He II

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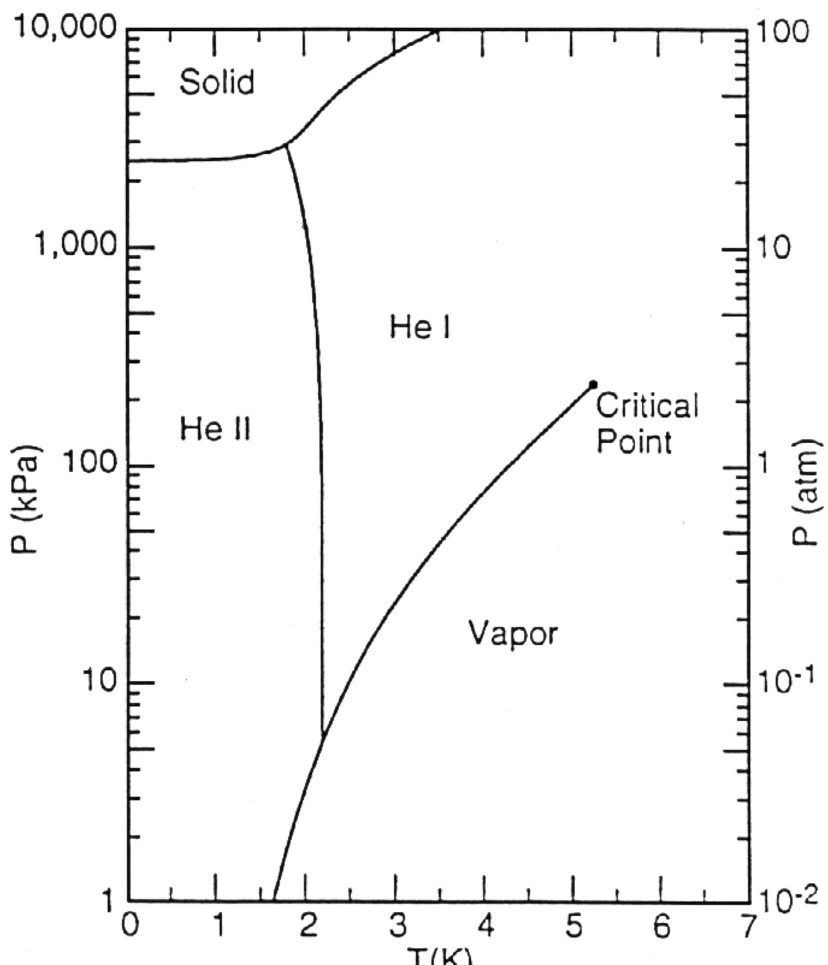
Goals

- Describe the physics and engineering of He II (superfluid helium)
- Show some He II cooling options for large scale accelerators

He II (Superfluid Helium)

- 2nd liquid phase of helium (hence He II)
- Phase transition is 2nd order (no latent heat) but there is a discontinuity in the specific heat (λ transition)
- $T_{\lambda max}$ = 2.2 K
- Has unique thermal and fluid properties
  - High effective thermal conductivity
  - Zero viscosity under certain conditions

Helium Phase Diagram



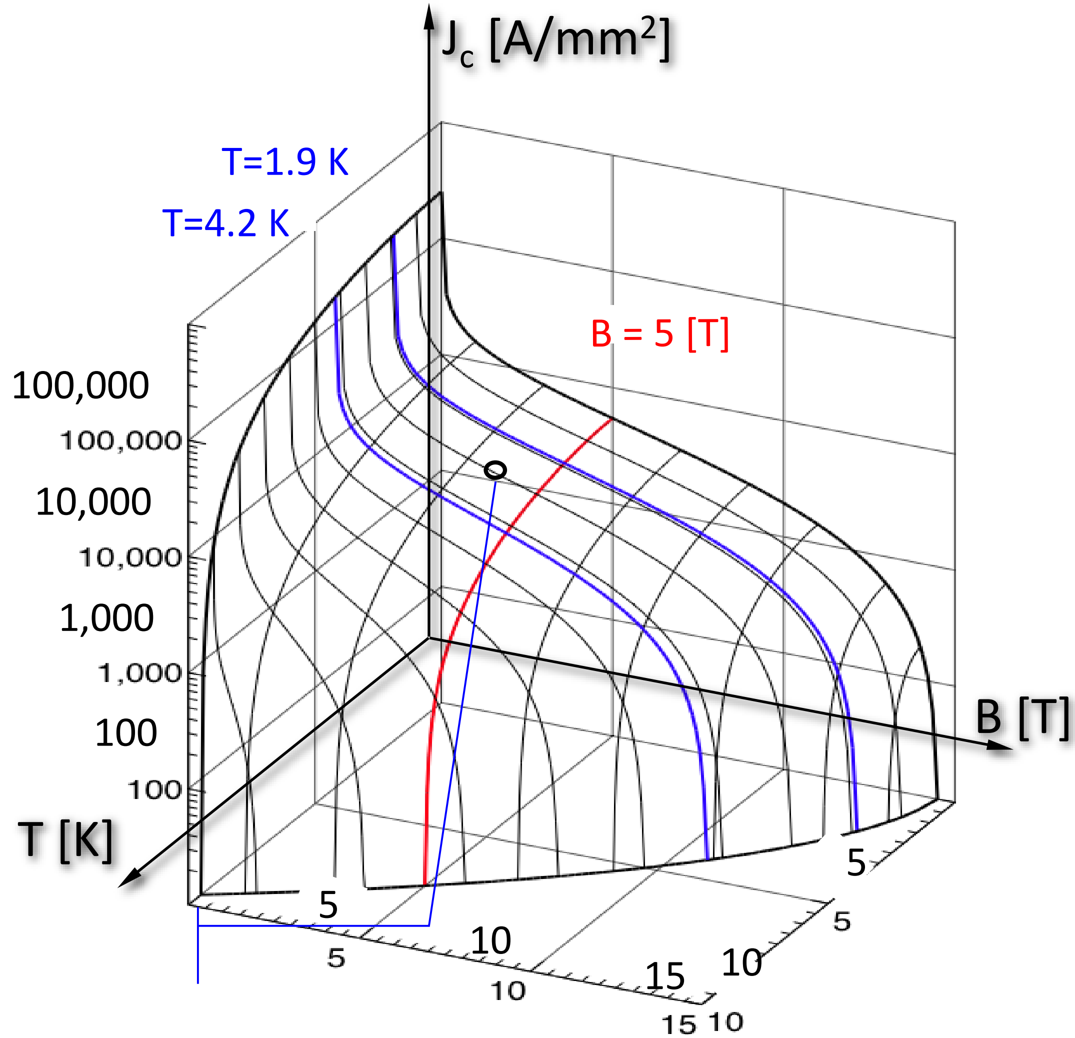
Why use He II in Accelerator Systems?

- The principal reason is the lower temperatures
- Lower temperatures (< 2.2 K) allow:
  - High critical fields and currents in superconducting magnets. This allows higher energy beams in existing tunnel geometries (LHC) Bending & Focusing the beam
  - In SRF applications, lower temperatures mean lower surface resistance and thus more RF energy for beam acceleration and less for heating the cavity & helium Accelerating the beam
- An additional advantage is the very efficient heat transfer mechanism in He II
  - This results in no bulk boiling which reduces microphonics in SRF cavities

