
Photo:
Reidar Hahn

Power couplers, higher-order mode (HOM) damping

Special thanks to Eric Montesinos (CERN)!


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What is a Power Coupler ?

- The Power Coupler has to transfer the RF power of the generator into the cavity ensuring the beam vacuum integrity
- In addition, with SRF cavities, Power Couplers have to cope with specific requirements such as cold to warm transition and integration with the cryomodule

- Several names for the same device
- FPC : Fundamental Power Coupler
- MPC : Main Power Coupler
- MC : Main Coupler
- PC : Power Coupler
- Coupler


Photo:
Reidar Hahn

What is a High Order Modes Coupler ?

- High Order Modes (HOM) are Eigenmodes parasitically excited by a beam in a resonant RF cavity, other than the operating frequency
- Each cavity has HOM couplers designed to extract the power and provide a transmission path at the HOM frequencies and act as a stop-band to the fundamental mode

- Several names for the same device
- HOM Couplers
- HOM Filters
- HOM Dampers
- HOM Suppressors

- With future machines (especially true for circular) the HOM couplers have to extract large amount of power (few kW), becoming like FPC


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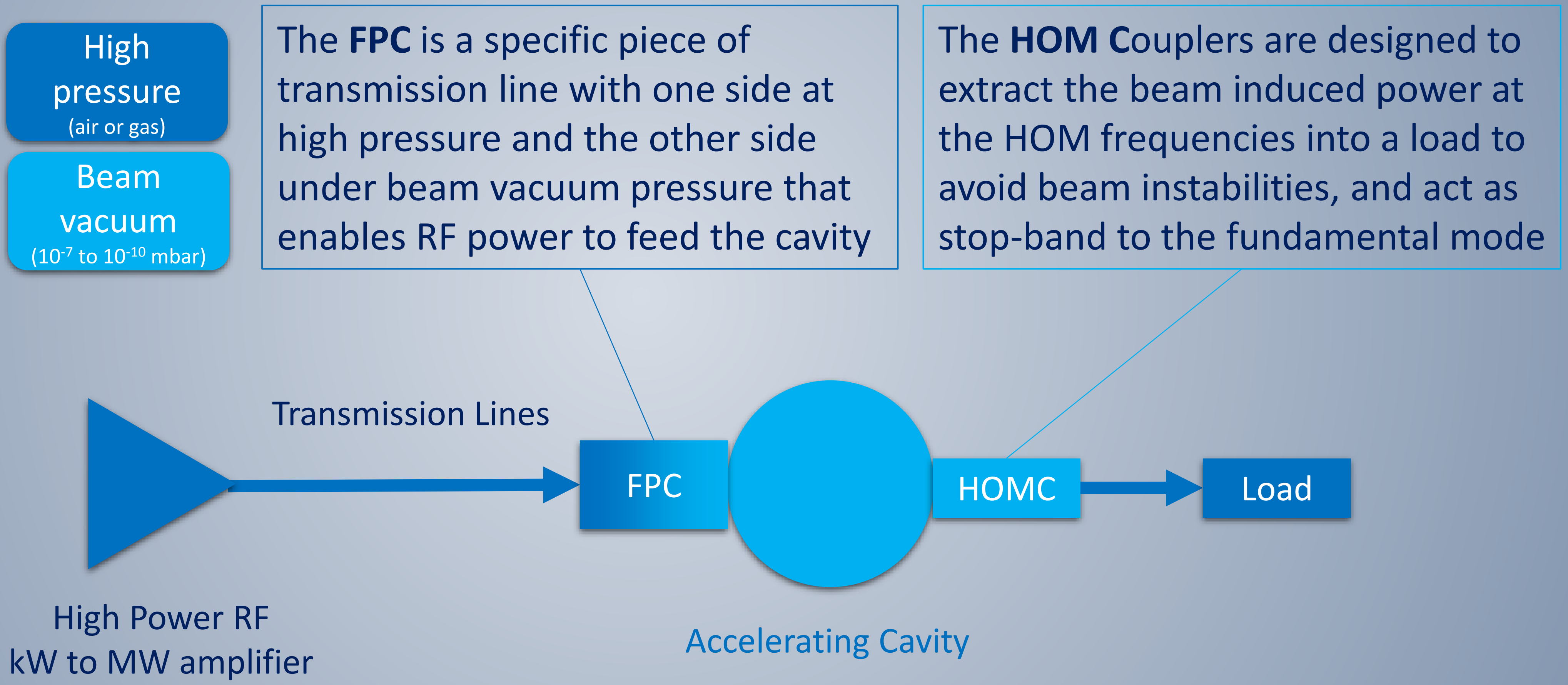
RF systems


High pressure (air or gas)

Beam vacuum (10^{-7} to 10^{-10} mbar)

The **FPC** is a specific piece of transmission line with one side at high pressure and the other side under beam vacuum pressure that enables RF power to feed the cavity

The **HOM C**ouplers are designed to extract the beam induced power at the HOM frequencies into a load to avoid beam instabilities, and act as stop-band to the fundamental mode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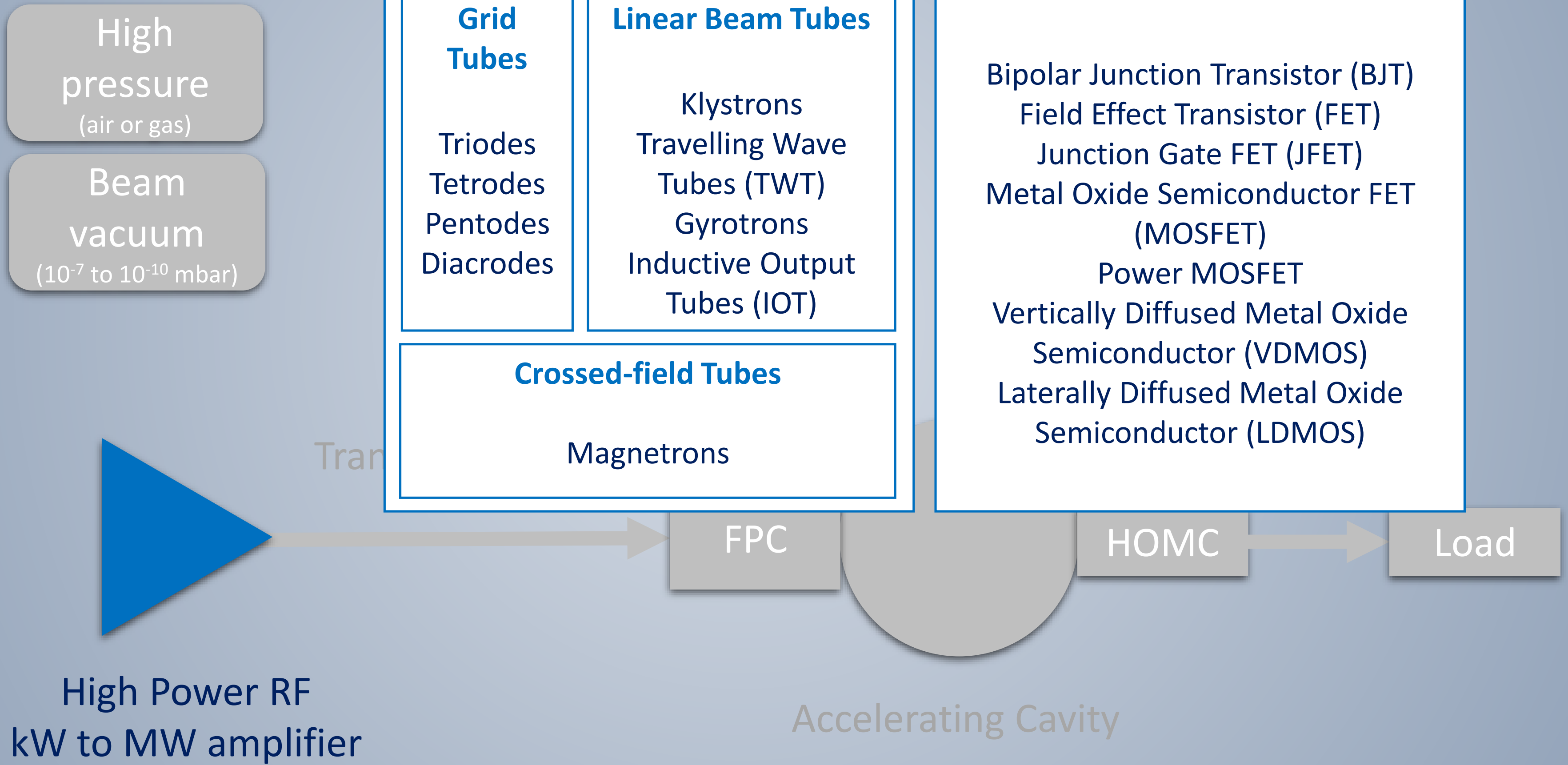
High Power RF amplifier



High Power RF
kW to MW amplifier

Vacuum Tubes

Grid Tubes

Triodes
Tetrodes
Pentodes
Diacrodes

Linear Beam Tubes

Klystrons
Travelling Wave Tubes (TWT)
Gyrotrons
Inductive Output Tubes (IOT)

Crossed-field Tubes

Magnetrons

Transistors

Bipolar Junction Transistor (BJT)
Field Effect Transistor (FET)
Junction Gate FET (JFET)
Metal Oxide Semiconductor FET (MOSFET)
Power MOSFET
Vertically Diffused Metal Oxide Semiconductor (VDMOS)
Laterally Diffused Metal Oxide Semiconductor (LDMOS)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Tetrode

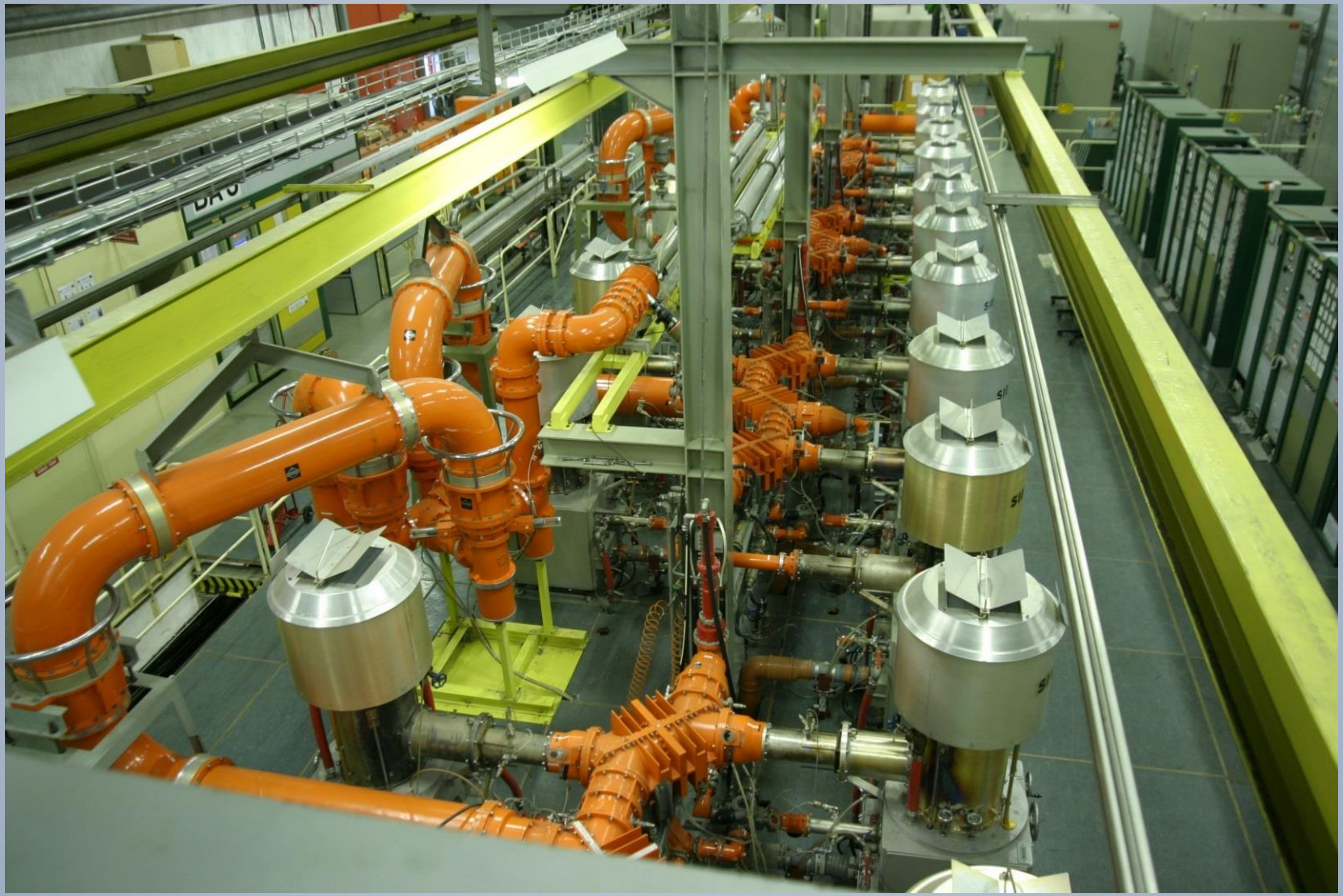
RS 2004 CERN SPS amplifier 1 MW @ 200 MHz

CERN SPS, RS 2004 Tetrode, Trolley (single amplifier), and transmitter (combination of amplifiers)
Two transmitters of eight tubes delivering 2 x 1 MW @ 200 MHz, into operation since 1976


Photo:
Reidar Hahn

Tetrode

RS 2004 CERN SPS amplifier 1 MW @ 200 MHz

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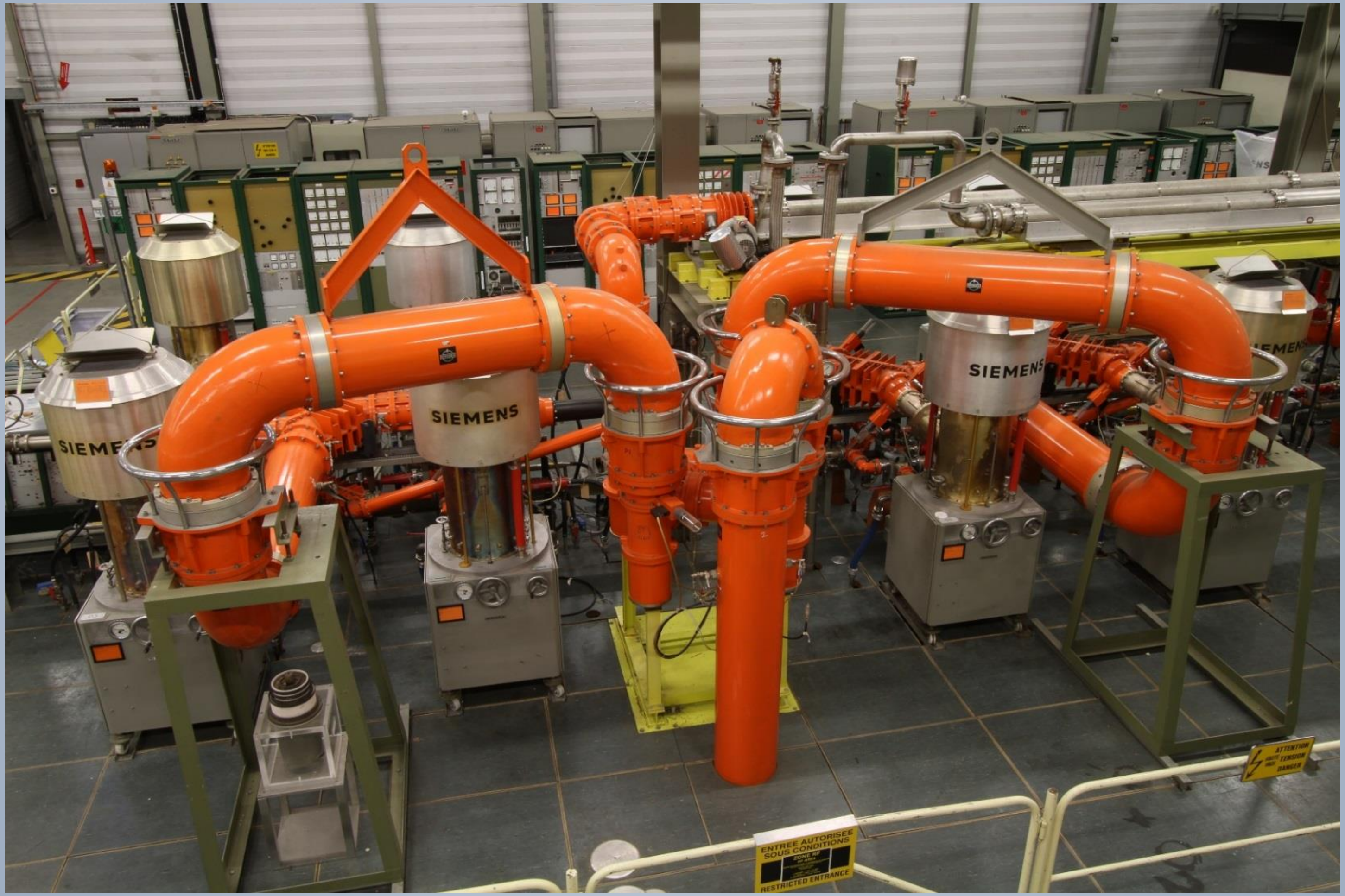
Tetrode

RS 2004 CERN SPS amplifier 1 MW @ 200 MHz



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IOT

TH 795 CERN SPS 220 kW @ 800 MHz

CERN SPS, TH 795 IOT, Trolley (single amplifier), and transmitter (combination of amplifiers)
Two transmitters of four tubes delivering 2 x 240 kW @ 801 MHz, into operation since 2014

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IOT

TH 795 CERN SPS 220 kW @ 800 MHz


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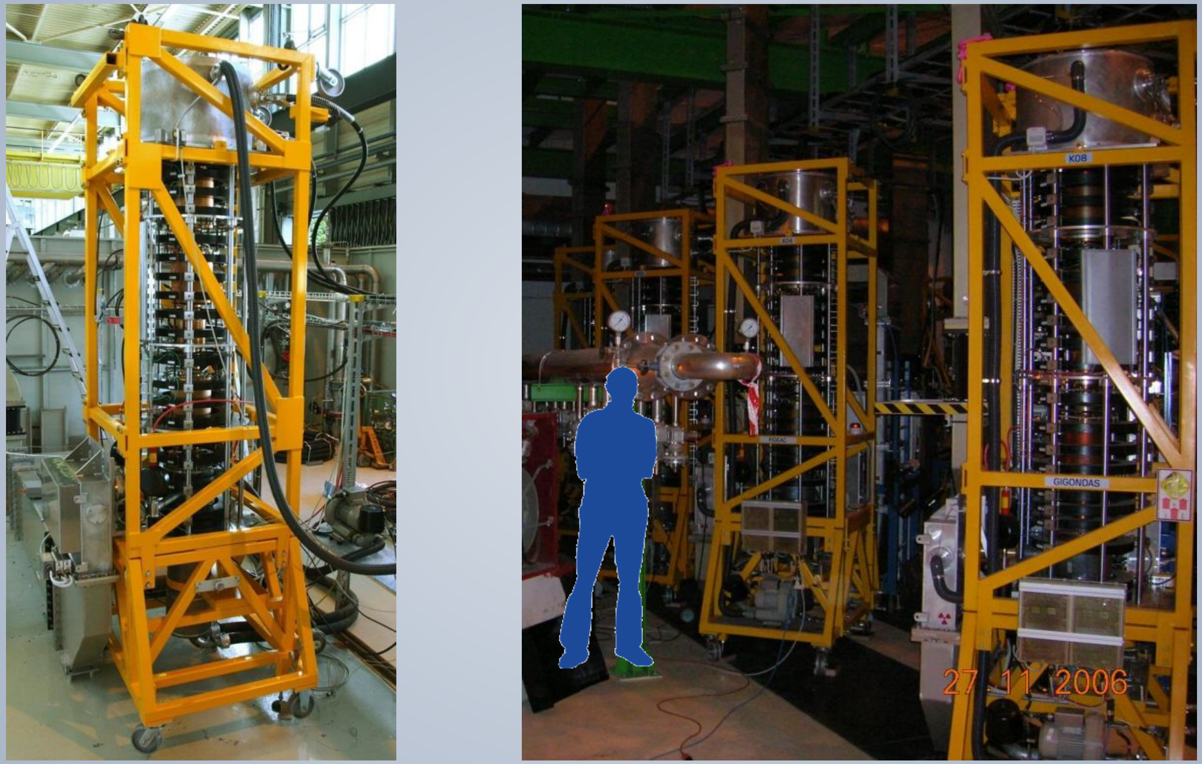
Klystron

TH 2167 CERN LHC 330 kW @ 400 MHz



CERN LHC, TH 2167 klystron in lab and in UX45 cavern
16 klystrons delivering 330 kW @ 400 MHz, into operation since 2008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Klystron

TH 2167 CERN LHC 330 kW @ 400 MHz


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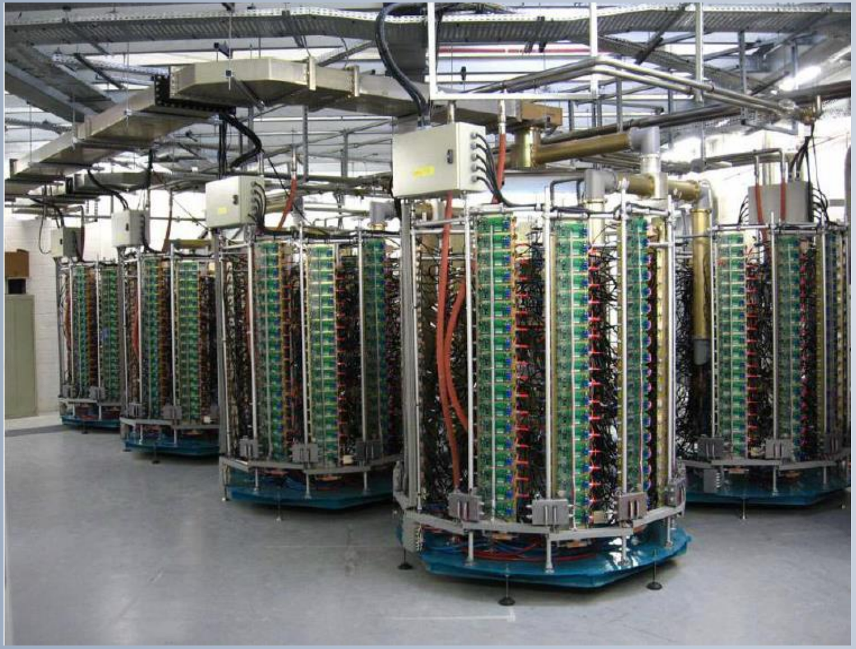
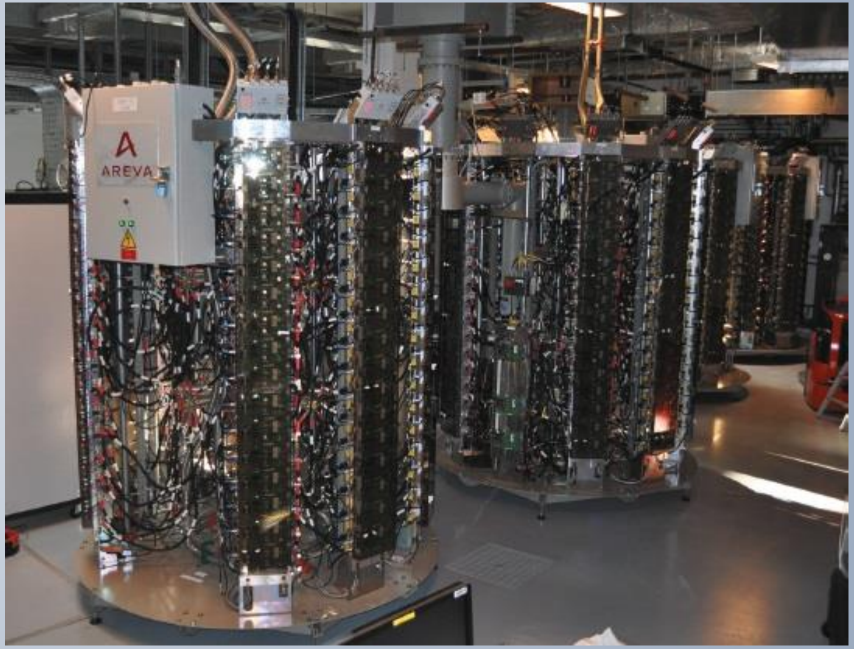
Transistors

SOLEIL 45 kW @ 352 MHz and ESRF 150 kW @ 352 MHz


SOLEIL 45 kW @ 352 MHz
solid state amplifier towers (2004 & 2007)



ESRF four 150 kW @ 352 MHz
solid state amplifiers (2012)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Transistors

