eric.montesinos@cern.ch

CAS course on "RF for Accelerators",

18 June - 01 July 2023, Berlin Germany

RF for Accelerators

RF power transport

1983
—2023
years

The CERN Accelerator School

HZB Helmholtz Zentrum Berlin

The CERN Accelerator School

Copyright statement and speaker's release for video publishing

Outlook

RF power transport basics

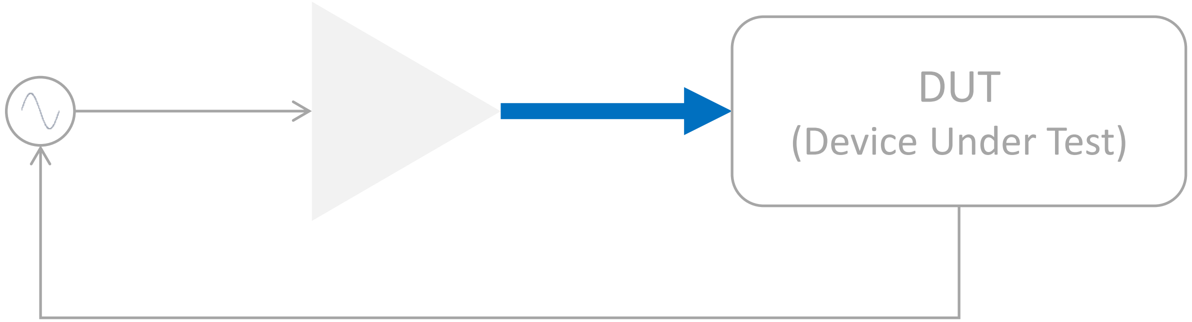
Waveguides

Coaxial lines

Circulator

Fundamental Power Couplers

RF Power Lines



Purpose

Transmission of RF power of several kW up to several MW at frequencies from the MHz to GHz range

The RF power generated by an RF generator must be transported and distributed to a load or cavity or a number of loads or cavities

Requirements

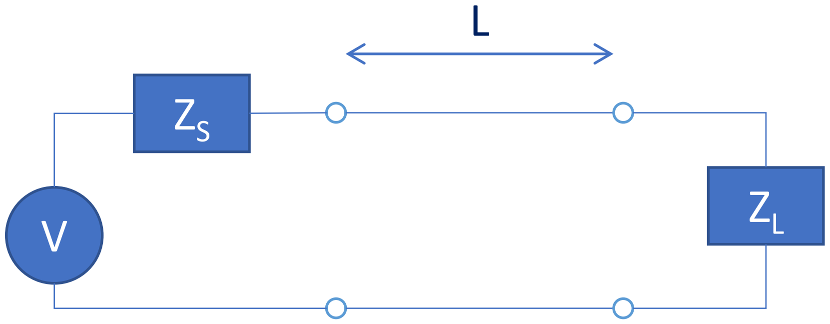
low loss, low reflections, high reliability, adjustment of phase and amplitude, …

Introduction to Transmission Lines

The way to connect the Device Under Test (DUT), that can be an RF cavity, a kicker, a pick-up, an oscilloscope… is through a Transmission Line

If you plug your laptop charger into a wall outlet, the chord (transmission line) that connects the power to the charger is 3 meters long, the power is supplied at 50 Hz, should transmission line effects be taken into account?

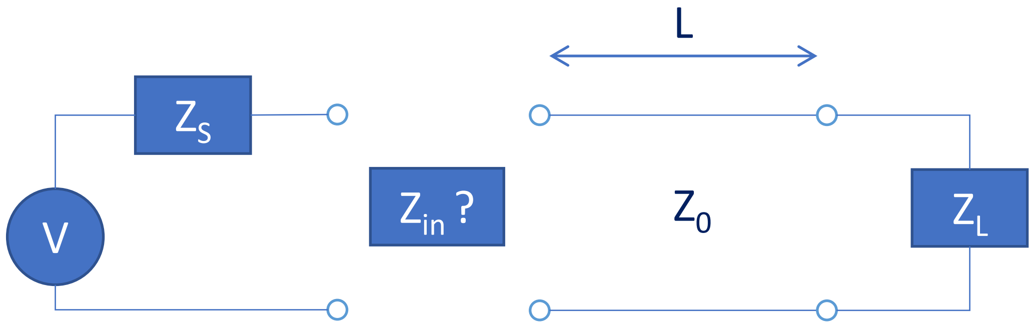
The wavelength at 50 Hz is 6’000 km (6 million meters) the transmission line in this case is 3/6’000’000 = 0.0000005 wavelengths long, so the transmission line is very short relative to a wavelength, and therefore will not have much impact on the device



