Time-dependent Cryogenic Models of the TUCAN Source

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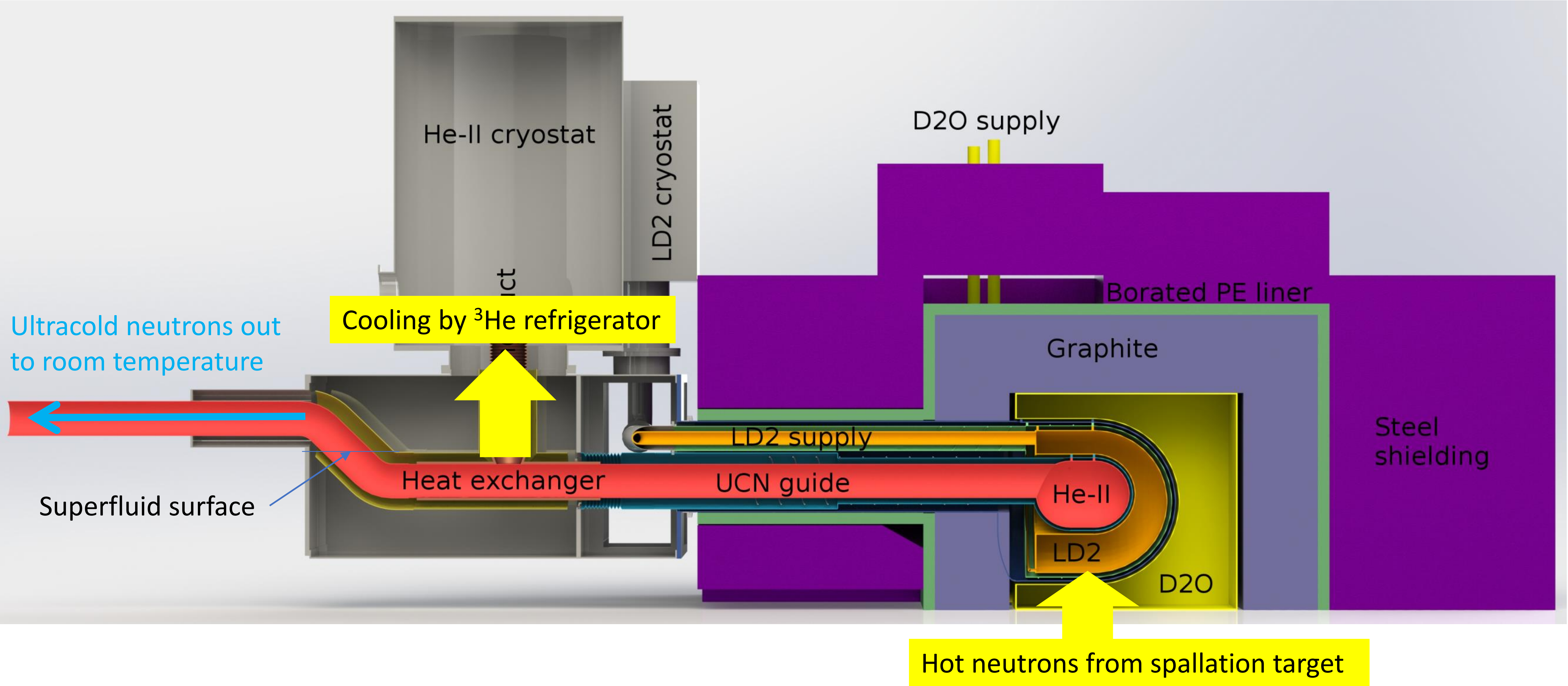
For the TUCAN collaboration

February 5, 2021

Structure of the TUCAN source (the "horizontal source")



