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Cryogenics for accelerator cavities

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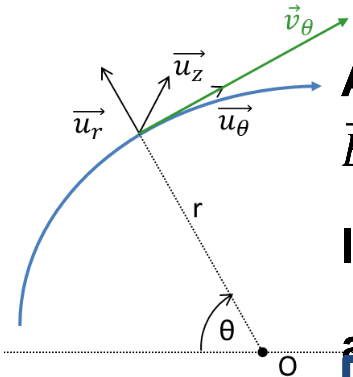
- **Cryogenics for SRF cavities**

Context: electric and magnetic fields



Assuming $\vec{E} \rightarrow E_\theta$ **and** $\vec{B} \rightarrow B_z$**, Lorentz Force:** $\vec{F} = \frac{d(\overrightarrow{mv})}{dt} = q\vec{E} + q\vec{v} \times \vec{B}$

In the coordinate system: $\frac{d(mv_\theta)}{dt}.\overrightarrow{u_\theta} - m\frac{v_\theta^2}{r}.\overrightarrow{u_r} = qE_\theta.\overrightarrow{u_\theta} + qv_\theta B_z.\overrightarrow{u_r}$

and then : $\frac{d(mv_\theta)}{dt} = qE_\theta$ and $\frac{(mv_\theta)}{q} = rB_z$

- The electric field acts on the energy and momentum of the particle
- The magnetic field bends the particle trajectory

- 2 types of major components in a particle accelerator:
  - ✓The focusing and bending components :

All along the acceleration, the particles have to be guided and focused (magnetic and electric fields).
⇒ Due to the limitation of room temperature magnets (saturation of iron < 2T), superconducting technology is required especially for heavy particles and at very high energy.

  - ✓The accelerating components :

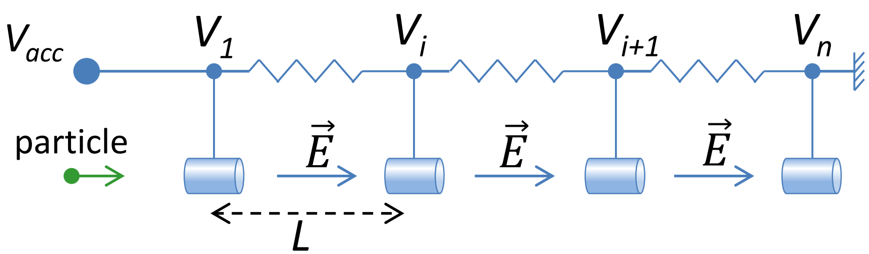
All accelerators use either a static or an oscillating electric field to accelerate.
⇒ Room temperature technology is easier to build but shows many constraints because of power dissipations. Superconducting technology is compulsory for CW high current applications.

EASITrain

SRF cavities for particles acceleration

Context: the need of RF field

- Electrostatic acceleration:



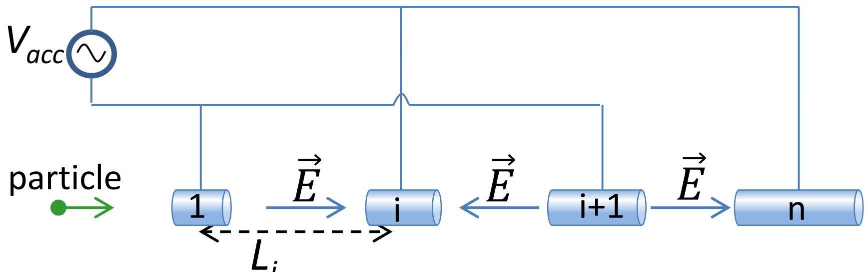
Gap length: L_{gap}**; electric field:** $E = \frac{\Delta V_i}{L_{gap}}$ **;**

Energy gain is proportional to the voltage applied between electrodes: $\Delta\left(\frac{1}{2}mv^2\right) = qVacc$

$\Rightarrow$ **total required voltage :** $V_{acc} = \sum_n \Delta V_i$

$\Rightarrow$ Limited by electrical breakdown at high voltage terminal (few MV in the best cases)

- RF Acceleration



Several small accelerations are used instead of a single large one:

$$\Rightarrow \Delta\left(\frac{1}{2}mv^2\right) = qnVa_{cc}$$

But to accelerate a particle, the electrical field must be turned on during 1/2 period only:

E.g.: f = 700MHz: for β = 0,5 $\Rightarrow$ L_{cell} = 10.7 cm

β = 1 $\Rightarrow$ L_{cell} = 21.4 cm

$\Rightarrow$ **synchronism condition:** $L_{gap\_i} = \frac{v_i}{2f} = \frac{\beta_i \lambda_i}{2}$ **with** $\beta_i = {v_i}/{c}$

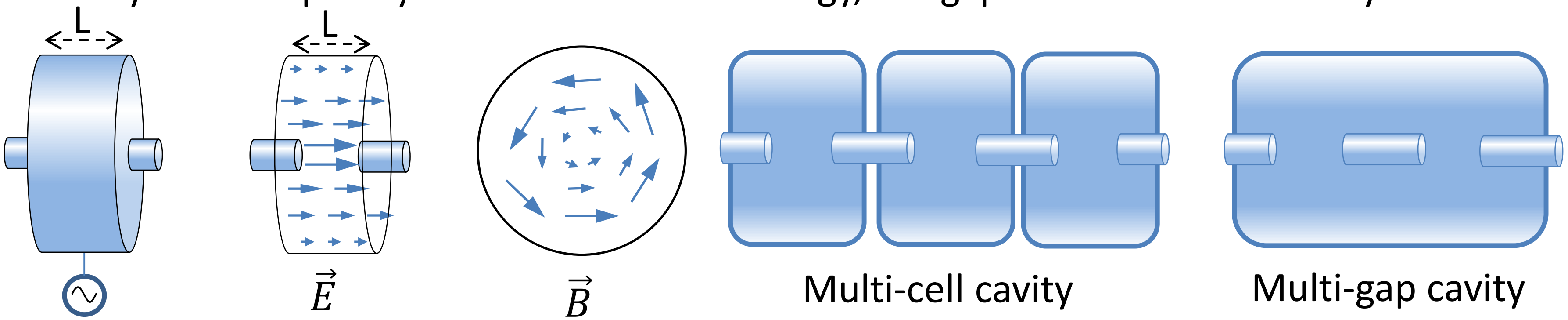
- The drift tube length **grows** as the particle velocity **increases**
- At high velocity, one must consider higher frequencies to limit length

Wideröe type RF linac

SRF cavities for particles acceleration

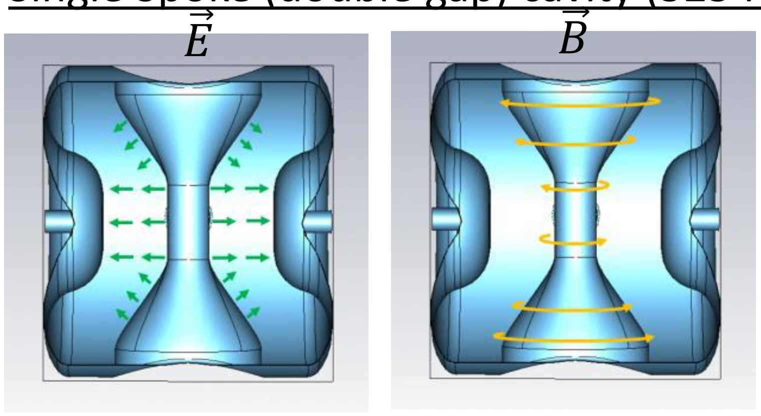
Context: cavities for RF fields

Current generated on surface of the conductors generates radiated power which increases linearly with frequency ⇒ to hold the EM energy, the gap is enclosed in a cavity.



1 cell cavity (“pill box”)

Single Spoke (double gap) cavity (325 MHz):



P. Berrutti, G. Romanov - PIP-II proto SSR2 RF Design, Fermilab

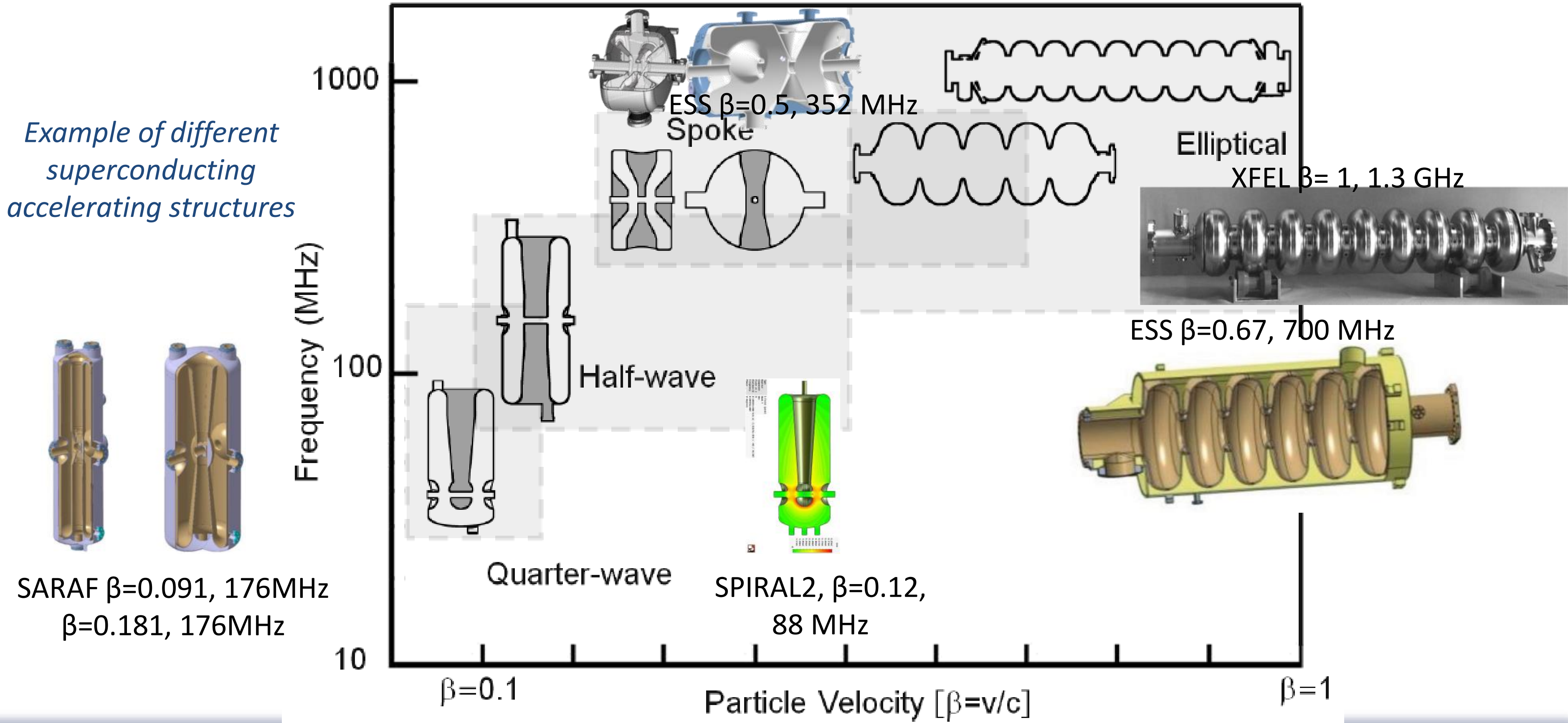
To keep in mind:
B (or H) is max at the cavity surface
E is max on the revolution axis

