Course of RF for Accelerators

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November/December 2020 cerncourier.com Reporting on international high-energy physics

ADVANCING
CAVITY
TECHNOLOGY

Neutrinos for peace
Feebly interacting particles
ALICE's dark side

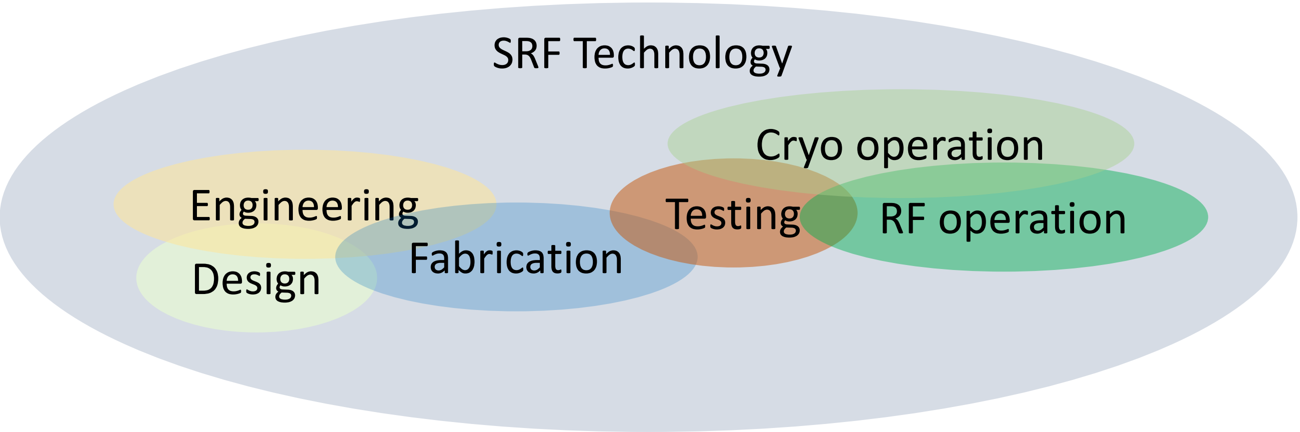
SRF Cavities

[Mostly about Technology]

Paolo Pierini, ESS

This week:

Theory of EM fields I-II
Overview Cavities I-II
RF measurements I-II
EM simulations I-II



SRF Technology

Engineering
Design
Fabrication
Testing
Cryo operation
RF operation

Next week:

LLRF I-III
Beam Loading
Power coupling

Multipacting
HOM

Glad Midsommar!

Credits, N.Elias, ESS

Outline

- Part I
  - Why SRF?
    - Surface resistance
    - Choice of temperature & thermodynamics aspects
  - From Design to Fabrication & Preparation
    - Material
    - Fabrication
    - Surface preparation (chemical processing) and preservation
    - Cavity ancillaries (tuners, couplers, …)
- Part II
  - The Environment: Cryomodule fundamentals
    - Carnot cycle & efficiency, cryoplants and cryomodules
    - Cooling, heat loads, mass flows
- Part III
  - Testing & operation of Cryomodules

Remember Thermodynamics & its laws
0 - Thermal Equilibrium
1 - Conservation of energy ($\Delta U = Q - W$)
2 - Entropy never decreases ($\Delta S \geq 0$)

The environment

Cryoplant and cryomodules

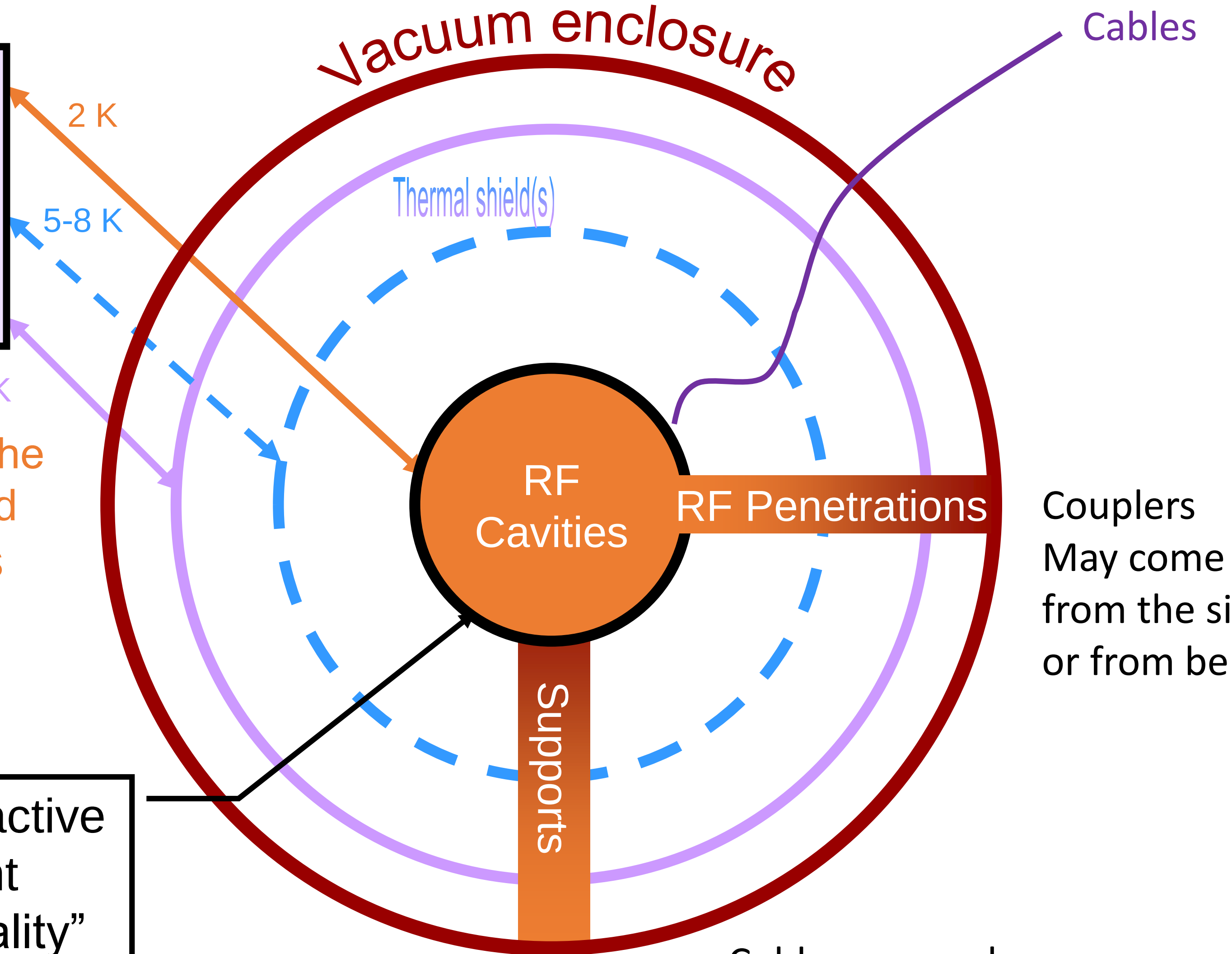
P. Pierini, Fundamental of Cryogenics for SRF, CAS School on High Power Hadron Machines, 2011

Basic Functions of cryomodules

- In SRF application the cryomodule provides:
  - **Cryogenic environment** for the cold mass operation
    - Cavities/Magnets in their vessels filled with sub atmospheric He at 2 K
    - He coolant distribution at required temperatures
    - Low losses penetrations for RF, cryogenics and instrumentation
  - **Shield for the sources of “parasitical” heat transfer** from room to cryogenics temperature produced by three mechanisms
    - thermal radiation
    - conduction
    - convection
  - **Structural support** of the cold mass
    - Issues concerning different thermal contractions of materials
    - Provide precise alignment capabilities and reproducibility with thermal cycling
- Contains a variety of complex technological objects: cavities, ancillaries, magnets, BPMs

The cryogenic environment: a“cartoon” view

To He production and distribution system



All “spurious” sources of heat losses to the 2 K circuits need to be properly managed and intercepted at higher temperatures (e.g. conduction from penetration and supports, thermal radiation)

Cavities are the accelerator active devices with alignment constraints for beam “quality”

Couplers
May come
from the side
or from below

Cold mass can be
supported/suspended from top

Cooling accelerator components

- Usually designer focus is on the component (cavities/magnets)
- The cooling mode, heat transfer mechanisms, fluid pressure drops, cooldown and warmup procedure, transient operation conditions need to be considered early in the component design
  - They can affect the complexity of the cooling system
- The cooled system has to be viewed as part of the overall cryogenic system
  - especially for big machines, where tradoff need to be made between components and support infrastructure

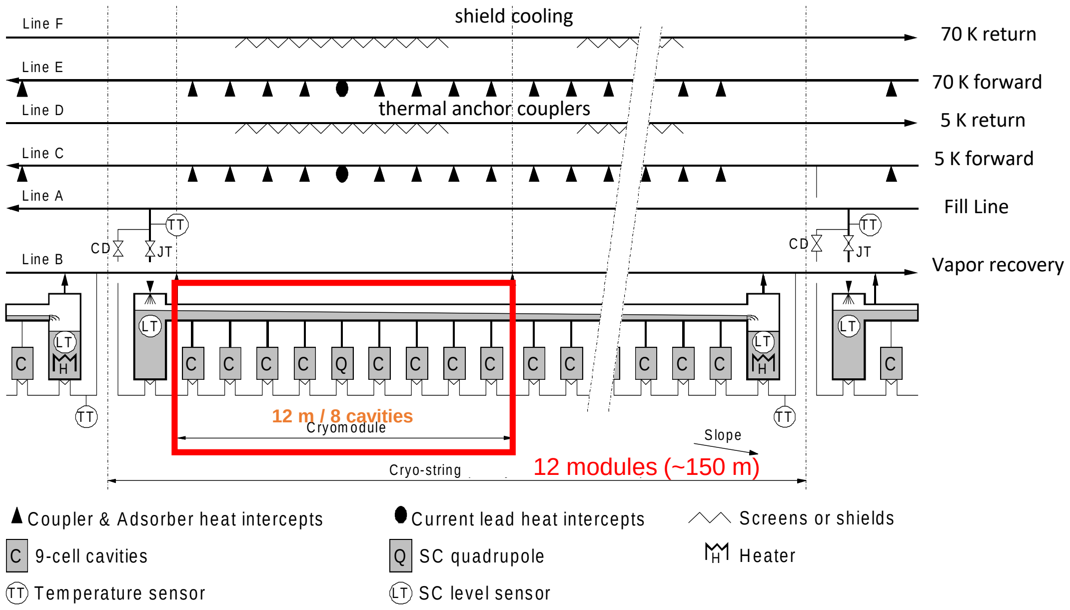
Engineering practices for cryomodule design

- **Thermal design**
  - Minimization of spurious heat loads at the coldest temperatures
  - Heat removal at various temperature levels (for the device operation and for the thermal intercepts)
  - Add provisions for cooldown and warmup, where the large enthalpy content of the cold mass need to be carried away
- **Mechanical design**
  - Support the devices with minimal heat losses
  - Support gravity, vacuum and pressure loads
  - Deal with stresses due to thermal gradients during transient conditions and operation
  - Implement alignment of the sensitive components, and their preservation under differential thermal contractions
- **“Hydraulics” design**
  - Integrate cooling circuits in the cryogenic system

Design at the two extremes

- String Concept (ILC/XFEL)
  - Cryo-strings of connected CM with many cavities
    - High Filling Factor, low cost
    - The CM integrates the He lines
    - Low static losses

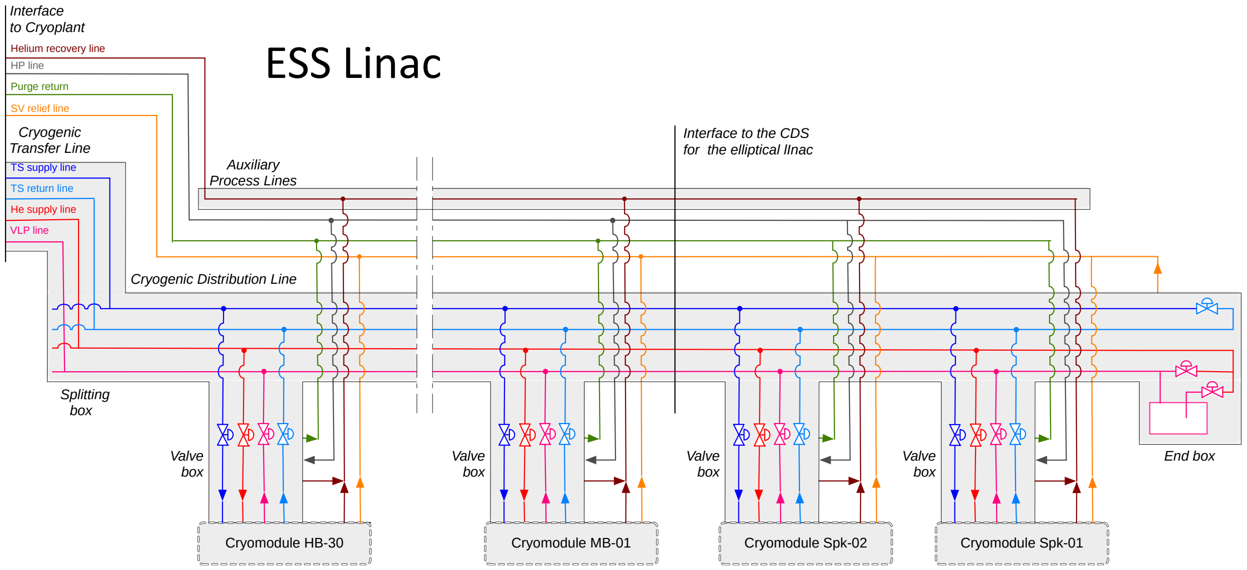
- Segmented linac
  - Each CM is fed individually
    - Lower filling factor, but warm Magnets
    - A separate He distribution line required
    - Higher static, meant for high RF load



