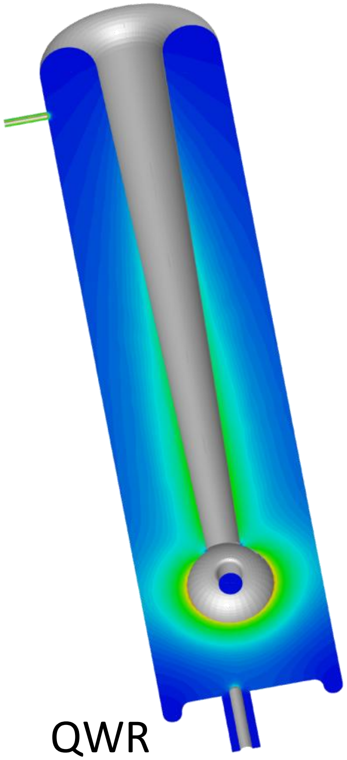
Coupler and tuners

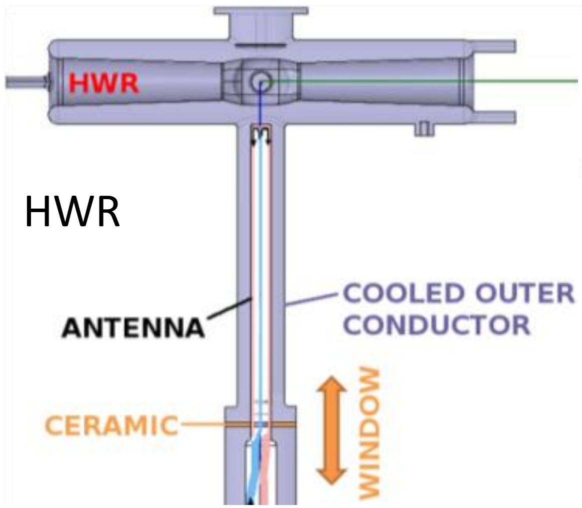
Coupler functions

- Inject RF power generated by the RF source into the cavity and beam,
- Maximize power transmission at the nominal frequency f0 (or eqv. minimizing reflection),
- Form a vacuum boundary for the cavity
- From a thermal interface between the cavity and room temperature conditions (especially important in the case of superconducting cavities)
- Other couplers (HOM couplers) are designed to couple the high order modes out of the cavity

Coupler port location

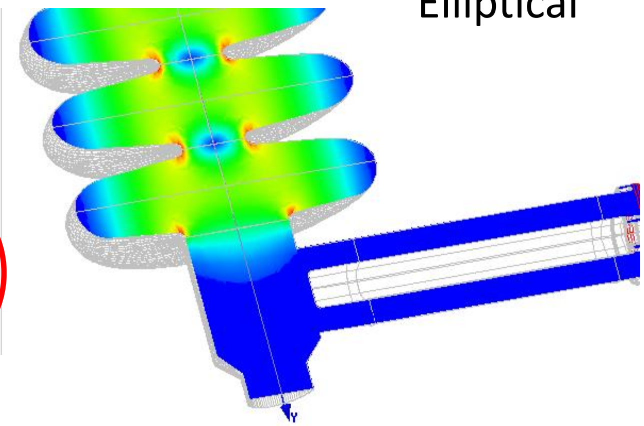


QWR



Spoke

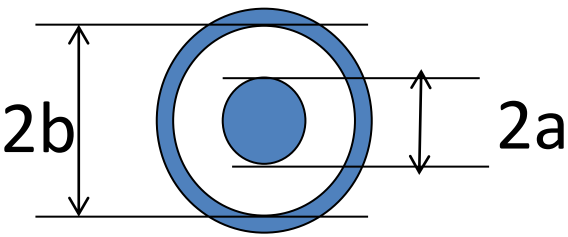
Elliptical



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

Standard waveguides



- 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 of higher impedance) by playing with the ratio b/a

$$Z = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln {}^{b}\!/_{a} = \frac{1}{2\pi} Z_C \ln {}^{b}\!/_{a} \qquad Z_C = \sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r}}$$

Fields vs travelling wave power

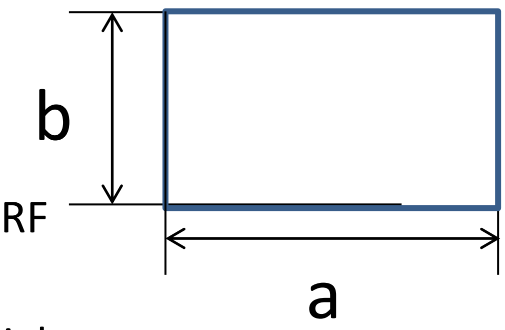
$$E(r) = \frac{1}{r}\sqrt{\frac{PZ_C}{\pi \ln {}^{b}\!/_{a}}}$$

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

Attenuation per unit length in travelling wave

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

Standard waveguides (cont'd)



- 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 a=2b (standard height) and a=4b (reduced height) compatible with high power equipments

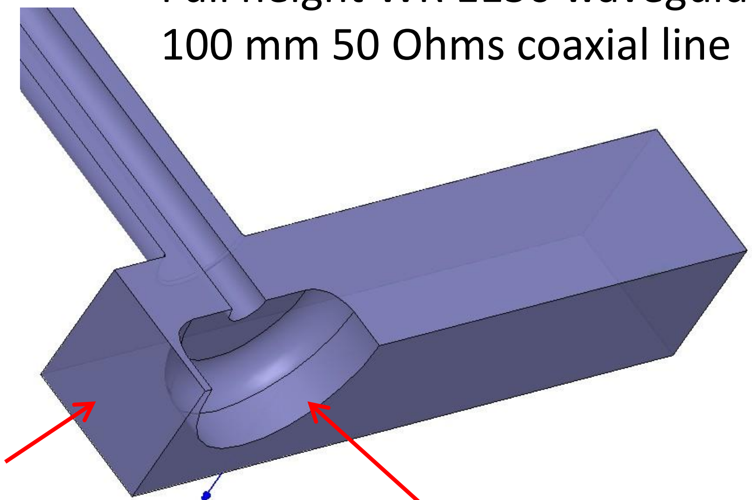
EIA standards	Frequency range (MHz)	a (inches)	Minimum attenuation (dB/m)
WR2300	320-490	23	0.0009
WR1800	410-620	18	0.0013
WR1500	490-750	15	0.0017
WR1150	640-960	11.5	0.0025
WR650	1120-1700	6.5	0.006

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 solution exist
  - Antenna transitions
  - Doorknob transition
  - T-bar
  - Stepped transformer
  - …

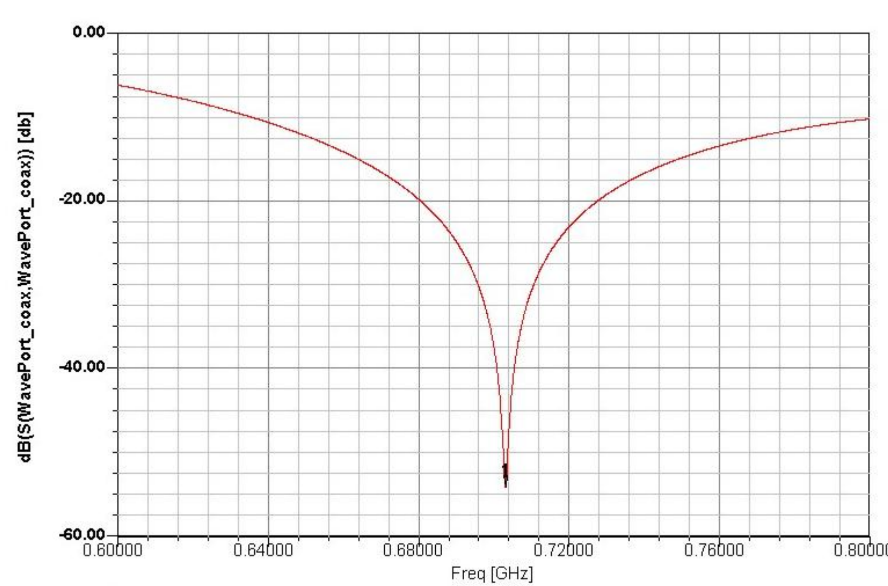
Doorknob

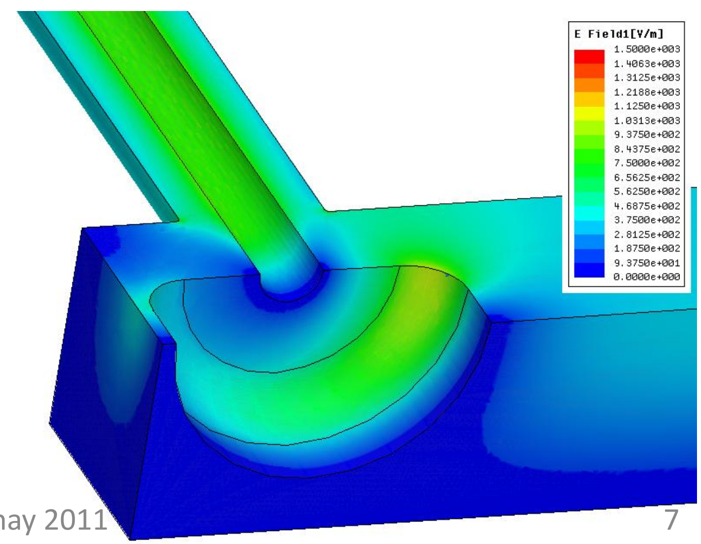
Full height WR 1150 waveguide to 100 mm 50 Ohms coaxial line



Short-circuit plate

doorknob

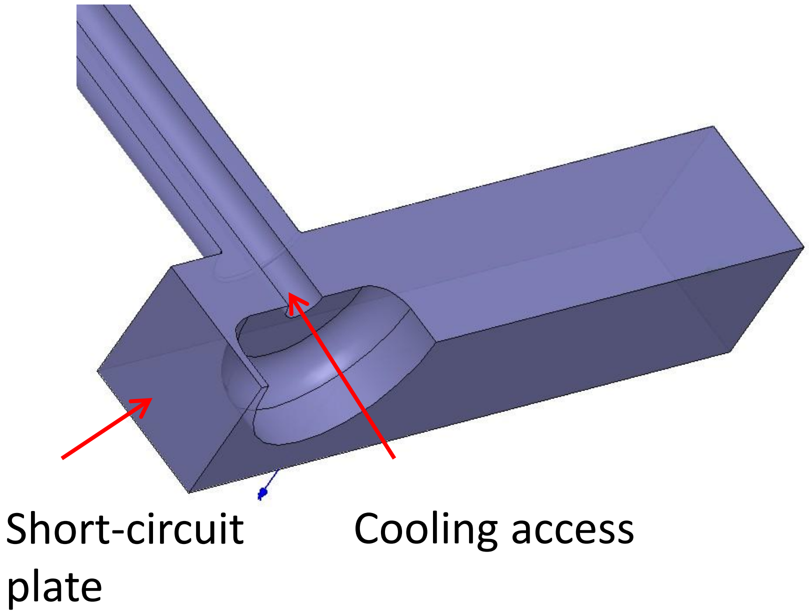




Design issues

- 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



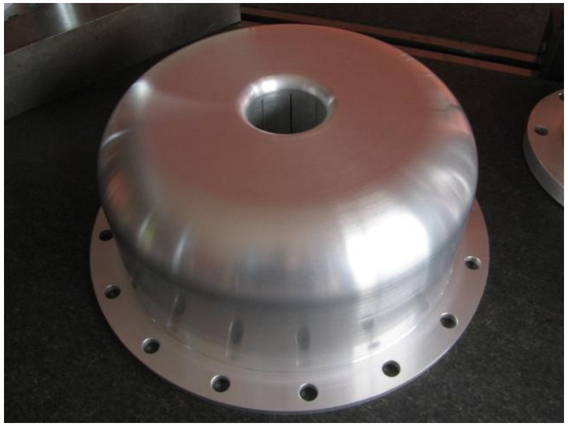
Can be built in several parts assembled using flanges and RF gaskets. This allows some geometrical tolerances to be met more easily:

- 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)

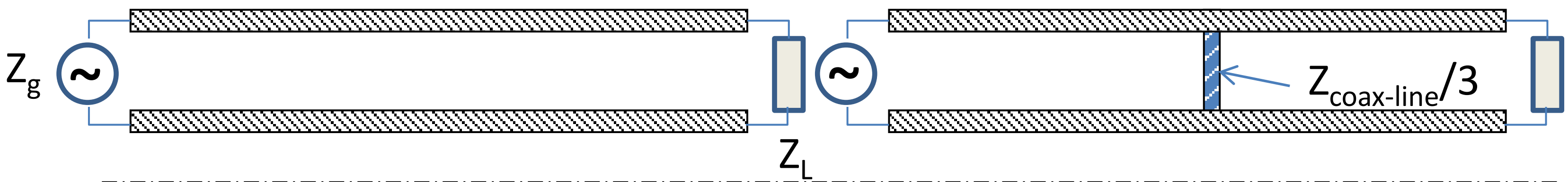
Air Doorknob



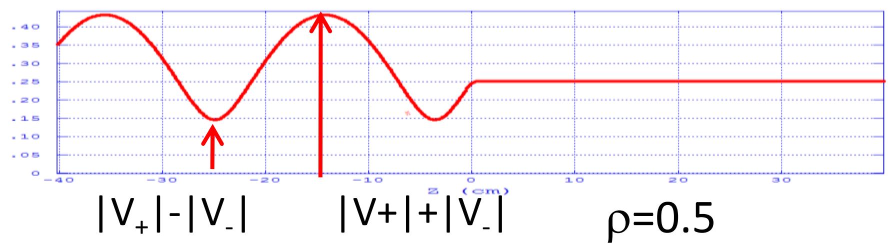
4 parts :
machined Al knob
Welded Al Waveguide (1150)+short plate
Cu antenna
Al coaxial outer conductor

