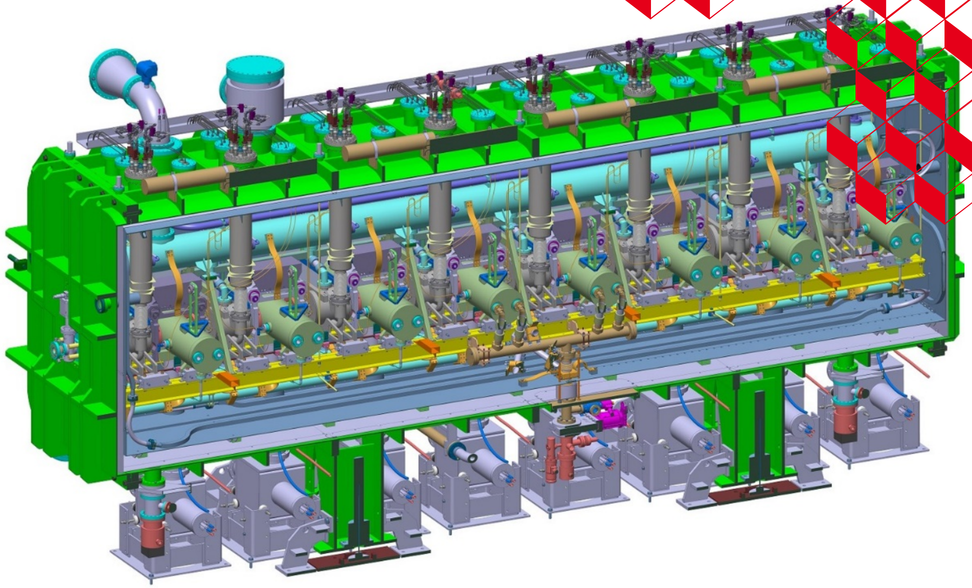
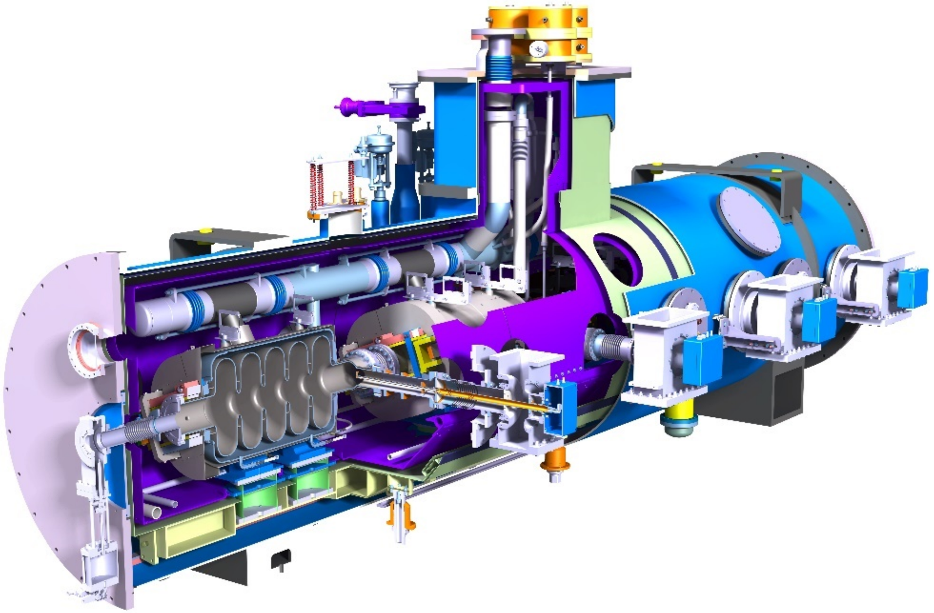
Cryomodule Design

Nicolas BAZIN

Tutorials of the 21st International Conference on Radio Frequency Superconductivity (SRF 2023), June 24th 2023





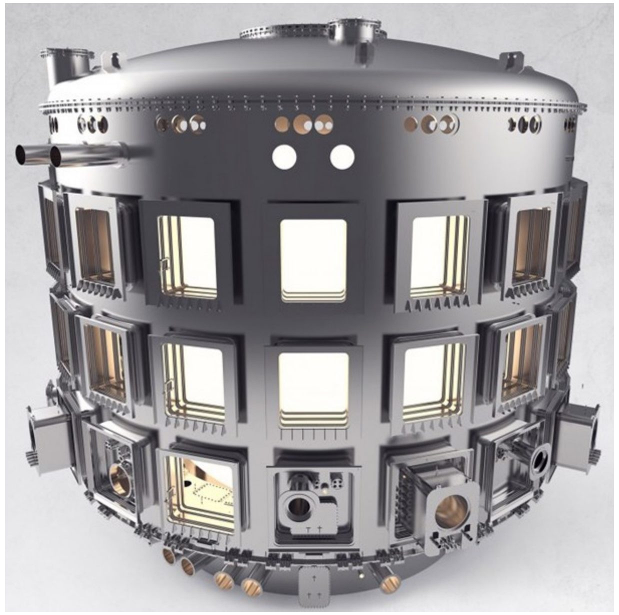
Outline

- The goal of this tutorial is to describe some of the options available to the cryomodule designer, focusing on things that guide the design process and ultimately lead to a design choice.
- This is an introduction to cryomodule design. It is not possible to cover all the details in 90-minute lecture.
- Topics discussed in the tutorial:
  - Heat transfers – heat loads
  - Thermo-mechanical design: cold mass supporting system, thermal shield, vacuum vessel
  - Magnetic shieling – magnetic hygiene
  - Safety: pressure vessel
- Topics not discussed: cryogenics and piping, alignment, instrumentation, manufacturing, assembly, quality assurance & quality control, transportation …

1. Introduction

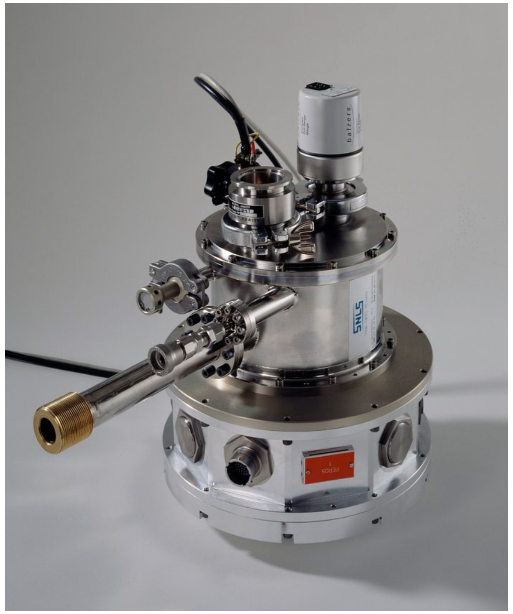
Cryostat - Cryomodule

- **Cryostat**
  - From *cryo* meaning cold and *stat* meaning stable.
  - Device used to maintain low cryogenic temperatures of samples or devices mounted within the cryostat



ITER Cryostat

Cryostat (in red) for ultra-stable cryogenic clock developed by FEMTO-ST

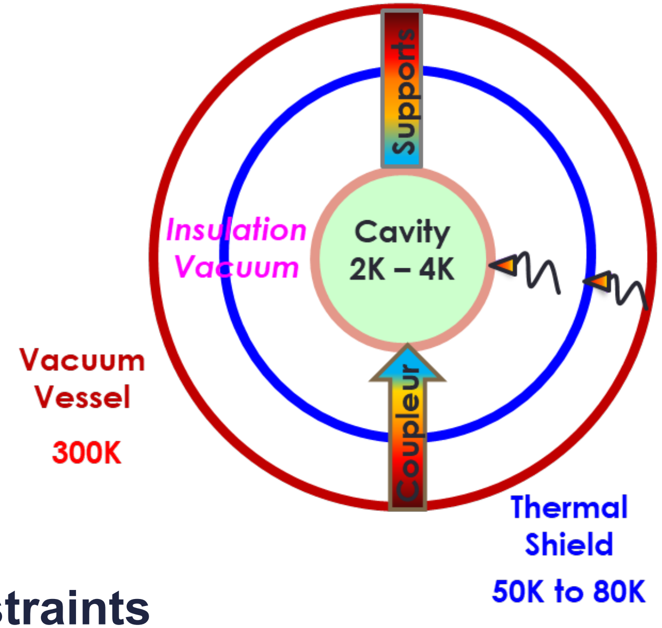


Cryostat for the camera of the European Southern Observatory

Cryostat - Cryomodule

- **Cryomodule**
  - Cryostat that houses one or several superconducting RF (SRF) acceleration cavities
  - May also house one of several superconducting magnets to focus the beam
  - Section of a particle accelerator

- **Funtions of a cryomodule**
  - Cool down and keeping the superconducting cavities at their operating temperature (2K or 4K) while limiting the heat loads as low as possible (thermal efficiency)
  - Mechanical housing of the superconducting cavities with respect to the alignment requirements given by the beam dynamics

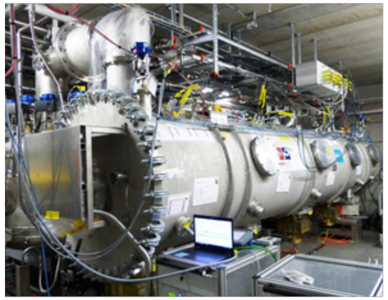
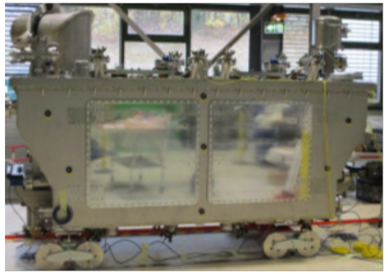


Mechanical and thermal functions often conflicting

➡ **The design of a cryomodule is a trade-off between several constraints**

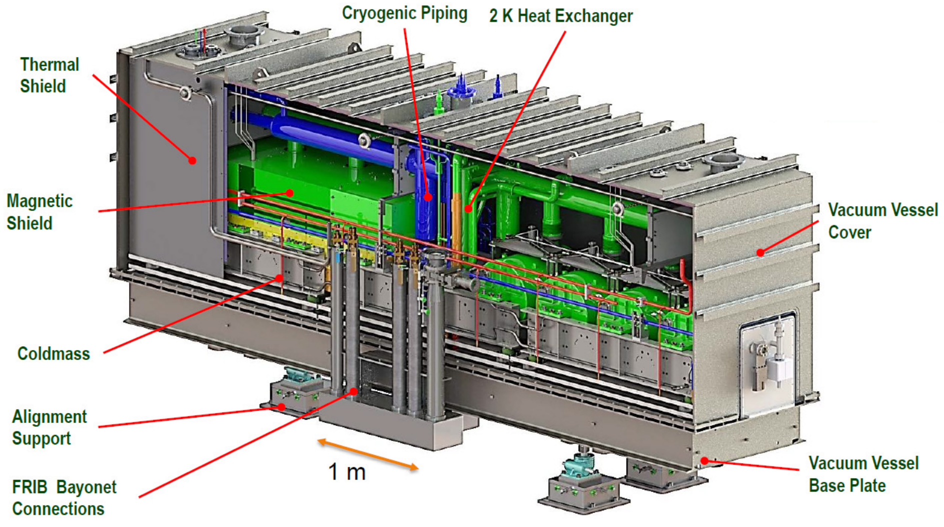
A Wide Range of Cryomodules

- **Type of cavity**
  - Elliptical: ESS, XFEL, LCLS-II, ARIEL, SNS, PIP-II …
  - Half-Wave Resonator (HWR): FRIB, IFMIF, SARAF, ISAC, ATLAS …
  - Quarter-Wave Resonator: Spiral 2, FRIB, HIE Isolde, SRILAC …
  - Spoke: ESS, PIP-II …
  - Crab: CERN …
- **Operating mode**
  - Pulsed: ESS, XFEL, SNS …
  - Continuous wave (CW): IFMIF, SARAF, LCLS-II, SRILAC …
- **Operating temperature**
  - Helium bath around atmospheric pressure ($T_{op} \approx 4\ K$): IFMIF, SARAF, SRILAC
  - Superfluid helium ($T_{op} \approx 2\ K$): XFEL, PIP-II, LCLS-II, FRIB …
- **Support of the cold mass**: posts, baseplate, tie rods, spaceframe, strongback …
- **Insertion mode** of the cold mass inside the vacuum vessel:
  - Top loading: SARAF, HIE Isolde, ARIEL, ATLAS …
  - Side loading: IFMIF, XFEL, PIP-II, ESS …
  - Bottom loading: FRIB
  - “Clam Shell”: SRILAC, Spiral 2

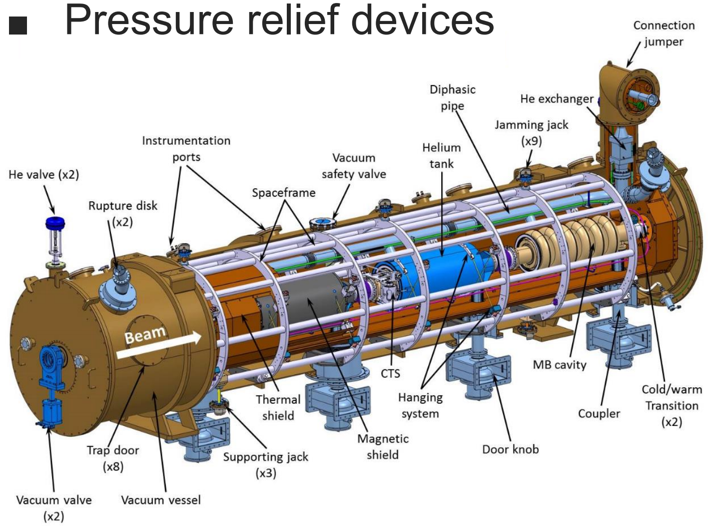




A Wide Range of Cryomodules

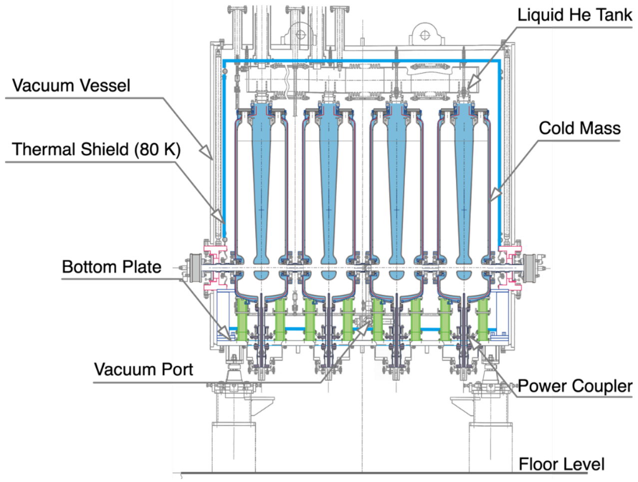
- In spite of this variety, all the cryomodules contain many common features:
  - Vacuum vessel
  - Thermal shielding (one or two shields)
  - Magnetic shielding (one or two layers)
  - Cold mass supporting system
  - Cryogenic piping
  - Beam vacuum gate valves
  - Instrumentation and cables
  - Pressure relief devices



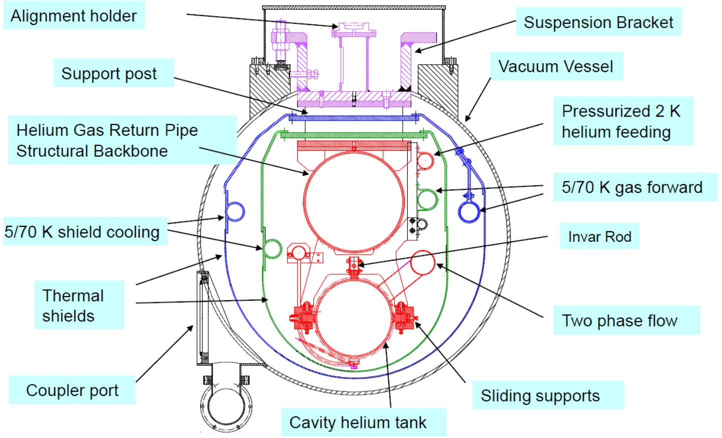
FRIB cryomodule



ESS cryomodule



SRILAC cryomodule



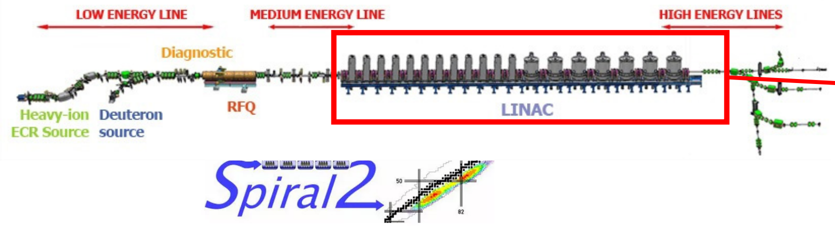
XFEL cryomodule

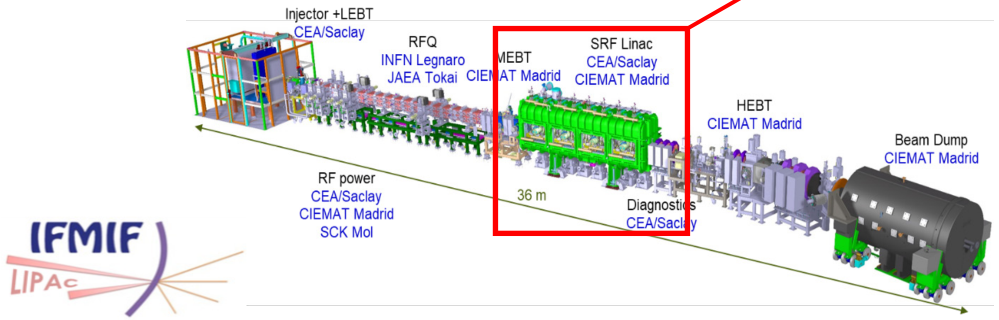
What is the optimal temperature of a superconducting linac?

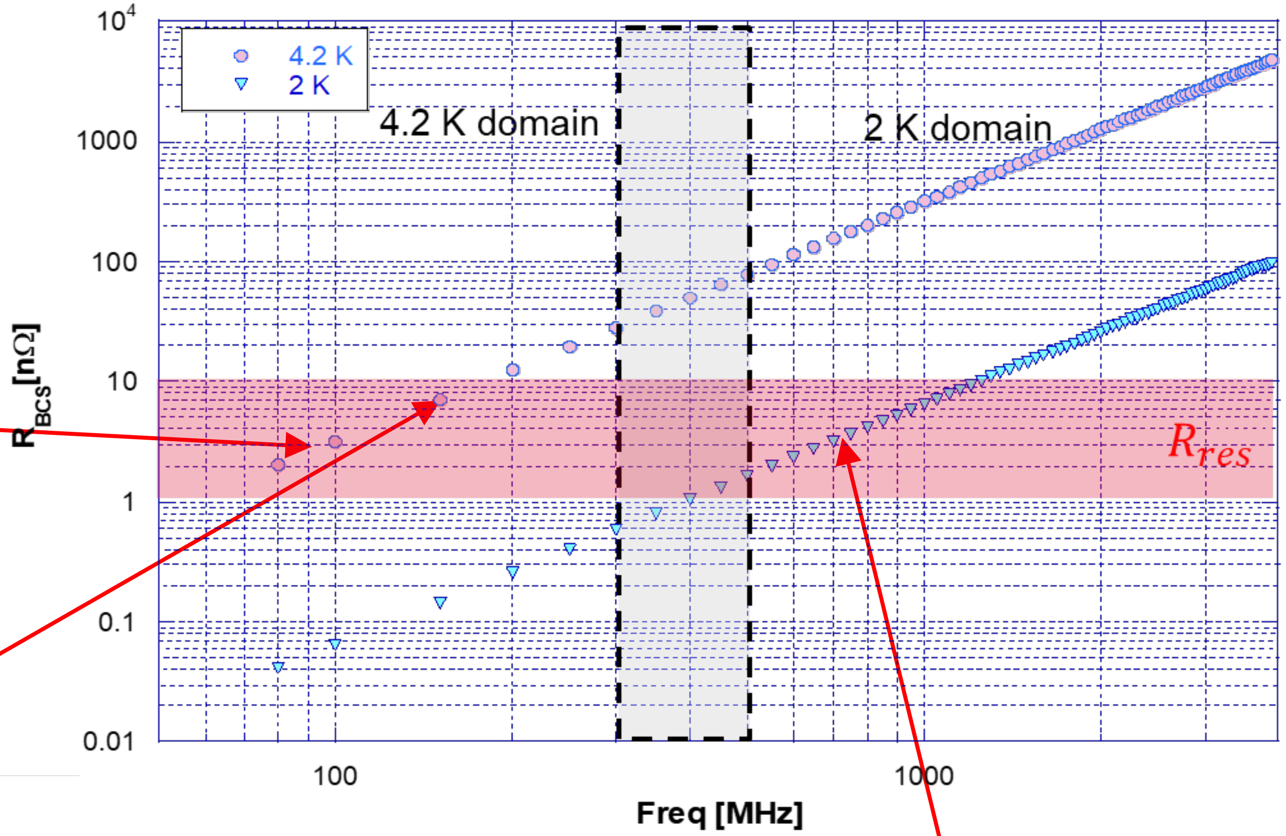
"As a rule of thumb it is preferable to reduce the BCS contribution as low as the residual resistance"

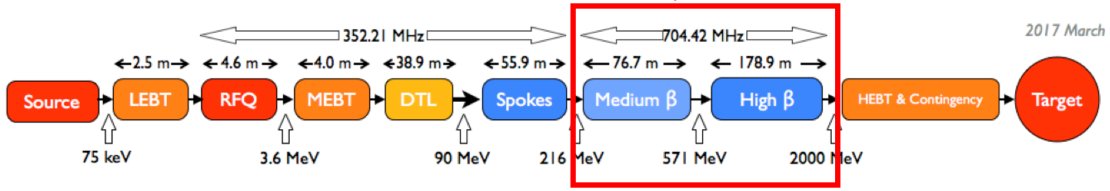
$$R_S = R_{BCS} + R_{res}$$

$$R_{BCS} \sim \lambda^3 \omega^2 l e^{-\frac{\Delta}{kT}}$$







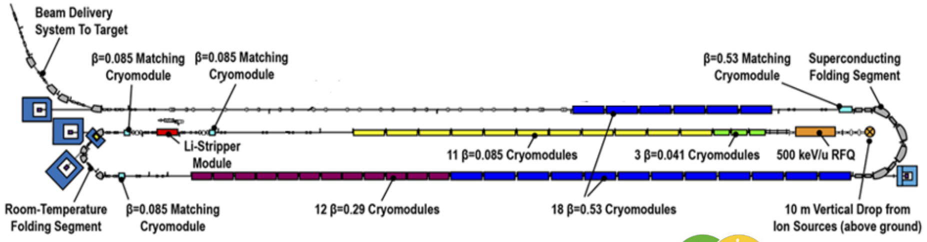


EUROPEAN SPALLATION SOURCE

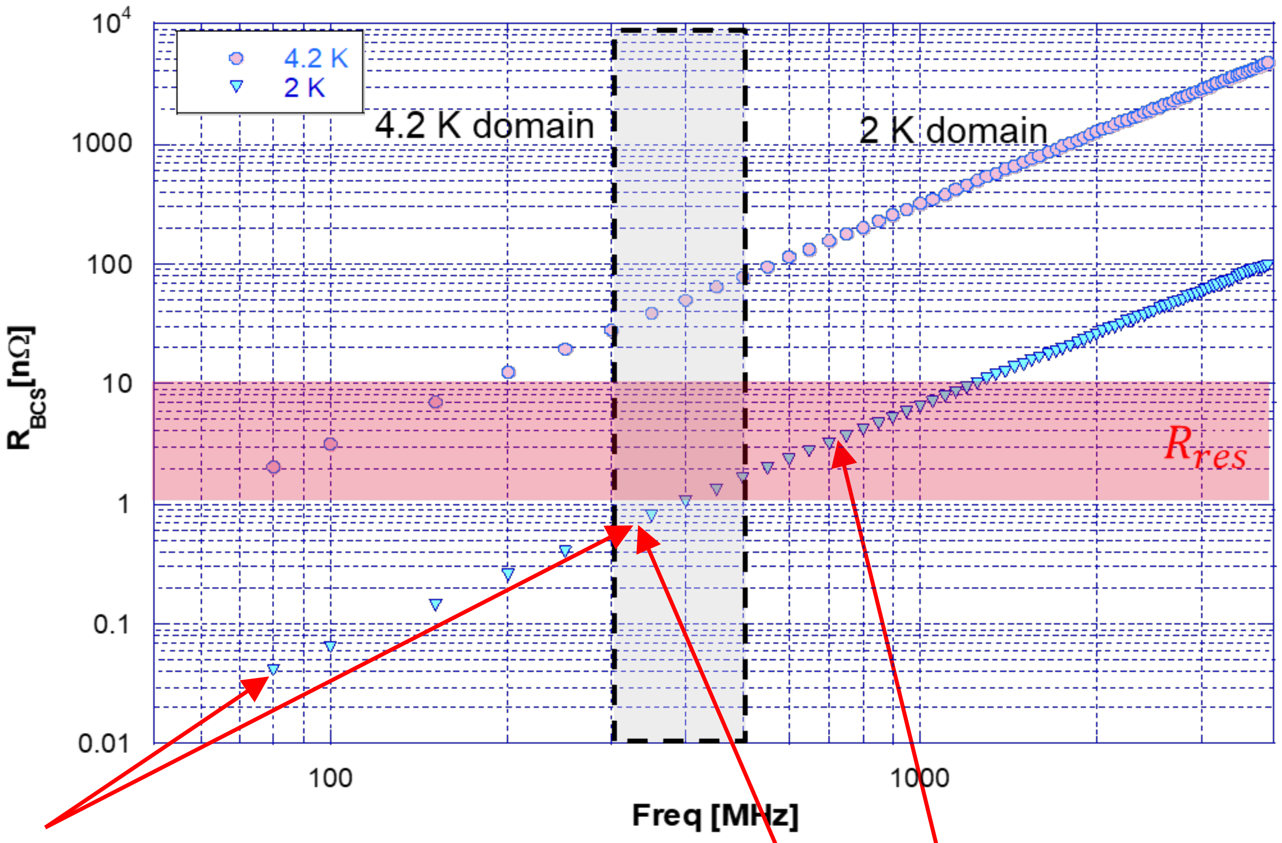
What is the optimal temperature of a superconducting linac?

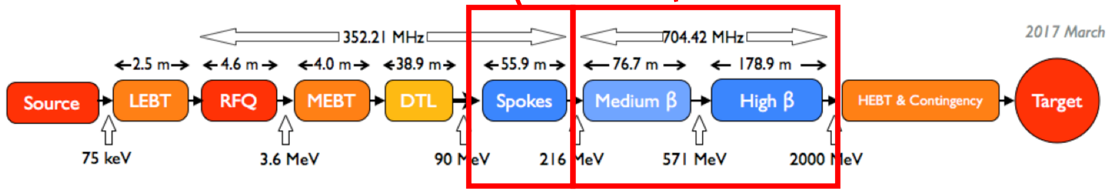
For low frequency superconducting linac, it could be interesting to operate the cavities around 2 K in some cases:

- Even the extra purchase costs of the cryogenic system and a more complex cryogenic circuits for the cryomodules, the long term integrated operating cost could be less with a large number of cavities
- Helium bath more stable
- Standardization of the cryogenic distribution system all along the superconducting linac



FRIB

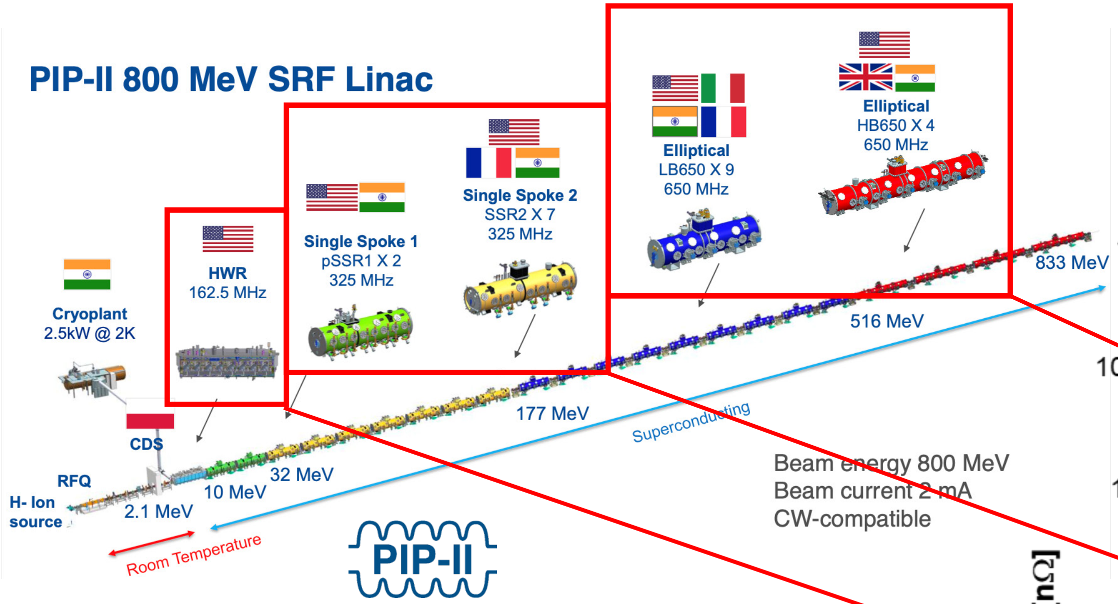


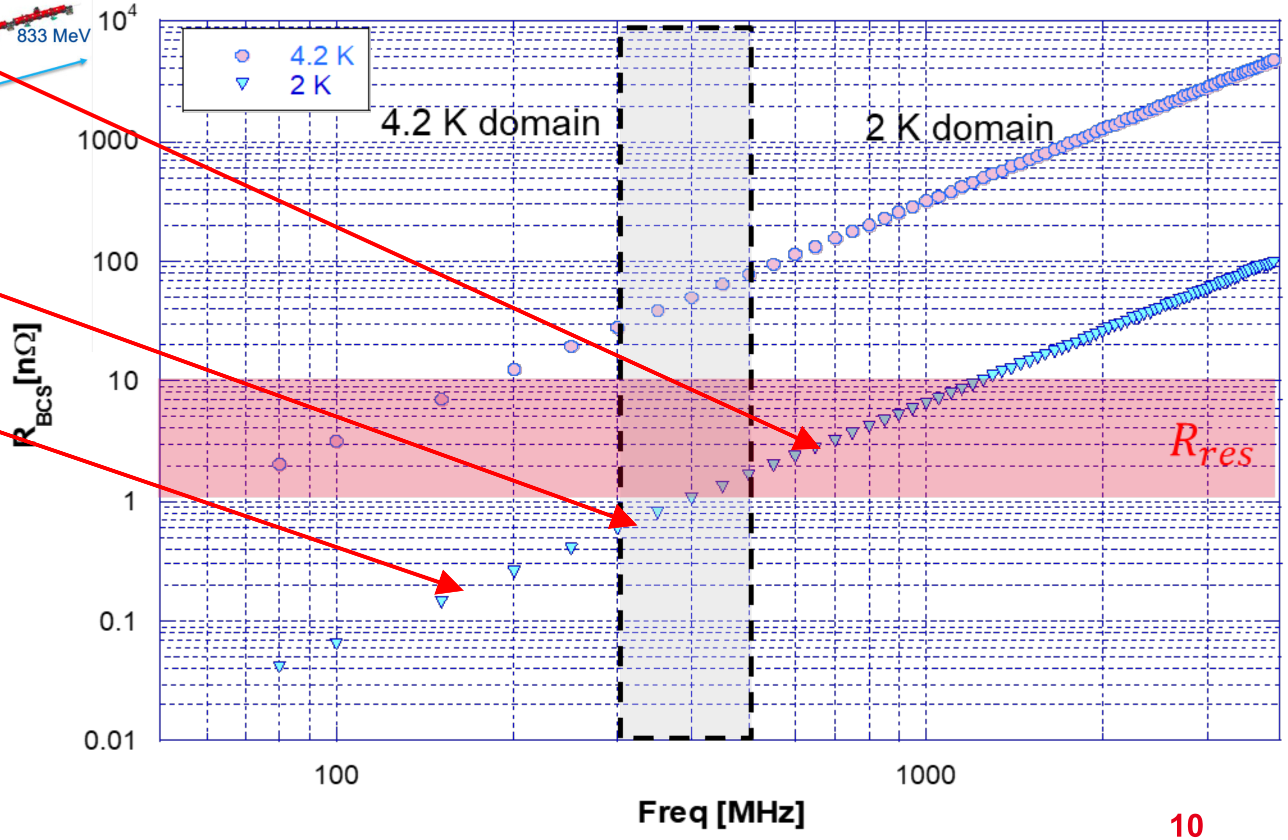


cea SRF 2023 GRAND RAPIDS

EUROPEAN SPALLATION SOURCE

What is the optimal temperature of a superconducting linac?





