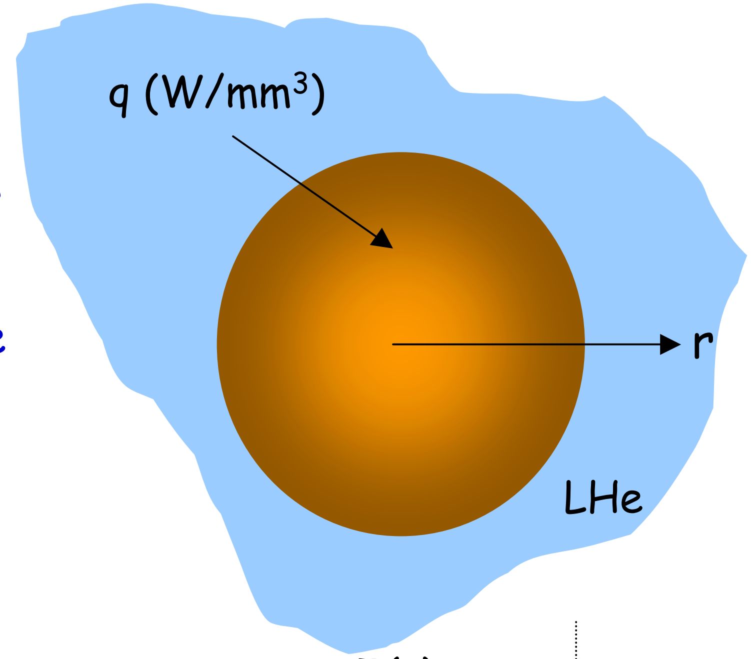
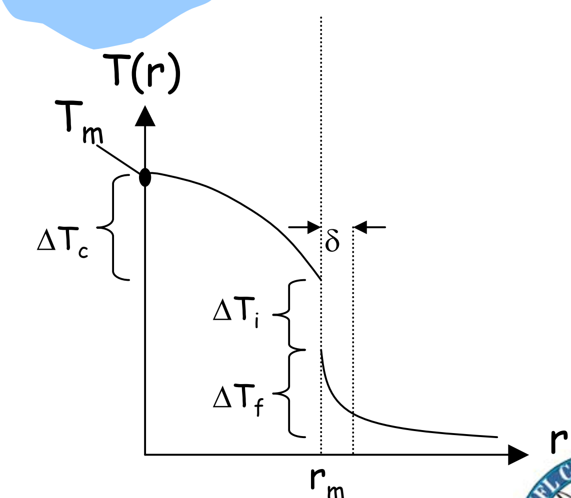
Heat Transfer Issues in Superconducting Magnets

- Radiation heat load causes temperature rise in magnet
  - Reduced J_c margin & stability
  - Magnet may need to incorporate "heat removal system"
- Comparison of He II vs He I cooling technology
- "Idea" for He II in cooling high current density superconducting magnets where normal cooling channels are not acceptable

Simplified Magnet Geometry

- Internal heat generation produces temperature increase in magnet
  - Thermal conductivity of composite magnet
  - Interface between magnet and coolant
  - Thermal boundary layer in LHe
- Comparison of He I vs He II
  - Boundary layer in He II >> He I
  - Interface (Kapitza) resistance larger in He II than He I, f(T)
  - Thermal conductivity increases with temperature, decreases ΔT_c
- What is the difference at T_m?





He I vs He II Comparison

He I

- Heat transport process is a combination of conduction, convection and nucleate boiling
- Peak heat flux [q*(t)]
  - Transient conduction (Schmidt model)
  - Steady convection

He II

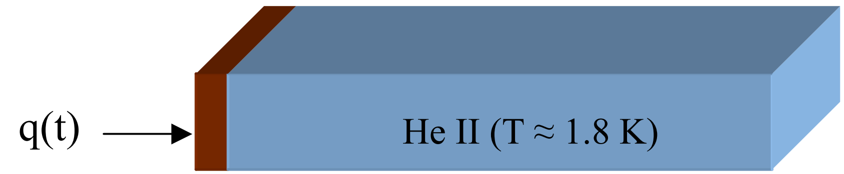
- Heat transport by counterflow provided T < 2.2 K. Otherwise converts to He I
- Peak heat flux associated with He T ~ 2.2 K
  - Transient heat diffusion
  - Steady conduction-like