12 m / 8 cavities

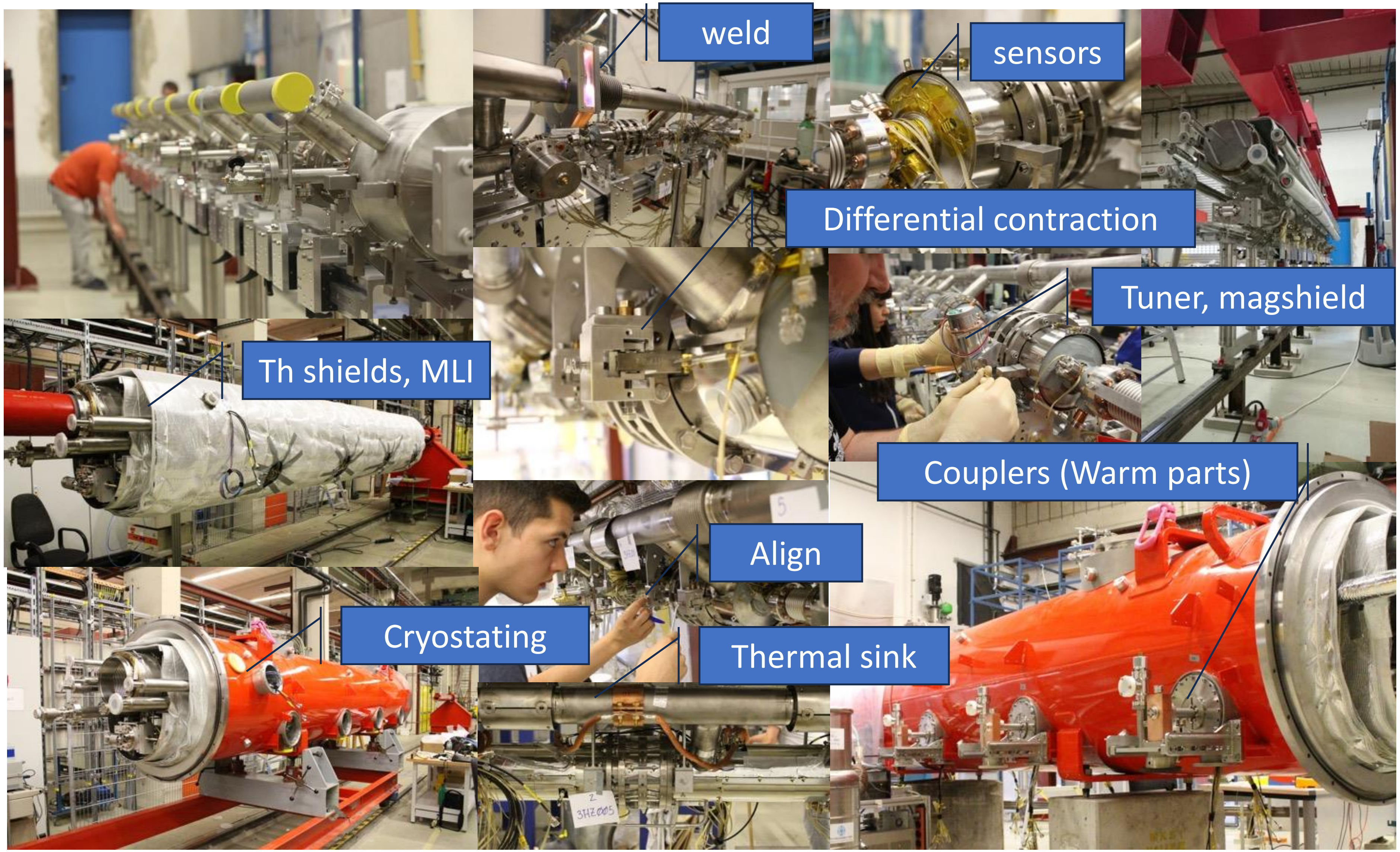
12 modules (~150 m)

1 CM static ~ 1-4 W (9 Cav, 1 Q, 12 m)


ESS Linac

1 CM static ~ 15-20 W (2-4 Cav, 2-6 m)

Building a CM: quite some work


weld

sensors

Differential contraction

Tuner, magshield

Th shields, MLI

Couplers (Warm parts)

Align

Cryostating

Thermal sink

Can’t beat Carnot

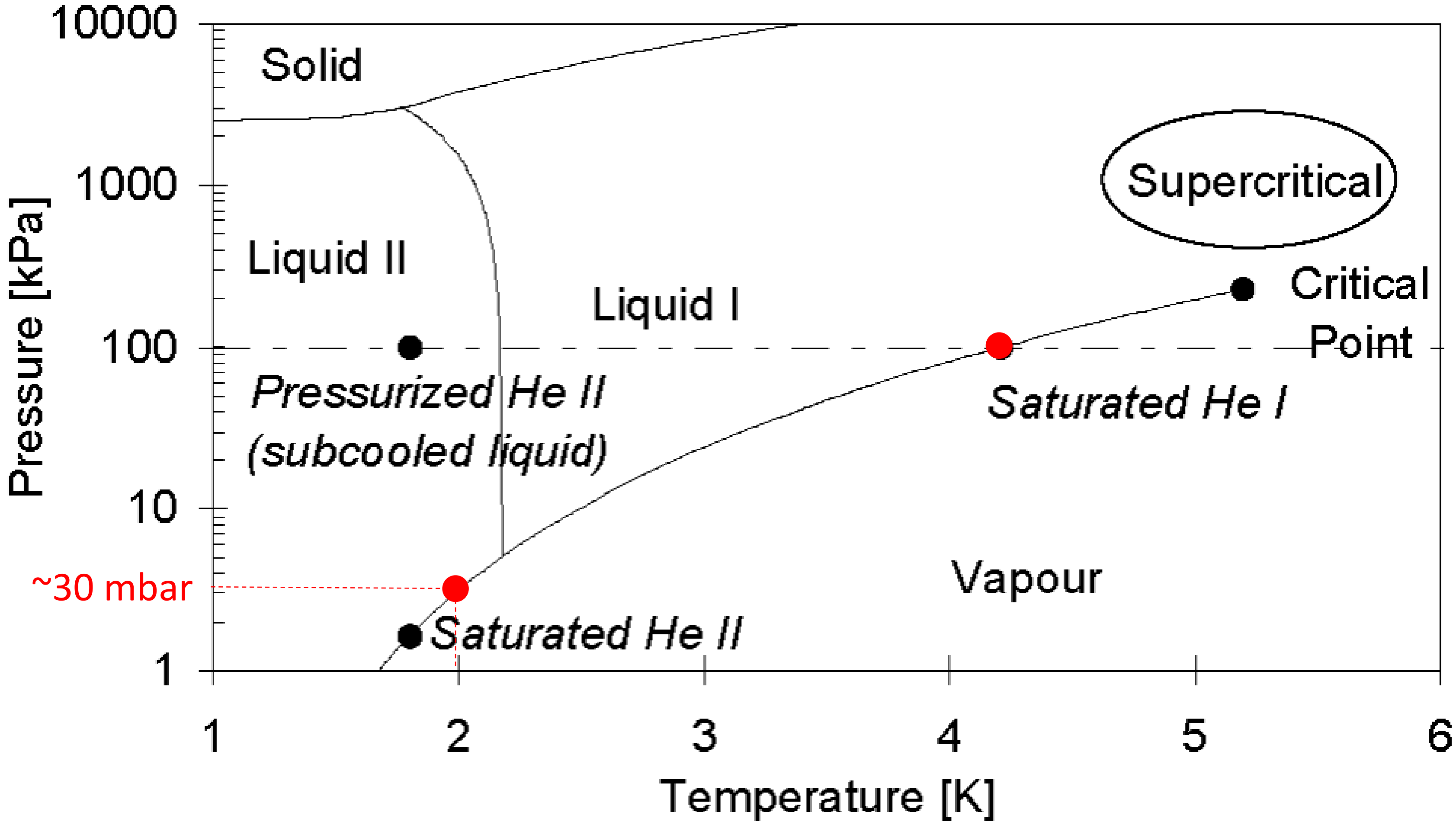
While we gain RF power dissipation with respect to a normal conducting structure

$$W = Q \cdot \frac{T_h - T_c}{T_c} \cdot \eta_{th}$$

- We have to pay the price of supplying coolant at 2K
  - This include ideal Carnot cycle efficiency
  - Mechanical efficiency of compressors and refrigeration items
  - Cryo-losses for supplying and transport of cryogenics coolants
  - Static losses to maintain the linac cold

The P-T phase diagram for ^{4}He

- Vapor saturated He II bath - 2 K 30 mbar
- Saturated He I bath - 4.2 K, 1 bar



Heat removal by He

- Generally speaking, heat is removed by increasing the energy content of the cooling fluid
  - Heating the vapor
    - e.g. in the thermal shields
  - Using the energy for the phase transition from liquid to vapor
    - In the 2 K bath this is the mechanism (He below superfluid transition!)
      - heat is absorbed by evaporation in isothermal conditions

Enthalpy!

- Cooling capacity is then related to the enthalpy difference between the input and output helium (and directly $\propto$ to the $\dot{m}$)
- The rest is “piping” design to ensure the proper **mass flow, convective exchange coefficient, pressure drop analysis, …**

Evaporative cooling

- LHe
  - subatmospheric @ 2 K
  - 1 bar boiling @ 4.2 K
  - ΔH ~ 20 J/g
- LN2 boiling at 77 K
  - ΔH ~ 200 J/g
- Water boiling at 100 °C
  - ΔH ~ 2200 J/g

- Note that big losses at the cold temperature of 2 K in LHe imply
  - big mass flow of low pressure gas
  - large volumetric flow

$$P_{removed}[\mathrm{W}] = m_{flow}[\mathrm{g/s}]/\Delta h[\mathrm{J/g}]$$

Fluid properties: He

J. Weisend; Handbook of Cryogenic Engineering, Taylor & Francis, 1998

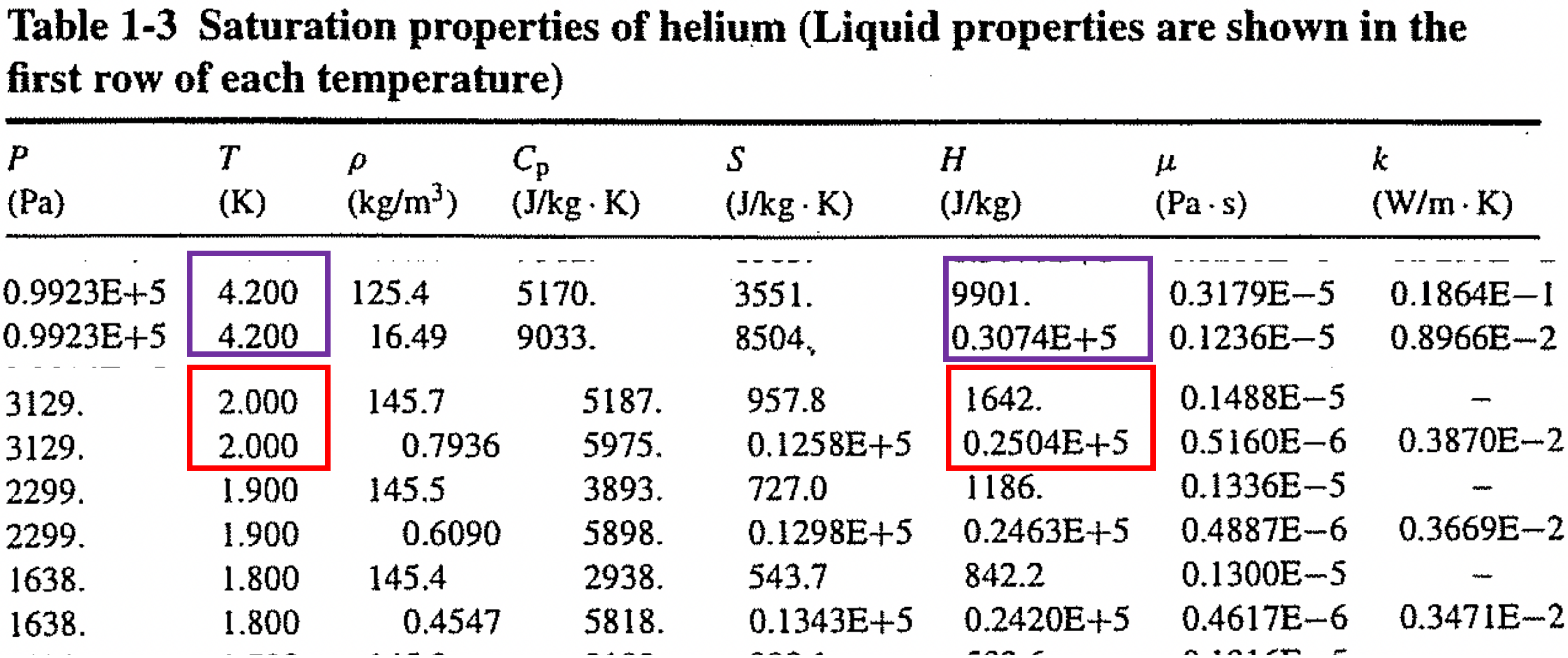


Table 1-3 Saturation properties of helium (Liquid properties are shown in the first row of each temperature)