LHC NbTi Wire

Courtesy L. Boturra of CERN

Note
Improvement in B
and Jc
@ T = 1.9 K



Jc (5 T, 4.2 K) ≈ 3000 A/mm^2

SRF Cavities: Surface Resistance, Frequency and Temperature

- The RF surface resistance (which we want to minimize) of a SRF cavity is given by:

$$R_s = A\left(\frac{1}{T}\right)f^2 e^{(-\Delta(T)/kT)} + R_0$$

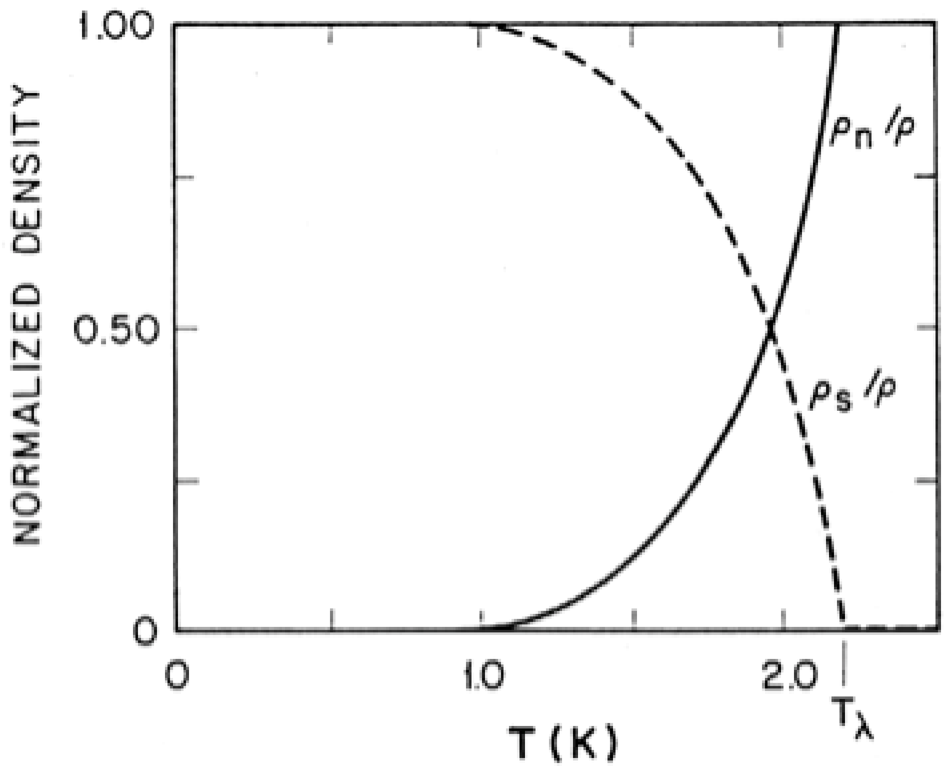
- The surface resistance goes up with frequency and down with temperature: lower temperature equals less resistance, particularly at higher frequencies
- He II refrigeration is more costly (due to Carnot & machine inefficiencies)
- Generally speaking, removing 1 W at 2 K is the equivalent of removing 3 W at 4.2 K
- What is the optimal temperature?
  - Above about 500 – 700 MHz you win by operating below 4.2 K (typically 1.8 – 2 K)
  - At lower frequencies (e.g. 80 MHz) you are better at 4.2 K thermodynamically but there may be other considerations (FRIB)
  - Between these limits it's a fairly broad minimum. Most systems operate ~ 2 K – He II

What is He II ?

- A “Bose – Einstein like” Condensate
  - A fraction of atoms in He II have condensed to the quantum ground state
  - He II was the first of these condensates discovered
  - The only one that has significant industrial applications
- The properties of He II can be understood via the two fluid model
  - Note that a similar modeling approach is seen in superconductivity

Two Fluid Model

- He II can be thought of a fluid with two interpenetrating components:
  - Normal fluid component
    - Finite viscosity
    - Finite entropy
  - Superfluid component
    - Zero viscosity
    - Zero entropy
- The interaction of these components can explain He II behavior



Relative Densities of Superfluid and Normal fluid components
(From Helium Cryogenics – Van Sciver)

Quantized Vortices (or does He II at 1 K rotate in a bucket)

- At 1 K He II is almost entirely the superfluid component and thus has almost 0 viscosity. This would imply that He at 1 K in a spinning bucket wouldn't rotate but it does. What's the answer?
  - The vortices are quantized: $$C = \int V_s \cdot dl = n\frac{h}{m}$$
- Solves rotating bucket problem
  - In the body of the fluid: $\nabla^2 V_s = 0$
  - At the wall: $\nabla^2 V_s \neq 0$
- This has been experimentally observed
- The quantized vortices in the superfluid component are an important part of heat transfer mechanism in He II

Direct Observation of Quantized Vortices via Electron Trapping

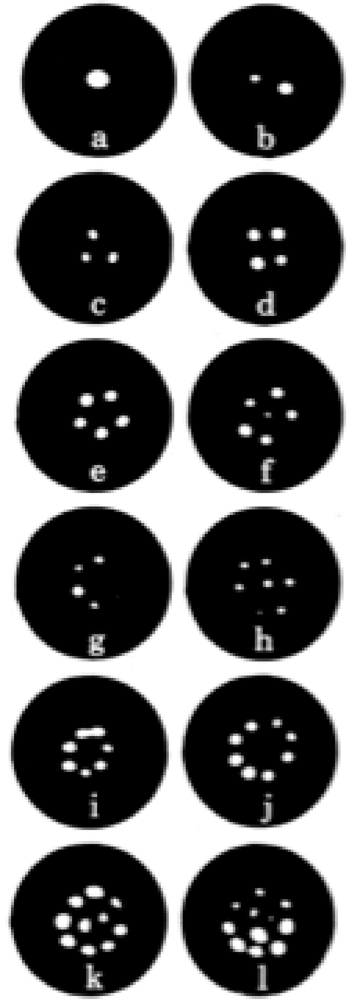
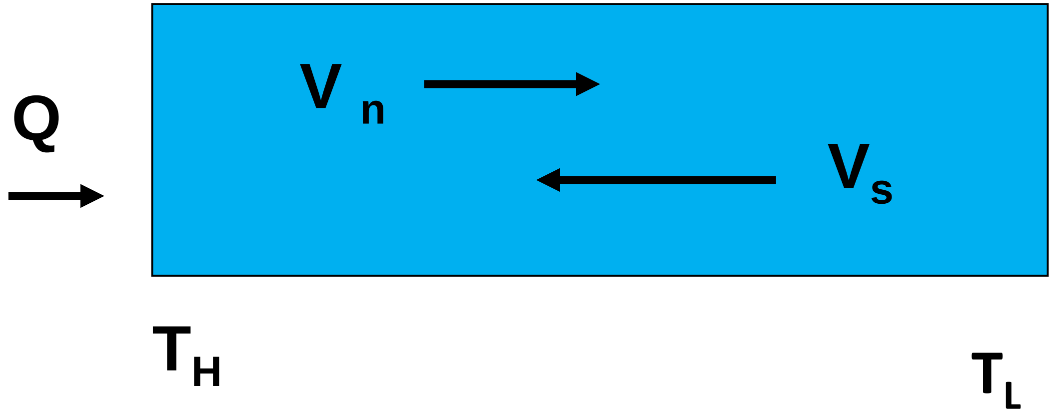


Fig. 4.26. Photographic reproduction of vortex line array in rotating He II (from Yarmchuk and Packard[17]): (a) through (l) indicate increasing angular frequency.

Heat Transfer in He II

- The basic mechanism is internal convection:



- No net mass flow
- Note that this is not conduction or classical convection but an entirely different heat transfer mechanism
- This can be extremely efficient (more than 1000x better than conduction through copper)

Heat Transfer in He II

- There are 2 heat transfer regimes:
  - $V_s < V_{sc}$

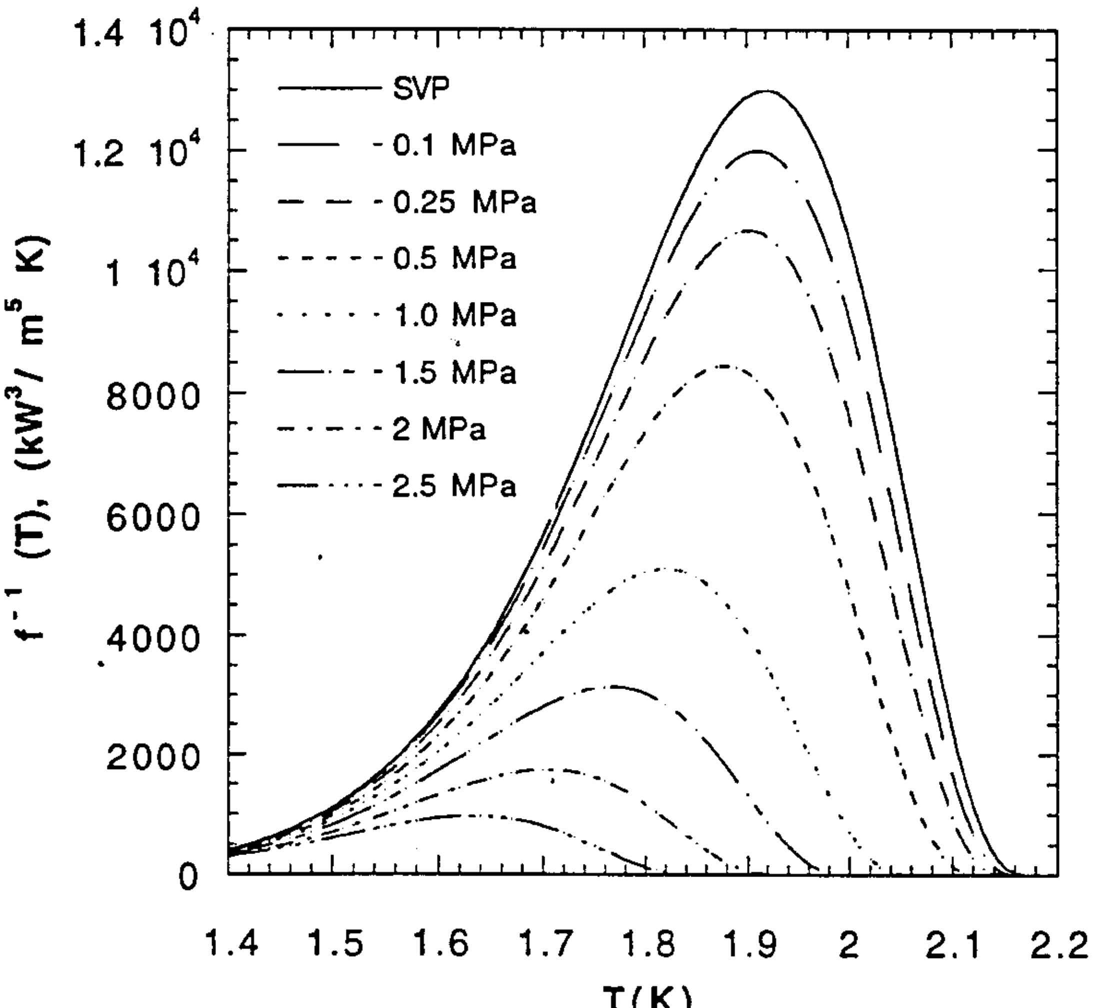
$$q = \frac{\left(\rho s d^2\right)T}{\beta \eta_n} \frac{dT}{dx}$$

