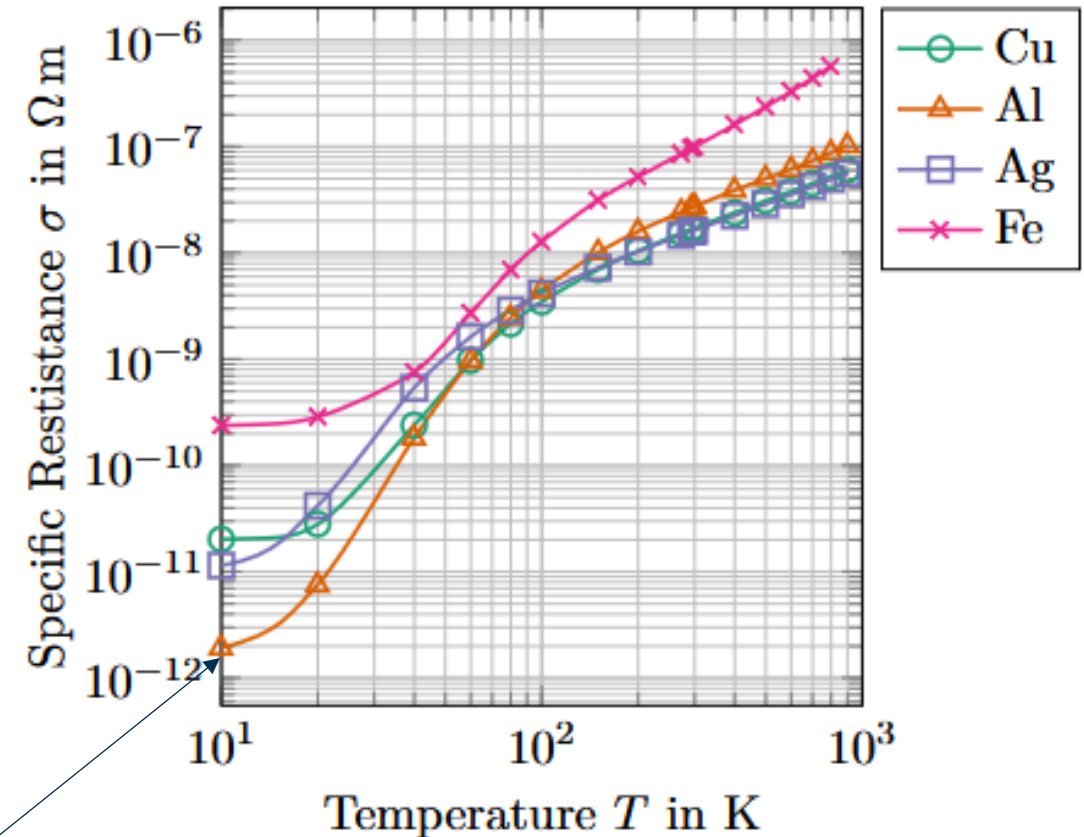
Hyperconductors

The depletion of high energy phonon states available in the lattice with decreasing temperature is reflected in a sharp increase of both electric and thermal conductivity.



Based on Voyiadjis et al. 10.1115/1.4028121

$$RRR = \frac{\rho_{293K}}{\rho_{4.2K}}$$



D. Filusch et al., "Design of a Hyperconducting Synchronous Machine for High-Torque Applications," 2018 XIII International Conference on Electrical Machines (ICEM), doi: 10.1109/ICELMACH.2018.8506697.