P (Pa)	T (K)	ρ (kg/m^3)	C_p (J/kg · K)	S (J/kg · K)	H (J/kg)	μ (Pa · s)	k (W/m · K)
0.9923E+5	4.200	125.4	5170.	3551.	9901.	0.3179E−5	0.1864E−1
0.9923E+5	4.200	16.49	9033.	8504.	0.3074E+5	0.1236E−5	0.8966E−2
3129.	2.000	145.7	5187.	957.8	1642.	0.1488E−5	–
3129.	2.000	0.7936	5975.	0.1258E+5	0.2504E+5	0.5160E−6	0.3870E−2
2299.	1.900	145.5	3893.	727.0	1186.	0.1336E−5	–
2299.	1.900	0.6090	5898.	0.1298E+5	0.2463E+5	0.4887E−6	0.3669E−2
1638.	1.800	145.4	2938.	543.7	842.2	0.1300E−5	–
1638.	1.800	0.4547	5818.	0.1343E+5	0.2420E+5	0.4617E−6	0.3471E−2

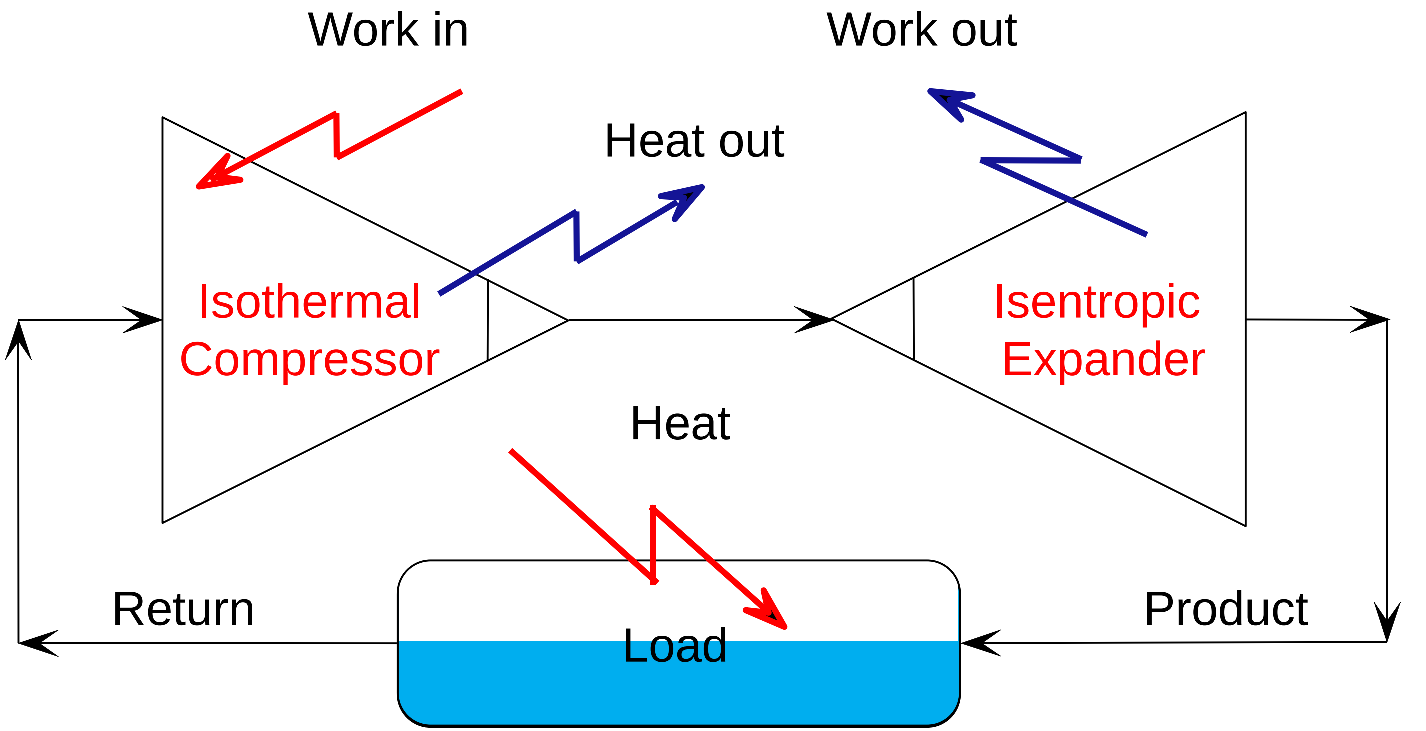
$\Delta h = 20.8\ \mathrm{J/g}$ $\Delta h = 23.4\ \mathrm{J/g}$

The helium refrigeration process

- A conceptually simple (but impractical) helium liquefier could consist of just two processes or steps
  - **Isothermal compression**
    - Reduce He entropy
  - **Isentropic expansion**
    - Removes energy as work
  - This process illustrates the derivation of the thermodynamic limits for a helium refrigerator
- Real processes add one more feature: heat exchangers

Ideal He process

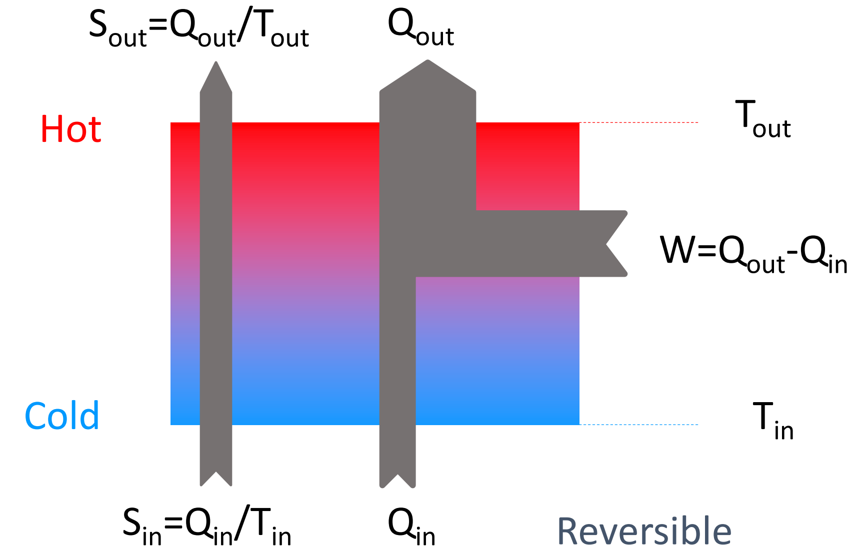
From T. Peterson, FNAL

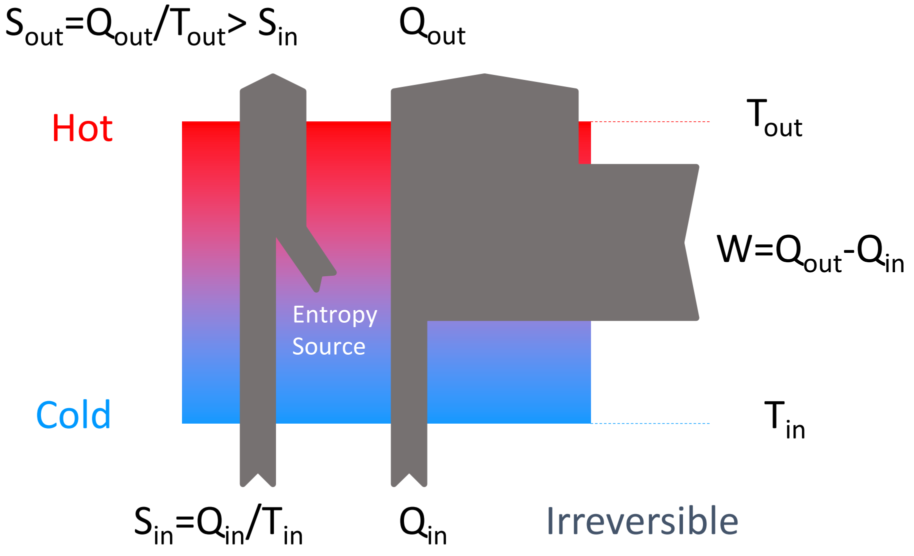


- Net ideal work goes into the system
- Heat load is absorbed by evaporation (isothermal load)
- Ratio of applied work to heat absorbed: $T_{amb}/T_{liquid} - 1 \sim T_{amb}/T_{liquid}$
- Real plants include several stages of intermediate temperature expanders

Heat pumps as Entropy pumps

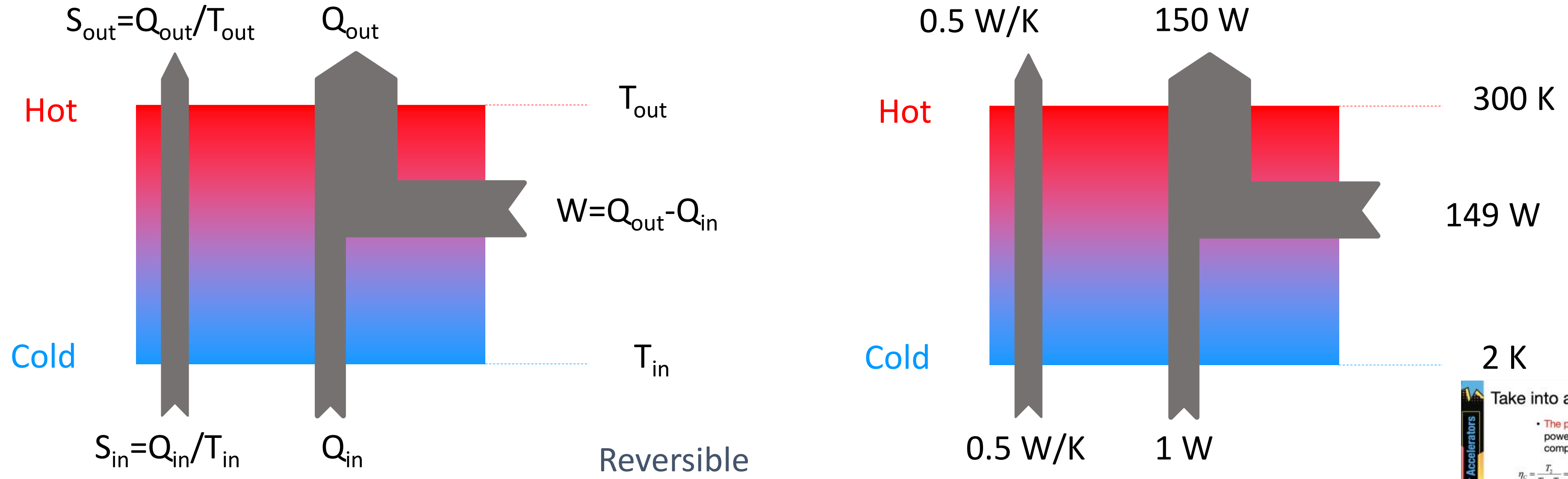
From J. Schmidt, CERN, CAS 1995





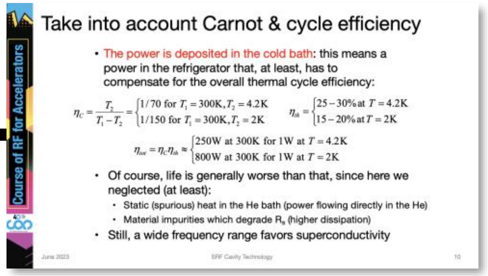
- Entropy is the function of state that allows understanding cryogenic systems
- Cryogenic systems are entropy pumps, which move entropy from the cold devices into a warmer environment
  - We need to provide them energy (i.e. perform work)
- All nonidealities (entropy sources associated to the thermal machine) lead to higher work needed
  - Spurious heat transfers, entropy changes due to compression, expansion, heat exhangers, gas leaks, etc.

What is our non ideality level?



