FROM RESEARCH TO INDUSTRY

SRF CAVITIES FOR PARTICLE ACCELERATORS

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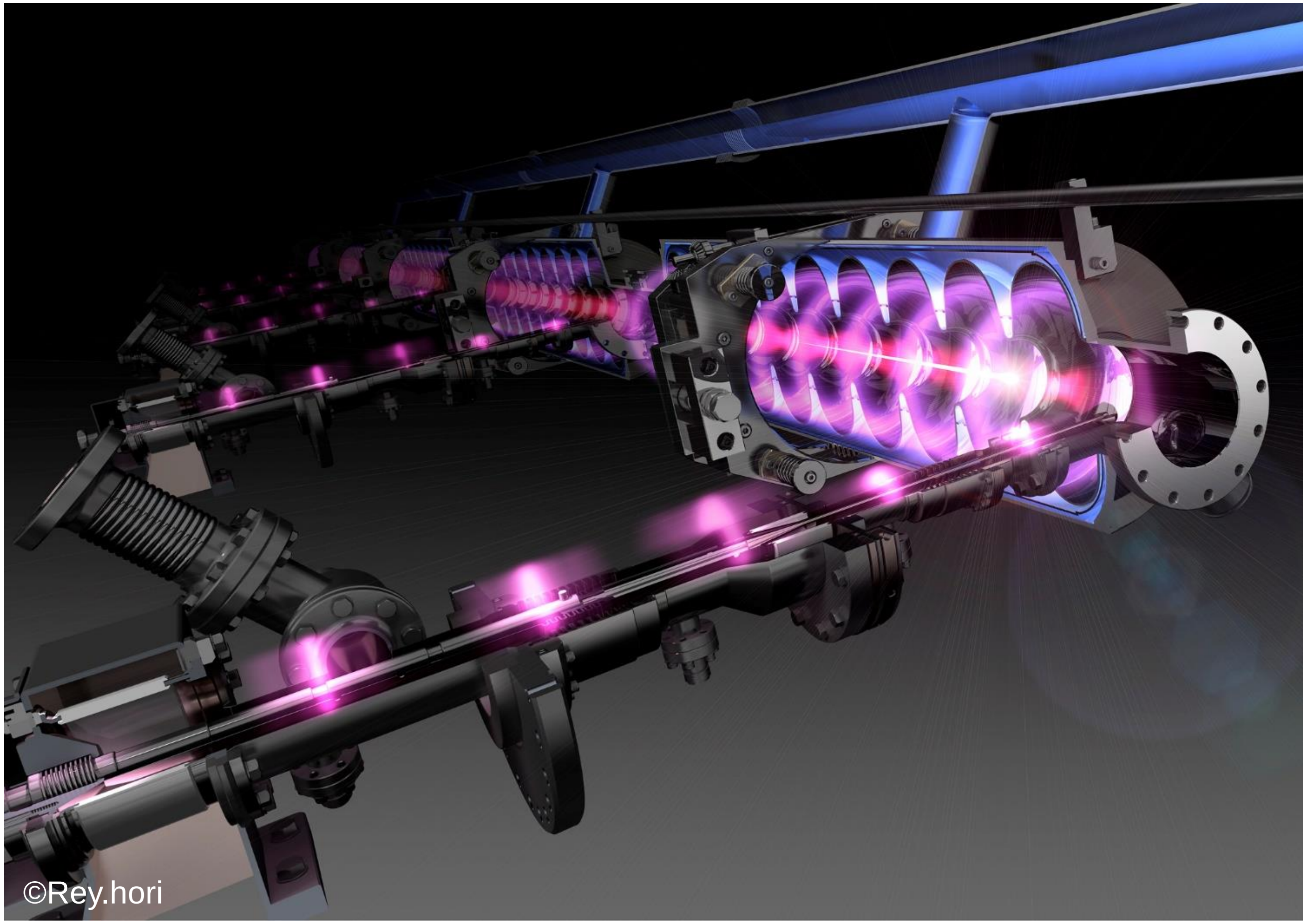
OUTLINE

- **Theoretical background**
  - **S**uperconductivity
    - BCS Theory
  - **RF** resonator
- **SRF cavities**
  - Worldwide overview
  - Cavity design
    - Figure of merit
  - Cavity manufacturing/preparation
  - Cryomodule concepts

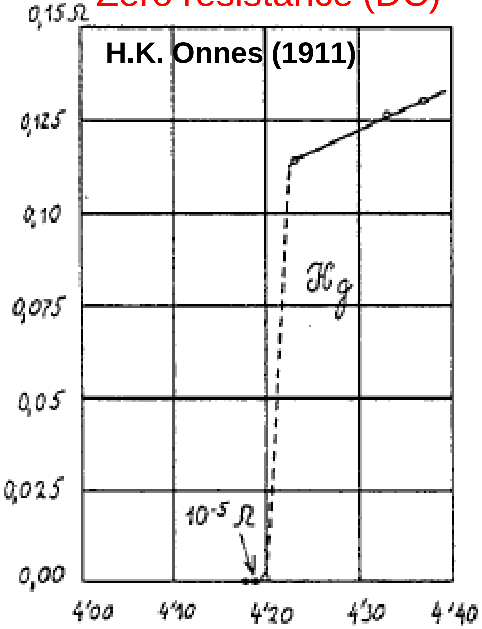
DISCLAIMER

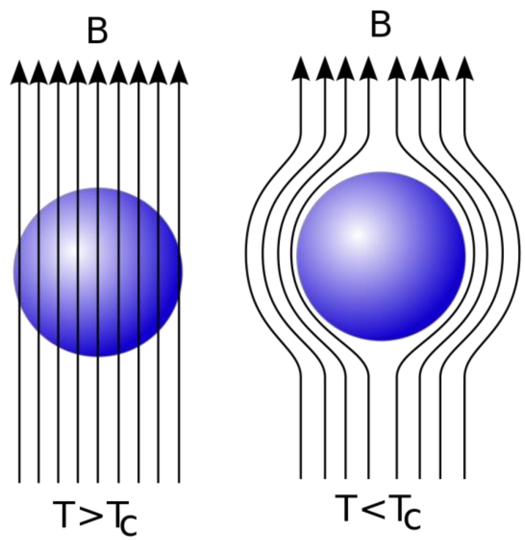


This talk would not be an exhaustive lecture on this vast field, but more like an overview for students that would like to deepen some of the topics. Superconducting Radio Frequency (SRF) cavities are one of the many application of superconducting materials.

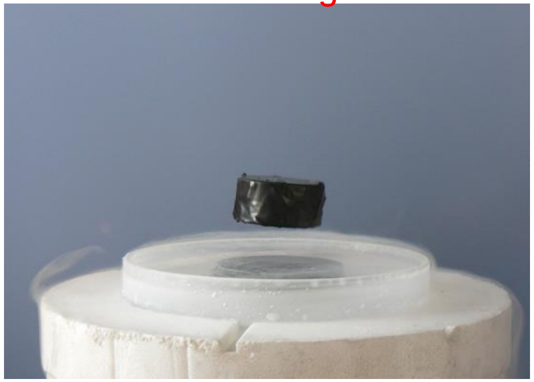
SUPERCONDUCTIVITY IN FEW PAGES…
THE "S" IN SRF

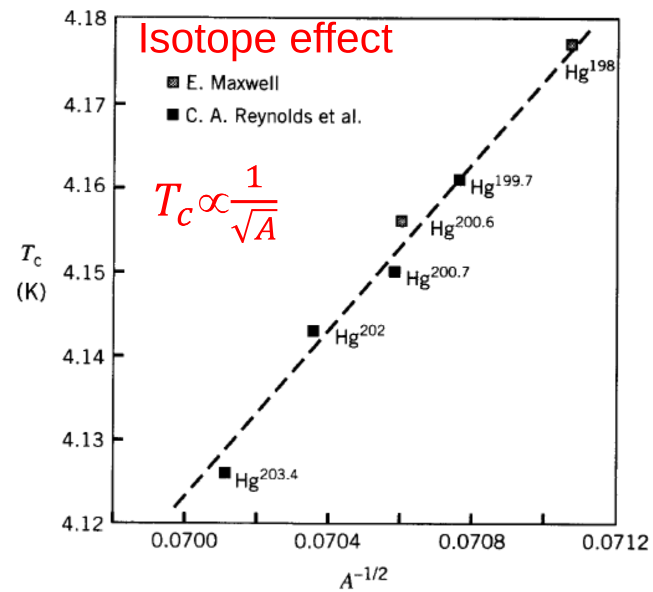
Zero resistance (DC)





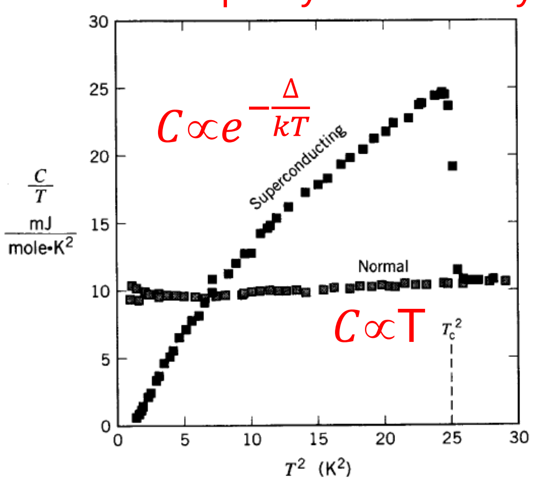
Meissner effect
Perfect diamagnetism



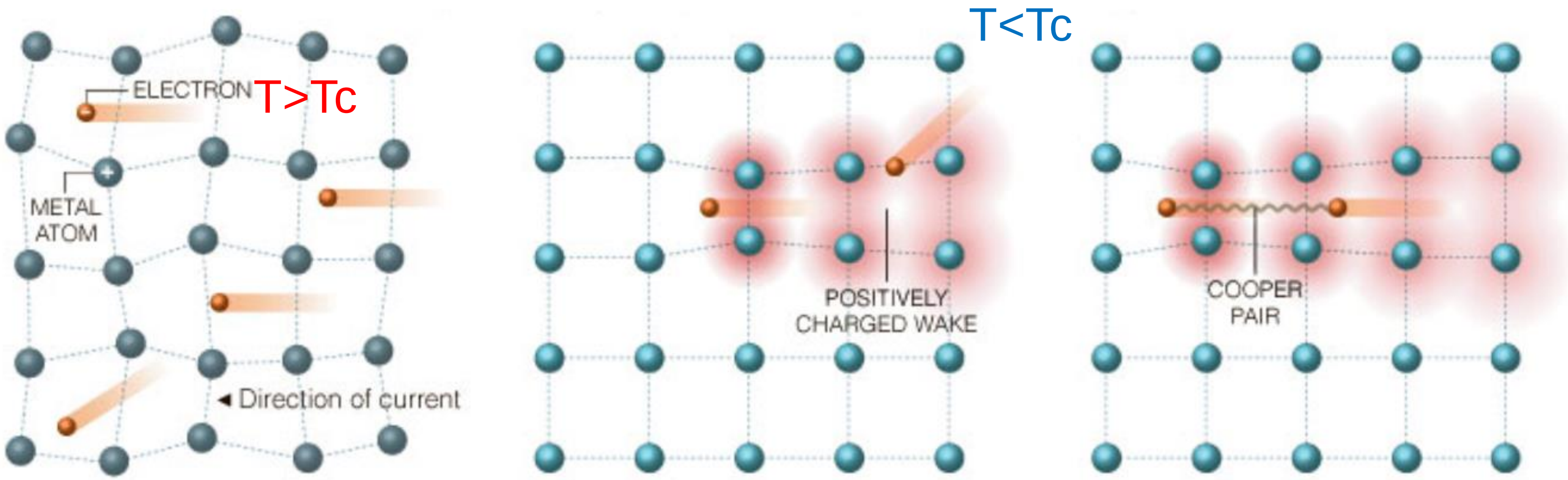


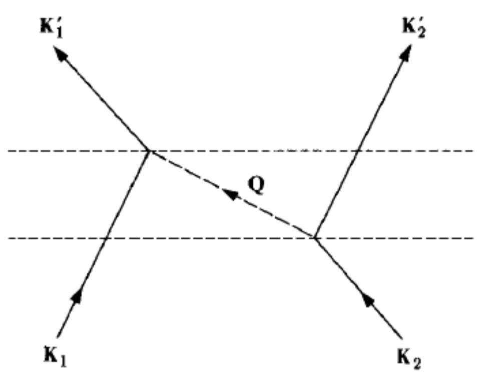
First clue that superconductivity has some link to the material lattice. *"It is not only about electrons"*

Heat capacity discontinuity



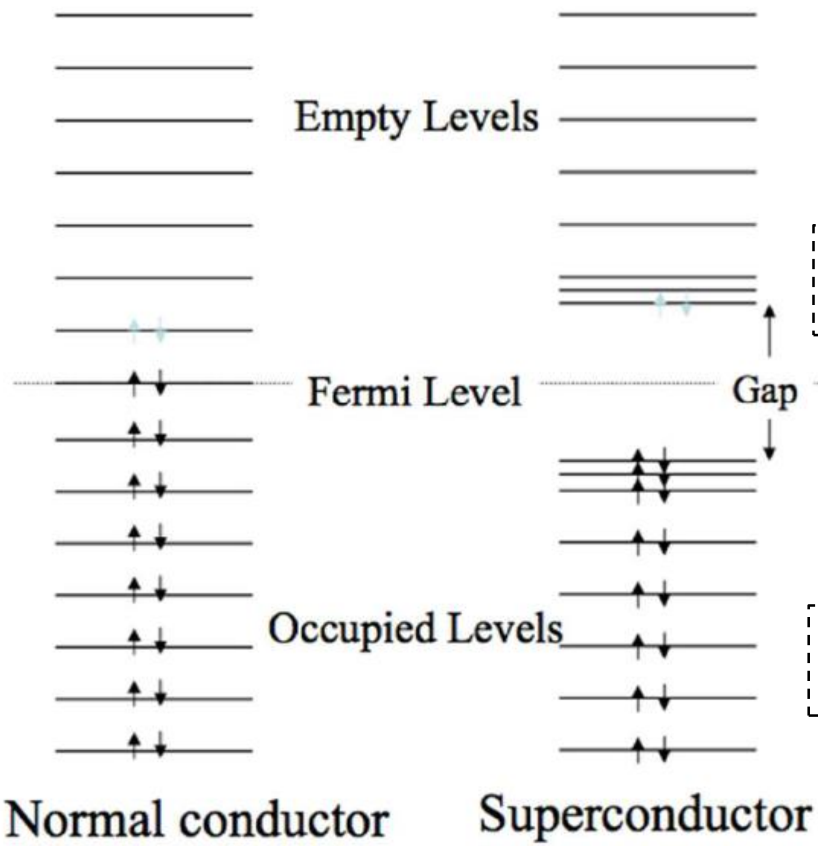
BCS THEORY





BCS theory explain at quantum mechanical level how superconductivity is originated. At its core demonstrate how a set of fermions (electrons) can interact through a lattice deformation (phonon) to generate an ensemble of bosons (cooper pairs)

P. Schmuser: "*Suppose you are cross-country skiing in very deep snow. You will find this quite cumbersome, there is a lot of 'resistance'. Now you discover a track made by another skier, a 'Loipe', and you will immediately realize that it is much more comfortable to ski along this track than in any other direction.*