CERN 150 kW @ 200 MHz

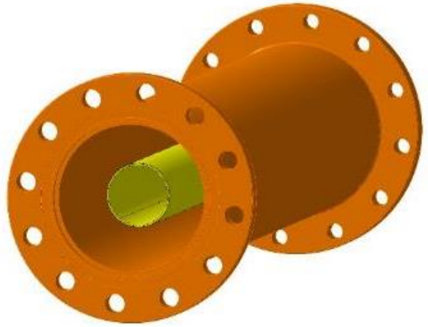

Photo: Reidar Hahn

Transmission lines

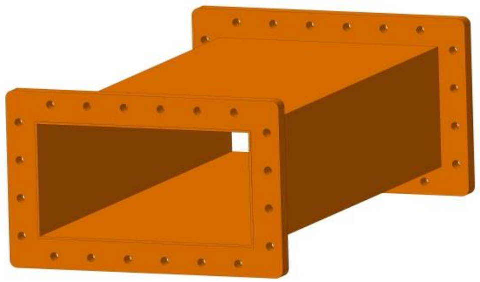
High pressure (air or gas)

Beam vacuum (10^{-7} to 10^{-10} mbar)

Coaxial Lines



Rectangular Waveguides




Transmission Lines

FPC

HOMC

Load

High Power RF
kW to MW amplifier

Accelerating Cavity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Transmission Lines

Coaxial 345 mm


Photo:
Reidar Hahn

Transmission Lines

Coaxial 345 mm

Photo:
Reidar Hahn

Transmission Lines

Coaxial 345 mm


Photo:
Reidar Hahn

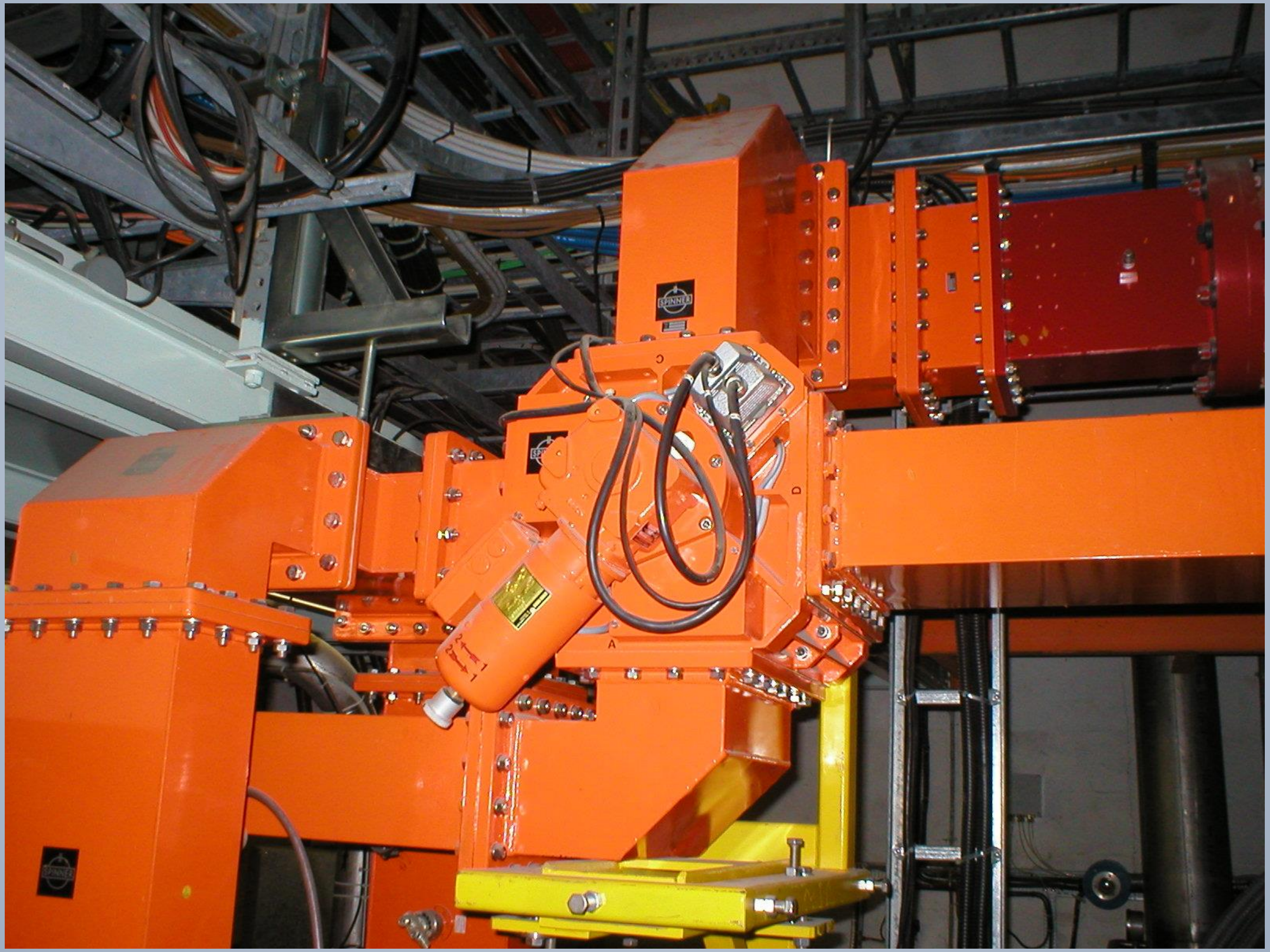
Transmission Lines

Coaxial 345 mm

Photo:
Reidar Hahn

Transmission Lines

WG 1150 rectangular WG

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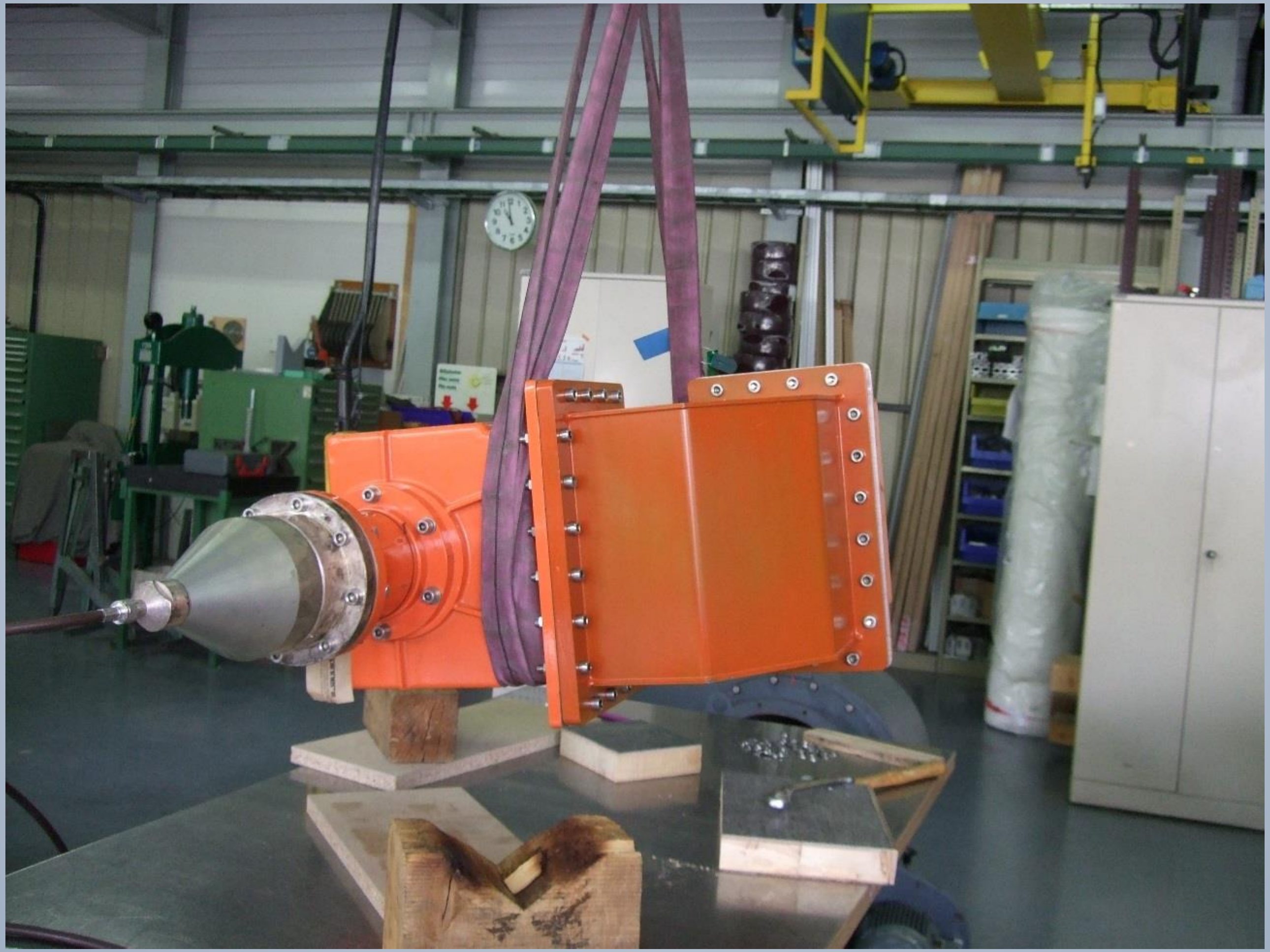
Transmission Lines

WG 1150 to N adaptor

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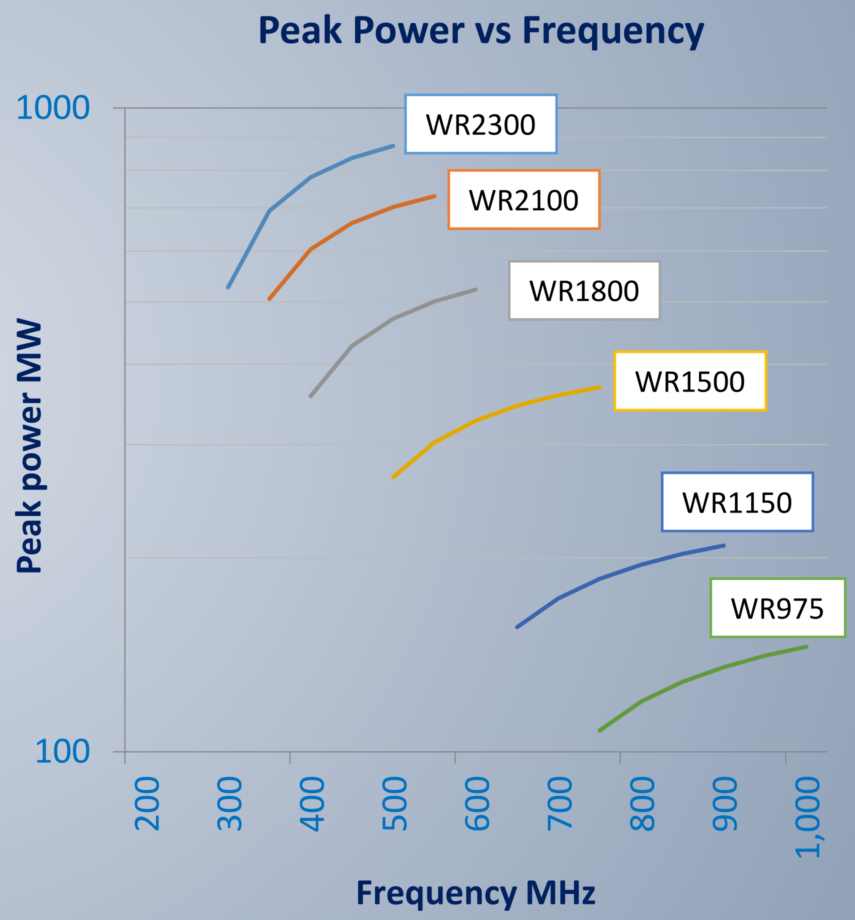
Rectangular waveguides - Maximum Power handling

- $P = 6.63\ 10^{-4}\ {E_{\max}}^2 \sqrt{b^2(a^2 - \frac{\lambda^2}{4})}$

with

P	power in W
a	waveguide width in cm
b	waveguide height in cm
λ	Free space wavelength in cm
$E_{\max}$	Breakdown field of dielectric filling in V/cm

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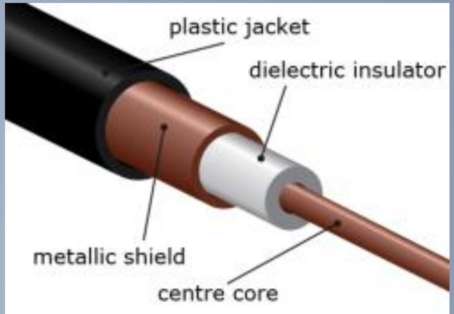
Coaxial lines

Characteristic impedance

- $Z_c = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{D}{d}\right)$
  with

Z_c	Characteristic impedance in Ohm
D	inner diameter of outer conductor
d	outer diameter of inner conductor
ε_r	relative dielectric constant

Coaxial cables are often with PTFE foam to keep concentricity



Flexible lines have spacer helicoidally placed all along the line

Rigid lines are made of two rigid tubes maintained concentric with supports

Size	Outer conductor		Inner conductor	
	Outer diameter	Inner diameter	Outer diameter	Inner diameter
7/8"	22.2 mm	20 mm	8.7 mm	7.4 mm
1 5/8"	41.3 mm	38.8 mm	16.9 mm	15.0 mm
3 1/8"	79.4 mm	76.9 mm	33.4 mm	31.3 mm
4 1/2"	106 mm	103 mm	44.8 mm	42.8 mm
6 1/8"	155.6 mm	151.9 mm	66.0 mm	64.0 mm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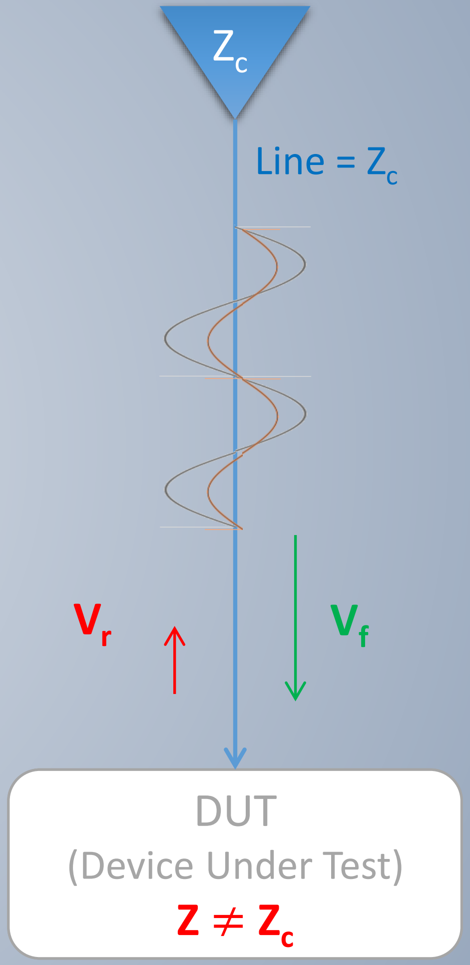
Reflection from Device Under Test (DUT)

- Standing Wave Ration SWR is a measure of impedance matching of DUT
- A wave is partly reflected when a transmission line is terminated with other than a pure resistance equal to its characteristic impedance
- The reflection coefficient is defined by
- $\Gamma = \frac{V_r}{V_f}$

$\Gamma = -1$	when the line is short-circuited complete negative reflection
$\Gamma = 0$	when the line is perfectly matched, no reflection
$\Gamma = 1$	when the line is open-circuited complete positive reflection



DUT
(Device Under Test)
$Z \neq Z_c$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Reidar Hahn

Reflection from Device Under Test (DUT)

At some points along the line the forward and reflected waves are exactly in phase

$$|V_{max}| = |V_f| + |V_r| = |V_f| + |\Gamma V_f| = (1 + |\Gamma|)\,|V_f|$$

full reflection

$$|V_{max}| = 2\,|V_f|$$

At other points they are 180° out of phase

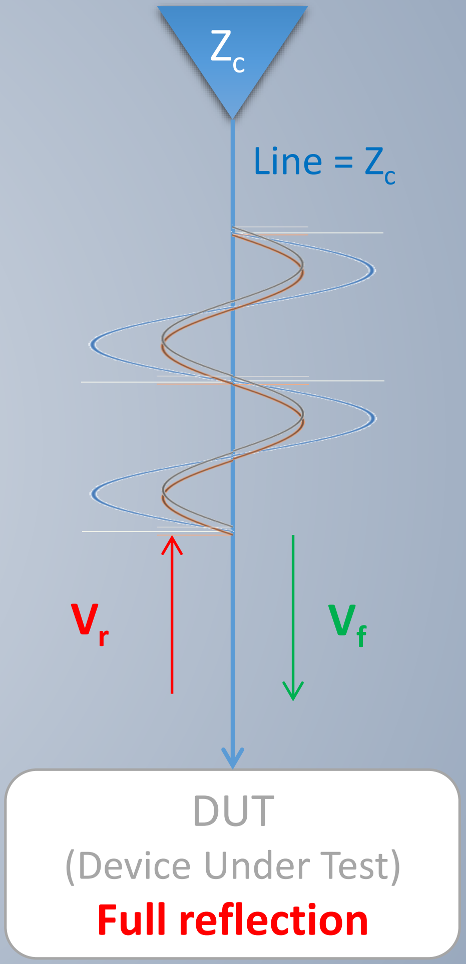
$$|V_{min}| = |V_f| - |V_r| = |V_f| - |\Gamma V_f| = (1 - |\Gamma|)\,|V_f|$$

full reflection

$$|V_{min}| = 0$$

The Voltage Standing Wave Ratio is equal to

$$VSWR = \frac{|V_{max}|}{|V_{min}|} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$



DUT
(Device Under Test)
Full reflection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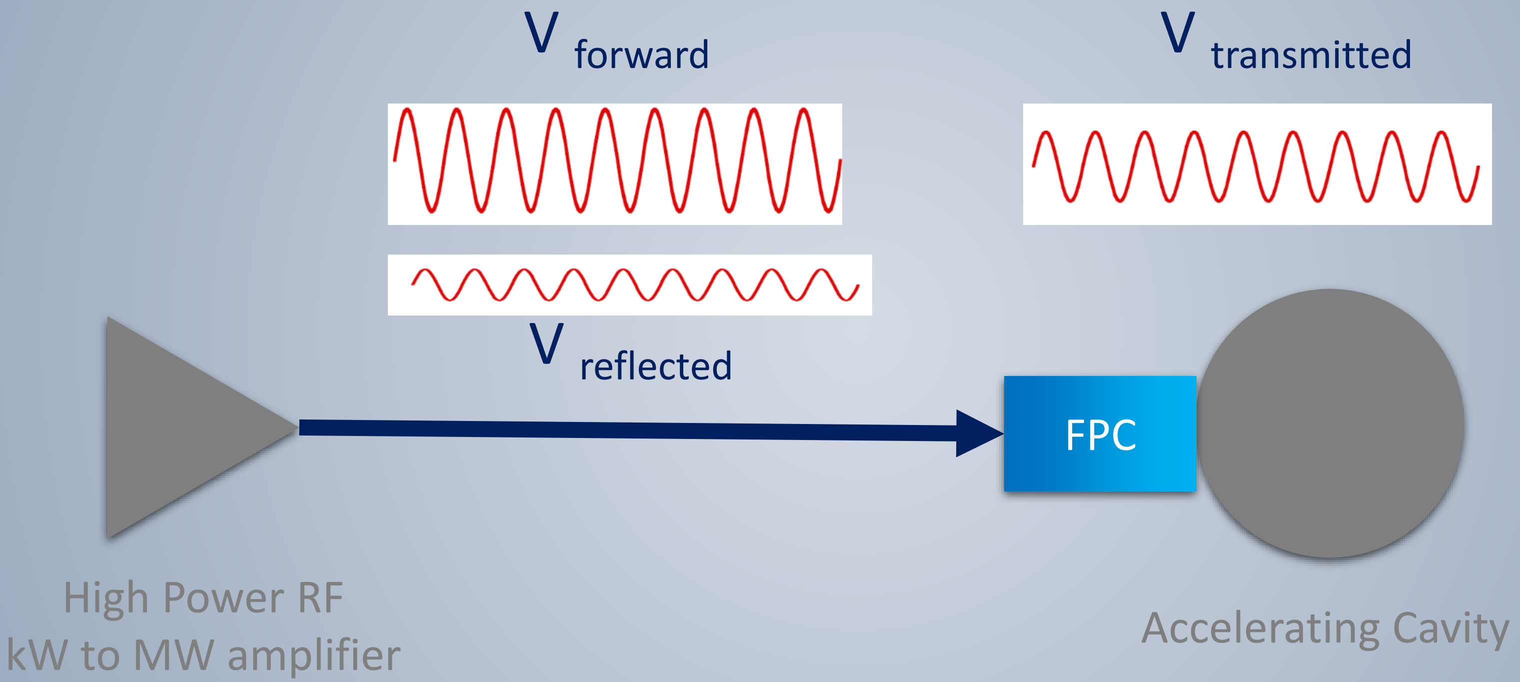
Mismatch

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Fundamental Power Coupler – FPC

High pressure (air or gas)

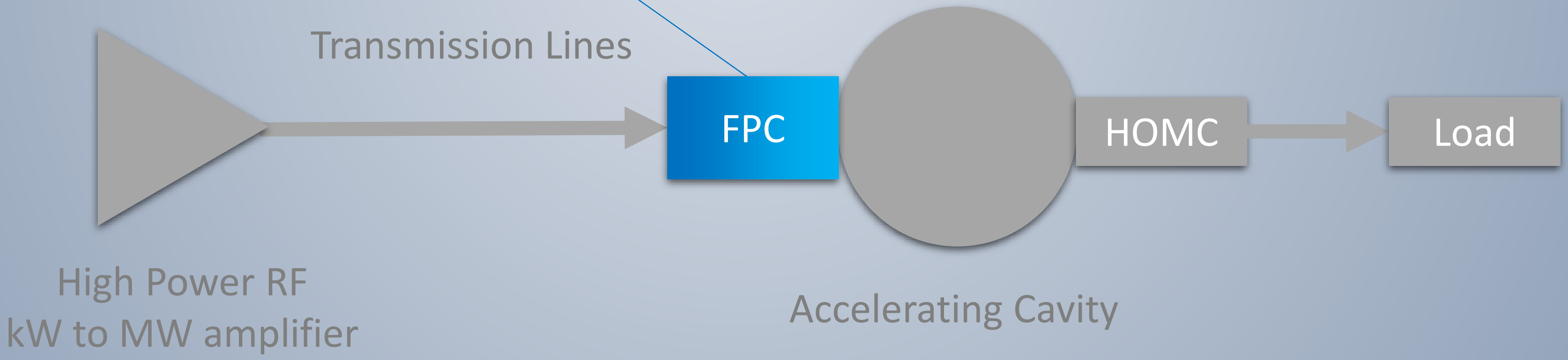
Beam vacuum (10^{-7} to 10^{-10} mbar)

The **FPC** is a specific piece of transmission line with one side at high pressure and the other side under beam vacuum pressure that enables RF power to feed the cavity

FPC, one of the most critical device of the RF cavity system in an accelerator.

It deserves a good RF design, a good mechanical design and a high quality fabrication for an efficient and reliable operation.

Even if not technical, the cost must be taken into consideration as FPC can easily become very expensive.