In traditional low-frequency circuit analysis, the transmission line would not matter, the current flowing in the circuit would simply be

$$\boldsymbol{I = \frac{V}{Z} \rightarrow I = \frac{V}{Z_S + ZL}}$$

Introduction to Transmission Lines



In the high frequency case, the length L of the transmission line can significantly affect the results, to determine the current that flows in the circuit, we would need to know what the input impedance Zin is viewed from the terminals of the transmission line

The best RF power source can be connected to the best DUT, but if it is done with a wrong length of wrong impedance transmission line at high frequencies, the system will not work properly

The input impedance of a load ZL is transformed by a transmission line as

$$\boldsymbol{Zin\ [L] = Z0 \left[\frac{ZL + jZ0\ tan\left(\frac{2\pi L}{\lambda}\right)}{Z0 + jZL\ tan\left(\frac{2\pi L}{\lambda}\right)}\right]}$$

This equation can cause ZL to be transformed radically

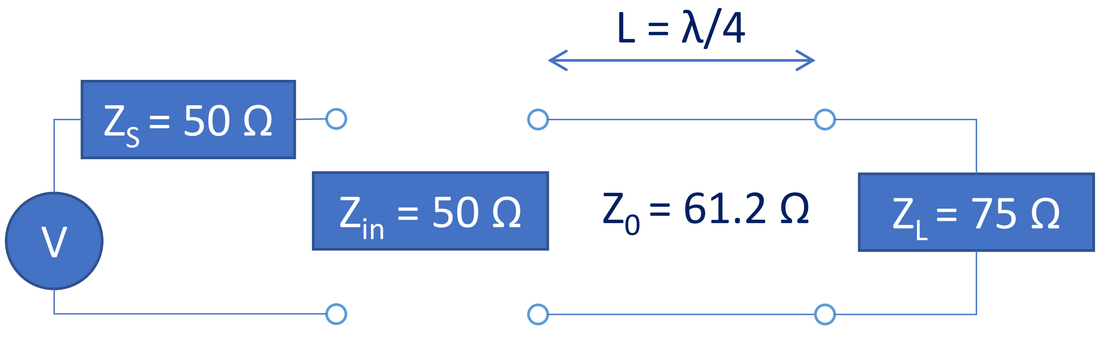
Introduction to Transmission Lines

An interesting thing happens when the length of the line is a quarter of a wavelength

$$\mathbf{Zin}\,[\mathbf{L}=\boldsymbol{\lambda}/4]=\mathbf{Z0}\left[\frac{\mathbf{ZL}+\mathbf{jZ0}\,\boldsymbol{tan}\left(\frac{2\pi}{\lambda}\frac{\lambda}{4}\right)}{\mathbf{Z0}+\mathbf{jZL}\,\boldsymbol{tan}\left(\frac{2\pi}{\lambda}\frac{\lambda}{4}\right)}\right]=\frac{\boldsymbol{Z0}^2}{\mathbf{ZL}}$$

The above equation is important as it states that by using a quarter-wavelength of transmission line, the impedance of the load (ZL) can be transformed following the above equation

We can match a load with impedance ZL=75 Ohms to be 50 Ohms using a quarter-wave transformer



$$\mathbf{Z0}\;=\sqrt{\boldsymbol{Zin}\;\boldsymbol{ZL}}$$

Doing so if a transmitter has an impedance of 50 Ohms and is trying to deliver power to the DUT no power will be reflected to the transmitter