- Helium bath more stable
- Standardization of the cryogenic distribution system all along the superconducting linac

2. Heat Tansfer Heat Loads

Introduction

- This section gives an introduction to heat transfers in a cryomodule.

- Heat transfers between the cryogenic fluids and the cavities is not discussed here.

- Details on heats transfers and material properties at low temperature could be found in the following lectures given at CERN Accelerator School on Superconductivity in 2013:

  - “Heat transfer and cooling techniques at low temperature”, B. Baudouy

    https://cas.web.cern.ch/sites/cas.web.cern.ch/files/lectures/erice-2013/baudouy1.pdf

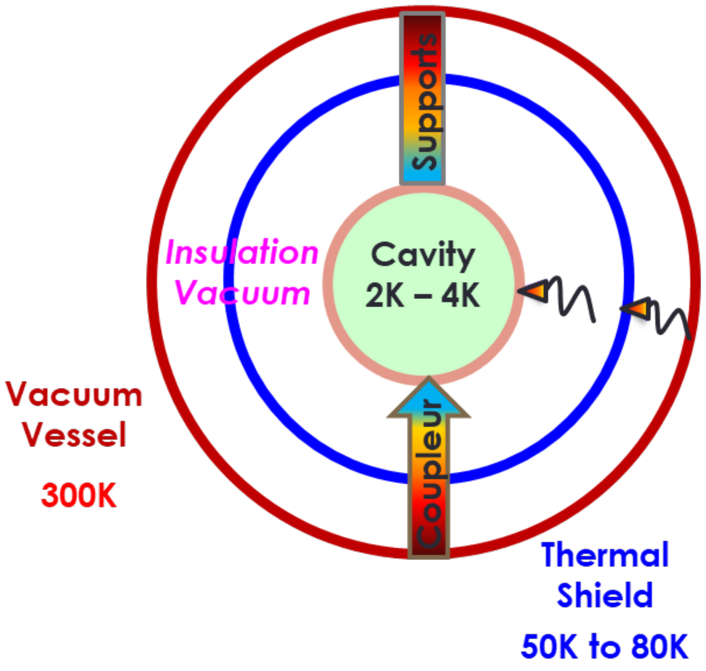
    https://cas.web.cern.ch/sites/cas.web.cern.ch/files/lectures/erice-2013/baudouy2.pdf

  - “Materials properties at low temperature”, P. Duthil

    https://cas.web.cern.ch/sites/cas.web.cern.ch/files/lectures/erice-2013/apr262duthil.pptx

Heat Transfers in a Cryomodule

- **Conduction:** heat transfer in solid or fluid at rest
  - Outer conductor of power coupler, support of the cold mass, instrumentation cables …
  - Because of the insulation vacuum (<10^{-4} Pa – 10^{-6} mbar), the viscous gas conduction is negligible
- **Convection:** heat transfer by movement of fluid
  - Because of the insulation vacuum (<10^{-4} Pa – 10^{-6} mbar), the natural convection is negligible
- **Radiation:** heat transfer by electromagnetic wave
  - Main sources: between the vacuum vessel and the thermal shield, the thermal shield and the cold mass
  - But don't forget the direct line of sight between room temperature components and the cold mass:
    - From the antenna tip of the power coupler to the cavity
    - From the viewports if alignment monitoring system is implemented



Conduction

Fourier's law

When a thermal gradient exists in a body (solid or fluid at rest), there is a heat transfer (without mass transfer) from the high temperature region to the low temperature region.

$$\boldsymbol{q = -k(T)\,\vec{\nabla} T}$$

q is the local heat flux density (W.m^{-2})

$k(T)$ is the material conductivity (W.m^{-2}.K^{-1})

$\vec{\nabla} T$ is the temperature gradient (K.m^{-1})

- In 1D with constant geometry (example: tie rod or tube)

$$q = -k(T)\frac{dT}{dx} \Rightarrow Q = \frac{A}{L}\int_{T_{cold}}^{T_{hot}} k(T).\,dT$$

- In 1D with with non constant geometry

$$Q\int_0^L \frac{dx}{A} = \int_{T_{cold}}^{T_{hot}} k(T).\,dT$$

$\int k(t)dT$ is the thermal conductivity integral (in W.m^{-1})
→ important parameter since the thermal conductivity strongly varies between room temperature and cryogenic temperatures

Conduction: Thermal Conductivity Integral

Thermal conductivity integrals are evaluated from a reference temperature T_{REF} (1K in the tables below). Thus conduction integrals of interest over a given temperature range is given by the difference:

$$\int_{T_C}^{T_H} k(T)dT = \int_{T_{REF}}^{T_H} k(T)dT - \int_{T_{REF}}^{T_C} k(T)dT$$

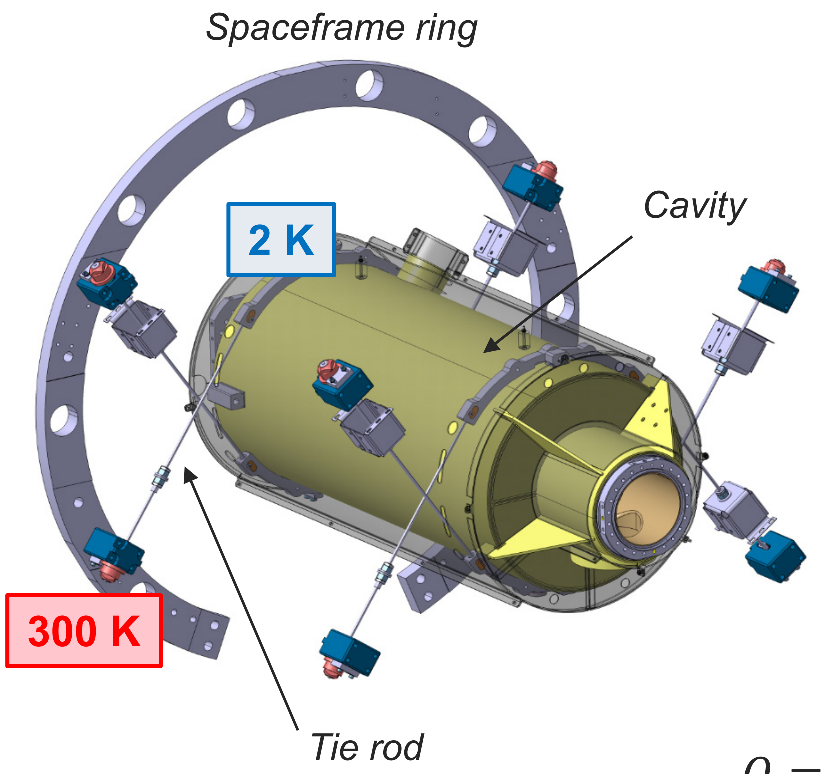
$\int_{1K}^{T} k(T)dT$ (W/m) — Thermal Insulators

Temp. (K)	Pyrex Glass	Teflon (PTFE)	Polycarbonate Amorphous	Nylon	G-10 (normal to cloth lay)	Epoxy	Carbon Reinforced Plastic, CRFP normal	Mylar, PET
1	0	0	0	0	0	0	0	0
2	0.0302	0.00831	0.0226	0.00271	0.0148	0.0262	0.00709	0.00174
4	0.165	0.0646	0.079	0.0154	0.0901	0.112	0.031	0.0115
6	0.358	0.171	0.143	0.041	0.214	0.212	0.065	0.0342
8	0.592	0.32	0.214	0.0803	0.381	0.322	0.109	0.0704
10	0.857	0.504	0.294	0.134	0.584	0.438	0.165	0.12
15	1.49	1.05	0.54	0.337	1.19	0.74	0.356	0.309
20	2.2	1.72	0.849	0.637	1.93	1.07	0.622	0.57
25	2.99	2.47	1.23	1.04	2.78	1.43	0.968	0.885
30	3.87	3.3	1.66	1.54	3.74	1.82	1.39	1.24
35	4.88	4.2	2.11	2.14	4.8	2.24	1.87	1.63
40	6.01	5.15	2.6	2.84	5.95	2.67	2.41	2.04
50	8.59	7.16	3.66	4.47	8.48	3.62	3.68	2.89
60	11.7	9.29	4.84	6.29	11.2	4.67	5.26	3.8
70	15.3	11.5	6.1	8.3	14.3	5.79	7.13	4.74
77	18.1	13.1	7.03	9.79	16.7	6.63	8.62	5.42
80	19.4	13.8	7.43	10.4	17.7	7	9.32	5.72
90	24.1	16.2	8.84	12.7	21.3	8.3	12	6.74
100	29.3	18.7	10.3	15.1	25.2	9.71	15.1	7.79
120	41.1	23.66	13.41	20.04	33.61	12.86	22.2	9.96
140	54.7	28.7	16.75	25.2	42.8	16.37	30.6	12.22
160	69.8	33.8	20.29	30.6	52.6	20.11	40.3	14.54
180	86.2	39	24	36.1	63	23.91	51.2	16.91
200	103.8	44.2	27.9	41.8	73.9	27.91	62.8	19.29
220	122.2	49.4	32	47.5	85.1	32.01	74.5	21.69
240	141.3	54.6	36.3	53.4	96.8	36.11	86.4	24.19
260	161.3	59.8	40.7	59.4	108.7	40.31	98.6	26.59
280	181.3	65	45.3	65.5	120.9	44.61	111.1	28.99
300	201.3	70.2	50	71.7	133.2	48.91	124.1	31.49

$\int_{1K}^{T} k(T)dT$ (W/m) — Metals and alloys

Temp. (K)	SS304	Cu-RRR=300	Cu-RRR=30	Brass	Constantan	Manganin	Inconel 718	K Monel	Invar-36	Ti-6Al-4V	Al-RRR=30	6061-T6	5083-T0	Niobium	NbTi
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0.0726		69	1.05	0.183	0.124	0.169	0.241	0.0388	0.174	42.8	3.46	1.06	0.968	0.04
4	0.4	3560	345	6.07	1.31	0.773	0.901	1.46	0.276	0.804	214	17.7	5.61	10.9	0.27
6	1.02	8360	807	16	3.87	2.12	2.24	3.91	0.819	1.78	501	41.4	13.7	46.2	0.756
8	1.96	14900	1450	31	8.03	4.22	4.19	7.72	1.7	3.07	900	74.6	25.3	107	1.5
10	3.28	22800	2270	51.2	13.9	7.15	6.77	13	2.95	4.67	1410	118	40.5	192	2.5
15	8.51	46600	5130	128	38.2	18.6	16.2	33.6	7.93	9.91	3190	272	95.2	515	6.04
20	16.7	72900	8910	235	74.8	35.9	29.2	63.8	15.6	16.7	5590	487	173	932	11.1
25	28.1	95800	13500	370	124	59.7	45.4	103	26	24.7	8560	765	273	1360	17.4
30	42.8	115000	18400	525	184	89.6	64.3	150	39.1	33.8	11900	1100	395	1800	25.2
35	61.2	130000	23300	697	252	125	85	204	54.7	43.8	15400	1480	538	2220	34.4
40	82.9	140000	28000	883	328	166	108	262	72.9	54.8	18900	1900	701	2620	45
50	136	155000	36200	1280	497	260	158	391	117	79.4	25300	2840	1080	3340	70.4
60	199	164000	42900	1730	679	367	213	530	170	107	30500	3900	1540	3970	101
70	271	171000	48400	2210	865	483	272	675	232	137	34800	5020	2050	4560	138
77	326	176000	51800	2580	997	569	315	781	281	160	37300	5830	2440	4960	167
80	350	177000	53300	2740	1050	607	334	828	302	171	38300	6180	2610	5130	180
90	436	182000	57800	3320	1250	739	401	985	379	207	41400	7370	3220	5690	228
100	527	187000	62000	3950	1440	877	470	1150	462	245	44200	8580	3870	6230	280.49
120	725	196200	70270	5330	1847	1165	617	1489	640	329	49240	11040	5280	7320	398
140	940	204900	78200	6860	2269	1467	775	1845	834	422	53830	13560	6820	8400	530
160	1170	213300	86100	8500	2700	1781	941	2210	1040	522	58300	16130	8490	9490	673
180	1414	221700	94000	10240	3140	2107	1114	2600	1258	630	62800	18780	10270	10580	824
200	1667	229900	101800	12080	3600	2447	1295	2990	1482	744	67300	21480	12170	11665	983.3
220	1937	238200	109600	13950	4060	2797	1480	3400	1732	865	71800	24180	14170	12750	1150
240	2207	246300	117400	16050	4530	3167	1680	3810	1982	993	76400	27080	16370	13840	1323
260	2487	254400	125100	18150	5000	3557	1880	4230	2242	1127	80900	30080	18570	14930	1503
280	2777	262500	132900	20350	5480	3967	2080	4660	2502	1265	85400	33180	20970	16020	1687
300	3077	270500	140600	22650	5970	4397	2300	5100	2772	1415	90000	36380	23470	17119	1875.4

Conduction: Case Study



ESS: cavity attached to the room temperature spaceframe thanks to tie rods

- Rod length = 490 mm
- Diameter = 6 mm

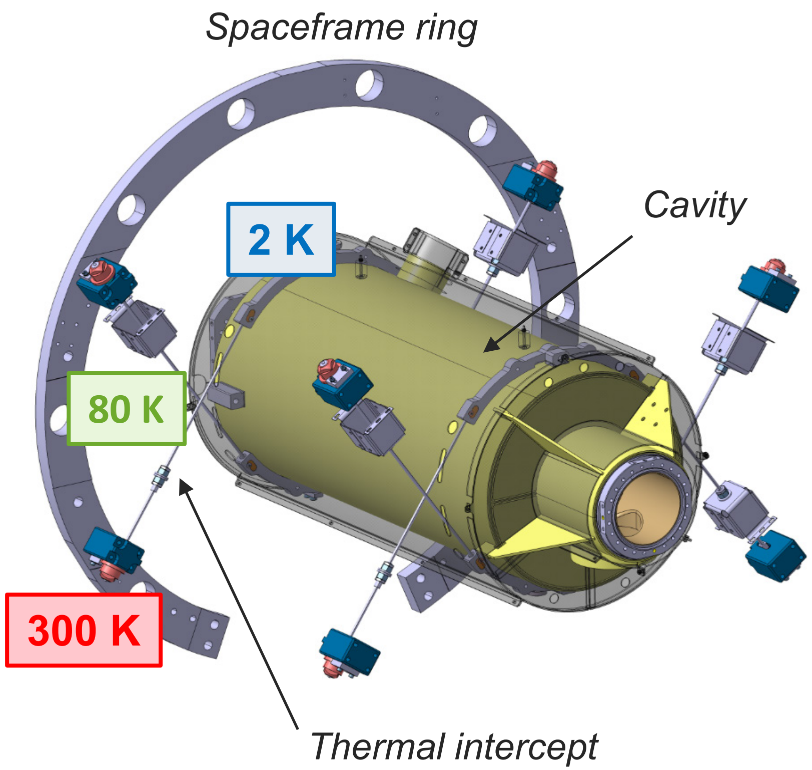
Stainless steel: $\int_{2K}^{300K} k_{SS304}(T).dT = 3076.92\ W.m^{-1}$

Titanium grade 5 (TA6V alloy): $\int_{2K}^{300K} k_{TA6V}(T).dT = 1414.82\ W.m^{-1}$

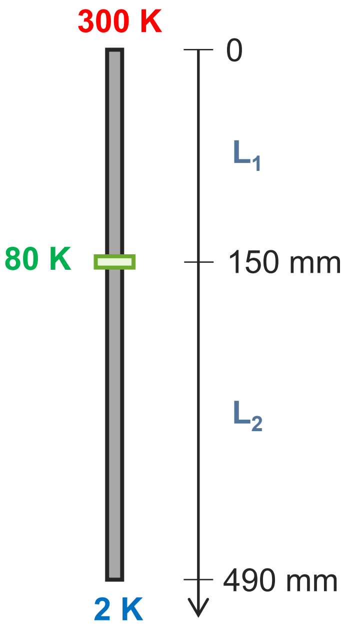
$$Q = \frac{A}{L}\int_{T_{cold}}^{T_{hot}} k(T).dT \Rightarrow \begin{cases} \text{Stainless steel: } Q_{2K} = 177.5\ mW \\ \text{Titanium grade 5: } Q_{2K} = 81.6\ mW \end{cases}$$

- In order to minimize the heat loads, titanium grade 5 is a better choice than stainless steel for the tie rods.
- Titanium grade 5 has also more advantages: better yield strength, non magnetic material.

Conduction: Principle of Thermal Intercept



It is possible to reduce the heat load by placing a thermal intercept



$$\int_{80K}^{300K} k_{TA6V}(T).dT = 1244\,W.m^{-1}$$

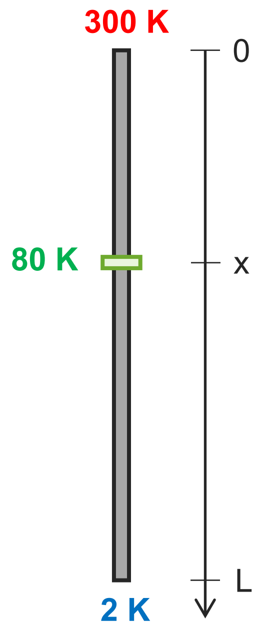
$$\int_{2K}^{80K} k_{TA6V}(T).dT = 170.8\,W.m^{-1}$$

$$Q_{80K} = \frac{A}{L_1}\int_{80K}^{300K} k_{TA6V}(T).dT \qquad Q_{80K} = 234.5\,mW$$

$$Q_{2K} = \frac{A}{L_2}\int_{2K}^{80K} k_{TA6V}(T).dT \qquad Q_{2K} = 14.2\,mW$$

- Without thermal intercept: $Q_{2K} = 81.6\,mW$
- With thermal intercept: $Q_{2K} = 14.2\,mW$

Conduction: Principle of Thermal Intercept



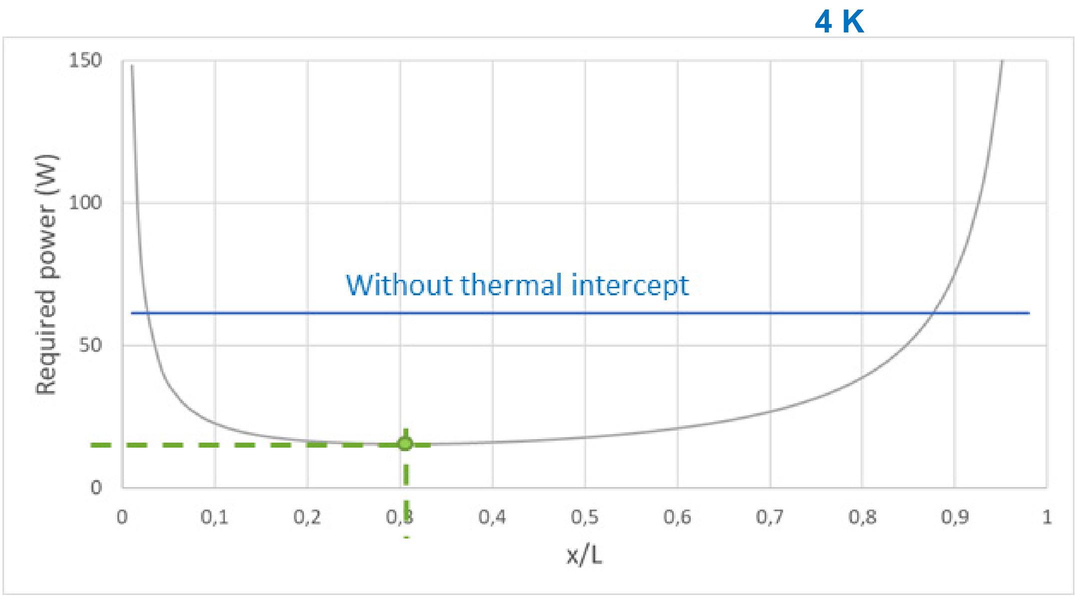
The optimal position *x* is obtained by minimizing the power necessary to evacuate the heat loads intercepted at 2K and 80K, taking into account the Carnot efficiency:

$$\dot{W} = \dot{W}_{80K} + \dot{W}_{2K} = C_{80K}.Q_{80K} + C_{2K}.Q_{2K}$$

Cost factors: $C_{80K} \approx 20\ W/W$ $\quad C_{2K} \approx 750\ W/W$

$$Q_{80K} = \frac{A}{x}\int_{80K}^{300K} k_{TA6V}(T).dT$$

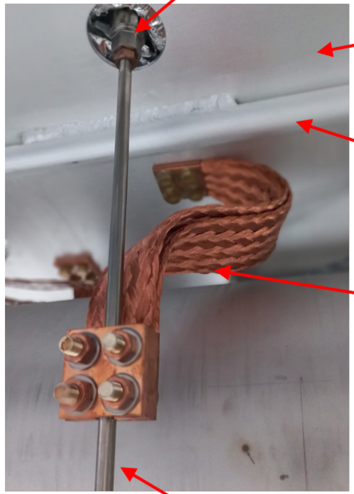
$$Q_{2K} = \frac{A}{L-x}\int_{2K}^{80K} k_{TA6V}(T).dT$$



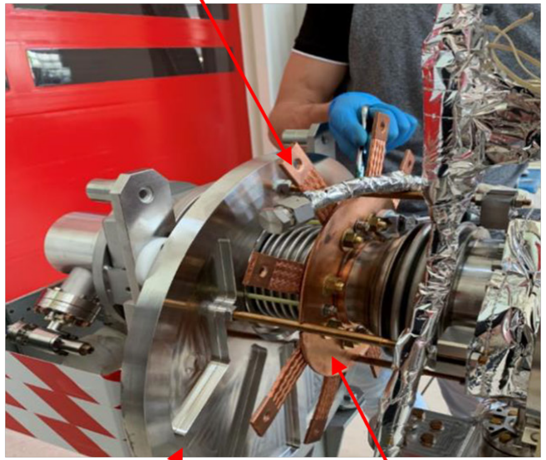
Sound engineering practice: $x = \frac{1}{3}L$

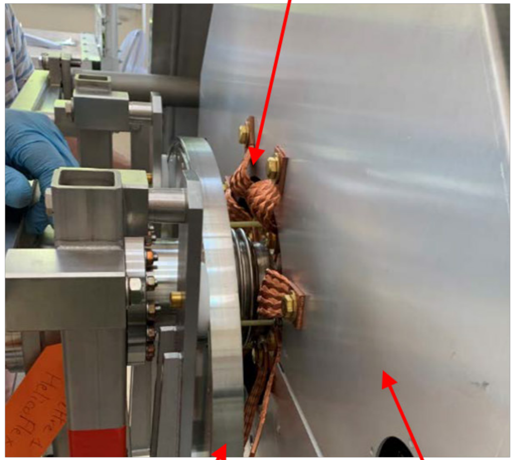
Example of Thermal Intercepts

- Copper braids are usually used to connect the parts to be heat sunk to the thermal shield
  - Flexible elements that can accommodate the difference of thermal shrinkage between the part and the thermal shield
  - Use of high purity copper to get high thermal conductivity



SARAF – Phase 2





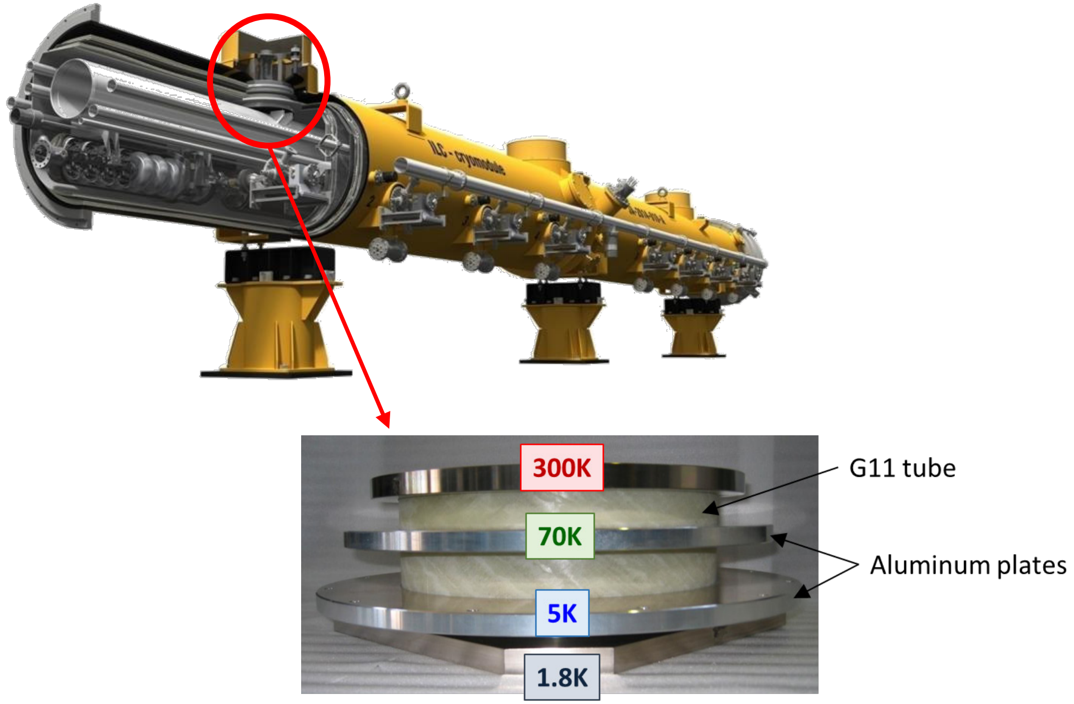
Cold-to-warm transition of the ESS cryomodule

Example of Thermal Intercepts

Example of cryomodules with two thermal intercepts

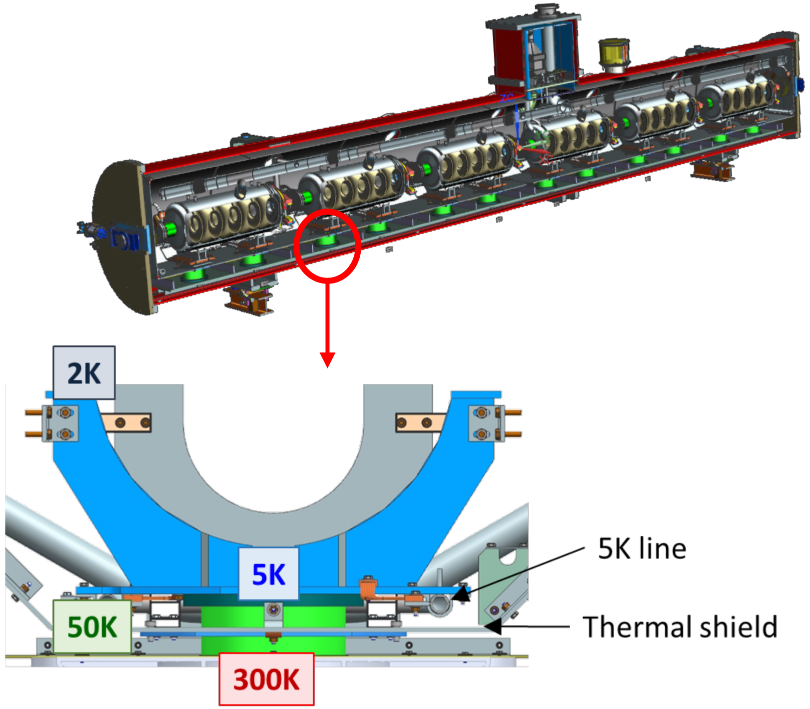
TTF type cryomodules (XFEL, LCLS-II, ILC)

- Two thermal shields: 70K and 5 K
- Support of the cold mass connected to the two shields



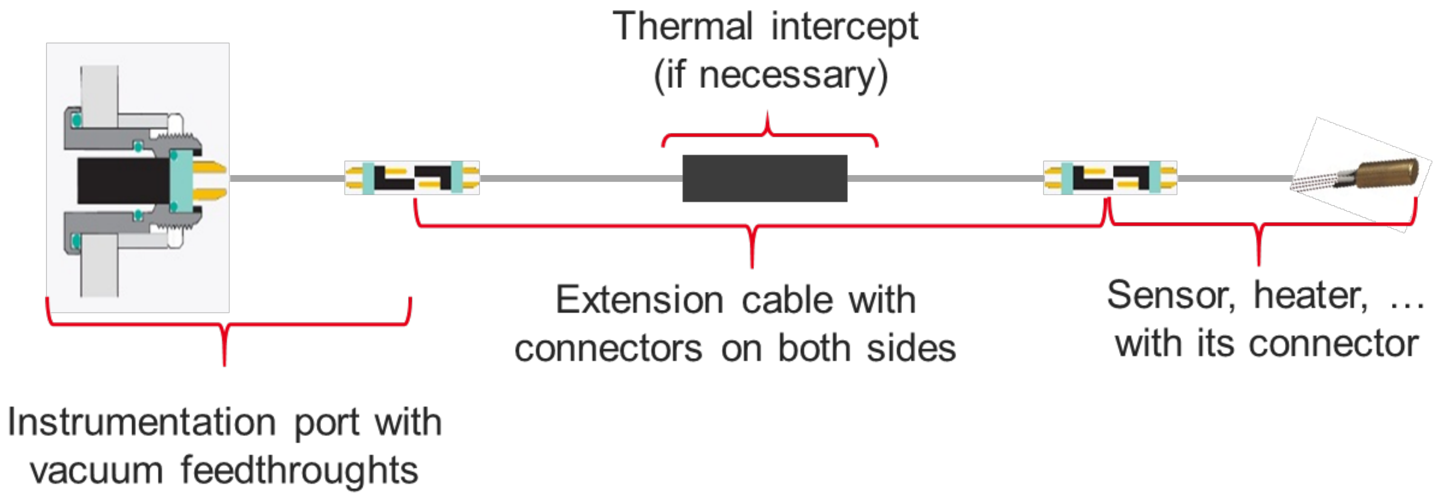
PIP-II cryomodules

- One thermal shields at 50K
- 5K line as a low temperature thermal intercept (with liquid helium flowing in the pipes)



Thermal Intercept: Wires

- Wires for the instrumentation installed in the cryomodule (temperature sensors, heaters, motors of the cavity frequency tuning systems, helium level gauge …) must be heat sunk at intermediate temperatures.
- To ease the assembly or the maintenance (change of a sensor or actuator) internal connectors and extension cables could be used.

