Thermosiphon Cooling
For the ANL Undulator Magnet

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Topics

- Thermosiphons
  - Review: flow generation
- Two phase flow
  - Filippov map – low quality limit
  - Calculations
    - flow regime
    - Heat transfer and ΔT
- Observations

Argonne National Lab Undulator

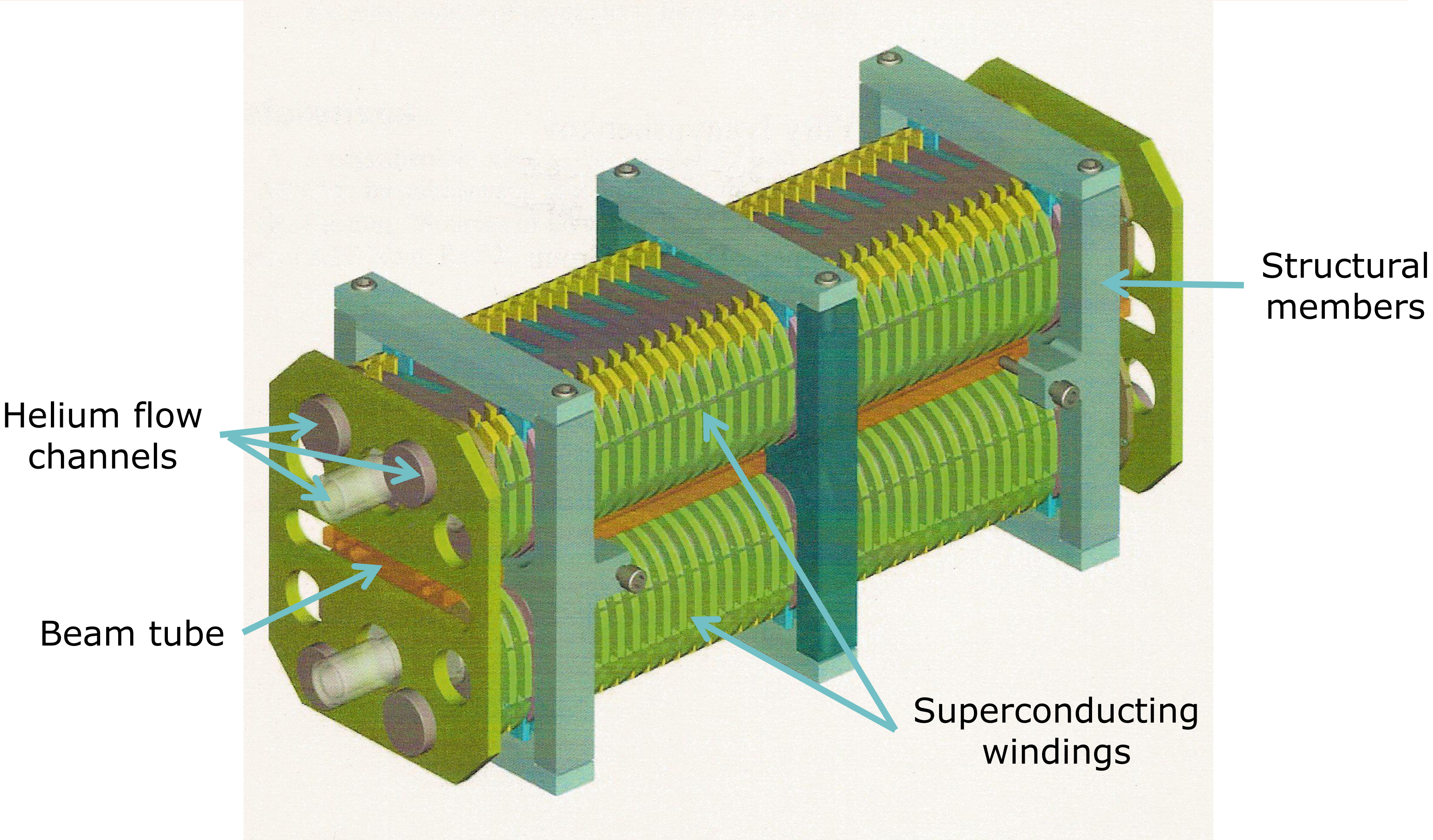


Figure 1. SCU cold mass layout.