Ultracold neutrons out to room temperature

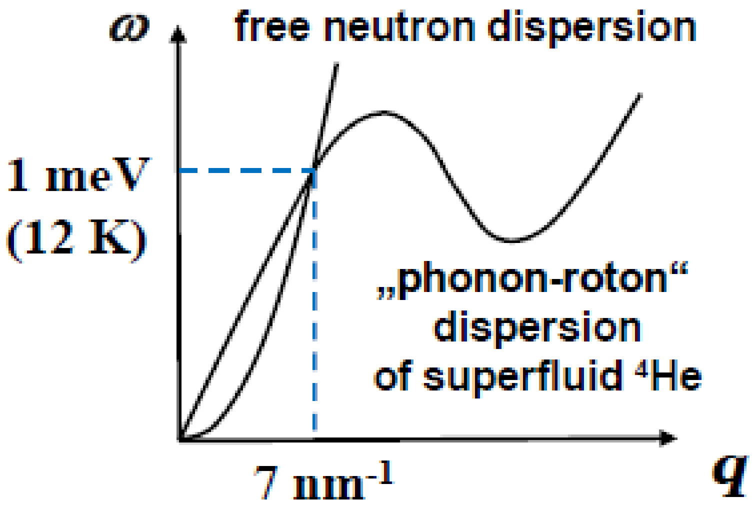
Cooling by ^{3}He refrigerator

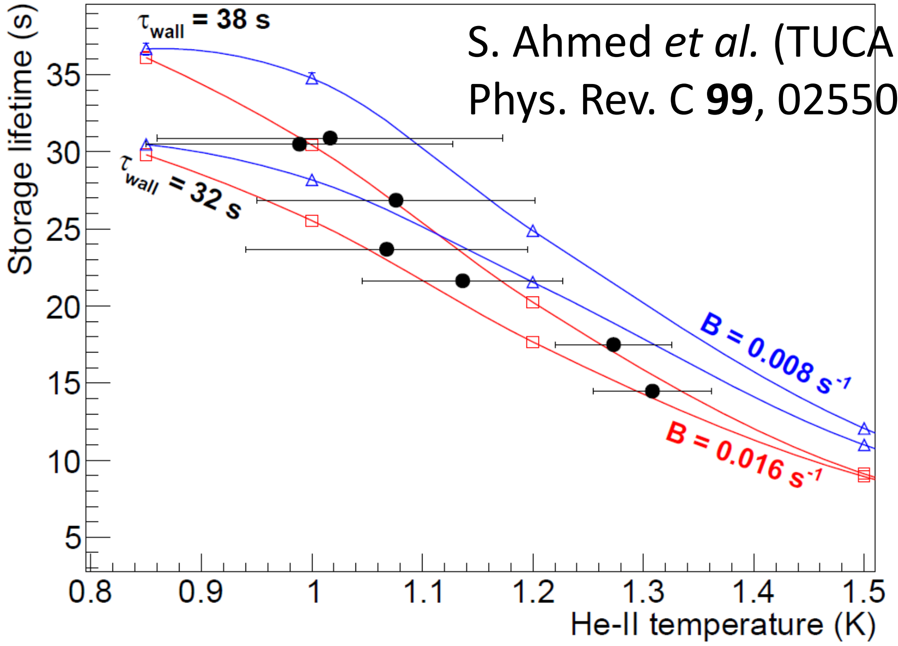
Superfluid surface

Hot neutrons from spallation target

- Key issues:
  - Making as many 1 meV neutrons as possible. These neutrons have a large cross-section to downscatter to zero energy in superfluid helium.
  - Keeping the superfluid helium as cold as possible (losses ~ BT^7)

- Solutions:
  - Liquid deuterium cold moderator
  - High power helium-3 refrigerator directly coupled to the UCN production volume through UCN-compatible HEX, long horizontal channel of He-II.





S. Ahmed *et al.* (TUCAN Collaboration)
Phys. Rev. C **99**, 025503 (2019)

This presentation

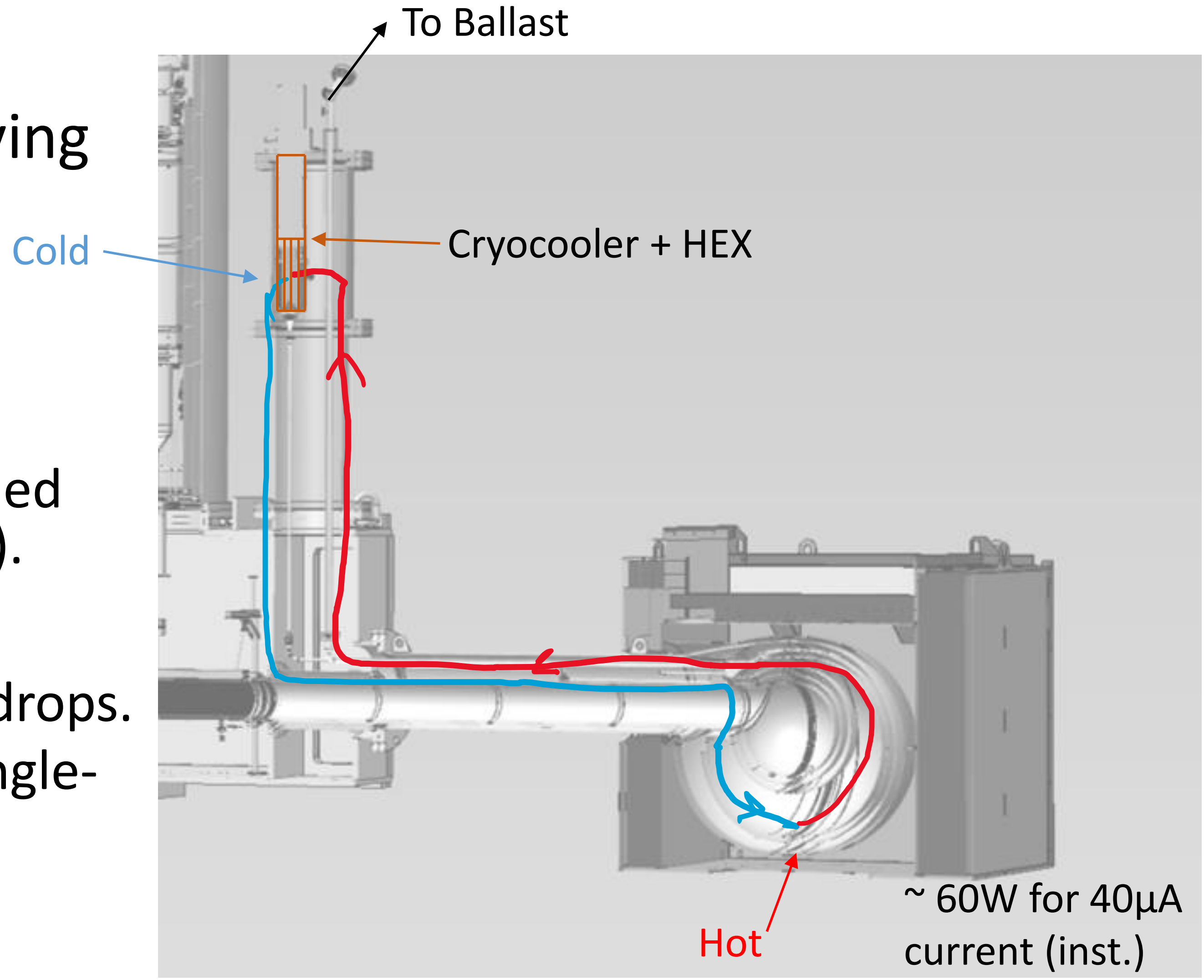
- Two time-dependent 1D models of thermodynamic performance of two different parts of our UCN source:

  1. A liquid deuterium thermosyphon, delivering 60 W of cooling power (15 W time-averaged) to the LD2 cold neutron moderator.