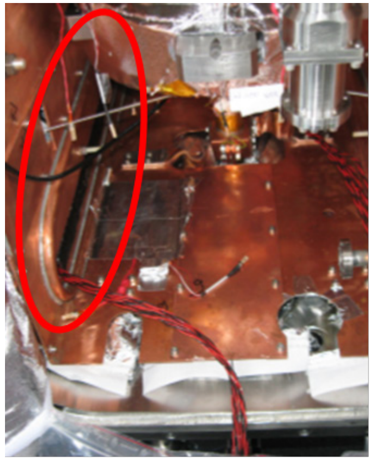


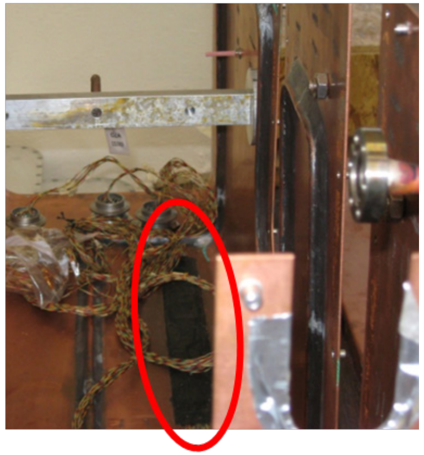
Thermal Intercept: Wires

- Wires can be heat sunk on the thermal shield using glue, aluminum tape or clamps.

Spiral 2 – Cryomodule A

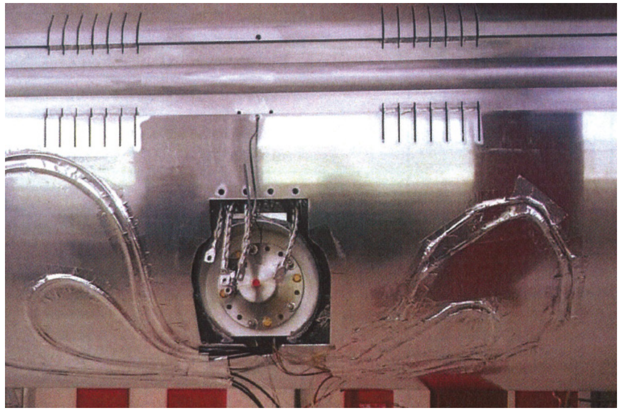
Wires glued to the thermal shield using thermally conductive epoxy encapsulant (Stycast)





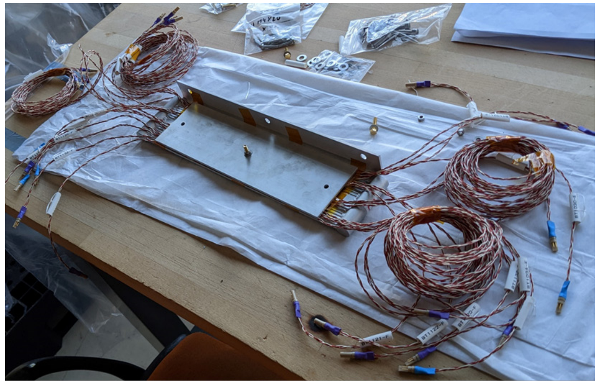
XFEL

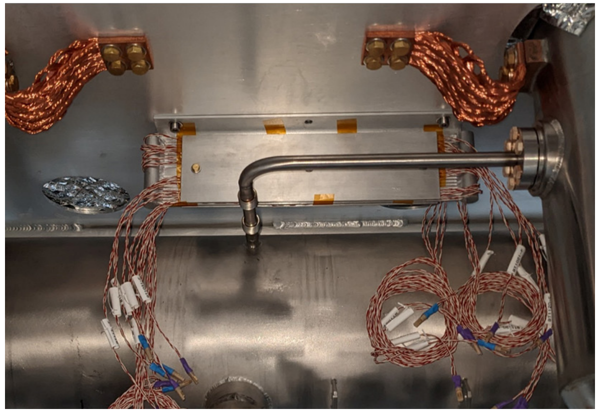
Use of aluminum tape



SARAF Phase 2

Wires clamped between two plates, use of vacuum grease with copper powder to increase the contact



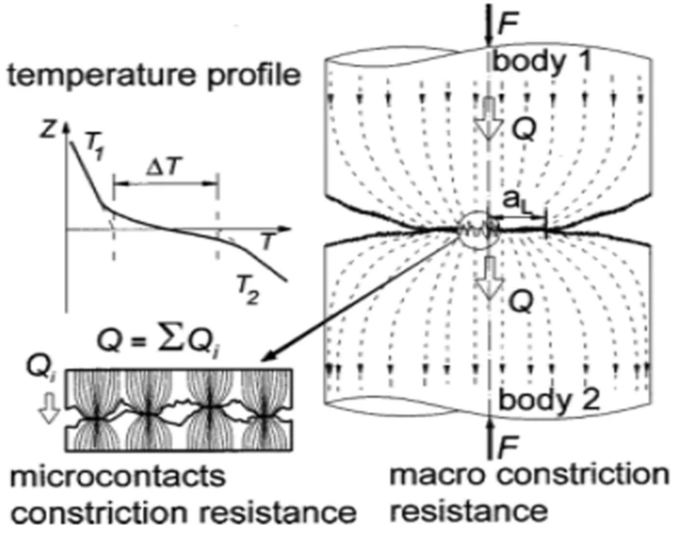


Conduction: Contact Resistance

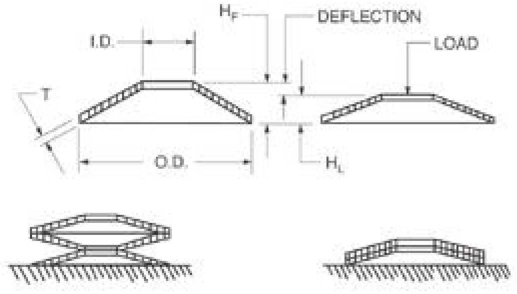
- **Contact between surfaces is not perfect** → made only at discrete locations, not over the full areas.
- This induces a temperature drop at the interface, resulting in the thermal contact resistance.
- The contact resistance depends on the materials, the surface roughness, the metal oxide film, the external force, the temperature …
  - Reduces with increasing force
  - Increases by several orders of magnitude from 200 to 20 K
  - Modeling is very difficult, the use of experimental data is recommended.

Sound engineering practice: 20% of the total gross area of the contact transmits the heat

- Reducing the contact resistance:
  - Insertion of conductive and malleable fillers (grease, indium or coatings)
  - Strong tightening. If screws, use of Belleville washers (spring washers) to accommodate shrinkage of the materials at cold temperature



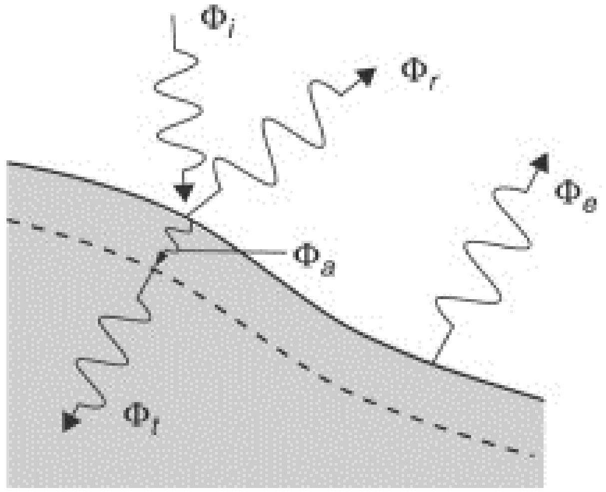
Picture taken from "Research Progress of Thermal Contact Resistance", Pan X., Cui X., Liu S. et al., Journal of Low Temperature Physics 201, 213–253 (2020) https://doi.org/10.1007/s10909-020-02497-0



Principle of the Belleville washer

Radiation

- Radiation: heat transfer by electromagnetic wave.
- All surfaces emit thermal radiation.
- The emitted radiation will strike other surfaces and will be partially reflected, partially absorbed, and partially transmitted.



Φ_e: emitted radiation

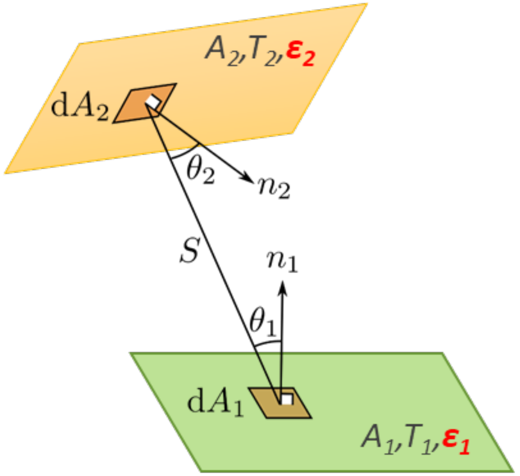
Φ_i: incident (received) radiation

Φ_r: reflected radiation

Φ_a: absorbed radiation

Radiation: Calculation

- Heat balance from surface A1 to surface A2:



$$q_{12} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$

with: $\sigma = 5.67x10^{-8}\, W.m^2.K^{-4}$ Stefan–Boltzmann constant

F_{12}: view factor

ε: emissivity of the material

with $$F_{12} = \frac{1}{A_1}\int_{A_1}\int_{A_2}\frac{\cos\theta_1\cos\theta_2}{\pi S^2}dA_2 dA_1$$

View factor can be difficult to calculate due to the complex geometry of cryomodules

Radiation

- In practice, simplified models can often be used

  - Large parallel plates

$$T_1 < T_2$$
$$A_1 = A_2$$
$$F_{12} = 1$$

$$q = \frac{\sigma A_1 (T_2^4 - T_1^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

  - Long concentric cylinders

$$T_1 < T_2$$
$$F_{12} = 1$$

$$q = \frac{\sigma A_1 (T_2^4 - T_1^4)}{\frac{1}{\varepsilon_1} + \frac{1 - \varepsilon_2}{\varepsilon_2}\left(\frac{A_1}{A_2}\right)}$$

Radiation

- It is also possible to use tables giving heat flux values

Configuration	Emissivity		Heat flux (W/m^2)		
	ε_1	ε_2	300 K ↓ ≤80K	80 K ↓ ≤20K	20 K ↓ ≤4K
Black body → black body	1	1	457	2.3	0.009
Metal → metal					
- Raw surface	0.2	0.2	51	0.18	7.10^{-4}
- Polished surface	0.1	0.1	24	0.083	3.10^{-4}
- Electropolished surface	0.03	0.03	7	0.024	1.10^{-4}
Black body → metal	1	0.2	91	0.46	2.10^{-3}
	1	0.03	14	0.07	3.10^{-4}

Radiation: Emissivity

- Black body = an idealized opaque, non-reflective body

  → emissivity ε = 1

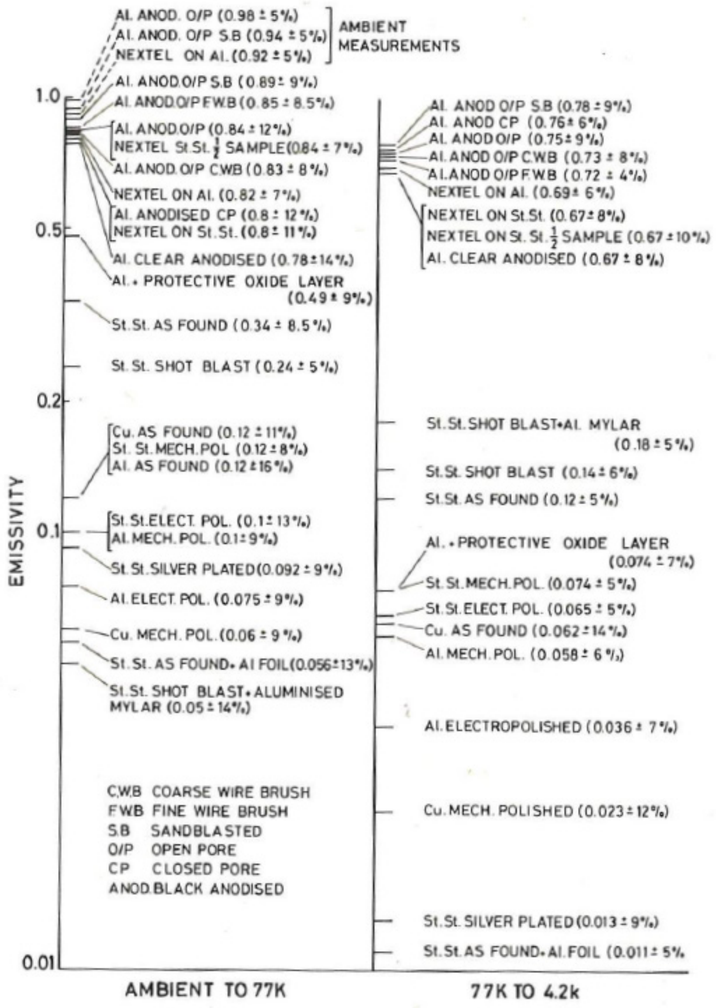
- Real surface is not a perfect emitter and the emissivity has to be taken into account

- Emissivity = ratio of the real surface to the blackbody radiation intensity

  → ε = number between 0 and 1

- The emissivity of a surface:
  - Decreases with temperature
  - Depends on the surface finish: polished surface has lower emissivity than raw surface
  - Increases with oxidation, impurities, dirt

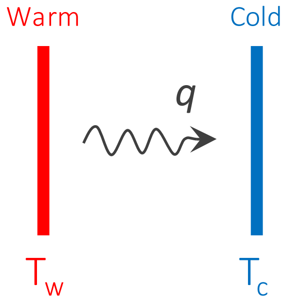
- Many data can be found in the literature



Obert W., "Emissivity measurements of metallic surfaces used in cryogenic applications" , Adv. Cryo. Eng. 27, Plenum Press 1982 p. 293-300

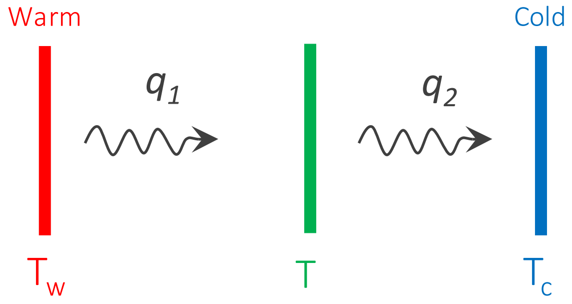
Radiation: Floating Shielding

- Considering two large parallel plates with the same emissivity ε and the same surface A



$$q = \frac{\varepsilon\sigma}{2-\varepsilon}(T_w^4 - T_c^4)$$

- Insertion of an intermediate ”floating” plate, same emissivity ε and same surface A

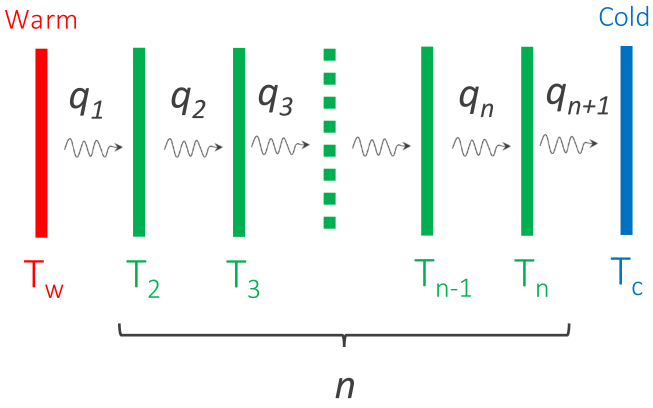


The intermediate plates reaches an equilibrium temperature *T* in such a way that:

$$q_1 = q_2 = \frac{1}{2}\frac{\varepsilon\sigma}{2-\varepsilon}(T_w^4 - T_c^4)$$

$$T^4 = \frac{T_w^4 - T_c^4}{2}$$

- Insertion of n intermediate ”floating” plates, same emissivity ε and same surface A



$$q_1 = q_2 = q_3 = \ \dots = q_n = q_{n+1} = q$$

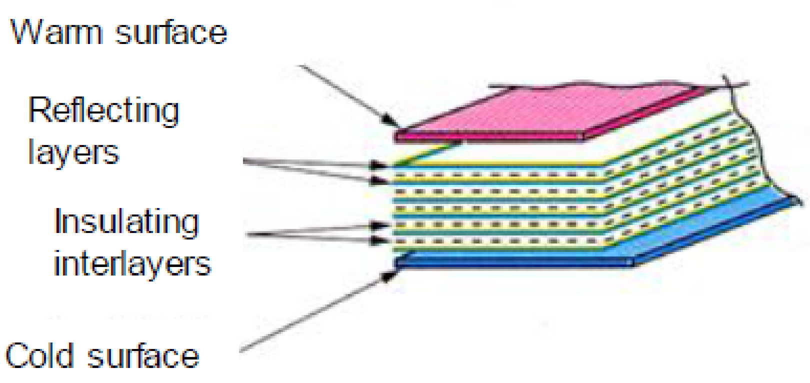
$$q = \frac{1}{n+1}\frac{\varepsilon\sigma}{2-\varepsilon}(T_w^4 - T_c^4)$$

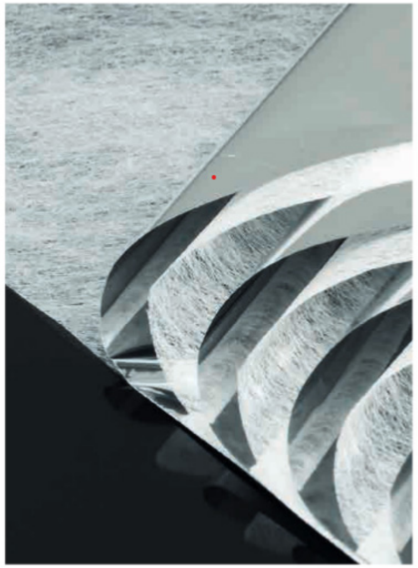
Temperature of an intermediate plate:

$$T_i^4 = T_c^4 + \frac{T_w^4 - T_c^4}{i+1}$$

Radiation: Multi-Layer Insultation (MLI)

- MLI is based on the principle of floating panels
- MLI = multiple superposition of:
  - A reflecting layer with low emissivity to reduce heat transfer by radiation (aluminum or aluminized material)
  - Insulating interlayer to reduce heat transfer by conduction between reflecting layers (mostly nest of polyester or fiber glass)

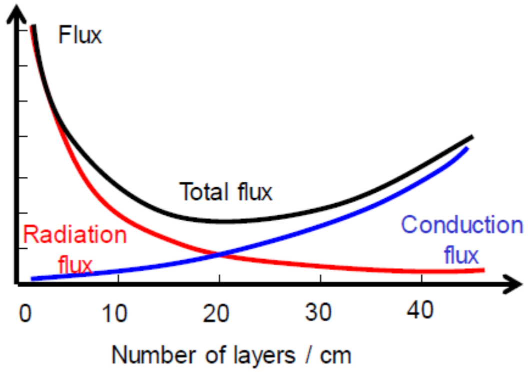


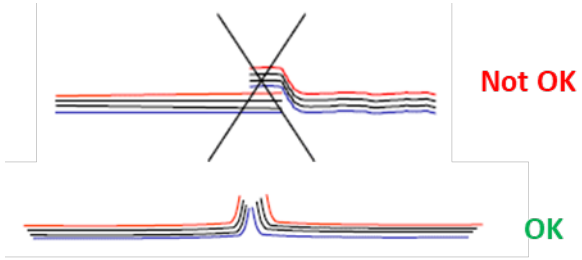


Ruag Coolcoat 2NW

MLI: Installation

- With proper care during design and installation, MLI can reduce radiative loads to:
  - 1 W/m² from room temperature to 80 K (30 layers, usually two blankets of 15 layers) .Value between 1.5 and 3 W/m² is used to assess the thermal load on the thermal shield
  - 0.1 W/m² from 80 K to lower temperature (usually one blanket of 10 layers)





Installing the MLI: some hints

- Do not compress the blankets → the optimum packing density is 20 – 25 layers/cm
- MLI blankets are usually not represented in the CAD model → do not forget them during the design phase
- Consider differential thermal contractions with regards to the supports (thermal shield, cold mass) → blankets must remain loose at cold
- But not too loose to avoid direct line of sight from the room temperature surfaces! Remember that black body radiation is as high as 470 W/m²
- When joining MLI blankets it is necessary to avoid thermal short circuits, putting in contact inner layers with the outer ones

Radiation: Case Study

Vacuum vessel

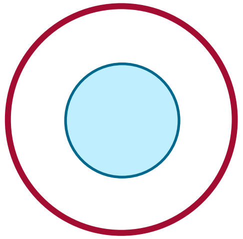
- Diameter: d_{VV} = 0.8 m
- Emissivity: ε_{VV} = 0.2
- Temperature: T_{VV} = 300 K

Cold mass

- Diameter: d_{CM} = 0.5 m
- Emissivity: ε_{CM} = 0.1
- Temperature: T_{CM} = 4 K

The formula for long concentric cylinders is used to assess the heat loads for a 1-m cryostat unit length.

▶ Without shielding



$$Q_{CM} = \frac{\sigma A_{CM}\,(T_{VV}^4 - T_{CM}^4)}{\frac{1}{\varepsilon_{CM}} + \frac{1-\varepsilon_{VV}}{\varepsilon_{VV}}\left(\frac{A_{CM}}{A_{VV}}\right)}$$

with

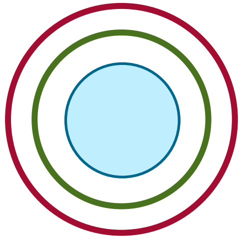
$$A_{VV} = \pi.\,d_{VV}$$

$$A_{CM} = \pi.\,d_{CM}$$

➡ $Q_{CM} \cong 58\,W$

▶ Addition of one floating shield

- Made of aluminum
- Emissivity: ε_{FS} = 0.1
- Diameter: d_{FS} = 0.65 m



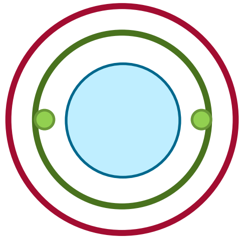
$$T_{FS} \cong 266\,K$$

$$Q_{CM} = Q_{FS} \cong 26.6\,W$$

Radiation: Case Study

▶ Actively cooling the shield

- Temperature: T_{TS} = 80 K
- Emissivity: ε_{TS} = 0.1
- Diameter: d_{TS} = 0.65 m

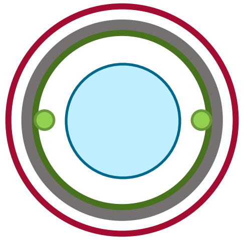


$$Q_{TS} \cong 70.5\ W$$

$$Q_{CM} \cong 0.22\ W$$

▶ Addition of MLI on the thermal shield

- 30 layers
- Room temperature heat flux: Φ_{TS} = 1.5 W/m²



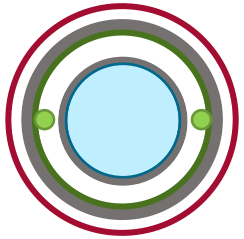
$$A_{TS} \cong 2.05\ m^2$$

$$Q_{TS} = \Phi_{TS}.A_{TS} \cong 3.1\ W$$

$$Q_{CM} \cong 0.22\ W$$

▶ Addition of MLI on cold mass

- 10 layers
- 80 K heat flux: Φ_{CM} = 0.1 W/m²



$$A_{CM} \cong 1.57\ m^2$$

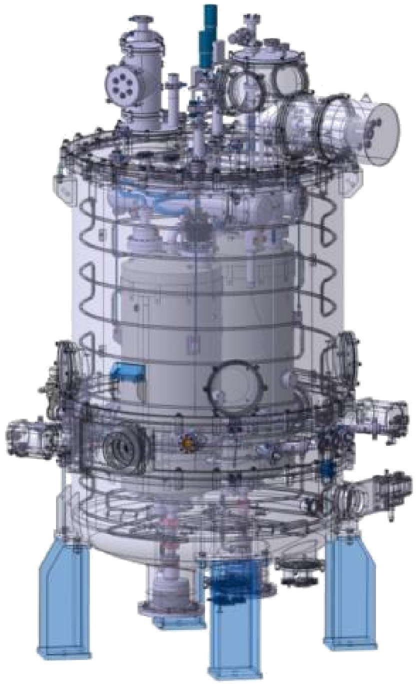
$$Q_{CM} = \Phi_{CM}.A_{CM} \cong 0.16\ W$$

$$Q_{TS} \cong 3.1\ W$$

▶ Summary

	Without shielding	Floating shield	Actively cooled shield without MLI	Actively cooled shield with MLI	Addition of MLI on cold mass
Thermal shield		26.6 W	70.5 W	3.1 W	3.1 W
Cold mass	58 W	26.6 W	0.22 W	0.22 W	0.16 W