SRF cavities for particles acceleration

Context: cavities for resonant RF fields

- Efficient acceleration consists of combining different RF structures in order to keep synchronism condition
- Independent phased and powered structures to ensure synchronism
- Design of cavity geometry is adapted to the particle which is accelerated

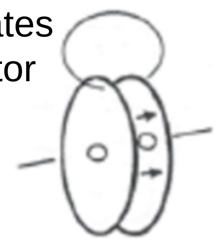
Example of different superconducting accelerating structures



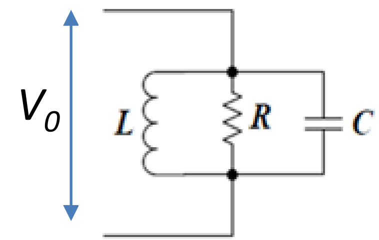
SRF cavities for particles acceleration

Context: cavities for resonant RF fields

2 capacitive plates with a // inductor



Inductor = many single loops of wire ~ accelerating RF cavity



RLC circuit :

Voltage	V_0
Stored Energy	$U = {}^{1}\!/_{2}\, C V_0^2$
Dissipated power	$P = {}^{V_0^2}\!/_{2R}$
Quality factor	$Q_0 = {}^{\omega_0 U}\!/_{P} = {}^{R}\!/_{\omega_0 L} = \omega_0 RC$
Shunt impedance	$R_{shunt} = {}^{V_0^2}\!/_{2P} = R$

RF cavity (acc. convention) :

$$V_{acc} = E_{acc} L_{gap}$$

$$U = \frac{1}{2}\mu_0 \iiint H^2 dV = \frac{1}{2}\epsilon_0 \iiint E^2 dV$$

$$P_{diss} = \frac{1}{2} R_S \iint H_S^2\, dS = \frac{\left(E_{acc} L_{gap}\right)^2}{R_{shunt}}$$

$$Q_0 = {}^{\omega_0 U}\!/_{P_{loss}} = {}^{G}\!/_{R_s}$$

$$R_{shunt} = {}^{V_{acc}^2}\!/_{P_{loss}} = {}^{Q_0 V_{acc}^2}\!/_{\omega_0 U}$$

SRF cavities for particles acceleration

Context: supeconducting material for RF cavities

RF electromagnetic field at frequency *f* applied near a conductor penetrates the material by the skin depth δ, creating electric currents, and leading to dissipations P_{diss}:

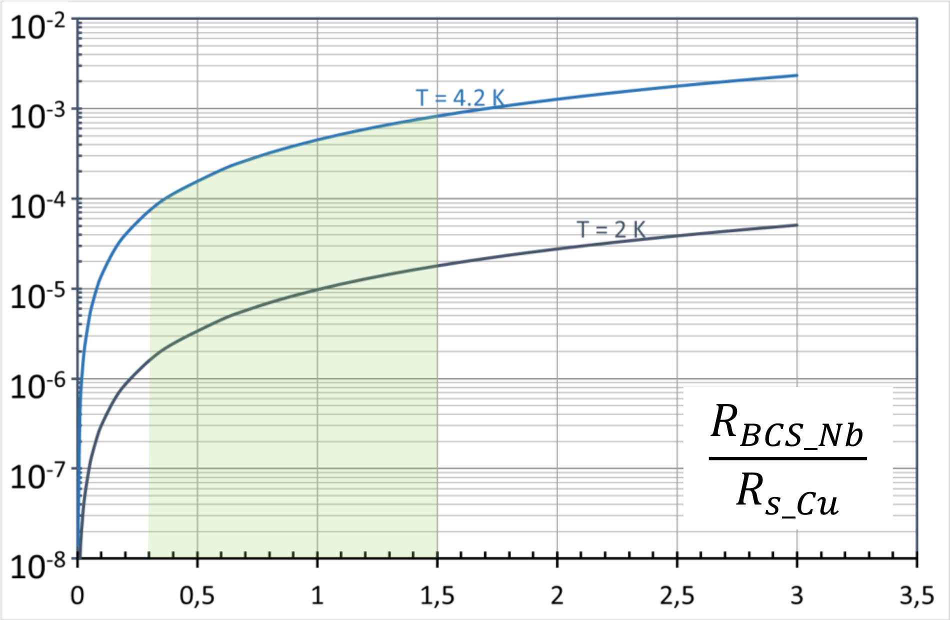
$P_{diss} = 1/2\, R_S\, H_S^2$ where **R_S : surface resistance** of the material
H_S : surface magnetic field

- For a normal conductor: $R_s = {}^{1}/_{\sigma\delta} = \sqrt{{}^{\pi f \mu_0}/_{\sigma}} \propto f^{1/2}$ is about a few mΩ.
  (σ = DC electrical conductivity)

- In a superconductor: $R_S = R_{BCS} + R_0$ with $R_{BCS} = {}^{A\omega^2}/_{T} \cdot e^{-BTc/T} \propto f^2$

$T \rightarrow 0$: $R_S = R_0$ is not strictly zero : RF dissipations occur, but remain quite weak *(a few normal electrons still exist at T>0K, that induce dissipations in RF regime)*

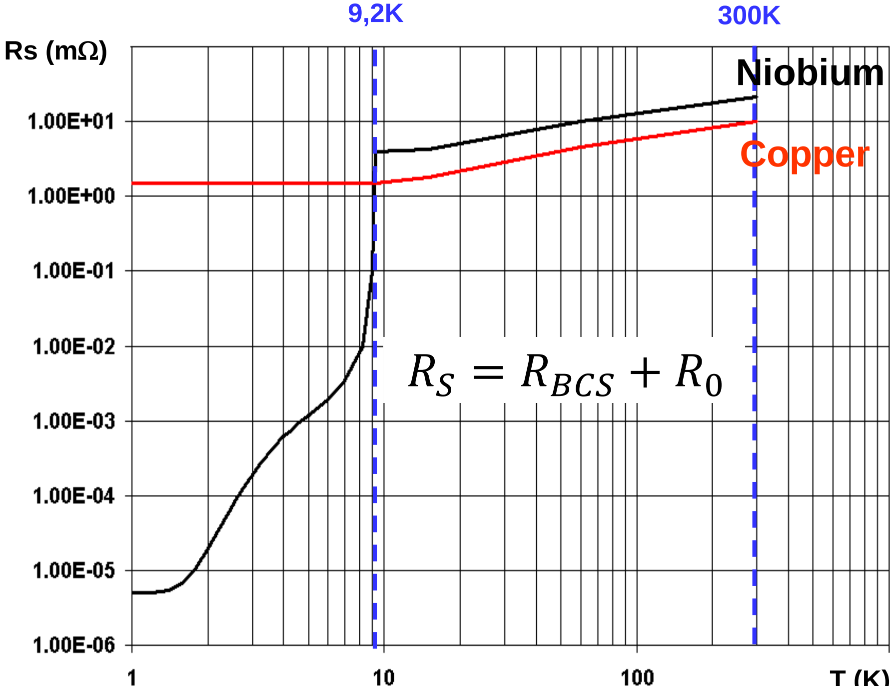
E.g. : in the range 300 MHz < f < 1.5 GHz R_{BCS_Nb} of Niobium is 3 to 6 orders of magnitude smaller than copper R_{s_Cu}
$\Rightarrow$ Great interest of superconductivity to reduce the dissipated power



Context: Niobium for RF cavities

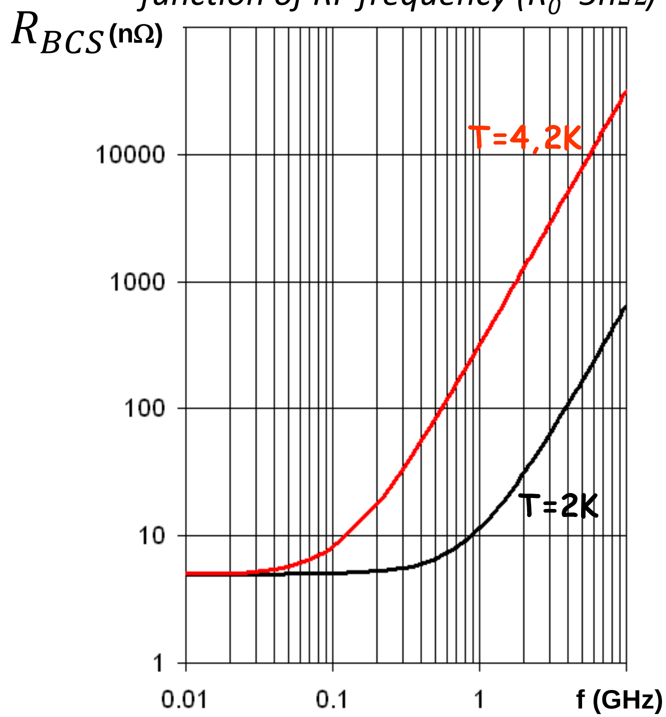
Bulk niobium is (now) the best compromise between:

- High enough critical temperature Tc (9.2 K) & magnetic field Bc_{RF} (200 mT @ 2 K and 190 mT @ 4,2 K)
- Low surface resistance (to minimise RF losses)
- Good thermal & mechanical behaviour (formability, workability and strength at low T°)



Niobium & copper surface resistance as a function of temperature (at f=1,5 GHz)

Surface resistance of niobium as a function of RF frequency (R_0=5nΩ)



RBCS (nΩ)	4.2K	2.2K	2K	1.8K	1.5K
1300 MHz	600	33	15	6.5	1.2
700 MHz	174	9.5	4.3	1.9	0.35
352 MHz	44	2.5	1	0.48	0.09
88 MHz	3	0.15	0.07	0.03	0.006

Normal vs superconducting cavities

- $R_s \sim f^{0.5}$ normal conducting (NC)
- $R_s \sim f^2$ superconducting (SC)