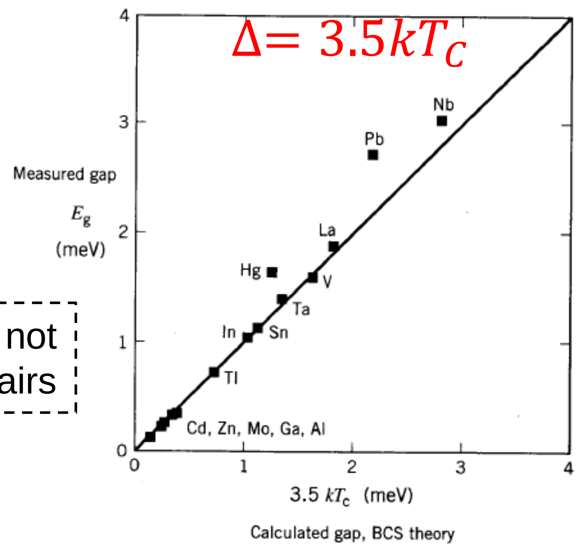
Number of electrons not condensed in Cooper pairs

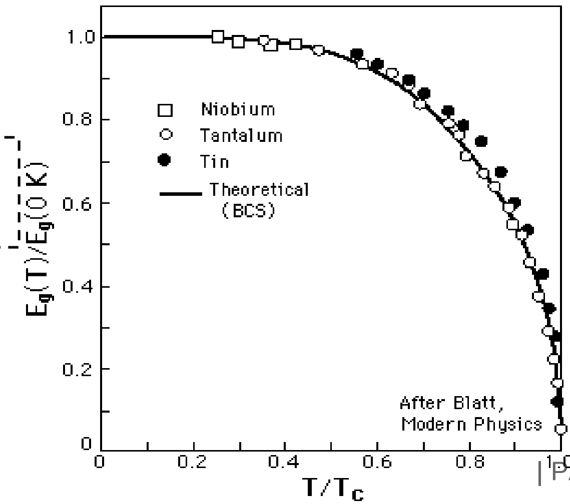
$$n_e \propto e^{-\frac{\Delta}{kT}}$$

Directly explain heat capacity behavior

Theory prediction

$$\Delta = 3.5kT_C$$





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

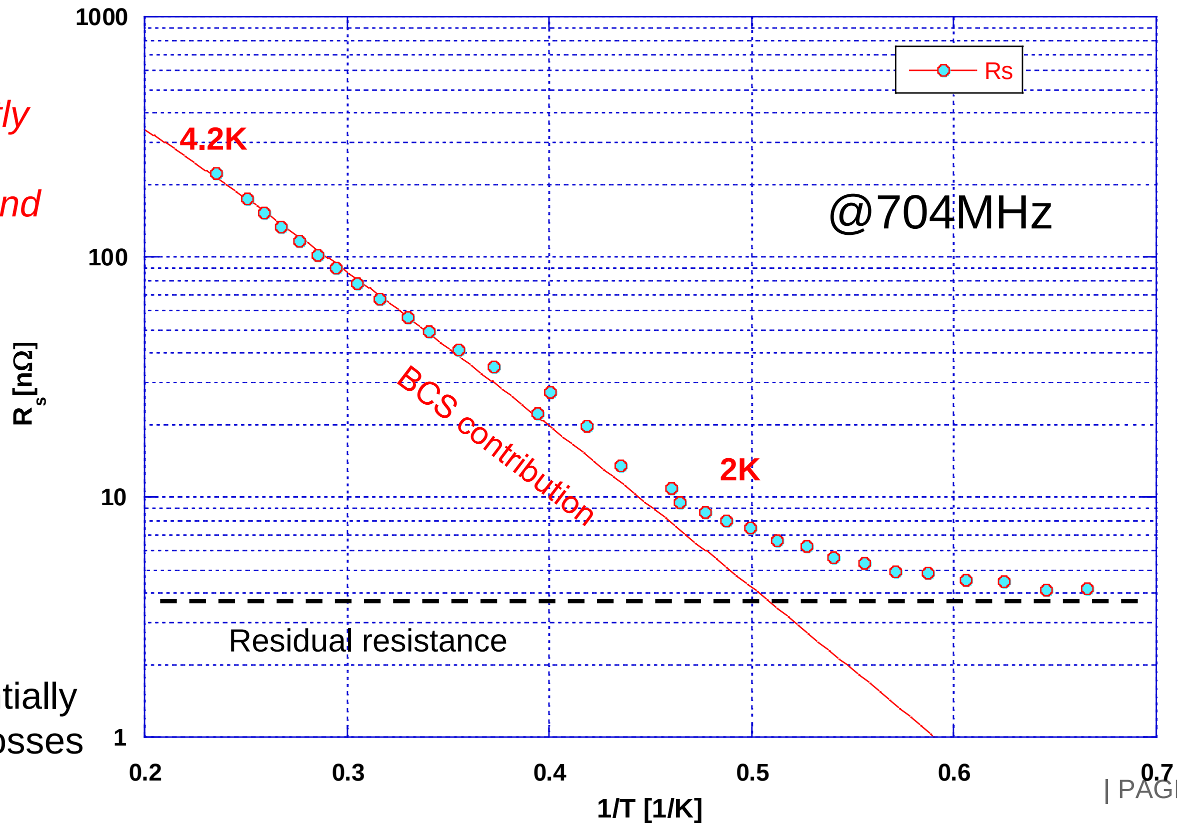
$$R_{BCS} \sim \lambda^3 \omega^2 l e^{-\frac{\Delta}{kT}}$$

- Proportional to the square of the frequency
- Decrease exponentially with respect to the temperature

"Cooper pairs have inertia
– They can not follow the RF field instantly
- Thus do not shield RF field perfectly
- The normal electrons are accelerated and dissipate power"

$$R_{res}$$

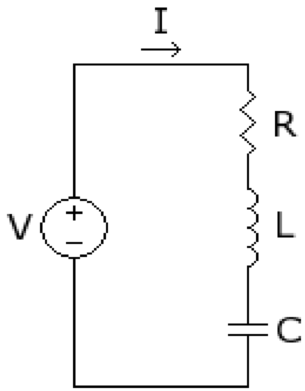
- Temperature independent
- Depends on material property and magnetic flux trapping during transition to superconductor



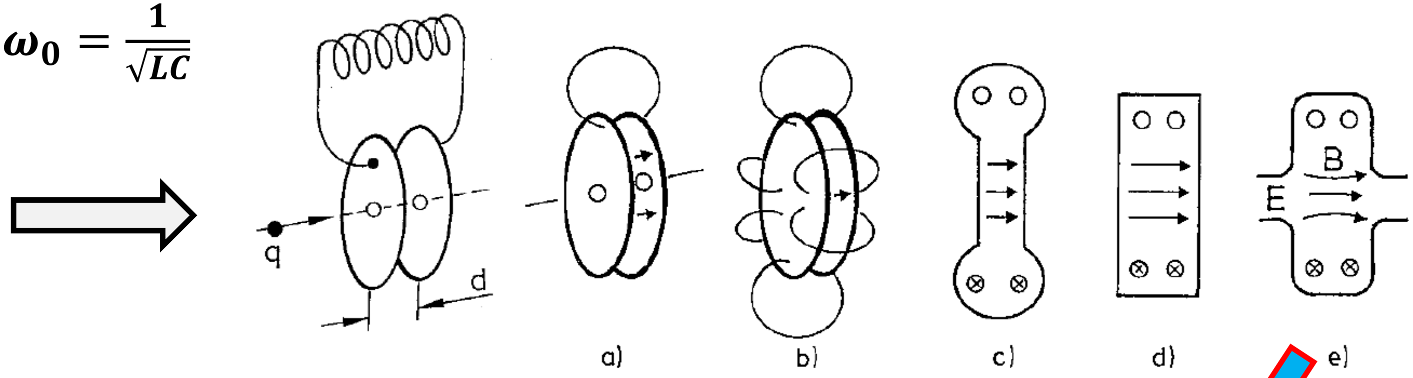
Qualitatively:

- Higher the Freq. less effective is the shielding from Cooper pair
- Higher the temperature and exponentially more electron will participate in the losses

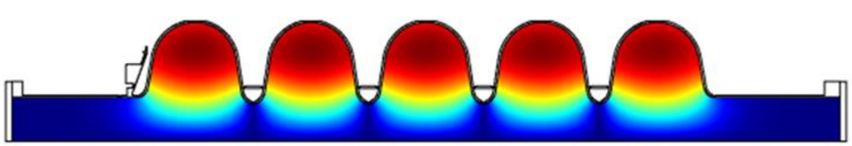
WHAT IS A RF RESONATOR?



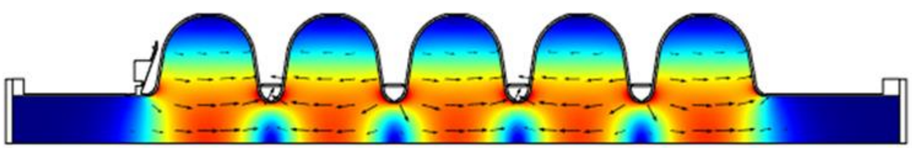
$$\omega_0 = \frac{1}{\sqrt{LC}}$$



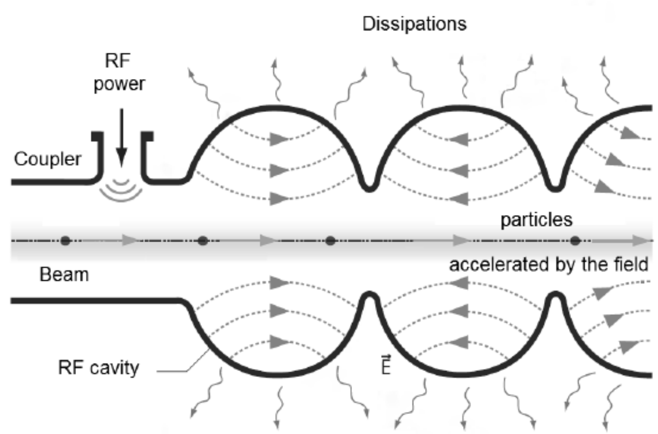
Magnetic field



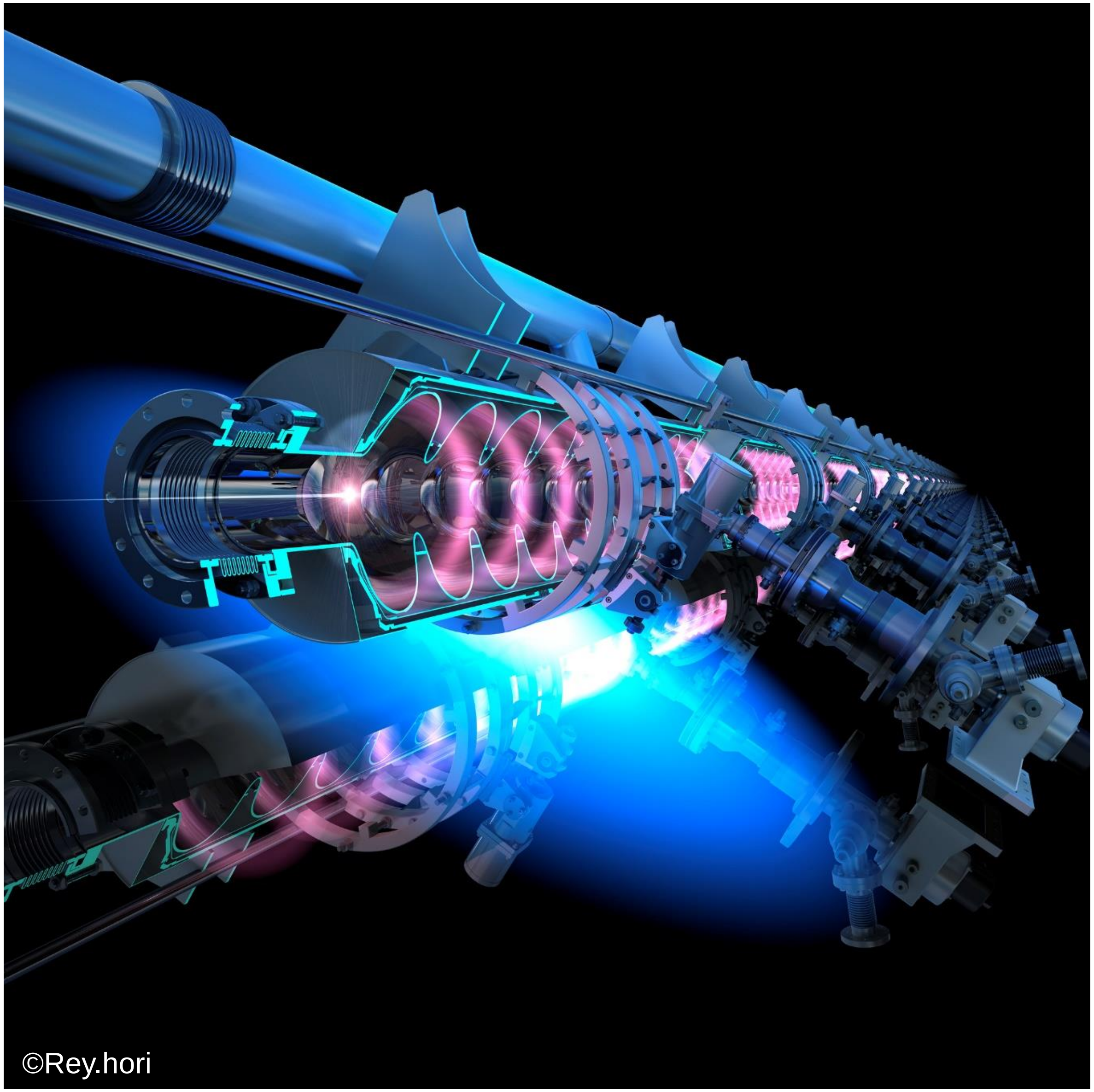
Electric field



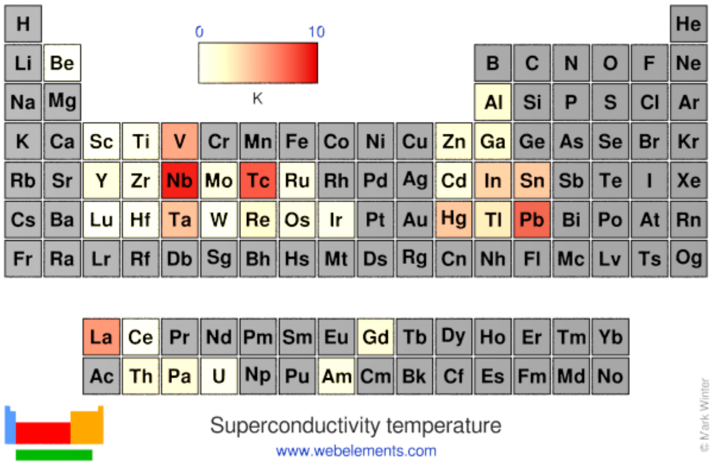
A RF resonator/cavity is a metal container for electromagnetic field, the stored energy is used to accelerate particles…



A NICER IMAGE…



NIOBIUM SRF CAVITY



The material of choice for SRF cavity is high purity Niobium.