Thermal Shield and MLI: Example



Spiral 2: cryomodule B

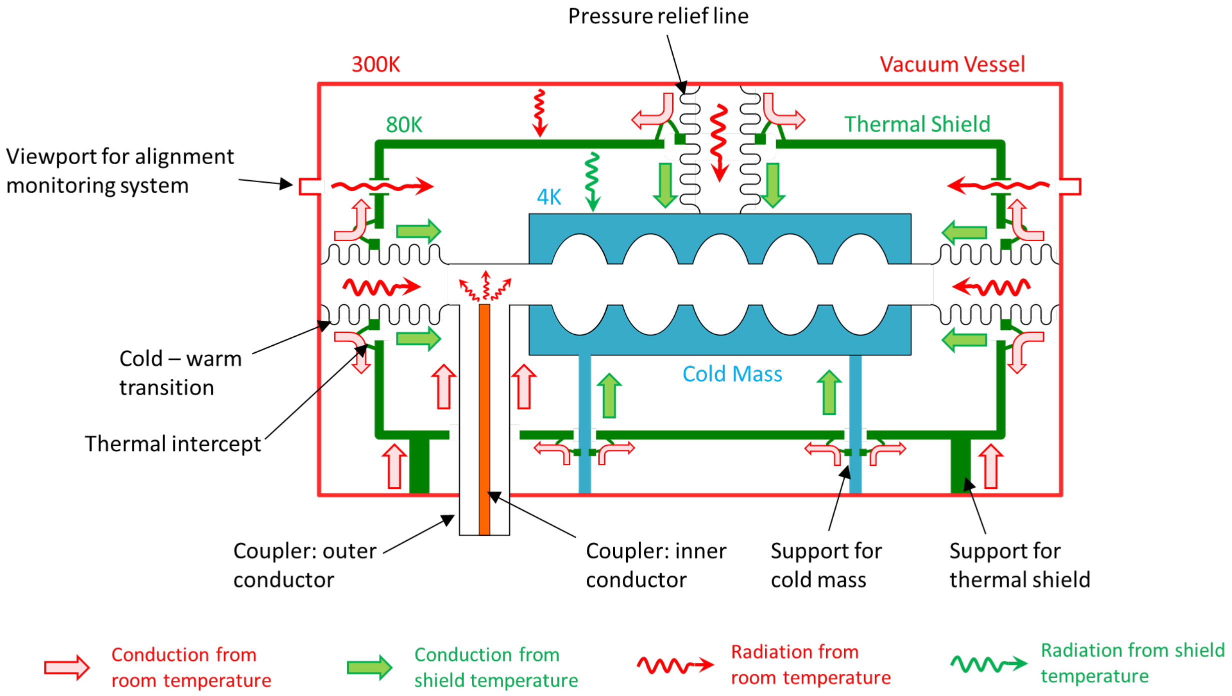
MLI installed on the cold mass: the two QWR and the cryogenic piping

Thermal shield in copper with brazed pipes for cryogenic fluid

MLI installed on the thermal shield

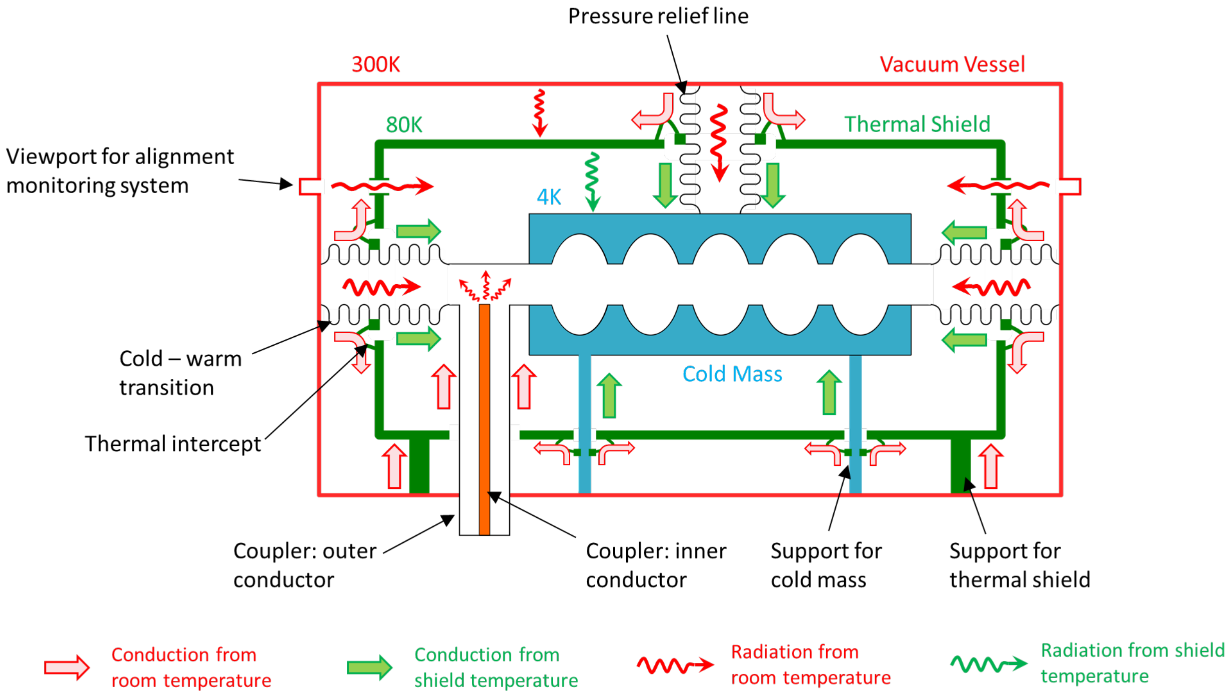
Heat Load Budget

- The heat load budget is required by the cryogenic group to define the characteristics of the cryogenic system (cryoplant + cryogenic distribution system).
- Static and dynamic heat loads of the cavity, the power coupler and the current leads for the solenoid (if any) shall be provided by the designers of theses systems
- Heat loads in a cryomodule:
  - Static heat loads on the thermal shield
    - Conduction: supports of the shield, thermal intercepts of supports of the cold mass, the cold – warm transitions, the pressure relief line, the outer conductor of the power coupler (if any – RF off), the current leads (if any), instrumentation cables
    - Radiation from room temperature components
  - Static heat loads on the cold mass
  - Dynamic heat loads: cavity, outer conductor of the power coupler (RF on), current leads (if any)



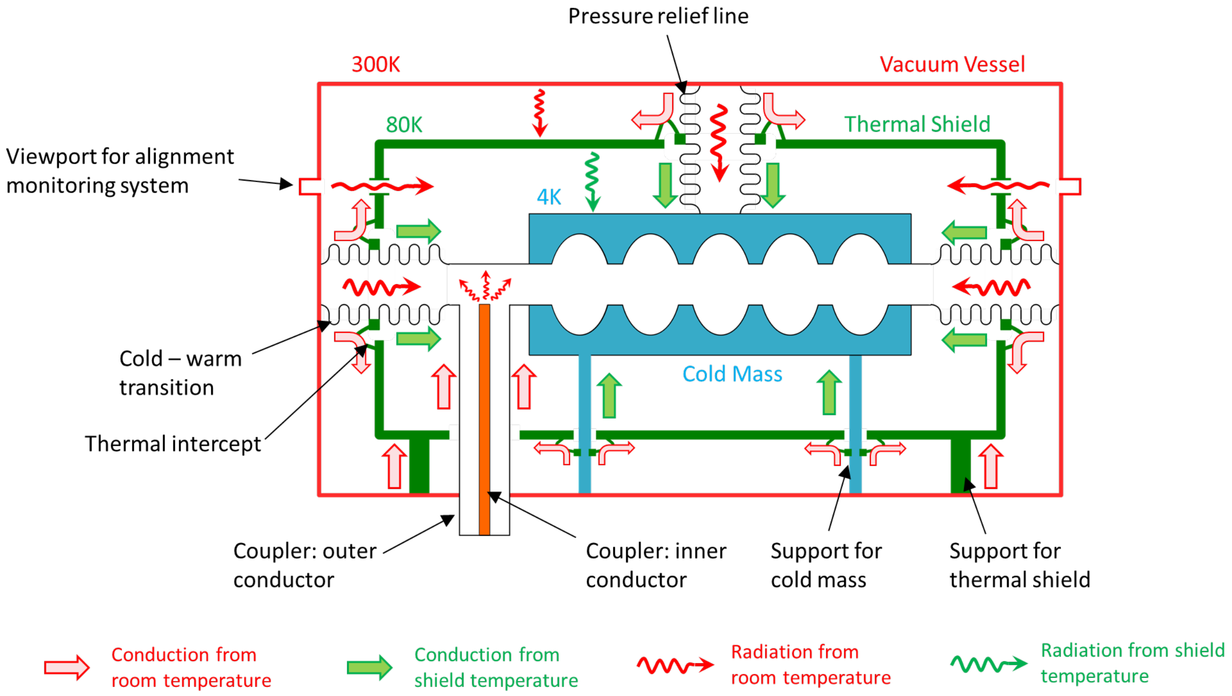
Heat Load Budget

- The heat load budget is required by the cryogenic group to define the characteristics of the cryogenic system (cryoplant + cryogenic distribution system).
- Static and dynamic heat loads of the cavity, the power coupler and the current leads for the solenoid (if any) shall be provided by the designers of theses systems
- Heat loads in a cryomodule:
  - Static heat loads on the thermal shield
  - Static heat loads on the cold mass
    - Conduction: supports, cold – warm transitions, pressure relief line, outer conductor of the power coupler (RF off), current leads (if any) , instrumentation cables
    - Radiation: from the thermal shield, direct line of sight from room temperature components (viewports, pressure relief line, cold – warm transitions, antenna tip of the power coupler)
  - Dynamic heat loads: cavity, outer conductor of the power coupler (RF on), current leads (if any)



Heat Load Budget

- The heat load budget is required by the cryogenic group to define the characteristics of the cryogenic system (cryoplant + cryogenic distribution system).
- Static and dynamic heat loads of the cavity, the power coupler and the current leads for the solenoid (if any) shall be provided by the designers of theses systems
- Heat loads in a cryomodule:
  - Static heat loads on the thermal shield
  - Static heat loads on the cold mass
  - Dynamic heat loads: cavity, outer conductor of the power coupler (RF on), HOM coupler or damper, current leads of superconducting solenoids (if any)
    - Details on the losses of cavity and power coupler are given in the tutorial lectures dedicated to these components

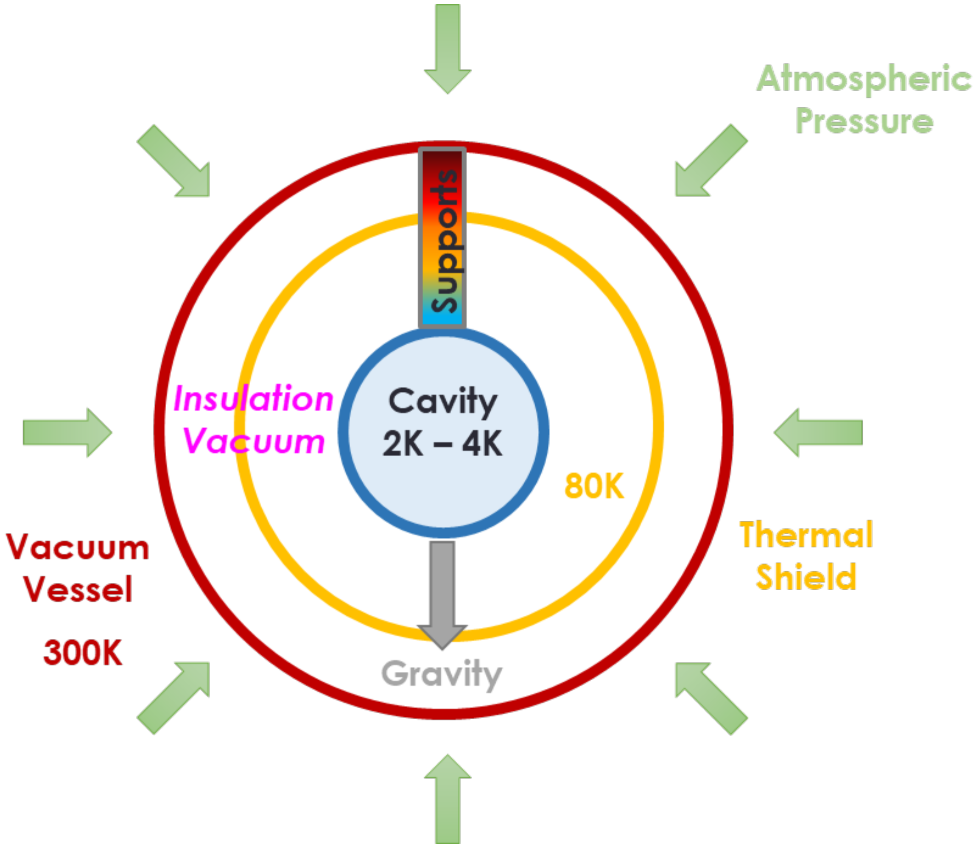


3. Thermo-Mechanical Design

Introduction: Thermo-Mechanical Loads

- It is mandatory to identify all the thermo-mechanical loads for each component of the cryomodule as these ones could size them but could also impact the alignment of the cavity string.

- The thermo-mechanical loads come from:
  - Different temperatures between two parts and thermal gradient in parts
    - Thermal shrinkage
    - Thermal stress in material
  - Insulation vacuum
    - Pressure forces on the vacuum vessel
  - Pressurized fluids in the cryogenic circuits
    - Pressure forces on the cavity, in the pipes
  - Mass of the components
    - Mechanical stress and deformation of the supports and vacuum vessel



Thermal Expansion

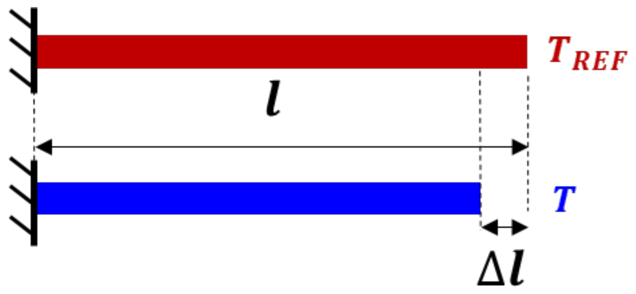
- Materials expand or contract when subjected to changes in temperature. Most materials expand when they are heated, and contract when they are cooled.

- The thermal expansion / contraction of solid is driven by the linear expansion coefficient *α(T)*:

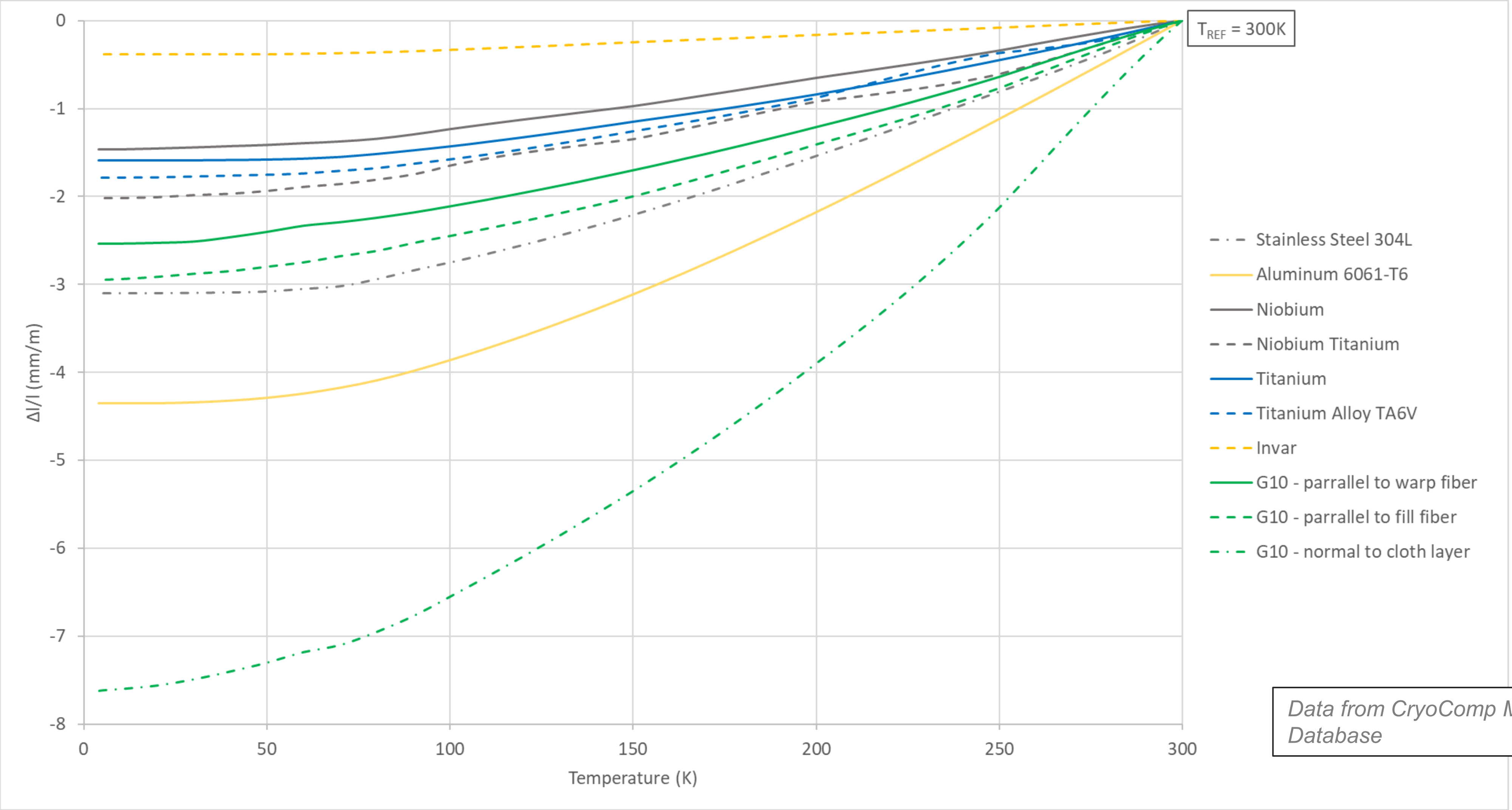
$$\alpha(T) = \frac{1}{l}\frac{dl}{dT} \quad (K^{-1})$$

- In practice, the expansion coefficient is computed from a reference temperature T_{REF} (300K):

$$\frac{\Delta l}{l} = \alpha(T)\Delta(T)$$



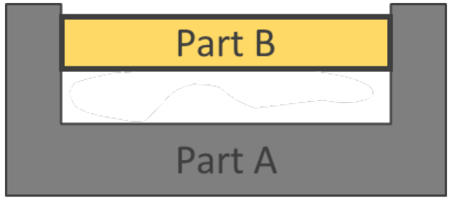
Thermal Expansion



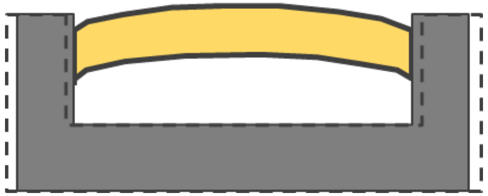
Data from CryoComp Material Database

Thermal Expansion: Assembly of Different Materials

- Assembly made of two different materials:
  - Room temperature setup
  - Part A: stainless steel

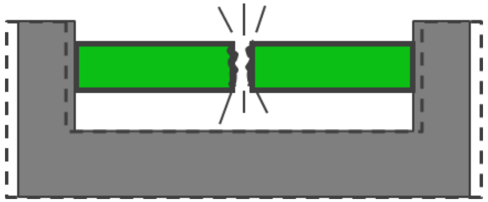


Part B: Invar

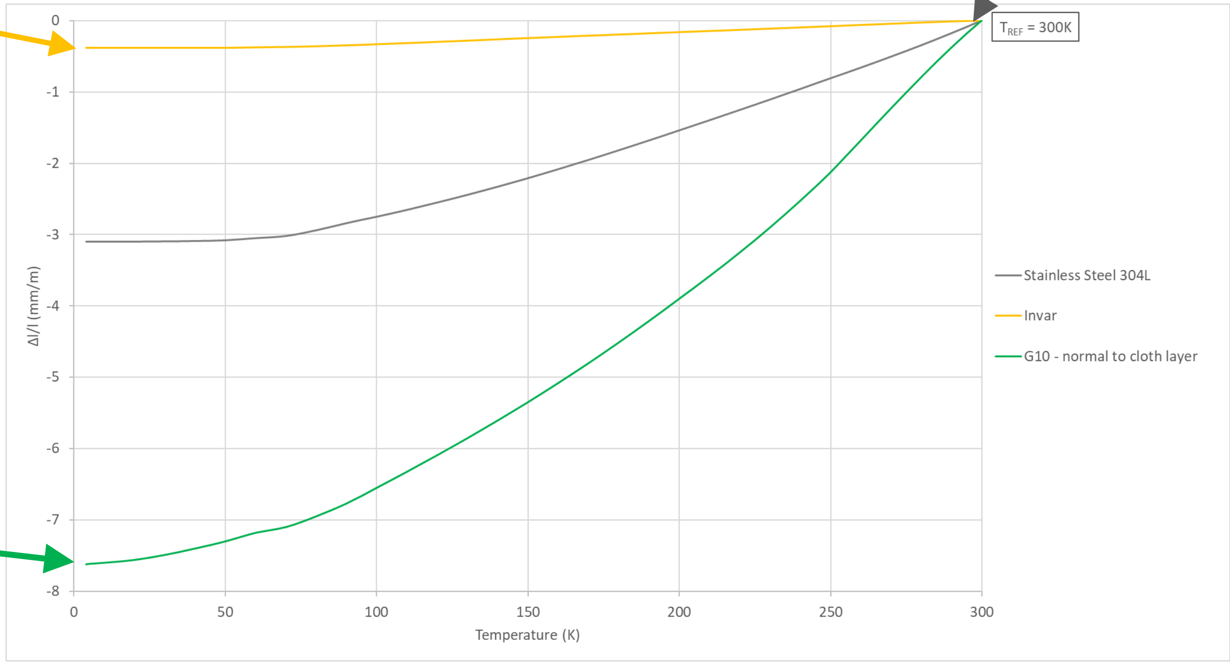


- Compression of the invar part that could lead to buckling

Part B: G10



- Strain in the G10 part
- If stress over the yield stress: plastic deformation, fracture

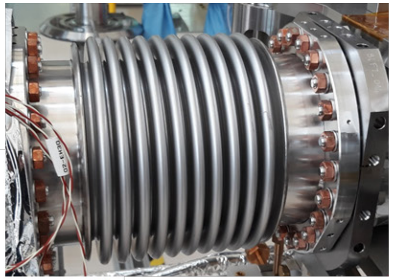


These two cases must be avoided → **For assembly of two materials with large difference in the expansion coefficient, bellows shall be used.**

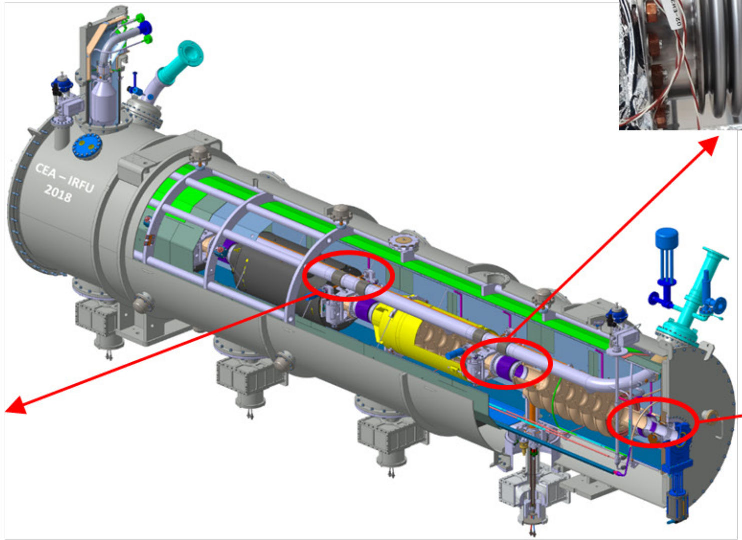
Bellows

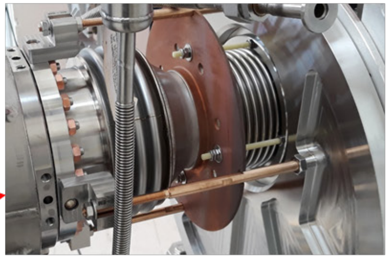
- Bellows are used in many places in a cryomodule as they have several advantages:
  - They accommodate thermal expansion and contraction during warm-up and cool down.
  - They allow some adjusting capability during alignment.
  - They ease the assembly and make up small differences in pipe locations.

- Example of the ESS cryomodule:



Bellows between two cavities





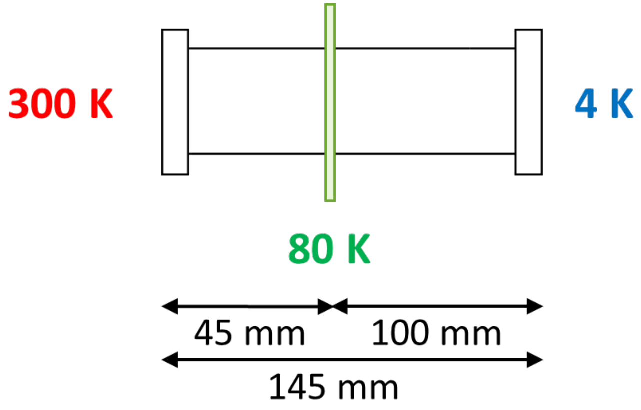
Bellows on the cold to warm transition

Bellows on the 2-phase pipe

Bellows are like springs!
When extended or compressed from its "relaxed" position, a force is inducted, given by the Hooke's law: $F = k.\Delta l$ where k is the stiffness (in N/mm).

Bellows

- Bellows are also useful to limit the thermal load, as length of the thermal path is longer than a straight tube
  - Case study 1: straight tube



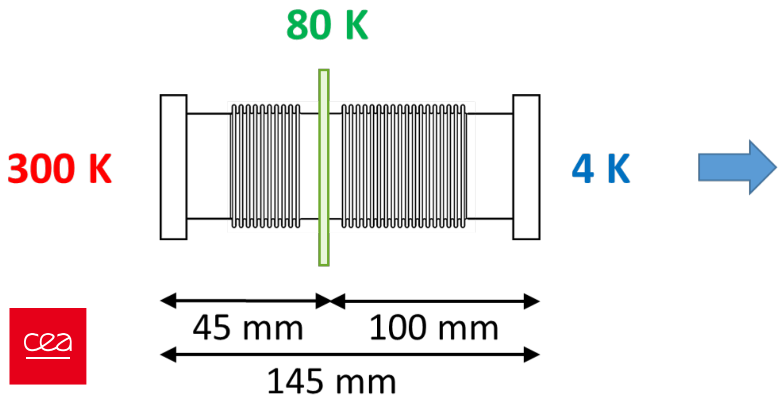
- Internal diameter = 40 mm
- Thickness = 0.15 mm

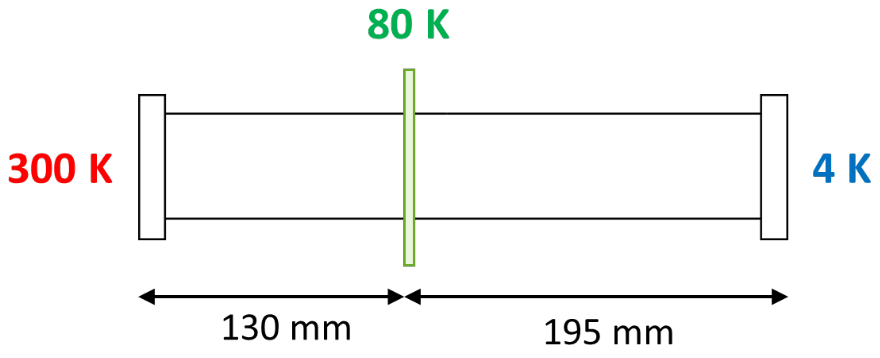
$$\int_{80K}^{300K} k_{SS304}(T).dT = 2727\ W.m^{-1}$$

$$\int_{4K}^{80K} k_{SS304}(T).dT = 349.6\ W.m^{-1}$$

$$Q_{80K} = 1146\ mW \qquad Q_{4K} = 66\ mW$$

- Case study 2: tube with bellows





$$Q_{80K} = 397\ mW$$

$$Q_{4K} = 35\ mW$$

Supporting the Cold Mass

Requirements for the supporting system

- Thermal transition from the room temperature vacuum vessel to the helium temperature of the cold mass

→ Heat loads from conduction shall be as small as possible

↳
- Use of materials with low thermal conductivity
- Long supports with small section

- Supporting of heavy devices
- Accurate and reproducible positioning to respect the alignment requirements

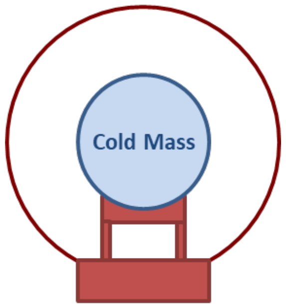
→ High flexural stiffness to limit the mechanical deformations

↳
- Use of Use of materials with low thermal expansion (but often with high thermal conductivity)
- Stiff and massive supports

The design is a trade-off between these conflicting requirements

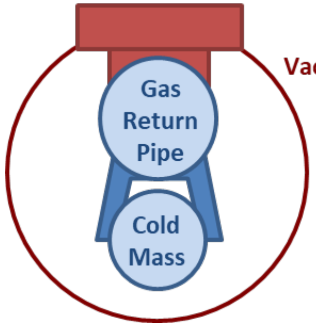
Supporting the Cold Mass: Some Concepts

- Bottom support



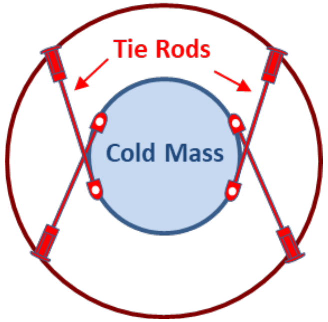
Example: PIP-II, FRIB, SRILAC

- Use the Gas Return Pipe (GRP) as a backbone



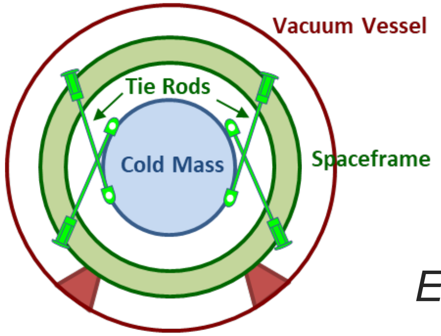
Example: XFEL, LCLS-II

- Use of tie rods
  - Antagonist tie rods



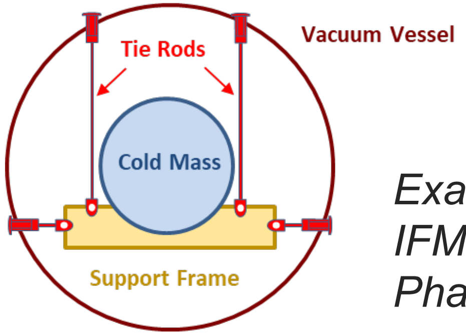
Example: Spiral 2

  - Use an intermediate structure: the "spaceframe"



Example: SNS, ESS

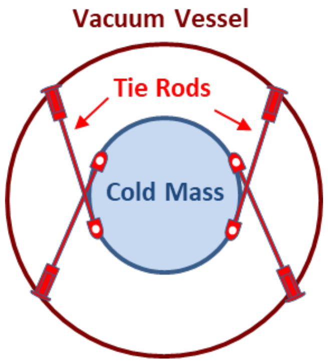
  - Use of a support frame attached to the top of the vacuum vessel

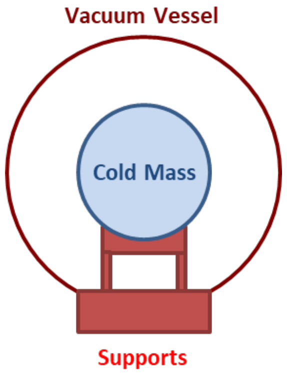


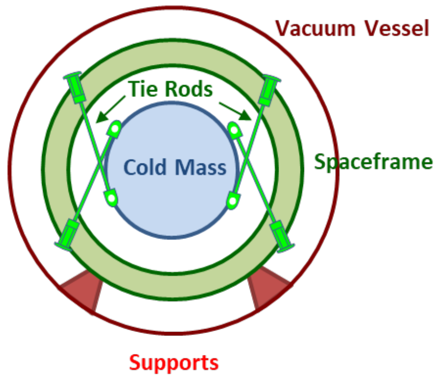
Example: ARIEL, IFMIF, SARAF Phase 2

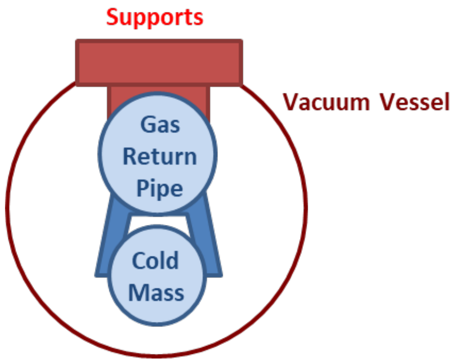
Supporting the Cold Mass: Some Concepts

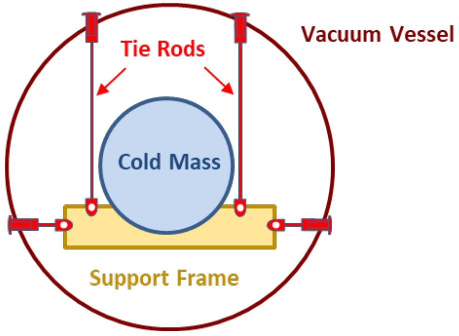
- Each concept has its specific advantages and drawbacks.
- The choice depends on many parameters:
  - the type of cavity
  - the assembly methods
  - the alignment process
  - transportation
  - the experience of the design and assembly teams
  - …





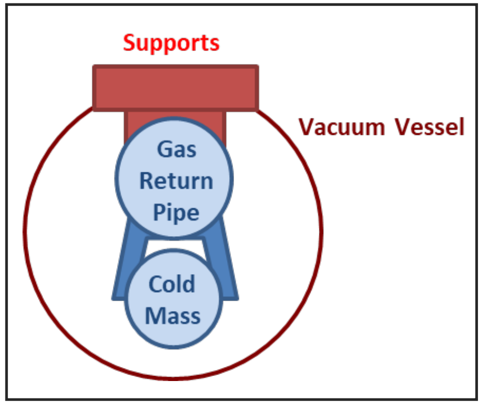






TTF-type Cryomodules (XFEL, LCLS-II, ILC)

- The helium gas return pipe (GRP) is the backbone where all the cavities are connected.
- The GRP is fixed to the vacuum vessel thanks to three composite support posts: a fixed one, the two others allowing sliding in the beam direction.
- An invar rod fixes the longitudinal position of each cavity.
- To deal with the difference of thermal contraction between the stainless steel GRP and the invar rod, the cavities are not directly fixed to the GRP but using sliding supports (C-clamps, that also allow adjusting the vertical and lateral position during the alignment process).