Reversible

Yesterday…


Take into account Carnot & cycle efficiency

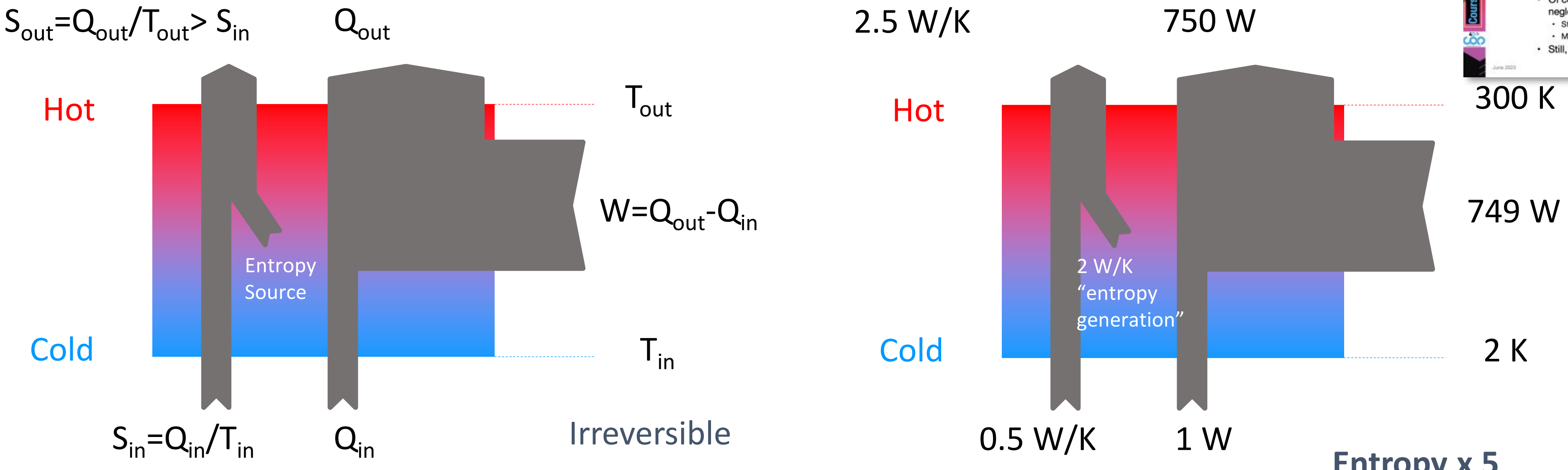
- The power is deposited in the cold bath: this means a power in the refrigerator that, at least, has to compensate for the overall thermal cycle efficiency:

$$\eta_C = \frac{T_2}{T_1 - T_2} = \begin{cases} 1/70 \text{ for } T_1 = 300\text{K}, T_2 = 4.2\text{K} \\ 1/150 \text{ for } T_1 = 300\text{K}, T_2 = 2\text{K} \end{cases} \qquad \eta_{th} = \begin{cases} 25-30\% \text{ at } T = 4.2\text{K} \\ 15-20\% \text{ at } T = 2\text{K} \end{cases}$$

$$\eta_{tot} = \eta_C \eta_{th} \approx \begin{cases} 250\text{W at } 300\text{K for } 1\text{W at } T = 4.2\text{K} \\ 800\text{W at } 300\text{K for } 1\text{W at } T = 2\text{K} \end{cases}$$

- Of course, life is generally worse than that, since here we neglected (at least):
  - Static (spurious) heat in the He bath (power flowing directly in the He)
  - Material impurities which degrade R_s (higher dissipation)
- Still, a wide frequency range favors superconductivity

June 2023 SRF Cavity Technology 10

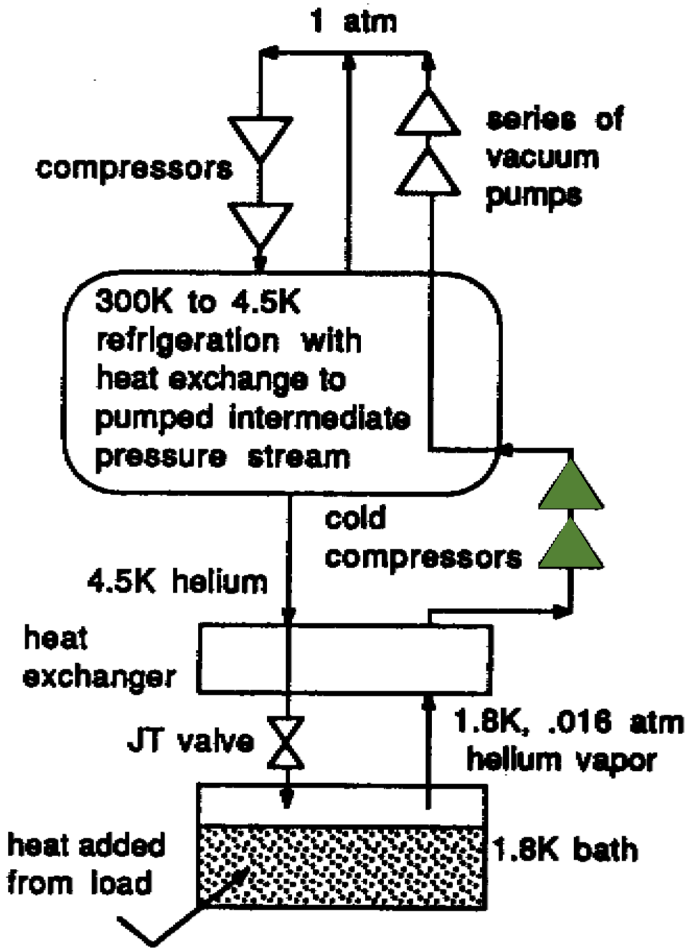


Irreversible

Entropy x 5

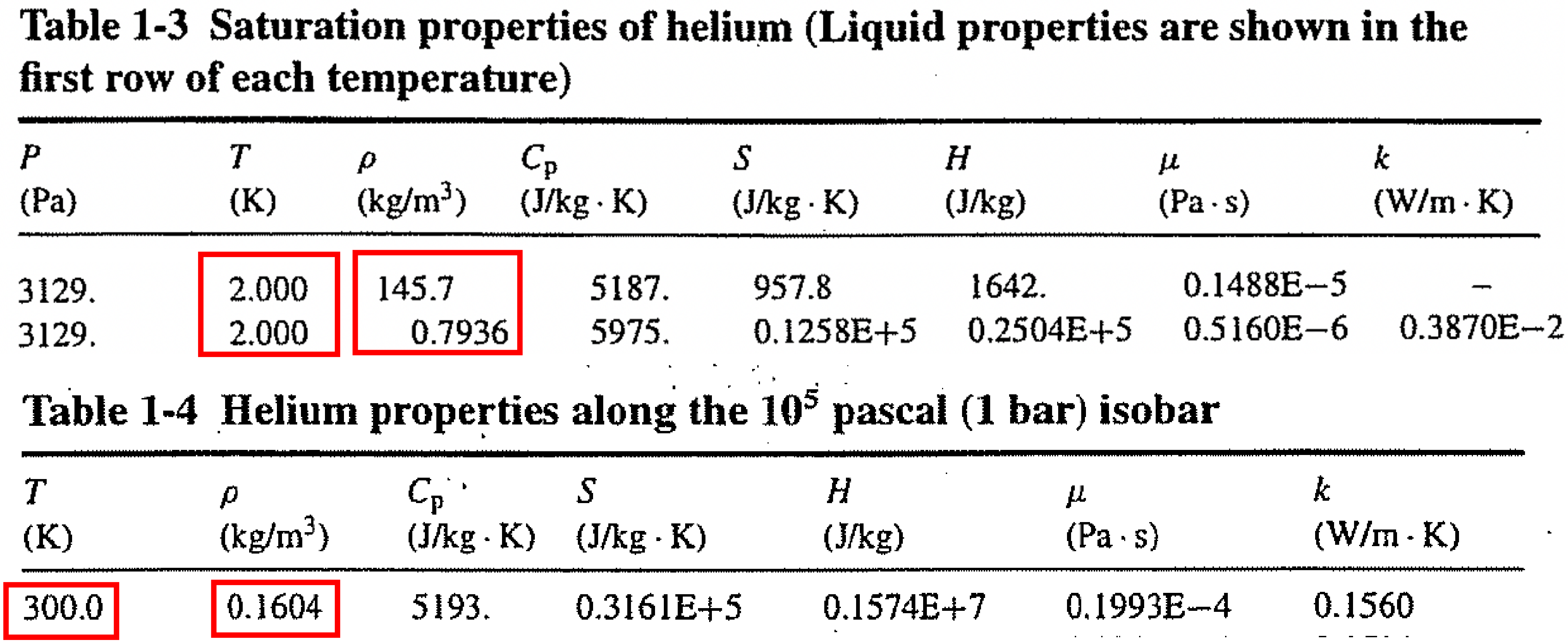
How to deploy large cooling < 4.2 K

- Temperatures lower than 4.2 K means sub-atmospheric pressure conditions for the He bath where we want to extract the dissipated power
- But with high heat loads and low pressures the gas volume flow from the bath becomes large
  - again, latent heat of evaporation is only approximately 20 J/g
  - cold compressors are needed to increase pressure conditions before the He gas reaches room temperature conditions



Fluid properties: He

J. Weisend; Handbook of Cryogenic Engineering, Taylor & Francis, 1998



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3129.	2.000	145.7	5187.	957.8	1642.	0.1488E−5	–
3129.	2.000	0.7936	5975.	0.1258E+5	0.2504E+5	0.5160E−6	0.3870E−2

Table 1-4 Helium properties along the 10^5 pascal (1 bar) isobar

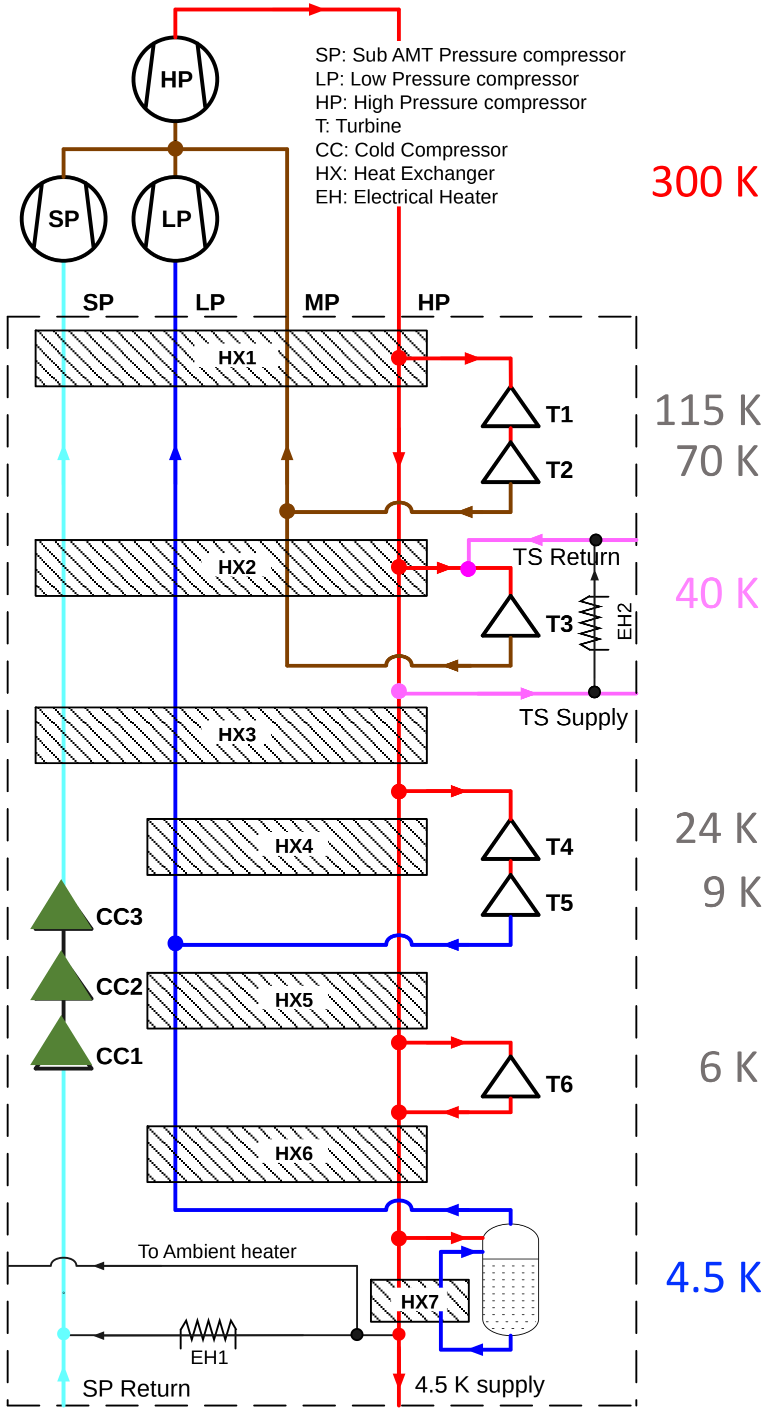
T (K)	ρ (kg/m^3)	C_p (J/kg · K)	S (J/kg · K)	H (J/kg)	μ (Pa · s)	k (W/m · K)
300.0	0.1604	5193.	0.3161E+5	0.1574E+7	0.1993E−4	0.1560

1 liter of 2K He goes into ~183 l of cold 2K vapor and eventually expands to ~888 l of room temperature gas at 1 bar…

ESS ACCP

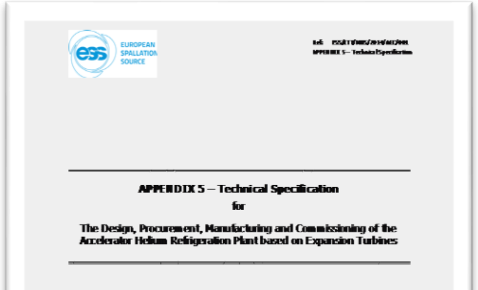
3 kW @ 2 K	Main isothermal load
9 g/s @ 4.5 K	Thermalizations
11 kW @ 40 -50 K	Thermal shields

