SRF 2015 tutorials : FPC and HOM couplers

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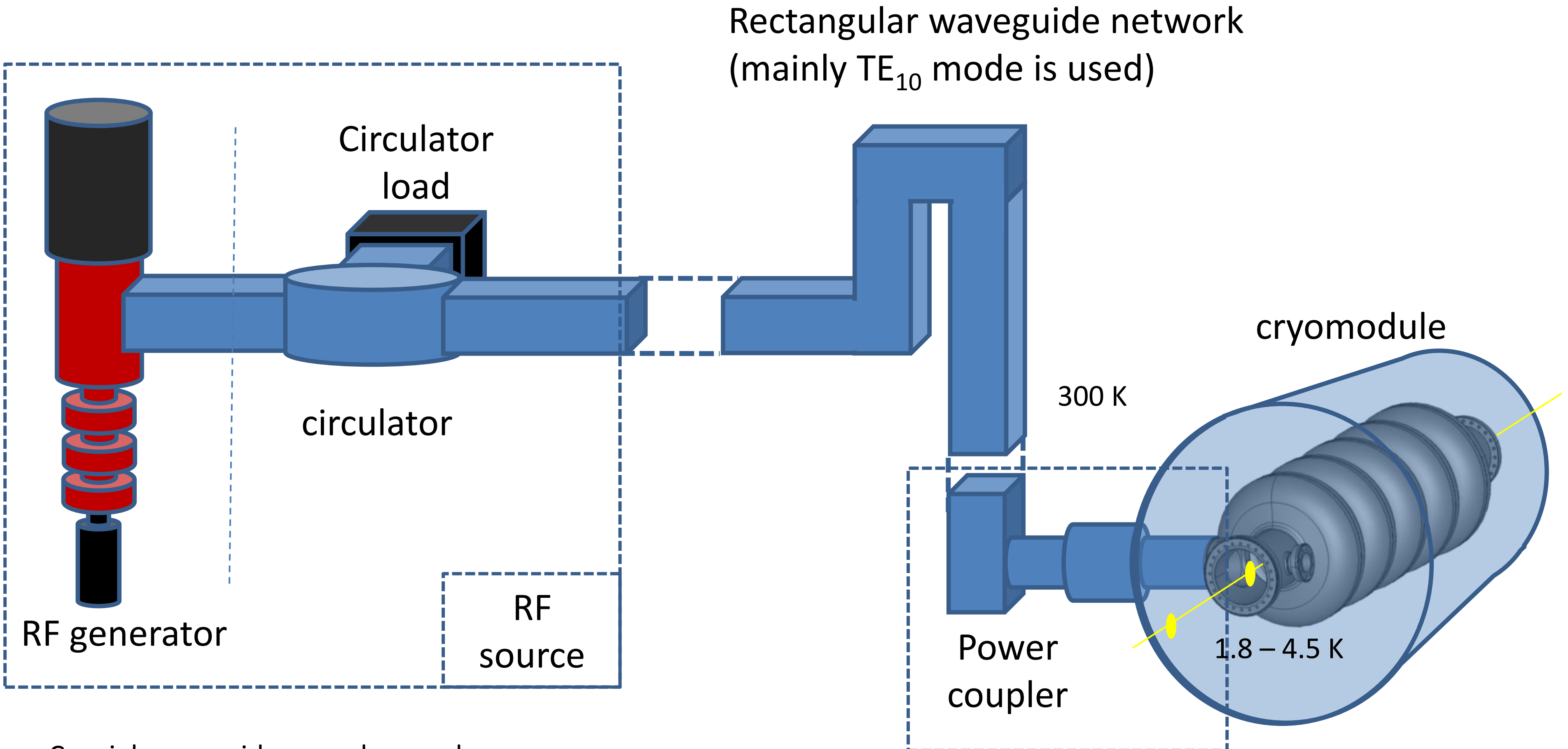
Couplers on SRF cavities

- Fundamental Power Coupler (FPC)

  fundamental because it injects energy in the fundamental mode (e. g. accelerating mode) of the cavity, also called
  - main coupler
  - or input coupler
  - or simply power coupler

- High Order Mode (HOM)coupler
  - Extracts energy from the cavity of modes excited by the beam in order to prevent this energy to be stored in the cold parts and generate heat
  - Not the same as a HOM damper which simply lowers the Q factor of HOMs in en effort to prevent energy to be stored

Feeding RF power to a cavity



Coaxial waveguides are also used :

- at lower frequency <350 MHz because the size of rectangular waveguides would become impractical
- When their lower power handling capability and higher power dissipation are not an issue

Power coupler functions

- Inject RF power generated by the RF source into the cavity and beam,
- Maximize power transmission at the nominal frequency f_0 (or eqv. minimizing reflection),
- Form a vacuum boundary for the cavity
- Act as a thermal interface between the cavity and room temperature waveguide distribution and minimize heat leak to the cryomodule parts and cavity
- Creates a mechanical interface between the cavity and the waveguide network and/or the cryomodule : it must not be a source of misaligment

Power coupler components

RF

- Interface to the waveguide distribution (coaxial or rectangular waveguide)
- One or two RF windows
- Transmission lines elements
- Coupling element (aperture, antenna, loop)

RF distribution	Mode conversion	Coupler line type	Window (s)	Coupling element	
Rectangular WG	→	rectangular	rectangular	aperture	
	TE →TEM (doorknob)	coaxial	Disk/cylindrical	antenna	
Coaxial WG	→	coaxial	Disk/cylindrical	Antenna/loop	

Existing generic RF configurations in SRF

Thermal

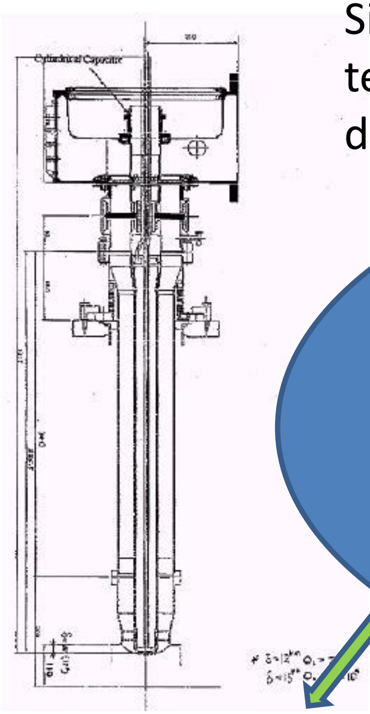
Cooling elements:

- Conduction :thermal links to cryomodule elements
- Convection : cooling channels

Mechanical

- Bellows
- Vacuum flanges
- Interface to cryomodule

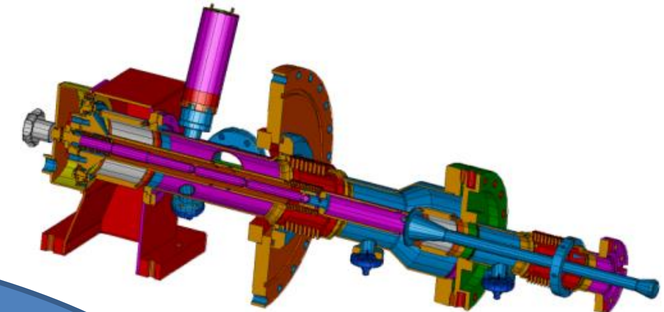
The archetypes and offsprings



Single room temperature disk window

Tristan coupler

KEK-B coupler
508 MHz
350 kW CW to beam
10 yrs+ beam operation



TTF 1.3 GHz
250 kW peak power
0.5 kW average power
10 yrs+ beam operation

Warm and cold cylindrical windows

Pulsed couplers

- KEK Compact ERL 1.3 GHz
- J-Parc 972 MHz
- SNS 805 MHz
- CEA-Saclay 704 MHz

CW couplers

- BNL 704 MHz
- IPN Orsay 704 MHz

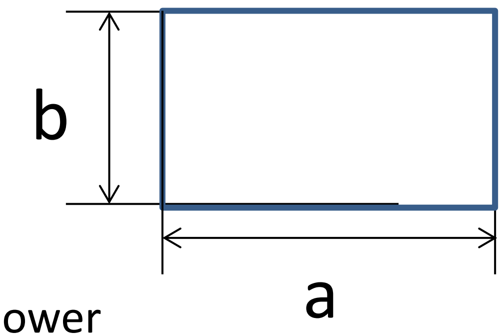
Pulsed couplers

- XFEL
- ILC

CW couplers

- Cornell ERL injector
- Cornell ERL main linac
- Daresbury ALICE

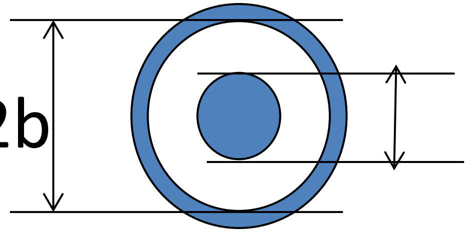
Rectangular waveguides



- Rectangular waveguides
  - TE10 mode, cutoff frequency : size impractical at low RF frequencies (below 320 MHz)
  - Low dissipation compared to coaxial lines, better for high power handling (table below for typical Al alloy).
  - Standard dimensions b=a/2 (standard height) and b=a/4 (reduced height) widely used with high power equipments

EIA standards	Frequency range (MHz)	a (inches)	Minimum attenuation (dB/m)
WR2300	320-490	23	0.0009
WR1800	410-620	18	0.0013
WR1500	490-750	15	0.0017
WR1150	640-960	11.5	0.0025
WR650	1120-1700	6.5	0.006

Coaxial lines



- TEM mode, no cutoff frequency : very useful at low RF frequencies!
- Power handling capability can be increased by increasing the diameter
- Can be tailored to favor low electric fields or low magnetic field (resp. lower or higher impedance) by adjusting the ratio b/a

$$Z = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln{}^{b}\!/_{a} = \frac{1}{2\pi} Z_C \ln{}^{b}\!/_{a}$$

$$Z_C = \sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r}}$$

Z_c = 377Ω in vacuum

Fields vs travelling wave power

$$E(r) = \frac{1}{r}\sqrt{\frac{PZ_C}{\pi \ln{}^{b}\!/_{a}}}$$

$$H(r) = \frac{1}{r}\sqrt{\frac{P}{\pi Z_C \ln{}^{b}\!/_{a}}}$$

Attenuation per unit length in travelling wave

$$\alpha = \frac{1}{\pi Z_C \ln{}^{b}\!/_{a}}\left(\frac{R_{S,a}(f)}{a} + \frac{R_{S,b}(f)}{b}\right)$$

RF ohmic losses (NC)

Electrical resistivity, skin depth and Rf surface resistance:

EM field is attenuated exponentially in conductors : $J_{inside}(x) = J_{surface} e^{-x/\delta}$

δ Is the skin depth $\delta = \sqrt{\dfrac{2\rho}{\omega\mu_0}}$

$R_S = \dfrac{\rho}{\delta}$ $R_S = \sqrt{\dfrac{\rho\omega\mu_0}{2}}$

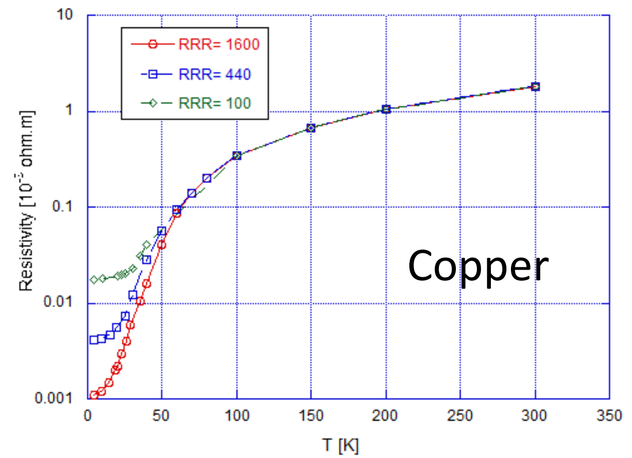
$$P_{diss} = \frac{1}{2} R_S \int_{Surface} |H|^2 dS$$

Frequency	100 MHz	500 MHz	1 GHz	1.5 GHz
Skin depth (μm)	6.7	3	2.1	1.7
Surface resistance (mΩ)	2.7	6	8.4	10.3

Example for Cu at 300 K, $\rho = 1.8\ 10^{-8} \Omega.m$

Anomalous skin effect

- electrical resistivity is temperature dependent, and depends on impurities
- Residual Resistivity Ratio RRR $= \frac{\rho_{300\mathrm{K}}}{\rho_{4\mathrm{K}}}$



- When Temperature T ↘:
  - Electrical resistivity ρ ↘
  - Skin depth δ ↘
  - ***But*** : Mean free path λ of conduction electrons↗

One expects $R_S \propto \sqrt{\rho}$ ↘, $R_{S\,4K} = R_{S\,300K}/\sqrt{RRR}$

- At some point, δ<< λ ,the number of electrons available to contribute to surface current decreases, the skin depth model is not accurate anymore,and the surface resistance is not decreasing at the expected rate with T

Anomalous skin effect

The anomalous skin effect theory predicts the following surface resistance (based on an interpolation formula for the so-called diffusion model [6, 8]):

$$R_s = R_\infty \left(1 + 1.157\alpha^{-0.276}\right), \quad \text{for } \alpha \geq 3, \tag{3}$$

where the dimensionless parameter α is given by

$$\alpha = \frac{3}{2}\left(\frac{\lambda}{\delta}\right)^2 = \frac{3}{4}\omega\mu_0(\rho\lambda)^2\rho^{-3} \tag{4}$$

and R_∞ is a quantity independent of temperature and impurity, having a $\omega^{2/3}$ dependence on frequency:

$$R_\infty = \left(\frac{\sqrt{3}}{16\pi}\rho\lambda(\omega\mu_0)^2\right)^{\frac{1}{3}}. \tag{5}$$

The product $\rho\lambda$ is a characteristic of the metal and for copper one has

$$\rho\lambda = 6.6 \times 10^{-16}\ \Omega\ \mathrm{m}^2,$$

which gives

$$R_\infty = 1.123 \times 10^{-3}\ \Omega \times \left(\frac{\omega}{2\pi\ \mathrm{GHz}}\right)^{\frac{2}{3}}.$$

Table 2: Skin depth δ and dimensionless parameter α for copper, assuming $\rho = 1.7 \times 10^{-8}$ Ωm at room temperature and $\rho = 2.8 \times 10^{-10}$ Ωm at $T = 4°$ K (RRR = 61).

Frequency	Room Temperature		Liquid Helium Temperature	
$\omega/2\pi$ [GHz]	δ [μm]	α	δ [μm]	α
0.96	2.1	5.0×10^{-4}	0.27	110
1.87	1.5	9.8×10^{-4}	0.19	220
7	0.8	3.7×10^{-3}	0.10	820

$$R_S = R_\infty(1 + 1.157\alpha^{-0.276})$$

$$\alpha = \frac{3}{2}\left(\frac{\lambda}{\delta}\right)^2 = \frac{3}{4}\omega\mu_0(\rho\lambda)^2\rho^{-3}$$

$$R_\infty = \left(\frac{\sqrt{3}}{16\pi}\rho\lambda(\omega\mu_0)^2\right)^{1/3}$$

Frequency	1 GHz	1.5 GHz
Surface resistance (mΩ) 300K	8.4	10.3
Surface resistance (mΩ) 4K –RRR=60	1.1	1.3
Surface resistance (mΩ) 4K-RRR=60 Anomalous skin	1.5	1.9

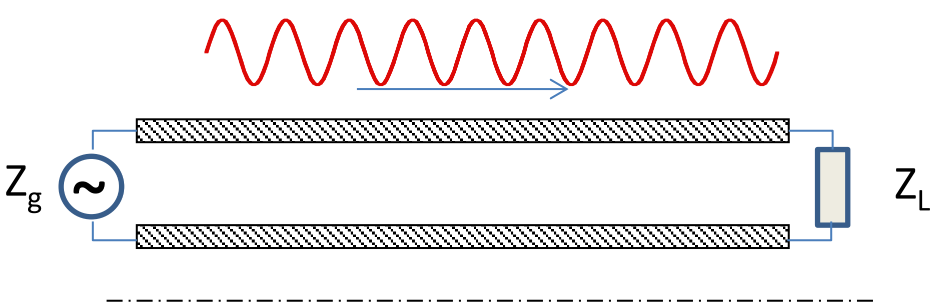
Example for the copper

From W. Chou CERN LHC project note 2

RF Matching

- RF power generation is expensive
- RF matching → minimization of reflected power in the circuit
- The transmission line and RF source are supposed to be matched here
- Simplest circuit generator+ line+ matched load

Forward travelling wave only



Rf power is absorbed in the load, nothing is reflected

$Z_g = Z_{line} = Z_L$, $\rho = 0$

Forward and backwards wave in transmission line

- Forward voltage V_+
- Backwards voltage V_-
- Forward current = V_+/Z_0
- Backwards current = V_-/Z_0
- At any given point on the line

$$V = (V_+ + V_-)$$

$$I = I_+ - I_- = (V_+ - V_-) / Z_0$$

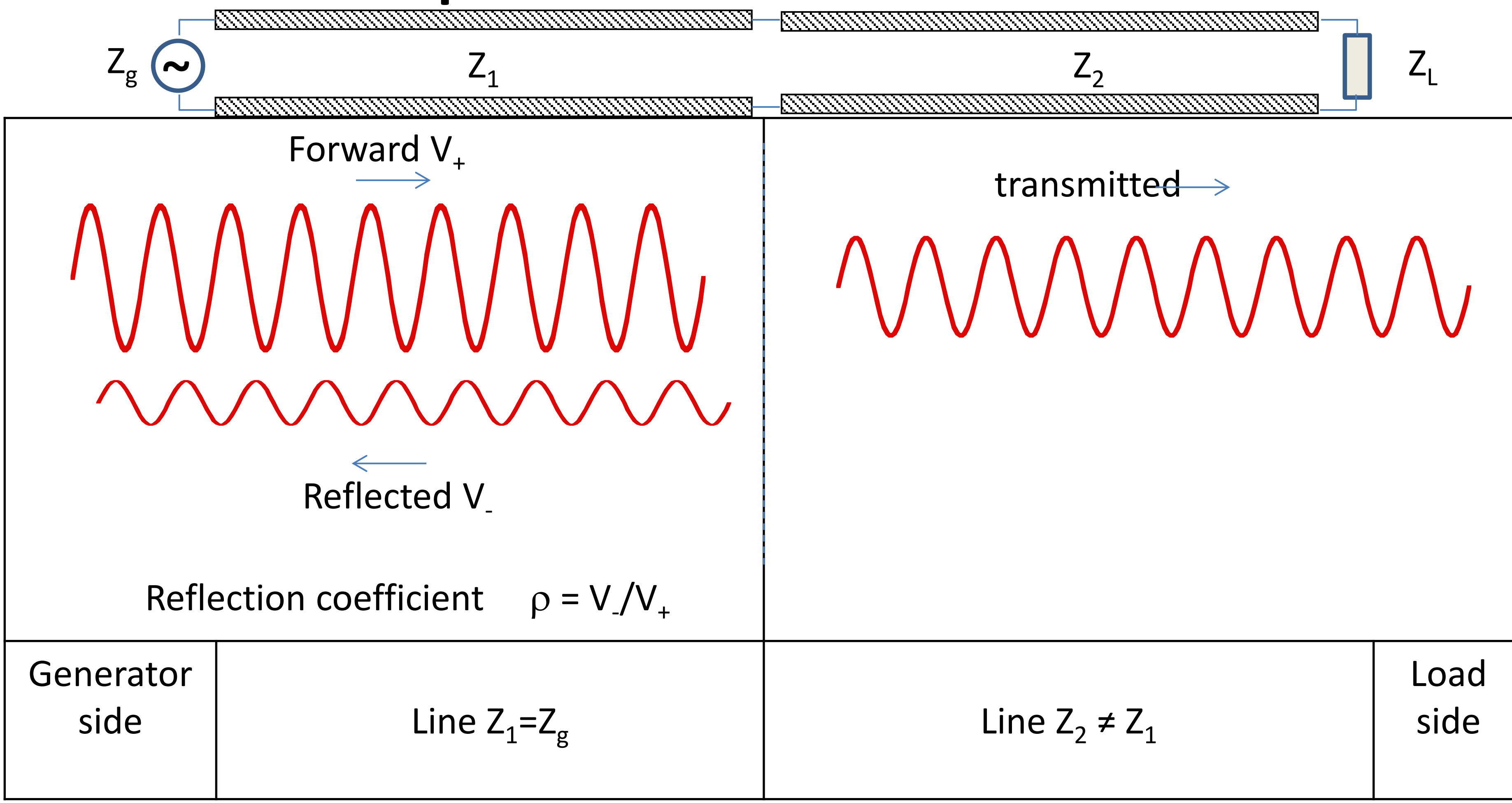
- Ohm's law at a given position of impedance Z is then

$$V = Z\,I \quad \rightarrow \quad (V_+ + V_-) = \frac{Z}{Z_0}(V_+ - V_-)$$

Then $$V_- / V_+ = \frac{(Z - Z_0)}{(Z + Z_0)}$$

Changing the impedance implies a backwards wave

Impedance mismatch

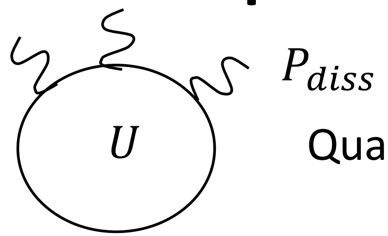


Voltage Standing Wave Ratio $= \text{VSWR} = \dfrac{V_+ + V_-}{V_+ - V_-} = \dfrac{1 + \rho}{1 - \rho}$

