CI-RF-312
Cryogenics

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Course outline

- Applications for accelerators
- Properties of cryogens
- Heat transfer and material properties at low temperatures
- Basic principles of cryogenic engineering
- Cryostat design
- Cryoplants, mechanical coolers
- Case study – Daresbury vertical test facility

Cryogenic temperatures

Cryogenics is defined by convention as the branch of science and technology of temperatures below 120 Kelvin

The upper limit of 120 K is chosen so as to include the boiling point under standard pressure of the main atmospheric gases, as well as methane (the main component of natural gas)

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Scurlock (1992)

Kelvin temperature scale

Unit of thermodynamic temperature => absolute zero where entropy equals zero and effectively all motion stops

3rd Law of Thermodynamics states that we can never actually reach absolute zero but we can come vanishingly close

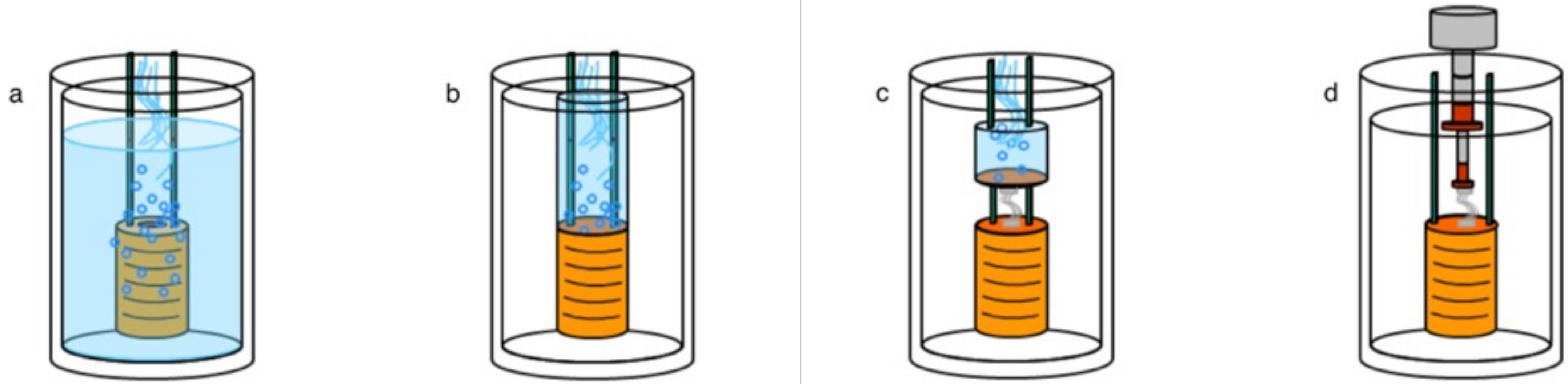
0 °C = 273.15 K

Cryostats

A system designed to maintain some system at cryogenic temperatures

Can be divided into “wet” (those using liquid cryogens) and “dry” (using mechanical coolers)

Cryostats



Direct cooling
Bath cooling

Indirect cooling
Bath cooling

Indirect cooling
Bath as cold source

Indirect cooling
Cryocooler as cold source
Thermal link

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Bauduoy (2015)

Cryostats

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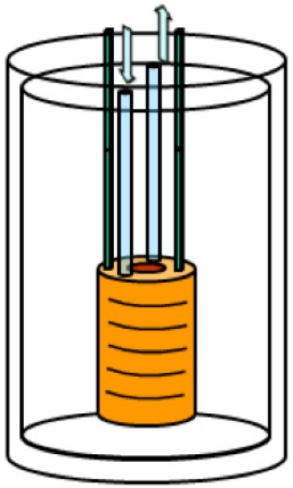

Direct cooling
Forced flow

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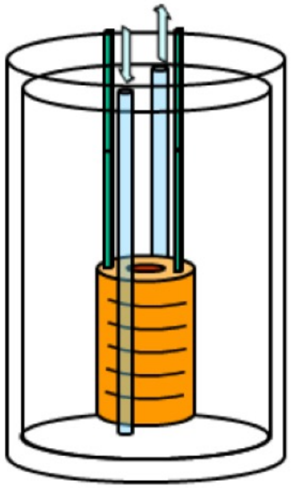

Indirect cooling
Forced flow

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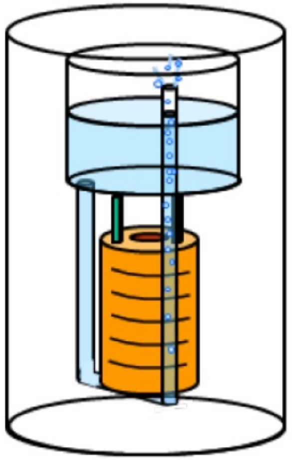

Indirect cooling
Two-phase thermosiphon

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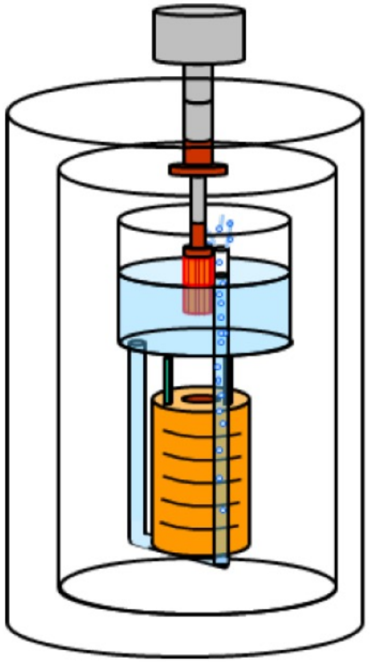


Indirect cooling
Two-phase thermosiphon
Coupled with a cryocooler

Bauduoy (2015)

Applications in accelerator science

Cryogenics plays a significant role in modern accelerators as it enables superconductivity

- SRF cavities for charged particle beam acceleration
- High field magnets for bending, focusing, and wiggling charged particle beams
- High field magnets in large detectors for particle identification from colliders

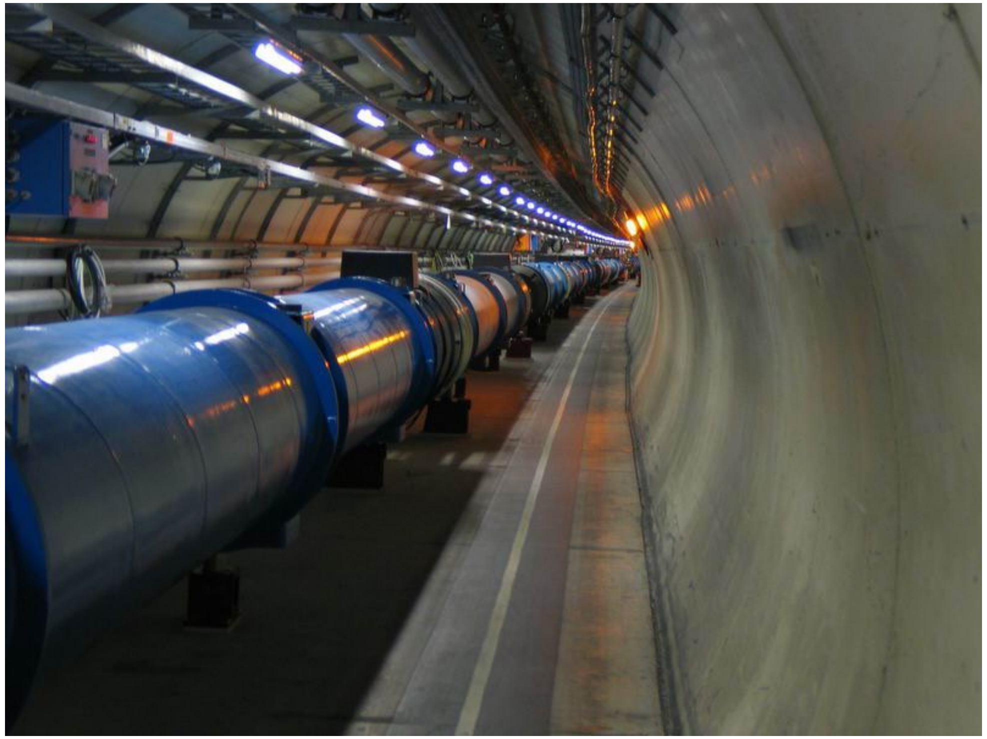
Applications in accelerator science

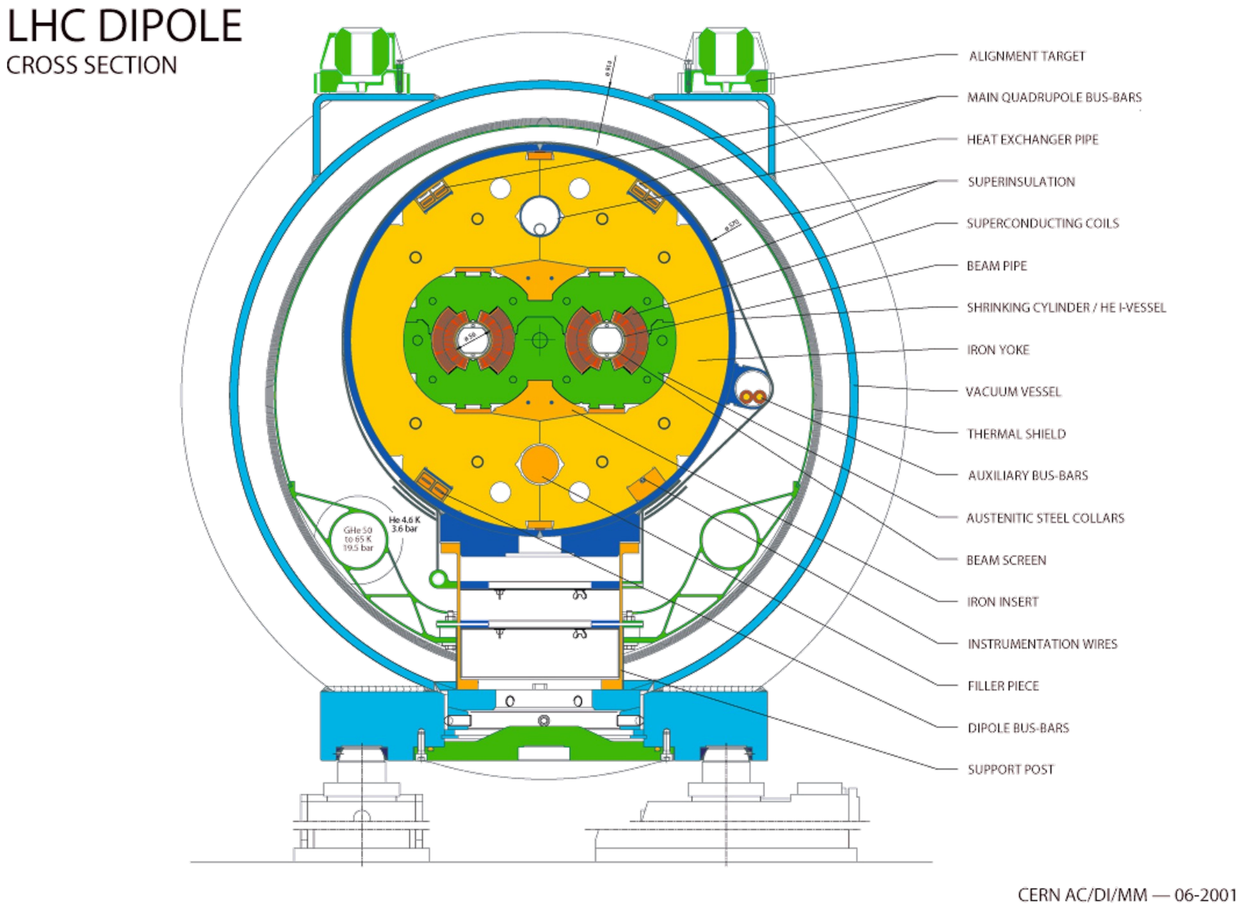
Cryogenics also allows us to produce dense pure liquids

- LAr calorimeters
- LH_2 targets, moderators and absorbers

Cryogenic sample environments widely used at neutron sources

Applications in accelerator science





Images courtesy CERN

Applications in accelerator science

In modern high energy machines, ~30% cost is cryogenics

Crucial therefore to consider

- cost (CAPEX and OPEX)
- performance (efficiency)
- reliability (availability 24 hours a day for several decades)

Superconducting RF accelerators

Name	Accelerator Type	Lab	T (K)	Refrigeration Capacity	Status
CEBAF	Electron Linac	JLab	2.1	4.2 kW @ 2.1 K	Operating
12 GeV Upgrade	Electron Linac	Jlab	2.1	4.2 kW @ 2.1 K	Operating
ESS	Proton Linac	ESS	2.0	3 kW @ 2 K	Under Construction
SNS	H^- Linac	ORNL	2.1	2.4 kW @ 2.1 K	Operating
E Linac	Electron Linac	TRIUMF	2.0	288 L/Hr	Operating
S-DALINAC	Electron Linac	TU Darmstadt	2.0	120 W @ 2.0 K	Operating
ERL	Electron Linac	Cornell	1.8	7.5 kW @ 1.8 K	Proposed
XFEL	Electron Linac	DESY	2.0 5 -8 40-80	2.5 kW @ 2 K 4 kW@ 5 -8 K 26 kW @ 40-80 K	Operating
ATLAS	Heavy Ion Linac	ANL	4.7	1.2 kW @4.7	Operating
LCLS II	Accelerator	SLAC	2.0 K	8 kW @ 2 K 30.6 kW @ 35 -55 K 2.6 kW @ 4.5 -6 K	Under construction TESLA Tech
ISAC - II	Heavy Ion Linac	TRIUMF	4		Operating
FRIB	Heavy Ion Linac	MSU	2.1 4.5 33/55	3.6 k W @ 2.1 K 4.5 kW @ 4.5 K 20 kW @ 35/55 K	Operating

Table courtesy J Weisend

Boiling temperatures

Boiling temperature under atmospheric pressure for some cryogenic liquids:

Substance	**O_2**	**Ar**	**N_2**	**H_2**	**^4He**	**^3He**
T_b (K)	90.1	87.2	77.2	20.3	4.21	3.19

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Data from Pobell (2007)

Liquid argon

Substance	Ar
T_b (K)	87.2

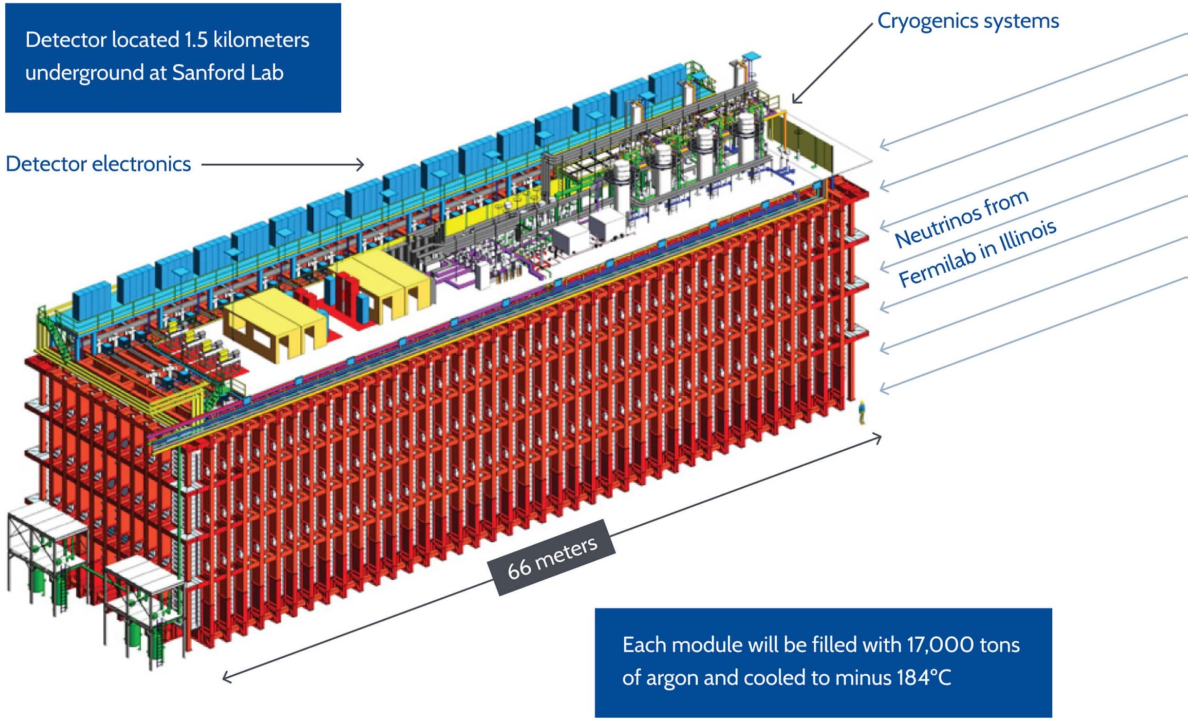
0.93% of atmospheric air

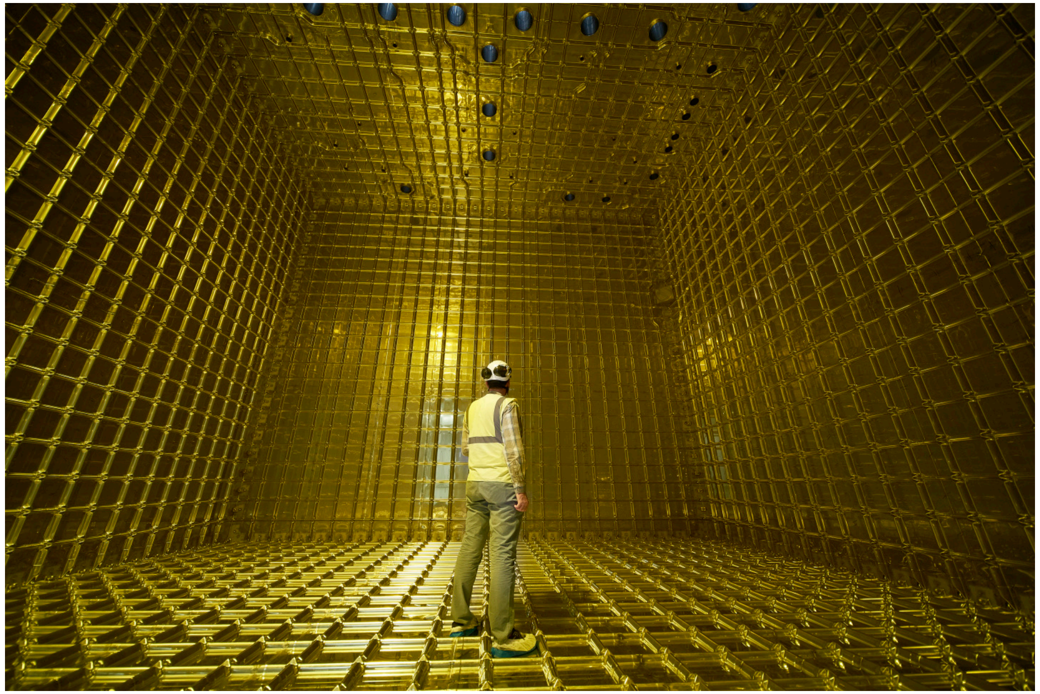
Monatomic, extremely inert (no known compounds)

Widely used as shielding gas to prevent oxidation in welding, purge gas in semiconductor industry, but also…

Liquid argon

Detectors for neutrino physics, e.g. DUNE (17 kiloton)





Images courtesy FNAL, CERN

Liquid nitrogen

Substance	N_2
T_b (K)	77.2

Primary component of atmosphere (78%)

=> cheap! ~£0.3 /liquid litre

Most commonly used cryogen, widely used to provide cooling to 77 K

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Liquid nitrogen

Commercial uses include food freezing, metal treating, biological sample preservation

Substance	N_2
T_b (K)	77.2

Also sometimes used to precool colder stages first to 77 K before being cooled further with other cryogens

Liquid hydrogen

Substance	H_2
T_b (K)	20.3

Can be explosive when mixed with air

Flammability range in air is 4% to 74%

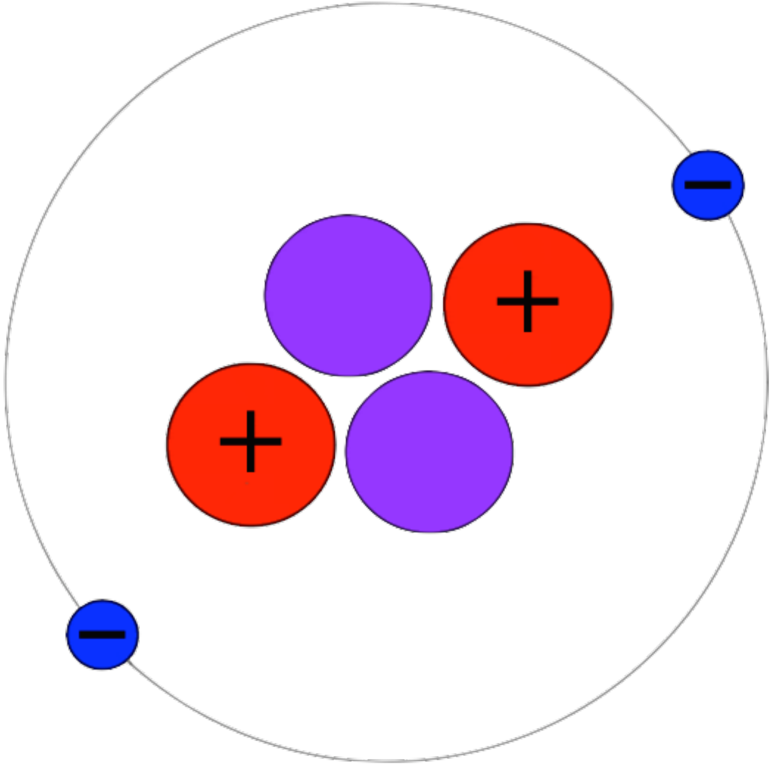
Uses include as raw material for chemical processes, as rocket fuel, in fuel cells, for internal combustion, and as neutron moderator (ISIS, ESS)

Helium-4

Substance	^{4}He
T_b (K)	4.21

The nucleus of ^{4}He contains two protons and two neutrons, each with anti-parallel spin orientation

The total nuclear spin $I = 0$ and ^{4}He is hence a boson (the superfluid obeying Bose-Einstein statistics)



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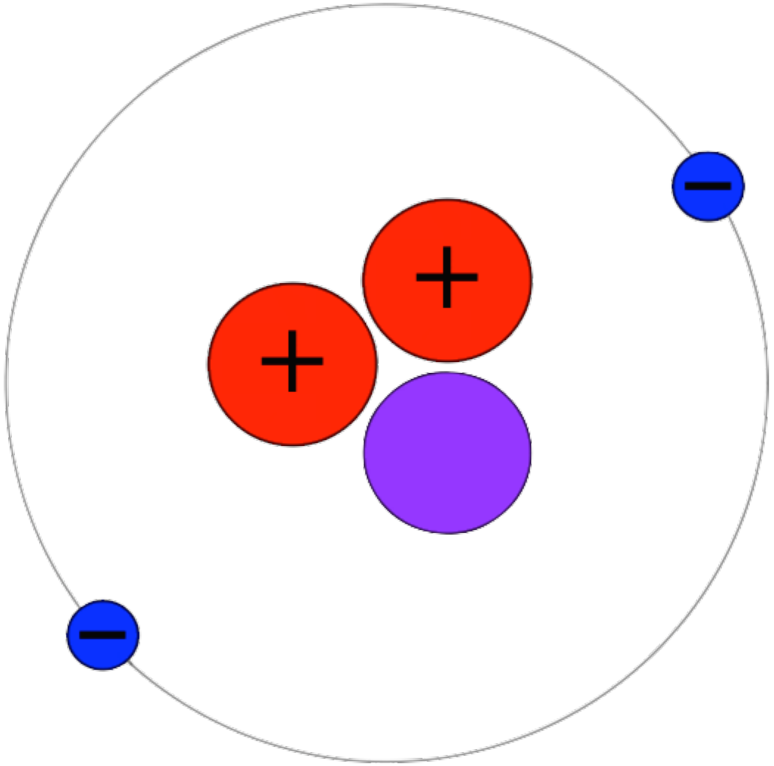
Helium-3

Substance	^{3}He
T_b (K)	3.19

The nucleus of ^{3}He by comparison contains only one neutron

Hence, I = 1/2 and is a fermion (the liquid obeying Fermi-Dirac statistics)



Helium-4 and Helium-3

Whilst the different statistics are related to the different properties discussed in the next few slides, both isotopes similarly exhibit a number of remarkable properties

Weak van der Waals forces (owing to the closed electronic s-shell) => low boiling temperatures (4.2 and 3.2 K respectively)

Helium-4 and Helium-3

Both, unlike any other liquids, do not solidify under their own vapour pressures, even at T = 0 K. This is due to small atomic mass *m* and hence large quantum mechanical zero-point energy E_0 given by

$$E_0 = \frac{h^2}{8ma^2}$$

where *a* is the radius to which the atoms are confined and *h* is the Planck constant

Latent heat of evaporation

Latent heat (when boiling under atmospheric pressure) for some cryogenic liquids:

Substance	O_2	Ar	N_2	H_2	^{4}He	^{3}He
T_b (K)	90.1	87.2	77.2	20.3	4.21	3.19
L (kJ/L)	243	224	161	31.8	2.56	0.48

Cooling power
(in equilibrium = heat load)

$$\dot{Q}_0 = L\dot{n}$$

Latent heat

Cryogen boil-off rate

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Data from Pobell (2007)

Vapour pressure

The vapour pressure P_{vap} is that exerted by a vapour in thermodynamic equilibrium with its condensed phase

This varies as a function of temperature; an approximation is given by the Clausius-Clapeyron equation as

$$\left[\frac{dP}{dT}\right]_{vap} = \frac{s_{gas} - s_{liquid}}{V_{m,gas} - V_{m,liquid}}$$

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Vapour pressure

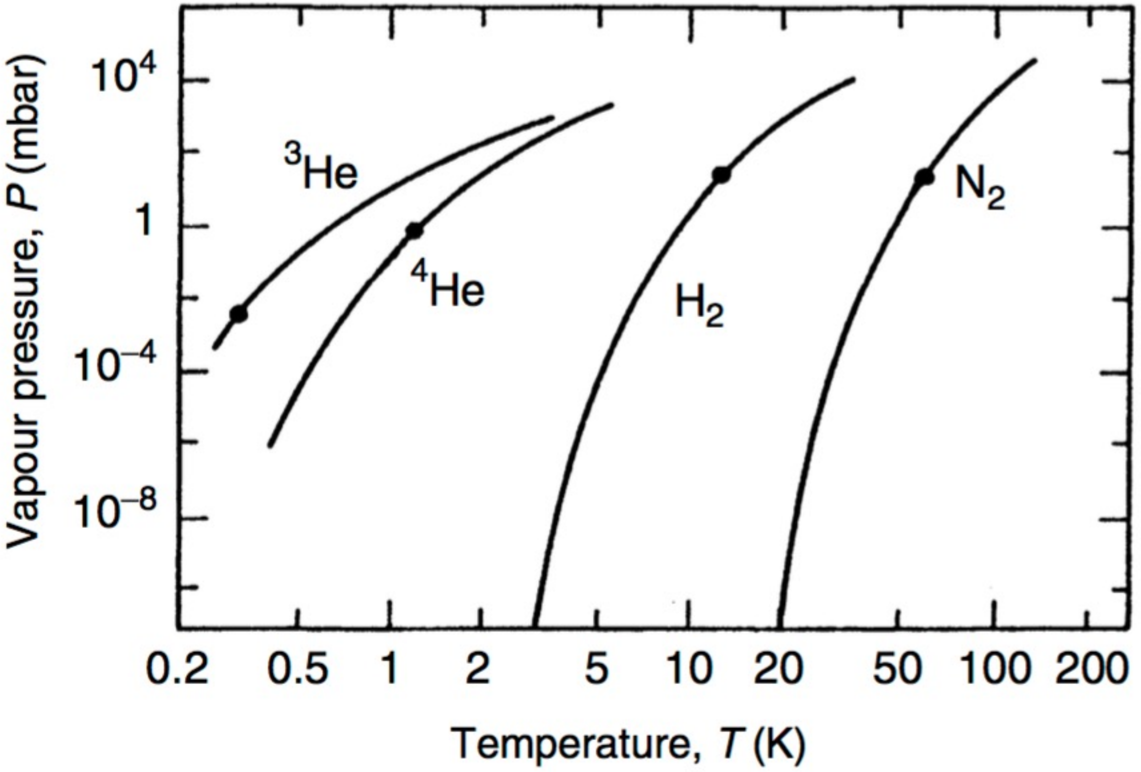
Taking the difference in entropies of the liquid and gaseous phases as *L/T*, the observation that $V_{m,liquid} << V_{m,gas}$ and, from the ideal gas equation, that $V_{m,gas} \sim RT/P$, then integrating the Clausius-Clapeyron equation gives

$$P_{vap} \propto e^{-L/RT}$$

Vapour pressure

Agreement is shown with experimental data:

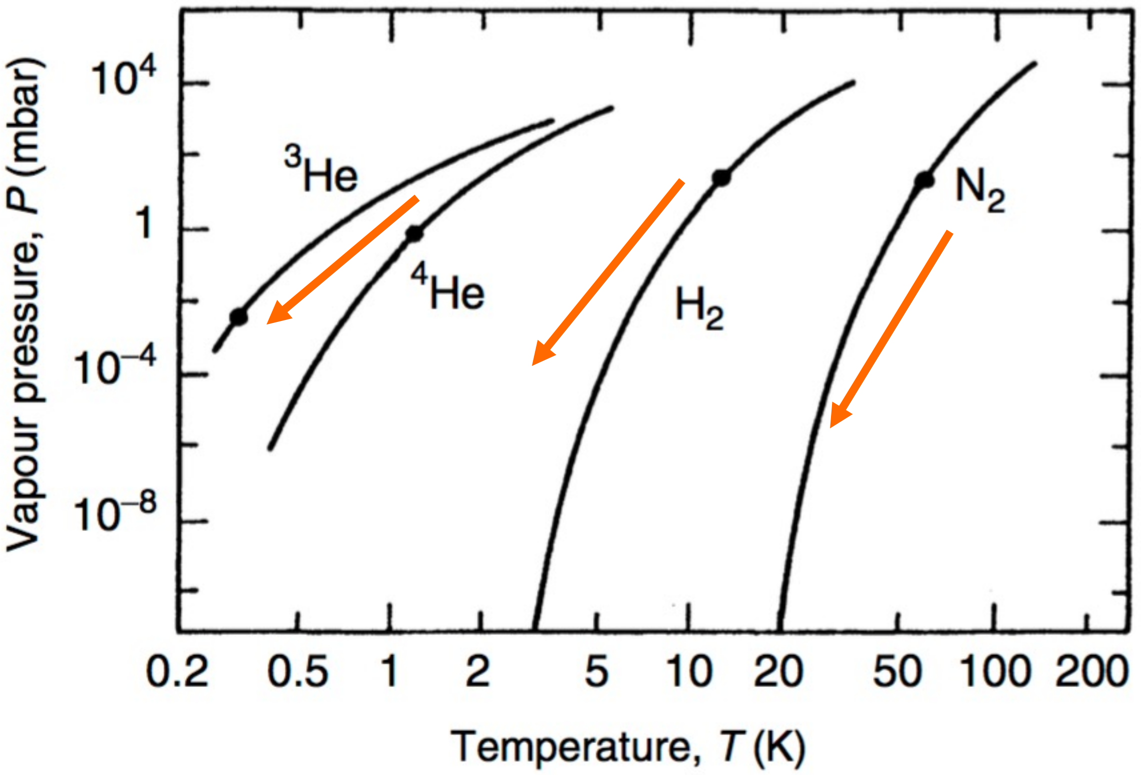
$$P_{vap} \propto e^{-L/RT}$$



Data from Pobell (2007)

Vapour pressure

It can be seen from this that we can cool liquids further by pumping on the vapour to reduce the pressure and therefore move down these curves



Data from Pobell (2007)

Helium-4 and Helium-3

Substance	^{4}He	^{3}He
T_b (K)	4.21	3.19
L (kJ/l)	2.56	0.48
Maximum superfluid transition temperature (K)	2.1768	0.0025
Density (at saturated vapour pressure, T = 0 K) (g/cm^3)	0.1451	0.082
Gas-to-liquid volume ratio (Liquid at 1 K, NTP gas)	866	662
Cost (£/l)	15 (liquid)	2000 (gas)

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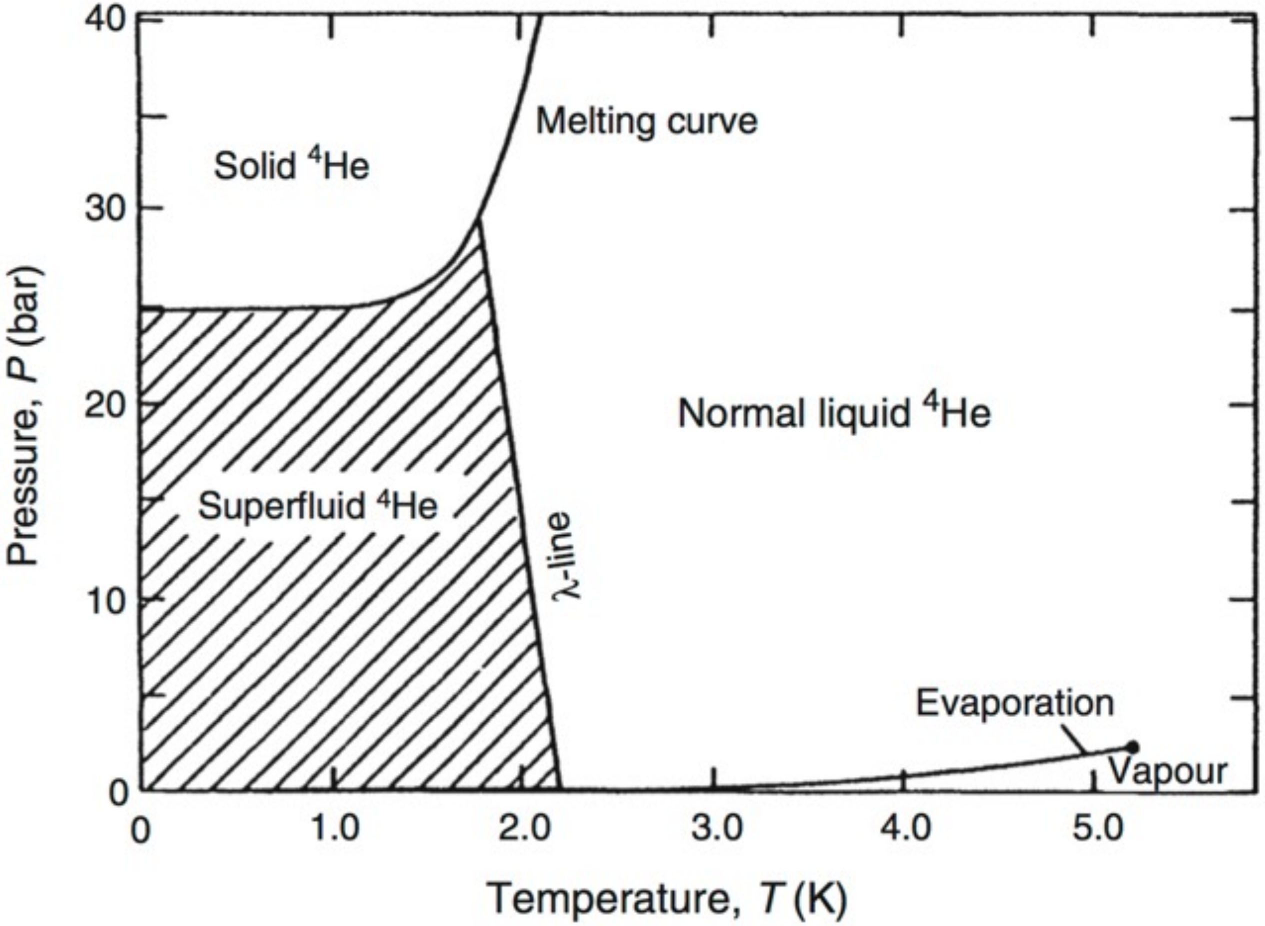
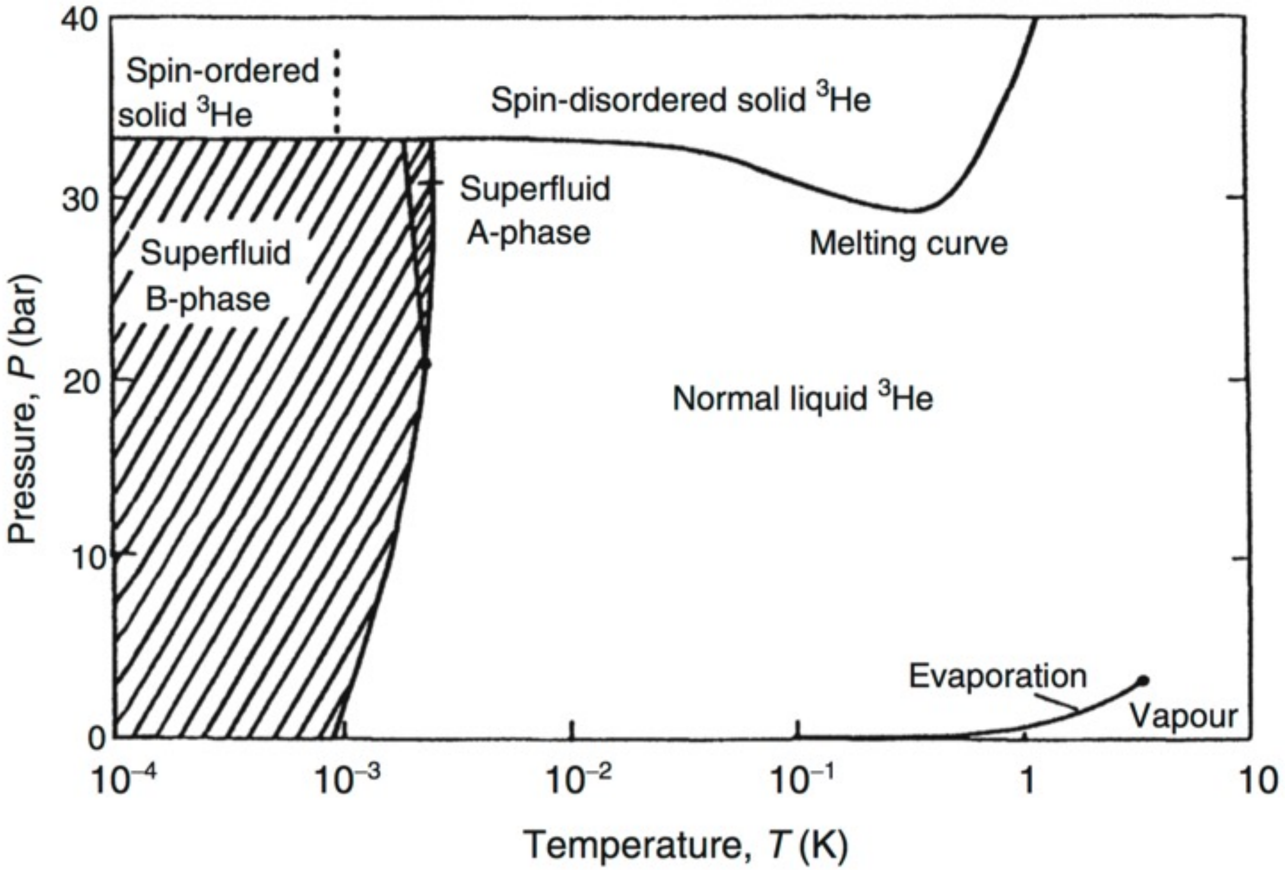
Data from Pobell (2007)

Helium-4



Data from Pobell (2007)

Helium-3



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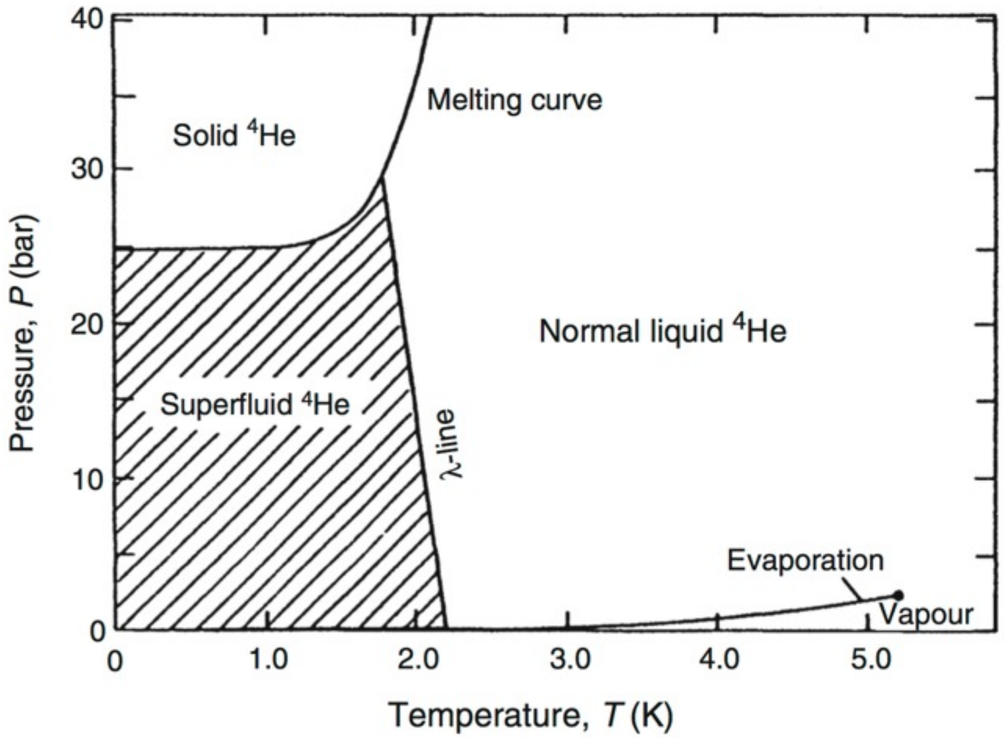
Superfluidity

Below the λ-line, Bose-Einstein condensation of ^{4}He results in the superfluid phase change

In this regime, helium (sometimes denoted He-II to distinguish it from the normal fluid He-I) behaves as a perfect fluid with zero viscosity



Data from Pobell (2007)

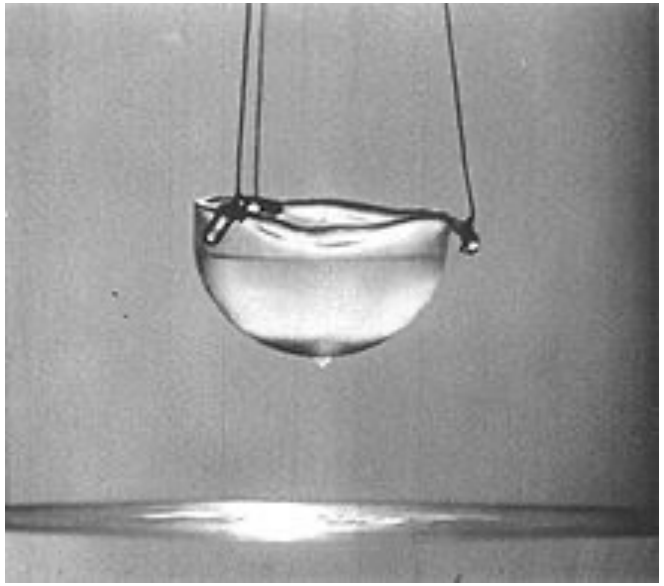
Superfluidity

Behaviour in its superfluid state is well described by the two-fluid model of Landau and Tisza, which considers He-II to be comprised of a normal-fluid component and a superfluid component, each with their own independent densities, viscosities, and entropies

This gives rise to many useful properties and interesting phenomena, along with some challenges

Van Sciver (2012)

Superfluidity



He-II has exceptionally high thermal conductivity

This is useful

a) in removing high heat loads from systems
b) for reducing vibration from bubble formation as essentially all boiling occurs from the liquid surface

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Van Sciver (2012)

Superfluidity

Superfluids will flow through extremely narrow channels and as a film which has many useful engineering applications

However, they will also leak through incredibly small gaps (that would otherwise appear leak tight to normal liquid or gaseous helium) => these are called superleaks and great care must be taken to avoid them