  - $V_s > V_{sc}$
    - Mutual Friction Regime (quantized vortices interact with the viscosity of the normal component

$$q = \left[f^{-1}(P,T) \frac{dT}{dx} \right]^{1/3}$$

- As $V_{sc} \sim d^{-1/4}$ (cgs units) the mutual friction regime is applicable in most engineering applications of He II

Heat Conductivity Function



He II Heat Transfer Limits

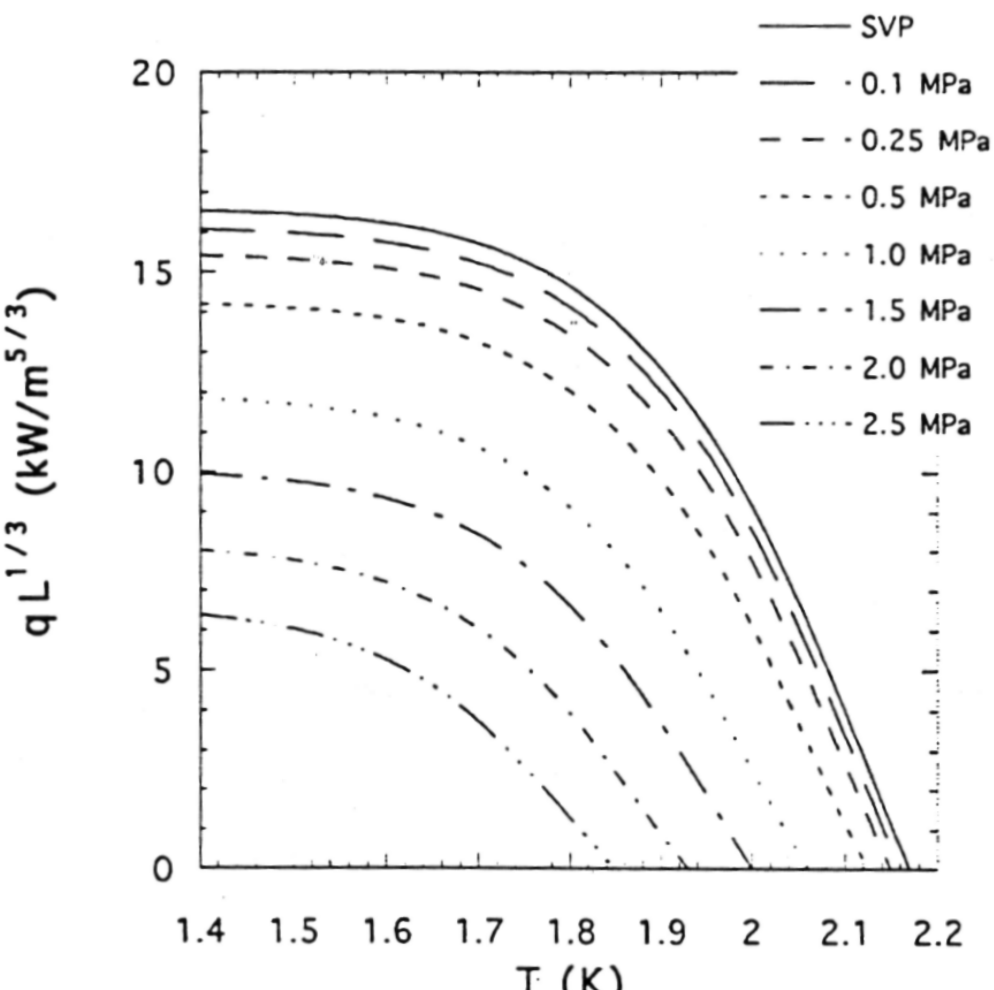
- In pressurized He II: T_h must be less than T_λ
- Thus the peak heat flux q* is:

$$q^* L^{1/3} = \left(\int_{T_b}^{T_\lambda} f^{-1}(T)\,dt \right)^{1/3}$$

- At 1.9 K and 1 bar :

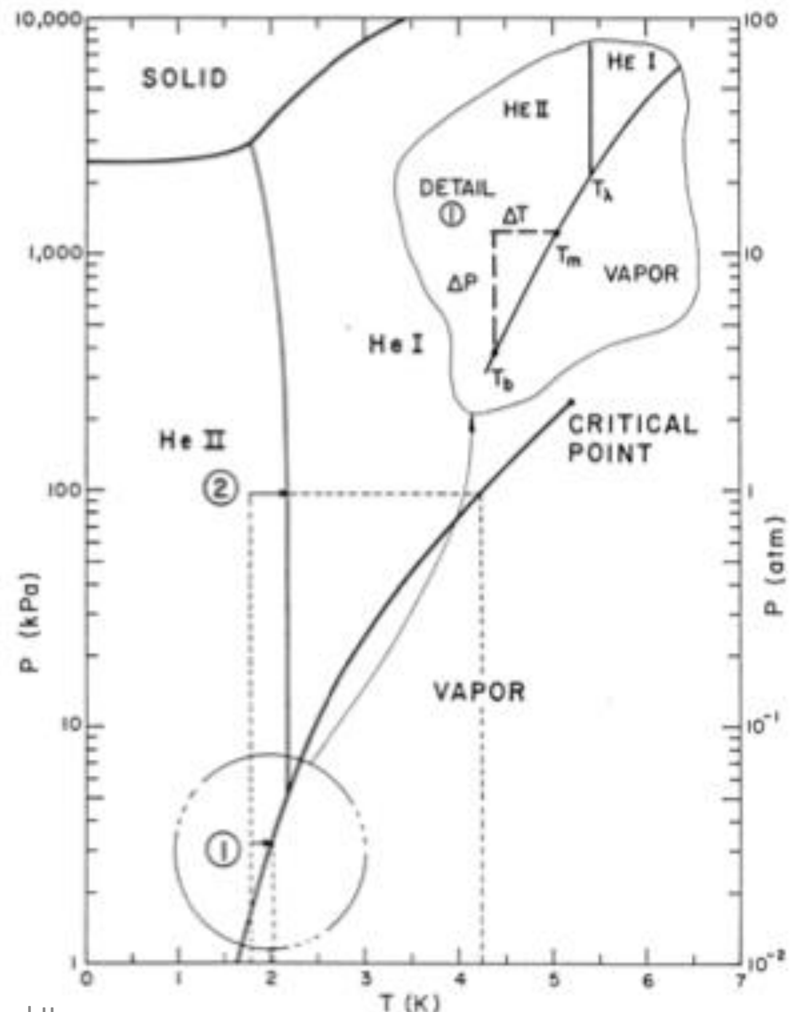
$$q^* L^{1/3} \sim 15 \text{ kW/m}^{5/3}$$

Peak Heat Flux (q*) in Pressurized He II



Limits on He II Heat Transfer

- In saturated He II, the limit is given by the local saturation temperature & the degree of local subcooling
- In the ILC cavity He vessel this works out to about 1 W/cm^2 or ~ 30 W total through the connection tube
  - More heat than that would require a redesign – LCLS II
- Exceeding the heat transfer limits in either the saturated or pressurized case results in conversion to He I and boiling at the heated surface