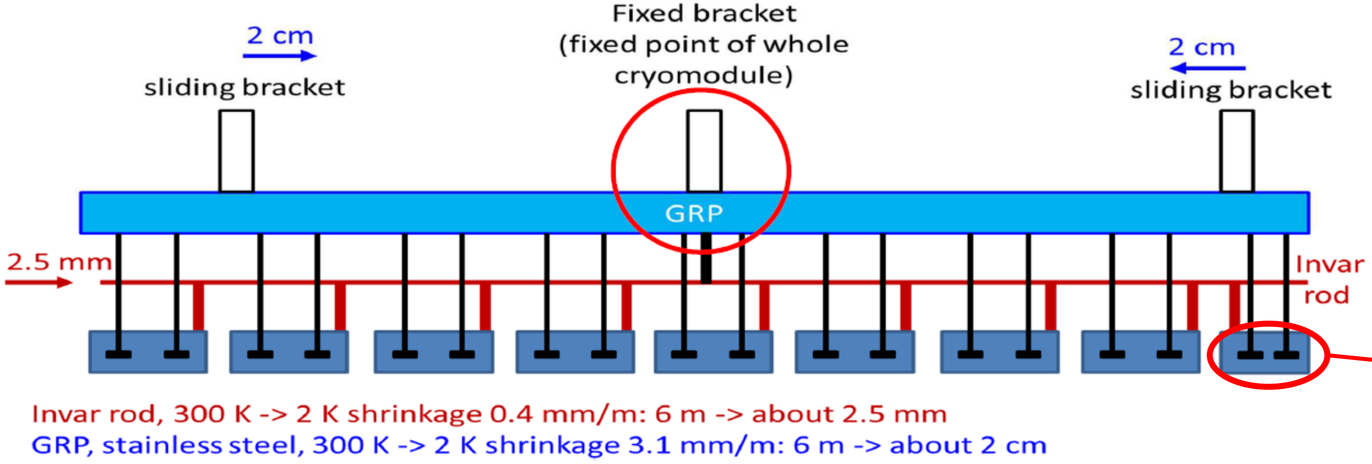
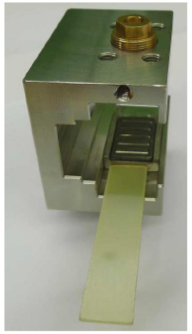
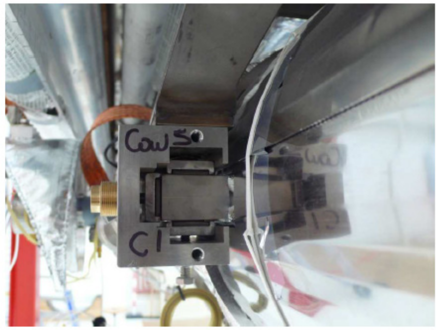


Figure taken from "Fundamentals of Cryomodule Design and Cryogenics", B. Petersen, SRF2019 Tutorial Lecture

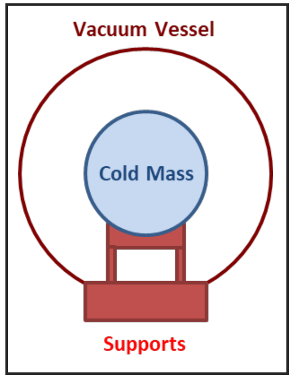


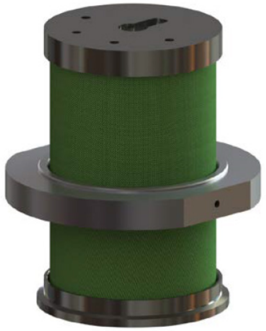


More details on C-clamps in "Advances in cryomodule design and new approaches", C. Pagani, SRF 1999, Berlin, Germany
http://accelconf.web.cern.ch/SRF99/papers/tha005.pdf

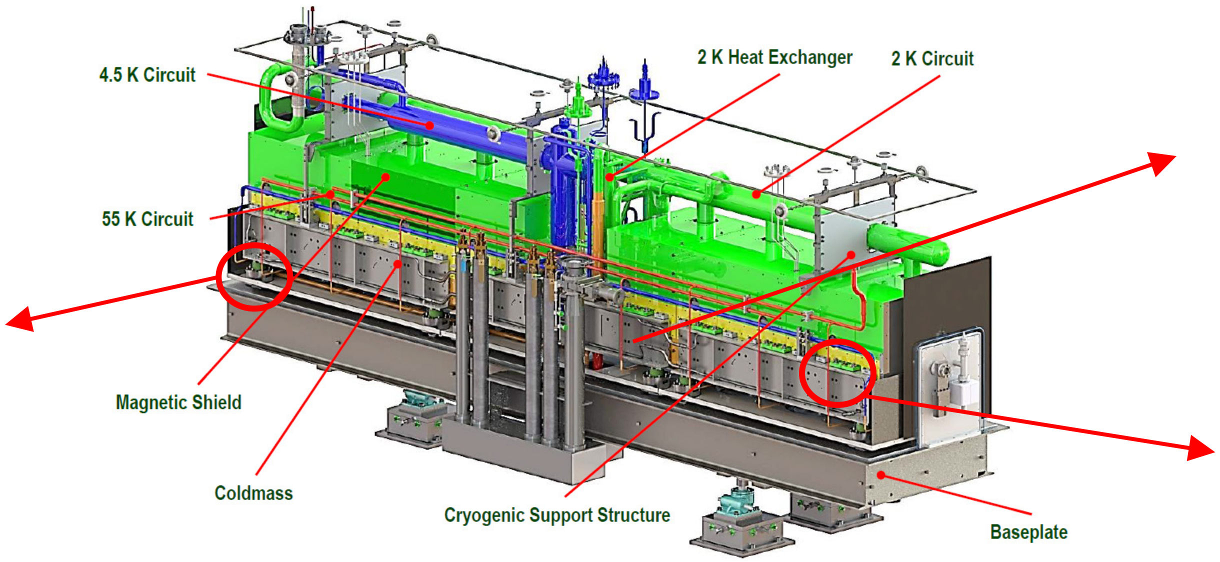
FRIB Cryomodules (MSU)

- Bottom-up design for the six types of cryomodules.
- Rigid baseplate provides stable and reliable platform for the cold mass.
- Cavities and solenoids installed on alignments rails using system providing stress free thermal contraction with significant anti-rocking stiffness.
- Alignment posts fabricated out of low thermal conductivity material (G10) support the rails system.

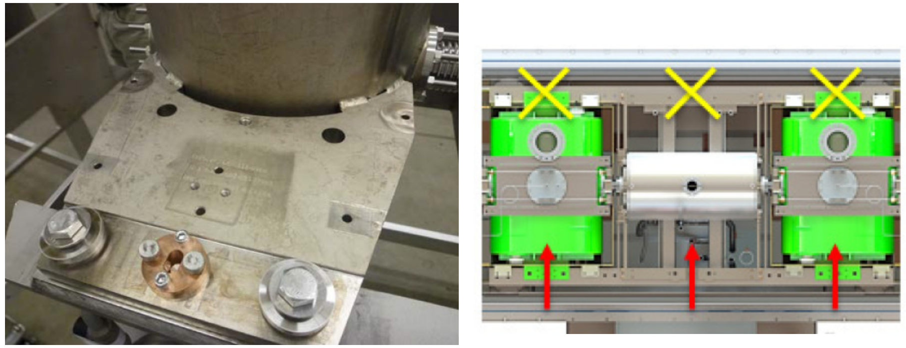




Alignment post



Alignment rail system



Cavity mount

FRIB Cryomodules (MSU)

- The alignment rail system is made of several modules, depending on the type of cryomodule.
- Each module is supported by 4 or 6 G-10 posts: one fixed, the others allowing sliding in one or two directions.

$\beta = 0.041$ QWR cryomodule
1 segment

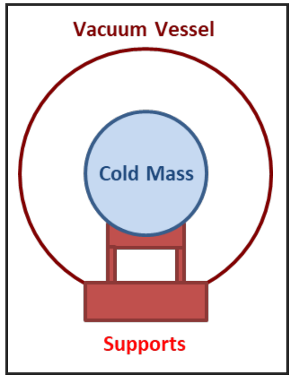
$\beta = 0.085$ QWR cryomodule
3 segments

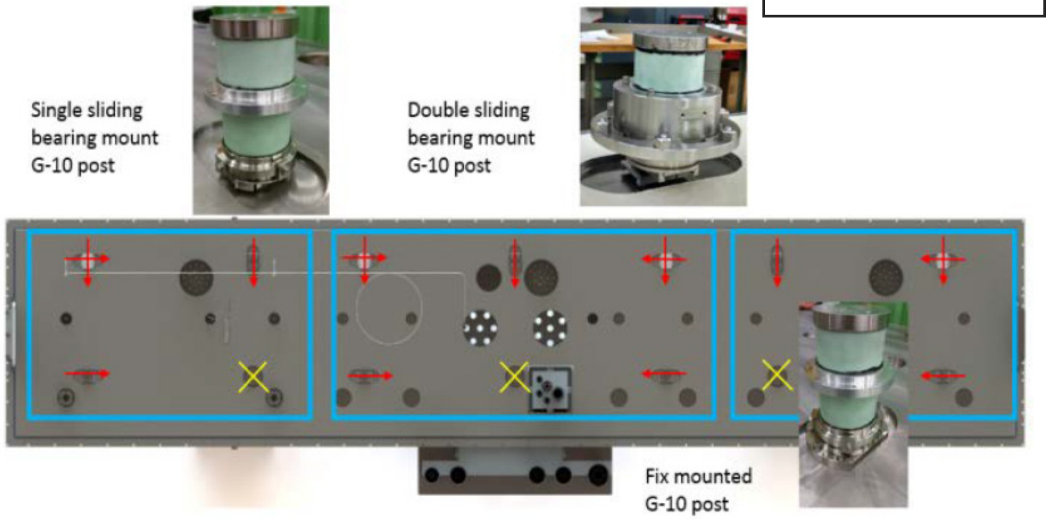
$\beta = 0.085$ QWR matching cryomodule
1 segments

$\beta = 0.29$ HWR cryomodule
2 segments

$\beta = 0.53$ HWR cryomodule
3 segments

$\beta = 0.53$ HWR matching cryomodule
1 segment

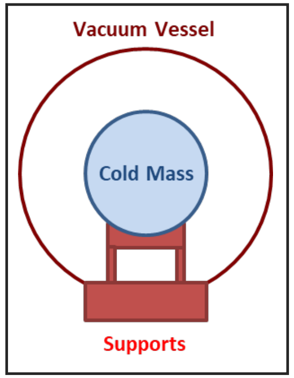


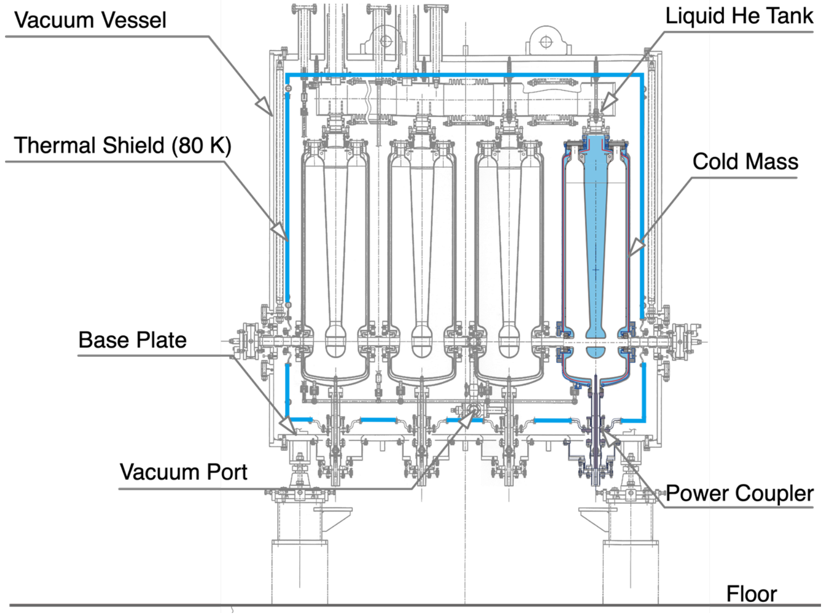


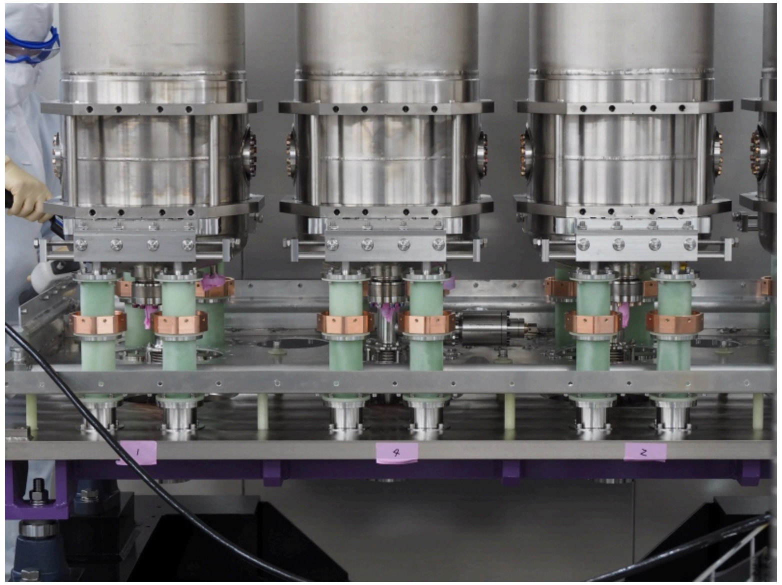
More details in "FRIB Cavity and Cryomodule Performance, Comparison with the Design and Lessons Learned", S. Miller, presentation at the 19th International Conference on RF Superconductivity (SRF 2019)
http://accelconf.web.cern.ch/srf2019/papers/wetea5.pdf
http://accelconf.web.cern.ch/srf2019/talks/wetea5_talk.pdf

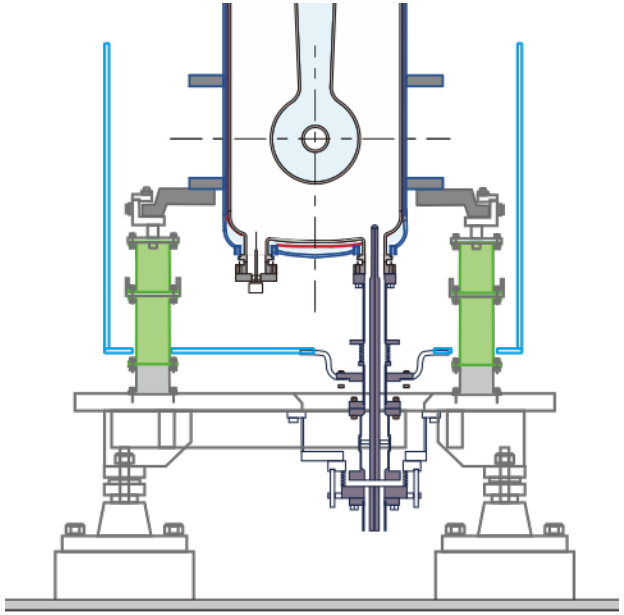
SRILAC cryomodules (RIKEN)

- Each cavity is supported by four pillars fixed to the base plate of the vacuum vessel.
- The pillars are made of low thermal conductivity material (G10) and are heat sunk on the thermal shield.
- The cavity can move freely on the plates supported by the pillars. Rods push the cavity towards one corner so that this one is at the right position after cool down.



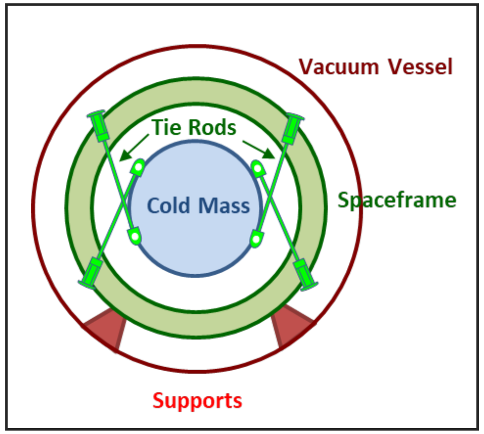




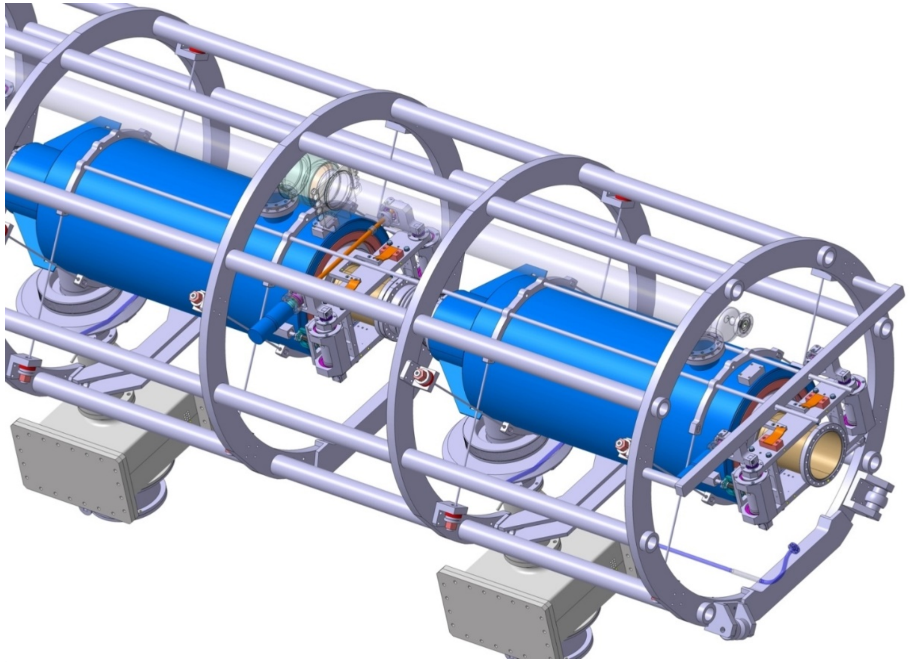


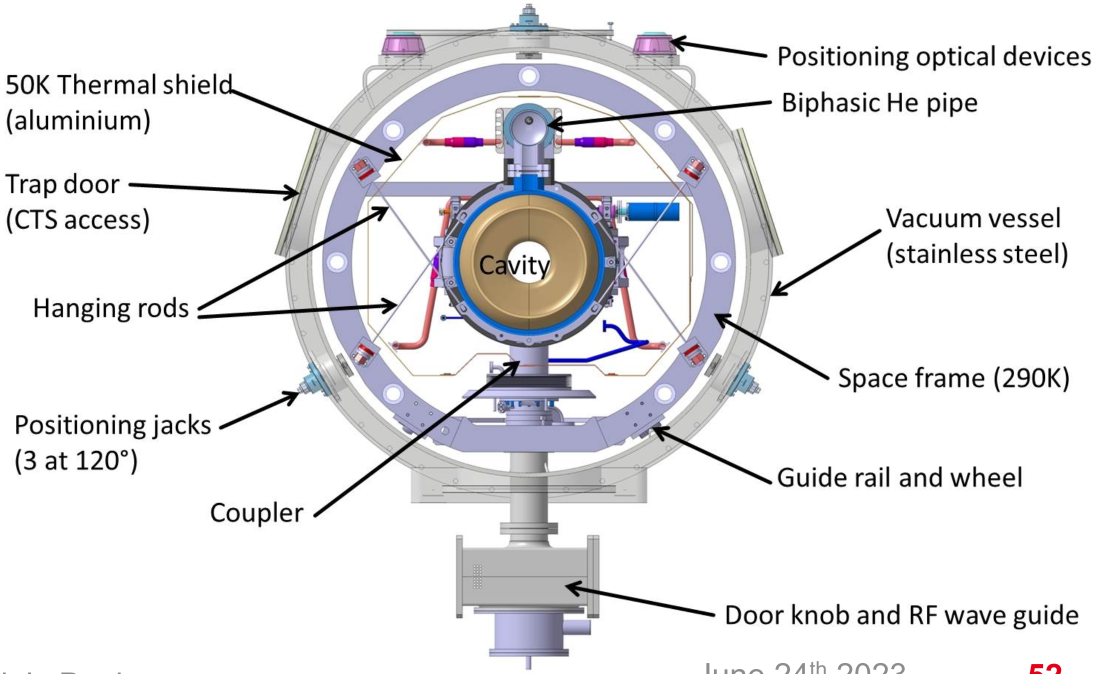
More details in "Development of SC-QWR and its cryomodule for low-beta ion accelerators at RIKEN RIBF", N. Sakamoto, presentation at the 19th International Conference on RF Superconductivity (SRF 2019)
http://accelconf.web.cern.ch/srf2019/papers/weteb1.pdf *http://accelconf.web.cern.ch/srf2019/talks/weteb1_talk.pdf*

ESS Elliptical Cryomodules (CEA – CNRS)



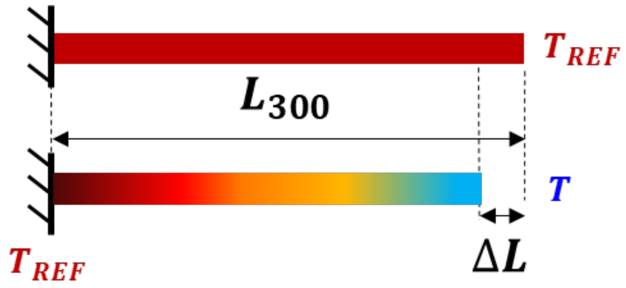
- Spaceframe design similar to CEBAF / SNS cryomodules: the cold mass is attached to a structure that remains at room temperature.
- Jacks to position the spaceframe with the cold mass inside the vacuum vessel.
- Each cavity is attached to the spaceframe thanks to eight tie rods.
- Principle of antagonist tie rods, with preloading to compensate difference in thermal expansion → no motion of the cavity in transverse direction during cool down.
- The longitudinal position (along the beam axis) is fixed by the power coupler.



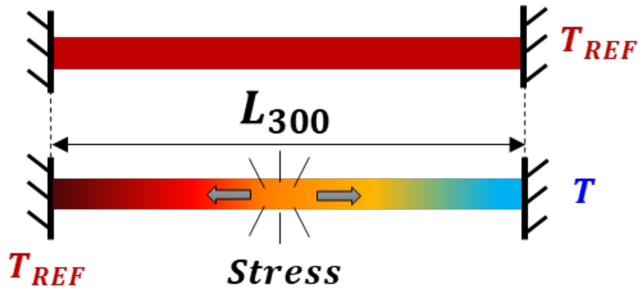


Thermal Stress

- Rod with one free end: the rod shrinks

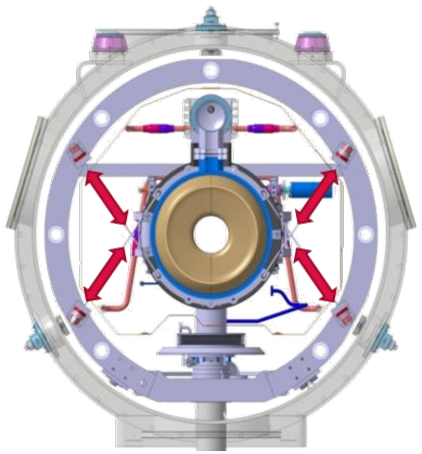


- Rod fixed on both ends: the rod cannot shrink, restricted contraction "converted" to thermal stress σ_{therm}



$$\sigma_{therm} = E\,\frac{\Delta L}{L_{300}}$$

with E = Young's modulus of the material (in *Pa* or *N/m²*)

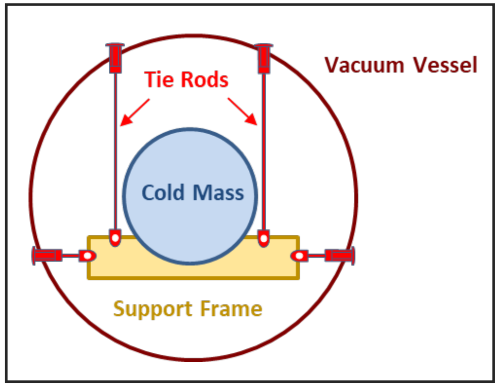


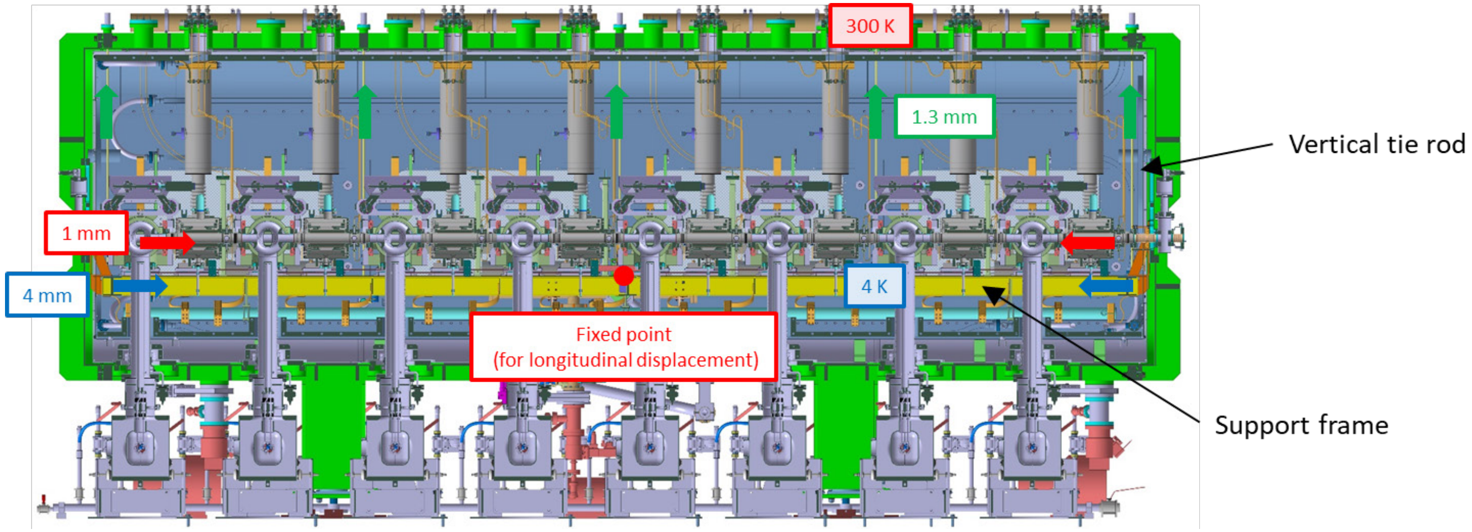
Application

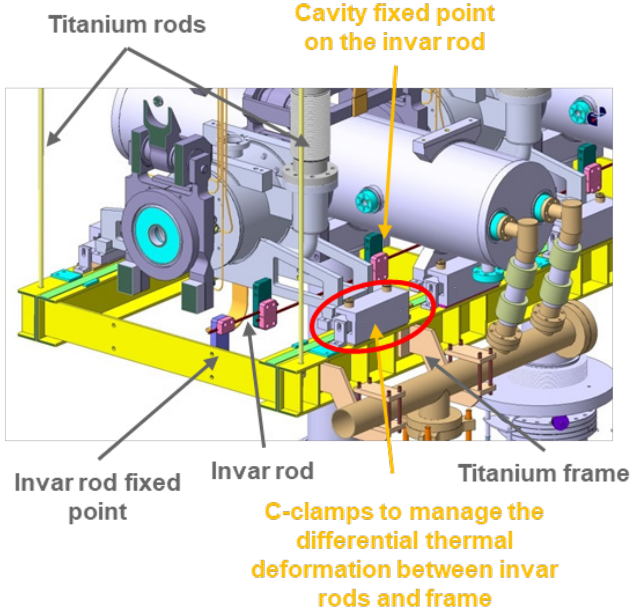
- Principle of antagonist tie rods: as the four rods have the same length and are submitted to the same thermal gradient, the induced thermal force cancel each other out and the cavity does not move during cool down.
- In addition to the strain due to the mass of the components and the preloading, the thermal stress shall be taken into account when setting the section of the tie rods to be sure that the yield strength is not exceeded.