- $Q_o \sim f^{-0.5}$ normal conducting
- $Q_o \sim f^{-2}$ superconducting

Parameters	NC	SC
f (MHz)	700	700
Radius $(R = 2{,}405c/2\pi f)$ (cm)	16,4	16,4
Length L (cm)	15	15
V_{acc} (V)	$0{,}95 \cdot 10^6$	$0{,}95 \cdot 10^6$
$E_{acc} = V_{acc}/L$ (V/m)	$6{,}3 \cdot 10^6$	$6{,}3 \cdot 10^6$
U (J)	1.5	1.5
R_s (Ω)	$\sim 7 \cdot 10^{-3}$	$\sim 10 \cdot 10^{-9}$
P_{loss_cav} (W)	$200 \cdot 10^{-3}$	0.3
Q_0	$3 \cdot 10^4$	$2 \cdot 10^{10}$
R_{shunt} (Ω)	$4 \cdot 10^6$	$3 \cdot 10^{12}$

the coefficient

$$\frac{1}{COP_C} = \frac{\text{Input power}}{\text{Usable power}} = \frac{T_{room}}{T_{cold}} - 1$$

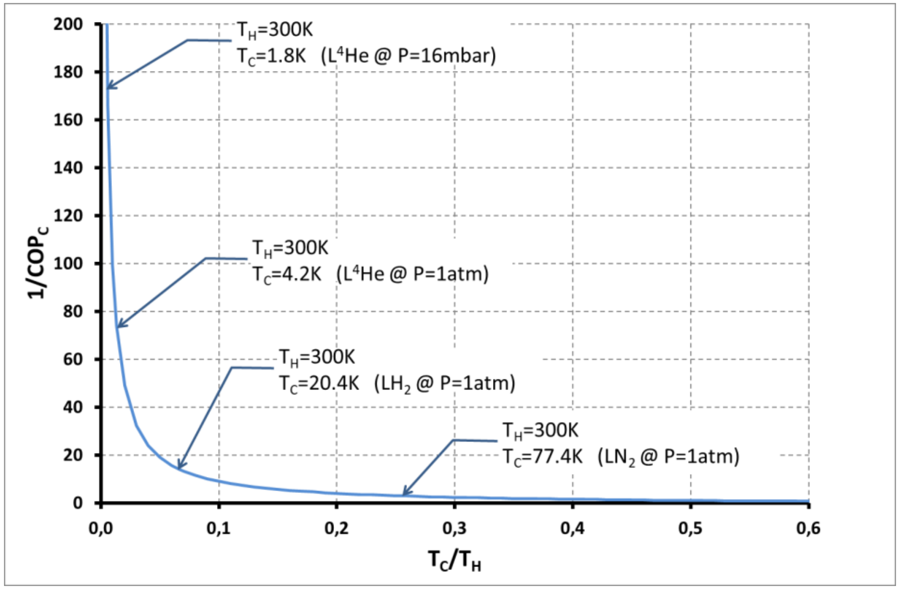
In cryogenics, we prefer to use the inverse of the coefficient of performance to estimate how much power we need to provide

Refrigeration machine

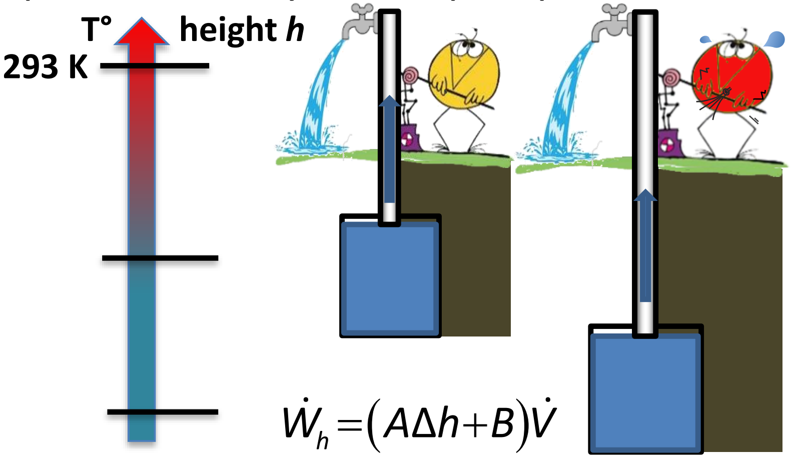
T_{cold}	80 K	4 K
COP_C	36%	1.3%
$1/COP_C$	2.3	75

T_C = 300 K (room)

75 W to provide to ideally extract 1 W at 4 K



Mechanical analogy: required power for a hydraulic pump



$$\dot{W}_h = (A\Delta h + B)\dot{V}$$

A and B are constants

Practically, reversibilities (generation of entropy) lower the efficiency:

$$\frac{1}{COP_C} = \alpha\left(\frac{T_{room}}{T_{cold}} - 1\right)$$

- to remove heat at 4.2 K : α~4 ;
- to remove heat at 2 K : α~5.

Choosing the temperature for operating SRF cavities

Compromise between:

- ✓ a low surface resistance de surface (i.e. low T)
- ✓ a not-too-expensive cryogenic system (i.e. T not too low)

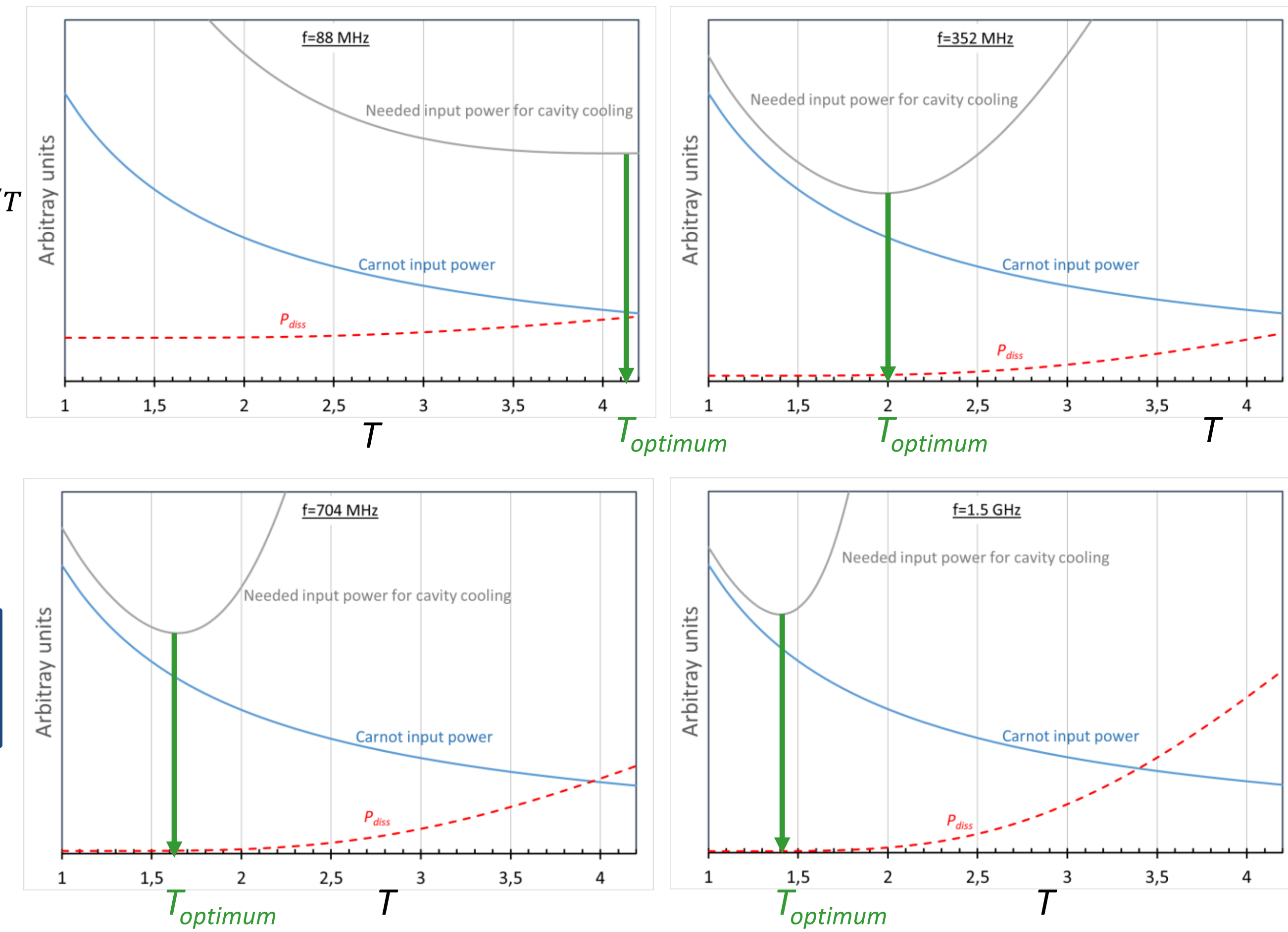
$$P_{diss} = {}^{R_S E_{acc}^2}/_{\omega} \propto f$$

with $R_S = R_{BCS} + R_0$

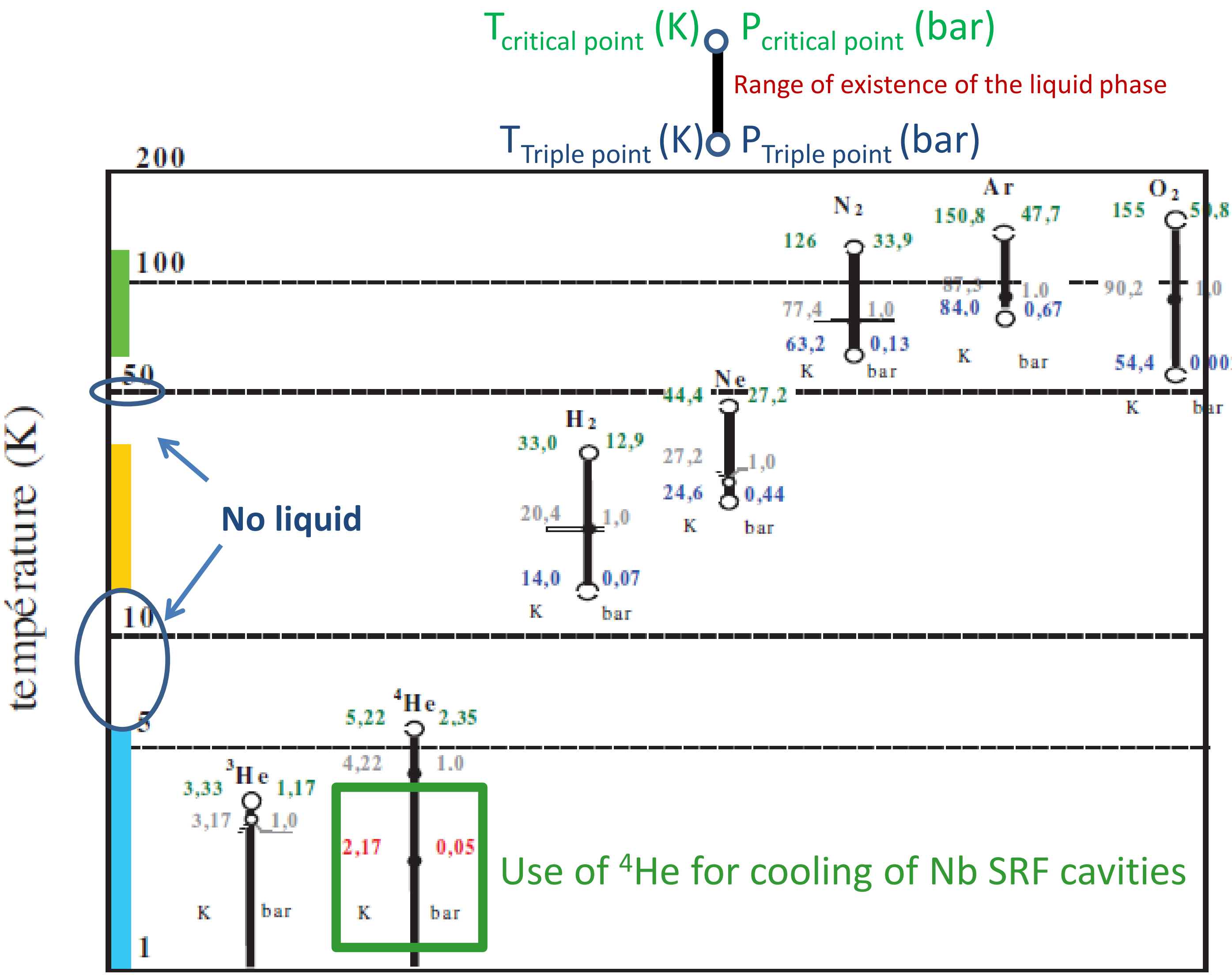
and $R_{BCS} = {}^{A\omega^2}/_{T} \cdot e^{-BTc/T}$