Surface Heat Transfer

- Heat transfer from a surface into He II is completely dominated by a fundamental inefficiency in moving energy from the surface to the fluid
- This effect exists but is not important in standard convection problems
  - Normally we assume $T_w = T_{fw}$ but this is not true in the case of He II
- This surface heat transfer effect is described by Kapitza Conductance
  - For q < 1 kW/m^2

$$q = h_K \Delta T_S$$

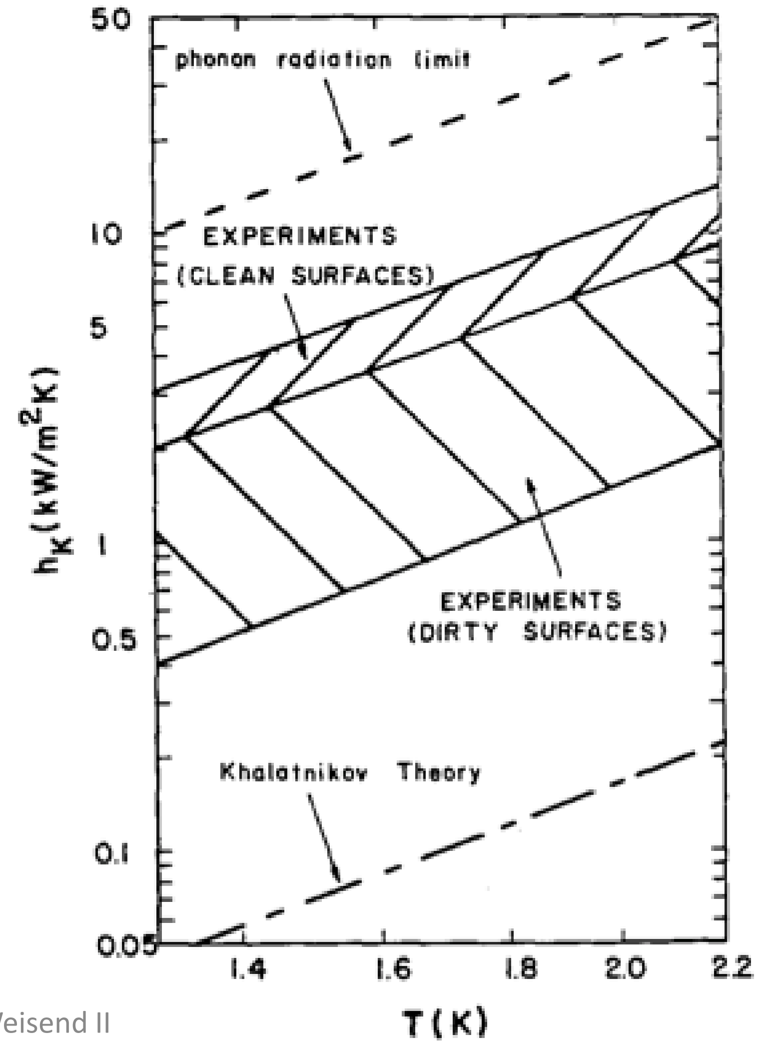
  - For q > 1 kW/m^2

$$q = a(T_s^m - T_b^m)$$

- h $_{k,}$ a and m are empirical and dependent on material, temperature and surface condition

Surface Heat Transfer

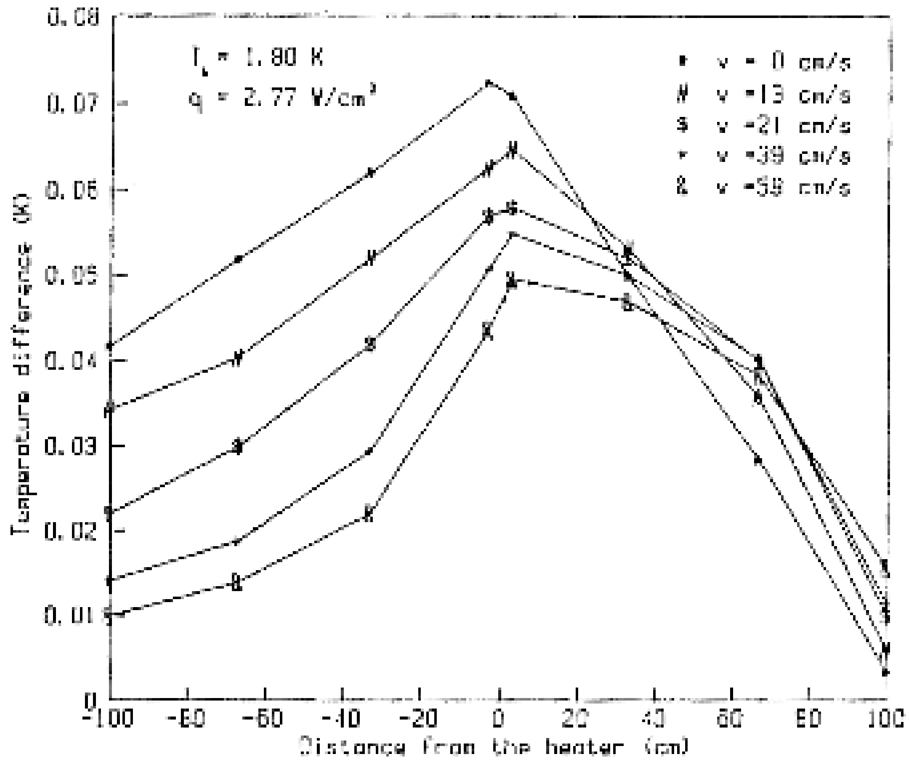
- m ~ 3
- Kapitza conductance is <u>not</u> dependent on helium flow rate



Forced Convection and He II

If Kapitza Conductance is independent of flow rate does forced convection in He II make any sense?

Yes! Forced convection has the effect of reducing the maximum temperature in the He II and thus allowing more heat to be transferred before reaching the peak heat flux



He II Fluid Dynamics

- Despite the presence of the superfluid component, in almost all engineering applications He II behaves as a classical fluid. This includes :
  - Pump performance
    - Except cavitation in saturated He II
  - Pressure drop in tubes, valves, bellows and fittings
  - Flow metering techniques
- This is likely a result of the quantized vortices in the superfluid component being coupled via mutual friction to the normal fluid viscosity
- However, keep in mind that the unique heat transfer properties still exist as described.

He II Fluid Dynamics

- He II does behave differently in cases of:
  - Film flow
  - Porous plugs
  - Two – phase flow (liquid/vapor) due to the large density difference between liquid and vapor in the case of He II

Second Sound

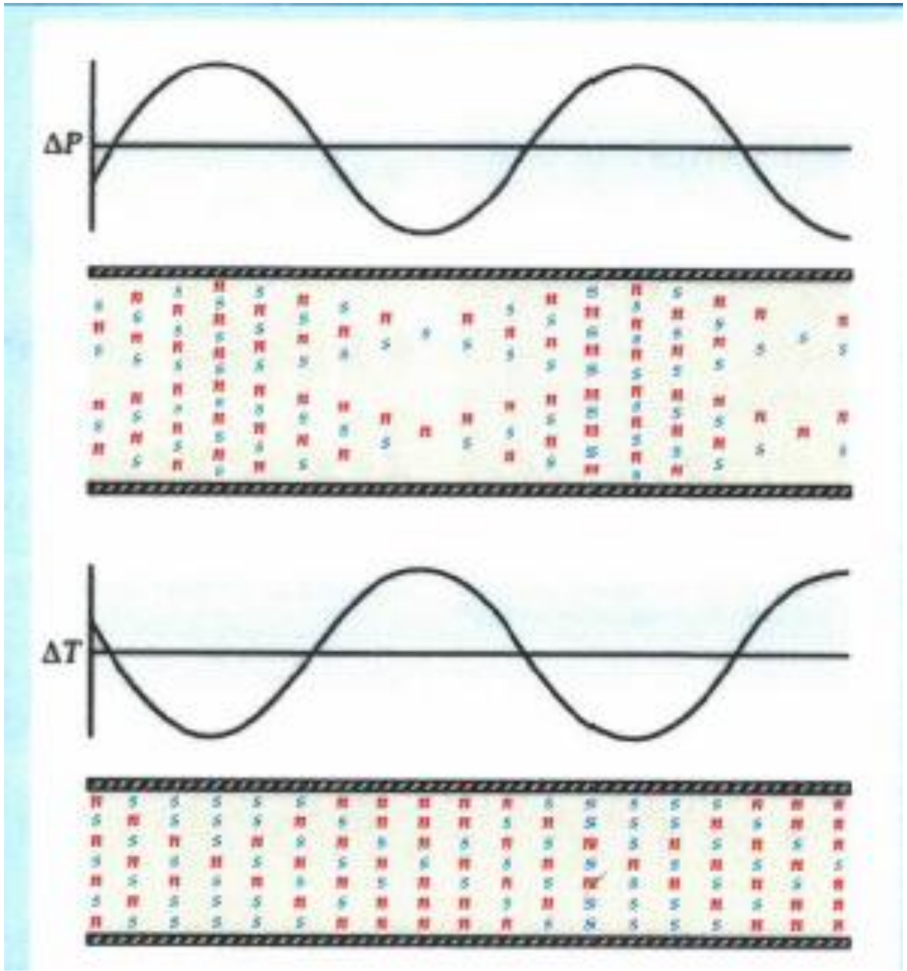
- The two-fluid model predicts and experiments show that temperature waves may be established in the He II due to oscillations in the local entropy. These temperature waves are known as second sound as they are analogous to density waves caused by pressure oscillations.
- Recall that the superfluid component has zero entropy