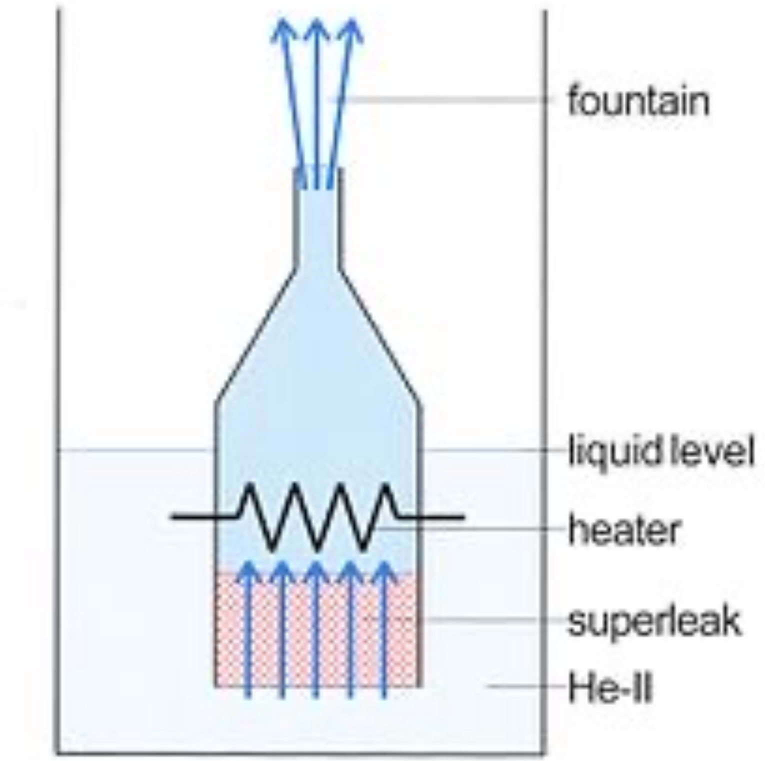
Van Sciver (2012)

Superfluidity

A further consequence of the two-fluid model is that the superfluid component will accelerate in the direction of positive temperature gradients

$$\frac{\partial \boldsymbol{v}_s}{\partial t} = -\frac{1}{\rho}\nabla P + s\nabla T$$

This gives rise to the so-called fountain pump effect



Van Sciver (2012)

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Physical adsorption

Adsorbent materials may be used to trap gases such as helium at cryogenic temperatures

Charcoals and zeolites are typically used sorbents due to their high specific surface areas (~1000 m^2/g) which result from their internal networks of pores

Physical adsorption

The binding of helium gas to charcoal at low temperatures occurs due to physical adsorption

This is distinct from chemical adsorption, for which the binding energies are much higher. In physical adsorption, forces involved are intermolecular (van der Waals' forces)

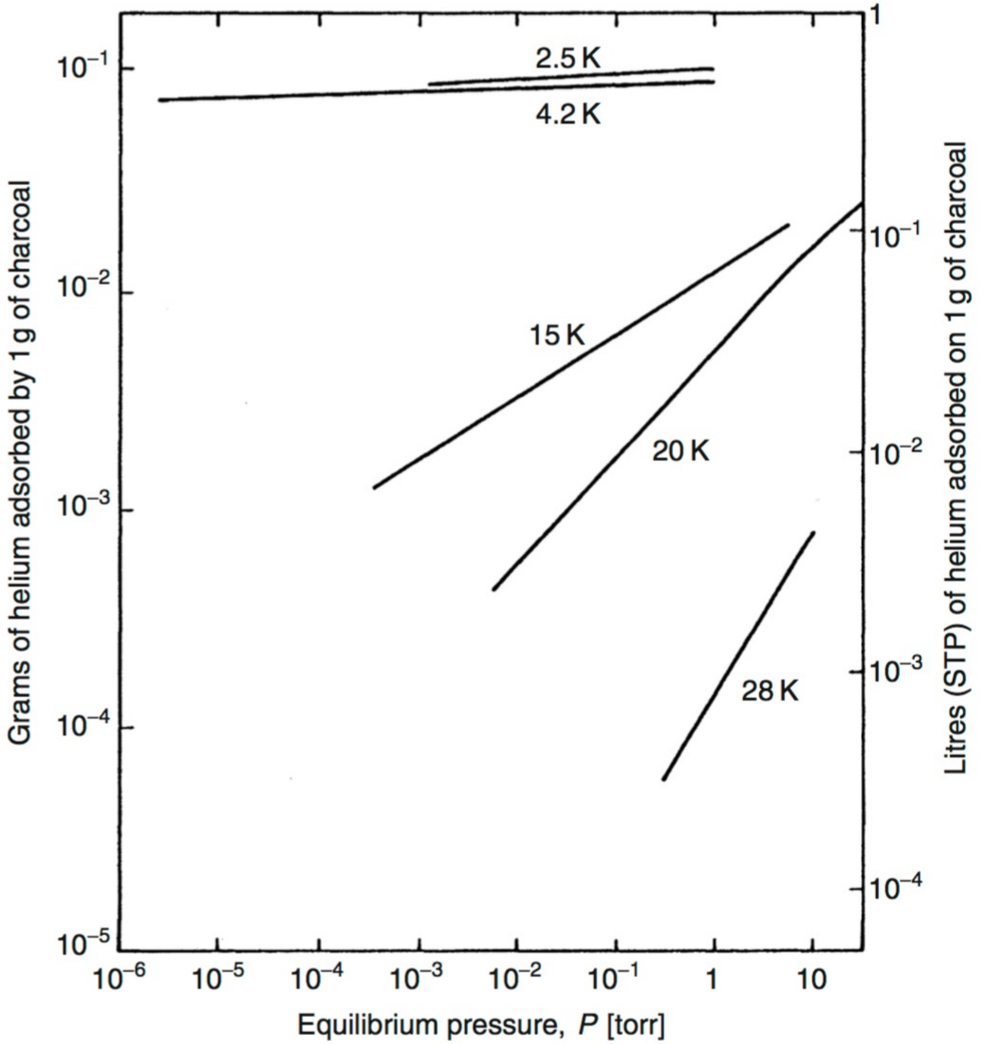
Physical adsorption

Cold gas (low kinetic energy particles) may sit in Lennard-Jones potential well of sorbent

Heating the sorbent can give sufficient excitation (‘kick’) to trapped particles to desorb (release) them

Physical adsorption

The amount of adsorption at a given pressure is temperature dependent => possible to provide a pressure increase (gas release) or decrease (gas trapping) by simply controlling the temperature of the material



Data from Pobell (2007)

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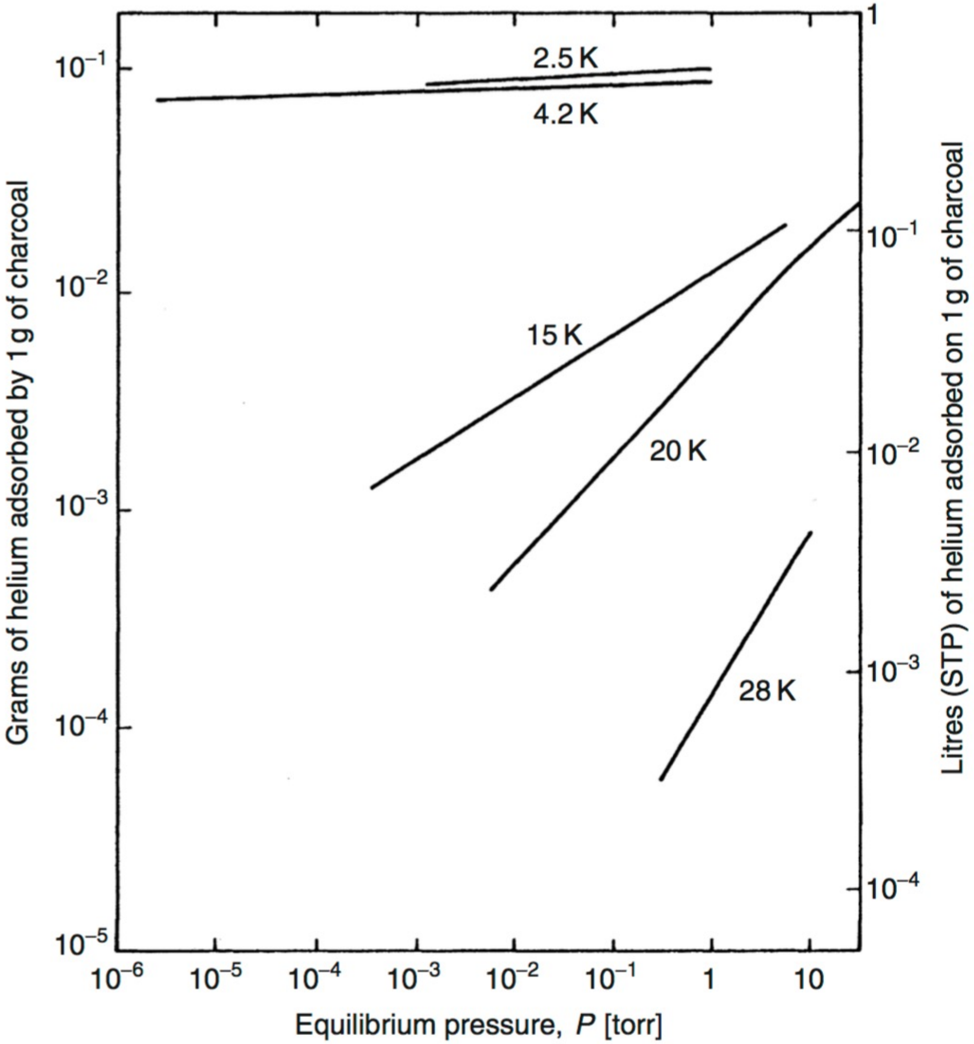
Physical adsorption

Temperature and pressure dependence of adsorption capacity is described by isotherms

Increase in capacity as sorbent is cooled (cryopumping)



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Data from Pobell (2007)

Cryopumping

Cryopumps generally can be used to provide high vacuum in cryostats

Applications in fusion and many other areas requiring extremely clean vacua

Also, small charcoal ‘getters’ can be used to offset small leaks in cryostats

Laboratory cryogens

Nitrogen and helium-4 are most commonly used laboratory cryogens

Substance	O_2	Ar	N_2	H_2	^4He	^3He
T_b (K)	90.1	87.2	77.2	20.3	4.21	3.19
L (kJ/L)	243	224	161	31.8	2.56	0.48

Data from Pobell (2007)

Laboratory cryogens

Cooling 1 kg of copper from 300 K to 4.2 K using latent heat of LHe only would require 32 l (~£500)

Substance	N_2	^4He
T_b (K)	77.2	4.21
L (kJ/L)	161	2.56
Cost (£/L)	0.1	15

Using LN_2 to cool the same copper from 300 K to 77 K would require 0.46 l (a few pence) and then LHe from 77 K to 4.2 K 2.2 l (~£35)

=> much more efficient and cost effective

Woodcraft (2007)

Laboratory cryogens

Also, possible to improve efficiency further by utilising enthalpy of cold gas

Important: if using LN_2, crucial to remove entirely before LHe as

a) N_2 has high heat of melting and so LHe will be wasted solidifying N_2

b) Solid N_2 will likely cause blockages in pipework which can be catastrophic

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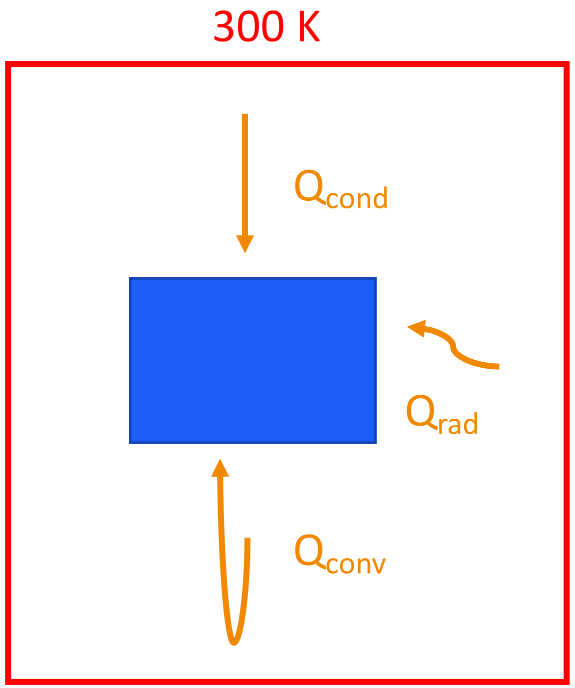
Heat transfer and design principles

Occurs in systems due to conduction, convection, radiation



Heat transfer and design principles

Occurs in systems due to conduction, convection, radiation

Generally, we want to minimise all three – this is largely the goal of cryostat design. Given the cost of cooling (more on this later) this can have huge impacts on project cost

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Conductive heat transfer

Occurs primarily within solids, although also within liquids and gases, without mass transport. Given by Fourier's law which can be written in one dimension as

$$\dot{q} = -k\left(T\right)\frac{dT}{dx}$$

where *q* is the conductive heat flux and *k(T)* is the conductivity of the material which is a function of temperature *T* and is generally non-linear (numerical integration over *T* is necessary in most practical cases)

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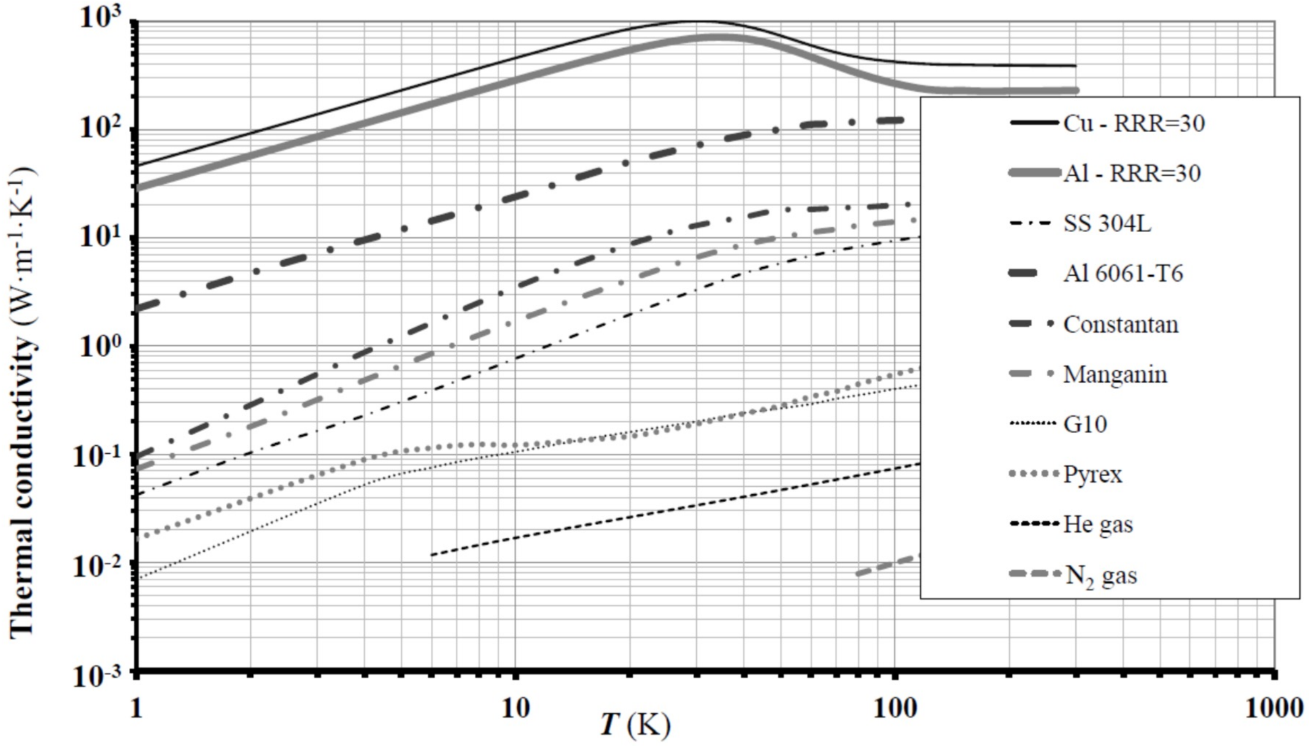
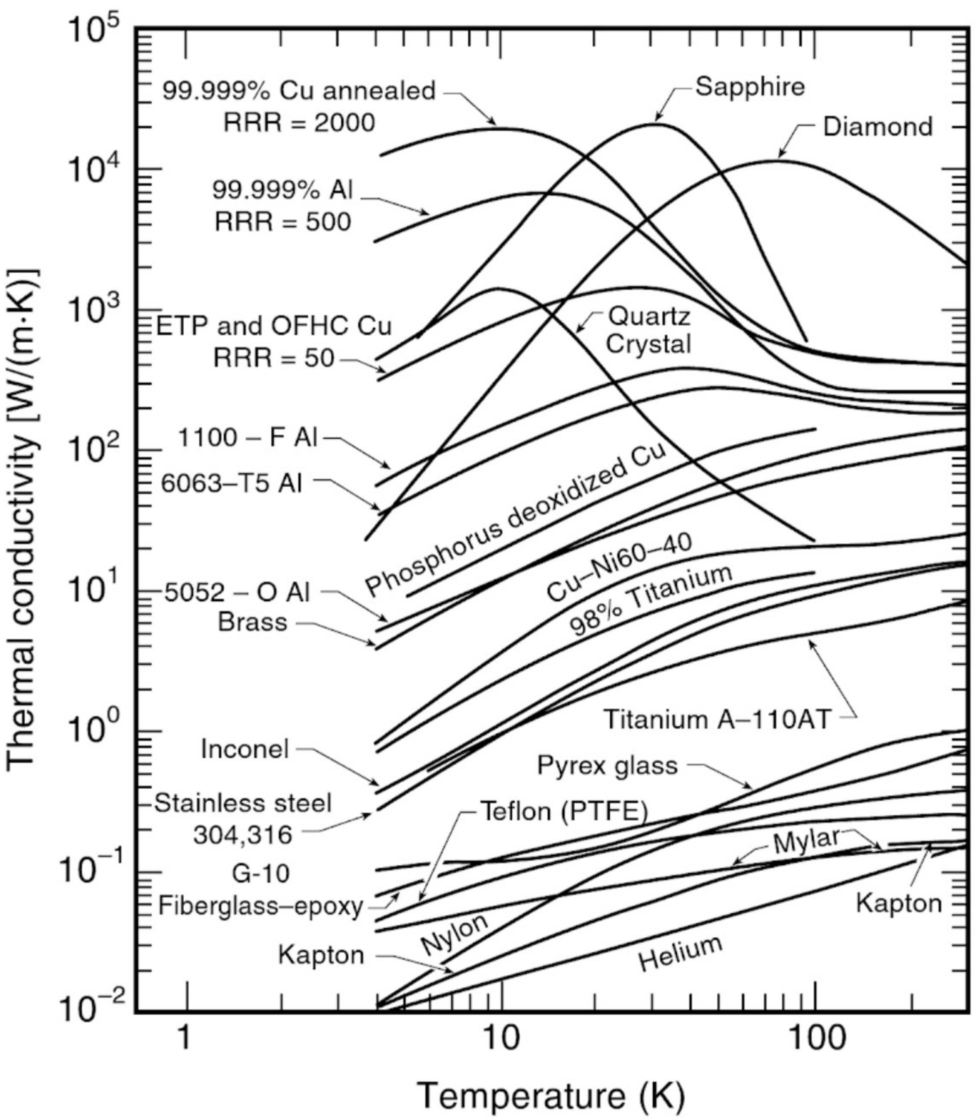
Conductive heat transfer





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Bauduoy (2015) and Ekin (2006)

Conductive heat transfer

In the case that *A* of the domain is constant, heat transfer is

$$\dot{Q}_{cond} = \frac{A}{L}\int_{T_{cold}}^{T_{hot}} k\left(T\right) dT$$

Therefore, use long, narrow, low *k* supports to minimise *Q*

Common to find thermal conductivity integrals in the literature

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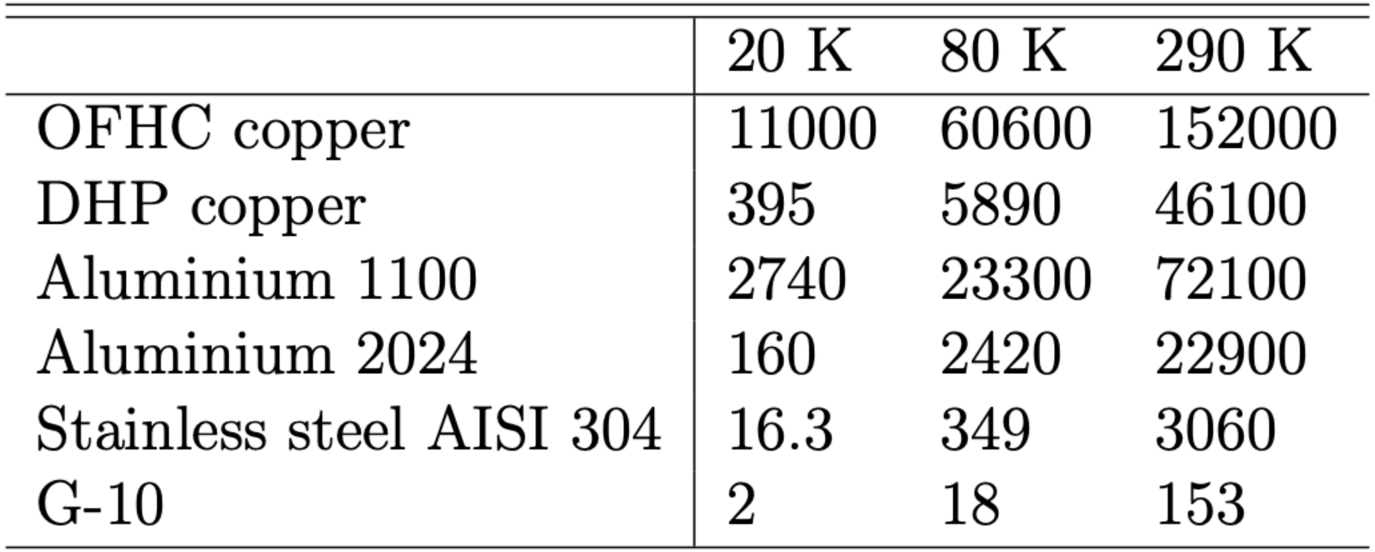
Bauduoy (2015)

Conductive heat transfer

Thermal conductivity integrals (W/m) for selected materials between indicated temperatures and 4.2 K

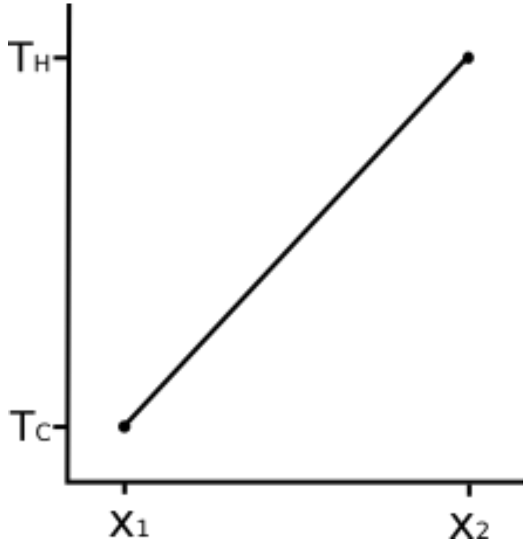


	20 K	80 K	290 K
OFHC copper	11000	60600	152000
DHP copper	395	5890	46100
Aluminium 1100	2740	23300	72100
Aluminium 2024	160	2420	22900
Stainless steel AISI 304	16.3	349	3060
G-10	2	18	153

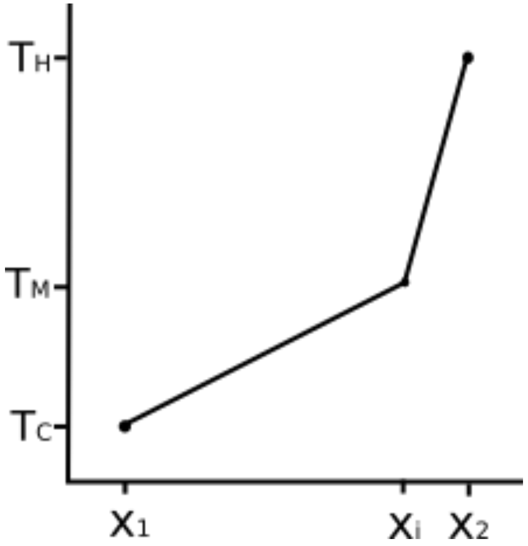
Bauduoy (2015)

Conductive heat transfer

As we'll see later, it is more thermodynamically efficient to remove heat at higher temperatures



Therefore, typical to have thermal intercepts along supports, minimises heat load to coldest stages



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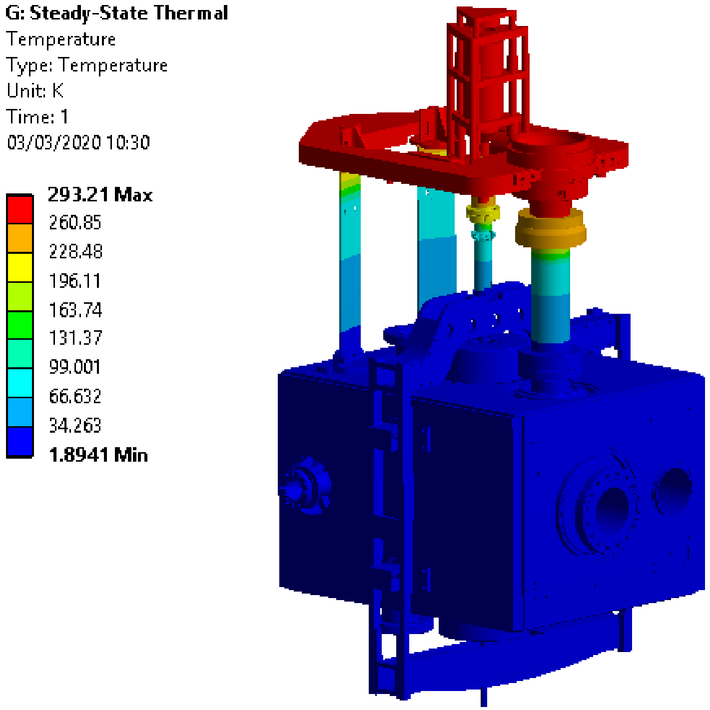
Conductive heat transfer

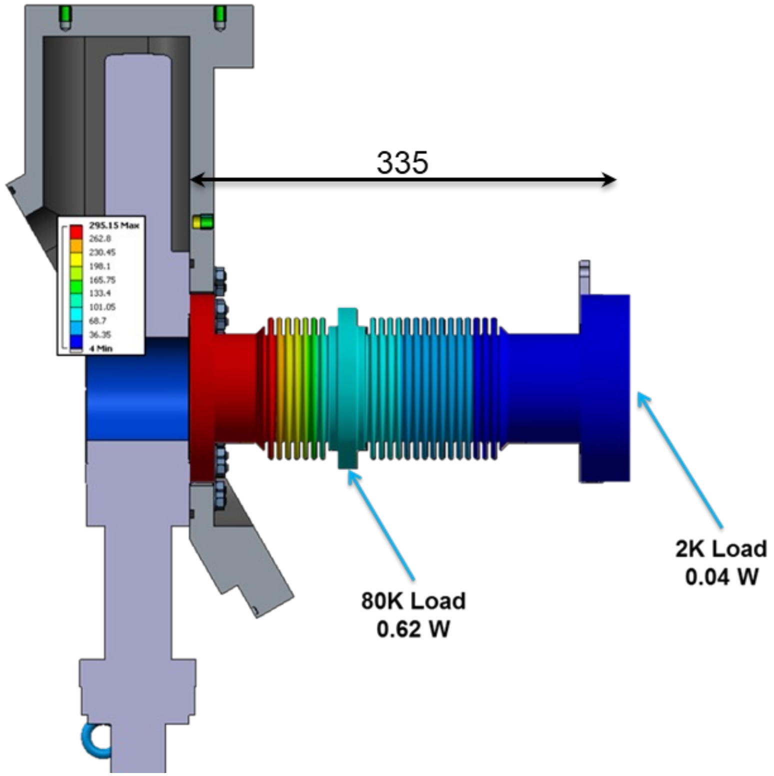
For complex geometries, finite element analysis is a powerful tool

FEA works by discretising geometry of system into cells and solving governing equations at nodes

Conductive heat transfer

Example of FEA used in design of HL-LHC CC cryomodules





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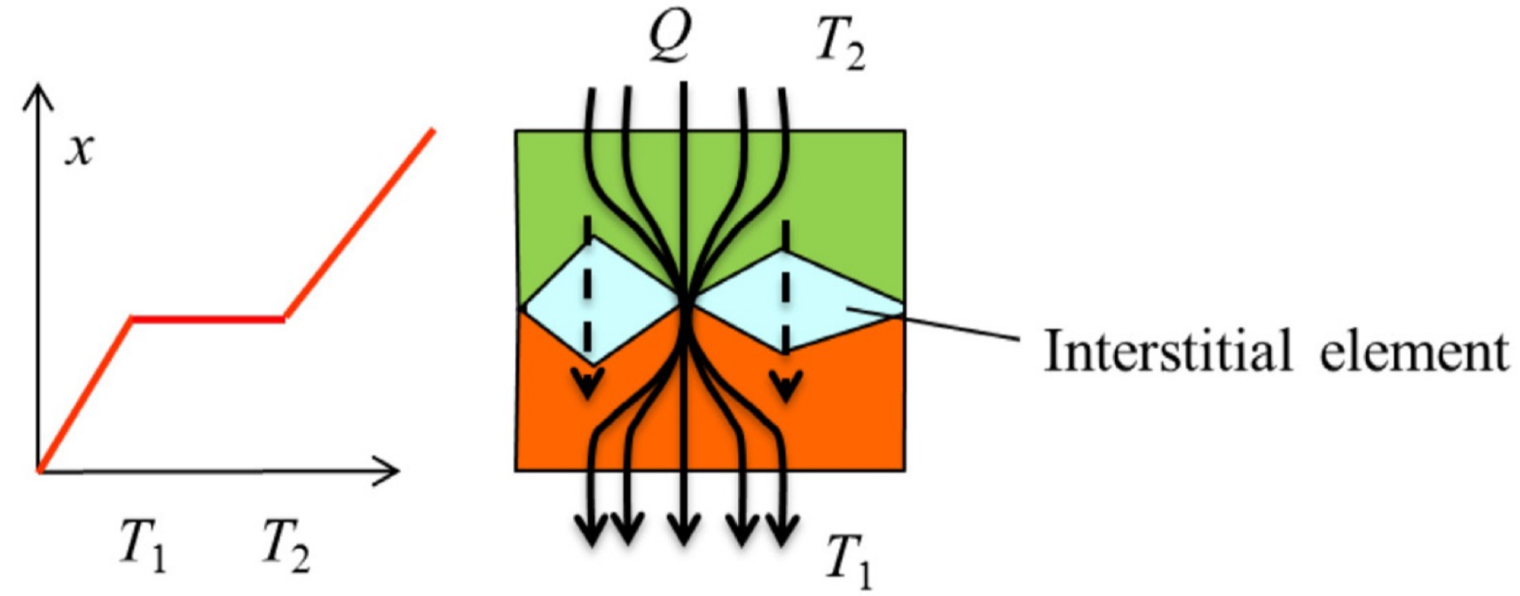
Courtesy of N Templeton

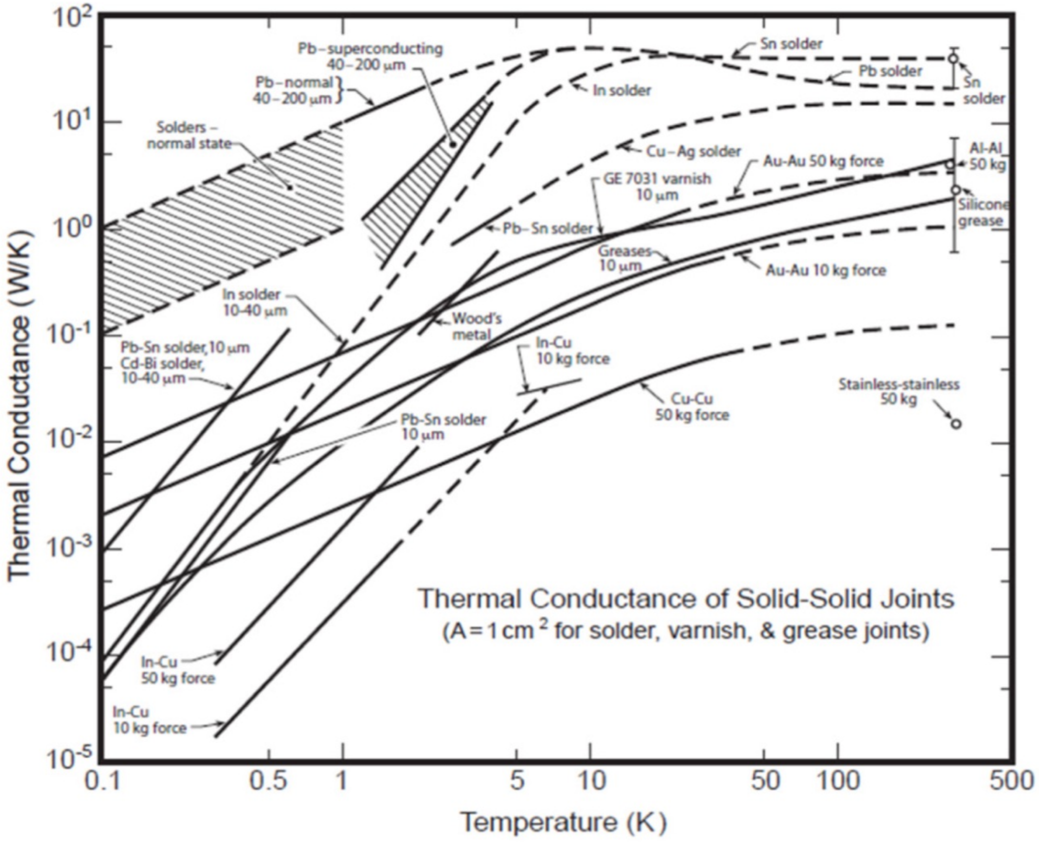
Conductive heat transfer

In any real case, the boundary between two media will not be in perfect thermal contact => thermal impedance R_c (=T/Q)



Conductive heat transfer

Boundary conductance strongly dependent on material combinations, surface cleanliness, compression force



Ekin (2006)

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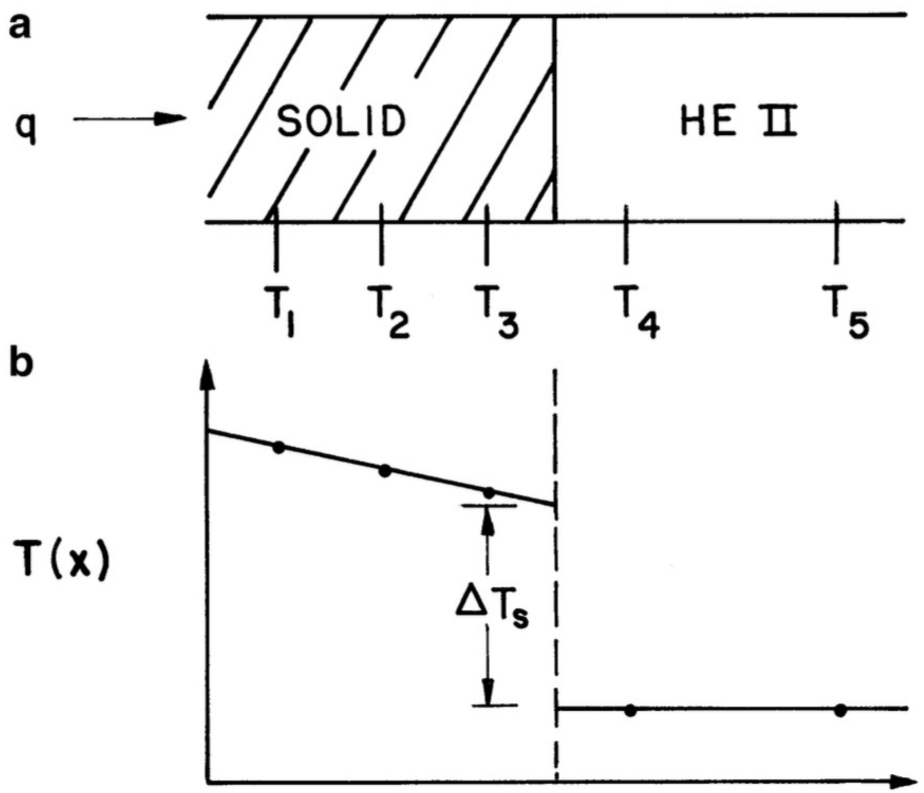
Conductive heat transfer

At solid-helium boundary, phonon scattering gives rise to Kaptiza resistance

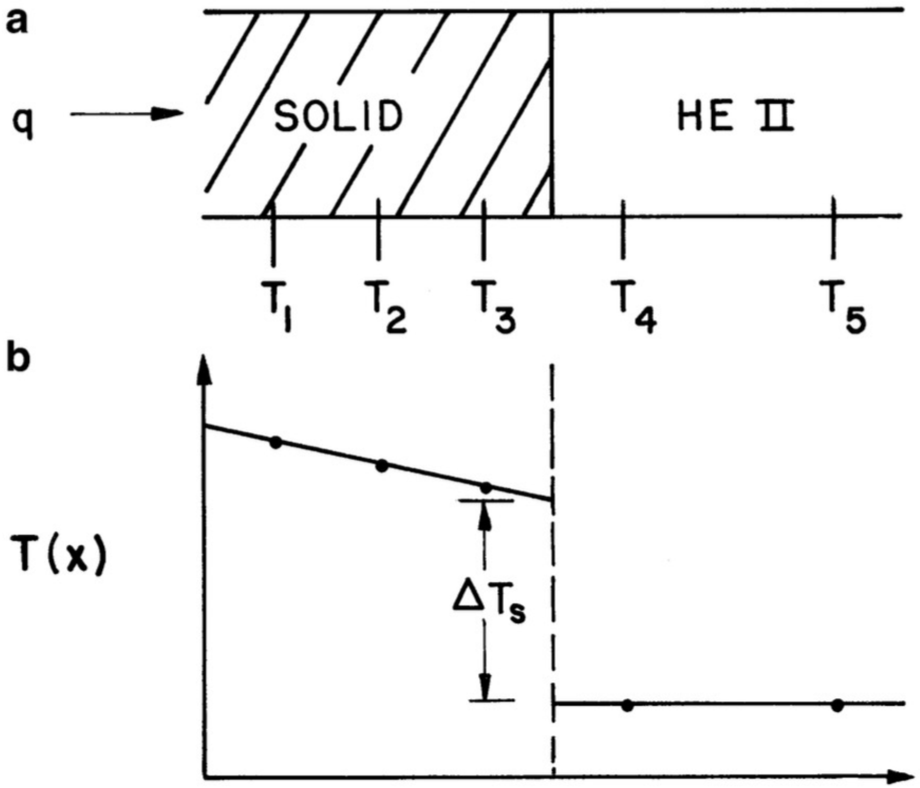
$$R_k = \frac{const.}{AT^3}$$



Conductive heat transfer

For a liquid helium-copper boundary, it has been shown experimentally that

$$R_K \approx \frac{0.025}{AT^3}$$



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Convective heat transfer

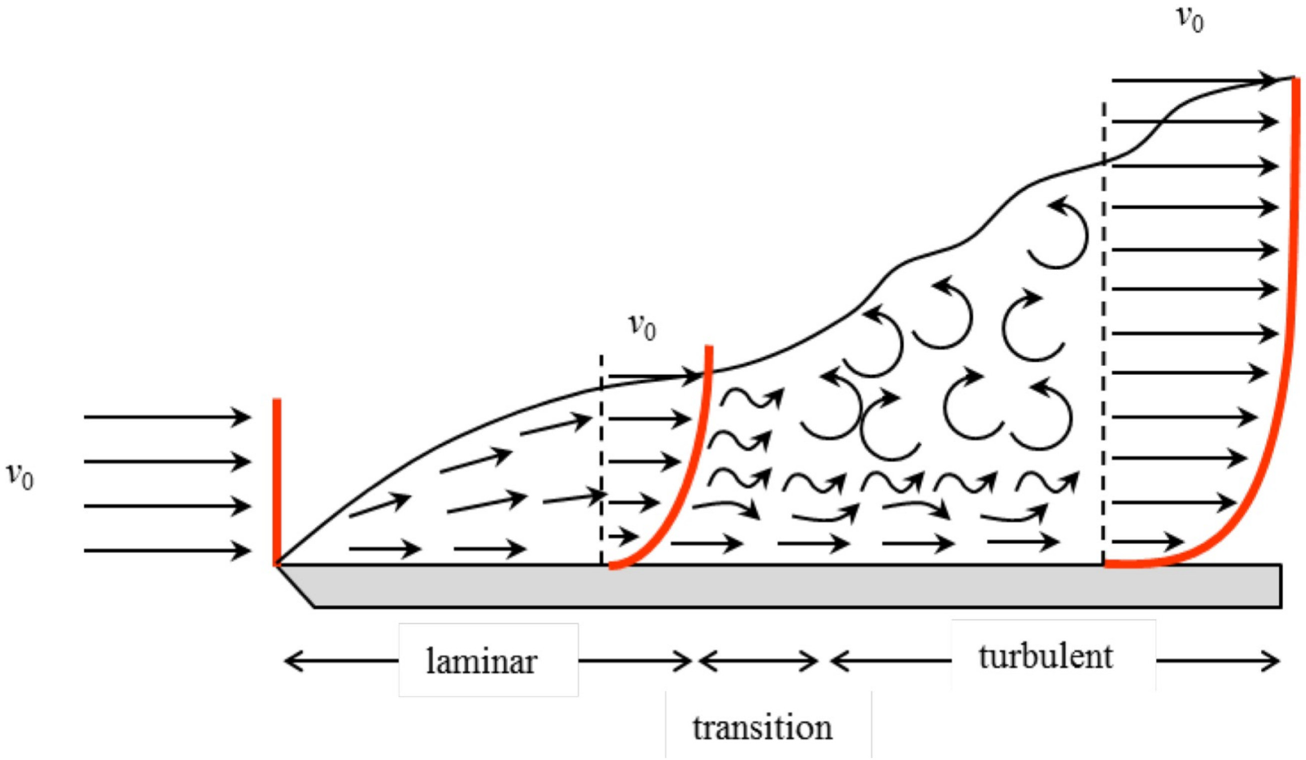
Fairly straightforward to eliminate => put cold mass in vacuum!