Objective: maintain SCU as close as possible to 4.2 K

Proposed cooling system

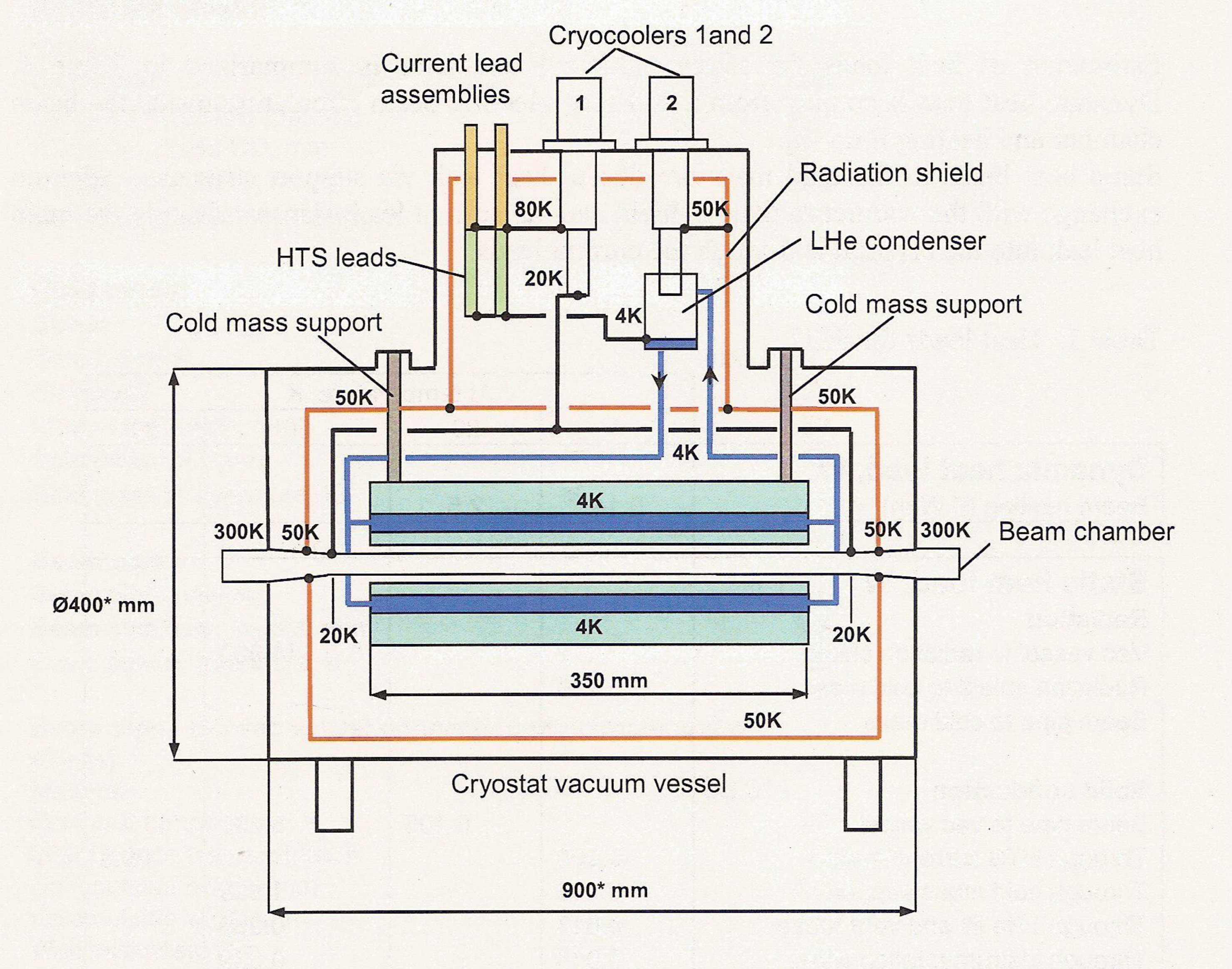
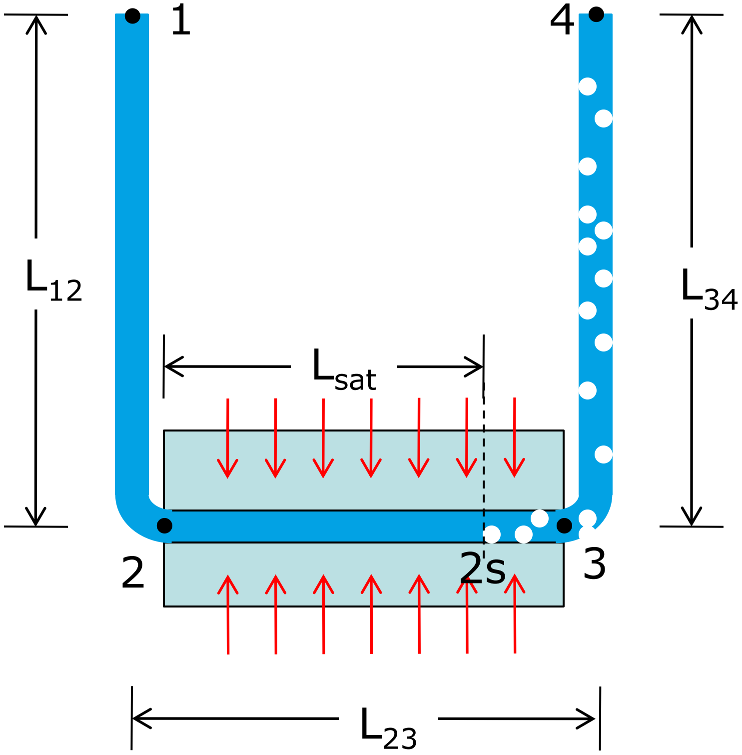


Figure 2. A possible SCU cryostat layout with cooling scheme circuits.

Thermosiphon basics

- Mass flow driven by hydrostatic head differential

$$\Delta P_h = g(\rho_{12} - \rho_{34})L_{12}$$



- Force balance determines mass flow rate $\Delta P_h = \Delta P_f + \Delta P_a$

$$\Delta P_f = \Delta P_{fI} + \Delta P_{fII} + \Delta P_{fIII}$$

$$\Delta P_{fI} = f\frac{\dot{m}^2 L_{12}}{2\rho_l A^2 D_h}; \quad \Delta P_{fII} = f\frac{\dot{m}^2 L_{34}}{2\rho_l A^2 D_h}\Phi_{2p}\left(X_{L_{34}}\right)$$

$$\Delta P_{fIII} = f\frac{\dot{m}^2 L_{23}}{2\rho_l A^2 D_h}\frac{1}{(X_3 - X_2)}\int_{X_2}^{X_3}\Phi_{2p}(X)dX; \qquad \Delta P_a = \frac{\dot{m}^2}{A^2}\left(\frac{1}{\rho_v} - \frac{1}{\rho_l}\right)X_3$$

LHe Thermosiphon

- Quality along L_{23}:
  - Subcooled from state 2 to L_{sat}
  - State 2:

$$P_2 = P_1 + \rho_{12} g L_{12} - \Delta P_{f1}$$

  - At L_{sat}:

$$P_{2s} = P_2 - \Delta P_{2-2s}$$

$$L_{sat} = \frac{q_{subcool}}{q}$$

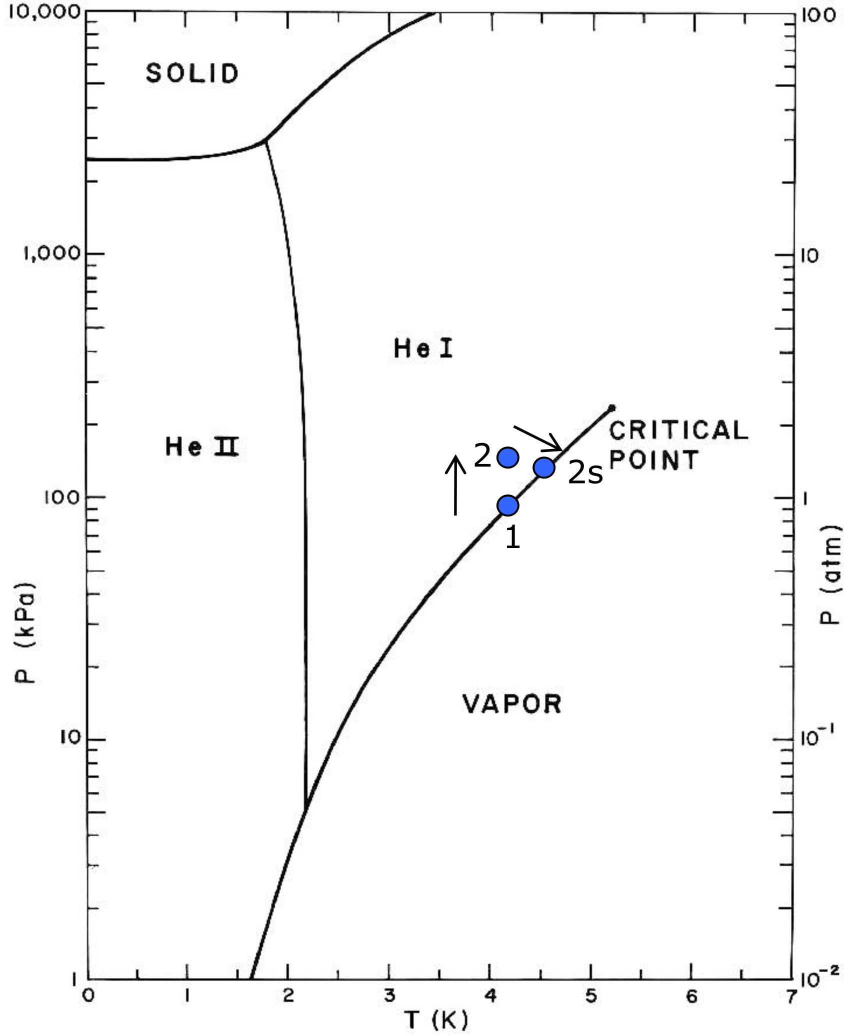
$$q_{subcool} = \dot{m}\left(h_{2s} - h_2\right)$$

$$h_{2s} : P_{2s}, x = 0; \quad h_2 : T_1, P_2$$

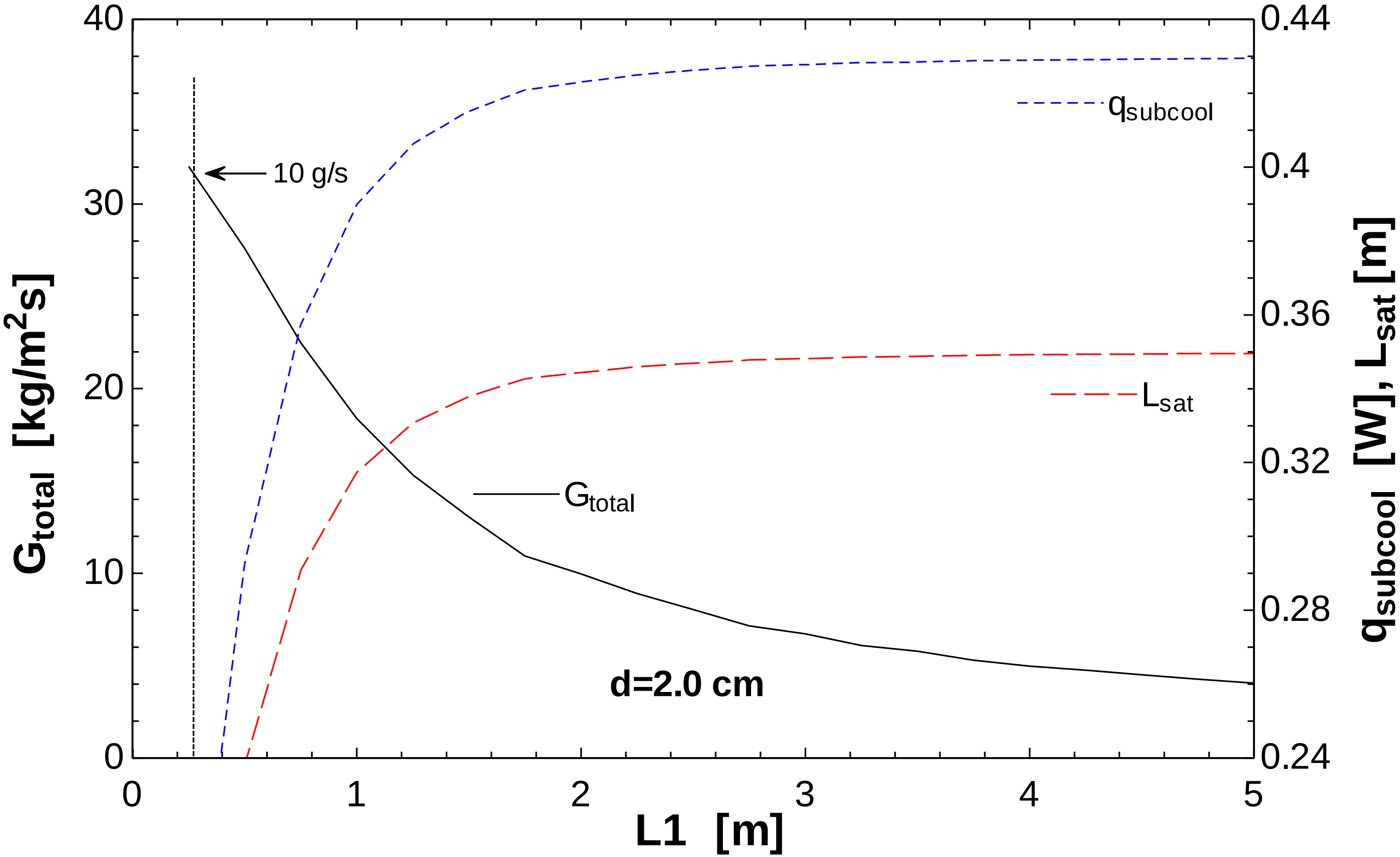
  - State 3:

$$\dot{m}_v = \frac{q - q_{subcool}}{h_{fg}}$$

$$X_3 = \frac{\dot{m}_v}{\dot{m}}$$

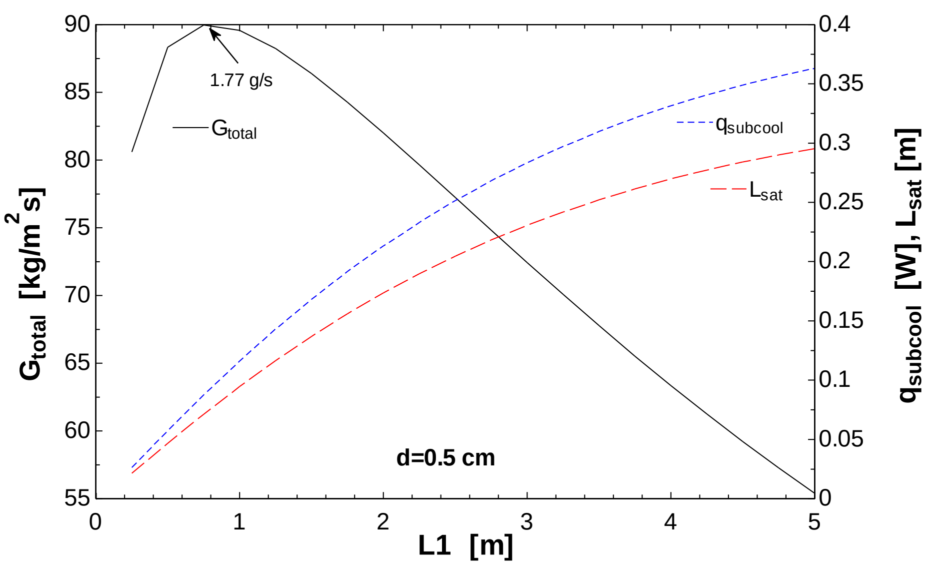


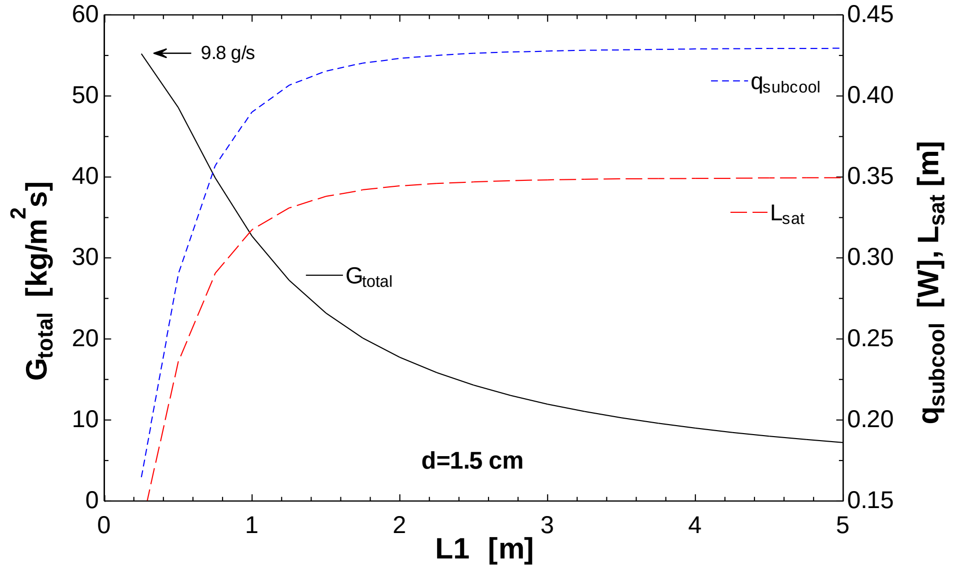
Thermosiphon: LHe mass flux

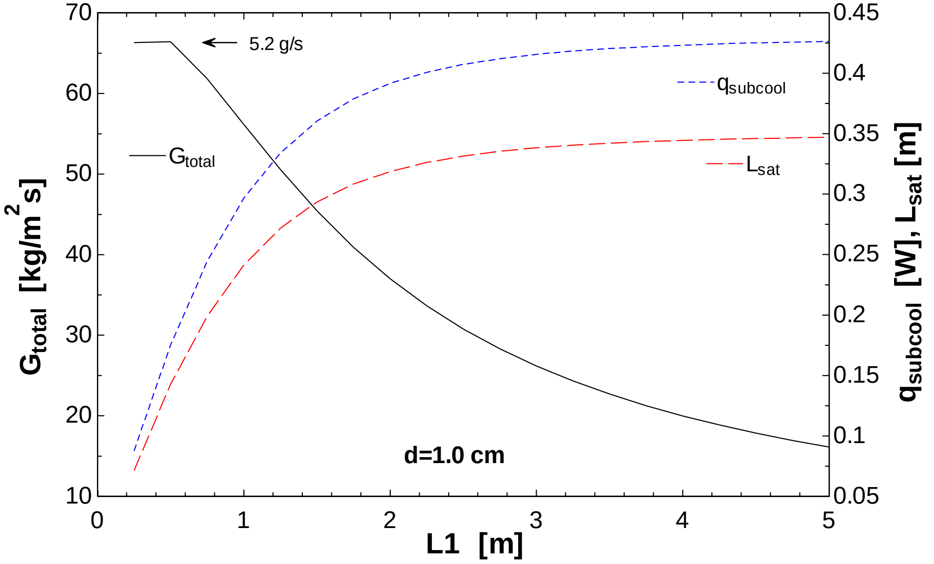


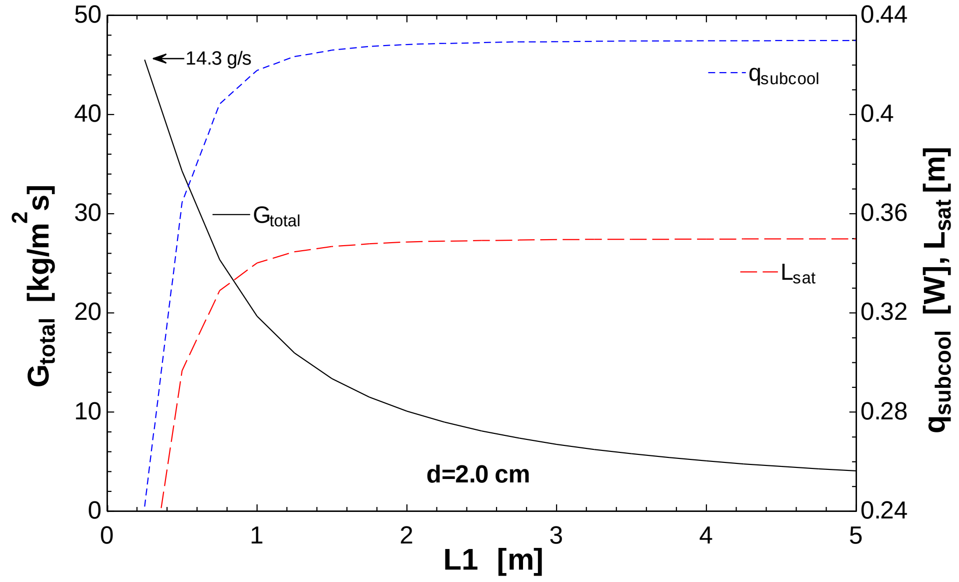
0.43 W over 0.35 m

Thermosiphon: LHe mass flux



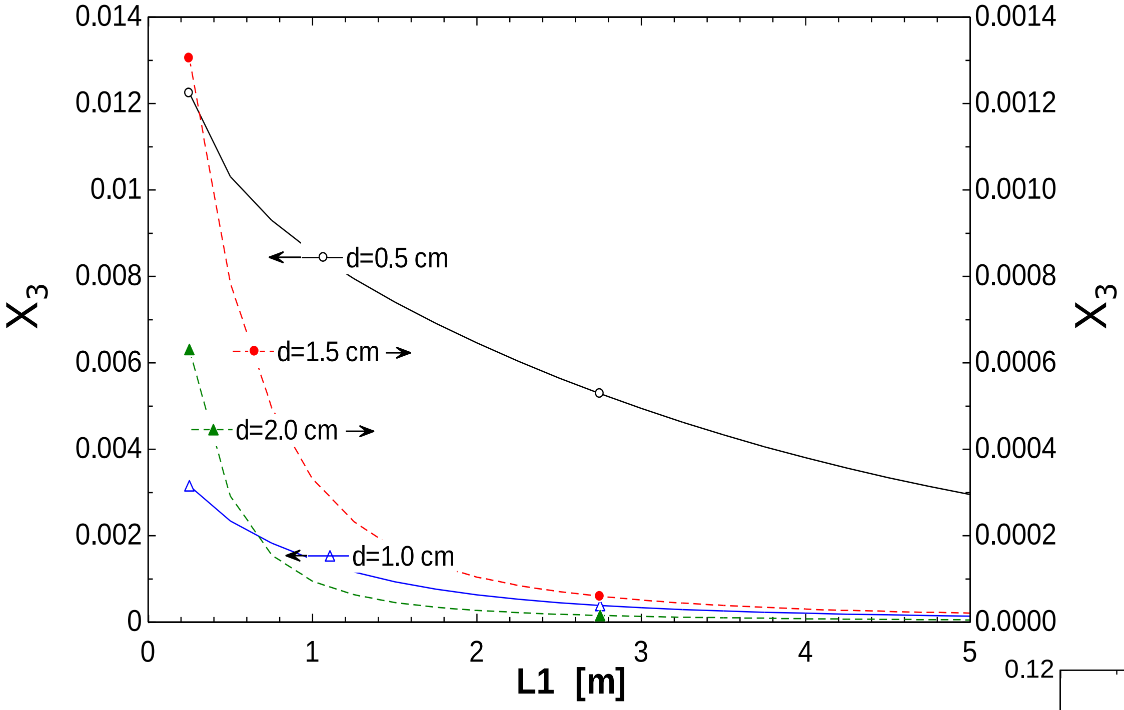