  2. Heat transport through He-II in our prototype “vertical” source, and how this will be different after our upgrade to the “horizontal” source.

LD_2 thermosyphon (natural circulation system)

- Features: single-phase, no moving parts
- Studies by Kiera A.:
  - 1D time-dependent model of circulation.
  - HEX studies (fins vs. multi-threaded helix, heat xfer vs. pressure drop).
- Studies by Shawn S.:
  - Detailed accounting of pressure drops.
  - HEX study (1D correlations) of single-helix geometry



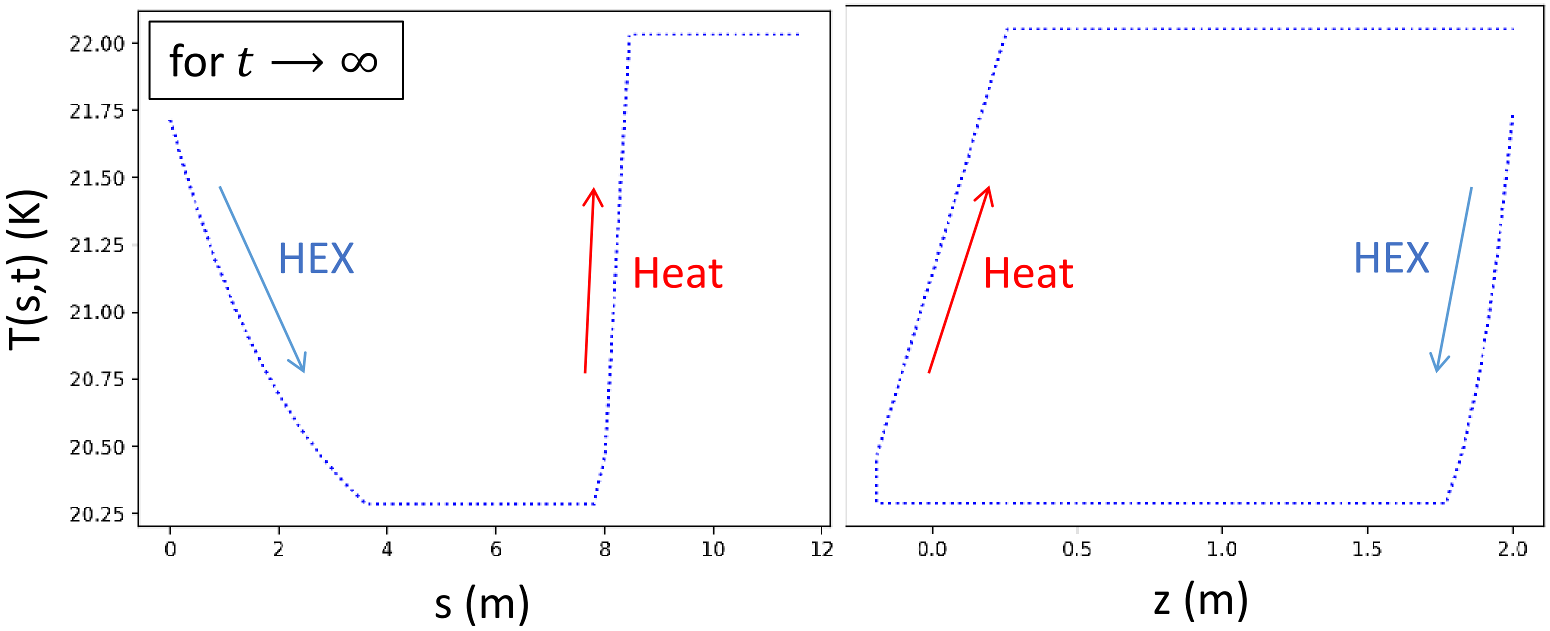
~ 60W for 40μA current (inst.)

Based on: Vijayan, Nayak, and Kumar, “Single-Phase, Two-Phase and Supercritical Natural Circulation Systems”

1D time-dependent model of circulation

- Solve for
  - mass flow rate w(t), and
  - temperature distribution T(s,t)