Reflection coefficient $\rho = V_-/V_+ = \dfrac{Z_2 - Z_1}{Z_2 + Z_1}$

Coupling to a cavity

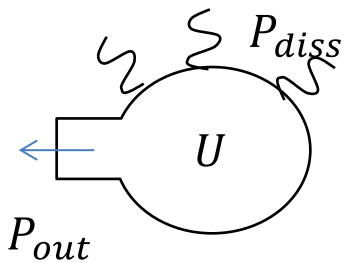
Cavity without port



Quality factor $$Q_0 = \frac{\omega U}{P_{diss}}$$

U : stored energy

Port added, energy flows



Quality factor $$Q_L = \frac{1}{\frac{1}{Q_0} + \frac{1}{Q_{ext}}}$$ $$Q_{ext} = \frac{\omega U}{P_{out}}$$

Coupling coefficient $\beta = \frac{P_{out}}{P_{diss}}$ $$Q_L = \frac{Q_0}{1+\beta}$$

when $\beta = 1$, critical coupling. As much energy is dissipated in the walls than flowing out through the port

$\beta < 1$, cavity is undercoupled

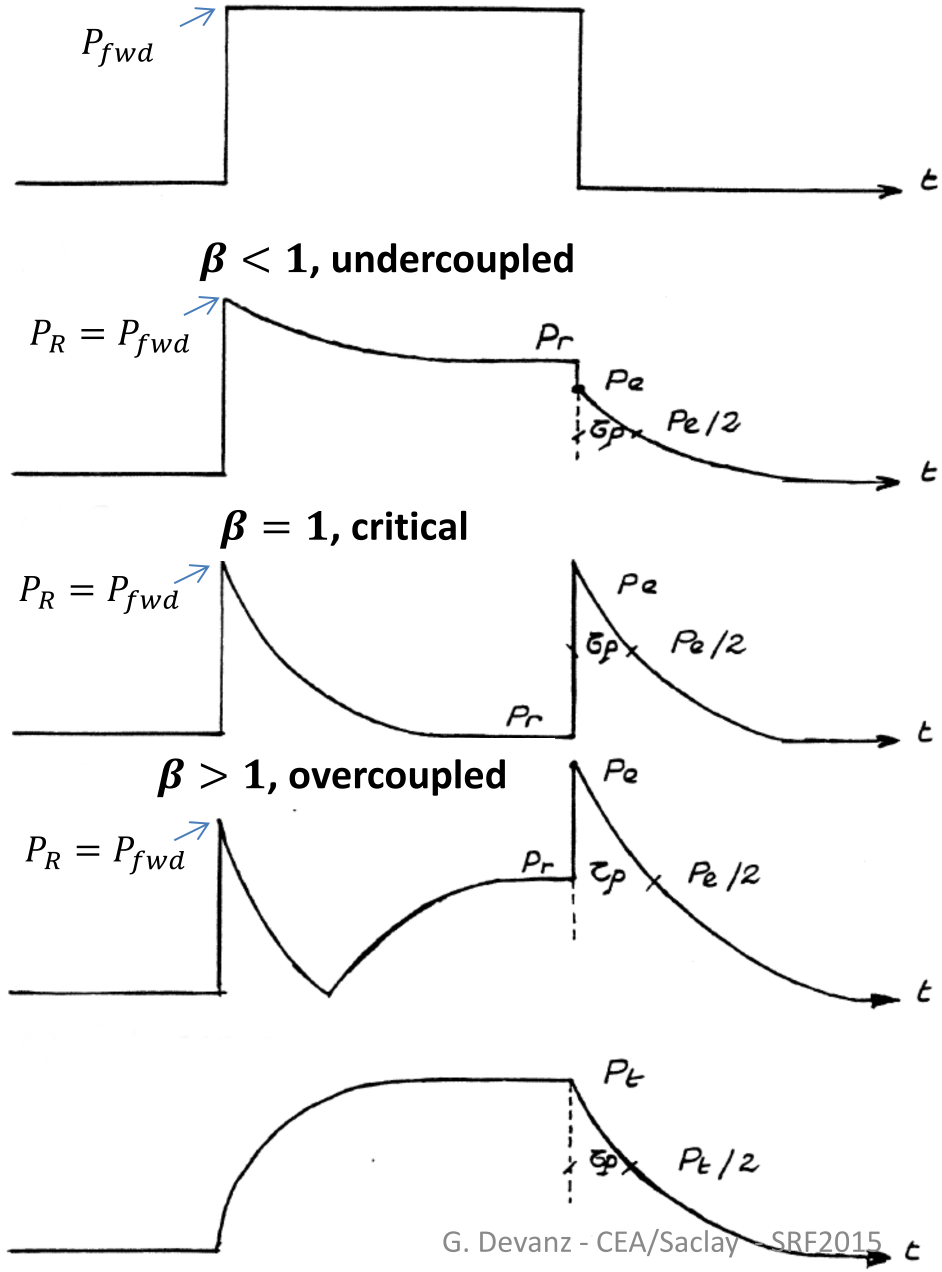
$\beta > 1$, cavity is overcoupled

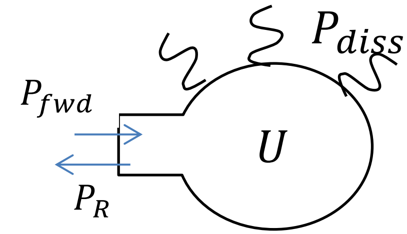
Response of a cavity to an RF pulse

Forward power
P_{fwd}

Reflected power
P_R

Power on a field probe





- The initially empty cavity starts by reflecting all forward power
- At the end of the pulse, it discharges through the port
- The decay time is related to the loaded Q :

$$\tau_P = ln2\,\frac{Q_L}{\omega}$$

With a beam

Now, If we want to keep the cavity voltage constant while a beam passes through the cavity:

- The beam acceleration takes energy from the cavity
- We need to replace this missing energy to keep the balance, at the proper rate

→ lets consider for a while the beam as a RF loss and give it a equivalent $Q_{beam} = \frac{\omega U}{P_{beam}}$

Consider a SRF cavity with :

- $\omega = 10^9 rad/s$
- $E_{acc} = 10\ MV/m$
- $L_{acc} = 1\ m$
- $r/_Q = 1000\ \Omega$ (linac def.)
- $Q_0 = 10^9$

It stores $U = 100\ J$ and the wall losses amounts to $P_{diss} = 100$ W

To accelerate a beam with $I_{beam} = 1\ mA$ with a phase angle $\varphi = 60°\ \rightarrow\ P_{beam} = 5\ kW$

In this case, $P_{beam} \gg P_{diss}$ and $Q_{beam} = 2\ 10^7$

The energy in the cavity is decaying in relation to the quality factor of the cavity with beam $Q' = \frac{1}{1/_{Q_0} + 1/_{Q_{beam}}} \approx Q_{beam}$, since $Q_{beam} \ll Q_0$

Intuitively, if the cavity is equipped with a port with $Q_{ext} = Q_{beam}$ we should be able to inject the energy at the same rate as it would otherwise decrease and keep the voltage constant

When a FPC is required on a SRF cavity, the FPC port has always $\beta \gg 1$, and $Q_L = Q_{ext}$

Optimal coupling

The Q_{beam} can be expressed in terms of cavity and beam parameters

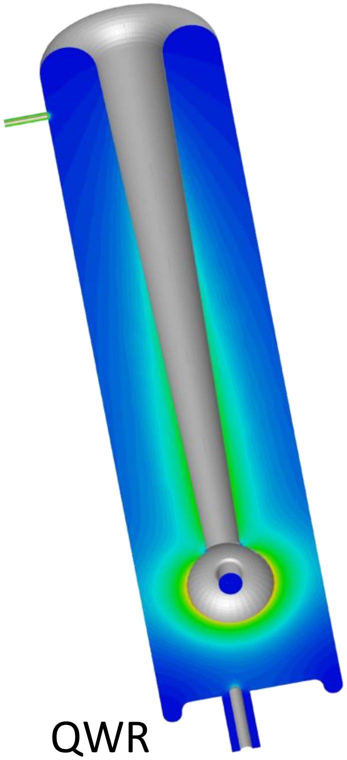
$$Q_{beam} = \frac{\omega U}{P_{beam}} = \frac{V^2{}_{acc}}{{}^r/_Q V_{acc} I_b cos\varphi} = \frac{E_{acc}L_{acc}}{{}^r/_Q I_b cos\varphi} \text{ (linac def.)}$$

So $$Q_{ext,opt} = \frac{E_{acc}L_{acc}}{{}^r/_Q \, I_b cos\varphi} \quad \text{(linac def.)}$$

The equivalent circuit representing the generator, coupler and beam can be analysed to get details on the cavity voltage, and the generator power:

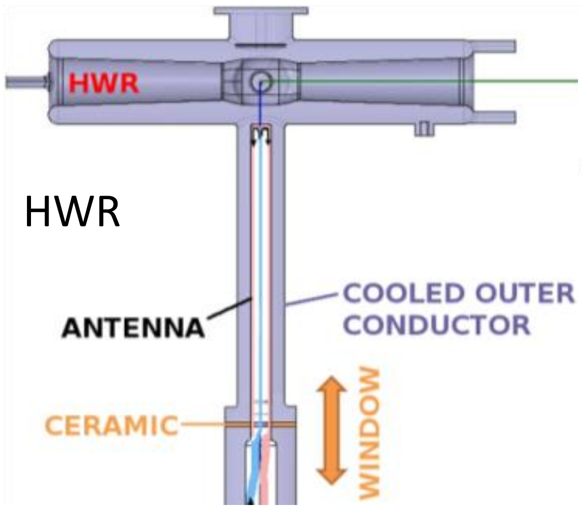
$$P_g = \frac{V^2{}_{acc}}{4\ {}^r/_Q\, Q_L}\left(1 + \frac{{}^r/_Q\, Q_L I_b cos\varphi}{V_{acc}}\right)$$

Coupler port location



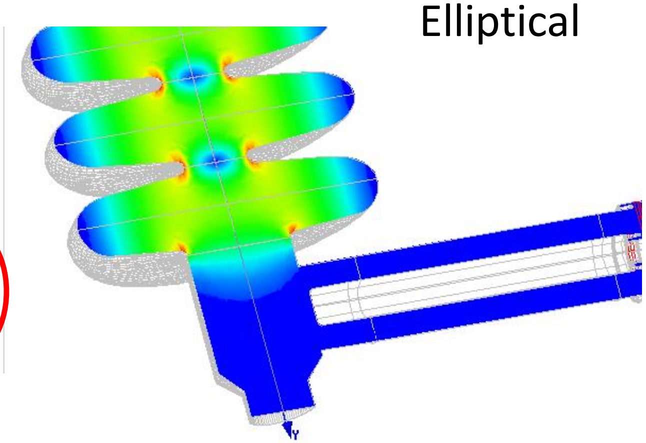
QWR

HWR



Spoke

Elliptical



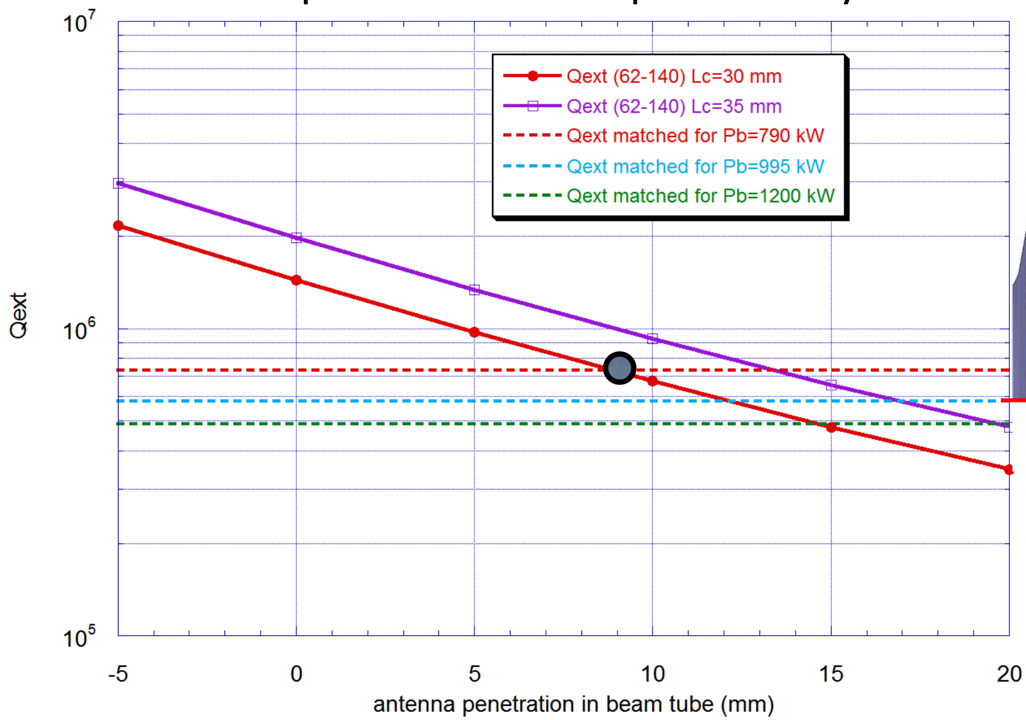
Achieve the correct Q_{ext} for beam matching

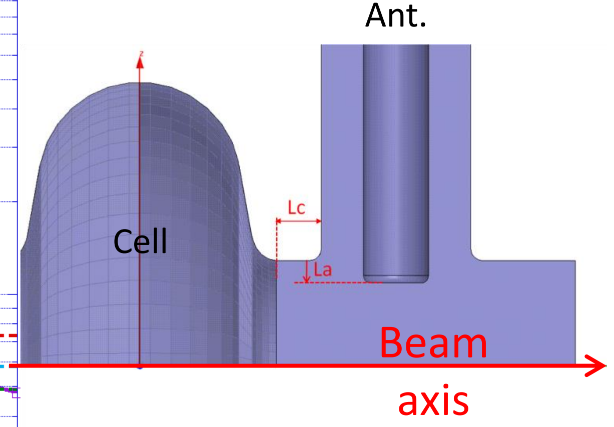
Accelerating structures	Coupling port location	Coupler type	Coupling type
Elliptical SC cavity	Beam pipe	Coaxial or waveguide	electric
Spoke SC cavity	Outer cylinder	Coaxial	electric
DTL	Outer cylinder	waveguide	magnetic
RFQ	Outer cylinder	Waveguide or loop	magnetic
Half wave	Half plane or top	Coaxial or loop	Electric of magnetic
Quarter wave	Bottom plate	Coaxial	electric

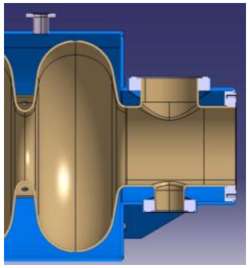
Achieving Qext

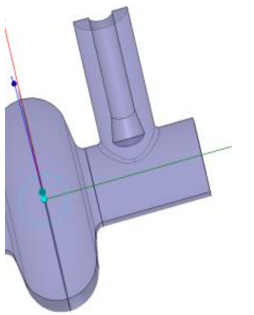
In the case of high beam power, it can become difficult to achieve a low enough Qext

Example of a 5-cell elliptical cavity









Antenna protuding can:

- Induce a kick on the beam
- Intercept stray particles

Other options exist in order to lower Qext :

- Using a conical tip
- Using an offset tip
- Using a different impedance for the coupler
- Increase the number of power couplers

The coupling increase (Qext decreases) if:

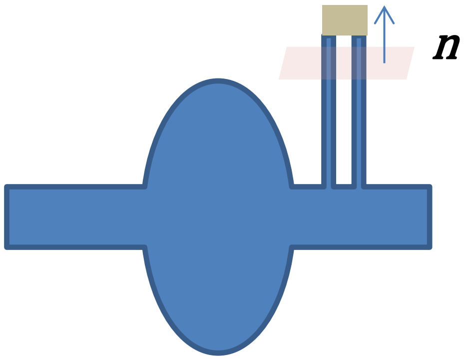
- The coupler get closer to the cells
- The antenna is lengthened

Q_{ext} calculation

Using a 3D Electromagnetic simulation software

- Complex eigenmode solver (solves for the complex field ,deals with absorbing materials and boundary conditions):
  - model the cavity , the coupler port and coupler base, terminated by a matched load
  - Solve for the fundamental mode.
  - Compute the stored energy U by integrating the fields in the volume of the cavity
  - Compute P_{out} : power transmitted to the load by integrating the Poynting vector on a plane intersecting the coupler waveguide at right angle
  - Simply get Q_{ext} using :

$$Q_{ext} = \frac{2\pi f_0 U}{P_{out}}$$



$$U = \int_{cavity} \left\{ \frac{1}{4} \varepsilon_0 \boldsymbol{E}.\boldsymbol{E}^* + \frac{1}{4} \mu_0 \boldsymbol{H}.\boldsymbol{H}^* \right\} dV$$

$$P_{out} = \int_S \frac{1}{2} Re(\boldsymbol{E} \times \boldsymbol{H}^*).\boldsymbol{n}\, dS$$

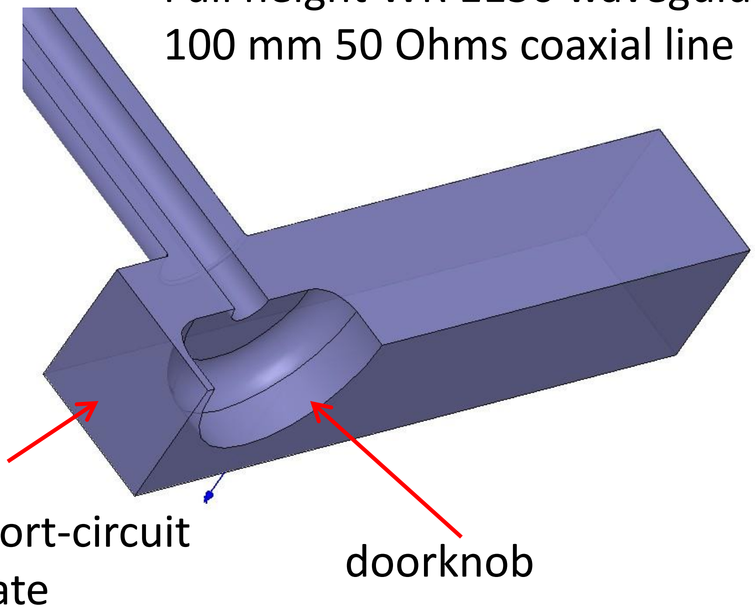
Other methods exist (S-parameters, bandwidth evaluation,superposition of real solutions,…)