RF windows

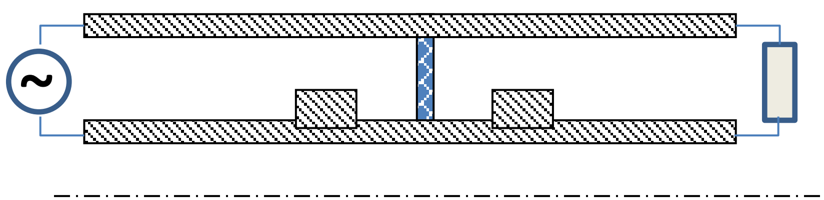
- Creates the physical barried between air and cavity vacuum using a leak- tight dielectric material : mostly alumina (purity from 95% to 99%) but also synthetic diamond, BeO, sapphire…
- Material discontinuity in a waveguide corresponds to a change in impedance, creates a standing wave, example 10 mm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



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

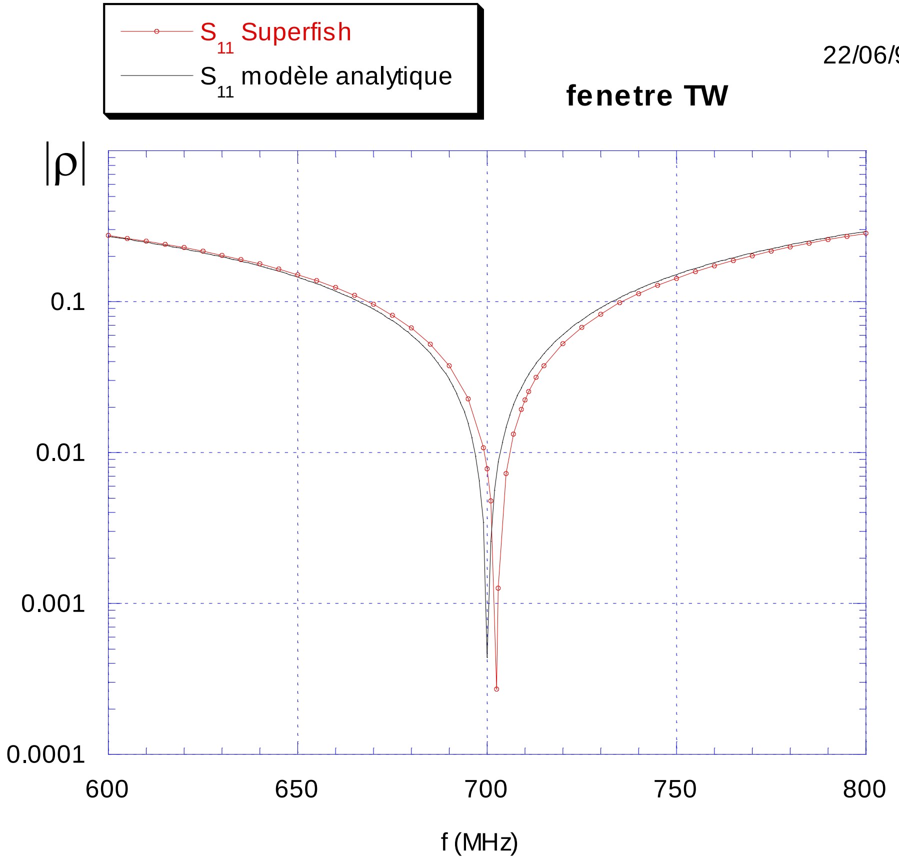


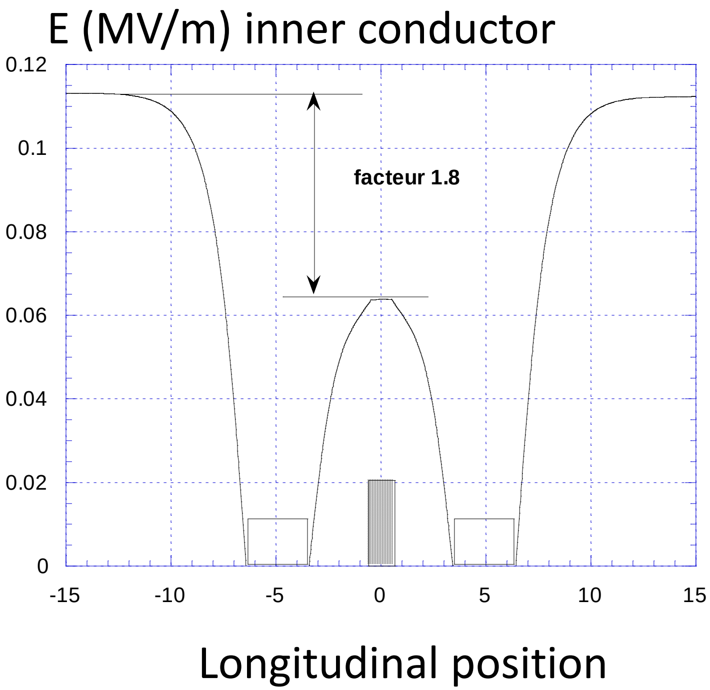
- In order to prevent this matching elements have to be inserted



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

RF windows

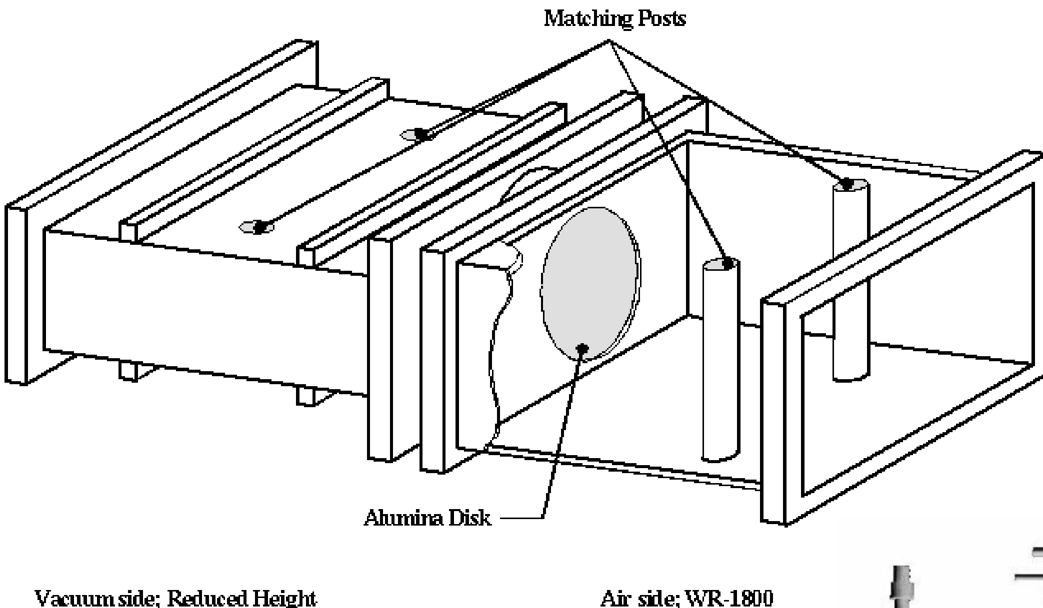


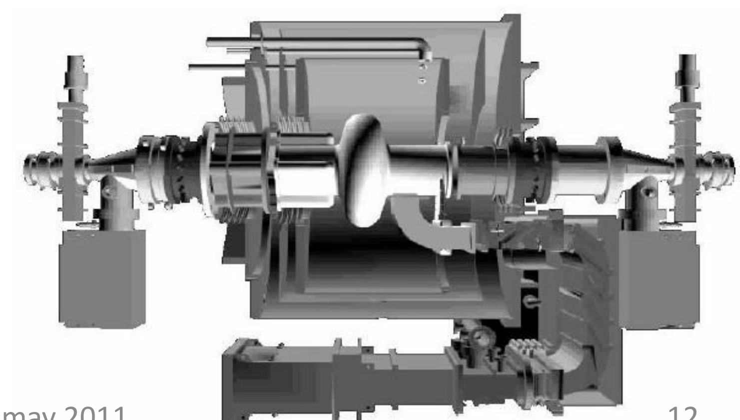


Matching options are very diverse (entire books on the subject of discontinuities in WG)
Using a semi analytical model helps finding solutions with enhanced properties like the TW window (Kazakov) with a reduction of E in the ceramic disk

