Linear Accelerator Technology

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Free Electron Lasers and Energy Recovery Linacs (FELs and ERLs)

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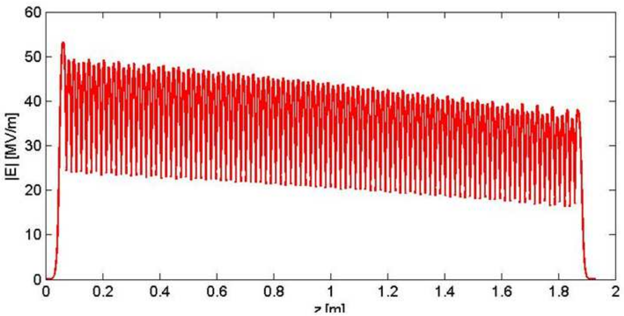
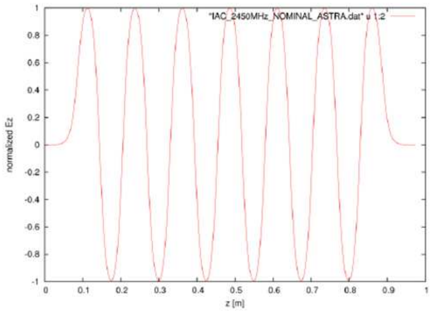
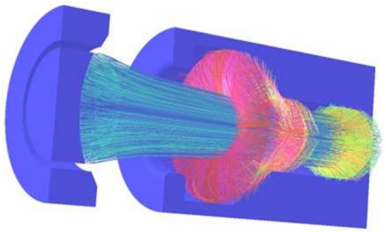
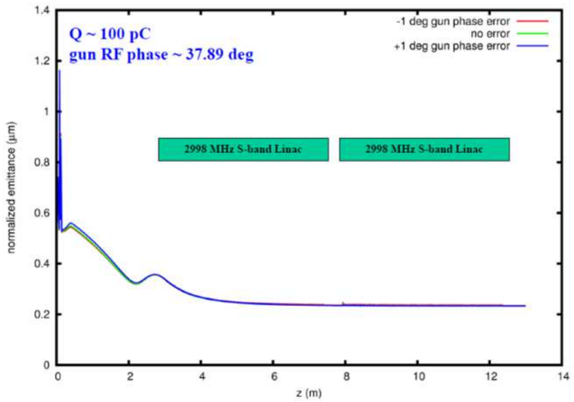
WHAT DOES IT MEANS LINAC TECHNOLOGY? *…For FEL and ERL…*

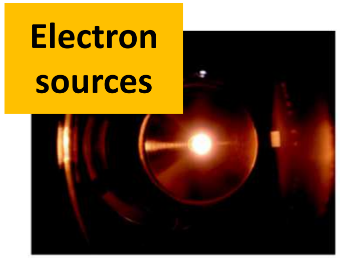


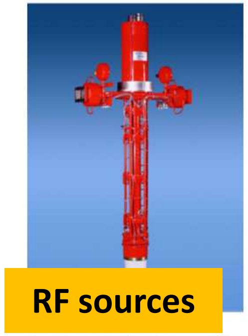


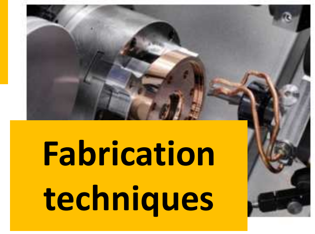


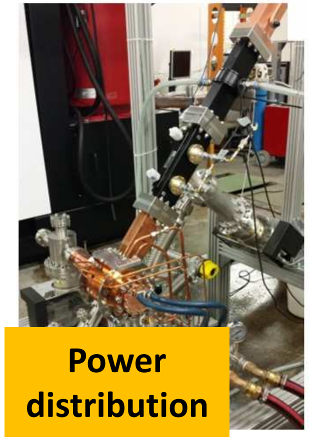


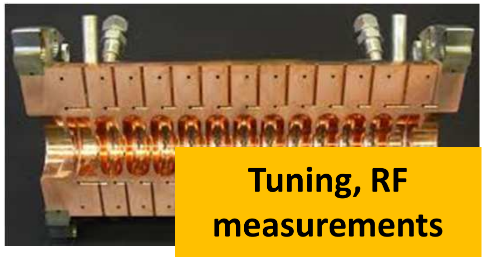
But also: quadrupoles, magnets, vacuum, beam diagnostics devices,…











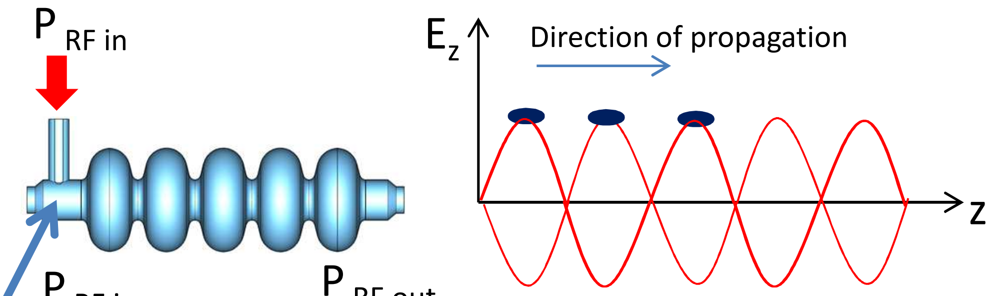
ACCELERATING CAVITIES

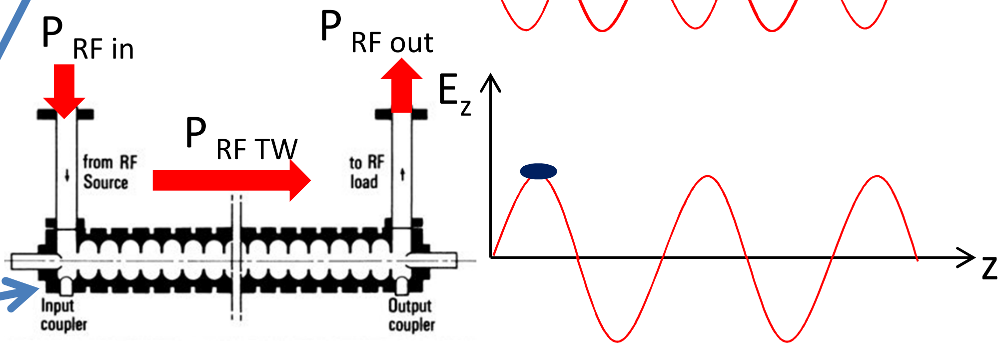
$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + v \times \vec{B}\right)$$

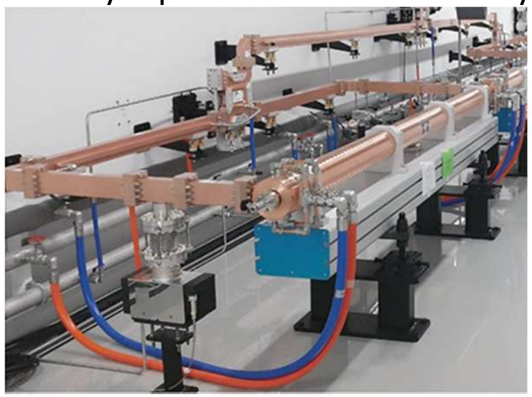
To accelerate charged particles, the RF wave must have an **electric field along the direction of propagation of the particle**. There are basically two possibilities:

1-Using **standing wave (SW)** TM010-like modes in a **resonant cavity** (or multiple resonant cavities) in which the beam is synchronous with the resonating field;

2-Using a **travelling wave (TW) disk loaded** structure operating on the TM01-like mode in which the RF wave is co-propagating with the beam with a phase velocity equal to the beam velocity (c for e^-).







⇒The structures are powered by RF generators (typically **klystrons**).

⇒The cavities (and the related LINAC technology) can be of different material:

- copper for **normal conducting (NC, typically TW)** cavities;
- Niobium for **superconducting cavities (SC, typically SW)**;

⇒We can choose between NC or the SC technology depending on the required performances in term of:

- **accelerating gradient** (MV/m);
- **RF pulse length** (how many bunches we can contemporary accelerate);
- **Duty cycle**: pulsed operation (i.e. 10-100 Hz) or continuous wave (CW) operation;
- **Average beam current**.

SW CAVITIES

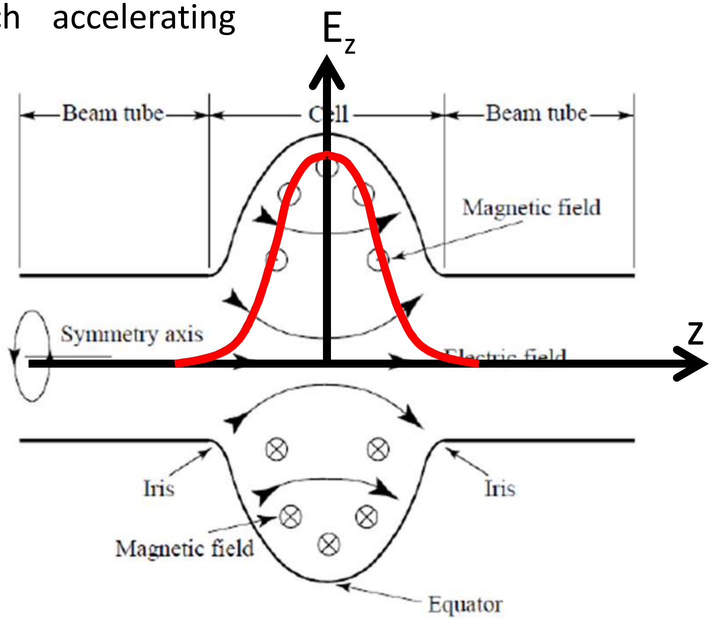
SW CAVITIES PARAMETERS: V_{acc}, P_{diss}, W

To compare different technologies is necessary to define some parameter that characterize each accelerating structure.

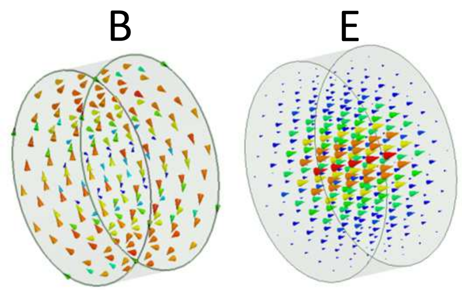
ACCELERATING VOLTAGE

We suppose that the cavities are powered at a **constant frequency f_{RF}**. The **maximum energy gain** of a particle crossing the cavity at a velocity v (~c for electrons) is obtained integrating the time-varying accelerating field sampled by the charge along the trajectory:

$$V_{acc} = \left| \int_{cavity} E_z(z) e^{j\omega_{RF}\frac{z}{v}} dz \right|$$



$$E_z(z,t) = \mathrm{Re}\left[E_z(z) e^{j\omega_{RF}t}\right]$$



MODE TM_{010}

DISSIPATED POWER

Real cavities have **losses**.
Surface currents (related to the surface magnetic field $\vec{J} = \vec{n} \times \vec{H}$) "sees" a **surface resistance R_s** and dissipate energy, so that a certain amount of RF power must be provided from the outside to keep the accelerating field at the desired level. The total dissipated power is:

$$P_{diss} = \int_{cavity\ wall} \overbrace{\frac{1}{2} R_s H_{tan}^2}^{\text{power density}} dS$$

NC cavity (Cu $R_s \approx 3$ mΩ at 1 GHz)
SC cavity (Nb at 2 K $R_s \approx 10$ nΩ at 1 GHz)

STORED ENERGY

The total energy stored in the cavity:

$$W = \int_{cavity\ volume} \overbrace{\left(\frac{1}{4}\varepsilon\left|\vec{E}\right|^2 + \frac{1}{4}\mu\left|\vec{H}\right|^2 \right)}^{\text{energy density}} dV$$

SW CAVITIES PARAMETERS: R, Q, R/Q

ACCELERATING VOLTAGE (V_{acc}) ***DISSIPATED POWER (P_{diss})*** ***STORED ENERGY (W)***

SHUNT IMPEDANCE

The shunt impedance is the parameter that qualifies the **efficiency of an accelerating mode**. The highest is its value, the larger is the obtainable accelerating voltage for a given power. Traditionally, it is the quantity to optimize in order to **maximize the accelerating field for a given dissipated power**:

$$R = \frac{V_{acc}^2}{2P_{diss}} \qquad [\Omega]$$

QUALITY FACTOR

$$Q = \omega_{RF} \frac{W}{P_{diss}}$$

NC cavity Q~10^4

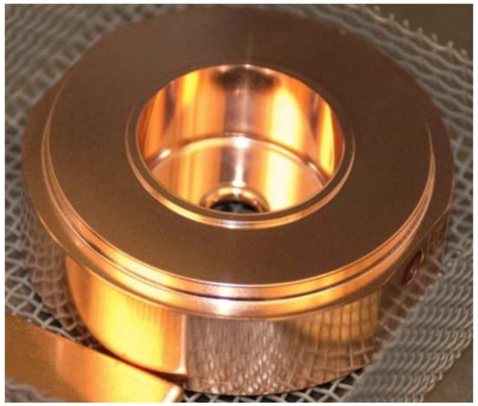
SC cavity Q~10^{10}

R/Q

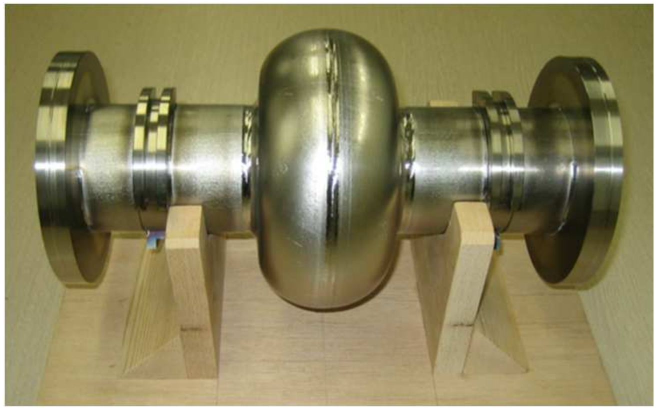
$$\frac{R}{Q} = \frac{V_{acc}^2}{2\omega_{RF} W}$$

The R/Q is a **pure geometric qualification factor**. It does not depend on the cavity wall conductivity. R/Q of a single cell is of the order of 100.

NC cavity R~1MΩ



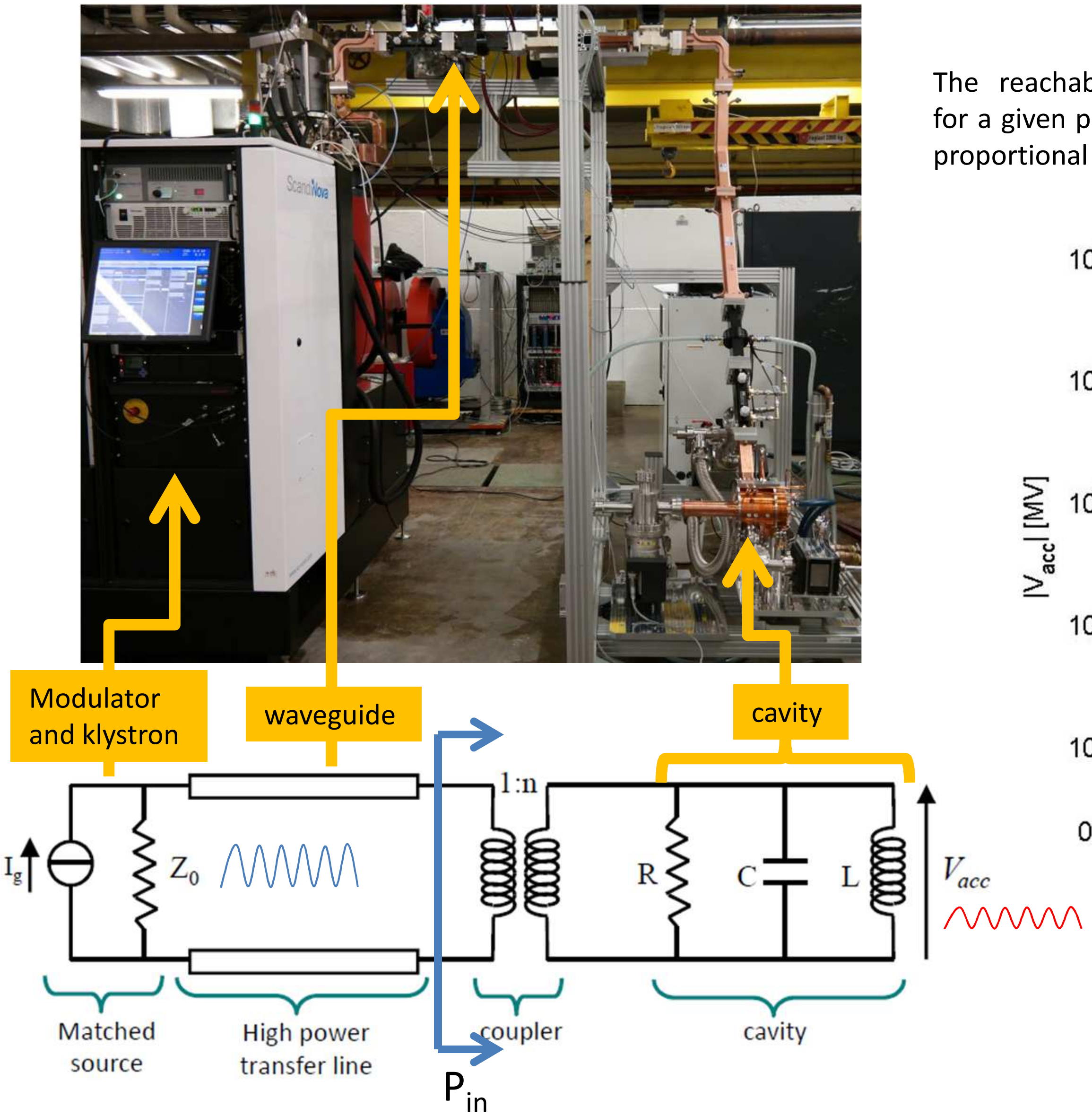
SC cavity R~1TΩ



SW CAVITIES : EQUIVALENT CIRCUIT AND BANDWIDTH

The previous quantities plays crucial roles in the evaluation of the **cavity performances**. Let us consider the case of a cavity powered by a source (klystron) at a constant frequency in CW and at a fixed power (P_{in}).

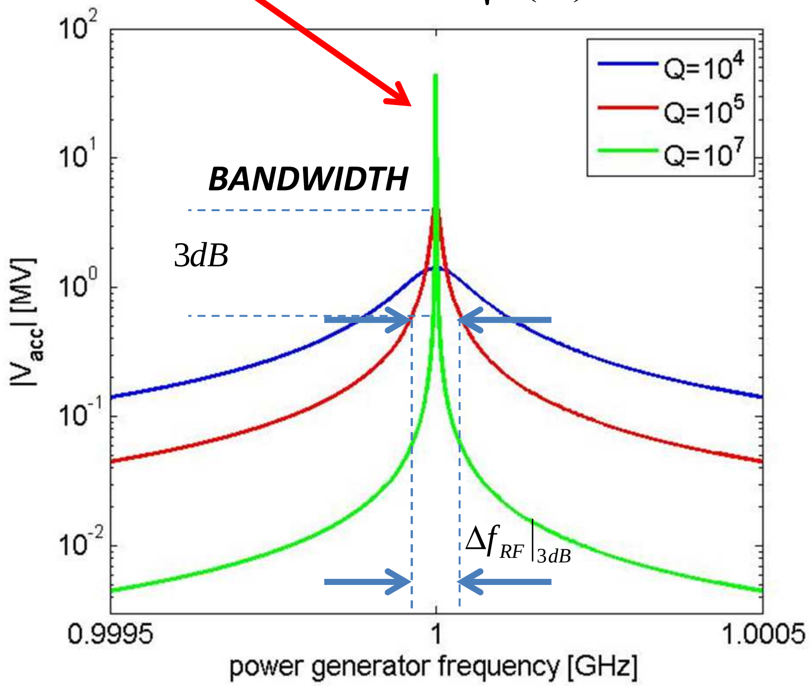
P_{in}=1 MW
R/Q=100
β=1 (no reflections, $P_{diss}=P_{in}$)
f_{res}=1 GHz



The reachable V_{acc} for a given power is proportional to √Q

Frequency domain

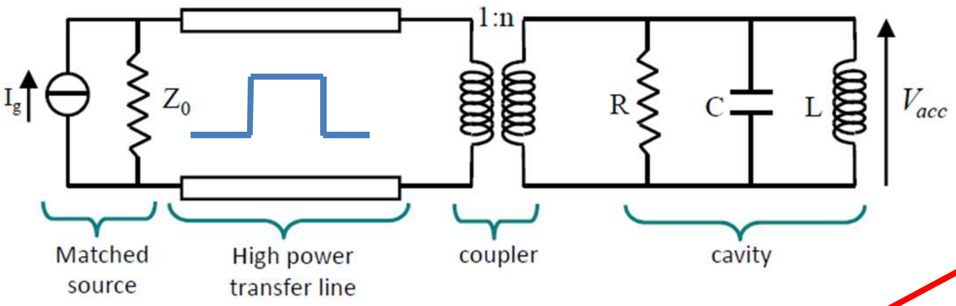
$$V_{acc} = \sqrt{2RP_{diss}} = \sqrt{2\left(\frac{R}{Q}\right)QP_{in}} \propto \sqrt{Q}$$



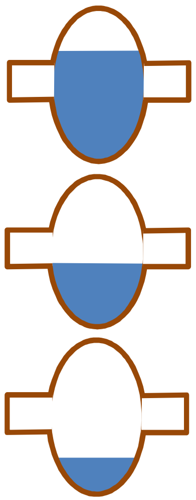
$$\frac{\Delta f_{RF}|_{3dB}}{f_{RF}} = \frac{1}{Q} \Rightarrow \begin{cases} \Delta f_{RF}|_{3dB}\big|_{NC} = 100kHz \\ \Delta f_{RF}|_{3dB}\big|_{SC} < 1Hz \end{cases}$$

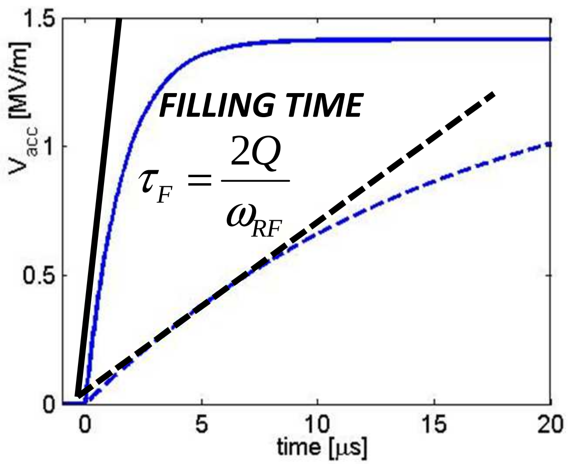
SW CAVITIES : FILLING TIME AND DISSIPATED POWER

Let us now consider the case of a cavity powered by a source (klystron) in **pulsed mode** at a frequency $f_{RF}=f_{res}$. Let as calculate the power we need from the klystron (and the dissipated one) to obtain a given accelerating voltage