IFMIF-LIPAc cryomodule (CEA)

- Cold mass suspended to the top of the vacuum vessel using 10 vertical tie rods made of titanium alloy (TA6V).
- Due to the thermal shrinkage of the tie rods, the cavity string is positioned at warm 1.3 mm below the beam axis.
- A titanium frame supports the cavities and solenoids.
- Cavities and solenoids not directly fixed to the frame but to an invar rod that fixes the longitudinal position. C-clamps are used (principle similar to TTF-type cryomodule).
- Four horizontal antagonist tie rods to position the cold mass in the horizontal plane of the vacuum vessel.

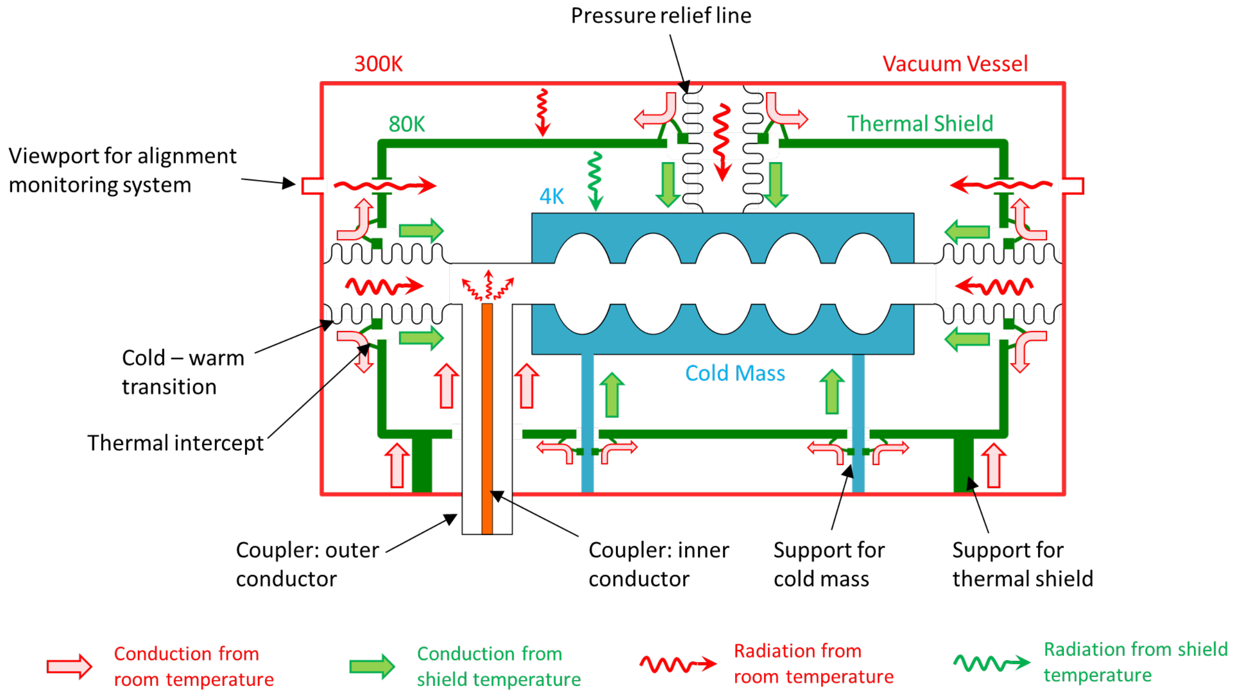






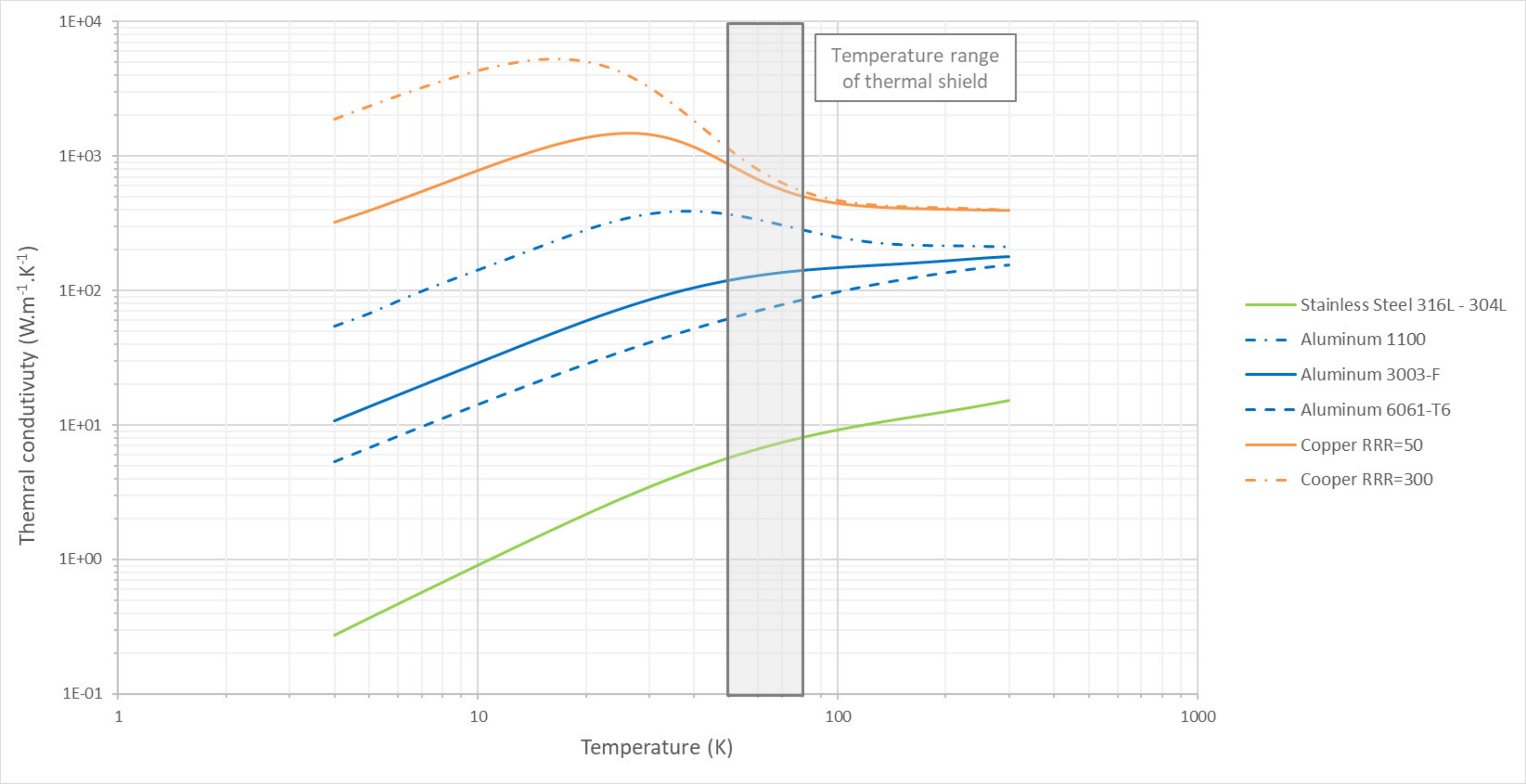
Thermal Shield

- Thermal shield(s) intercept the heat radiated from the surfaces of the components higher than the operating temperature of the superconducting devices.
- It is also provides thermal interception for all penetrations (cavity supporting system, power couplers, cold – war transitions, cables …).
- There is always a thermal shield operating in the 50-80 K range (depending on the cryogenic system).
- There is sometimes a second shield (or a low temperature thermal source) in the 5-20 K range.



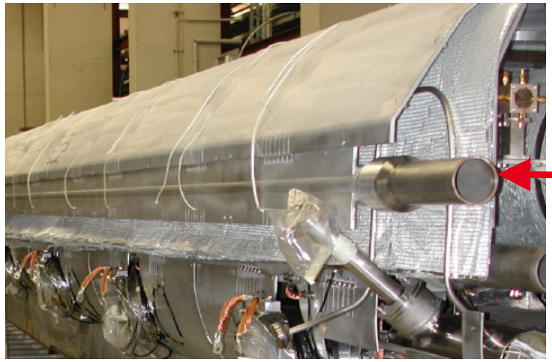
Thermal Shield: Material Choice

- The material shall have a good thermal conductivity at the operating temperature of the shield → aluminum and copper are usually used.
- For high temperature shield (50-80 K), there is no need of high purity copper.
- Aluminum: 1100 is the best, 3003-F and 6061-T6 could also be used.
- Other considerations: cost, weight, structural strength, attachment needs, ease of fabrication …



Thermal Shield: Design

Aluminum Shield
TTF Cryomodules



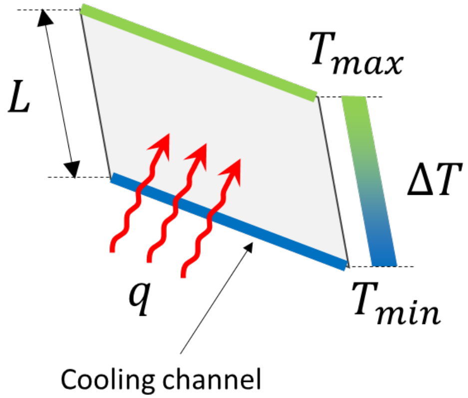
Cooling pipe

Copper Shield
Spiral2 Cryomodules

- Possibility to use analytical models to quickly assess the maximum temperature, the thickness of the shield or the location of the cooling pipes.
- FEM (Finite Element Method) analysis is used :
  - For complex geometry.
  - To check that local heat loads do no create unacceptable hot points.
  - To study the cool down of the shield (transient analysis), taking into account the fluid mass flow inside the cooling pipes.

Thermal Shield: Analytical Calculation

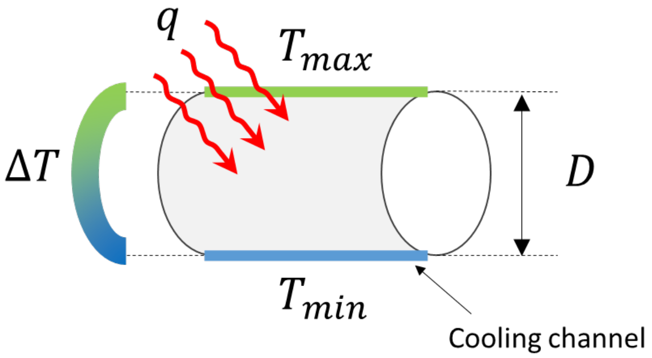
- Analytical calculations on simple models could be used to assess the thermal gradient (if thickness is fixed) or minimum thickness (if maximum gradient is fixed).
- Thermal gradient in a plate with an active cooling on one side:



$$\Delta T = \frac{qL^2}{2kt}$$ with

t: thickness of the plate
q: unifor heat deposition (W/m^2)
k: average heat conductivity between T_{min} and T_{max} ($W.m^{-1}.K^{-1}$)

- Thermal gradient in an open cylinder with one active longitudinal cooling channel:

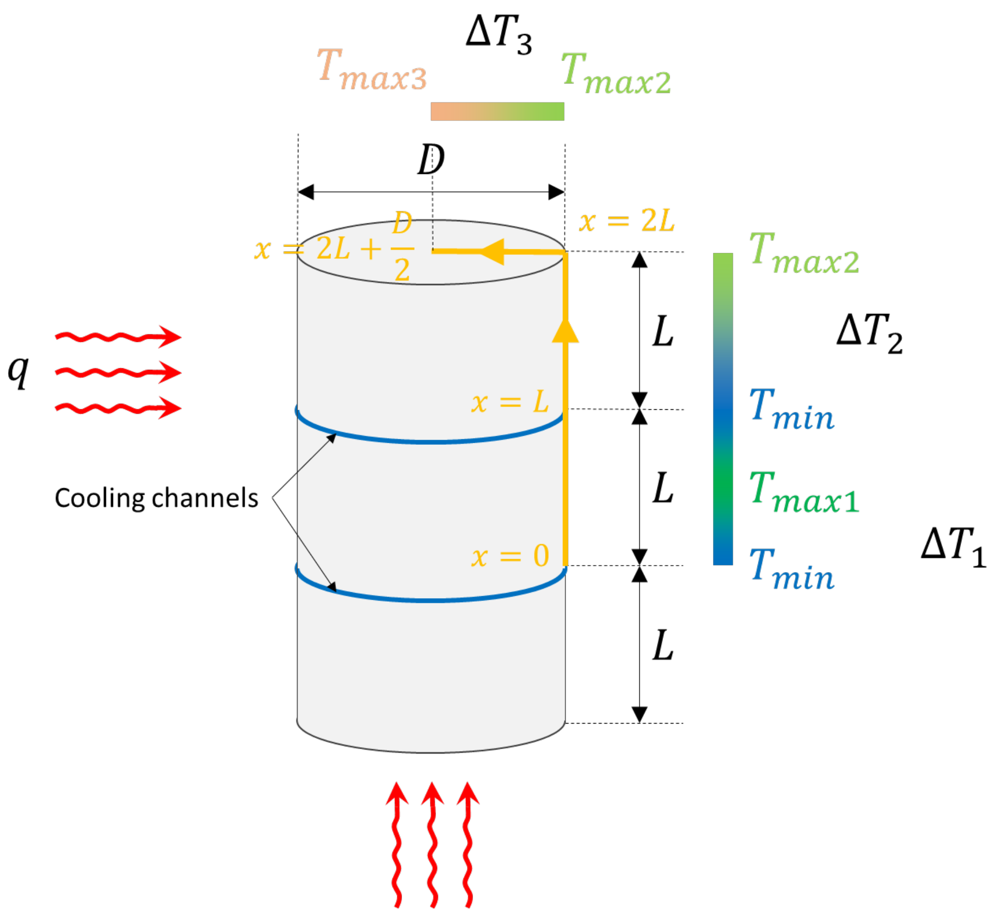


$$\Delta T = \frac{q\pi^2 L^2}{8kt}$$ with

D: diameter of the cylinder
t: thickness of the cylinder

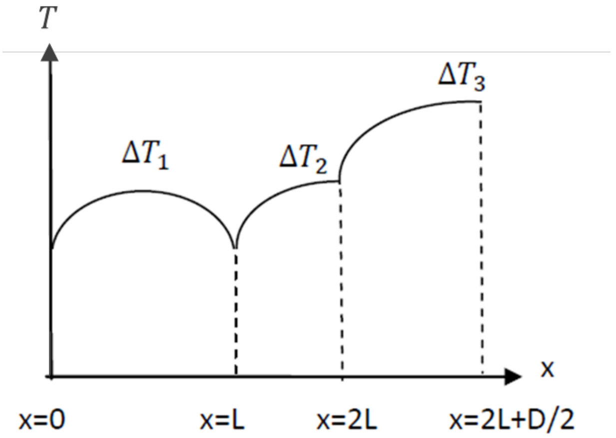
Thermal Shield: Analytical Calculation

- Cylindrical thermal shield with radial cooling channels:



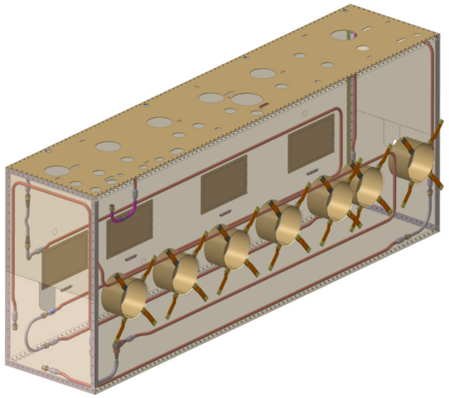
t: thickness of the cylinder and the end plates
q: uniform heat deposition on all surfaces of the cylinder (W/m^2)
k: average heat conductivity between T_{min} and T_{max} ($W.m^{-1}.K^{-1}$)

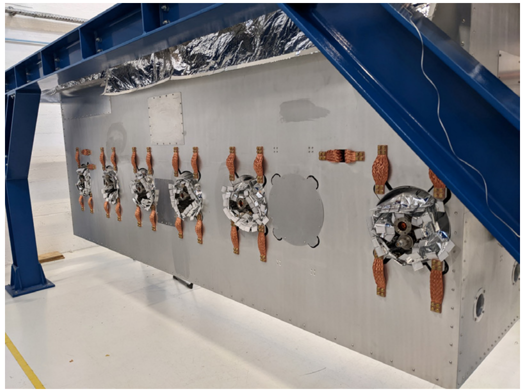
- Cylinder with fixed temperature on both ends: $\Delta T_1 = \frac{qL^2}{8kt}$
- Close cylinder with fixed temperature on one end: $\Delta T_2 = \frac{qL^2}{2kt} + \frac{qDL}{4kt}$
- Circular plate: $\Delta T_3 = \frac{qD^2}{16kt}$
- Temperature profile:



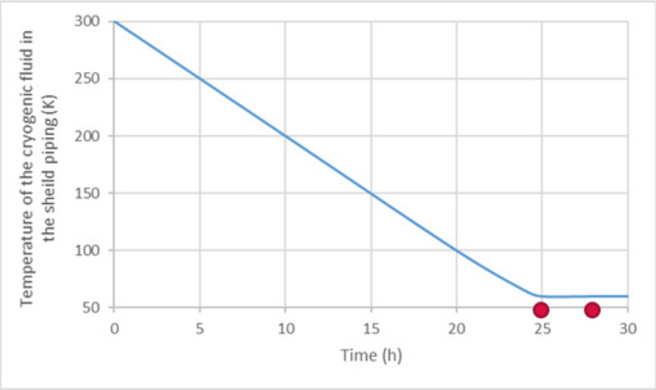
Thermal Shield: FEM Study

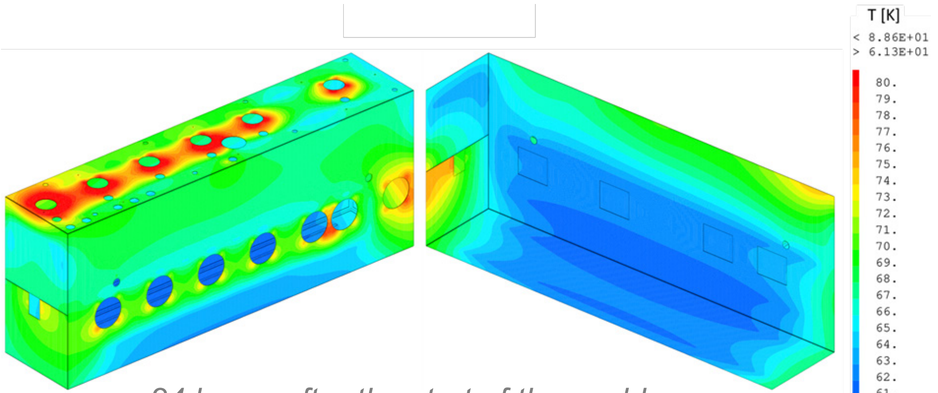
Example: SARAF Phase 2 cryomodule



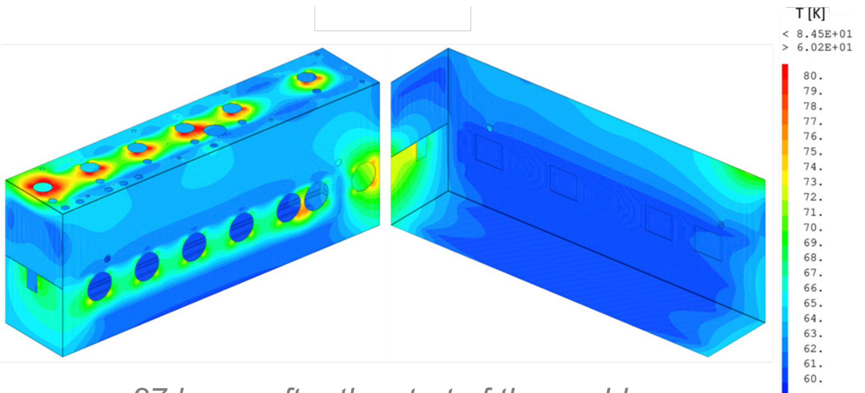


- Thermal shield made of 4-mm thick aluminum 6061-T6 panels.
- In addition to the uniform radiative heat loads on every panels, local heat loads where the thermal intercepts are fixed (power couplers, cold – warm transition, tie rods, current lead clusters, cabling).
- Time depend temperature of the cryogenic coolant fluid: 24 hours from room temperature to 50 K.
- Steady-state 27 hours after the start of the cooldown.





24 hours after the start of the cooldown

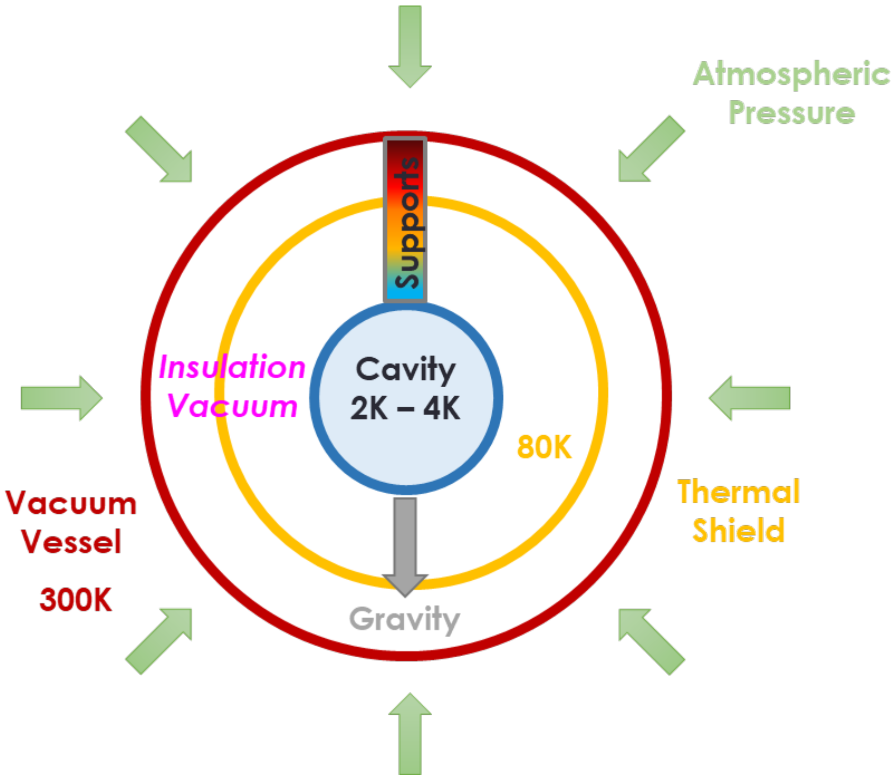


27 hours after the start of the cooldown

Vacuum Vessel

Main requirements

- Shall sustain the atmospheric pressure with vacuum inside (generally in the 10^{-6} mbar range)
- Shall sustain the mass of the components
- Shall sustain the internal overpressure in case of an accident*

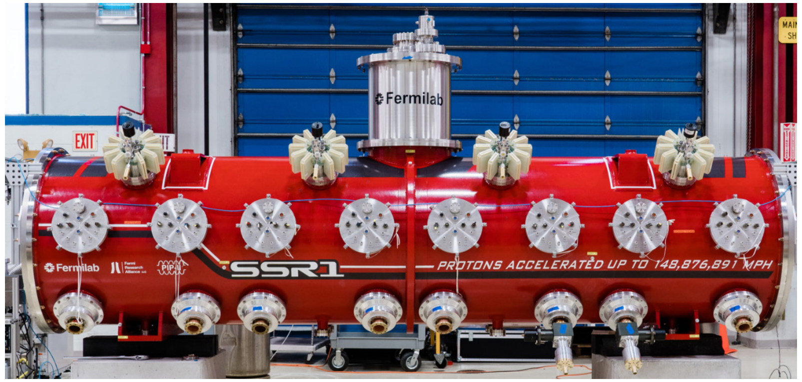


* A pressure relief device (PRD) is usually installed on the vacuum pressure to prevent overpressure. This is not the sizing scenario as the differential pressure is often below 500 mbar.

Vacuum Vessel

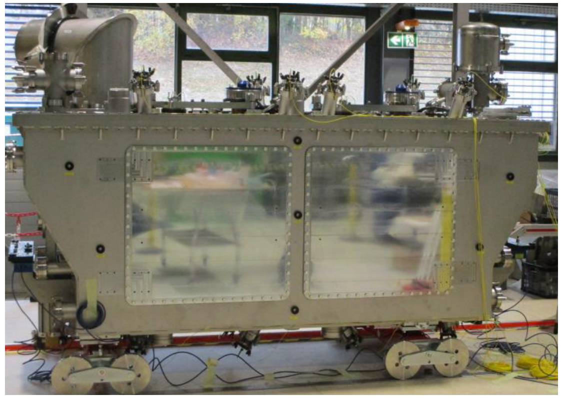
Secondary requirements

- Deformation on the connection points of the cold mass supporting system shall be small to limit the impact on the alignment of the cavity string.
- Think about maintainability! Place trapdoors to access the components of the cold mass that could failed and need to be replaced: motors of tuning systems, temperature sensors, heaters … It prevents from disconnecting the cryomodule from the beam line and the ancillaries systems and from removing the cold mass from the vacuum vessel.



Cylindrical vacuum vessel

PIP-II SSR1 cryomodule (FNAL)

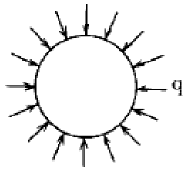
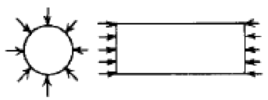


Parallelepiped vacuum vessel

DWQ cryomodule (CERN)

Cylindrical Vacuum Vessel: Roak's Formulas - Buckling

- Formula to quickly assess the buckling pressure of a thin tube:

19. Thin tube under uniform lateral external pressure (radius of tube $= r$)  $\frac{r}{t} > 10$	19a. Very long tube with free ends; length l	$q' = \frac{1}{4}\frac{E}{1-\nu^2}\frac{t^3}{r^3}$ Applicable when $l > 4.90r\sqrt{\frac{r}{t}}$ (Ref. 19)
	19b. Short tube, of length l, ends held circular, but not otherwise constrained, or long tube held circular at intervals l	$q' = 0.807\frac{Et^2}{lr}\sqrt[4]{\left(\frac{1}{1-\nu^2}\right)^3\frac{t^2}{r^2}}$ approximate formula (Ref. 19)
20. Thin tube with closed ends under uniform external pressure, lateral and longitudinal (length of tube $= l$; radius of tube $= r$)  $\frac{r}{t} > 10$	20a. Ends held circular	$q' = \frac{E\frac{t}{r}}{1+\frac{1}{2}\left(\frac{\pi r}{nl}\right)^2}\left\{\frac{1}{n^2\left[1+\left(\frac{nl}{\pi r}\right)^2\right]^2} + \frac{n^2t^2}{12r^2(1-\nu^2)}\left[1+\left(\frac{\pi r}{nl}\right)^2\right]^2\right\}$ (Refs. 19, 20) where $n =$ number of lobes formed by the tube in buckling. To determine q' for tubes of a given t/r, plot a group of curves, one curve for each integral value of n of 2 or more, with l/r as ordinates and q' as abscissa; that curve of the group which gives the least value of q' is then used to find the q' corresponding to a given l/r. If $60 < \left(\frac{l}{r}\right)^2\left(\frac{r}{t}\right) < 2.5\left(\frac{r}{t}\right)^2$, the critical pressure can be approximated by $q' = \frac{0.92E}{\left(\frac{l}{r}\right)\left(\frac{r}{t}\right)^{2.5}}$ (Ref. 81) For other approximations see ref. 109 Values of experimentally determined critical pressures range 20% above and below the theoretical values given by the expressions above. A recommended probable minimum critical pressure is $0.80q'$.