$$P_{input} \propto P_{diss}\left({}^{T_{room}}/_{T} - 1\right)$$

$\Rightarrow$ as f increases, $T_{optimum}$ decreases

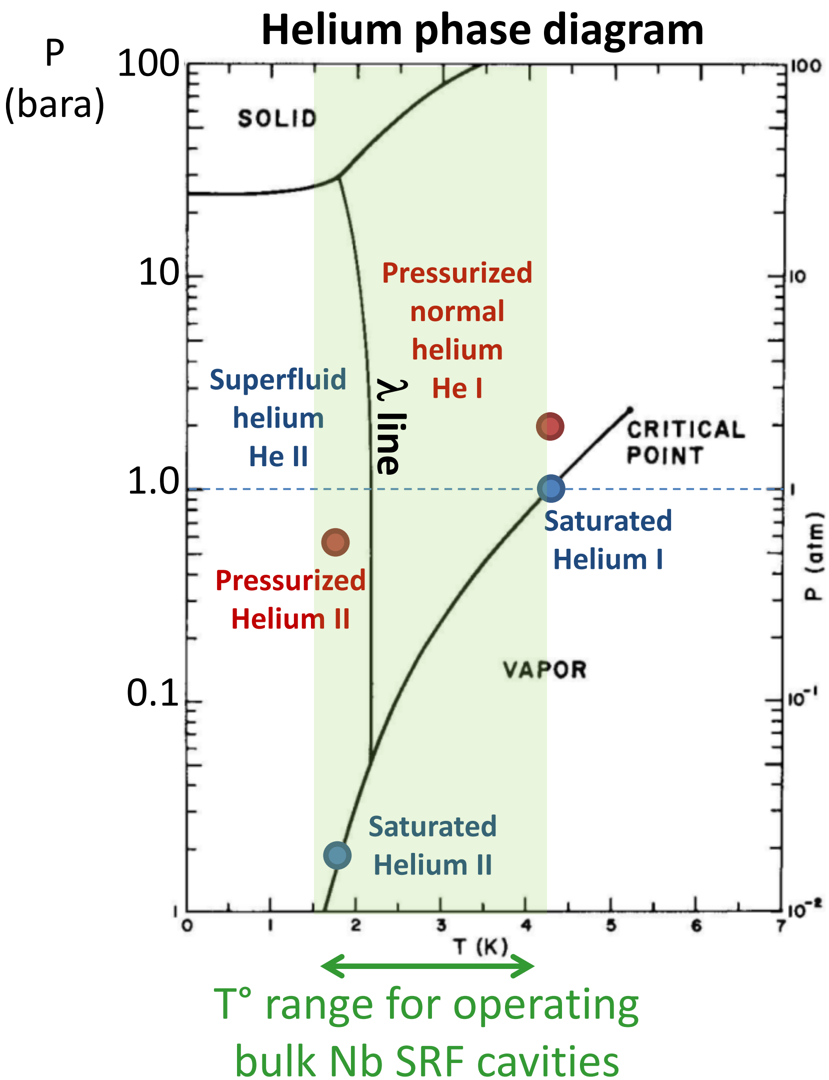


Domain of existence of cryofluids



Element	T_{liq} (K) @1 bar
Oxygen	90.2
Nitrogen	77.4
Neon	27.1
Hydrogen	20.4
Helium	4.2

^4He : a special cryofluid



General trend for cavities:

- if f < 352 MHz → T ~ 4,2 K
- if f ≥ 352 MHz → T ~ 2 K or lower

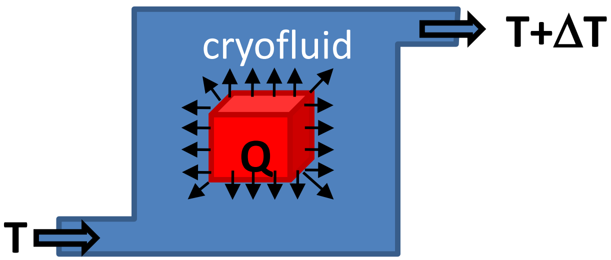
● 1 phase: bivariant → (P,T) to be set

● 2 phases co-existing: monovariant → P (or T) to be set and thus T (or P) related.
- P=1 bara for T = 4,2 K
- P=0,031 bara for T = 2 K

Cooling SRF cavities

❑ By use of sensible heat

Sensible heat: quantity of heat which is exchanged with no phase transition but with a temperature change



ΔT is proportional to Q:

$$Q = m.c_p.\Delta T$$

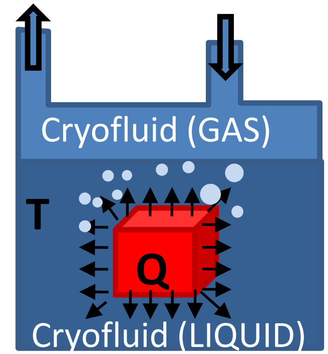
- Q : Heat transfered (J)
- m : mass (kg)
- c_p : specific heat ($J.kg^{-1}.K^{-1}$)
- ΔT : temperature change (K)

- to cool down an objet to low temperature
- a pressurized liquid or gas: sensible heat; T changes

to maintain an object at low temperature (i.e. to remove heat flowing from the room environment)

❑ By use of latent heat

Quantity of heat which is exchanged during a phase change (at constant temperature)



T=constant

$$Q = m.L_v$$

- Q : Heat transfered (J)
- m : mass of fluid transformed (liquid) (kg)
- L_v : latent heat of vaporization ($J.kg^{-1}$)

Use of:

- a saturated liquid: latent heat and fixed T,p
- both: the latent heat of the saturated liquid which vaporizes and then the sensible heat of the cold vapours which warm up.

Cooling SRF cavities

- At 4.2 K : use of a normal helium saturated pool (LHe I)
- Below 4,2 K use of a saturated superfluid helium pool (LHe II)

Why cooling SRF cavities with a saturated helium bath (liquid-vapour equilibrium) instead of pressurized helium?

- The CONS reasons:
  - ✓**Saturated LHe means low thermal margin from boiling (low vaporization heat of helium)**

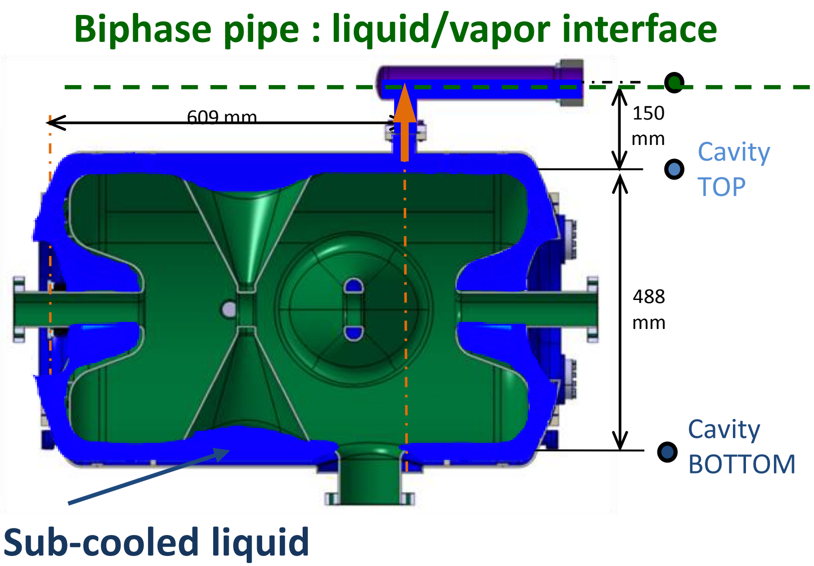
    Boiling i.e. crossing the saturation curve (and possibly the Lambda line) yields to some vapour production in the vinicity of the cavity walls which might dramatically reduce the heat transfer due to the low thermal conduction of helium vapour (and helium I).
    It might also alter the operation of the cavities (pressure variations).
  - ✓**Saturated LHe II bath means operating below the atmospheric pressure**

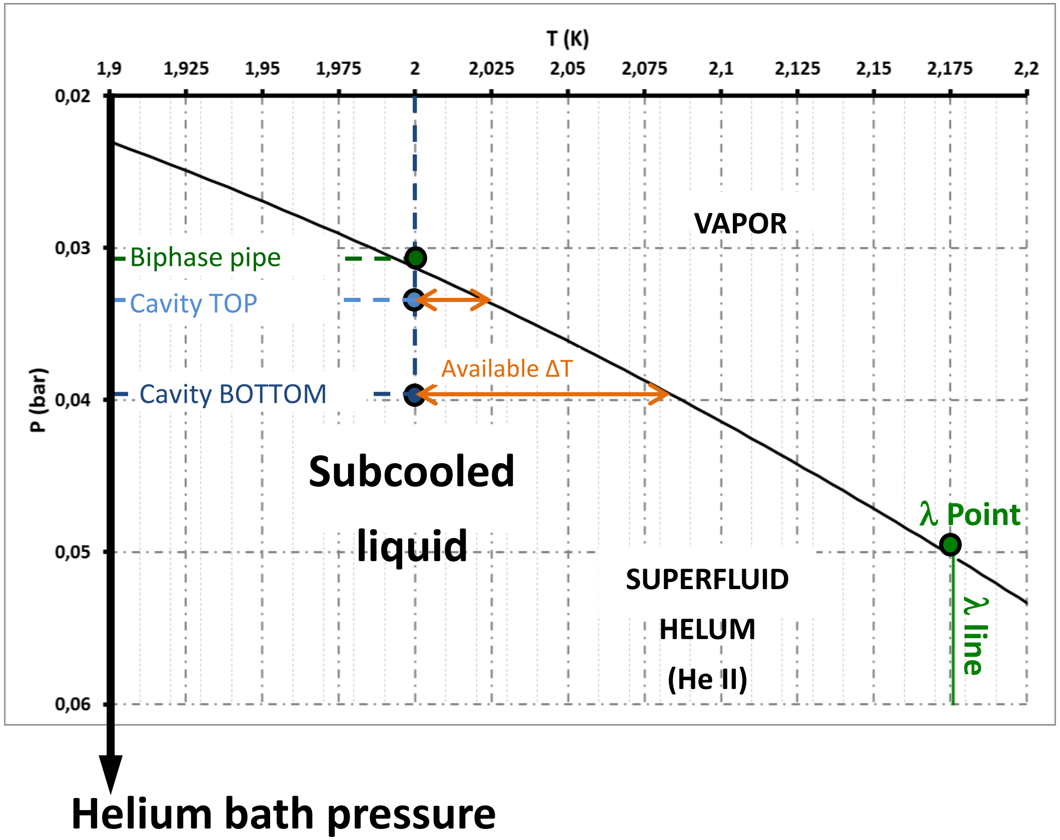
    → risks of contamination or incident (ice blockage) due to air inleaks in the helium process;