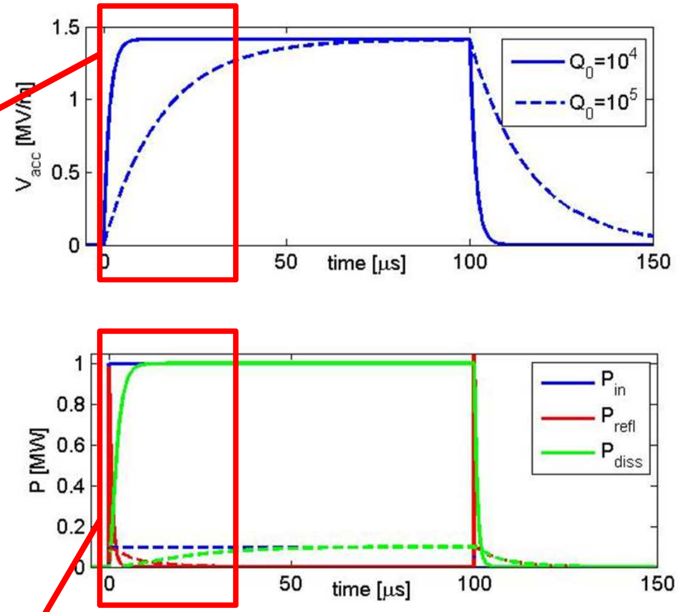


One needs several filling times to completely fill the cavity





Time domain

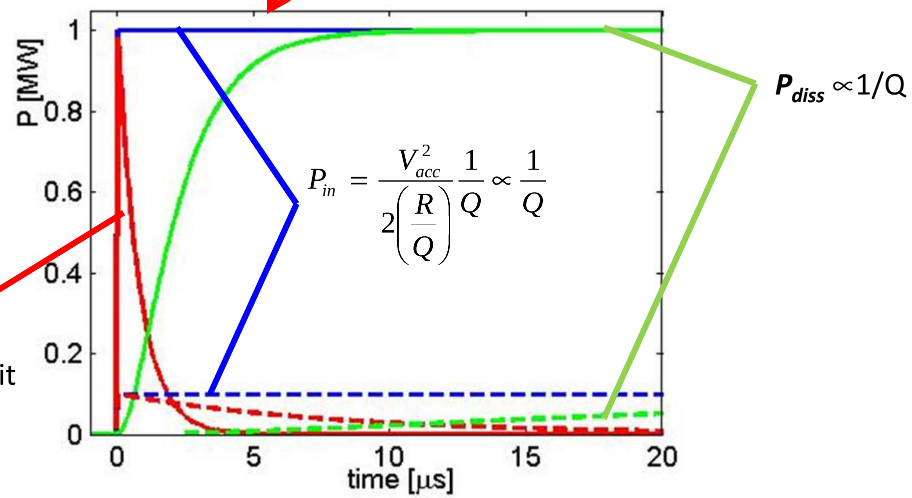


The reachable V_{acc} for a given power is proportional to $\sqrt{Q}$ but, on the other hand, the filling time is $\propto Q$

$$\tau_F\big|_{NC} \approx \mu s$$

$$\tau_F\big|_{SC} > 100 ms$$

P

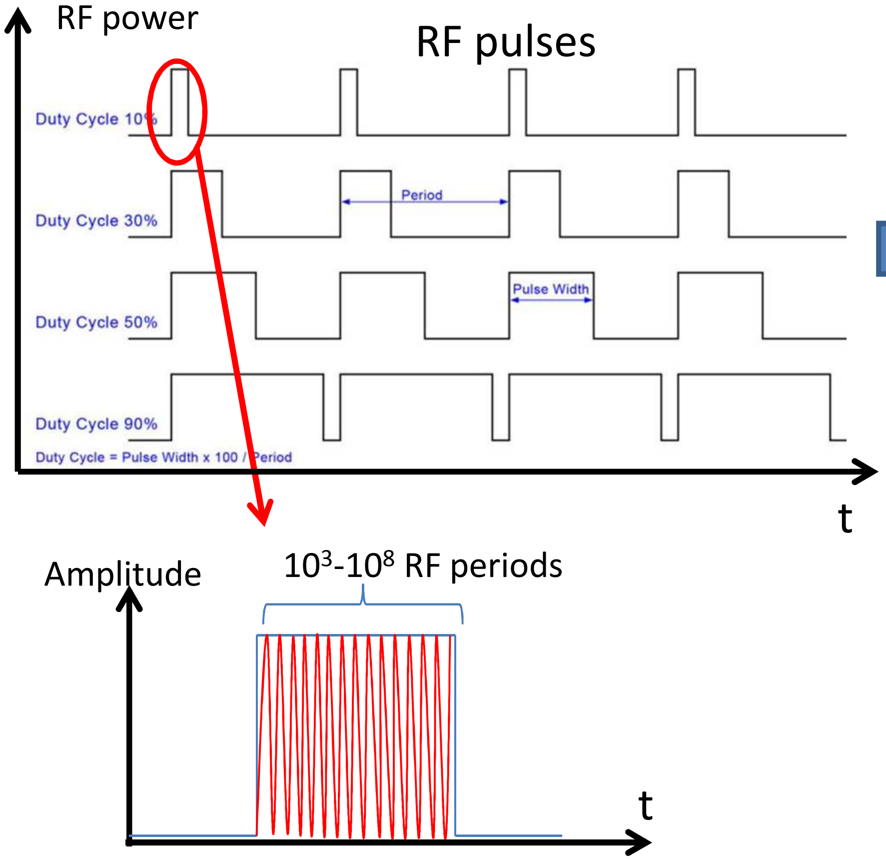


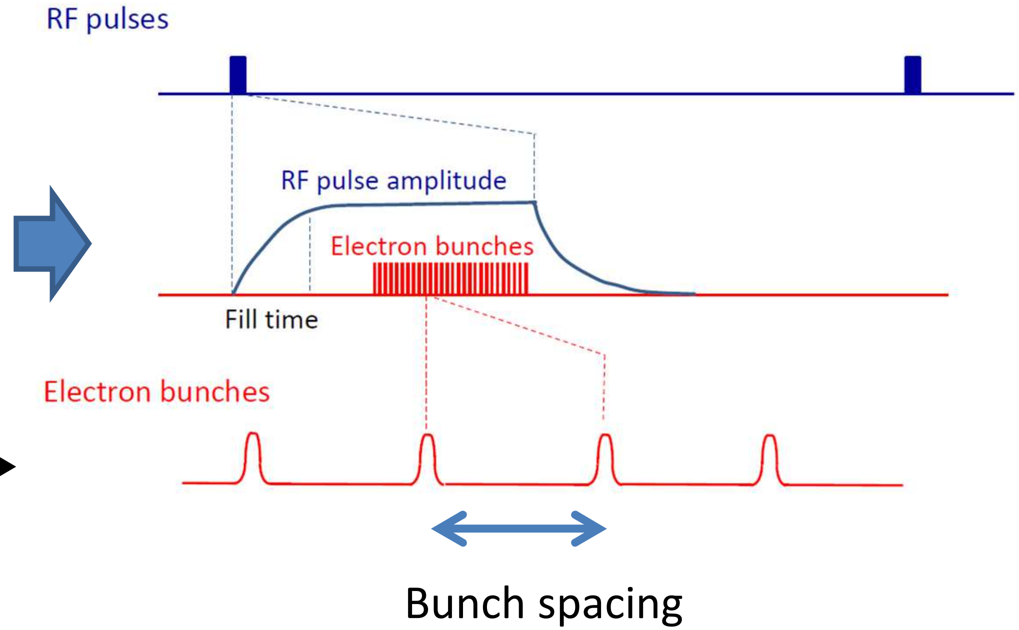
P_{refl} to the generator (it that has to be protected!)

SW CAVITIES : RF STRUCTURE AND BEAM STRUCTURE

The "**beam structure**" in a LINAC (or ERL) is directly related to the "**RF structure**". There are basically two possible type of operations:

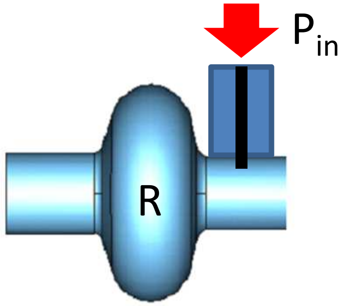
- CW (continuous wave) $\Rightarrow$ allow, in principle, to operate with a continuous beam
- PULSED OPARATION $\Rightarrow$ there are RF pulses at a certain repetition rate (Duty Cycle (DC)=pulsed width/period)

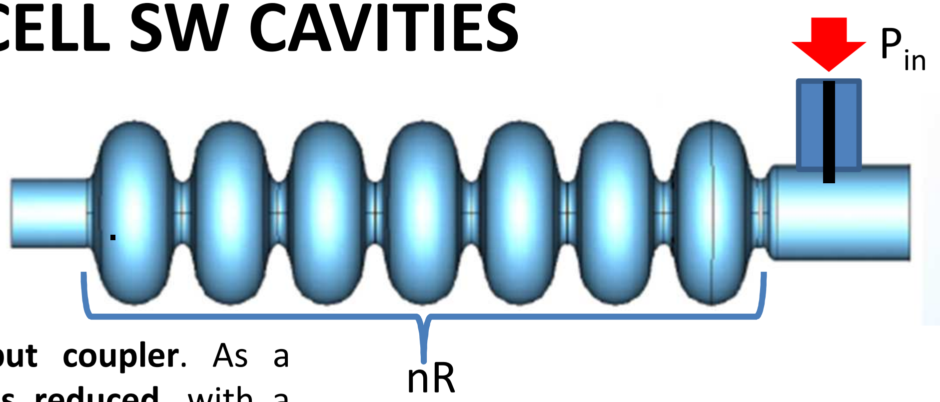




Because of the very low power dissipation and low RF power required to achieve a certain V_{acc}, the **SC structures allow operation at very high Duty Cycle (DC) up to a CW operation**.

MULTI-CELL SW CAVITIES





- In a multi-cell structure there is **one RF input coupler**. As a consequence the **total number of RF sources is reduced**, with a **simplification of the layout and reduction of the costs;**

- **The shunt impedance is n time the impedance of a single cavity**

- They are **more complicated** to fabricate than single cell cavities;

- The fields of adjacent cells couple through the cell **irises** and/or through properly designed coupling **slots**.

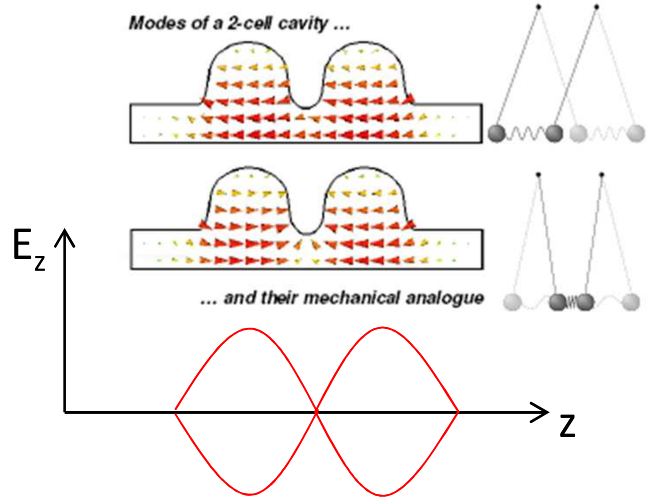
- The N-cell structure behaves like a system composed by **N coupled oscillators** with **N coupled RF modes**. The modes are characterized by a cell-to-cell phase advance given by:

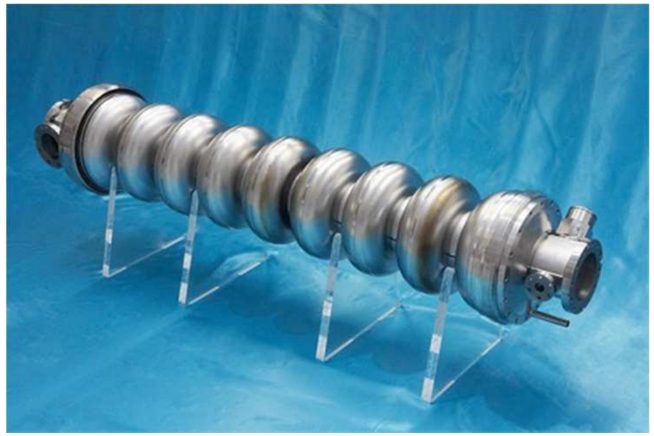
$$\Delta\phi_n = \frac{n\pi}{N-1} \qquad n = 0, 1, \ldots, N-1$$

- The most efficient mode (and generally used) is the **π mode**.

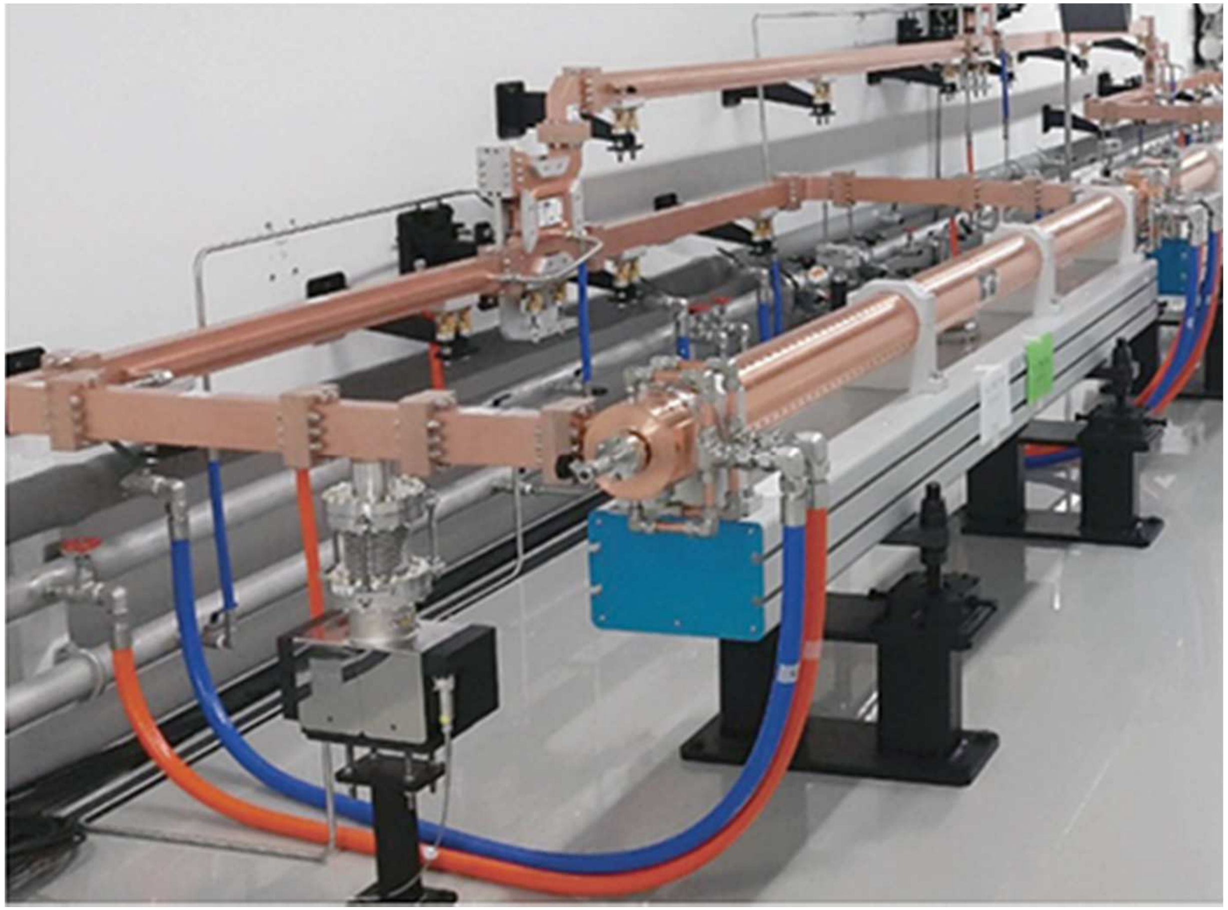
- Field amplitude variation from cell to cell should be small for maximum acceleration efficiency⇒ necessity of **tuning**

- It is possible to demonstrate that **over a certain number of cavities** (>10) the overlap between adjacent modes can be a problem from the tunability and operational point of view.





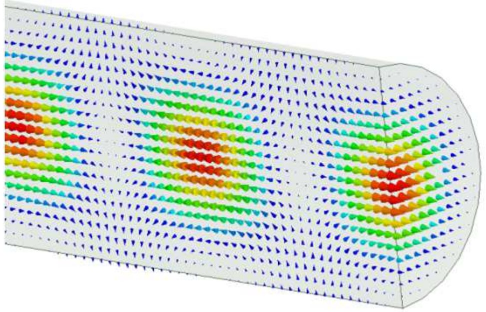
TW CAVITIES



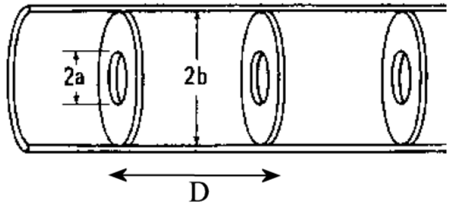
TW CAVITIES: BASICS

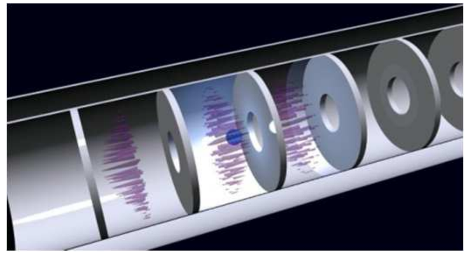
In **TW structures** an e.m. wave with $\mathbf{E_z \neq 0}$ travel together with the beam in a special guide in which the **phase velocity of the wave matches the particle velocity (v)**. In this case the beam absorbs energy from the wave and it is **continuously accelerated**.

CIRCULAR WAVEGUIDE

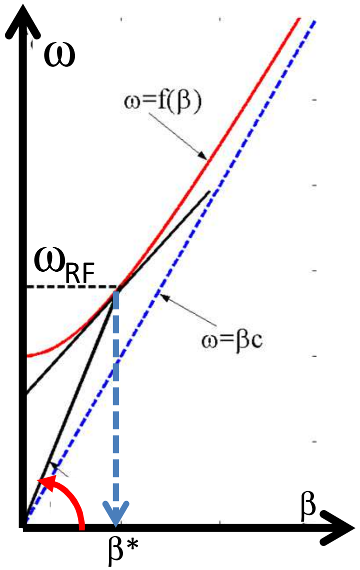


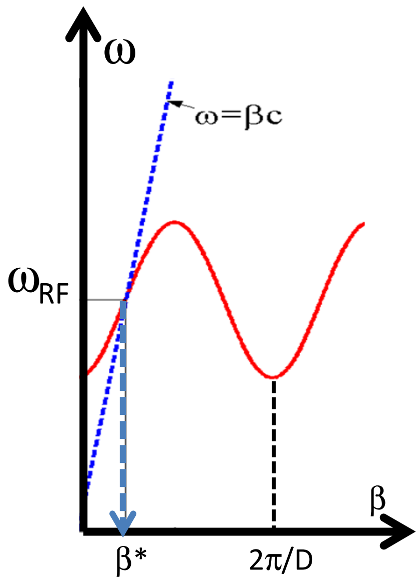
IRIS LOADED STRUCTURE





By solving the wave equation it turns out that an e.m. wave propagating in a **constant cross section waveguide** will **never be synchronous with a particle beam** since the phase velocity is always larger than the speed of light c. The first propagating mode with $\mathbf{E_z \neq 0}$ is the TM_{01} mode





In order to **slow-down the wave phase velocity, iris-loaded periodic structure are used**. The field in this kind of structures is that of a special wave travelling within a spatial periodic profile. The structure can be designed to have the phase velocity equal to the speed of the particles. This allows acceleration over large distances.

$$E_z\big|_{TM_{01}} = E_0 J_0\left(\frac{p_{01}}{a} r\right)\cos(\omega_{RF} t - \beta z)$$

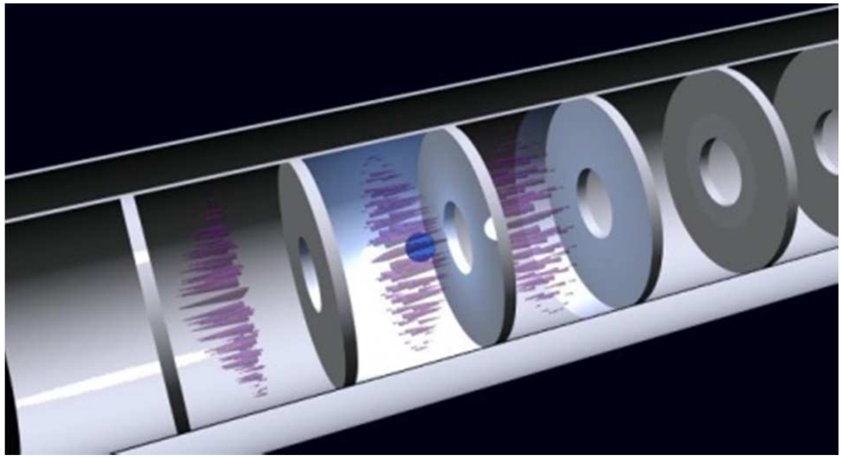
Periodic in z of period D

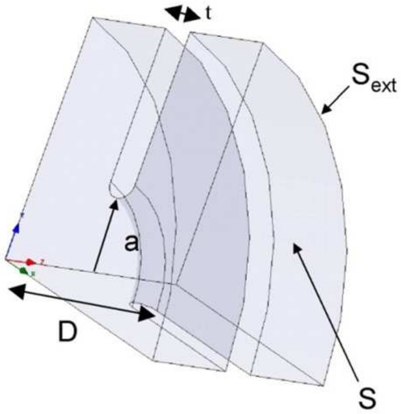
$$E_z\big|_{TM_{01-like}} = \underbrace{E_P(r,z)}_{\text{Periodic in z of period D}}\cos(\omega_{RF} t - \beta z)$$

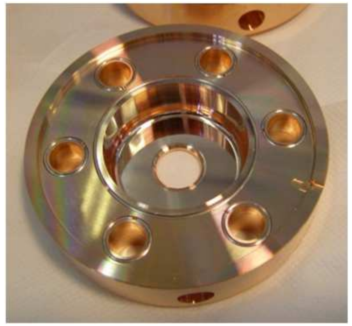
MODE TM_{01} → MODE TM_{01}-like

TW CAVITIES PARAMETERS: r, α, v_g

Similarly to the SW cavities it is possible to define some figure of merit of the TW structures







$$V_z = \left| \int_0^D E_z \cdot e^{j\omega_{RF}\frac{z}{c}} dz \right|$$ single cell accelerating voltage

$$E_{acc} = \frac{V_z}{D}$$ average accelerating field in the cell

$$P_{in} = \int_{Section} \frac{1}{2} \mathrm{Re}\left(\vec{E} \times \vec{H}^*\right) \cdot \hat{z} dS$$ average input power (flux power)

$$P_{diss} = \frac{1}{2} R_s \int_{cavity\ wall} \left|H_{tan}\right|^2 dS$$ average dissipated power in the cell

$$p_{diss} = \frac{P_{diss}}{D}$$ average dissipated power per unit length

$$W = \int_{cavity\ volume} \overbrace{\left(\frac{1}{4}\varepsilon\left|\vec{E}\right|^2 + \frac{1}{4}\mu\left|\vec{H}\right|^2\right)}^{\text{energy density}} dV$$ stored energy in the cell

$$w = \frac{W}{D}$$ average stored energy per unit length

$$r = \frac{E_{acc}^2}{p_{diss}}$$

$$\alpha = \frac{p_{diss}}{2P_{in}}$$

$$v_g = \frac{P_{in}}{w}$$

$$Q = \omega_{RF} \frac{w}{p_{diss}}$$

$$\Delta\phi = \beta D$$

Shunt impedance per unit length. Similarly to SW structures the higher is r, the higher the available accelerating field for a given RF power.

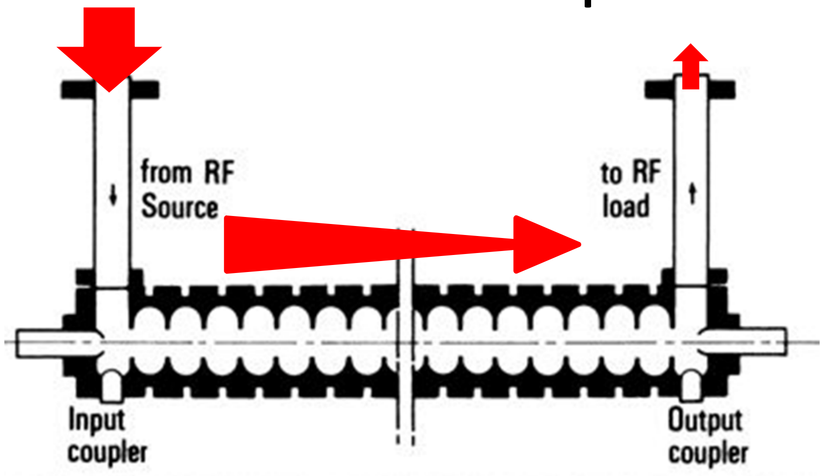
Field attenuation constant: because of the wall dissipation, the RF power flux and the accelerating field decrease along the structure.

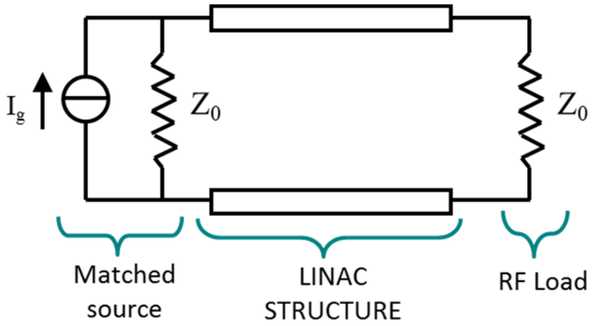
Group velocity: the velocity of the energy flow in the structure (~1-2% of c).

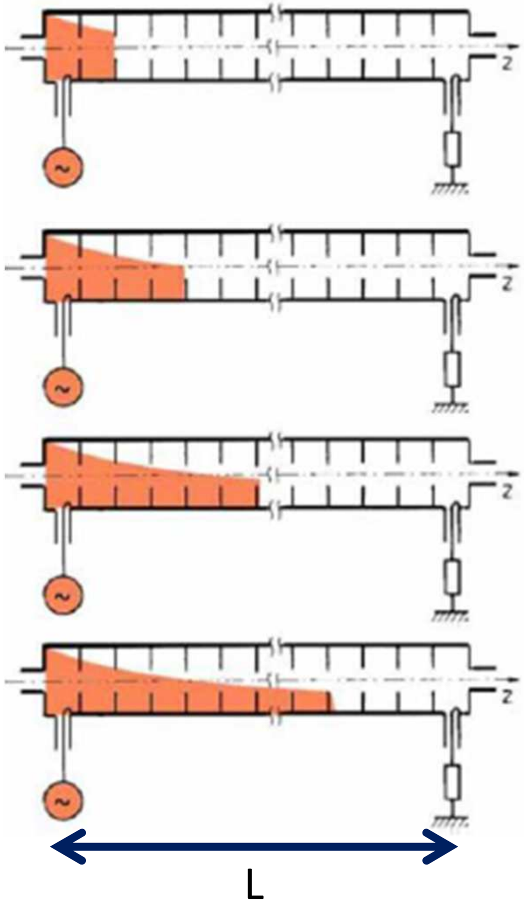
Working mode: defined as the phase advance of the fundamental harmonic over a period *D*. For several reasons the most common mode is the **2π/3**

TW CAVITIES: EQUIVALENT CIRCUIT AND τ_F

In a TW structure, the **RF power enters** into the cavity through an **input coupler**, flows (travels) through the cavity in the same direction as the beam and an **output coupler at the end** of the structure is connected to a **matched power load**.
If there is no beam, the input power reduced by the cavity losses goes to the power load where it is dissipated.
In the presence of a large beam current, however, a fraction of the TW power is transferred to the beam.







In a purely periodic structure, made by a sequence of **identical cells** (also called "**constant impedance structure**"), α does not depend on z and both the RF power flux and the intensity of the accelerating field decay exponentially along the structure :

$$E_z(z) = E_0 e^{-\alpha z}$$

The **filling time** is the time necessary to propagate the RF wave-front from the input to the end of the section of length *L* is:

$$\tau_F = \frac{L}{v_g}$$

Differently from SW cavities after **one filling time the cavity is completely full of energy**

High group velocities allow reducing the duration of the RF pulse powering the structure. However since:

Low group velocity is preferable to increase the effective accelerating field for a given power flowing in the structure.