Waveguide window

500 MHz window (Cornell)

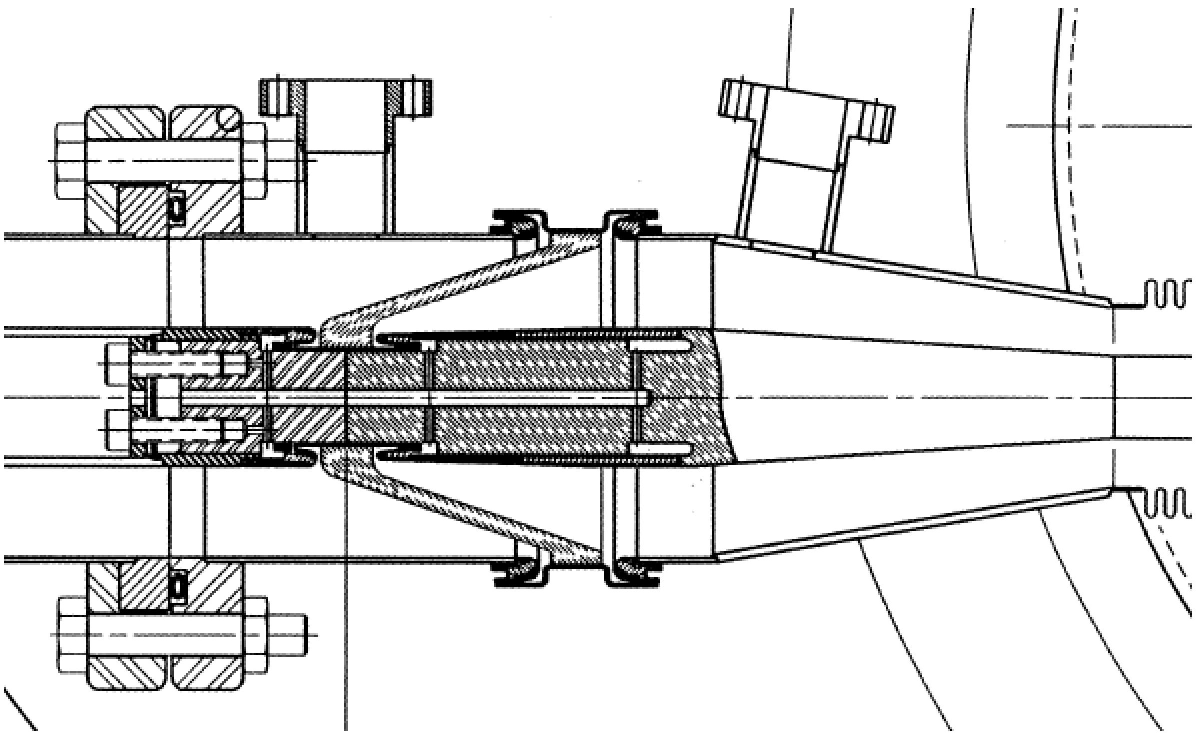




Is used as the window of a waveguide coupler

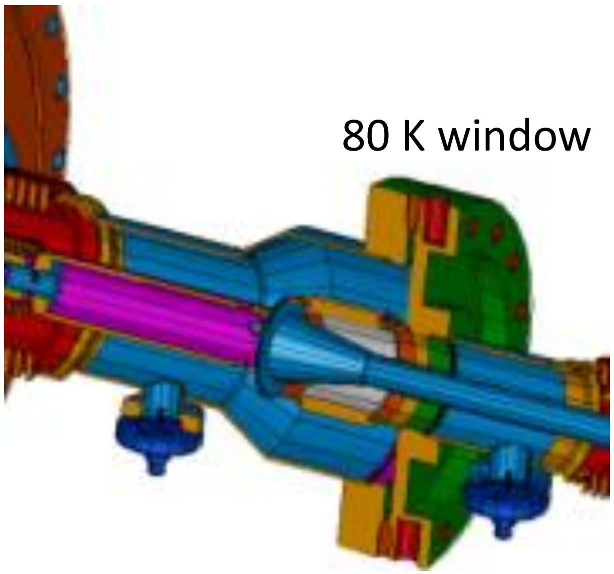
Conical window

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

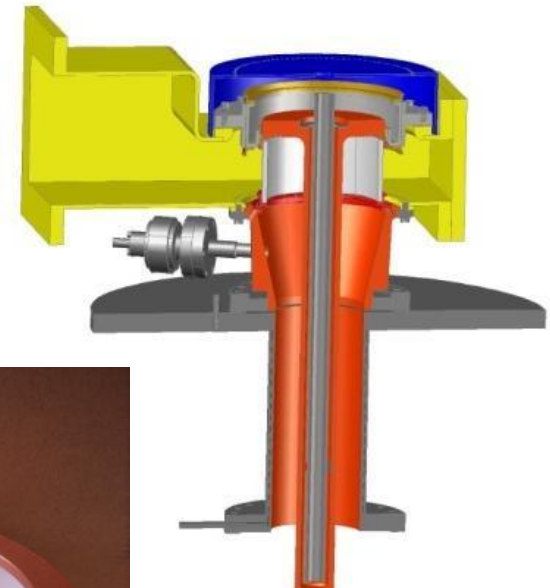


Cylindrical window

DESY ttf coupler



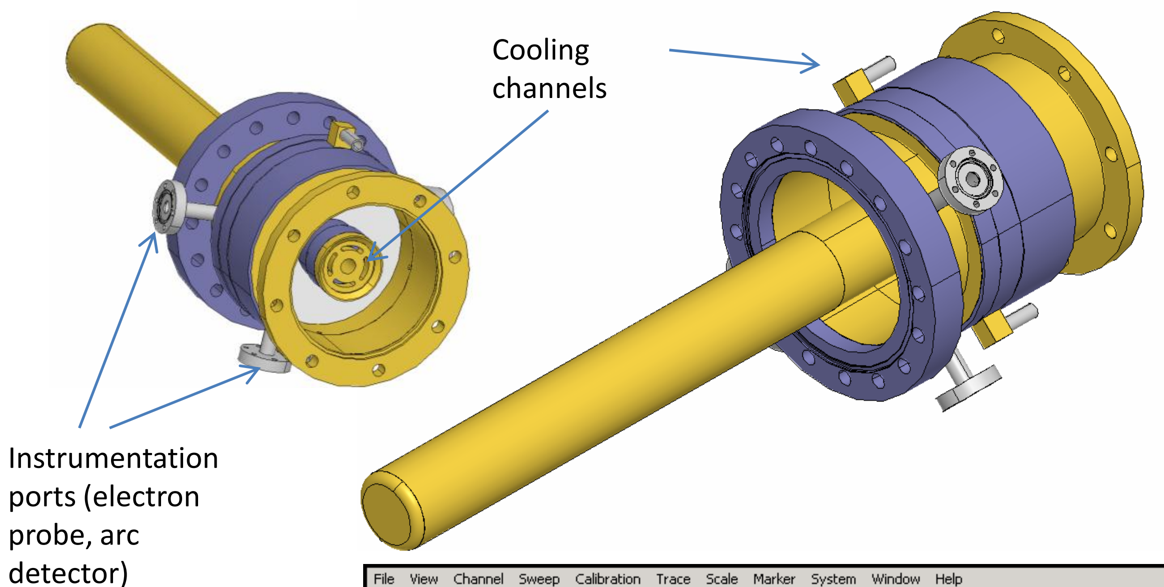
SPL-CERN 704 MHz coupler

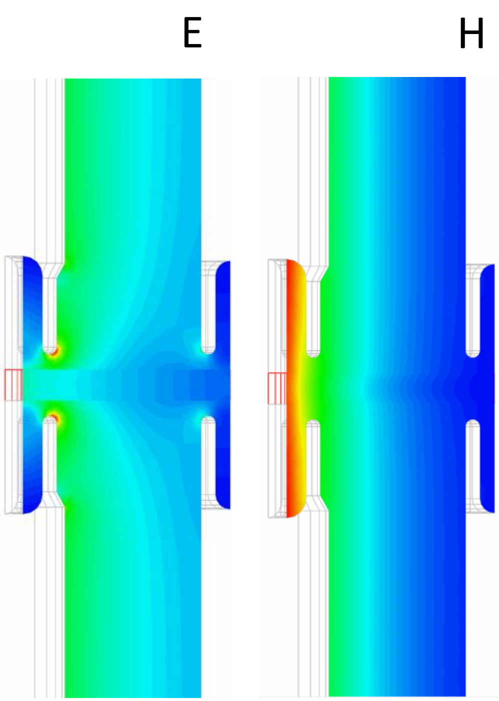


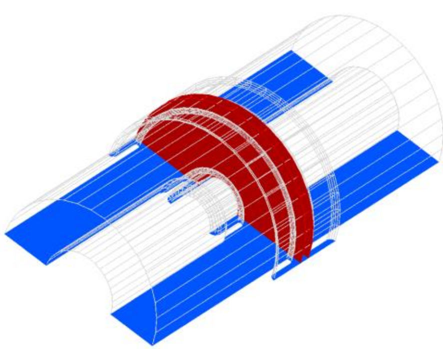
Coaxial disk windows

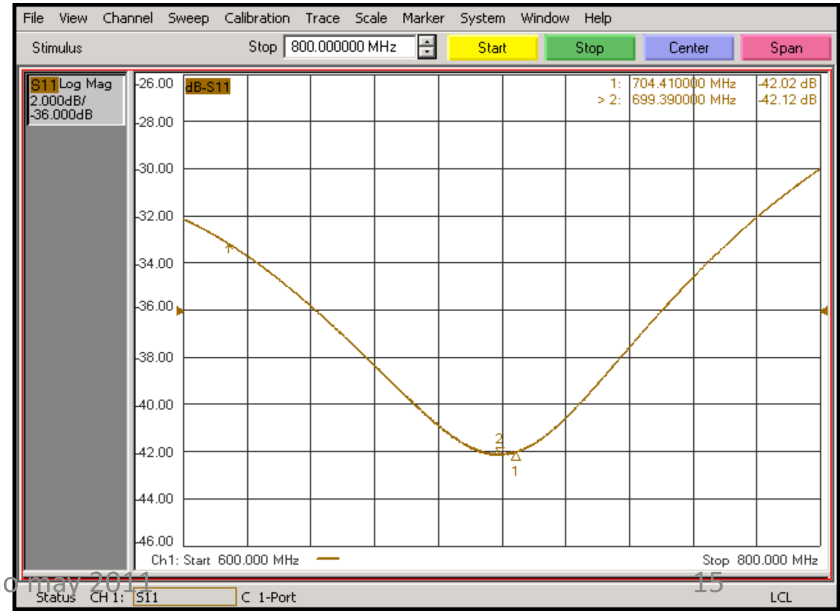
KEK design adapted to 704 MHz

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









Coaxial disk 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)
- 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 : during cooldown, the copper inner conductor shrinks more than the ceramic, this time with a solidified braze. Alumina has a small resistance to elongation (in contrast to its high resistance to compression) 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

- Heating generated by RF
  - Resistive losses on RF boundaries: use copper coating on vacuum parts (thickness 3 to 5 times the skin depth δ)
  - Dielectric losses in the window material
- Resulting mechanical stress
  - Thermal expansion of metallic boudaries is non uniform (different materials, local heating, non uniform cooling)
  - Dielectic losses in the coupler ceramics are never uniform, interna stress occur. FEM analysis is required to look at the complete load case (pressure+thermo-mecanical)

$$P_{ohmic} = \frac{1}{2}\int_S R_S H^2 dS \quad R_S = \sqrt{\frac{\pi f \mu_0}{\sigma}} = \frac{1}{\sigma\delta}$$

Surface resistance R_s
Conductivity σ

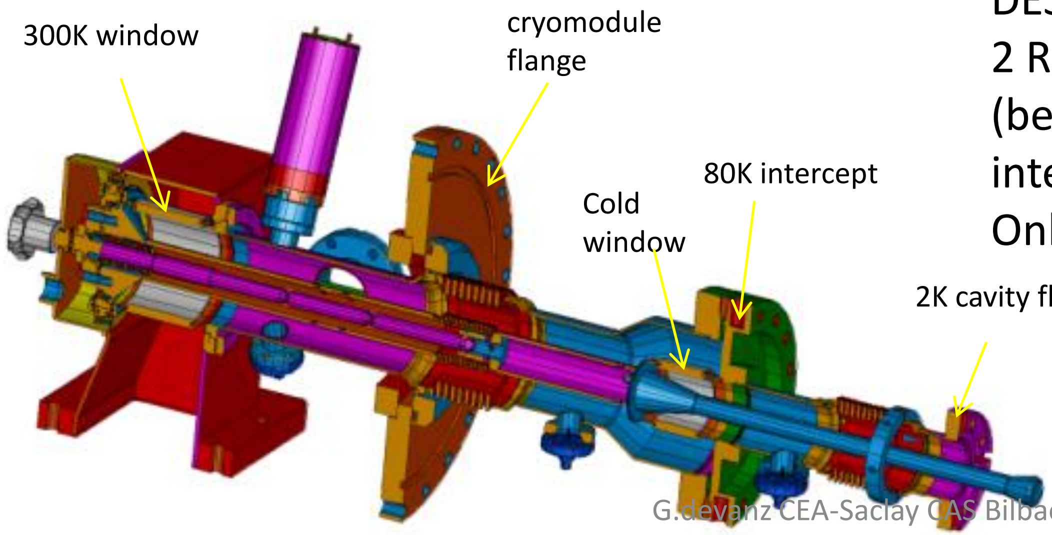
$P_{diel} = \frac{1}{2}\int_V \varepsilon_0 \varepsilon_r tg\delta 2\pi f E^2 dV$ with $tg\delta = \frac{\varepsilon''}{\varepsilon'}$ the dielectric loss tangent, $\varepsilon = \varepsilon' - j\varepsilon''$

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}

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)

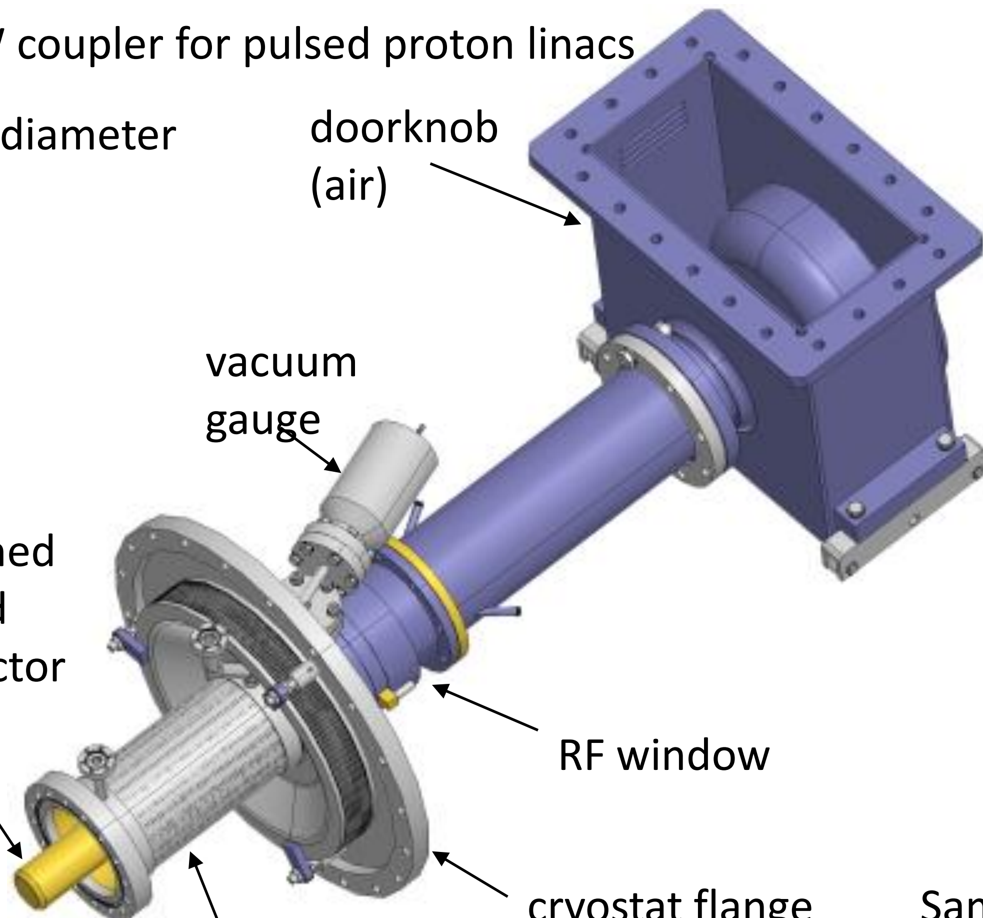


DESY TTF-3 coupler :
2 RF windows, heat leak fully minimized, (bellows, thin walls, 80K and 5K thermal intercepts…)
Only 60mW static losses at 2K