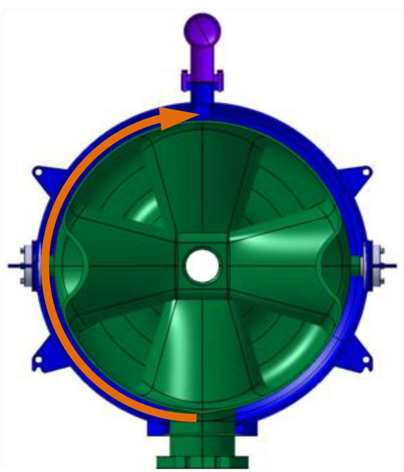
    → increase of the cost for the cryogenic distribution (complexity for large scale cryogenic process);

    (e.g. all non welded interfaces facing the ambiant air are helium guarded; helium gas a room T° surround the interface)

Cooling SRF cavities







Because of (thanks to) the hydrostatic pressure head, SRF cavity is operating in a subcooled (slightly pressurized) liquid which can absorb heat in its bulk without phase change up to the temperature at which the saturation line is crossed.

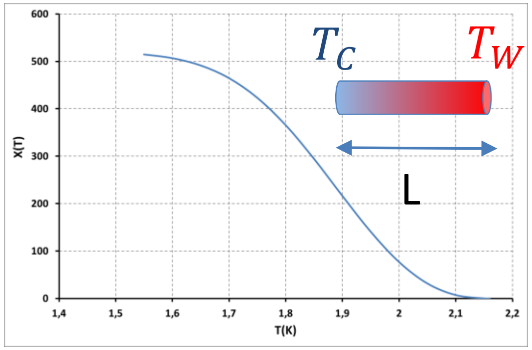
Cooling modes and surface heat flux

- Superfluid helium

Parameters		T = 2 K
Δρg/h	(mbar/m)	14
Clapeyron relation: $dP/dT = \Delta h_{12}/\Delta v_{12}$	(mbar/mK)	0,093
ΔT available for sub-cooling per unit height	(mK/m)	150

Conduction into supefluid helium: superfluid helium

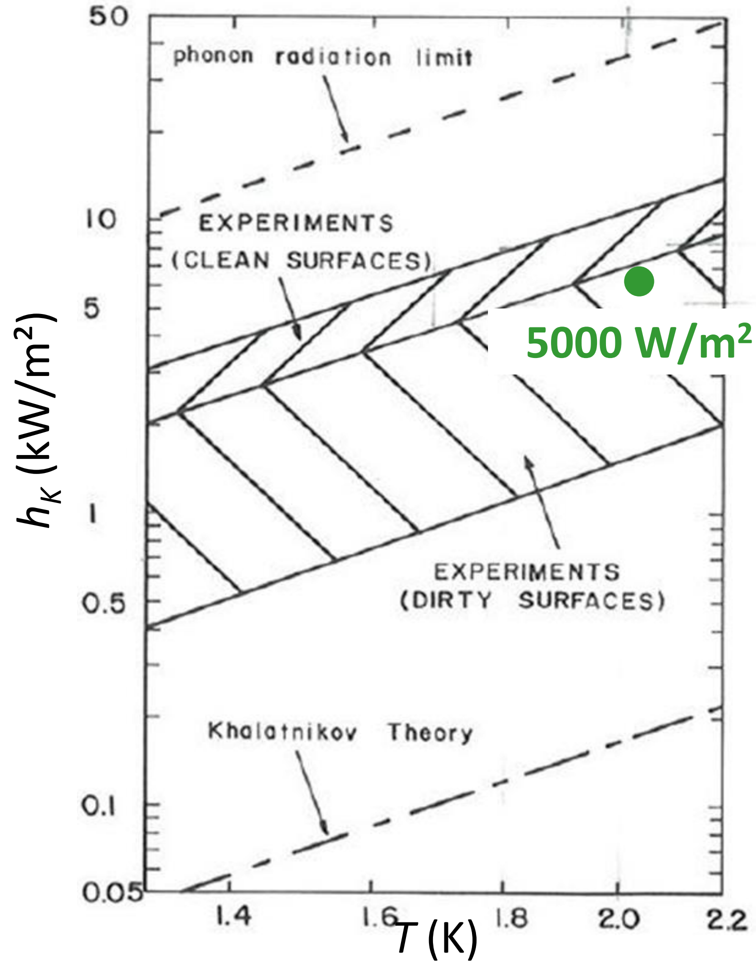
$$\dot{q}^{3.4} L = X(T_C) - X(T_W) \quad \text{(W/cm}^2\text{)}$$



We want to keep $T_W < T_{sat}$

X is analog to a thermal conductivity integral

Nb/LHeII: the Kapitsa resistance

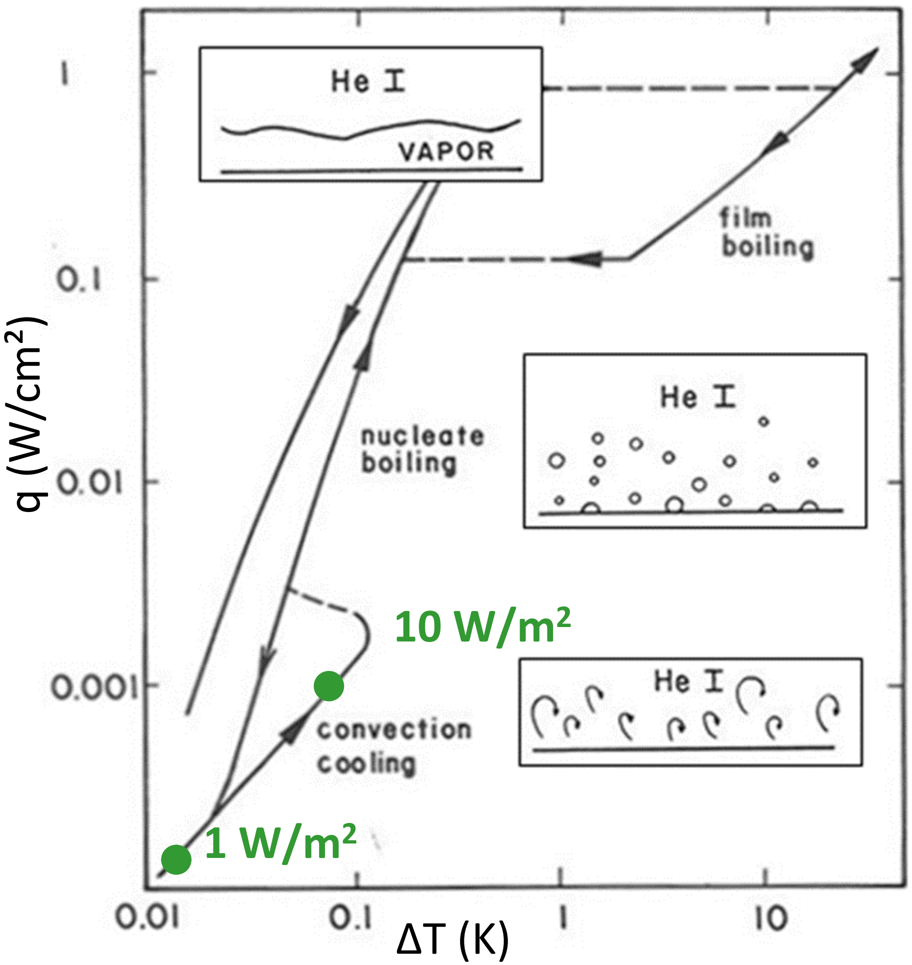


S. W. Van Sciver, "Helium cryogenics", Plenum press, 1986

Cooling SRF cavities

- Normal helium

Convective heat exchange at horizontal wall surface



And "usual" relations for heat transport in fluids (conduction, laminar, turbulent or 2 phases convection)

S. W. Van Sciver, “Helium cryogenics”, Plenum press, 1986

Why cooling SRF cavities with a saturated helium bath (liquid-vapour equilibrium) instead of pressurized helium?

- The PROS reasons

✓**Heat to transfer**

Surface of a SRF cavity is large (of course it depends on the application): of the order of 1 to 2 m^2 in an accelerator.

For a CW accelerator, dissipated power P_{loss} is of the order of some tens of Watts (up to 20 W @2 K) (in nominal operation !).

Stored energy in a cavity is small (some Joules). There is no need for large energy release when a quench occurs.

Large heat transfer in a saturated LHe bath (usefull for local "hot pots").

✓**Cavity is (very) sensitive to mechanical pertubations:**

Mech. perturbations, such as mechanical vibrations (pumps, valves, flows, etc) deform the SRF cavity inducing a detuning (the cavity is shifted from its resonant frequency). They are equipped with cold tuning systems but a gain in reliability for accelerators operation is to use them as less as possible (!).

T° of saturated LHe is set by its pressure (monovariant system) and the pressure stability. In a pumped LHeII pool, pressure variations are much less than 1 mbar.