Insulating vacuum chamber is typically evacuated to $<10^{-4}$ mbar using rotary and then turbomolecular vacuum pumps, in order to prevent convective loading and minimise residual gas conduction

See Oleg Malyshev’s course for in-depth treatment

Convective heat transfer

In many wet cryostats, both forced and free convection of both liquids and gases provides useful heat transfer



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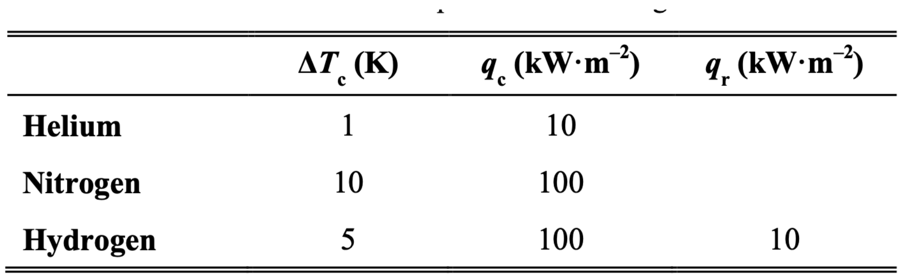
Bauduoy (2015)

Convective heat transfer

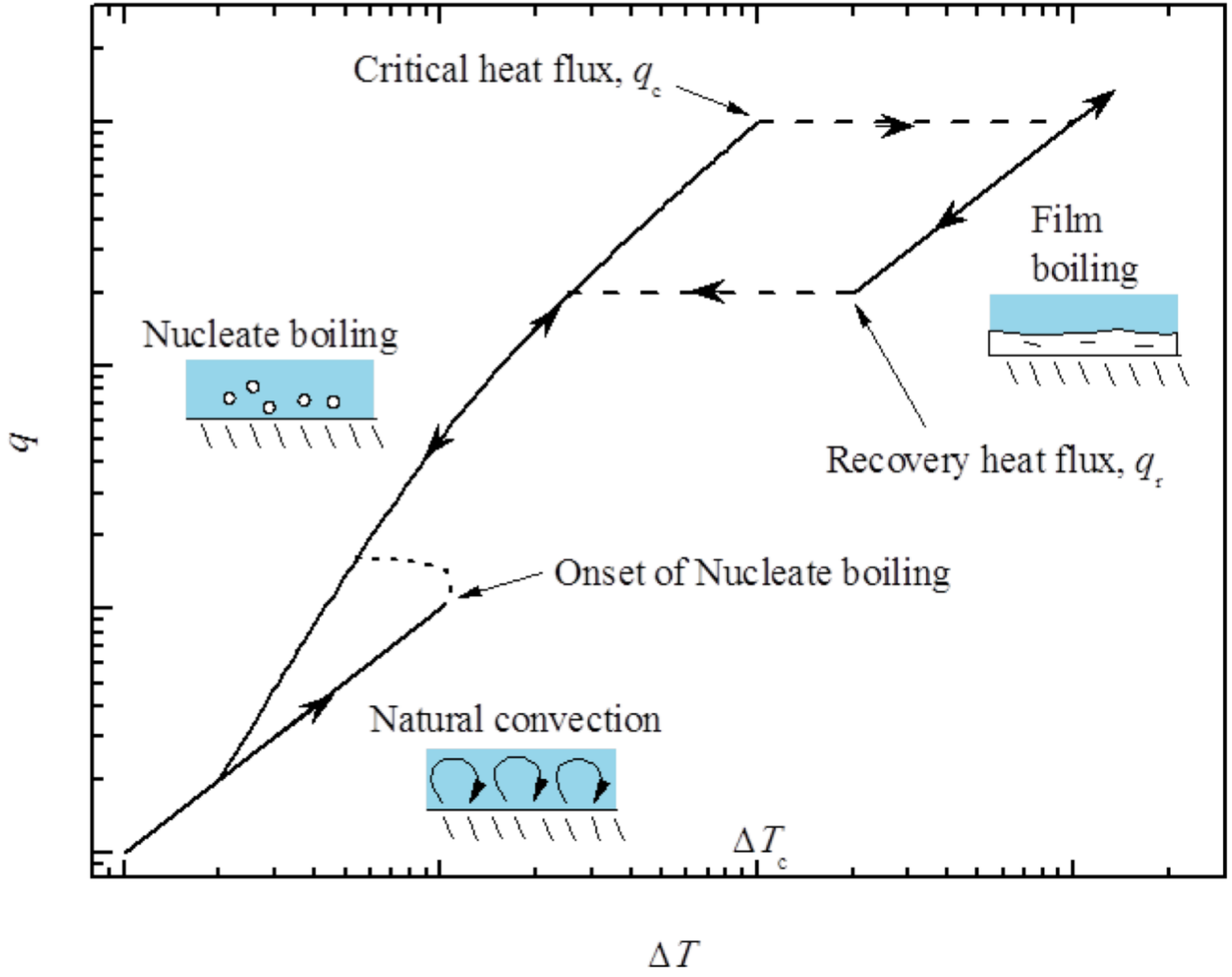
For flow over a surface, heat transfer is strongly dependent on the flow regime (Reynolds, Prandtl, and Grashof numbers)

Can be modelled analytically as well as numerically (CFD is a powerful tool for this but can be very challenging)

Convective heat transfer – boiling



	ΔT_c (K)	q_c (kW·m^{-2})	q_r (kW·m^{-2})
Helium	1	10	
Nitrogen	10	100	
Hydrogen	5	100	10



Bauduoy (2015)

Radiative heat transfer

A surface at a given temperature absorbs, reflects, and emits electromagnetic radiation. The spectrum of the emitted power for a blackbody is described by Planck's law – integrating wrt frequency gives

$$\dot{q}_{rad,bb} = \sigma T^4$$

which gives the total hemispherical blackbody emissive power per unit area *q* at *T*, where σ is the Stefan-Boltzmann constant (= 5.67E-8 $Wm^{-2}K^{-4}$)

Radiative heat transfer

The ratio of the power emitted by a real surface to that emitted by a blackbody is the emissivity ε, hence

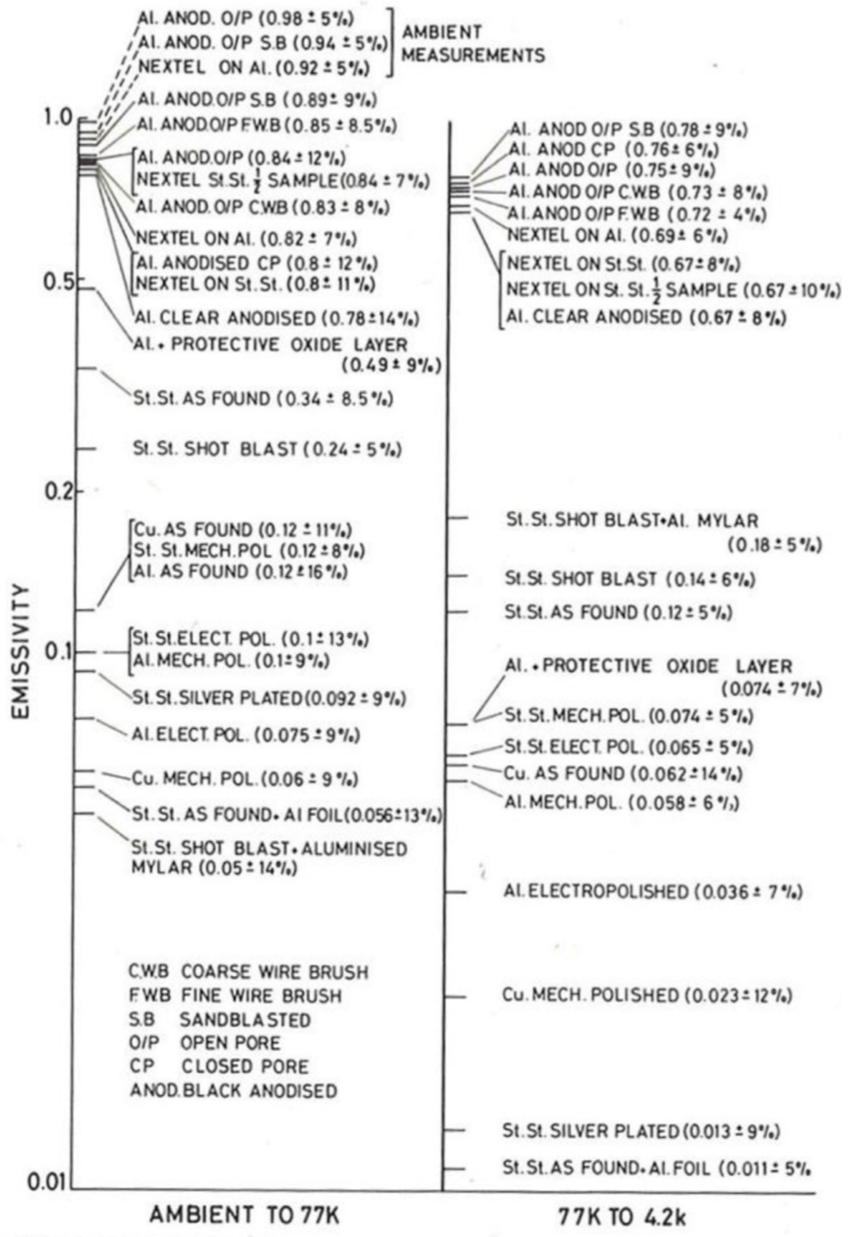
$$\dot{q}_{rad} = \varepsilon \sigma T^4$$

We can measure ε experimentally for any real surface

Radiative heat transfer

ε is highly dependent on surface finish

Values for a range of materials readily available in the literature



Obert (1982)

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Radiative heat transfer

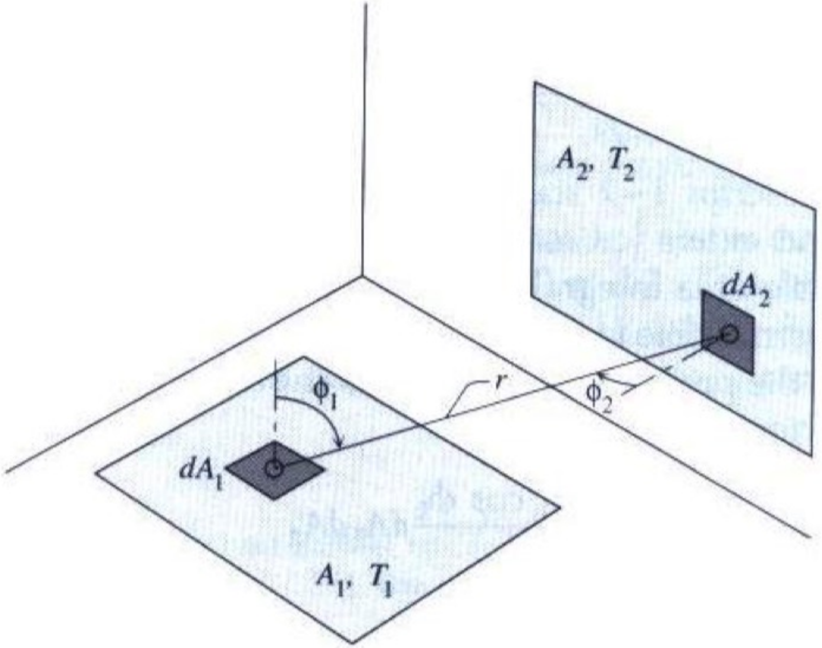
It may be seen that the rate of radiative heat exchange between two surfaces is simply the difference between the heat emitted from the first surface and absorbed by the second, and that emitted by the second surface and absorbed by the first; the general form is given by

$$\dot{q}_{rad,1-2} = \sigma \left(T_1^4 - T_2^4\right) / \left(\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2} \right)$$

Radiative heat transfer

View factors account for the geometry of the system

For common geometries, these can be found in the literature, e.g. Parma (2015)



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Radiative heat transfer

Multi-layer insulation (MLI) blankets consist of sheets of highly reflective layers, typically aluminized mylar, stacked alternately with insulating spacers. The mylar sheets then are floating temperature screens between T_1 and T_2

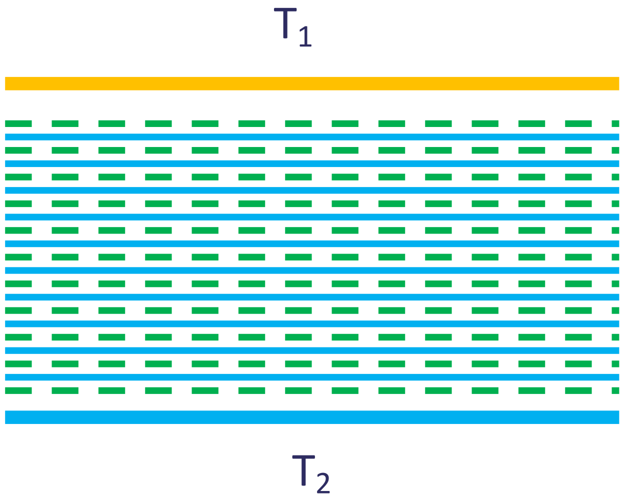

Image courtesy B Shaughnessy

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Radiative heat transfer

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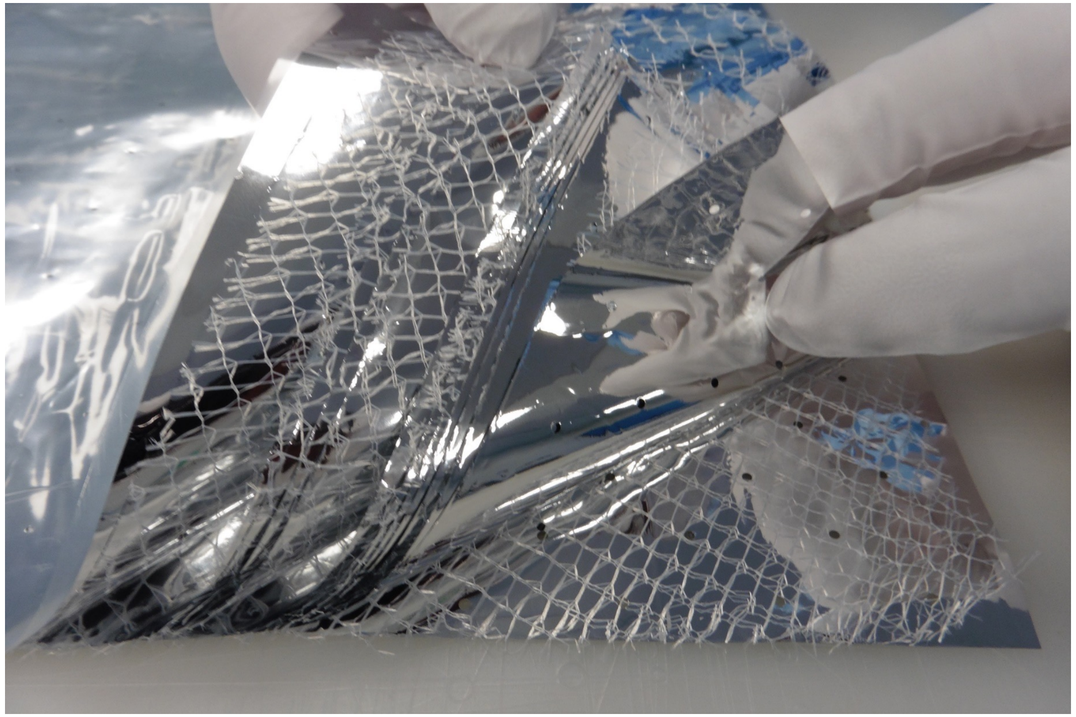

Image courtesy B Shaughnessy

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Radiative heat transfer

A simplified thermal model (Parma, 2015) considers contributions from radiation and residual solid conduction across the blanket thickness as

$$\dot{q}_{MLI} = \left[\frac{\beta}{N+1} \cdot \left(T_1^4 - T_2^4\right)\right] + \left[\frac{\alpha}{N+1} \cdot \frac{T_1 + T_2}{2} \cdot \left(T_1 - T_2\right)\right]$$

where α and β are coefficients that may be found experimentally (in the case of the LHC dipole cryostats, $\alpha = 1.401\text{e-}4$ and $\beta = 3.741\text{e-}9$

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Radiative heat transfer

It may also be considered that an optimal packing density exists; this has been found experimentally to be 15 to 20 layers/cm

Some useful rules of thumb for design are 1 W/m^2 from 300 K to 40 K with 30 layers of MLI and 100 mW/m^2 from 40 K to 2 K with 10 layers of MLI

Material properties

Many material properties are temperature dependent, including heat capacity, thermal conductivity, coefficient of thermal contraction, mechanical strength, stiffness

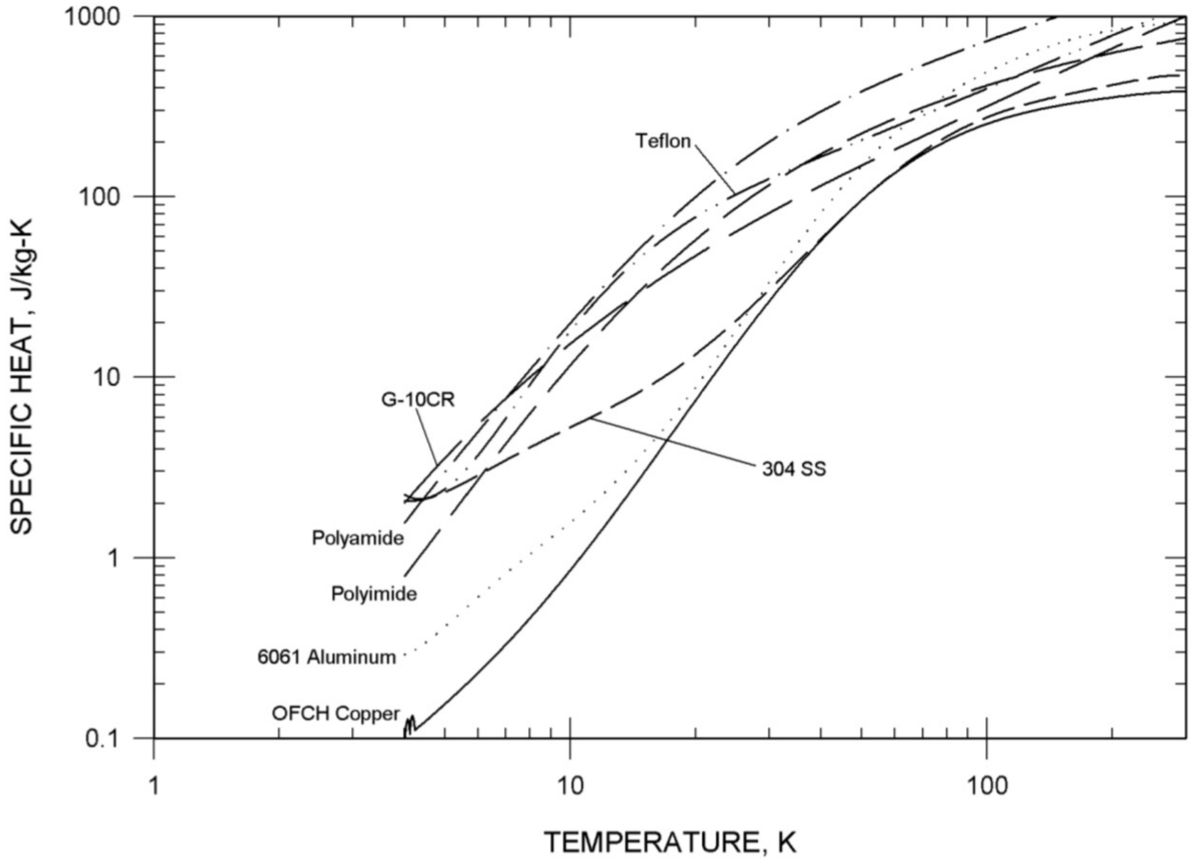
Essential that these are accounted for during design of cryogenic systems

Heat capacity

Specific heat

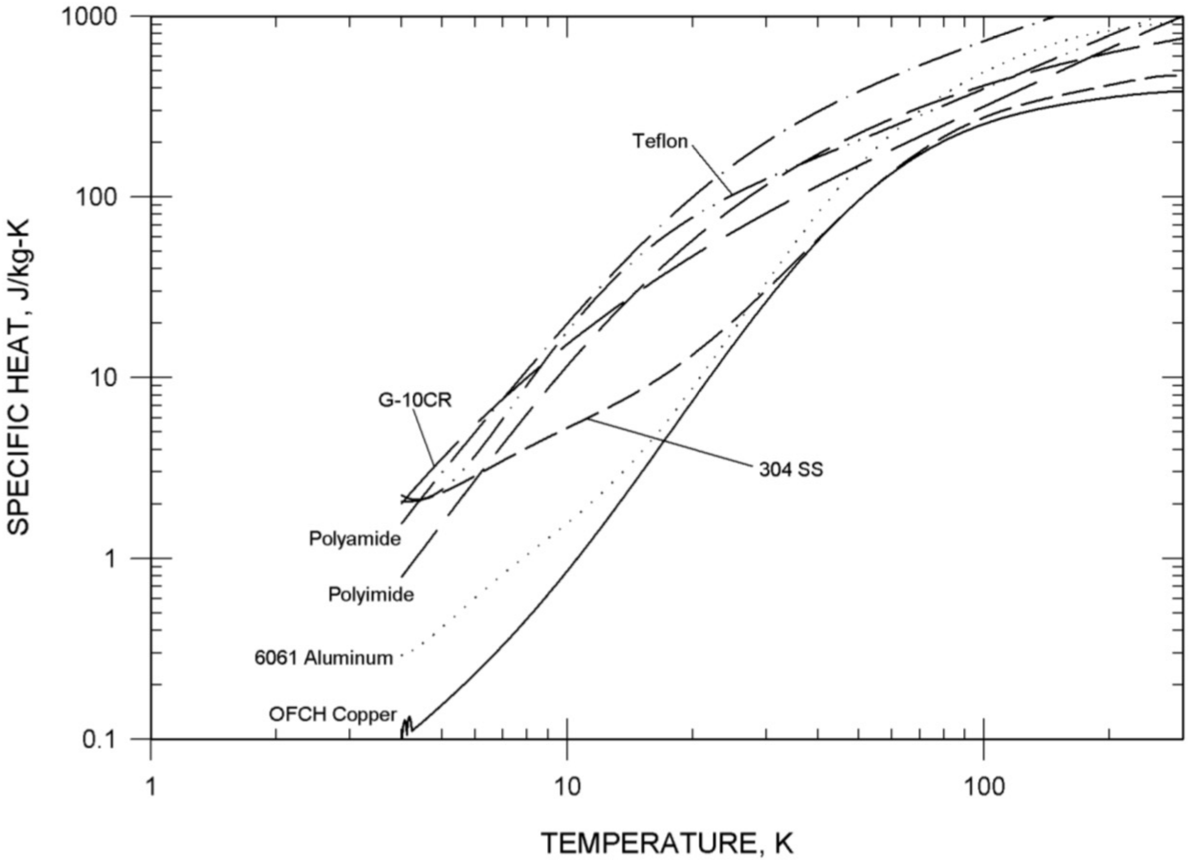
$$c = \frac{1}{m}\frac{dQ}{dT}$$

Integrals in literature



Heat capacity

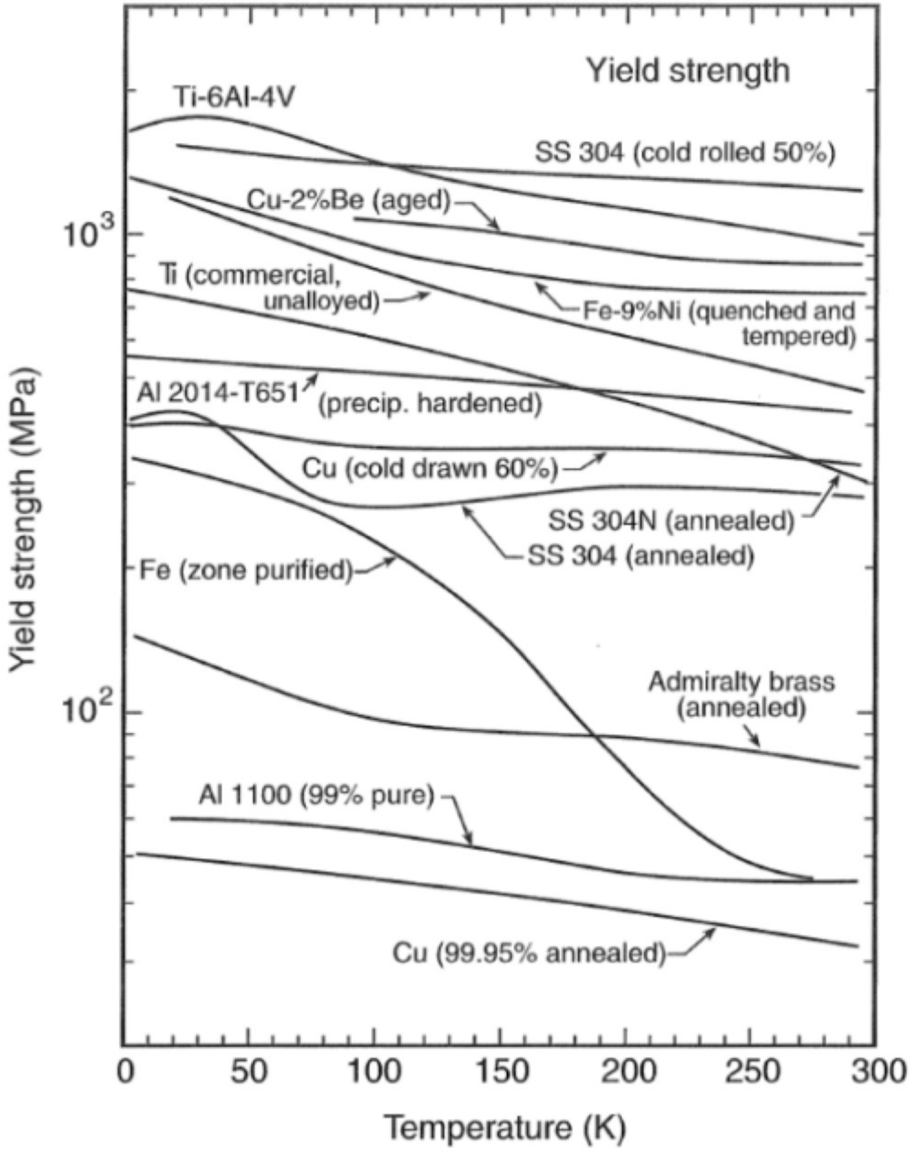
In general, specific heat capacity decreases with temperature. Hence, materials cool faster as they get colder, but also at low temperatures a small heat leak will cause a large temperature rise



Mechanical strength

Not sufficient to simply consider room temperature values!

In many cases however, strength improves as material cools



Duthil (2015)

Thermal expansivity

Results from vibration of lattice structure of material

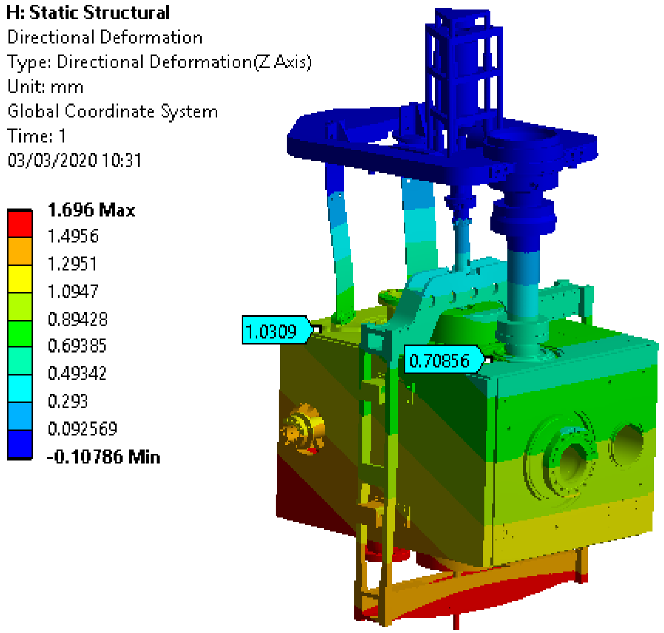
Most contraction happens above 77 K (=> components can be thermally cycled using LN2 only)

Must be considered in cryostat design (impact on alignment, interferences or gaps where dissimilar materials are used, etc.)

Thermal expansivity

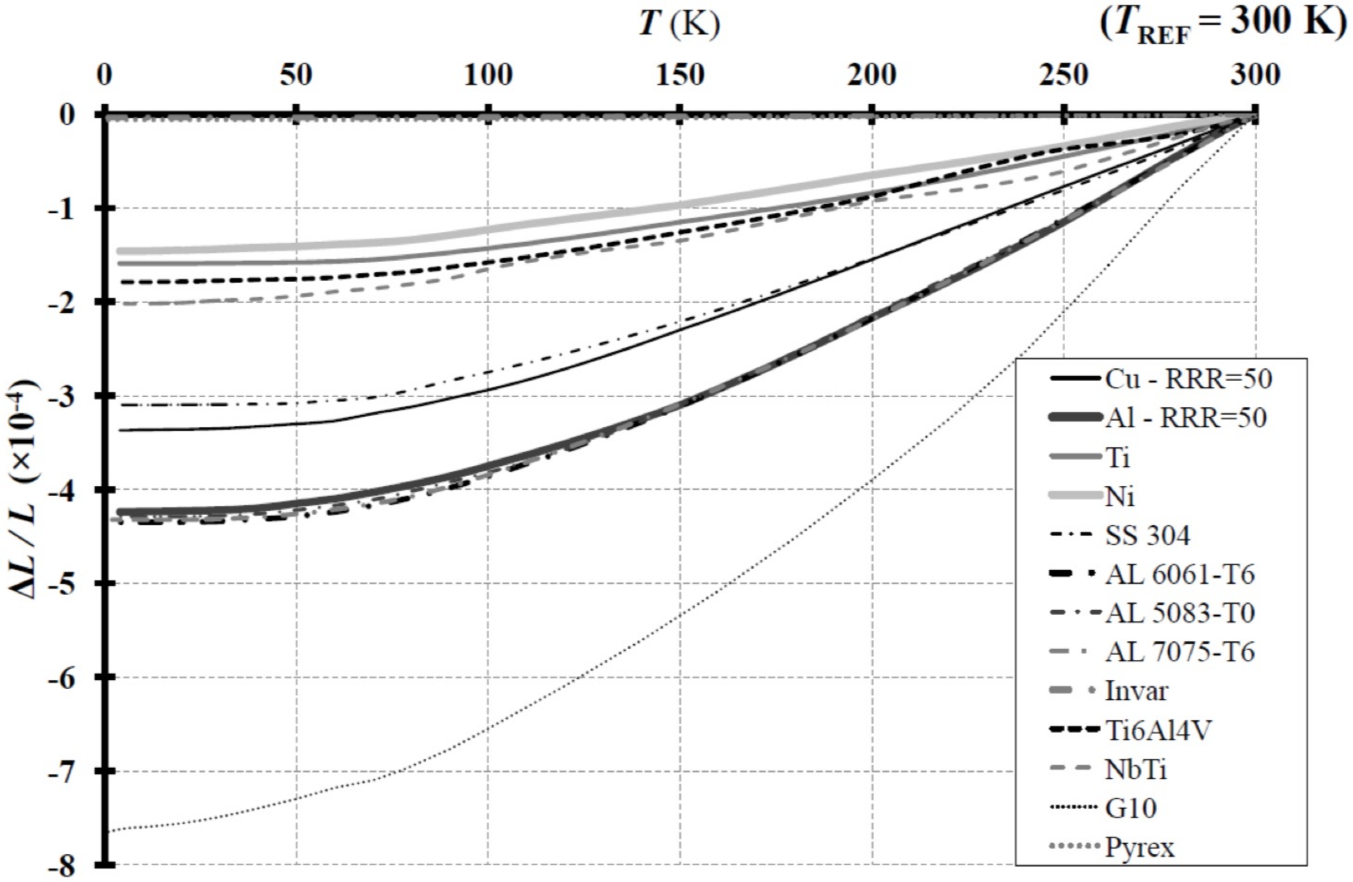
FEA can be used to analyse thermal contraction

Typically managed by use of flexible sections (e.g., bellows) and configuring geometry to balance contractions or building in slack at room temperature



Courtesy of N Templeton

Thermal expansivity



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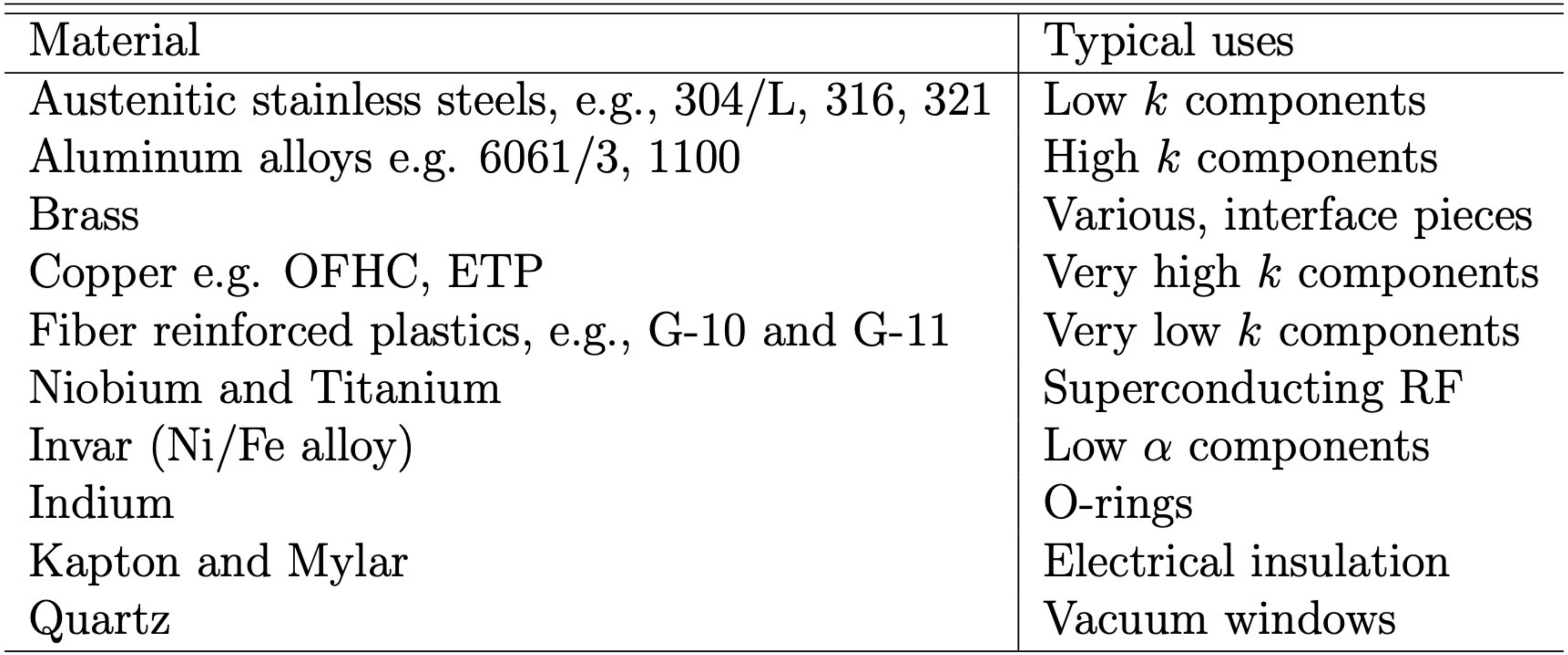
Duthil (2015)

Thermal expansivity

Material	$\Delta L / L$ (300 – 100)	$\Delta L / L$ (100 – 4)
Stainless Steel	296×10^{-5}	35×10^{-5}
Copper	326×10^{-5}	44×10^{-5}
Aluminum	415×10^{-5}	47×10^{-5}
Iron	198×10^{-5}	18×10^{-5}
Invar	40×10^{-5}	-
Brass	340×10^{-5}	57×10^{-5}
Epoxy/ Fiberglass	279×10^{-5}	47×10^{-5}
Titanium	134×10^{-5}	17×10^{-5}

Table courtesy J Weisend

Some commonly used materials



Material	Typical uses
Austenitic stainless steels, e.g., 304/L, 316, 321	Low k components
Aluminum alloys e.g. 6061/3, 1100	High k components
Brass	Various, interface pieces
Copper e.g. OFHC, ETP	Very high k components
Fiber reinforced plastics, e.g., G-10 and G-11	Very low k components
Niobium and Titanium	Superconducting RF
Invar (Ni/Fe alloy)	Low α components
Indium	O-rings
Kapton and Mylar	Electrical insulation
Quartz	Vacuum windows

Unsuitable materials

Include (but are not limited to!) martensitic stainless steels, cast iron, carbon steels, rubber, and Teflon

These all become brittle when cooled

Instrumentation and controls

Typically require the ability to measure temperature, pressures (including vacuum), liquid level, valve position, flow rates, radiation levels, leak rates, pump speeds

Control requirements usually control valves, heaters, magnetic coils, pumps

Instrumentation and controls

Require sensors inside cryostat → wire routing through system → connector feedthrough out of cryostat (hermetic seals) → cabling to rack → monitor/readout → GUI and data logging

Good rule of thumb is £1000 per parameter

Thermometry

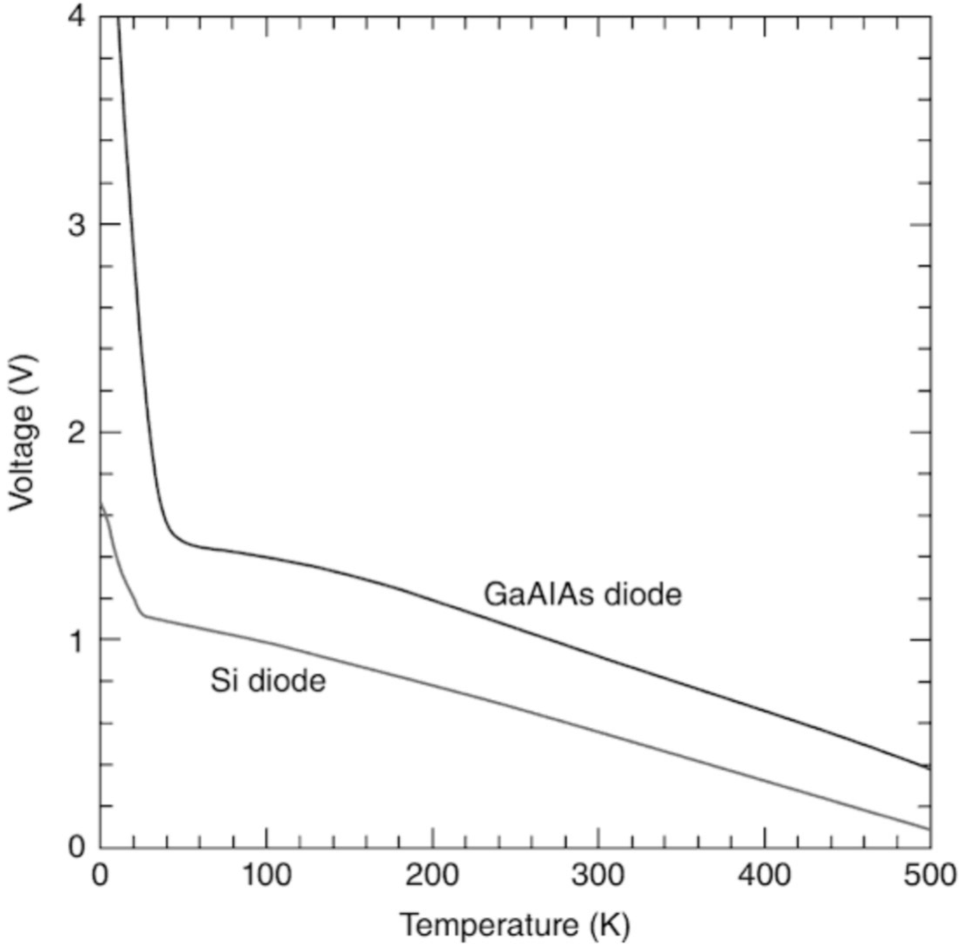
Select type on basis of

- temperature range
- accuracy
- resolution
- stability
- power dissipation
- response time
- sensitivity to magnetic fields
- sensitivity to radiation
- price
- packaging (ease of installation)
- durability

Thermometry

Diodes may be used as thermometers as, under a constant current excitation, the forward voltage varies with temperature

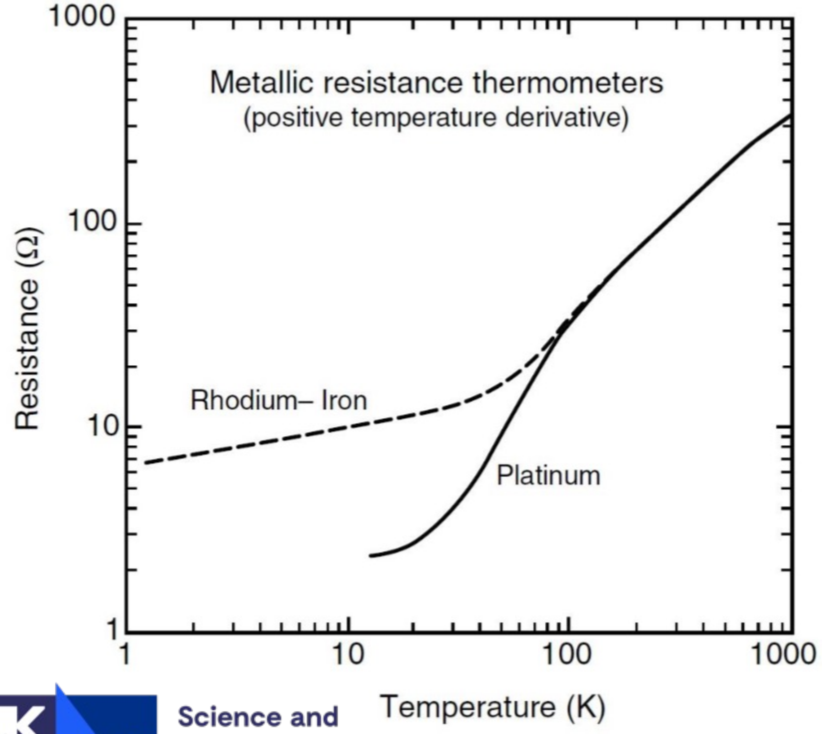
Can have sufficient repeatability so as to be accurate to within 0.25 K from a standard calibration curve

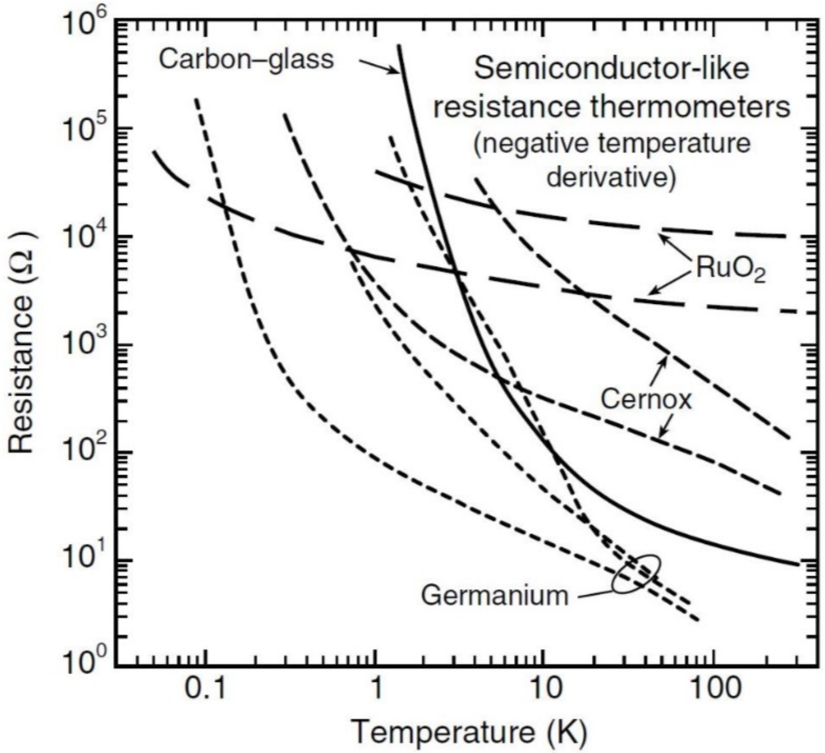


Radebaugh (2016)

Thermometry

RTDs work by measuring resistance which is a strong function of temperature for some suitable sensor





Radebaugh (2016)

Thermometry

RTDs read out using ac resistance bridges for high-resolution, low-power measurements

Selectable current excitation levels are used to minimise self-heating at lower temperatures (where R is high) and loss of resolution at higher temperatures (where R is low)

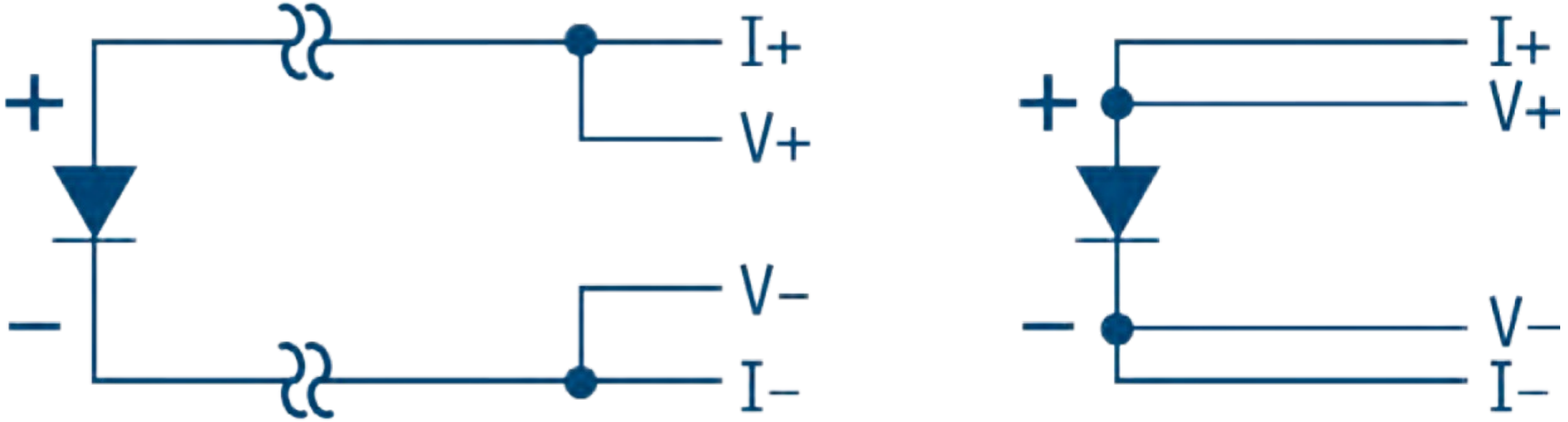
Thermometry

In addition to self-heating, the temperature of a sensor may be higher then the experiment due to heat leak through the wiring and poor thermal contact with the mounting position