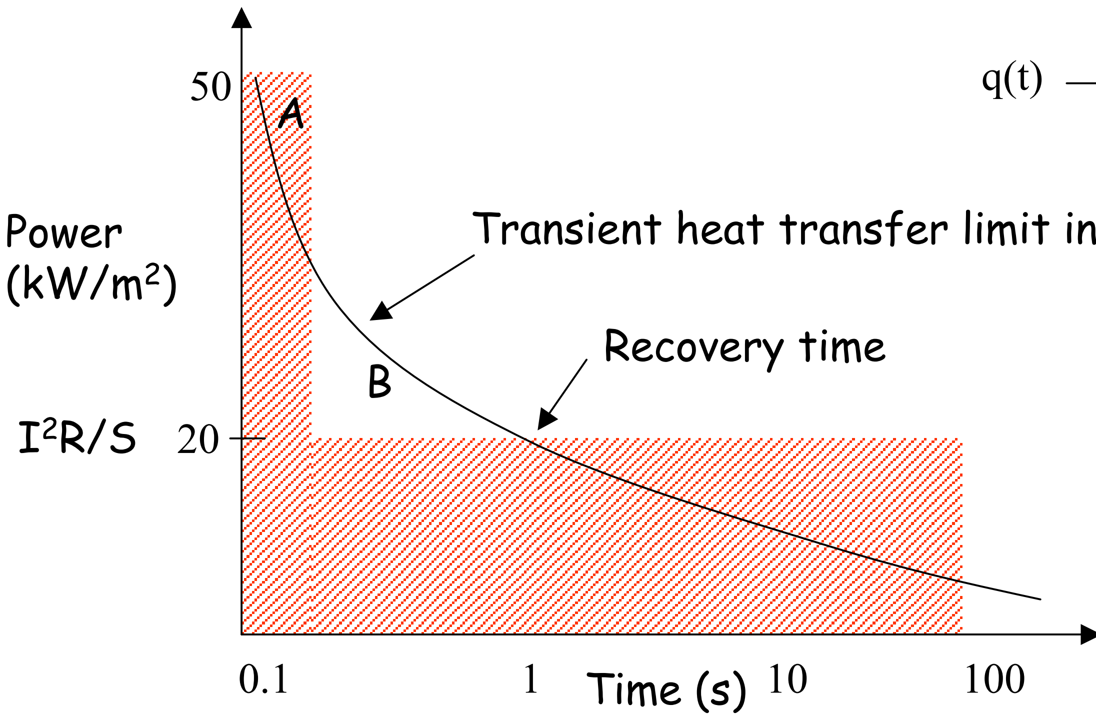
Quasi-Steady Thermal Stability for He II

<u>Stability is achieved by ensuring that:</u>

excess heat generation (area A) < excess heat transfer (area B)

Must recover before t_{max} to avoid quench





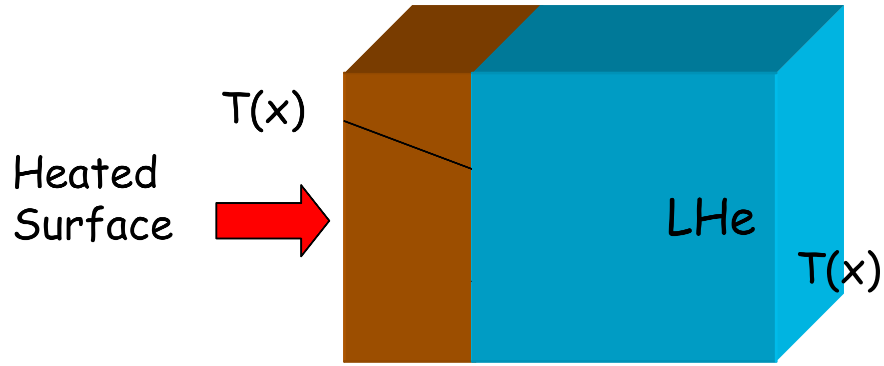
- In He II, conductor is stable against large local disturbance (≈ 10 kJ/m^2)