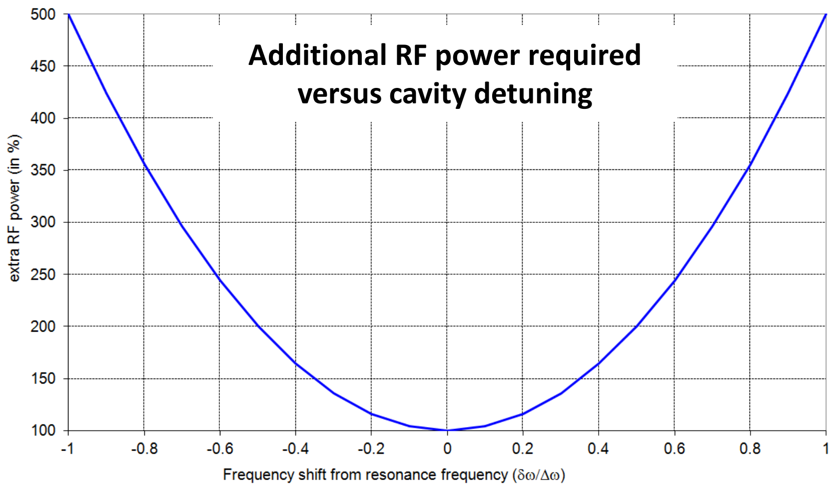
Cryogenics for SRF cavities

Frequency shift

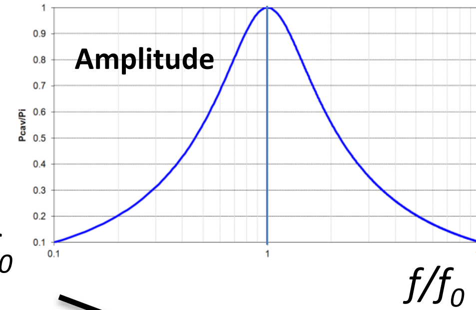
❑ The frequency of RF cavities has to be exactly synchronized to the beam frequency (bunched beam).

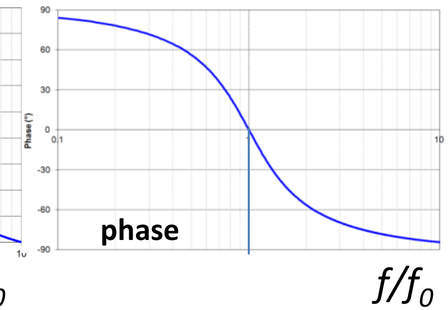
❑ RF power is generated at fixed frequency <u>but</u> cavity is a resonator with a resonance frequency f_0 which might be subjected to perturbations.

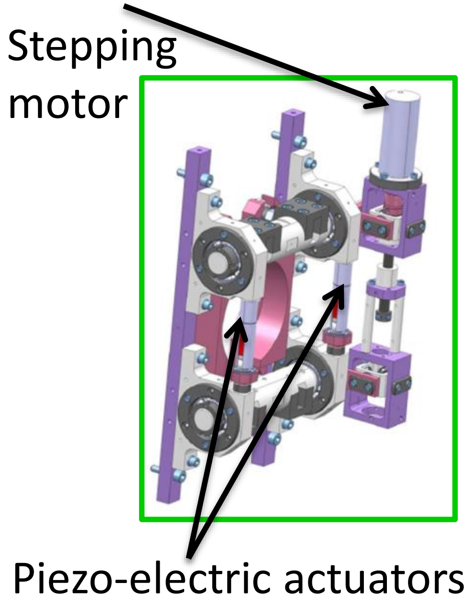
$\Rightarrow f_0$ has to be tuned permanently to match RF frequency

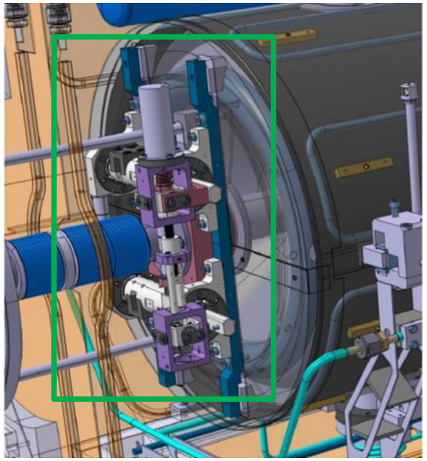


<u>Effect of detuning :</u>









For ESS double Spoke cavity (f_0 = 352 MHz)				
	Stepping motor	Coarse range	~ 150 kHz @ 2 K (limited by max. stress)	Slow dynamics
	Piezos	Fine range	< 150 Hz	Fas dynamics

Frequency shift

- RF regulation loop to compensate several type of frequency perturbations :
  - Static or very slow perturbations : manufacturing tolerances or defects, thermal shrinkage, pressure forces, Lorentz forces (CW), …

    $\Rightarrow$ Compensated by frequency tuning system (motor)
  - Dynamic perturbations: mechanical resonances (microphonics), Lorentz forces (pulsed operation), …

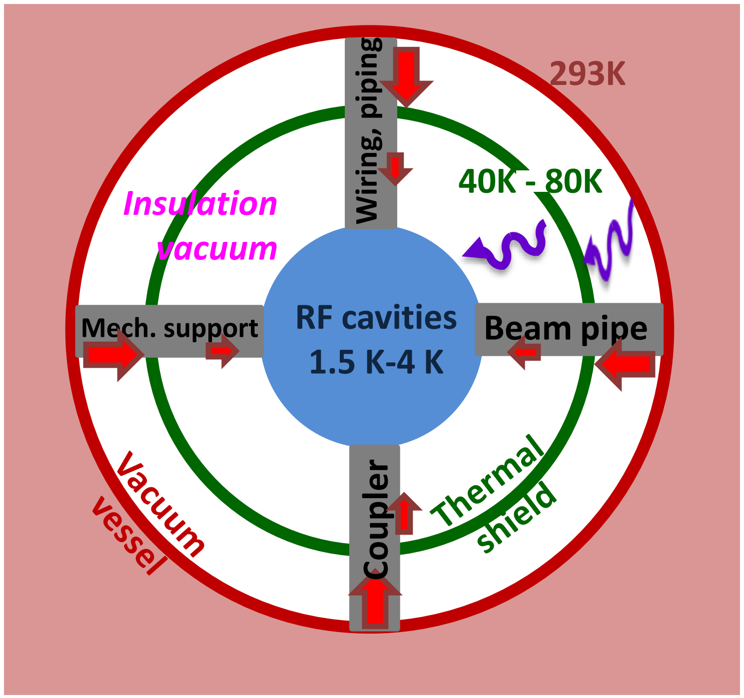
    $\Rightarrow$ Compensated by frequency tuning system (piezo) and RF regulation loop (LLRF)

Vibration sources	area	Frequency range
Primary pumping system	Close to cryostat	50 Hz
Turbo pump	Close to cryostat	kHz
Valves / motors	Cryostat	pulse
Helium boiling	Cavity	Depends on dissipations
Lorentz forces (pulsed)	cavity	RF pulse
Human activity	Environment	Tens of Hz

Providing a cryogenic environment: the cryomodule

Conduction heat transfer

Radiation heat transfer



RF feeding: the power coupler
Cryogenic feeding: piping

<u>Limit heat losses by reducing :</u>

- Conduction: ↑ thermal resistivity (material), ↓ surface area, ↑ length , heat intercept at intermediate T°
- Convection: under vacuum
- Radiation: shielding at intermediate T°, multi-layer insulation

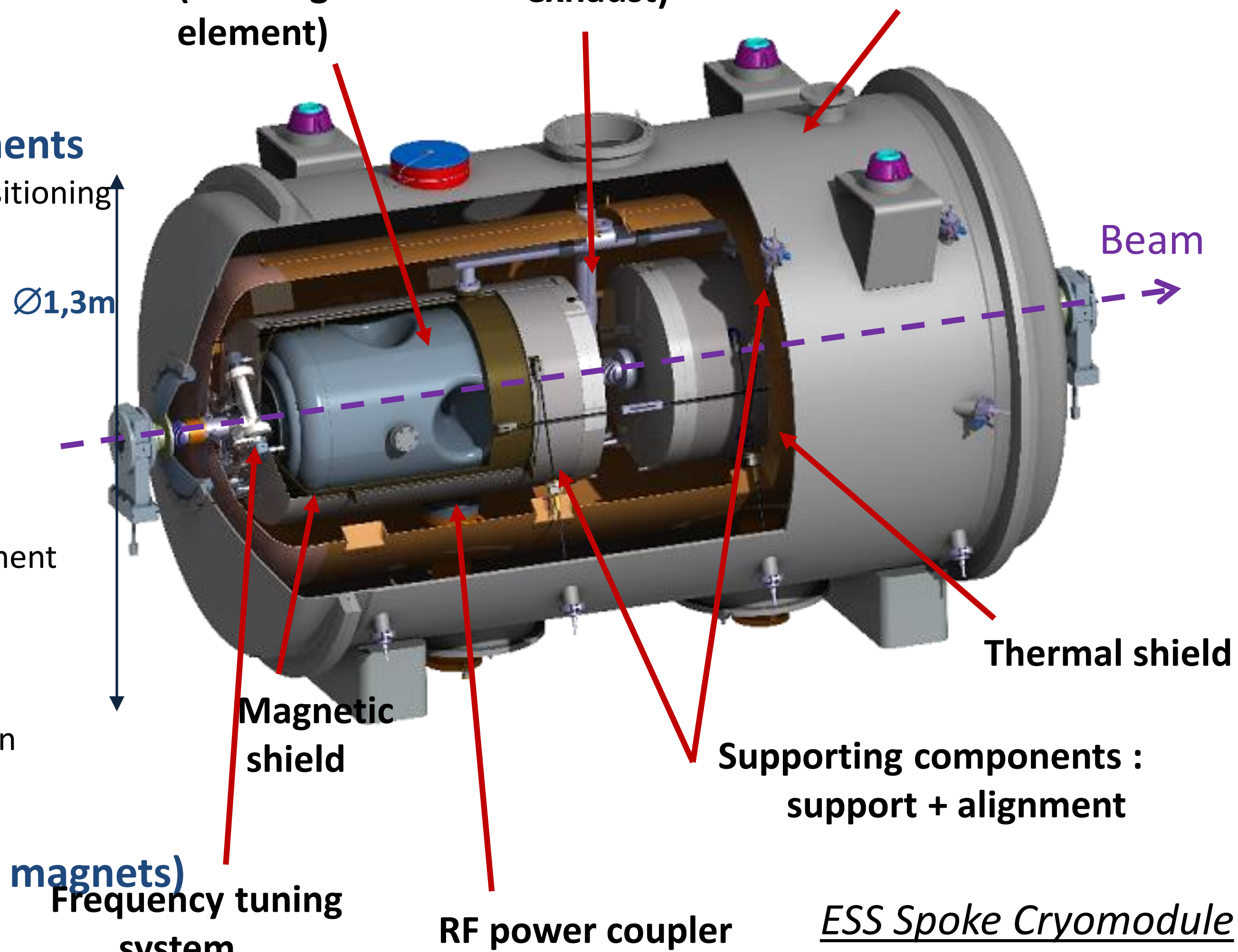
⇒ <u>Do not disturb cavity operation :</u>

- Thermal stability: constant and homogeneous temperature of cavity even with power losses.
- Interfaces : RF/cryo feeding, instrumentation.
- Mechanical stability : keep alignment although thermal contractions, pressure forces, low mechanical vibration transmission.