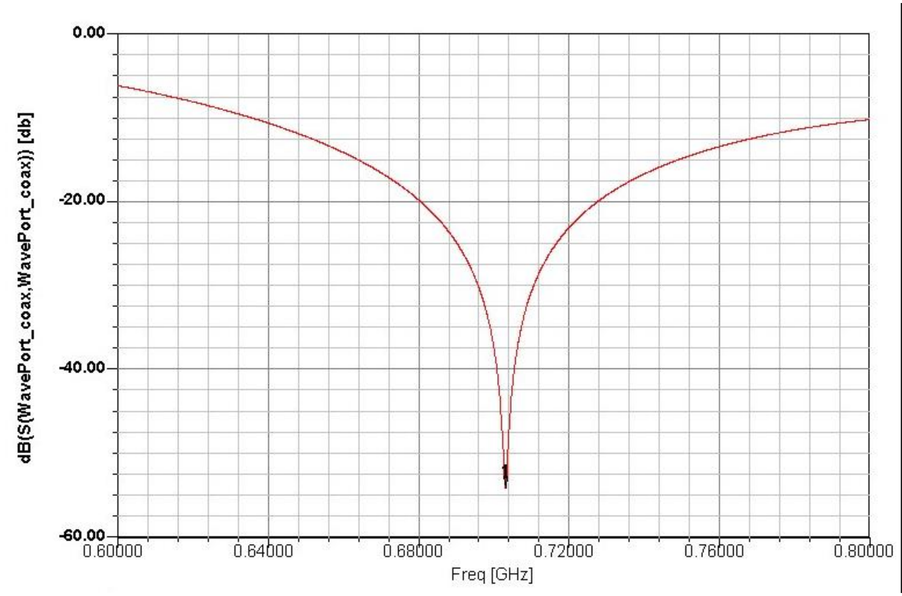
Mode converters

- In many cases, need to carry high power efficiently with retangular WGs, but use a coaxial coupler
- The mode converter couples the TE mode of the rectangular WG to the TEM mode of the coaxial part.
- Several solutions exist
  - Antenna transitions
  - Doorknob transition
  - T-bar
  - Stepped transformer
  - …

Doorknob

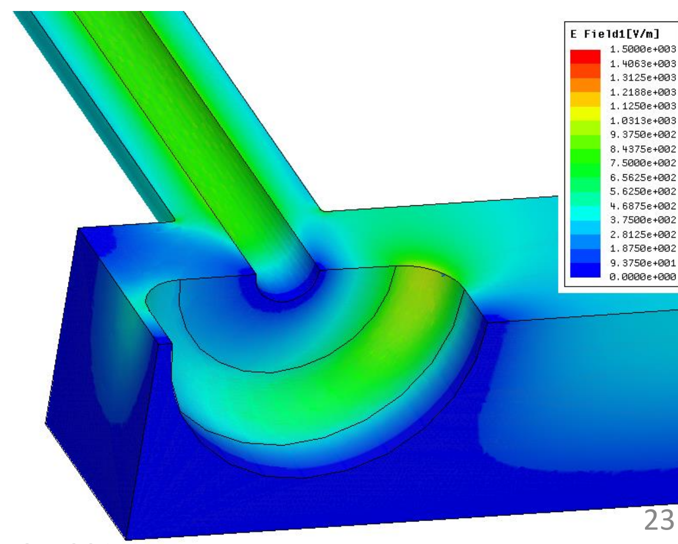
Full height WR 1150 waveguide to 100 mm 50 Ohms coaxial line



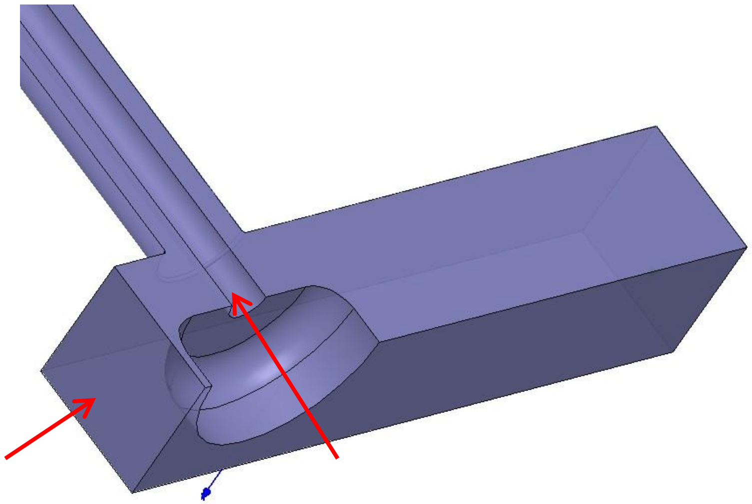


Design issues

- Mechanical tolerances and bandwidth
- If the doorkonb operates at atmospheric pressure the reduction of peak electric field is even more important in order to prevent arcs (E < 30 kV/cm)



Air doorknob



Short-circuit plate

Cooling access

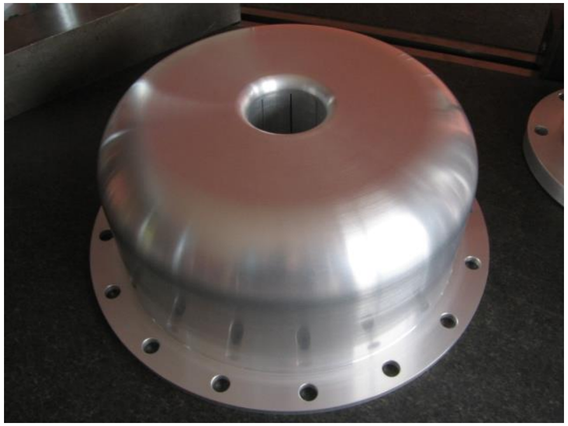
Can be built in several parts assembled using flanges and RF gaskets. This allows some geometrical tolerances to be met more easily:

- less welds and deformations
- re-machining (or shimming) at some flange for final adjustment combined with RF measurement of the device (e.g. short-circuit plate)

Provides easy acces for cooling the inner conductor of the coaxial part of the window

Can be built completely built out of Aluminum except the antenna (same as standard WGs), unless high average power requires a reduction of losses and the use of copper parts (e.g. knob)

Air Doorknob



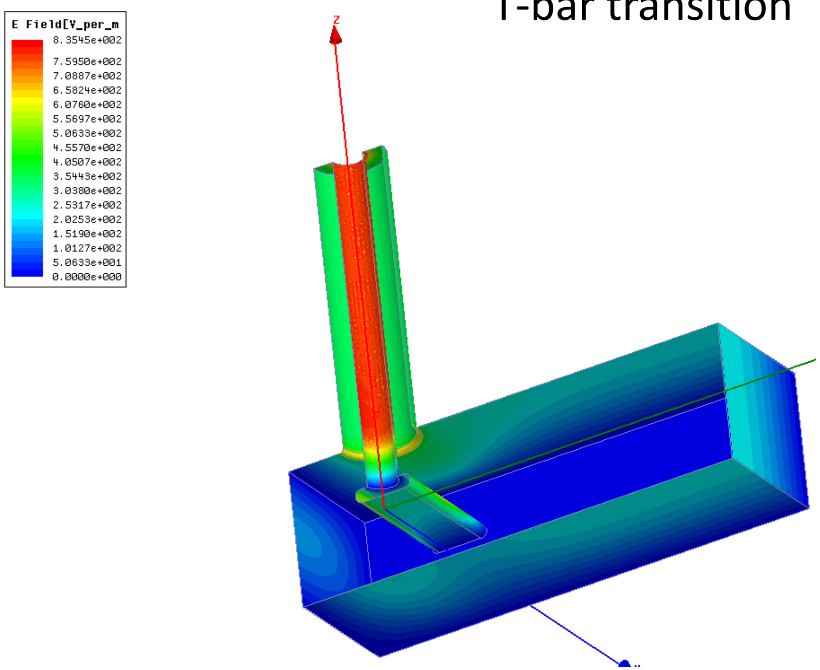
4 parts :
machined Al knob
Welded Al Waveguide (1150)+short plate
Cu antenna
Al coaxial outer conductor

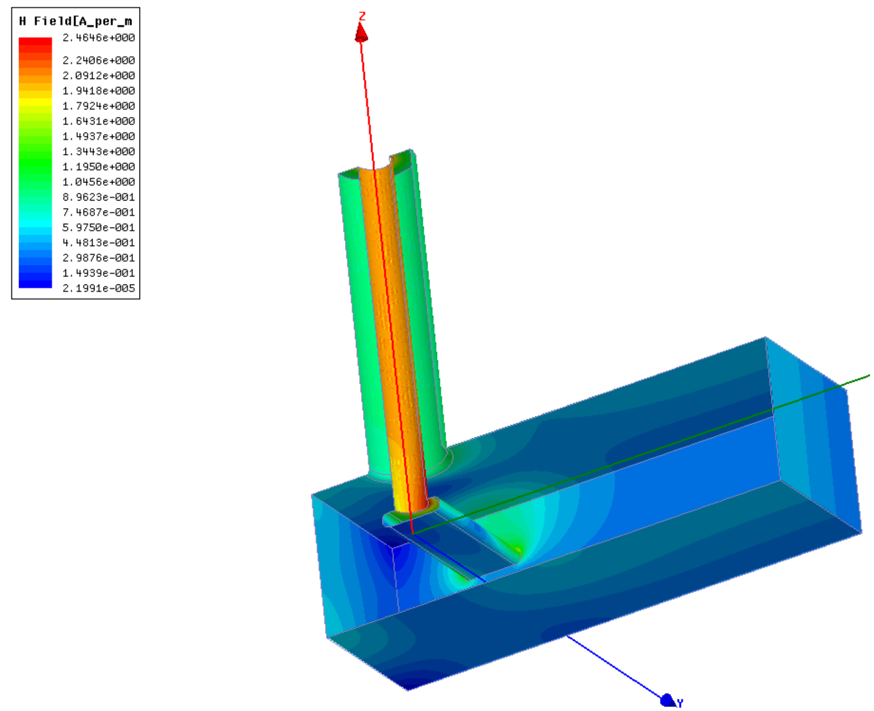
T-bar transition

Also used in high power RF components

Cooling channels for the coaxial part ca be inserted inside the bar

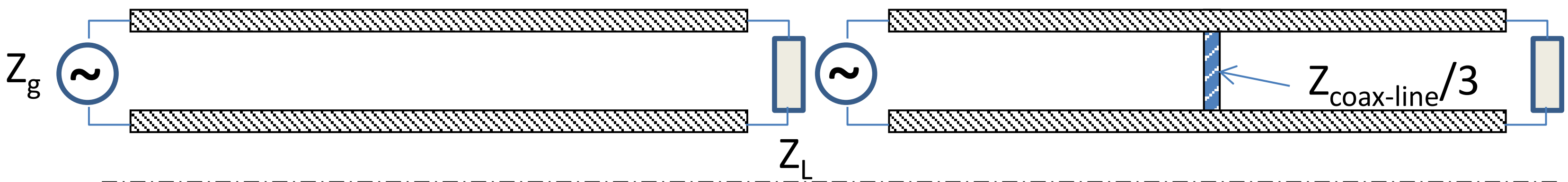
T-bar transition



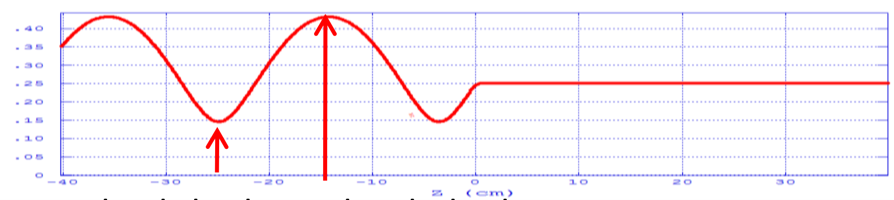


RF windows

- Creates the physical barried between air and cavity vacuum using a leak- tight dielectric material : mostly alumina (purity from 95% to 99%) but also synthetic diamond, BeO, sapphire…
- Material discontinuity in a waveguide corresponds to a change in impedance, creates a standing wave, example 10 mm thick alumina $\varepsilon_r \approx 9$ in a coaxial line, 50Ω, 150mm OD, 702 MHz

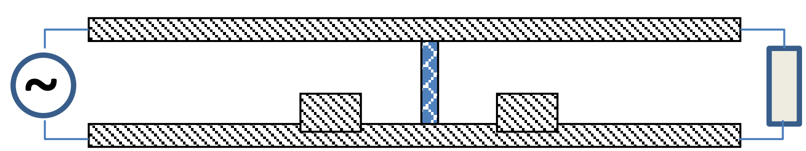


$Z_g = Z_{coax\text{-}line} = Z_L$, $\rho=0$



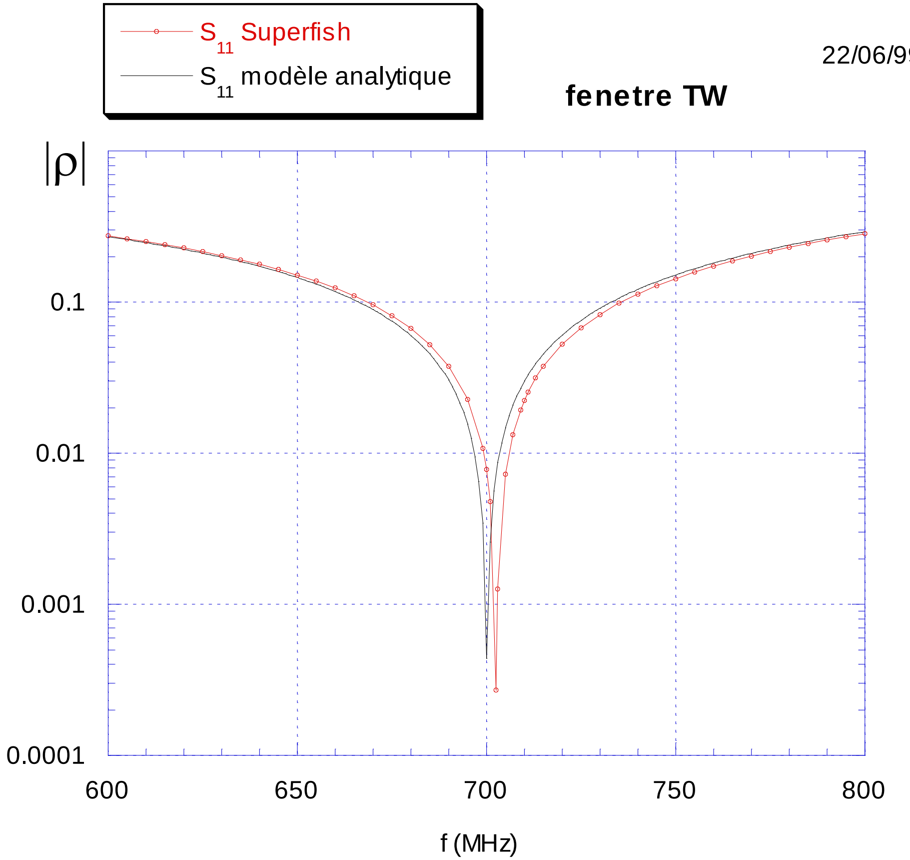
$\rho=0.5$

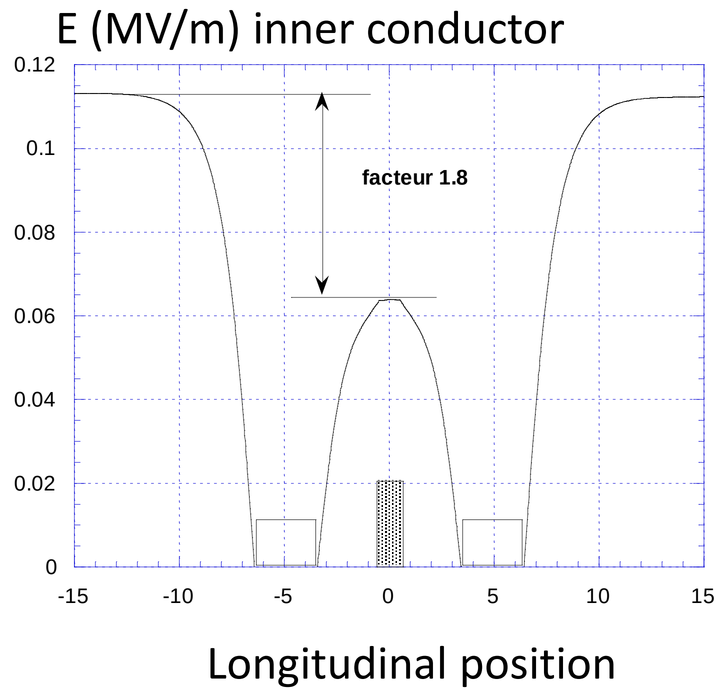
- In order to prevent this matching elements have to be inserted



Matching at the nominal frequency is not enough, the bandwith must be sufficient to accomodate fabrication tolerances, or operational frequency changes.