Table 6.2 Comparison of sound propagation in He II   From Helium Cryogenics S.W. Van Sciver (2013)

	First sound	Second sound
Driving force	δp	δT
Propagator	$\delta \rho$	δs
Density (ρ)	Wavelike	$\sim$ constant ($\rho_n \mathbf{v}_n \approx -\rho_s \mathbf{v}_s$)
Temperature (T)	$\sim$ constant ($\mathbf{v}_s \approx \mathbf{v}_n$)	Wavelike
Speed	$c_1 = \left(\frac{\gamma}{\rho\kappa}\right)^{1/2} \approx 240$ m/s	$c_2 = \left(\frac{\rho_s}{\rho_n}\frac{Ts^2}{C_v}\right)^{1/2} \approx 20$ m/s
Relationship	$\nabla^2 p = \frac{\partial^2 \rho}{\partial t^2}$	$\nabla^2 T = \frac{\rho_n}{s^2 \rho_s}\frac{\partial^2 s}{\partial t^2}$

Second Sound

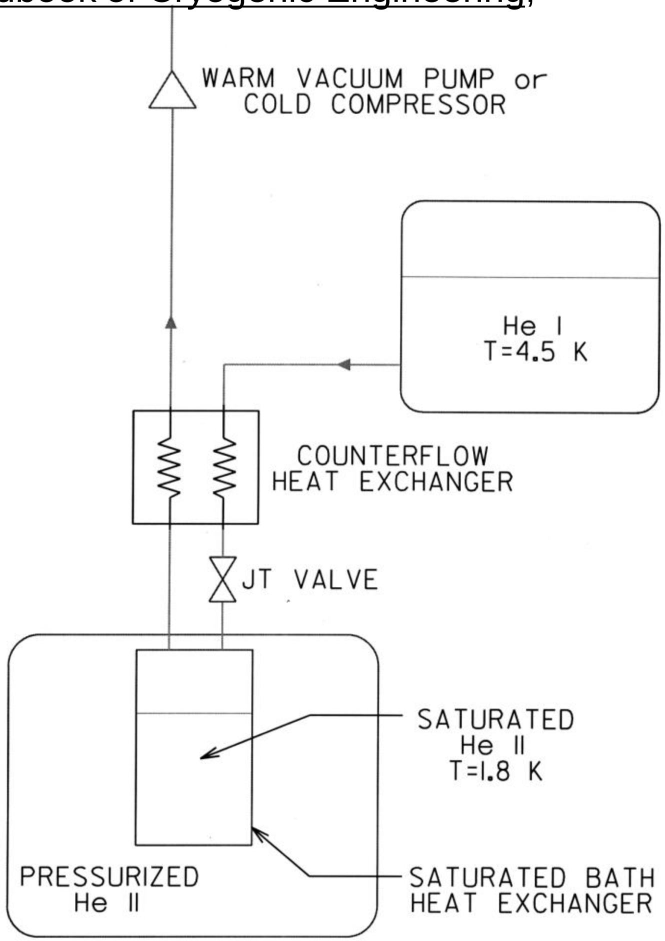
- Second sound can be detected via
  - thermometry (either time or flight or resonance techniques)
  - Oscillating Superleak Transducers
- Second sound is attenuated by mutual friction and has been used extensively quantum turbulence
- More recently second sound has been used to locate quenches in SRF cavities



From Donnelly *Physics Today* October 2009

Typical He II Refrigeration System

He II (Superfluid Helium) S. W. Van Sciver, in Handbook of Cryogenic Engineering,



Note: This arrangement for a case in which pressurized He II is required - typically a S/C magnet application

For SRF systems, such an arrangement ends at the saturated He II bath

Internal convection is the heat transfer mechanism within the He II itself

He II Cooling in Large Accelerator Systems

- There are 2 general approaches to proving He II cooling in large accelerator systems

Discrete Cooling: He II is created at each individual cryomodule or magnet - A heat exchanger and JT valve exists at each component.

Advantages:

- Flexibility
- Lower overall heat leak to the He II space

Disadvantages:

- Cost

This approach is used in ESS, SNS, FRIB, 12 GeV

He II Cooling in Large Accelerator Systems

Continuous Cooling: He II is created at a refrigerator or at the start of a string of components and then distributed to individual components.

Advantages:

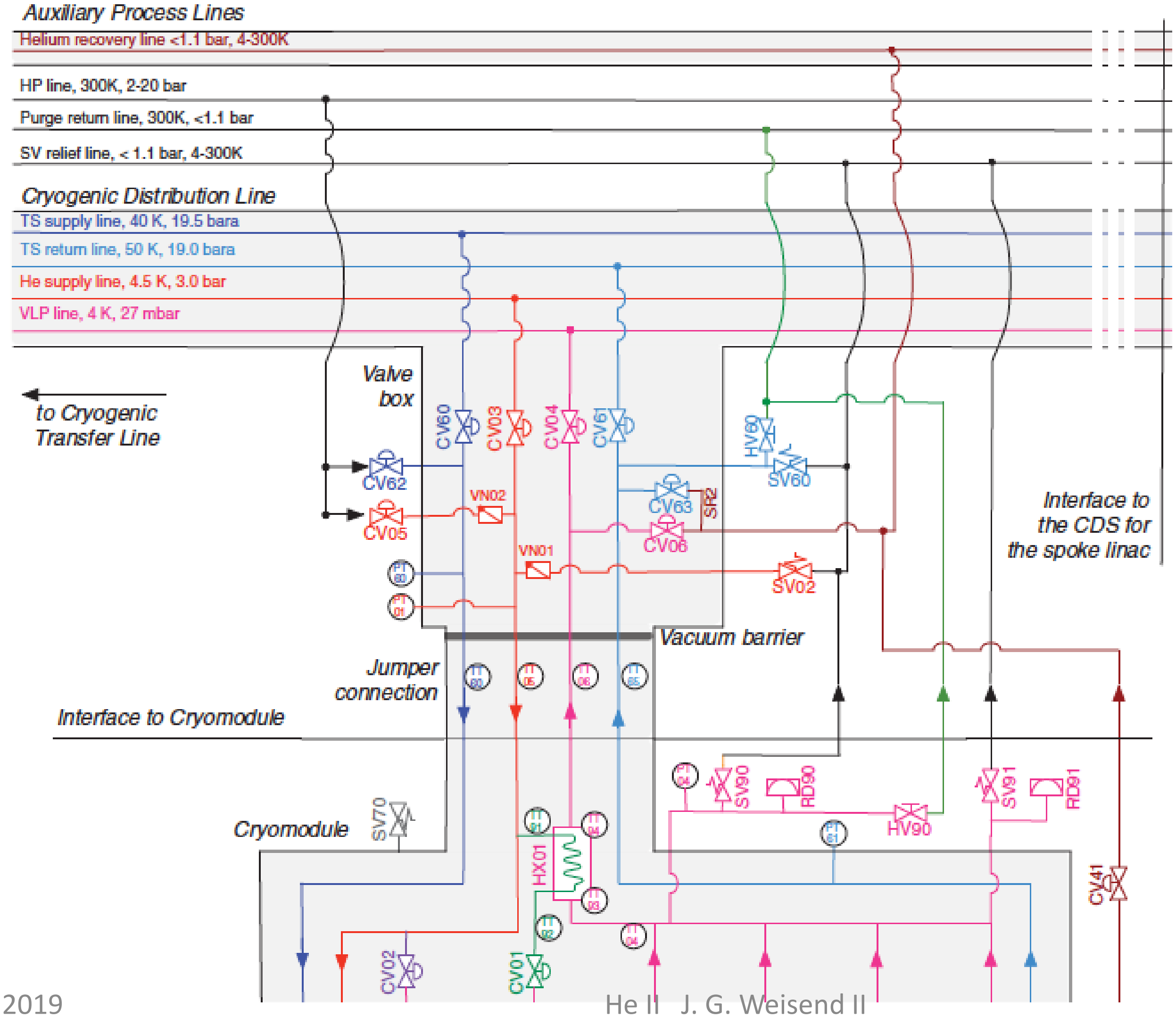
- Less expensive

Disadvantages:

- Less flexibility
- More heat leak to the He II space
- May not be able to handle high heat loads in individual components

This approach is used in LHC, XFEL, ILC

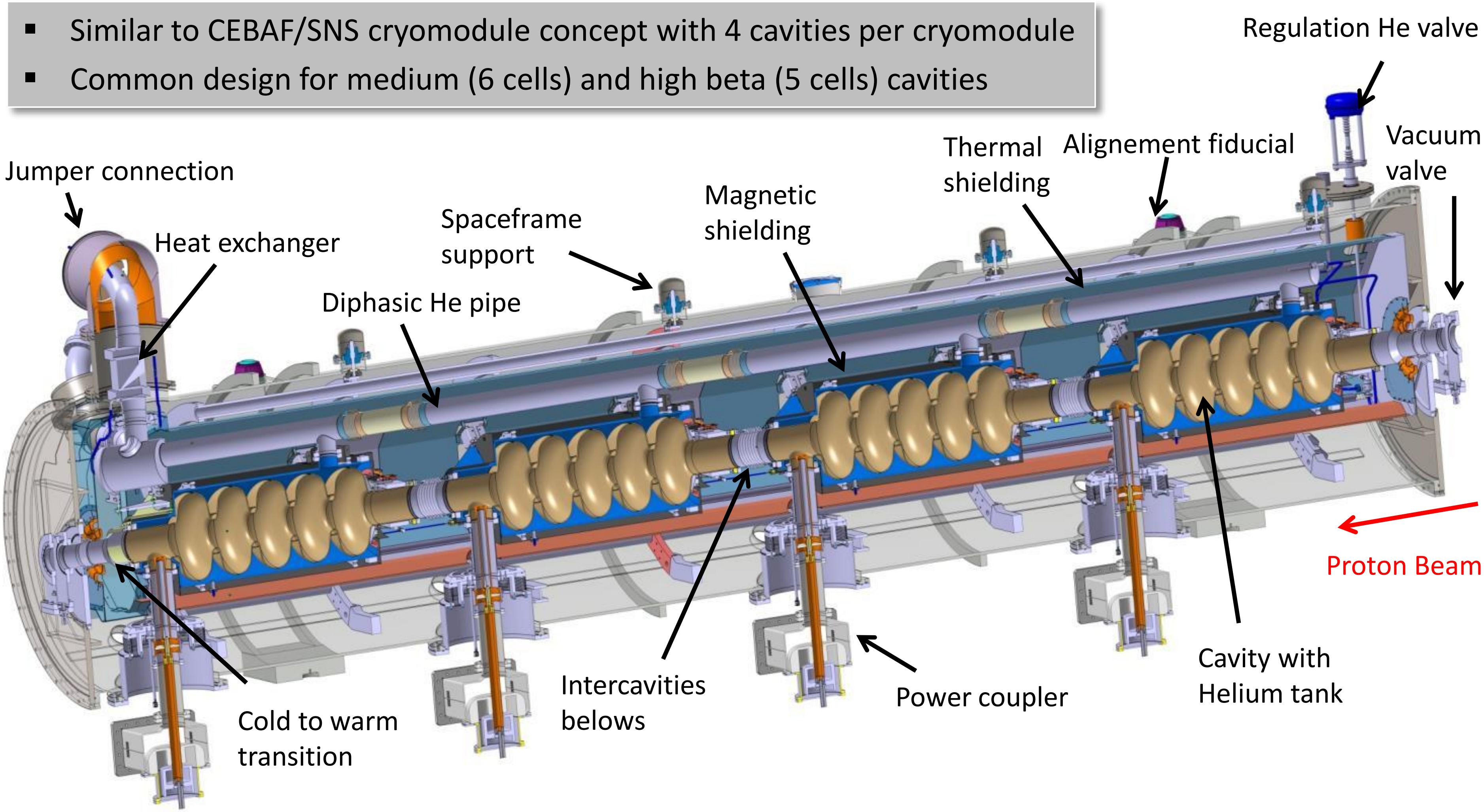
He II Cooling in The European Spallation Source (Discrete Cooling)



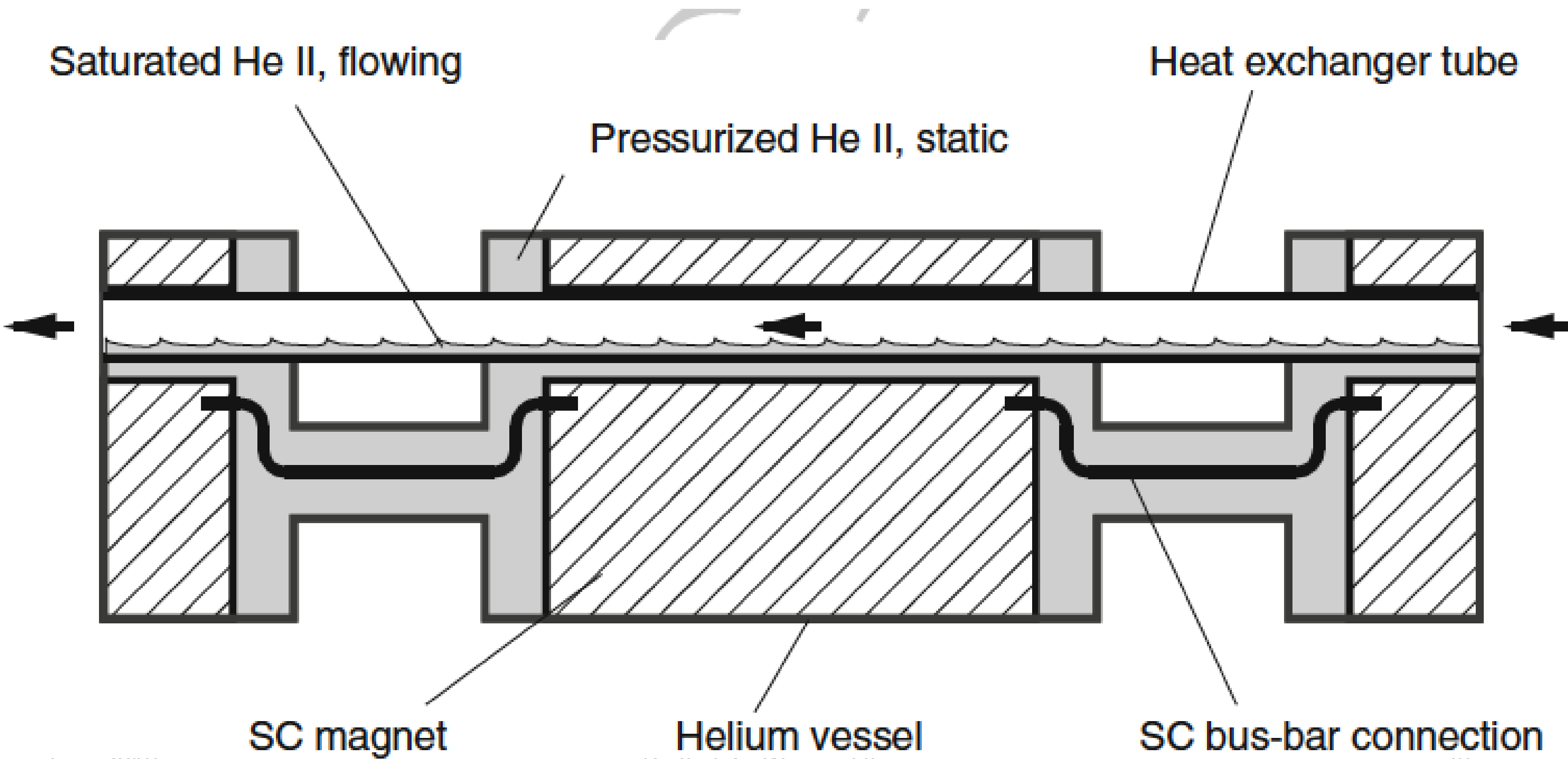
Each cryomodule has a dedicated HX and JT valve