Full power coupler

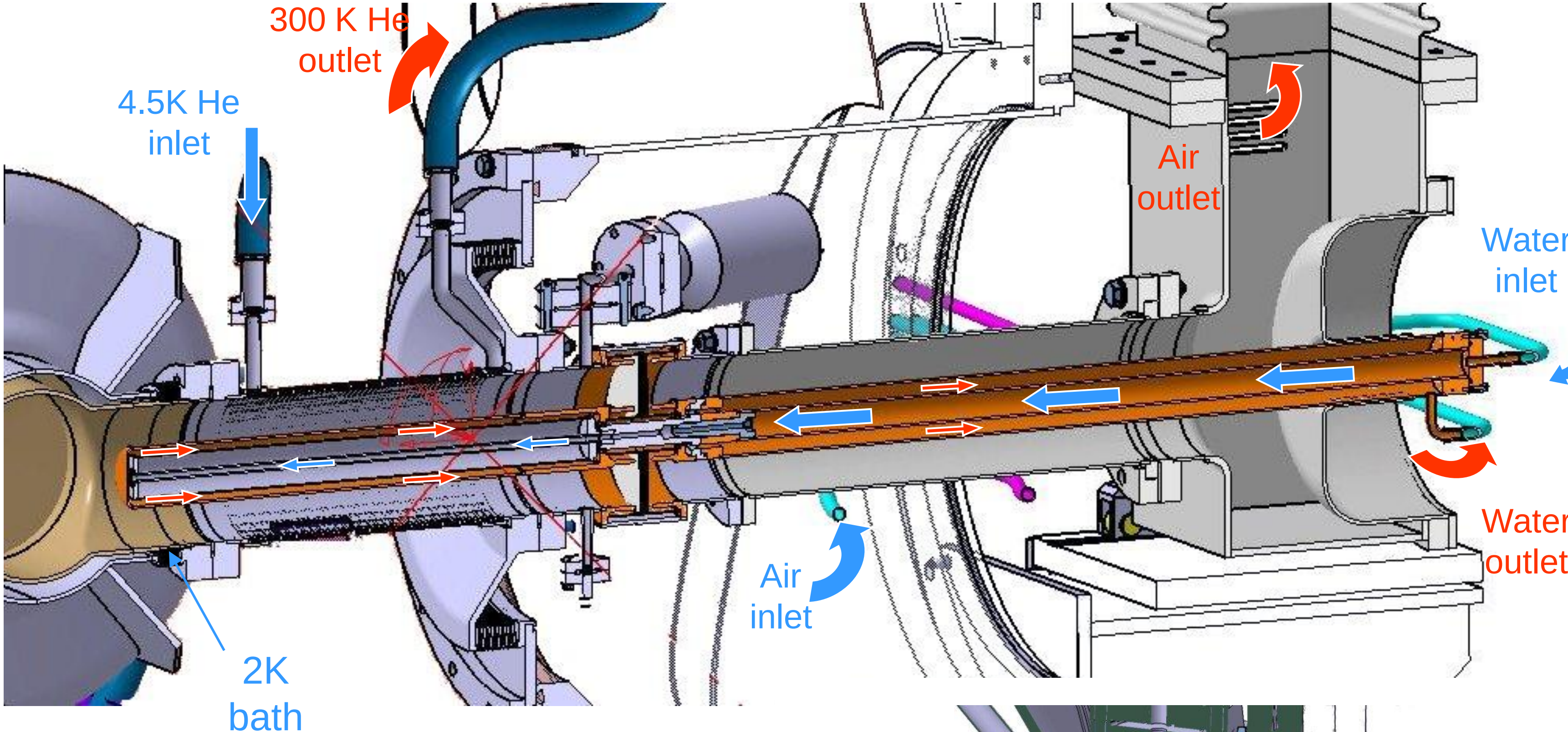
CEA-Saclay 1 MW coupler for pulsed proton linacs

100 mm outer diameter
50 Ω



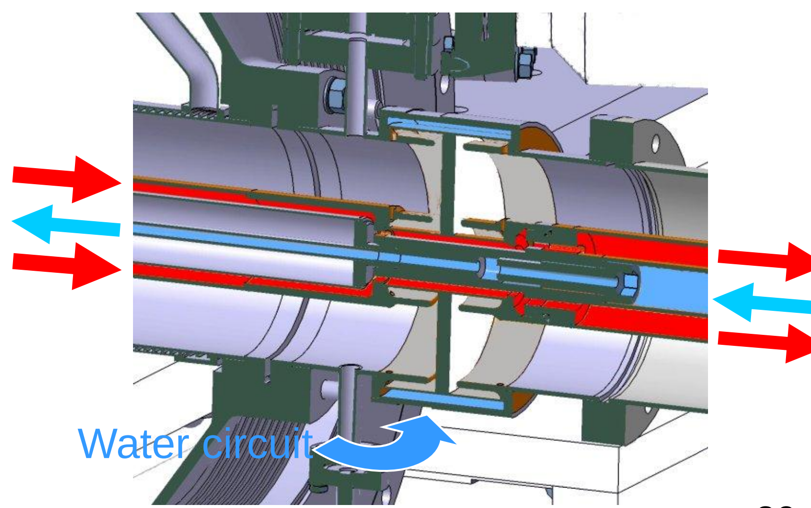
Same general layout as SNS coupler

Single window CEA coupler cooling



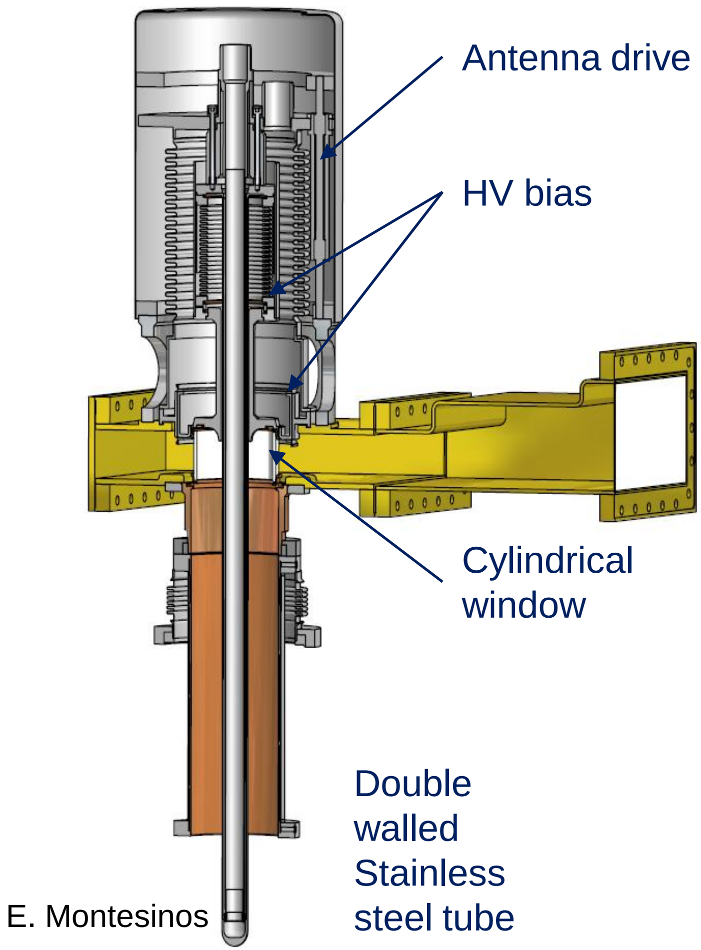
Vacuum side
- Outer conductor (OC) He cooled
- Internal conductor (IC) water cooled
- ceramic outer water cooling channel

Air side
- blown air on the ceramic
- IC also water cooled



Window in transition power coupler

LHC 400 MHz 300 kW CW coupler



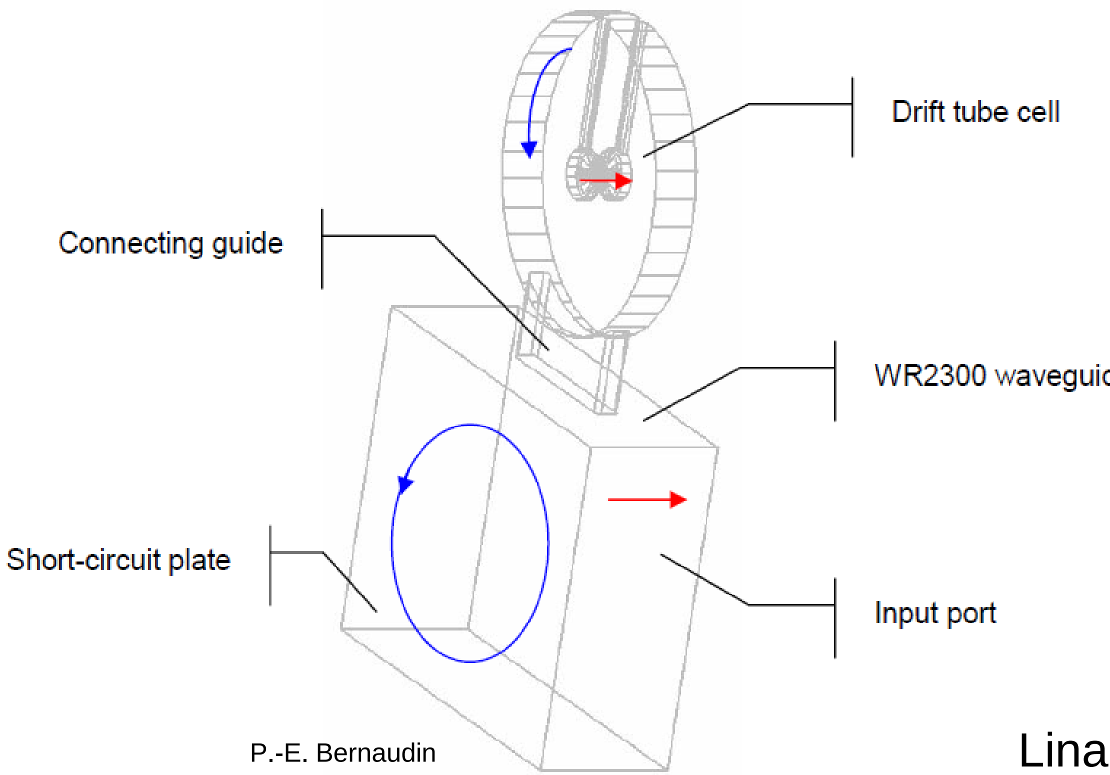
Adjustable coupler (60 mm antenna stroke, factor 20 on Q_{ext}

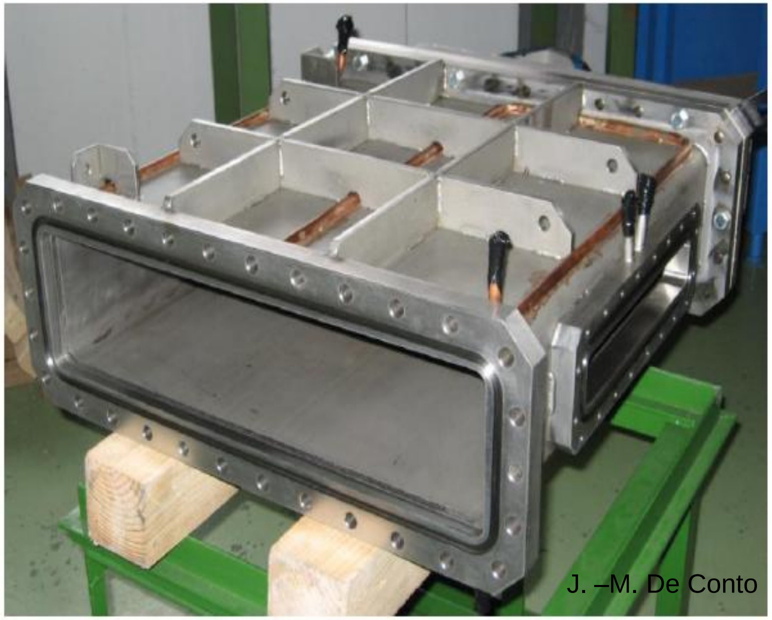
Antenna inner conductor is a copper tube cooled by forced air

A Reduced height waveguide provides matching to the coaxial line

To suppress multipactor during operation two DC bias levels are applied

DTL coupler





Linac4 slot coupler waveguide part before Cu plating

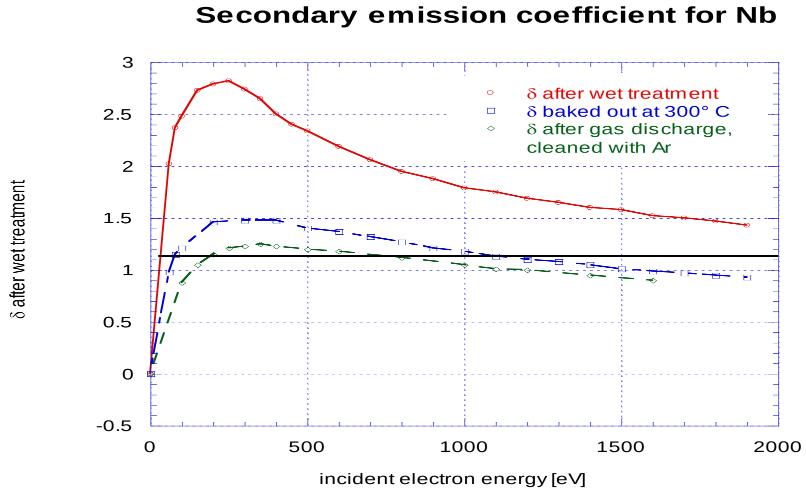
Linac4 DTL slot coupler
Vacuum part : mechanical stiffening and cooling are necessary

Multipacting (MP)

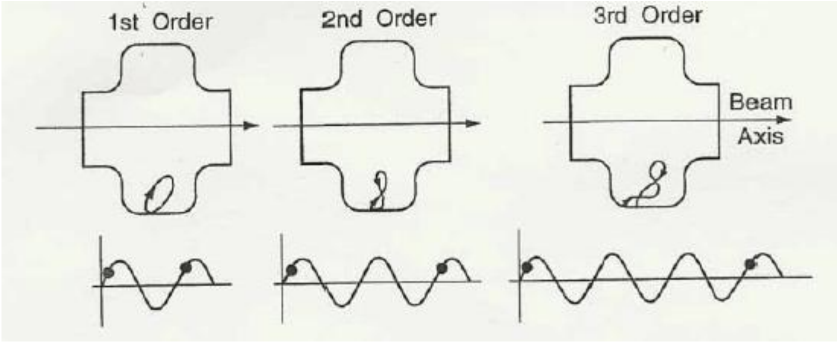
This parasitic phenomenon occurs in vacuum RF devices when :

- Electron (initially emitted from the surface of 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.