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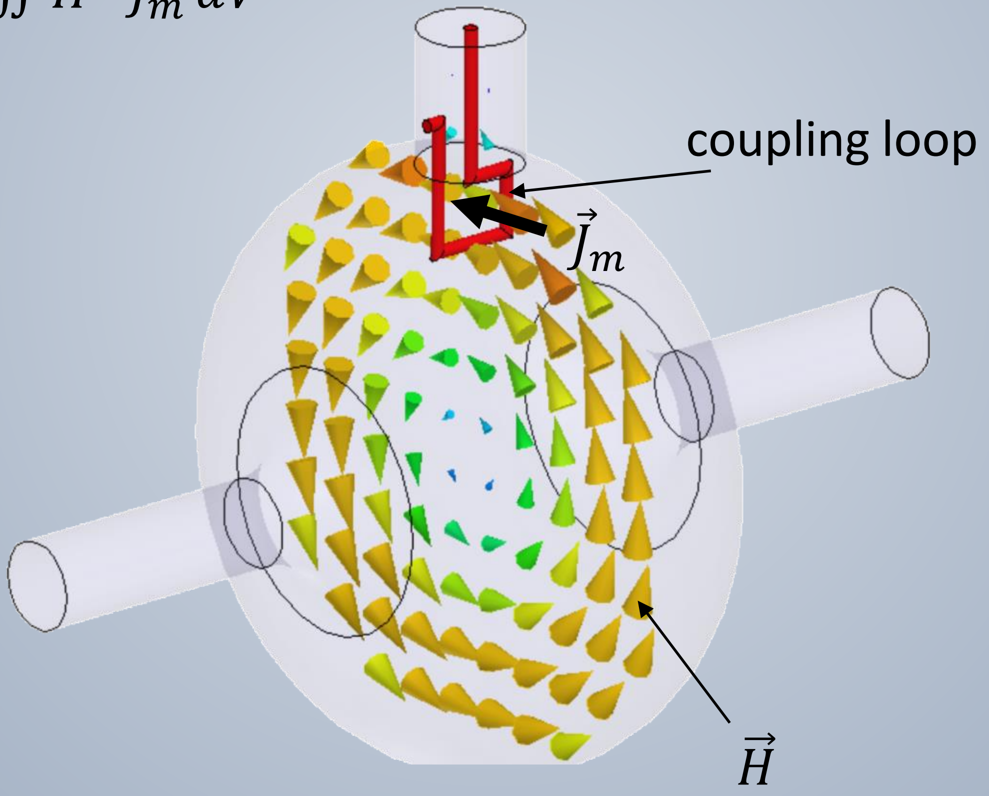
Magnetic (loop) coupling

- The magnetic field of the cavity main mode is intercepted by a coupling loop
- The coupling can be adjusted by changing the size or the orientation of the loop.
- Coupling: $\propto \iiint \vec{H} \cdot \vec{J}_m \, dV$



courtesy: David Alesini/INFN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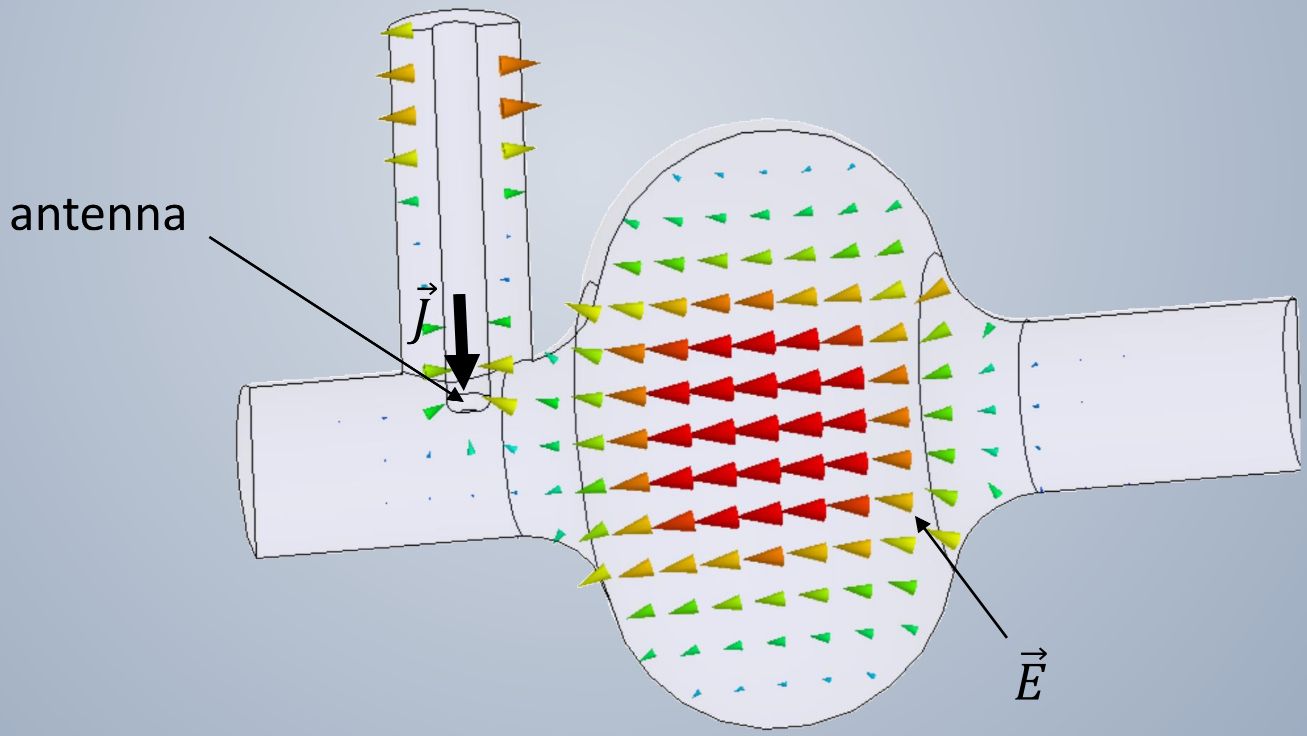
Electric (antenna) coupling

- The inner conductor of the coaxial feeder line ends in an antenna penetrating into the electric field of the cavity.
- The coupling can be adjusted by varying the penetration.
- Coupling $\propto \iiint \vec{E} \cdot \vec{J}\, dV$



courtesy: David Alesini/INFN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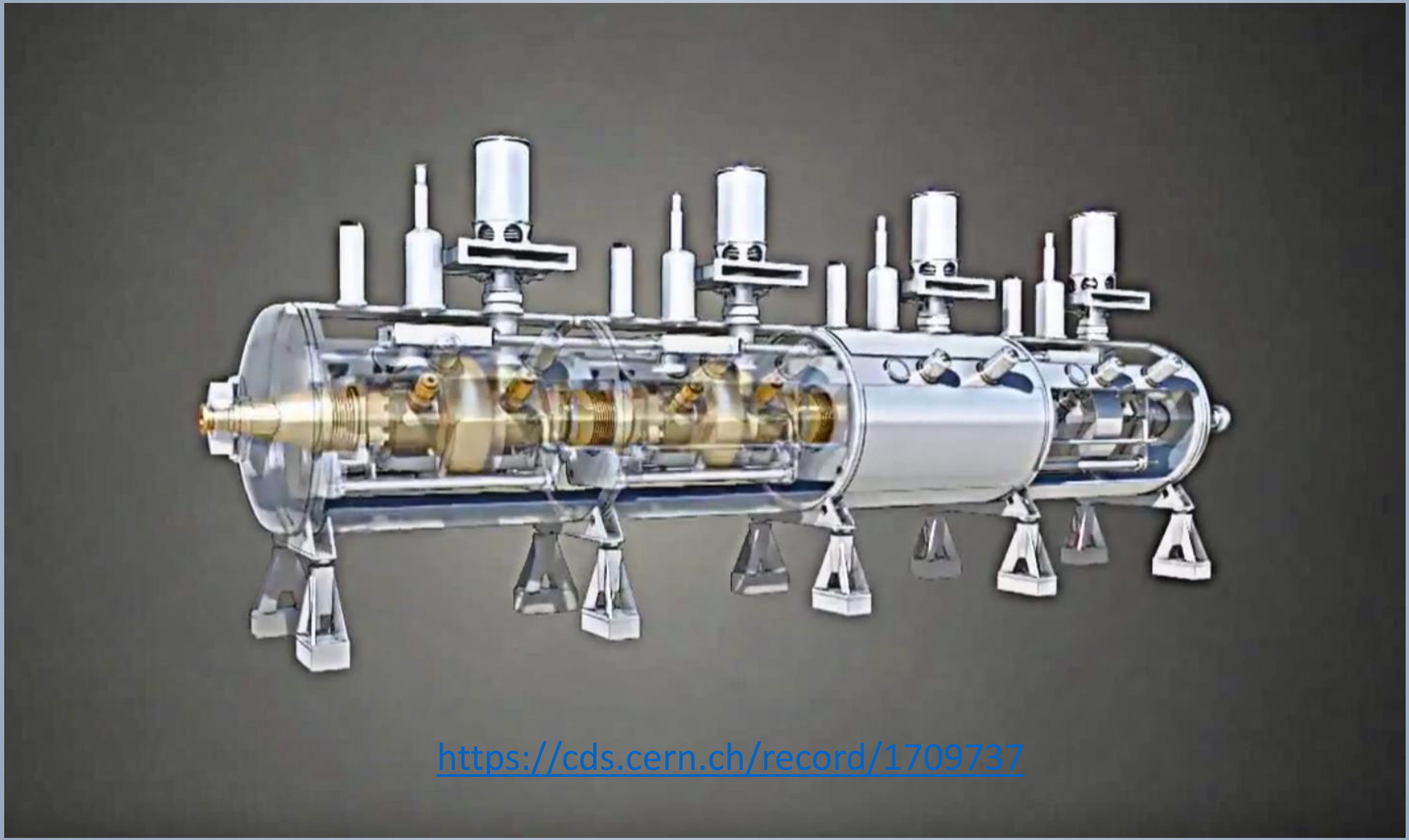
LHC SRF module


https://cds.cern.ch/record/1709737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LHC SRF module


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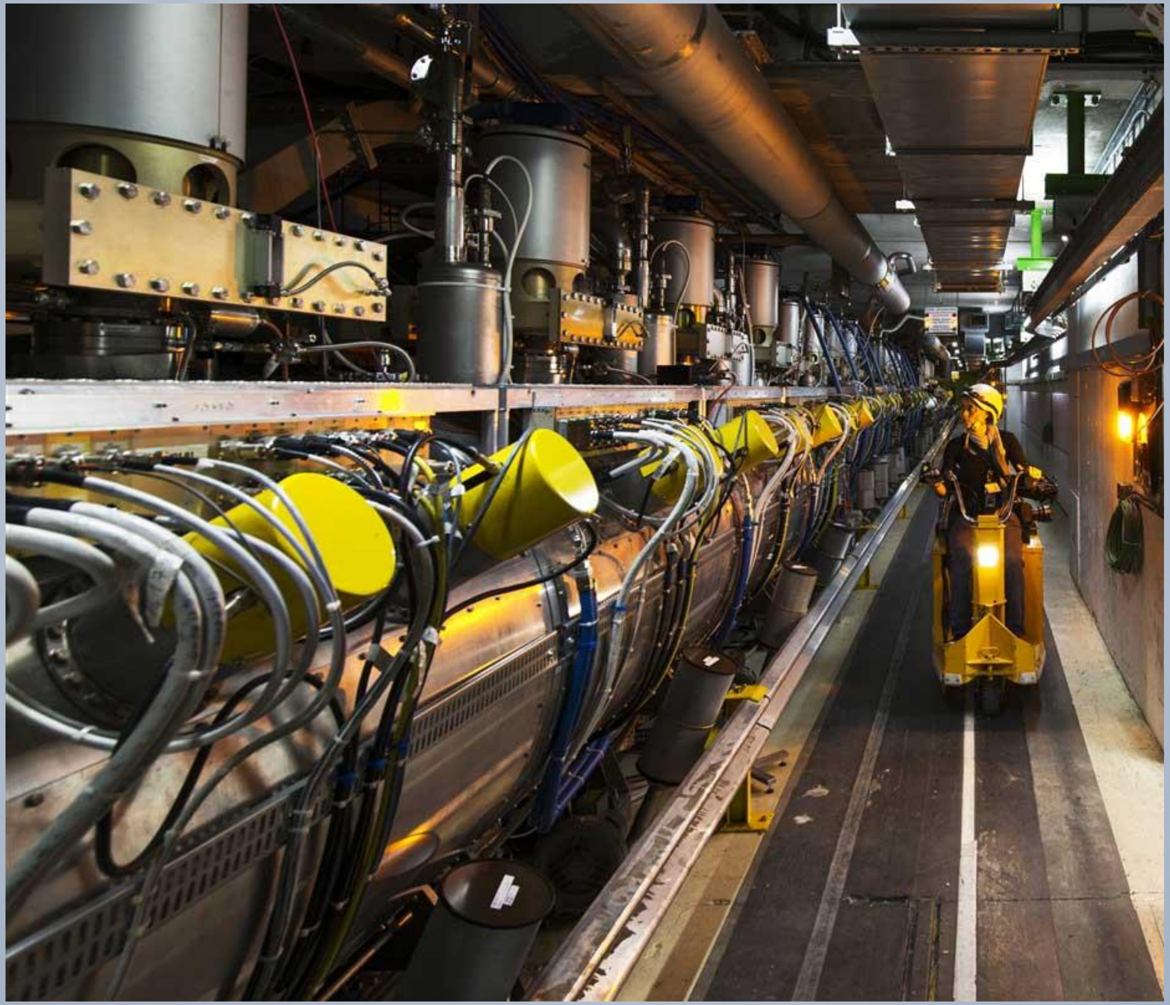
LHC SRF module

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LHC SRF module

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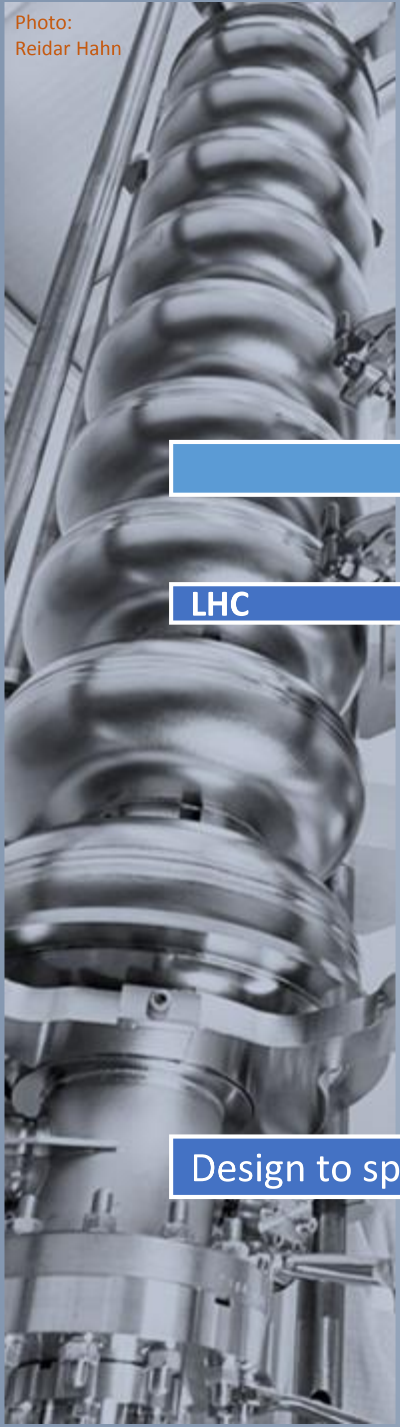
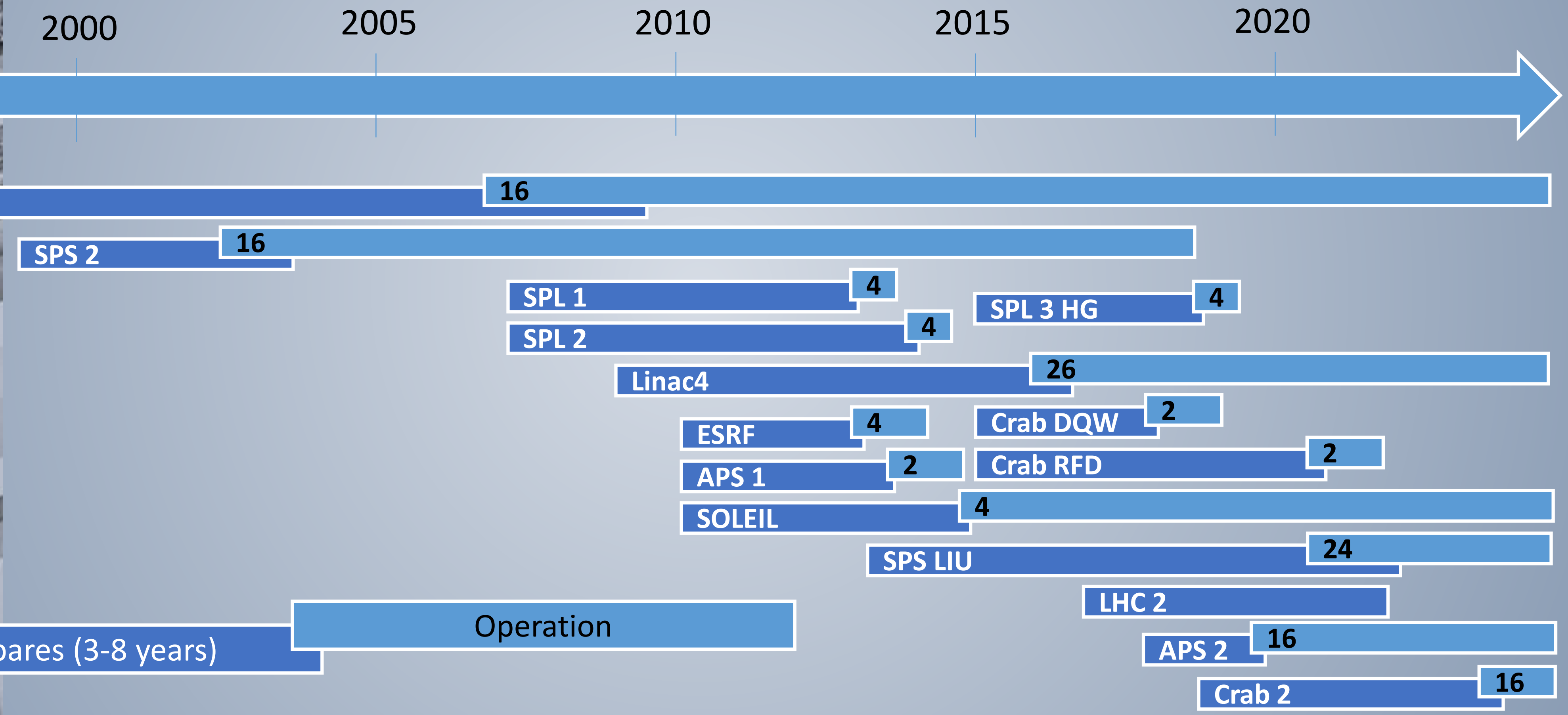


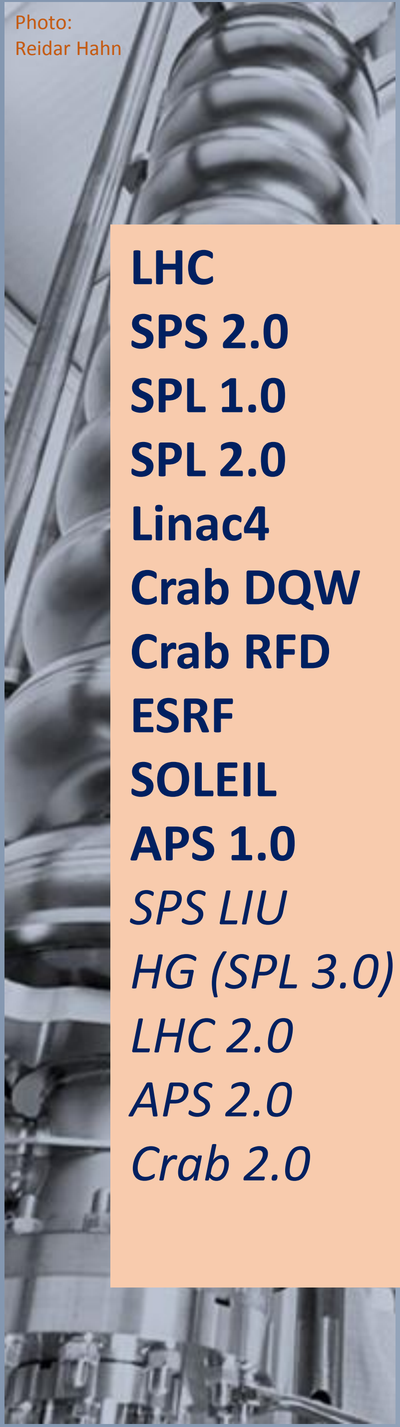
Overview of the CERN power couplers since the 2000's



2000
2005
2010
2015
2020

LHC 16
SPS 2 16
SPL 1 4
SPL 2 4
SPL 3 HG 4
Linac4 26
ESRF 4
APS 1 2
SOLEIL 4
Crab DQW 2
Crab RFD 2
SPS LIU 24
LHC 2
APS 2 16
Crab 2 16

Design to spares (3-8 years)
Operation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Overview of the CERN power couplers since the 2000’s

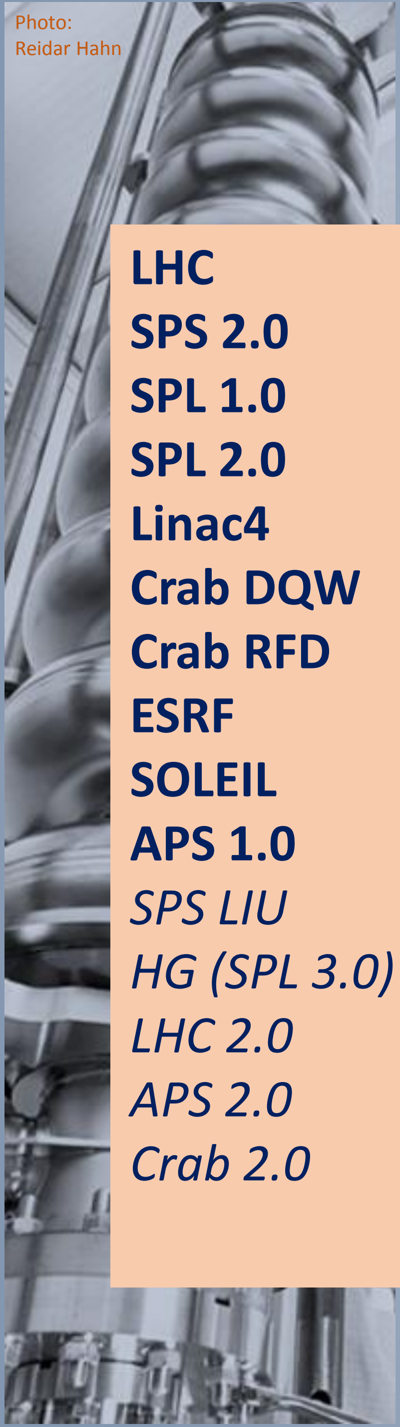
LHC	**400 MHz, 500 kW CW SW**
SPS 2.0	**200 MHz, 750 kW CW TW**
SPL 1.0	**704 MHz, 900 kWp 10 % SW**
SPL 2.0	**704 MHZ, 1000 kWp 10 % SW**
Linac4	**352 MHz, 1000 kWp 10 % SW**
Crab DQW	**400 MHz, 100 kW CW SW**
Crab RFD	**400 MHz, 100 kW CW SW**
ESRF	**352 MHz, 200 kW CW SW**
SOLEIL	**352 MHz, 200 kW CW SW**
APS 1.0	**352 MHz, 200 kW CW SW**
SPS LIU	*200 MHz, 800 kW CW TW*
HG (SPL 3.0)	*704 MHz, 1500 kWp 10 % SW*
LHC 2.0	*400 MHz, 500 kW CW SW*
APS 2.0	*352 MHz, 250 kW CW SW*
Crab 2.0	*400 MHz, 100 kW CW SW*