Losses in hyperconductors

$$P_T(T) := \int_{0 \cdot s}^{6.3 \cdot s} \left(\underbrace{\rho_{Cu}(T) \cdot \frac{L_{coil}}{A_{cond}(T)}}_{\text{DC losses}} \cdot I(t)^2 + \underbrace{\frac{\pi \cdot L_{coil} \cdot D_{cond}^4}{64 \cdot \rho_{Cu}(T)} \cdot B_{dot}(t)^2}_{\text{Eddy current losses}} \right) dt$$

Skin effect

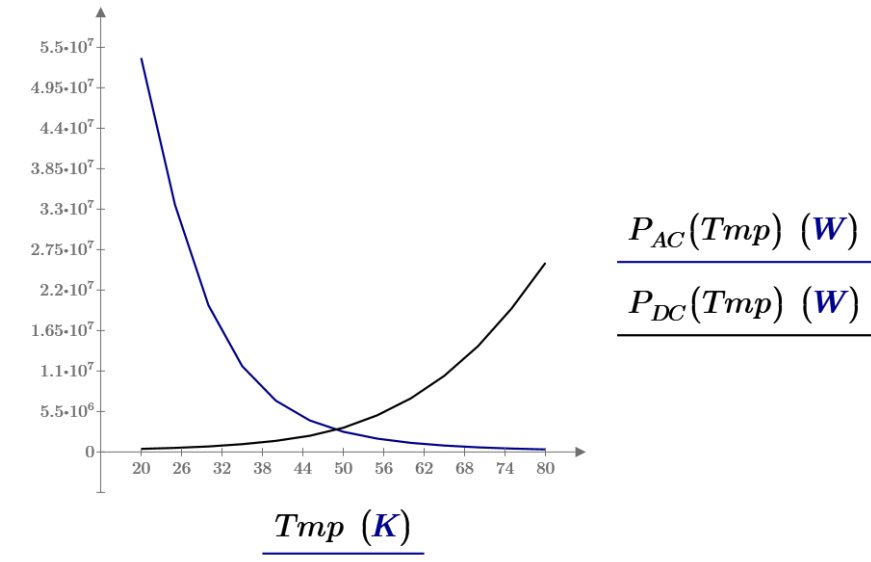
Total losses: DC + Eddy current

- Skin effect, minimised by design
- Eddy current losses, induced by field variation

Resistivity has opposing contributions:

Depending on the temperature DC or Eddy currents will prevail

There is a value of purity of the material (RRR) that minimises the losses



Central Solenoid optimisation

For 15 Vs and that load profile we get:

2 m diam coil

32 mm diam OFHC cable

400 turns

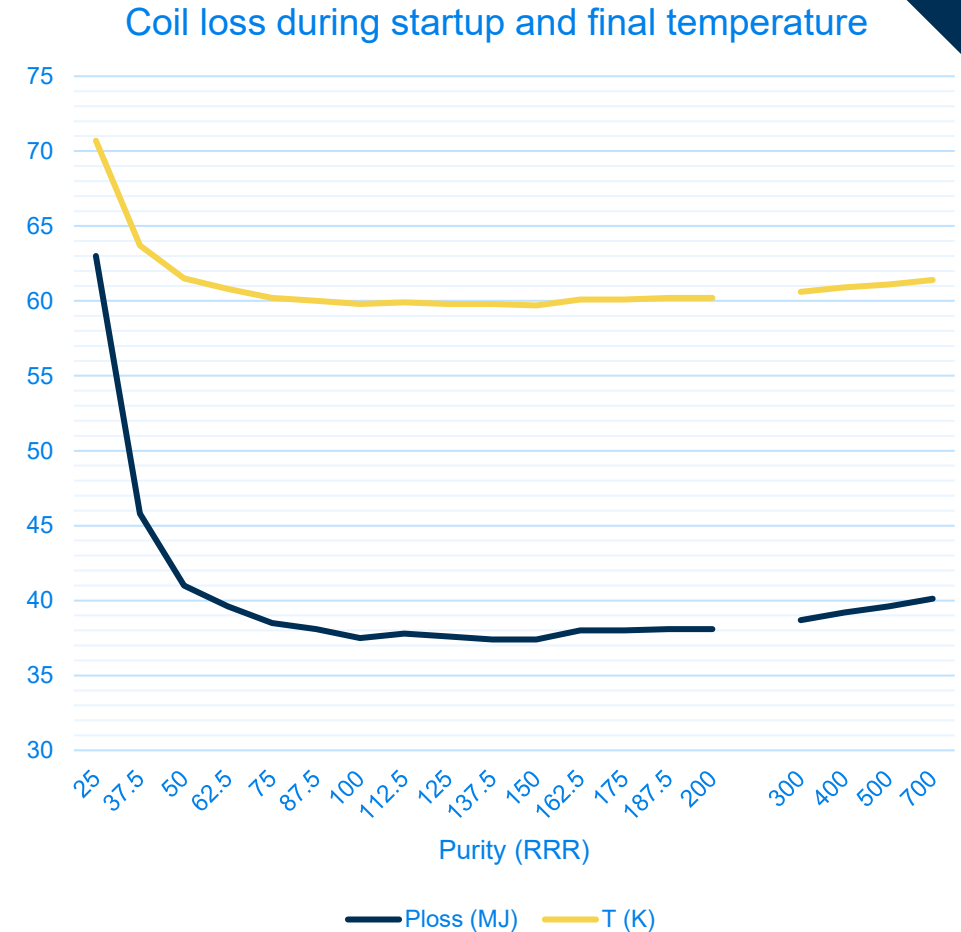
8 m long coil in two layers,

Losses varying with purity according to diagram:

There is little else to gain for RRR > 75

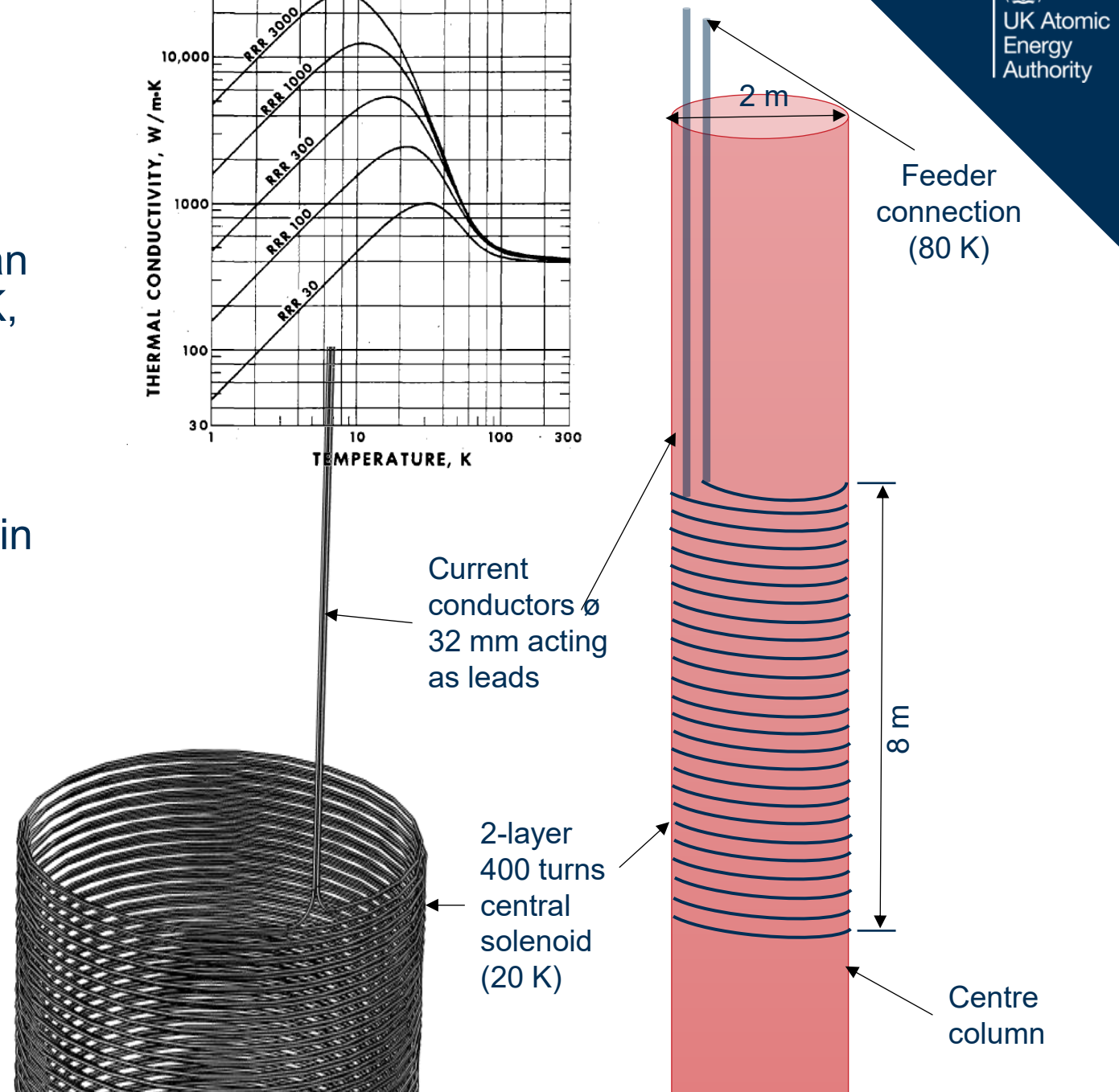
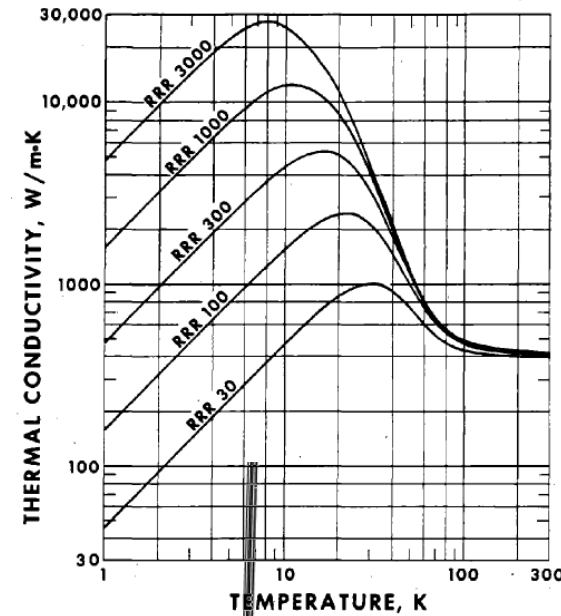
*Higher heat capacity damps the temperature rise
< 77 K*