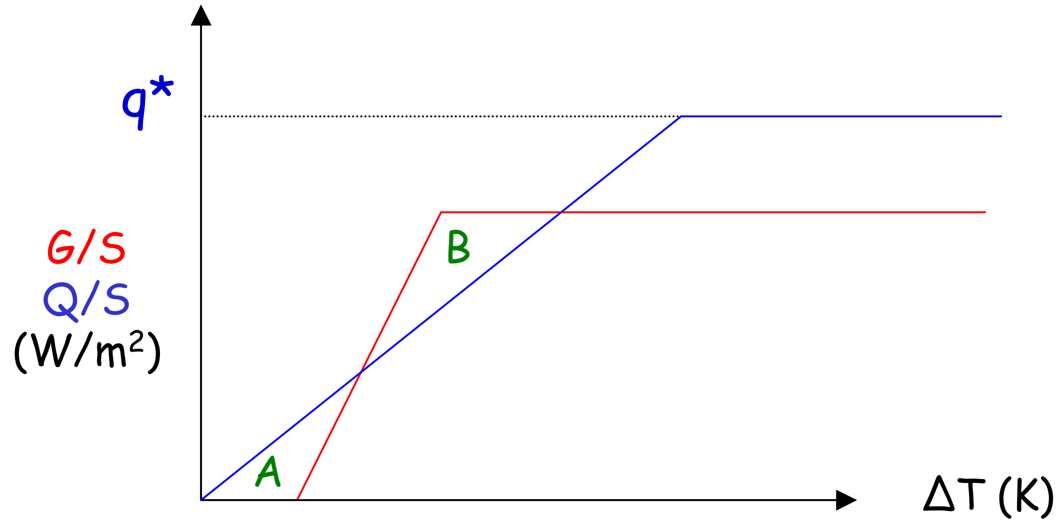
- Joule heating (I^2R) can be larger than in He I (I^2R/S ≈ 20 kW/m^2) if recovery occurs in 1 second

Surface Heat Transfer Coefficient Limit

- Metal-He II heat transfer governed by Kapitza Conductance for $Q/S < q^*$ (Peak heat flux)
- Instability occurs due to finite heat transfer coefficient

  Definition: $h = Q/S\Delta T_s$
- Instability well below critical temperature
- Solution: Provide large conductor surface area to minimize ΔT





Note: This issue supports the use of CICC conductor in 45 T hybrid at NHMFL

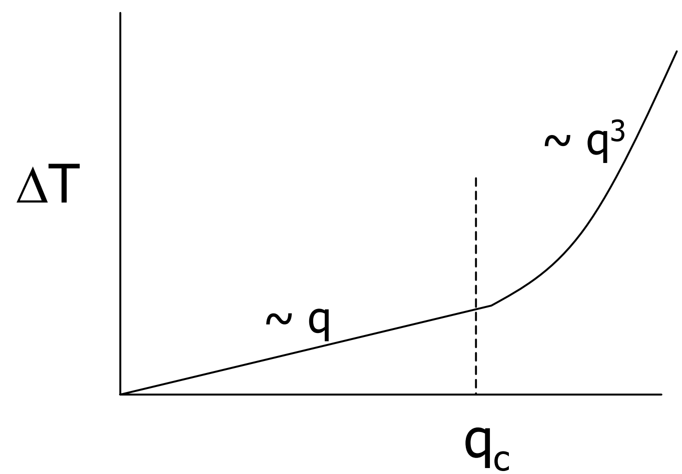
Heat Transport in He II (Revisited)