In order to minimise this, the sensor packaging should be designed so as to provide excellent thermal contact and heat sinking of the wires

Thermometry

In order not to measure the resistance drop across the sensor leads, 4-wire measurements may be used where the excitation current is applied across one wire pair (I+, I-) and the voltage drop is measured across the second wire pair (V+, V-)



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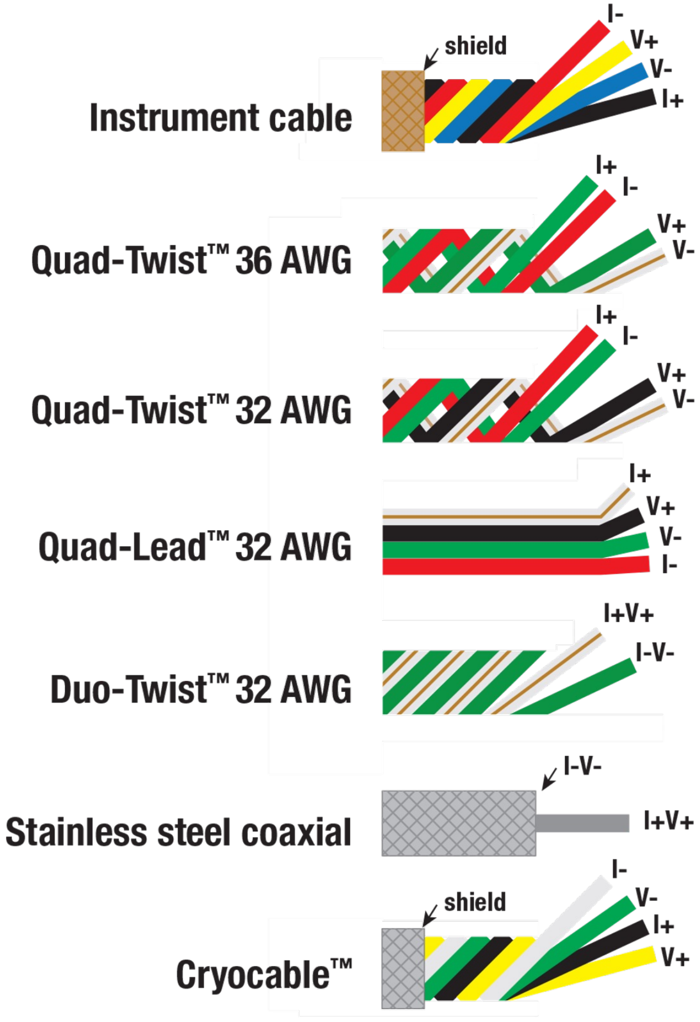
Courtesy Lake Shore Cryotronics

Thermometry

Low thermal conductance wiring is used (e.g. manganin) => each wire is a heat load

Sensor leads are also typically arranged as twisted pairs; this aids in both cancelling microphony and shielding from magnetic interference



Courtesy Lake Shore Cryotronics

Dewar design

Designed to store, transport, and dispense liquid cryogens

Insulating vacuum, neck support, MLI, countercooling => losses ~1% /day

Image courtesy Wessington

Dewar design

Designed to store, transport, and dispense liquid cryogens

Insulating vacuum, neck support, MLI, countercooling => losses ~1% /day

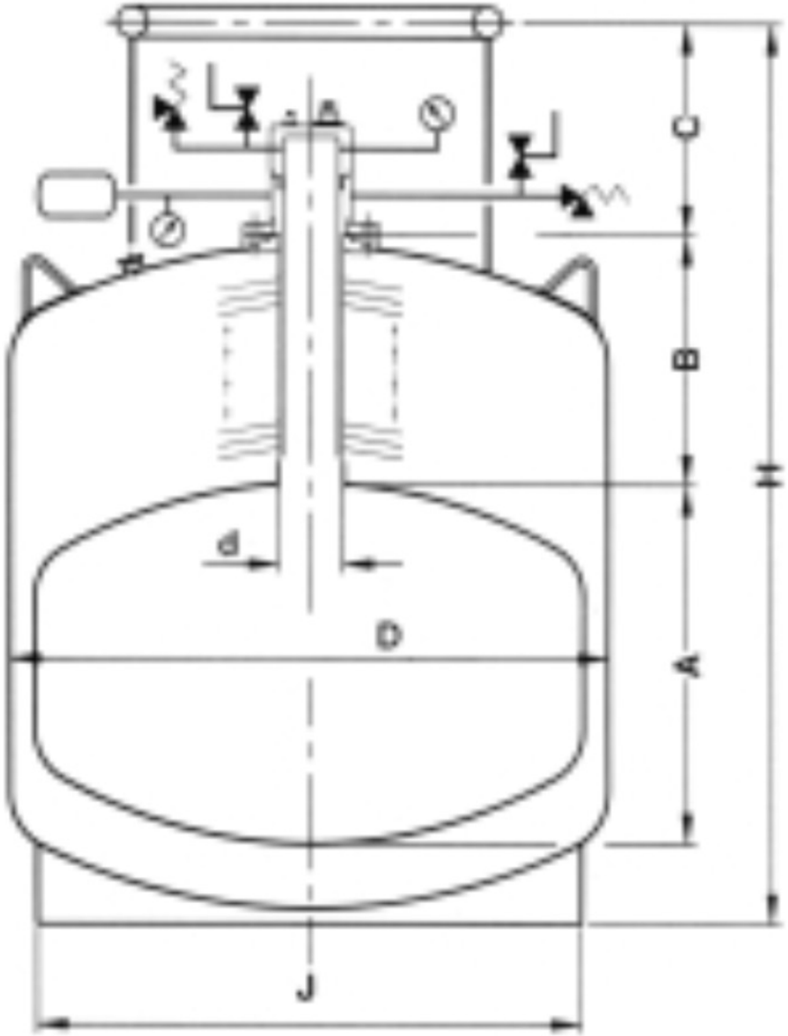


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Image courtesy C Monroe

Cryomodule design

Cryomodules are specialised cryostats

Designed to provide required environment for operating SRF cavities in an accelerator

Design approach strongly dependent on cavity geometry (frequency) and operating temperature

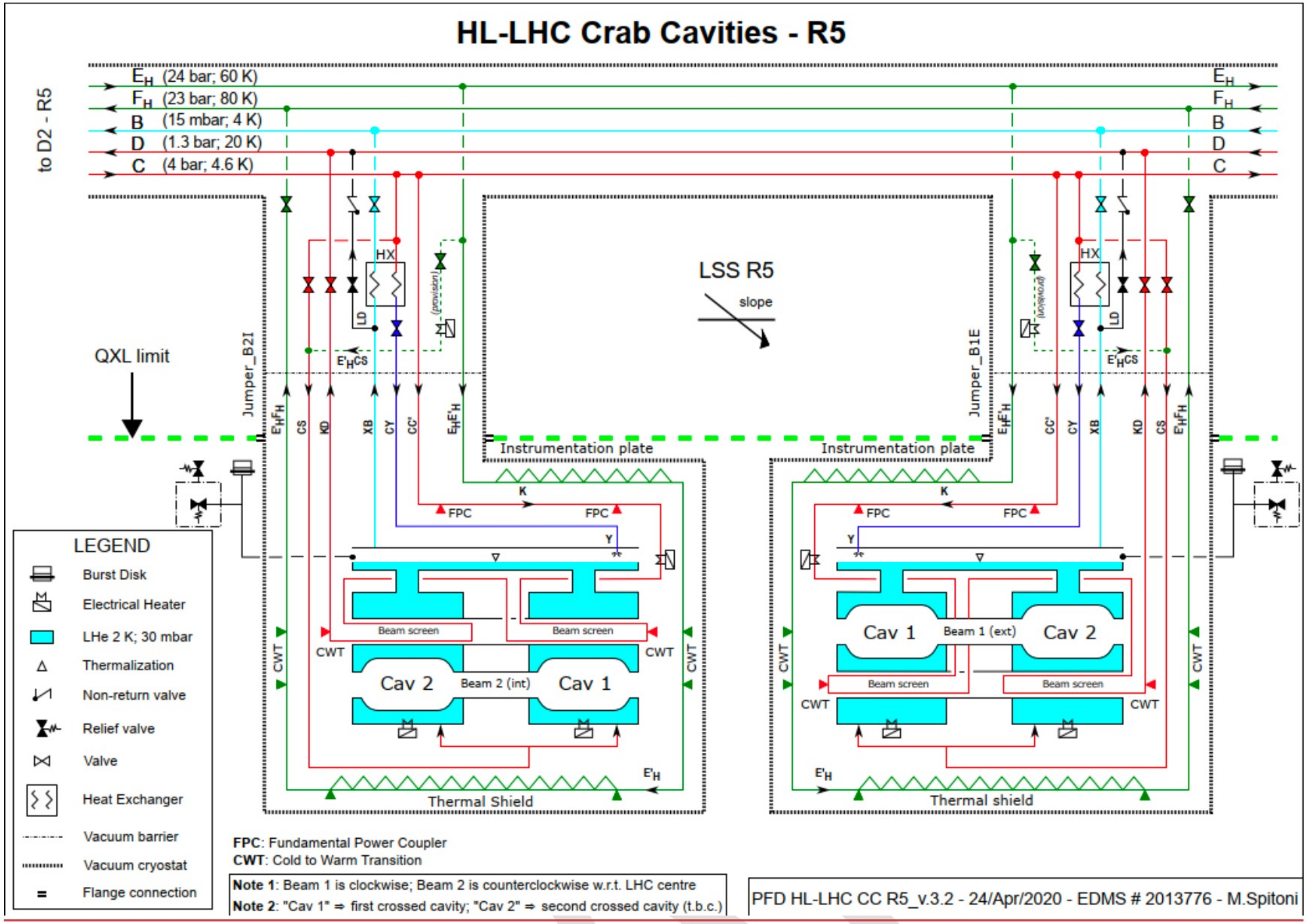
Cryomodule design

<500 MHz, typically operate in He-I at 4.2 K

>500 MHz more energy efficient to operate in He-II at 2 K (recall rf surface resistance is inversely proportional to temperature)

He-II => excellent temperature and mechanical stability

HL-LHC crab cavity cryomodule P&ID (draft)



FPC: Fundamental Power Coupler
CWT: Cold to Warm Transition

Note 1: Beam 1 is clockwise; Beam 2 is counterclockwise w.r.t. LHC centre
Note 2: "Cav 1" ⇒ first crossed cavity; "Cav 2" ⇒ second crossed cavity (t.b.c.)

PFD HL-LHC CC R5_v.3.2 - 24/Apr/2020 - EDMS # 2013776 - M.Spitoni

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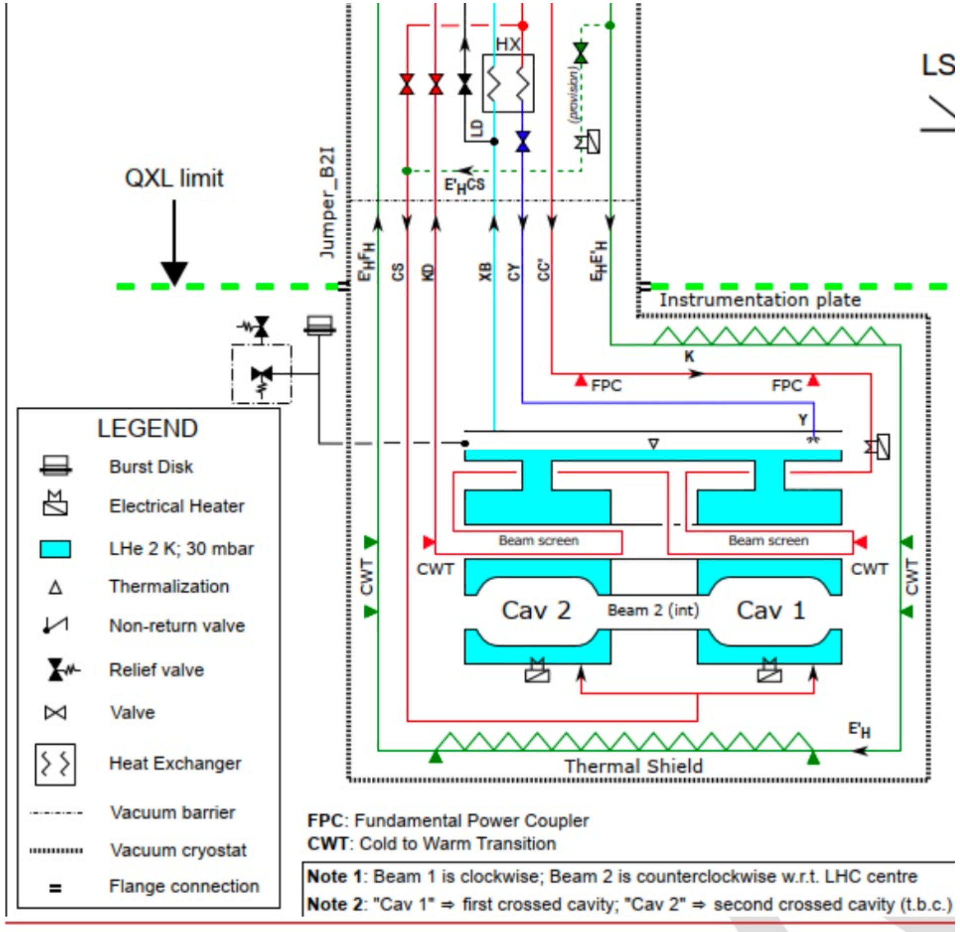
HL-LHC crab cavity cryomodule CAD



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Note 1: Beam 1 is clockwise; Beam 2 is counterclockwise w.r.t. LHC centre
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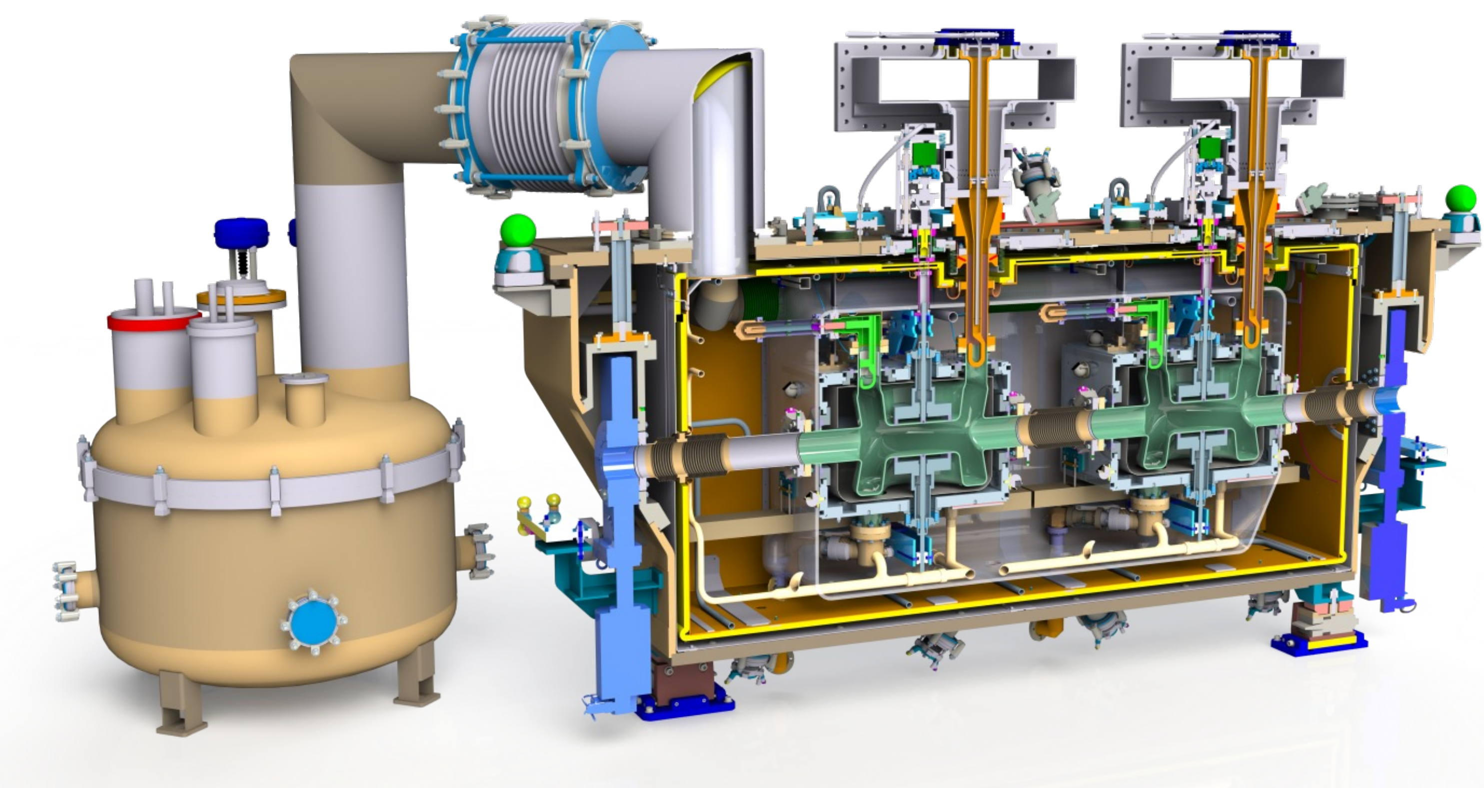


Cryomodule design

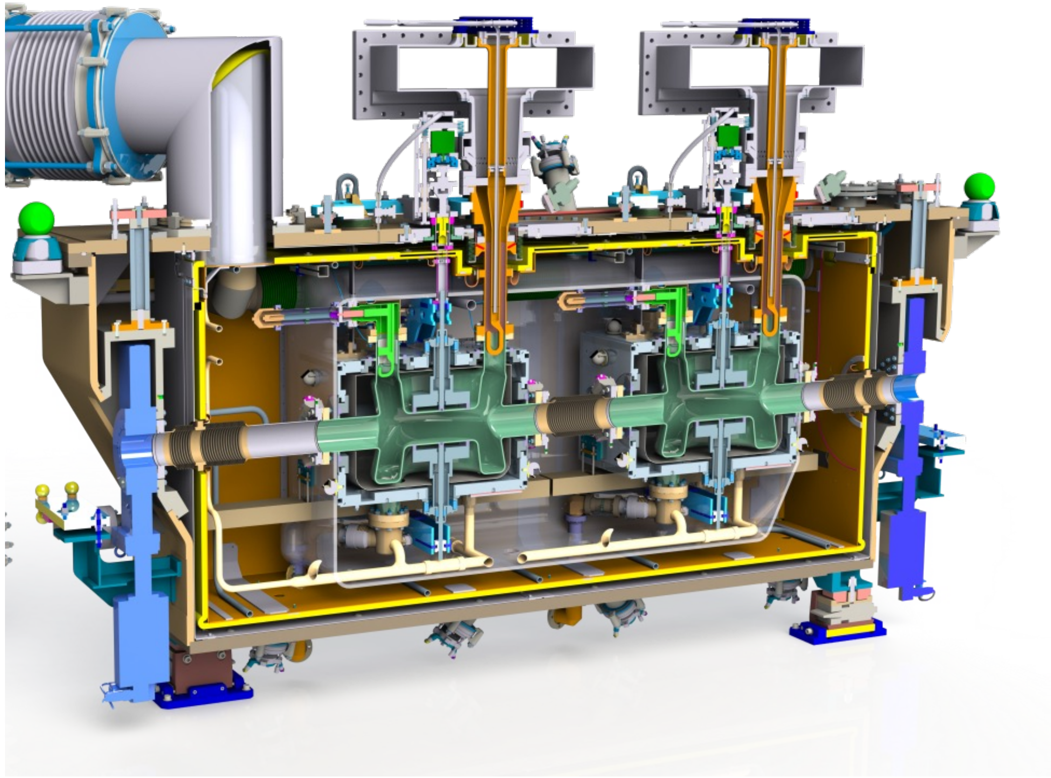
Major components:

- Dressed SRF cavities
- RF power couplers
- Tuners
- Thermal shield(s)
- Support structures
- Cryogenic lines
- Magnetic shield(s)
- Instrumentation
- Vacuum vessel
- Waveguide for RF supply
- Safety devices
- Bayonet connection for cryogen supply/recovery

Dressed cavities

Cavities assembled under cleanroom conditions (typically ISO4), typically integrated into cavity strings

Cavities typically have individual tanks welded around them to contain He-II



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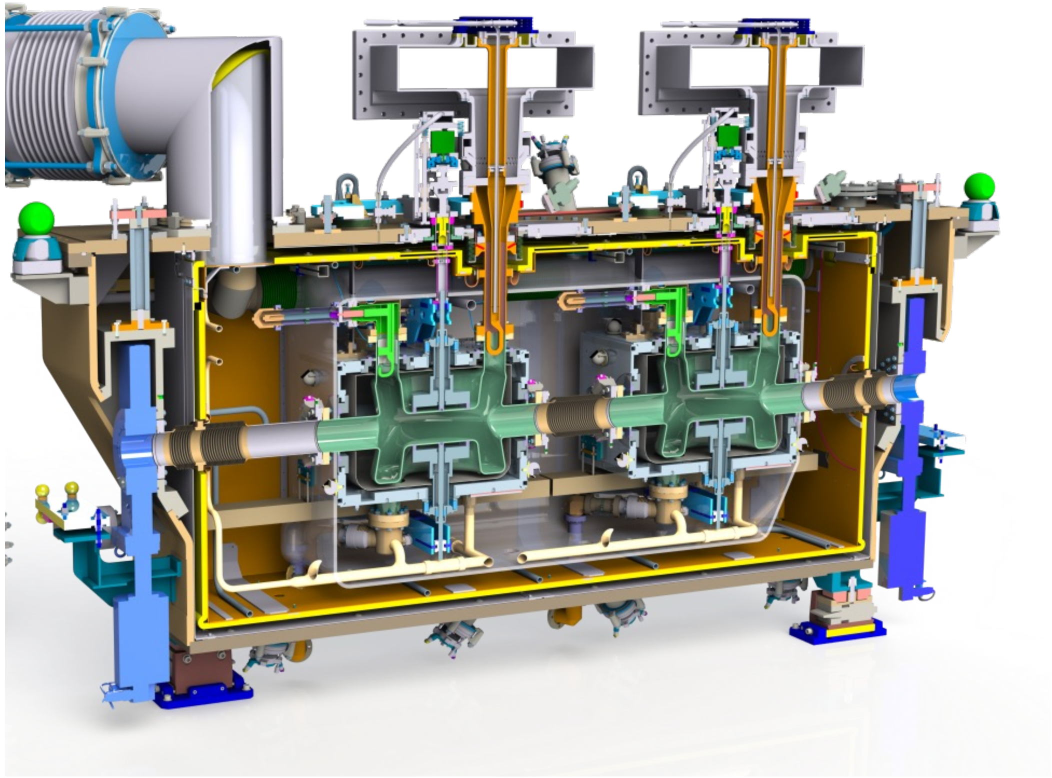
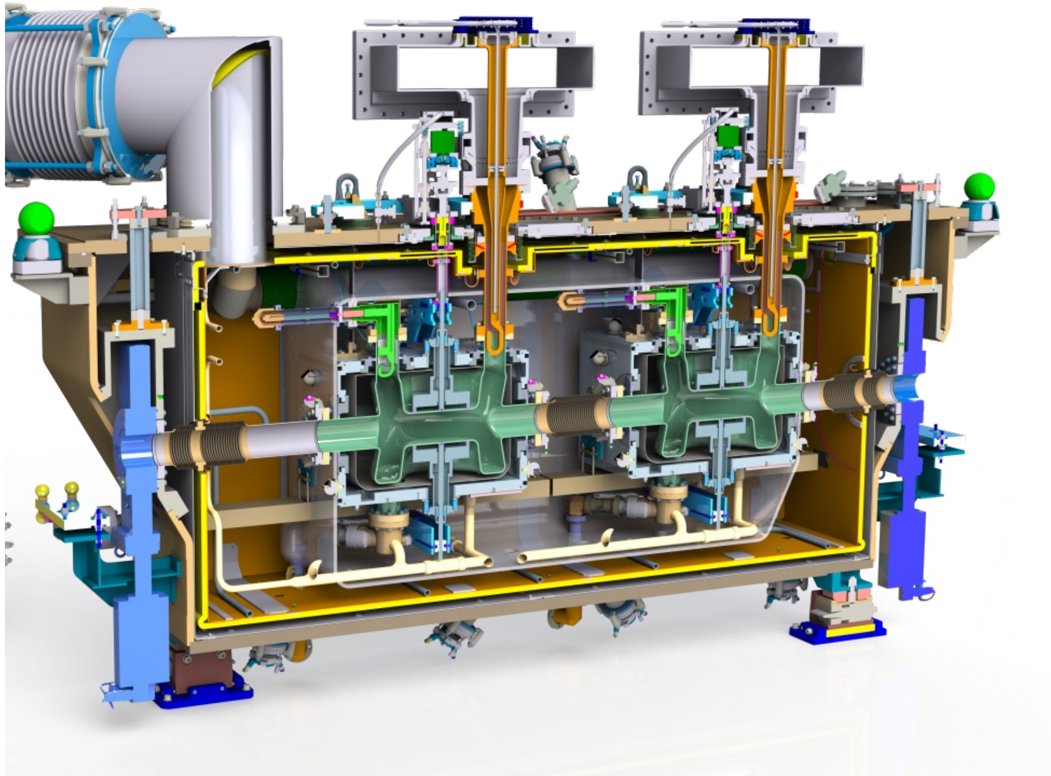
Magnetic shielding

Trapped flux in Nb decreases Q => shielding required from ambient fields



Magnetic shielding

This may be achieved at the level of <1 μT using some combination of active (i.e., a solenoid), warm passive (typically a high magnetic permeability nickel-iron alloy such as Mu-metal), and cold passive shielding (eg Cryoperm)



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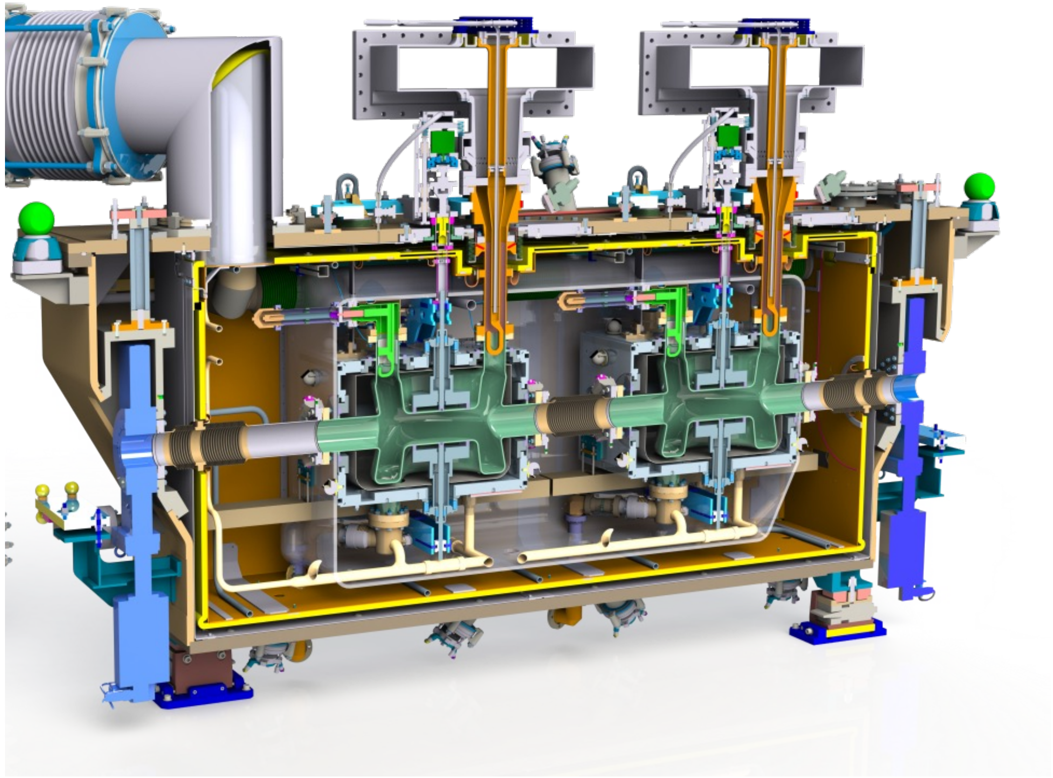
RF power couplers

Couplers are installed to provide RF power and HOM pick-up from the cavity, and are generally either coaxial or waveguide with ceramic windows to provide environmental isolation for the cavity



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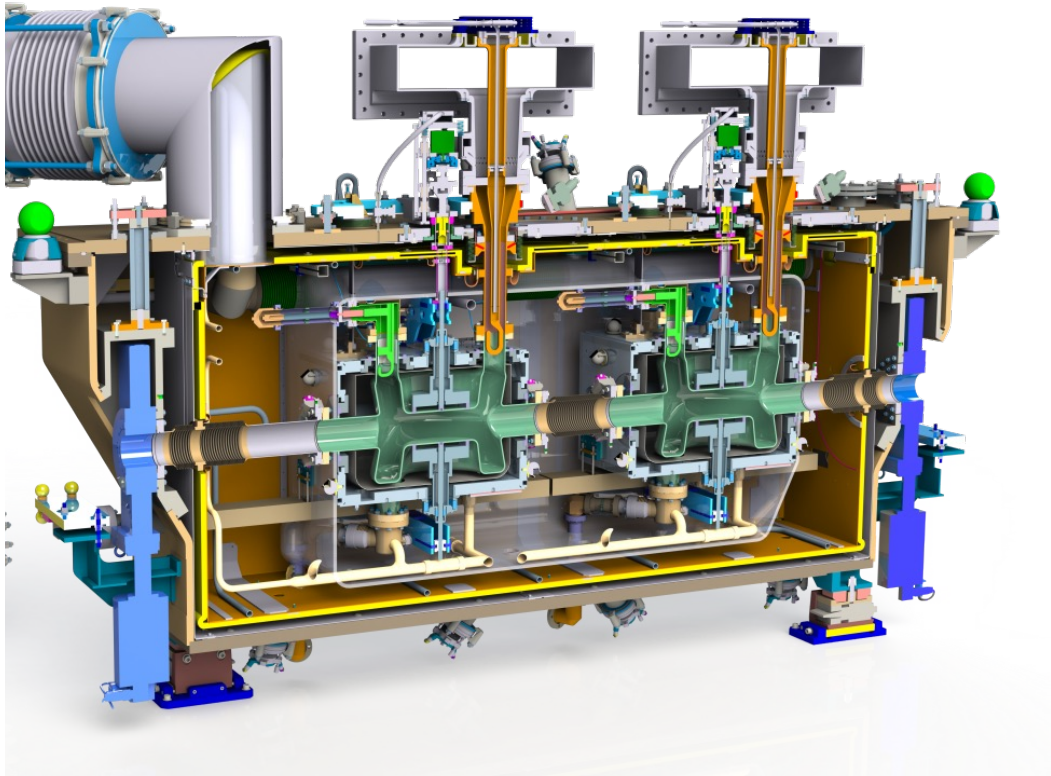
Tuners

Tuners installed on each cavity are used to ensure operation at the correct frequency



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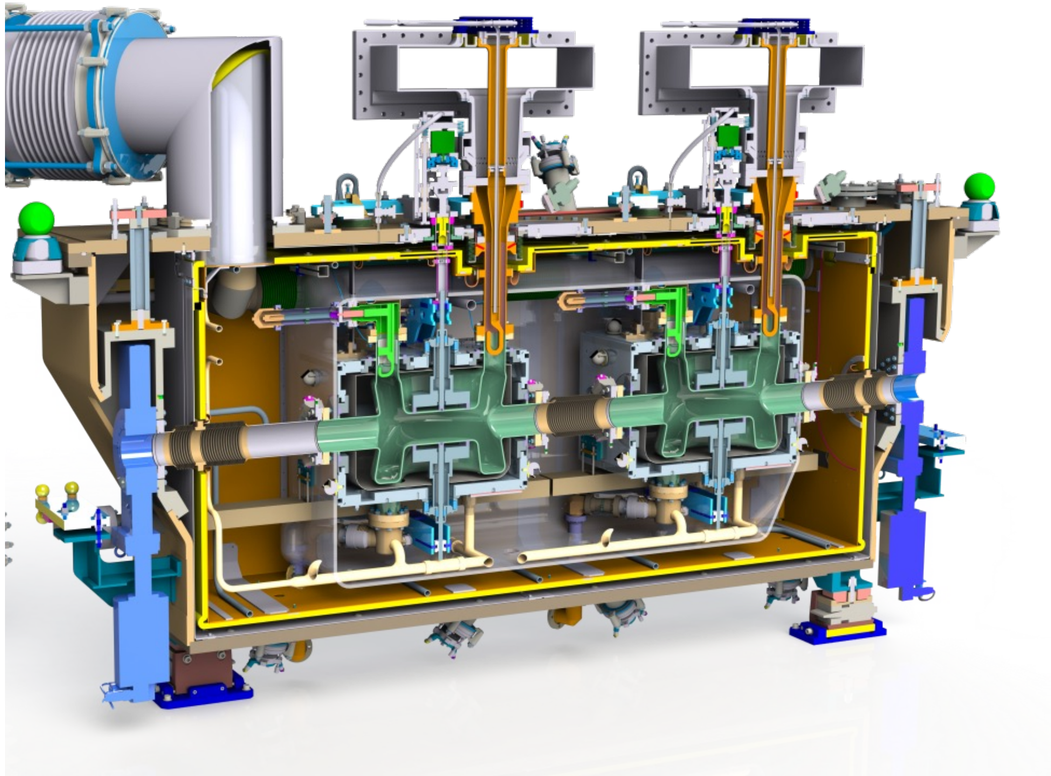
Tuners

Cavities may be detuned by pressure changes and mechanical stresses, requiring “slow” correction by a mechanical tuner, as well as by Lorentz forces which require “fast” correction by a piezoelectric cartridge



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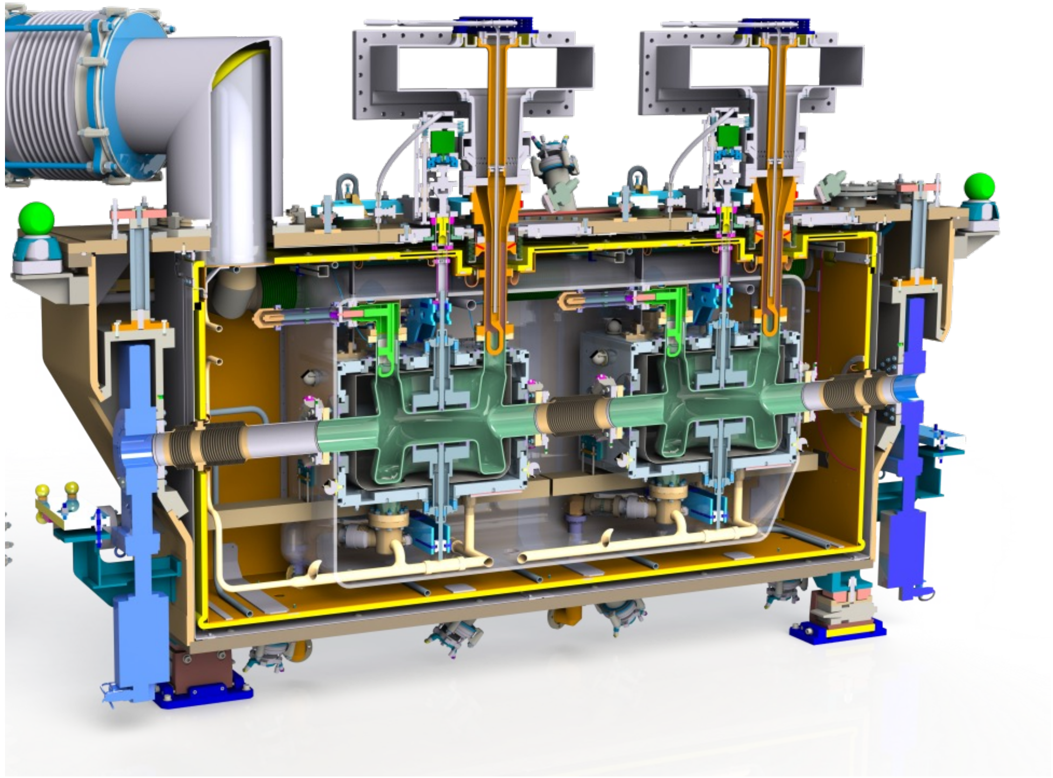
Thermal shielding

Cooled to intermediate temps using GHe (or in some cases LN_2)

MLI used to minimise radiative heat transfer



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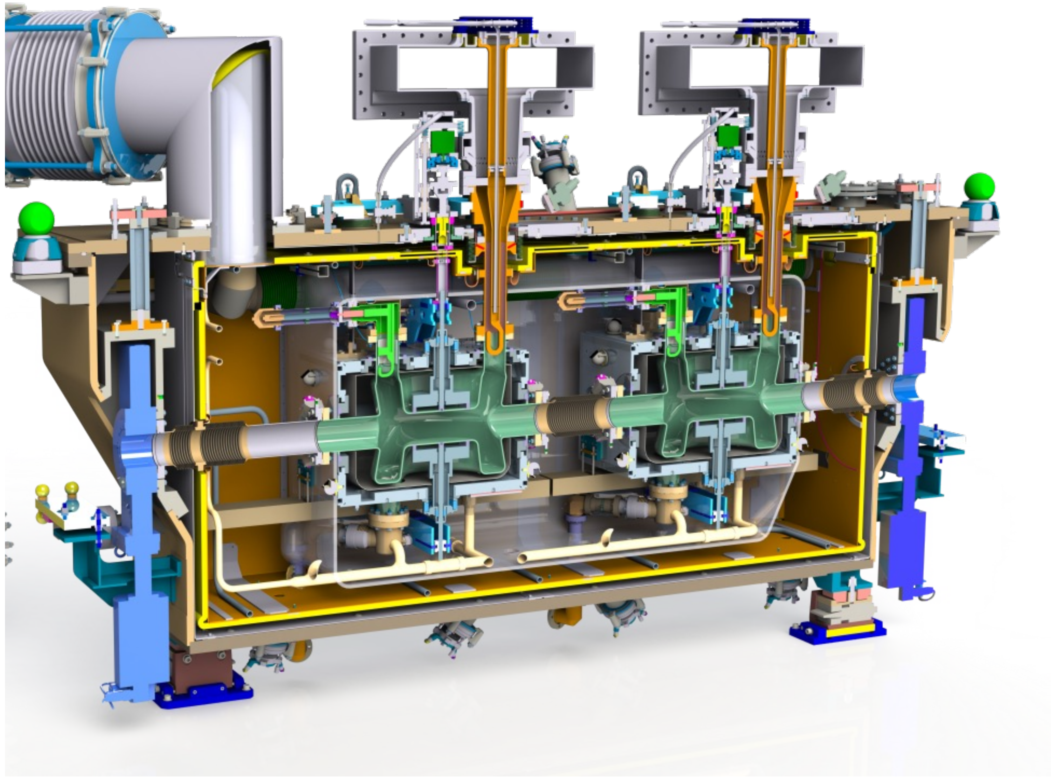
Thermal shielding

Typical radiative heat fluxes:

1 W/m^2 for the radiation shield at 40 K dressed with 30 layers of MLI

100 mW/m^2 for the cavities at 2 K with 10 layers of MLI



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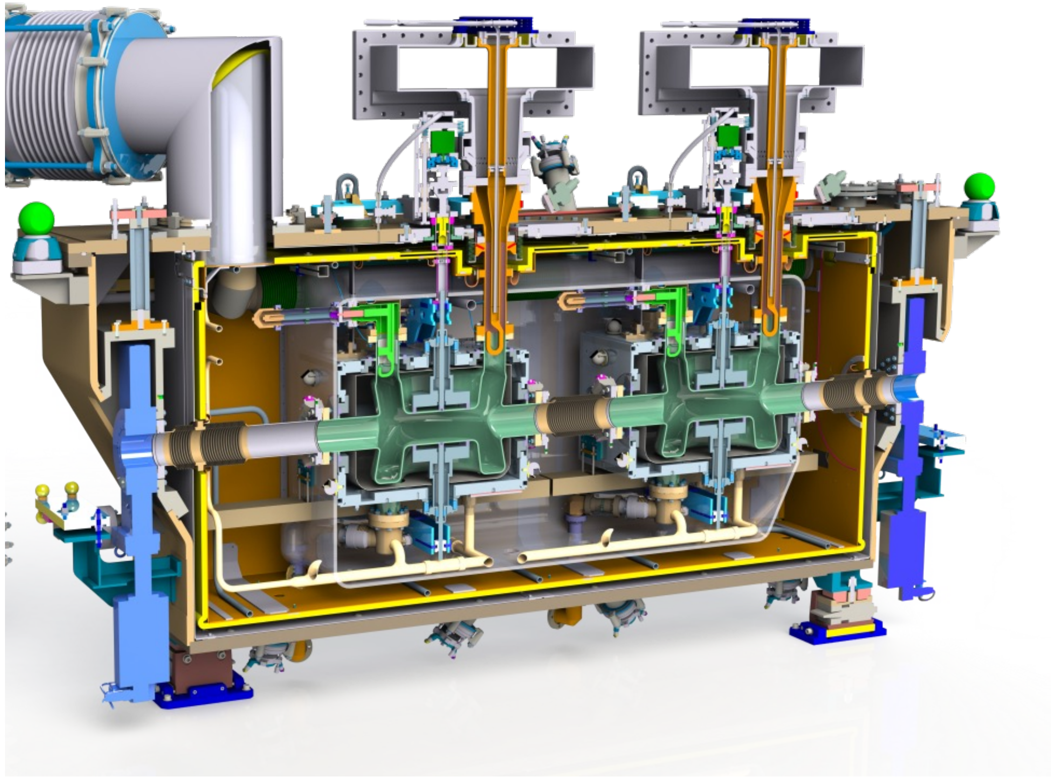
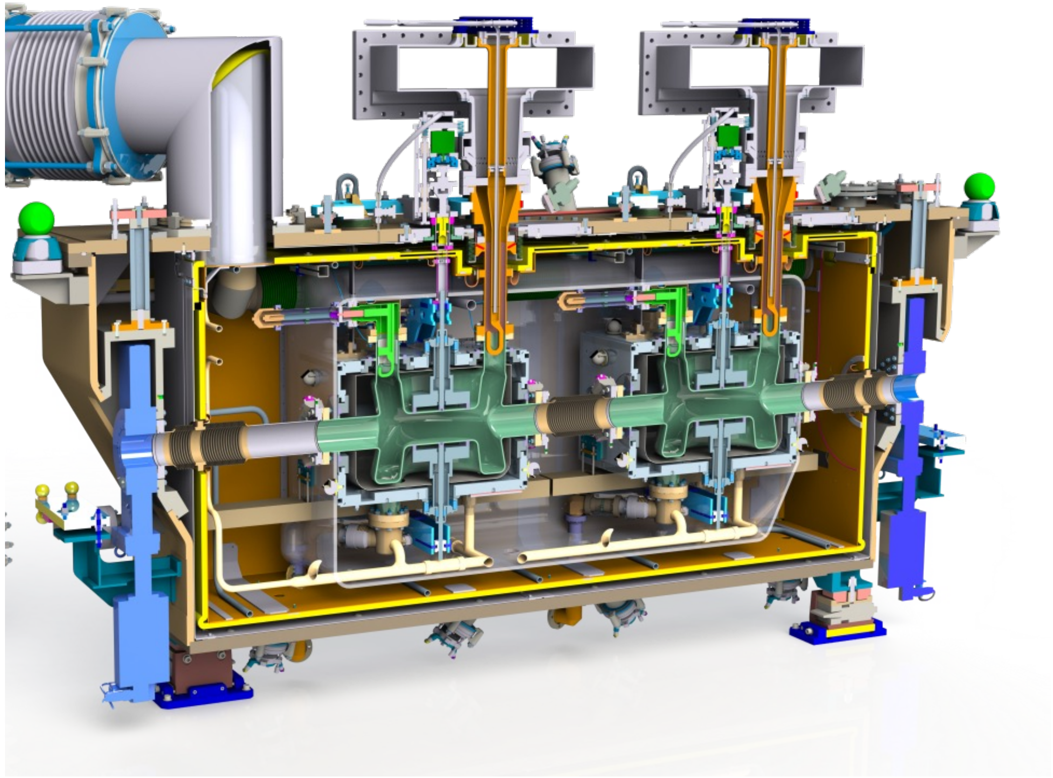
Supports