- Subcooling at state 2 diminishes generated mass flux

Thermosiphon: X_3 in undulator



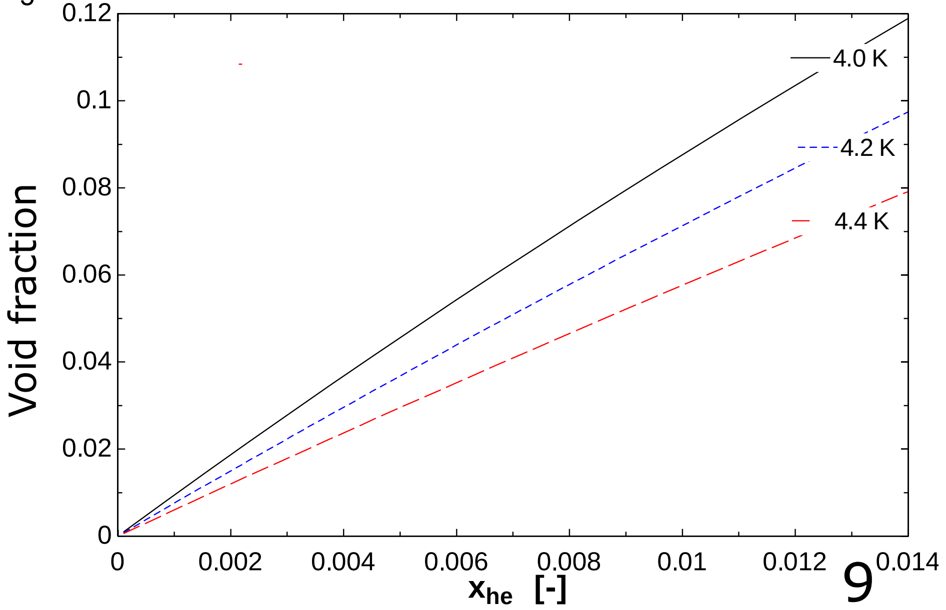
X : quality

α : void fraction

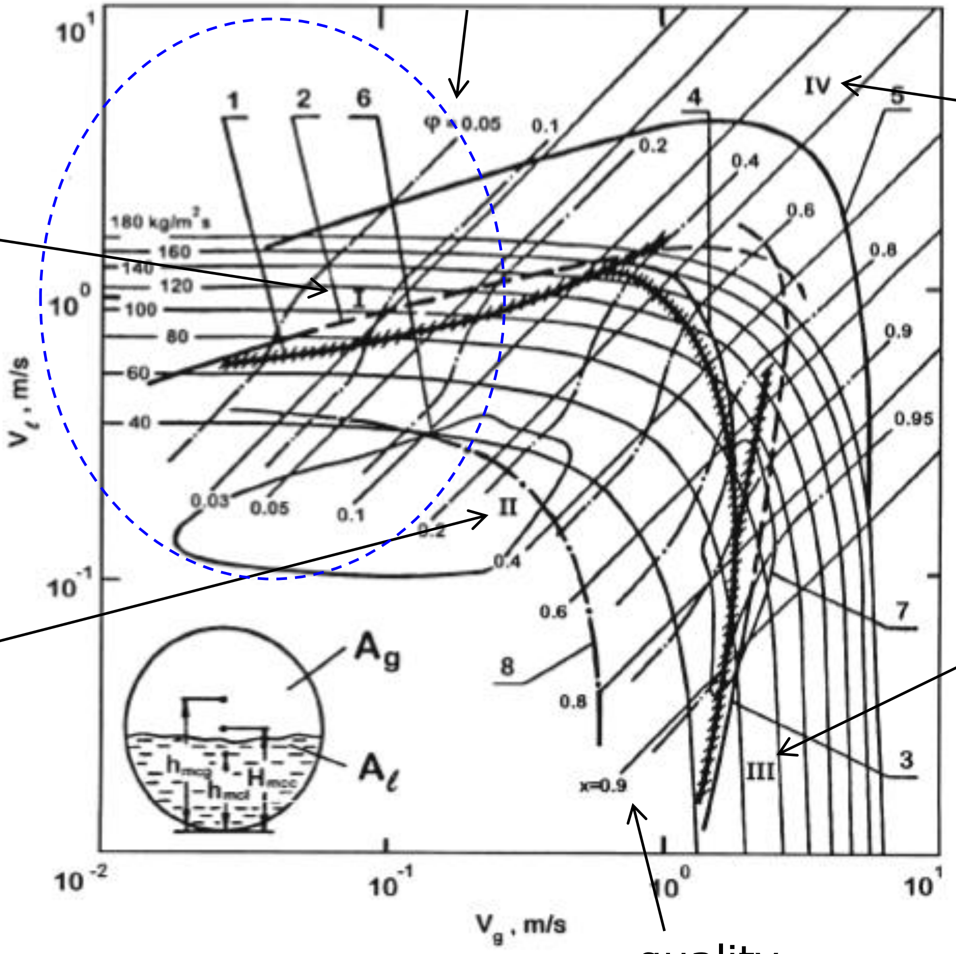
$$X = \frac{\alpha \rho_v}{(1-\alpha)\rho_l + \alpha \rho_v}$$

$$\alpha = \frac{x \rho_l}{(1-x)\rho_v + x \rho_l}$$

- Low heat flux, combined with subcooling effect produces very low quality at magnet outlet