RF windows

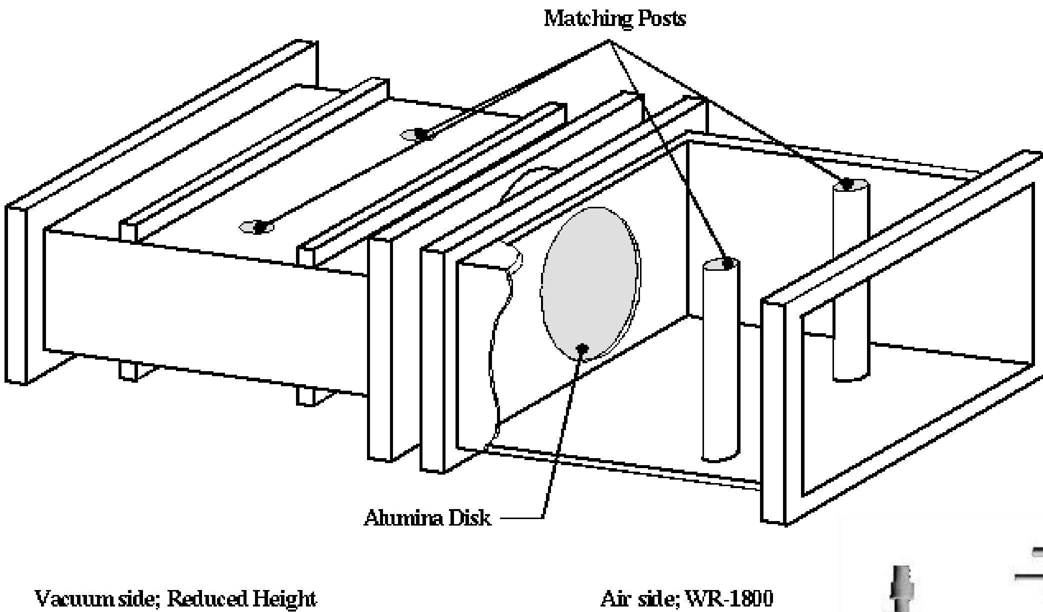




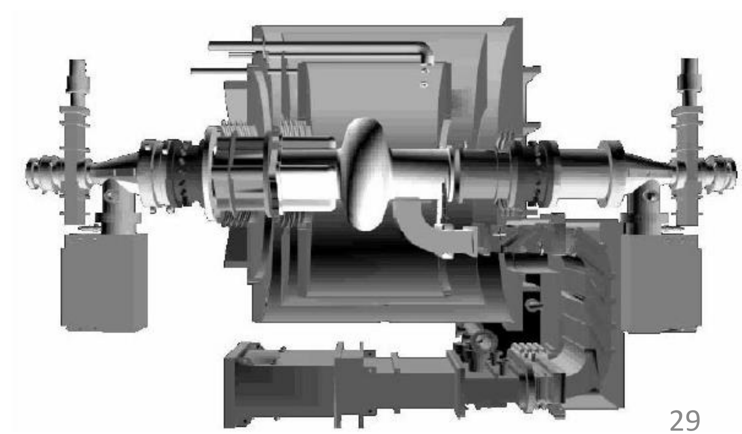
Matching options are very diverse (entire books on the subject of discontinuities in WG)
Using a semi analytical model helps finding solutions with enhanced properties like the TW window (Kazakov) with a reduction of E in the ceramic disk

Waveguide window

500 MHz window (Cornell)

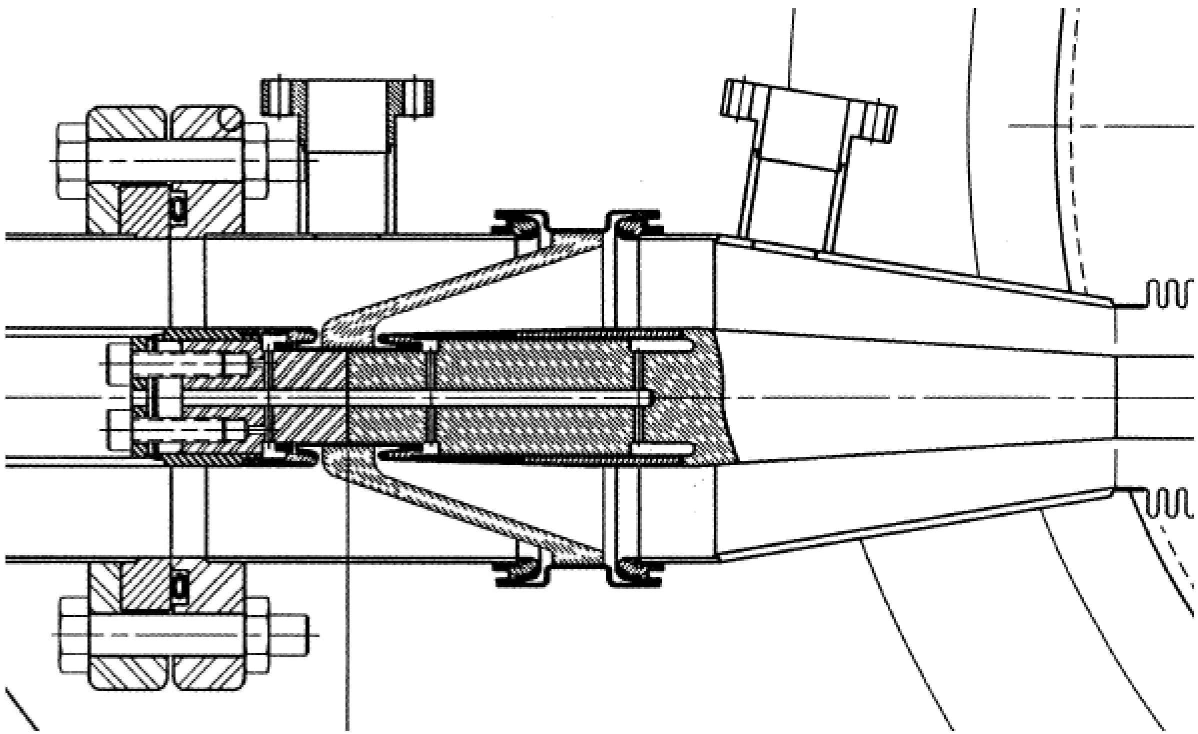


Is used as the window of a waveguide coupler



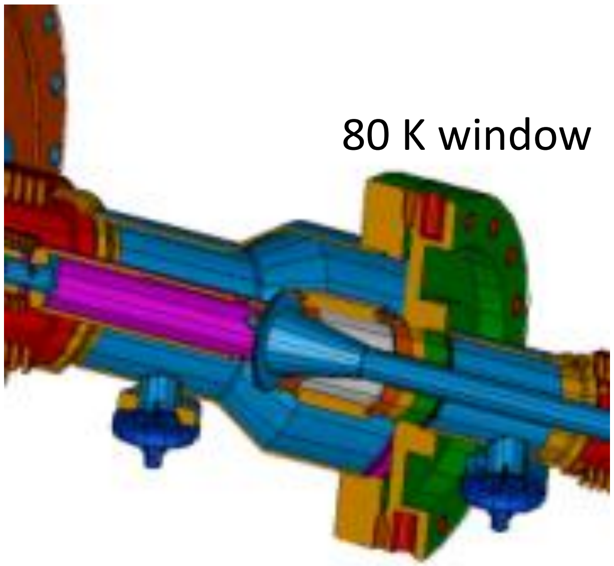
Conical window

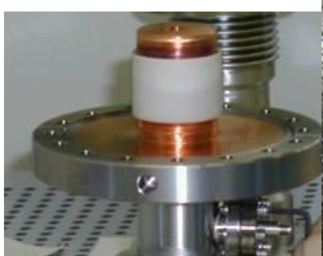
First versions of the TTF coupler (1.3 GHz) from FNAL



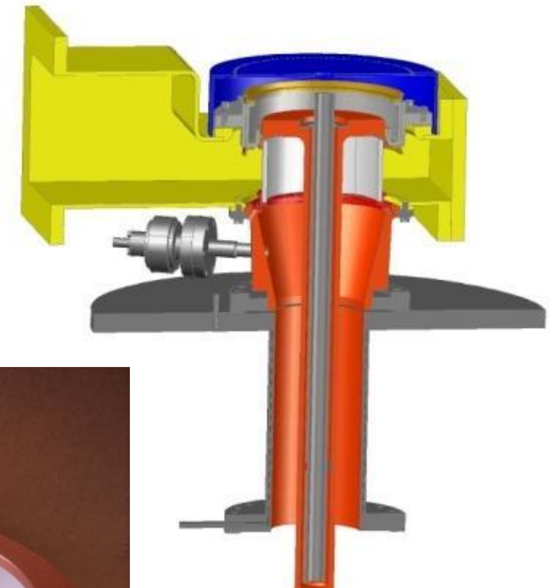
Cylindrical window

DESY TTF-3 coupler





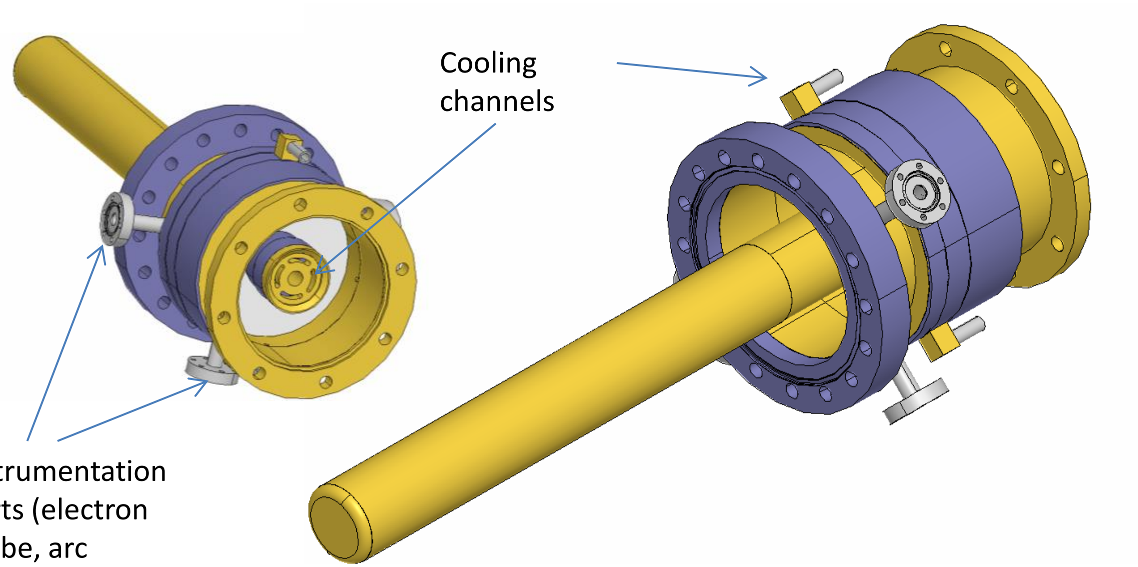
SPL-CERN 704 MHz coupler

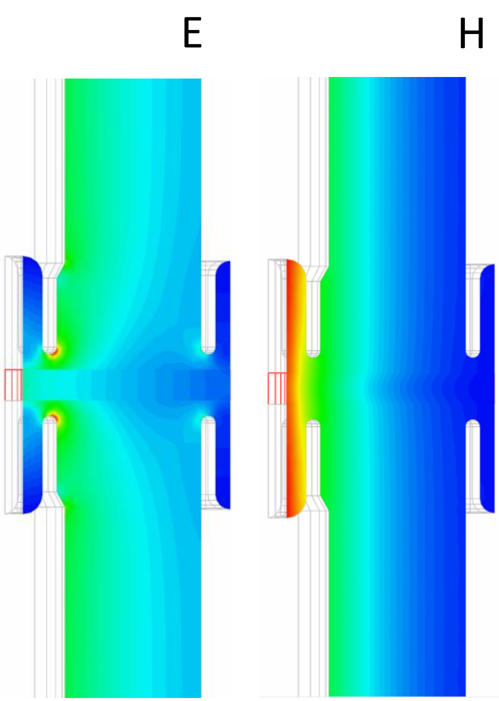


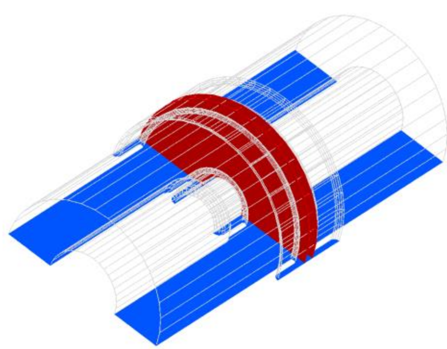
Coaxial disk windows

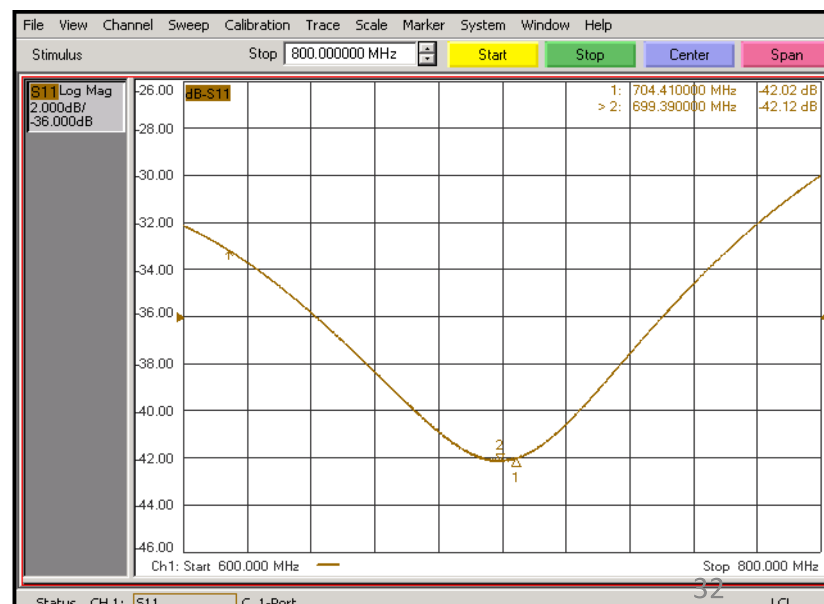
KEK design adapted to 704 MHz

- 50 Ohms
- 100 mm OD
- RF matching is done using chokes (inner and outer conductor)
- Measured bandwidth @ -30 dB : 200 MHz









Alumina windows brazing

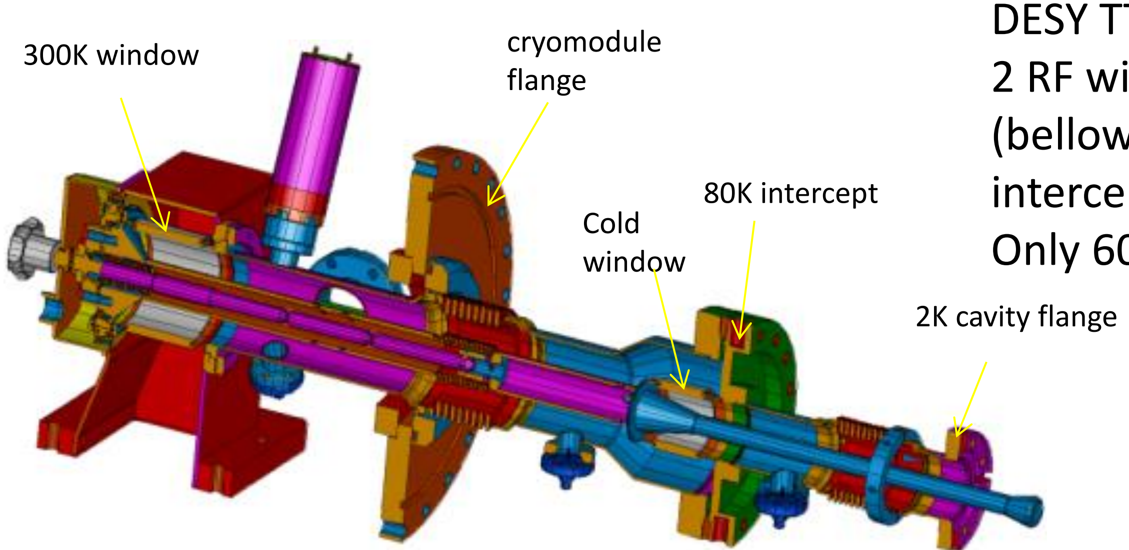
The brazing process between Alumina and copper requires:

- a brazing compound working below copper melting point (ex. gold based),
- Specific machining of the ceramic to insert the brazing compound (wire or foil)
- Proper surface preparation of ceramic interface (MoMn metalization)
- tooling to ensure the gaps between the parts are compatible with the thermal cycle in the oven, differential thermal expansion of materials, the quantity of braze material
- and copper parts with mechanical compliance : example for a disk windows : during cooldown in the brazing cycle, the copper inner conductor shrinks more than the ceramic, this time with a solidified braze joint. Alumina has a small resistance to elongation (in contrast to its high resistance to compressive stress) and fails if the copper tube is too thick

The final braze joint must be homogenous, free of solidified braze droplets or run-outs (especially on the alumina disk), and vacuum tight.

Thermal aspects of couplers

- Heat conduction to a SC cavity
  - Heat leak from 300 K to LHe temperature must be minimized.
  - For low average power : use thin stainless steel coupler walls, with thermal intercepts, bellows
  - For high average power : use active He cooling
- Heat radiation to a SC cavity
  - Coaxial coupler with single window: radiation of room temperature antenna on the cavity and the coupler outer conductor : lower the emissivity of copper surfaces (polished surface finish, electropolishing)
- The sum of above contributions are *static losses* (RF is off)

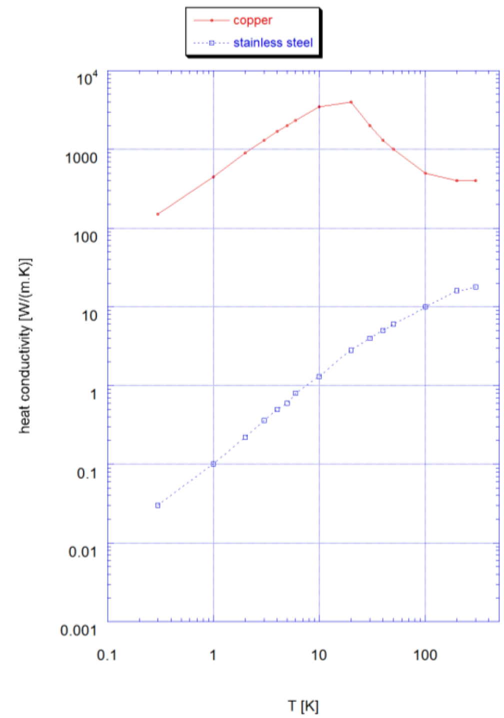


DESY TTF-3 coupler :
2 RF windows, heat leak fully minimized, (bellows, thin walls, 80K and 5K thermal intercepts…)
Only 60mW static losses at 2K

Thermal aspects of couplers

- Heating generated by RF
  - Resistive losses on RF boundaries: use copper coating on vacuum parts (thickness more that 4 times the skin depth δ)
  - Increasing copper coating thickness will increase the static heat load on the cavity. At room temperature, Cu thermal conductivity can be 20 times higher than stainless steel's : a layer of 25 μm of copper is equivalent to a stainless steel wall of 0.5 mm as far as heat conduction is concerned.

  → static and RF heat load need to be analysed carefully and optimized



  - Dielectric losses in the window material

$$P_{diel} = \frac{1}{2}\int_V \varepsilon_0 \varepsilon_r tg\delta 2\pi f E^2 dV$$ with $$tg\delta = \frac{\varepsilon''}{\varepsilon'}$$ the dielectric loss tangent, $\varepsilon = \varepsilon' - j\varepsilon''$

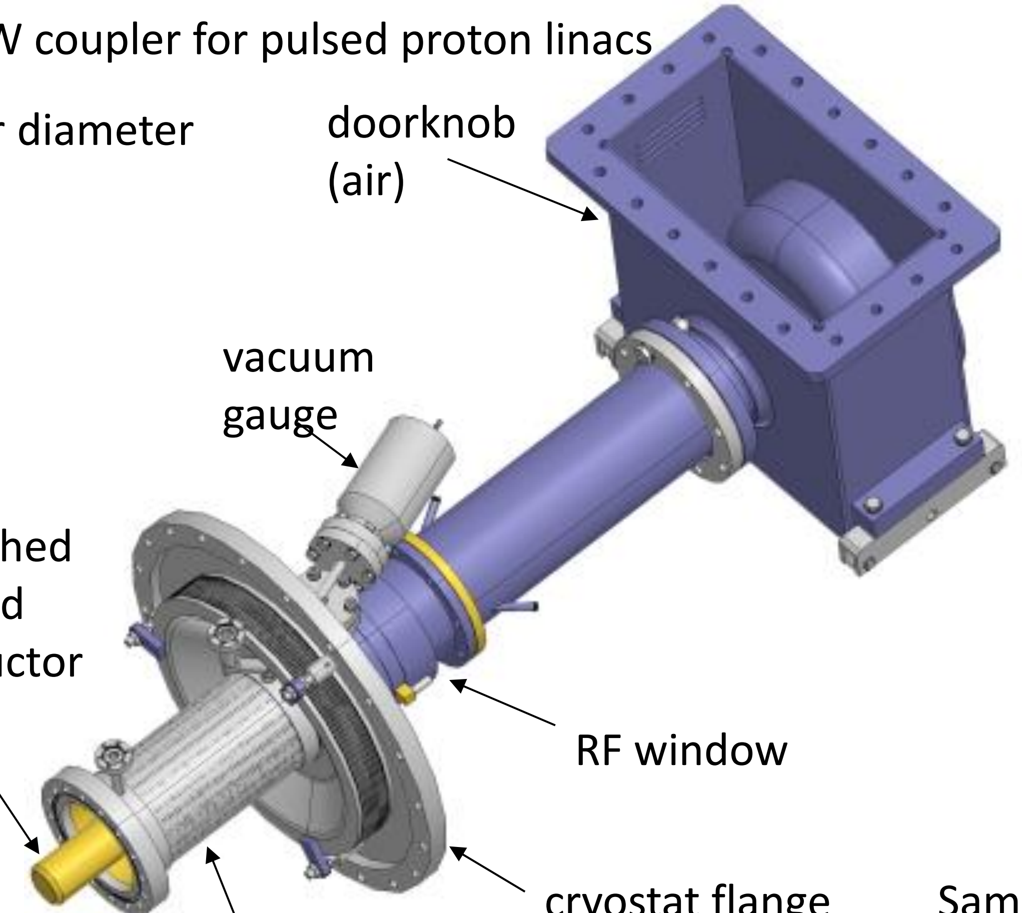
Not the same 'delta' as the skin depth !