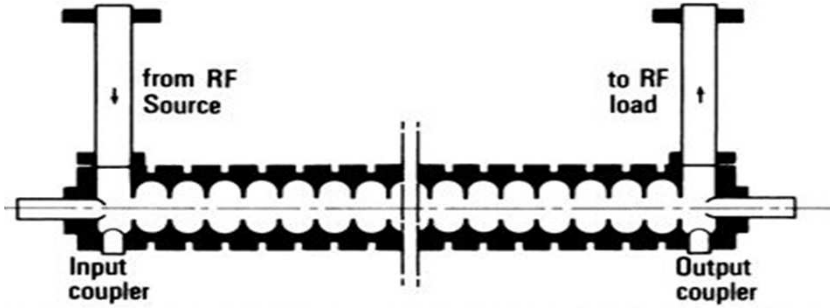
$$v_g = \frac{P_{in}}{w}$$

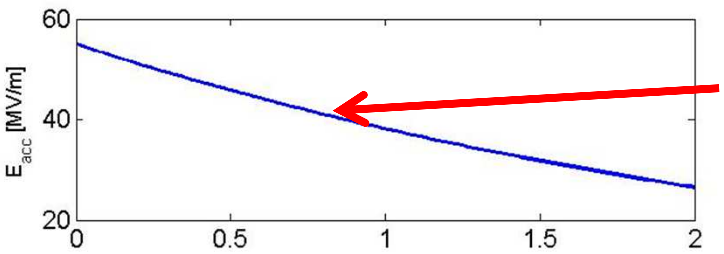
$$w \propto E^2$$

TW CAVITIES: PERFORMANCES (1/2)

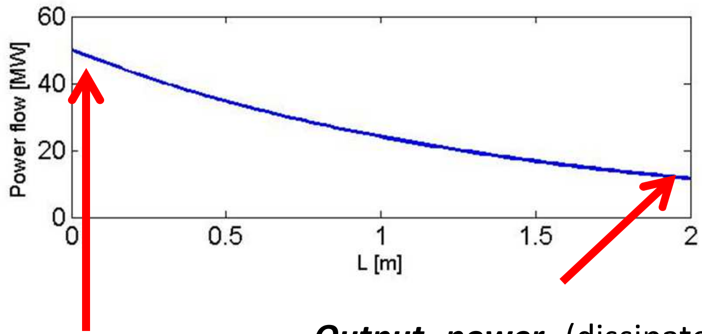
Just as an example we can consider a C-band (5.712 GHz) accelerating cavity of 2 m long made in **copper**.

$r = 82$ [MΩ/m]
$\alpha = 0.36$ [1/m]
$v_g/c = 1.7\%$
$\tau_F = 400$ ns (**very short if compared to SW**!)



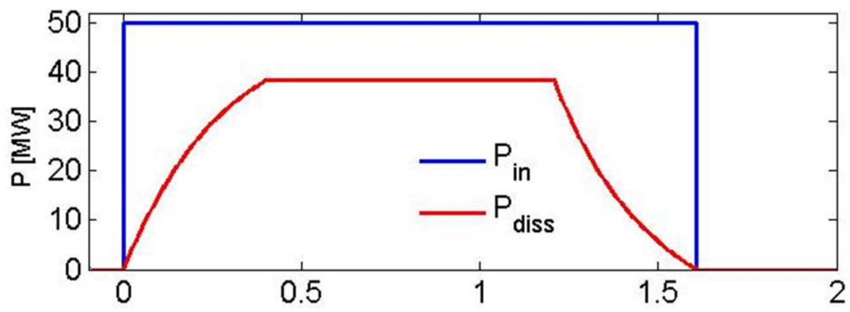


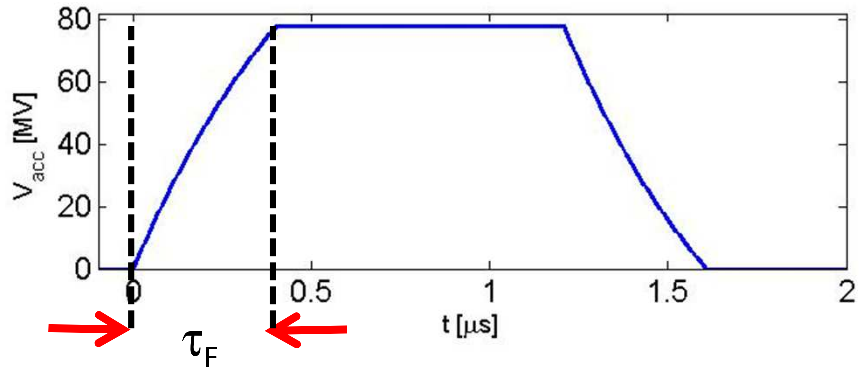
Field attenuation due to the copper dissipations



Input power

Output power (dissipated into the RF load): it is not convenient to have very long RF structures because their efficiency decreases over a certain length (2-3 m depending on the operating frequency).





RF STRUCTURE AND BEAM STRUCTURE

TW structures have **very short filling time (<1μs)** and allow operation in **pulsed mode** with **high peak power** (tens of MW per structure) and relatively **high accelerating field** (>50-100 MV/m), with **short RF pulses** (1 μs) and **low repetition rate** (10-100 Hz) and **low DC** (10^{-3}-10^{-2} %) in **single or few bunches**

TW CAVITIES: PERFORMANCES (2/2)

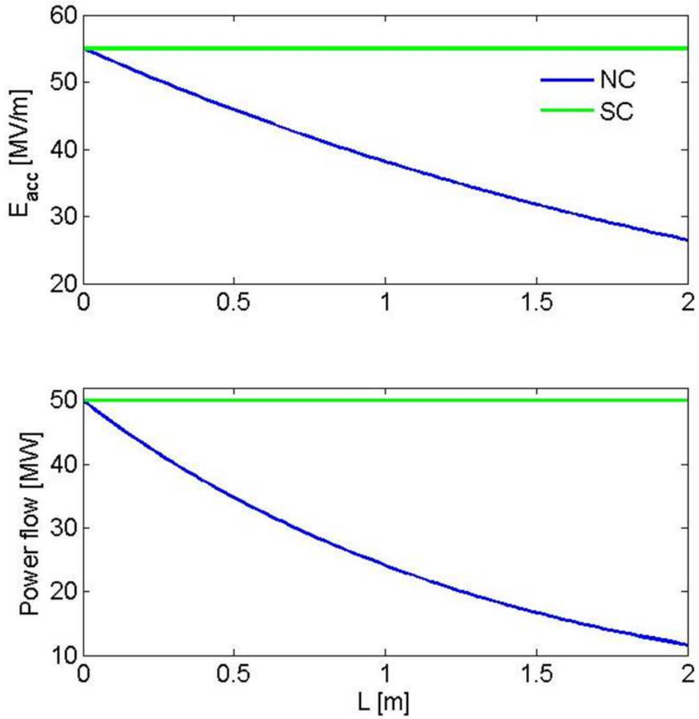
If we compare the performances of this copper structure with the same cavity made on a **superconducting material** it is quite easy to understand that it is **not convenient** to use TW SC structures:

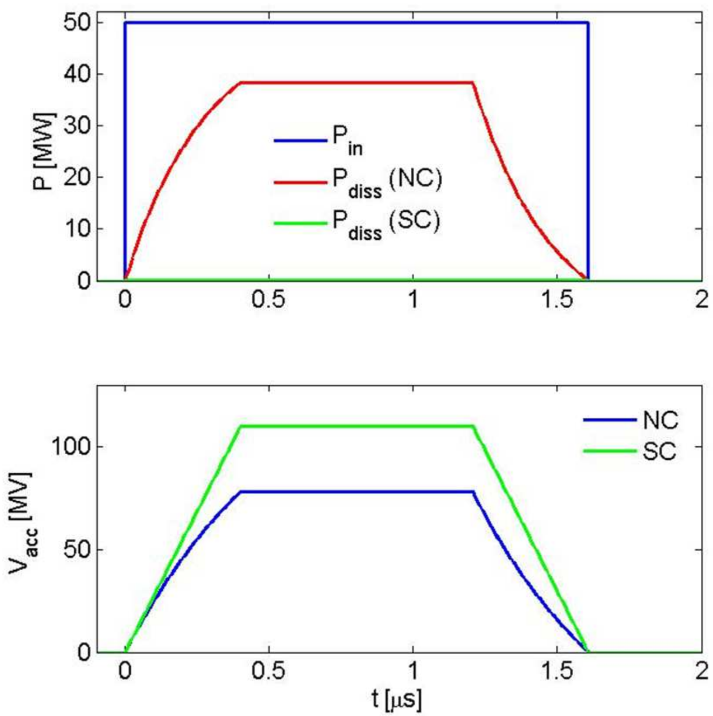
$r=82$ [MΩ/m]$\Rightarrow$[TΩ/m]
$\alpha=0.36$ [1/m]$\Rightarrow\sim 0$
$v_g/c=1.7\%$
$\tau_F=400$ ns

$\Rightarrow$**we do not gain in term of E_{acc}** as we do for SW structures and as a consequence **we do not gain in term of V_{acc}**$\Rightarrow$ direct consequence of the TW mechanism (no field build up effects!)

$\Rightarrow$for a short structure **all power is dissipated into the RF load**

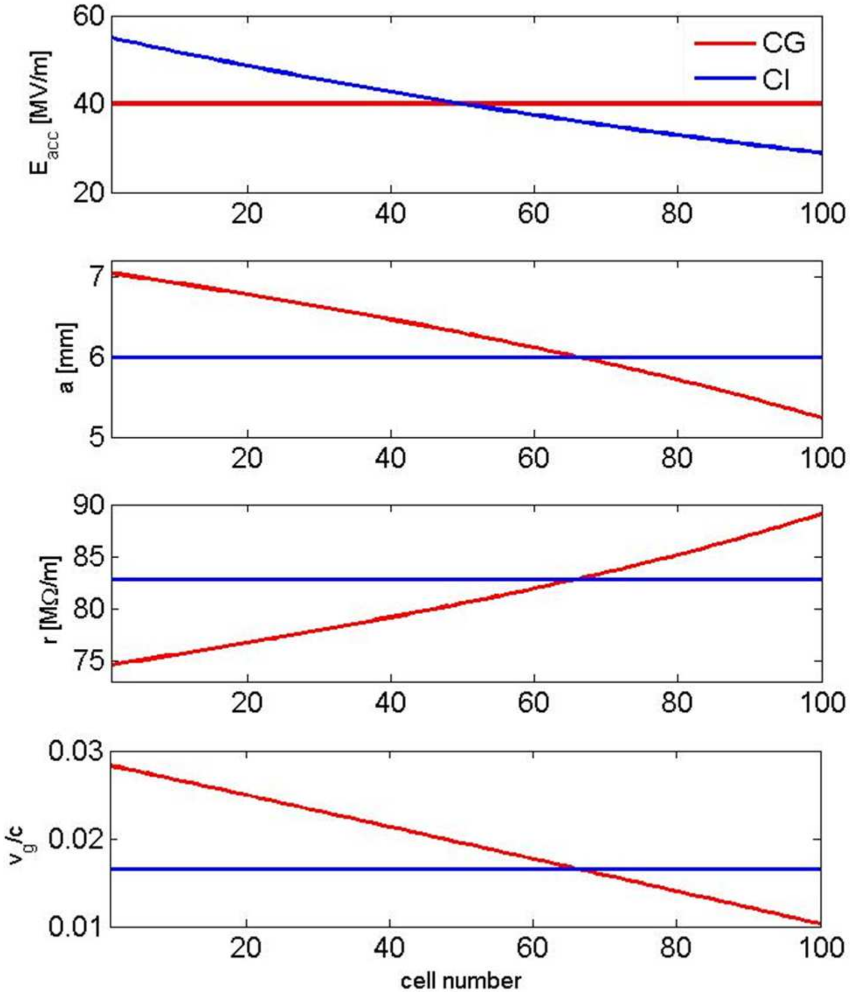
$\Rightarrow$It is, in principle possible to gain with TW SC if we increase the length of the structure and, as a consequence, the RF pulse length but we have problems of available power sources (high power/long RF pulses) and cavity construction

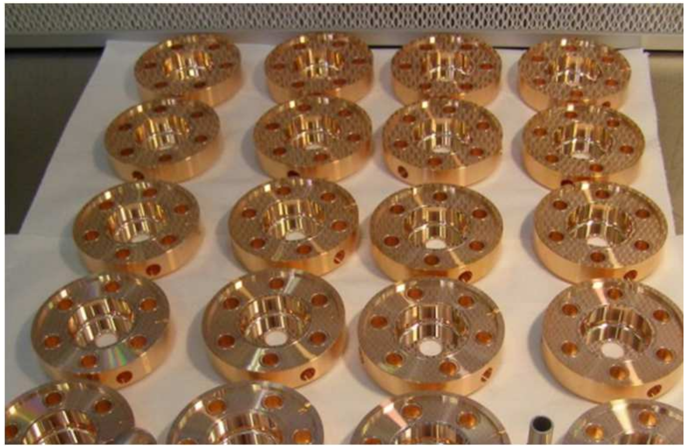


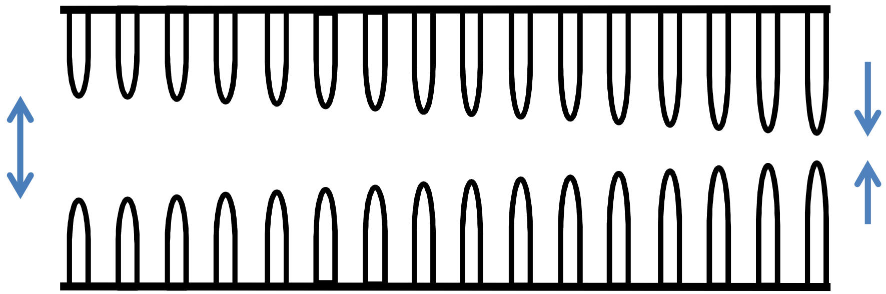


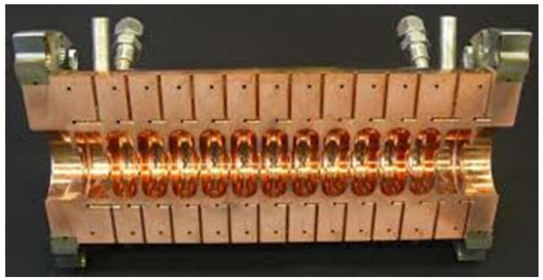
TW CAVITIES: CONSTANT GRADIENT STRUCTURES

It is possible to demonstrate that, in order to keep the **accelerating field constant** along the structure, the **iris apertures have to decrease along the structure** in such a way that the field attenuation is compensated by the increase of the stored energy (with consequent decrease of the group velocity).







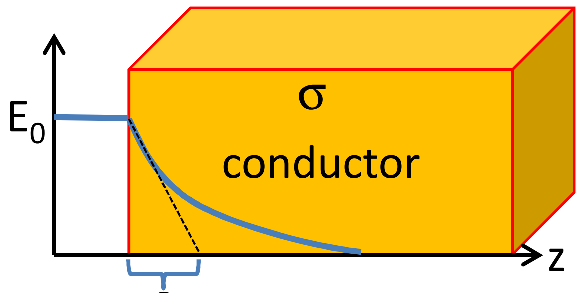


In general the constant gradient structures are **more efficient** than constant impedance ones, because of the more uniform distribution of the RF power along them.

MATERIAL

NORMAL CONDUCTING (NC) MATERIAL: COPPER

$$P_{diss} = \int_{\substack{cavity \\ wall}} \overbrace{\frac{1}{2} R_s H_{tan}^2}^{\text{power density}} dS$$

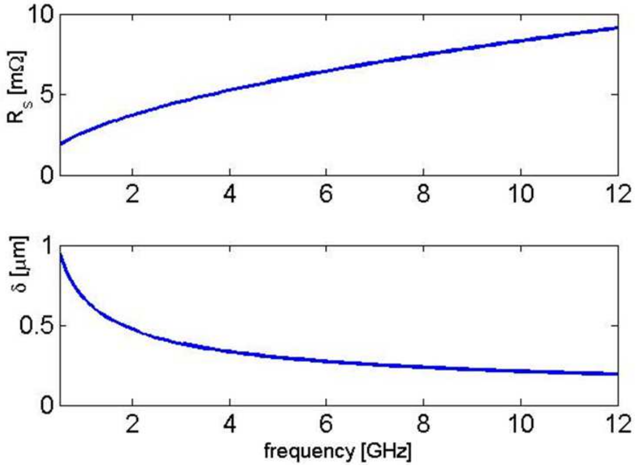


R_s vs RF FREQUENCY

The microwave surface resistance of a **normal metals** is expressed by:

$$R_s = \sqrt{\frac{\pi f_{RF} \mu_0}{\sigma}} = \frac{1}{\sigma\delta} \qquad \delta = \frac{1}{\sqrt{\pi f_{RF} \mu_0 \sigma}}$$

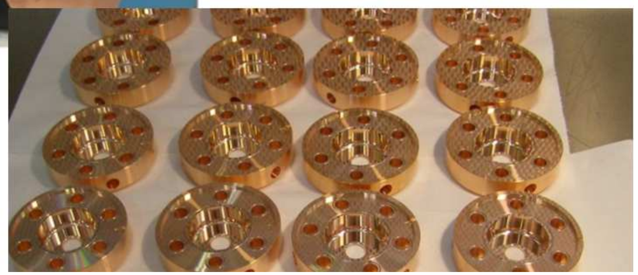
Skin depth: penetration of the EM field ans surface currents inside the metal



For copper: $\sigma = 5.7 \times 10^8$ S/m $\Rightarrow R_s(@1\text{ GHz}) \cong 3\text{m}\Omega$, $\delta < 1\ \mu$m

R_s AT LOW TEMPERATURE ANOMALUS SKIN EFFECT

At **low temperature** and at high frequency, NC material there is a mechanism called "**anomalous skin effect**" that increases the conductivity with respect to the DC case. For copper, as example, at microwave frequencies and cryogenic temperatures, one can see that, although the DC conductivity increases by a factor 100, the anomalous skin effect allows only a decrease of a factor 6 in the surface resistance. **This shows that it is definitely not convenient to cool an NC metal to cryogenic temperatures.**



COPPER

The most widely used NC metal for RF structures is **OFHC copper** (Oxigen free high conductivity) for several reasons:

1) Easy to machine (good achievable roughness at the few nm level)
2) Easy to braze/weld
3) Easy to find at relatively low cost
4) Very good electrical (and thermal) conductivity
5) Low SEY (multipacting fenomena)
6) Good performances at high accelerating gradient

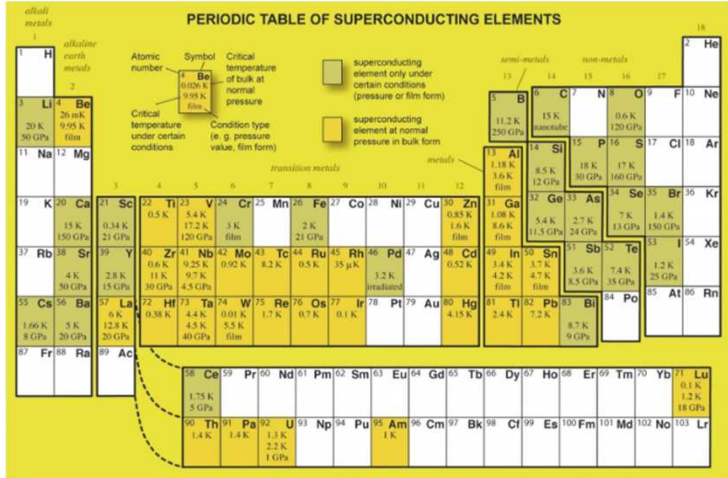
SUPERCONDUCTING (SC) MATERIAL: NIOBIUM (Nb)

⇒The SC was discovered in 1911.

⇒ For SC elements at $T<T_c$ in **DC regime the resistance is 0**.

⇒ In **AC (RF) regime the surface resistance of a SC is always larger than 0** (even if very small if compared to NC element).

⇒For frequencies below 10 GHz (and $T<T_c/2$) the experimental data are well described by the empirical relation:



Depends on the material

exponential decrease with temperature (high frequency cavity >1 GHz have to be cooled to reduce the dissipation)

$$R_s = A\frac{\omega^2}{T}e^{-\alpha\frac{T_c}{T}} + R_{res}$$

Square dependence with frequency

Two fluid model or BCS resistance R_{BCS}

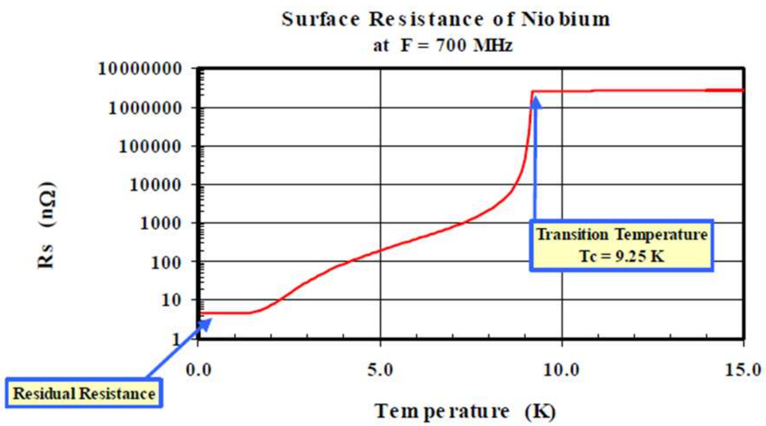
Residual resistance (typically 5-20 nΩ) this term dominate the low frequency (10-150 MHz) resonators. Caused by: magnetic flux trapped in at cooldown, surface contaminations, defects,…

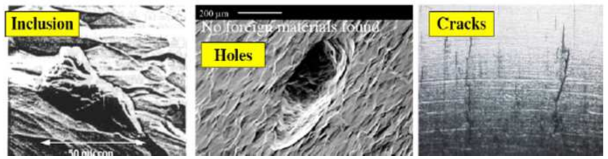
$$R_{BCS} \approx 2\times10^{-4}\left(\frac{f[\mathrm{MHz}]}{1500}\right)^2 \frac{1}{T} e^{\left(\frac{-17.67}{T}\right)} [\mathrm{Ohm}]$$

NIOBIUM

The **most common material for SC cavities is Nb** because:

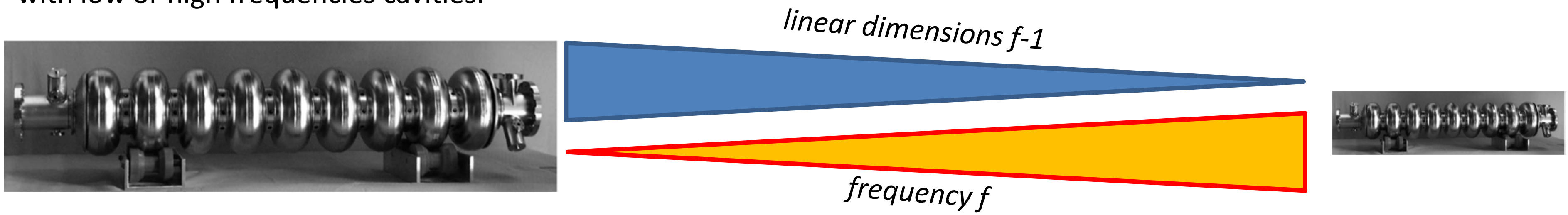
- Nb has a relatively **high transition temperature** (Tc=9.25 K).
- SC can be destroyed by magnetic field grater than a critical field H_c ⇒ Pure Nb has a **relatively high critical magnetic field Hc**=170-180 mT.
- It is chemically inert
- It can be **machined and deep-drawn**
- It is available as bulk and sheet material in any size, fabricated by forging and rolling
- Large grain sizes (often favoured) obtained by e-beam melting Instead of bulk or sheet, it can also be coated (e.g. by sputtering) on Cu
- Other advantages: thermal stability, material cost, possible optimisation of R_s





PARAMETERS SCALING WITH FREQUENCY

We can analyze how all parameters (r, Q) scale with frequency and what are the advantages or disadvantages in accelerate with low or high frequencies cavities.



parameter	NC	SC
R_s	$\propto f^{1/2}$	$\propto f^2$
Q	$\propto f^{-1/2}$	$\propto f^{-2}$
r	$\propto f^{1/2}$	$\propto f^{-1}$
r/Q	$\propto f$	
$w_{//}$	$\propto f^2$	
$w_{\perp}$	$\propto f^3$	

Wakefield intensity: related to BD issues

$\Rightarrow$**r/Q increases at high frequency**

$\Rightarrow$for **NC structures** also r increases and this push to adopt **higher frequencies**

$\Rightarrow$for SC structures the power losses increases with f^2 and, as a consequence, r scales with 1/f this push to adopt **lower frequencies**

$\Rightarrow$On the other hand at very high frequencies (>10 GHz) **power sources** are less available

$\Rightarrow$Beam interaction (**wakefield**) became more critical at high frequency

$\Rightarrow$Cavity fabrication at very high frequency requires **higher precision** but, on the other hand, at low frequencies one needs more material and **larger machines**

$\Rightarrow$**short bunches** are easier with higher f

Compromise between several requirements

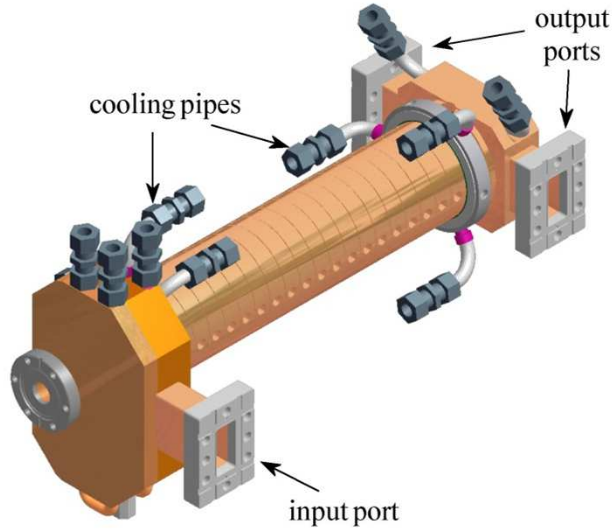
For FEL and ERL basically:

SW SC: 500 MHz-1500 MHz
TW NC: 3 GHz-6 GHz
SW NC: 0.5 GHz-3 GHz

LINAC TECHNOLOGY: NC TW CAVITIES

NC TW STRUCTURES: ACCELERATING CELLS

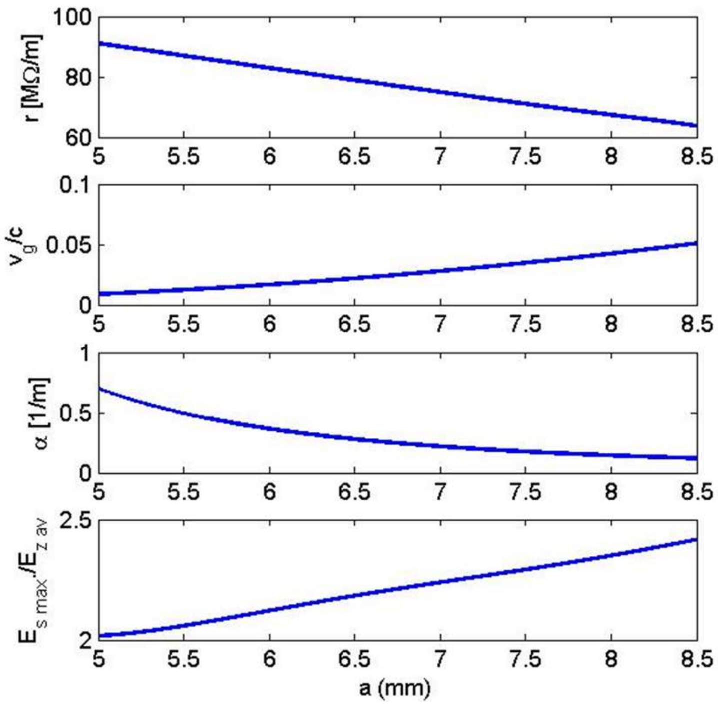
⇒**Copper structures with many cells (hundred)**, and input coupler, and an output coupler connected to an RF load;



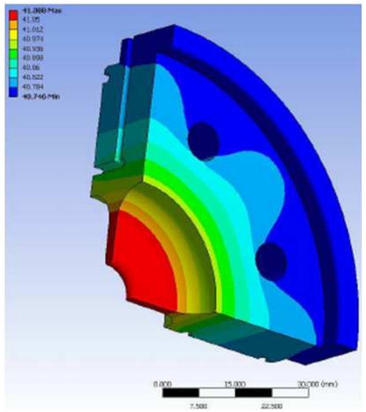
⇒The structures operate typically:

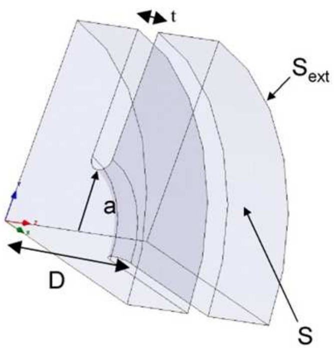
- with short RF pulses (~0.5-2μ) in single bunch (or few bunches)
- at high peak power (~50 MW)
- at high accelerating field (20-40 MV/m)
- on the $2\pi/3$ mode
- in pulsed mode at a low rep. rate (10-100 Hz) and low DC
- in S or C band (3 GHz, 6 GHz)

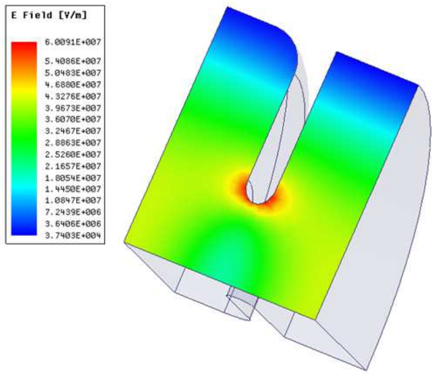
⇒the TW cells are optimized to have high shunt impedance, low filling time and the most important role is played by the **iris dimensions**.