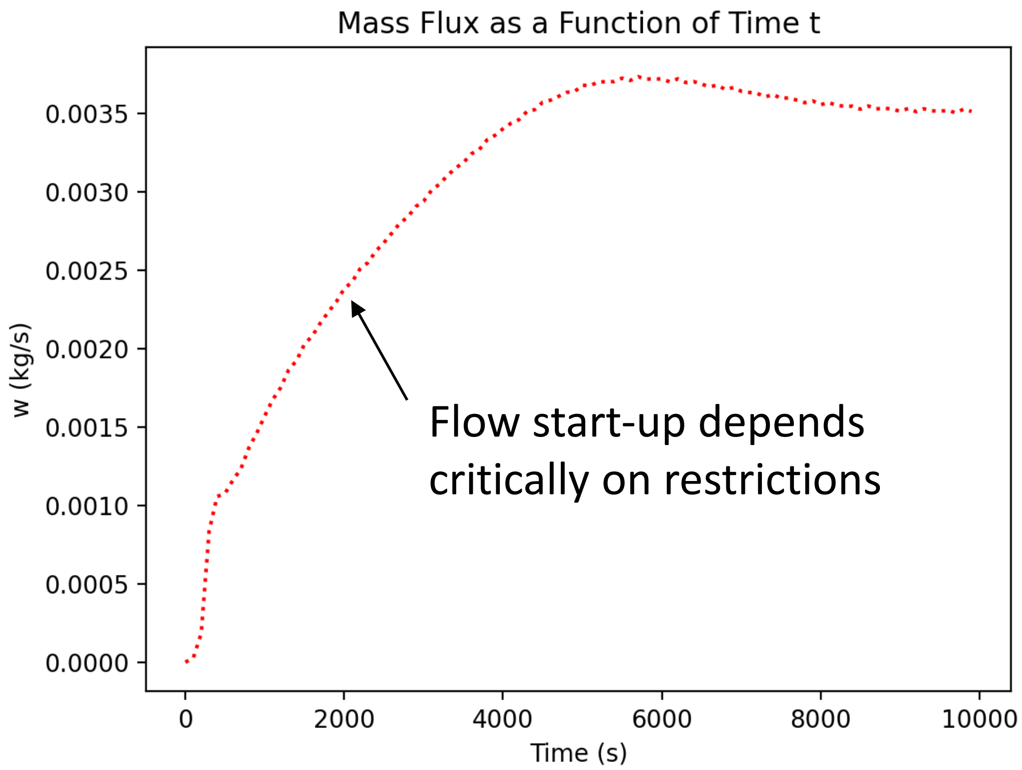
  around the loop.



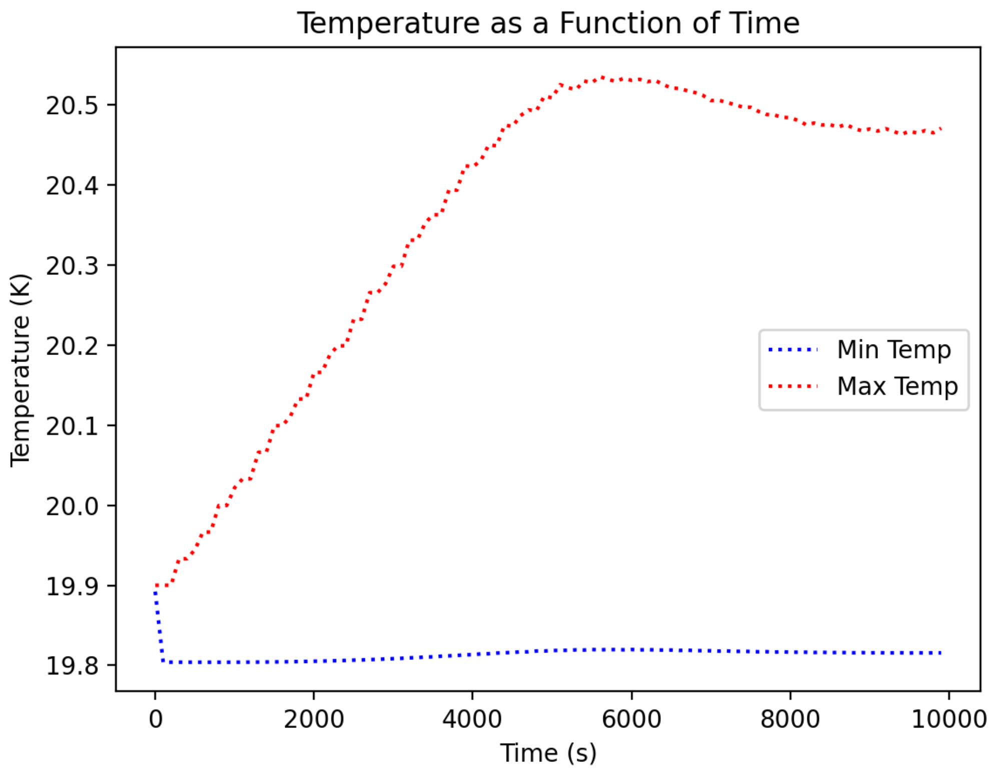
$$\frac{\partial T}{\partial t}+\frac{w}{A\rho_0}\frac{\partial T}{\partial s}=\begin{cases}\frac{Q}{V\rho_0 C_p} & \text{for } s \text{ in the heater}\\ 0 & \text{for } s \text{ in the connecting (insulated) pipes}\\ -\frac{4h_c(T-T_s)}{D\rho_0 C_p} & \text{for } s \text{ in the cooling heat exchanger}\end{cases}$$

$$\Gamma\frac{dw}{dt}+\frac{w^2}{2\rho_0}\sum_i\left(\frac{fL_{\text{eff}}}{DA^2}\right)_i+\rho_0\beta g\oint T(s,t)dz=0$$

1D time-dependent model of circulation



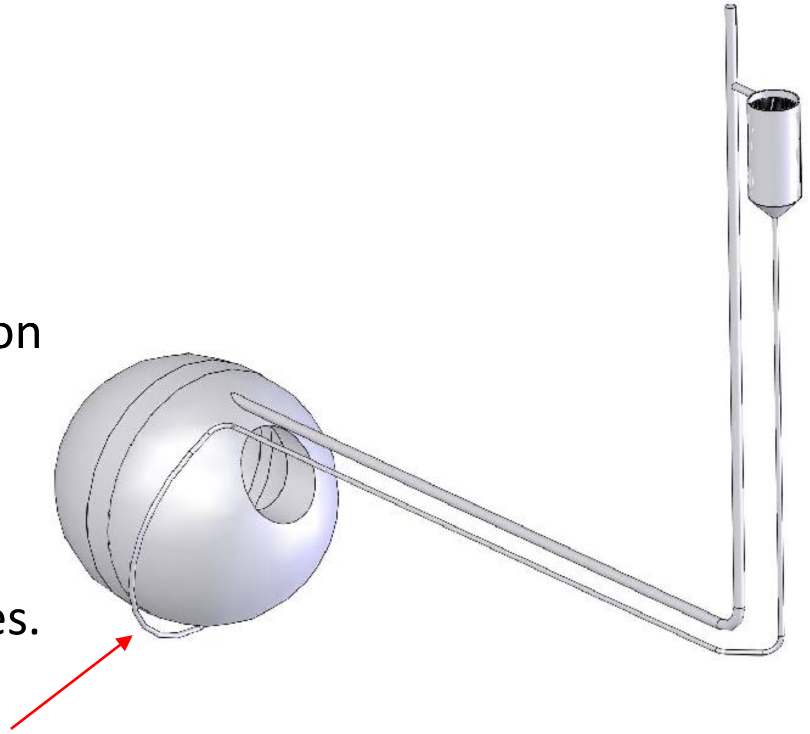
Flow start-up depends critically on restrictions