37.5 MJ losses, around 60 K final temperature



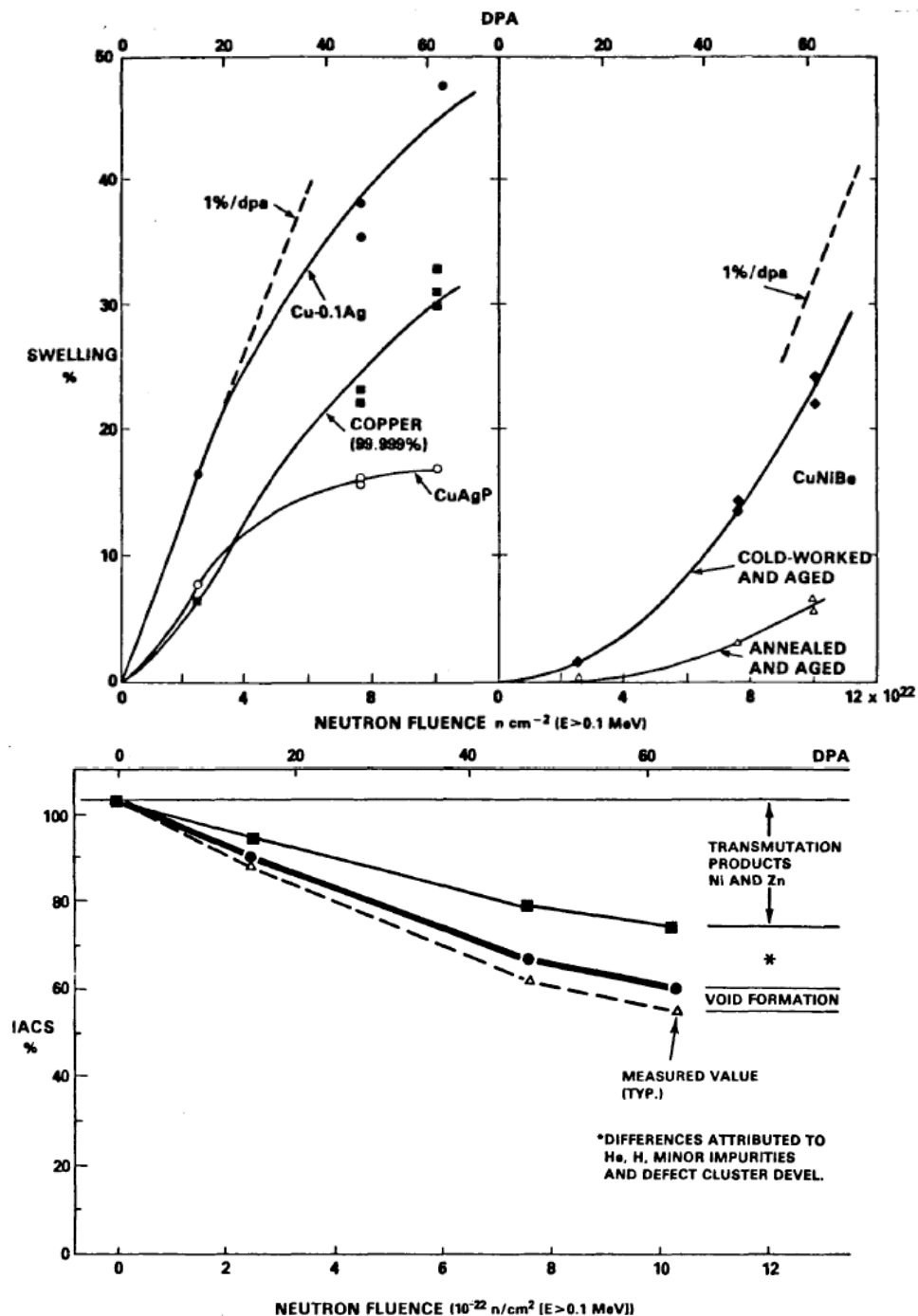
Current leads

- OHFC between 40 K and 80 K has a much reduced thermal conductivity
- The 32 mm diam conductors themselves can act as current leads between 20 K and 80 K, given its length and small diameter
- Around 50 W of heat transfer when not energised
- When operating: eddy current losses lower in current leads -> reduced losses
- 4.3 kW when energised
- No SC or different cable needed as CL between 20 K and 80 K
- No quenching possible in CS
- CL between 80 K and ambient would need different cable