- Three warm compressors
  - Subatmospheric, low pressure and high pressure
- Six expansion turbines
- Several stages of heat exchangers
- Three cold compressors on the return line
- Capacity control
  - Floating pressure cycle for HP compressor
  - VFD for SP, LP compressors and CCs
  - Exchange of CCs parts
- Energy recovery & efficiency



ACCP - Specification

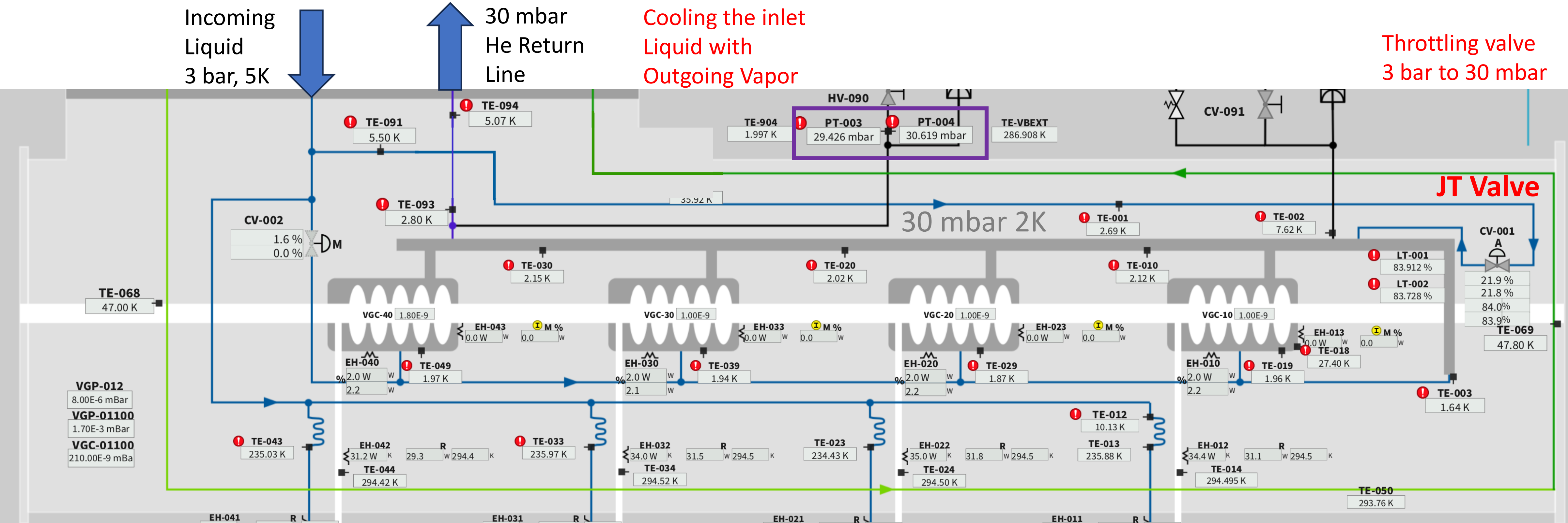
- **Heat loads**:
  - 3 kW @ 2 K (static and dynamic RF)
  - 9 g/s @ 4.5 K (coupler cooling)
  - 11380 W @ 40 -50 K (thermal shields)
- Continuous operation:
  - 24 h per day / 7 days per week
  - 2 years without scheduled shut-down
- Availability: > 99 %
  - not counting utilities & process control
- Two stages and four main opmodes each stage
  - Nominal Design,
  - Nominal TurnDown,
  - TS Standby,
  - 4.5 K Standby
  - Max. Liquefaction mode


EUROPEAN SPALLATION SOURCE

APPENDIX 5 – Technical Specification
for
The Design, Procurement, Manufacturing and Commissioning of the Accelerator Helium Refrigeration Plant based on Expansion Turbines

The last bit… 4K to 2 K

- Usually inside the CM or the valve boxes in the distribution line
- Joule Thompson expansion
  - Needle valve to subatmospheric environment to cool along saturation line
  - Assisted by counterflow HX



Incoming
Liquid
3 bar, 5K

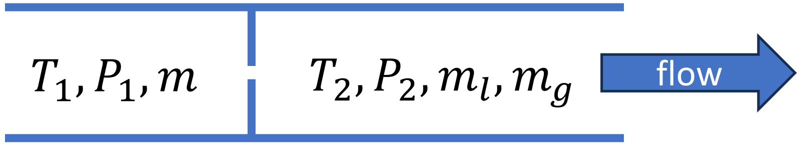
30 mbar
He Return
Line

Cooling the inlet
Liquid with
Outgoing Vapor

Throttling valve
3 bar to 30 mbar

JT Valve

JT: isoenthalpic



- A mass of liquid m enters at T_1 and cools to a mass m_l of liquid and a mass of m_g at 2.0 K. Mass is conserved so $m = m_l + m_g$

$$m h^l_{T_1} = m_l h^l_{2.0} + (m - m_l) h^g_{2.0}$$

Yielding

$$\frac{m_l}{m} = \frac{h^g_{2.0} - h^l_{T_1}}{h^g_{2.0} - h^l_{2.0}}$$

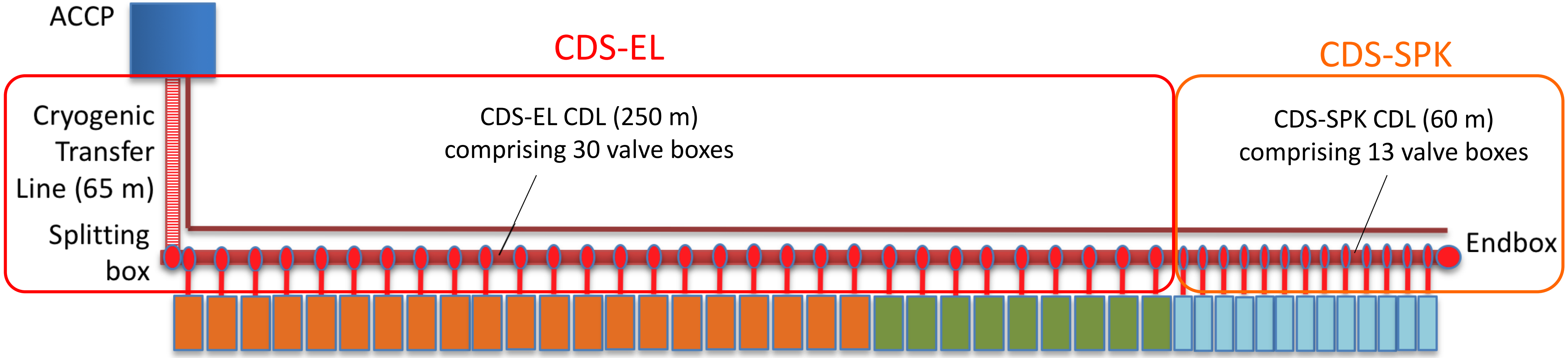
- No HX, $T_1 = 5.0$ K
- HX, $T_1 = 2.7$ K

$$\frac{m_l}{m} = \frac{25.04 - 15.92}{25.04 - 1.642} = 39\%$$

$$\frac{m_l}{m} = \frac{25.04 - 2.155}{25.04 - 1.642} = 97\%$$

The energy to cool the incoming flow is taken from the latent heat of evaporation
Subcooling the flow with the HX improves the efficiency of the process

Cryo distribution system for the ESS linac



ACCP

CDS-EL

CDS-SPK

Cryogenic Transfer Line (65 m)

Splitting box

CDS-EL CDL (250 m) comprising 30 valve boxes

CDS-SPK CDL (60 m) comprising 13 valve boxes

Endbox

21 High-Beta Cryomodules (174 m)

9 Medium-Beta Cryomodules (75 m)

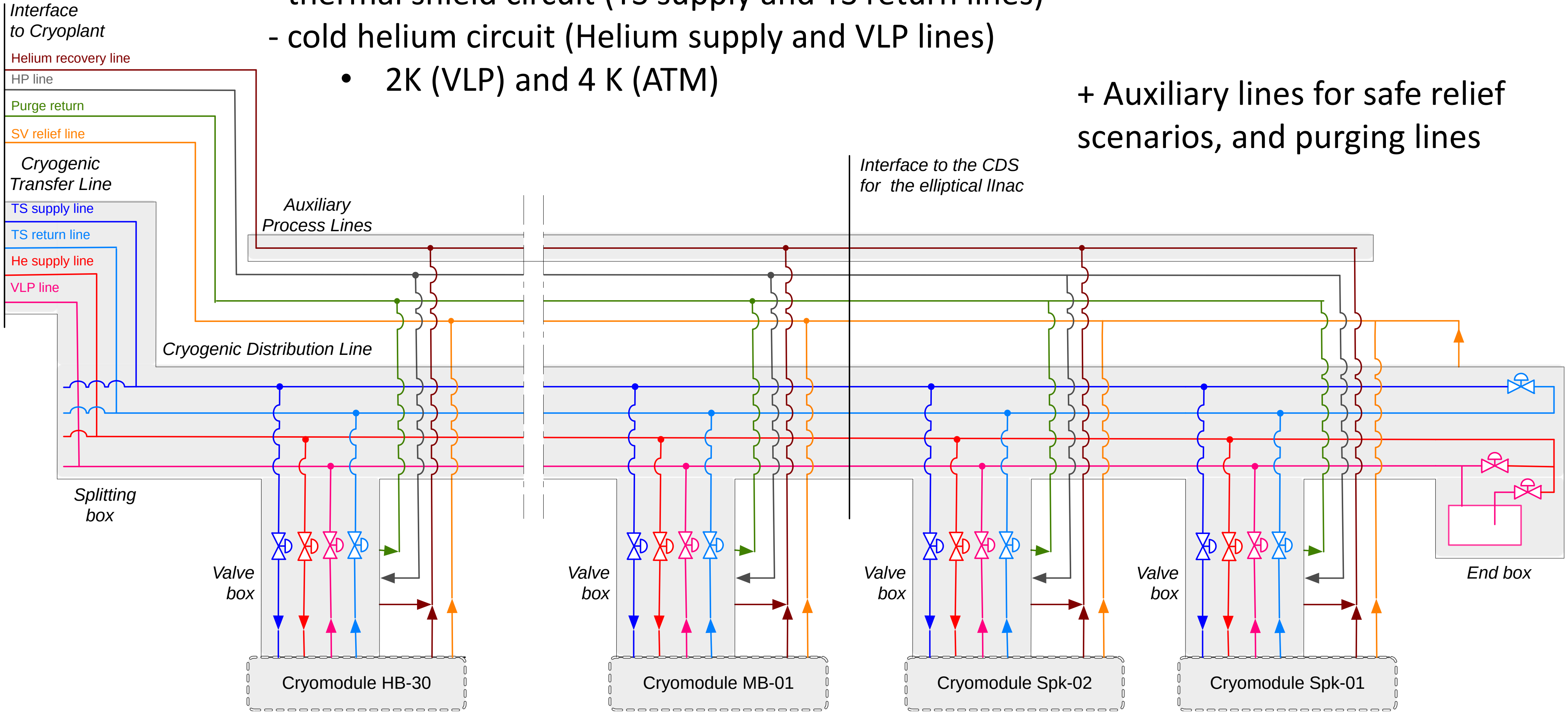
13 Spoke Cryomodules (54 m)

ESS Linac CDS - General flow scheme

Two main cryogenic circuits:

- thermal shield circuit (TS supply and TS return lines)
- cold helium circuit (Helium supply and VLP lines)
  - 2K (VLP) and 4 K (ATM)