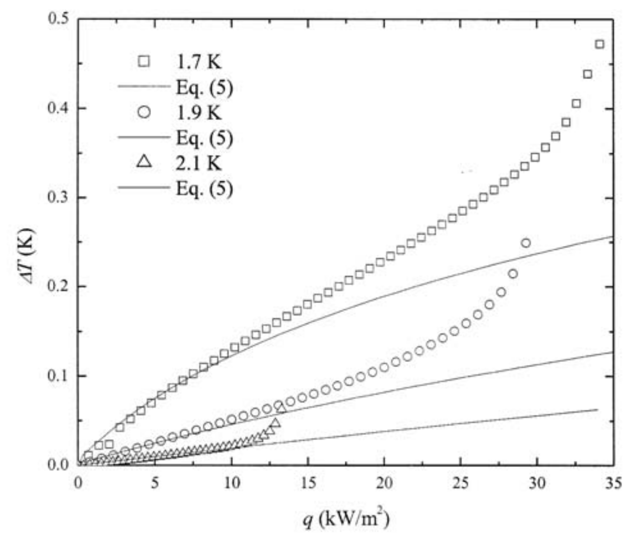
Actual process of heat transport in He II is more complex than presented so far

- In narrow channels, at moderate heat flux, the heat transport is governed by laminar viscous flow

$$q \approx -g(T)\frac{d^2}{\beta}\frac{dT}{dx}$$

- Although most experiments have studied this process in narrow capillaries (d ~ 1 μm), it can also be observed in porous media



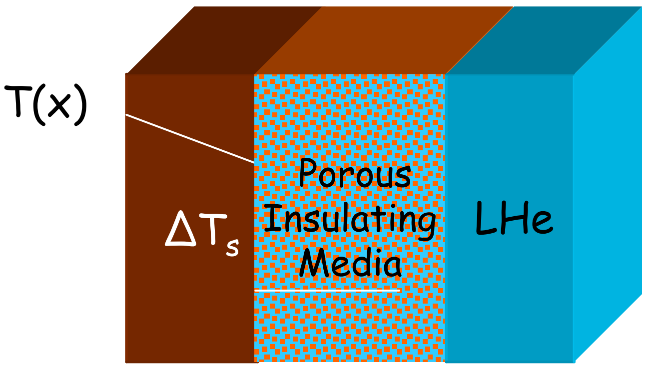


Maekawa & Baudouy, CEC2003

Use of Porous Media (continued)

#2 Put porous media in insulation system for better thermal contact to surrounding He II bath

- Porous insulation can provide good mechanical and electrical stand-off while still allowing heat exchange with the surroundings.
- Nb_3Sn magnet insulation systems may require ceramics, which are suitable for porous media

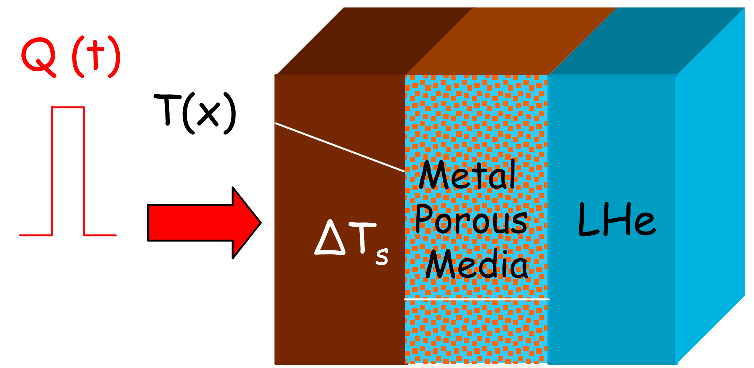


Use of Porous Media in Superconducting Magnets

#1. Put porous metal in contact with conductor (Wilson)

- Heat pulse diffuses through conductor and is transferred to He II/porous media
- Surface temperature difference

  is reduced because the cooled area (S) is much larger, $\Delta T_K = Q/h_K S$
- Take-off power is equivalent to energy to raise He II contained in the porous media to T_λ = 2.2 K



Downsides:

1. Porous material can reduce $J_{overall}$
2. Making good thermal contact is a challenge