ESS
Elliptical Cavity Cryomodules

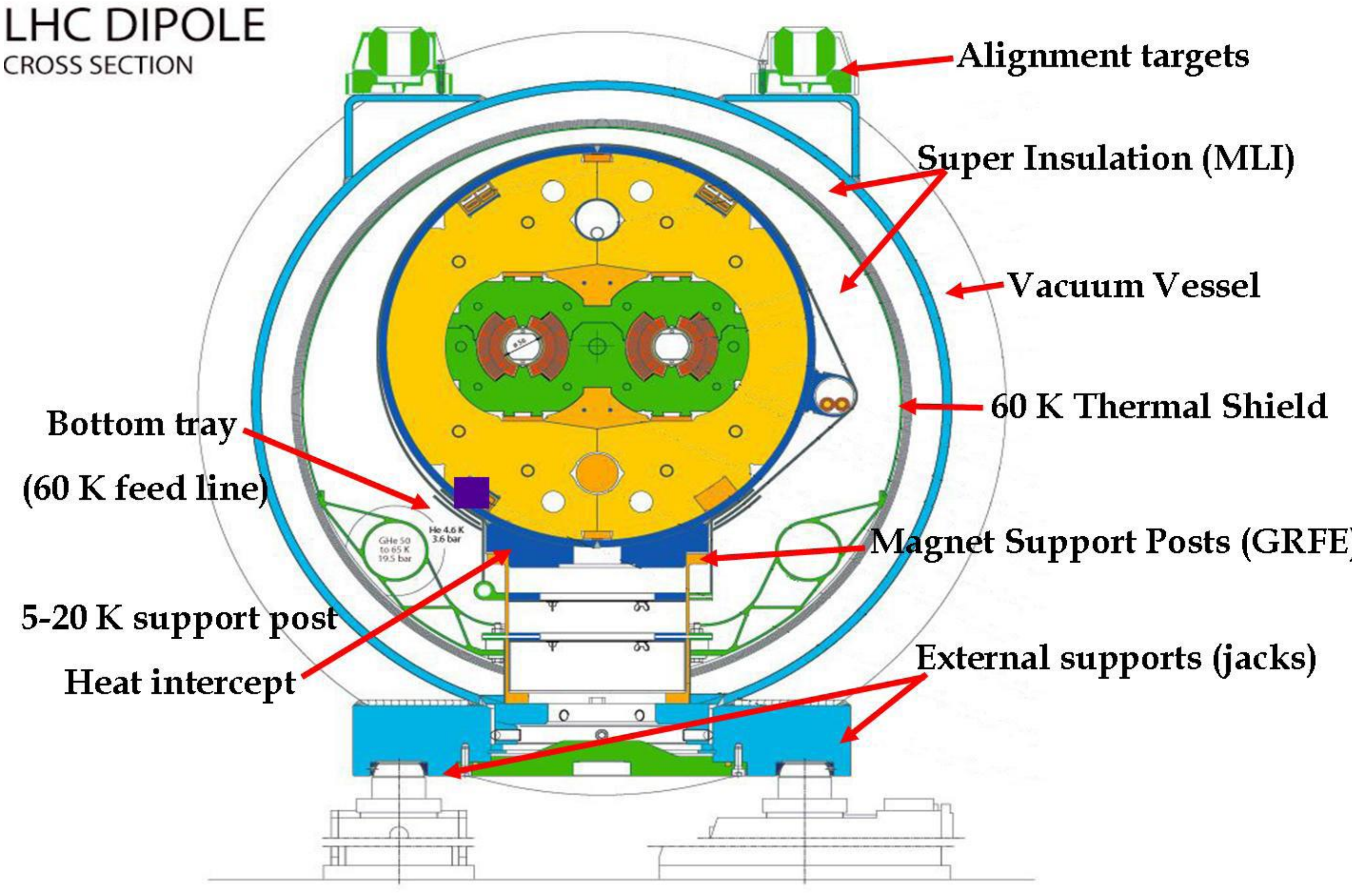
- Similar to CEBAF/SNS cryomodule concept with 4 cavities per cryomodule
- Common design for medium (6 cells) and high beta (5 cells) cavities



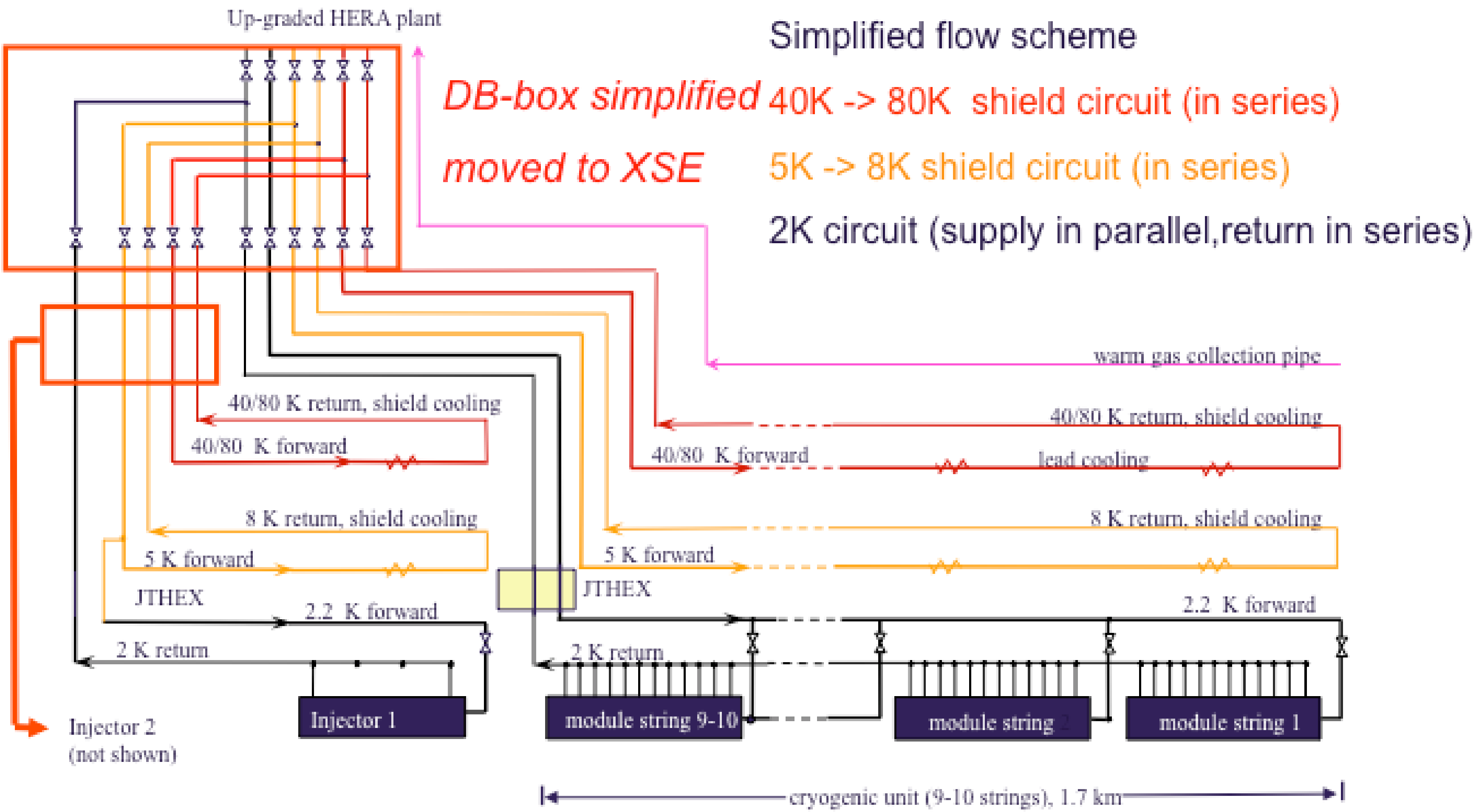
Large Hadron Collider (Continuous Cooling)