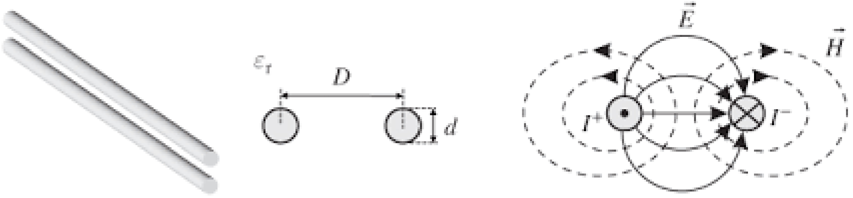
It is relatively simple to match a single frequency, but becomes very difficult if wideband impedance matching is desired

Transmission line families

Two-wire lines

often used for indoor antenna, radio or TV

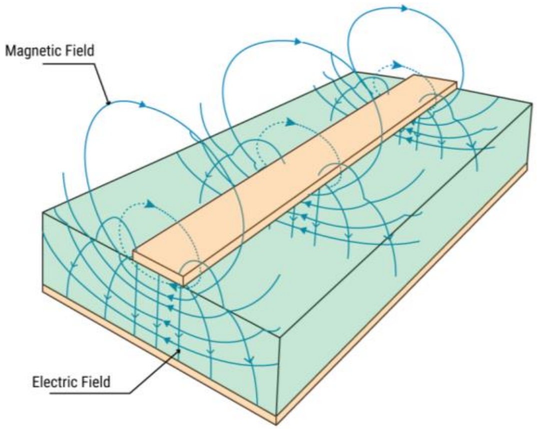
Radiation to the environment, cannot be used for high power Transportation



Strip-lines

often used for microwave integrated circuits

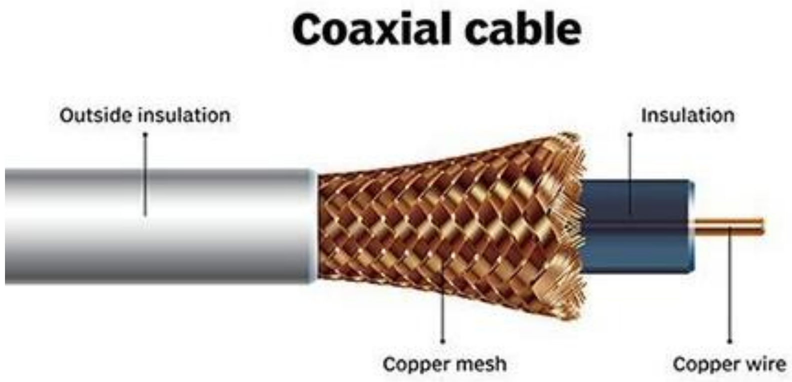
Radiation to the environment and limited power capability, cannot be used for high power transportation

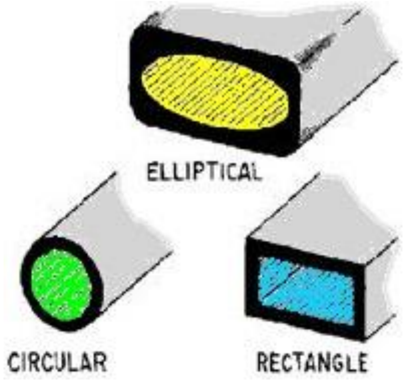


Transmission line families

Coaxial lines
often used for power RF transmission and connection of RF components
High loss above a certain frequency due to heating of inner conductor and dielectric material and limited power capability at higher frequencies due to small dimensions

Waveguides (rectangular, cylindrical, elliptical)
often used for high power RF transmission (mostly rectangular)
Waveguide plumbing, rigidity