- In these simulations, beam-pulsing is switched on with ¼ duty cycle, one minute on, three minutes off.
- Very similar results for CW beam at ¼ power.

1D circulation simulation status/results

- Simulation now includes:
  - Flow and temperature profile of liquid (as shown)
  - Heat transfer to walls, temperature profile of walls
  - Heat conduction (thermal diffusivity) in both LD_2 and walls
  - Ability to turn on/off beam at will
- A few key conclusions:
  - Flow response to heat is very slow. Initiating a flow depends on geometry. We will use a heater in low position to help this.
  - Regular beam pulsing doesn't affect flow, once flow has been established.
- To do (S. Stargardter):
  - Revise 1D time-dependent model with detailed pressure losses.
  - Special attention to heat deposited in the 2nd downcomer inside LD_2 bulb, to check that flow can be established



Time-dependence of He-II temperature

- A question often asked: what's better about your new UCN source?
- Partial answer: It can handle more power from beam heating.
  The He-II stays cold, even at considerably higher power.
- More informative answer: Compared to our old "vertical" source, the way heat is removed from the He-II in new "horizontal" source is completely different.
- In this work, we created a time-dependent model of heat transport in our He-II involving quantum turbulence (the Gorter-Mellink regime of heat transport)

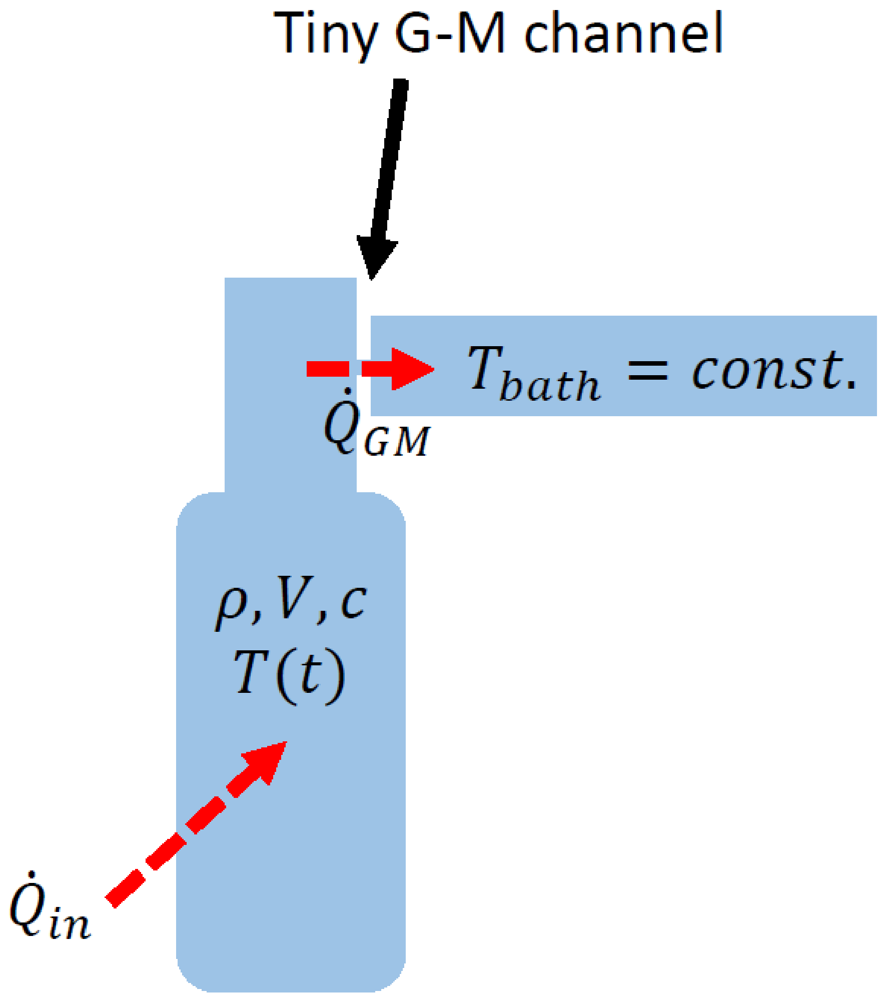
1D Model of He-II conduction, vertical source

$$\rho V c \frac{dT}{dt} = \dot{Q}_{\rm in} - \dot{Q}_{\rm GM}$$

$$dT/dx = -f(T,p)q^m$$

$$\boxed{\rho V c \frac{dT}{dt} = \dot{Q}_{\rm in} - A\left[\frac{1}{\ell}\int_{T_{\rm bath}}^{T(t)} dT' f^{-1}(T', {\rm SVP})\right]^{1/m}}$$