Structural elements such as posts, tension members, and space frames, are required to support the cold mass under mechanical loading from shipping and handling, cooldown, fluid flow, and ground motion



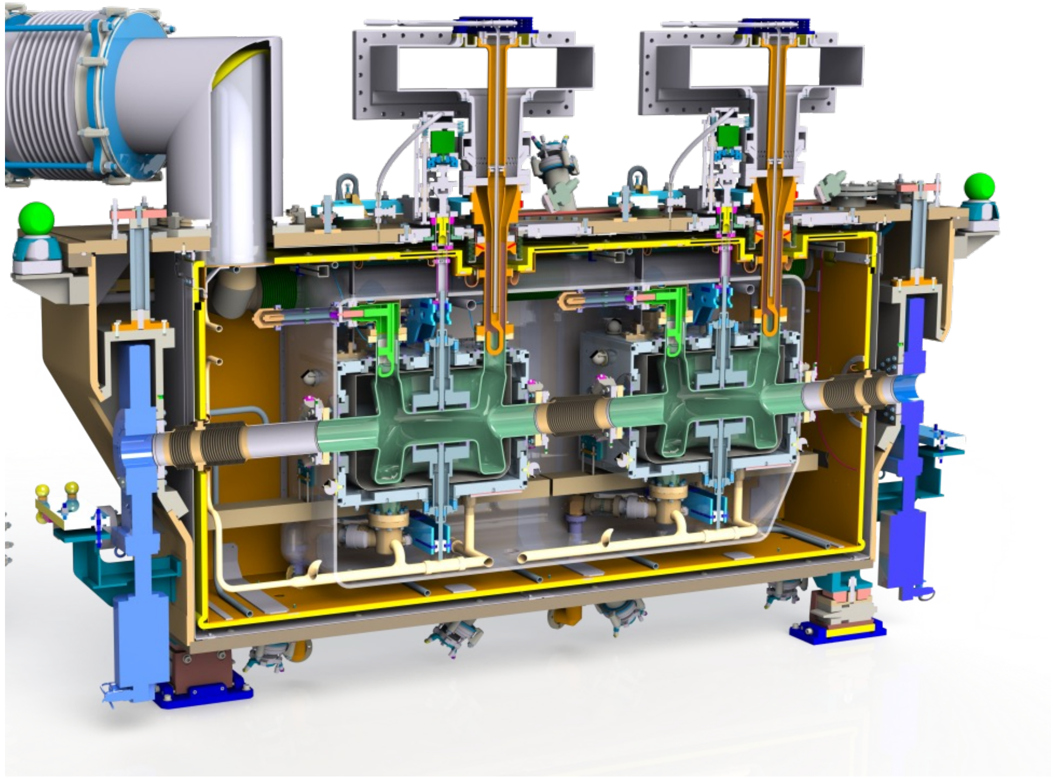
Supports

Commonly used approaches include using a spaceframe or strongback, where the cold mass alignment is done outside and translated horizontally into the vacuum vessel, and top loading



Supports

Support elements must contribute as low a heat load to the cold stages as possible; accordingly, these are typically fabricated from high strength, low conductivity materials including fibre-epoxy composites such as G-10 and G-11, stainless steel, and Ti



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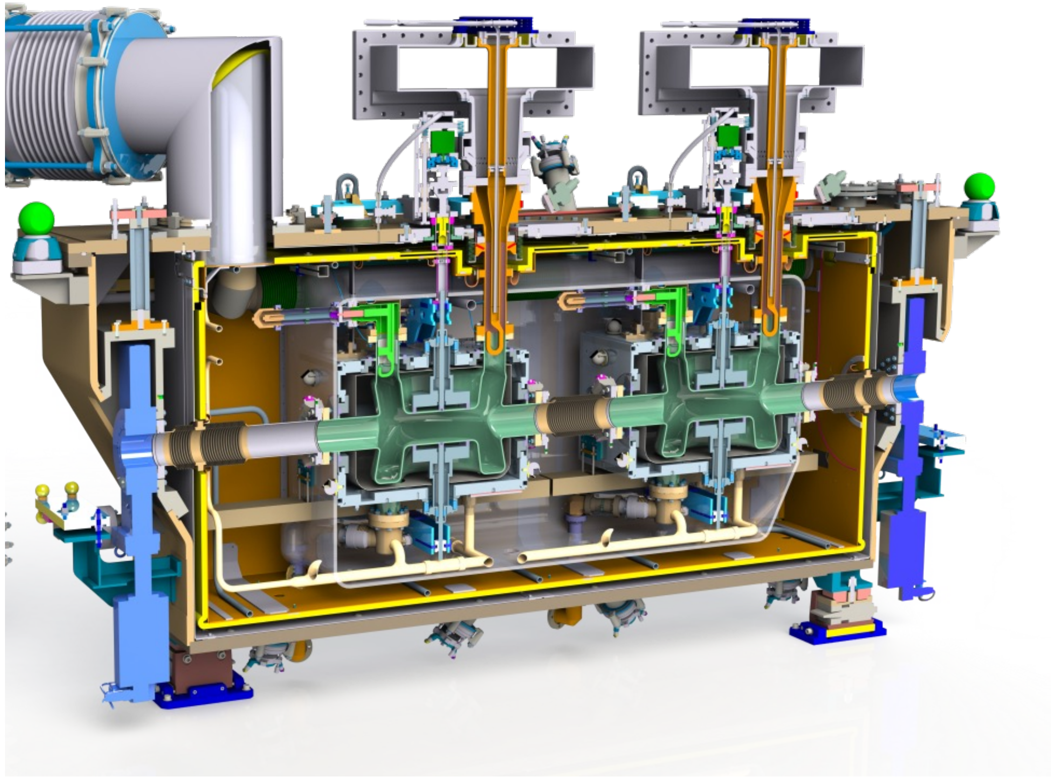
Vacuum chamber

Contains the insulating vacuum (typically on the order of 10^{-6} mbar)

Also provides pressure containment in the event of an internal cryogen line failure



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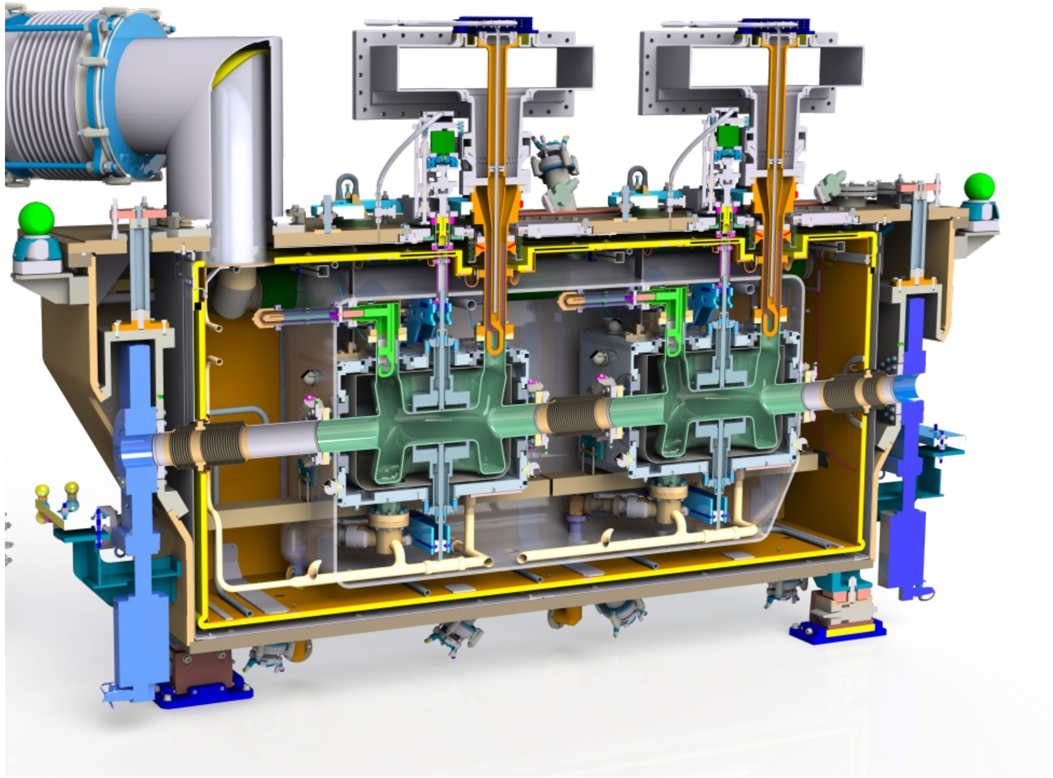
Interfaces

Include input RF power from the amplifiers, RF signals for control, HOM power extraction, electrical feeds for motors and actuators, and instrumentation signals including temperature, vacuum, pressure, and liquid level



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Cryomodule design

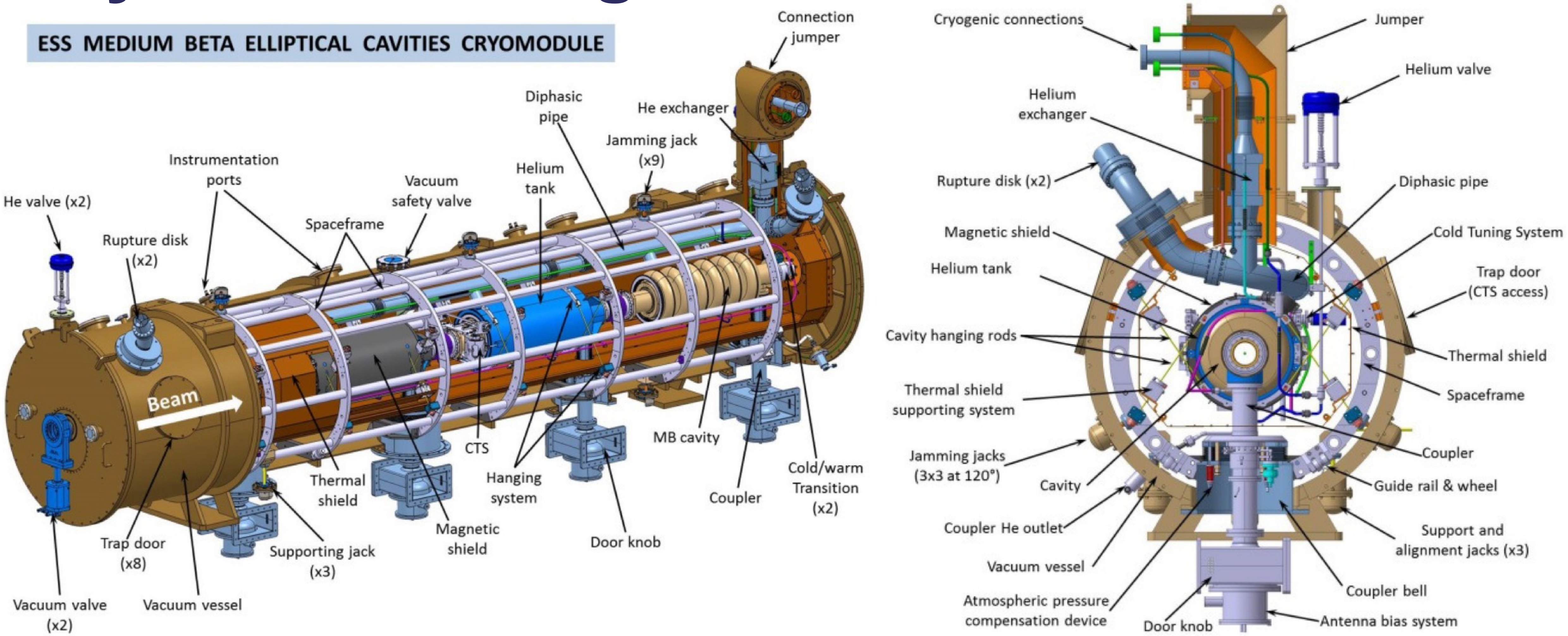

Fig.: ESS elliptical cryomodule, taken from Darve et al. (2017)

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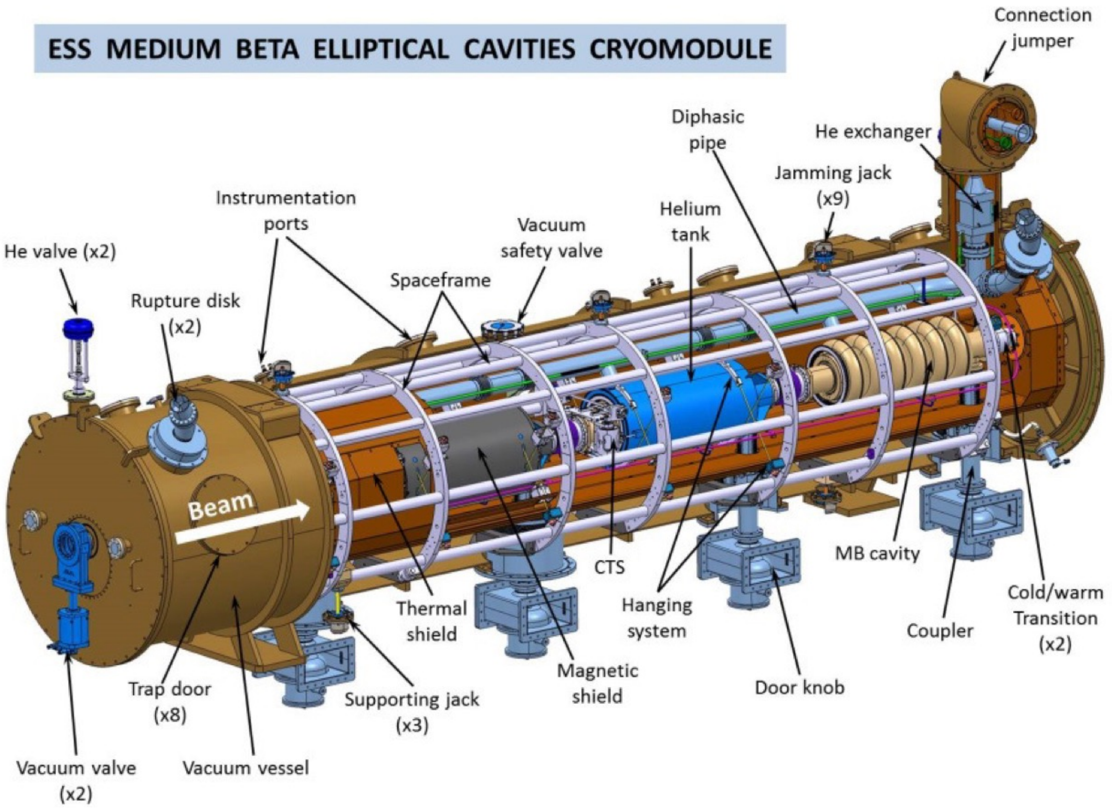
Cryomodule design



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Images courtesy ESS, CEA

Cryogenic safety training

Use of cryogenic systems immediately introduces range of potential hazards. Will mention some here, but not exhaustive!

If planning to work with cryogenic systems, can contact myself or Shrikant Pattalwar

Cryogenic safety training course taught by Rob Done (RAL)

Cryogenic safety

Use of cryogenic systems immediately introduces range of potential hazards

Cold temperatures => contact burns, frostbite, hypothermia

Expansion ratio => ODAs, pressure systems

Cryogenic safety

E	Eliminate
R	Reduce
I	Isolation
C	Controls
P	PPE
D	Discipline

Cryogenic safety – examples

High expansion ratios mean that boil-off of liquid cryogens can potentially lead to an oxygen depleted atmosphere in the surrounding environment. Can and has been fatal

Essential to calculate safe quantity of cryogens that can be used in area and design system accordingly. Additionally, O_2 depletion monitors (both area and personal) are essential safety devices

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Cryogenic safety – examples

Cryostats are pressure vessels

Vital that all systems are designed according to pressure safety codes (Pressure Equipment Regulations in UK, PED in EU, ASME in USA)

Once in service, must comply with PSSR 2000 (assembly, maintenance and modifications)

Cryogenic safety – examples

Failure of insulating vacuum => room temperature air onto cold surface, massive heat load on cold stages

~3.8 W/cm^2 to bare surfaces at 2 K and ~0.6 W/cm^2 to those insulated with MLI

Safety devices including pressure relief valves and burst discs must be sized accordingly

Cryogenic safety – examples

When carrying out cryogen transfers etc, correct use of PPE is essential

Courtesy Rob Done

Cryomodule heat loads

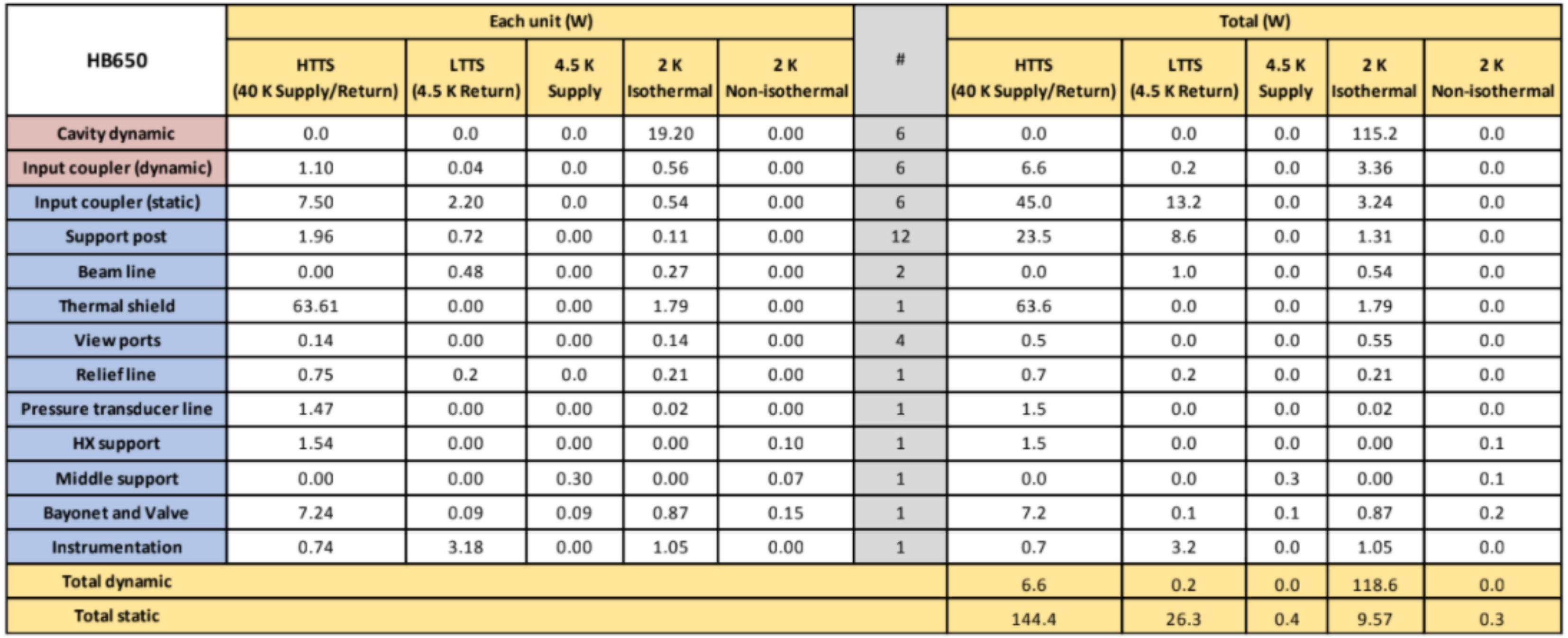

Table 6: HB650 cryogenic heat load

HB650	Each unit (W)					#	Total (W)				
	HTTS (40 K Supply/Return)	LTTS (4.5 K Return)	4.5 K Supply	2 K Isothermal	2 K Non-isothermal		HTTS (40 K Supply/Return)	LTTS (4.5 K Return)	4.5 K Supply	2 K Isothermal	2 K Non-isothermal
Cavity dynamic	0.0	0.0	0.0	19.20	0.00	6	0.0	0.0	0.0	115.2	0.0
Input coupler (dynamic)	1.10	0.04	0.0	0.56	0.00	6	6.6	0.2	0.0	3.36	0.0
Input coupler (static)	7.50	2.20	0.0	0.54	0.00	6	45.0	13.2	0.0	3.24	0.0
Support post	1.96	0.72	0.00	0.11	0.00	12	23.5	8.6	0.0	1.31	0.0
Beam line	0.00	0.48	0.00	0.27	0.00	2	0.0	1.0	0.0	0.54	0.0
Thermal shield	63.61	0.00	0.00	1.79	0.00	1	63.6	0.0	0.0	1.79	0.0
View ports	0.14	0.00	0.00	0.14	0.00	4	0.5	0.0	0.0	0.55	0.0
Relief line	0.75	0.2	0.0	0.21	0.00	1	0.7	0.2	0.0	0.21	0.0
Pressure transducer line	1.47	0.00	0.00	0.02	0.00	1	1.5	0.0	0.0	0.02	0.0
HX support	1.54	0.00	0.00	0.00	0.10	1	1.5	0.0	0.0	0.00	0.1
Middle support	0.00	0.00	0.30	0.00	0.07	1	0.0	0.0	0.3	0.00	0.1
Bayonet and Valve	7.24	0.09	0.09	0.87	0.15	1	7.2	0.1	0.1	0.87	0.2
Instrumentation	0.74	3.18	0.00	1.05	0.00	1	0.7	3.2	0.0	1.05	0.0
Total dynamic							6.6	0.2	0.0	118.6	0.0
Total static							144.4	26.3	0.4	9.57	0.3

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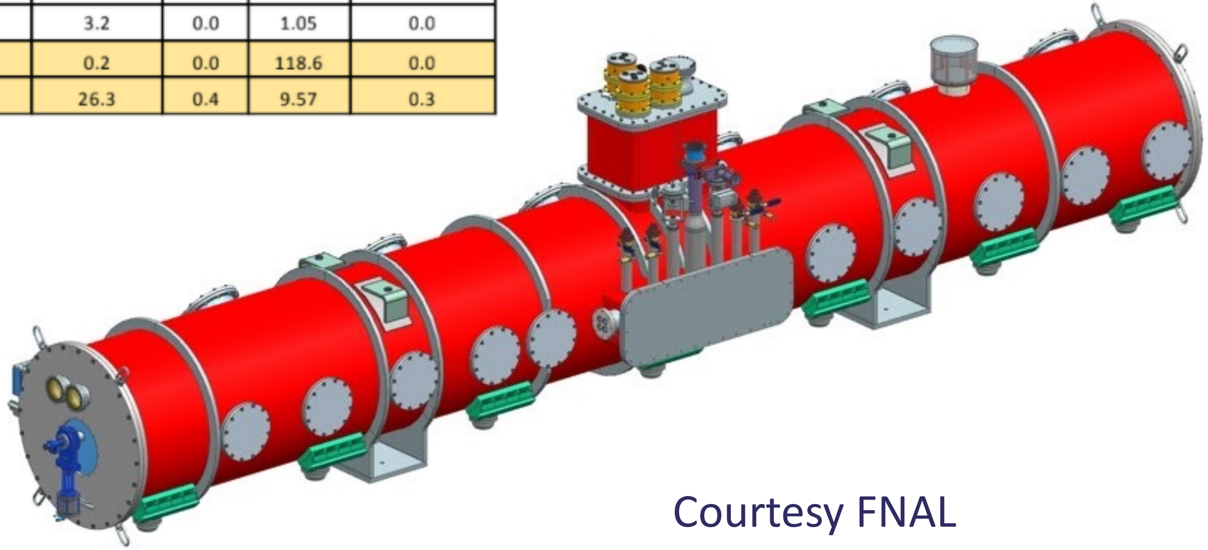


Courtesy FNAL

Cryomodule heat loads

These are modelled during design, verified experimentally during commissioning

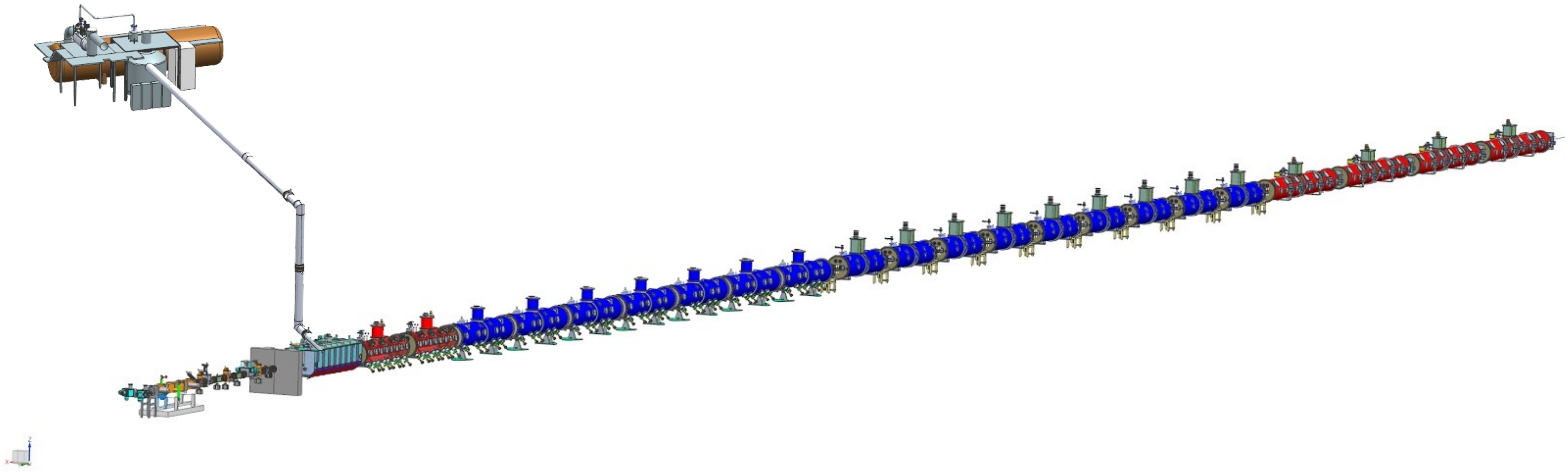
Heat loading to the thermal shield circuit can be found by measuring the inlet and outlet temperatures and pressures, calculating the associated increase in enthalpy, and multiplying by the measured mass flow rate

Cryomodule heat loads

Loading to the 2 K circuit can be found by measuring the mass flow rate at the cold compressor/vacuum pumps, subtracting the vapour generated at J-T expansion, and multiplying by the latent heat of evaporation of helium at 2 K

Cryomodule heat loads

Incredibly important when scaled up to entire accelerator!



Courtesy FNAL

Cryogen distribution

Distribution system to get liquid and cold gaseous helium from cryoplant where it is produced across some distance (can be several km!) to the cryomodules

Huge infrastructure requiring complex network of transfer lines and individual cryostats housing valves, distribution, auxiliary, feed, splitting, end, subcoolers, etc.

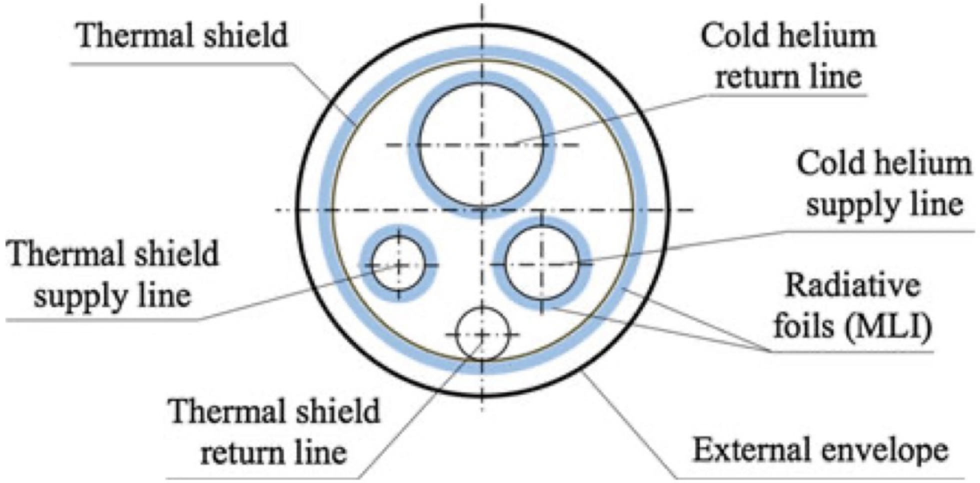
Cryogen distribution

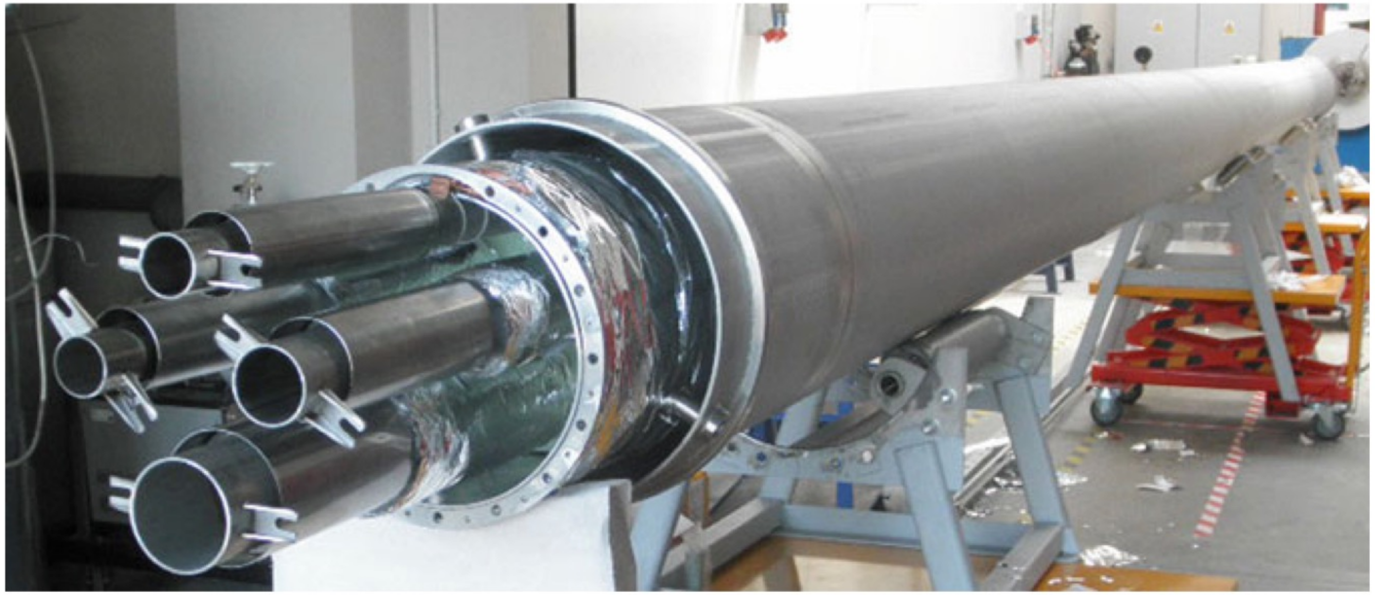
Vacuum jacketed transfer line to minimise heat leak

Stainless steel vacuum pipe with concentric volumes wrapped in MLI for cryogens

Plastic or composite supports (eg G-10, G-11 epoxy-fibreglass)

Cryogen distribution





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Fydrych (2016)

Cryogen distribution

Simplified view of ESS linac distribution system

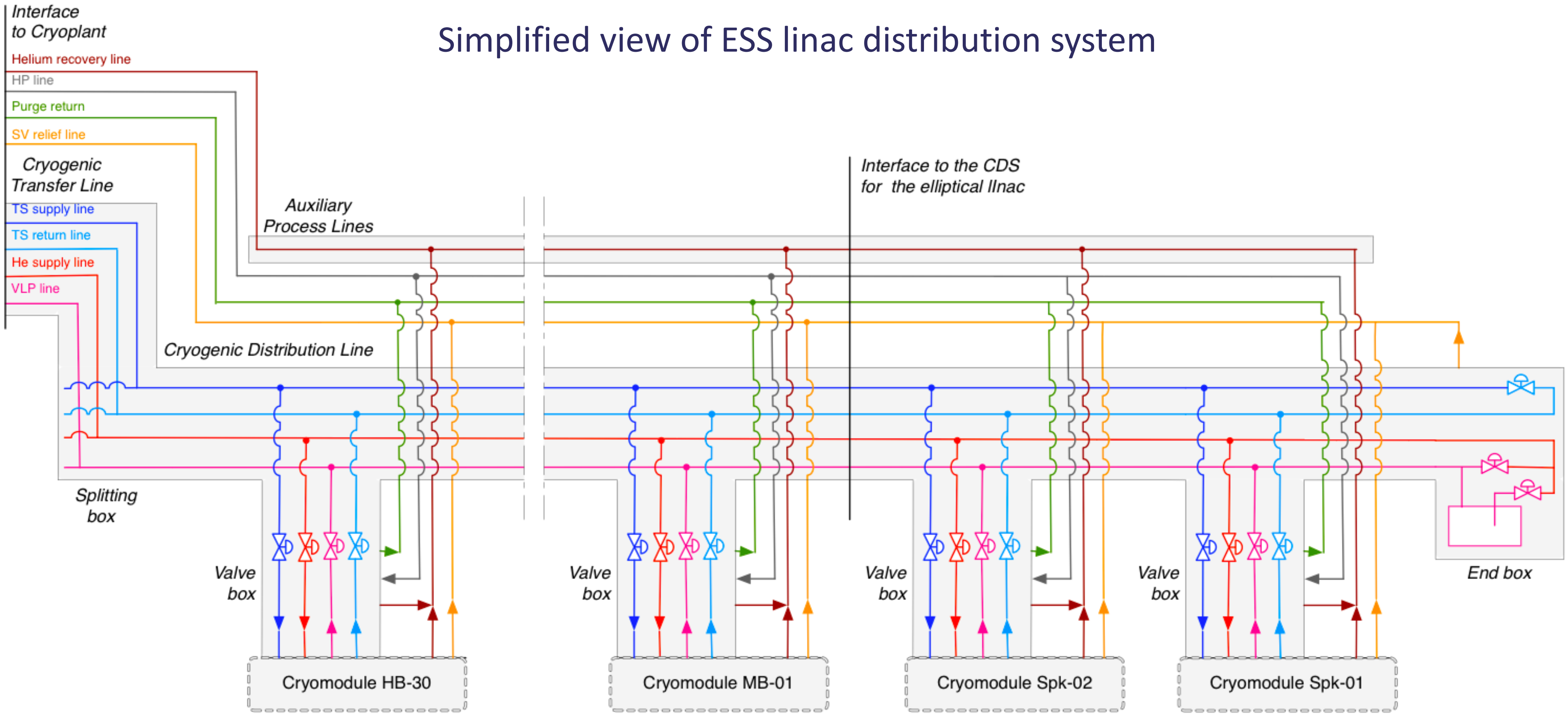


Figure courtesy J Fydrych

Producing cold

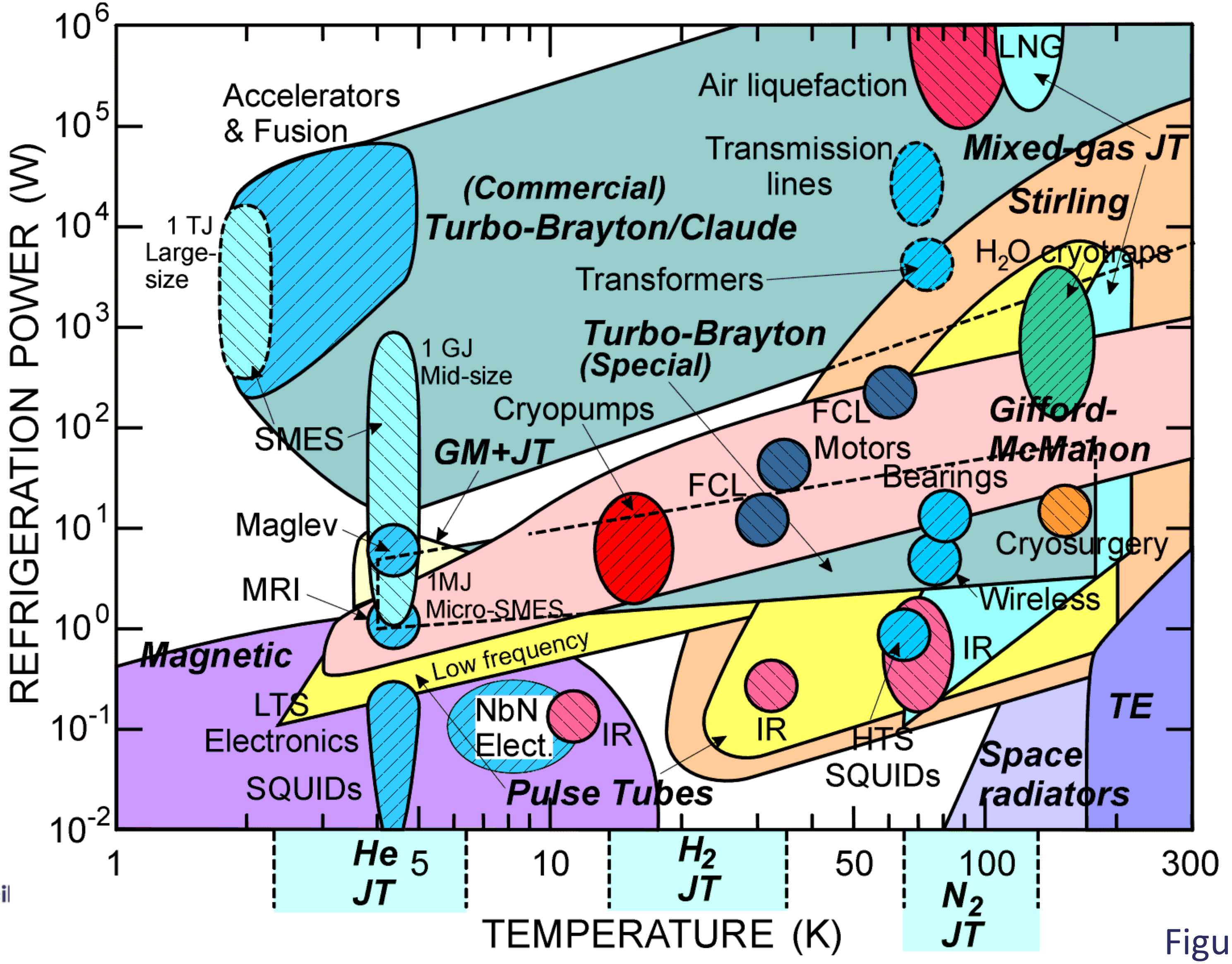


Figure courtesy R Radebaugh

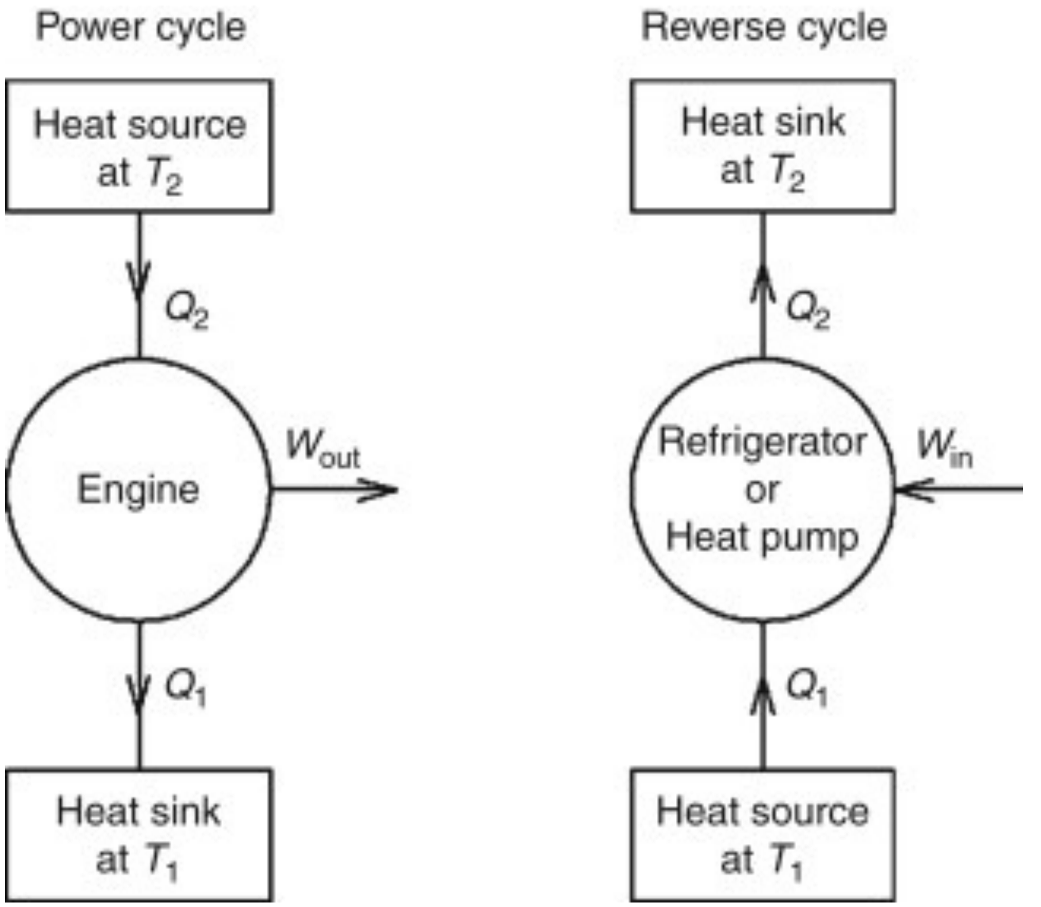
Producing cold

Only a few ways to make a pure fluid (eg helium) colder:

- Reduce pressure above liquid bath (move down vapour pressure curve)
- Heat exchange with a cold surface
- Extract work from fluid (eg expand through a turbine) whilst keeping it thermally isolated (=> isentropic expansion)
- Cause fluid to do internal work (eg expand through a valve) whilst keeping it thermally isolated (=> isenthalpic expansion)

Carnot cycle

Cycle is a series of thermodynamic processes, involving transfer of heat and work in and out of a system along with changes in state variables (pressure, temperature, etc.), that returns system to initial state



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Carnot cycle

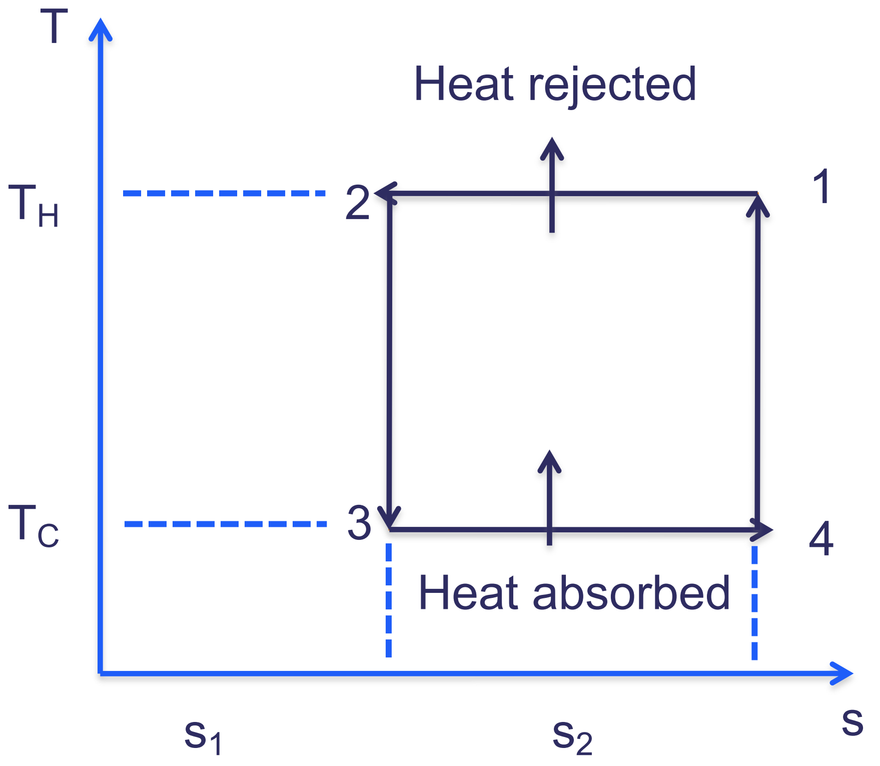
Theoretically the most efficient heat engine cycle (reversible)