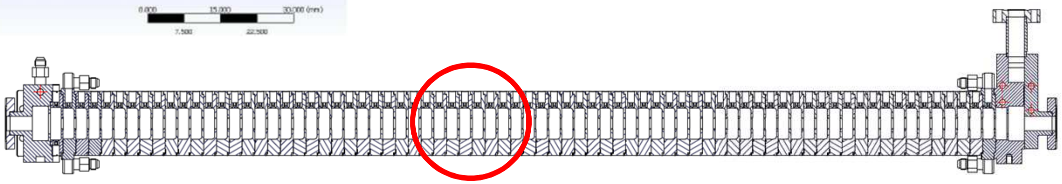


⇒**Cooling pipes** are inserted or brazed around the cells to guarantee the temperature stability of the structures avoiding detuning of the structure under high power feeding .





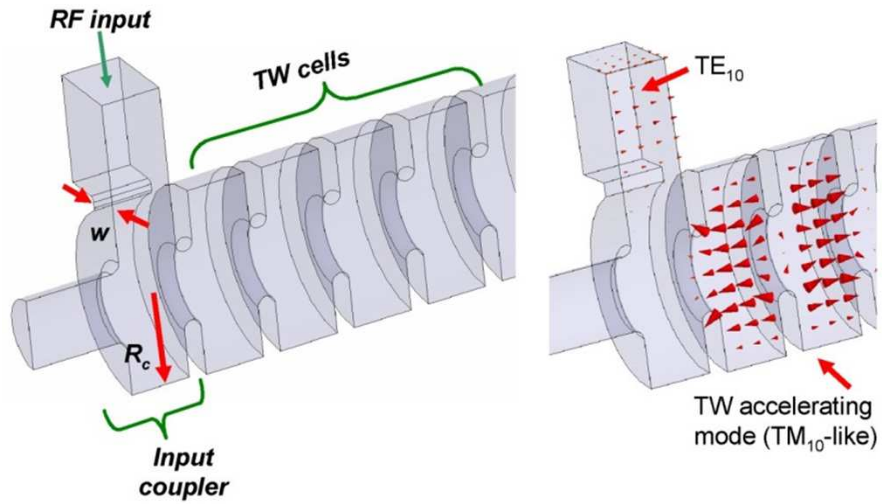


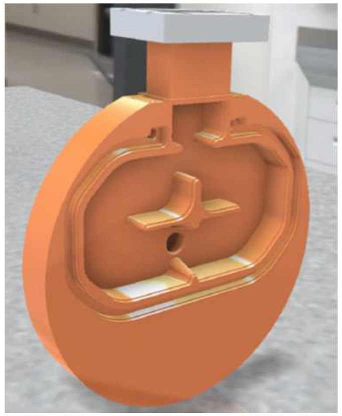


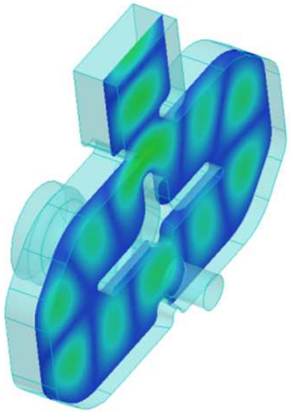
NC TW STRUCTURES: COUPLERS

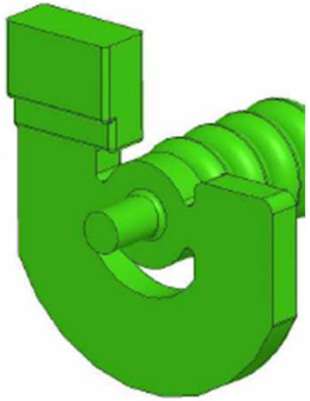
The structures are fed by waveguides. The coupler, realized by a **slot in the waveguide,** matches the TE_{10} mode of the waveguide with the traveling wave mode (TM_{01}-like).

J-type couplers or integrated **splitters** allow compensating the dipole kick in the coupling cells.



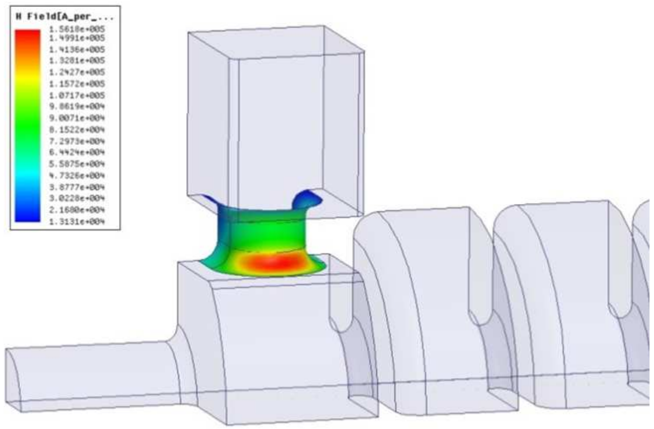


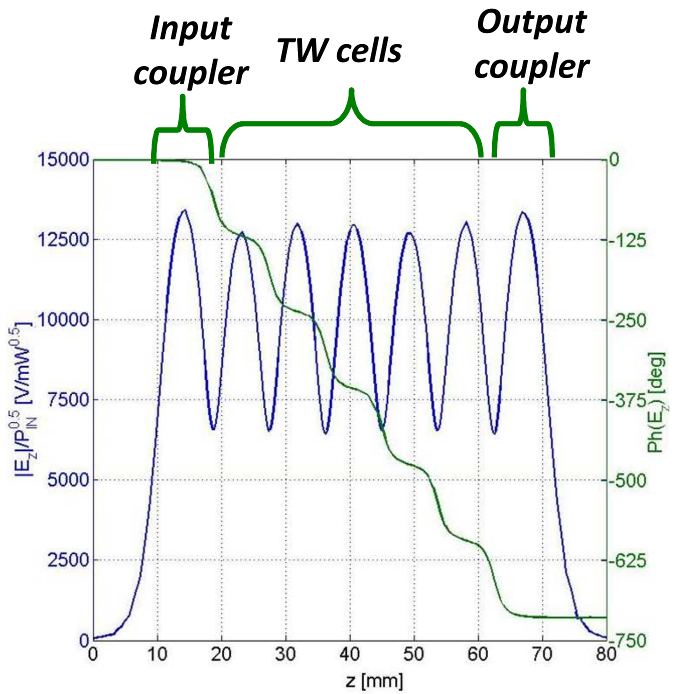




Rounded shapes in the couplers (low magnetic filed) allows to reduce the **pulsed heating**.

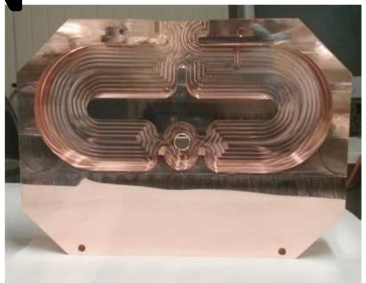
Race track profiles allow to compensate the **quadrupole distortions** of the field in the coupling cells

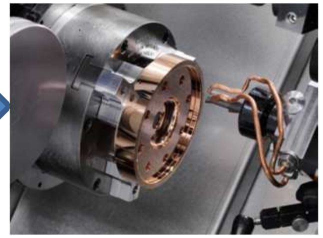


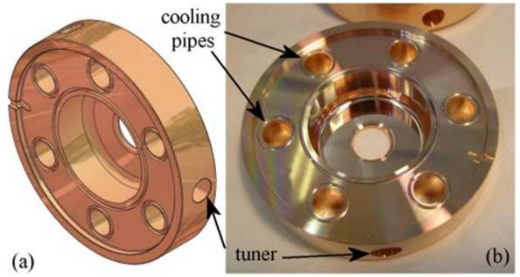


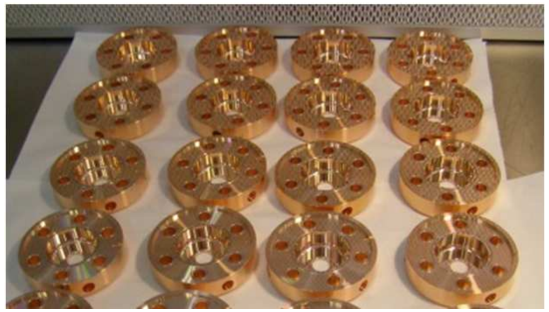
NC TW STRUCTURES: FABRICATION

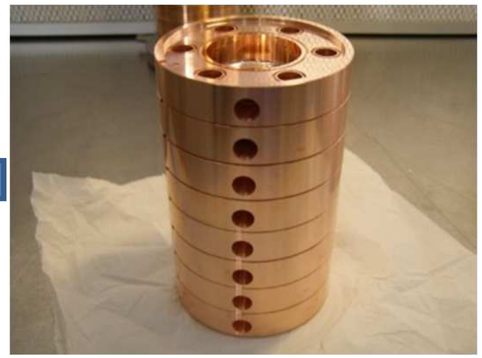
The cells and couplers are fabricated with milling machines and lathes starting from **OFHC forged or laminated copper** with precisions that can be of the order of few um and surface roughness <50 nm.



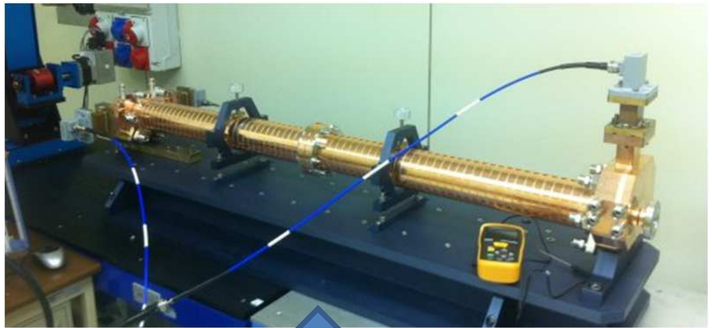






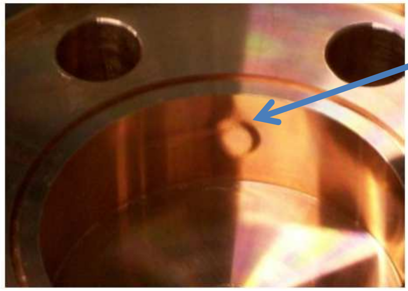


The cells are then piled up and **brazed** together in vacuum or hydrogen furnace using different alloys at different temperatures (700-1000 C) and/or in different steps.

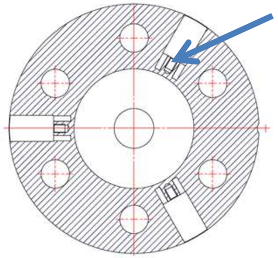


NC TW STRUCTURES: TUNING

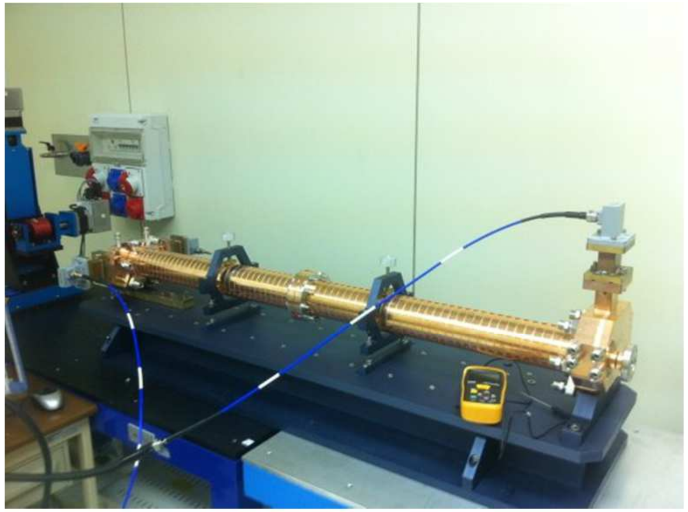
To **compensate deformations and imperfections** that can also occur during the brazing process, tuning is often necessary. The standard method is to measure the field inside by a perturbation technique (Steele method) and to “tune” the phase advance per cell to the correct value by deforming the outer volume of the cells with deformation tuners.

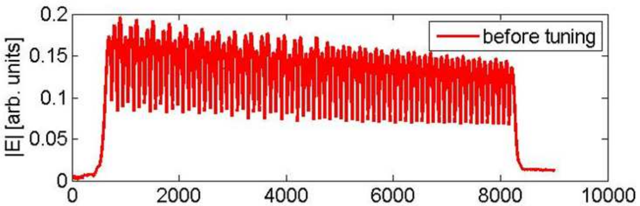


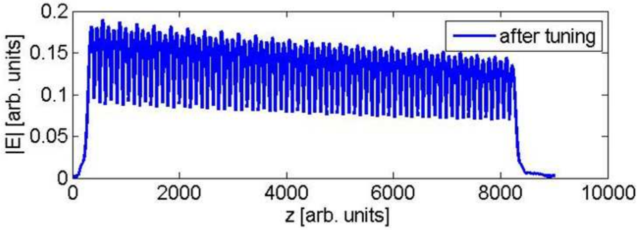
Deformation of the volume

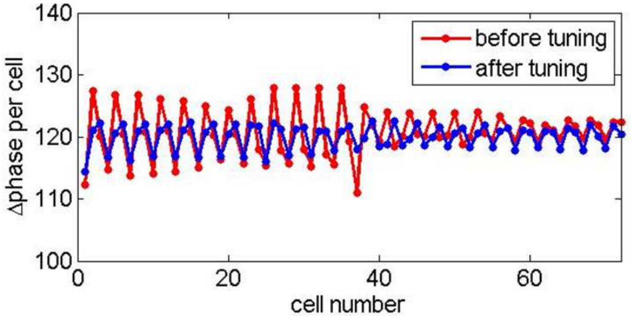


tuner

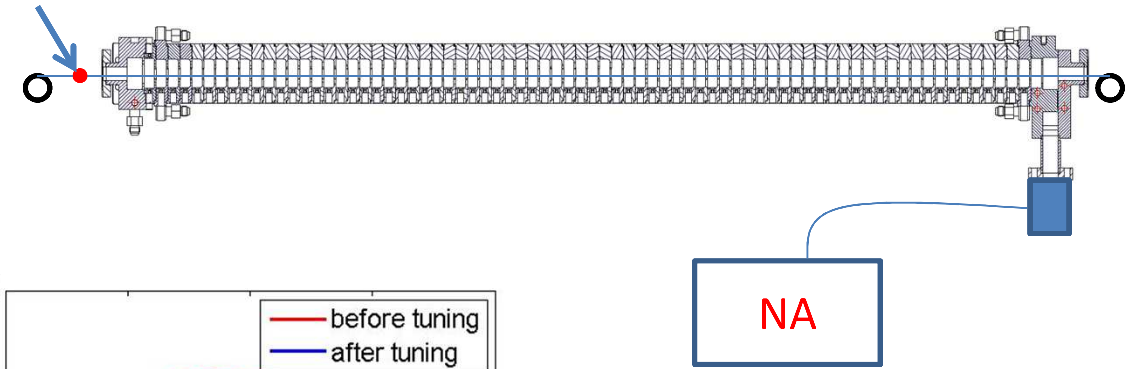


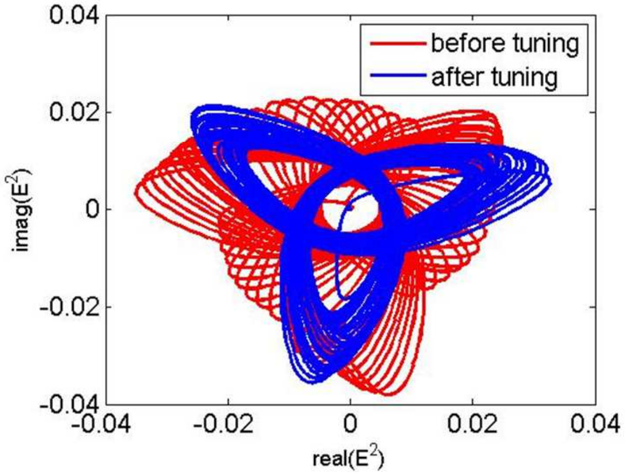






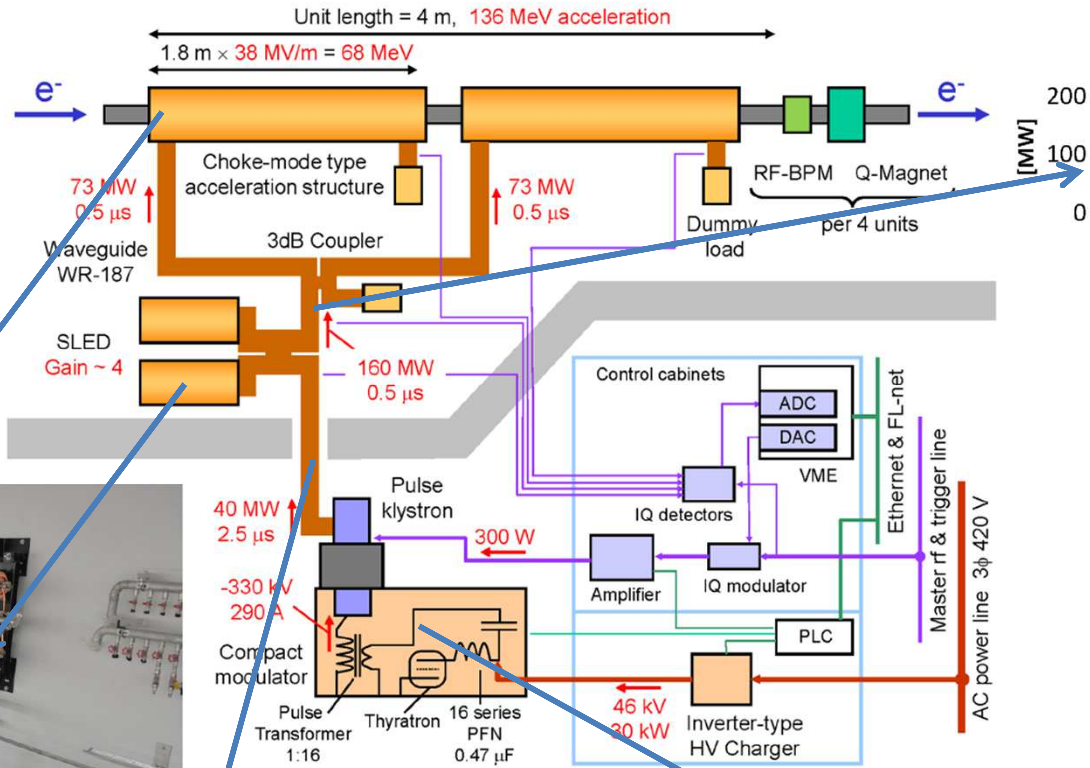
Metallic or dielectric bead

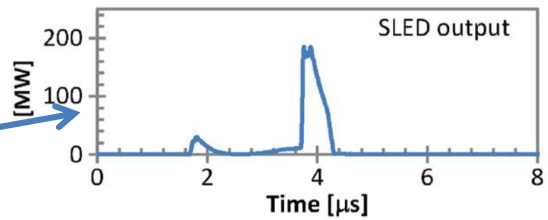




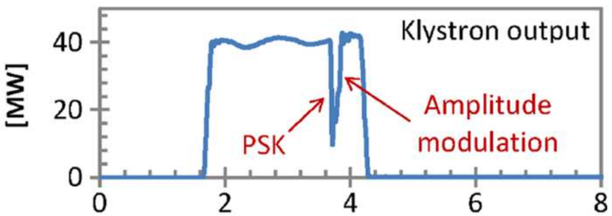
NC TW STRUCTURES: RF WAVEGUIDE NETWORK AND POWER SOURCES

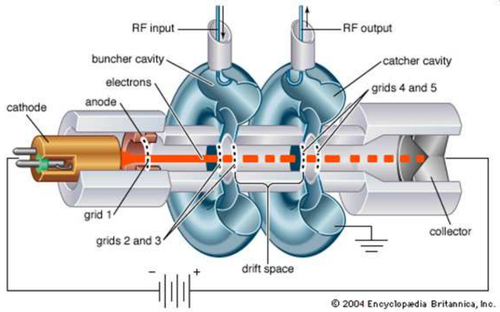
TW structures require high peak power pulsed sources. To this purpose **klystron+RF compression systems** (SLED) are usually adopted

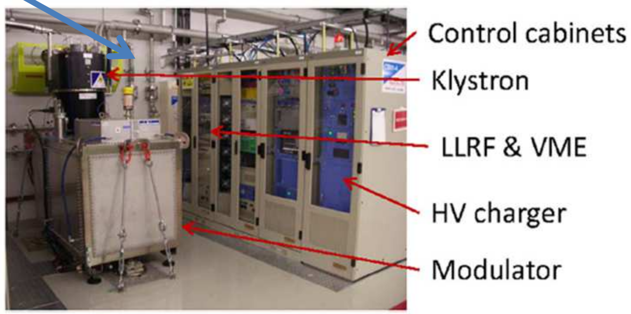




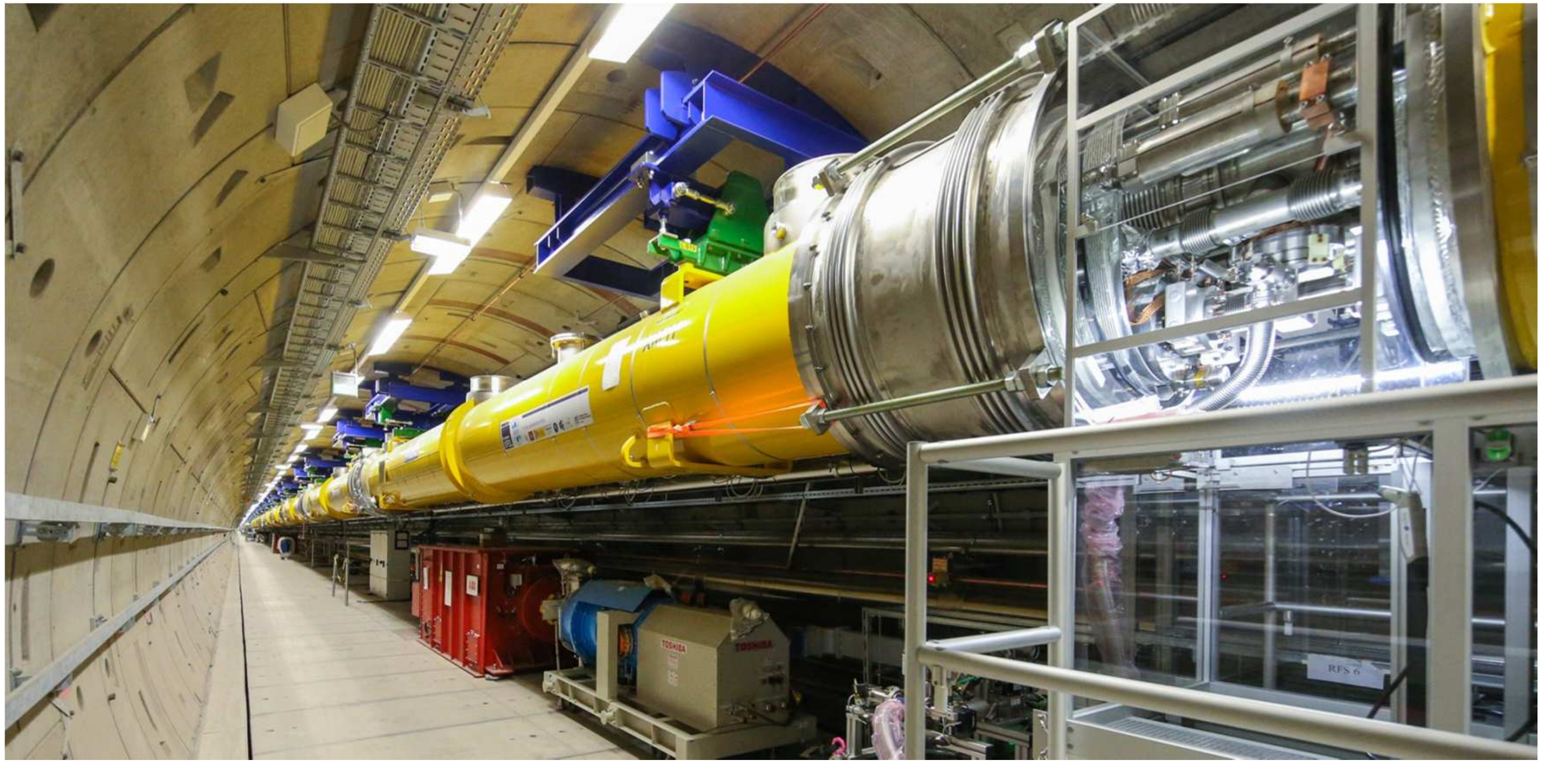
Courtesy T. Inagaki et al.