- Solve for T(t)
- Somewhat unknown:
  - A (area of the channel)
  - ℓ (length of the channel)
  - T_{bath} (He-II temperature close to HEX)
  - Background heat



Sample results, after some tweaking

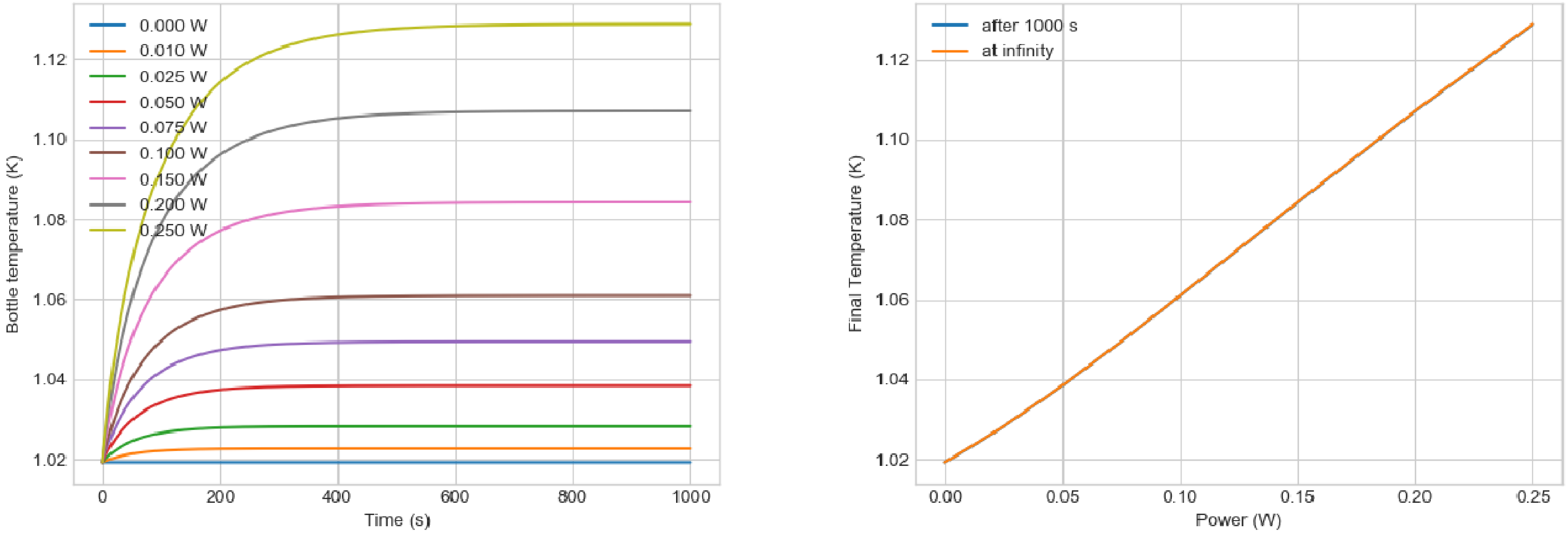
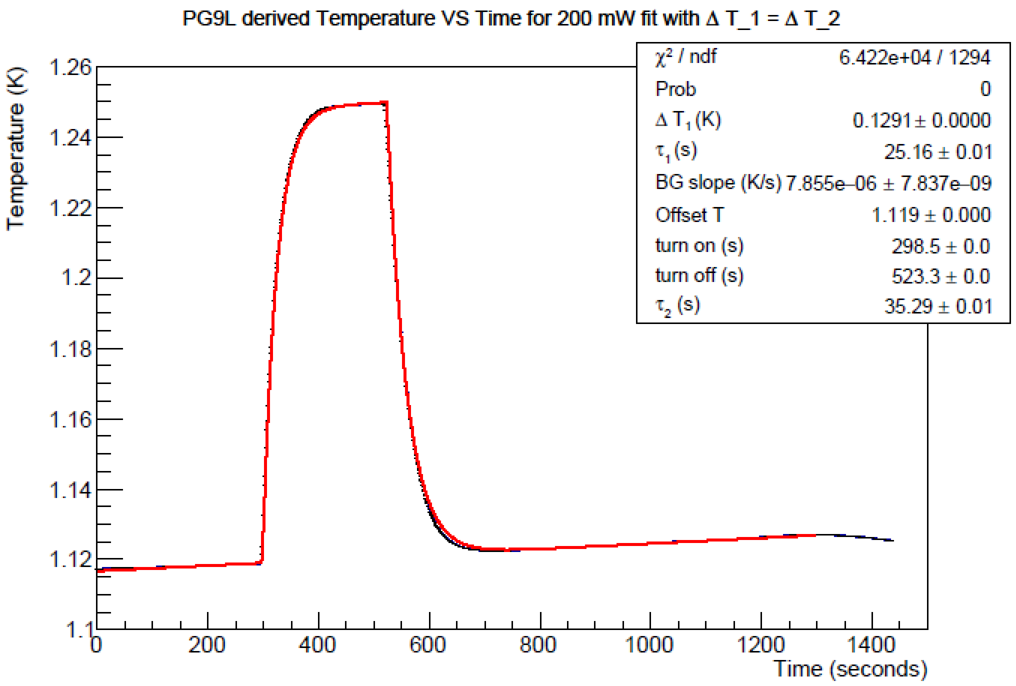
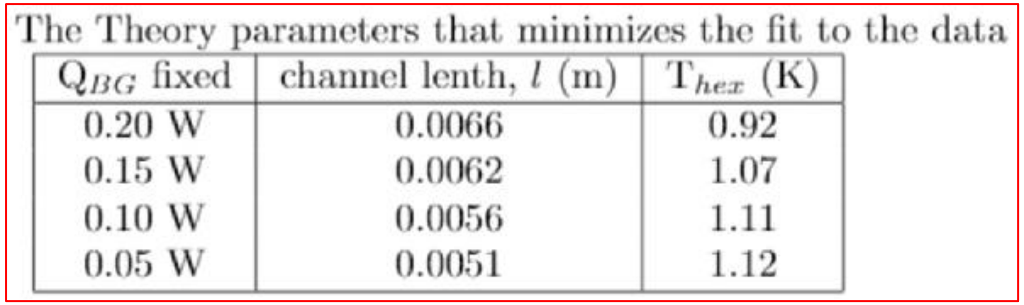