Typical values for tg δ in alumina used for windows is 10^{-4} to 5 10^{-4}

Full power coupler

CEA-Saclay 1 MW coupler for pulsed proton linacs

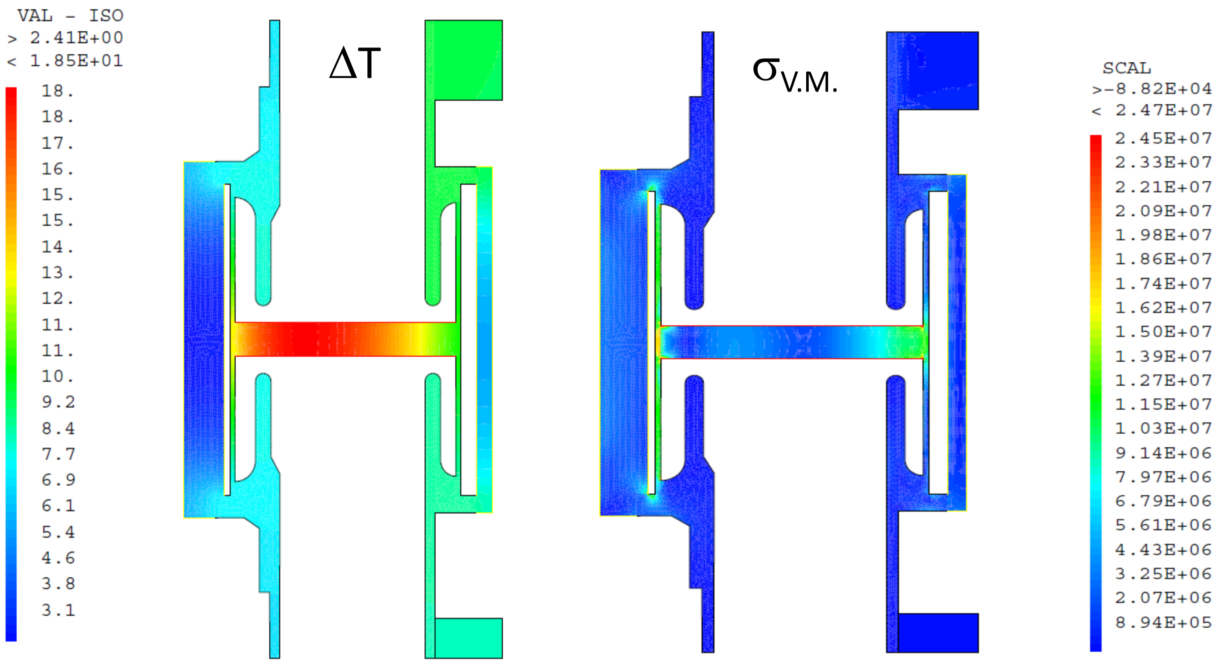
100 mm outer diameter
50 Ω



Same general layout
as SNS coupler

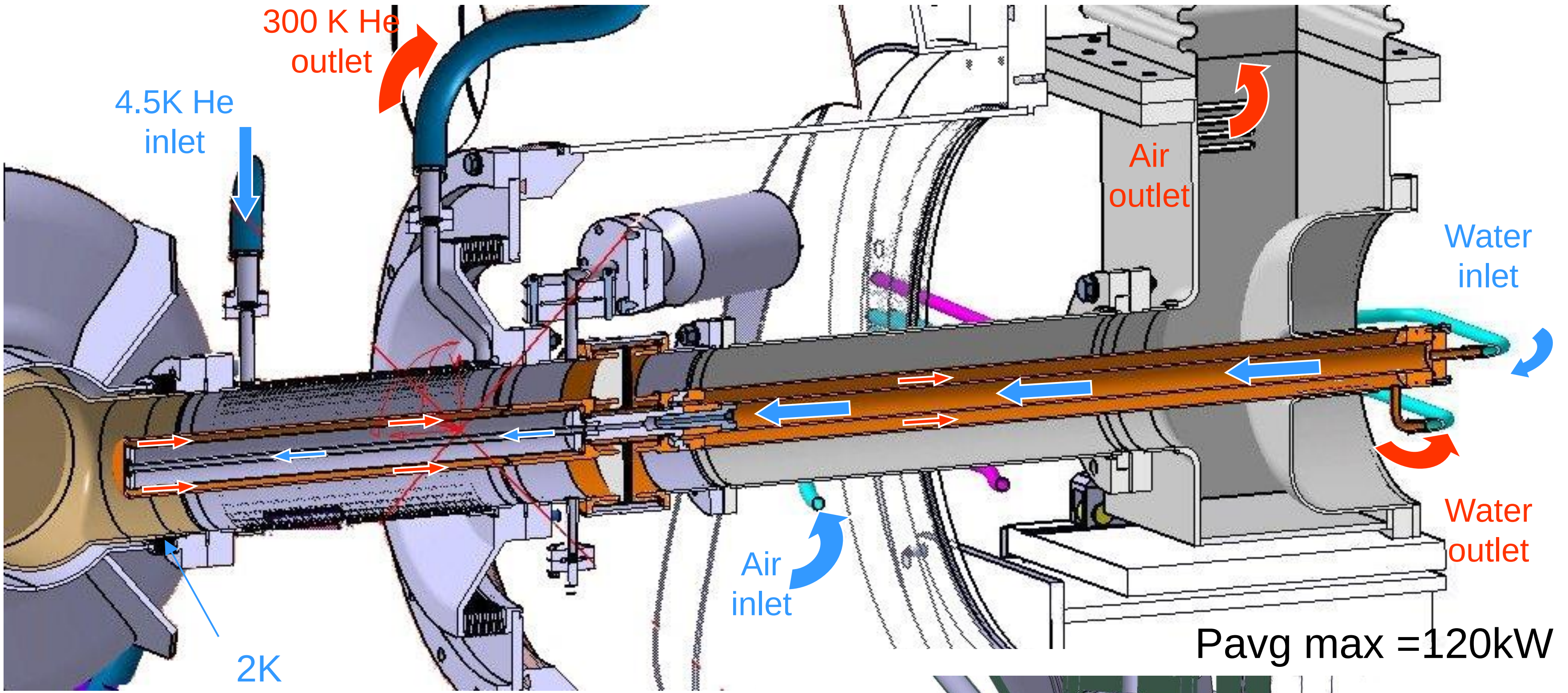
Thermo mechanical stress in windows

– Thermal expansion of metallic boudaries is non uniform (different materials, local heating, non uniform cooling)
– Dielectic losses in the coupler ceramics are never uniform, internal stress occur. FEM analysis is required to look at the complete load case (pressure+thermo-mecanical)

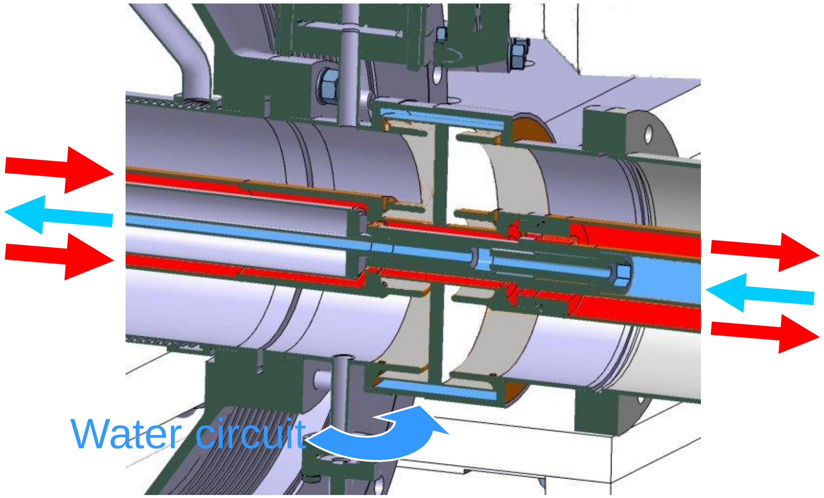


- 700 MHz window,
- 120 kW avg. RF power
- Assymetric cooling
- Thermal gradients and thermally induced stress

Multiple cooling channels for high average power



Pavg max =120kW



Vacuum side

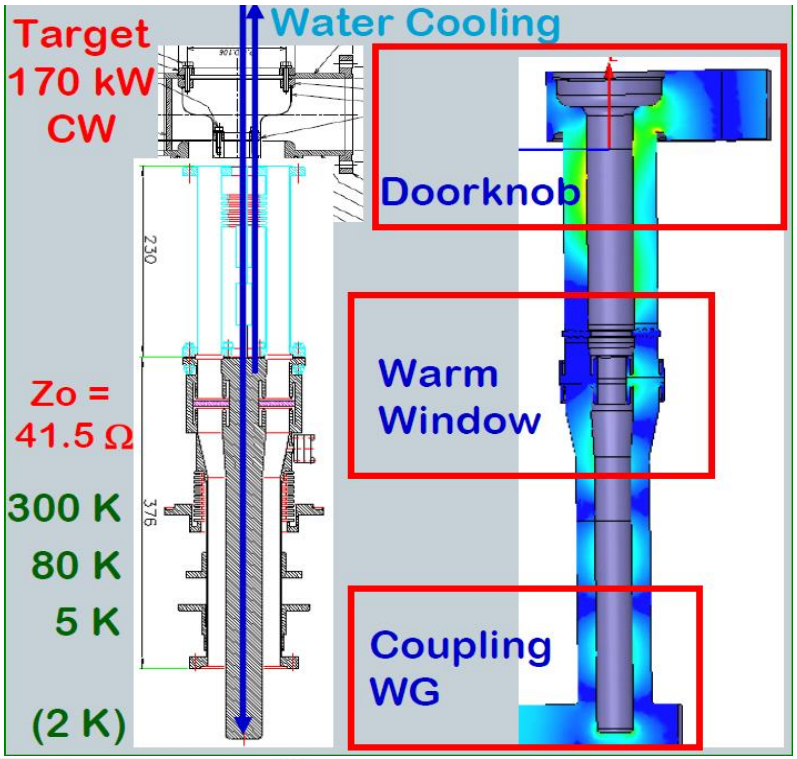
- ❖ Outer conductor (OC) He cooled
- ❖ Internal conductor (IC) water cooled
- ❖ ceramic outer water cooling channel

Air side

- ❖ blown air on the ceramic
- ❖ IC also water cooled

Multiple thermal intercepts

KEK ERL injector coupler



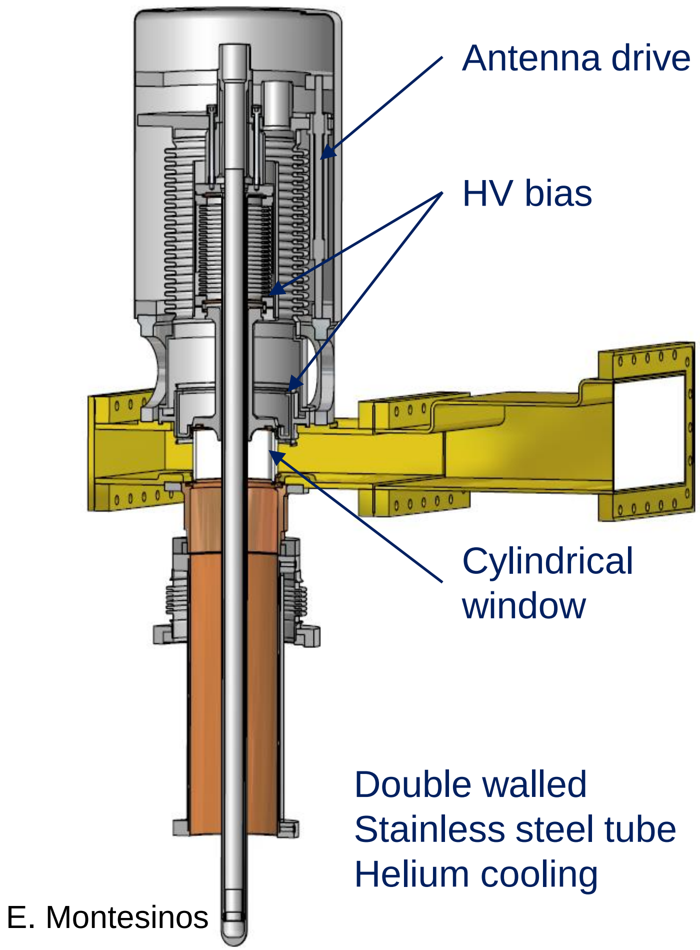
	Injector
Frequency (MHz)	1300
Beam current (mA)	50 (100)
Qext	4.5 (3.3) 10^5
Max. Power per coupler (kW)	58 (167)

2-cell ERL cavity

Courtesy E. Kako

Window in transition power coupler

LHC 400 MHz 300 kW CW coupler



Adjustable coupler (60 mm antenna stroke, factor 20 on Q_{ext}

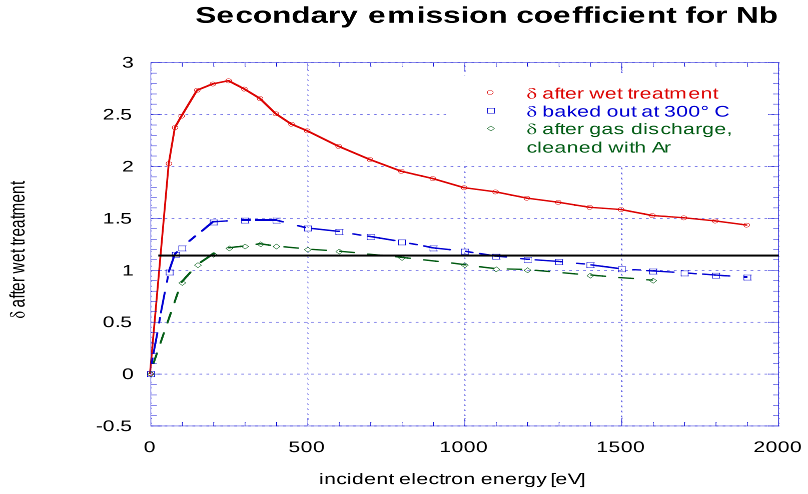
- Antenna inner conductor is a copper tube cooled by forced air
- A Reduced height waveguide provides matching to the coaxial line
- To suppress multipactor during operation two DC bias levels are applied

Multipacting (MP)

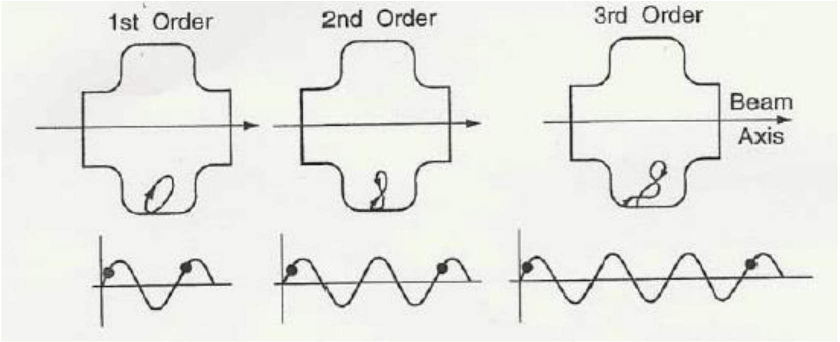
This parasitic phenomenon occurs in vacuum RF devices when :

•Electrons (initially emitted from the surface or residual gas) have resonant trajectories (at given power levels)
•Their impact energy on the surface is such that secondary emission occurs
•The material of the surface has a secondary emission yield (SEY) greater than 1

The result is an increase of the population of electron participating to the resonance, absorbing RF power, or creating a short-circuit in the device, preventing normal operation



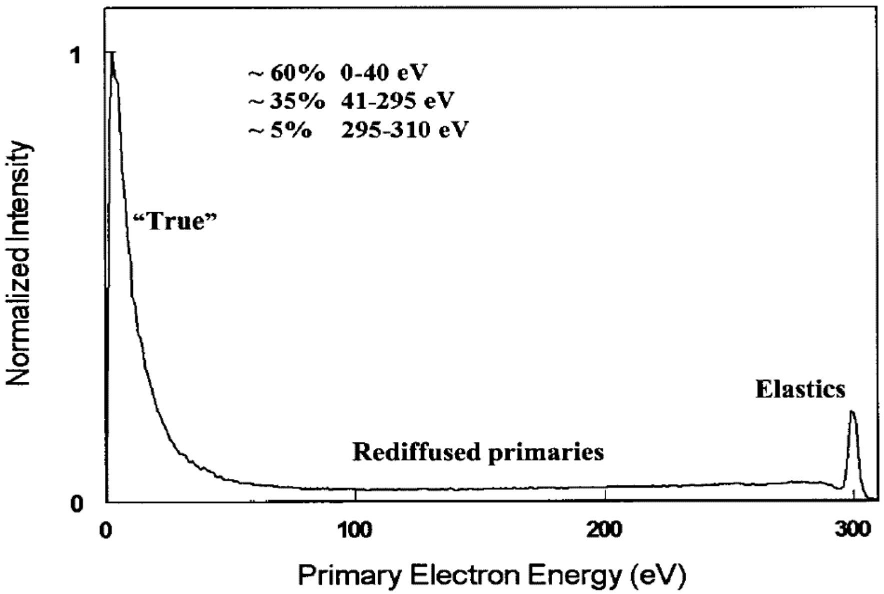
This happens in cavities and couplers



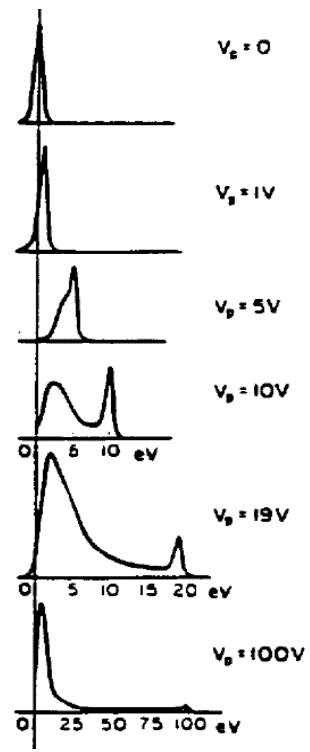
Cu and Alumina are critical materials for secondary emission
MP occuring on a ceramic can build up charges on the surface, leading to breakdown.