- It has the highest transition temperature among pure metals
- It can be formed
- It can be welded
- It has good mechanical properties

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

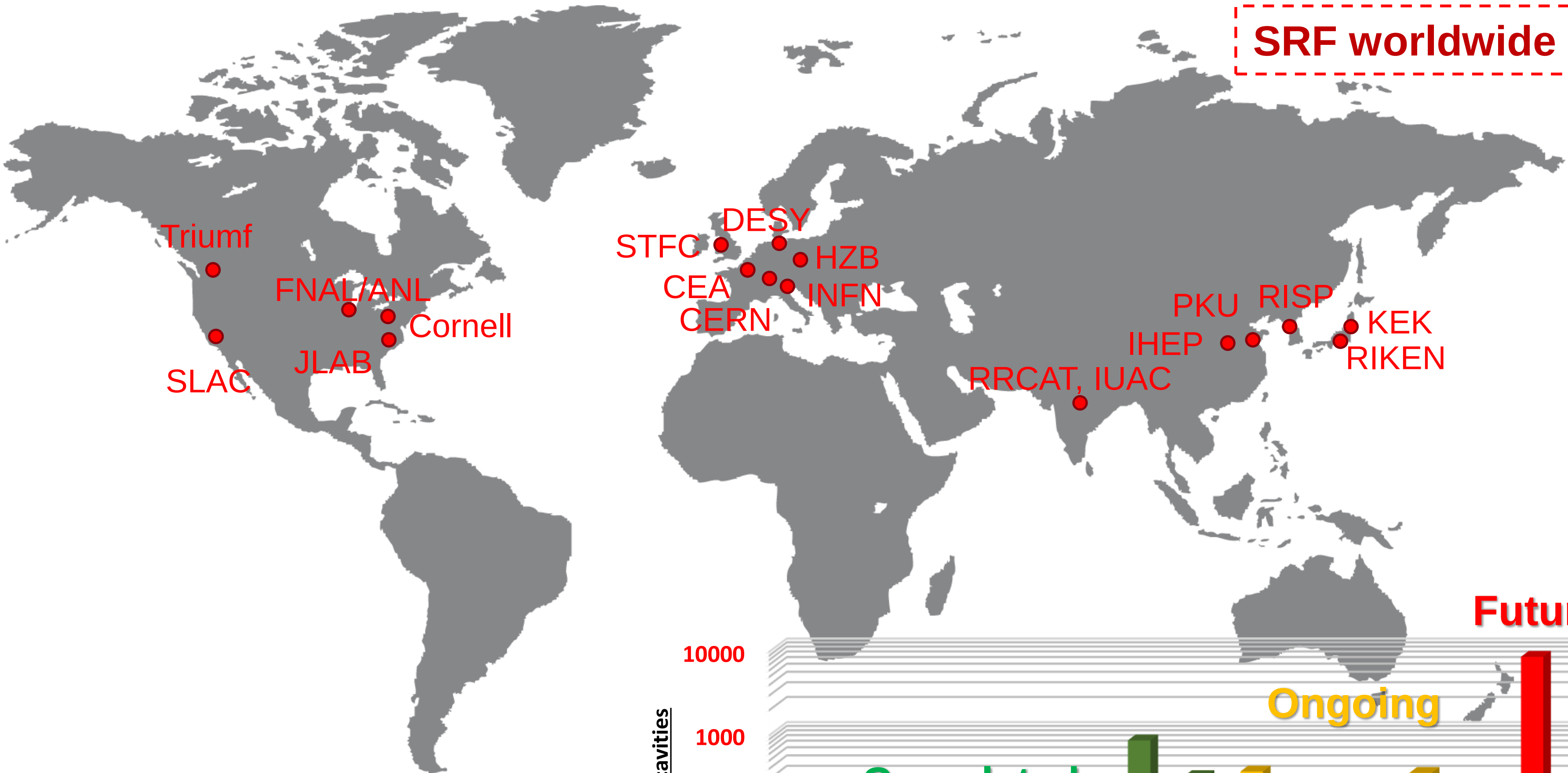
Property	Value
T_C	9.22 K
$\Delta(0)$	3 meV
$H_C(0)$	171 mT
λ	39 nm
ξ	38 nm

Due to Niobium transition temperature we need to use liquid Helium as cryogenic fluid

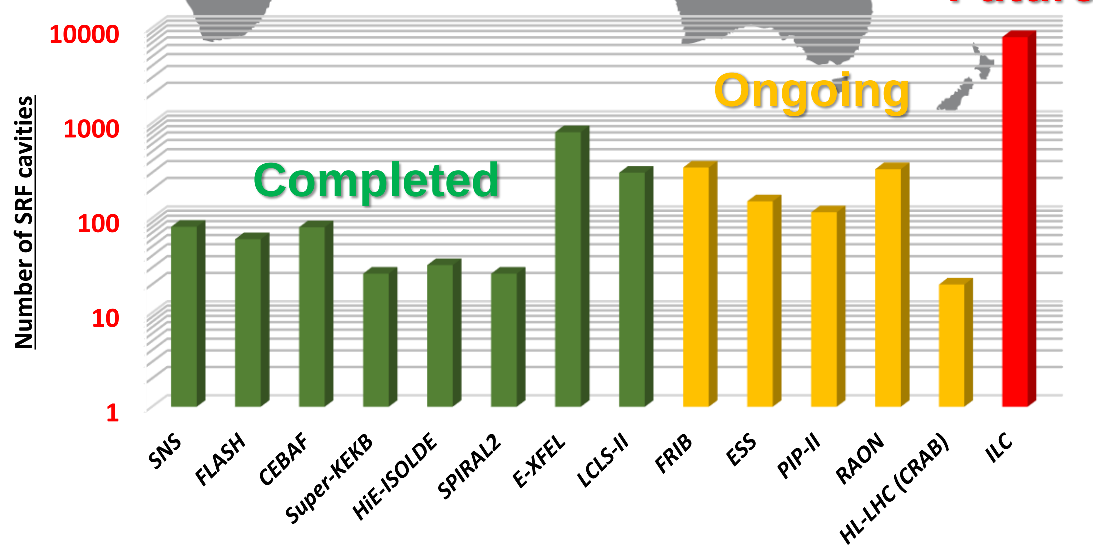
	$_4He$	H_2	Ne	N_2	Ar	O_2
Normal boiling point	4.22	20.28	27.09	77.36	87.28	90.19

SRF cavities

Laboratories active on SRF…not complete

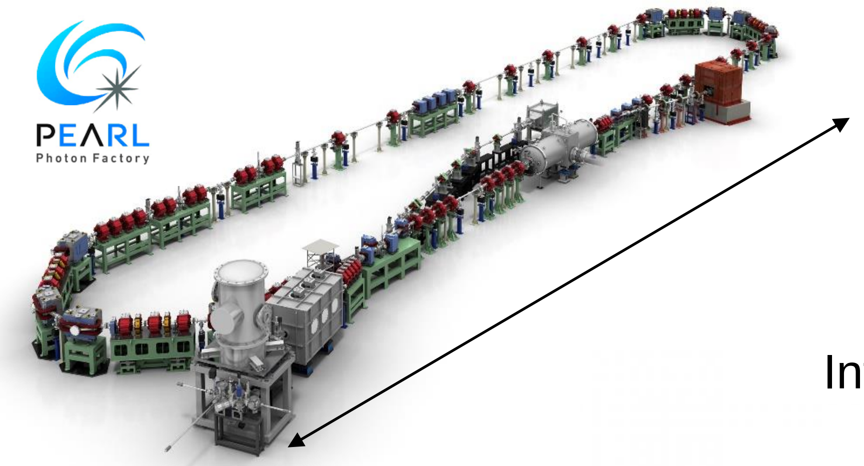


In the last 20 years



SRF CAVITIES ARE USED FROM SMALL TO BIG SCALE PROJECTS

Compact Energy Recovery Linac (cERL)



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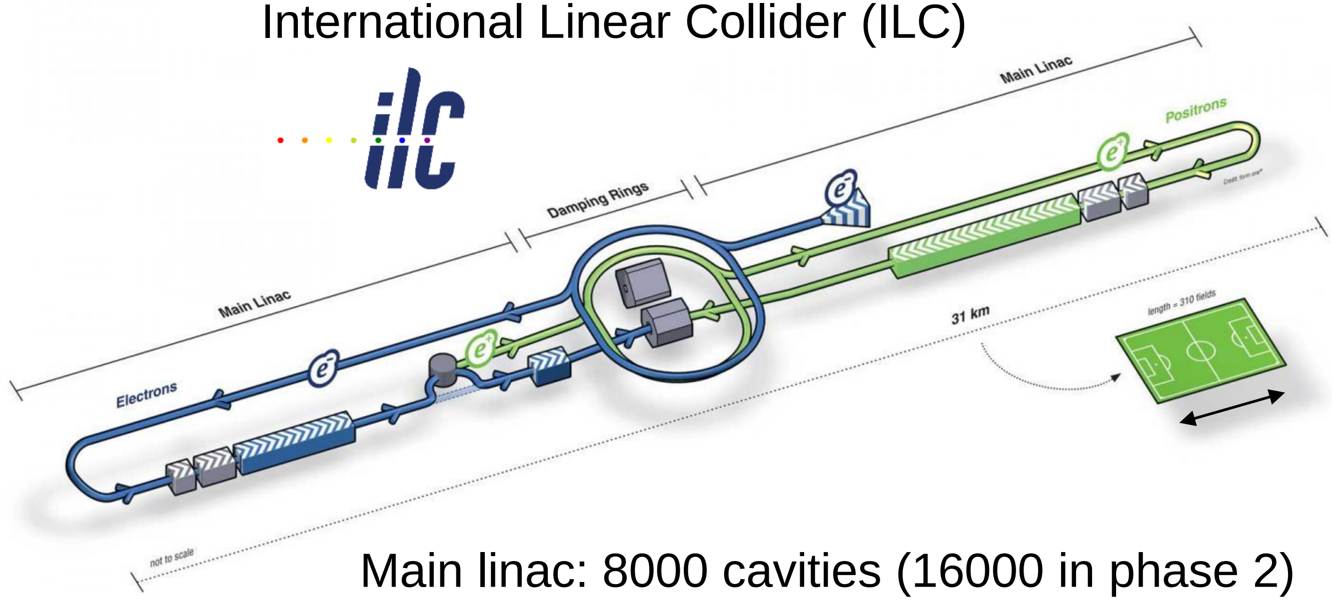
Main Linac: 2 cavities
Injector: 3 cavities
Footprint: Smaller than a football field

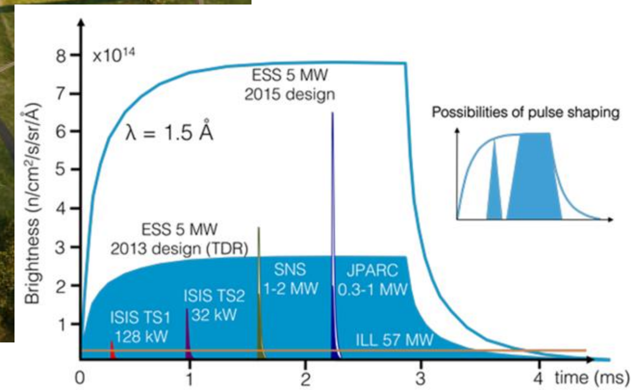
International Linear Collider (ILC)

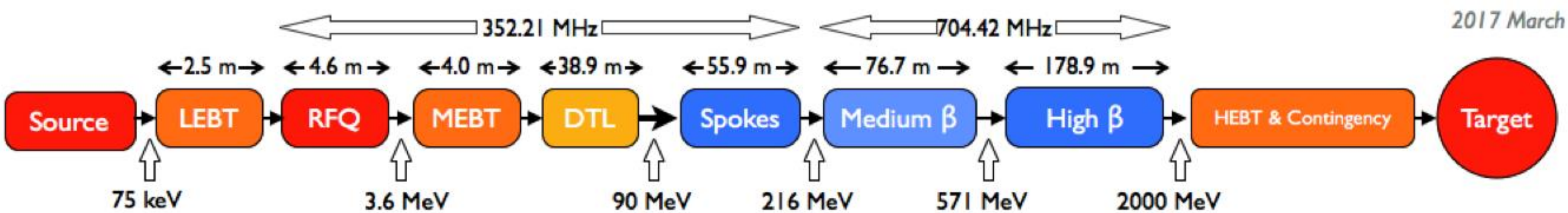


Main linac: 8000 cavities (16000 in phase 2)
Footprint: 20-30 km underground tunnel

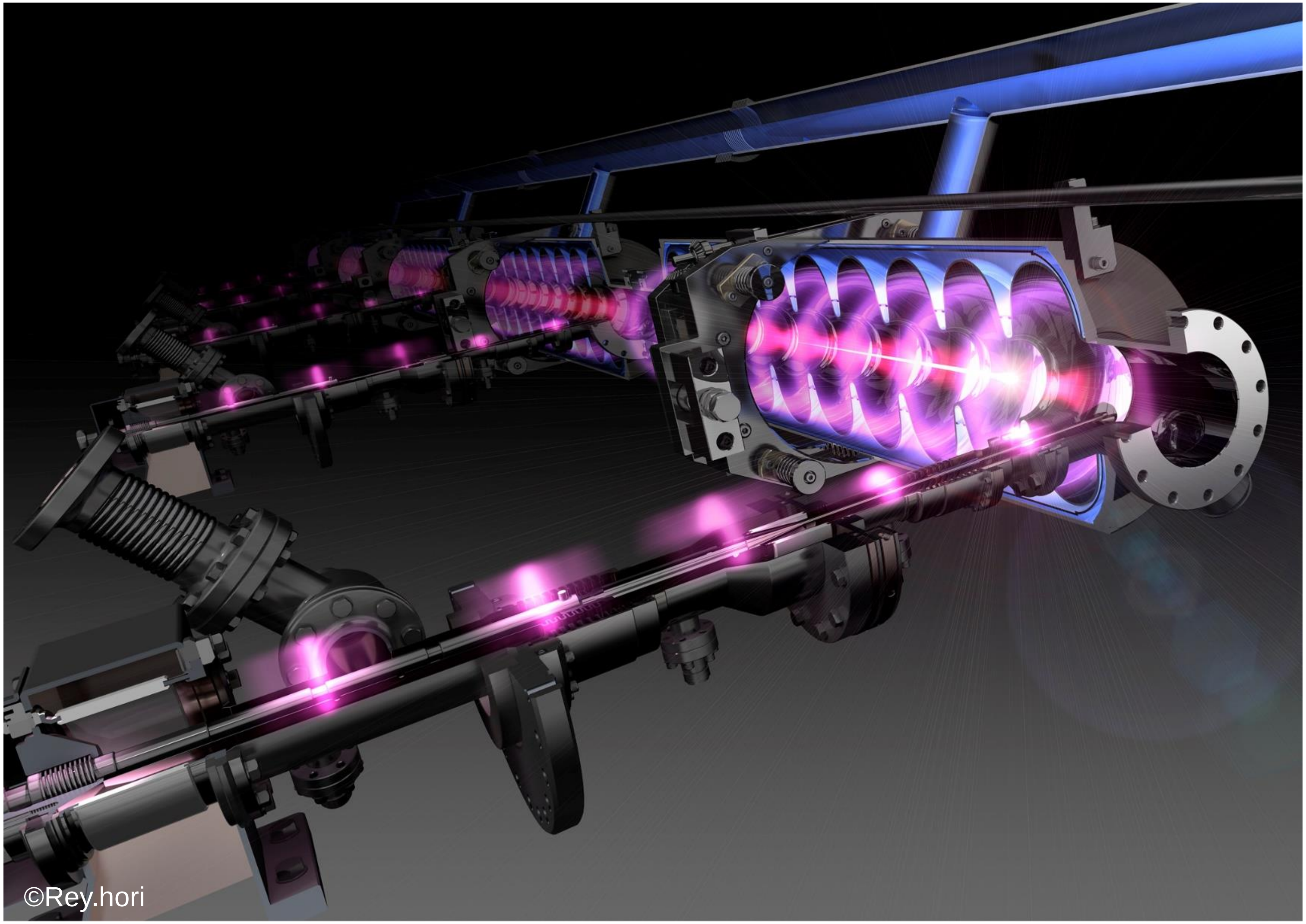
EUROPEAN SPALLATION SOURCE (ESS)