Filippov helium map



Void fraction

I. Bubble

II. Stratified

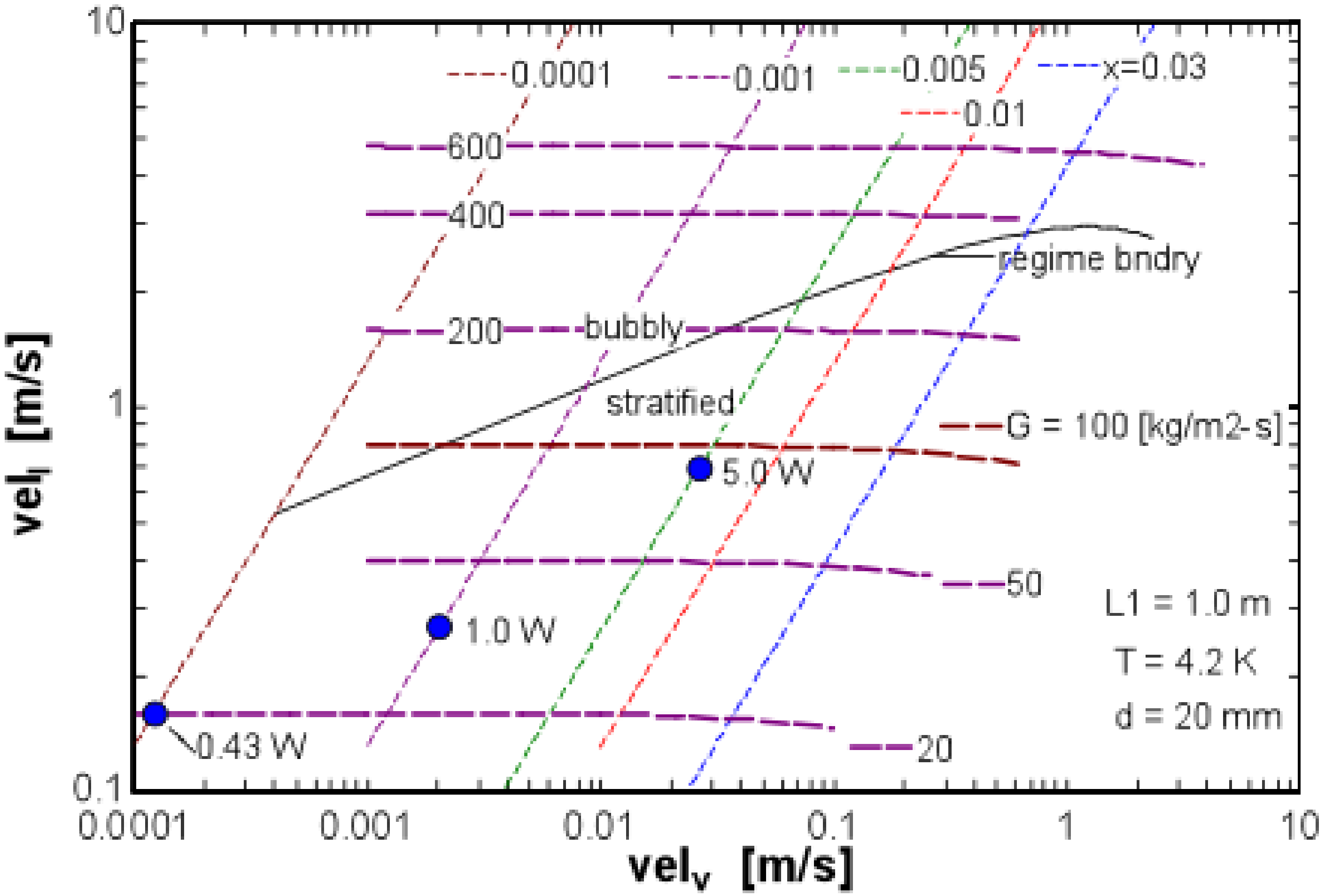
IV. Mist

III. Dispersed

quality

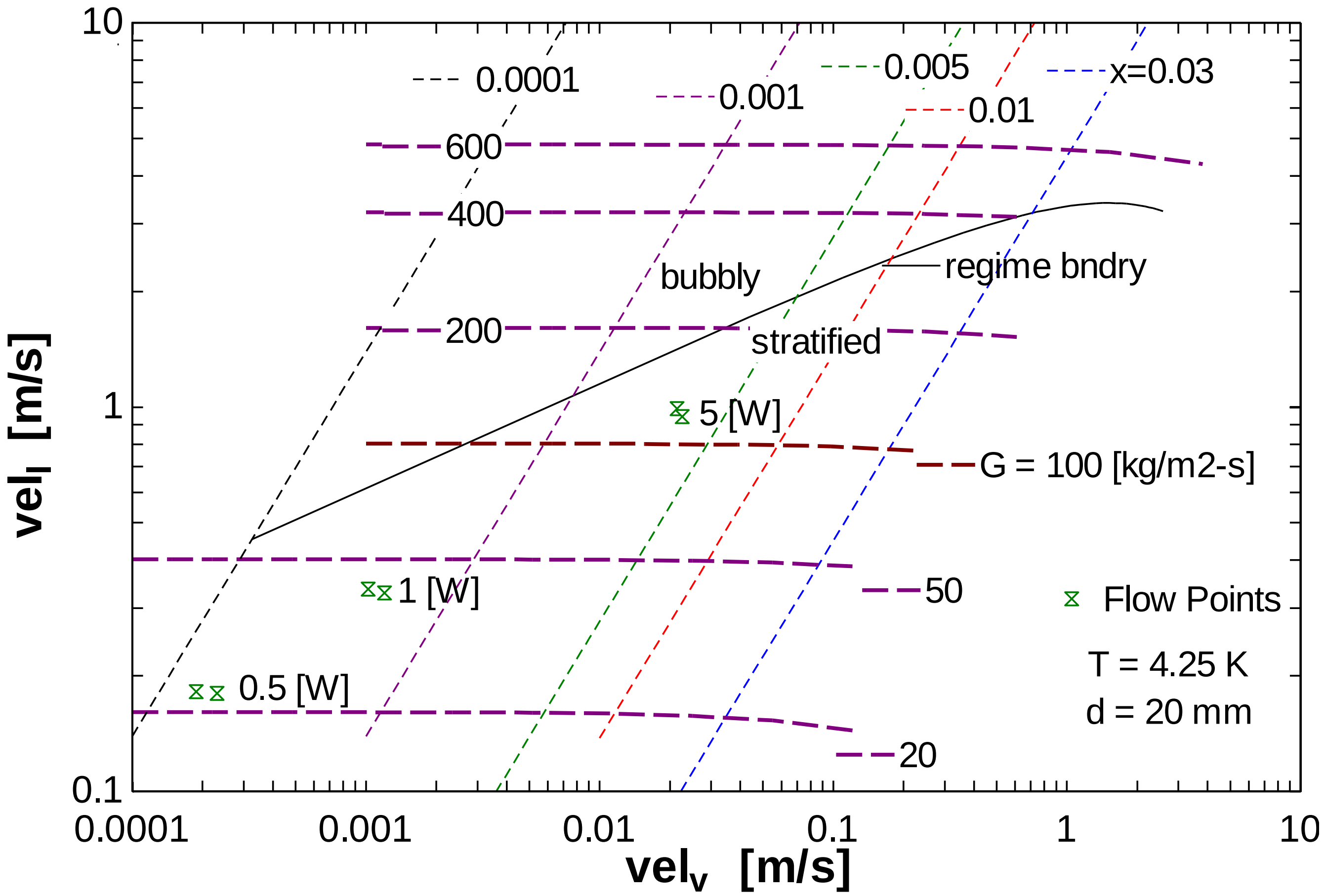