Secondary electrons

Example for 300 eV incident energy

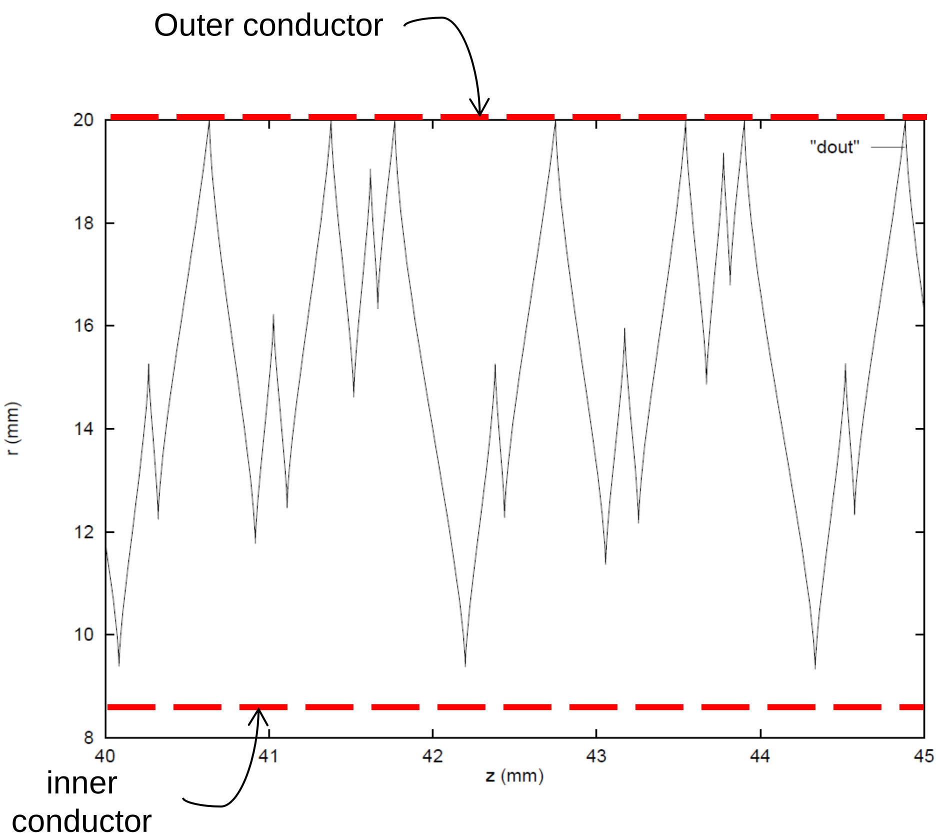


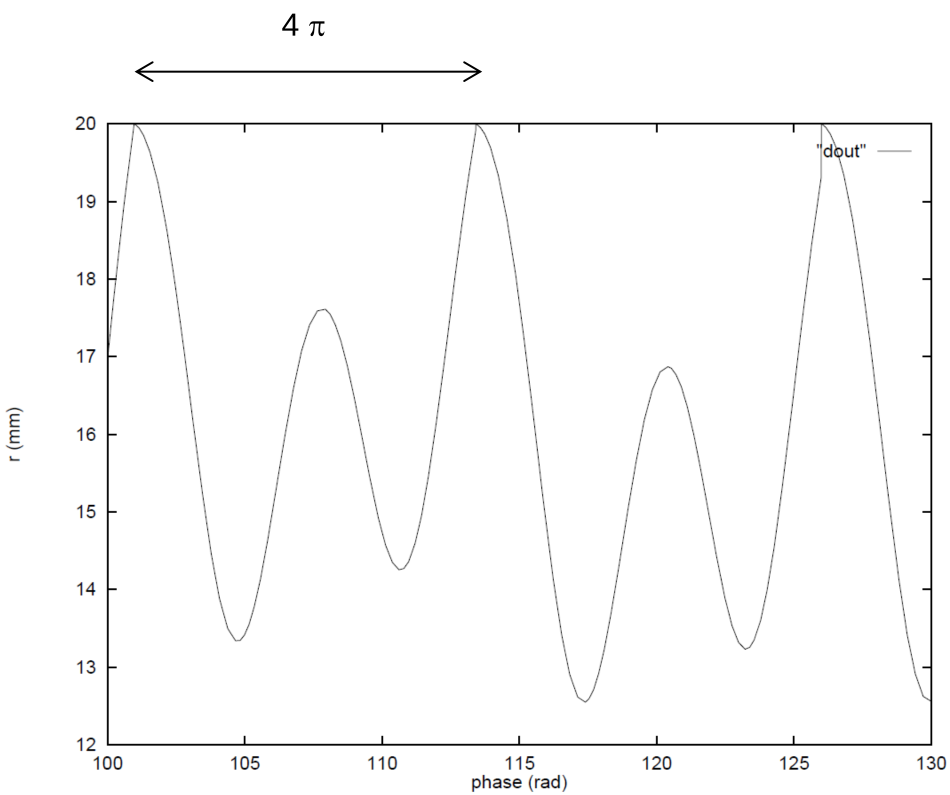
Peaked at ~ 3 eV



Distribution depends on the incident energy, especially at low values (< 30 eV)

MP Electron trajectories

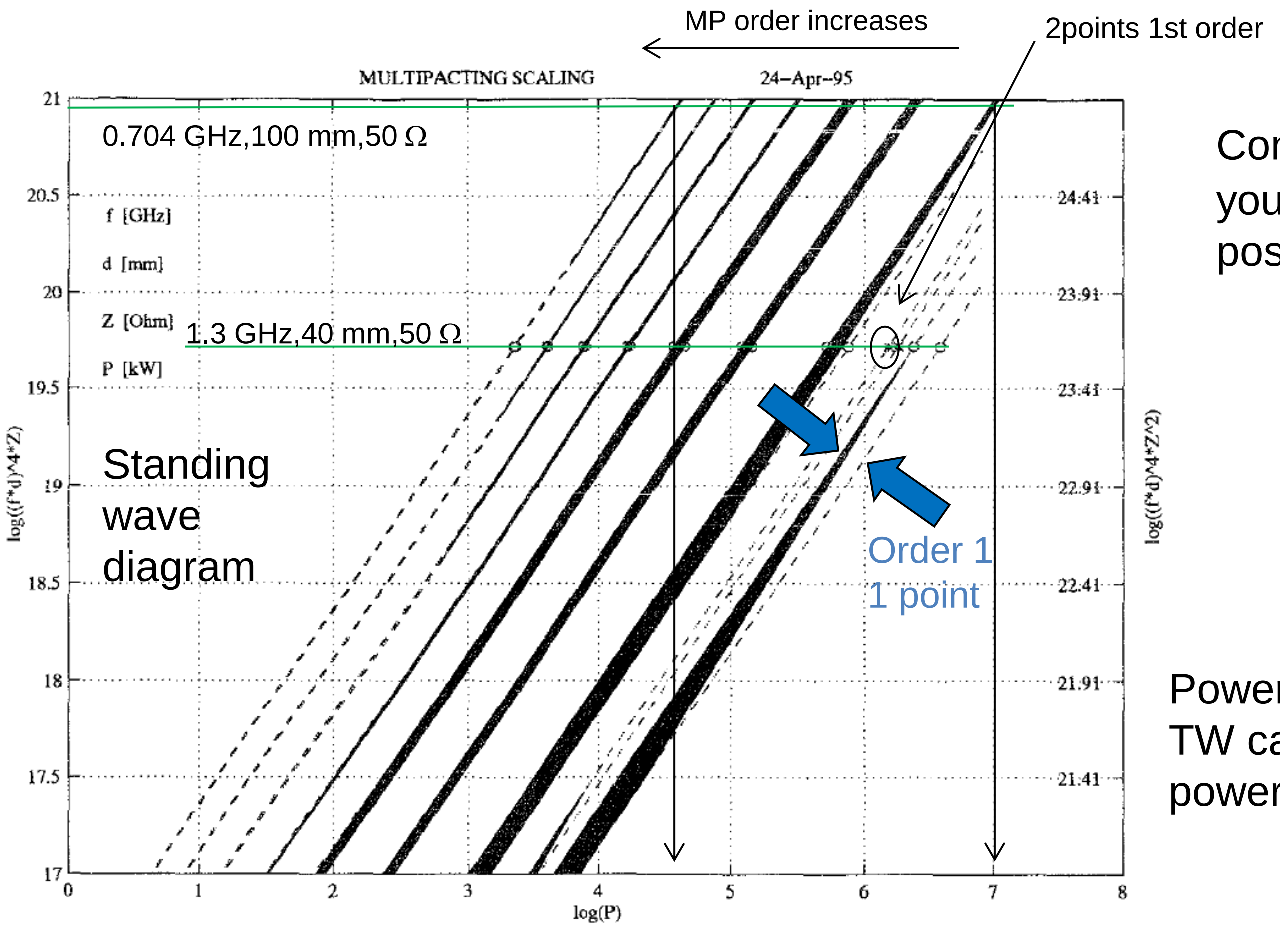




Close to resonant trajectory in a 40mm 50 Ω coaxial line, TW

- Impacts on the outer conductor only (most common situation)
- 2 RF periods between successive impacts

MP Scaling laws in coaxial lines



Compute $\ln\left((fd)^4 Z\right)$ for your design and get the position of MP bands

Power at which MP occurs in TW can be computed from the power it occurs in SW simply:

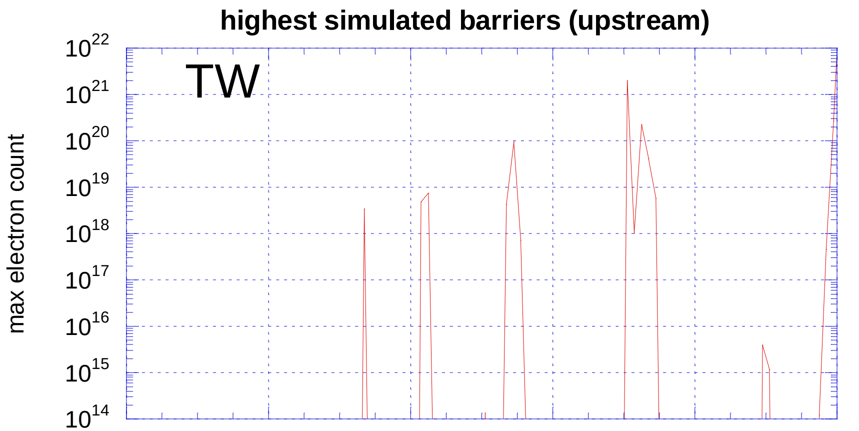
$$P_{TW} = 4\,P_{SW}$$

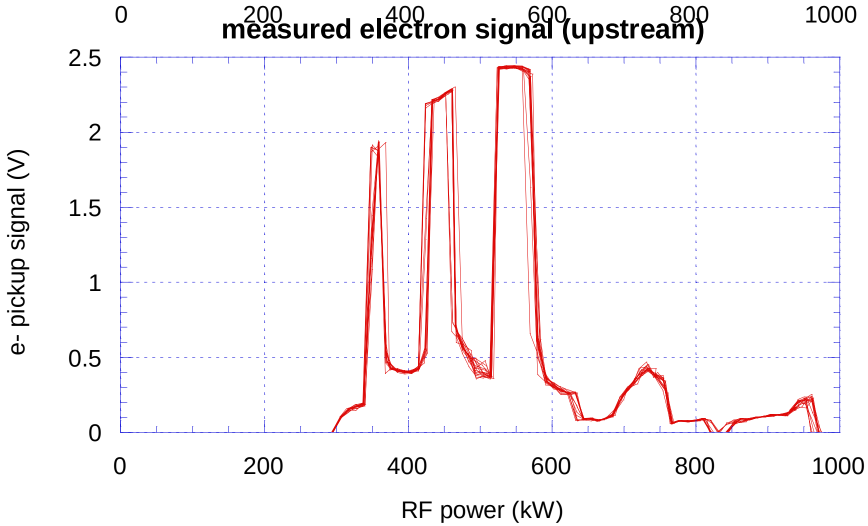
E. Somersalo et al.1996

- 1 point (most proeminent) $P \propto (f\,d)^4 Z$
- 2 points $P \propto (f\,d)^4 Z^2$
- …

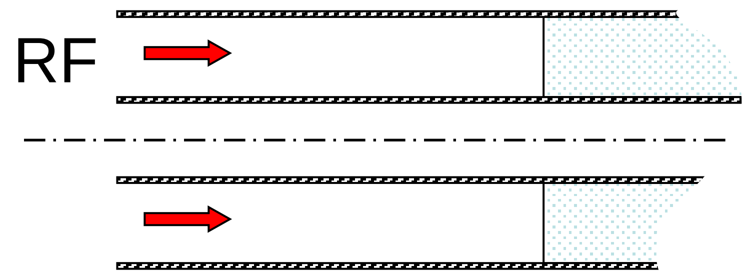
Multipacting

MP in coaxial lines is well modeled (many 2D simulation codes)

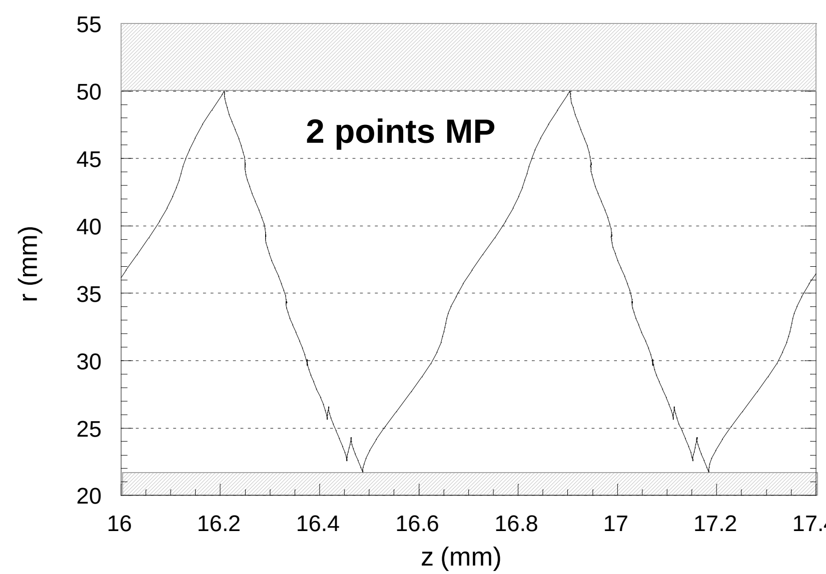




1.3 GHz coaxial line 50 Ohms 60 mm OD



Resonant trajectory with 2-surface impact
Coaxial line 100 mm OD 50 Ohm



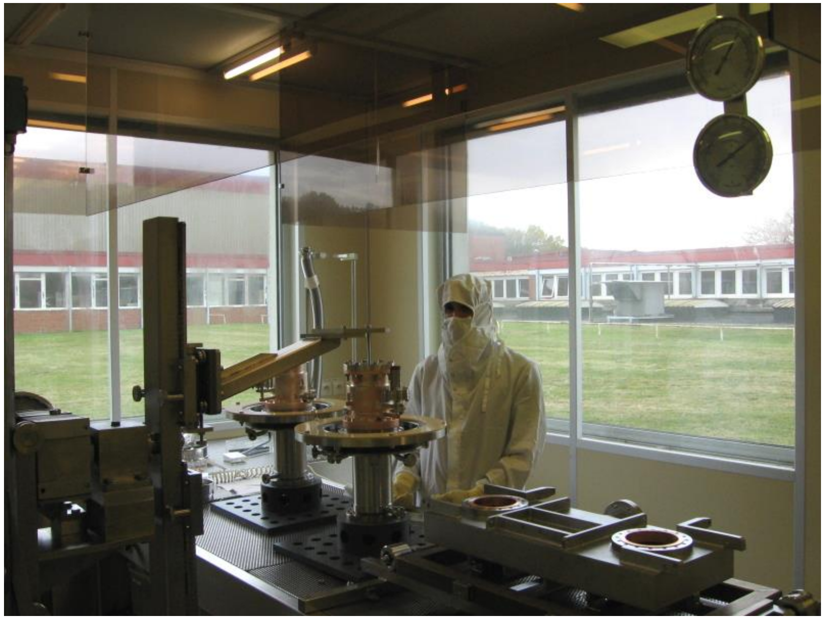
MP cures

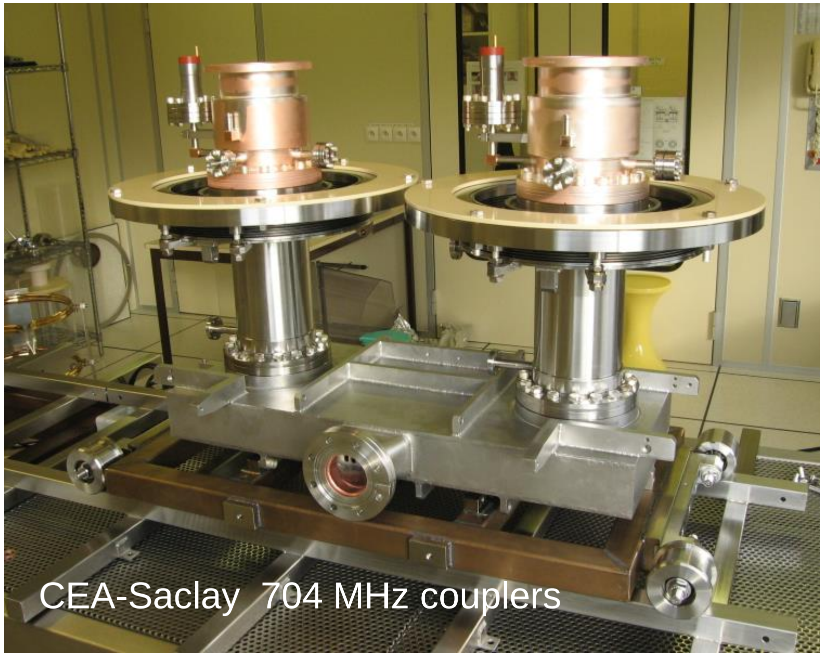
- Design a Multipactor-free coupler or/and window
- Reduce the SEY of materials using Ti orTiN deposition on Alumina windows. This is a critical operation: the repeatability of the typical 10nm thickness on batch production can be an issue.
- Bias the antenna of the coupler to modify the electron trajectories and prevent it to occur during machine operation (this happened for LEP). HV in the 2-5 kV range is needed, so a special capacitor has to be designed. Most of the high power coupler designs include this option.

- remark : MP can be useful to clean the surfaces of the coupler

DESY TTF-3 HV capacitor

Coupler preparation in clean room





CEA-Saclay 704 MHz couplers

Couplers for SC cavities must be prepared in the same cleanliness conditions as the cavities.

• clean room assembly
• dry vacuum pumps
• dry and filtered nitrogen, slow venting

Coupler conditioning

- Conditioning is both a necessary RF/vacuum cleaning process and a validation process
- A coupler is expected to experience the full range of its power on the final machine. It also needs to sustain the full reflection of power from the cavity regardless of its detuning. During conditioning it has to go through all this and then some.
- Several interpretations of the sentence ‘the coupler is conditionned’ among the people involved…

- A strict interpretation:

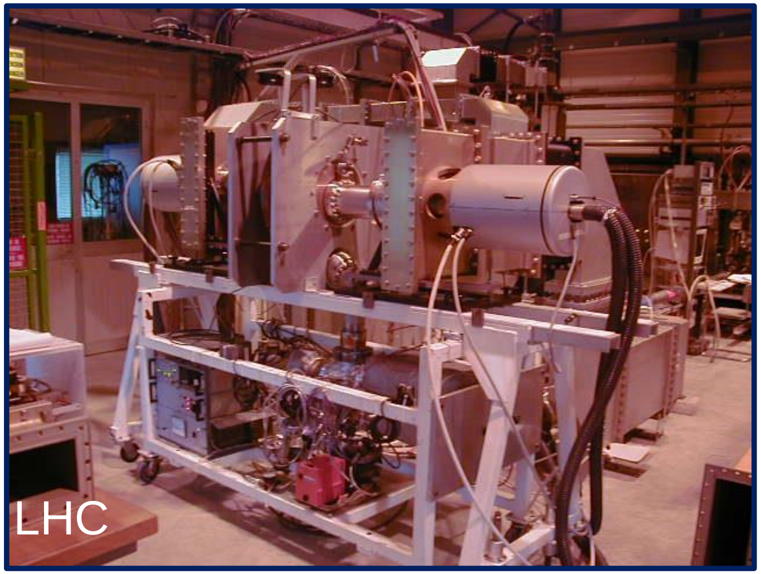
  IF
  - No more outgassing occurs on the full range of power, in traveling wave (TW) and standing wave mode (SW) (p of the order of 10^{-9} mbar)
  - And the coupler sustains the maximum power over long time periods (several hours in a row)

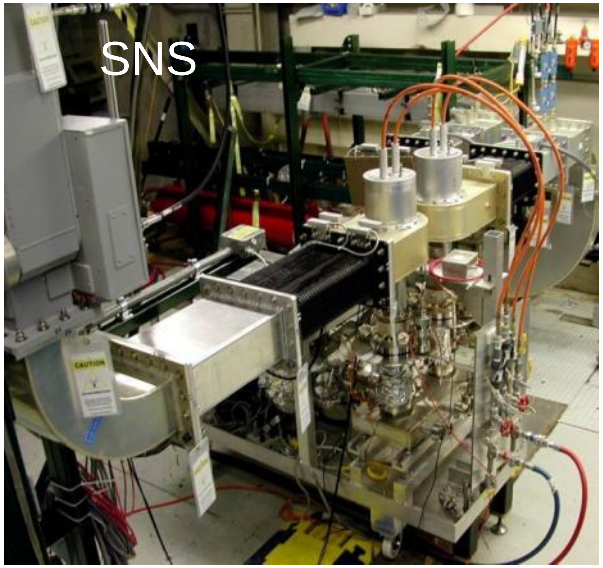
  The coupler is conditioned

- A widespread conditioning strategy :
  - Start with TW, short pulses and ramp the power from 0 to Pmax
  - Increase pulse length by step by step and perform conditioning ramps for each duration. The decision to go to increase pulse length is taken when no outgassing occurs anymore above a fixed limit
  - Repeat the process in SW, moving the SW pattern at each stage in order to scan to whole surface of the coupler with the highest peak fields
  - Perform a long term run at constant maximum power
- Conditioning can be automated
  - Vaccum feedback loop controls the increase of power (LHC setup)
  - Interlocks shut down RF power in case of specific events (electron activity, arc detection, pressure above threshold)

Travelling wave setups

- A pair of couplers are required for TW conditioning, both connected to a specially designed cavity, or connected through a suitable piece of waveguide.
- The coupling coefficient to this cavity must be high enough that the losses in the cavity are small (no energy stored)
- The cavity must no be the system limitation, so it has to be carefully designed with respect to peak fields, multipactor, and vacuum





Protection of the couplers

While subjected to RF power, specific events are harmful:

- On the air side : Arcing
  - Arcs can be so energetic that they melt the surface of conductors. They both damage the conductors by leaving pits and sputter the material on the nearby window. Once the ceramic is metalized, it heats up. This can be fatal to the ceramic. In worst cases, it cracks, leaks
- On the vacuum side :
  - Outgassing above 10^{-5}mbar pressure leads to a vacuum discharge. Possible consequences:
    - Sputtering of copper coating,
    - Generation of spikes or pits on the surface
    - Metalization of the window, heating up, cracks, leaks
  - Multipacting, charging up and breakdown of the ceramic window

→ Instrumentation and interlocks

Instrumentation and interlock

A coupler interlock channel is composed of :
- A sensor,
- Electronics which processes the signal into a logic level
- A control element which shuts down (or adjusts) the RF power as fast as possible

- Pressure gauge (~ms)
- Arc detector (~10 μs)
- Electron pick-up antenna (~10 μs)

Ports are required for these diagnostics, preferably close to the ceramic window (most critical part)

How to start with a coupler design?