Figure 7: Left: time-dependence of temperatures for $\ell = \sqrt{A} = 0.01$ m with a background heat of 150 mW. Right: values at $t = \infty$ compared with final value from time-dependent calculation.

Comparison with Temperature data from vertical source (S. Hansen-Romu)



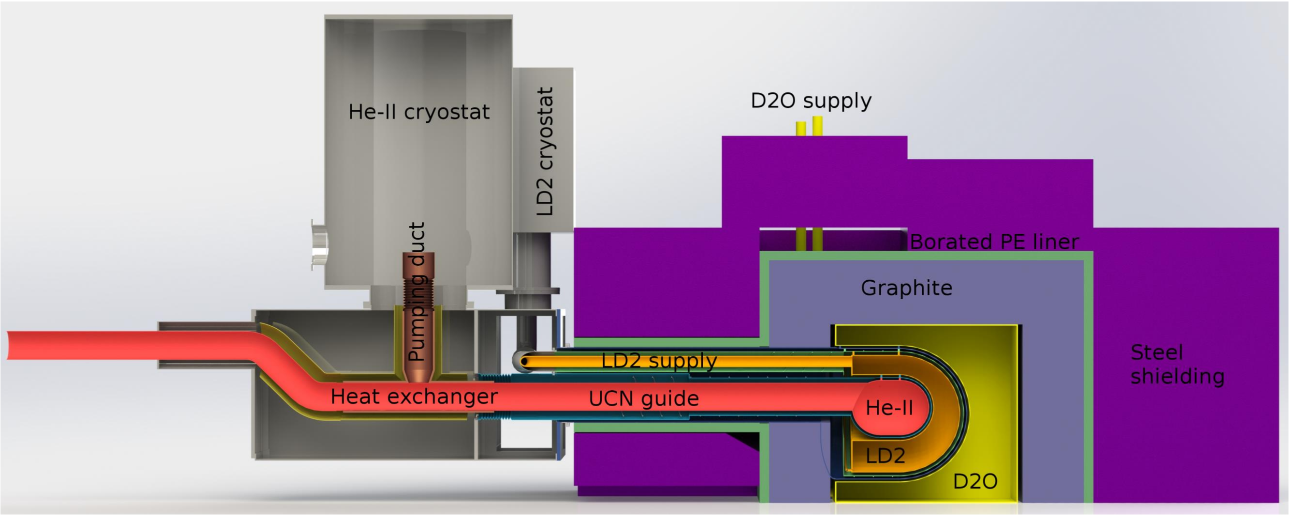


The Theory parameters that minimizes the fit to the data

Q_{BG} fixed	channel lenth, l (m)	T_{hex} (K)
0.20 W	0.0066	0.92
0.15 W	0.0062	1.07
0.10 W	0.0056	1.11
0.05 W	0.0051	1.12

- Simple 1D model gives good agreement with scale of heat flow restrictions, temperature rise, timescale, and background heat.

How is this different for the horizontal source?