EUROPEAN SPALLATION SOURCE



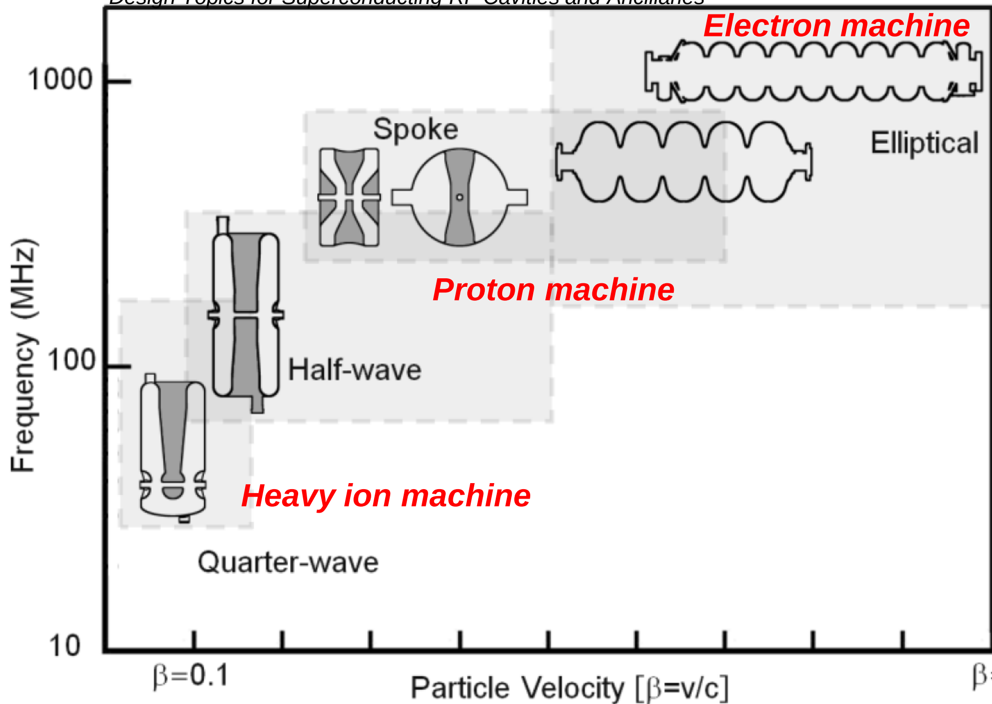


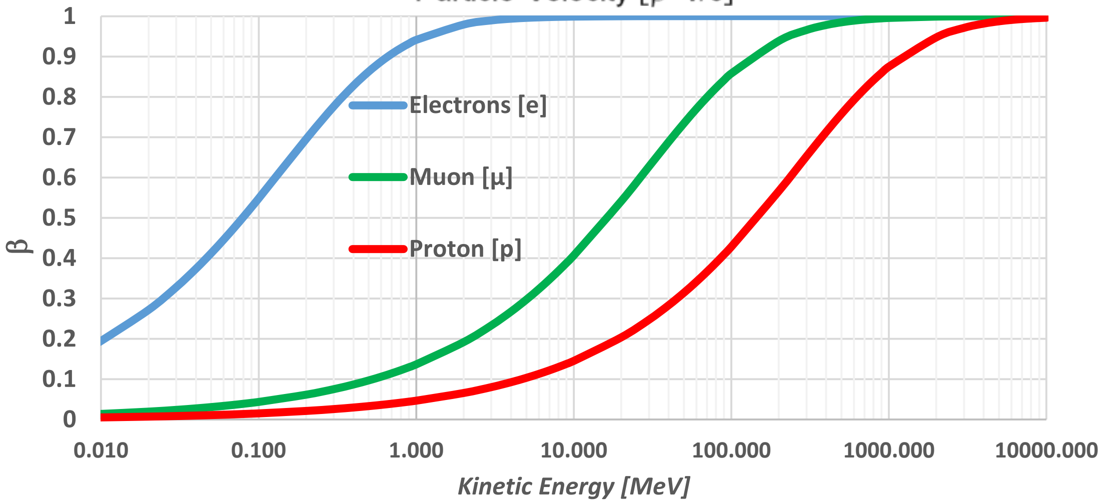
CAVITY DESIGN



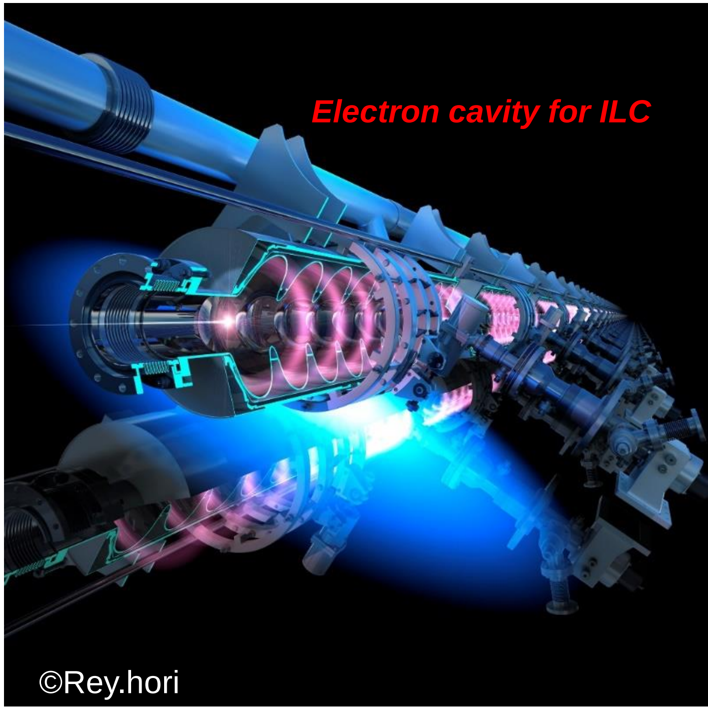
CAVITY DESIGN

From: H. Padamsee
Design Topics for Superconducting RF Cavities and Ancillaries





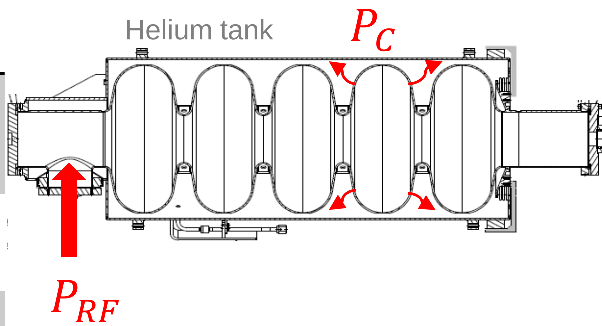
- Typically a cavity design is performed with top-down requirements.
- The accelerator design ("The Machine") and its beam characteristics impose, frequency and cavity shape and maximum cryogenics consumption.

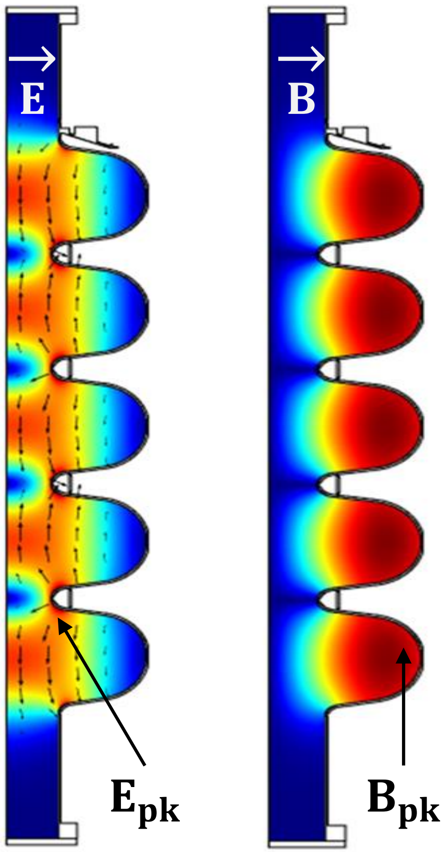


CAVITY FIGURE OF MERIT

Figure of Merit	Description	Optimization
$P_C = \frac{1}{2} R_s \int_S \left\lvert \vec{H}^2 \right\rvert dS$	Dissipated power on cavity surface	Minimize
$Q_0 = \frac{\omega_0 U}{P_C}$	Quality factor, how efficient the cavity is to store energy	Maximize
$G = \frac{\omega_0 \mu \int_V \lvert \vec{H}^2 \rvert dV}{\int_S \lvert \vec{H}^2 \rvert dS}$	Geometry factor, it is independent from material properties. It only depends on geometry.	Maximize
$V = \int_{-\frac{L}{2}}^{\frac{L}{2}} \vec{E}_z e^{i\frac{\omega z}{\beta c}} dz$; $E_{acc} = \frac{V}{L}$	Accelerating voltage and accelerating electrical field.	
$R_{shunt} = \frac{V^2}{P_C}$	Shunt impedance, describe how much accelerating voltage can be attained for a given dissipated power.	Maximize
$\frac{R}{Q} = \frac{V^2}{\omega_0 U}$	How effective is the cavity to “convert” the stored energy U into accelerating voltage V.	Maximize
$\frac{E_{pk}}{E_{acc}}$	Maximum surface electric field on the surface, normalized to the accelerating field. It determines how prone the cavity is to field emission.	Minimize
$\frac{B_{pk}}{E_{acc}}$	Maximum surface magnetic field on the surface, normalized to the accelerating field. It determines the ultimate attainable accelerating field	Minimize

Cavity geometry optimization is guided with the above parameters, some parameter is in competition with others, optimization is needed.

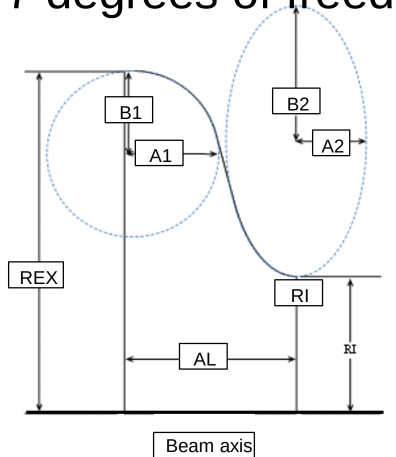




CAVITY DESIGN/OPTIMIZATION

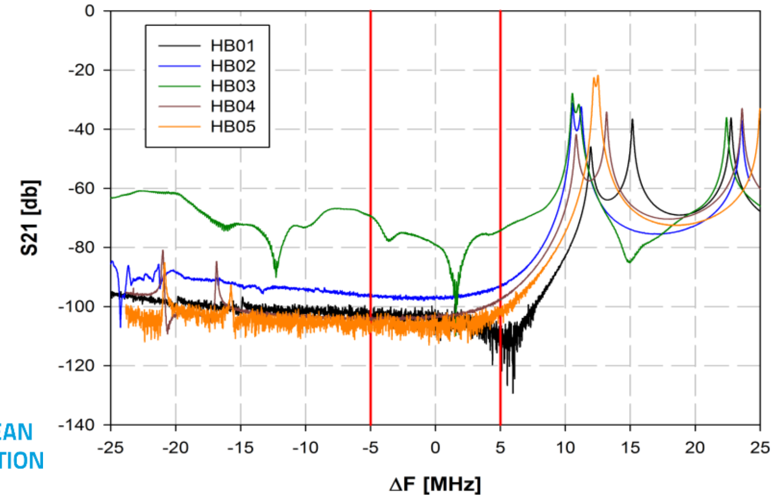
ESS Requirements	ESS high beta
Operating field	19.9 $\frac{MV}{m}$
Operation mode	Pulsed (4%DF)
β	0.86
$\omega_{0\ TM010}$	704 MHz
Temperature	2 K
Maximum dissipated power	6 W
HOMs	ΔF>5MHz

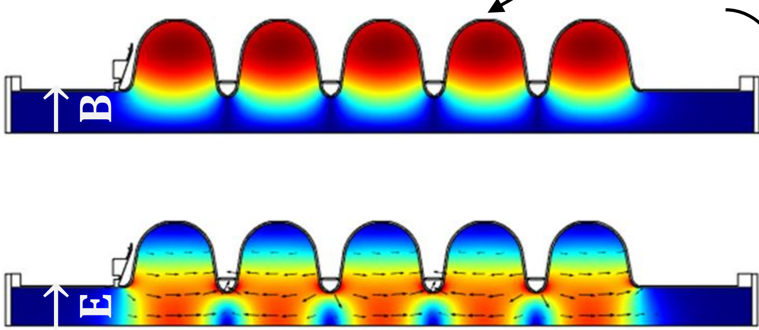
7 degrees of freedom



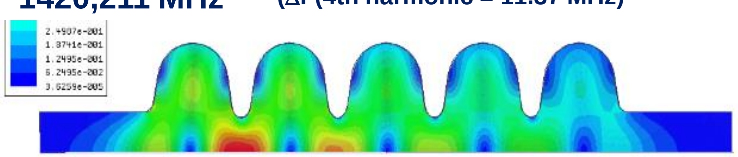
HOMs 4th Harmonic *(incoming inspection)* (1408.84MHz)