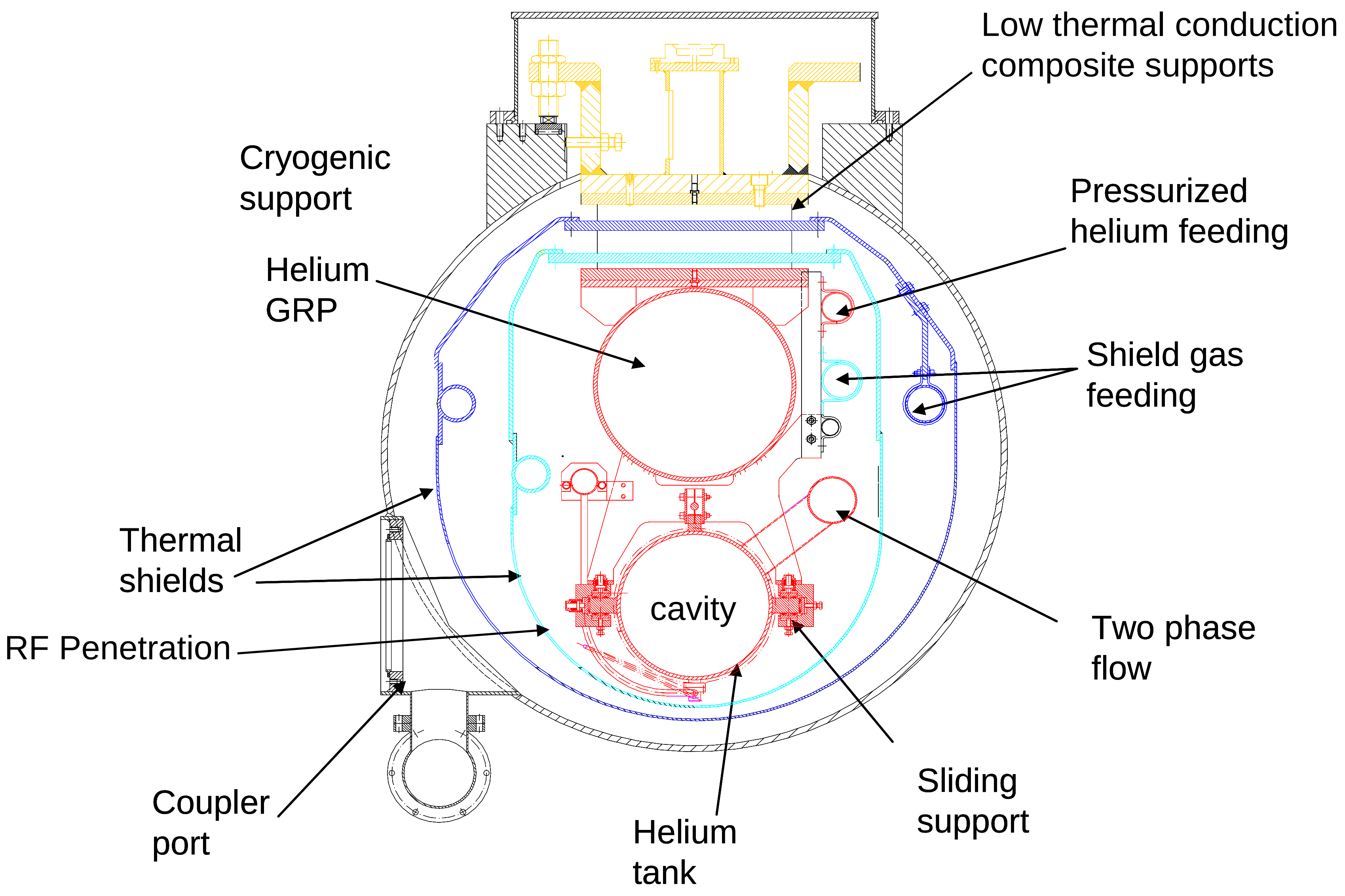
+ Auxiliary lines for safe relief scenarios, and purging lines



30 x Elliptical cryomodules

13 x Spoke cryomodules

Another design – XFEL integrates CM-CDS



CM design

Heat losses issues: Physical mechanisms

- Thermal radiation

$$\dot{Q} = S\varepsilon\sigma_{SB}\left(T_h^4 - T_c^4\right)$$

  - Radiated power from hot surfaces to vanishingly temperatures is proportional to T^4 (Stephan-Boltzmann). σ_{SB} = 5,67·10^{-8} [W m^{-2} K^{-4}]
    - Reduce the surface emissivity, ε (material and geometry issue)
    - Intercept thermal radiation at intermediate temperatures by means of thermal shields
- Heat conduction

$$\dot{Q} = \frac{S}{L}\int_{T_c}^{T_h} k_{th}(T)\,dT$$

  - A SRF module has many penetration from the room temperature environment (RF couplers, cables, …)
    - Proper choice of low thermal conduction, k_{th}, materials whenever possible
    - Minimize thermal paths from r.t. and provide thermalization at intermediate temperatures.
- Convection

$$\dot{Q} = S\,h\left(T_h - T_c\right)$$

  - Convective exchange from r.t. is managed by providing insulation vacuum between the room temperature vessel and the cold mass

Mamagement of radiative load

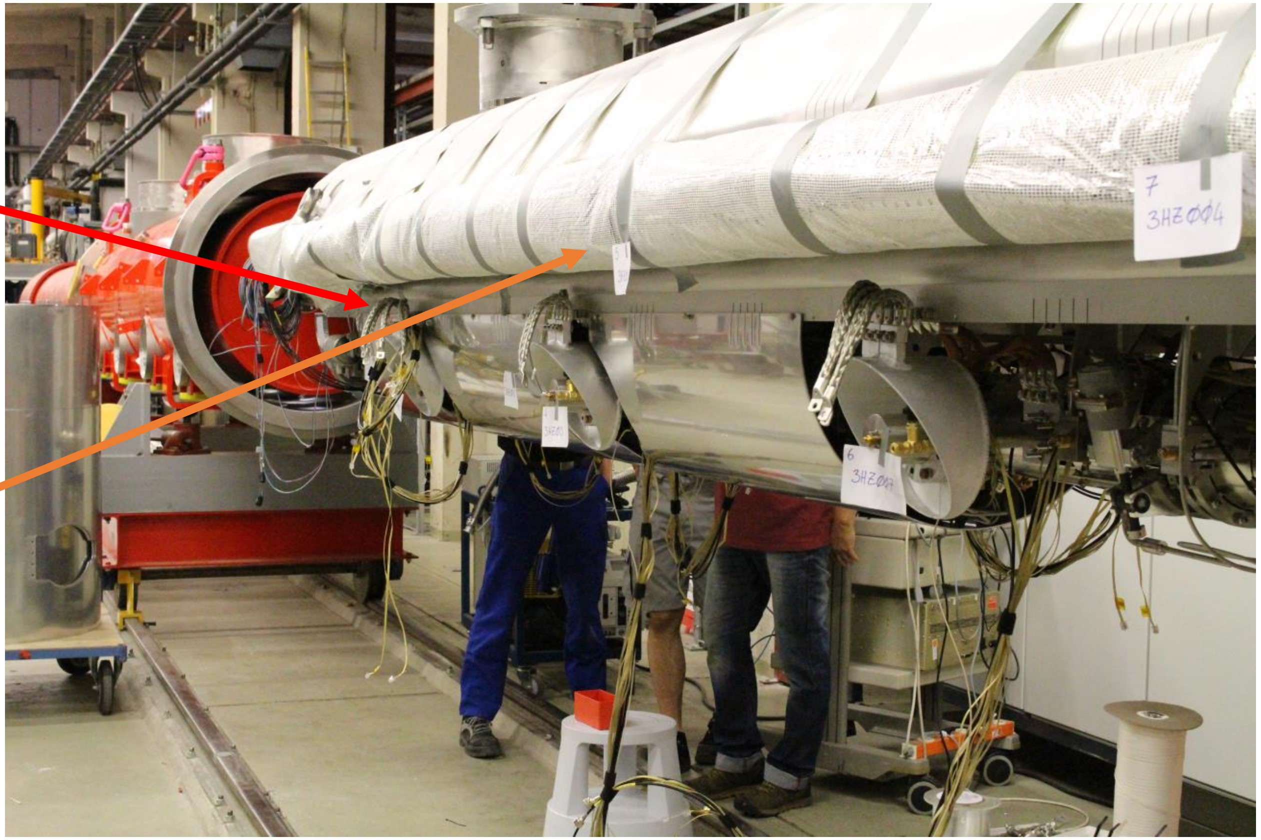
- The first measure is to intercept the thermal flux impinging on the cold surfaces from the room temperature environment with one (or more) thermal screen at actively cooled at higher temperatures
  - E.g. 40 to 80 K Cu or Al shield in all designs for magnets and SRF cavities
- A second effective way to protect the surfaces from radiation load is to wrap them with many “floating” (i.e. radiation cooled) reflective screens
  - Multi Layer Insulation (MLI)
    - Reflective aluminum foils (or aluminized/double aluminized polyester films) separated by an insulating spacer material (a glass-fiber or polyester net or paper foil)
    - Packing density of the layers affects performances, but even more important are the installation procedures
      - don’t leave holes and don’t short circuit layers!

Thermal shields and MLI

- Roles of thermal shield at intermediate temperature:
  - The internal cold mass “sees” a surface at T < 300 K, consequently heat load is reduced
  - Provides thermal interception point to all penetration (couplers, cables, etc)
- Role of MLI (multilayer insulation)
  - “floating” radiation shields to reduce flux

$$\dot{Q} = S\varepsilon\sigma_{SB}\left(T_h^4 - T_c^4\right)$$

Radiation load from 300 K to low temperatures ~ 500 W/m^2 for ε=1 !



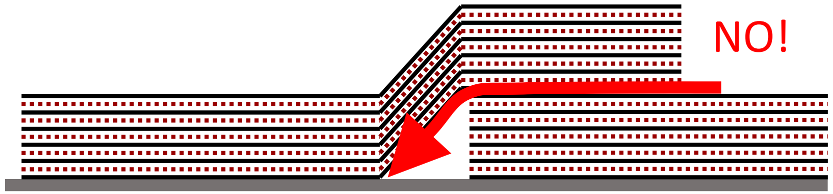
Effective Heat Flux (CERN Data)	W/m^2
MLI (30 layers) from 300 K, P< 1 mPa	1-1.5
MLI (10 layers) from 80 K, P< 1 mPa	0.05

Thermal radiation

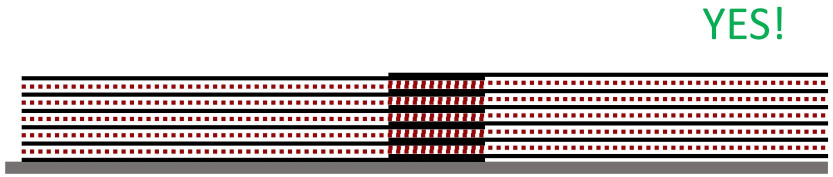
- From hot surfaces to cold mass

Blackbody radiation to negligible temperatures	
Temperature (radiating surface)	Specific heat flux [W/m^2]
300 K	460 W/m^2
70 K	1.4 W/m^2
4.5 K	22 10^{-6} W/m^2

With MLI Insulation	
Temperature (radiating surface)	Specific heat flux [W/m^2] at low T
From 300 K, 30 layers	1.2 W/m^2
From 80 K, 10 layers	0.06 W/m^2



Cold Surface



Cold Surface

Conduction

- Obeys Fourier law

$$\dot{Q} = k(T)\, S\, \nabla T$$

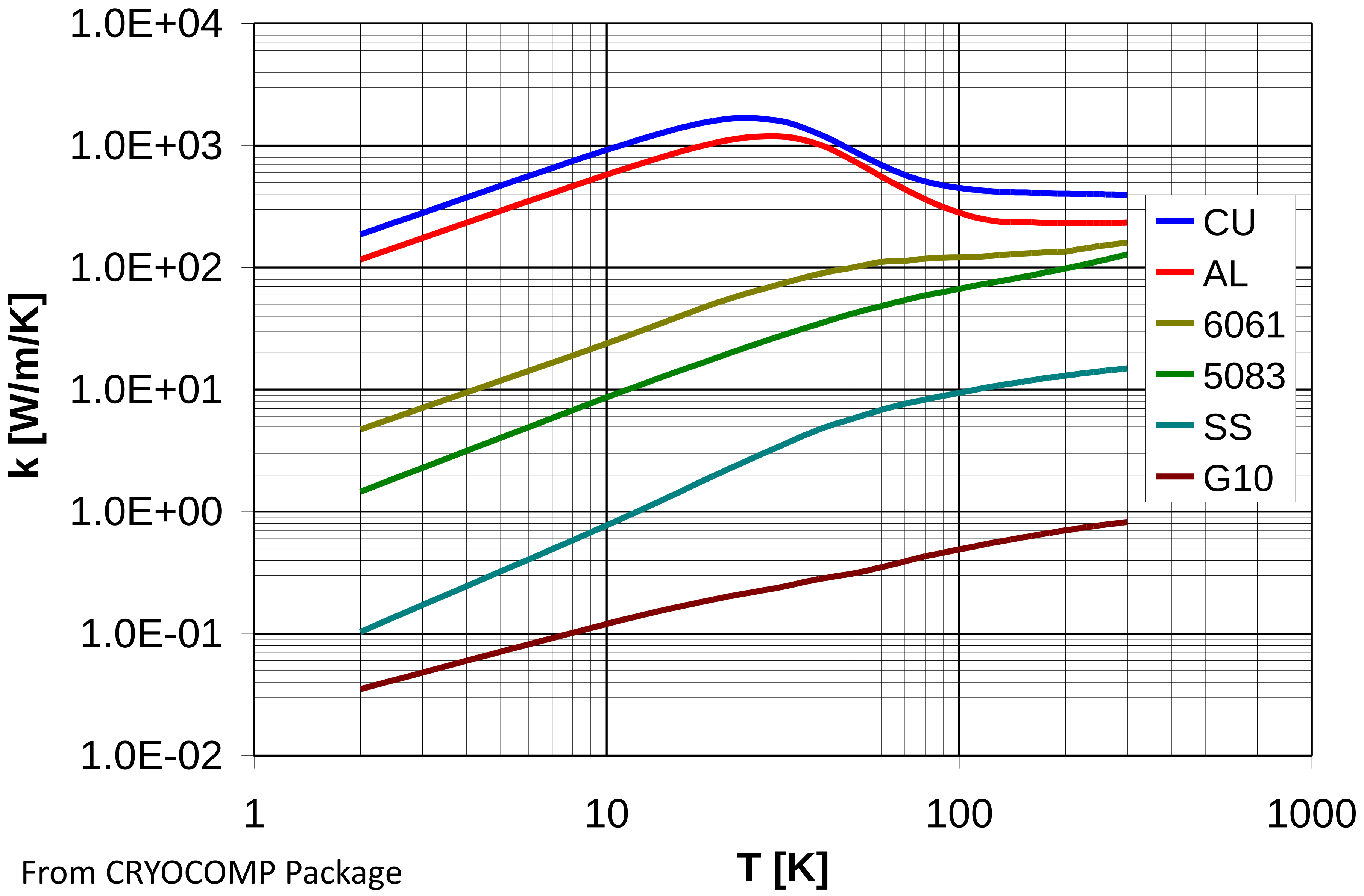
- For a 1D steady state conduction problem of flow through an area *S* over a length *L* with fixed temperatures T_{hot} and T_{cold}, we can write it in the form