Fundamental parameters are $\omega \quad V_{acc} \quad r/Q \quad I_b \quad \varphi_S$

Then you can define:

- The optimal coupling coefficient
- The nominal peak power

Operational margins are required to take into account

- Rf power overhead linked to field stabilization (typically 30%)
- Reliability requirements
- Upgradability

→ a design peak power is defined

Combining the design peak power and the duty cycle → design average power

- The design power and frequency will define the input waveguide type and size
- The next thing to define is the FPC port on the cavity (location, geometry), combined with the choice of waveguide type for the cold part (coaxial, rectangular)

What will be the coupler architecture?

Other aspects will give strong desing orientations:

- Thermal aspect : budget for heat load :
  - Availability of intermediate temperature circuits in the croymodule
  - conduction and RF load at cold end, or also at intermediated temperatures (i. e. thermal shield(s))
  - thermal radiation into the cavity

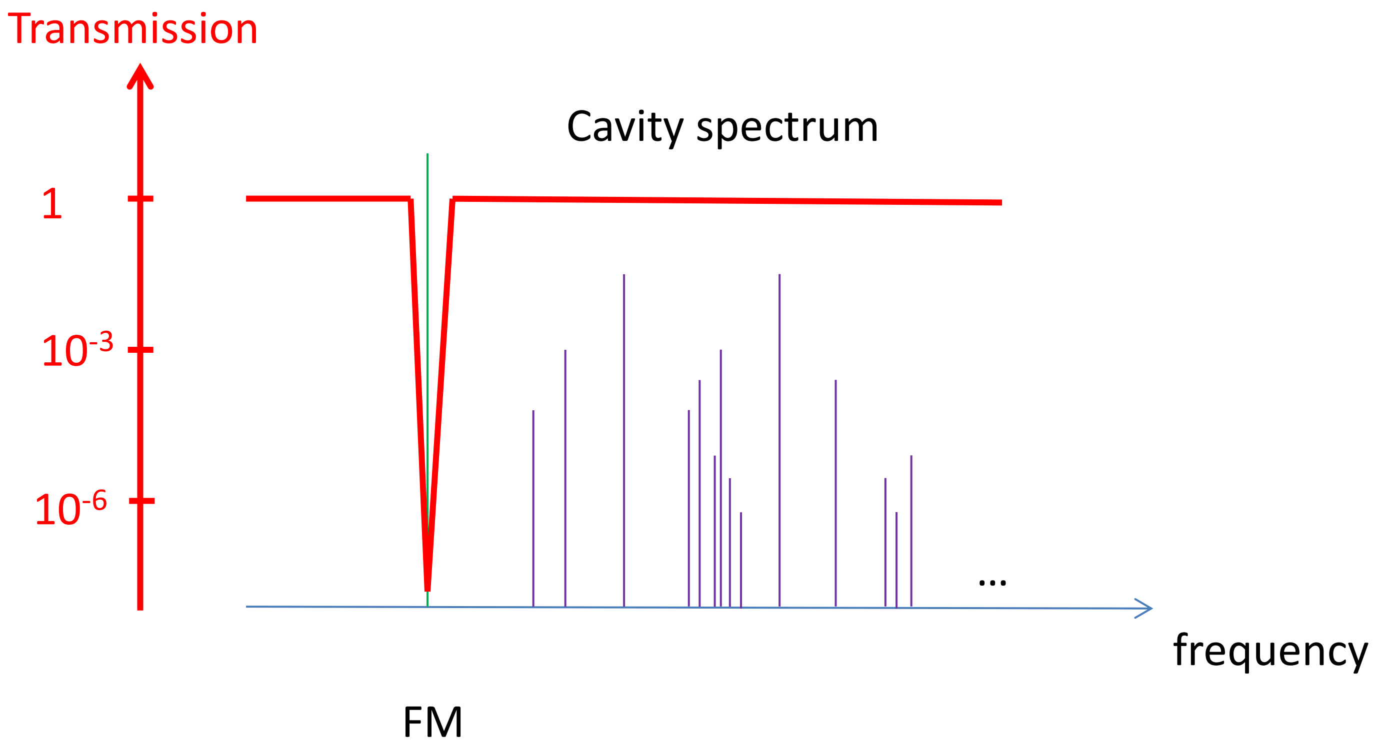
- Range of mechanical compliance to cavity movements during thermal cycles :

  - How many bellows are required (for thermal and mechanical aspects)?
  - If bellows are needed how is the antenna kept coaxial with the coupler port?
  - How many windows are required?

- Cryomodule type
- Insertion method of the cavity string sealed in clean room with at least one window of the coupler

High order mode couplers

Ideal HOM coupler



It should couple to HOMS, but not to the fundamental mode (FM)
It has a notch filter character : rejects the FM

Damping requirements

In order to design a real HOM coupler for a machine, a set of requirements are given by beam dynamics, relative to the risk of beam instability :

- BBU : Beam Break Up
- CBI : Coupled Bunch Instabilities
- etc

In general, this is a requirement in terms of impedance at given frequencies or in frequency ranges

Example : One mode m1 in a cavity at frequency f_1 is declared 'dangerous'

- f_1 is a property of the cavity design
- $r/Q\ (m_1)$ is a property of the cavity also
- $Q_{ext}(m_1)$ is determined by the HOM coupler (filter design, position on the cavity)

For beam stability reasons, it might be asked to the designers to obtain

$$Z(f_1) = r/Q \times Q_{ext} < Z_{safe}$$

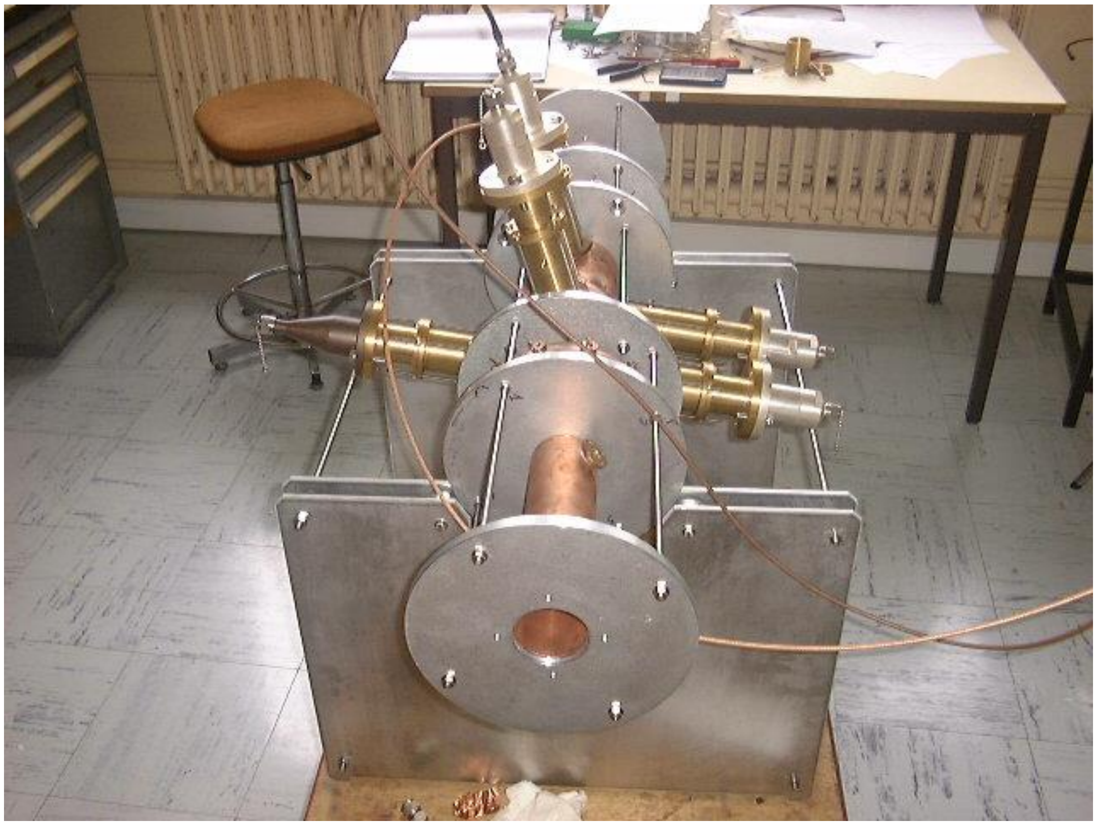
Since it is not possible to set all frequencies and r/Q in cavity EM design, the HOM coupler is there to reduce the resonant characteristics of cavity modes of interest.

HOM couplers function

- Lower the Qext of specific modes or sets of modes
- Can be specialized for a given type of modes (longitudinal, transverse)
- Interface to a RF transmission line (cable or high power waveguide) directing the RF power on a load, out of the cryomodule
- Vacuum barrier

- Need to be superconducting
- Need identical preparation as the SRF cavities (etching, rinsing, clean assembly)
- The notch filter needs to be tuned

Not so long ago (15 yrs)

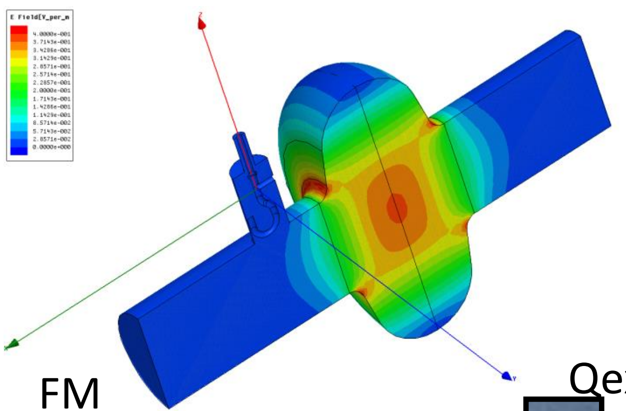


Copper models were still used to optimize the geometry of HOM couplers:

- 3D RF code were slow
- Difficult to generate quality mesh for representation of full structure with dimensions > 1m and details <10^{-4} m

Loop type HOM

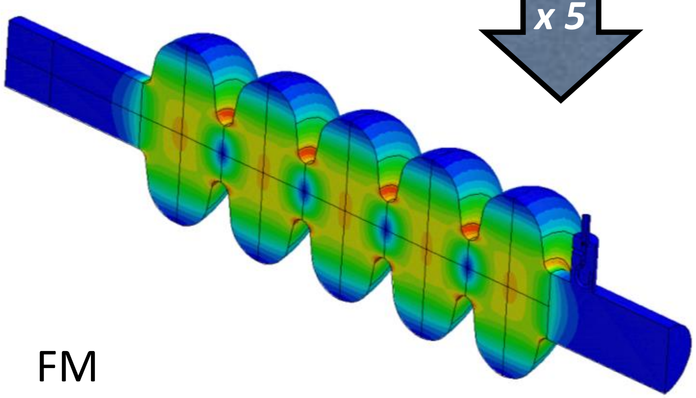
Simulation with hfss complex eigensolver. External Q obtained from the solver directly



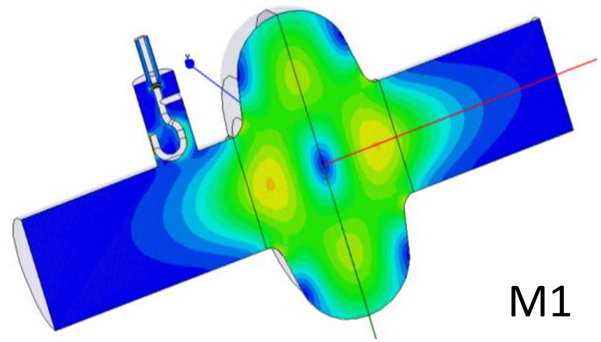
FM

Qext

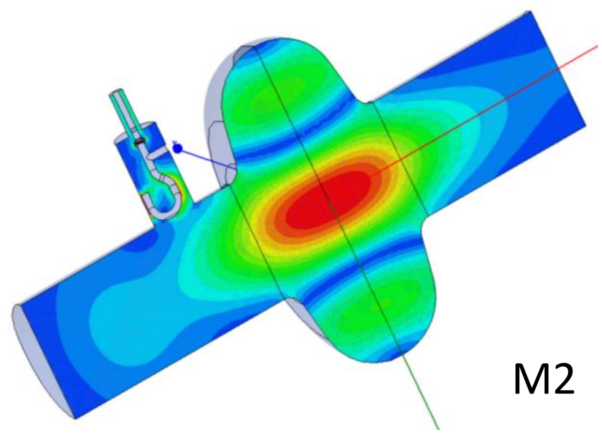
x 5



FM



M1



M2

Single cell mode	Single cell Qext
FM	4.4e10
M1	3.4e4
M2	6.0e3

Loop type HOM

Loop material is bulk Nb

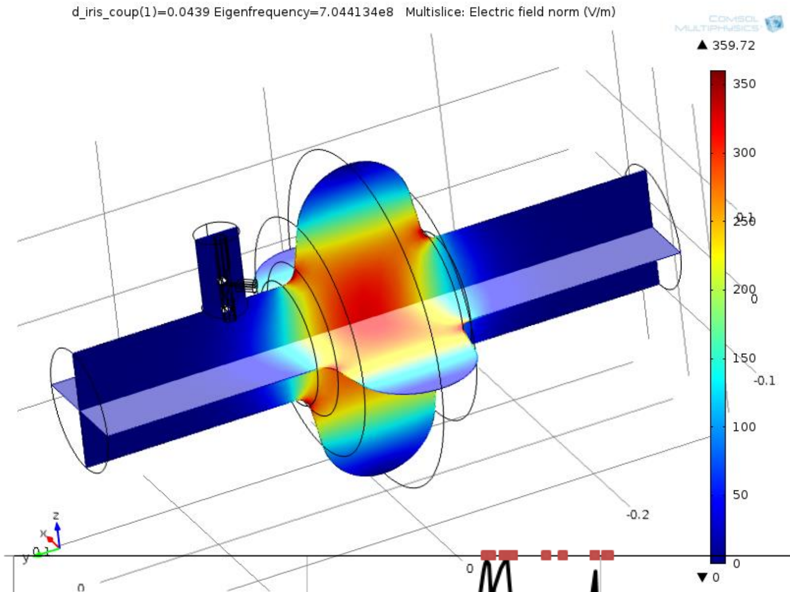
Rod Nb for 1.5GHz

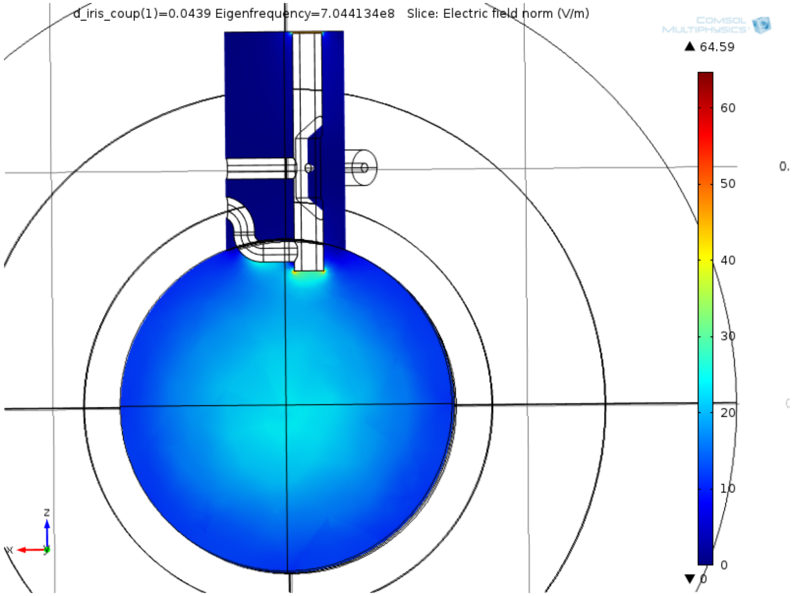
Ceramic window

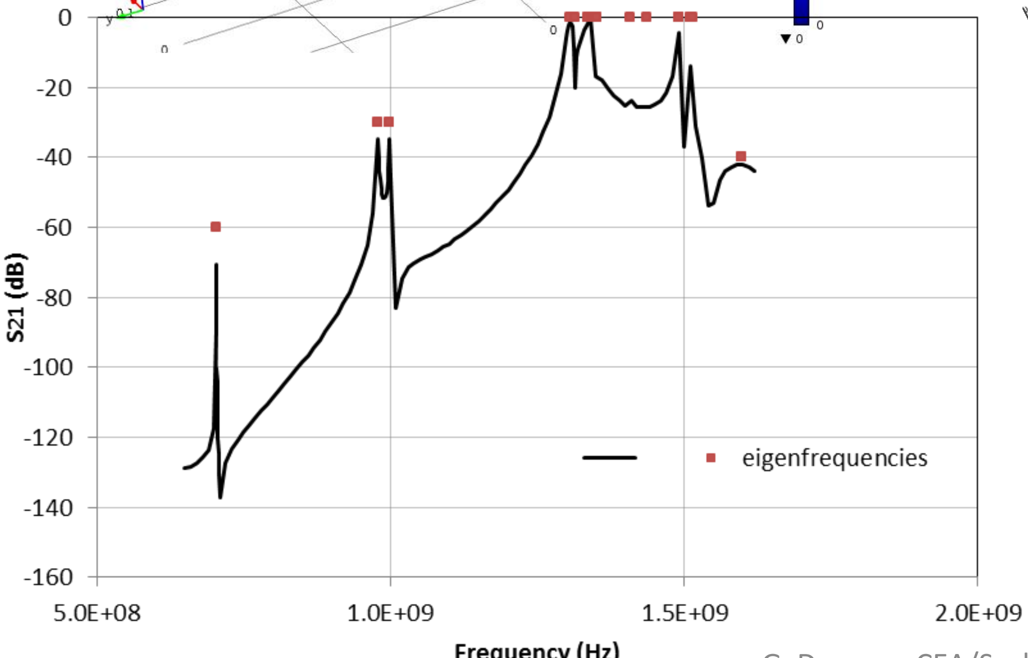
Hollow Nb tube with internal liquid He cooling, 352 MHz SOLEIL SR