Tube size = 7.9 mm, P = 140 kPa

Filippov map: d = 20 mm



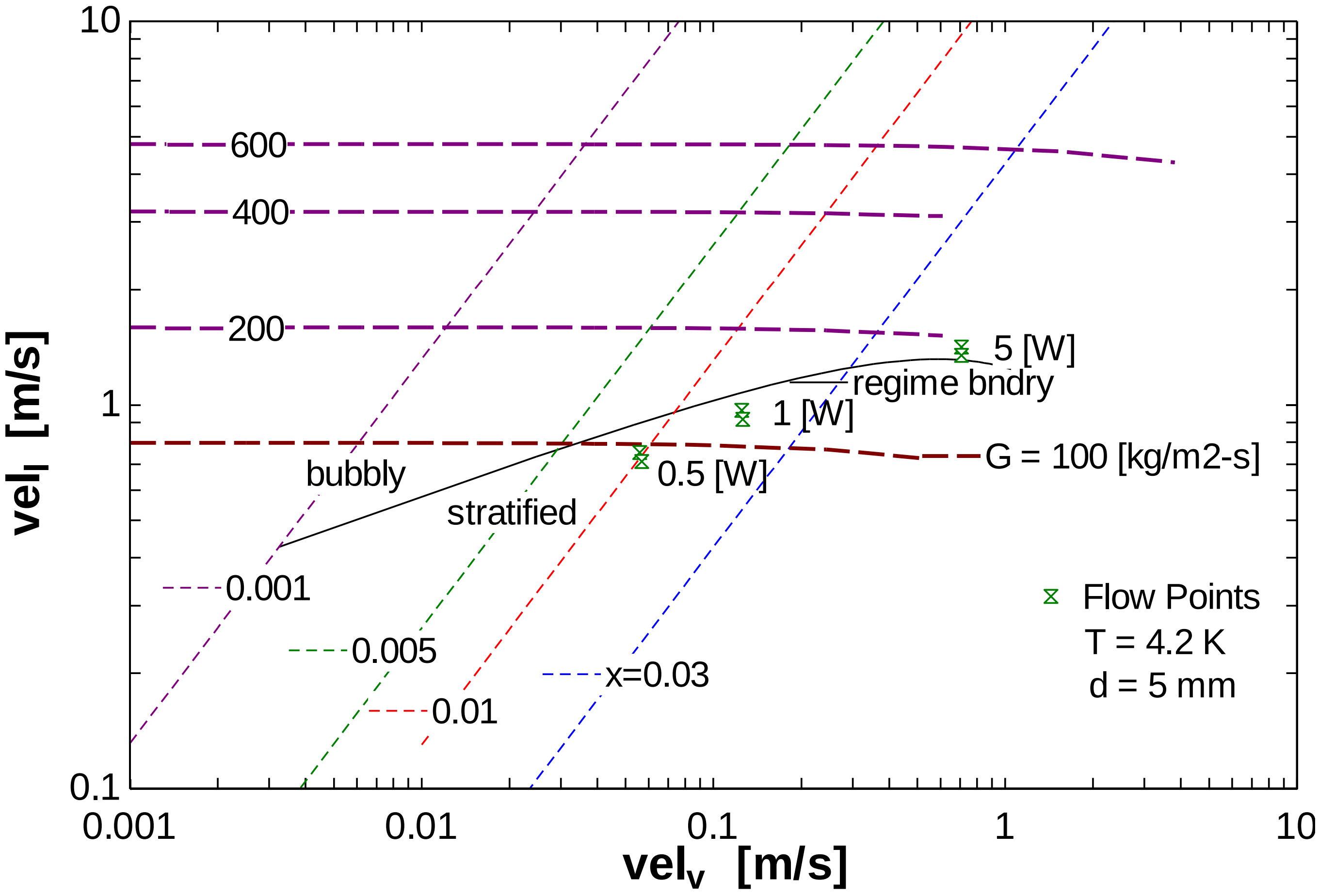
- All reasonable heat loads produce <u>stratified</u> flow
- How large are the associated ΔT's?