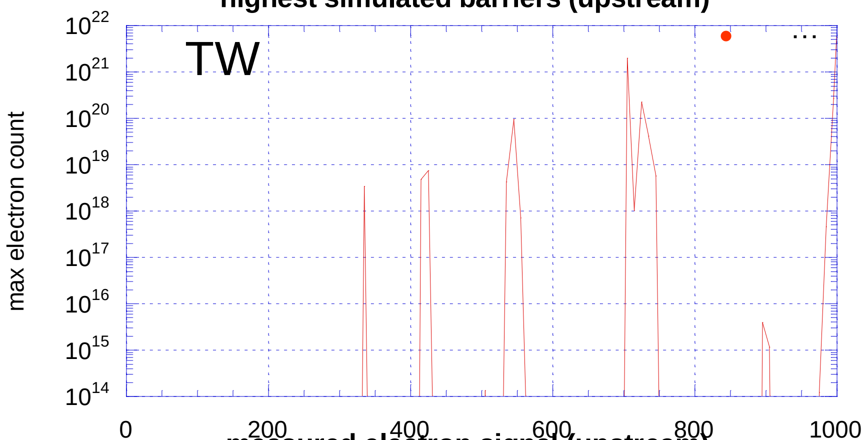
Multipacting

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

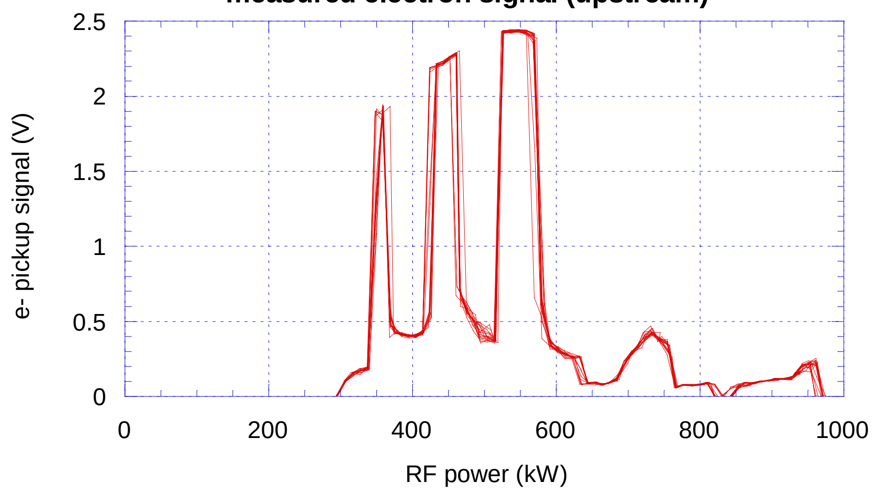
Also scaling laws:

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

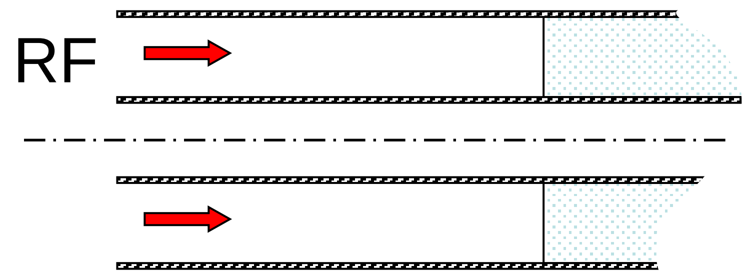
highest simulated barriers (upstream)



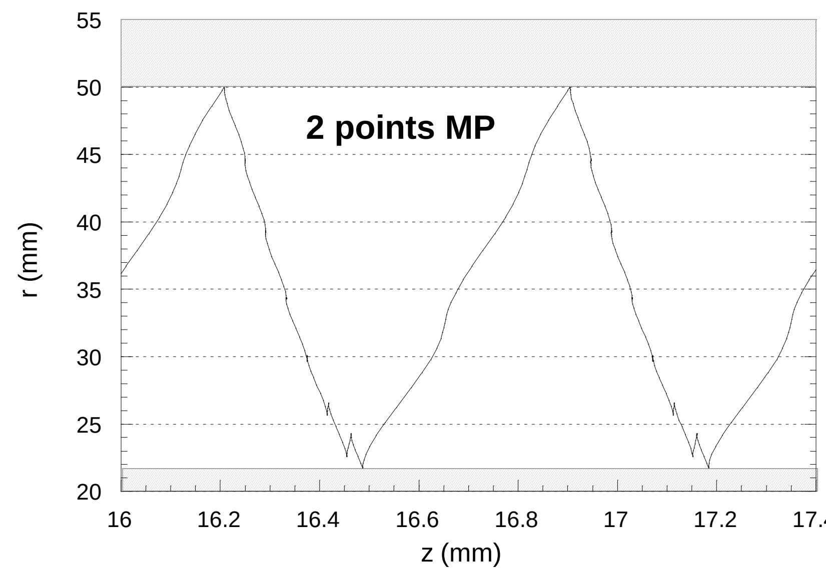
measured electron signal (upstream)



1.3 GHz coaxial line 50 Ohms 60 mm OD



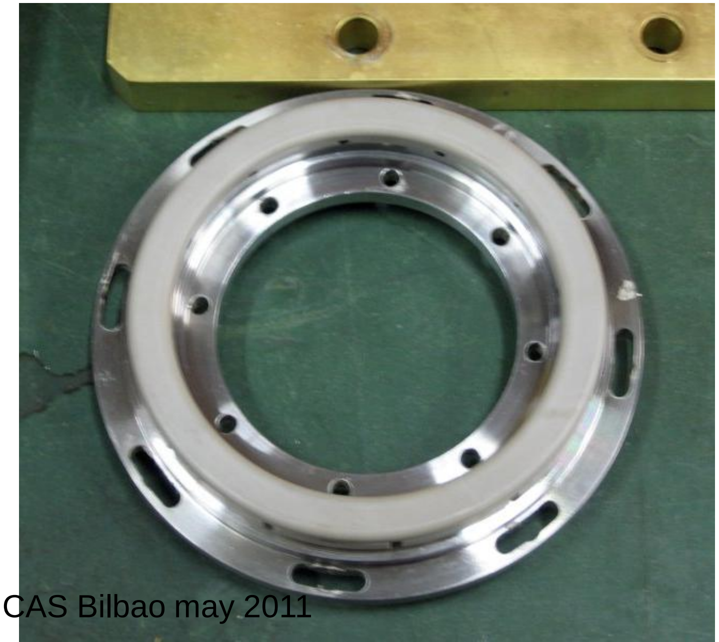
Resonant trajectory with 2-surface impact
Coaxial line 100 mm OD 50 Ohm



MP cures

- Design a MP free coupler
- Reduce the SEY of materials (e.g. TiN deposition on Alumina windows)
- 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 power coupler designs include this option.

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



DESY TTF-3 HV capacitor

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:

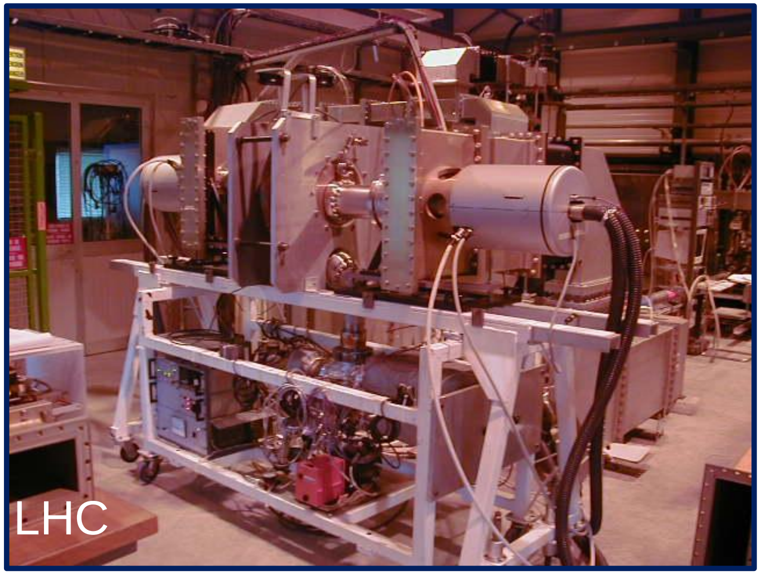
  IF
  - No more outgassing occurs on the full range of power, in traveling wave (TW) and standing wave mode (SW) (p of the order of 10^{-9} mbar)
  - And the coupler sustains the maximum power over long time periods (several hours in a row)

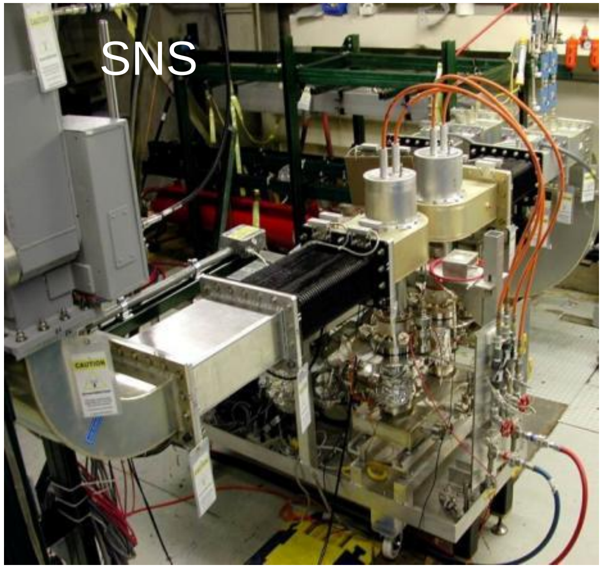
  The coupler is conditioned

- A widespread conditioning strategy :
  - Start with TW, short pulses and ramp the power from 0 to Pmax
  - Increase pulse length up to nominal one, or CW, repeat the power ramp at each stage
  - 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)

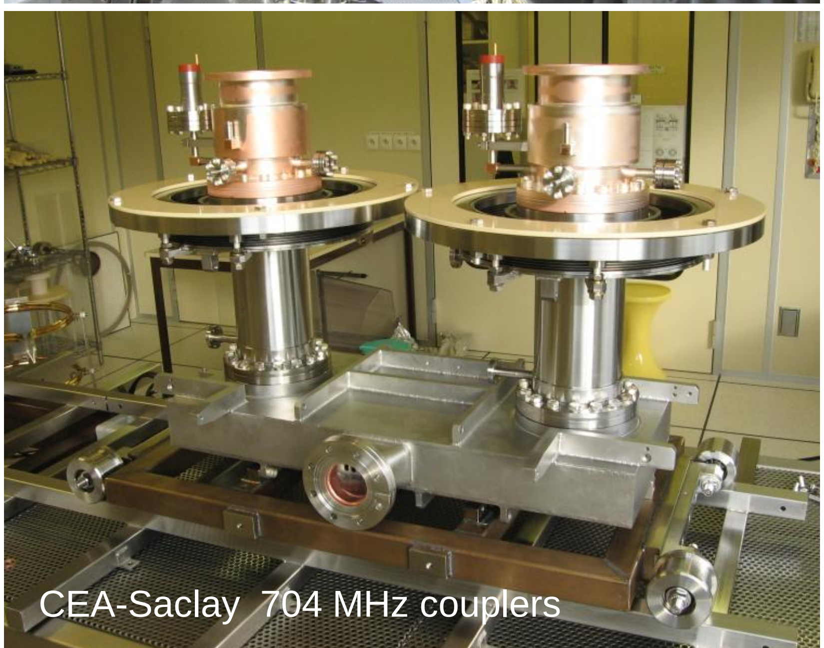
Travelling wave setups

- 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





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

Tuners

What are tuners for?

Or why would we like to change the frequency of a cavity?