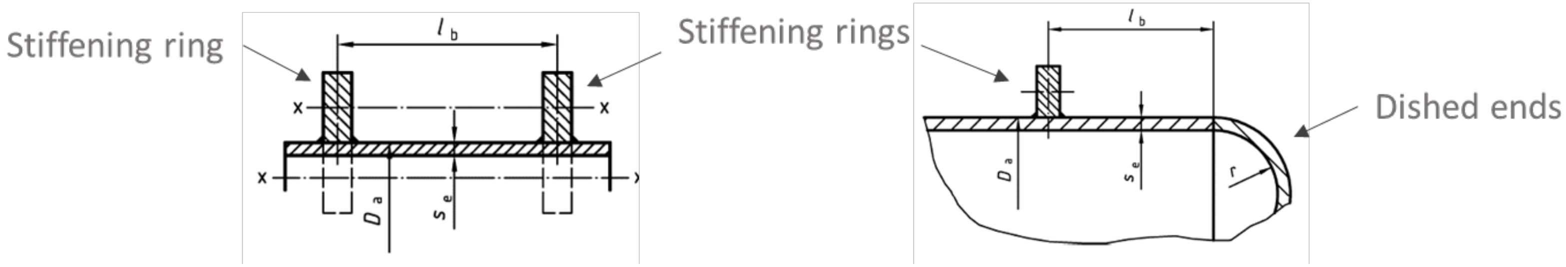
q' = critical pressure
ν = Poisson's ratio
E = modulus of elasticity
t = thickness

From "Roark's Formulas for Stress and Strain", Warren C. Young, Richard G. Budynas, Seventh Edition

- In practice, vacuum vessel shall respect the pressure vessel regulation and local codes and standards shall be applied: ASME Boiler and Pressure Vessel Code (BPVC) in North America, EN 13458-2 (Cryogenic Vessels – Static vacuum insulated vessels), EN 13445 (Unfired Pressure Vessels) in Europe, CODAP in France …

EN 13458-2 (Cryogenic Vessels – Static vacuum insulated vessels)

- The European Standard EN 13458-2 provides formula to assess in the critical pressure P_c for elastic buckling and for plastic deformation, depending on the vessel dimensions (diameter D_a, thickness s_e, length of buckling l_b).
- The length of buckling l_b depends on the geometry of the vessel and if stiffening rings are implemented.



- The standard also provides formula to size the stiffening rings (minimum moment of inertia and area), the openings, the ends (flat or dished), the nozzles.
- But the deformations calculated by the formula given by the codes and standards are usually higher than the acceptable values for the connection points of the cold mass supporting system

Vacuum vessel for cryomodules = not only a cryogenic vessel as defined by the codes standards, but also part of the alignment system of the cavity string.

- EN 13458-2 allows FEM analysis and provides the methodology and the stress categories (general primary membrane stress, local primary membrane stress, primary bending stress, secondary stress).

Analytical Case Study: PIP-II LB650 Vacuum Vessel

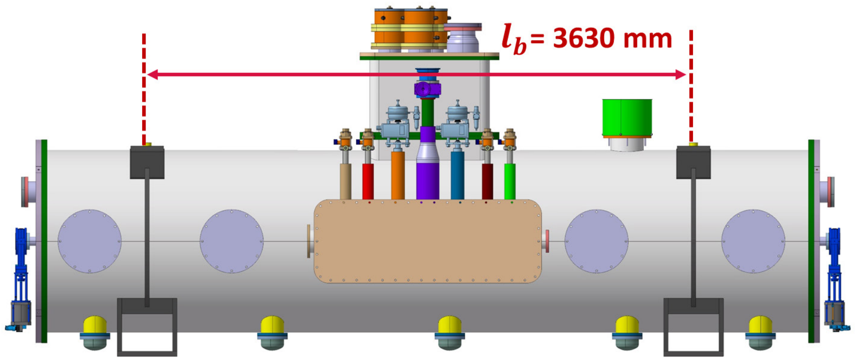
- PIP-II LB650 Vacuum Vessel:
  - 1.2 meter diameter tube, 5.25 meter long. Material: carbon steel P355gh.
  - Safety factor = 3 → critical pressure must be over 3 bar.
- Critical pressure for different length of buckling l_b and vessel thickness s according EN 13458-2:
  - Plastic deformation

s \ l_b	1500 mm	2000 mm	2600 mm	3630 mm	3950 mm	5250 mm
5 mm	3.7 bar	3.5 bar	3.5 bar	3.4 bar	3.4 bar	3.3 bar
6 mm	5.2 bar	5.0 bar	4.9 bar	4.7 bar	4.7 bar	4.7 bar
7 mm	6.9 bar	6.6 bar	6.5 bar	6.3 bar	6.3 bar	6.2 bar
8 mm	8.8 bar	8.4 bar	8.2 bar	8.0 bar	8.0 bar	7.9 bar
9 mm	10.8 bar	10.4 bar	10.2 bar	9.9 bar	9.9 bar	9.8 bar
10 mm	13.1 bar	12.6 bar	12.3 bar	12.0 bar	12.0 bar	11.8 bar

  - Elastic buckling

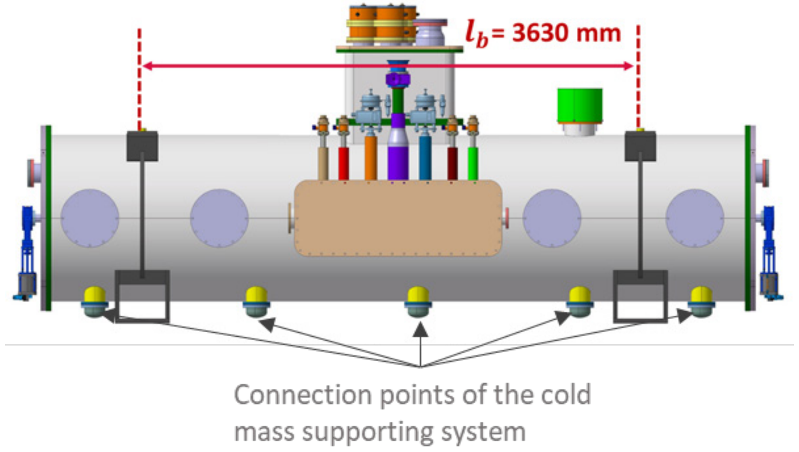
s \ l_b	1500 mm	2000 mm	2600 mm	3630 mm	3950 mm	5250 mm
5 mm	2.5 bar	1.9 bar	1.5 bar	1.0 bar	1.0 bar	0.7 bar
6 mm	4.1 bar	2.97 bar	2.3 bar	1.7 bar	1.6 bar	1.1 bar
7 mm	6.0 bar	4.5 bar	3.3 bar	2.5 bar	2.3 bar	1.6 bar
8 mm	8.2 bar	6.5 bar	4.6 bar	3.5 bar	3.0 bar	2.2 bar
9 mm	11.0 bar	8.4 bar	6.2 bar	4.5 bar	4.0 bar	3.0 bar
10 mm	14.5 bar	10.7 bar	8.2 bar	5.7 bar	5.1 bar	4.0 bar

- Discussion:
  - 6-mm thick vessel if three stiffening rings equally distributed.
  - 7-mm thick vessel with only central stiffening ring is possible.
  - As it is difficult to implement a central stiffening ring due to the side and top ports, it was decided to have two rings. Because of the other ports, these ones are spaced by 3630 mm → minimum thickness = 8 mm.



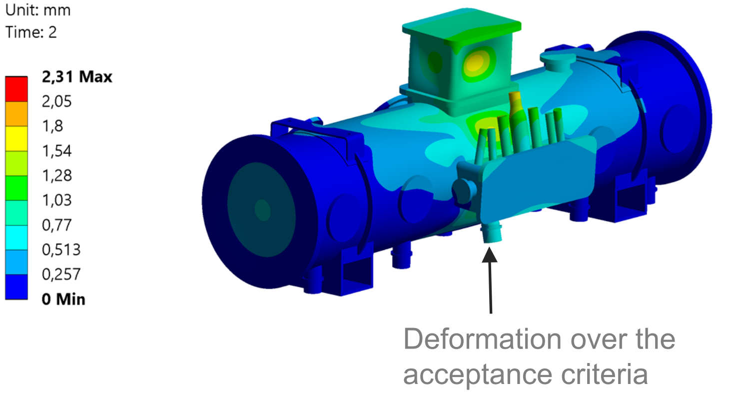
FEM Case Study: PIP-II LB650 Vacuum Vessel

- Acceptance criteria: maximal deformation of the connection points of the cold mass supporting system = 0.5 mm.

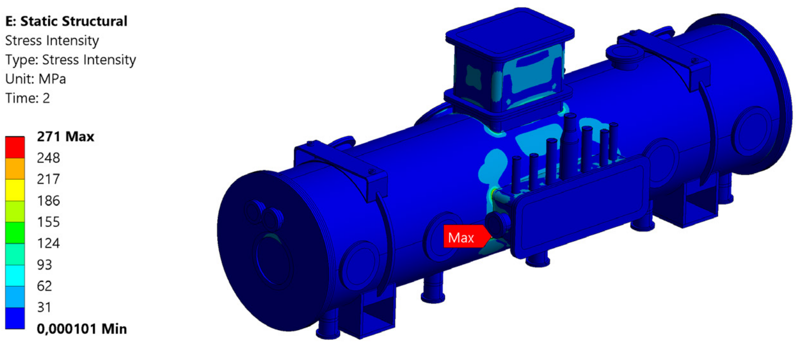


- FEM analysis performed on the vacuum vessel (preliminary design)
  - 8-mm thick vessel (minimum thickness given by analytical calculations) = deformation over 0.5 mm
  - 10-mm thick vessel to respect the acceptance criteria

8-mm thick vessel



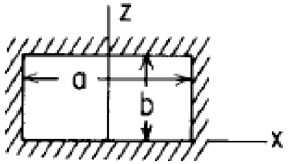
10-mm thick vessel



Parallelepiped Vacuum Vessel: Roak's Formulas

- Analytical calculation for preliminary design: use of the Roak's formula on plate to determine the minimum thickness and the location of the stiffeners.
- Formula to asses the bending stress σ and the maximum deformation y_{max}:

8. Rectangular plate, all edges fixed



8a. Uniform over entire plate

(At center of long edge) $\sigma_{max} = \frac{-\beta_1 q b^2}{t^2}$

(At center) $\sigma = \frac{\beta_2 q b^2}{t^2}$ and $y_{max} = \frac{\alpha q b^4}{E t^3}$

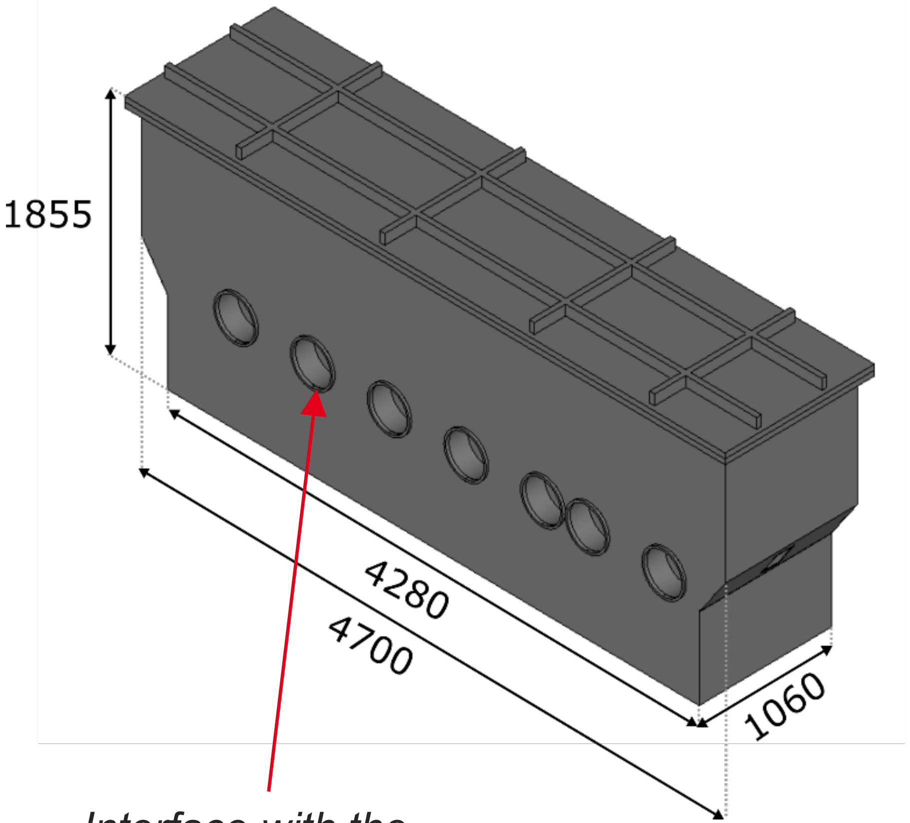
a/b	1.0	1.2	1.4	1.6	1.8	2.0	∞
β_1	0.3078	0.3834	0.4356	0.4680	0.4872	0.4974	0.5000
β_2	0.1386	0.1794	0.2094	0.2286	0.2406	0.2472	0.2500
α	0.0138	0.0188	0.0226	0.0251	0.0267	0.0277	0.0284

E = modulus of elasticity
t = thickness

From "Roark's Formulas for Stress and Strain", Warren C. Young, Richard G. Budynas, Seventh Edition

- Then, perform FEM analysis to demonstrate that the design follows the codes and standards as defined by the pressure vessel regulation.

Analytical Case Study: SARAF Phase 2 Vacuum Vessel



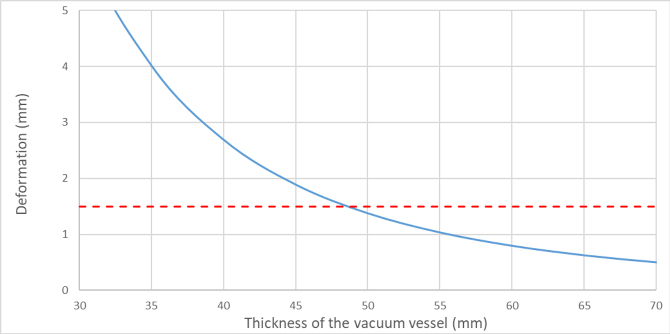
Interface with the power coupler (x8)

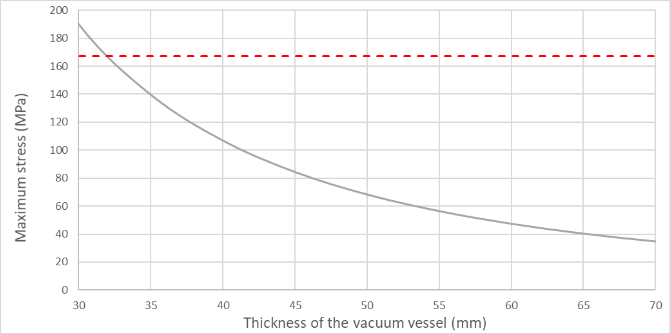
- Requirement on the maximum displacement of the power couplers: below 1.5 mm with vacuum inside the vessel
- Material: stainless steel 304L
- Maximum allowable stress: 167 Mpa
- Young's modulus E: 193 GPa

What is the minimum thickness of the vessel to respect the maximum deformation requirement?

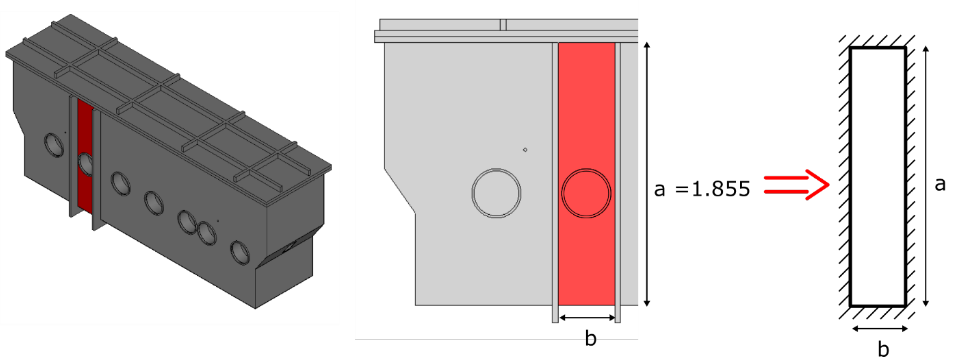
Analytical Case Study: SARAF Phase 2 Vacuum Vessel

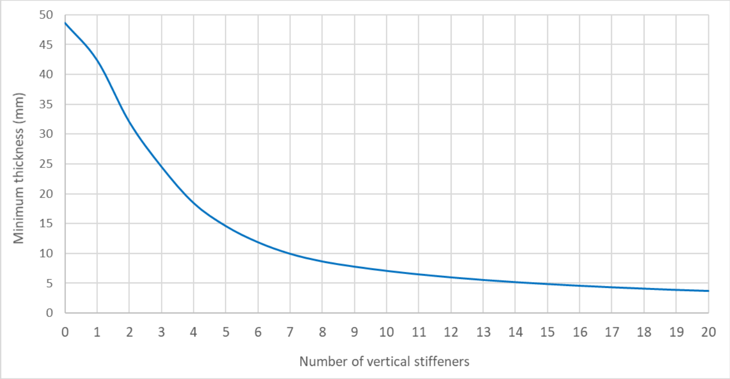
- Roak's formula applied to a 1.85 m x 4.5 m plate:
  - $a/b = 2.43 \rightarrow \alpha = 0.0284$ and $\beta_1 = 0.5$
  - Plate thickness to respect the deformation criteria ≥ 49 mm!
  - Weight ≈ 3270 kg!





- Vertical stiffeners equally distributed along the length:



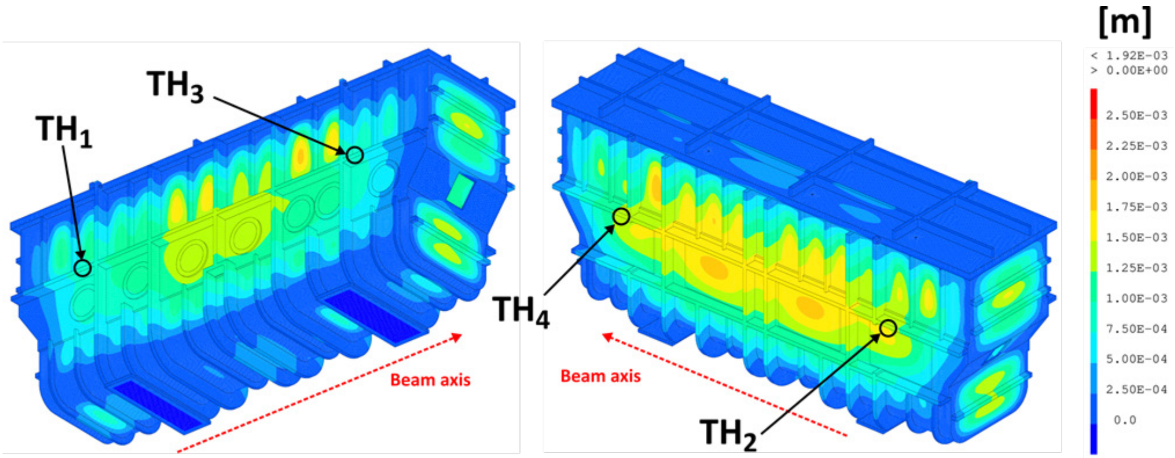


→ 12 stiffeners minimum for a 6-mm thick vessel

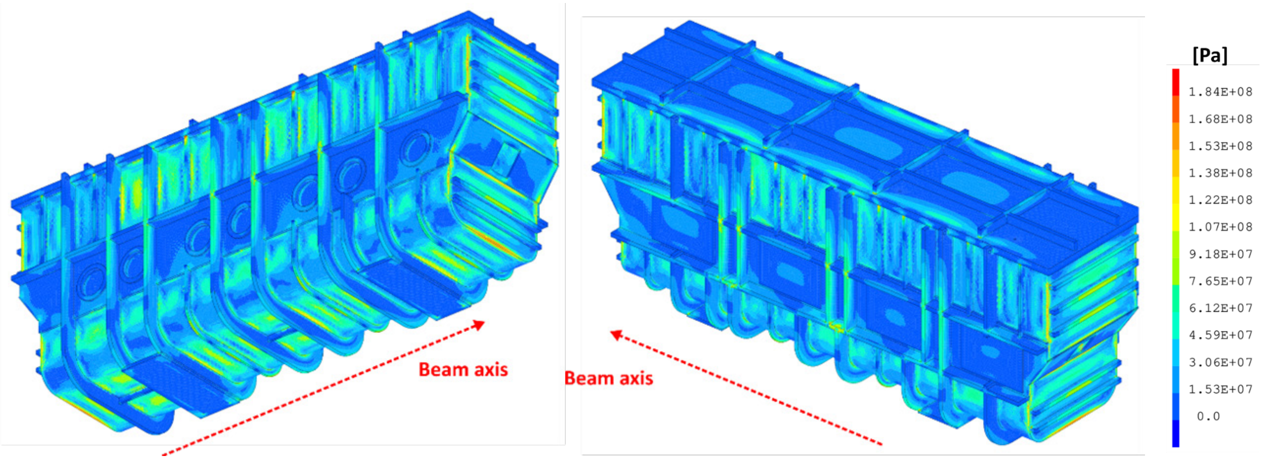
- Same method used to quickly define the thickness and stiffeners for the other panels of the vacuum vessel.

FEM Case Study: SARAF Phase 2 Vacuum Vessel

- Deformation due to an external pressure of 1 bar



- Equivalent Tresca stress



- Elastic stress analysis performed according to the European Standard EN 13458-2. In some areas, stresses locally exceed the maximum admissible stress. The linearization method given by the code is applied to check whether this stress is acceptable or not.

4. Magnetic Shielding Magnetic Hygiene

Motivation

- A superconducting cavity can trap magnetic flux while cooling down through transition, increasing the residual surface resistance of the niobium.
- Reducing the residual resistance from trapped flux becomes increasingly important as cavity performances improve:

$$R_s \downarrow \rightarrow Q_0 \uparrow \rightarrow P_{diss} \downarrow \rightarrow \text{Operating costs} \downarrow$$

⇨ It is mandatory to protect the cavity against the ambient magnetic field

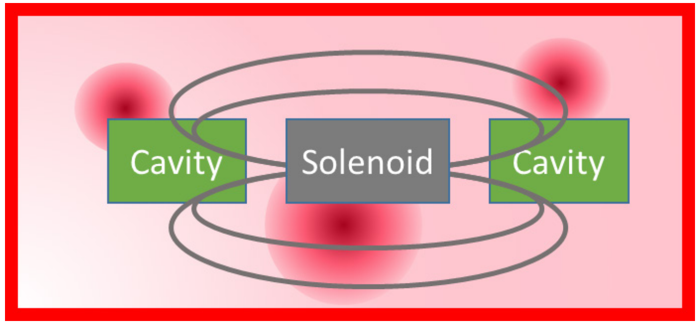
  - Earth's magnetic field
  - Internal magnetic fields: magnetized components, field induced by focusing solenoids

- Residual field on the cavity: example of requirements
  - LCLS-II specification (elliptical cavities – 2K)

    B_{res} < 5 mG (0.5 µT) to reach $Q_0 > 2.7 \times 10^{10}$ @ E_{acc_nom} = 16 MV/m
  - IFMIF specification (half-wave resonator – 4K)

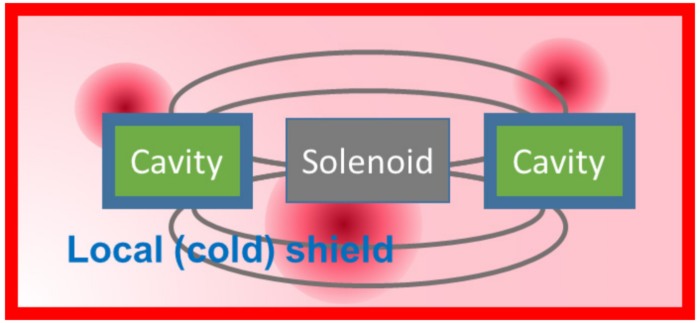
    B_{res} < 20 mG (2 µT) to reach $Q_0 > 5 \times 10^{8}$ @ $_{Eacc\_nom}$ = 4.5 MV/m

How to deal with Superconducting Solenoids?



- Solenoid if strong enough can drive the cavity in normal conducting state
- Solenoid can magnetically pollute the environment
- Solenoid can degrade cavity performance during quench through trapped flux

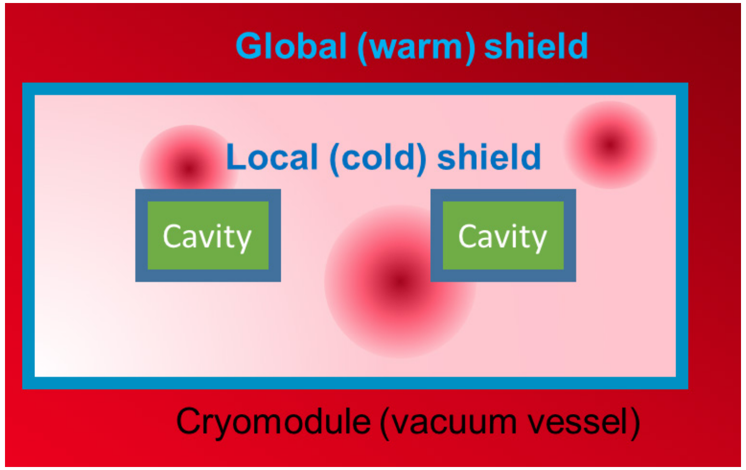
Possible mitigation actions



- Isolate the cavity from the environment → implementing a local shield around the cavity
- Minimize the fringe field of the solenoid → design of the solenoid with active compensation
- Choose material that are not easily magnetized → magnetic hygiene plan
- Degaussing procedure

More details in "Review of the Magnetic Shielding Design of Low-Beta Cryomodules", R. Laxdal, presentation at the 16th International Conference on RF Superconductivity (SRF 2013)
http://accelconf.web.cern.ch/SRF2013/talks/weiod01_talk.pdf

Local Shield Vs Global Shield



Global shield

- High permeability nickel alloy mu-metal installed on the inner surface of the vacuum vessel and operates at room temperature
- **Pros:**
  - Simplicity in the design and manufacturing
- **Cons:**
  - Shields only the external field
  - Size of the shield: assembled on the inner surface of the vacuum vessel

Local shield

- Cold service special mu-metal (CRYOPERM or CRYOPHY) placed locally around the cavity
- **Pros:**
  - Fringe field from the solenoid can be shielded in addition to the external field
  - Shield much smaller
- **Cons:**
  - More complex to design, fabricate and install

The choice between local and / or global shield depends on the specifications of the project

Examples

Accelator	Type of cavity	Focusing solenoid	Global shield	Local shield	Vacuum vessel material
FRIB (MSU)	QWR, HWR	Yes		Yes	Carbon steel
SRILAC (RIKEN)	QWR			Yes (inside the helium jacket)	Carbon steel
XFEL	Elliptical			Yes	Carbon steel
LCLS-II	Elliptical			Yes Two layers	Carbon steel
IFMIF-LIPAc	HWR	Yes	Yes		Stainless steel
SARAF – Phase 2	HWR	Yes	Yes		Stainless steel
ESS	Elliptical			Yes	Stainless steel
HL-LHC (CERN)	Crab		Yes	Yes (inside the helium jacket)	Stainless steel
PIP-II (FNAL)	Spoke (SSR1)	Yes	Yes		Carbon steel
PIP-II (FNAL)	Elliptical		Yes	Yes	Carbon steel

NOTE: because of the high magnetic permeability of carbon steel, a vessel made of this material helps the shielding of the external magnetic field. However it may require to demagnetize it.

Global Shield: Examples

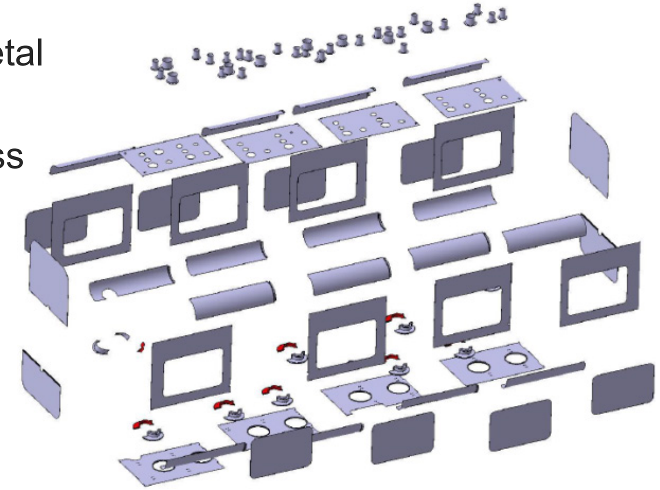
- Warm magnetic shield installed on the inner walls of the vacuum vessel → many interfaces between the magnetic shield and the vacuum vessel that could cause trouble

More details in "CEA experience of low beta cryomodules", N. Bazin, presentation at TTC 2014, MSU
https://indico.fnal.gov/event/12662/contributions/15273/attachments/10187/13101/CEA_low_beta_cryomodule_experience_NBazin_TTC2017.pdf

- The many apertures of the cryomodule are critical for the shielding, and overlap of mu-metal sheets is mandatory.
- Be aware of the dimensions of the oven used for the heat treatment for the size of the panels.