(1-2) Isothermally compress fluid, reject heat

(2-3) Adiabatic expansion

(3-4) Isothermally expand fluid, absorb heat

(4-1) Adiabatic compression



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Carnot cycle

Idealised cycle because all processes are reversible

Isentropic expansion/compression essentially impossible

In reality, compressing fluid isothermally is incredibly difficult

Carnot cycle

However, Carnot sets theoretical maximum efficiency of a thermodynamic cycle

We can define a coefficient of performance as the heat absorbed from the cold sink divided by the net work required to remove this heat

$$\eta_{carnot} = COP = -\frac{Q_a}{W_{net}} = \frac{T_c}{T_h - T_c}$$

Carnot cycle

$$\eta_{Carnot} = COP = -\frac{Q_a}{W_{net}} = \frac{T_c}{T_h - T_c}$$

For Carnot, a function only of temperature

For T_h = 300 K and T_c = 77 K, η_{Carnot} = 0.34

For T_h = 300 K and T_c = 4.2 K, η_{Carnot} = 0.014

For T_h = 300 K and T_c = 2 K, η_{Carnot} = 0.0067

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Carnot cycle

Inverse of COP is useful as it gives us the number of W required to produce 1 W of cooling, e.g. for 4.2 K system this would be 70 W/W

Furthermore, real cycles are less efficient than this so we will be working much higher than this in practice. We therefore talk about % Carnot (also Figure of Merit)

$$\%_{carnot} = FOM = \frac{COP}{COP_{Carnot}}$$

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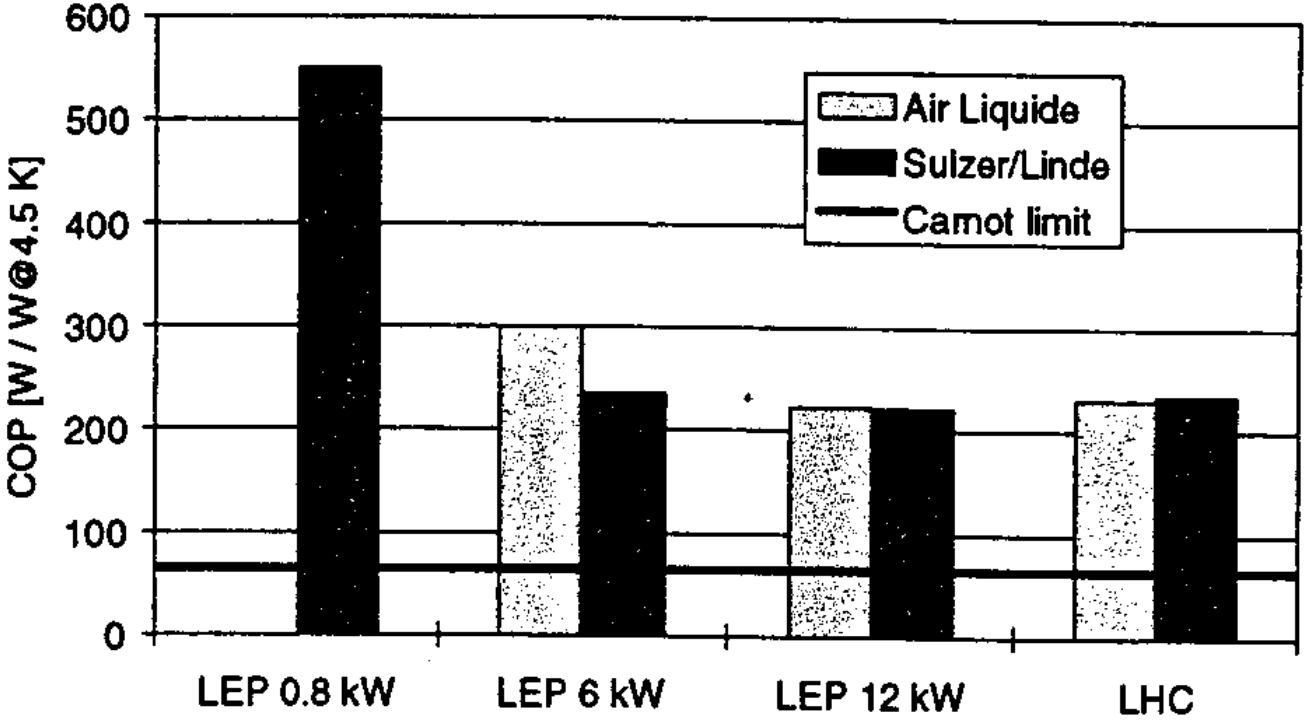
Carnot cycle

Best current cryoplants operate at 220 W/W (~32%$_{\text{Carnot}}$)



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Justification for SRF

Consider wall plug power for normal vs s/c accelerator

Microwave surface resistance of a superconductor is 5 to 6 orders of magnitude lower than for copper cavities

Allowing for Carnot at 2 K [2/(300 - 2) = 0.0067] and modern plant at 30% of Carnot, still have a net gain on the order of 200 [= 10^5 * 0.0067 * 0.3] using SRF

Cryoplants

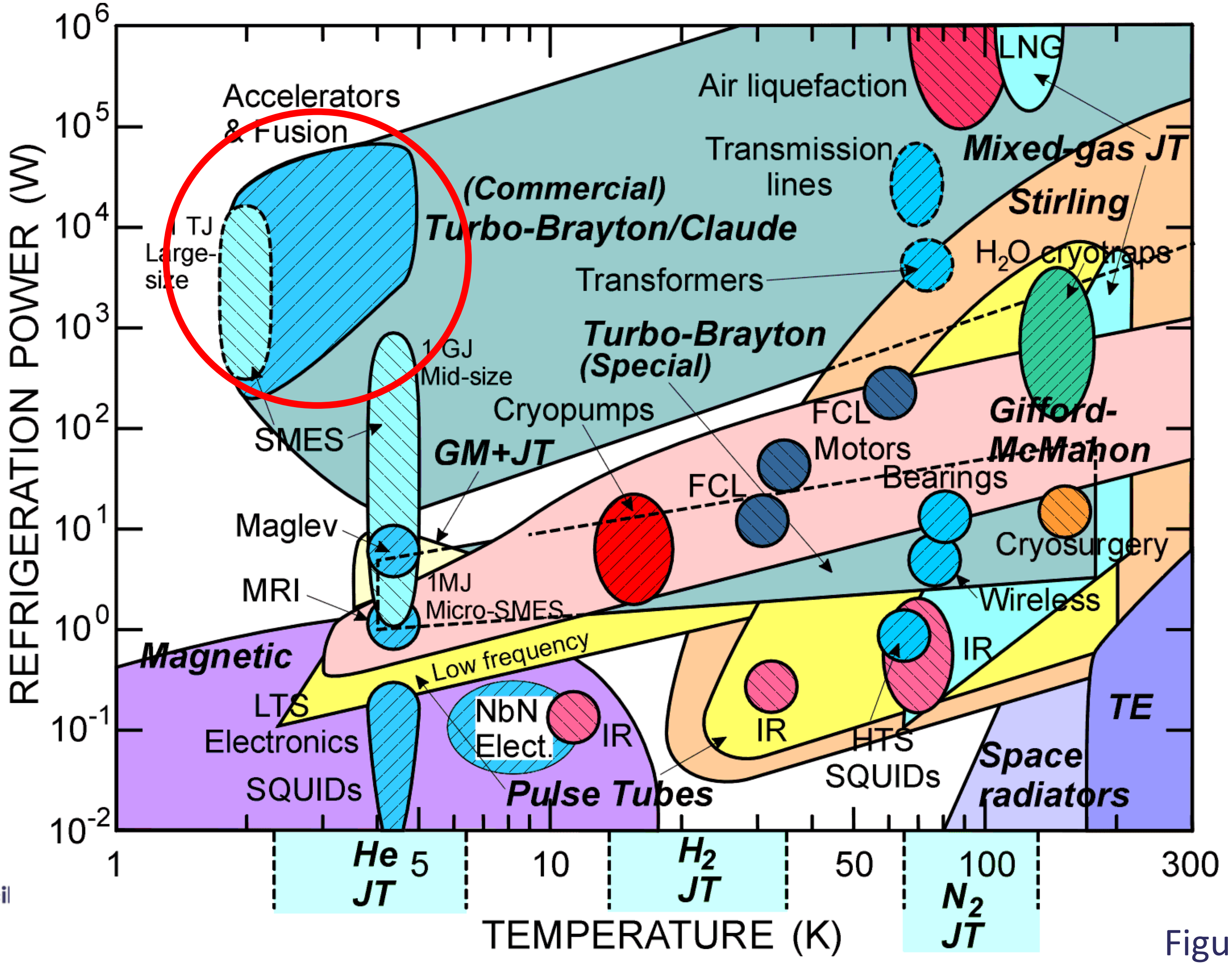
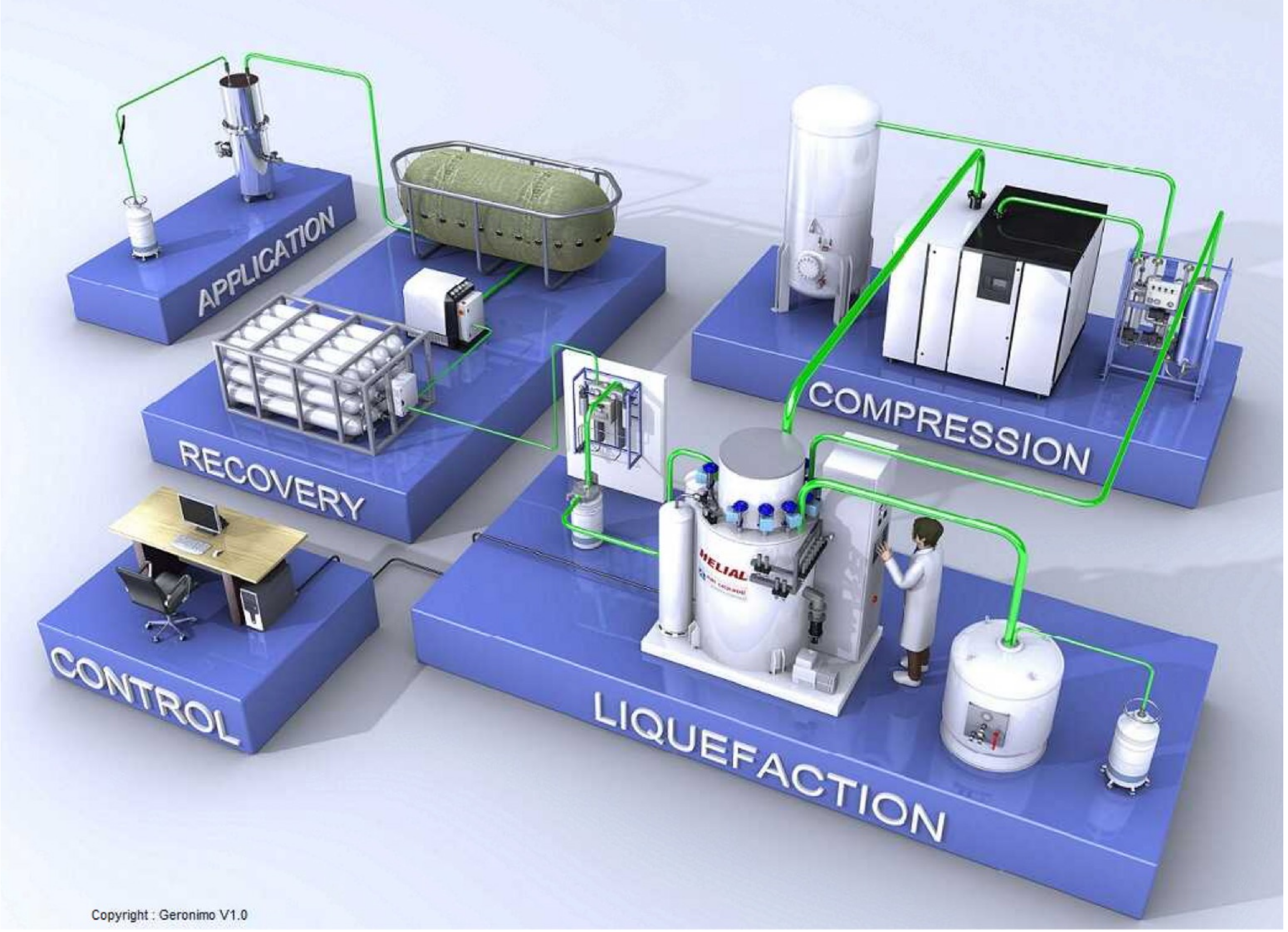


Figure courtesy R Radebaugh

Cryoplants



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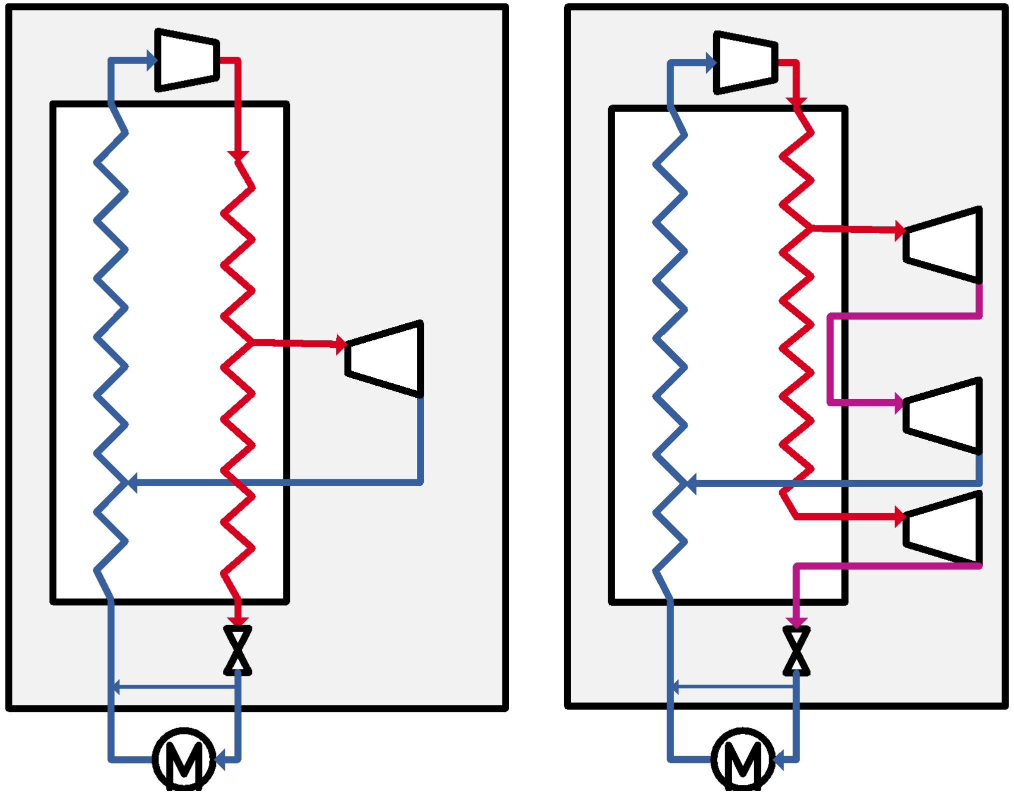
Cryoplants

Claude cycle

Can add additional turbines (Collins cycle) to increase efficiency

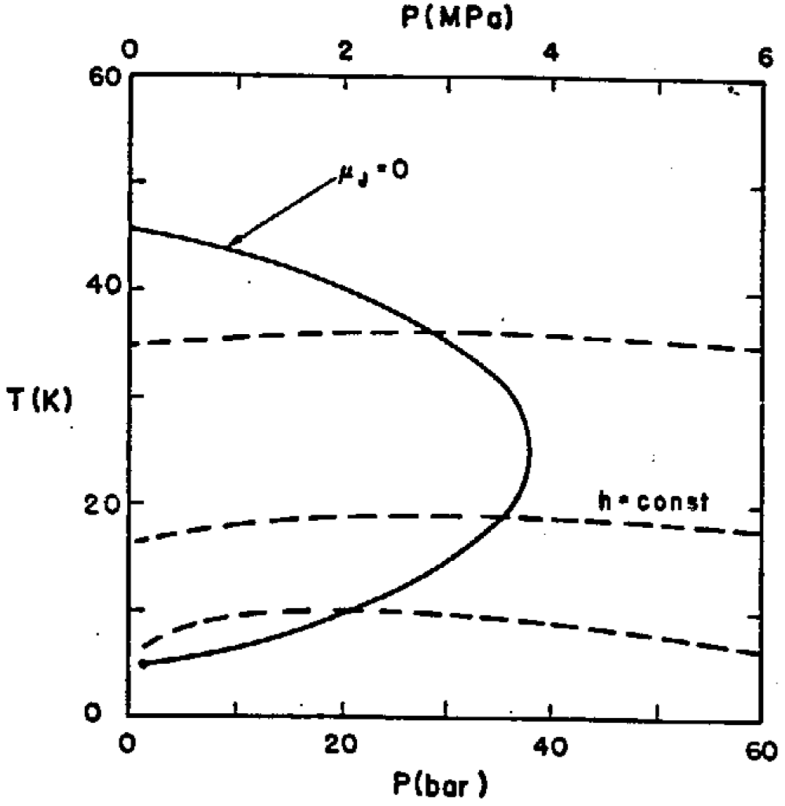


Figures courtesy Pascale Dauguet

Joule-Thomson effect

Fluids can be cooled by expanding at constant enthalpy through a constriction (orifice or valve)

Joule-Thomson coefficient must be positive for cooling to occur



Fluid	Max Inversion Temperature (K)
Nitrogen	623
Argon	723
Hydrogen	202
He	43

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Data courtesy John Weisend

Cryoplants

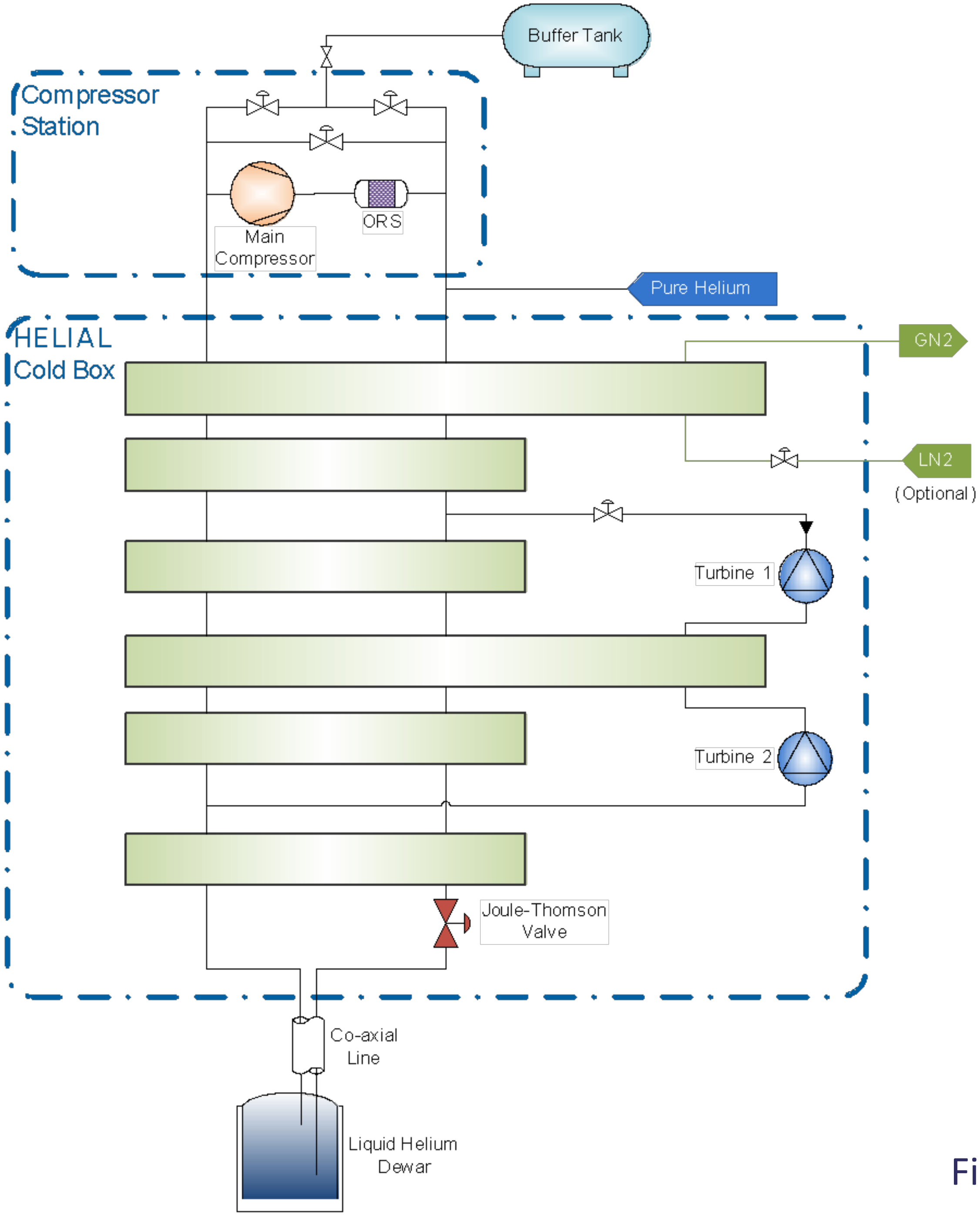

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Figure courtesy Pascale Dauguet

Cryoplants

- Specialised helium screw compressors
- Oil removal systems
- High pressure gas storage
- Plate fin heat exchangers
- Cryogenic turbines
- Purifiers

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Figure courtesy Pascale Dauguet

Cryoplants

- Specialised helium screw compressors
- Oil removal systems
- High pressure gas storage
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Figure courtesy Pascale Dauguet

Cryoplants

- Specialised helium screw compressors
- Oil removal systems
- **High pressure gas storage**
- Plate fin heat exchangers
- Cryogenic turbines
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Figure courtesy Pascale Dauguet

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Cryoplants

- Specialised helium screw compressors
- Oil removal systems
- High pressure gas storage
- **Plate fin heat exchangers**
- Cryogenic turbines
- Purifiers

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Figure courtesy Pascale Dauguet

Cryoplants

- Specialised helium screw compressors
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- **Cryogenic turbines**
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Figure courtesy Pascale Dauguet

Cryoplants

- Specialised helium screw compressors
- Oil removal systems
- High pressure gas storage
- Plate fin heat exchangers
- Cryogenic turbines
- Purifiers

Figure courtesy Pascale Dauguet

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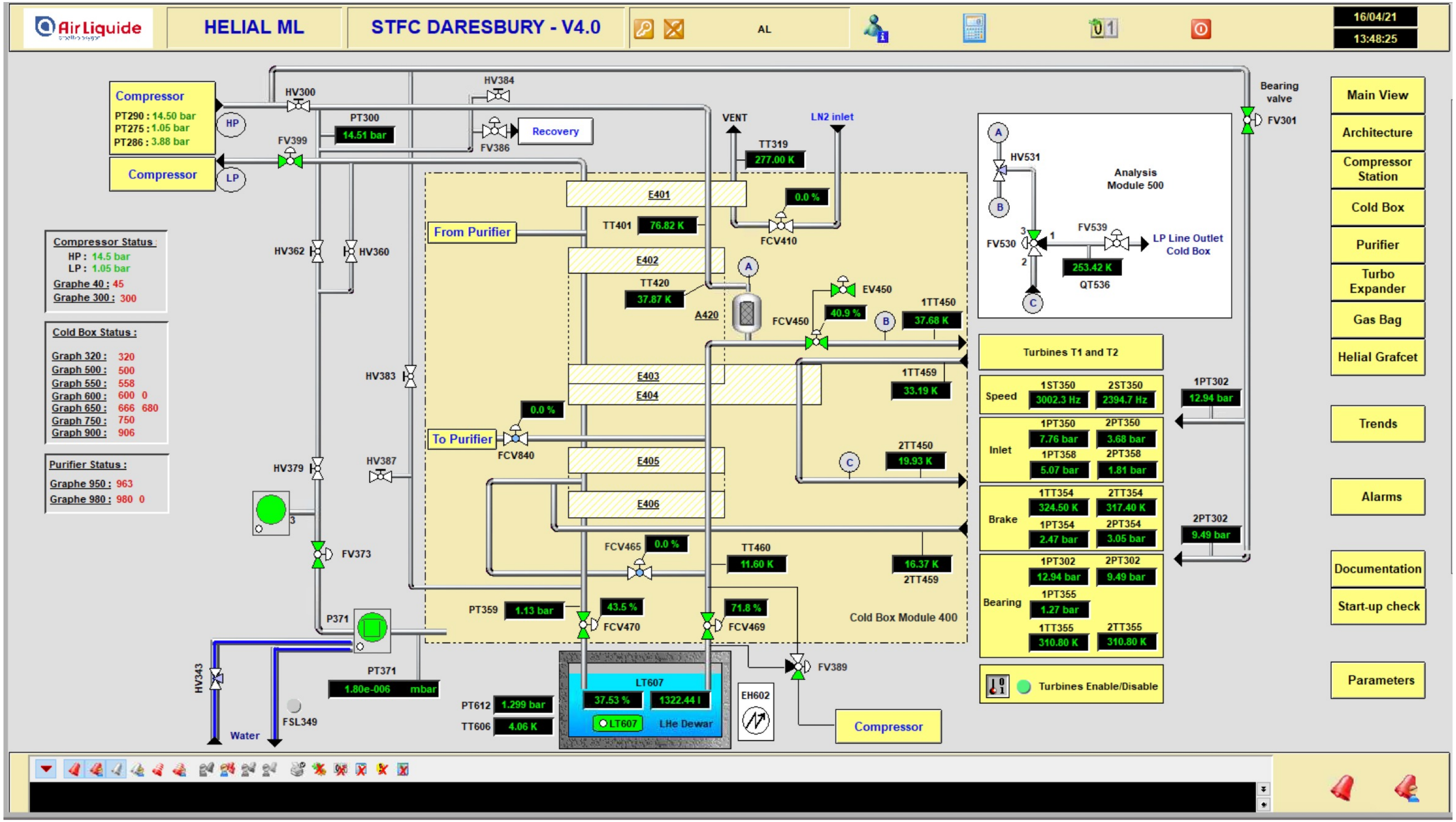
Daresbury cold box



Compressor
PT290 : 14.50 bar
PT275 : 1.05 bar
PT286 : 3.88 bar

Compressor Status :
HP : 14.5 bar
LP : 1.05 bar
Graphe 40 : 45
Graphe 300 : 300

Cold Box Status :
Graph 320 : 320
Graph 500 : 500
Graph 550 : 558
Graph 600 : 600 0
Graph 650 : 666 680
Graph 750 : 750
Graph 900 : 906

Purifier Status :
Graphe 950 : 963
Graphe 980 : 980 0

PT300: 14.51 bar
TT319: 277.00 K
FCV410: 0.0 %
TT401: 76.82 K
TT420: 37.87 K
FCV450: 40.9 %
1TT450: 37.68 K
1TT459: 33.19 K
FCV840: 0.0 %
2TT450: 19.93 K
FCV465: 0.0 %
TT460: 11.60 K
2TT459: 16.37 K
PT359: 1.13 bar
FCV470: 43.5 %
FCV469: 71.8 %
PT371: 1.80e-006 mbar
PT612: 1.299 bar
TT606: 4.06 K
LT607: 37.53 % 1322.44 l
QT536: 253.42 K
1PT302: 12.94 bar
2PT302: 9.49 bar

Turbines T1 and T2

Speed	1ST350 3002.3 Hz	2ST350 2394.7 Hz
Inlet	1PT350 7.76 bar	2PT350 3.68 bar
	1PT358 5.07 bar	2PT358 1.81 bar
Brake	1TT354 324.50 K	2TT354 317.40 K
	1PT354 2.47 bar	2PT354 3.05 bar
Bearing	1PT302 12.94 bar	2PT302 9.49 bar
	1PT355 1.27 bar	
	1TT355 310.80 K	2TT355 310.80 K

Cryocoolers

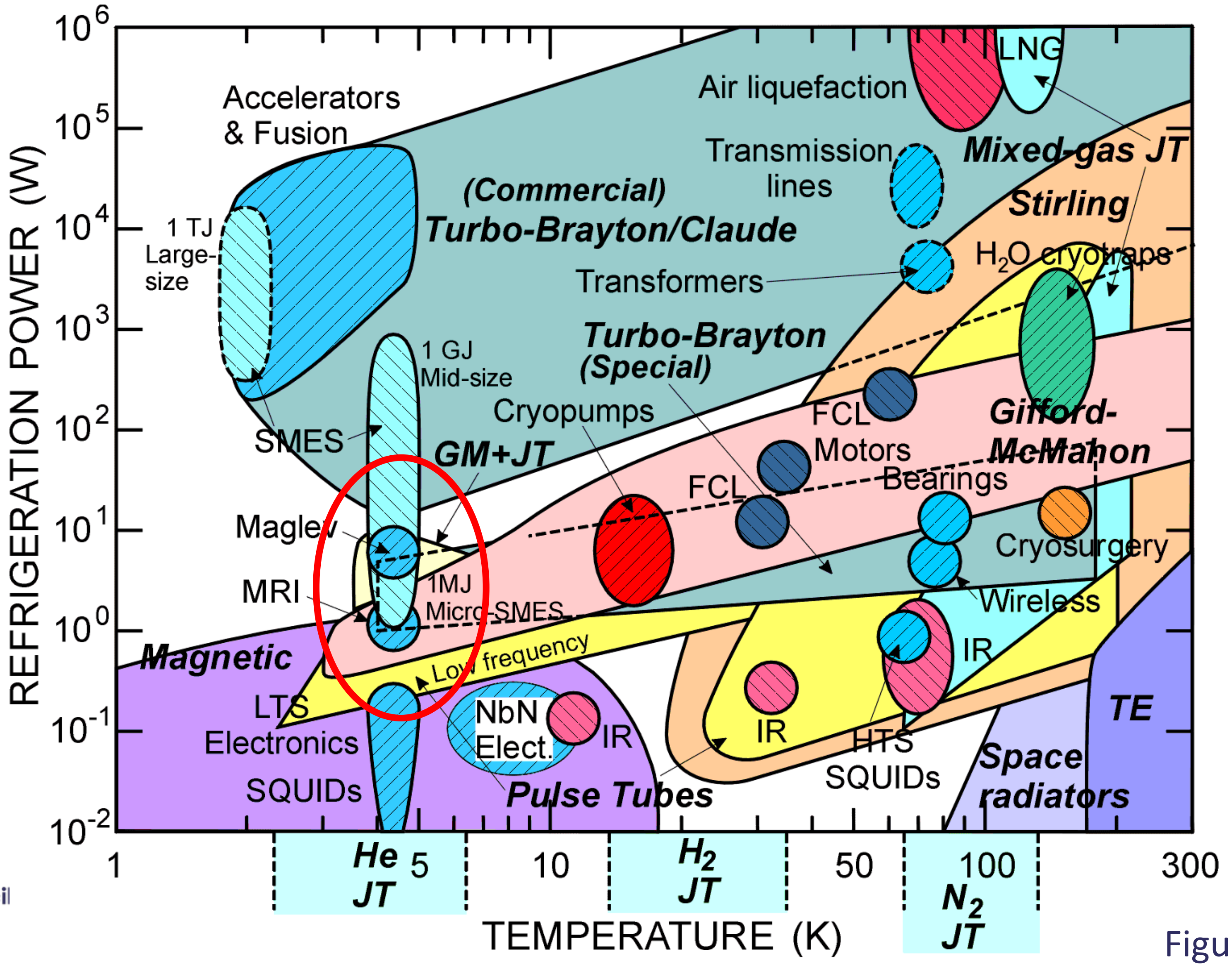


Figure courtesy R Radebaugh

Cryocoolers

Commonly used mechanical cryocoolers include Gifford-MacMahon (G-M) and pulse tube cryocoolers (PTC)

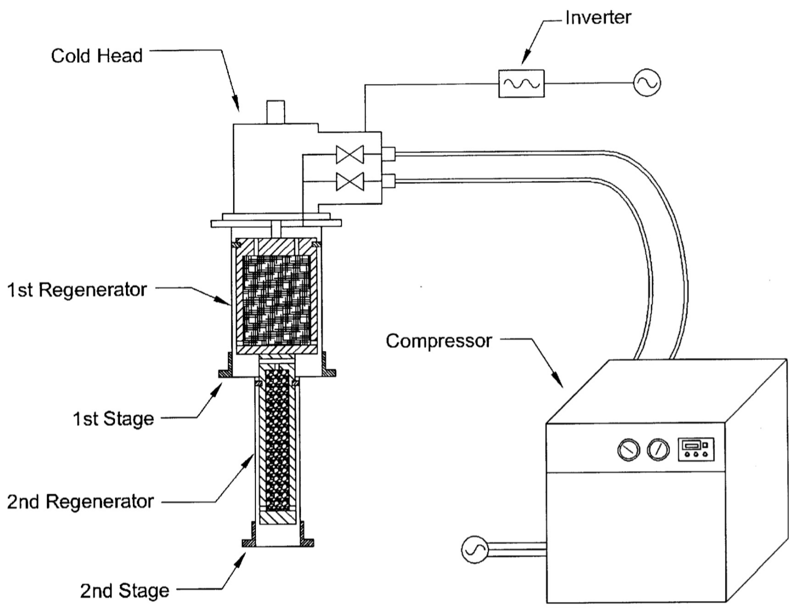
G-M cheaper, higher cooling power (few W at 4 K)

PTC more expensive, lower vibration (1 W at 4 K)

GM cryocoolers

Operate in an isobaric-isothermal Ericsson cycle

Achieved by synchronising the operation of the rotary valve with the regenerator, usually ~1 Hz



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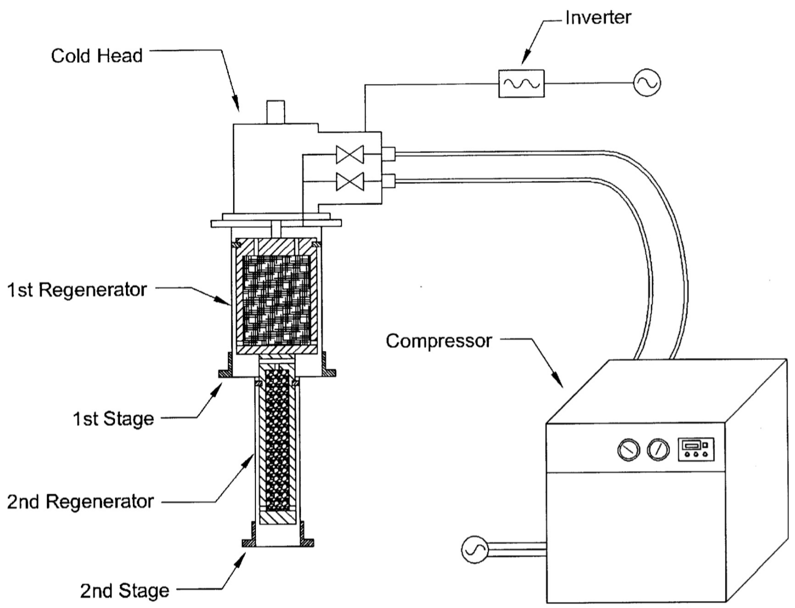
Images courtesy SHI Cryogenics

GM cryocoolers

(i) With the displacer at the bottom of the cold head, the rotary valve is opened to the high-pressure side. High-pressure gas fills the space above the displacer and the regenerator at ambient temperature.



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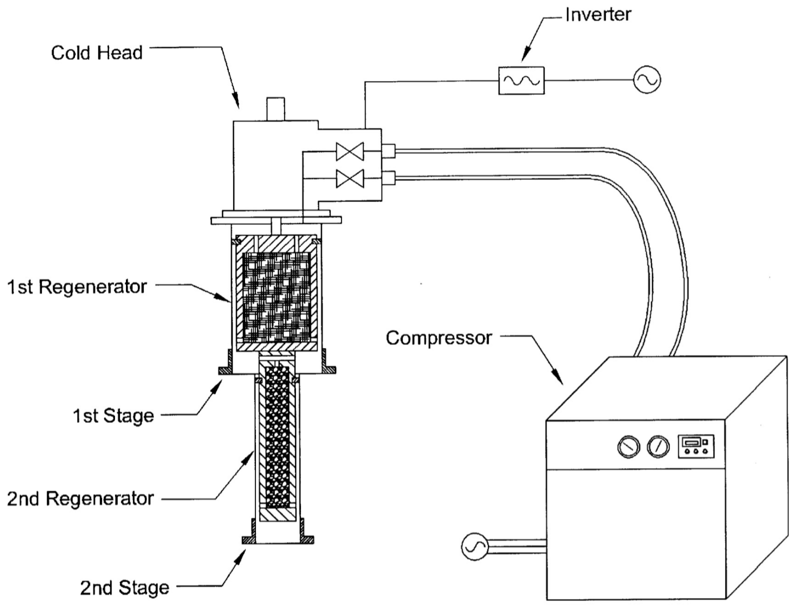
Images courtesy SHI Cryogenics

GM cryocoolers

(ii) With the valve to the high-pressure side still open, the displacer is moved to the top of the cold head. The gas passes through the regenerator matrix where it exchanges heat and is cooled isobarically. The gas fills the space below the displacer at low temperature.



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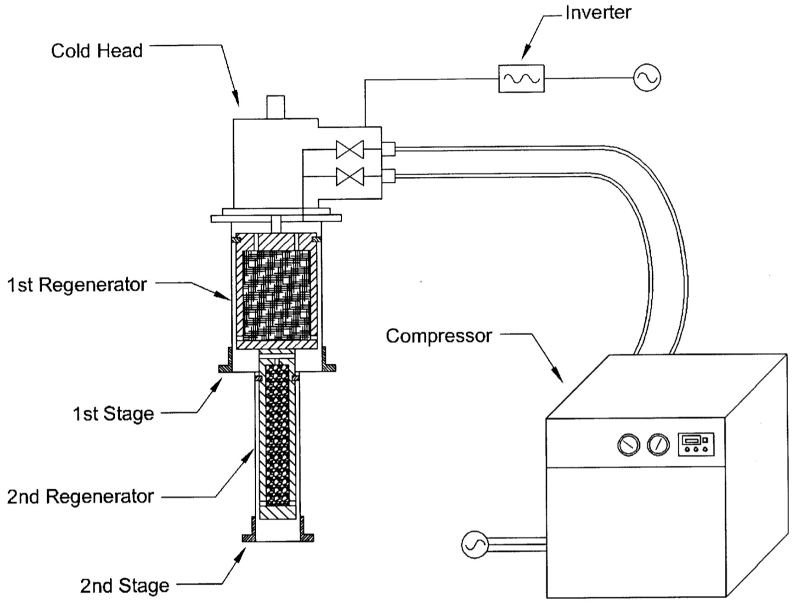
Images courtesy SHI Cryogenics

GM cryocoolers

(iii) With the displacer in its upper position, the rotary valve is closed to the high-pressure side and opened to the low-pressure side. The gas within the coldhead (both in the regenerator and the cold space) expands, taking in heat from the environment surrounding the cold side (i.e., producing the useful heat lift).