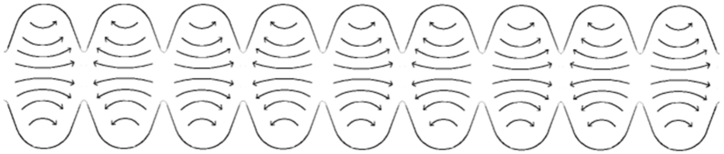
LINAC TECHNOLOGY: SC SW CAVITIES



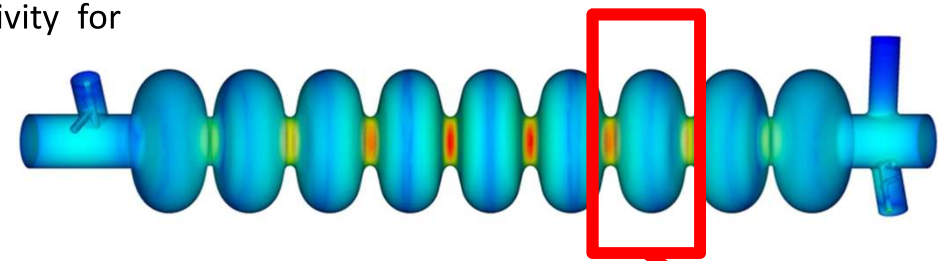
SC SW STRUCTURES: ACCELERATING CELLS

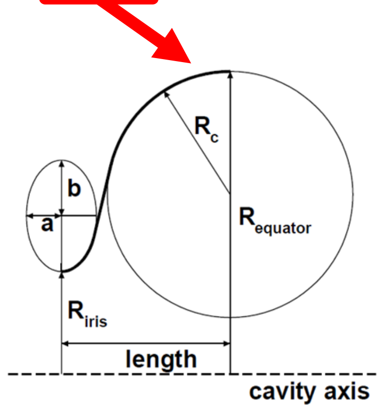
Typically the SC SW structures are:

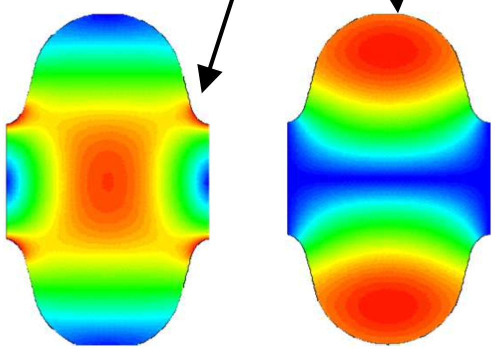
⇒ **Single and multi cell** structures (up to ~10)
⇒ Operating on the **π mode**
⇒ The **irises have an elliptical shape** to:



- minimize E_{surf}/E_{acc} (and then the electrons field emission)
- minimize B_{surf}/E_{acc} (break-down of superconductivity for Nb is 170-190 mT)
- suppress multipacting
- increase the machinability and cleanability



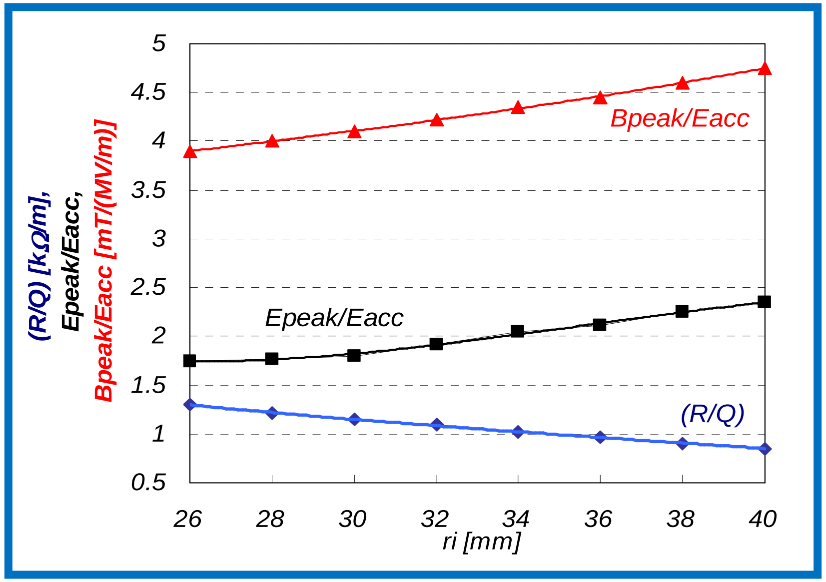




$$\frac{B_{surf}}{E_{acc}} = 4.2 \frac{mT}{MV/m}$$

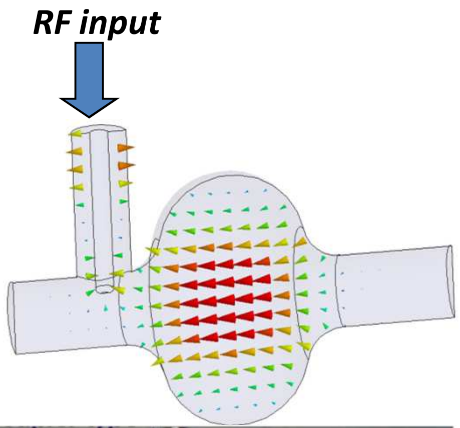
For TESLA cavities and then theoretically the maximum achievable E_{acc} is about 40-45 MV/m

Also for this type of cavities the iris radius play a fundamental role in the design of the structures



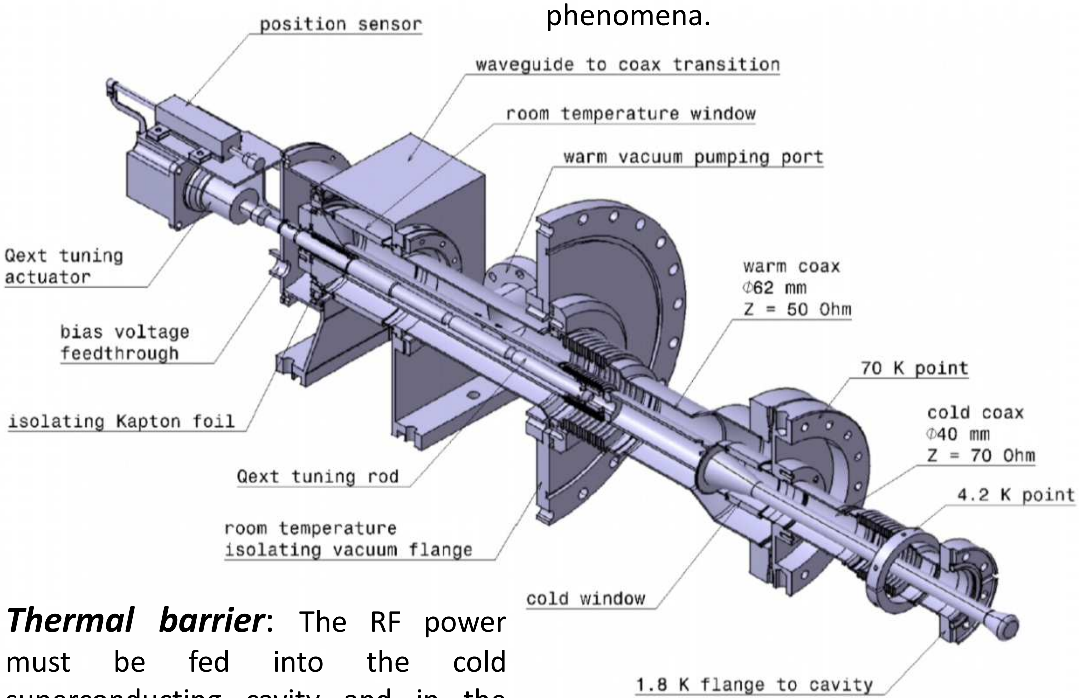
SC SW STRUCTURES: POWER COUPLERS

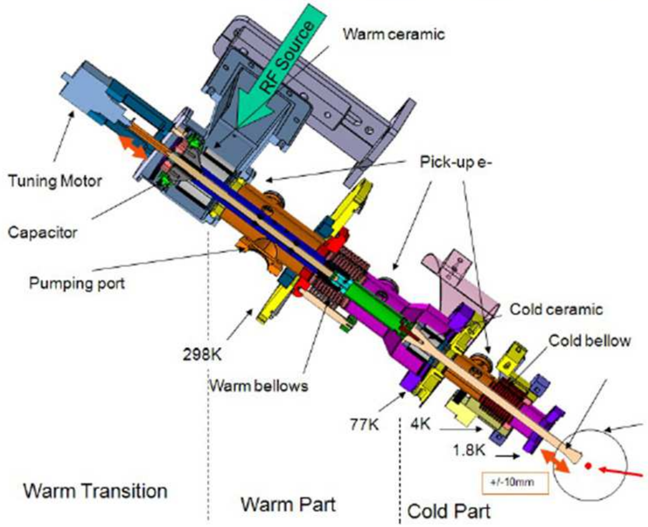
Coaxial-type electric couplers have the widest applications, because magnetic coupling with waveguides or loops can create hot spots in the cavities with additional design complications



Q_{EXT} tunability. For many accelerators it is necessary to tune the coupling changing the penetration of the antenna in the pipe.

Vacuum barriers (windows). They prevent contamination of the SC structure. Obviously these barrier are necessary also in normal conducting accelerators but the demand on the quality of the vacuum and reliability of the windows are less stringent. The failure of a window in superconducting accelerator can necessitate very costly and lengthy in repart. They are made, in general, in Al_2O_3. Ceramic material have a SEY that stimulates the multipacting activity. Ti-coating can reduce this phenomena.

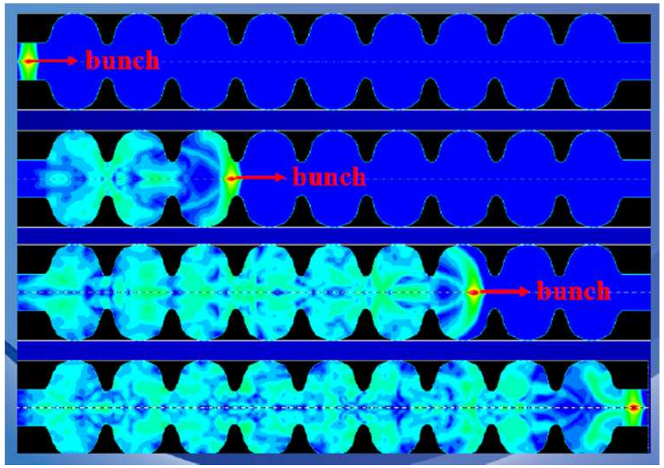




Thermal barrier: The RF power must be fed into the cold superconducting cavity and in the coupler we cross the boundary between the room temperature and the low-temperature environment

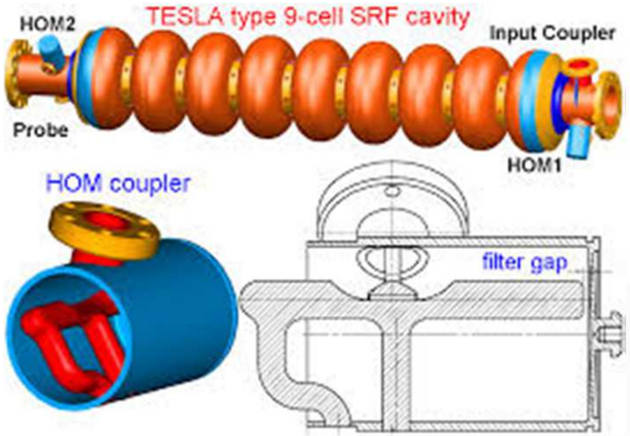
SC SW STRUCTURES: HOM DAMPERS

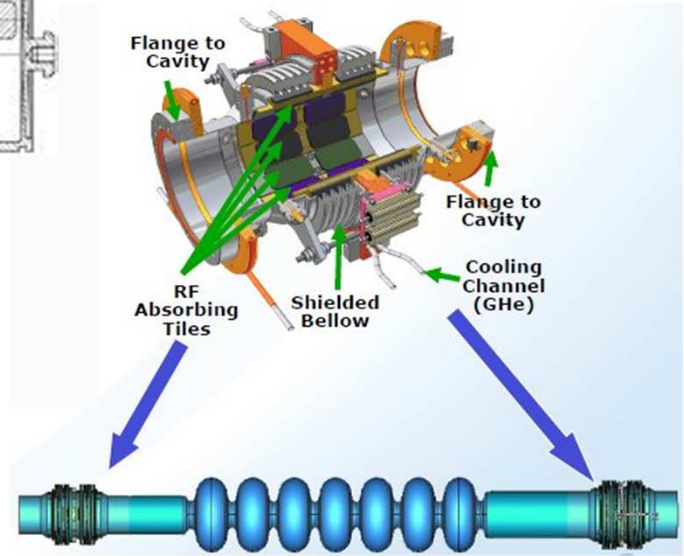
SC cavities can be used to accelerate train of bunches. As bunch traverses a cavity, it deposits electromagnetic energy on Higher order modes (HOM) described in terms of **long range wakefields**. Subsequent bunches (or the same bunch in several turns like in ERLs) may be affected by these fields causing instabilities and additional heating of accelerator components.



Several approaches are used:

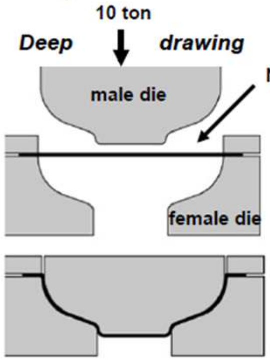
- **Loop** couplers (several per cavity for different modes/orientations)
- **Waveguide** dampers
- Beam pipe **absorbers** (ferrite or ceramic)

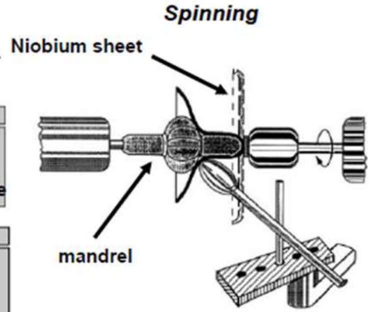


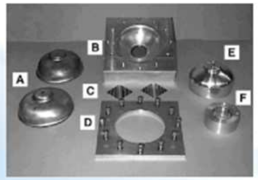


SC SW STRUCTURES: FABRICATION

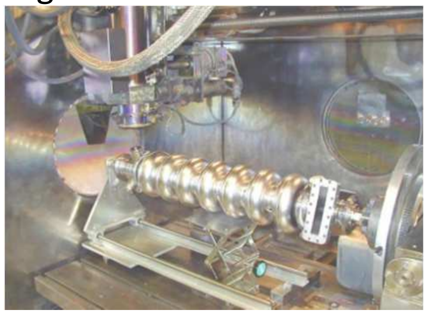
Nb is available as **bulk and sheet material** in any size, fabricated by forging and rolling. **High Purity Nb** is made by **electron beam melting** under good vacuum.
The most common fabrication techniques for the cavities are to **deep draw or spin half-cells**.
Alternative techniques are: hydroforming, spinning an entire cavity out of single sheet or tube and Nb sputtering

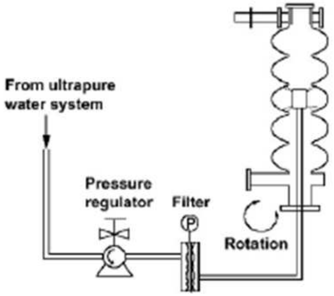


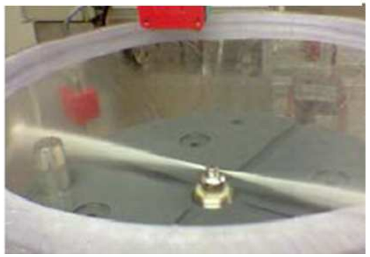




After forming the parts are **electron beam welded** together



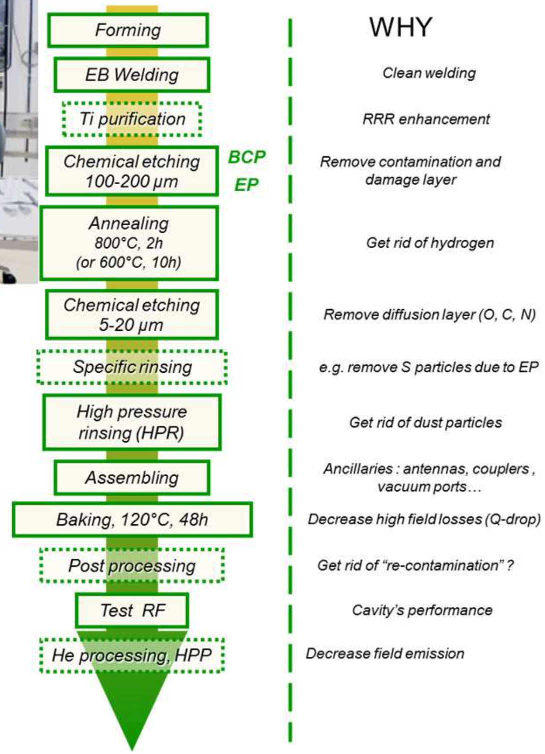




CAVITY TREATMENT

The cavity treatment after the welding is quite complicated and require several steps between:

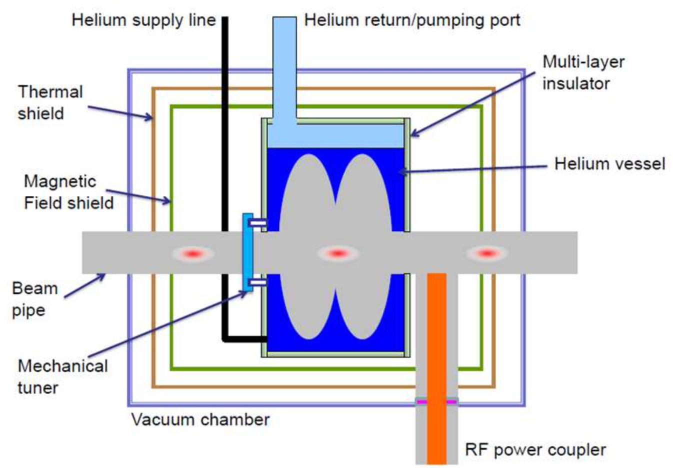
- buffered **chemical polishing** (BCP), **electropolishing** and etching to remove surface damaged layers of the order of 100 μm
- **rinsed with ultraclean water** also at highpressure (100 bar)
- **Thermal treatments** up to >1000 C to diffuse H_2 out of the material increasing the Nb purity (RRR)
- **high-temperature treatment** with Ti getter (post-purification)
- RF tuning



SC SW STRUCTURES: CRYOMODULE

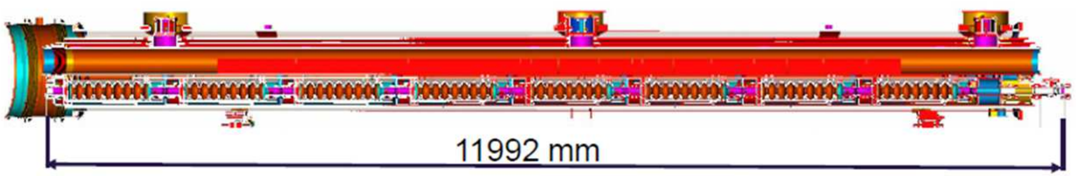
The **cavity is immersed in a liquid helium bath**, which is pumped to remove helium vapor boil-off as well as to reduce the bath temperature.
An **RF input coupler** and other penetrations create “spurious” sources of heat losses.
Proper design methods must be used (material choice, heat intercepts, etc.)
The cold portions of the cryomodule need to be extremely well insulated, which is best accomplished by a vacuum vessel surrounding the helium vessel and all ancillary cold components

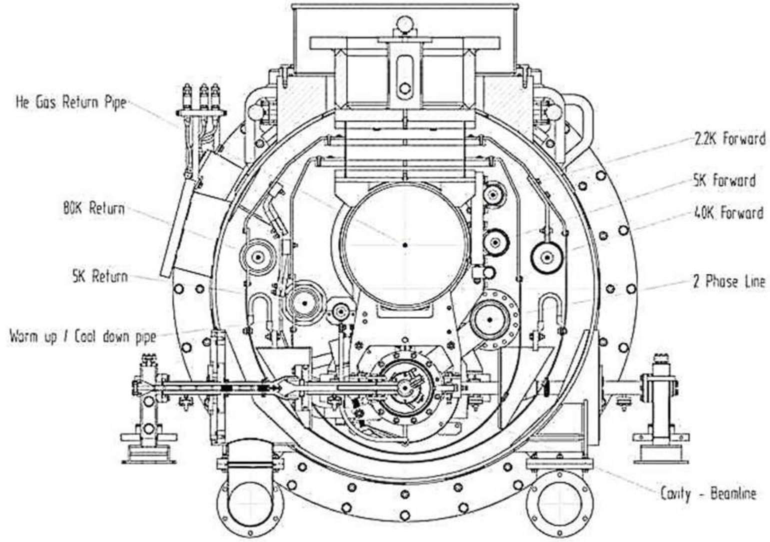
Schematics of cryomodule



European XFEL

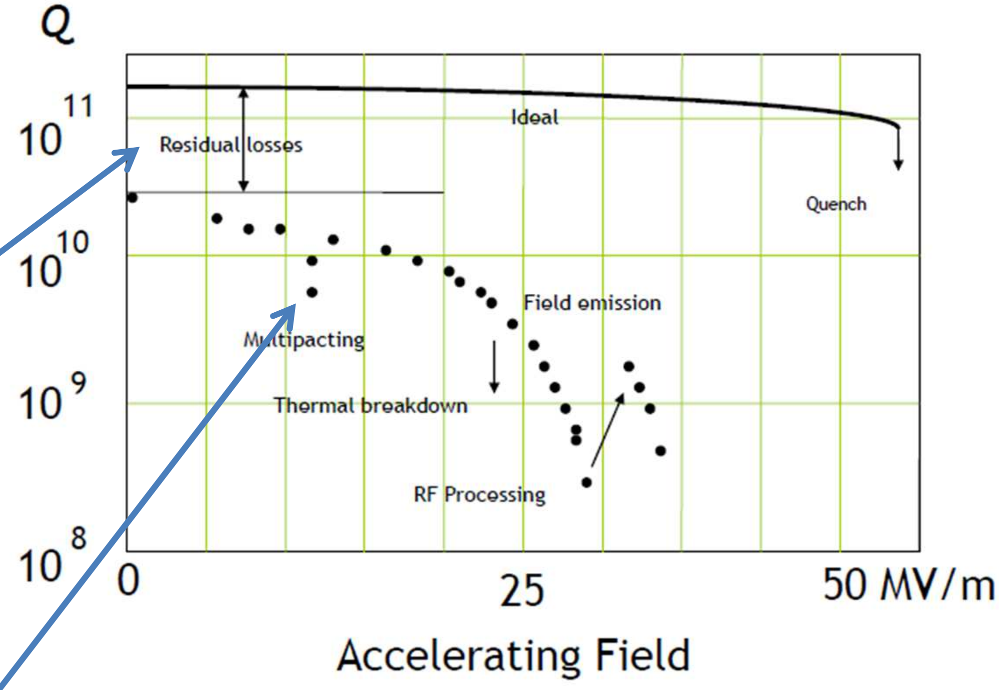
Cryomodule housing: 8 cavities, quadrupole and BPM





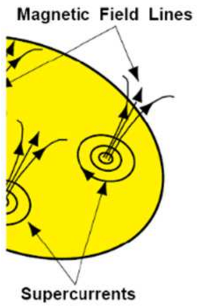
REAL PERFORMANCES OF SC CAVITIES: Q vs Eacc (1/2)

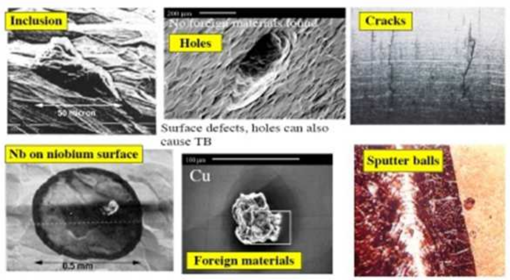
Usually the performances of SC cavities are analyzed by plotting **dependence of their quality factor on the accelerating field**.
There are several mechanisms responsible for **additional losses under high power**.



The measured **surface resistivity is larger than predicted by BCS theory**. Causes are:

- magnetic flux trapped in at cool down
- dielectric surface contaminations (chemical residues, dust,…)
- NC defects and inclusions
- surface imperfections
- hydrogen precipitates

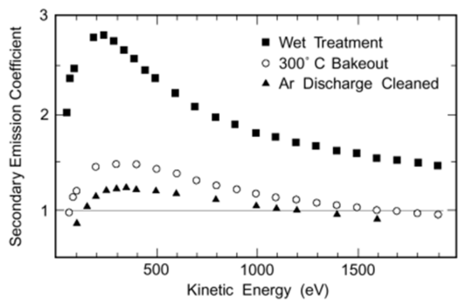


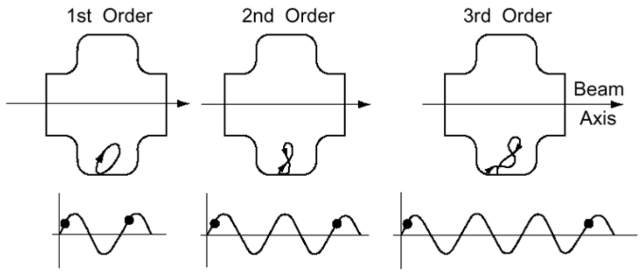


Multipacting=*multi*ple im*pact* electron amplification (MP) is a resonant process, when a large number of electrons build up under influence of RF field (input couplers, cavities, etc.). It needs two conditions:

- electron **synchronization** with RF field
- electron **multiplication** via secondary electron emission (SEY).