CERN LHC SPS SPL

L4 LHC Injectors Upgrade HiLumi HL-LHC PROJECT

FCC hh ee he ilc

ESRF SOLEIL SYNCHROTRON Argonne NATIONAL LABORATORY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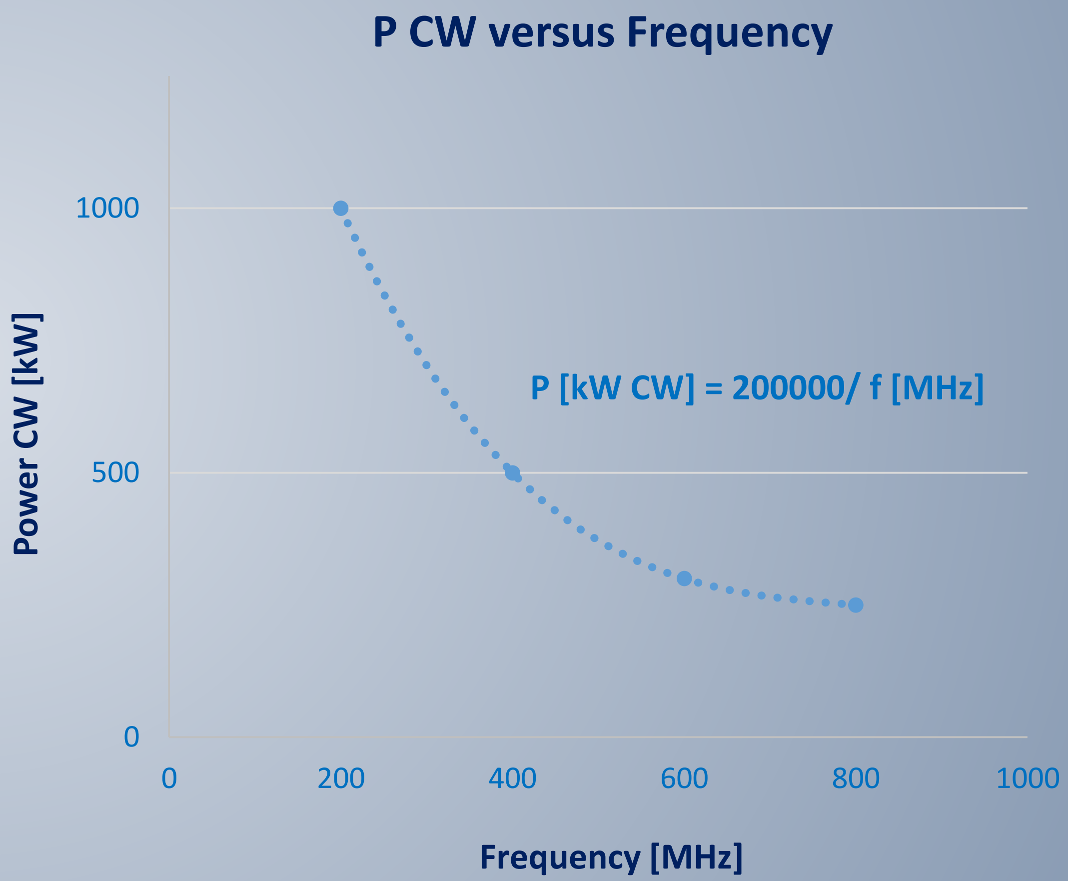
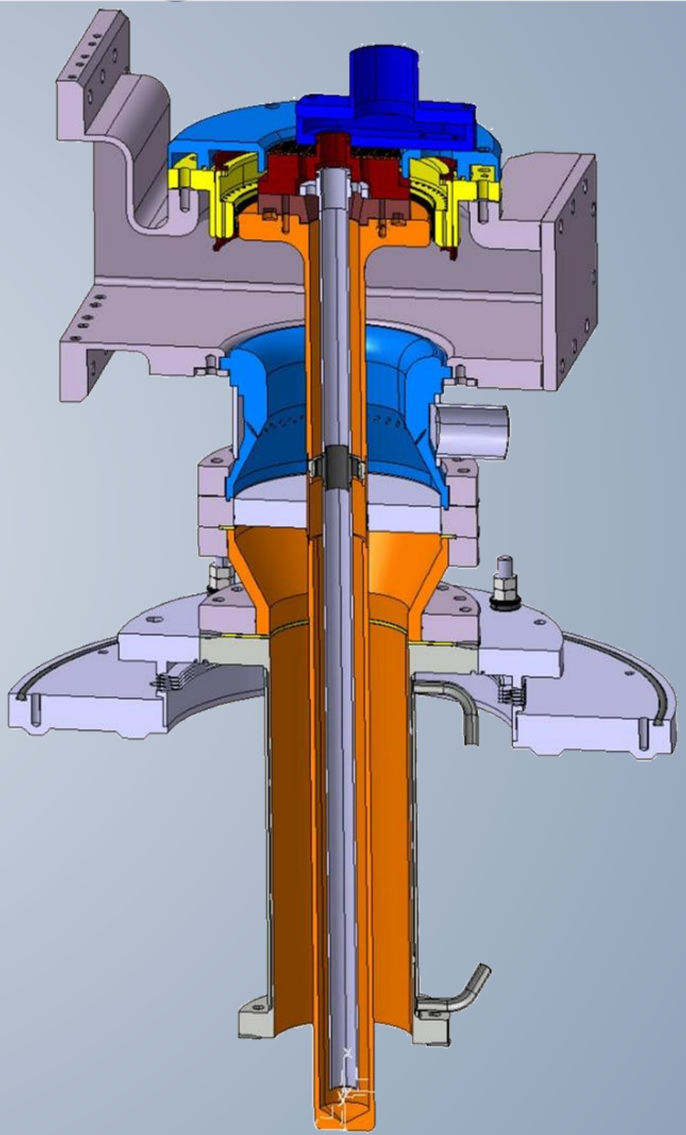



Photo:
Reidar Hahn

Example of a design

- For the CERN Superconducting Proton Linac (SPL) R&D programme, we designed two couplers,
- Both operated at 704 MHz pulsed 4 ms at 14 Hz and were tested up to almost 1 MW,
- A third version capable of even more power has been designed,
- We will look at all the design considerations in order to show how a FPC is designed



Ceramic

- This is the most important device of a FPC,
- It ensures the vacuum leak tightness of the FPC, and of the entire machine!
- Any leak on the window immediately leads into degradation of the cavity and of the machine,
- It is commonly a ceramic brazed with metal.

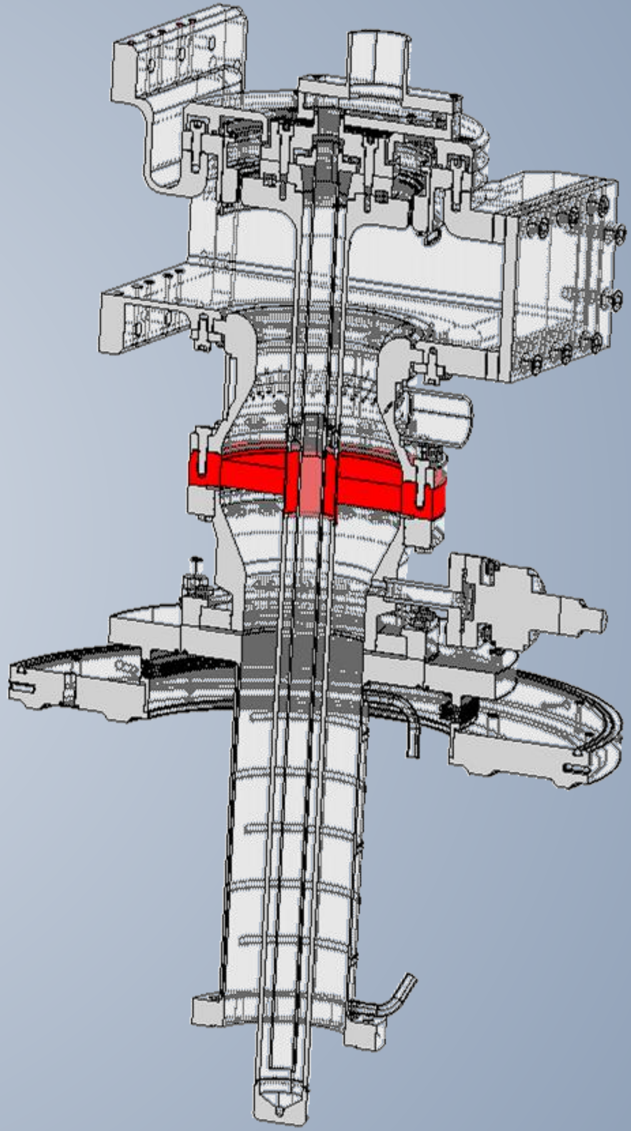



Photo:
Reidar Hahn

Ceramics

- Most of the windows are built form an Al_2O_3 ceramic
- A very important parameter is the purity of the ceramic
- A too pure ceramic will be with very few losses, that is perfect for RF power, but will be very difficult to braze as the metallization will not adhere
- A ceramic with impurities will be much easier to braze, but will have a lot of losses that will induce a difficult cooling

	Purity	**RF losses**	**Brazing**
Al_2O_3	99.9 %	Very Low	Very difficult
Al_2O_3	97.6 %	Medium	Medium
Al_2O_3	95 %	Higher	Easier

- CERN published a reference document in 1996 (10 pages) explaining all the parameters that a ceramic for RF window shall fulfil
- http://cds.cern.ch/record/91419?ln=fr
- It is still in use, and all our ceramics are the Al_2O_3 - 97.6 % purity ones


Photo:
Reidar Hahn

Metallization

- Before brazing the metallic line, the window has to be metallized.
- The most common medium used is a Molly-Manganese deposition on the surfaces to be brazed.
- It is often painted by hands.
- This paint is very sensible and must be kept in movement at any time, under a controlled temperature and humidity.
- The metallic lines will be brazed onto that MoMn support, it is of the highest importance.


A default in the metallization of the ceramic, one can easily understand that it will not be possible to braze any metallic part onto it.


Photo:
Reidar Hahn

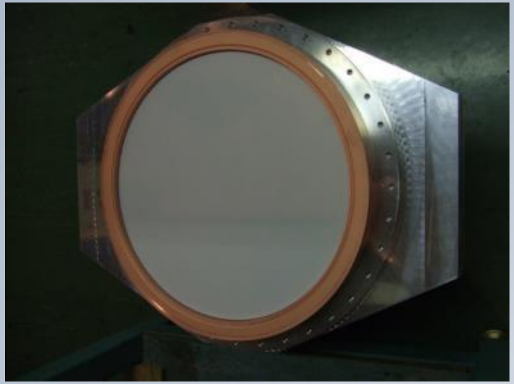
Windows

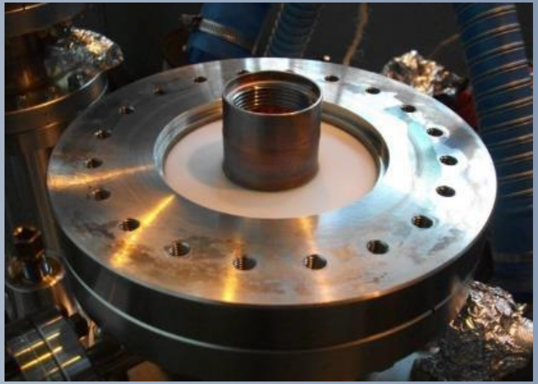
There are three main families that define the FPC type

Disk window

Cylindrical window

Coaxial disk window



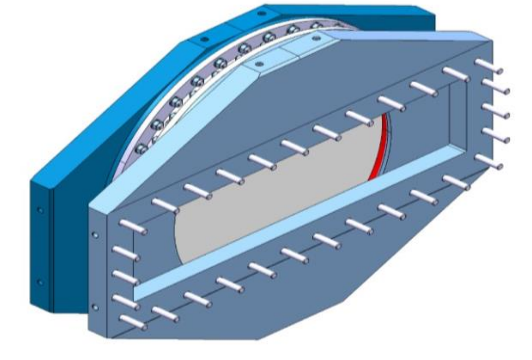


Disk windows	**Cylindrical windows**	**Coaxial disk windows**
SPS, 800 MHz 150 KW CW	LHC, 400 MHz 500 kW CW	HL-LHC Crab, 400 MHz 100 KW CW
Linac4, 352 MHz 1 MW 10 % duty	ESRF-SOLEIL-APS, 352 MHz 250 kW CW	SPL 2.0, 704 MHz 1 MW 5 % duty
LHC 2, 400 MHz 1 MW (expected) CW	SPL, 704 MHz 1 MW 5 % duty	SPL 3.0, 704 MHz 2 MW (expected) 5 % duty


Photo:
Reidar Hahn

Disk windows

- Robust and compact (in length) design
  - 12 kg ceramic
  - 400 mm diameter
  - 25 mm thickness
- As simple as possible
  - 1-2-3-4 : Ceramic assembly
  - 5 : spacer
  - 6 : Helicoflex seal
  - 7-8 : Stainless Steel flanges
- Massive stainless Steel flanges, not copper plated
- More difficult design than it looks like
  - Copper ring of 1.25 mm thickness machined from massive copper
  - Two shapes, cylindrical and rectangular, with integrated screws
- 26 windows in operation in the Linac4



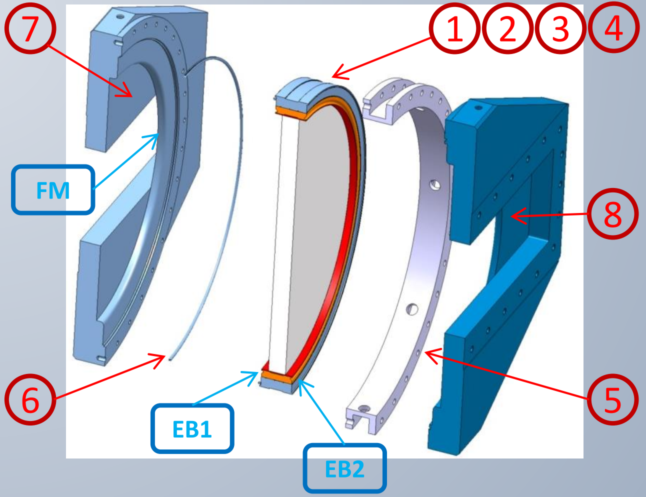
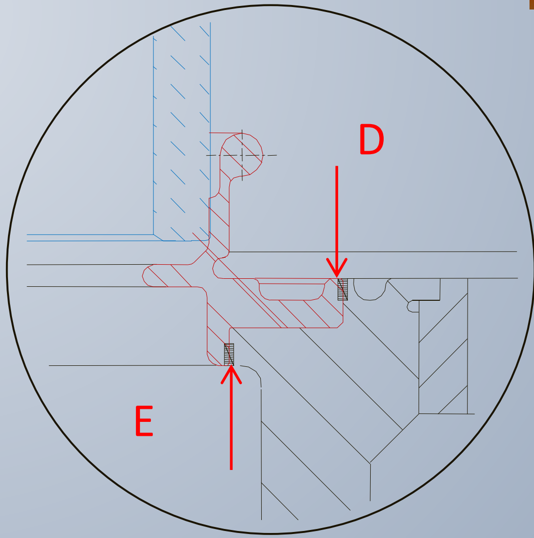



Photo: Reidar Hahn

Cylindrical window

- Solid copper rings directly brazed to the ceramic to lower the RF losses and increase the thermal capability
- Long and difficult process to make the ceramic reliable
- more than six years studying different ways to braze the solid copper rings to the ceramic
- we had to fight against semi-cracks developing with time
- Finally, powers up to 575 kW cw full reflection all phases were achieved for some hours, local peak power of 2.3 MW SW
- 16 couplers in operation in the LHC



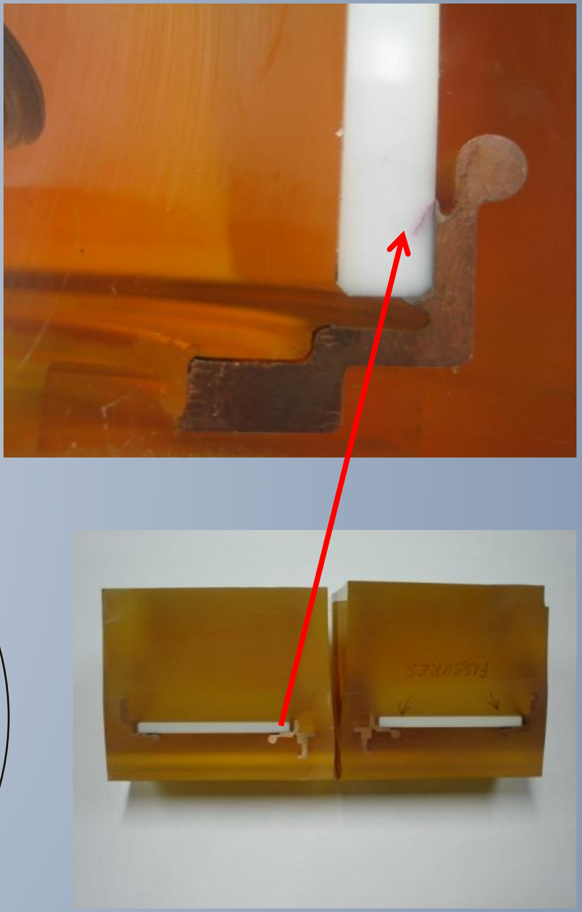



Photo:
Reidar Hahn

Coaxial disk

- Simplest way to make a window with
    - An inner tube of copper, maximum 1.5 mm thickness due to brazing limitation
    - A coaxial disk ceramic
    - A titanium flange
- All dimensions must be pre-machined keeping some additional material, and each set of components must be final machining taking into account each ceramic real sizes

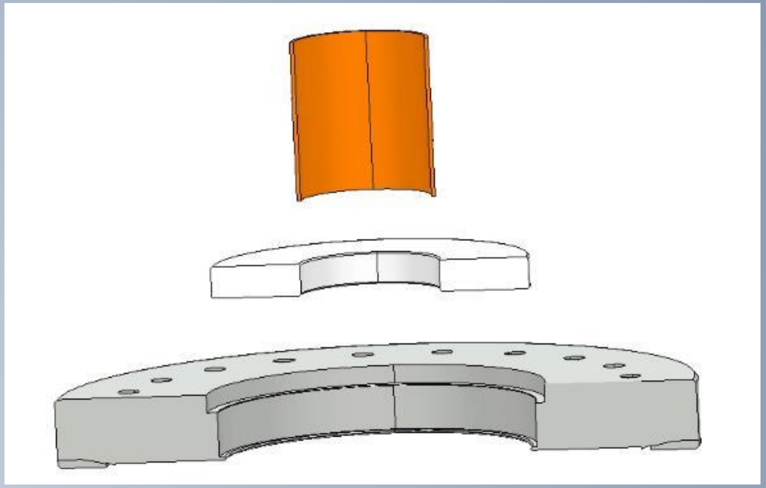
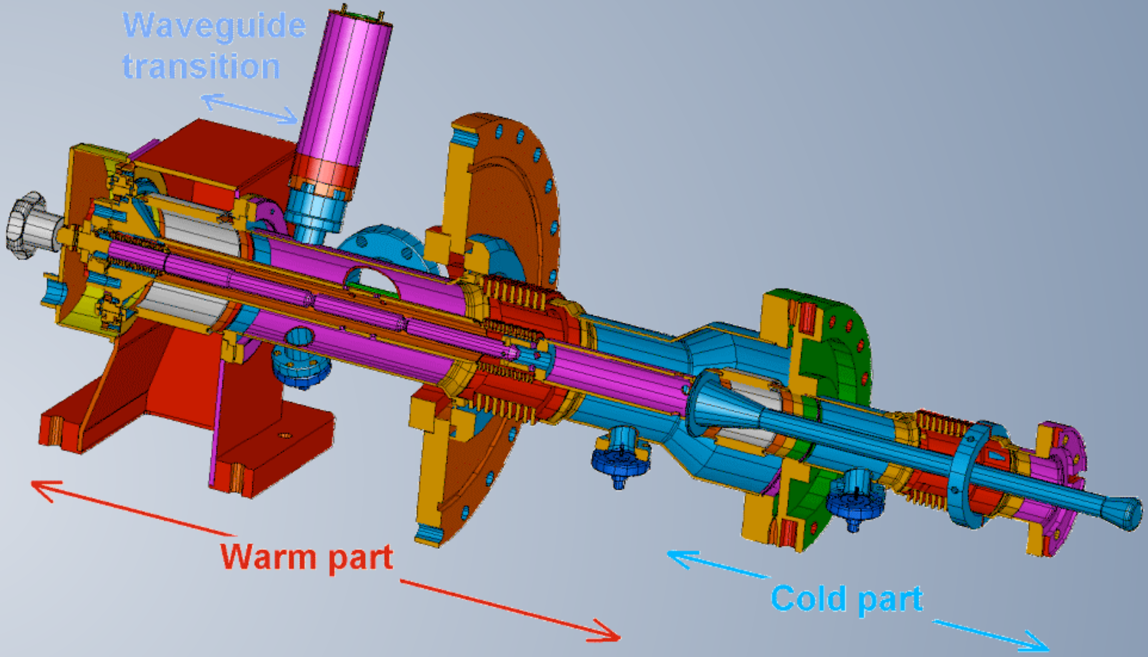



Photo: Reidar Hahn

Two windows coupler

- Two main reasons for the two windows
  - Ensure a clean beam vacuum
  - Guaranty a safe operation of the machine, a window crack not affecting the beam side
- Typical example of double window couplers is the fantastic TTF – XFEL family couplers (1.3GHz, 1MW pulsed peak, 5kW average)
- No coolant (water, gas) in contact with the "cold window", really floating inside vacuum



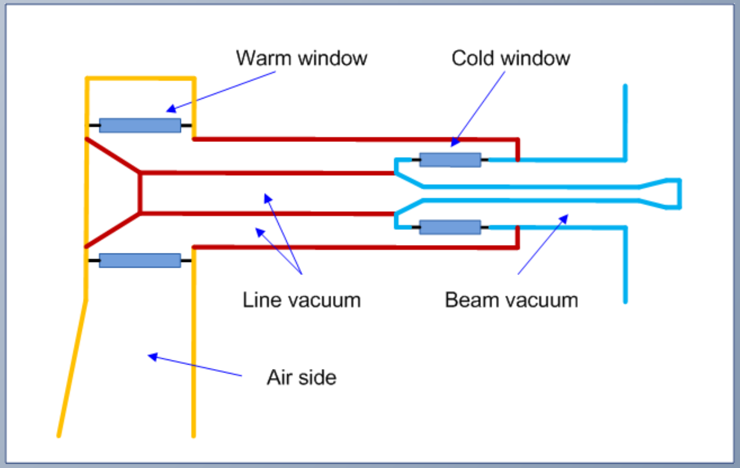
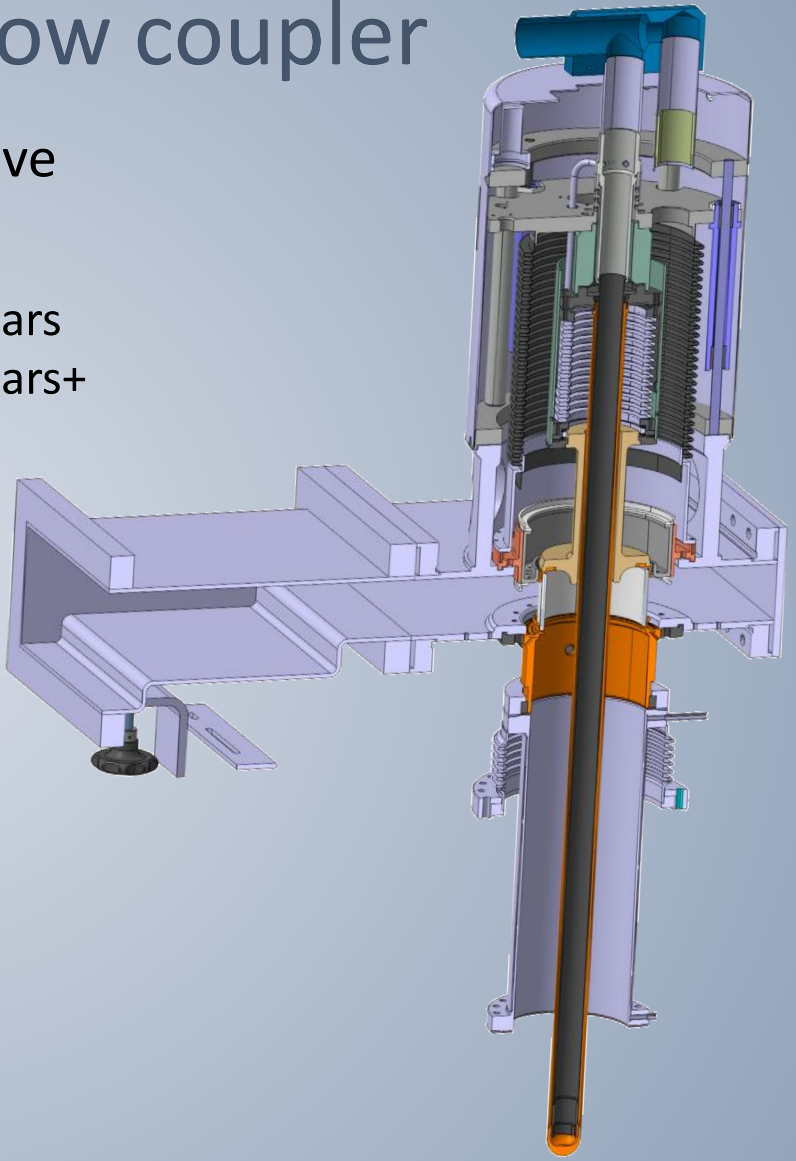



Photo:
Reidar Hahn

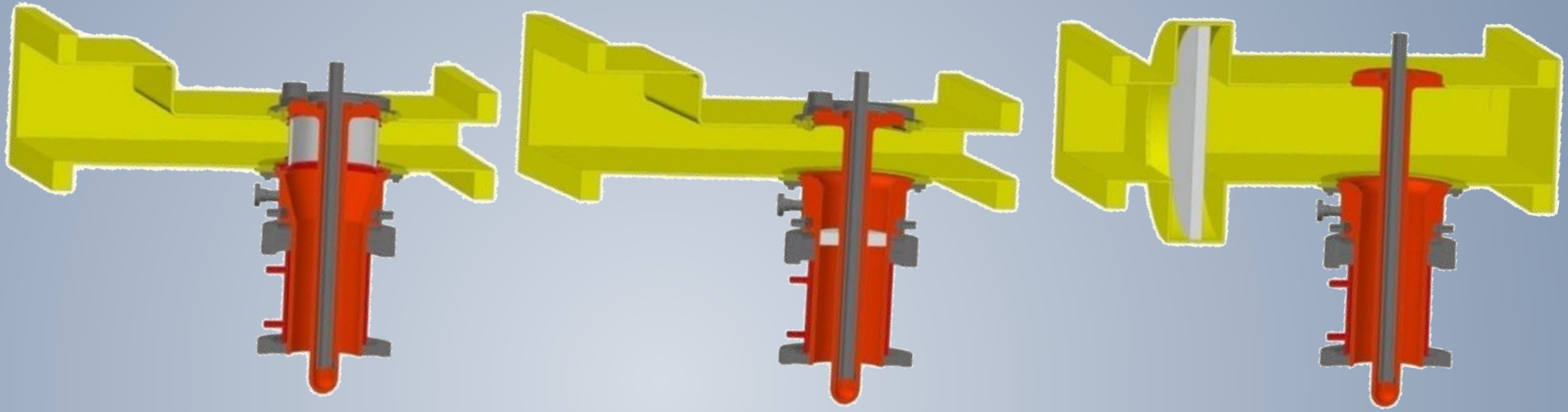
Single window coupler



- A lot of high average power projects have been designed with single window couplers (non exhaustive list)
  - 16 SPS v01 @ 200 MHz 375 kW CW, 20 years
  - 16 SPS v02 @ 200 MHz 550 kW CW, 15 years+
  - 250 LEP @ 352 MHz 150 kW CW, 12 years
  - 16 LHC @ 400 MHz 500 kW CW, 9 years+
  - 81 SNS @ 352 MHz, 12 years+
- Single window couplers have proven to be reliable
- However, we must have spare modules for exchange, and this has to be taken into account for vacuum sectorization.