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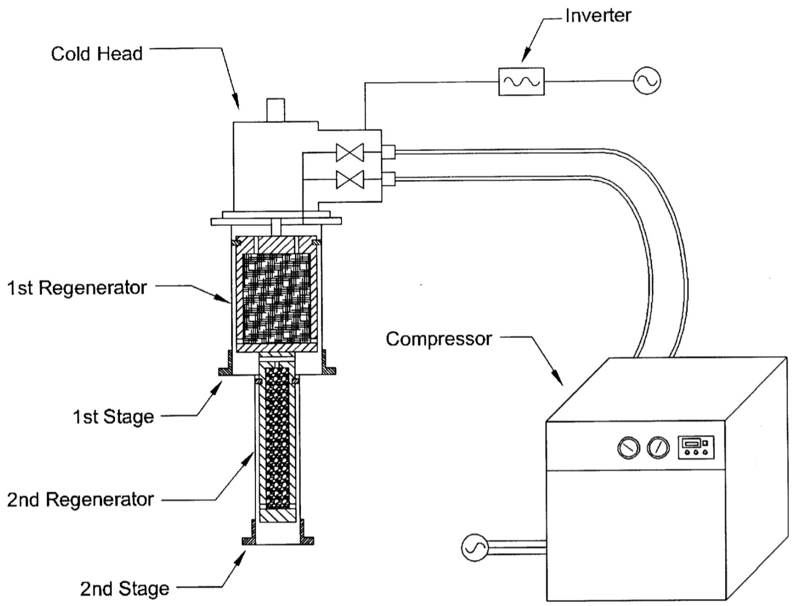
Images courtesy SHI Cryogenics

GM cryocoolers

(iv) With the rotary valve still open to the low-pressure side, the displacer is moved back to the bottom of the cold head. The gas passes back through the regenerator matrix where it is warmed isobarically and fills the space above the displacer at ambient temperature



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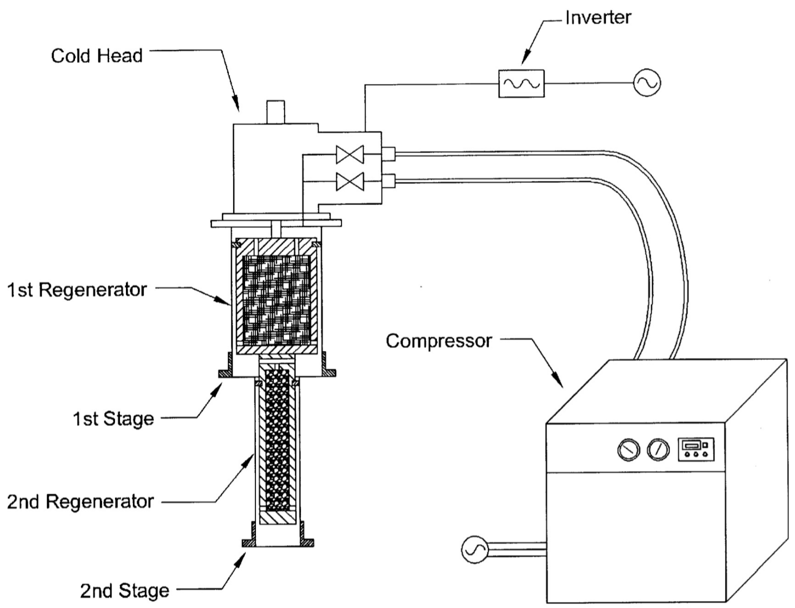
Images courtesy SHI Cryogenics

GM cryocoolers

This can easily be extended to provide two cooling stages

Will provide cooling as long as electrical power is supplied to compressor and cold head (rotary valve and displacer)



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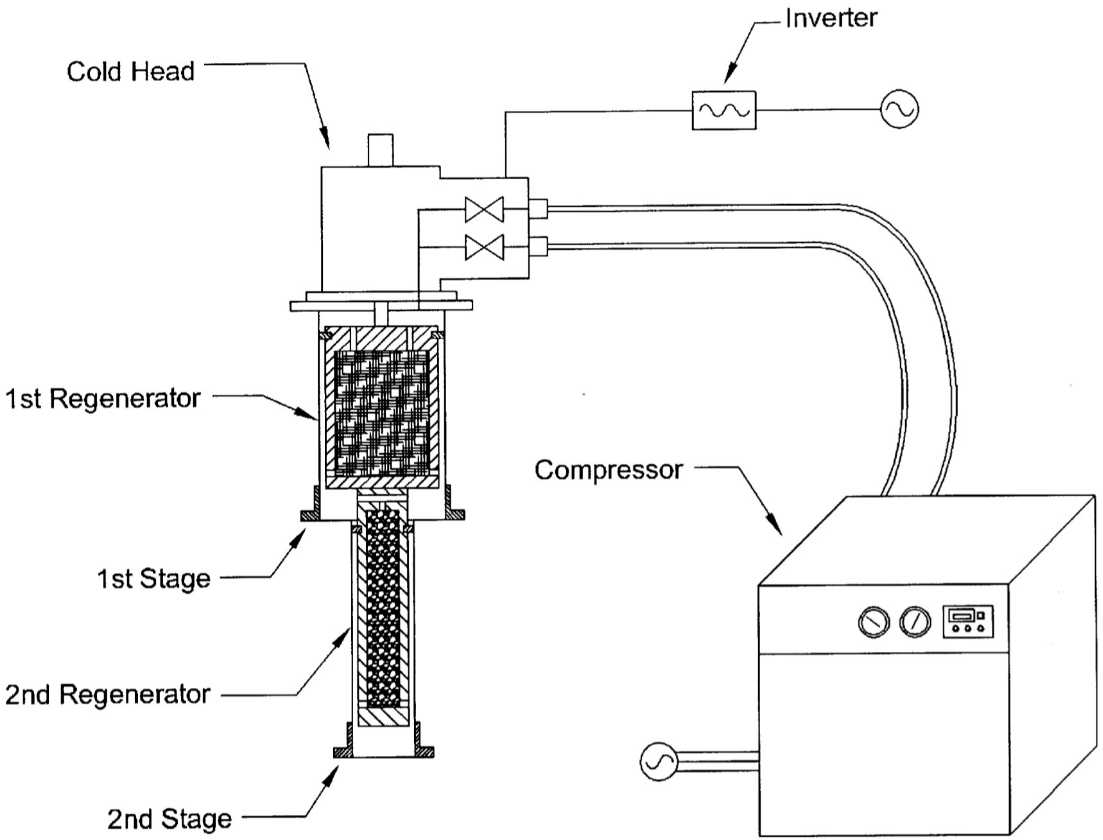
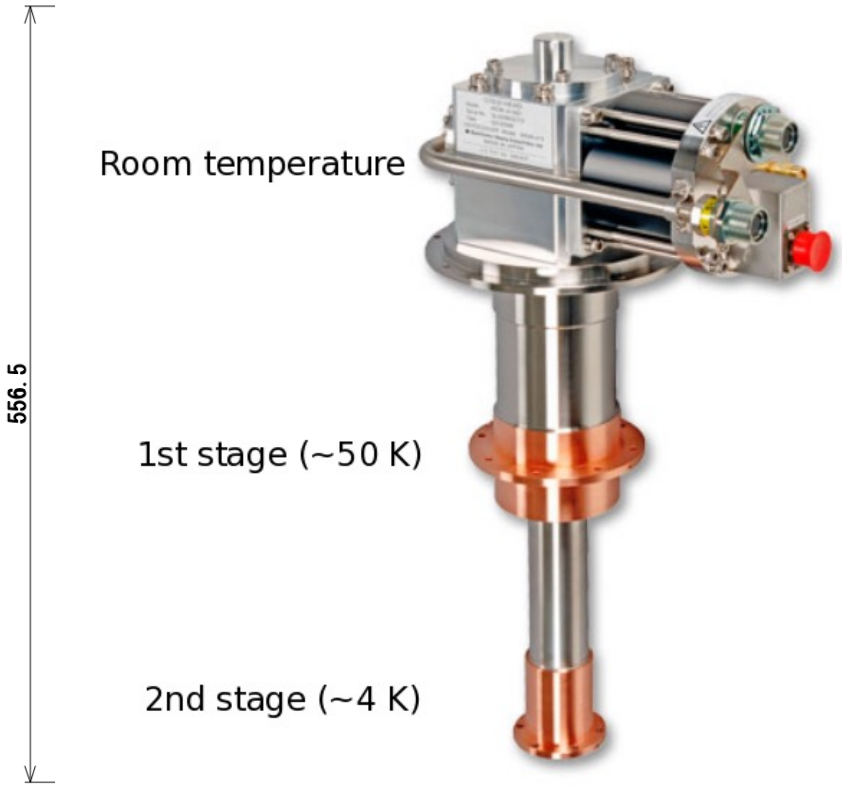
Images courtesy SHI Cryogenics

GM cryocoolers





Images courtesy SHI Cryogenics

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GM cryocoolers

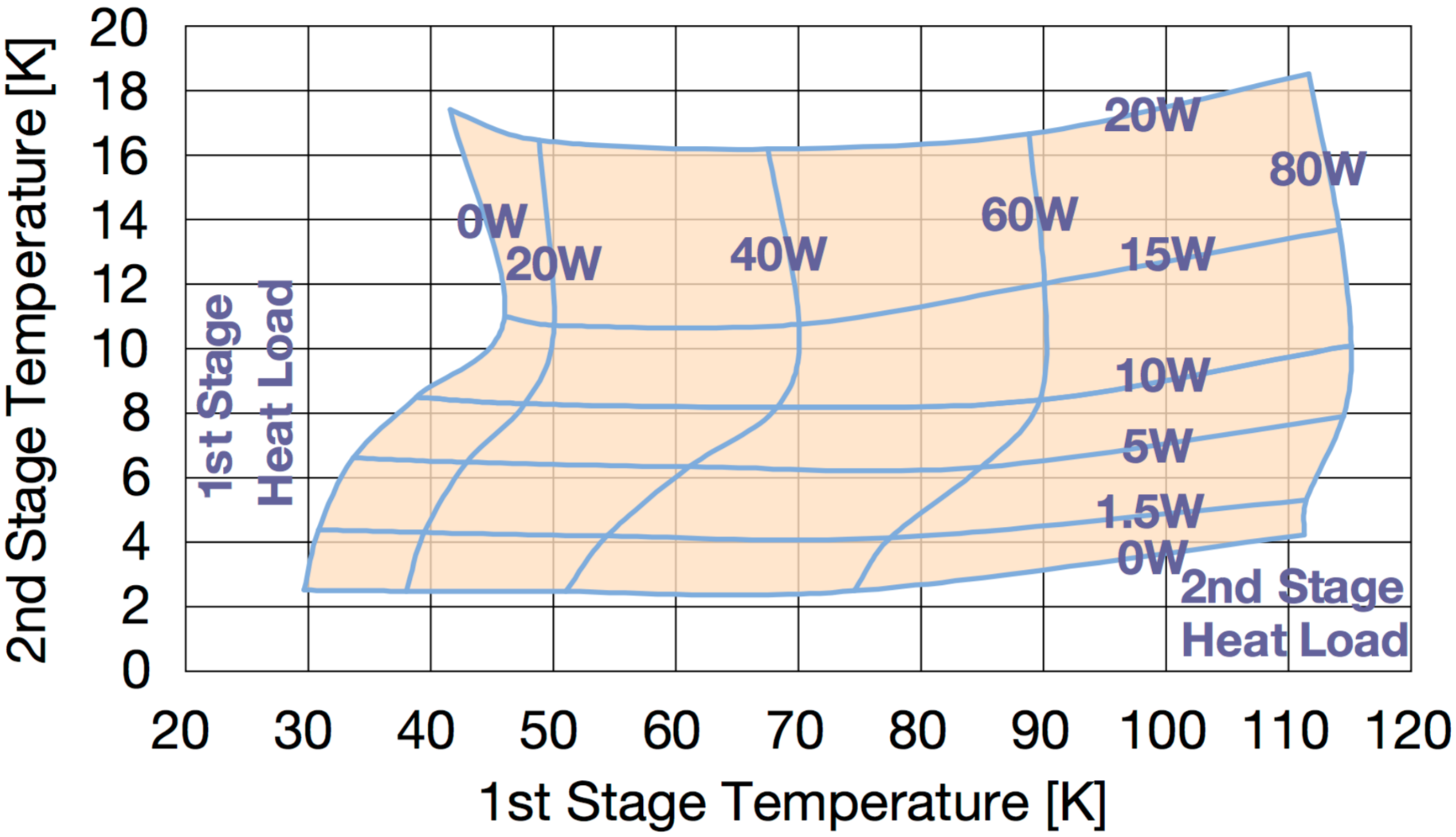

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Image courtesy SHI Cryogenics

PT cryocoolers

PTC operates using same cycle

Consists of a pressure-wave generating subsystem, a first tube containing a stationary regenerator, and a second (hollow) tube

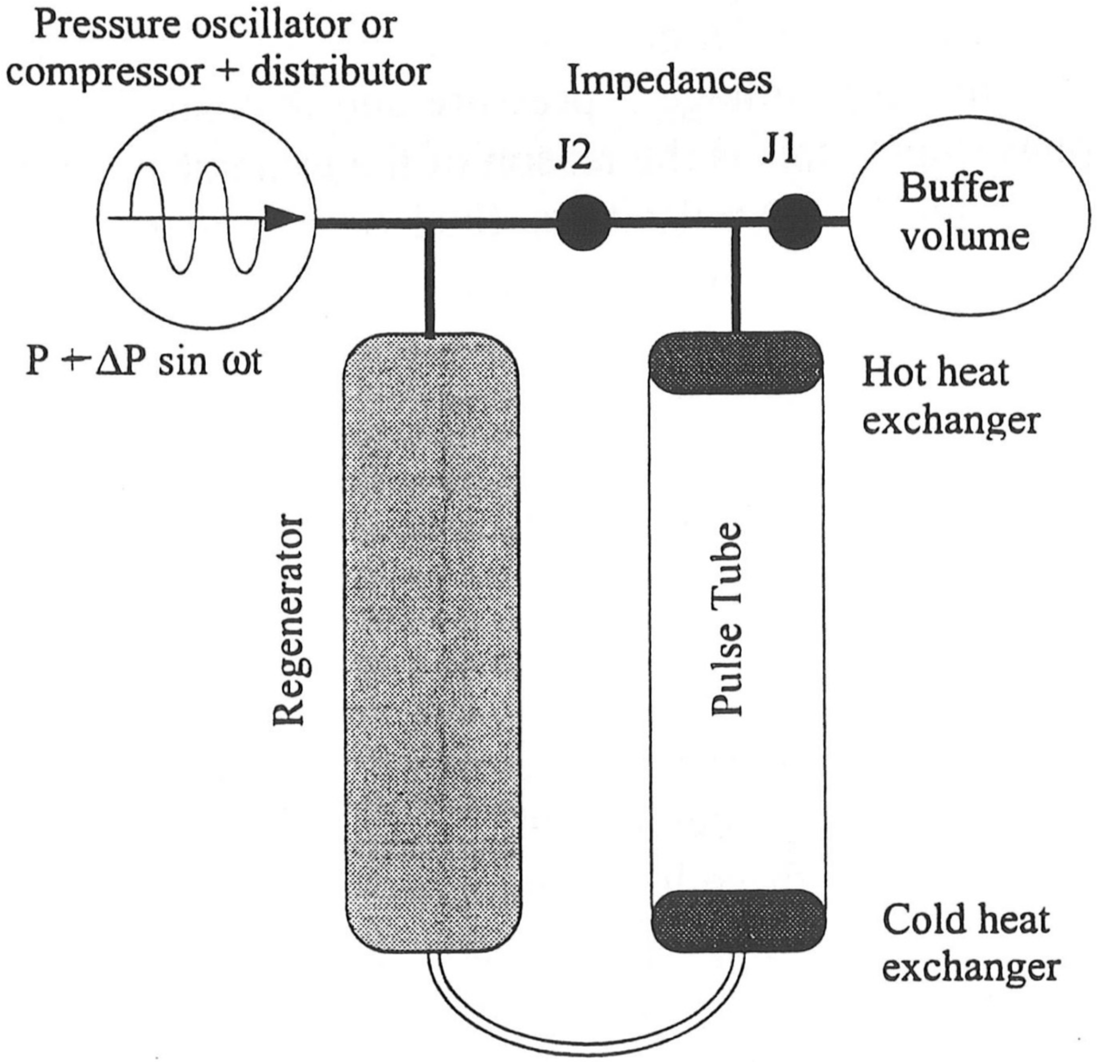

Image courtesy Cryomech

PT cryocoolers

Impedance gives phase difference to support Ericsson cycle

No moving parts => huge reduction in vibration at the expense of some cooling power

Image courtesy Cryomech

Case study - VTF cryostat at Daresbury

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SuRF Lab team

A. Akintola, A. J. Blackett-May, R. Buckley, P. Corlett, K. Dumbell, M. Ellis, A. Goulden, M. Hancock, S. Hitchen, P. Hornickel, C. Jenkins, M. Jones, M. Lowe, D. Mason, P. McIntosh, K. Middleman, A. Moss, J. Mutch, A. Oates, P. Owens, N. Pattalwar, S. Pattalwar, M. D. Pendleton, I. Skachko, T. Sian, P. A. Smith, P. Sollars, A. Wheelhouse, A. White, S. Wilde, and J. Wilson

CEA Saclay

DESY

ESS

JLab

+ many others

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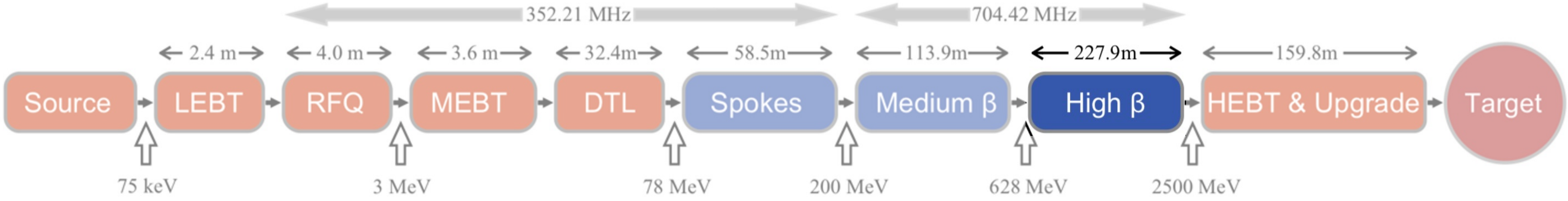
ESS high-β cavities

As part of the UK's IKC to the ESS, Daresbury is responsible for the manufacture and qualification of 84 high-β SRF cavities



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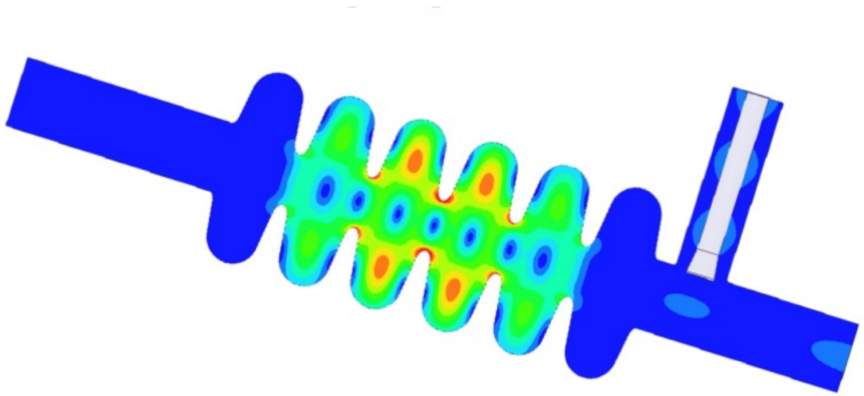
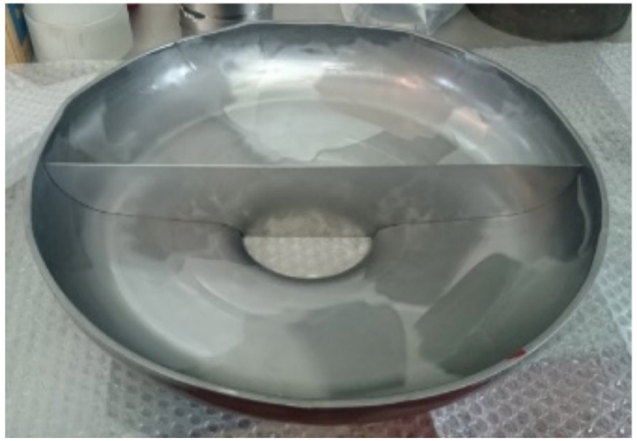
Concept → accelerator

EM modelling of RF cavity → Manufacturing →





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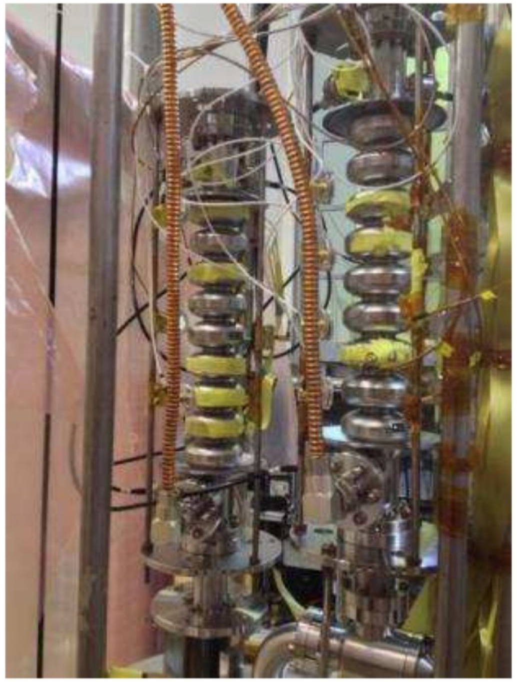
Michelato et al. (2016)

Concept → accelerator

→ Bare cavity test → Jacketing



Sertore et al (2015)
Kako et al (2010)

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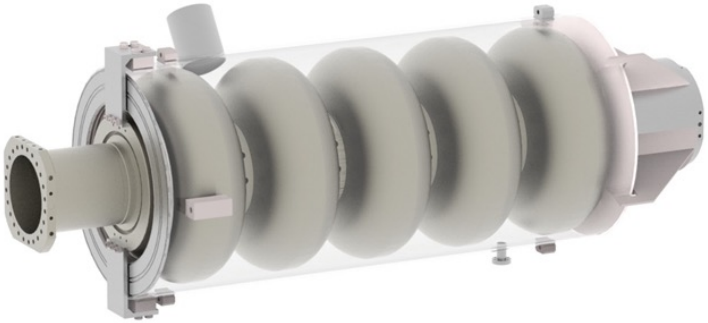
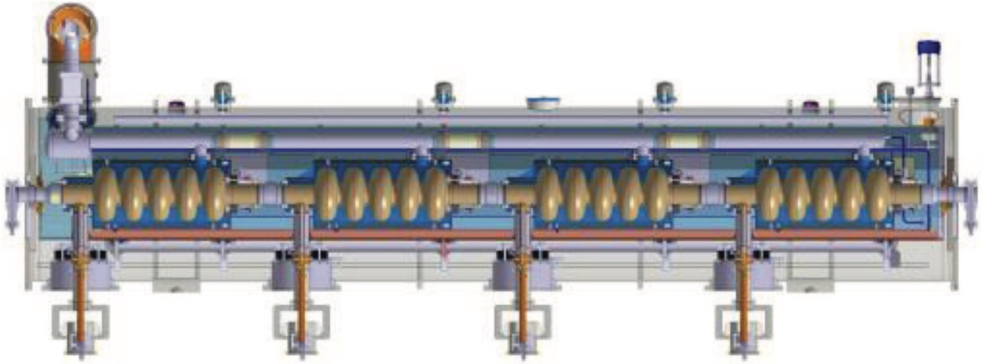
ESS high-β cavities

	Medium-β	High-β
Geometrical β	0.67	0.86
Frequency (MHz)	704.42	
No. of Cryomodules	9	21
Cavities /Cryomodule	4	4
No. of Cavities	36	**84**
Cryomodule length (m)	6.584	
Nominal Accelerating gradient (MV/m)	16.7	**19.9**
Nominal Accelerating Voltage (MV)	14.3	18.2
Q_0 at nominal gradient	**> 5e9**	





VTF key design requirements

Cavity frequency	704 MHz → dimensions
Operating temp	2 K → He-II
# cavities to test	84
Estimated retests	30%
Total anticipated tests	115
Time scale	2 years → 1 cavity/week

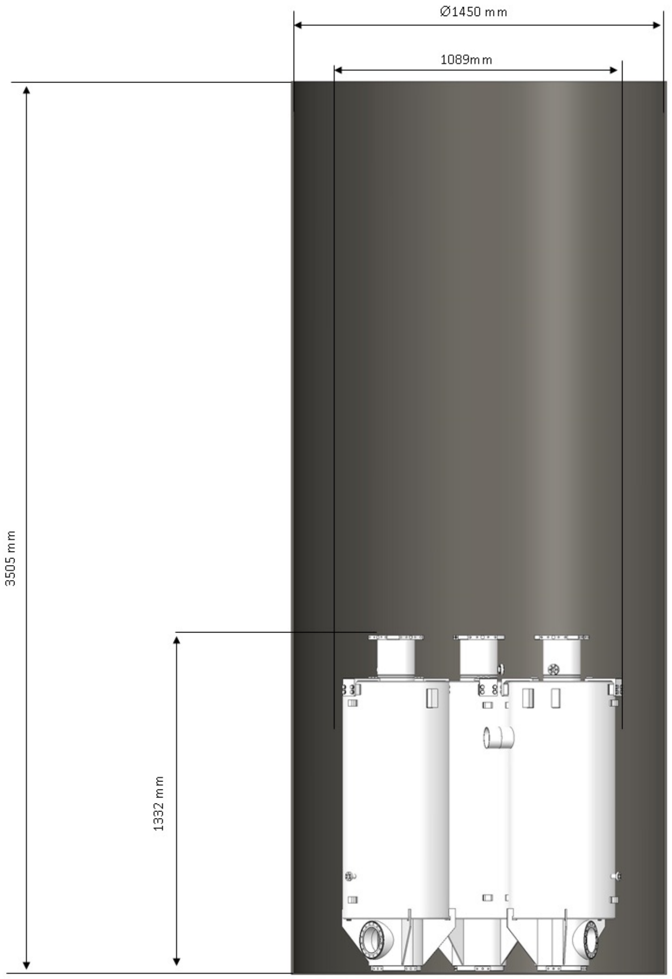
Conventional VTF approach

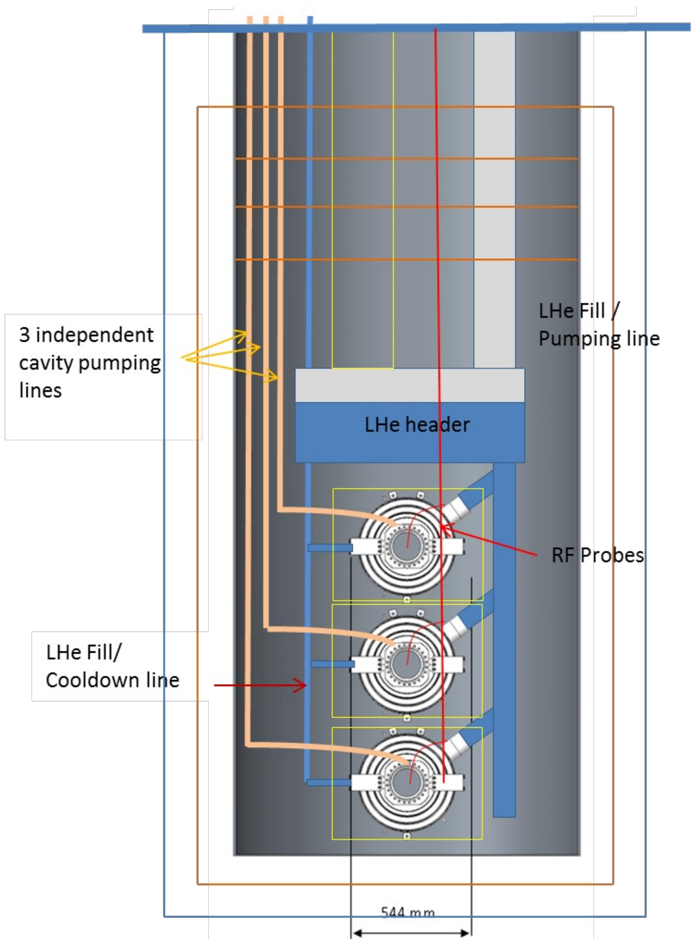
Immerse cavities in bulk LHe bath, pump to 30 mbar (2 K), use 2 K HEX + JT valve to maintain LHe level

Used successfully at DESY, CERN, FNAL

Requires ~7500 L LHe per test and GHe handling (2 K HEX, 2 K pumps, distribution pipework, valves, safety devices, etc.) for 20 g/s

‘Horizontal’ VTF approach



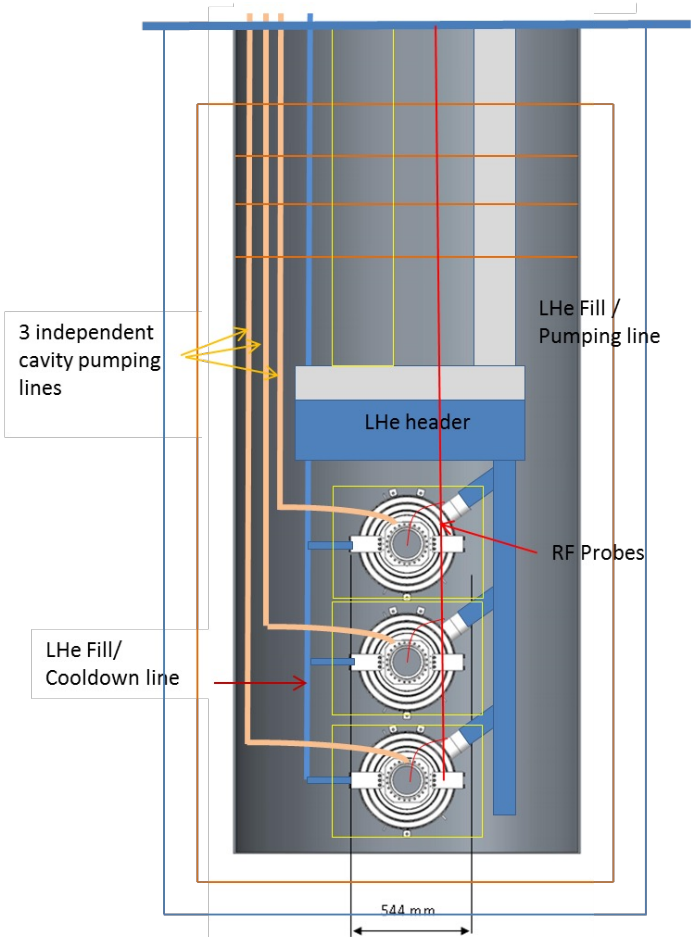

3 independent cavity pumping lines

LHe Fill / Pumping line

RF Probes

LHe Fill/ Cooldown line

‘Horizontal’ VTF approach



Individual LHe jackets, each ~50 L

Cryostat sized to accommodate horizontal cavity mounting (closer to linac configuration)

3 cavities tested per cooldown

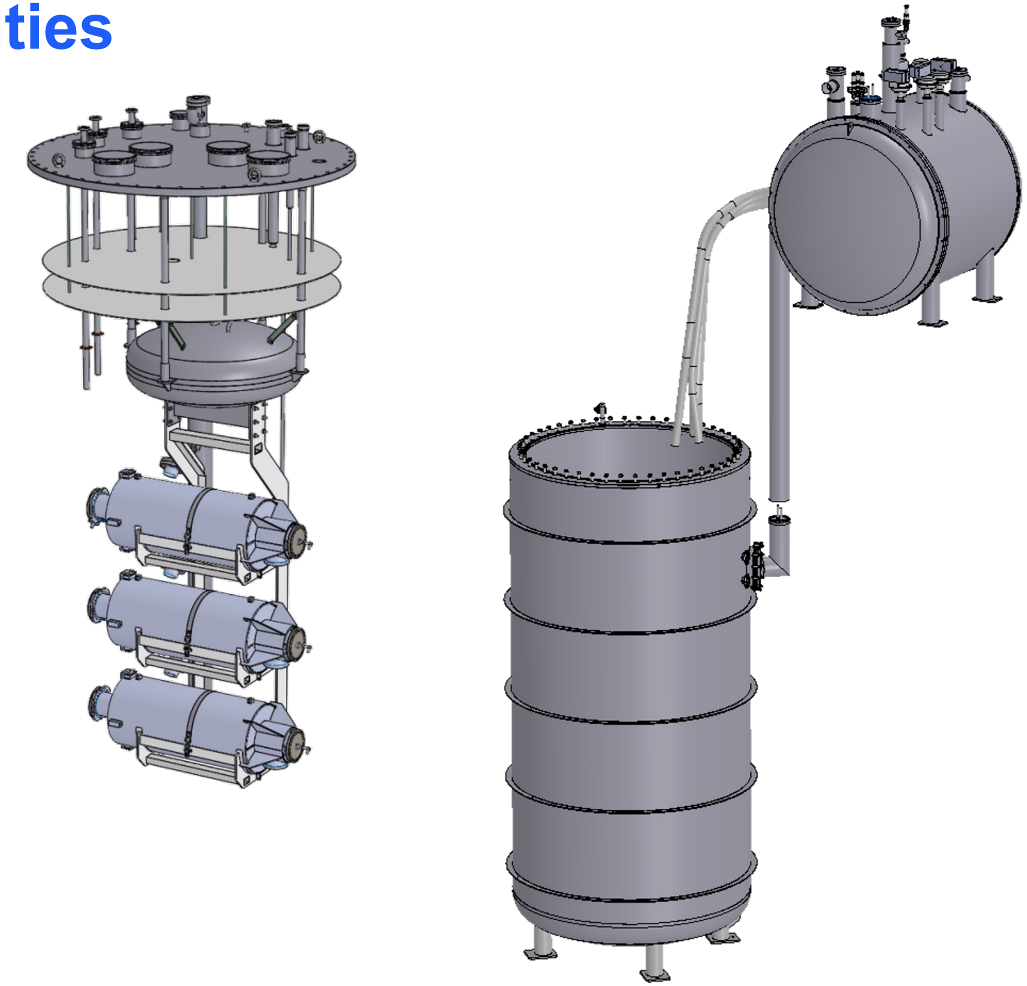
~1500 L required per test (vs 7500 L)

< 2 g/s in steady state under static load (vs 20 g/s)

Cavity support insert design

Pair of identical CSIs with common cryostat to allow simultaneous testing and preparation of next set of cavities

Component	Volume for 3 cavities (L)
CSI top header	213.0
LHe column Section 1 Section 2 Section 3	 33.4 15.2 4.4
Di-phase connection	23.1
Cavity helium jacket	155.7
Total:	444.8



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Cavity loading and preparation on CSI

Cryo connections made + RF, mechanical, UHV

Cernox RTD thermometers mounted on cavities

MLI jackets installed

Input coupler cooling link installed

“Mode-2” checks carried out on stand, inc.

- Safety checks
- Thermometry
- Leak checks of He circuit

+ RF, mechanical, UHV checks

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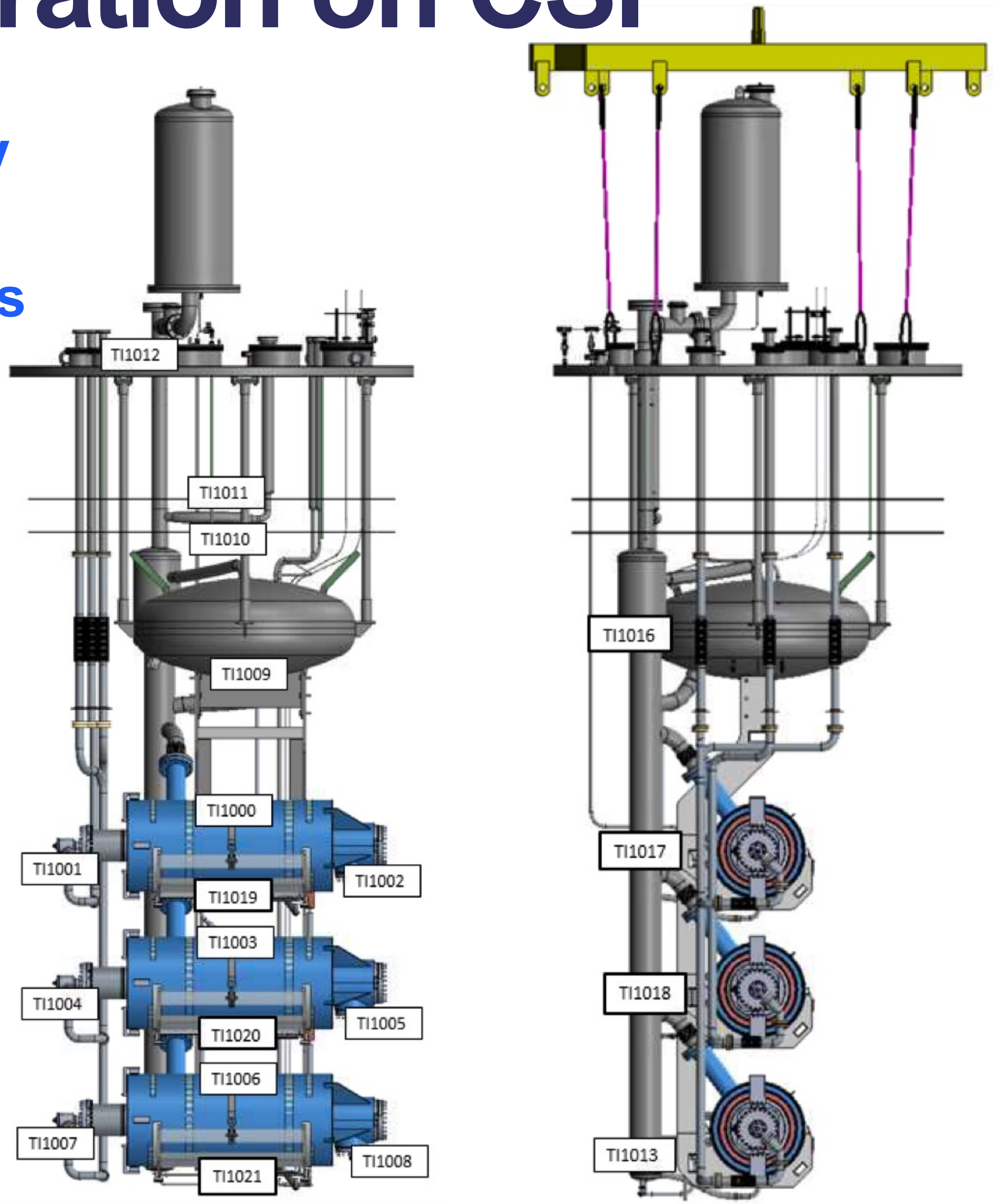

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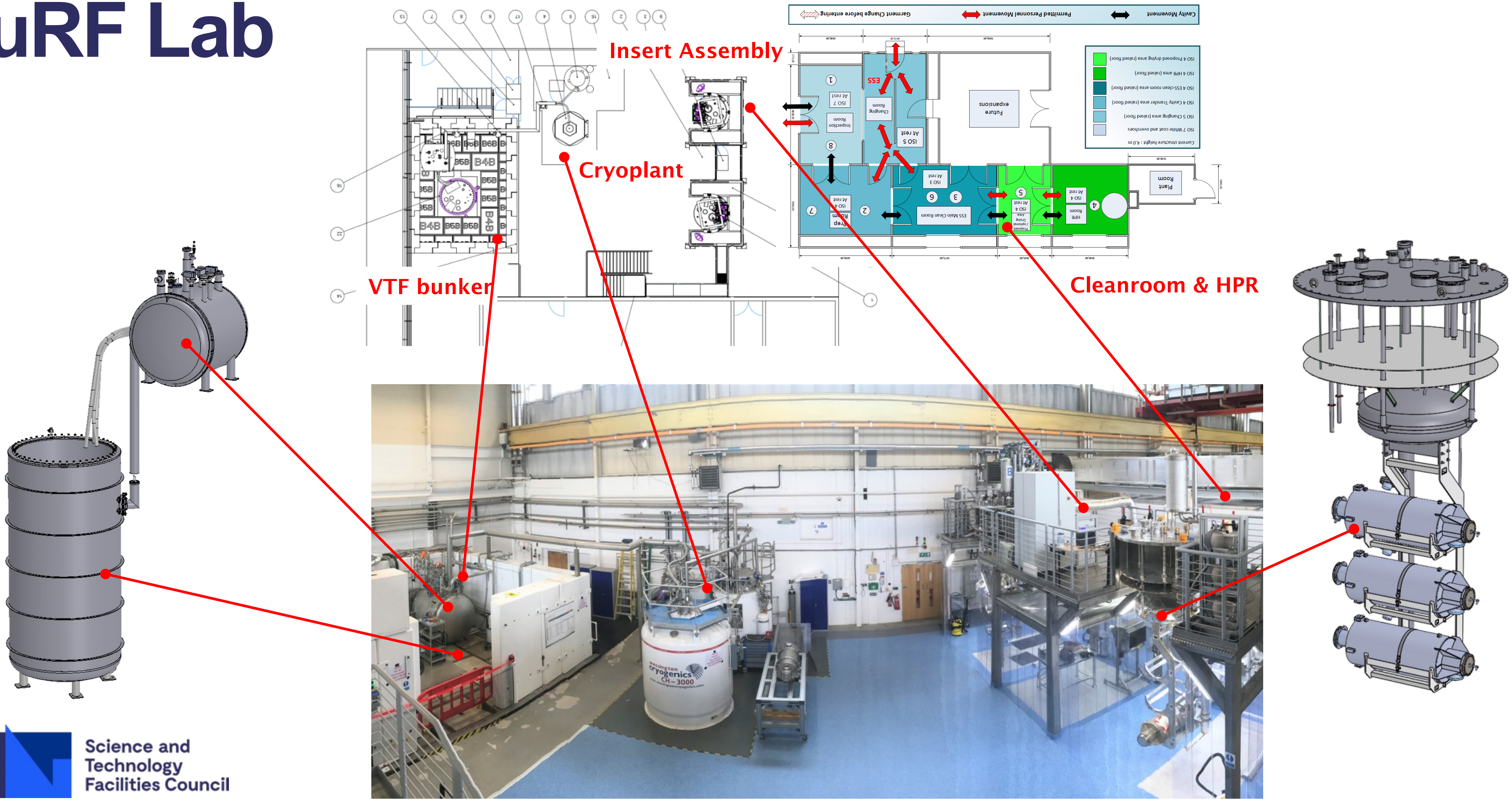
SuRF Lab



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CSI transfer

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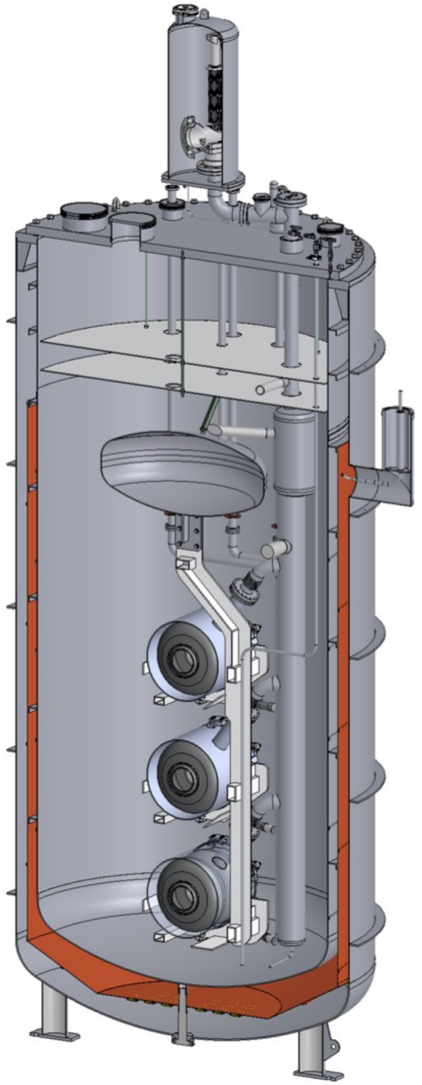
VTF cryostat and bunker

Single vacuum chamber (OVC+IVC) in bunker (inc. thermal and magnetic shielding)

2 K valve box

2 K pumps (>1 g/s @ 30 mbar/2 K)
+ redundant set/additional capacity being installed mid-2021

Recovery circuit => closed-cycle



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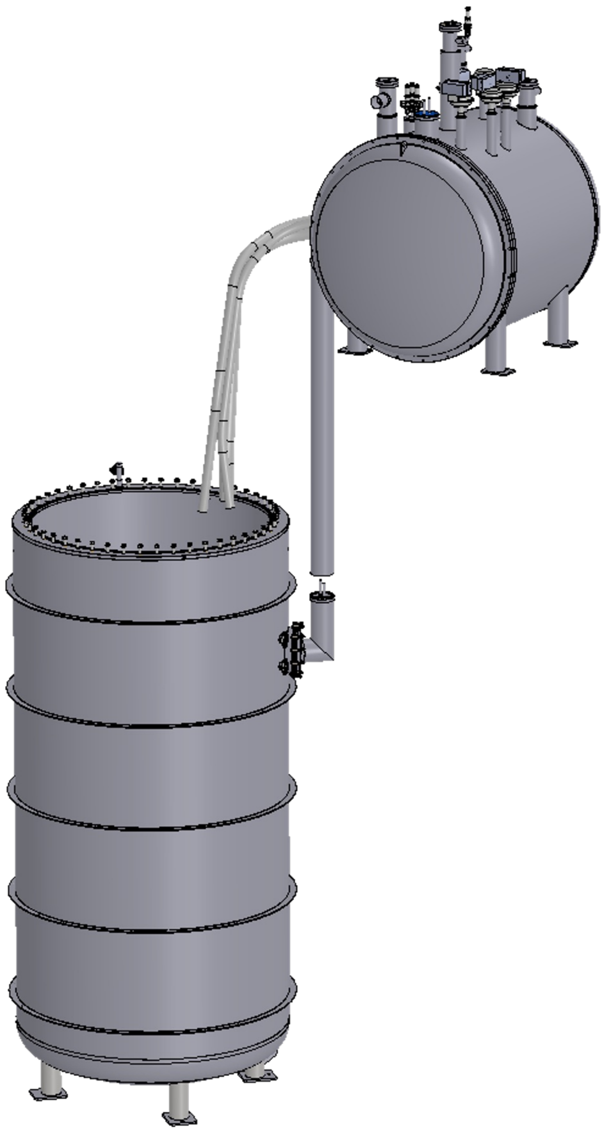

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Recovery circuit => closed-cycle

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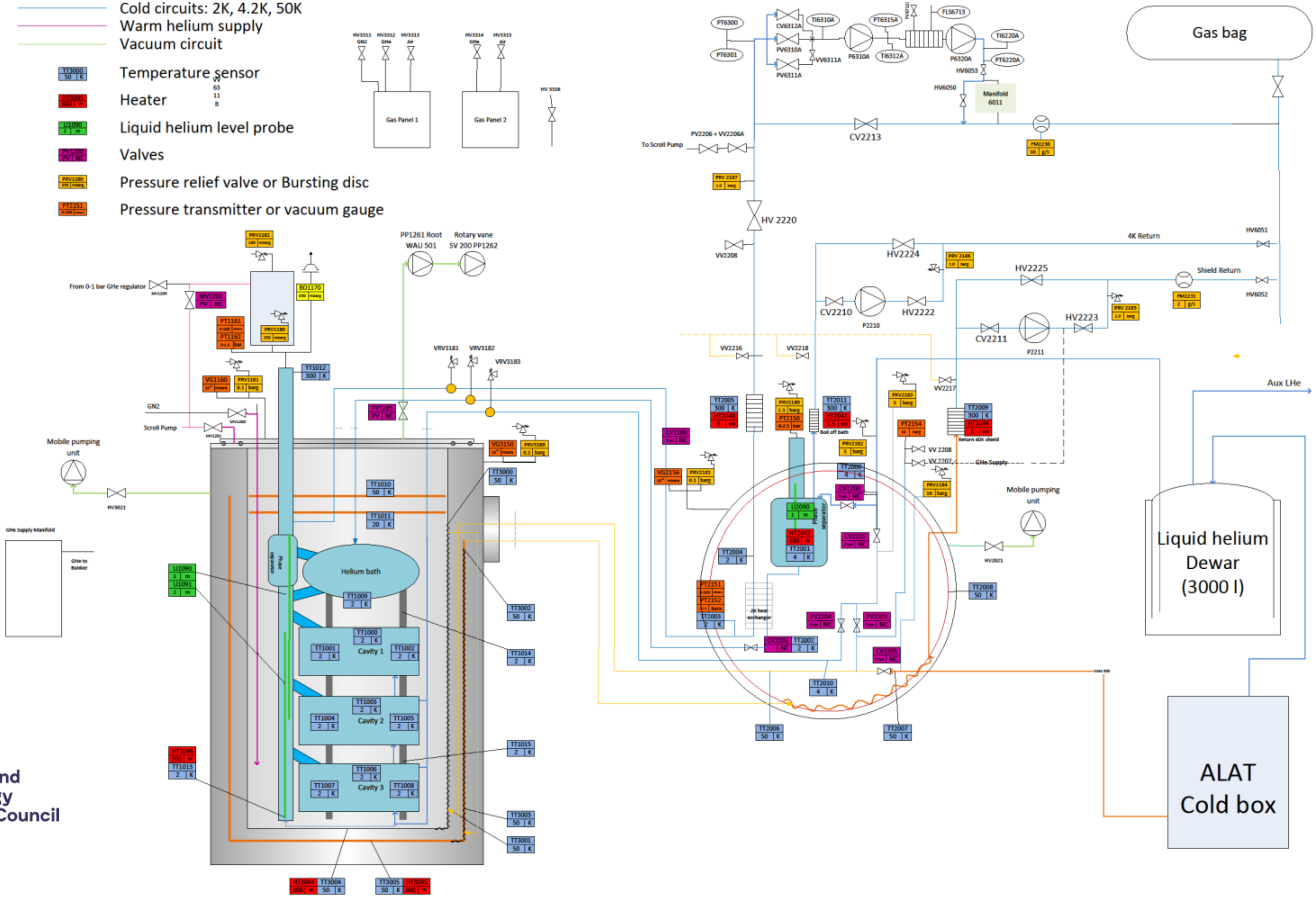
P&ID