Large Hadron Collider



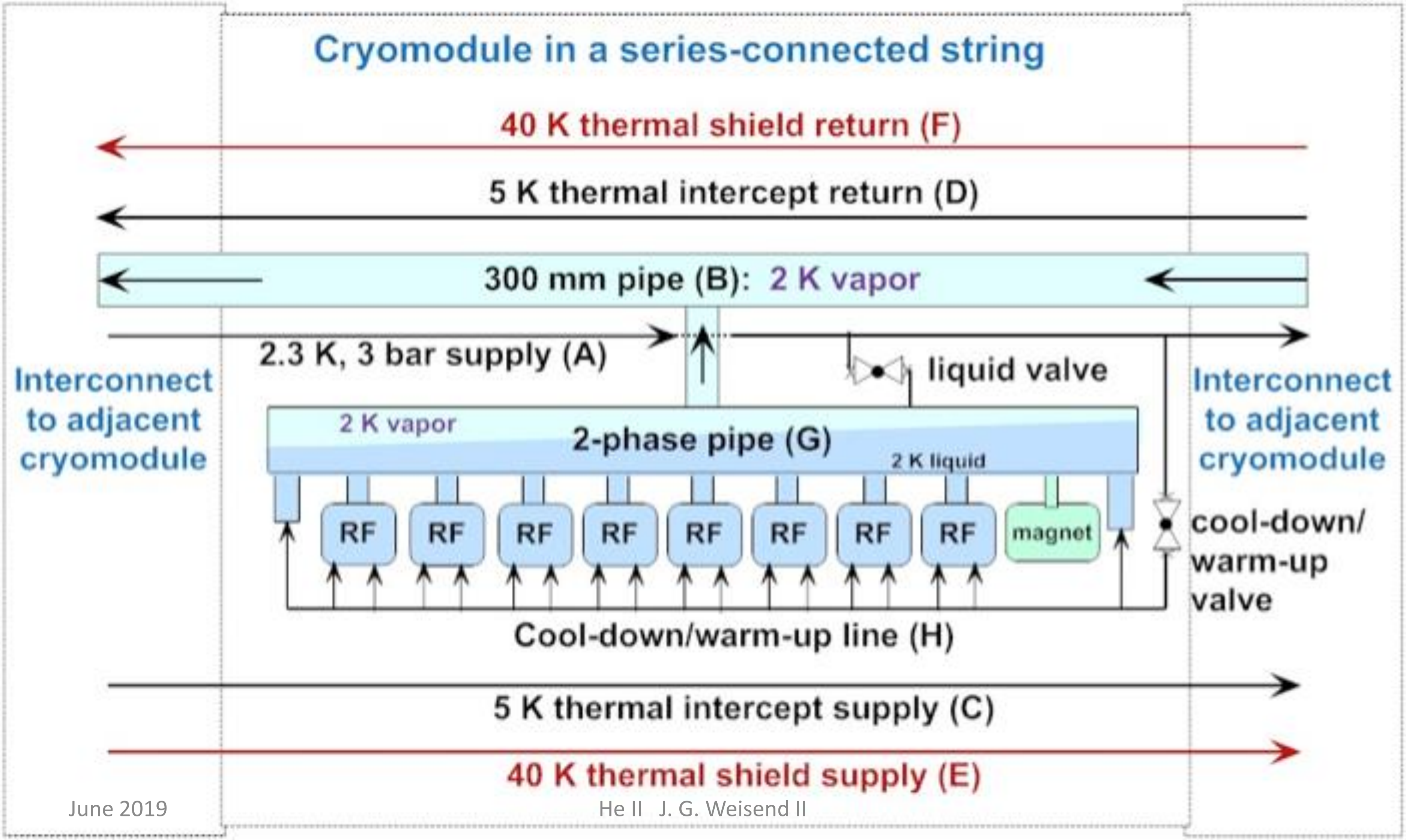
He II Cooling in The European XFEL (Continuous Cooling)



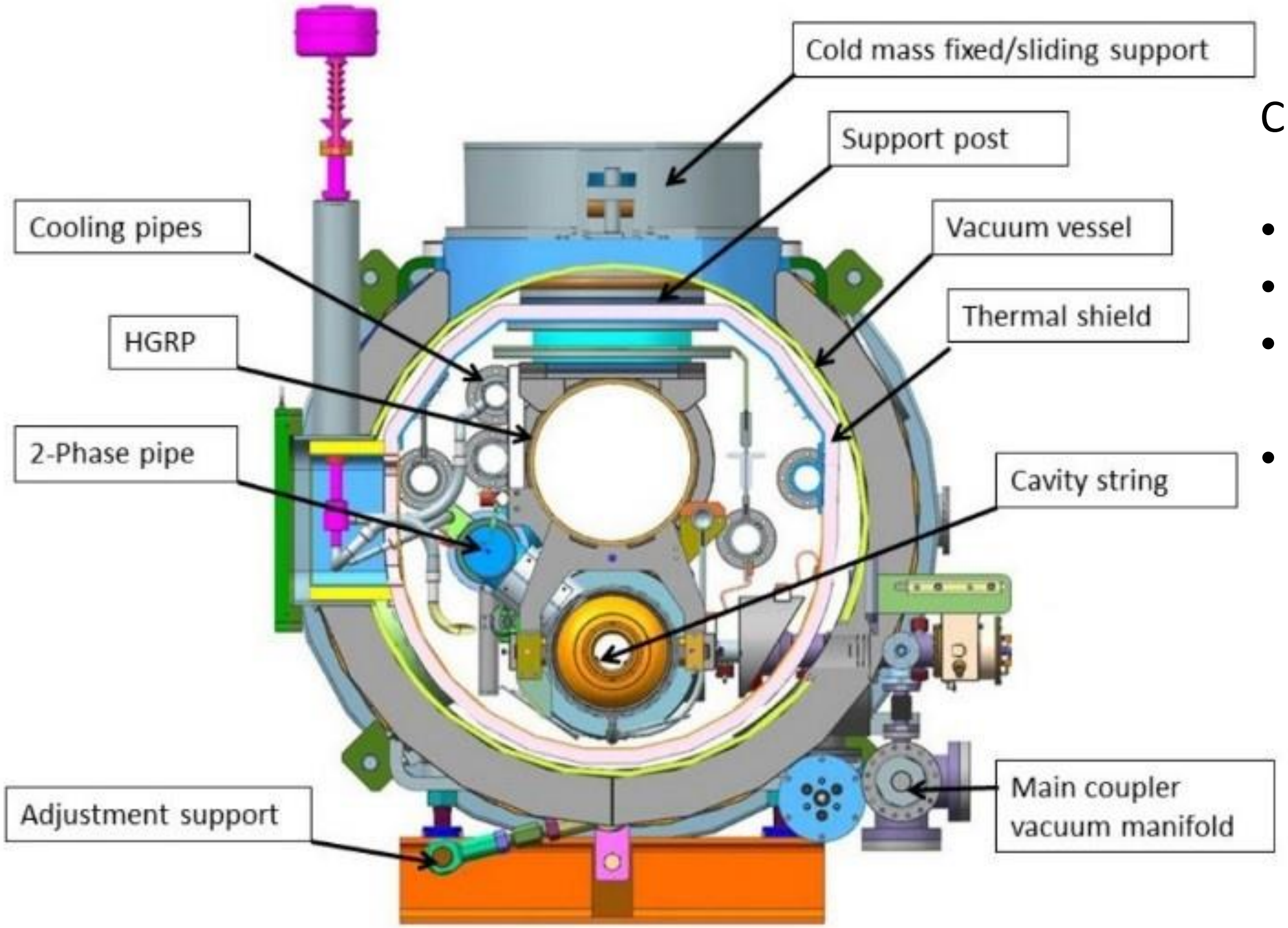
He II Cooling in LCLS II

- LCLS-II uses a version of continuous cooling
  - 2/4 K heat exchanger at the at the distribution boxes in the start of each linac (upstream and downstream)
  - Distribution of 2 K pressurized He throughout each linac
  - Individual JT valves at each cryomodule
  - Individual 2 phase lines at each cryomodule
  - Shared low pressure gas return line in each linac
- Why the difference?
  - High dynamic heat loads in each cryomodule and tunnel slope make this an optimum solution
    - Otherwise, very large flows of two-phase He II would be required
    - Tunnel slope makes individual 2 phase lines at each cryomodule desirable

He II Cooling in LCLS II



Cross Section of LCLS II Cryomodule



Changes from ILC/XFEL design

- Larger 2 He II Chimney
- Larger HGRP
- Individual JT and Cooldown valves
- No 5 K thermal shield
    - Higher heat load
    - Fewer cryomodules

He II Summary

- He II is a unique fluid that displays quantum behavior on a macroscopic scale
- He II has significant applications in large scale cryogenics for scientific research & has become the most common approach for cooling SRF systems
- Depending on requirements, a number of different cooling arrangements exist for SRF systems
  - All start with internal convection within the He II bath
- Despite its unique properties, the use of He II in industrial scale engineering applications is well understood and significant experience exists: ESS, LHC, Jlab, LCLS II