Cryomodule: the main components

MAIN COMPONENTS

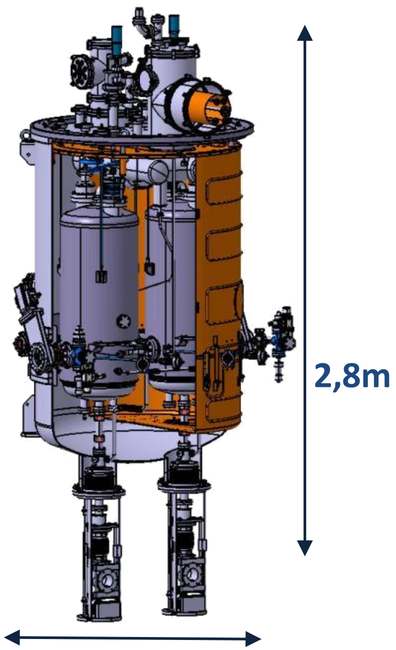
- **Vacuum vessel**
  - Thermal Insulation
  - Interface
- **Supporting components**
  - Supporting and positioning
- **Thermal shields**
  - Thermal Insulation
- **Cryogenic piping**
  - Cryogenic environment
- **Magnetic shield**
  - Magnetic protection
- **Cold mass (cavities, magnets)**



ESS Spoke Cryomodule

Cryomodules: some examples

Low energy cryomodules (small RF *f*)

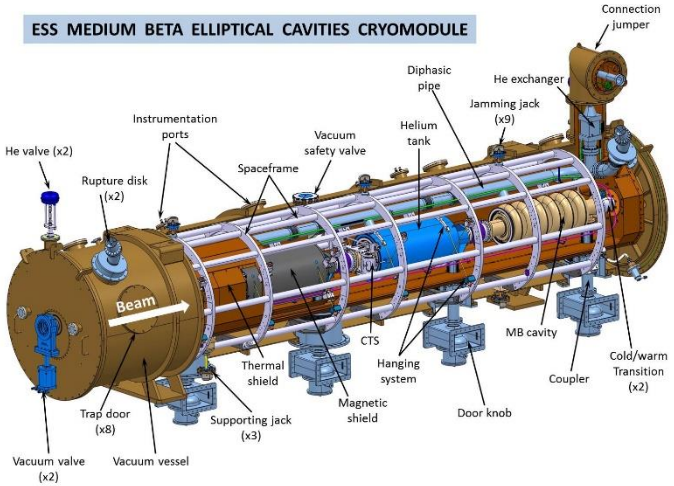


SPIRAL2 cryomodule B (Ganil)

ISAC2 cryomodule @ TRIUMF

High energy cryomodules (large RF *f*)

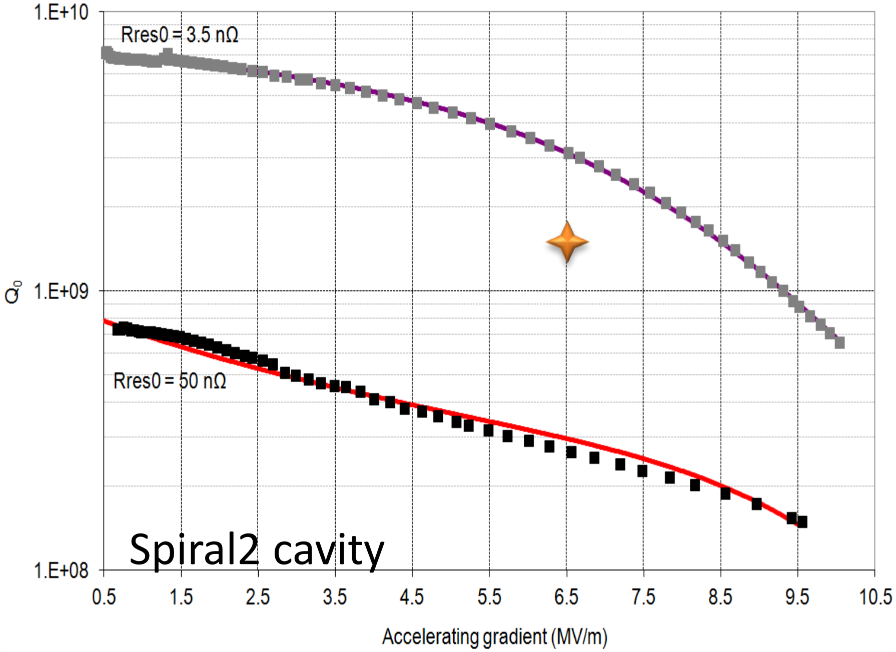
XFEL



Cryogenics for SRF cavities

SRF cavity cool-down: the Q-disease or 100 K effect

- ✓ When a cavity is cooled down or warmed up too slowly, the quality factor (i.e power dissipation) could drop by one order of magnitude.
- ✓ The hydrogen trapped in Niobium precipitates in an ordered phase (β), which shows no superconducting properties ⇒ surface resistance is degraded
- ✓ Hydrogen sources = surface treatment (chemical etching), residual gas in atmosphere.
- ✓ If fast cool down, no time to precipitate (i.e. < 1 h between 150 K-50 K) ⇒ impact on cryogenics
- ✓ Solution to avoid Q-disease : high temperature degassing at 600°C during 6h.



SRF cavity cool-down

✓**Cavity = inner wall of a helium tank**

⇒ **Pressure Equipment Directive 2014 (2014/68/UE) ; EN13458 ; ASME (USA)**

Niobium used for cavity manufacturing is very costly (bulk Nb with very large RRR>250)

Taking into account manufacturing (spining, deep drawing and welding) and preparation (field flatness, heat treatment)

→ Need to reduce the walls thicknesses

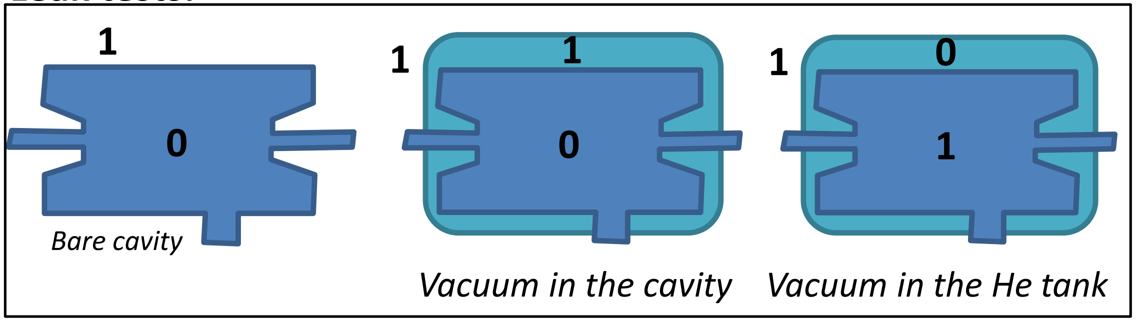
→ One hence might think this is a good reason for operating SRF cavities in a low pressure helium bath

→ But at cool-down helium is pressurized (some hundreds of mbar above the atmospheric pressure)

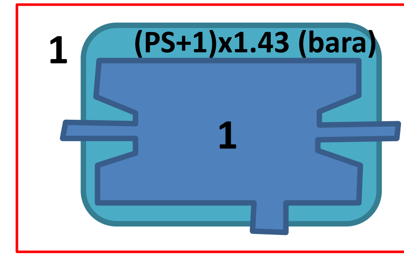
SRF cavity cool-down

Manufacturing acceptance tests

Leak tests:

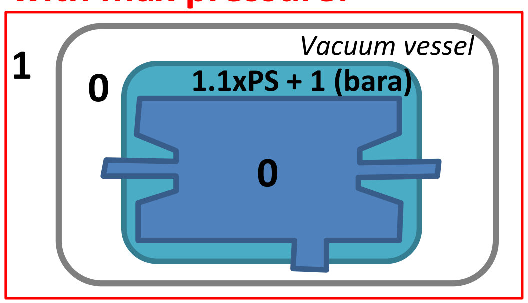


Pressure test:

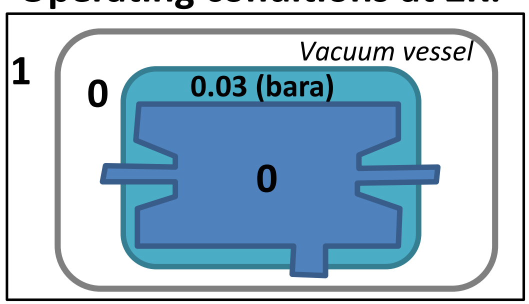


Cryogenic operations:

Cool down from RT to 2K with max pressure:



Operating conditions at 2K:



The most stringent operations for a cavity occurs at (near the) room T°
→ max. stress which might permanently deforms (and detune) the cavity
- pressure test
- start of cooling-down

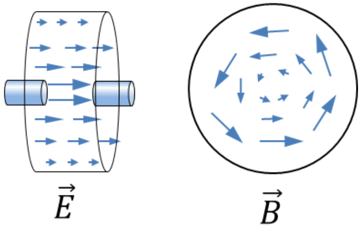
Niobium mechanical properties:

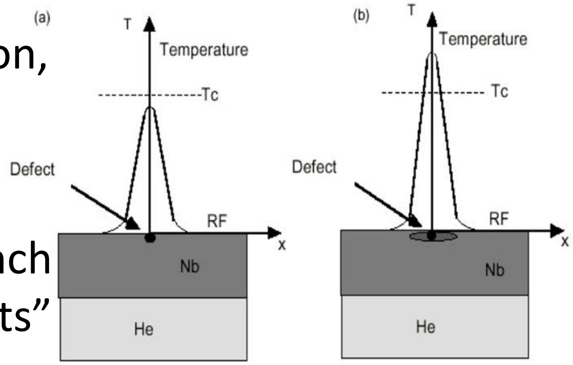
T (K)	Young modulus (Gpa)	Yield Strength (Mpa)	Ultimate Strength (Mpa)	Allowable stress (Mpa)
295	105	60-70	150	40
2	108	300	600	170

Cavity quench

- ❑ For cavities, superconducting properties are lost because of :
  - ⇒ a too high magnetic field (for, Nb critical magnetic field around 200 mT)
  - ⇒ a too high temperature

❑Quench can happen at lower magnetic field or temperature than theoritical one because of
  - ⇒ Surface defect : local enhancement of magnetic field
  - ⇒ Surface pollution : local heating (field emission, resistive defect, vortices…)