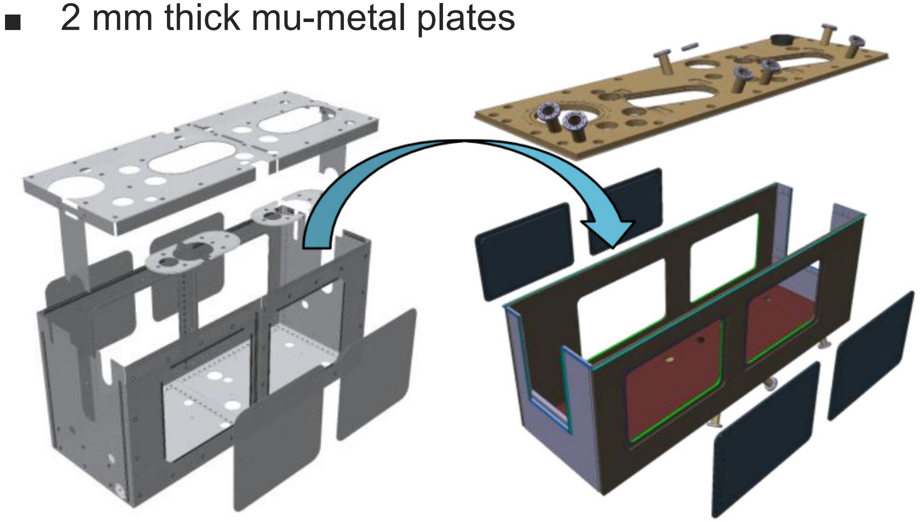
IFMIF-LIPAc

- FEM calculation: 1 mm thick mu-metal sheets are sufficient
- For mechanical issues, 2 mm thickness



HL-LHC (DQW cryomodule)

- 2 mm thick mu-metal plates

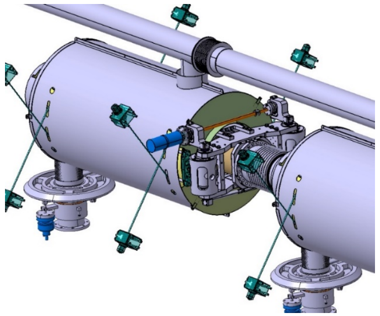


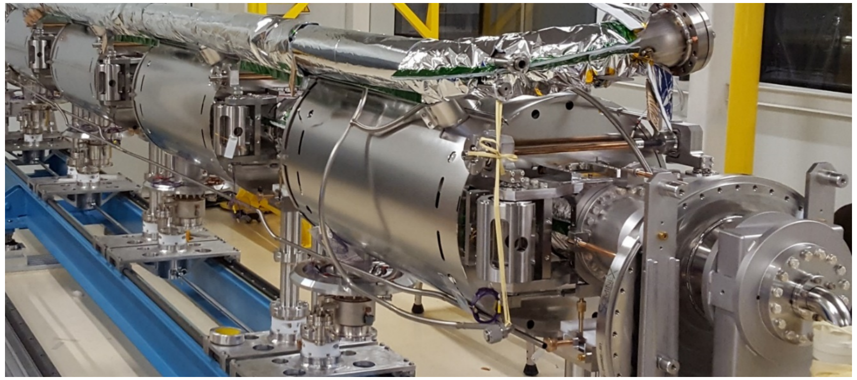
Local Shield: Examples

- Cold magnetic shield installed around the helium tank of the cavity.
- Openings not only for the ports of the cavity, but also for the connection of the tuning system and the supports of the cavity (tie rods for ESS, lugs for C-clamps for XFEL).
- MLI could be installed between the helium tank and the magnetic shield that holds it in place.

ESS elliptical cryomodules

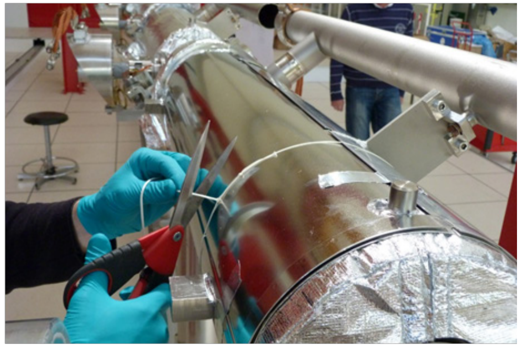
- 1.4 mm thick sheets

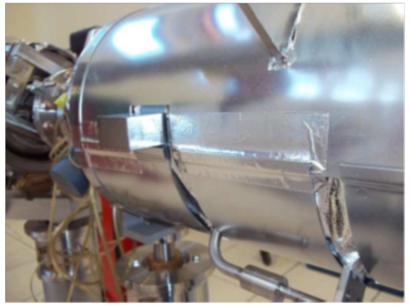




XFEL

- 1 mm thick sheets

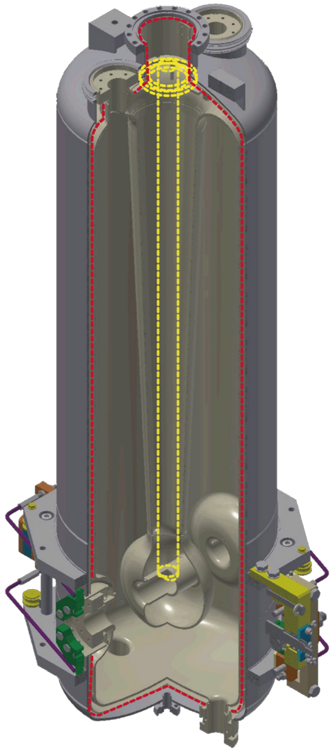




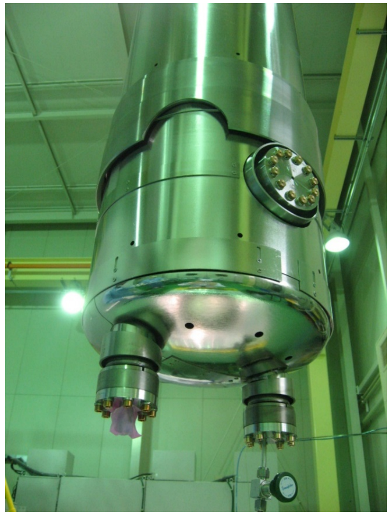
Local Shield: Examples

SRILAC (RIKEN): magnetic shield installed inside the helium jacket between the niobium cavity and the titanium tank

- Simple structure, easy to handle
- Few and small openings (little bigger than the diameter of the ports of the cavity)

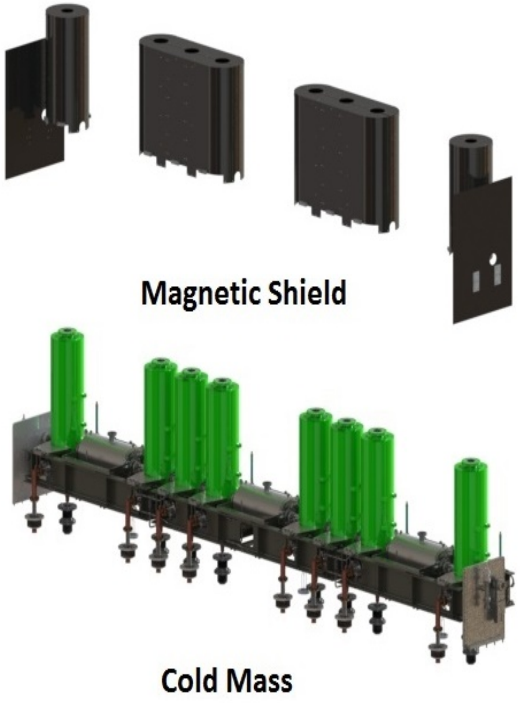


In red: magnetic shield

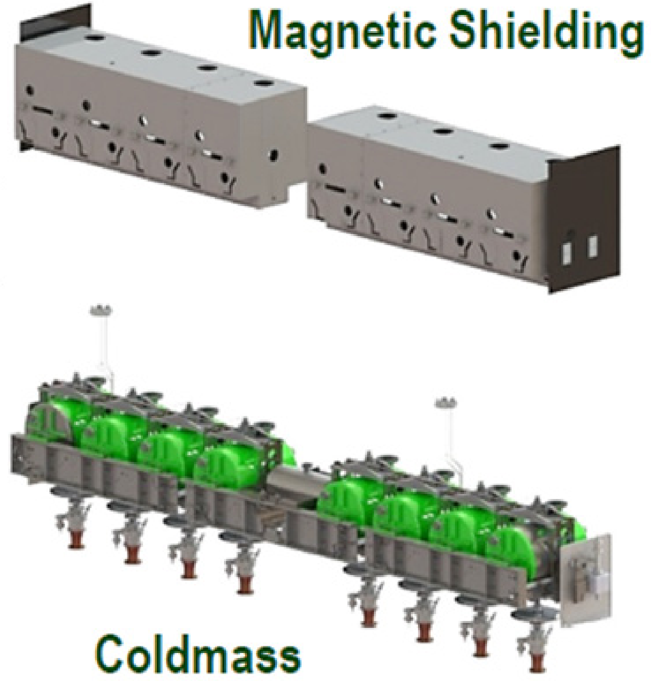


Local Shield: Examples

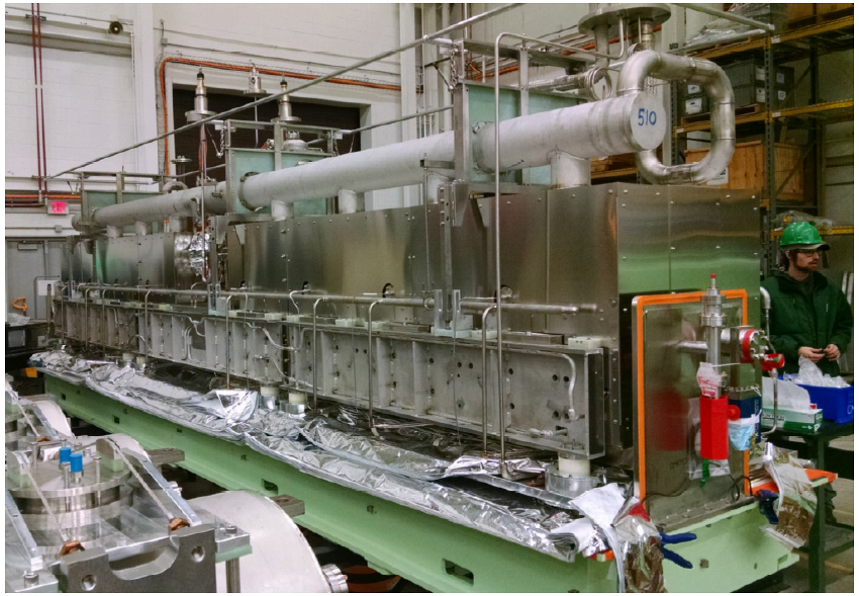
FRIB: “local” cold magnetic shield that incorporate a group of cavities that are between two solenoids (or one solenoid and one cold – warm transition) to be cost effective



β=0.085 cryomodule

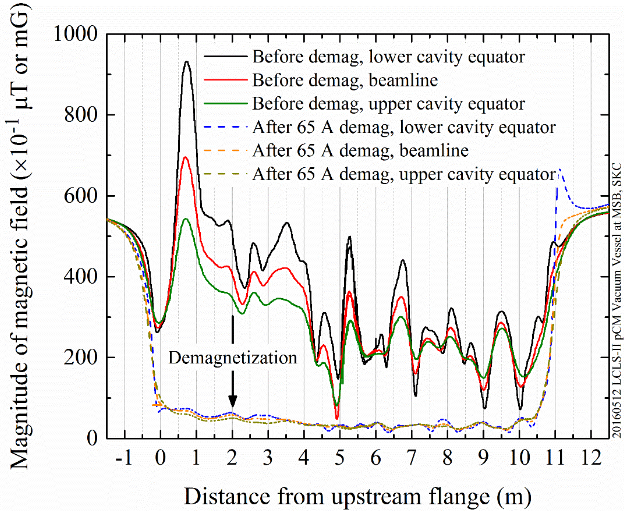


β=0.53 cryomodule

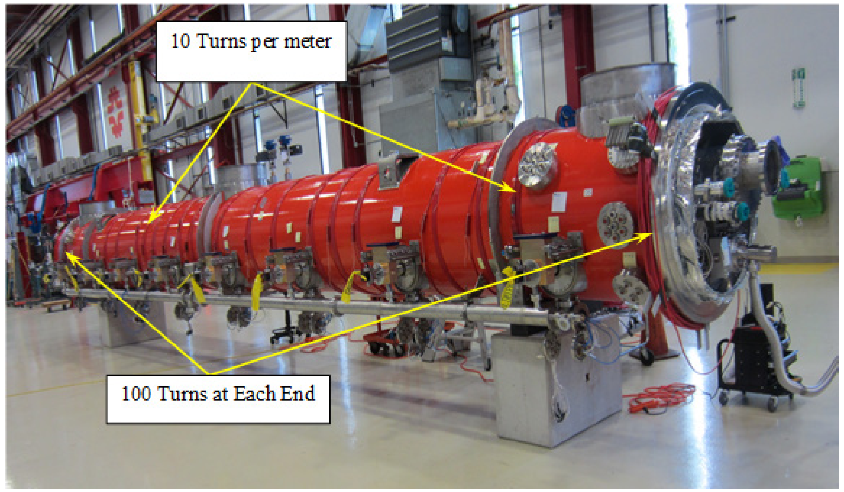


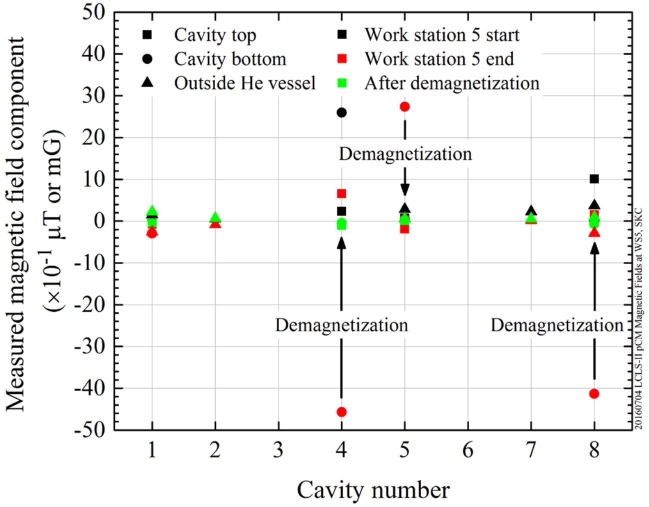
Demagnetization

- Cryomodule demagnetization addresses higher permeability materials.
- Example of the LCLS-II cryomodules:
  - Demagnetization of vacuum vessel



  - Demagnetization of assembled cryomodule





More details in "Magnetic Field Management for SRF", S. Chandrasekaran, presentation at TTC/ARIES Topical workshop on flux trapping and magnetic shielding, 2018

https://indico.cern.ch/event/741615/contributions/3179886/attachments/1748967/2833006/20181108-Saravan-TTC-Magnetic_Shielding.pdf

Magnetic Hygiene Plan

- In order to proscribe presence of magnetized elements close to the cavity, a magnetic hygiene plan is mandatory:
  - Identification of the parts close to the cavities which could cause magnetic pollution.
  - Material choices:
    - Use of non magnetic materials whenever it is possible: brass, bronze, titanium …
    - If not, use of low magnetic permeability materials: stainless steel 316L or 316LN (better).
  - During the manufacturing:
    - Material specification and certifications.
    - Incoming material inspection → procurement of "good" raw material is mandatory to achieve the required final magnetic permeability.
    - Inspection after manufacturing → manufacturing processes (cutting, welding, forming) could increase the magnetic permeability. Annealing could be a solution, but the process must be qualified.
  - During cryomodule assembly:
    - Beware of the tools that could magnetized the parts → experience of LCLS-II: table top demagnetizer proved sufficient to demagnetize.
    - Possible demagnetization of the assembled cryomodule (LCLS-II).

5. Safety: Pressure Vessel

Introduction

- 1 liter of liquid helium ≈ 750 liters of gas at room temperature
  - 1 dm^3 (0.035 ft^3) @ 4.2 K → 750 dm^3 (24.48 ft^3) @ 300 K / 1 bar

⇨ **In case of a sudden increase of heat loads, the pressure in the cryomodule could dramatically raise if no pressure relief device is implemented (or if not properly sized)**

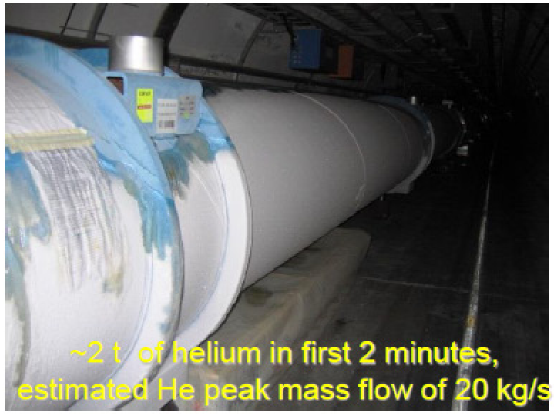
- Cryomodule = equipment that contains pressurized helium

➡ **Must not be dangerous for safety and health of persons while being installed, in operation or maintained.**

Example: LN2 dewar explosion at GANIL (2005)

- September 21st 2005, 7:30 PM: explosion of a 70-liter LN2 dewar
- Cause: safety device directly implemented on the dewar (old equipment)
- Consequence: destruction of 200 m² of experimental rooms and offices, no casualties

Example: LHC, September 19th 2008

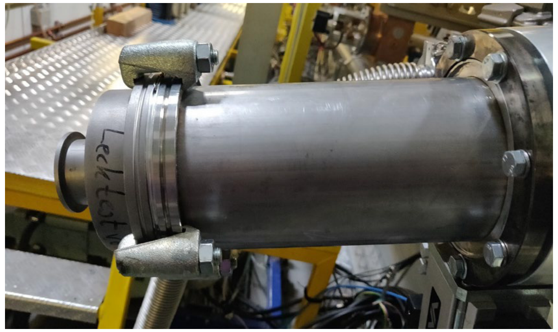


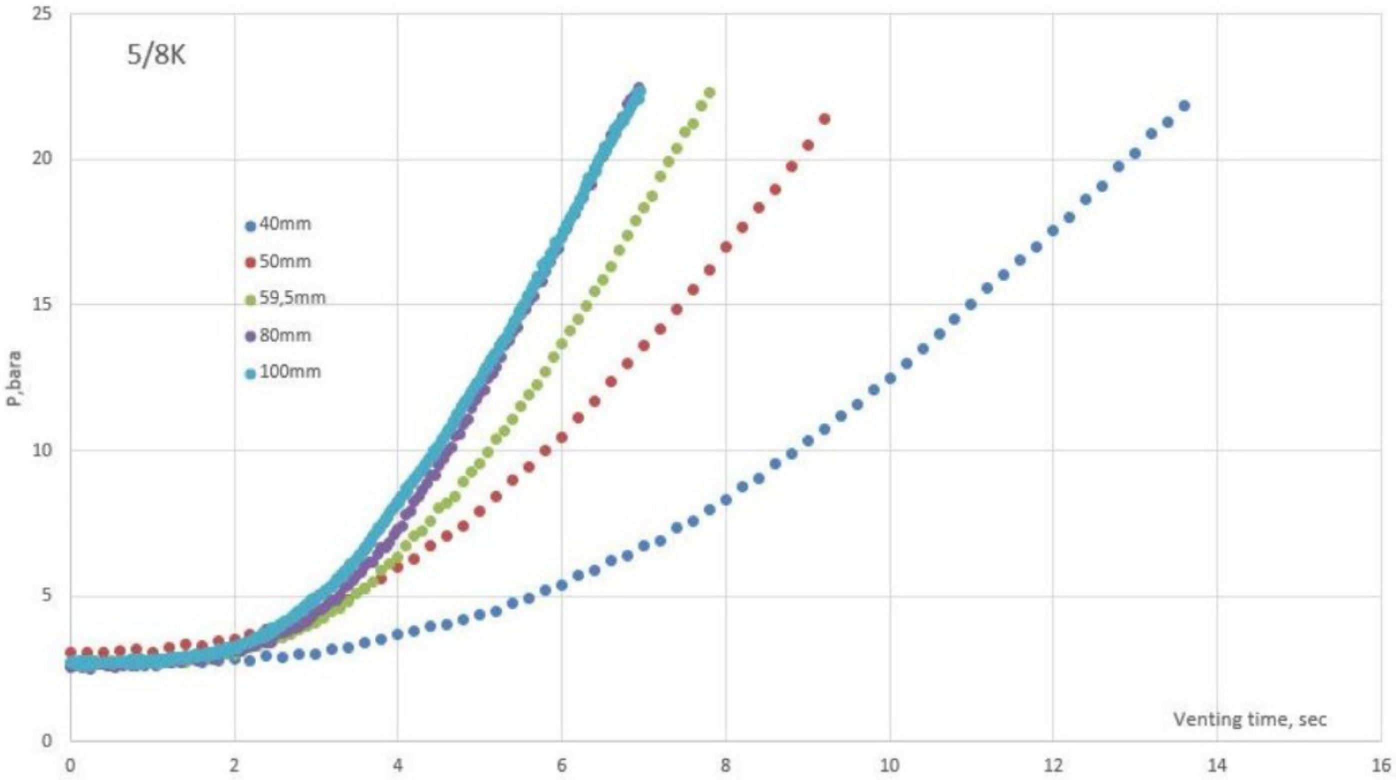
Taken from "Cryostat design", V. Parma, CERN Accelerator School (CAS) on Superconductivity, 2013

http://cas.web.cern.ch/sites/cas.web.cern.ch/files/lectures/erice-2013/may11and3parma.pptx

Example: XFEL crash test

- Crash test performed at DESY on one XFEL-like 1.3 GHz cryomodule
- Simulated accident: venting of a DN40 – DN100 pipe to air
- Pressure rises from 2.5 to 20 bars in a few seconds (6s for a DN80 pipe)

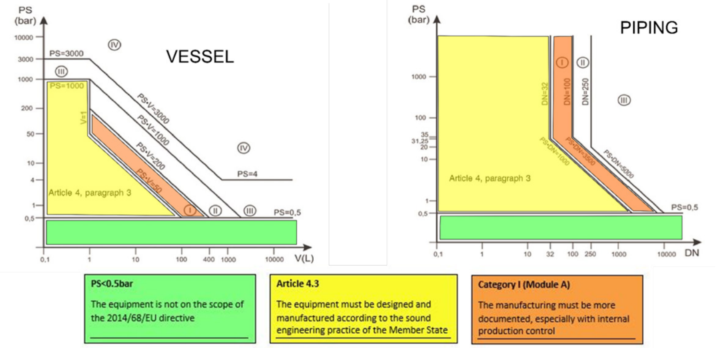




Taken from "Certification of the XFEL cold linac and lessons learnt", S. Barbanotti, presentation at the 2021 International Workshop on Future Linear Colliders (LCWS2021)
https://indico.cern.ch/event/995633/contributions/4257524/attachments/2208230/3736704/Barbanotti_LCWS2021_XFEL-coldLinacCert_noVideo.pdf

Licensing Frame

- The applicable standards for the design and manufacturing of pressure vessels depends on where the cryomodule is installed and in operation:
  - North America: ASME (American Society of Mechanical Engineers)
    - Boiler and Pressure Vessel Code (BPVC) if the internal diameter of the equipment is over 6 inches (152 mm)
    - ASME B31.3 for the piping (internal diameter < 6 inches)
  - Europe: European Pressure Equipment Directive (PED) (2014/68/EU)
    - Vessel' means a housing designed and built to contain fluids
    - 'Piping' means piping components intended for the transport of fluids
    - Vessel: the category depends on the working pressure (PS) x volume (V)
    - Piping: the category depends on the working pressure (PS) x internal diameter (DN)
  - Japan: High Pressure Gas Safety Law (HPGSL)
- State and local codes may also be applicable!



Some Lessons Learnt

- The certification of the cavity is the most complicated:
  - Niobium and niobium-titanium are non referenced materials in the pressure codes.
  - Low yield strength of niobium at room temperature → limits the maximum allowable working pressure (MAWP) due to the room temperature pressure test required by the codes.
- The certification of other components of the cryomodule is easier because of the use of standard materials such as stainless steel and aluminum.
- In order to avoid delays and extra costs, it is mandatory to define the licensing frame at the early stage of the project, with the requirements and the precise list of tests to be performed during all stages of the project.
- For the same reason, qualification procedures and tests must be anticipated in order to purchase the material in addition to the one needed for the production.

Licensing of cryomodule installed in Europe, USA and Japan discussed at the 2021 International Workshop on Future Linear Colliders (LCWS2021) (https://indico.cern.ch/event/995633/timetable/?view=standard)

- "Certification of the XFEL cold linac and lessons learnt", S. Barbanotti
- "Licensing of pressurized cryomodule components manufactured in Europe and installed in Japan: example of the IFMIF/EVEDA cryomodule", N .Bazin
- "SRF Pressure Safety at Fermilab", A. Klebaner and S. Belomestnykh

General Approch

- The Maximum Allowable Working Pressure (MAWP) shall be set in accordance with the cavity and cryogenic system designers.
- Perform a risk analysis of the system and evaluate the risk hazards.
- Identify the accident situations and assess the heat inputs for each of them.
- To size the safety relief system:
  - Single failure principle is applied → for each identified accident scenario, a single accident-initiating event and not several cumulative events
  - Thus use the worst case for sizing
  - Take into account the recovery system downstream the safety device: adopt a direct discharge venting to the atmosphere whenever it is possible or use a wide diameter pipe to ensure that the pressure drop is negligible

Example of a Risk Analysis

Accident	Possible Cause	Pressurized devices	Heat Loads	Pressure Relief Devices
Loss of insulation vacuum	Break of a connector or a seal on the cryostat (vacuum loss with air)	Helium circuit	6.2 kW/m^2 (if surfaces of helium containers covered with MLI)	▪ Relief valve ▪ Burst disc
	Break of cold mass bellows or thermal shield hose (vacuum loss with cold helium gas)	▪ Helium circuit ▪ Vacuum vessel	1.5 kW/m^2 (if surfaces of helium containers covered with MLI)	Relief valve
Loss of beam vacuum	Break of the beam vacuum valve or power coupler ceramic (vacuum loss with air)	Helium circuit	38 kW/m^2 (air directly in contact with the cold surfaces of helium containers)	▪ Relief valve ▪ Burst disc
	Perforation of a cavity or a solenoid. Liquid helium flows inside the beam vacuum.	▪ Helium circuit ▪ Beam vacuum		▪ Relief valve and burst disc on helium circuit ▪ Burst disc on the beam vacuum
Excessive heat loads	Dynamic heat loads, solenoid or cavity quench, control malfunction	Helium circuit		▪ Relief valve ▪ Burst disc

6. Conclusion

Summary

- A cryomodule with superconducting cavities is not a simple cryostat, but is challenging due to cleanliness and alignment requirements.
- Cryomodule design requires a close collaboration with the other systems: cavity, power coupler, cryogenic distributions system, ancillaries …
- For high intensity hadron machine, it is even more challenging because of the compactness of the design due to beam dynamic constraints: the distances between the components of the cavity string are made as short as possible.
- To conclude, the cryomodule engineer is confronted with a multidisciplinary environment where he needs to master “a little bit of everything”:
  - RF superconductivity
  - Heat transfer, low temperature physics, material sciences
  - Mechanics, cryogenics, vacuum
  - Sheet metal work, machining, welding, brazing
  - System integration, quality assurance, clean room process, alignment
  - Instrumentation
  - …

Some References

- Previous SRF Conference Tutorials:
  - SRF 2019: *Fundamentals of Cryomodule Design and Cryogenics*, B. Petersen
    http://accelconf.web.cern.ch/srf2019/talks/satu3_talk.pdf
  - SRF 2015: *Cryomodules and Cryogenics*, J. Weisend
    https://meetings.triumf.ca/event/0/contributions/16/attachments/3/4/Weisend_SRF_Tutorial_Part_1.pptx
    https://meetings.triumf.ca/event/0/contributions/16/attachments/3/4/Weisend_SRF_Tutorial_Part_2.pptx
  - SRF 2013: *Cryogenics*, H. Nakai
    https://indico.in2p3.fr/event/9782/contributions/50512/attachments/40906/50683/01_-_cryogenics_-_Nakai.pdf
- CERN Accelerator School (https://cas.web.cern.ch/):
  - 2017: Vacuum for Particle Accelerator
  - 2013: Superconductivity
  - 2011: High Power Hadron Machine
- TESLA Technology Collaboration Meetings (https://tesla.desy.de/meetings/collaboration_meetings_and_ttc_workshos/)
- Proceedings of accelerator conferences on the Joint Accelerator Conferences Website (JACoW - https://jacow.org/)

Acknowledgments

The author would like to thanks:

- The International Scientific Program Committee (ISPC) for giving me the opportunity to give this tutorial lecture
- P. Duchesne (IJCLAB), O. Capatina (CERN), S. Miller (FRIB), N. Sakamoto (RIKEN), D. Passarelli (FNAL) and S. Chandrasekaran (FNAL) for the information on the cryomodules developed in their respective institutes
- My colleagues from the IFMIF, ESS and PIP-II collaborations for the materials
- My CEA colleagues for the discussion and the materials to prepare this tutorial: R. Cubizolles, E. Cenni, G. Devanz, T. Plaisant, J. Plouin, A. Madur, C. Madec, A. Bouygues, S. Berry, T. Proslier

Thanks for your attention

Nicolas Bazin
CEA SACLAY
91191 Gif-sur-Yvette Cedex
France
nicolas.bazin@cea.fr