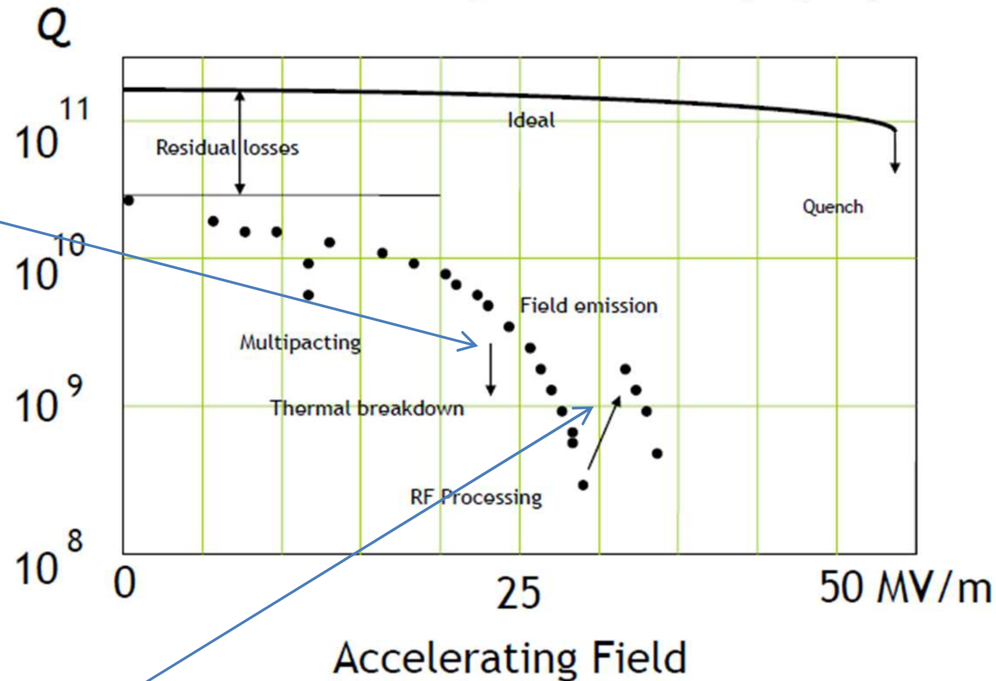
MP was an early limitation of SRF cavities' performance.
It was overcome by **adopting spherical/elliptical cell shapes**.
In severe cases MP may cause quench and limit the cavity field.
Also the **RF conditioning** can reduce the MP

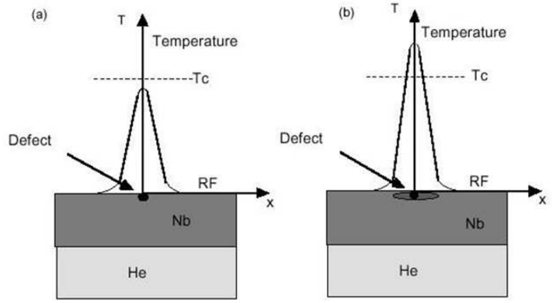


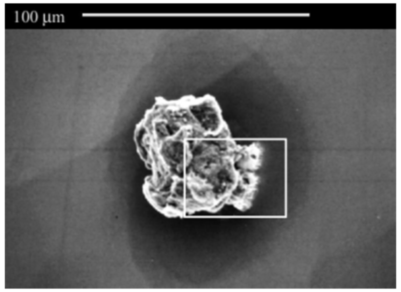


REAL PERFORMANCES OF SC CAVITIES: Q vs Eacc (2/2)

Thermal breakdown occurs when the heat generated at the **hot spot** is larger than that can be transferred to the helium bath causing $T>T_c$ and, as a consequence, **"quench" of the superconducting state**





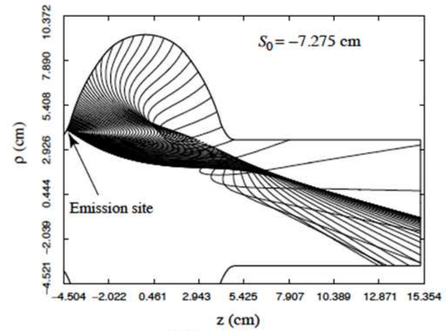


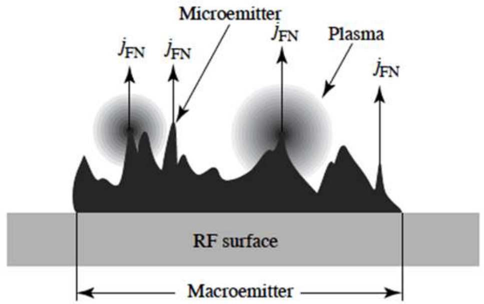
Exponential increase of losses due to acceleration of Field Emitted electrons. Associated with production of X-rays and dark current.

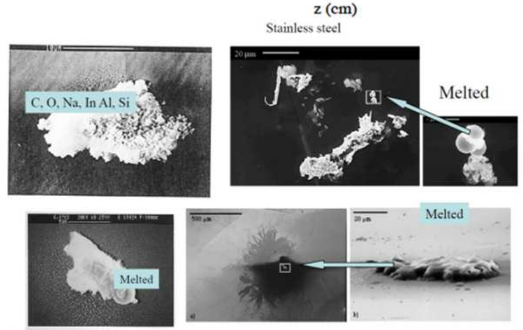
The main cause of FE is particulate **contamination.**

FE can be prevented by proper **surface preparation** and contamination control.

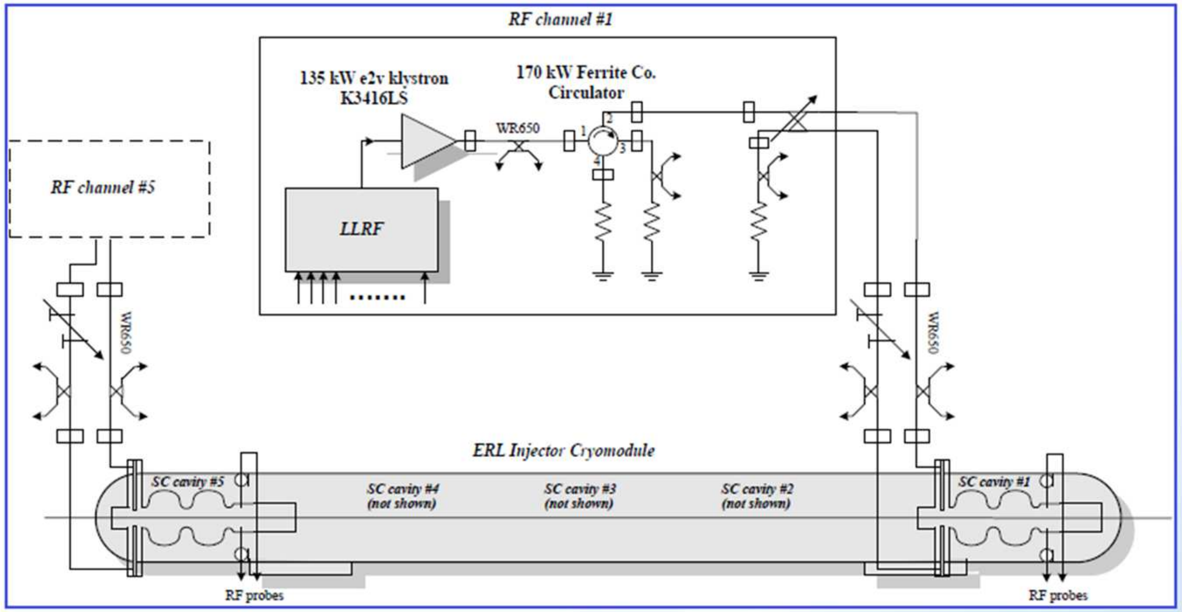
It is possible to reduce using High-power Pulsed Processing (HPP) and/or Helium processing.

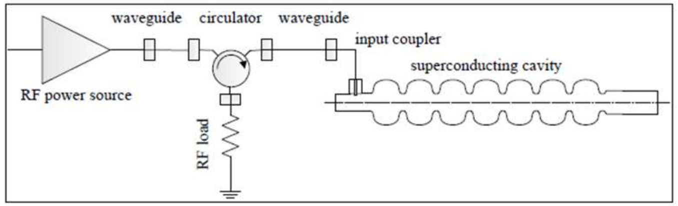




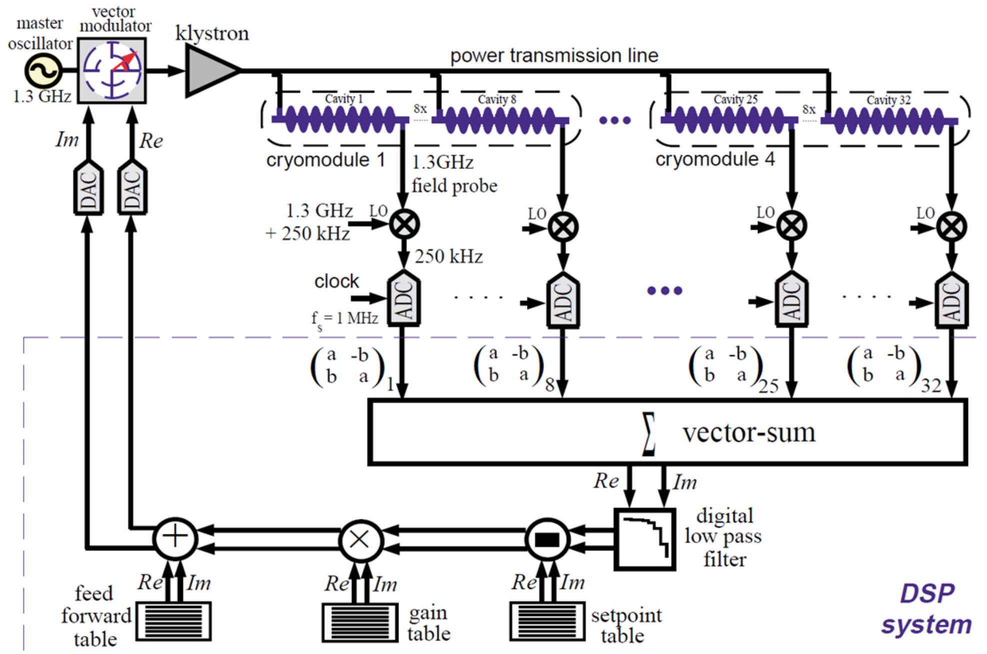


SC SW STRUCTURES: RF FEEDING SYSTEM

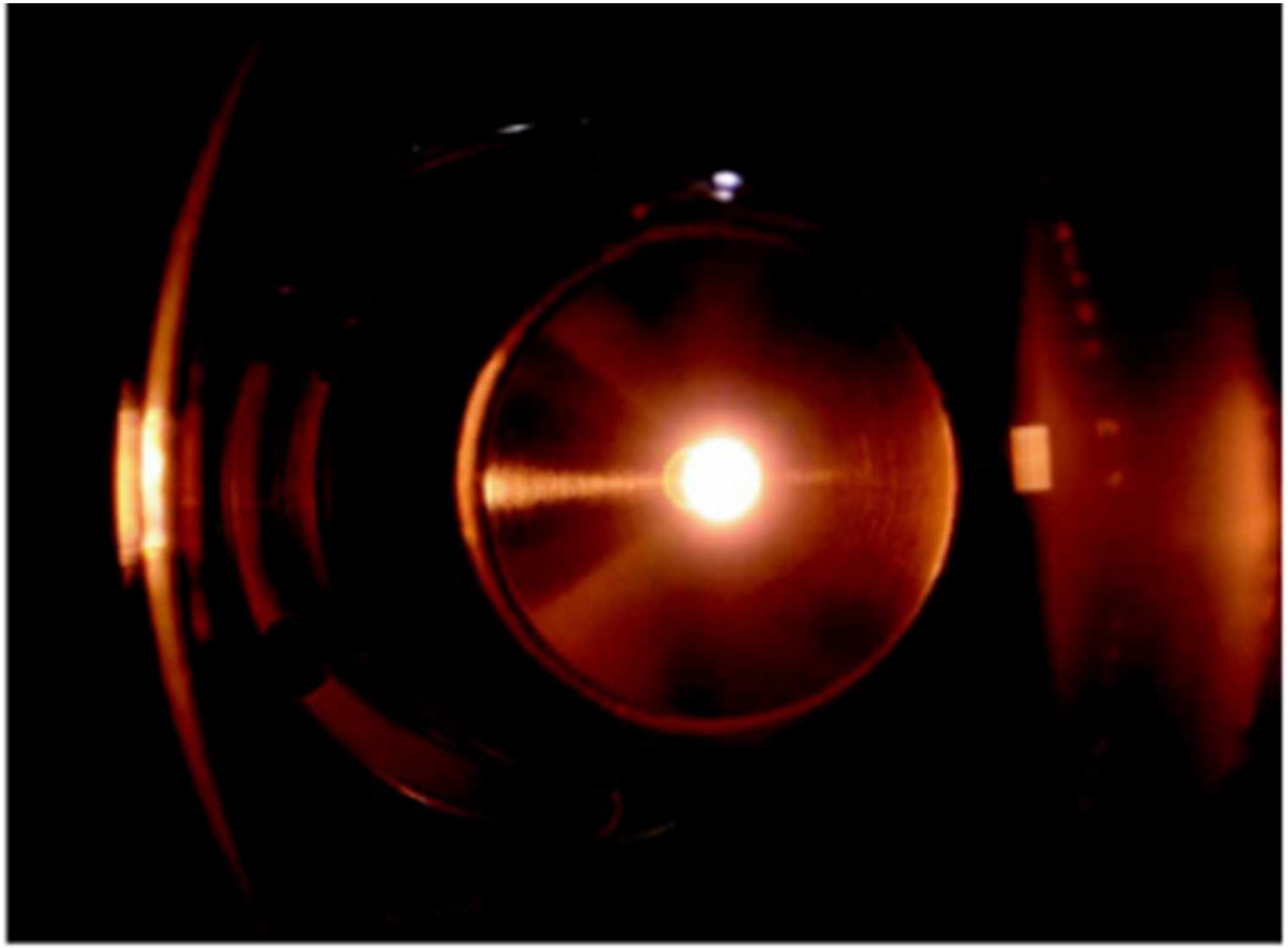




The requirements on the stability of the accelerating field in a superconducting acceleration structure are comparable to those in a normal-conducting cavity. However, the nature and magnitude of the perturbations to be controlled are rather different. Superconducting cavities possess a **very narrow bandwidth** and are therefore highly susceptible to mechanical perturbations. Significant phase and amplitude errors are induced by the resulting **frequency variations**. Perturbations can be excited by mechanical vibrations (**microphonics**), changes in helium pressure and level, or Lorentz forces. Slow changes in frequency, on the time scale of minutes or longer, are corrected by a frequency tuner, while faster changes are counteracted by an amplitude and phase modulation of the incident rf power.



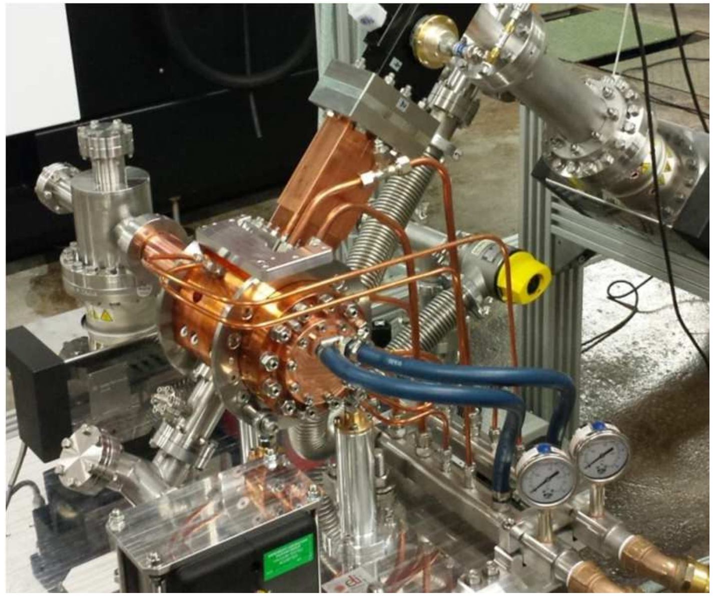
ELECTRON SOURCES

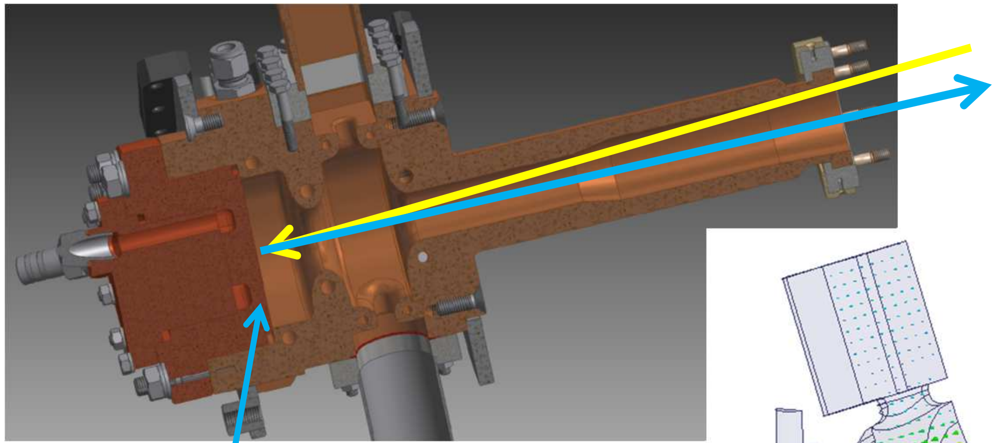


NC SW STRUCTURES: RF PHOTO-GUNS

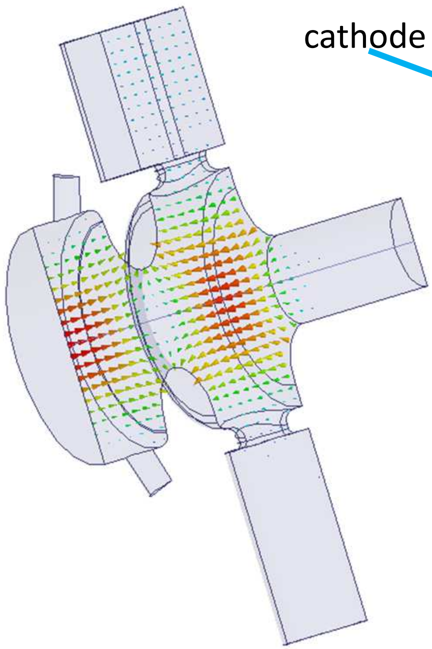
RF guns are used in the first stage of electron beam generation in FEL and acceleration.

- Multi cell: typically 2-3 cells
- SW π mode cavities
- operate in the range of 60-120 MV/m cathode peak accelerating field with up to 10 MW input power.
- Typically in L-band- S-band (3-1 GHz) at 10-100 Hz.
- Single or multi bunch (L-band)
- Different type of cathodes (copper,…)

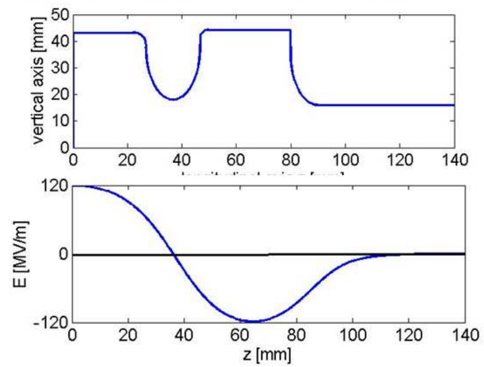




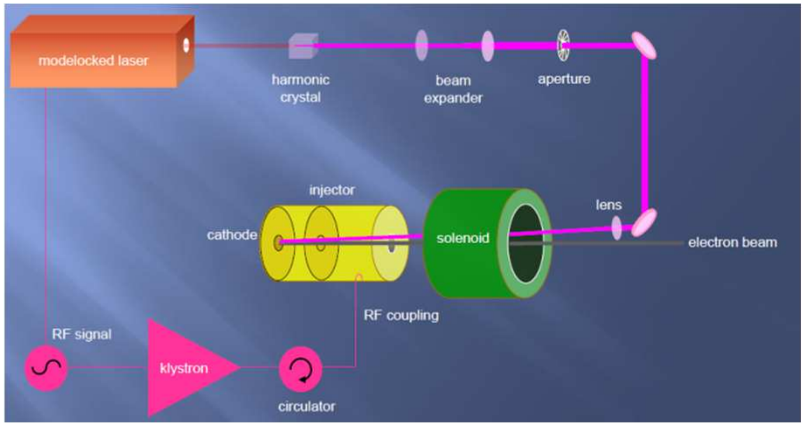
The electrons are emitted on the **cathode** through a laser that hit the surface. They are then accelerated trough the electric field that has a longitudinal component on axis TM_{010}.

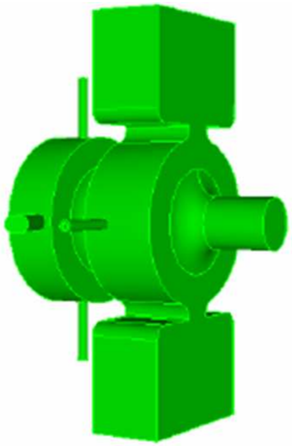


cathode



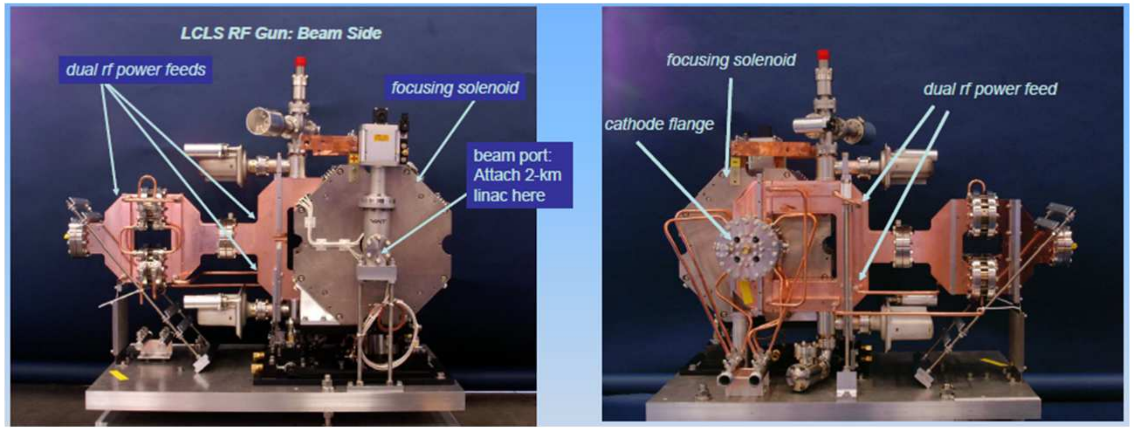
RF PHOTO-GUNS: EXAMPLES





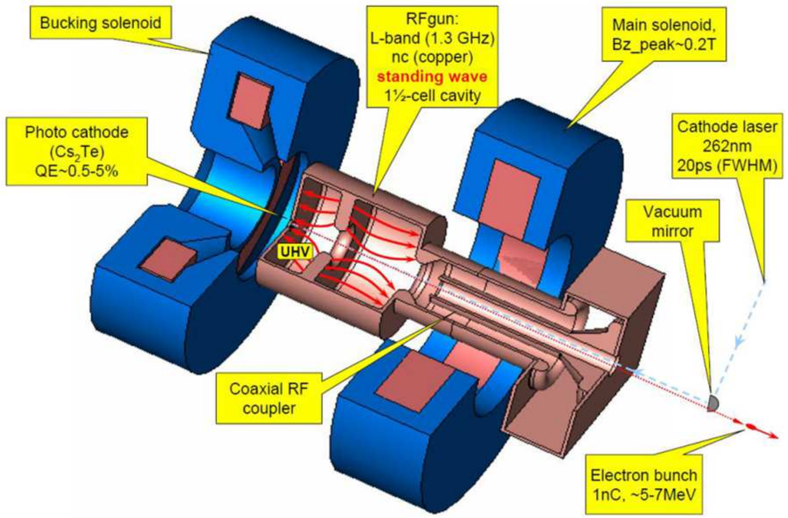
LCLS I

Frequency = 2,856 MHz
Gradient = 120 MV/m
Exit energy = 6 MeV
Copper photocathode
RF pulse length ~2 μs
Bunch repetition rate = 120 Hz
Norm. rms emittance
0.4 mm·mrad at 250 pC