- Correct the static frequency
  - Actual geometry differs from the theoretical one
    - Temperature is different than foreseen
    - The cavity experiences deformations in its normal operating environment, which were not fully known at the design stage (external pressure, supports or mechanical parts with different expansion coefficients)
    - Fabrication errors (mechanical tolerances)
    - Surface treatments (Nb cavities) or deposition have modified the cavity ‘volume’ differently than predicted
  - Lorentz detuning (electromagnetic radiation pressure)
  - Need to adapt the frequency to beam operation
    - Change the tuning angle for beam loading as current changes
    - Reduce the beam-cavity interaction in case of a faulty component,
    - ‘switch off’ a cavity for machine calibration purposes (commissioning : cavity phase scans, time of flight)
- Compensate for fast variations
  - Dynamic Lorentz detuning (pulsed RF) – timescale 1 ms
  - Microphonics – timescale 10 ms – 10 s

Material	$\lvert\Delta L/L\rvert$ 273K-4K (%)
Nb	0.13
Ti	0.13
Stainless steel	0.27
Cu	0.3

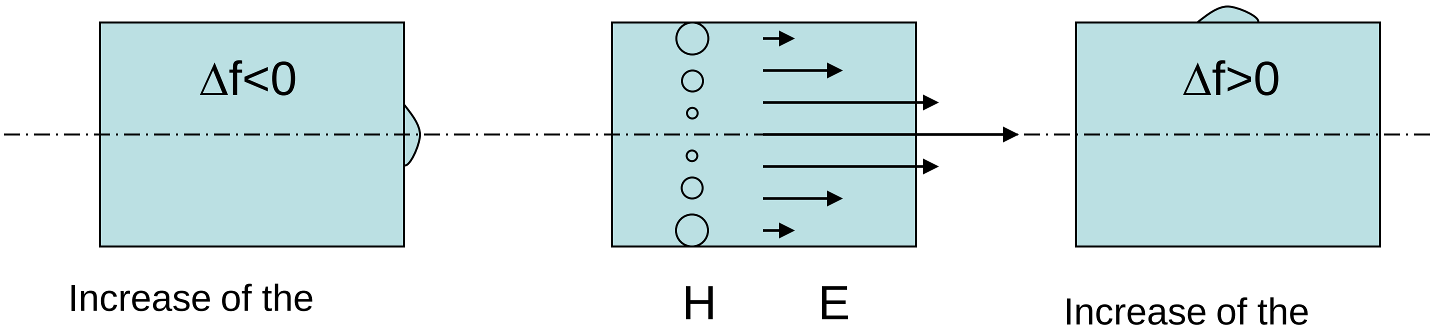
Tuning by changing the EM boundaries

Slater theorem for small displacements of the cavity surface

$$\frac{\Delta f}{f} = \frac{1}{4U}\int_{\delta V}(\varepsilon_0 E^2 - \mu_0 H^2)dV$$

Pill box cavity example with localized bumps:

Pillbox TM01mode



Increase of the cavity volume where H is small (H=0 on axis only), E is large

Increase of the cavity volume where H is large and E=0

In some cases it is preferable to move the surface on a large area but a small amplitude rather than using a large deformation on a small surface area (field distribution

Cooling system

- Obvious solution for room temperature cavities, but limited in range: linear thermal expansion coefficients of the order of 1.710^{-5} (Cu and stainless steel).This means +1°C shifts a 1GHz cavity frequency by 1.7kHz if the whole cavity is expanding freely (not much in the case of a Q_L of 1000, to be compared to a bandwidth of 1MHz)
- Water cooling systems have a single (and only adjustable in a small range) temperature and each cavity has its individual frequency. In this setup the variable is the flow in the cavity cooling channels (and a flow controller for ***each*** cavity). The water flow settings change with power dissipated in the cavities (depending both on field level and frequency itself…)
- Multiple cooling channels can act on different parts of the cavity, and have different effects on the frequency (4-vanne RFQ)
- Not so obvious in fact, can even be unstable

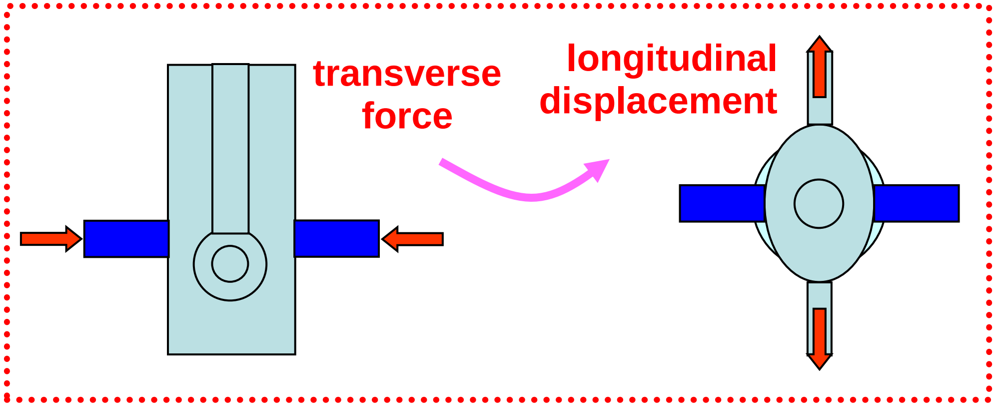
Plunger tuner

- Extensively used for room temperature cavities.
- Require a flexible element
  - bellow : large stroke
  - Flex plate : small stroke
- Warning: the side effect of using a coaxial geometry for plungers creates a RF coupler (short circuited). This is a coupled cavity (quarter wave). By changing the length of the inner conductor (bellow plungers) the plunger resonant frequency is swept. If it crosses the cavity frequency, high losses are likely to occur in the plunger. There are cures:
  - Use several sections with different impedances to change the resonant behavior,
  - Reduce the stroke and use several plungers

Deformation tuners

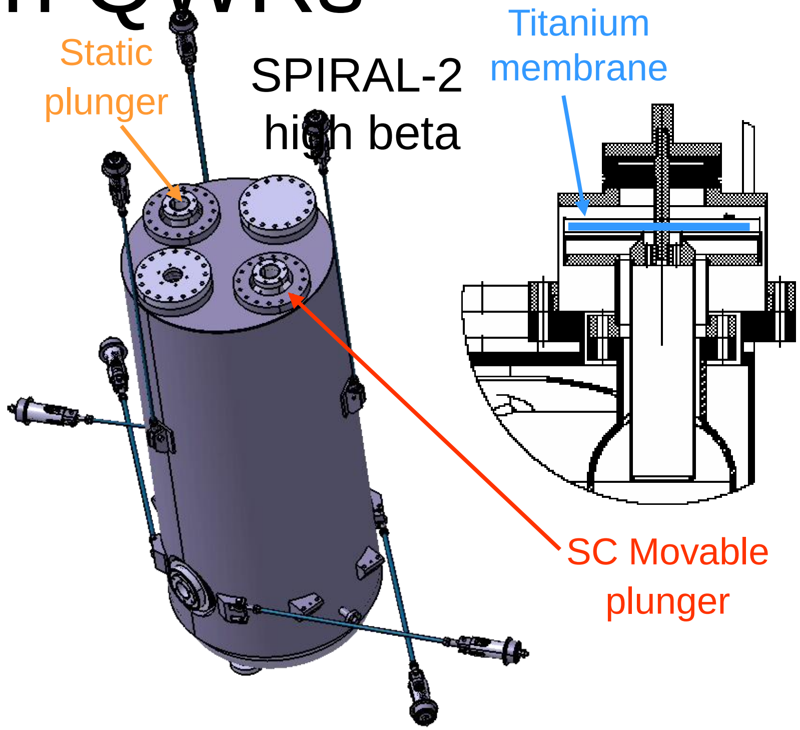
- Their use is restricted to cavities built from sheet-material with a sufficient ***elastic*** range (plastic deformation is used after fabrication to adjust frequency and field distribution in many cavities)
- Mainly used for superconducting cavities
  - Quarter wave resonators acting on the E-field region
  - Elliptical cavities (bellow-like shape): change the cavity length
- Activated by a stepper motor or pneumatic action

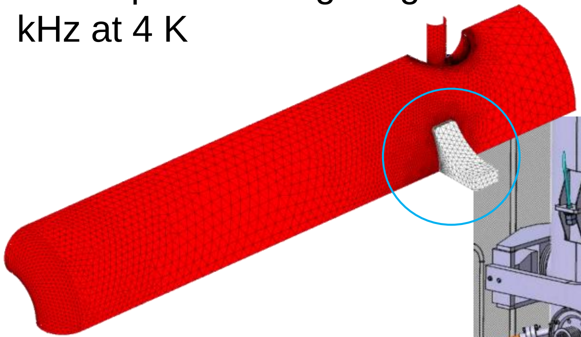
3 approaches on QWRs

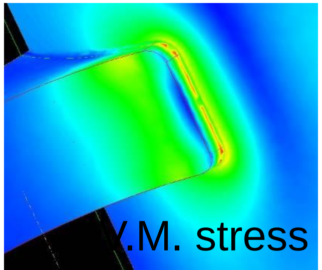


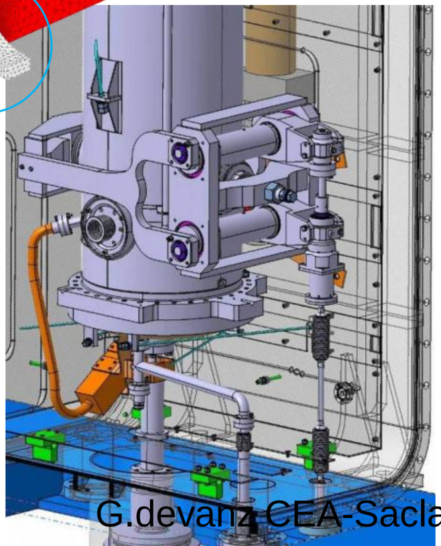
- ❖ transverse mechanical tuner
- ❖ saves longitudinal space
- ❖ low stress on drift tube welds
- ❖ computed tuning range ± 24 kHz at 4 K

SPIRAL-2
low beta









Challenges of tuners for SC cavities

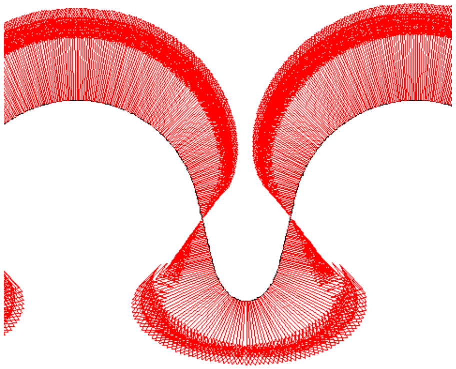
- A part or the whole tuner sits at liquid He temperature (1.8 to 4.5 K in real machines) and under vacuum. This includes:
  - Moving parts (gears, bearings) : solid lubrication (MoS_2) and seizing issue if different materials coexist or cooling rate is inhomogenous
  - And/or flexible parts : elastic properties at low temperature
  - In many designs motors have to work in the same chalenging conditions (this was solved for space industry beforehand)
- A nice feature is the extended elastic range of Nb at LHe temperature (σ_y approx. 400 Mpa), generally the tuning range is limited by the mechanical tuner.
- Some cavities are stiff, require a lot of force from the tuner (up to tens of kN)
- The tuner needs to be much stiffer than the cavity to be efficient
- Piezo electric elements used for fast tuning have reduced stroke at Lhe temperature (10 times less than at room temperature)

Lorentz detuning

- Compensation of microphonics (CW machines, LHe at 4.5K)
- Dynamic Lorentz force detuning compensation

radiation pressure is generated by EM field on the cavity walls

$$P_{rad} = \frac{1}{4}(\mu_0 H^2 - \varepsilon_0 E^2)$$



resulting in cavity deformation and detuning

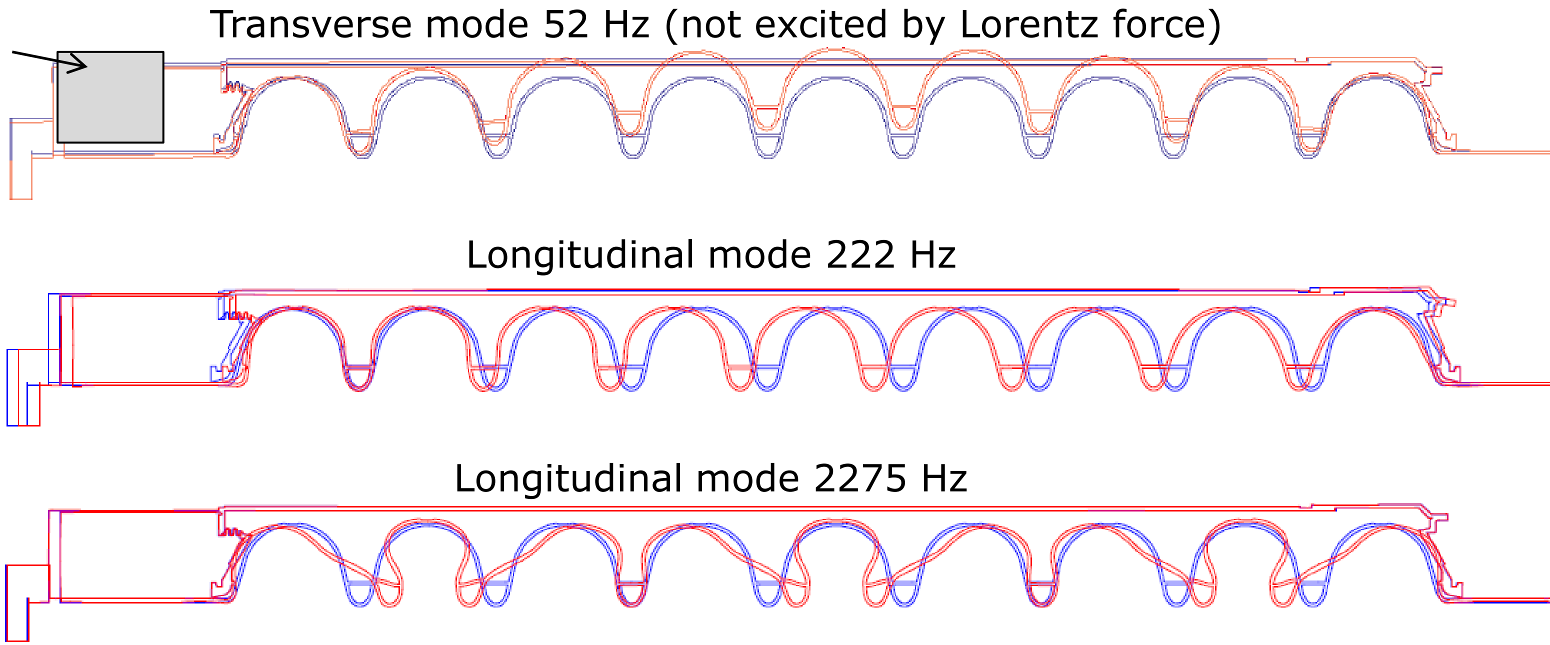
$\Delta f = -K_L E_{\mathbf{acc}}^2$ (static case – CW)