Cold circuits: 2K, 4.2K, 50K
Warm helium supply
Vacuum circuit

- TT3000 50 K — Temperature sensor
- HT3045 600 W — Heater
- LI1090 2 m — Liquid helium level probe
- PV1205 PV NC — Valves
- PRV1180 250 mbarg — Pressure relief valve or Bursting disc
- PT2151 0-100 mbara — Pressure transmitter or vacuum gauge



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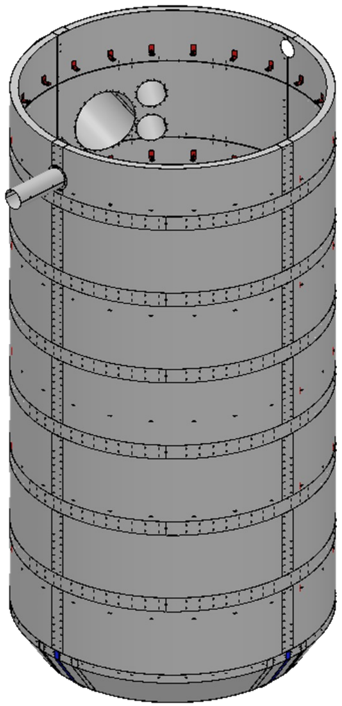
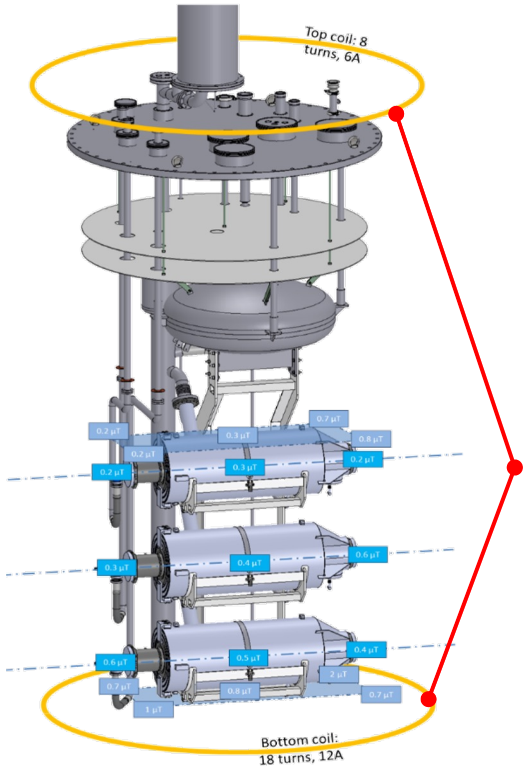
Magnetic shielding

Stray field attenuation to <1.4 µT by static Mu-metal shield





Further attenuation <1.0 µT by two active coils

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Cryoplant and recovery infrastructure

Air Liquide Helial ML
~130 L/hour (w/ LN2 precool)
Gas @ 50 K, currently run ~2 g/s

3000 L LHe dewar
Currently run at 2000 L

Recovery circuit

Total current operating inventory
~ 2700 L liquid equivalent

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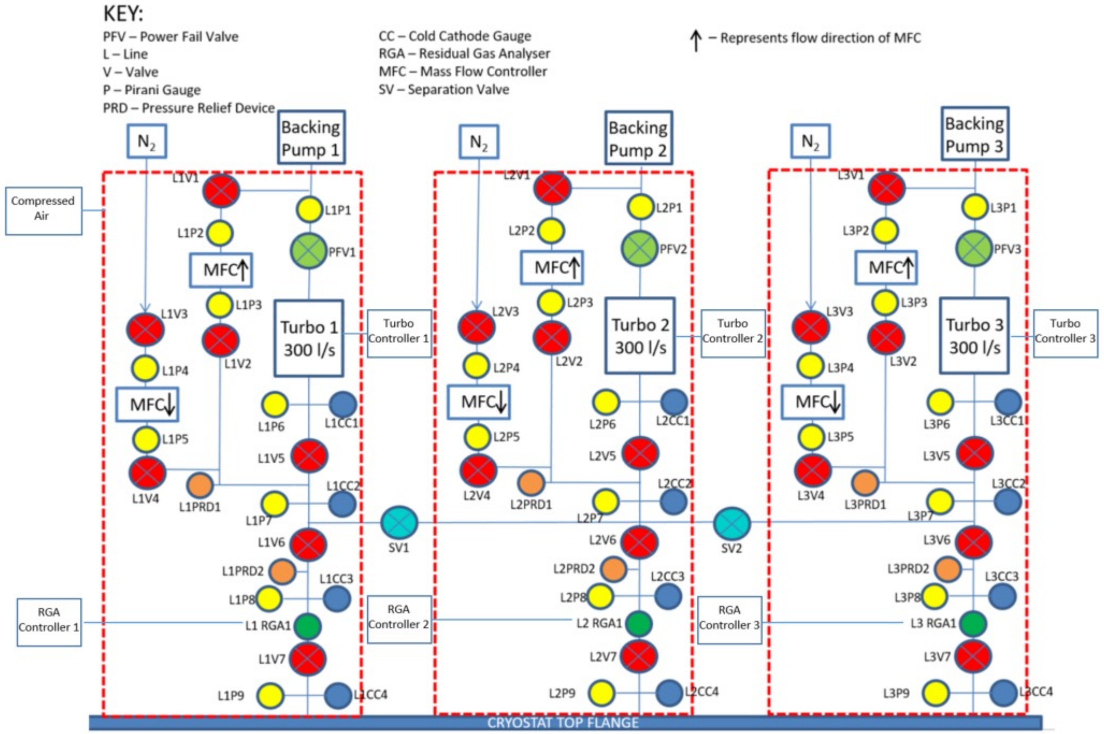
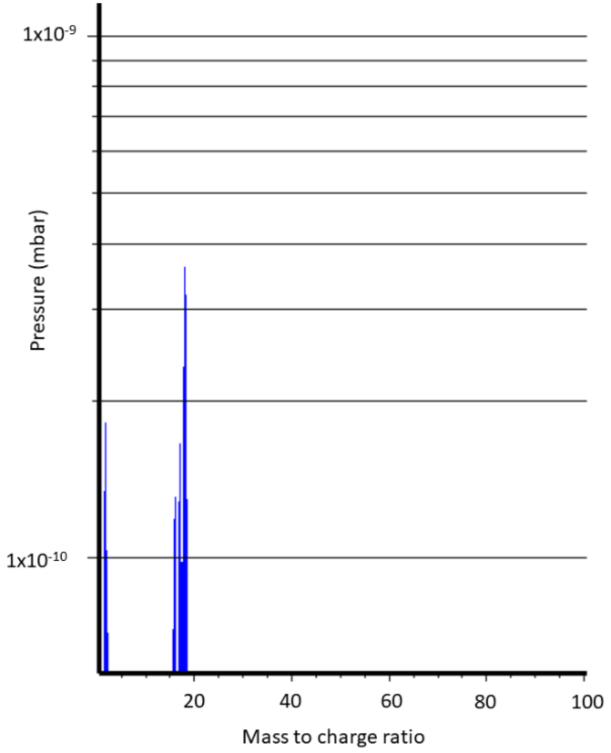
UHV system

Custom slow pump/slow vent systems developed to operate down to 10^{-7} mbar





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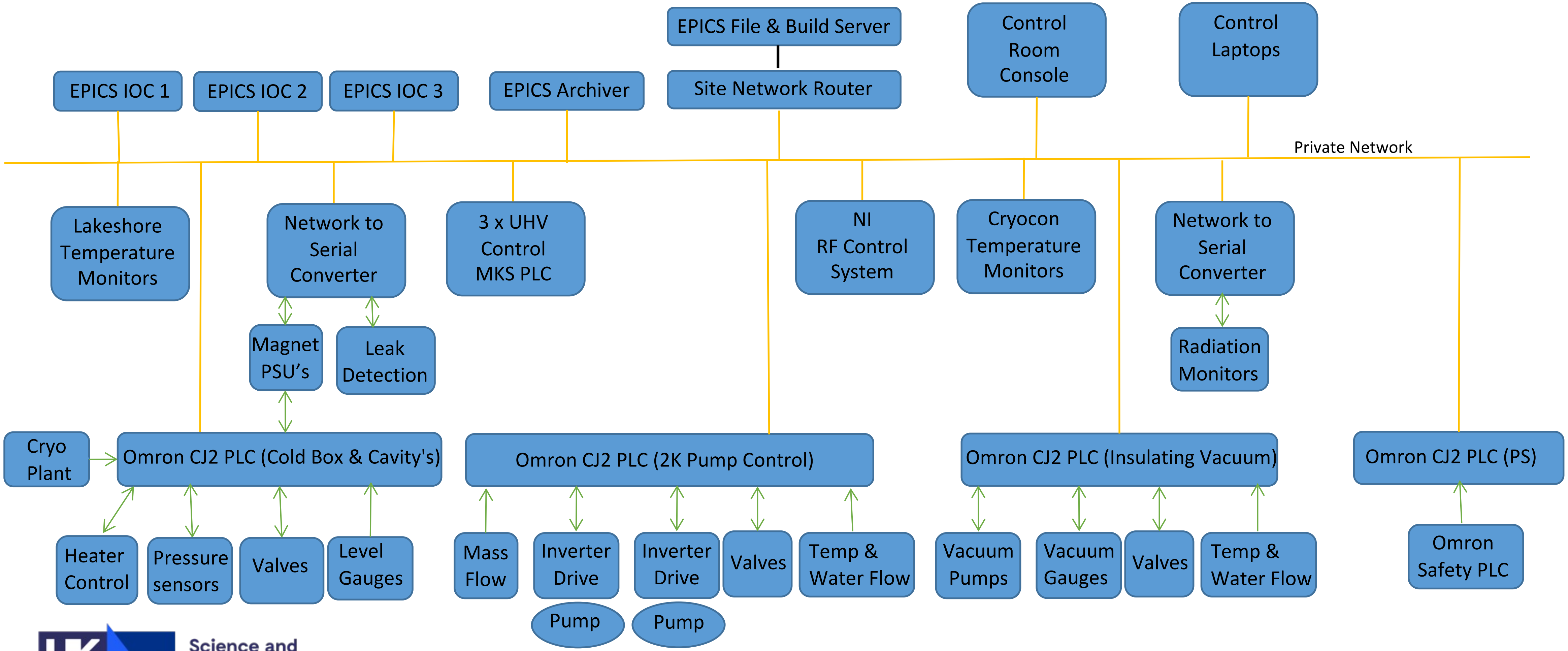
Instrumentation and controls


EPICS File & Build Server
Site Network Router
Control Room Console
Control Laptops
EPICS IOC 1
EPICS IOC 2
EPICS IOC 3
EPICS Archiver
Private Network
Lakeshore Temperature Monitors
Network to Serial Converter
3 x UHV Control MKS PLC
NI RF Control System
Cryocon Temperature Monitors
Network to Serial Converter
Magnet PSU's
Leak Detection
Radiation Monitors
Cryo Plant
Omron CJ2 PLC (Cold Box & Cavity's)
Omron CJ2 PLC (2K Pump Control)
Omron CJ2 PLC (Insulating Vacuum)
Omron CJ2 PLC (PS)
Heater Control
Pressure sensors
Valves
Level Gauges
Mass Flow
Inverter Drive
Pump
Inverter Drive
Pump
Valves
Temp & Water Flow
Vacuum Pumps
Vacuum Gauges
Valves
Temp & Water Flow
Omron Safety PLC

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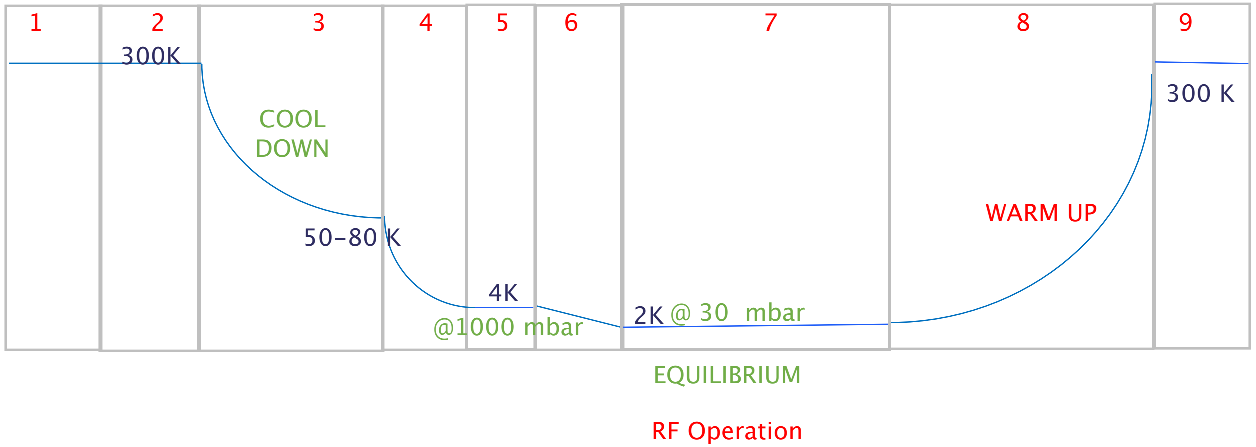
Slide by Adrian Oates (STFC, DL, TECH)

Modes of operation

Mode-1 Cavity assembly on CSI
Mode-2 CSI loading and checks on stand
Mode-3 Shield and cavity cooldown to 40 K
Mode-4 Cavity cooldown to 4.2 K
Mode-5 RF operations at 4.2 K



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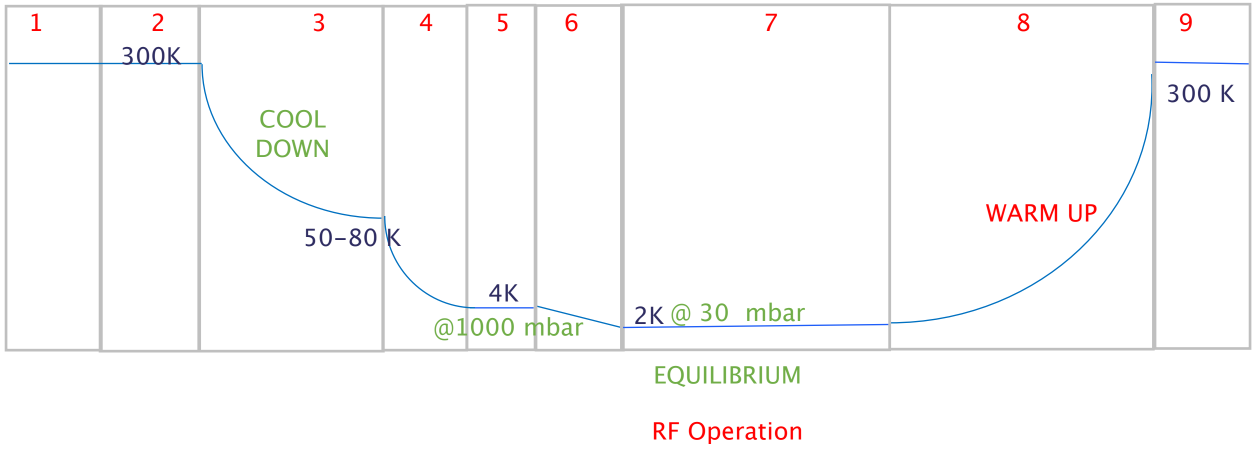
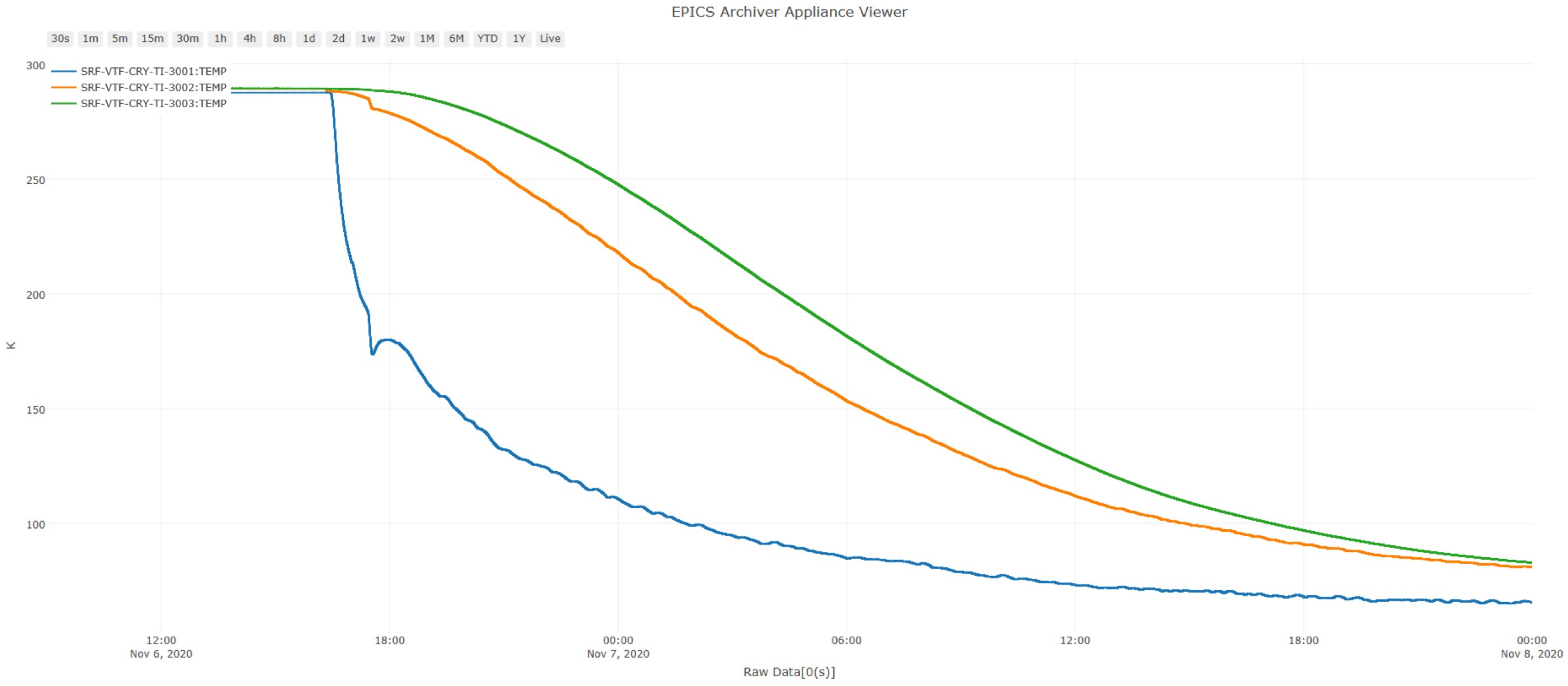
Modes of operation

Mode-6 Cavity cooldown to 2 K
Mode-7 RF operations at 2 K
Mode-8 Warmup to 300 K
Mode-9 CSI removal
Mode-10 Cavity disassembly on CSI

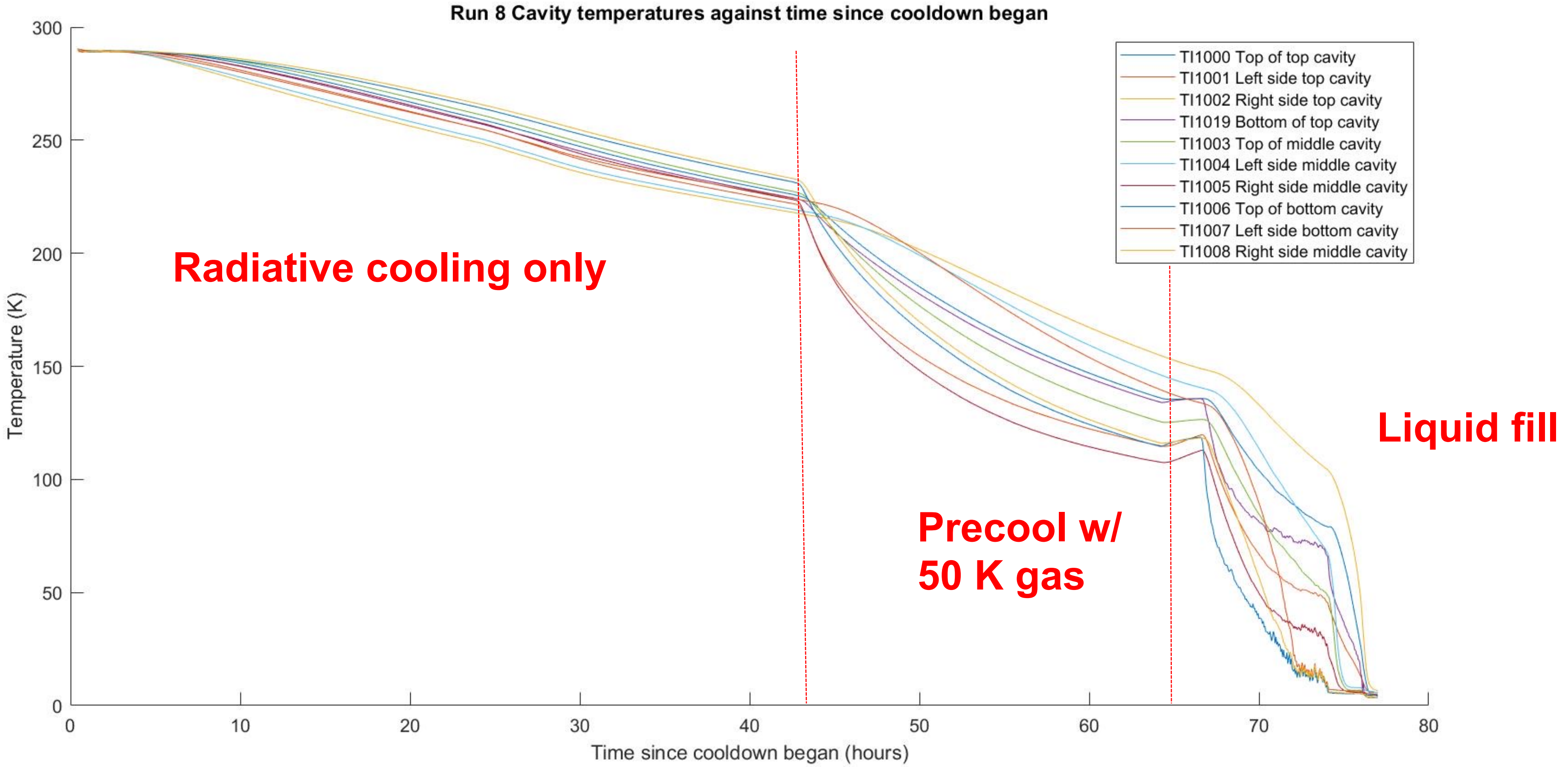


Shield cooldown



24 hours

Cavity cooldown



Further optimisation of cooldown tbd

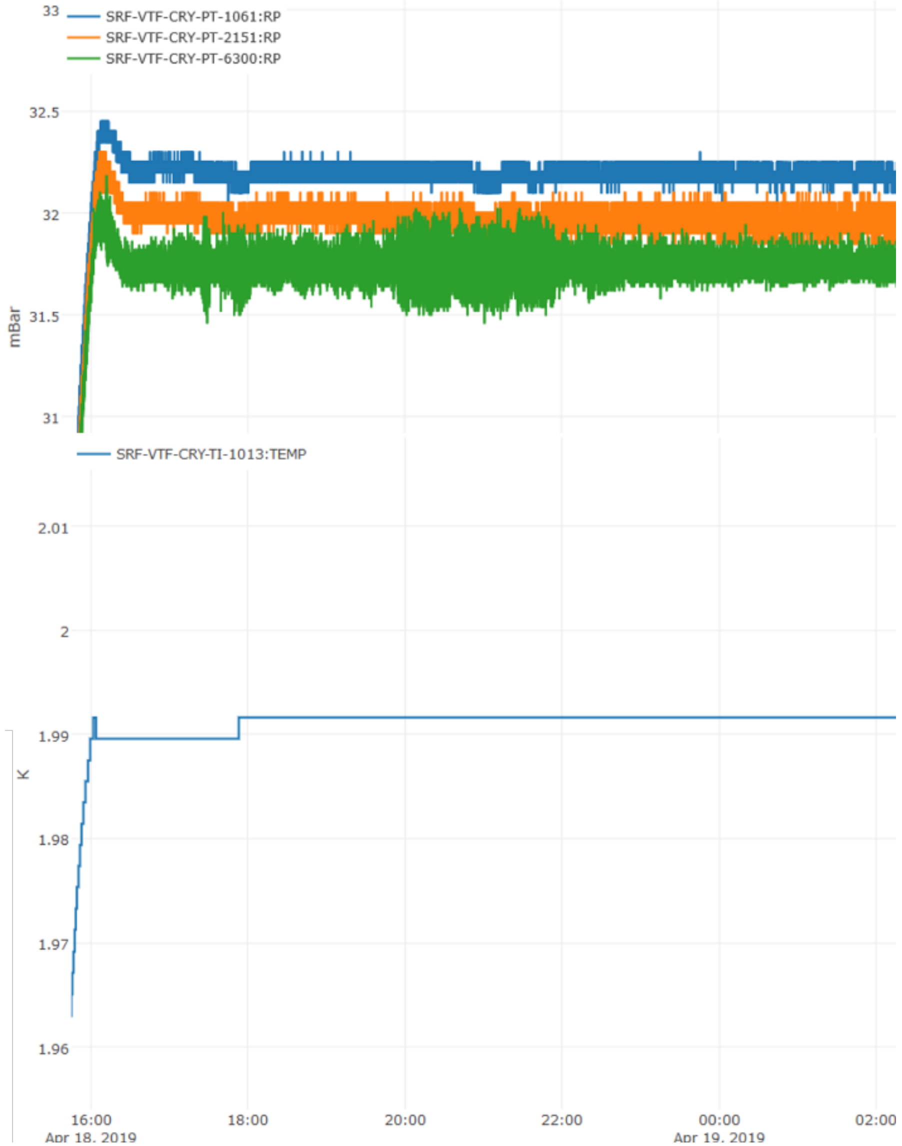
Courtesy: A White

Pressure and temperature stability at 2 K

Excellent pressure and temperature stability under static load at 2 K with PID control of 2 K pumps

±0.1 mbar
±1 mK

Stability under dynamic load subject of ongoing work



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Cryo + RF ops at 2 K

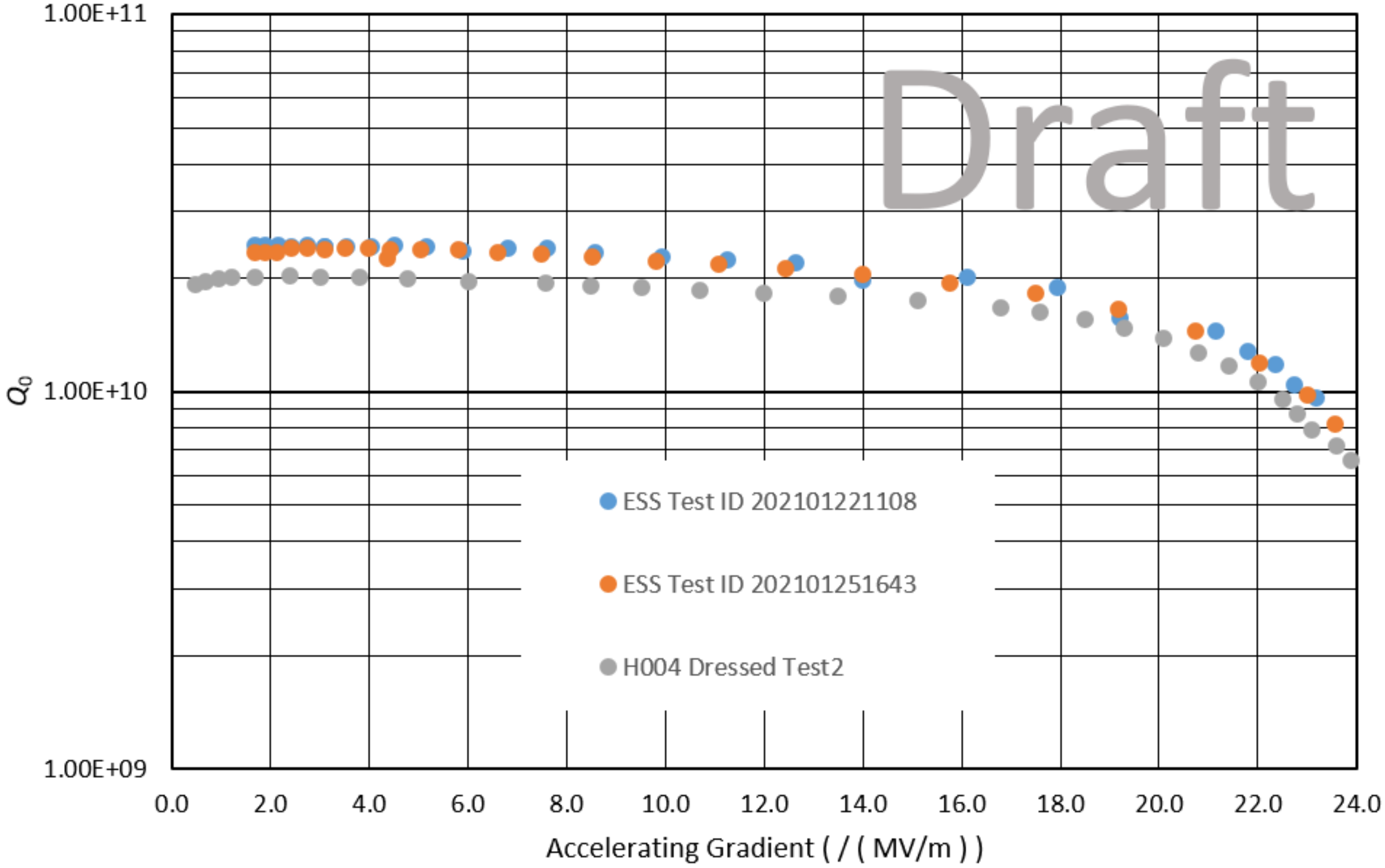
Minimum liquid level to keep cavity immersed is 70%

With CSI filled to top of header tank (i.e. 100%), hold time at 2 K under static loading >18 hours

Actual duration available during testing will depend on RF power dissipated, typically ~8 hours

Top up duration ~2.5 hours; in practice fills carried out daily to support RF ops

Cavity test results – H004



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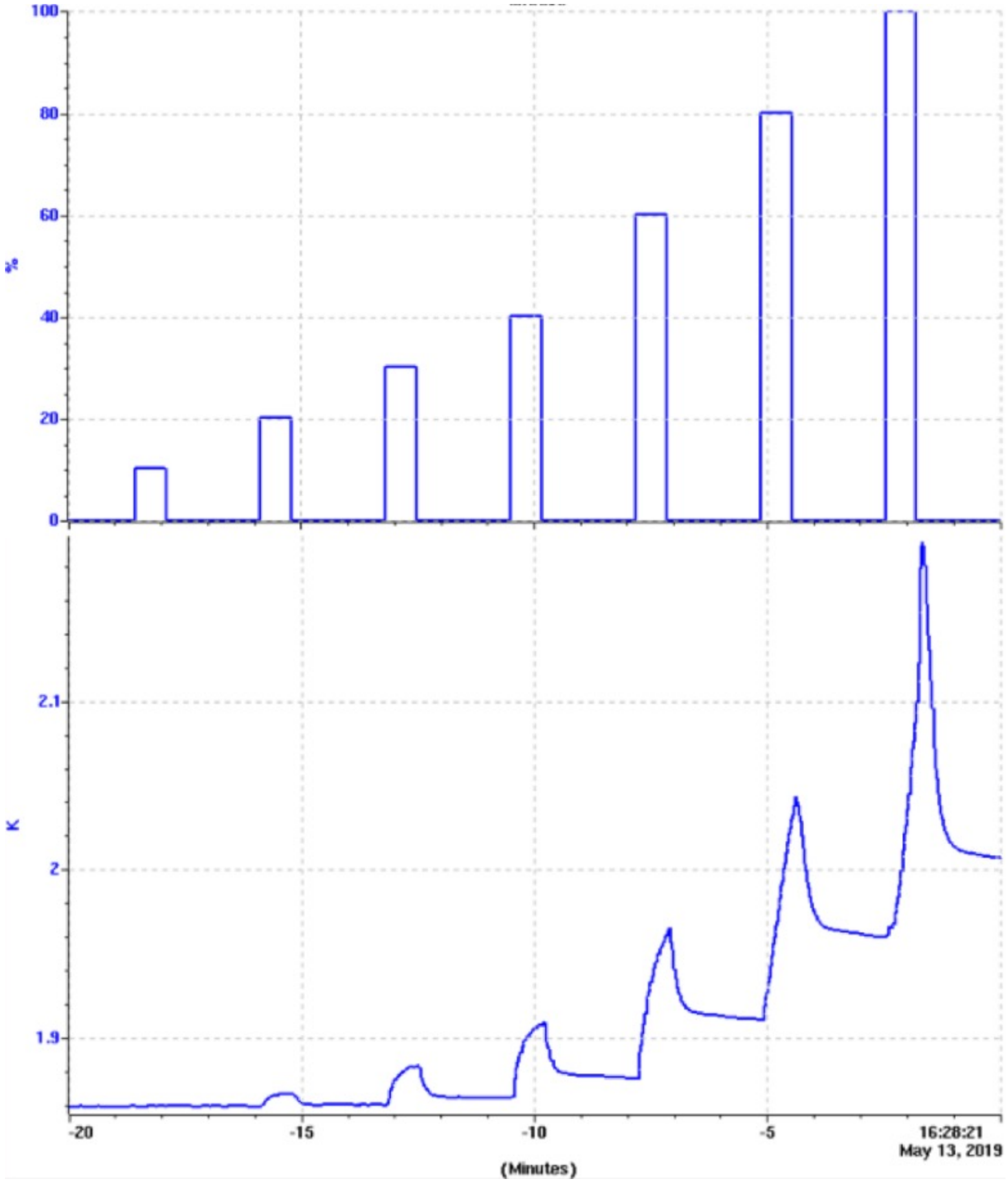
Response to loading

Tests carried out to simulate RF loading

Series of 40 s pulses applied up to 200 W



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Warm up

Speedy warm up carried out by boiling off remaining LHe and employing recirculation pumps to drive warm GHe through cooling circuits

~72 hours for warm up to 300 K

Cryogenic performance allows us to test 3 cavities / 2 weeks

Safety

Significant efforts have been devoted to safety considerations during design

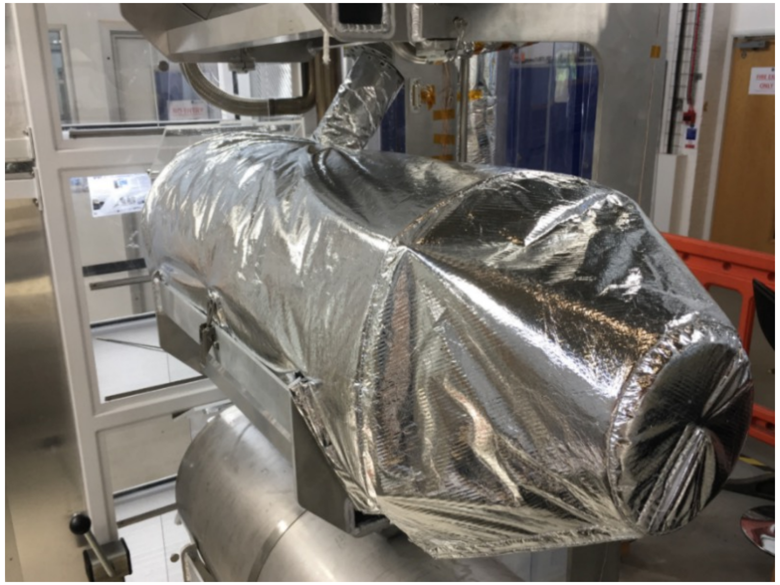
Worst-case failure scenarios considered to be:

- cryostat vacuum failure
- beam pipe vacuum failure
- contamination of helium circuit

Safety – cryostat vaccum failure

Cryostat vacuum loss → immediate leak of 300 K air onto cold surfaces

MLI on cavity jackets retards heat transfer from warm gas



	Loss of vacuum heat load	Ø safety valve required
Without MLI on cavities	170 kW	64 mm
With MLI on cavities	42 kW	32 mm

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Safety – beam pipe vacuum failure

Immediate leak of 300 K air onto inside surface of cavity

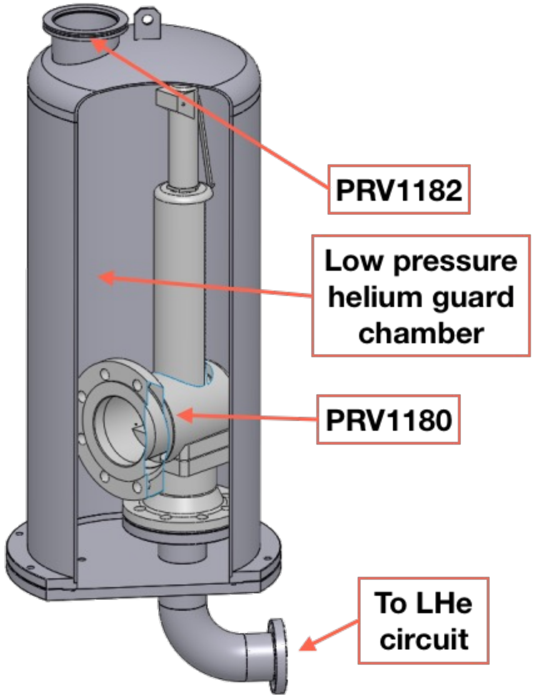
3 independent UHV lines → extremely unlikely all three would fail simultaneously

Loading found to be lower than for previous case, hence not limiting scenario

Safety – contamination of helium circuit

If PRV does not close properly following He boil off from transient event, air ingress possible

In order to mitigate this, low pressure helium guard around PRV used



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Operational history and future plans

Commissioning completed 2019

ESS high-β cavity testing programme late 2020 to mid 2023

Summer 2023 upgrade work to prepare for PIP-II

From end of 2023 facility will be used for testing HB650 cavities for PIP-II

Longer term plans for thin film cavity testing

Daresbury VTF summary

"Horizontal" VTF developed at STFC Daresbury allowing test of 3 high-β SRF cavities per run whilst requiring ~70% less LHe than conventional facilities

Demonstrated cooldown of 3x ESS high-β cavities to 2 K with excellent pressure/ temperature stability

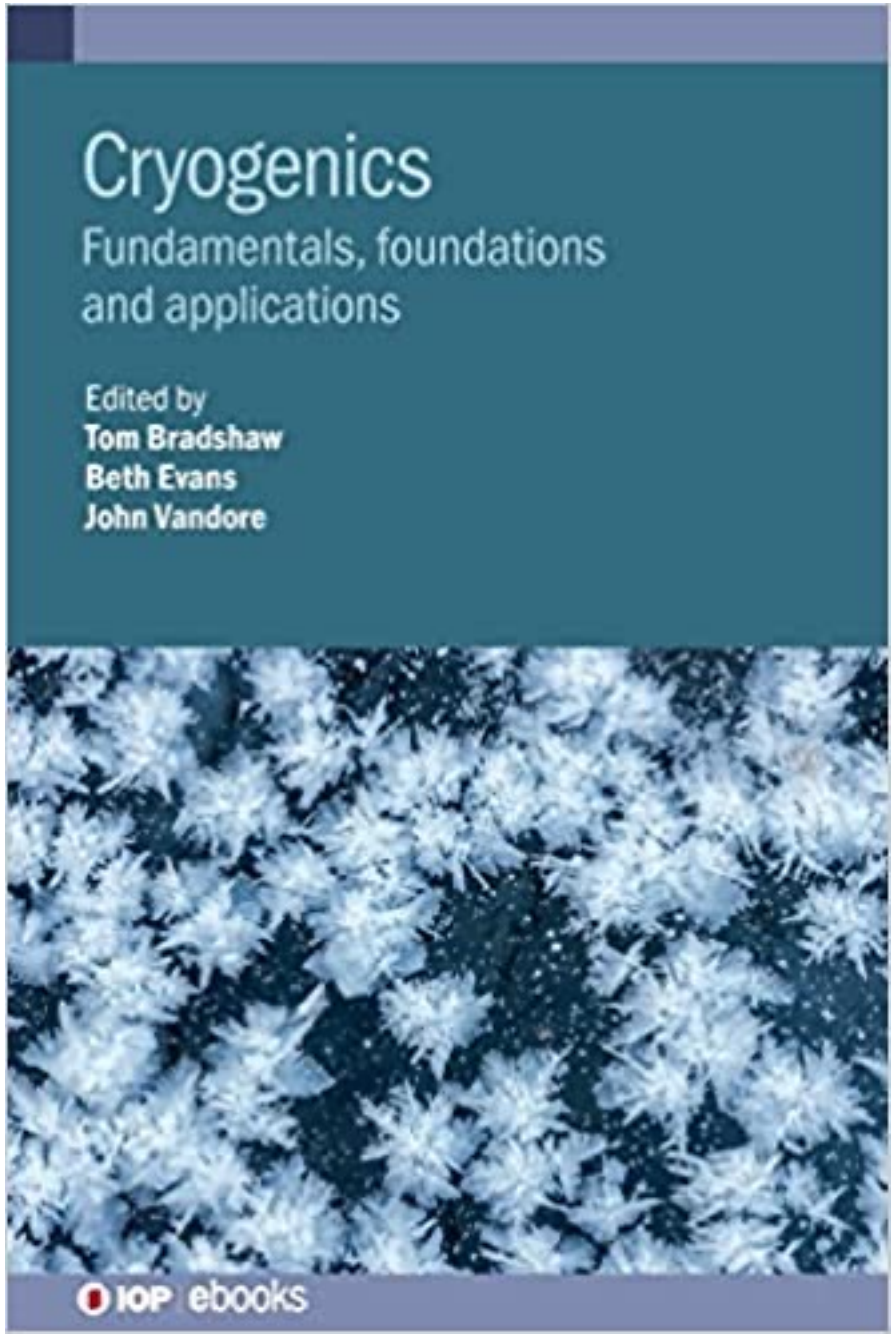
Cryogenic performance validated for high-power RF tests at 2 K

Nearing end of successful ESS cavity testing programme

Preparing for PIP-II HB650 modifications this Summer

Overall summary

- Applications for accelerators
- Properties of cryogens
- Heat transfer and material properties at low temperatures
- Basic principles of cryogenic engineering
- Cryostat design
- Cryoplants, mechanical coolers
- Case study – Daresbury vertical test facility



Cryogenics

Fundamentals, foundations and applications

Edited by
Tom Bradshaw
Beth Evans
John Vandore

IOP ebooks

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References and further reading

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Thank you

Questions?

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