Photo:
Reidar Hahn

Back to the SPL example: ceramic choice



This R&D program was to look at a production of more than 250 couplers

For the SPL project, we proposed three different designs

- Cylindrical
- Coaxial disk
- Disk

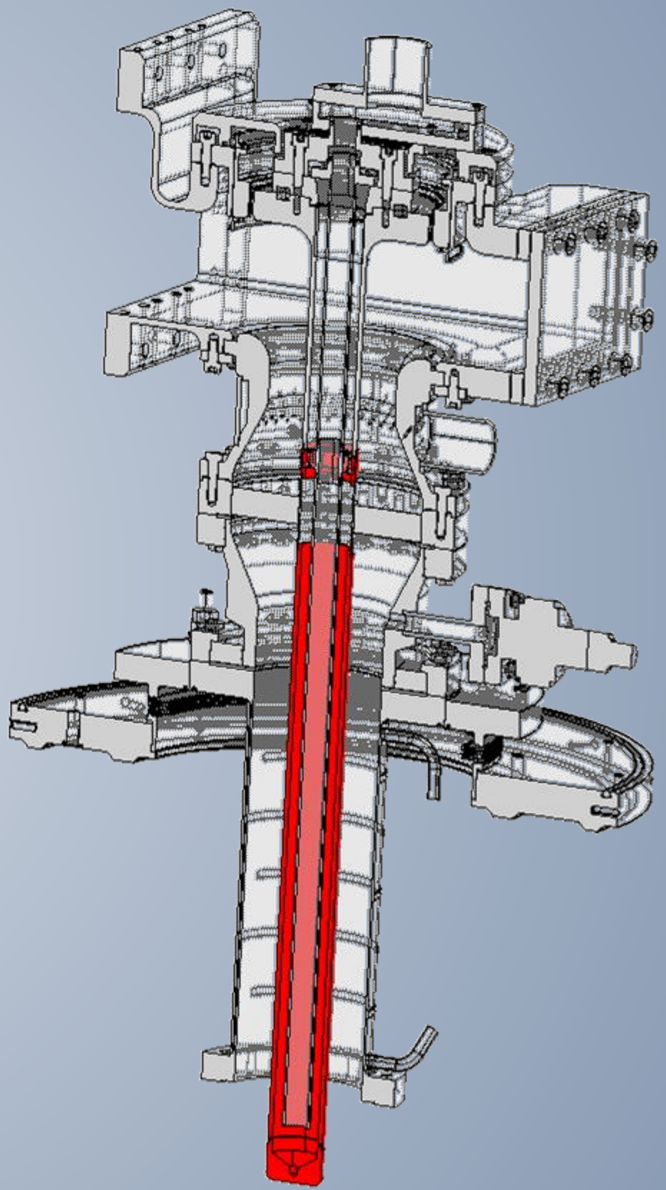
With the design of these SPL couplers, we would like to always keep in mind some key parameters

- As reliable as possible
- Easy for operation and maintenance
- Avoid mass production difficulties
- As simple as possible
- Reducing the costs

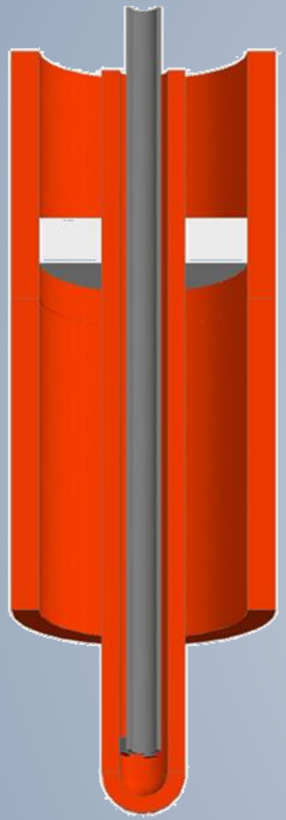

Photo:
Reidar Hahn

Antenna

- The antenna will be EBW to the ceramic window
- Always try to make it as simple as possible
- If possible try to minimize the mechanical stresses given to the ceramic



Adjustable coupler or not ?



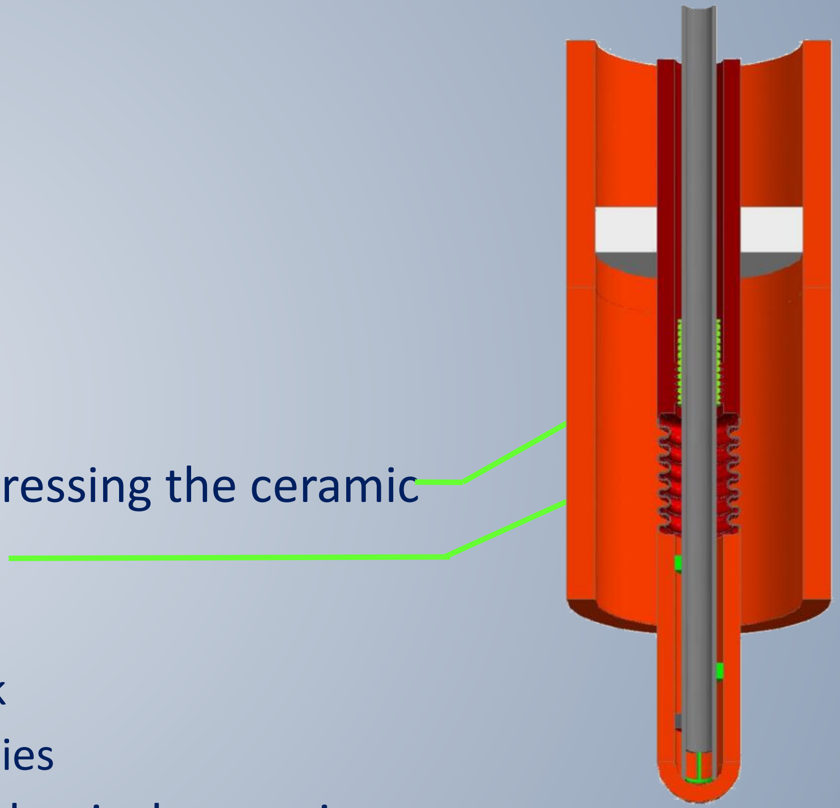
Disk window
fixed coupler

Advantages

- Better for Qext matching
- Better for power distribution

Drawbacks

- More complex to design
- Need a moving system not stressing the ceramic
- Need bellows somewhere
  - More EB welding
  - Increases the vacuum leak risk
  - Increases mutipacting difficulties
- Increases the number of mechanical operations
- Subsequently increases the total price

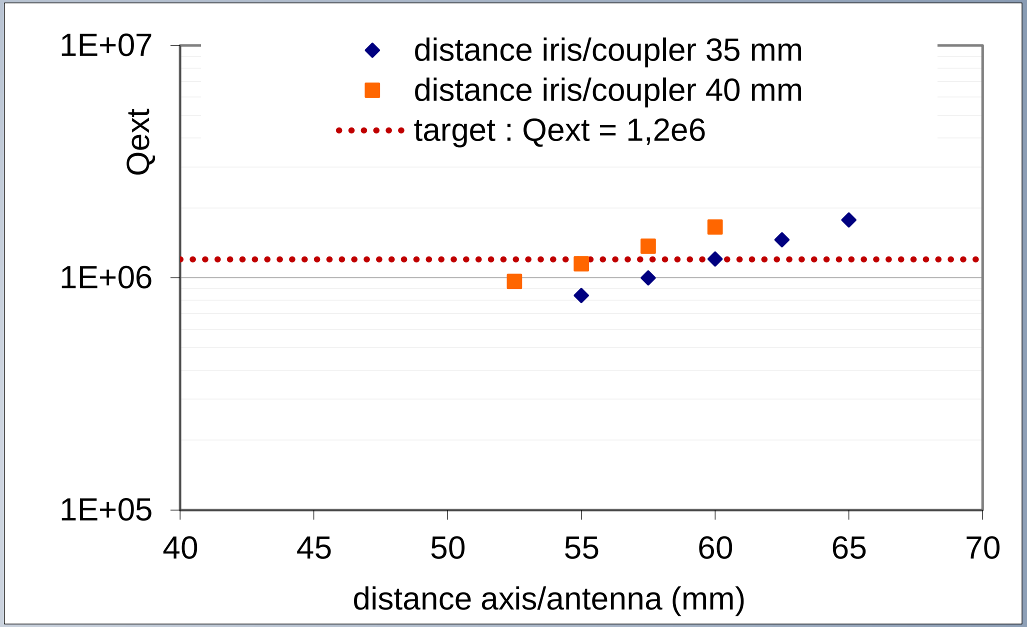


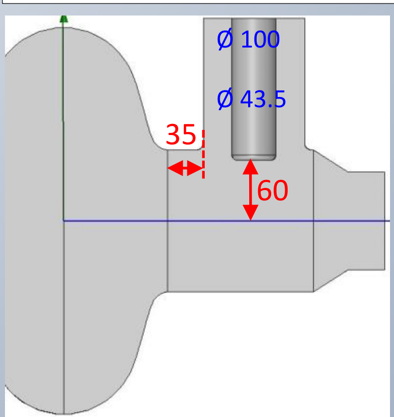
Disk window
adjustable coupler

Photo:
Reidar Hahn

Adjustable coupler or not ?

- For the SPL we would have one power source per cavity
- The coupler will probably be machined accurately enough with an antenna position within $\pm 3\ \mathrm{mm}$, this should guarantee a Q_{ext} spread within $(1.18 \ldots 1.23)10^6$, corresponding to acceptable variation of Q_{ext} of $\pm 2\%$.
- The cavity will be previously measured, so we can choose which coupler to combine with which cavity to reduce the total error





Juliette Plouin
CEA-Saclay
25th February 2010


Photo:
Reidar Hahn

Antenna shape

- There are several shapes possible for your end tip antenna
- Magnetic coupling with grounding imposes two fixed point to the ceramic, cooling must be perfect in order to guaranty a minimum of stress
- Always try to use the simplest one
- As soon as you move to a complex shape, there will be a lot of impact
  - Mechanical accuracy more difficult to obtain
  - Thermal behaviour implies a stronger cooling plant
  - Preparation for clean room is more difficult
  - Assembly in clean room need additional tooling
  - Cost (money, manpower, risk) increases


Photo:
Reidar Hahn

Outer antenna line

- In order to ensure thermal shielding between the FPC and the cavity the outer antenna can be with thermal anchor(s) or with a Double-walled tube,
- It is a part of the coupler as being the outer line of the FPC antenna coaxial line,
- From an RF point a view, it is a simple outer conductor tube,
- Its contraction must be perfectly pre-calculated, because this will give the coupling value (Q_{ext}).

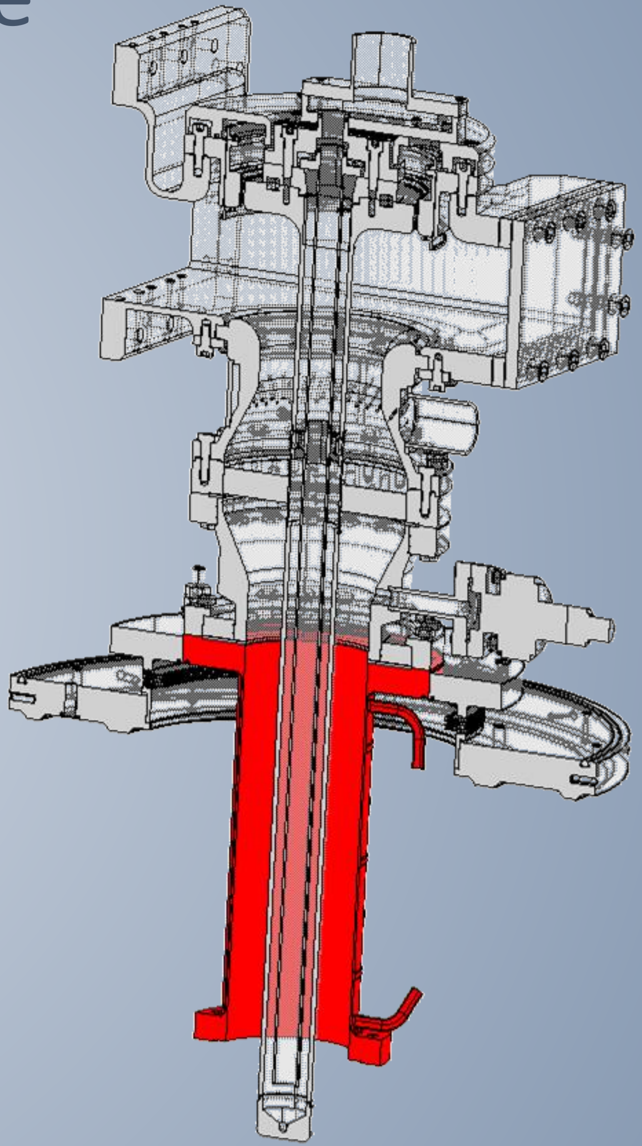
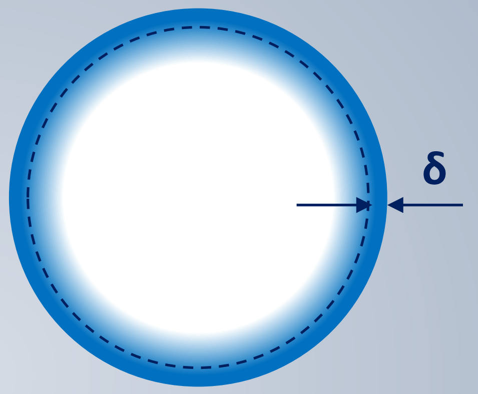
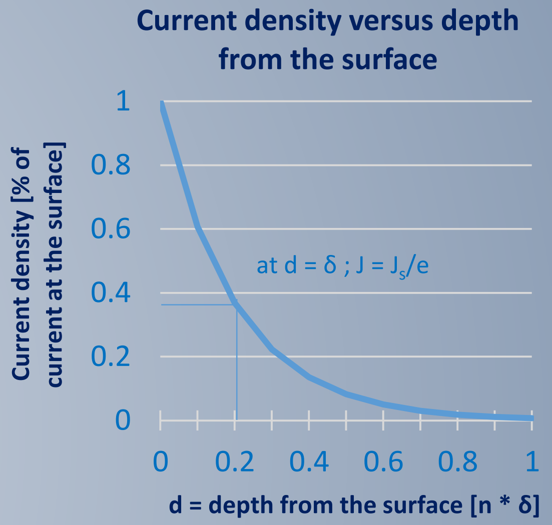


Photo: Reidar Hahn

Outer antenna line

- The inner line (antenna) of the FPC can remain at warm temperature (E-field antenna),
- The outer line has a flange connected to the cavity and another flange connected to the external ambient air,
- There is a gradient of $> 300\ \mathrm{K}$ from the cold to the warm side
- RF needs only few $\mu\mathrm{m}$ of good electrical layer as cryogenic requests an as good as possible thermal isolation.





Current density versus depth from the surface

$$J = Js\, e^{-\left(\frac{d}{\delta}\right)} \qquad \delta = \sqrt{\frac{2\rho}{\omega\mu}}$$

With: J = current density, J_s = current density at the surface, d = depth from the surface, δ = skin depth in which 63 % of the current flows, ρ = resistivity of the conductor, ω = 2πf, $\mu = \mu_r * \mu_0$, μ_r = relative magnetic permeability of the conductor, μ_0 = permeability of free space. For copper at 400 MHz, $\rho = 1.678 * 10^{-8}\ \Omega\mathrm{m}$, $\mu_r = 0.999991$, δ = 3.26 µm


Photo:
Reidar Hahn

Outer antenna line

- Since LEP time, as we experienced a lot of difficulties with this component, we decided to have the Stainless Steel part built from a single block of massive 316LN,
- This is to prevent any multipacting troubles due to any change in the RF nor thermal structure,
- At that time we did Nickel flash + 7 µm copper sputtering (better uniformity of the layer),
- When we tried to redo for SPL, with almost the same dimensions, it has been difficult as the fabrication process is very strict,
- This copper coating is one of the key processes for all the couplers over the world.

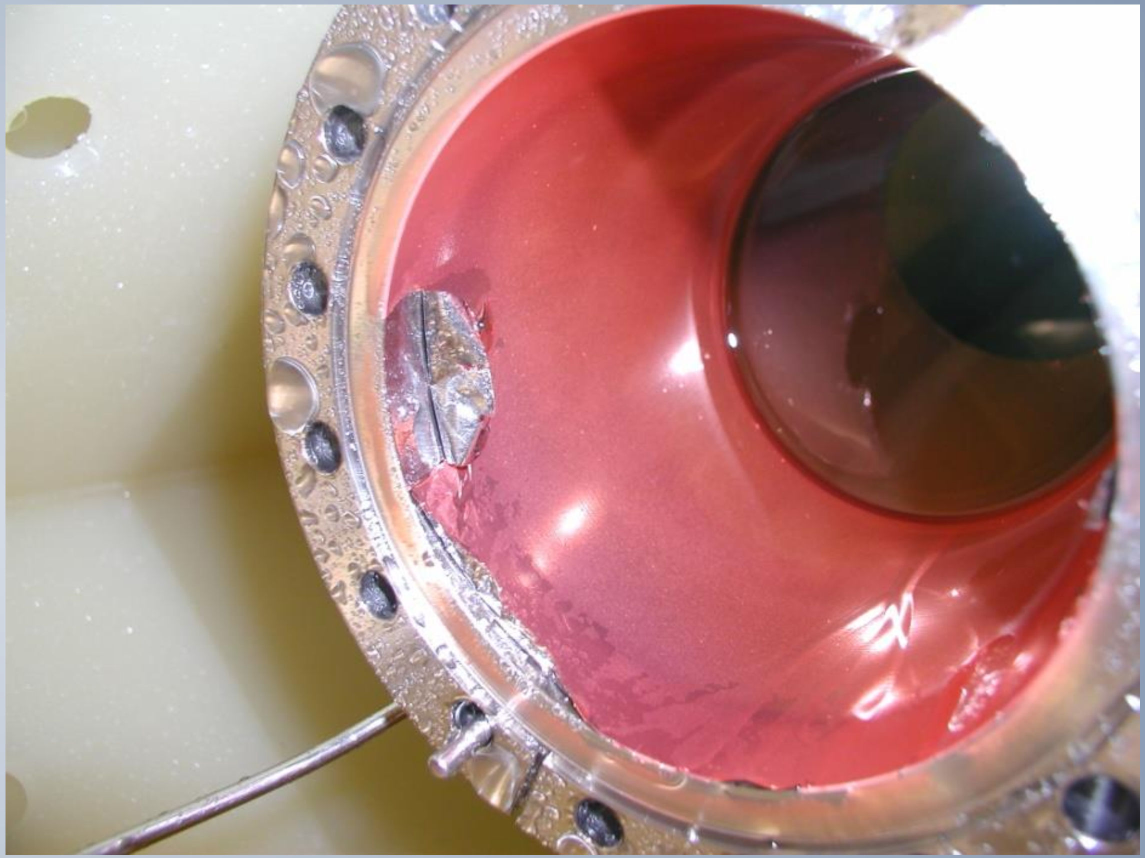

A SPL outer line with its copper layer peeling from the Stainless Steel support. More than one year of work lost in a few second, more than half a year to repair


Photo:
Reidar Hahn

Protection of the coupler

- The coupler being a very sensible device, we must have enough monitoring systems in order to protect it,
- A SRF cavity is probably the best vacuum pumping system that you will find around the FPC,
- This will prevent you to monitor any vacuum activity with the cavity vacuum gauge that will be on the beam pipe,
- So at minima, the FPC should have its own vacuum gauge,
- This impact a lot its overall integration size.

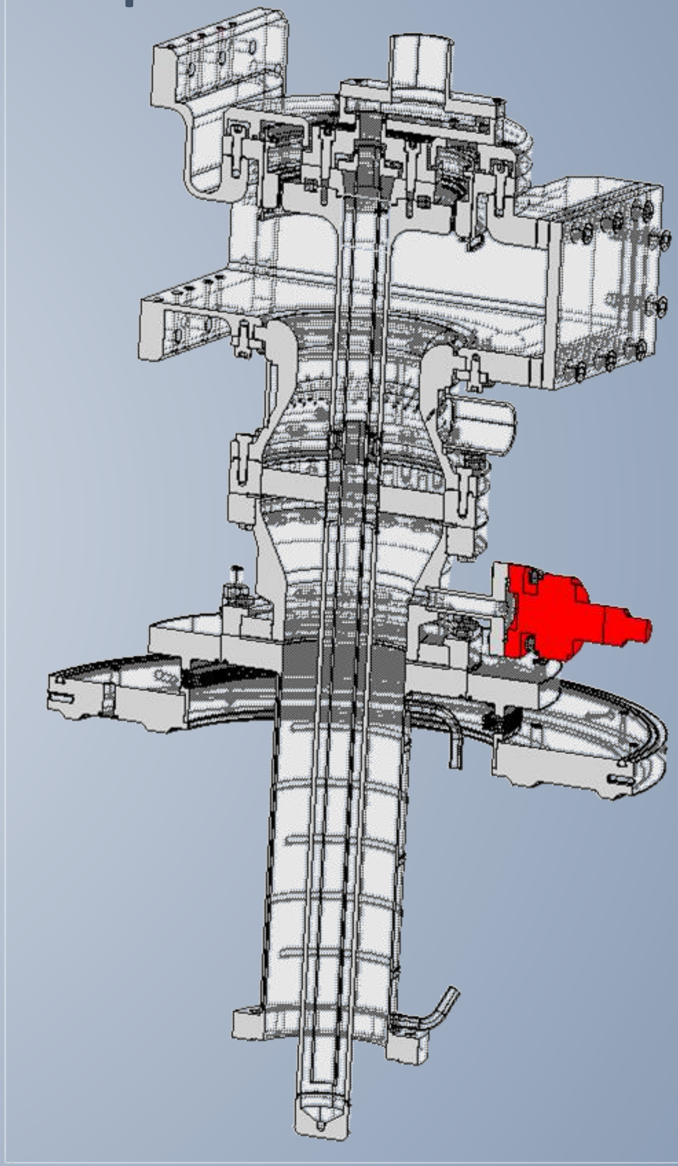
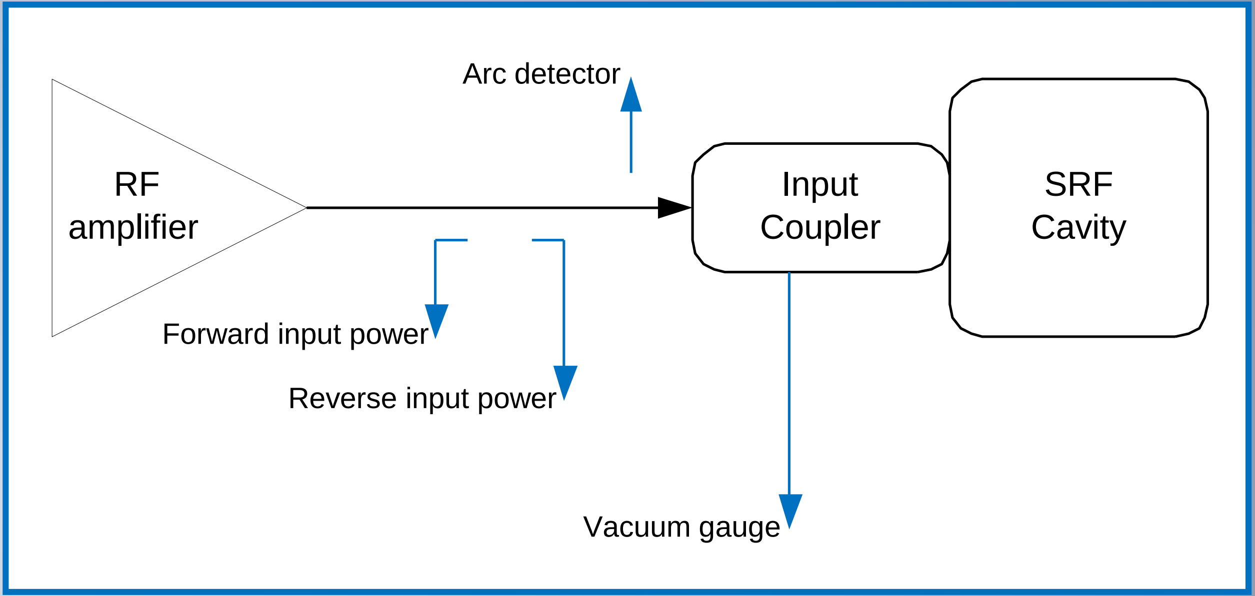



Photo:
Reidar Hahn

Protection of the coupler

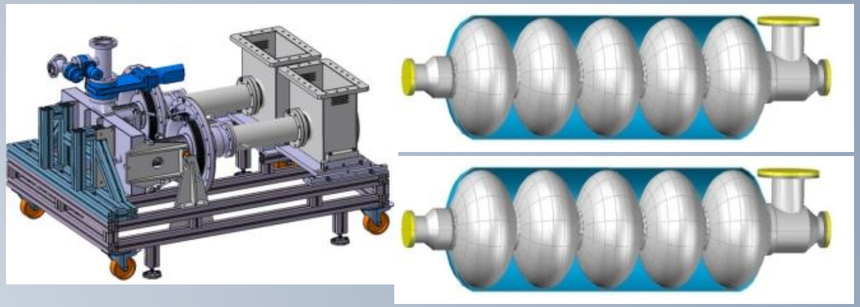


- In addition to the vacuum gauge we can add a electron pickup antenna, a vacuum side and an air side arc detector, a thermal sensor.
- At CERN we instrument a lot our prototype couplers, but minimize the instrumentation of the series FPC,
- The only protection system we keep are the vacuum gauge and the air side arc detector.
- In a machine like the LHC, the radiation being quite high, the electronic is sensitive, and special arc detector have been designed to avoid fake events stopping the beam,
- However, not protecting enough could lead into destructive event such as large vacuum discharge damaging the window by sputtering the ceramic, generating overheat and finally cracks in the window,
- A good balance between monitoring and protecting, and adding sources of default must be find.