$$\dot{Q} = \frac{S}{L}\int_{T_{cold}}^{T_{hot}} k(T)\,dT = \frac{S}{L}\left(\int_{T_{reference}}^{T_{hot}} k(T)\,dT - \int_{T_{reference}}^{T_{cold}} k(T)\,dT\right) =$$

$$= \frac{S}{L}\left(K_{\text{int}}(T_{hot}) - K_{\text{int}}(T_{cold})\right)$$

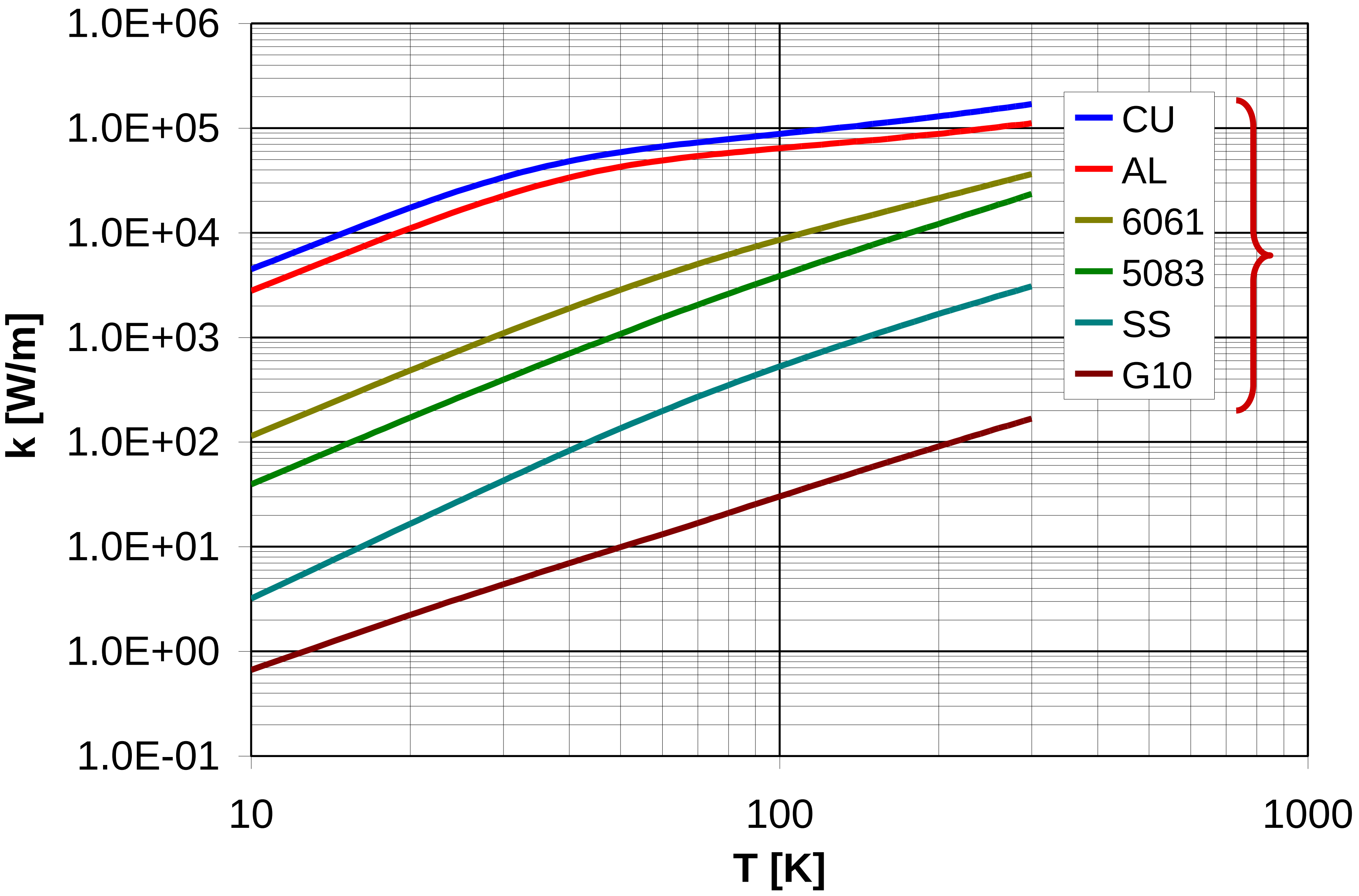
- Thermal conductivity integrals tabulated in literature
- Varies greatly with temperature and with materials, proper choice of material and thermal intercepts for conduction paths to the cold environment is necessary

Temperature dependent thermal conductivity



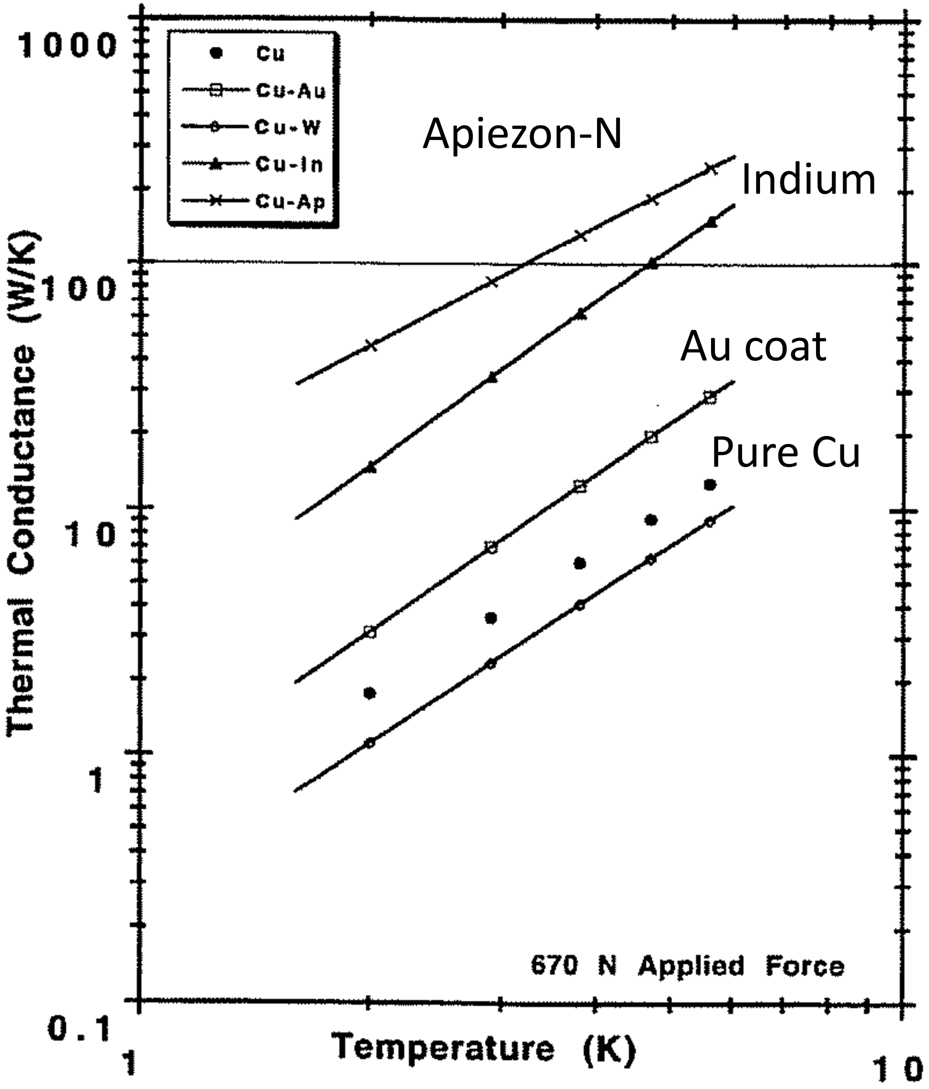
From CRYOCOMP Package

Thermal conduction integral, from 2 K



Thermal contact at interfaces

- Contact between surfaces is made only at discrete locations, not over the full areas
  - Thermal conductance of pressed contacts depend on the applied force and surface finish
  - Oxyde layers on the surface increase the thermal resistance
  - Indium foils or high thermal conductance grease (Apiezon-N) may be used to enhance the thermal contact
- Important issue when making provision for thermal intercepts to prevent heat leaking into cold environment
  - Indium foils most common

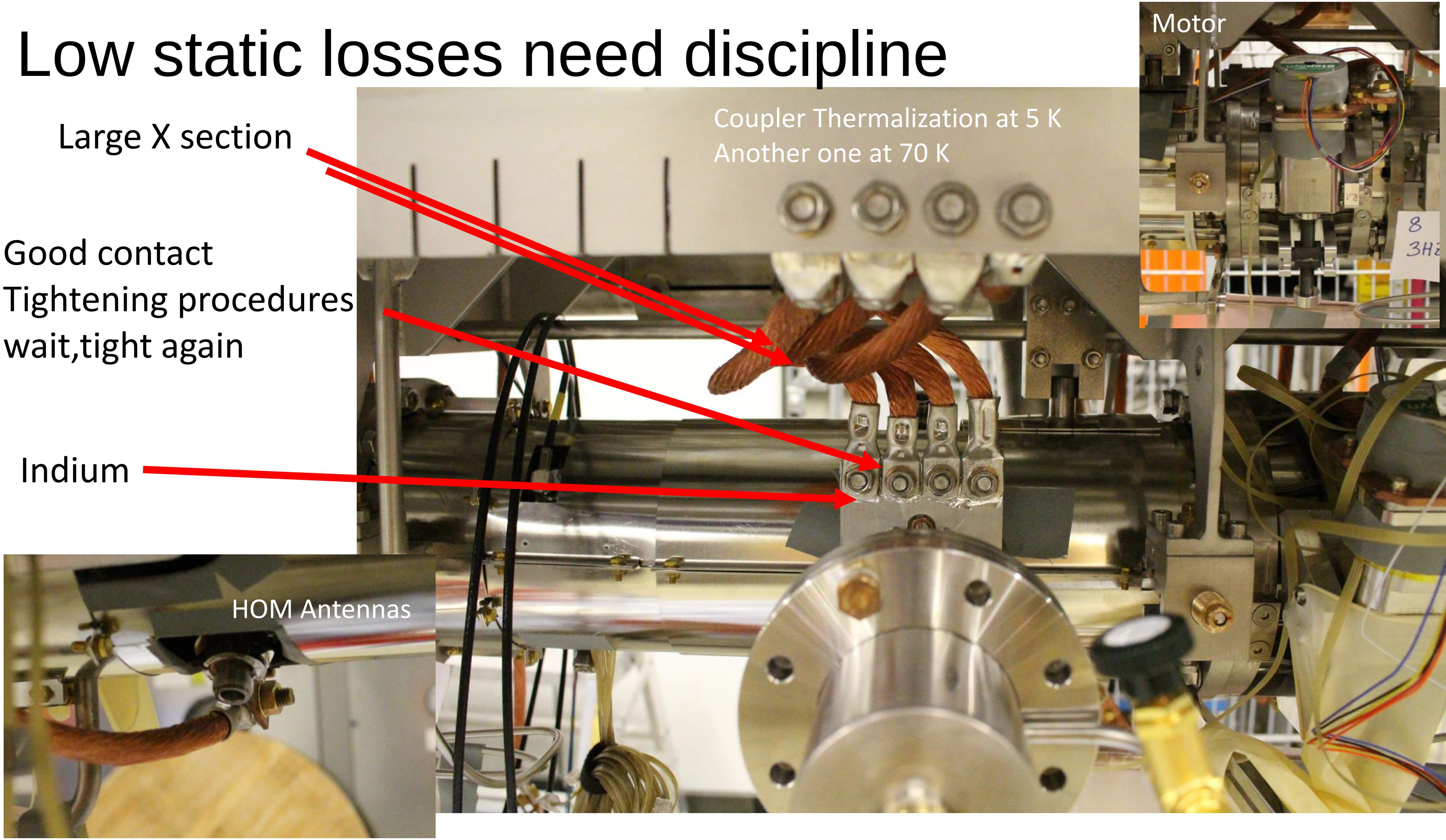


Low static losses need discipline

Large X section

Good contact
Tightening procedures
wait,tight again

Indium



Convection

- Convection is one of the physical mechanism by which we are able to extract heat from our devices and to route it to the cooling fluids flowing in the cryogenic piping
  - Analysis of the convection exchange is necessary to make proper provisions for the cooldown and warmup procedures and for the good work of the thermal intercepts preventing conductive heat leaks
- But also, we need to prevent convective exchanges from the ambient temperature environment to the cold region
  - That's why all the cold devices are ultimately places in a vacuum vessel, where a pressure of 10^{-4}-10^{-3} mbar prevents convective exchange to the low temperature regions
  - i.e. remove the fluid to prevent convective exchanges...