Filippov map: d=20 mm



- Anticipated temperature rise at saturation location within the magnet produces very little change relative to 4.2 K calculation
- Two adjacent flow points represent 0.35m and 0.7m heated lengths: no appreciable difference

Filippov map: d=5mm

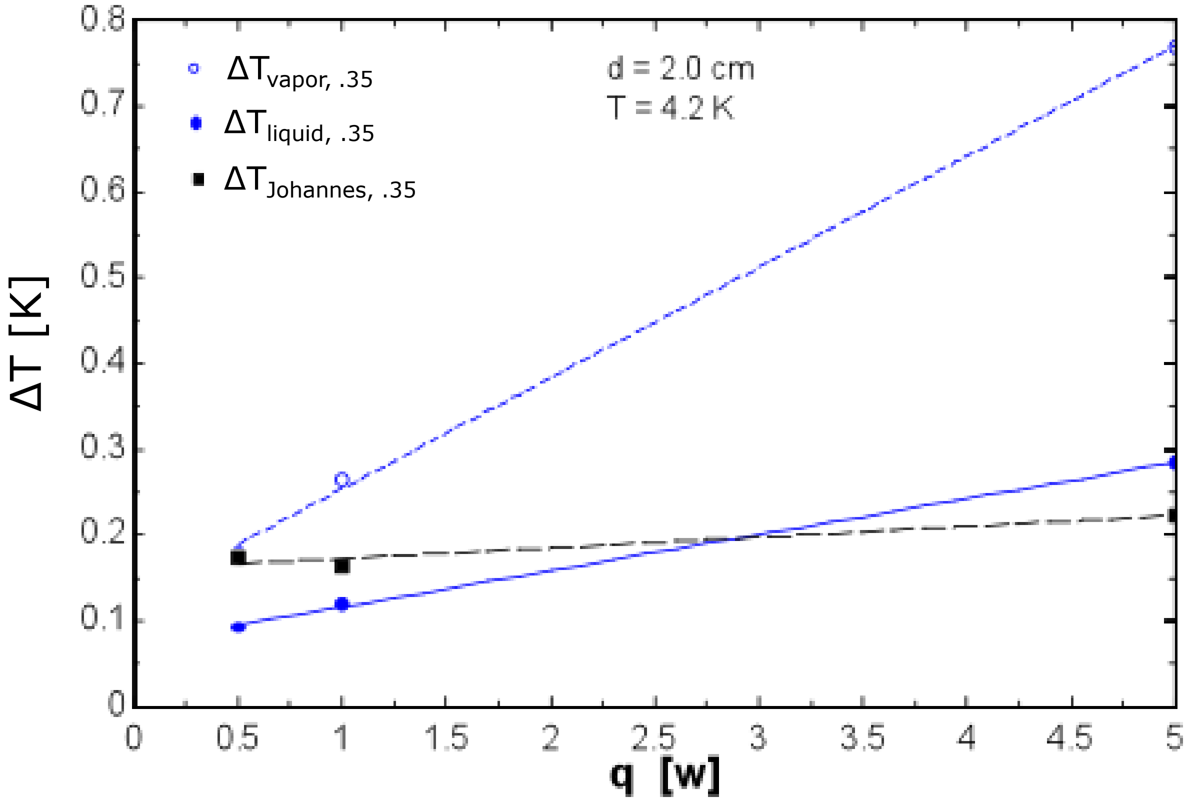


- 5 mm diameter cooling tubes result in <u>near</u>-bubbly flow
- Higher quality and mass flux, although lower mass flow rates

Heat transfer calculations

- Dittus-Boelter correlation: single phase, fully developed
  - Nusselt number: $Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$
  - Heat transfer coefficient: $h = \dfrac{k \cdot Nu}{d}$
  - Temperature difference through boundary layer: $\Delta T = \dfrac{q''}{h}$
- Two phase forced (vertical) convection: C. Johannes (1970)
  - Calculated Nusselt number: $Nu_{calc} = 0.023\left[\dfrac{DG(1-x)}{\mu_l}\right]^{0.8} \mathrm{Pr}^{0.4}; \quad G = \dfrac{\dot{m}_{total}}{A_{total}}?$
  - Experimental Nusselt number: $Nu_{\exp} = 5.4\,Nu_{calc} X_{tt}^{-0.385}$
  - Martinelli parameter: $X_{tt} = \left(\dfrac{1-x}{x}\right)^{0.9}\left(\dfrac{\rho_v}{\rho_l}\right)^{0.5}\left(\dfrac{\mu_l}{\mu_v}\right)^{0.1}$

2-phase heat transfer: d=20 mm



q	q_flux	X	G	h_{l3}	ΔT_{l3}	h_{v3}	ΔT_{v3}	h_{J3}	ΔT_{J3}
[W]	[W/m²]	-	[kg/m²K]	[W/m²K]	[K]	[W/m²K]	[K]	[W/m²K]	[K]
0.5	22.74	0.00042	20.86	248.4	0.092	127	0.18	131	0.17
1.0	45.47	0.00011	35.46	379	0.12	172	0.27	277	0.16
5.0	227	0.0055	88.97	800	0.28	295	0.77	1017	0.22

Observations

- Maintain overall heat load to magnet below 2 watts
- Low heat load required by cryocooler performance produces extremely low vapor quality
  - Add heater to vertical return section
  - Introduce vapor into vertical return section
- Smaller cooling channels reduce total mass flow, but provide more even cross-sectional temperature profile (at no loss of cooling power)