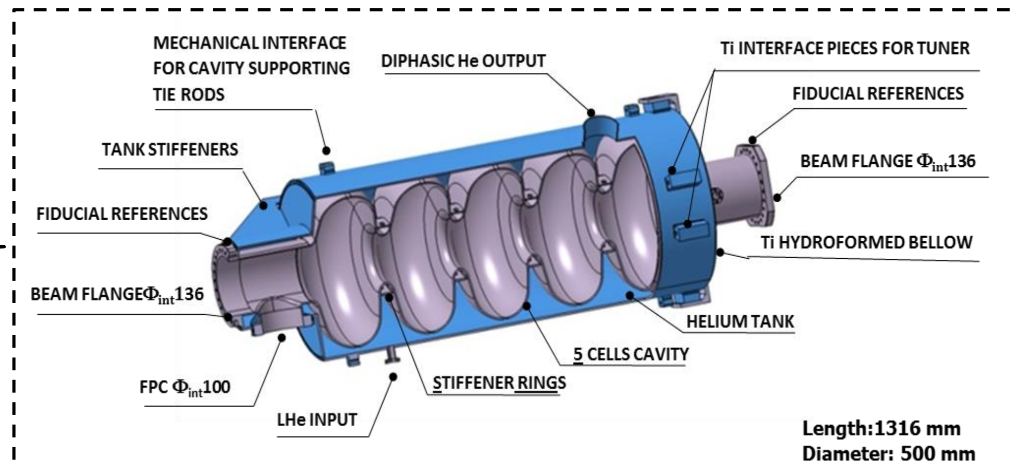
RF design verified after manufacturing



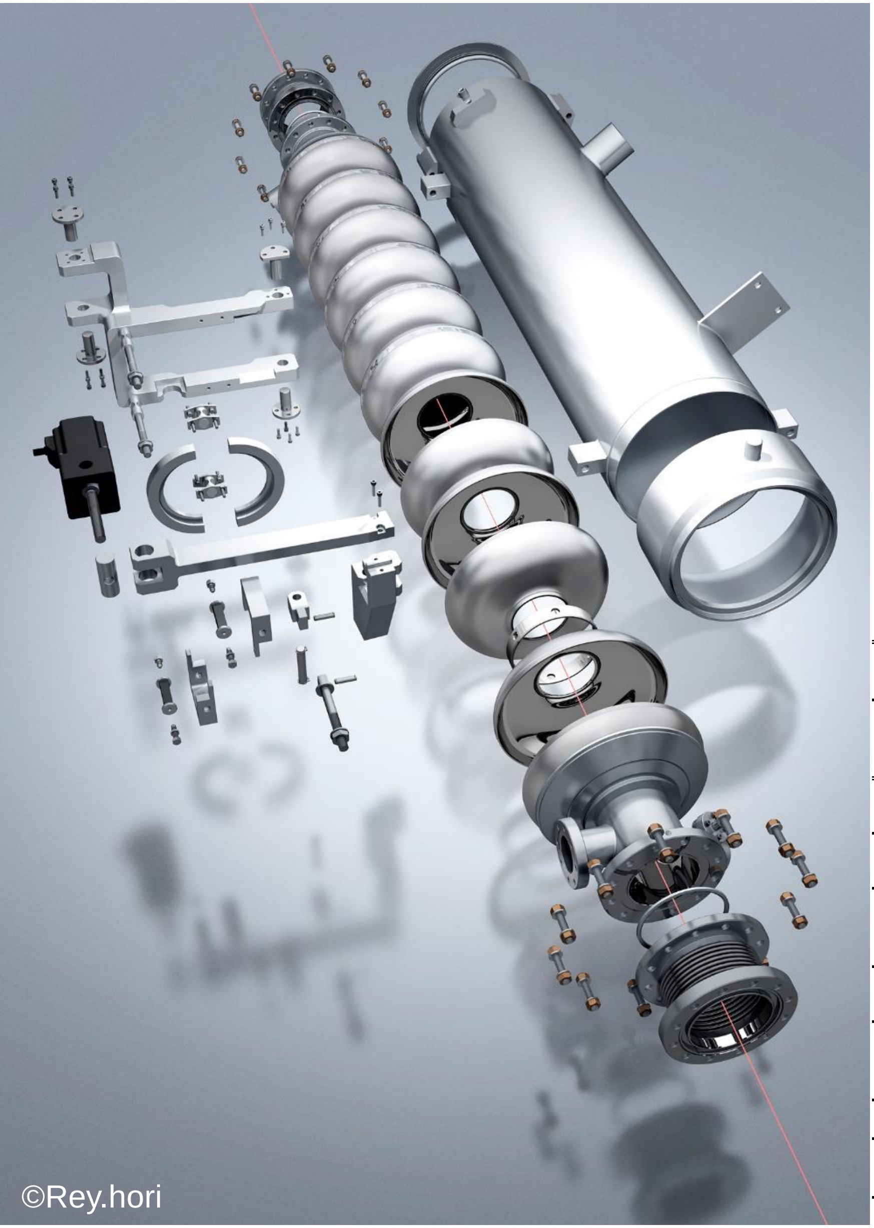


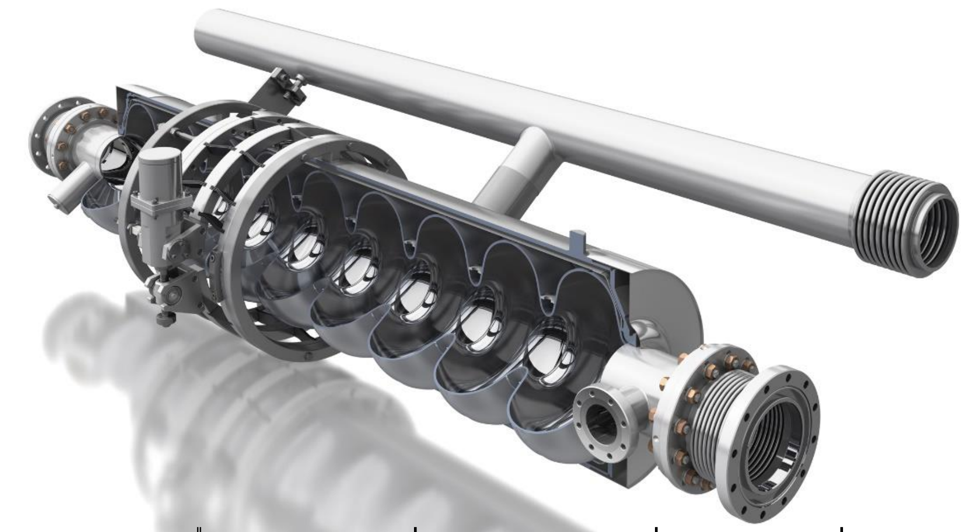
1420,211 MHz (ΔF(4th harmonic = 11.37 MHz)





CAVITY DESIGN (ELECTRON ACCELERATOR)





Property	KEK-ERL mod2	ILC	Medium beta (ESS)	High beta (ESS)
Operating field	$15\ \frac{MV}{m}$	$35\ \frac{MV}{m}$	$16.7\ \frac{MV}{m}$	$19.9\ \frac{MV}{m}$
Operation mode	CW	Pulsed (1%)	Pulsed (4%)	Pulsed (4%)
$\omega_{0\ TM010}$	1300 MHz	1300 MHz	704MHz	704MHz
Temperature	2K	2K	2K	2K
Quality factor (Q_0)	10^{10}	10^{10}	$5x10^9$	$5x10^9$
R/Q [Ω]	896	1018	367	435
G [Ω]	289	277	196.6	241
E_{pk}/E_{acc}	3.0	2.0	2.36	2.2
B_{pk}/E_{acc}	$4.2\ \frac{mT}{MV\ m^{-1}}$	$4.2\ \frac{mT}{MV\ m^{-1}}$	$4.79\ \frac{mT}{MV\ m^{-1}}$	$4.3\ \frac{mT}{MV\ m^{-1}}$

COOLING THE CAVITY

Niobium SRF cavities dissipate only few watts, far less then their copper counterpart…but it comes with a cost!

The power needed at ambient temperature shall take into account the Carnot cycle efficiency (η_C) and the real thermal machine efficiency (η_{Th}) in order to remove the heat load at cryogenic temperature.

The minimum amount of work needed at room temperature is $W_{min} = \frac{Q_{in}}{\eta_C \eta_{Th}}$ where Q_{in} is the heat load at low temperature (T_c).

$$\eta_C = \frac{T_c}{T_h - T_c} \approx \begin{cases} 1/70 \text{ for } T_h = 300\text{ K}, T_c = 4.2\text{K} \\ 1/150 \text{ for } T_h = 300\text{ K}, T_c = 2\text{K} \end{cases}$$

$$\eta_{th} = \begin{cases} 25 - 30\% \text{ at } T = 4.2\text{K} \\ 15 - 20\% \text{ at } T = 2\text{K} \end{cases}$$

To remove 1 W at 4.2 K we need ~250 W at 300 K
To remove 1 W at 2 K we need ~750 W at 300 K

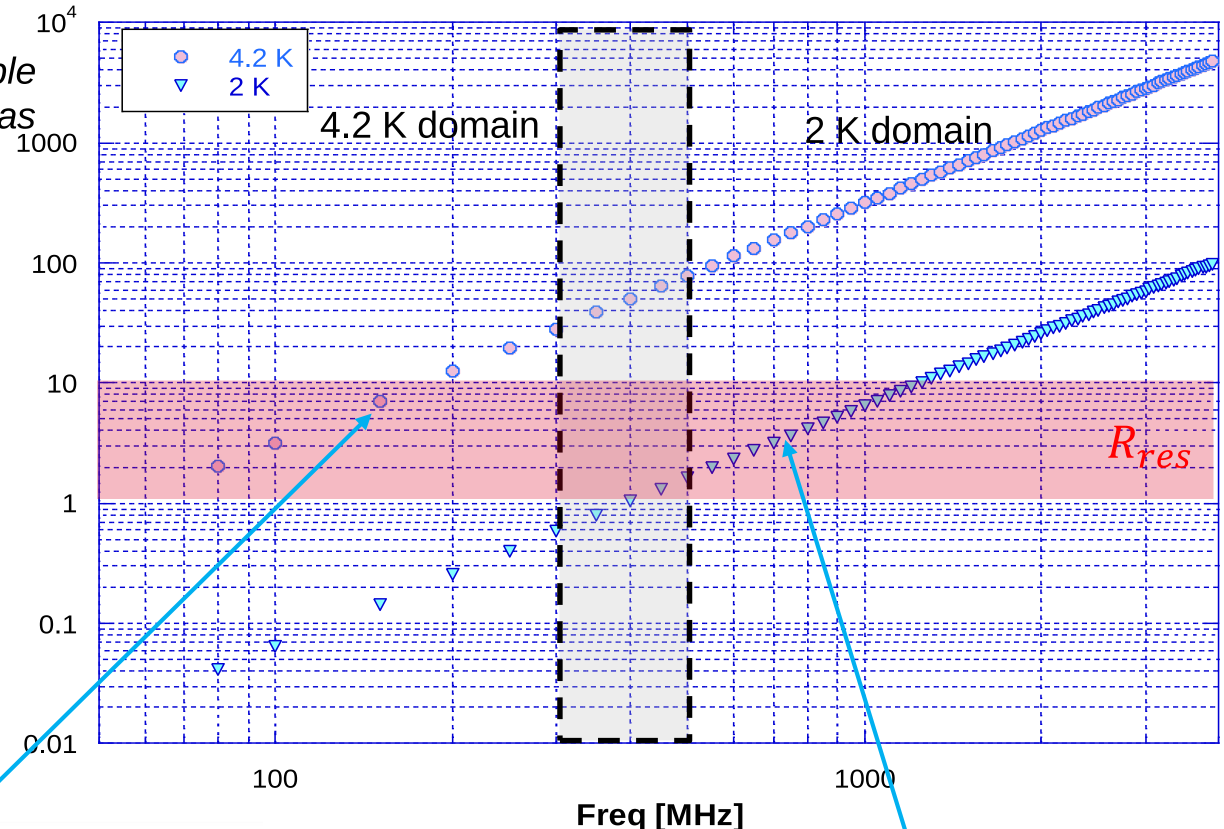
For high duty (CW), high current and high gradient application SRF cavities remains the better choice.

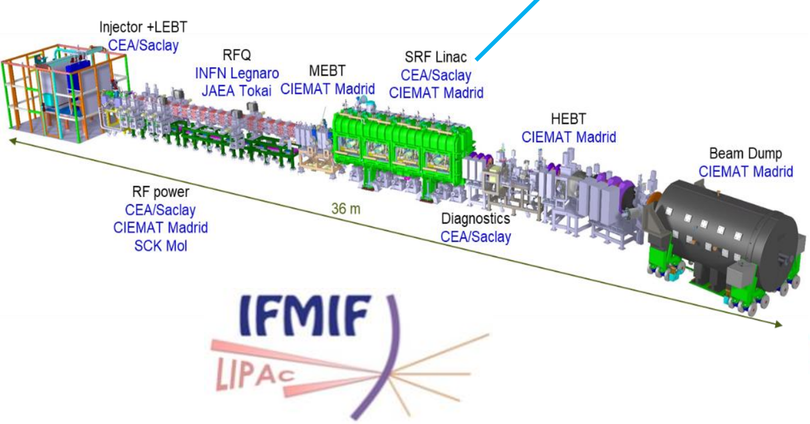
WHICH IS THE OPTIMAL TEMPERATURE?

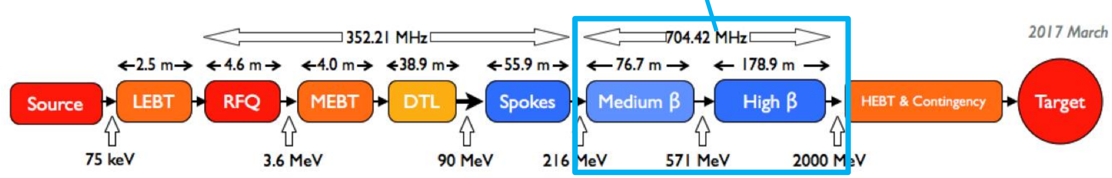
“As a rule of thumb it is preferable to reduce the BCS contribution as low as the residual resistance”

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

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

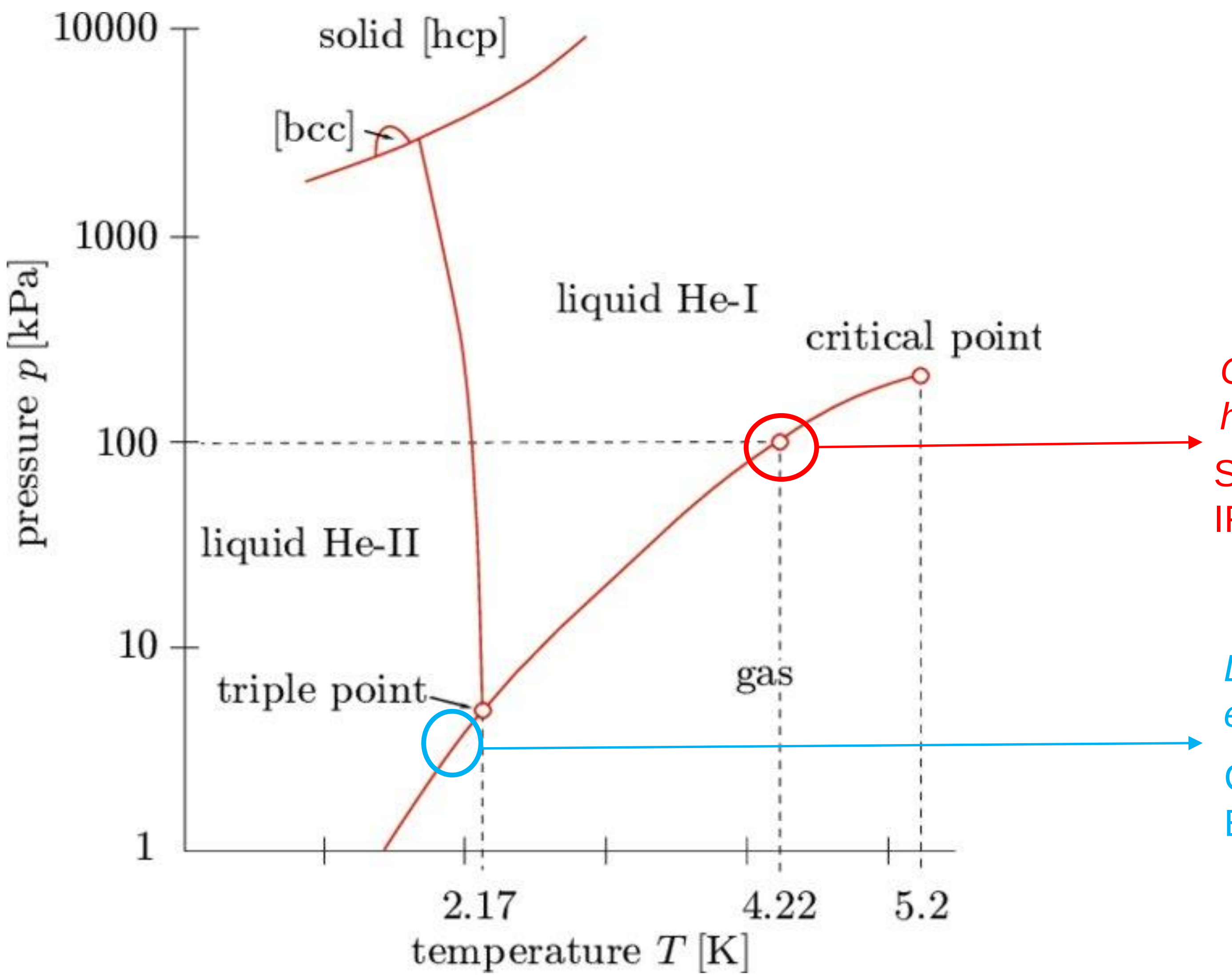






EUROPEAN SPALLATION SOURCE

HELIUM PHASE DIAGRAM (PT)