Convection heat transfer

- Heat transfer between a bulk fluid at temperature T_b and a surface of area S at temperature T_w is described by

$$\dot{Q} = S\,h\left(T_w - T_b\right)$$

- Determination of h can be challenging, and is usually done from experimental correlations, via the dimensionless groups

$$Nu = \frac{hD}{k_{th}} \quad \text{(convection/conduction exchanges)}$$

$$Re = \frac{\rho\, v\, D}{\mu} \quad \text{(inertia/viscous forces)}$$

Laminar (<2000) or turbulent (>10^4) flow

$$Pr = \frac{C_p \mu}{k_{th}} \quad \text{(momentum/thermal transport)}$$

Fluid related

Correlations

- Generally

$$Nu = f\left(Re, Pr\right)$$

- Except for the case of HeII, frequently the same correlations used for non-cryogenic fluids can be used
- But correlations are valid for given flow conditions, and the fluid properties need to be evaluated at the proper temperature and pressure conditions
- Many correlations exist in literature, for various geometrical flow configurations and regimes
  - Natural convection
  - Liquid and Gas monophase flows

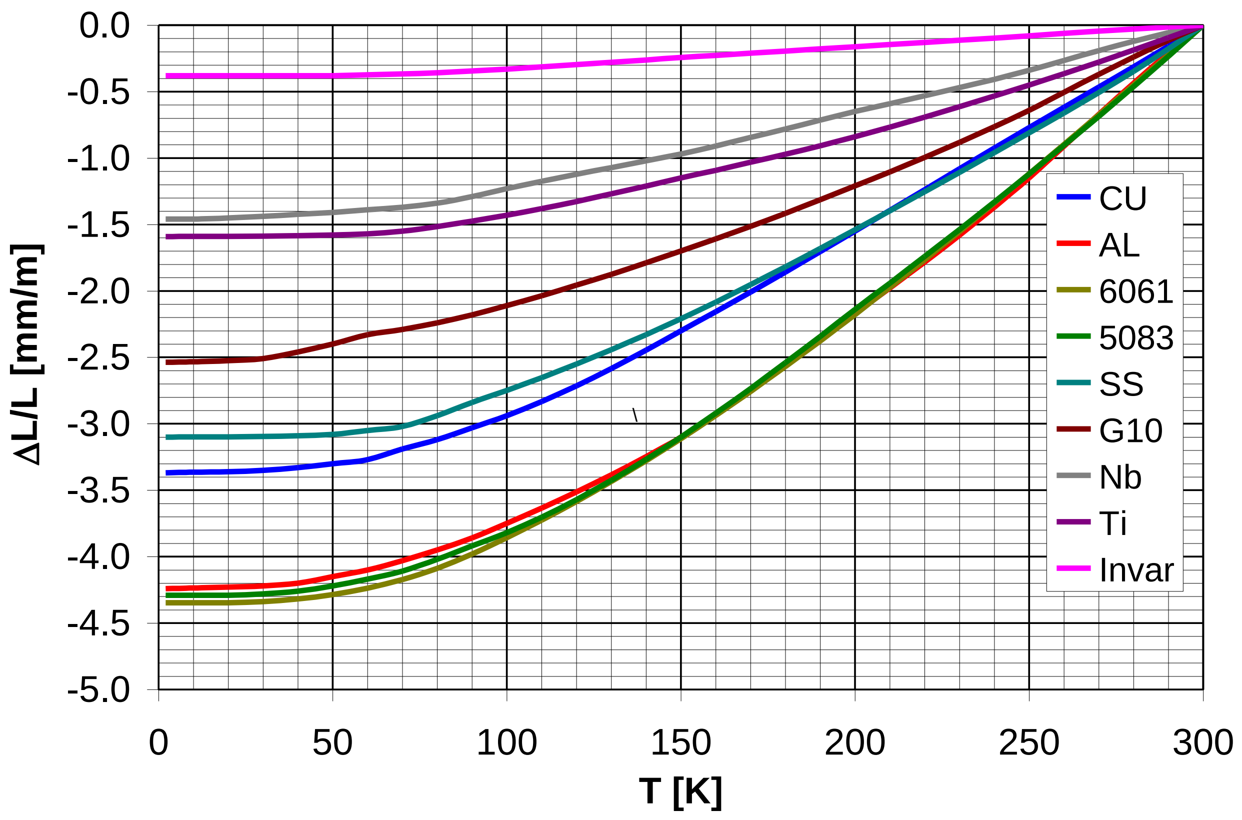
$$Nu = 0.023\, Re^{0.8} Pr^{0.4}$$

- **Recipe:** Evaluate regime via *Re*, then *Pr* through fluid properties, and compute *Nu* from correlation
  - Calculate *h* from *Nu*

Role of material properties

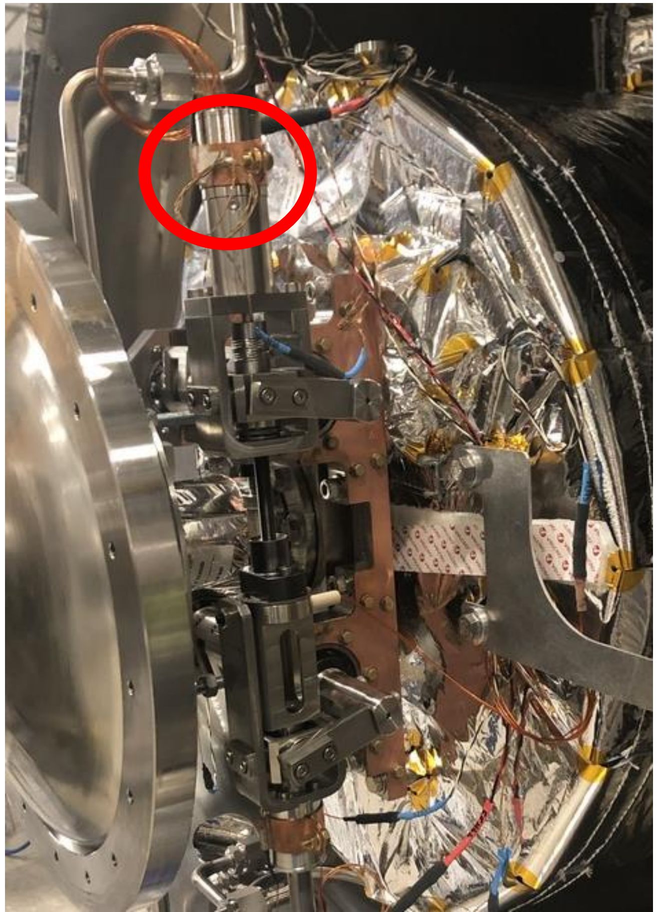
- Differential contraction can be big!
  - Can lead to unacceptable stresses if not taken into account
  - Choose proper combination of materials/bellows
    - e.g. Nb/Ti vs Nb/SS

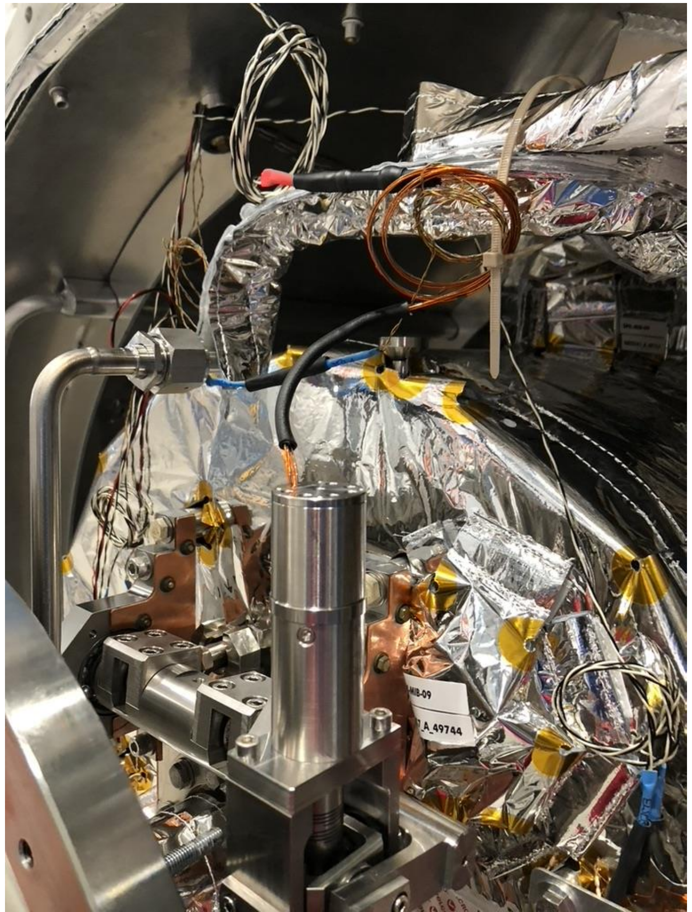
Material	$(L_{300}-L_2)/L_{300}$
Nb	0.146%
Ti	0.159%
Stainless Steel (304)	0.310%
Al 6061	0.419%
Invar	0.038%
G10 composite	0.274%



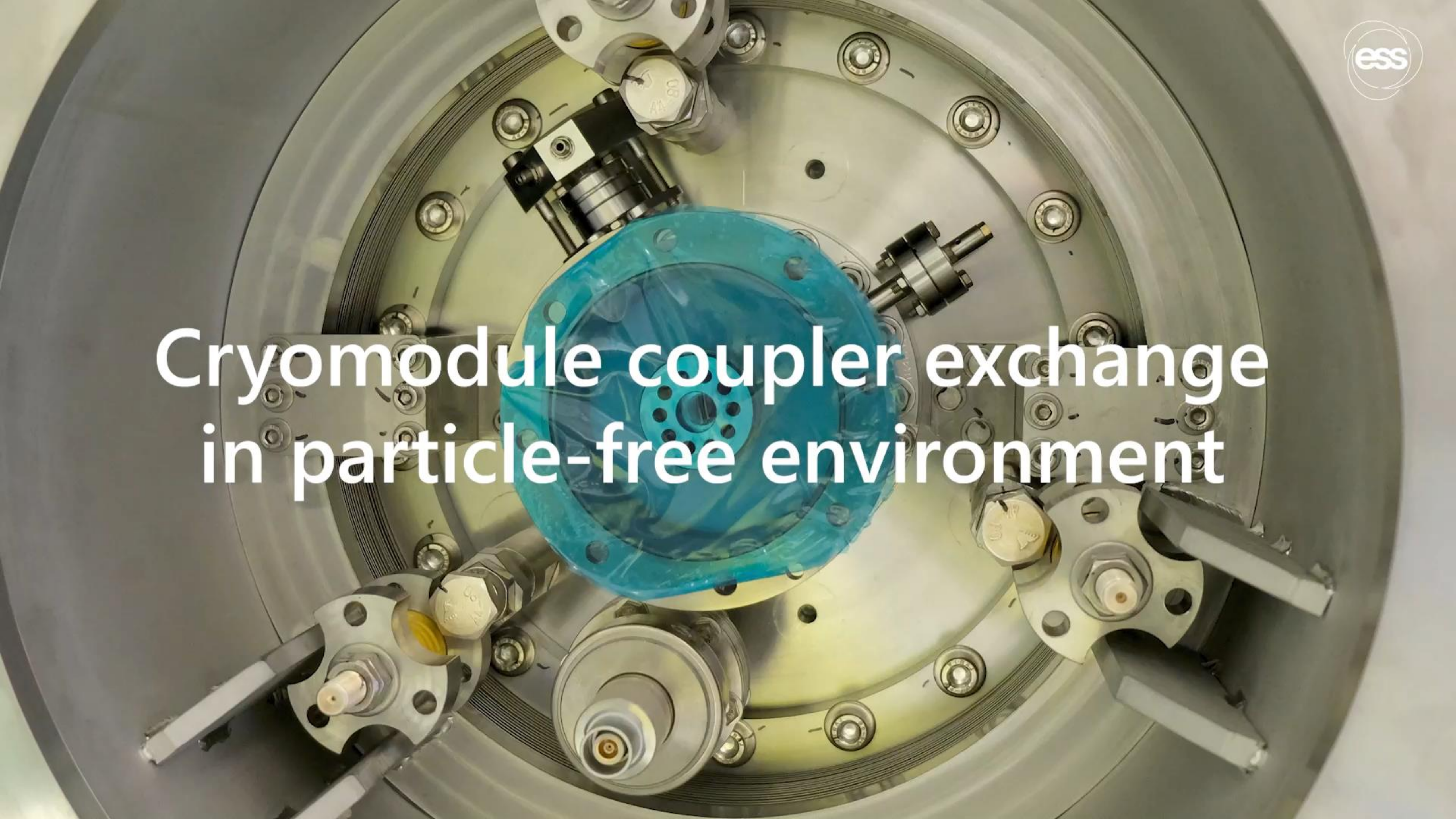
May seem trivial: ESS SPK Motor

- An ‘innocent’ copper collar on the motor body for pt100
- Clearance stator/motor minimal, motor can get stuck
- Open 12 CM at ESS for a 10 min fix…





CMs were tested at UU, ready for installation
Time to disassemble and reassemble
Time to perform electrical/vacuum tests



Cryomodule coupler exchange in particle-free environment