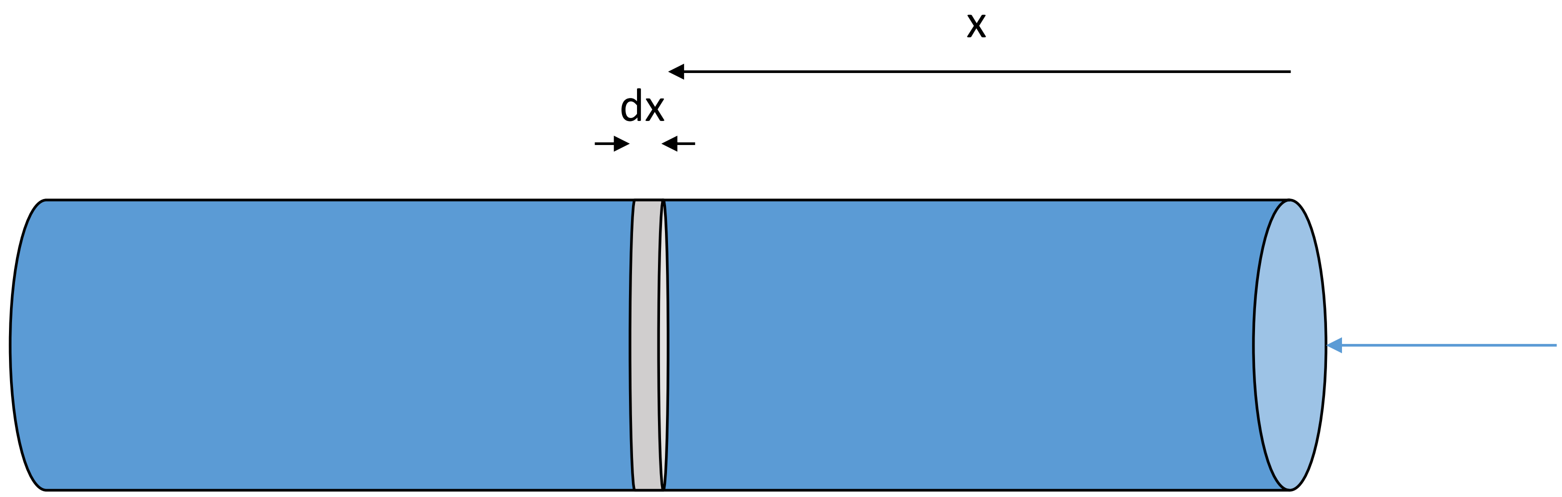
Conventional

$$q = k\frac{\partial T}{\partial x}$$

Gorter-Mellink

$$q^3 = f(T)^{-1}\frac{\partial T}{\partial x}$$

$$\frac{\partial T}{\partial t} = -\frac{1}{\rho c_p}\frac{\partial q}{\partial x}$$



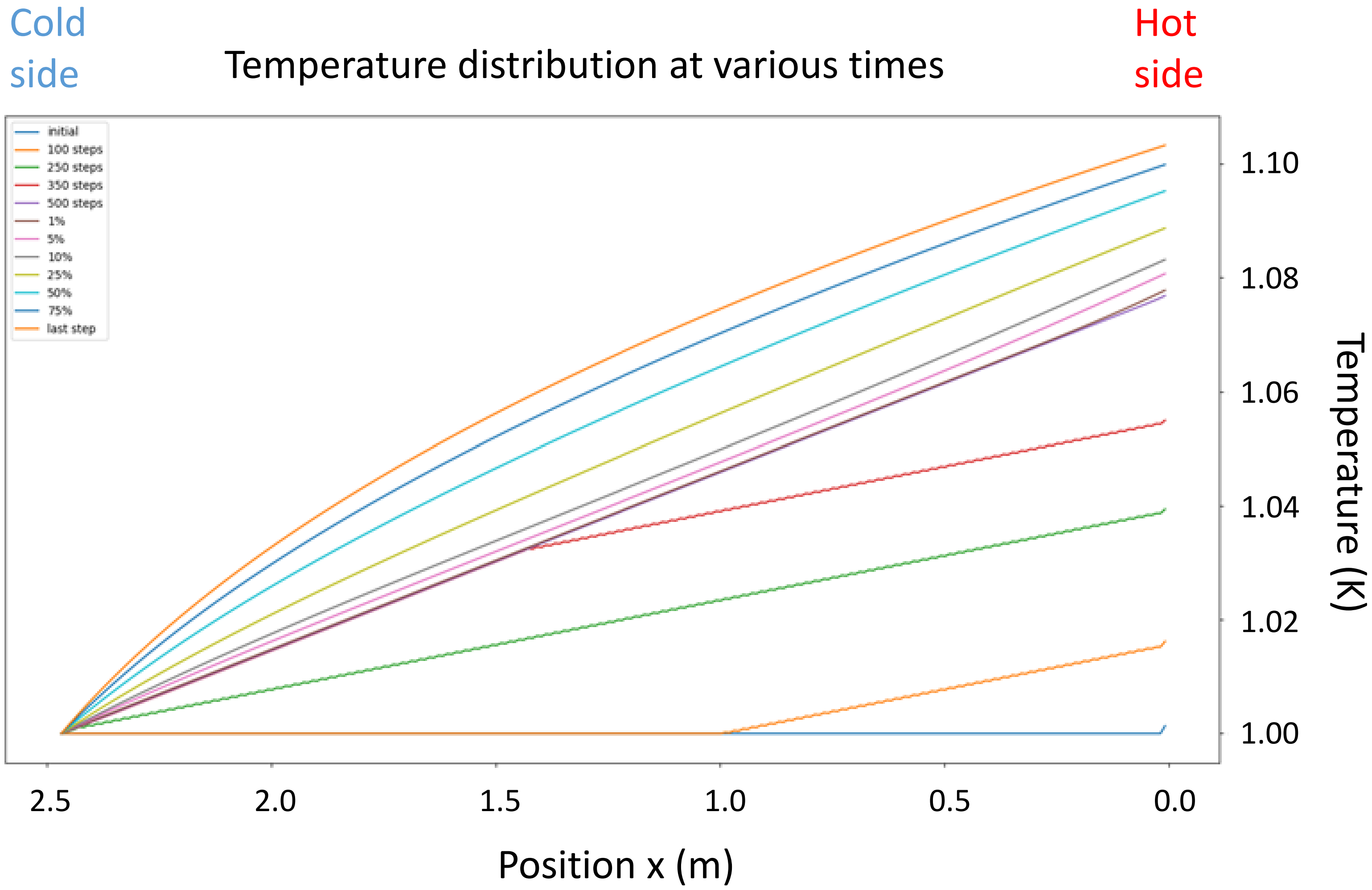
$$T_o = 1.0K$$

$$\frac{q}{A} = 10\,{}^{W}\!/_{m^2}$$

Horizontal source

- Total simulation time 10 s
- Time step - 0.1 ms
- Step size – 10 cm

Conclusion: equilibrium reached after about 10 s.



Conclusions

- Thermodynamics is useful to design particle physics experiments!
- 1D time-dependent model for LD_2
  - Gives time-dependence of thermosyphon start-up and beam pulsing.
  - Beam pulsing not a huge issue.
  - Start-up will be studied again to account for detailed pressure-drop model
- 1D time-dependent model for He-II
  - Model describes temperature rises and time constants in the vertical source rather well, with few “fit parameters”.
  - Comparing to the future horizontal source gives a more quantitative assessment of how the horizontal source will be superior, cryogenically.

Thank you!

Questions?