Circular collider and heavy ion machine

SuperKEKB, HERA, LEP, IFMIF

Linear accelerator and electron machine

CEBAF, SNS, XFEL, ESS, LCLS2, ILC

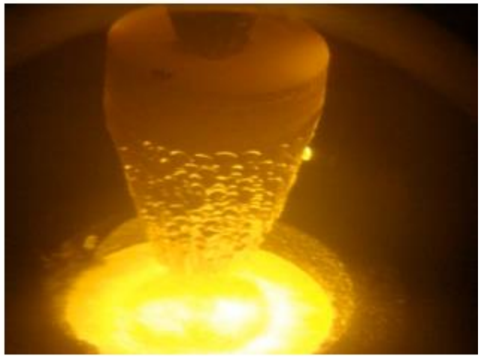
CAVITY MANUFACTURING/PREPARATION

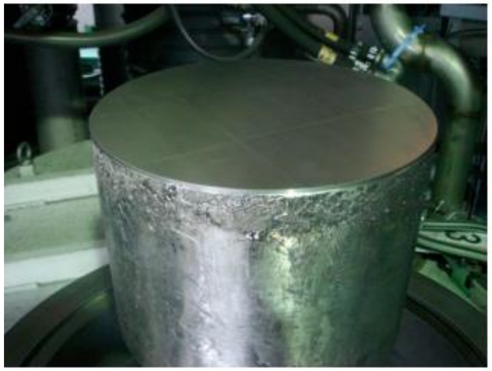
- **High purity Niobium** — Improve Rs and thermal conductivity
- **Deep drawing** — Half cell forming, avoid excessive stress and contamination
- **Electron beam welding** — Clean welding, in vacuum better than 10^{-5}mbar
- **Bulk BCP/EP** — Remove damaged layer 150-200µm
- **High temperature treatment** — Outgas hydrogen and helps recrystallization
- **Flash BCP/EP** — Remove contamination from heat treatment

- **High pressure rinsing** — Remove particles on cavity surface, reduce/eliminate field emission. Use UPW@100bar
- **Clean room assembly** — ISO4/5, avoid surface contamination
- **Low temperature baking** — Improve cavity performance at high field, especially for EP treated
- **Vertical cryostat test** — Cavity fully immersed in liquid helium 4.2K or 2K
- **Cryomodule integration**

CAVITY MANUFACTURING/PREPARATION

High purity Niobium	Deep Drawing	Electron Beam welding	Bulk BCP/EP	High temperature treatment	Flash BCP/EP	High pressure rinsing	Clean room assembly	Vertical test	Cryomodule integration





CAVITY MANUFACTURING/PREPARATION

High purity Niobium	Deep Drawing	Electron Beam welding	**Bulk BCP/EP**	High temperature treatment	**Flash BCP/EP**	High pressure rinsing	Clean room assembly	Vertical test	Cryomodule integration

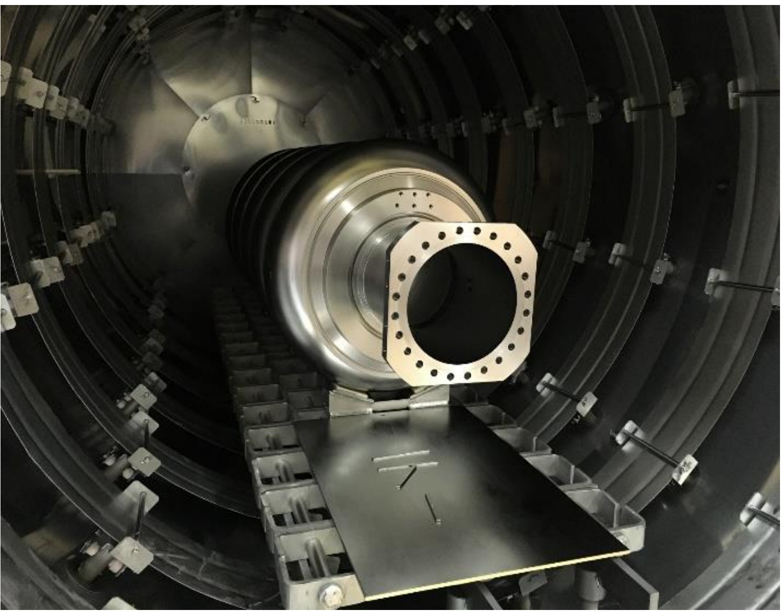
Two established procedure exist:

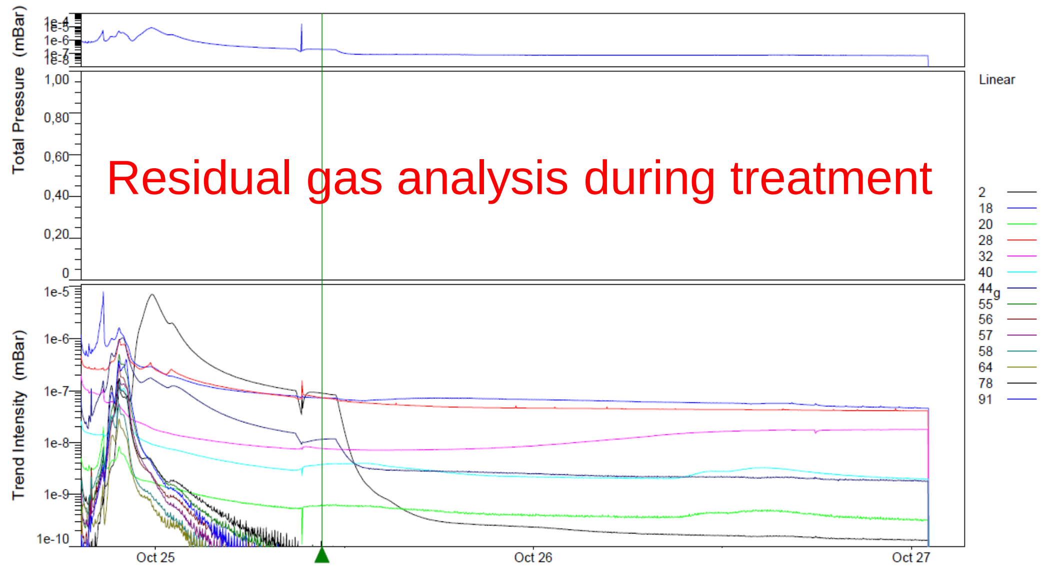
- Buffered chemical polishing: Hydrofluoric+Nitric acid within Phosphoric acid as buffer
- Electro Polishing: Hydrofluoric+Sulfuric acid between a cathode and the cavity (anode)

This process allow to remove the damaged layer ~150-200µm (formed during manufacturing) and expose a clean niobium surface.
"*In the superconducting state the RF fields penetrate about 50 nm in the material*."

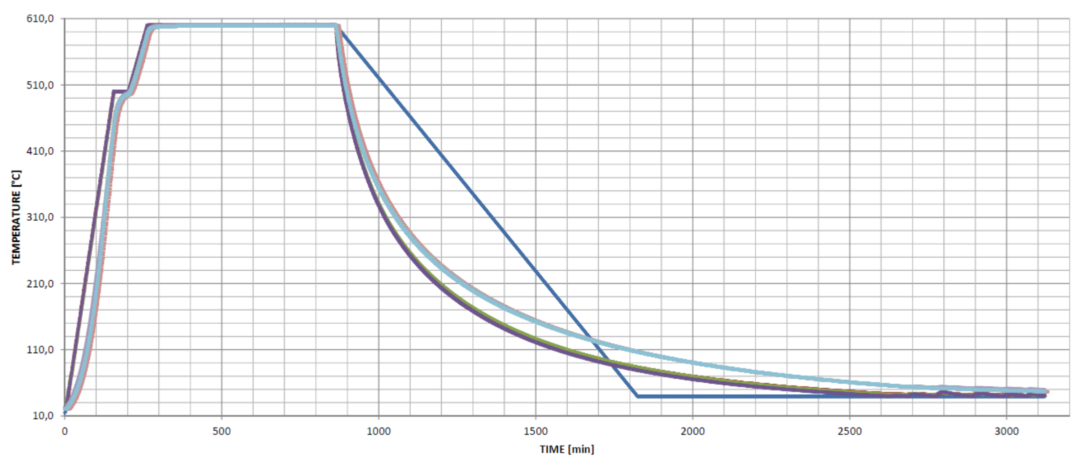
CAVITY MANUFACTURING/PREPARATION

High purity Niobium	Deep Drawing	Electron Beam welding	Bulk BCP/EP	**High temperature treatment**	Flash BCP/EP	High pressure rinsing	Clean room assembly	Vertical test	Cryomodule integration





The cavity is kept at 600-650°C for 10 hours, mostly to outgas hydrogen.
Higher temperatures can be used to improve niobium recrystallization and hence reduce surface resistance.



CAVITY MANUFACTURING/PREPARATION

High purity Niobium	Deep Drawing	Electron Beam welding	Bulk BCP/EP	High temperature treatment	Flash BCP/EP	**High pressure rinsing**	**Clean room assembly**	Vertical test	Cryomodule integration

High pressure (100 bar) ultra pure water is injected through a nozzle in the cavity while it is moving. It helps to remove dusts and contaminants from the cavity surface.

Cavity ancillaries are installed in ISO4 or ISO5 clean room, the cavity surface shall be preserved clean.


Courtesy E. Zanon

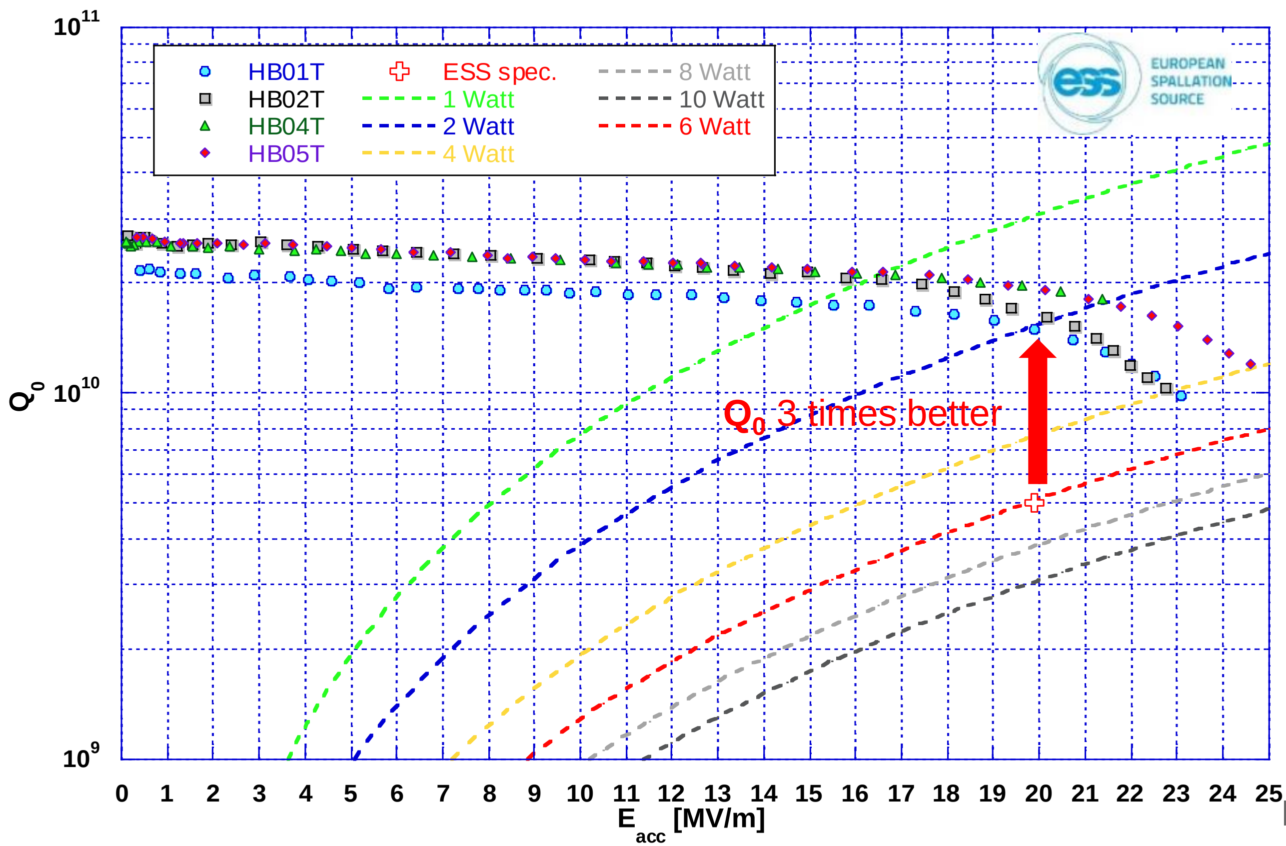
CAVITIES TESTS IN VERTICAL CRYOSTAT

High purity Niobium	Deep Drawing	Electron Beam welding	Bulk BCP/EP	High temperature treatment	Flash BCP/EP	High pressure rinsing	Clean room assembly	**Vertical test**	Cryomodule integration

All the manufacturing process and preparation are performed in order to obtain a good niobium surface down to a depth of 50-100 nm.

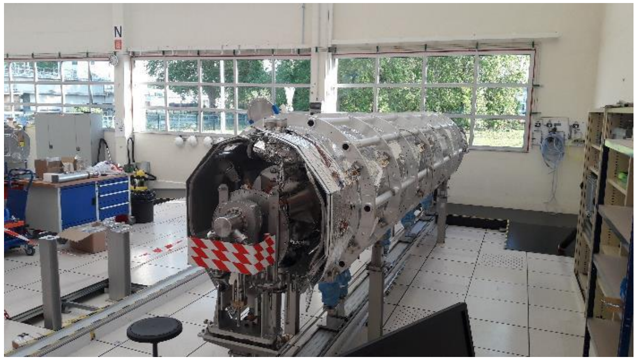
Finally, if everything worked fine you can obtain some cavity above specification!