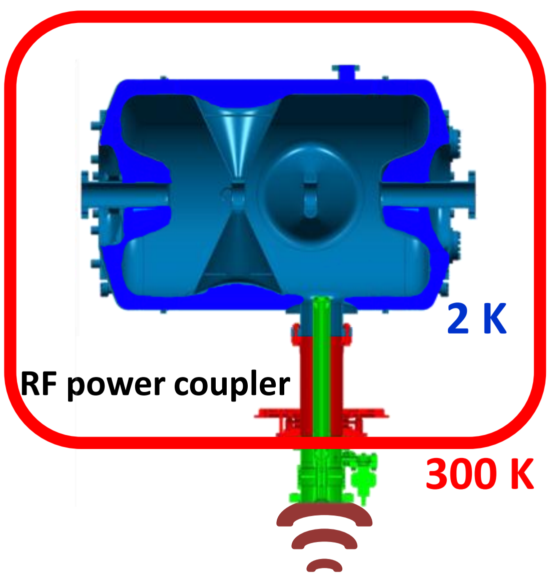


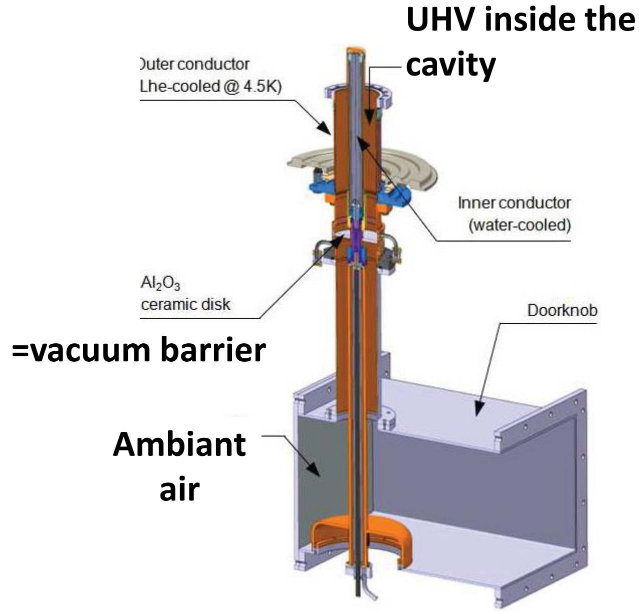
Thermal quench induced by "hot spots"

❑Cavities can be "trained" to push away the quench if possible
  - ⇒ when a quench occur, cavity is detuned and les RF power feed the cavity
  - ⇒ possible to recover from a quench (even lowering the RF magnitude)
  - ⇒ For cavities not so dangerous as no energy is stored but careful in case of high current beams

Security: the worst scenario for the cryogenics of SRF cavities

Breaking the RF power coupler window

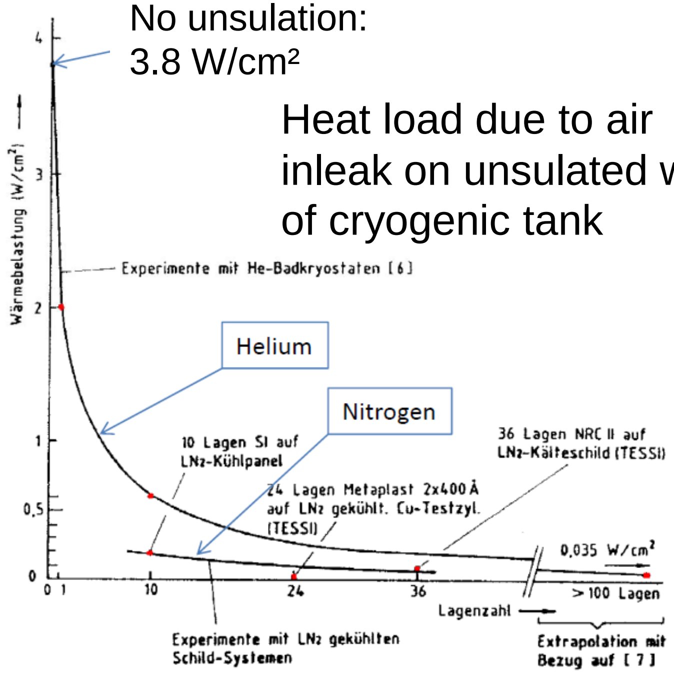




The ceramic window of a RF power coupler is a vacuum barrier separating the ambient air and the ultra high vacuum of the cavity.
If this windows breaks (due to overheating induced by RF for example), ambient air will flow into the cold cavity and start to condensate onto the inner wall of the cavity (inner wall is facing RF and beam vacuum and is hence not thermally insulated).
The heat extracted during this condensation is transferred to the cavity and to the helium bath…

Security: the worst scenario for the cryogenics of SRF cavities

Breaking the RF power coupler window



W. Lehmann, *Sicherheitstechnische Aspekte bei Auslegung und Betrieb von LHe-badgekuhlten Supraleiter-Magnetkryostaten*, KIT

Without unsulation:

Orifice diameter (mm)	Q (kW/m²)
25	9
35	18
50	36

For larger ∅ the air mass-flow rate (above 0.5 kg/s) overcomes the cryopumping rate. Larger mass-flow will not contribute to an increase of the heat load.

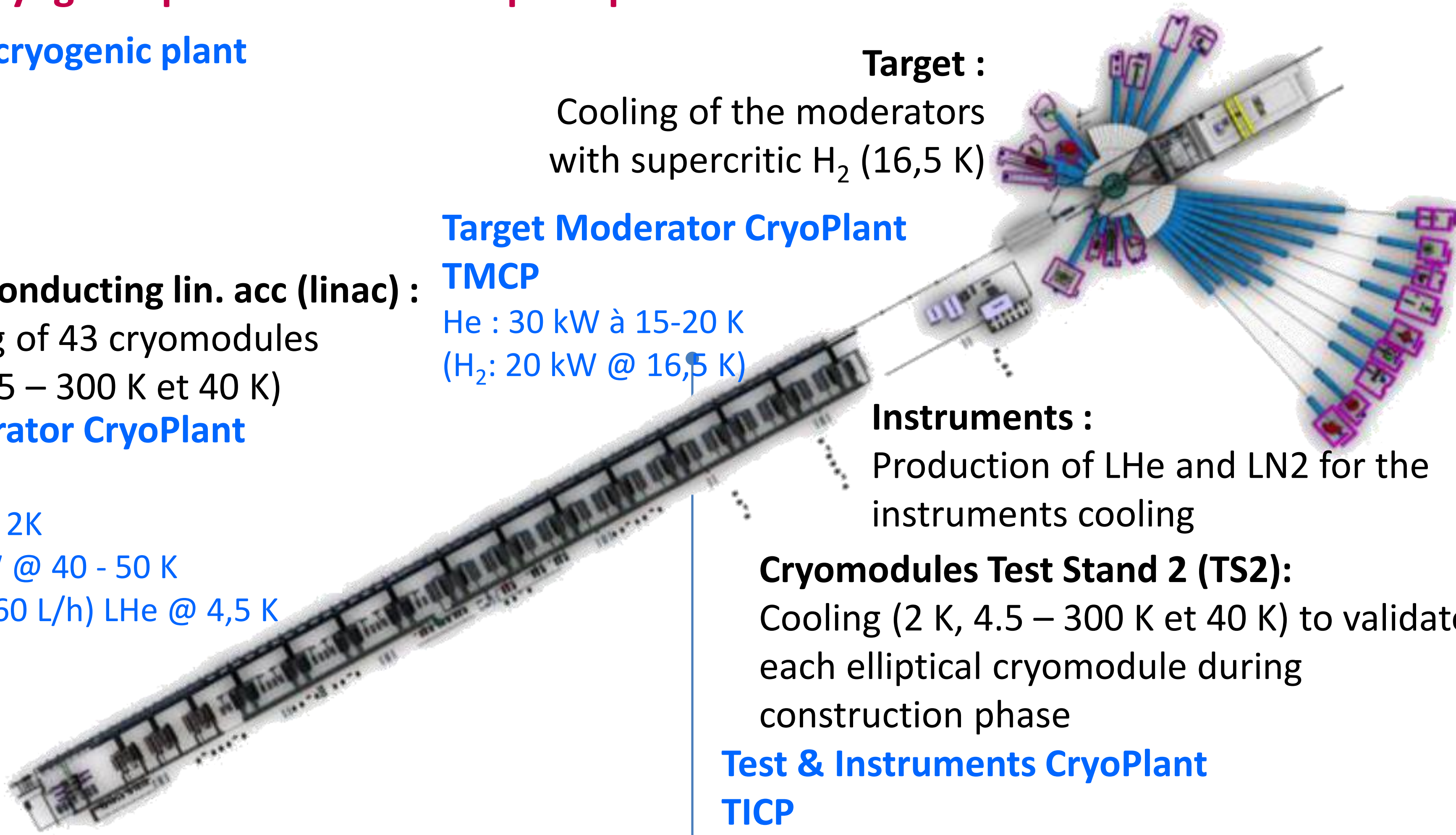
C. Parente, Sizing and selection of pressure relief systems for cryogenic quipment, CERN, 2013

Example: for 1 ESS (European Spallation Source) cavity (Spoke or elliptical), S~2 m²
→ at ~2 bara (opening of a burst disk), $\dot{m}$ = 4 kg/s
→ the safety device is a large burst disk (DN100). NB: VL_{He} ~ 50 L per cavity

Cryogenics for linac

Cryogenic plants for the Europan Spallation Source

⇒ **3 cryogenic plant**



Target :
Cooling of the moderators
with supercritic H_2 (16,5 K)

Target Moderator CryoPlant
TMCP
He : 30 kW à 15-20 K
(H_2: 20 kW @ 16,5 K)

Superconducting lin. acc (linac) :
Cooling of 43 cryomodules
(2 K, 4.5 – 300 K et 40 K)

Accelerator CryoPlant
ACCP
3 kW @ 2K
11,3 kW @ 40 - 50 K
9 g/s (260 L/h) LHe @ 4,5 K

Instruments :
Production of LHe and LN2 for the instruments cooling

Cryomodules Test Stand 2 (TS2):
Cooling (2 K, 4.5 – 300 K et 40 K) to validate each elliptical cryomodule during construction phase

Test & Instruments CryoPlant
TICP
LHe @ 4,5 K : 130 L/h → TS2
7500 L/month
390W @ 33 – 53 K

Recovery, storage, purifying…

CONCLUSION

✓SRF cavities are fine resonators with large quality factor

– now made of bulk niobium in accelerators

» Larger accelerating field and lower losses (impact on cryo)

– usually operated in a saturated helium bath (LHe I or LHeII)

» Optimal operating T° is driven by the operating frequency of the cavities

» For the extraction of heat from the cavity, heat transfer is driven by the cryofluids state

» For the thermal unsulation of the cavity from the ambiant environment heat transfer is reduced by limiting radiation, convection and conduction.

✓SRF cavities are a part of a helium tank

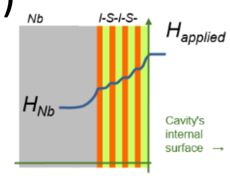
– framework: applicable standards for design and construction

– applicable standards for safety devices (adapted to cryogenics – see presentation by E. Ercolani in Friday)

✓R&D for (and using) SRF cavities in labs:

– new materials (e.g. thin layer deposition on Niobium or multilayer (SIS))

– other means of cooling: cooling pipes (no bath), cryogenerators



Thank you for your attention

I especially thanks:

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P. Duchesne

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EASITrain