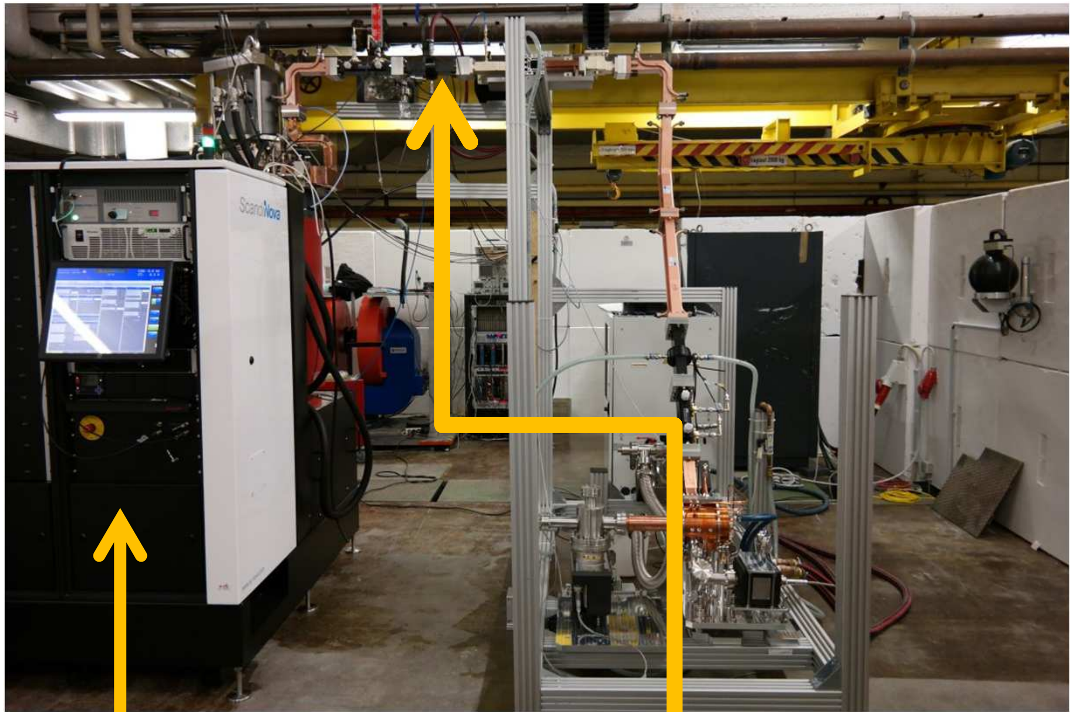


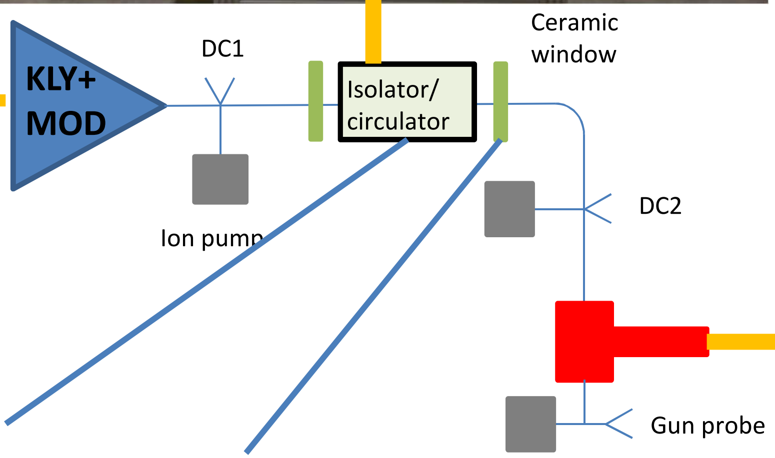
PITZ L-band Gun

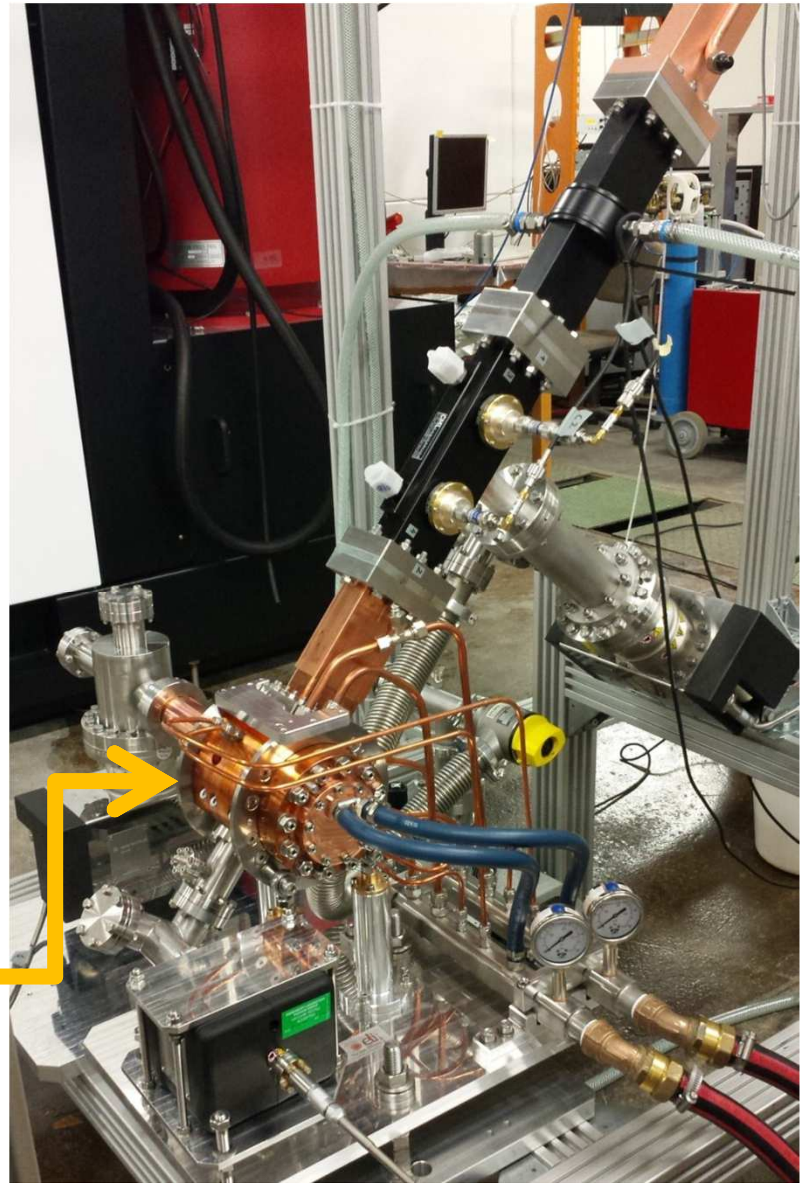
Frequency = 1,300 MHz
Gradient = up to 60 MV/m
Exit energy = 6.5 MeV
Rep. rate 10 Hz
Cs_2Te photocathode
RF pulse length ~1 ms
800 bunches per macropulse
Normalized rms emittance
1 nC 0.70 mm·mrad
0.1 nC 0.21 mm·mrad



RF PHOTO-GUNS: RF WAVEGUIDE DISTRIBUTION





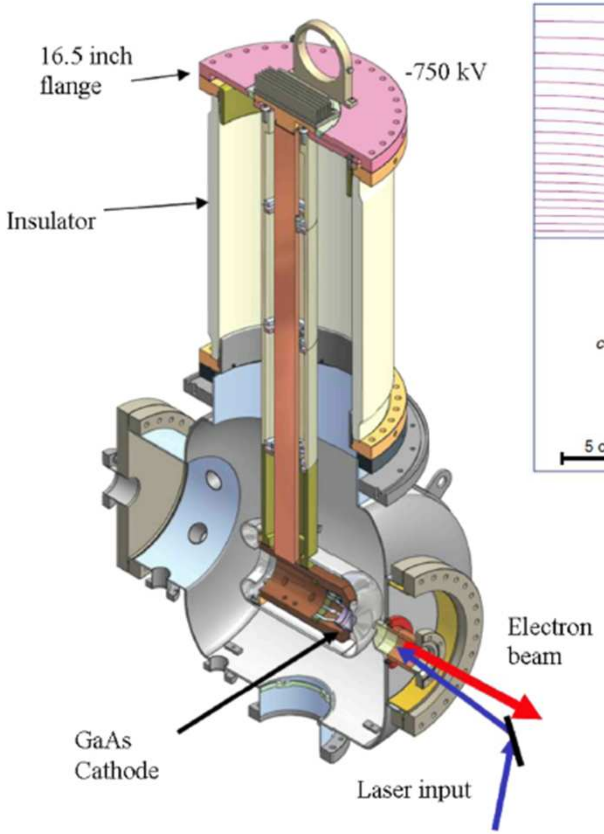


protect the klystron from reflected power. SW structures always reflect power (during RF transients)

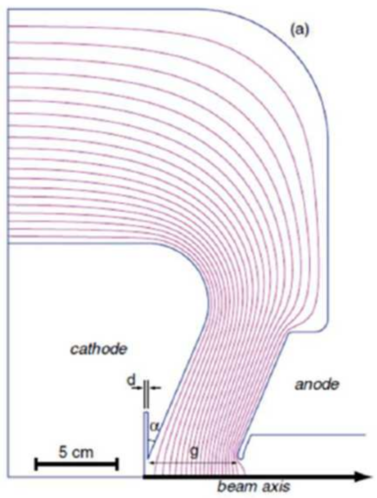
Isolate the vacuum of the waveguides from that of the gun

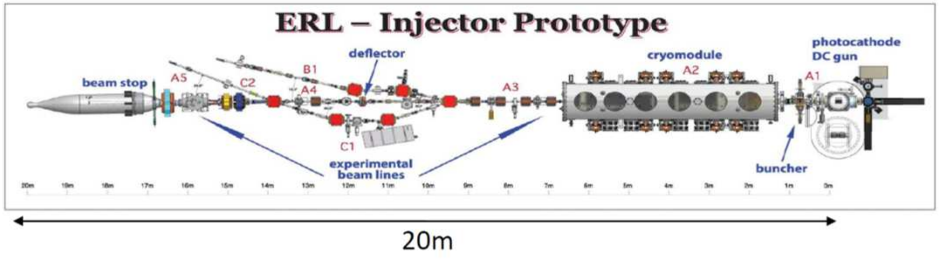
DC PHOTO-GUNS

DC photoguns can be used as electron sources for high average current accelerator (CW, ERL). In this case the cathode of GaAs(Cs) is used in a DC system. Average currents up to 100 mA can be achieved.



The Cornell Photoemission Gun.





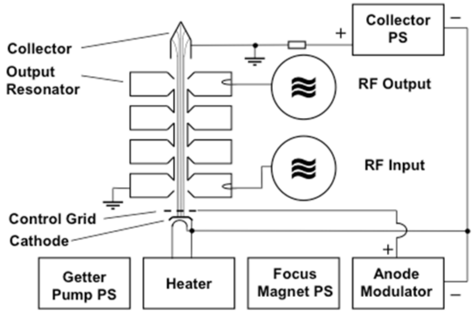
Cornell DC gun

Gradient = 5 – 10 MV/m
Gun exit energy = 0.35 MeV
GaAs and K_2CsSb photocathodes
Bunch repetition rate = 1300 MHz
Norm. rms emittance = 0.5/0.3 μm at 80 pC
Average current = 65 mA (at 50 pC)

POWER SOURCES AND POWER DISTRIBUTION

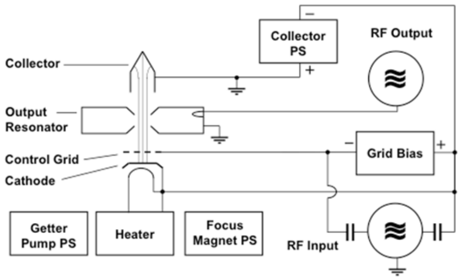
RF SOURCES

Klystron



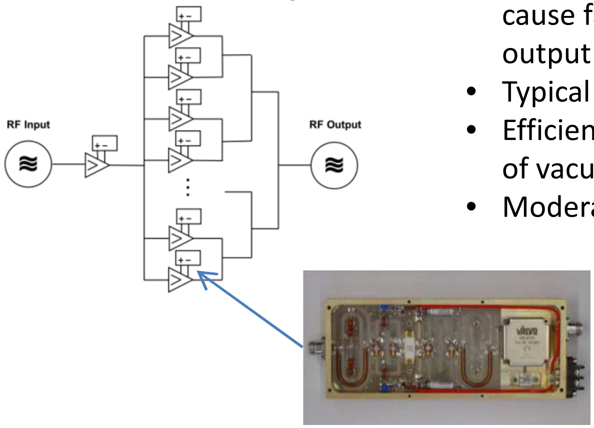
- Intensity modulation of DC beam by cavity
- Output cavity
- Both ppulsed and CW
- Typical 0.3-30 GHz
- High power >50 MW´s
- High gain (>40dB)

Inductive Output Tube (IOT)

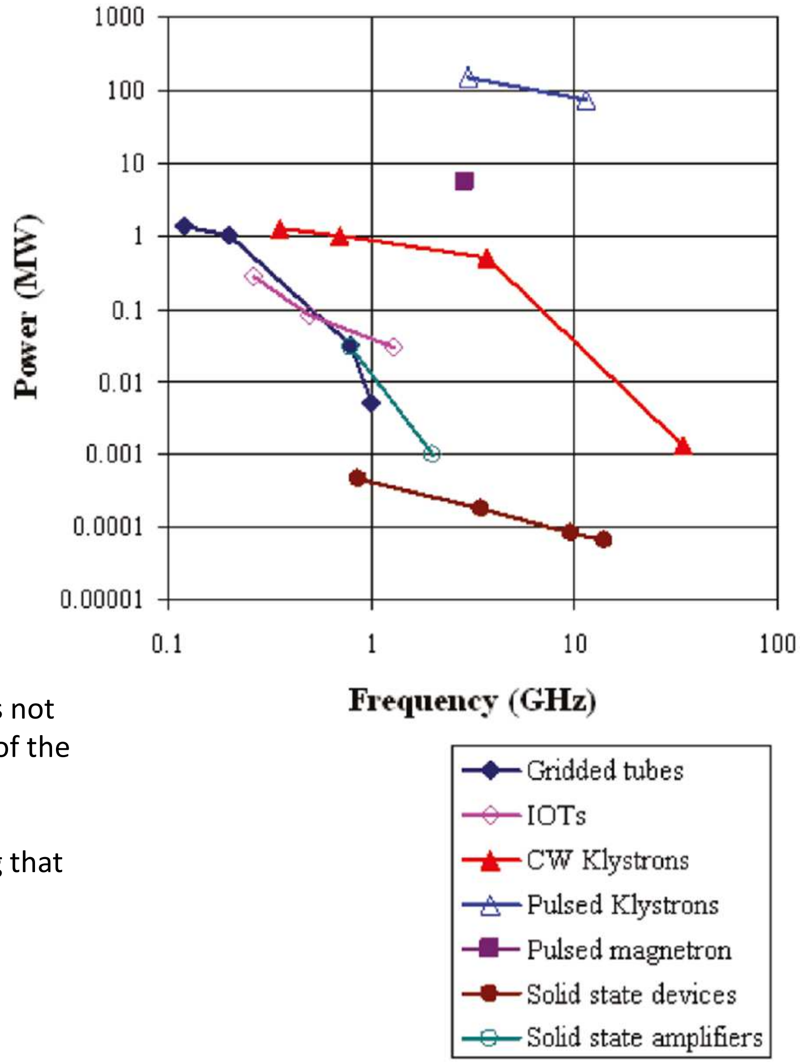


- Intensity modulation of DC beam by control grid
- Typical up to 2 GHz
- Higher efficiency than klystron
- Moderate power (<100 kW)

Solid state amplifier

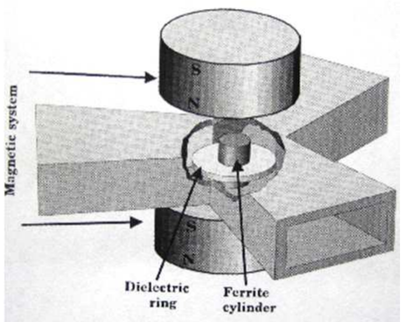


- Combines power of many transistors
- Soft failure mode (single module failure does not cause failure of the amplifier, just reduction of the output power)
- Typical up to 2 GHz
- Efficiency is approaching and even exceeding that of vacuum tubes
- Moderate high power



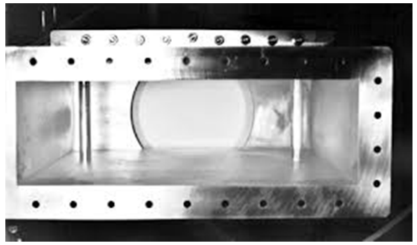
WAVEGUIDE RF COMPONENTS

Isolators/circulators

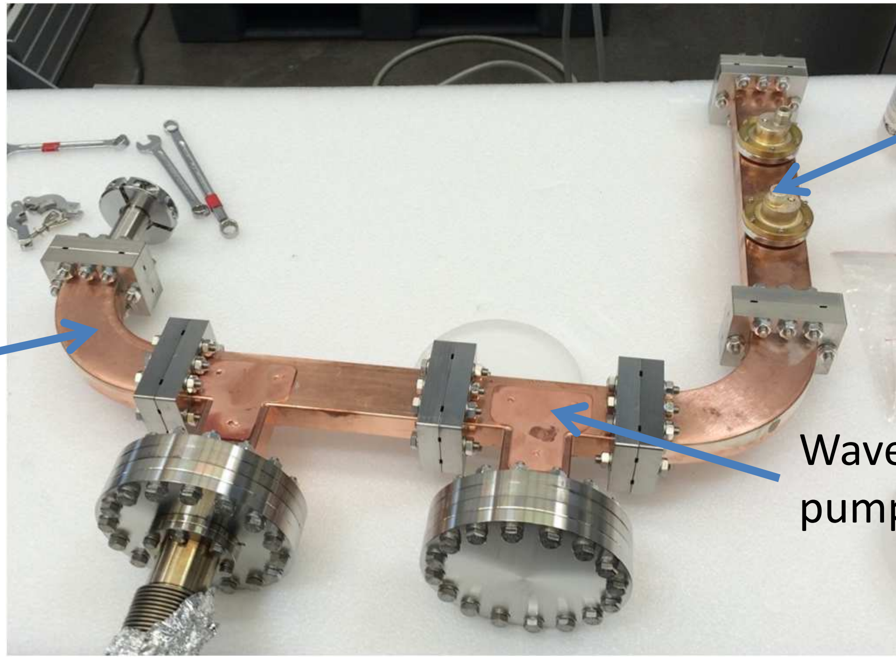


The circulator is a passive non-reciprocal device with 3 or more ports, and protect (isolate) the RF power sources from microwave power reflected back from a non-ideal loads. This is possible due to unique magnetic properties of ferrites that, when properly magnetized, introduce different phase shift for electromagnetic waves traveling in opposite directions.

High power RF loads



Ceramic windows

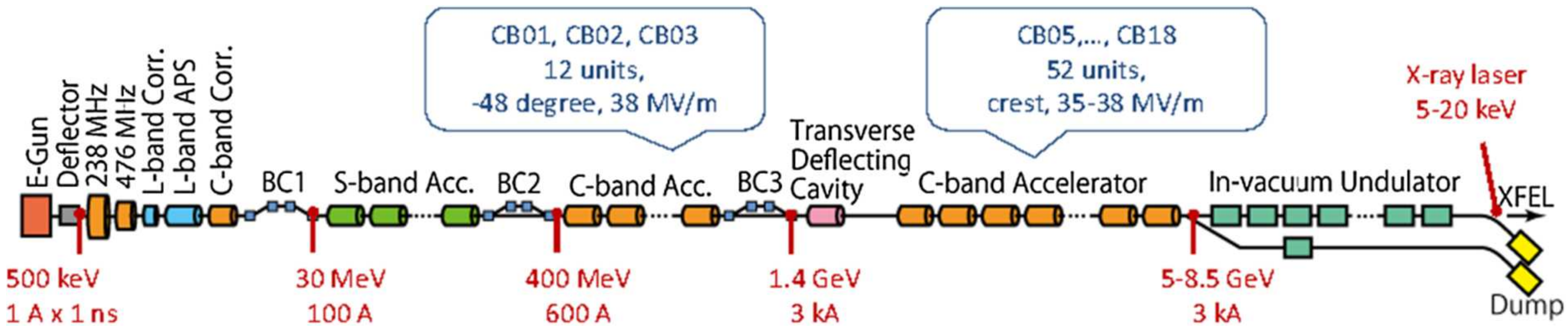


Directional couplers

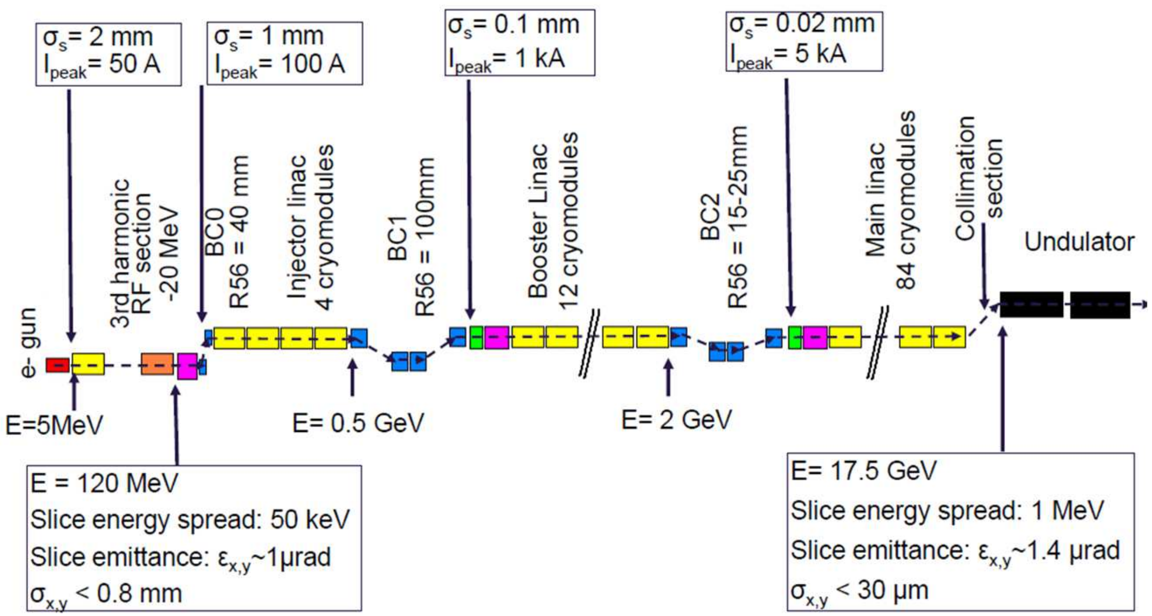
Waveguide bend

Waveguide pumping port

EXAMPLES

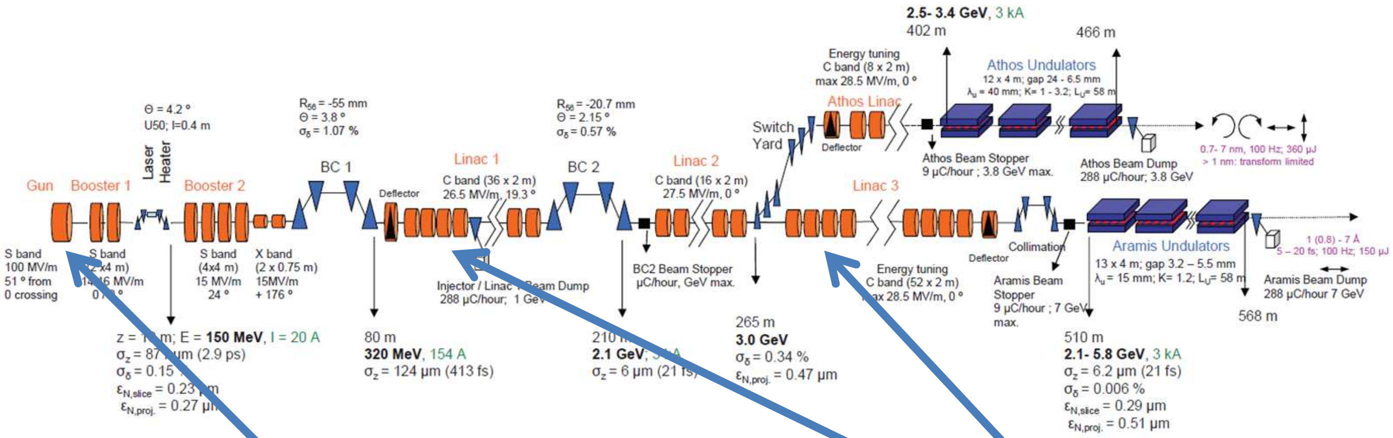


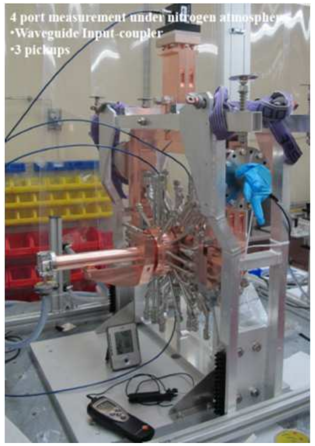
CB01, CB02, CB03
12 units,
-48 degree, 38 MV/m
CB05,..., CB18
52 units,
crest, 35-38 MV/m
X-ray laser
5-20 keV
E-Gun
Deflector
238 MHz
476 MHz
L-band Corr.
L-band APS
C-band Corr.
BC1
S-band Acc.
BC2
C-band Acc.
BC3
Transverse Deflecting Cavity
C-band Accelerator
In-vacuum Undulator
XFEL
Dump
500 keV
1 A x 1 ns
30 MeV
100 A
400 MeV
600 A
1.4 GeV
3 kA
5-8.5 GeV
3 kA

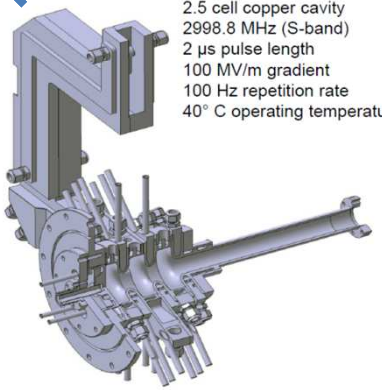


σs= 2 mm
Ipeak= 50 A
σs= 1 mm
Ipeak= 100 A
σs= 0.1 mm
Ipeak= 1 kA
σs= 0.02 mm
Ipeak= 5 kA
e- gun
3rd harmonic RF section -20 MeV
BC0 R56 = 40 mm
Injector linac 4 cryomodules
BC1 R56 = 100mm
Booster Linac 12 cryomodules
BC2 R56 = 15-25mm
Main linac 84 cryomodules
Collimation section
Undulator
E=5MeV
E= 0.5 GeV
E= 2 GeV
E = 120 MeV
Slice energy spread: 50 keV
Slice emittance: εx,y~1μrad
σx,y < 0.8 mm
E= 17.5 GeV
Slice energy spread: 1 MeV
Slice emittance: εx,y~1.4 μrad
σx,y < 30 μm

EXAMPLE: SWISSFEL LINAC (PSI)