ESS HIGH BETA CAVITIES (VT@2K)

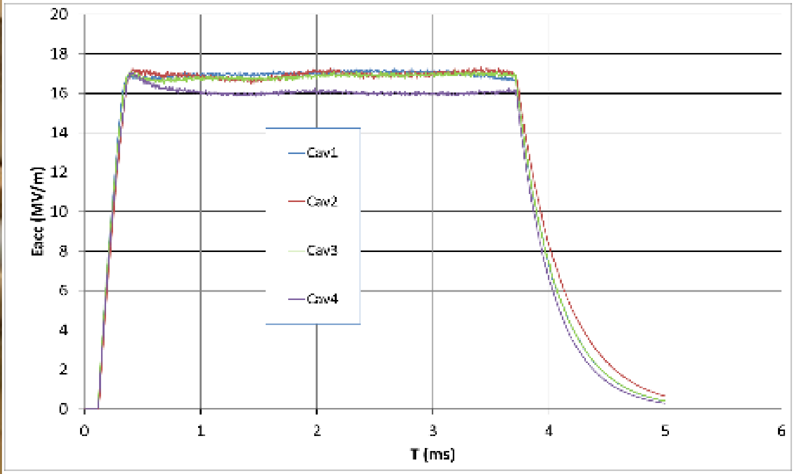


CAVITY MANUFACTURING/PREPARATION

High purity Niobium	Deep Drawing	Electron Beam welding	Bulk BCP/EP	High temperature treatment	Flash BCP/EP	High pressure rinsing	Clean room assembly	Vertical test	**Cryomodule integration**

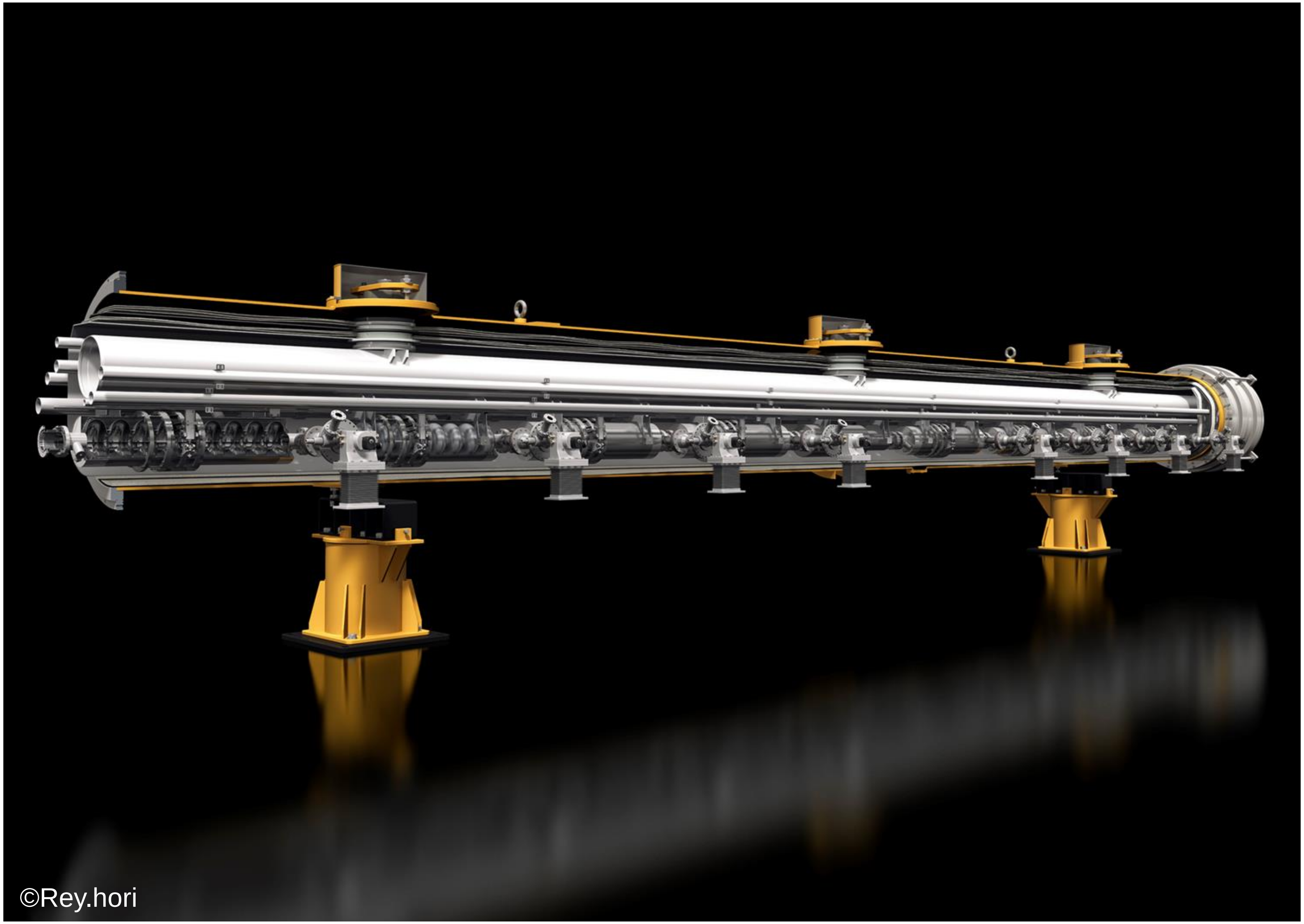


CRYOMODULE TEST FACILITY IN CEA



The 4 cavities tested separately at the nominal field (or close to for cav4)

CRYOMODULE CONCEPTS



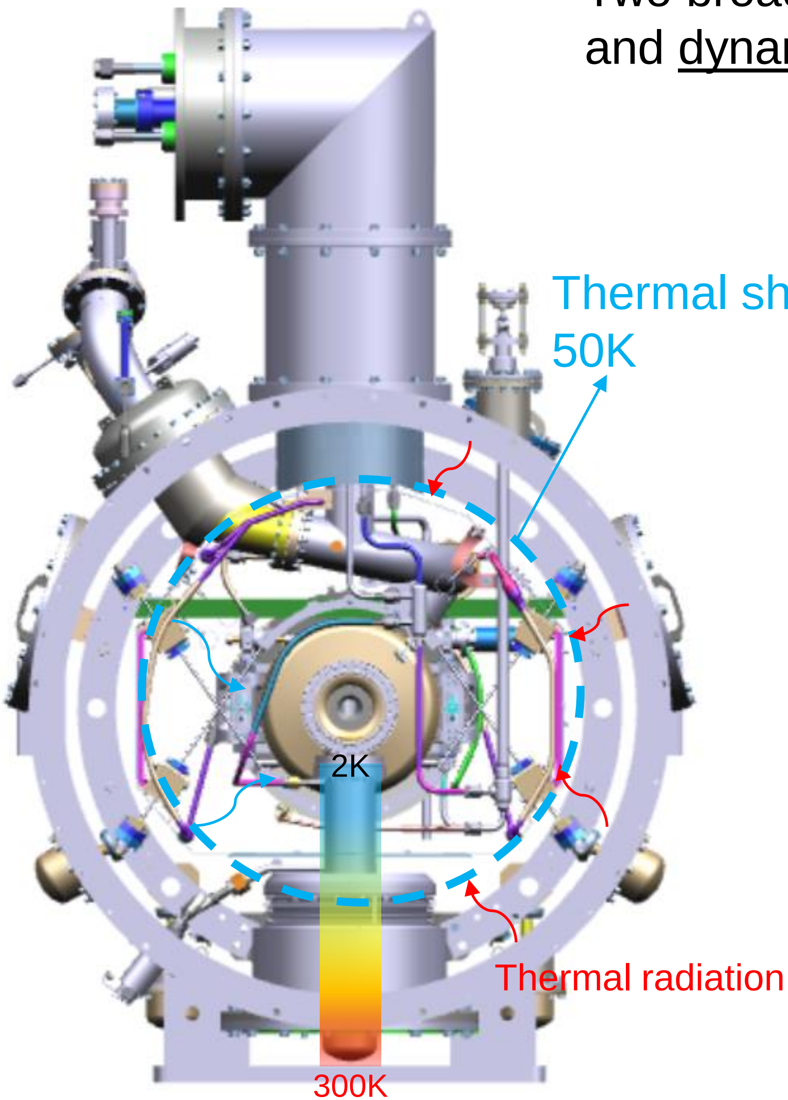
CRYOMODULE CONCEPTS

Some general consideration:

- The cryomodule is one of the fundamental building block of the accelerator
- It needs to:
  - Provide mechanical support for cavities, input coupler and magnets (if necessary)
  - Guarantee alignment preservation during operation (from room to cryogenic temperature)
  - Maintain the cryogenic environment for accelerator operation
  - Preserve cavity package performance
  - Manage heat loads (with some margin)

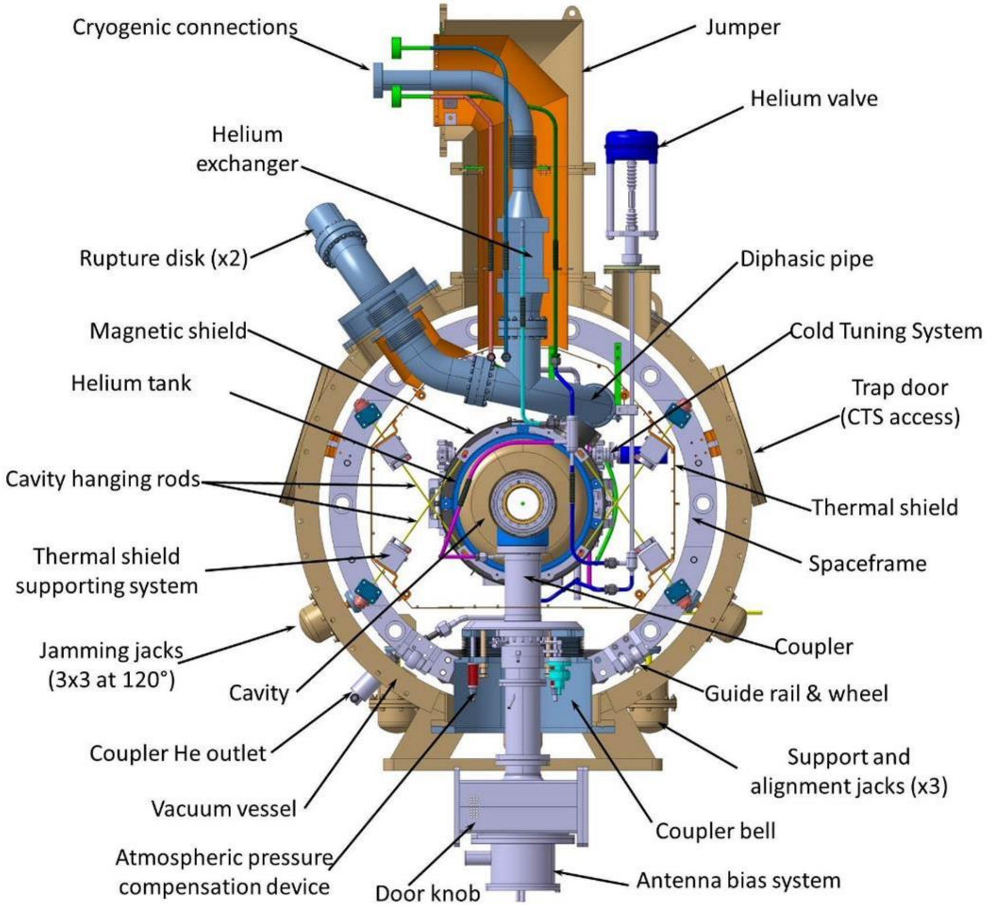
There are different approaches to address the above issues, here I present just some of them…
You will see many other in today presentations.

Two broad family of heat loads shall be considered: statics and dynamics



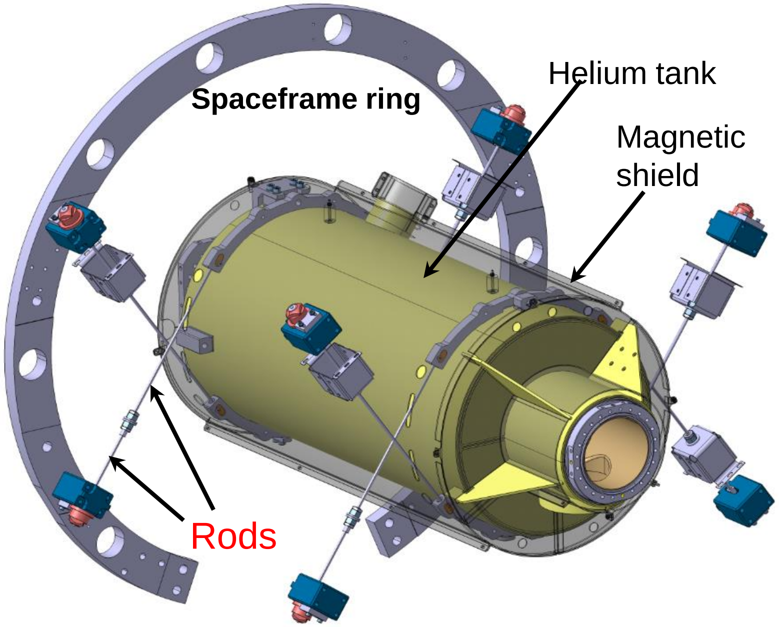
- **Statics heat load**
  - Cavity supports
  - Power input couplers
  - Transition at cryomodule ends
  - Current leads (if magnets are inside)
  - Safety elements (valves, overpressure release)
  - Instrumentation cables
  - Thermal radiation
- **Dynamic heat loads**
  - RF power dissipated by the cavities
  - RF power dissipated by the couplers
  - Cooling for couplers
  - *Cooling for current leads*