The static Lorentz coefficient K_L depends on :

- cavity wall thickness
- extra stiffening design (rings)
- tuner/tank stiffness

Mechanical eigenmodes excitation

virtual
tuner



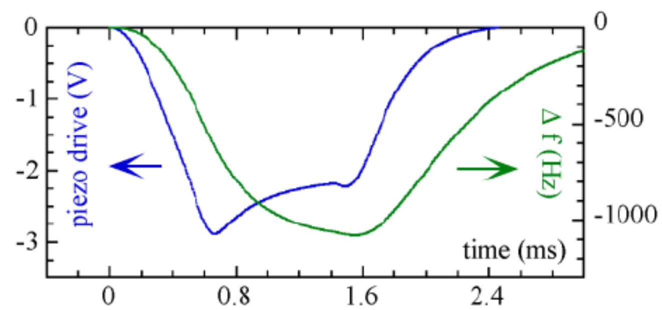
examples for a TTF 9-cell cavity with Saclay-II tuner

For each mechanical mode :

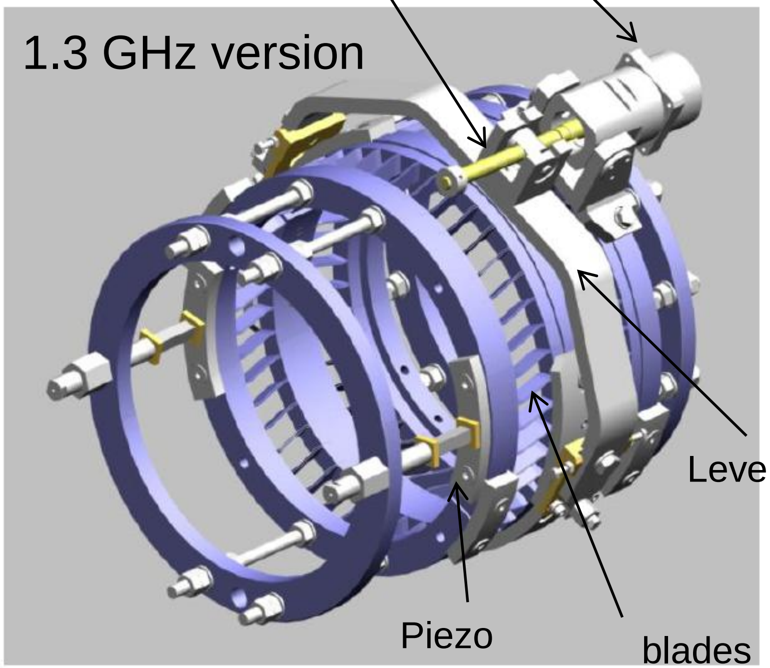
- resonant frequency
- Quality factor
- coupling coefficent to the cavity detuning

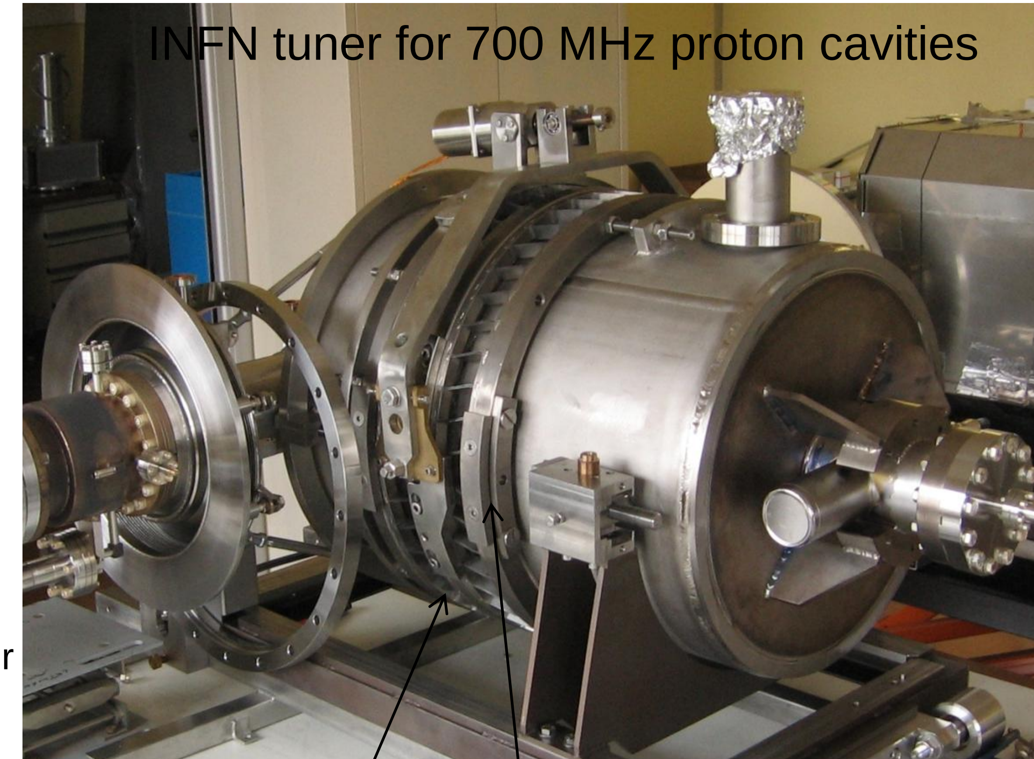
In pulsed operation :

- Lorentz force is an impulse-like excitation
- The time varying cavity detuning is the sum of the contribution of individual modes



Blade tuner

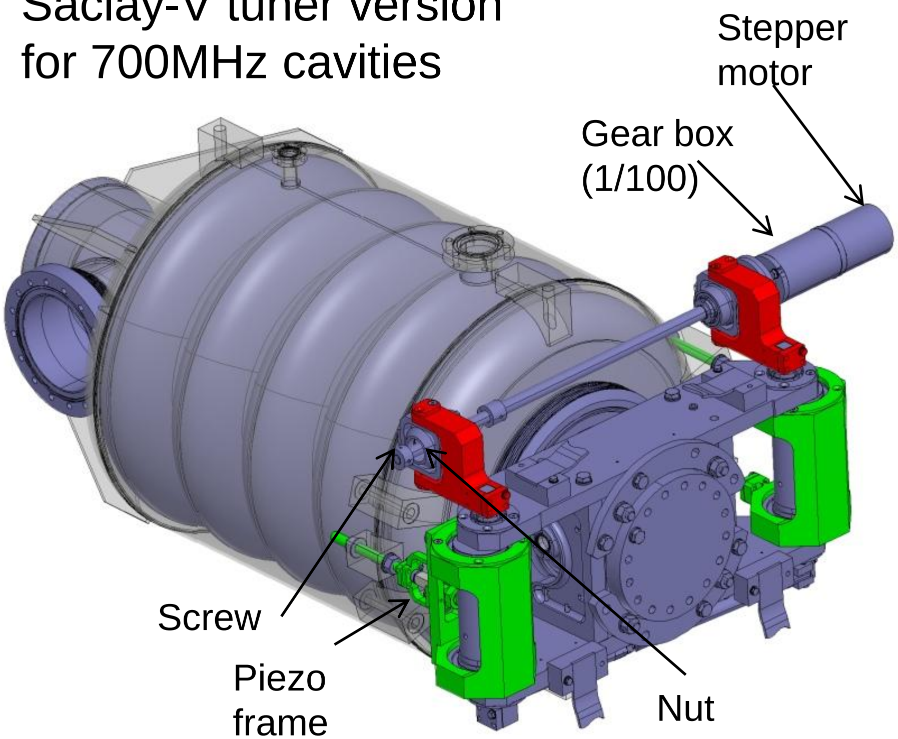


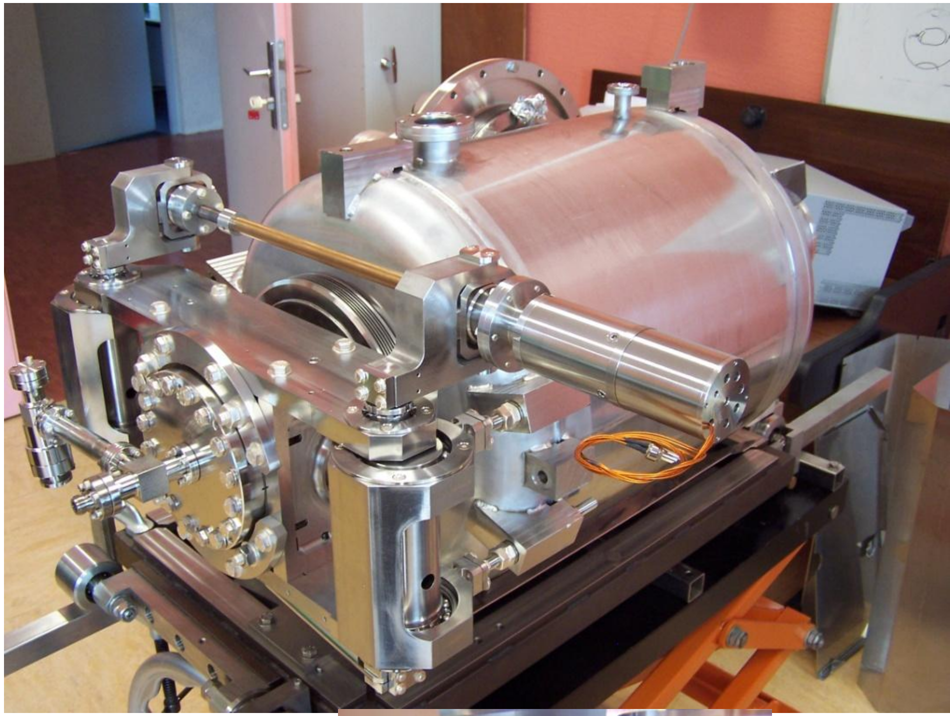


A bellow is located at the center of the He vessel (hidden by the blades)
The screw rotation moves the lever. The torque generated is used to rotate the center flange with respect to the 'fixed' flanges. Since they are connected by blades at an angle, longitudinal force is produced with moves apart both halves of the He tank

Symmetric lever arm tuner

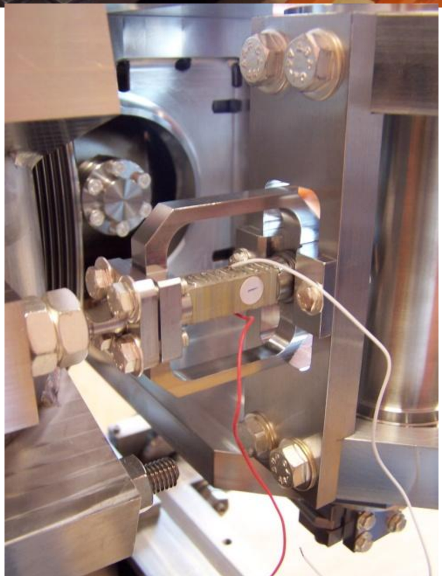
Saclay-V tuner version
for 700MHz cavities