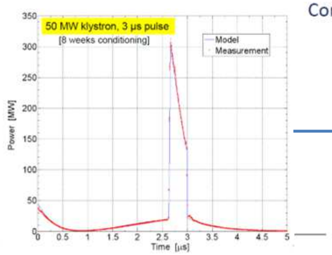


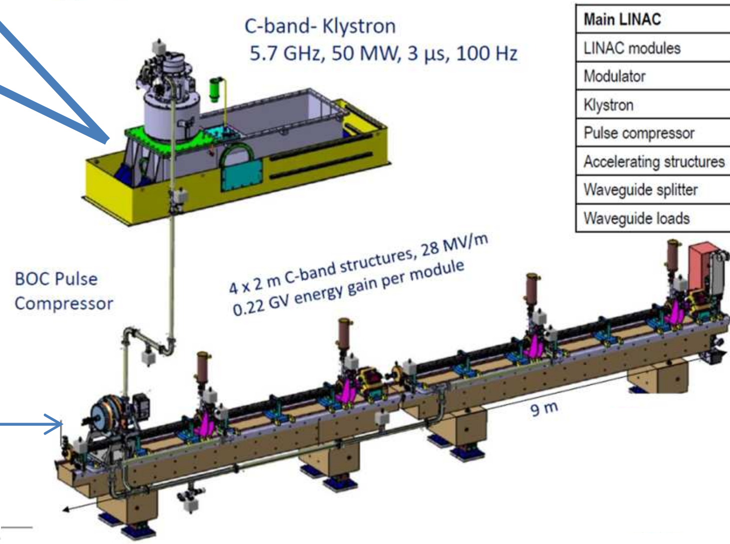


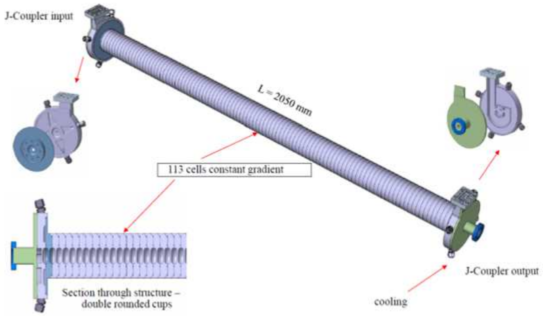


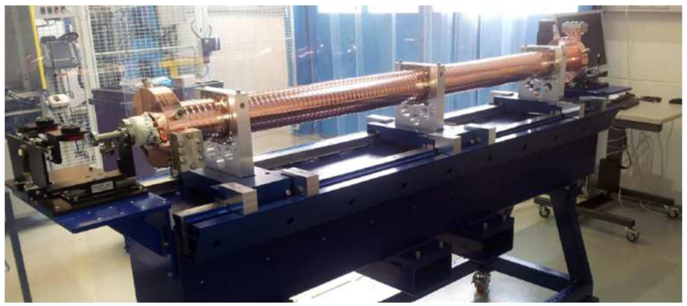
2.5 cell copper cavity
2998.8 MHz (S-band)
2 μs pulse length
100 MV/m gradient
100 Hz repetition rate
40° C operating temperature

Main LINAC	#
LINAC modules	26
Modulator	26
Klystron	26
Pulse compressor	26
Accelerating structures	104
Waveguide splitter	78
Waveguide loads	104

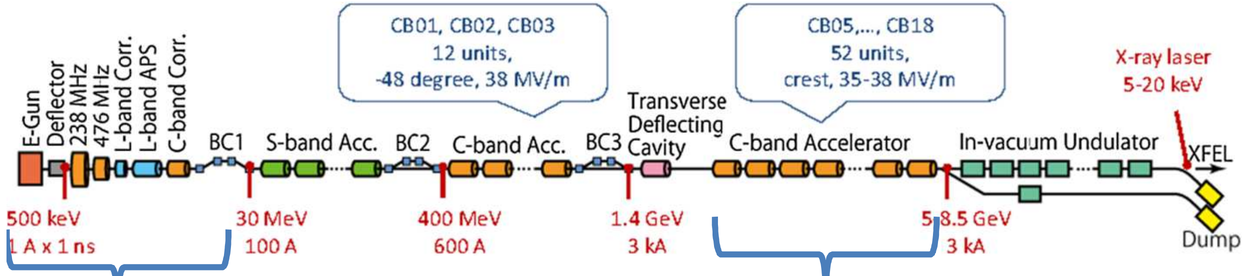




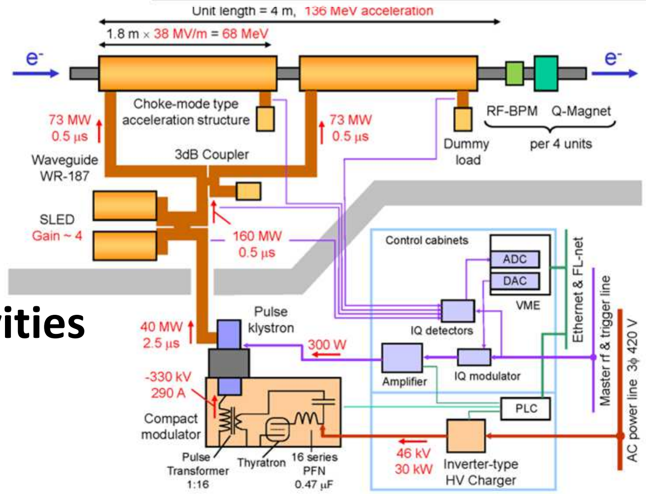




EXAMPLES: JAPANESE XFEL (SPRING-8)

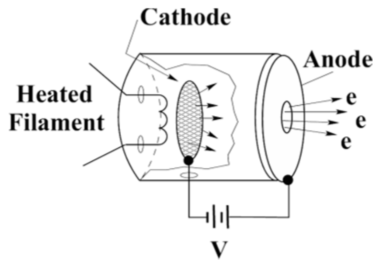


Structure type	Traveling wave, quasiconstant gradient
Phase advance per cell	$3\pi/4$
Active accelerator length	1.79 m
Number of cells	91 cells (including two coupler cells)
Cell length	19.7 mm
Iris aperture (2a)	13.6–17.3 mm
Iris thickness	4 mm
Accelerator cavity diameter (2b)	44.0–45.7 mm
Operating frequency	5712 ± 0.2 MHz
Average phase error	< 5 degree
Attenuation parameter (τ)	0.53 ± 0.02
Fill time	300 ns
Cell Q factor	> 10000
Average shunt impedance	54 MΩ/m
Straightness	$< \pm 0.2$ mm
HOM damper	SiC absorber + choke structure
Choke frequency	5712 ± 11 MHz
Coupler type	J-type double feed

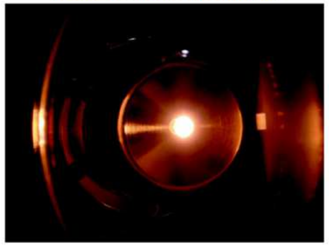


Thermionic gun

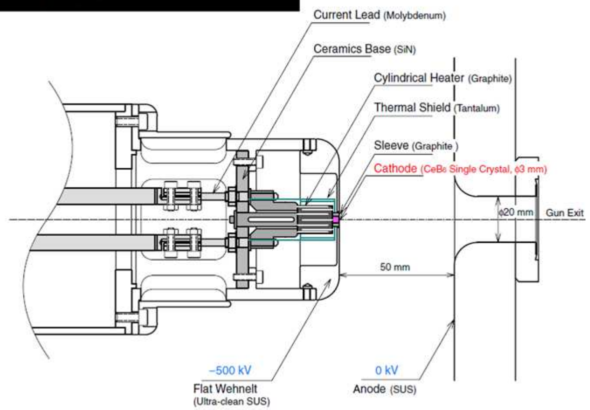
The most remarkable feature of the injector is employing a **thermoionic gun** (500 keV CeB6 single crystal). RF beam manipulations with multi-stage RF cavities are the necessary to not degrade the initial emittance.



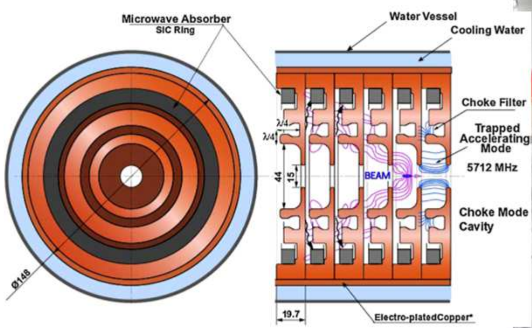
Heated Cathode in Chamber



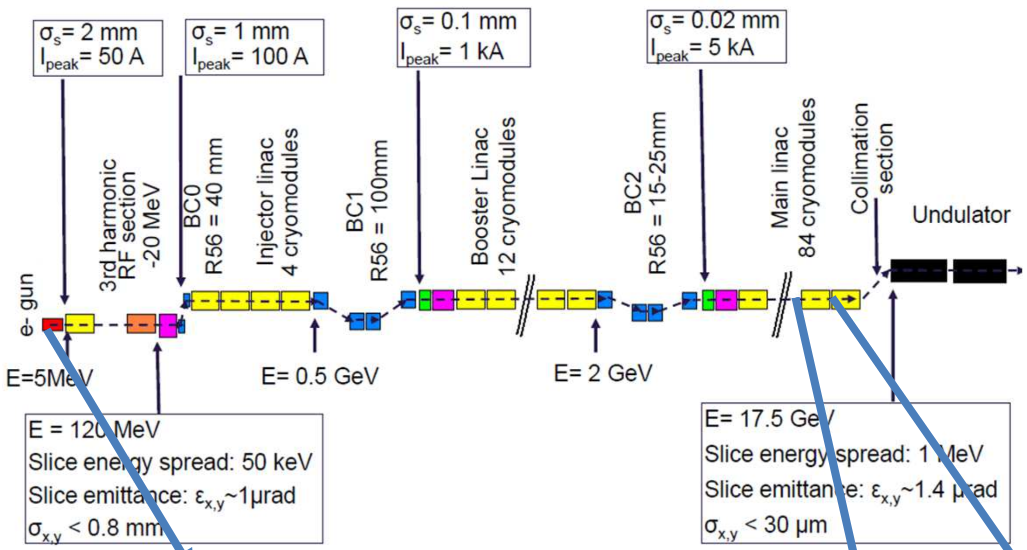
CeB₆ Single Crystal (φ3 mm)



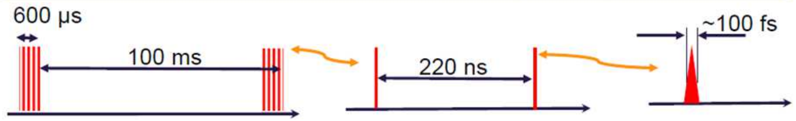
Damped C-band cavities

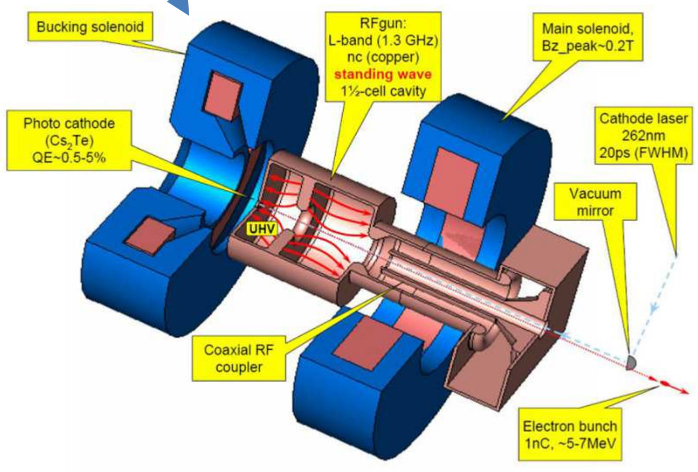


EXAMPLES: EUROPEAN XFEL



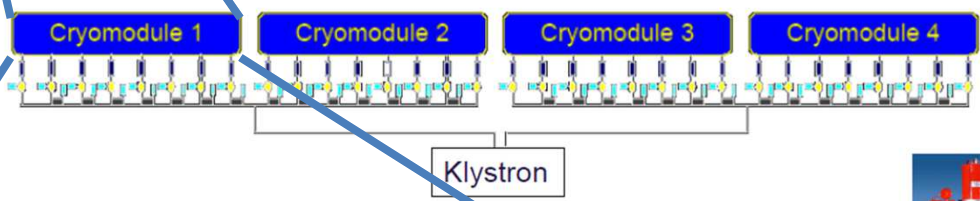
Nominal Energy	GeV	17.5
Beam pulse length	ms	0.60
Repetition rate	Hz	10
Max. # of bunches per pulse		2700
Min. bunch spacing	ns	220
Bunch charge	nC	1
Bunch length, σ_z	μm	< 20
Emittance (slice) at undulator	μrad	< 1.4
Energy spread (slice) at undulator	MeV	1

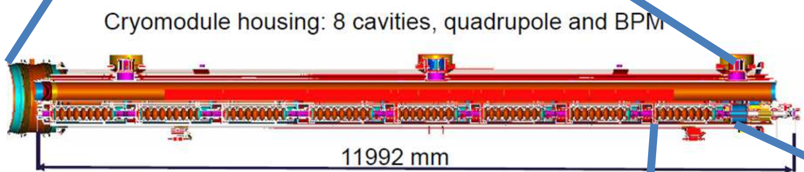




101 cryomodules in total

RF system: 25 RF units. The unit = 4 cryomodules + RF-power source (klystron)



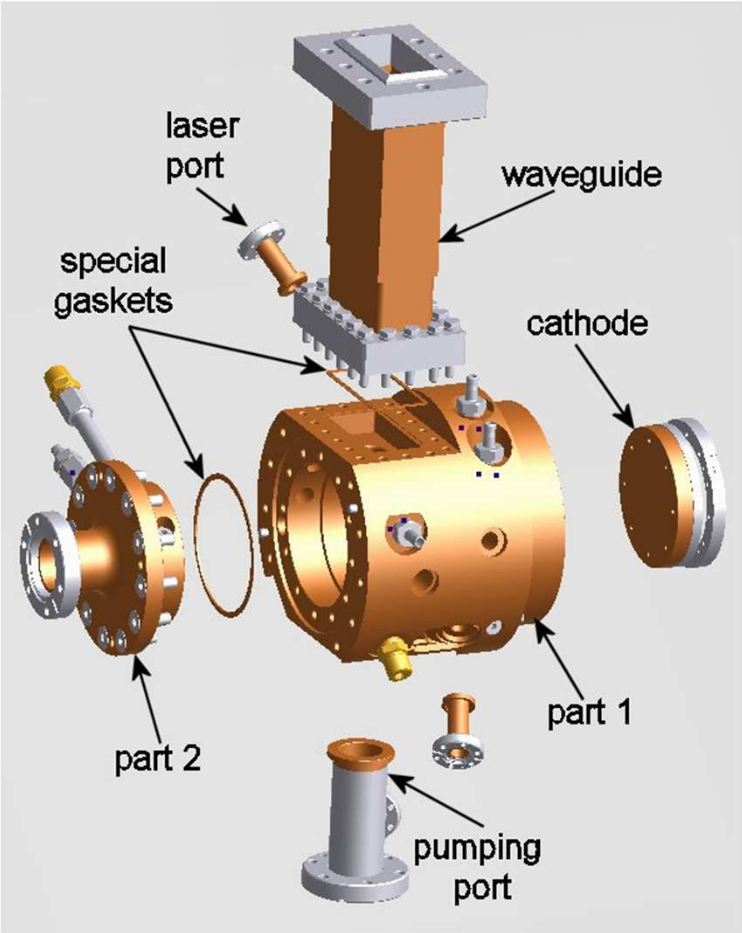


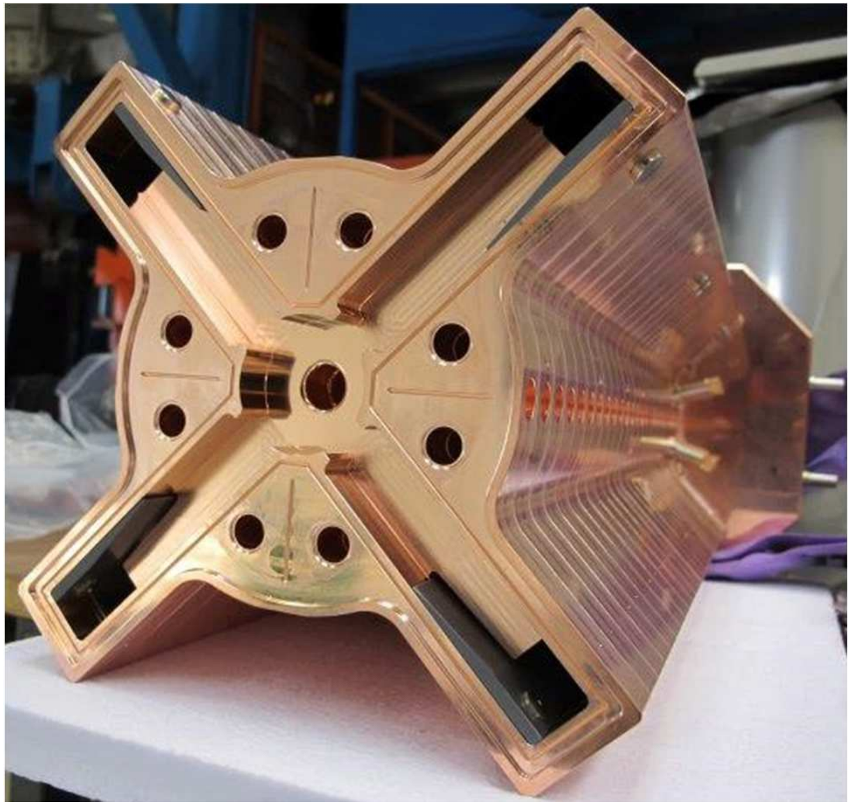
25 RF stations
5.2 MW each

Frequency = 1.3 GHz
Gradient = up to 60 MV/m
Exit energy = 6.5 MeV
Cs_2Te photocathode

800 accelerating cavities
1.3 GHz / 23.6 MV/m

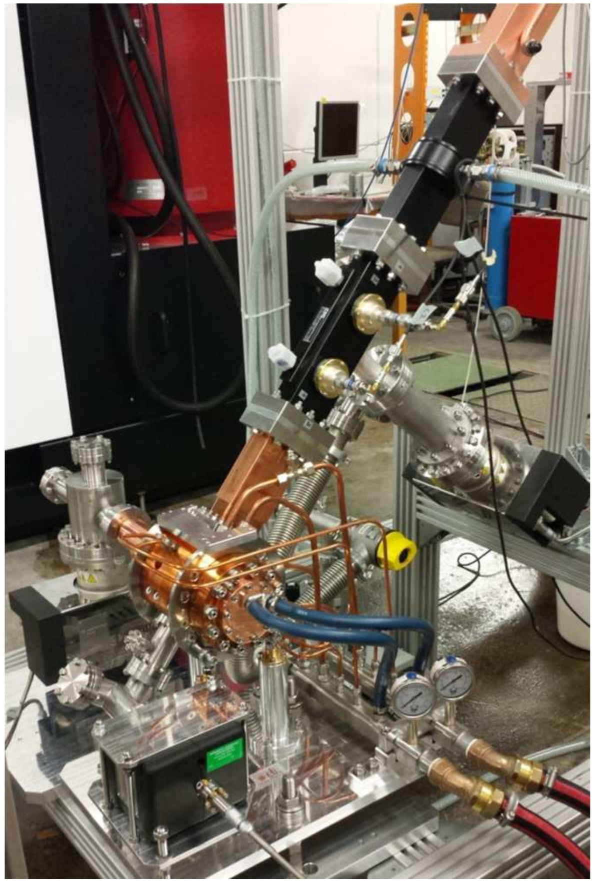
NEW TECHNOLOGIES

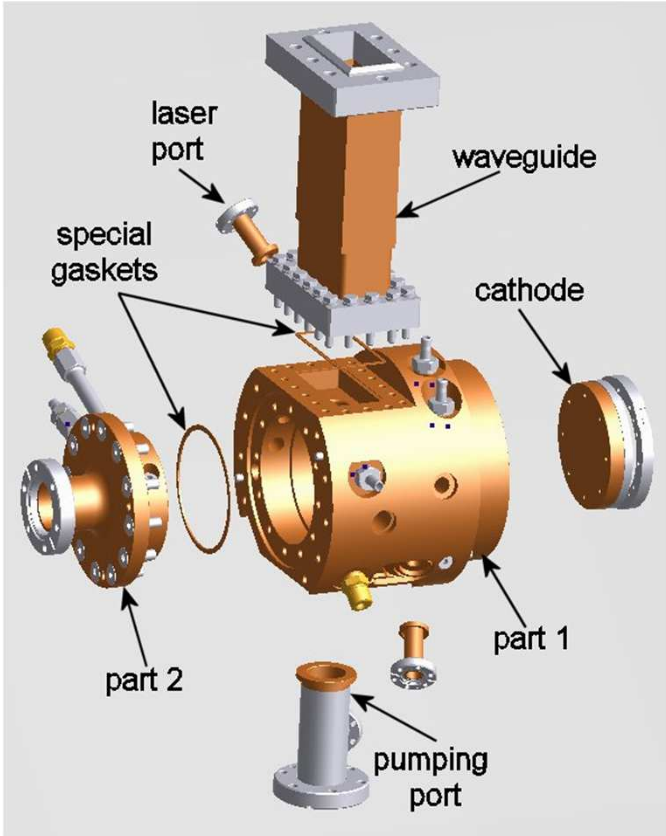


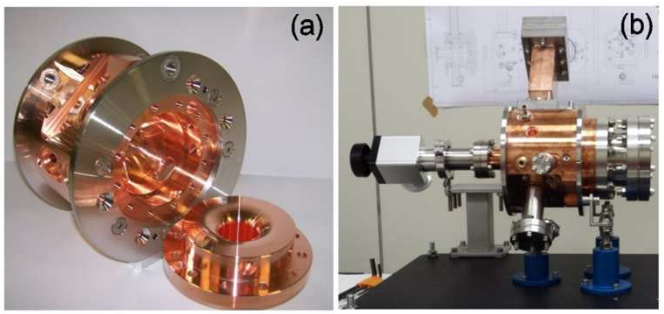


NEW TECHNOLOGY BASED ON CLAMPING FOR HIGH GRADIENT RF PHOTOGUN

⇒The new SPARC GUN and the ELI-NP one have been realized **without brazing** using a novel process developed at LNF-INFN involving the use of **special vacuum/RF gaskets.**



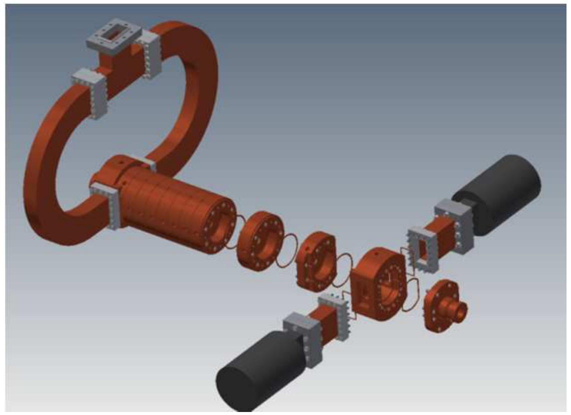




⇒The guns have been tested at high power and with beam

⇒The results **demonstrate the use of this novel technique for a high brightness photoinjectors and can be extended to more genral RF structures**

⇒The new technique could be applied to other RF structures (S-Band, X band,…) and more high power tests (in **X band** as example) would be very useful to understand the criticalities and the limits of this new technology.



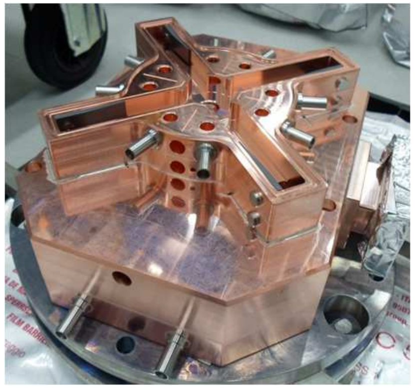
DAMPED/HIGH GRADIENT/HIGH REPETITION RATE C-BAND ACCELERATING STRUCTURES FOR THE ELI-NP LINAC

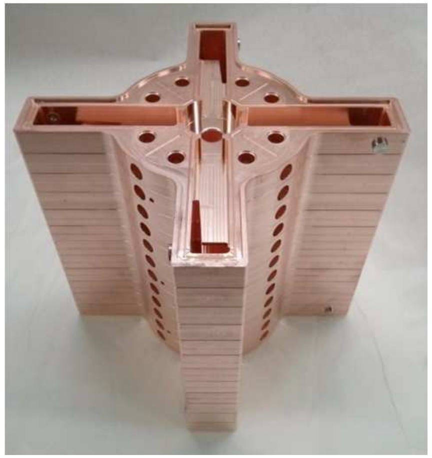
⇒ The linac energy booster of the European ELI-NP proposal foresees the use of 12, 1.8 m long, travelling wave C-Band structures.

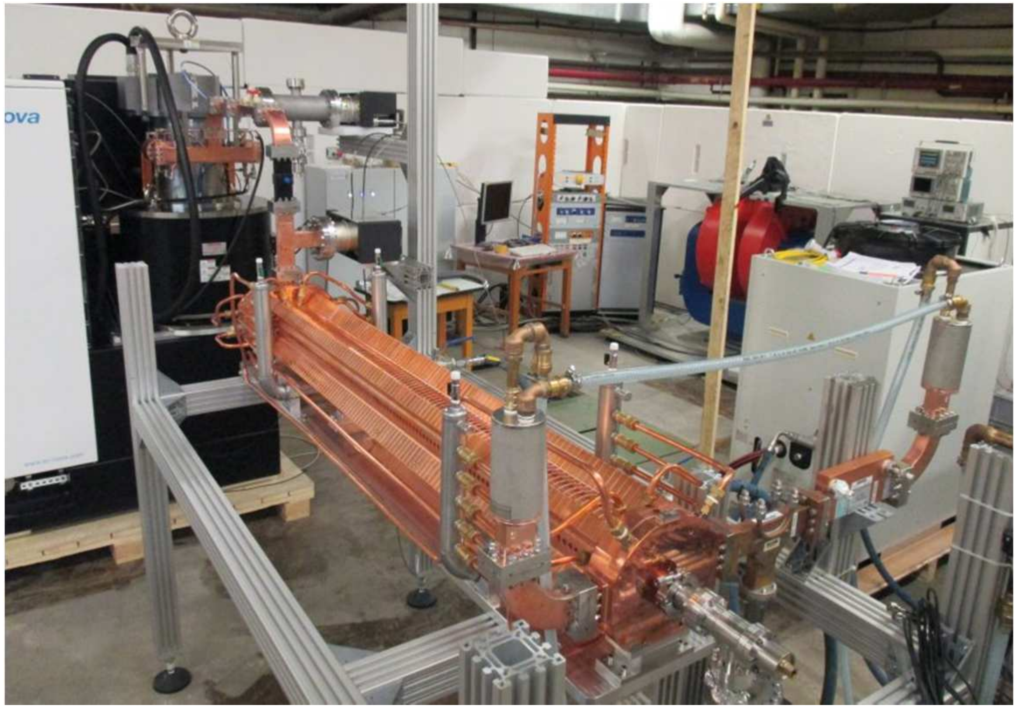
⇒ Because of the **multi-bunch operation**, the structures integrate a very **effective dipole HOM damping system** to avoid beam break-up (BBU).

⇒ An optimization of the electromagnetic and mechanical design has been done to simplify the fabrication and to reduce their cost.

⇒ The high power test on the first full scale structure shown the feasibility of the **33 MV/m, 100 Hz, long RF pulse operation**







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