ESS APPROACH

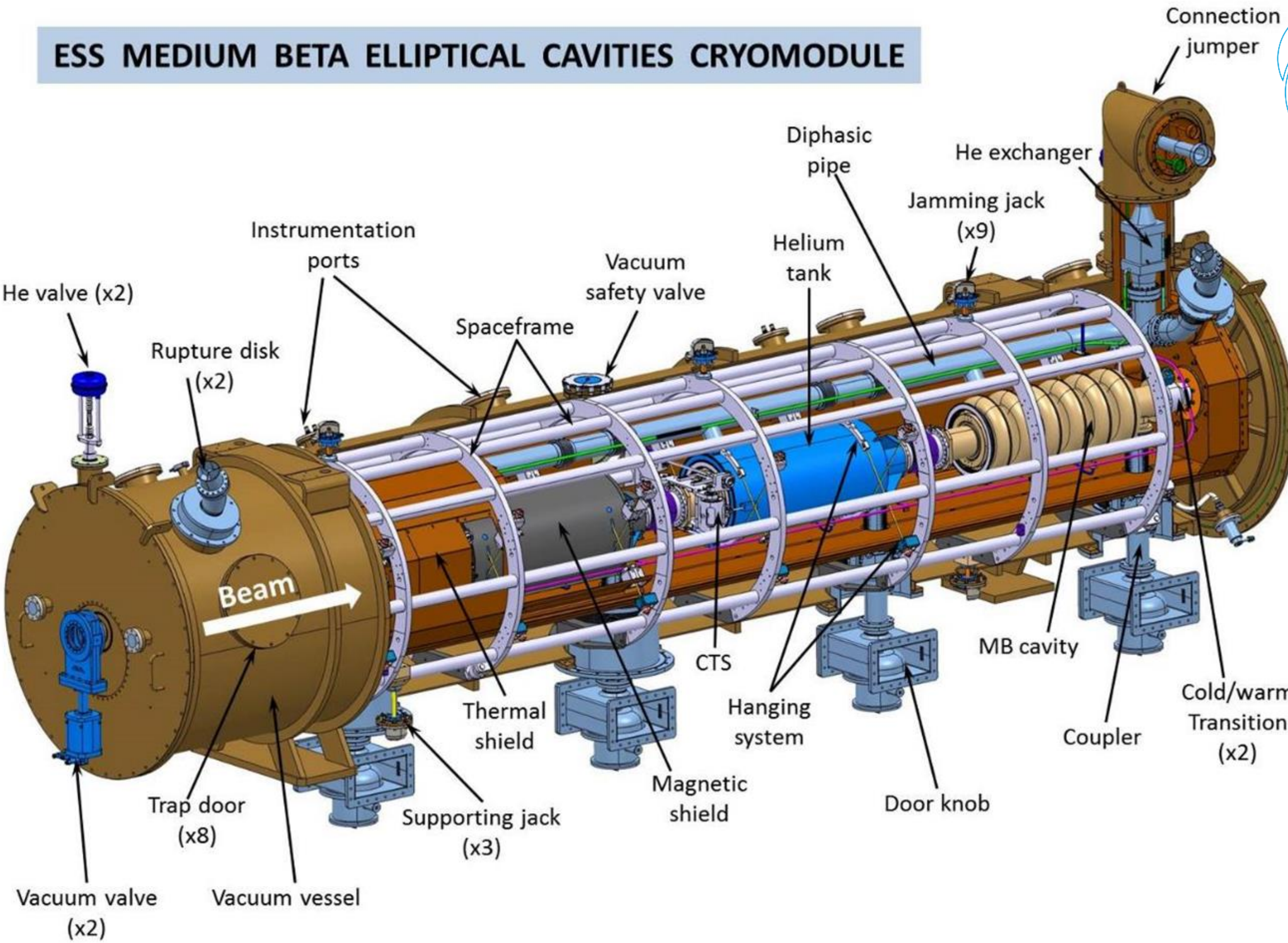


- Cavity suspended by Ti rods
- Space frame
- Input coupler on the bottom
- Thermal shield at 50 K

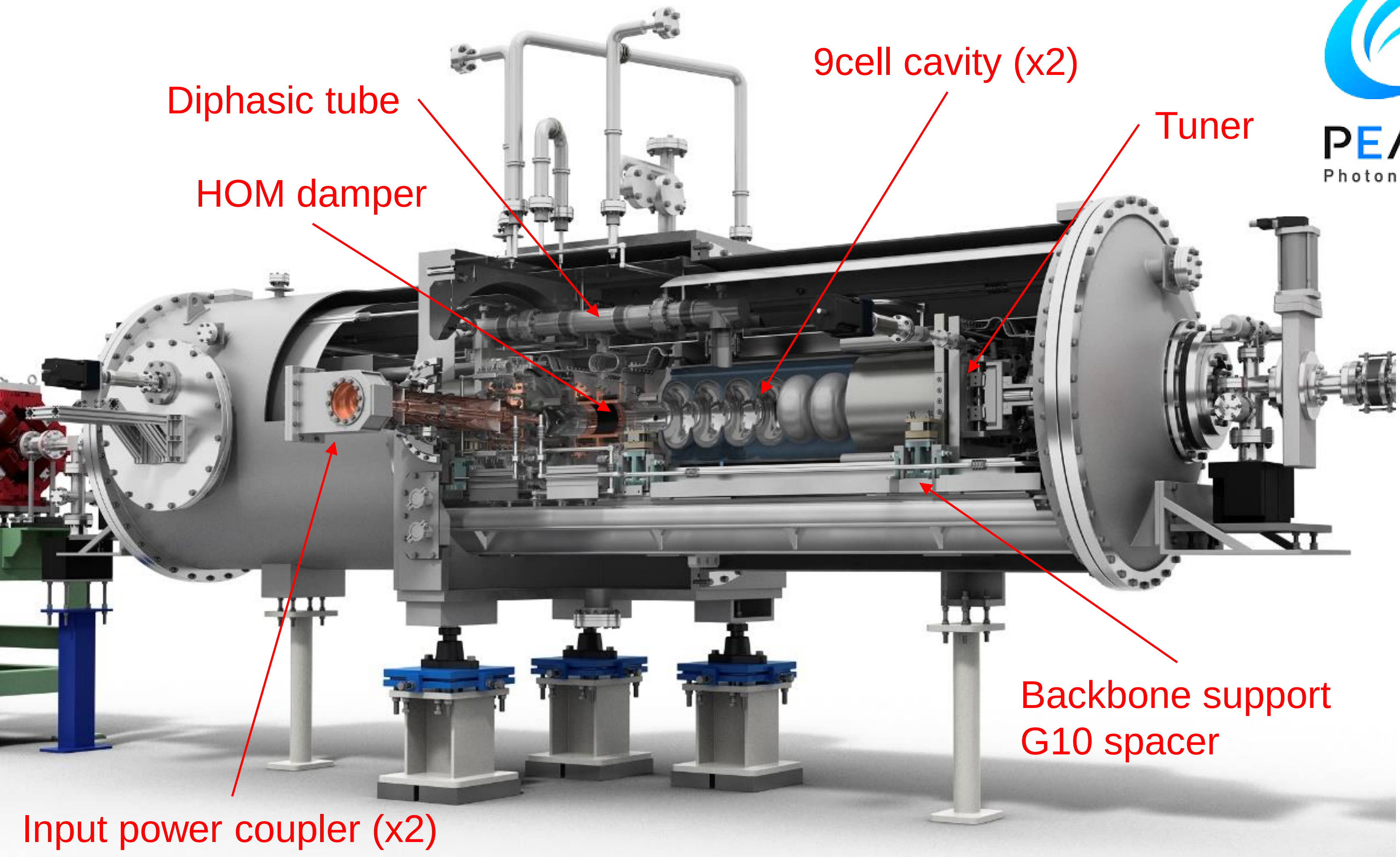
	Heat load (W)	Temperature (K)	Pressure (bar)	Mass flow (g/s)
Thermal shield	76	40 - 50	19.5 - 19	1.4
Coupler		5 - 280	3	0.023
2 K static	7.5	2.0	0.031	0.33
2 K total	38	2.0	0.031	2



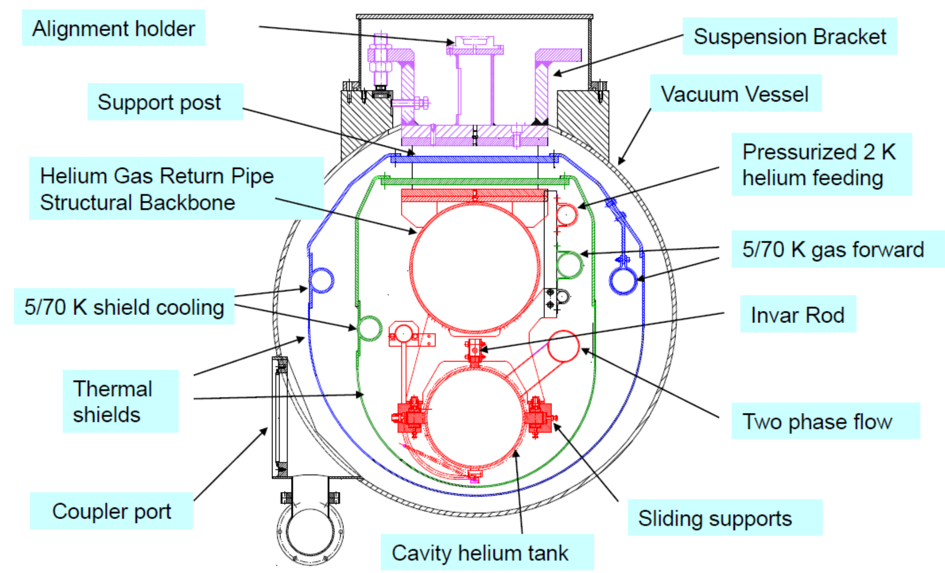
ESS ELLIPTICAL CAVITIES CRYOMODULE

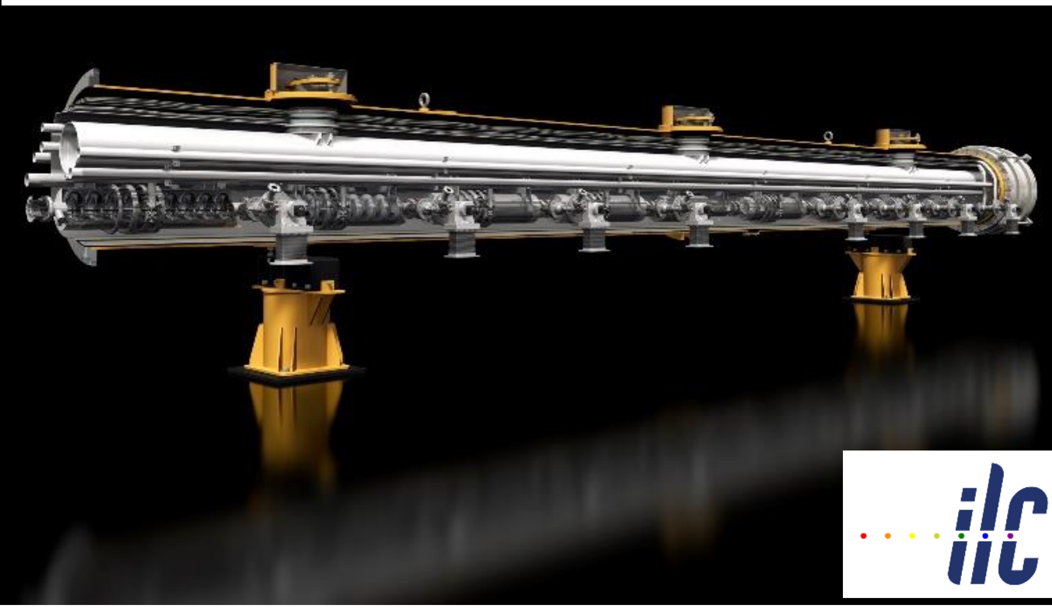


CERL CRYOMODULE



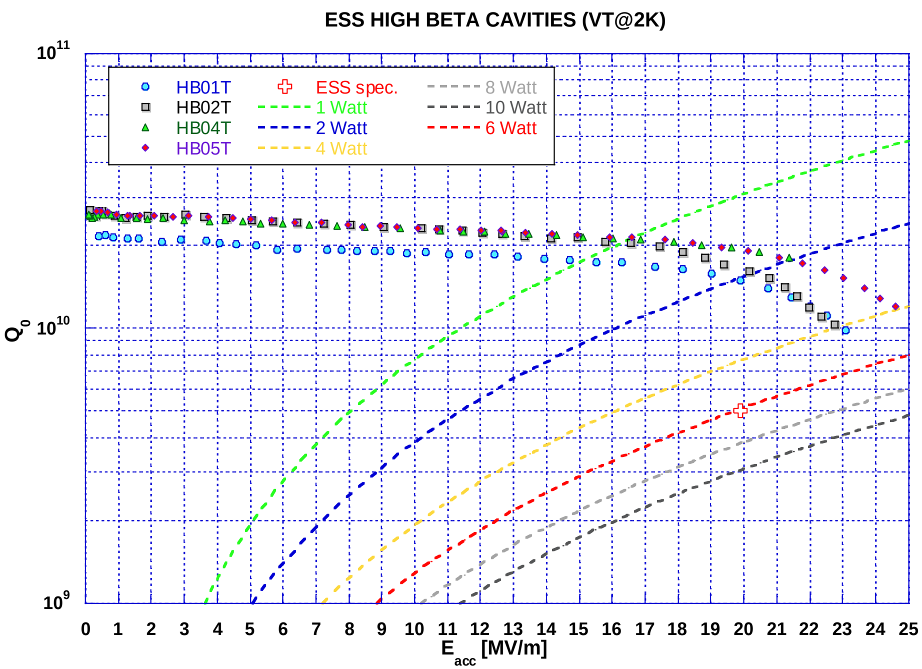
ILC CRYOMODULE (XFEL TESLA STYLE)

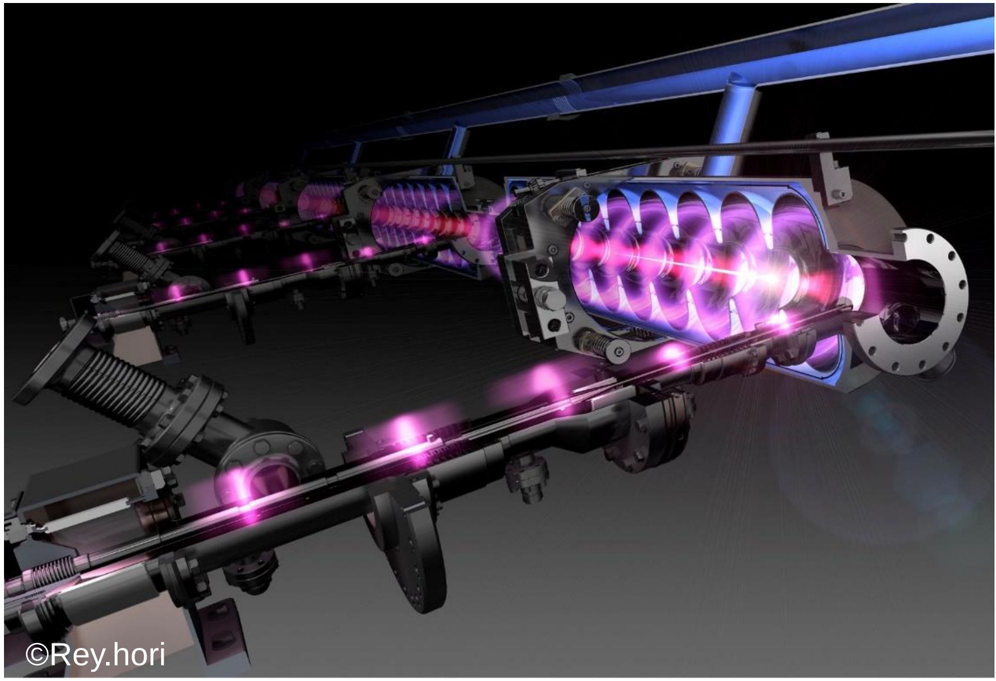




SUMMARY AND OUTLOOK

- A lot of effort is put in order to obtain and maintain high quality Niobium surfaces able to achieve high quality factor and accelerating electric fields.
- It is a very exciting period in SRF community, more and more projects are involved in this field.
- New discoveries are emerging in recent years allowing to improve even more SRF cavity performances.
- New applications, like quantum computing are on the horizon.





Thank you for your attention

Merci à: N. Bazin, P. Bosland, P. Pierini, G. Olivier, Rey Hori.

Thanks Bertrand for the invitation…

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    - 2004-08 Superconductivity and Cryogenics for Accelerators and Detectors
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- **R. Geng**, Superconducting RF Cavity Basics
- **C. Antoine**, Materials and surface aspects in the development of SRF Niobium cavities
- SRF conference proceedings (JACOW)
- LINAC conference proceedings (JACOW)

CEA - Saclay

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