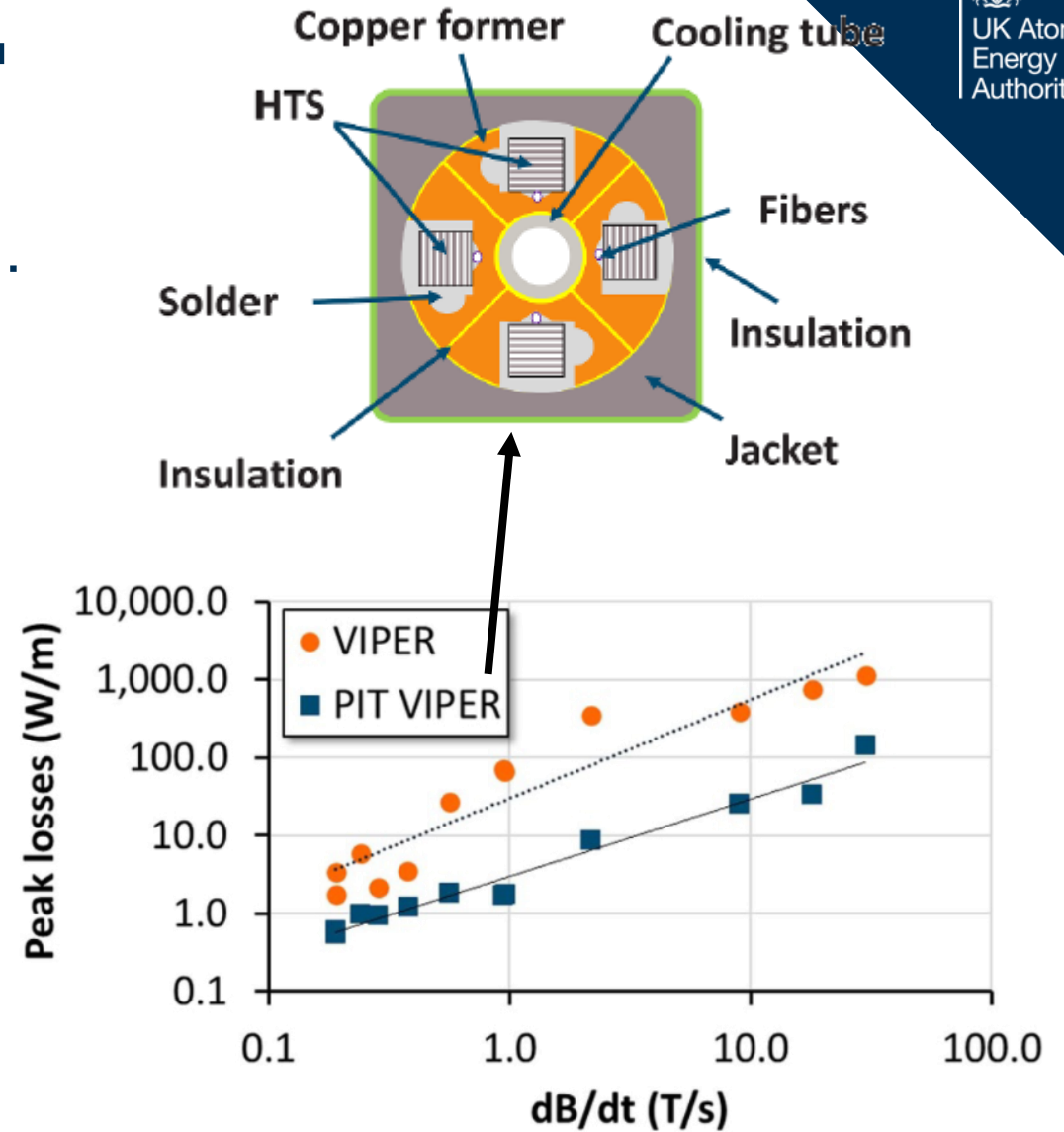
Radiation resistance

- Neutron flux of around $1 \cdot 10^{11}$ /cm²·s
- Copper swelling unimportant at those levels and temperatures
- No loss of conductive properties
- Less lasting radionuclides produced
- Lower RRR Cu value environmentally friendlier



Loss if superconducting...

- HTS cable for CS characteristics published* ...
... although only magnetisation losses
- Bdot already computed
- Integration on the load cycle yields:
1.65 MJ for VIPER cable
0.08 MJ for optimised PIT VIPER
- T final below 30 K < current sharing
- HTS central solenoid allows longer inductive heating



*by Commonwealth Fusion Systems: C. Sanabria et al., "Development of a high current density, high temperature superconducting cable for pulsed magnets," *Supercond. Sci. Technol.*, vol. 37, p. 115010, 2024.

Conclusions

- A hyperconducting central solenoid might be feasible for spherical tokamak
- Need not be very high purity Cu due to AC losses
- Flux level, final temperature correct
- No quenching even under full voltage swing
- Simpler construction: no need of current leads between 20 K and 80 K
- Radiation resistant

But...

- Only half of the voltage cycle utilised
- Losses one or two order of magnitudes higher than SC
- Shorter induction heating stage possible
- Appalling cooling thermodynamic efficiency