Probe type HOM

Simulation with comsol





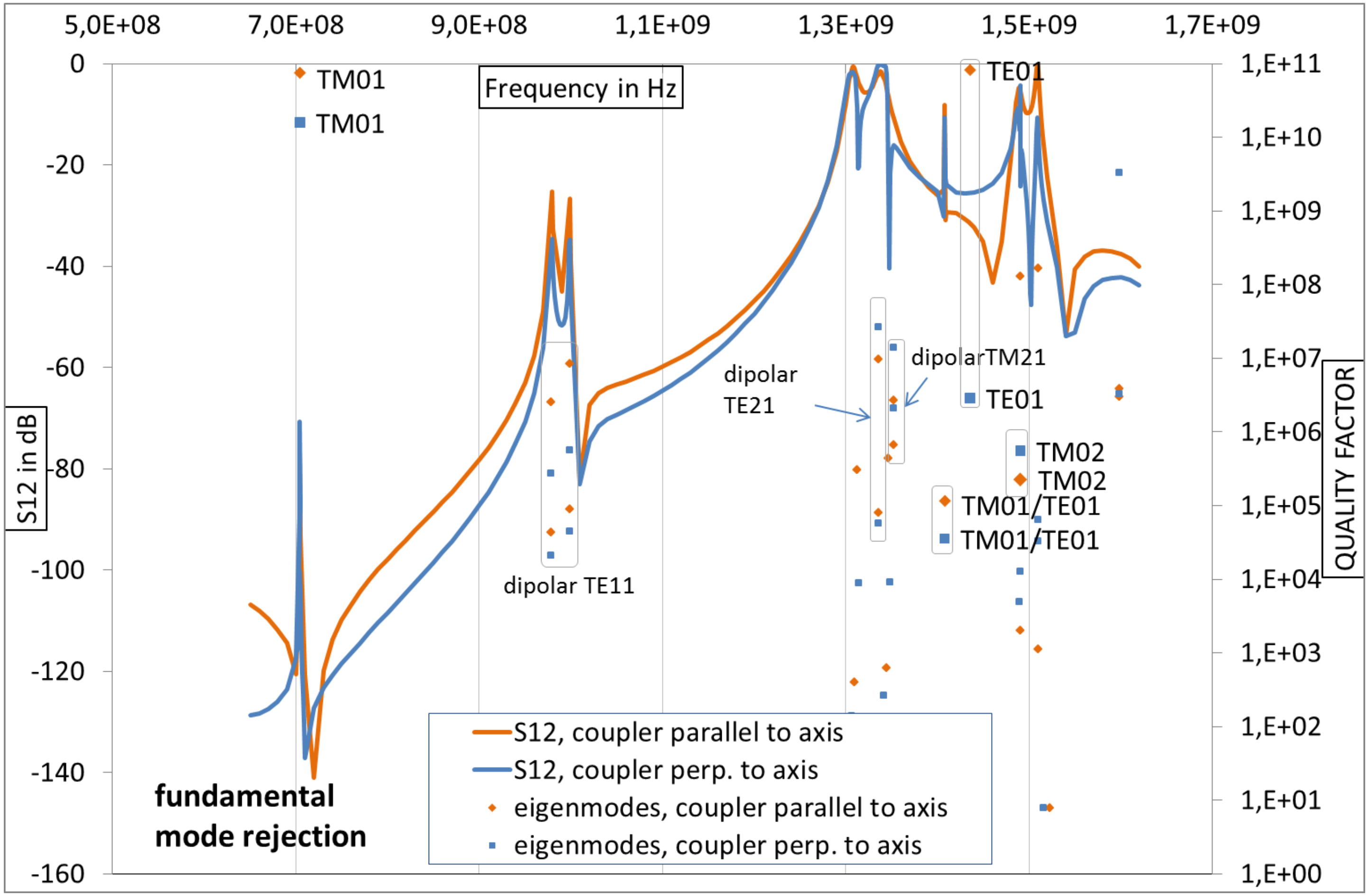


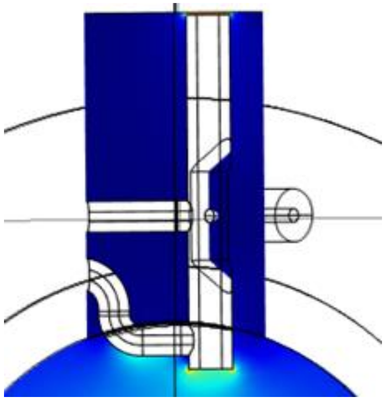
Comparison of eigenmode frequencies vs S-Parameter frequency scan

HOM couplers design

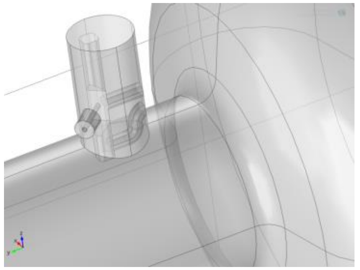
Loop type, *Ø 50 mm port*

characteristics on a ***single cell***

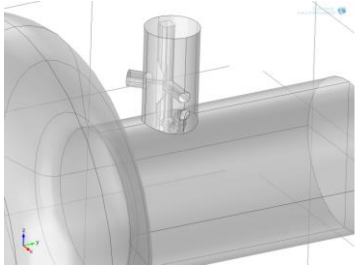




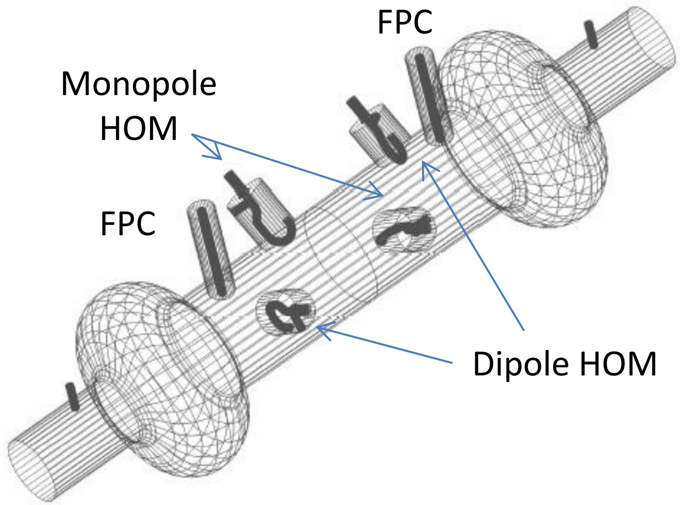
Coupler parallel to axis



Coupler perp. to axis

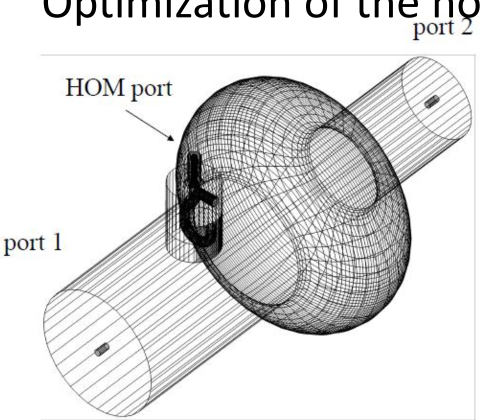


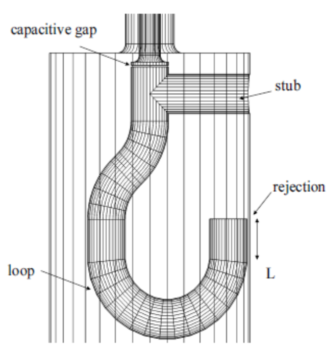
Heavily damped SRF cavity

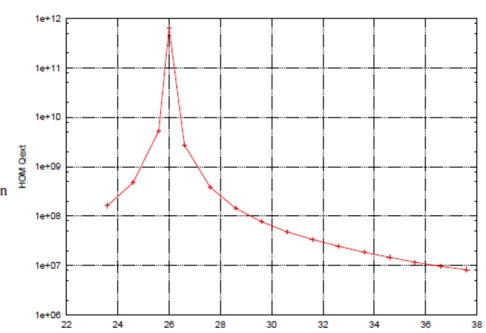


SOLEIL cavity

Optimization of the notch filter by varying the capacitance



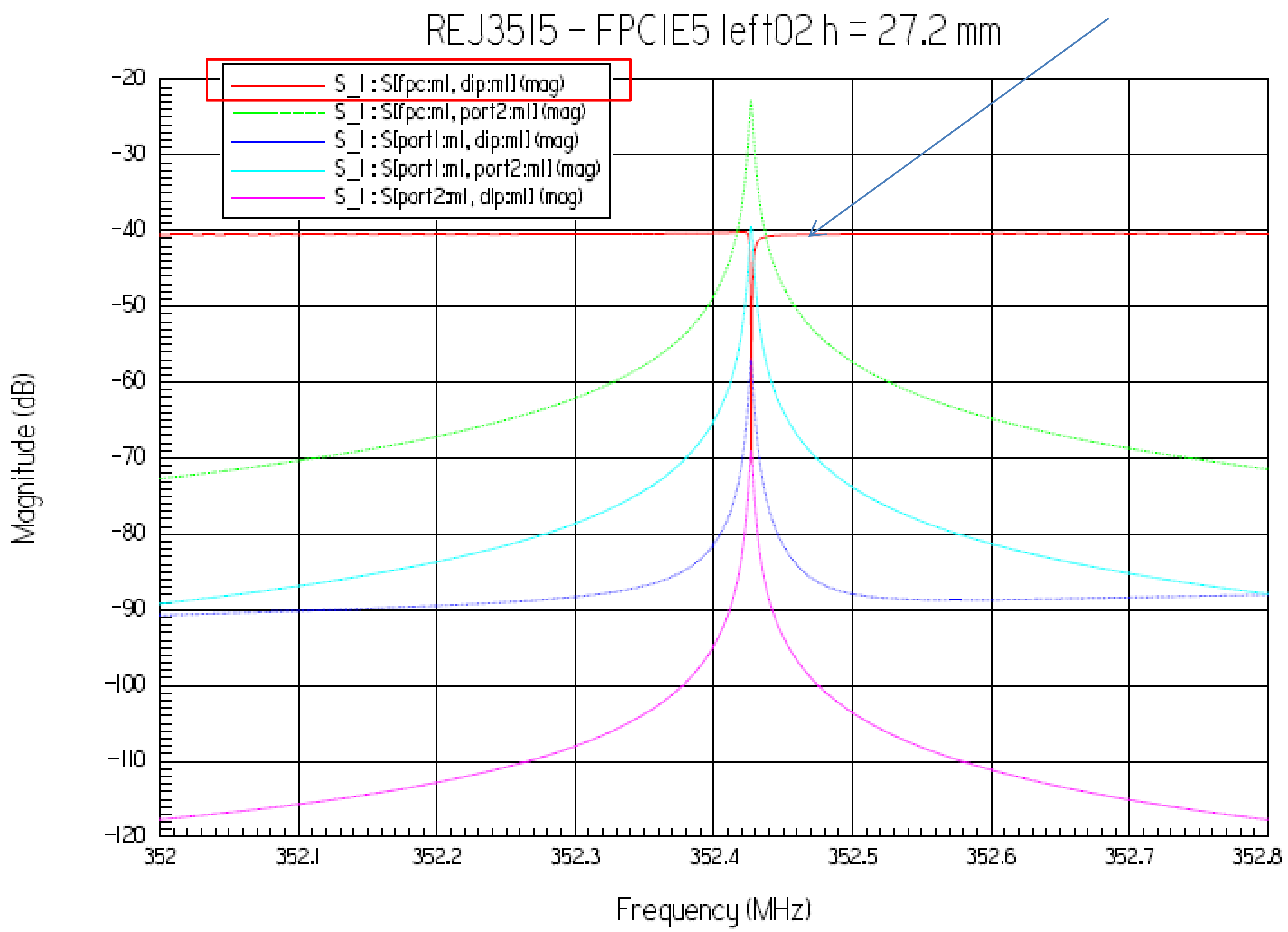




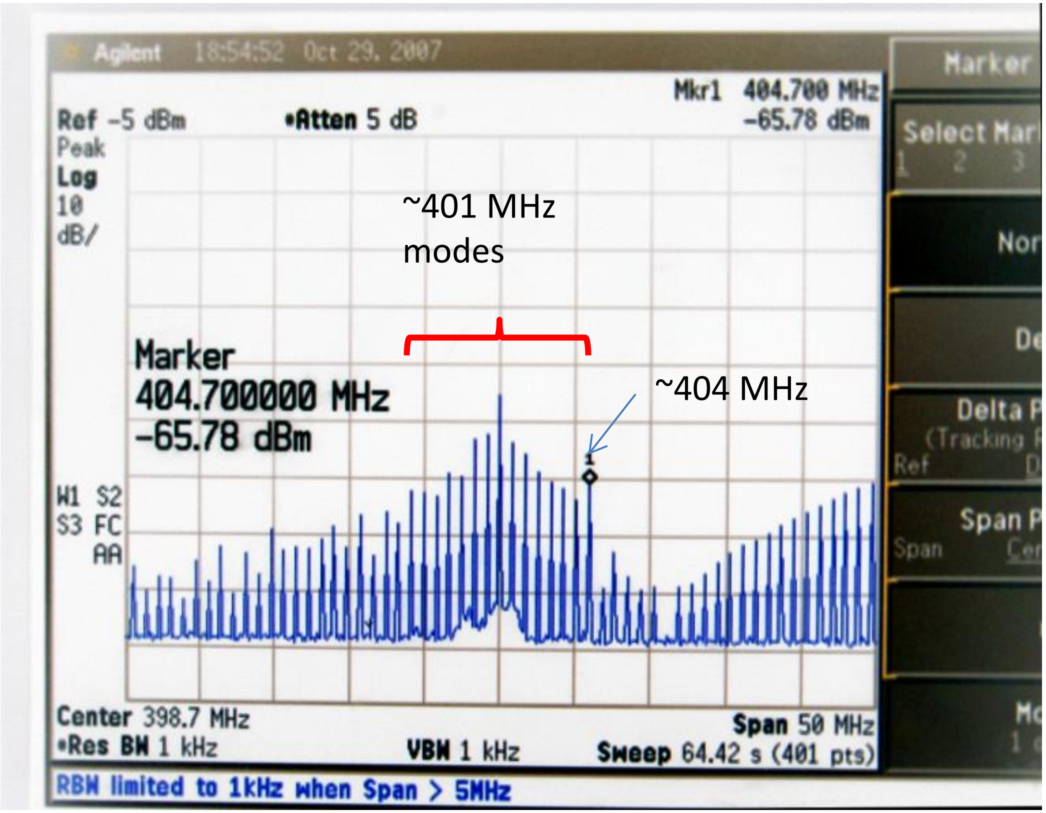
mode	frequency [MHz]	Q_{ext}
1a	400.705	74
1b	401.191	72
2a	403.942	1850
2b	404.225	1890
3a	455.895	150
3b	456.550	71
4a	483.876	92
4b	484.642	50
5a	495.207	1443
5b	495.279	953
6a	505.314	162
6b	505.993	94

FM rejection

Notch characteristic obtained



HOM in action with beam



Predictions of 3D simulations

mode	frequency [MHz]	Q_{ext}
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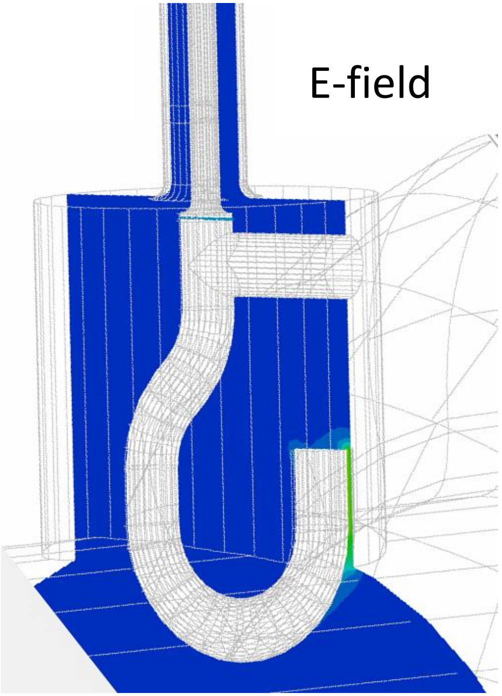
Large bandwidth

Small bandwidth

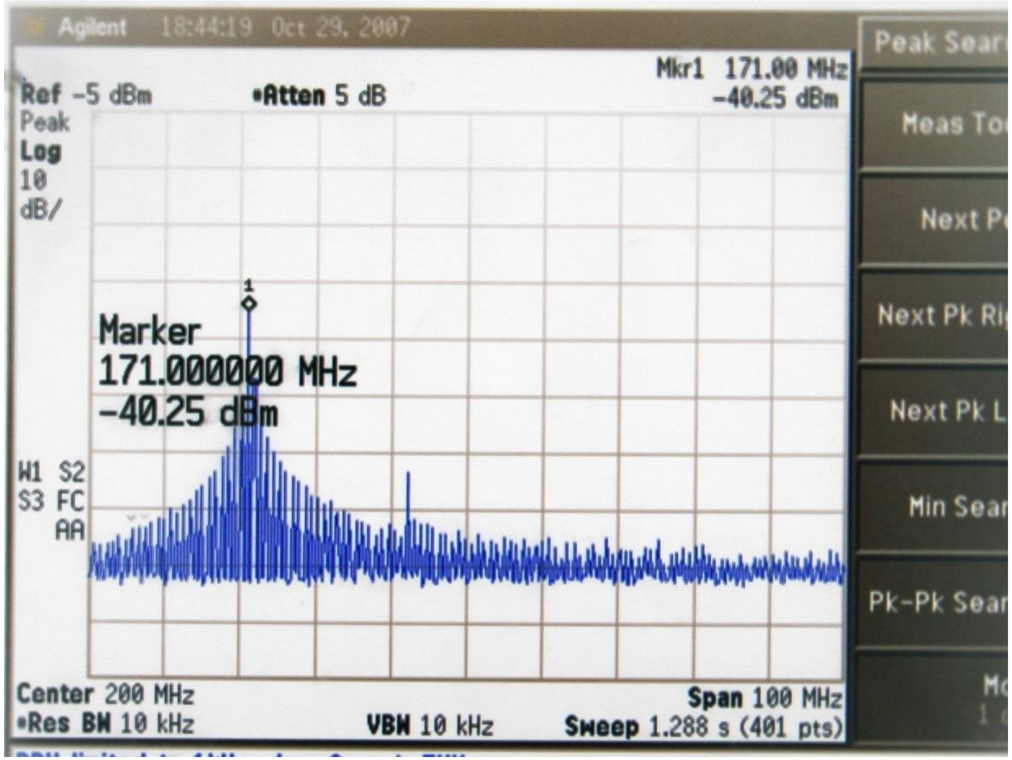
SOLEIL SR ***single bunch*** mode 10mA
output of a dipole-HOM coupler

HOM eigenmodes

A HOM coupler has its own resonant modes!



HOM eigenmode @ 160 MHz



Signal generated at the output of the HOM coupler during single bunch operation in Soleil SR

Conclusion

- Fundamental power couplers and High Order Mode couplers are part of the cavity design
- They are critical components:
  - Difficult to build (brazing, TiN layer, high quality copper coating, cleanliness)
  - They can break during operation with potentially severe consequences on cryomodules : reliable instrumentation and coupler interlocks are key to protect them

Thanks!

- Thanks to my collegues I borrowed illustrations from