Photo:
Reidar Hahn

Cryomodule integration requirements

- The RF conditioning of the couplers will be done prior to assemble the couplers to the cavity,
- A pair of couplers will be brought into the clean room with two cavities,
- The couplers will be mounted onto the cavity with its double walled tube, the HOM couplers and the field antenna, to not pollute the cavity.



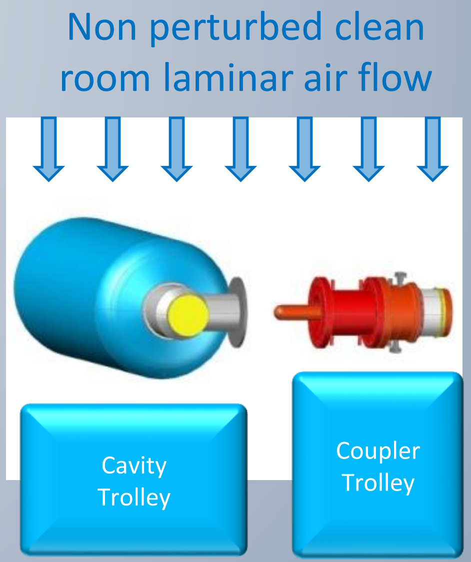
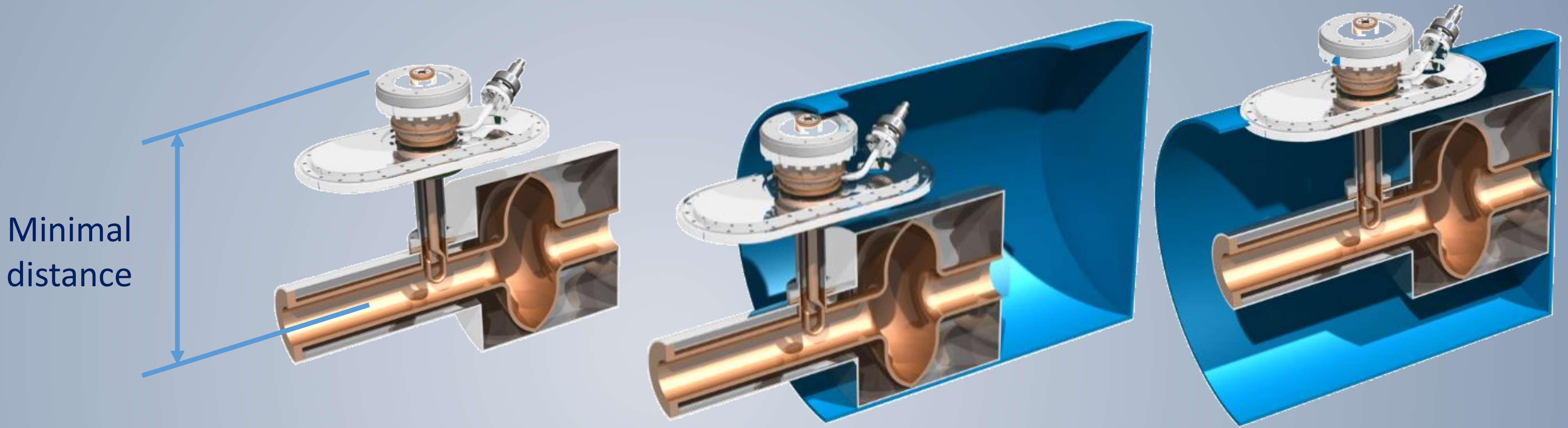



Photo:
Reidar Hahn

Cryomodule integration requirements



- The string of cavities will be connected together
- After that, the beam vacuum should remain closed until installation into the machine
- Very important decision for the design of the coupler
- → imposes a short distance from the ceramic to the beam axis …

Photo:
Reidar Hahn

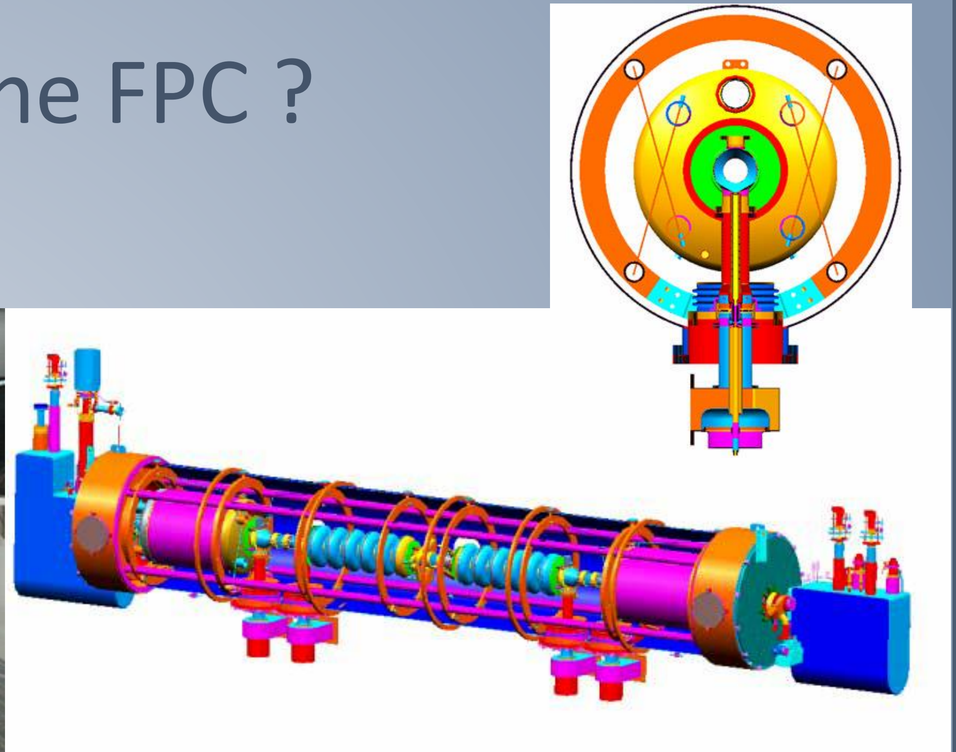
Cryomodule integration requirements

Orientation of the FPC ?


Photo:
Reidar Hahn


LHC cryomodule
couplers above the cavities

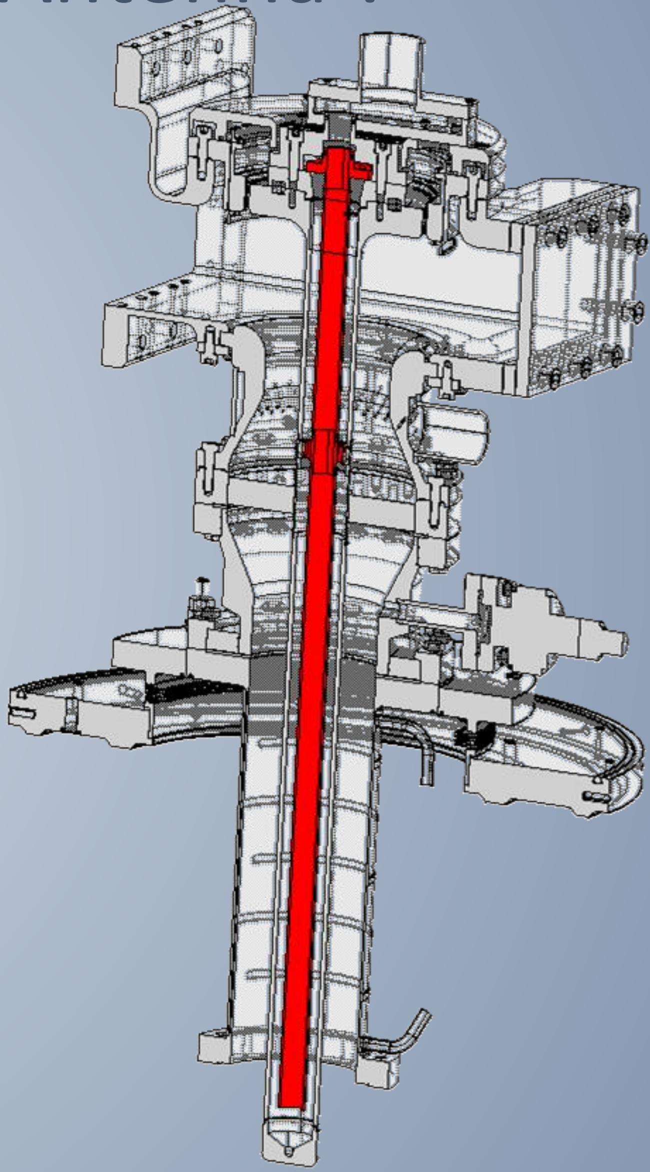

XFEL cryomodule
couplers on the side of the cavities


SNS cryomodule
couplers below the cavities

Always a lot of discussions, but from the FPC point of view, there are always pros and cons, and at the end, many projects, with many angles, not clear which is the best.


Photo:
Reidar Hahn

How to cool down the inner Antenna ?



- Mandatory from vacuum considerations:
  - NO water directly in contact with brazing making vacuum/water insulation
  - (except… exceptions…)
- Water cooling of the antenna:
  - Machine access in case of fault ?
  - Risk of freezing water ?
  - Time to warm-up a cavity ?
  - More complex to apply the DC biasing, need “insulating” pipes
- No major difficulties to run air cooled coupler with LHC and SPS SC cavities couplers


Photo:
Reidar Hahn

WG to coax transition

- In many FPC we have a WG to coaxial transition
- It is often use with a doorknob system that allows the impedance matching of the FPC
- At CERN we prefer to design the couplers doorknob free use the step and the ‘tunable’ WG short circuit side as matching system
- Nowadays we always have WG machined from a single block of aluminium, this allows to get rid of any soldering or brazing processes that have induced difficulties with several projects

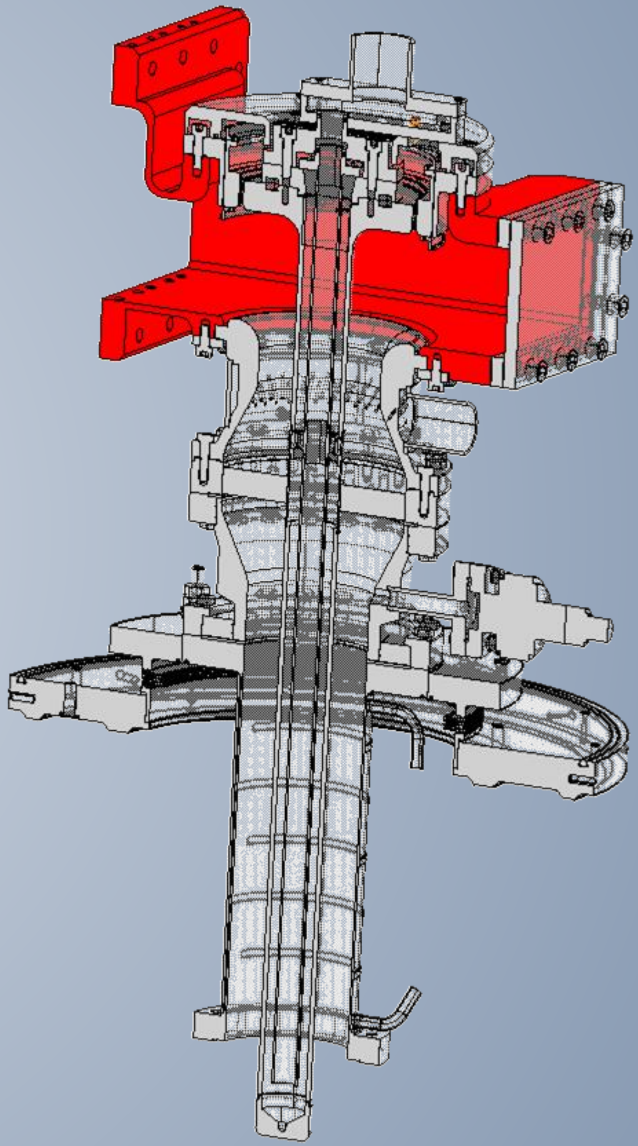
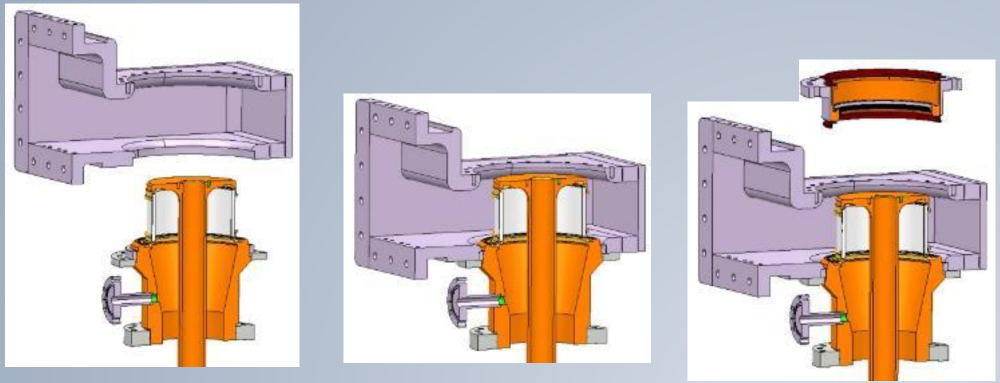
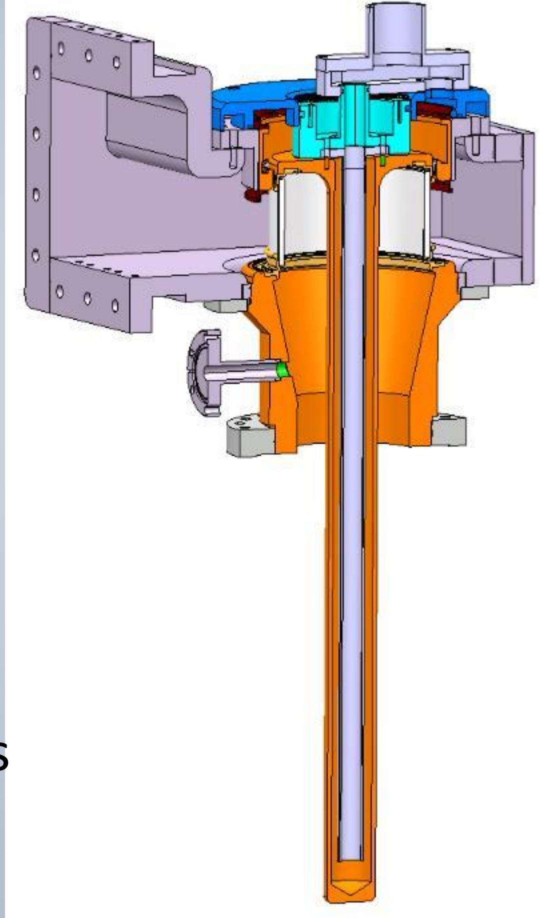



Photo:
Reidar Hahn

‘Plug and Play’ waveguide





- ‘Plug and Play’ waveguide with matching step and DC capacitor included

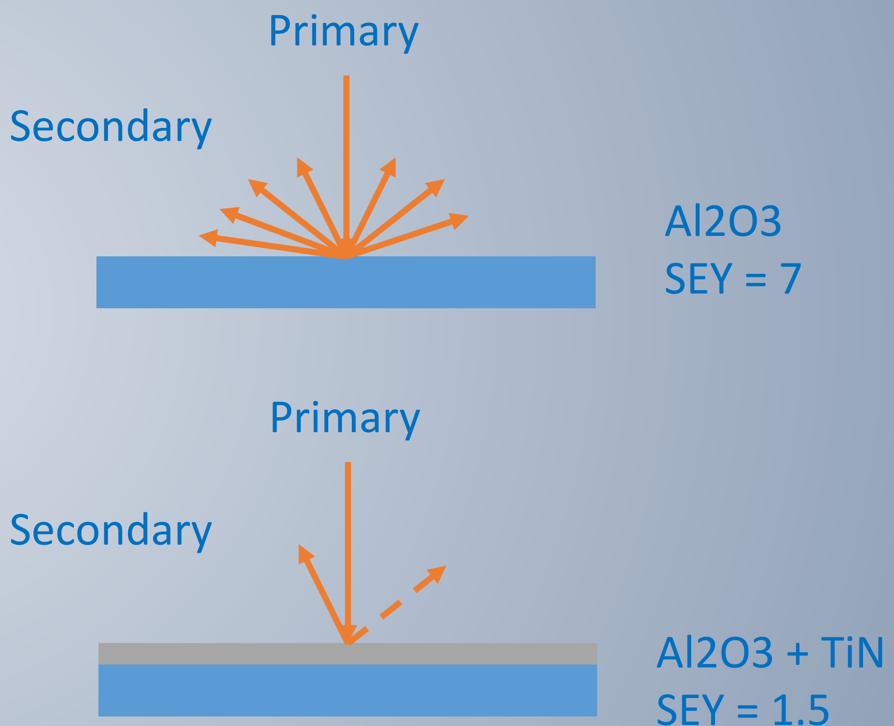
1-2 connect the monobloc waveguide to the body line

3 Insert the contacts ring, without stress given to the ceramic

4 Final assembly of air cooling system

SEY (Secondary Emission Yield)

- Another difficulty of having a ceramic in the transmission line path, is that on the vacuum side, there could be multipacting
- Ceramic has a propensity to provide electrons to the multipacting phenomena (SEY = 7!)
- In order to reduce it, a good solution is to apply a TiOx or TiN sputtering to the vacuum face of the ceramic (SEY ~ 1.5)



Primary

Secondary

Al_2O_3
SEY = 7

Primary

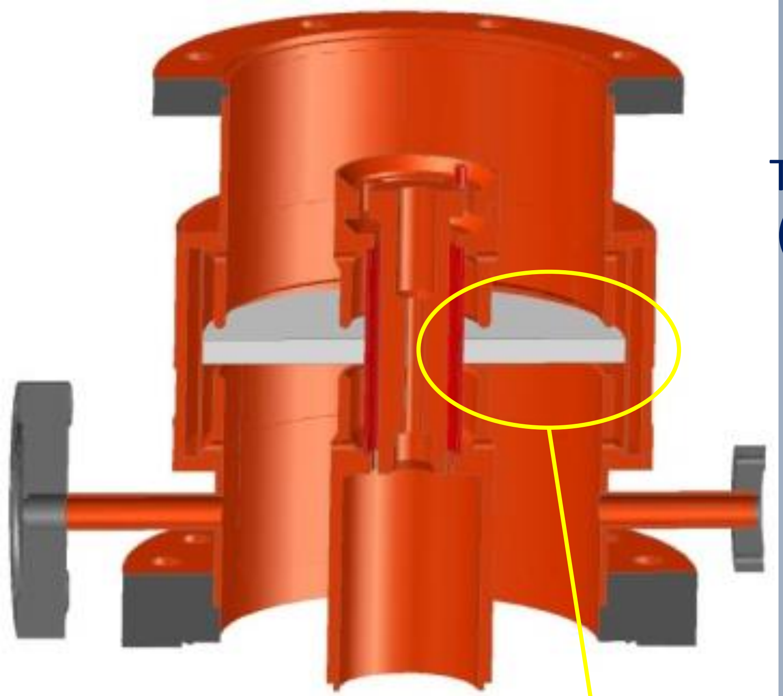
Secondary

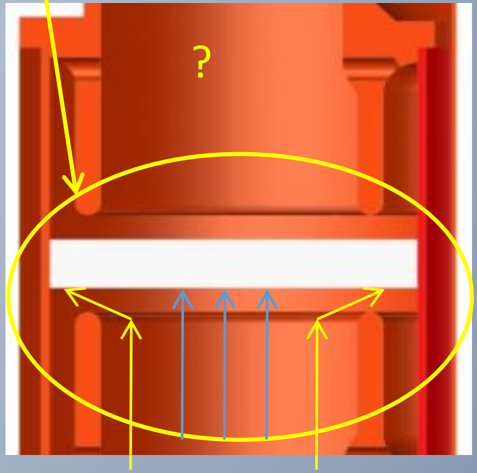
Al_2O_3 + TiN
SEY = 1.5


Photo:
Reidar Hahn

TiN or TiOx coating

- Secondary Electron Emission Yield (SEY) of ceramic is not very good (SEY ~7), so to avoid multipacting, vacuum side of the window is Ti (or TiN) coated (SEY ~1.5)
- In addition, it provides a high resistive layer tha help to remove electrostatic discharge
- Ti coating is a well mastered process at CERN, however :
  - Do not really know how to measure Ti coating
  - Too thin, not multipactor suppressor
  - Too thick, adding a layer with RF losses, break the ceramic
  - In case of special shape, how guaranty Ti coating is really everywhere ?


Toshiba window (SNS, CEA, KEK)



How to ensure the TiN coating behind the chokes ?