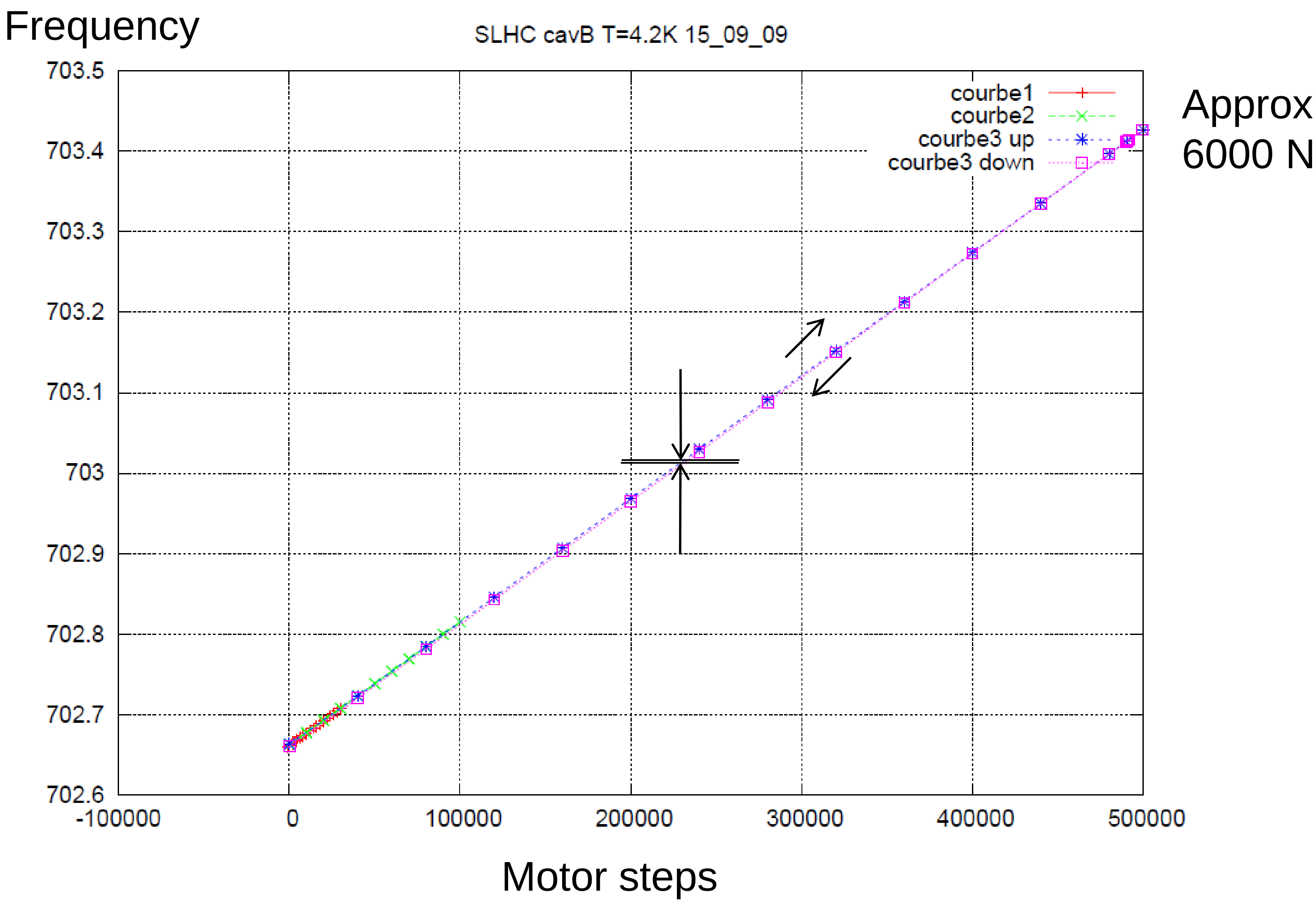


Screw rotation spreads the arms connected to the cam spindles, which translate the rotation in longitudinal force.
Displacement range is +/- 3.5 mm

Low voltage
piezo-stack
in preload frame



Tuner linearity



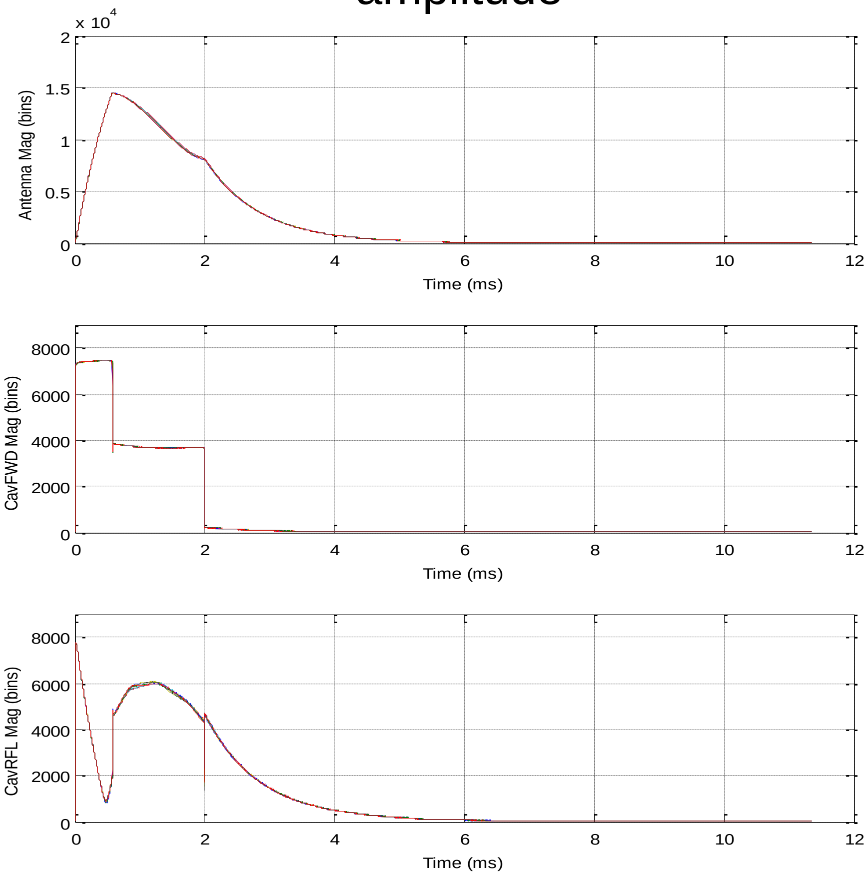
Linearity: the tuner is efficient, does not experience deformation

Hysteresis : friction, play

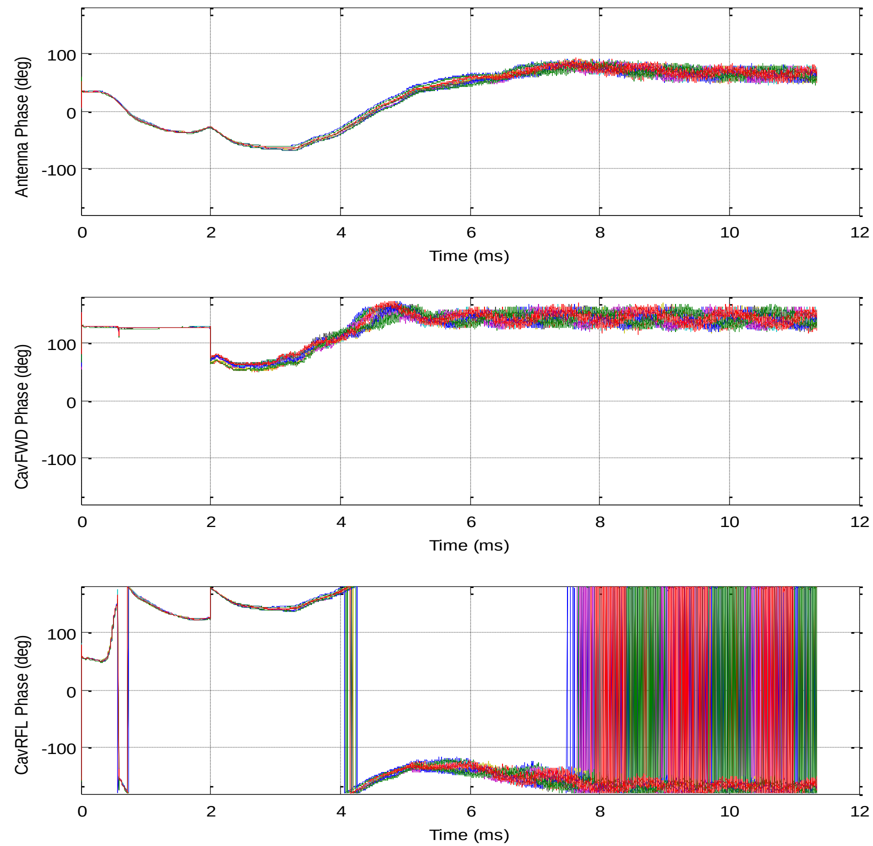
Lorentz detuning compensation (off)

Piezo off

amplitude



phase

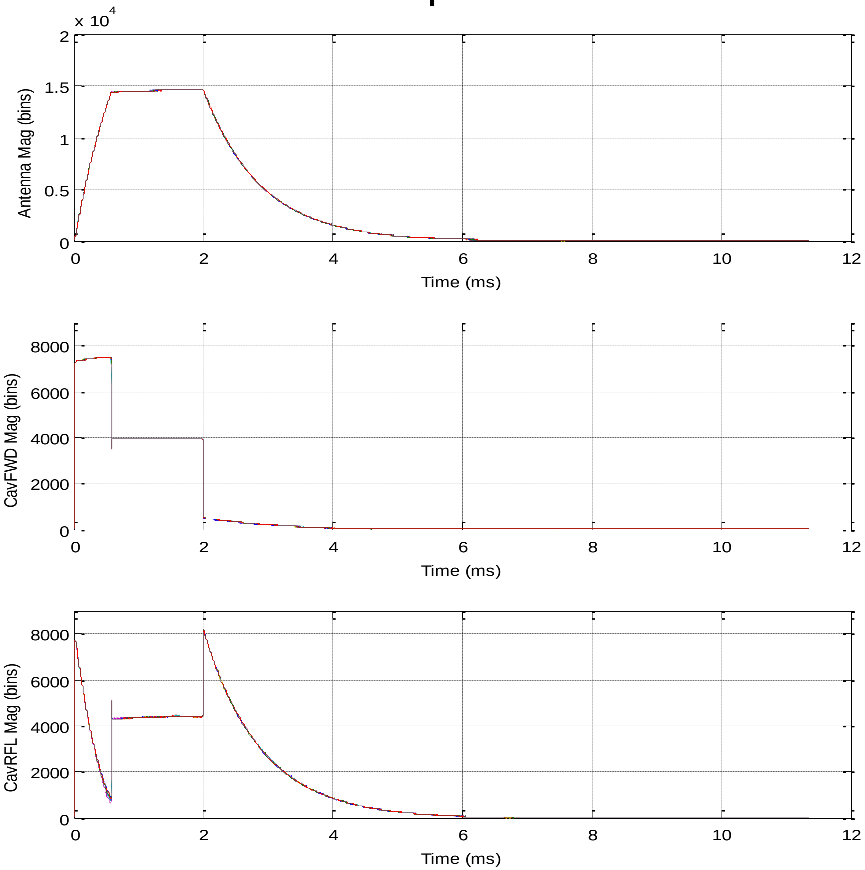


Cavity beta 0.47 : Eacc=13 MV/m
RF: Repetition frequency = 50Hz, pulse length 2ms

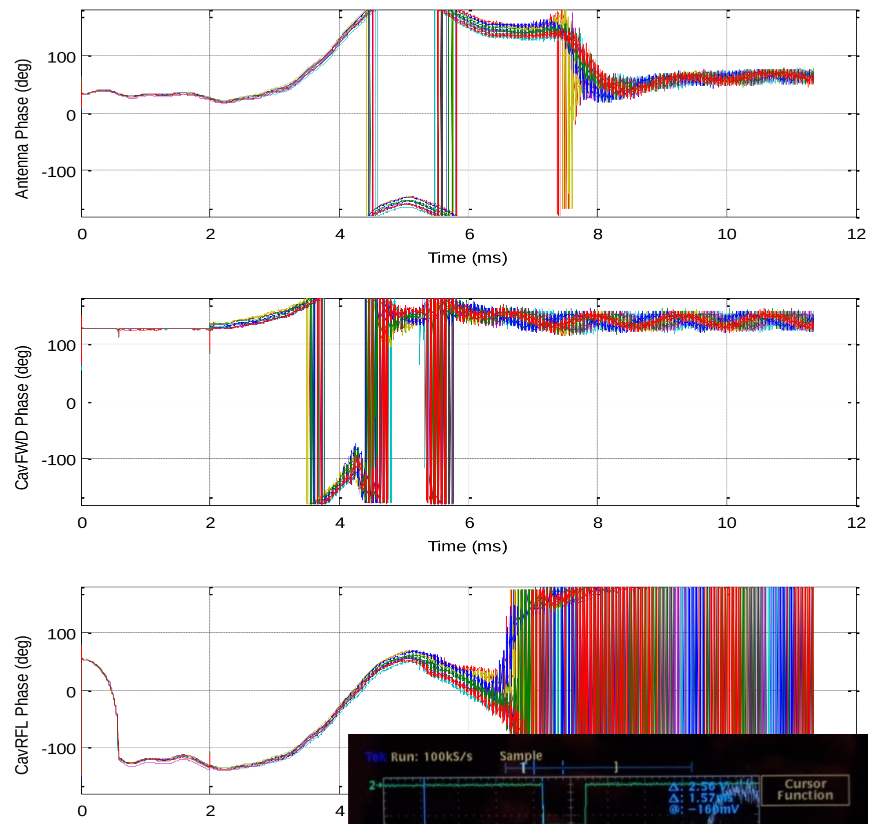
Lorentz detuning compensation (on)

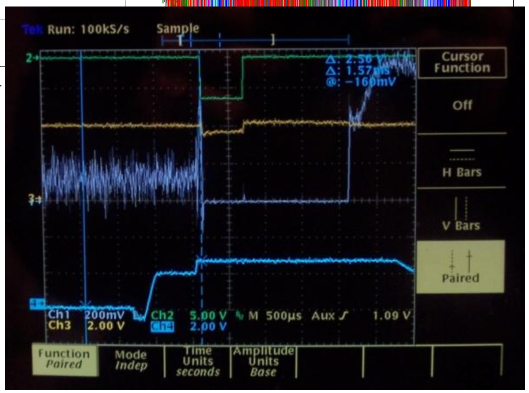
Piezo ON

amplitude



phase





LFD Compensation achieved setting manually signal generators driving the piezo actuator. The piezo drive signal starts 940 μs before the RF pulse (Saclay-V)