Photo:
Reidar Hahn

DC polarisation

- A good multipacting suppressor is to apply DC polarisation on the antenna,
- This will modify the electron trajectories and prevent the multipacting to occur,
- HV in the range of 2 to 5 kV DC range is needed,
- It should not be used during conditioning of the couplers, but can be applied during operation of the machine if needed or in prevention of the troubles

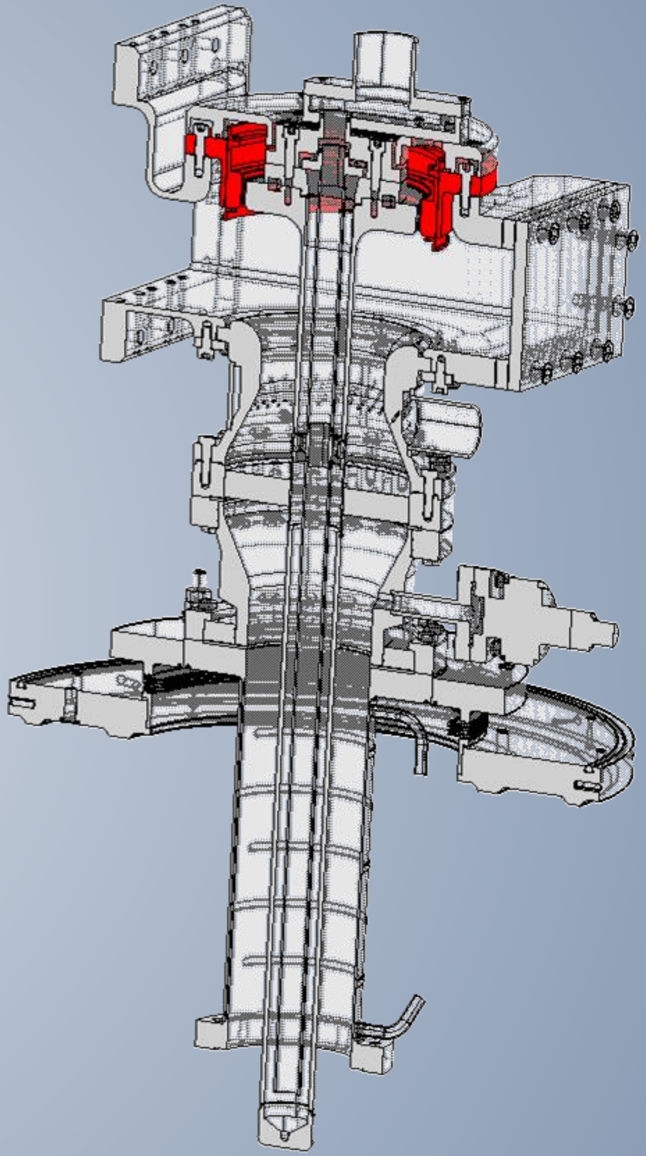



Photo:
Reidar Hahn

Ceramic choice – cylindrical design

- Advantages
  - High power capability, LHC proven
  - Very easy to cool down the antenna
  - Antenna with sliding contacts
  - Possible DC HV biasing
  - No dilatation constraint (bottom of the double tube)
  - Ceramic not seen by the beam
- Disadvantages
  - Difficult ceramic brazing process, however well known now at CERN

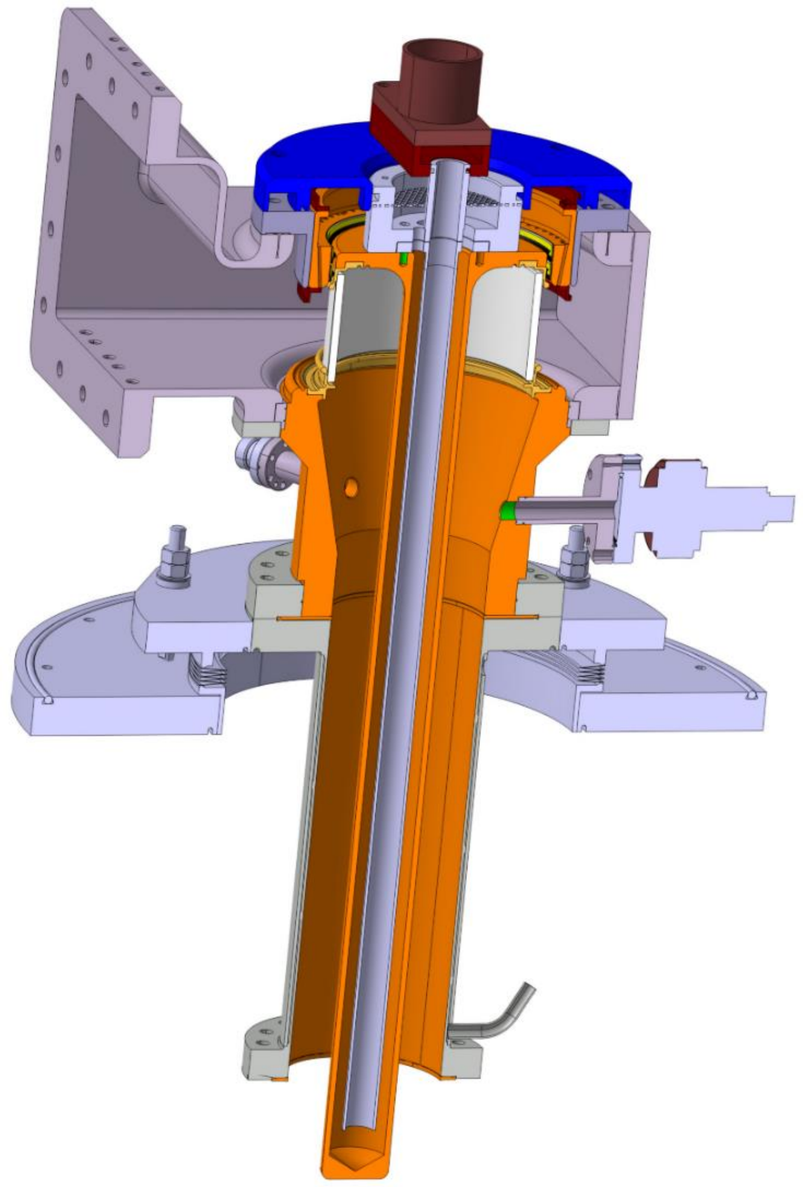



Photo:
Reidar Hahn

Ceramic choice – coaxial disk design

- Advantages
  - Very easy to cool down the antenna
  - Antenna with sliding contacts
  - Possible DC HV biasing
  - No dilatation constraint (bottom of the double tube)
  - High power capability, CEA-HIPPI proven
- Disadvantages
  - Dust directly on the ceramic (top or bottom mounted)
  - Ceramic directly seen by the beam

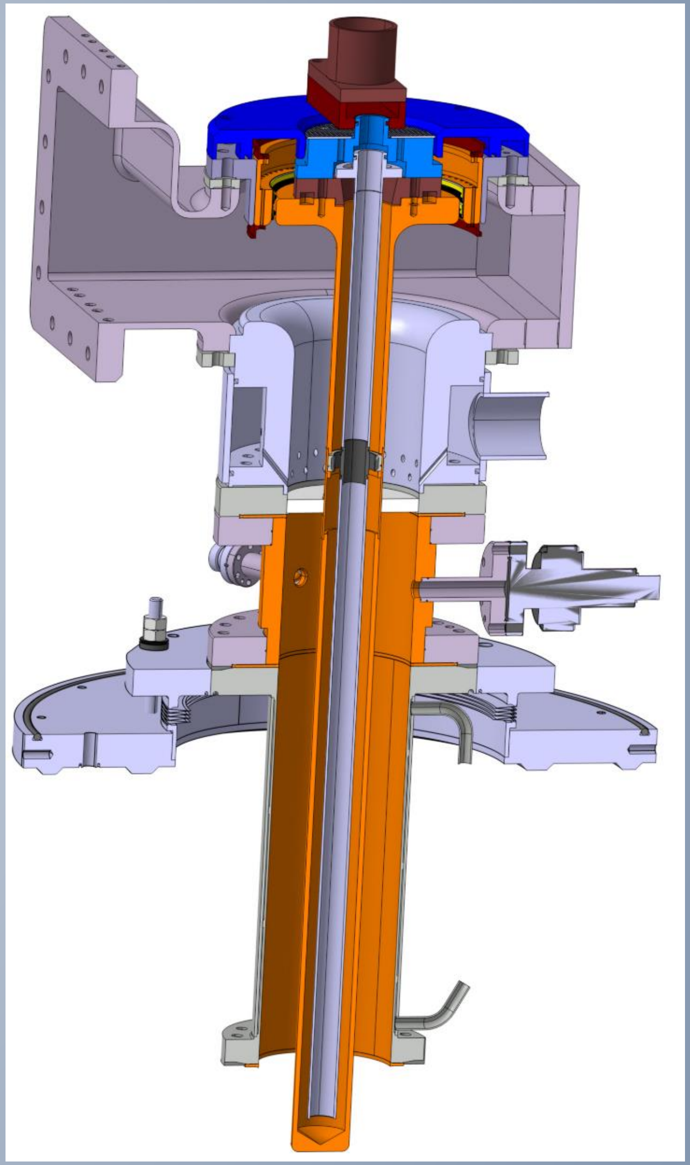



Photo:
Reidar Hahn

Ceramic choice – disk design

- Advantages
  - Very simple antenna system
  - Full waveguide height, maximum power capability
  - Ceramic not seen by the beam
  - Mechanically very robust
- Disadvantage
  - Integration to the cryomodule for high gradient

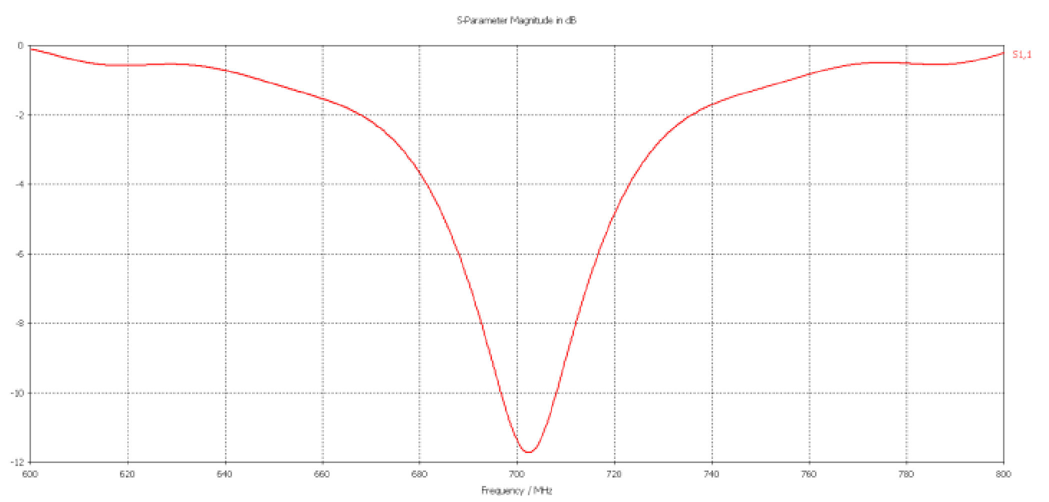



Photo:
Reidar Hahn

Construction (12 to 24 months)


Photo:
Reidar Hahn

FPC RF processing or FPC conditioning

- Being part of the most important interface between the RF power source and the cavity, the power couplers must ensure the transfer of RF power up to several hundred kilowatts and could have to withstand peak power up to MW
- Design problems and construction defaults of these couplers can be the cause of many physical phenomena when the coupler is placed under vacuum and crossed by the RF
- These phenomena can be damaging for delicate parts of couplers such as ceramic windows providing barrier between the vacuum cavity and the atmospheric pressure
- This function can be guaranteed only after a RF conditioning of the couplers, consisting in the gradual adaptation of the coupler to withstand electromagnetic fields created by the passage of the RF power


Photo:
Reidar Hahn

FPC RF processing or FPC conditioning

- It reduces the violence of these phenomena and allows to identify some couplers with construction problems
- The conditioning allows the gradual reduction of these phenomena by a controlled increase of the power, it must be SAFE and FAST
- Thus, the internal surfaces of the coupler receive doses of controlled electron impact that have for effect to change their secondary emission coefficient, and clean surfaces gradually
- The FPC are considered as conditioned or RF processed when no more outgassing occurs in TW neither in any SW mode at any power level and over hours


Photo:
Reidar Hahn

FPC ceramic crack

Photo:
Reidar Hahn

RF processing or FPC conditioning

Photo:
Reidar Hahn

Conditioning process

Vacuum gauges reading used for interlocking the RF switch if vacuum pressure value exceeds maximum ratings (5 x 10^{-7} mbar based on experience)

Vacuum analog loop to reduce the RF drive in cas of vacuum outgassing

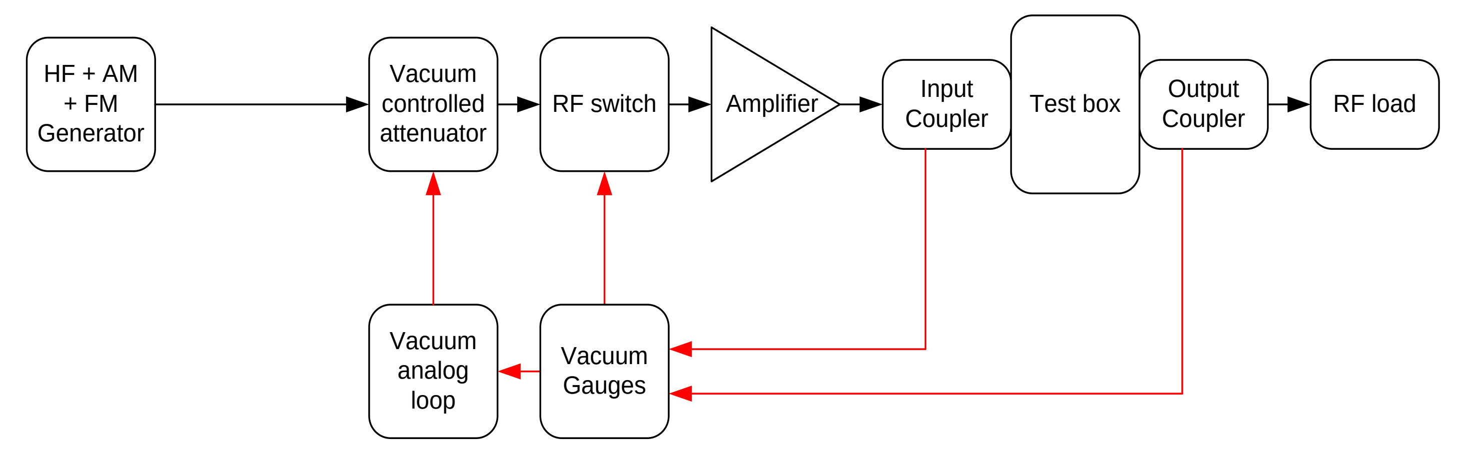



Photo:
Reidar Hahn

From short pulses to longer pulses (CW)

In order to be safe, what we applied since 1998 with the first loop in operation, is the ramping with very short pulses from zero to full power.

We then restart with longer pulses, again from zero to full power.

We repeat the process until maximum pulse duration, that could be CW.

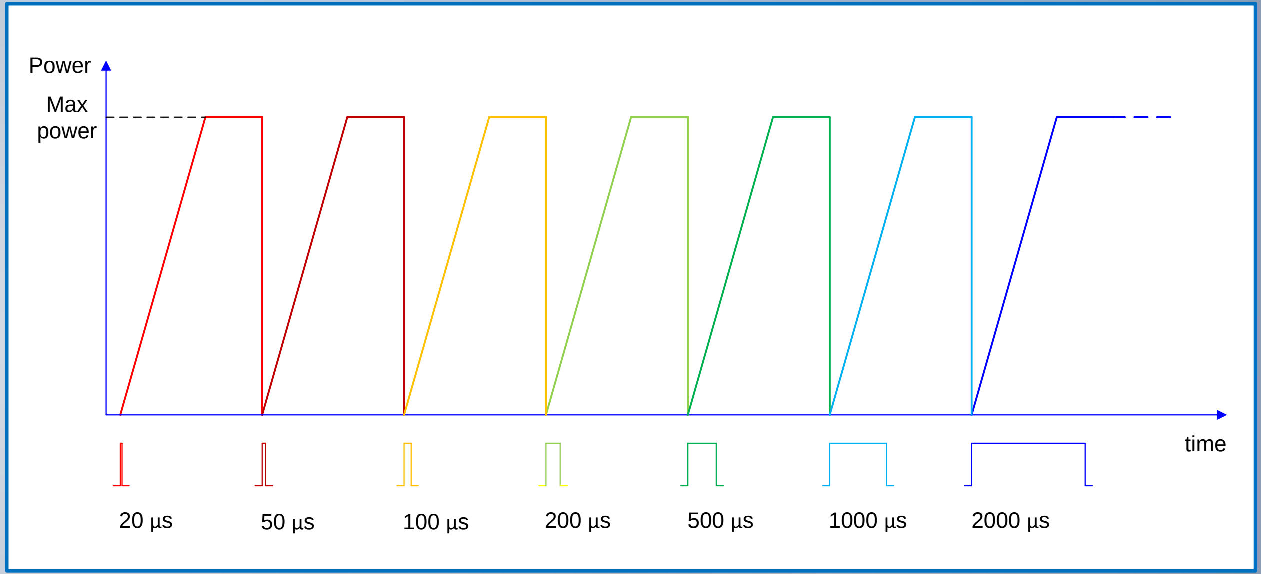


Photo:
Reidar Hahn

Ramping

What we also noticed is that making a ‘straight ramping’ could be dangerous.

Indeed, a higher power level can ‘de-condition’ a lower power level previously processed.

So inside one envelope, we ramp up and we ramp down to guaranty that ALL power levels have been processed with the shorter pulses.

This process ensures that the lowest energy is deposited into an arc if it should occur.

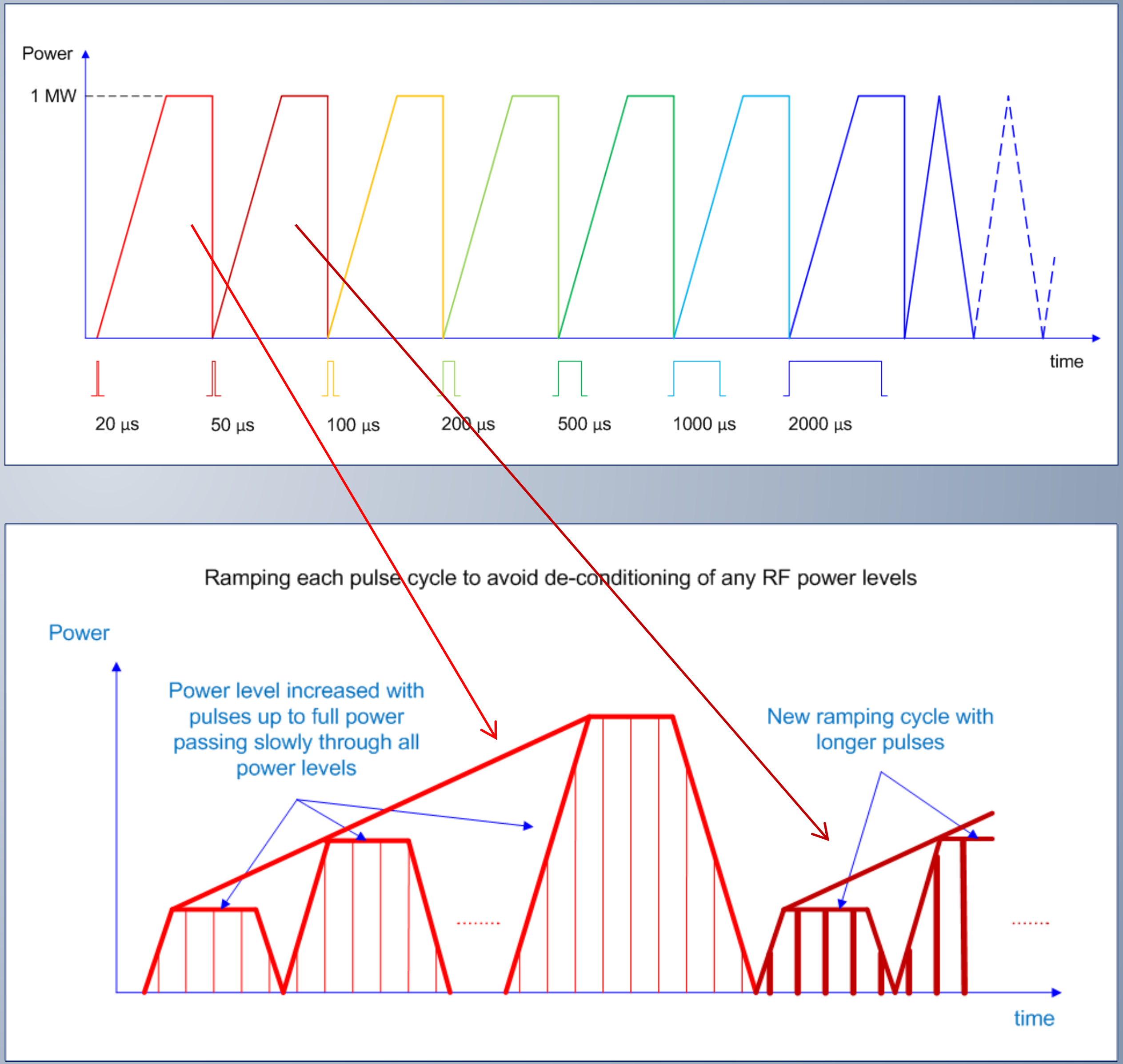



Photo:
Reidar Hahn

Long repetition rate with respect to vacuum gauge

It is important to keep the repetition rate low enough to allow enough time to the vacuum gauge to detect the pressure rise.

This allows not to stop the system, only few pulses are missed.

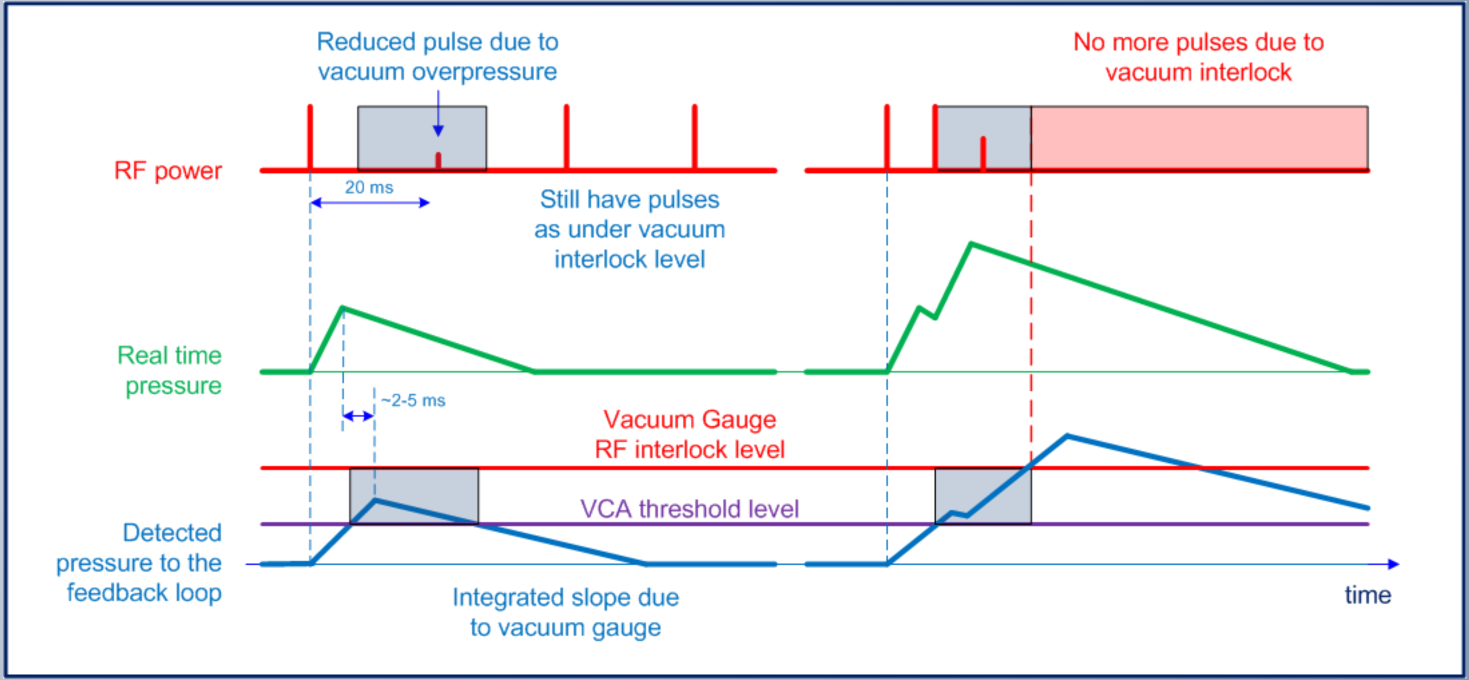



Photo:
Reidar Hahn

Automated process for processing

In order to speed-up the process, it can be automated.

A second loop, computer controlled, was added,

The CPU is also monitoring the vacuum pressure, and also acts in case of outgassing,

Its main task is to safely increase as quick as possible the RF power level.

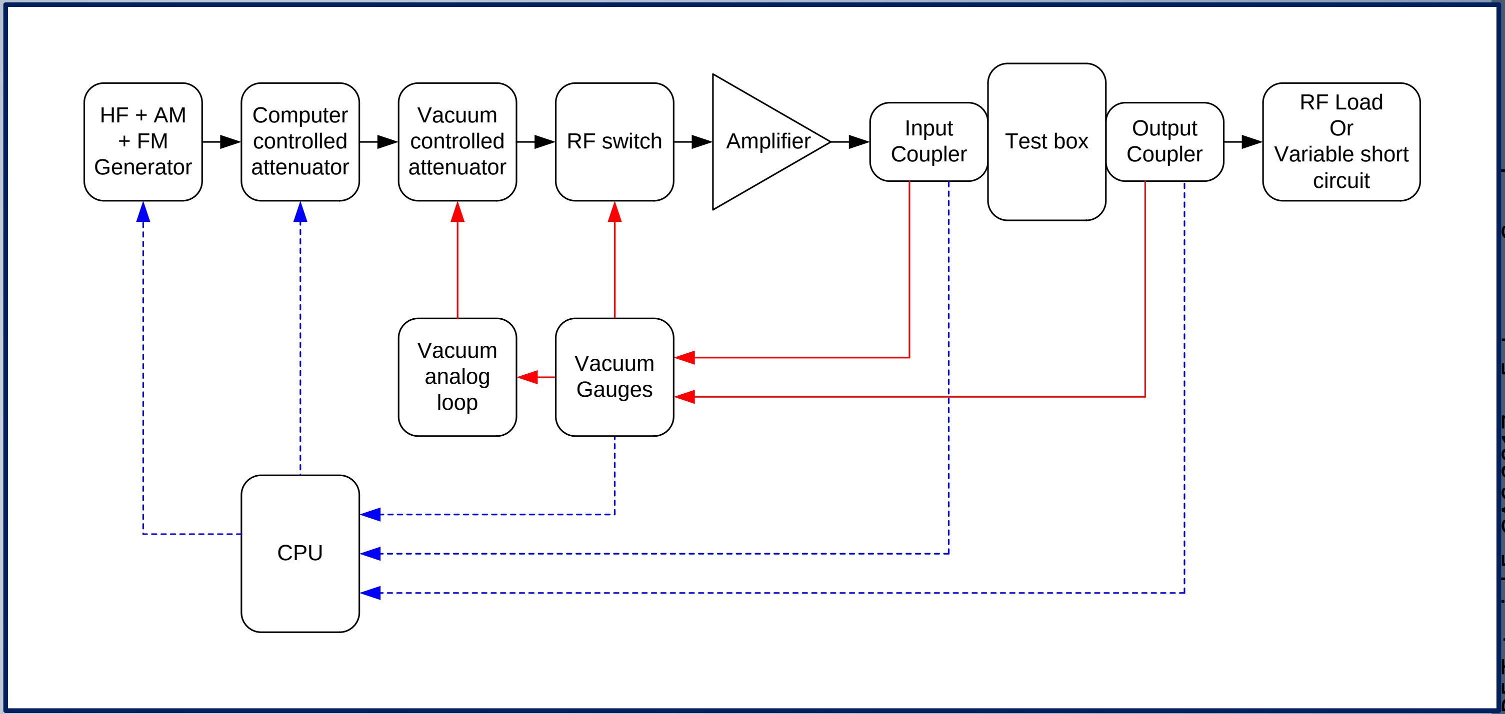


Photo:
Reidar Hahn

Automated processing

SETTINGS

Start Pulse Length: MS_1

End Pulse Length: CW

SETTINGS

Central Frequency [Hz] 1: 4.007E+8

Sweep Range [Hz] 1: 2000

Output Level [dB] 1: 0

Sweep Frequency [Hz] 1: 1

Central Frequency [Hz] 2: 3E+8

Sweep Range [Hz] 2: 0

Output Level [dB] 2: -80

Sweep Frequency [Hz] 2: 0

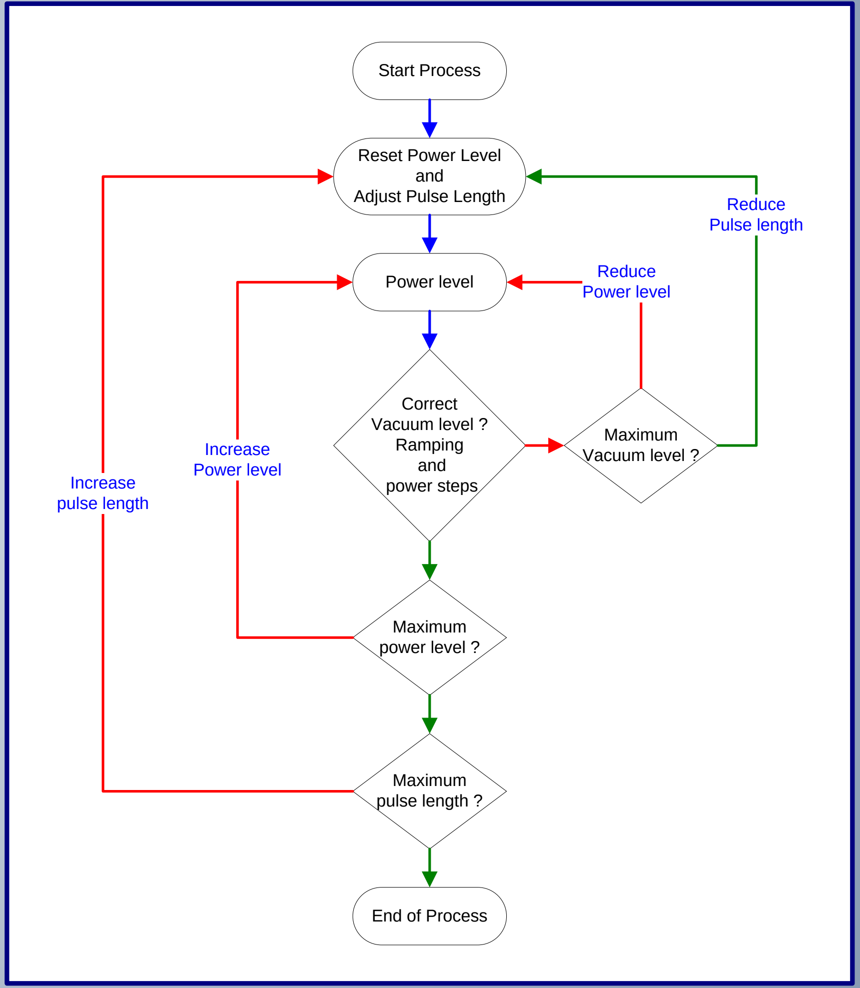
FESA Instance Name: SM18ALLConditionningDDS

Last power loop #: 4

Wait Hours: 10

Pulse Length: 30m [S]

Current Power: 130k [W]



Start Process

Reset Power Level and Adjust Pulse Length

Power level

Correct Vacuum level ? Ramping and power steps

Maximum Vacuum level ?

Reduce Power level

Reduce Pulse length

Maximum power level ?

Increase Power level

Maximum pulse length ?

Increase pulse length

End of Process

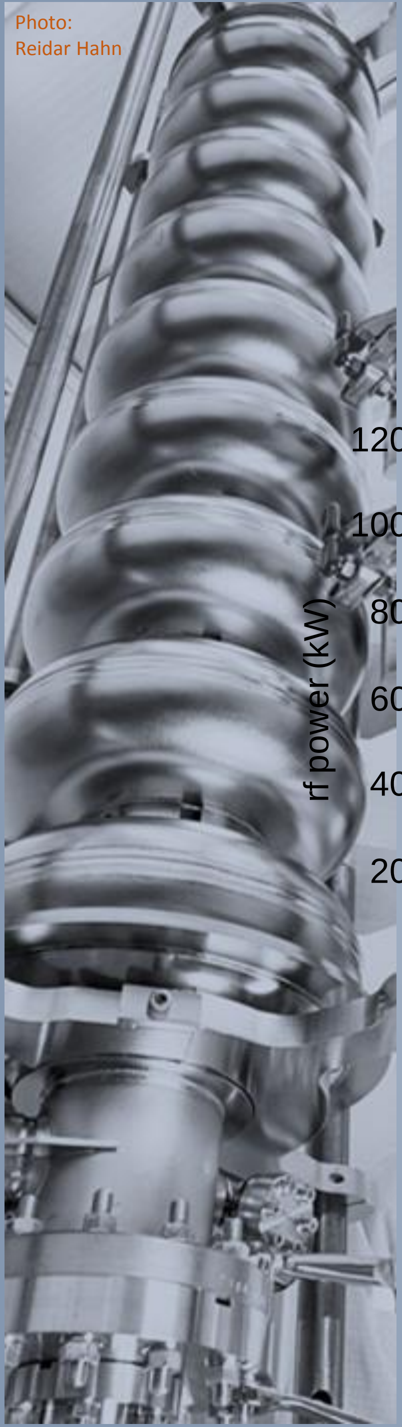
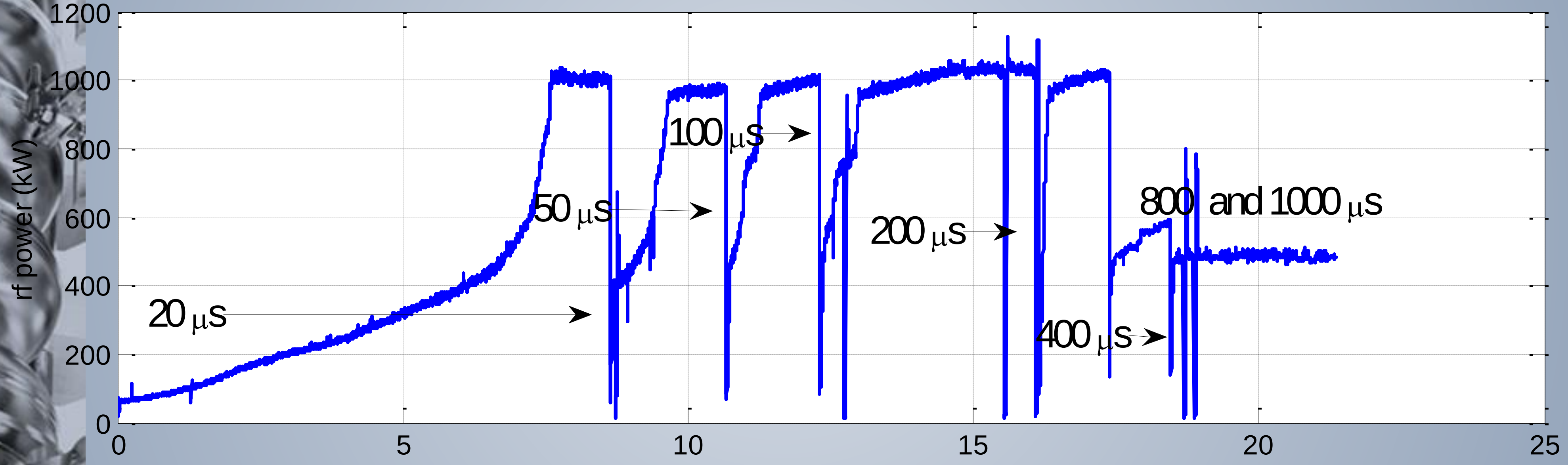


Photo:
Reidar Hahn

Processing time, short pulses is the most demanding step



LCLS-II Couplers processing, courtesy of C. Adolphsen (SLAC)


Photo:
Reidar Hahn

RF Conditioning – Summary of 20 years of experience

Key parameters for a safe process

- Loop with vacuum pressure modulating RF power
- Automated process with short pulses first

Key parameters for a quick process

- Assembly in clean room is mandatory, particularly for SRF cavities
- Bake out of all systems is mandatory
- Several test boxes is mandatory
- Multi couplers in series is a good option
- AM and FM do not make it quicker

HOM couplers


Photo:
Reidar Hahn

High pressure
(air or gas)

Beam vacuum
(10^{-7} to 10^{-10} mbar)

The **HOM C**ouplers are designed to extract the beam induced power at the HOM frequencies into a load to avoid beam instabilities, and act as stop-band to the fundamental mode

The transmission line has to sustain quite a large amount of power from cold to warm minimizing the thermal load to the cryomodule as HOM couplers could be cooled down with liquid helium

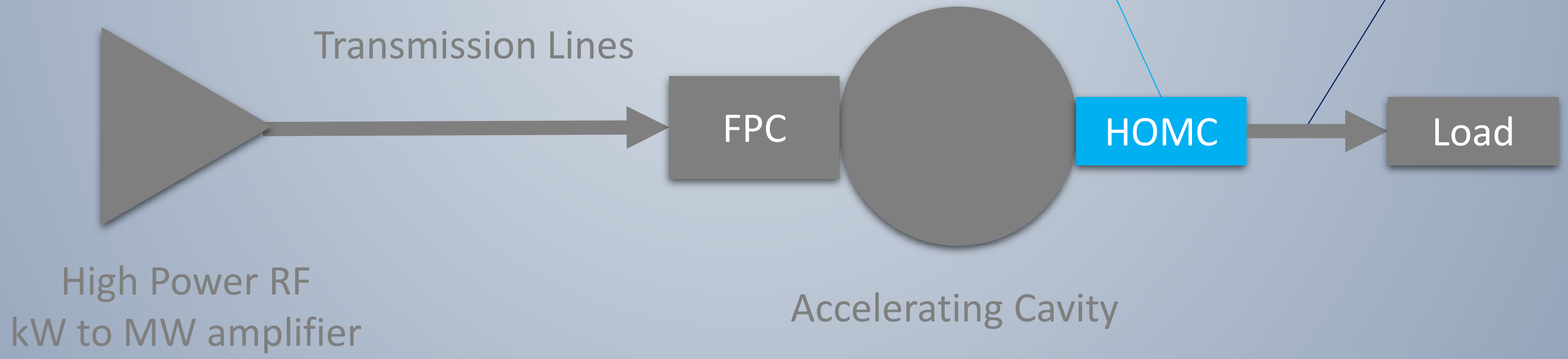


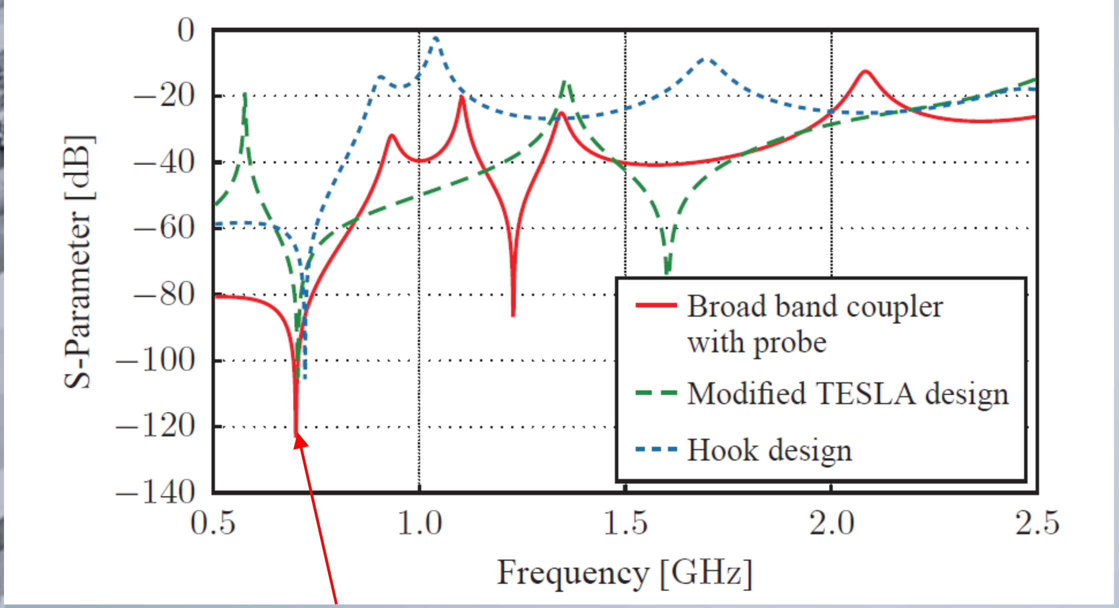

Photo:
Reidar Hahn

HOM coupler functions

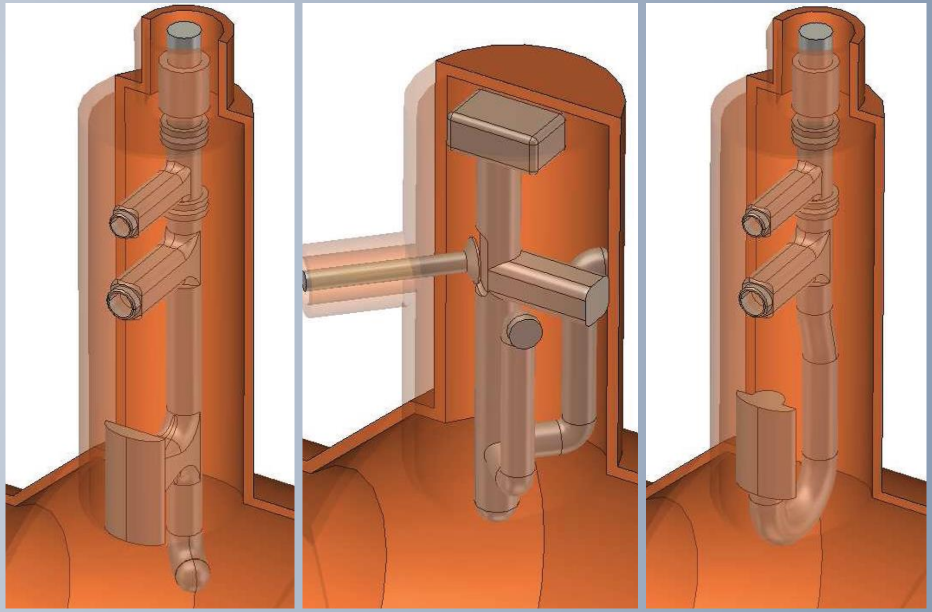
- HOM couplers are also a vacuum barrier
- Need to be superconducting as being inside the cryostat
- Need the same preparation as the SRF cavities themselves, they have the same cleanliness issues
- Interfaced to a RF power transmission line in order to transmit the extracted to a power load located outside the cryomodule


Photo:
Reidar Hahn

SPL HOM coupler



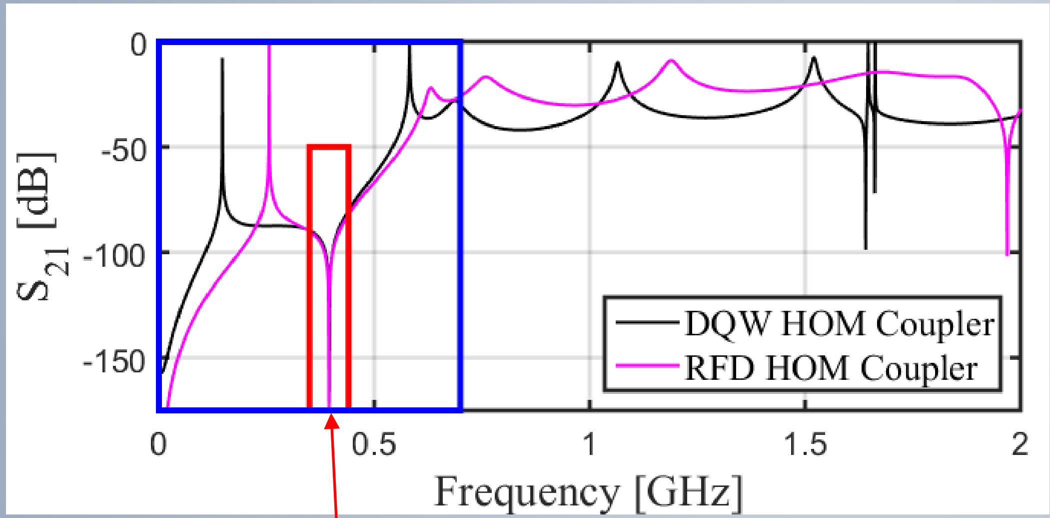
No transmission at the operating frequency



Design approaches of HOM coupler
probe coupler, modified TESLA design, hook coupler

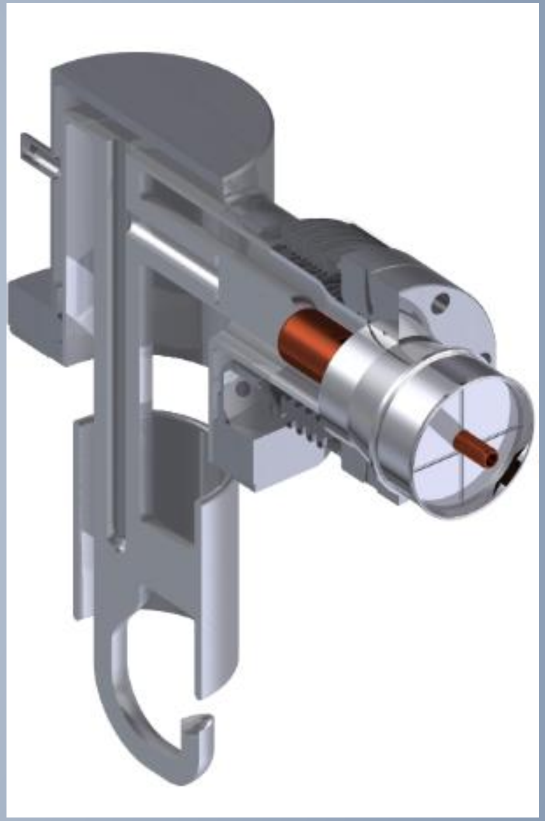

Photo:
Reidar Hahn

HL-LHC crab HOM couplers



No transmission at the operating frequency

HOM coupler HL-LHC type “RFD”



HOM coupler HL-LHC type “DQW”


Photo:
Reidar Hahn

RF power lines from HOM couplers to load

- As the HOM couplers are now requested to extract power in the order of 1 kW, the transmission line doing that job has to be designed to sustain $4\ P_{max} +$ margin $\approx 5\ \mathrm{kW}$.
- Indeed, in case a power load is disconnected or broken, there will be full reflection at the load side, and we cannot afford to open a cryomodule to repair the line (this happened in 1996 when we tested the first LHC prototype cavities in the SPS).
- The new line is designed with 0.5 mm Stainless Steel 5 µm copper coated, plus a ceramic for thermal anchor, plus specific RF fingers allowing flexibility with respect to thermal cycles.

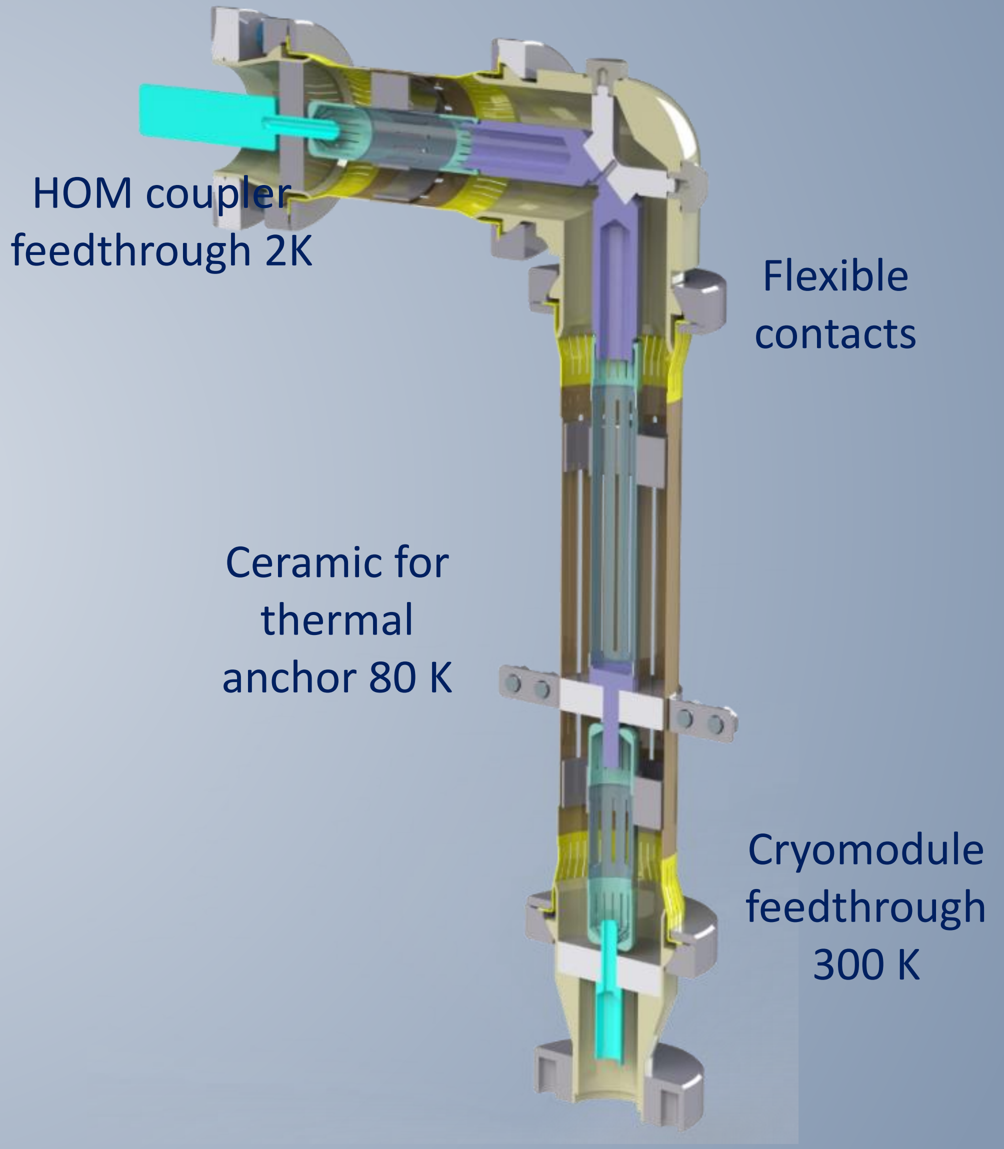



Photo:
Reidar Hahn

End of “Power couplers, higher-order mode (HOM) damping”

Thank you very much!