RF flowing only through first layers of the material

RF needs only few µm of good electrical layer to flow along

at the surface, conductivity is 100%

at one skin depth, it is decreased to 36.8%

at two skin depths, 13.5%

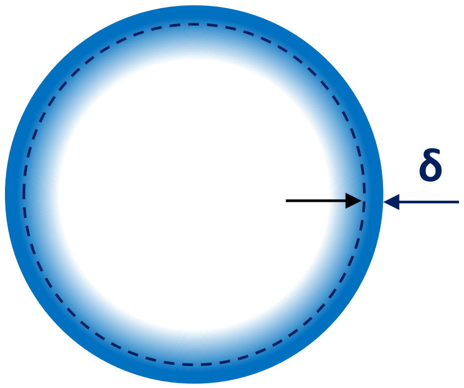
at three skin depths, 5.0%

at four, 1.8%

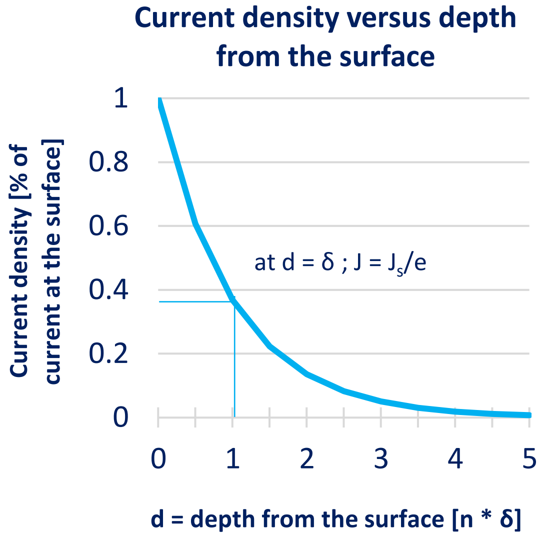
at five, 0.7%

When d = 5 x δ,

more than 99 % of the current flows in the conductor



RF current is flowing through only the first layers of a plain cable


Current density versus depth from the surface

$$J = Js\, e^{-(\frac{d}{\delta})}$$

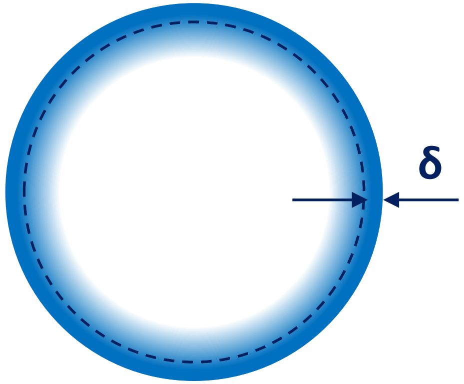
$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}$$

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, $\rho = 1.678 * 10^{-8}$ Ωm, $\mu_r = 0.999991$, δ = 3.26 µm

Skin depth effect



$$\delta = \sqrt{\frac{\rho}{\pi f \mu}}$$

With

ρ = resistivity of the conductor

f = frequency

$\mu = \mu_r * \mu_0$

μ_r = relative magnetic permeability of the conductor

μ_0 = permeability of free space

material	P [nΩm]	μ_r	δ @ 200 MHz [µm]	5 x δ @ 200 MHz [µm]
Gold	24.4	1	5.56	27.8
Silver	15.9	1	4.49	22.5
Copper	17.2	1	4.67	23.4
Aluminium	28.2	1	5.97	29.9
Tin	109	1	11.75	58.8
Lead	220	1	16.70	83.5

Outlook

RF power transport basics

Waveguides

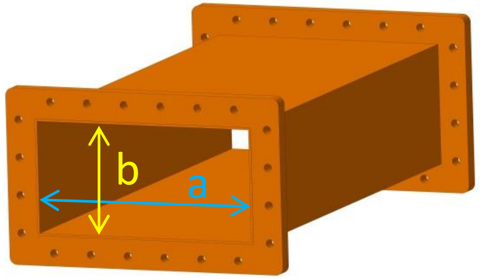
Coaxial lines

Circulator

Fundamental Power Couplers

Rectangular waveguides

The main advantage of waveguides is that waveguides support propagation with low loss

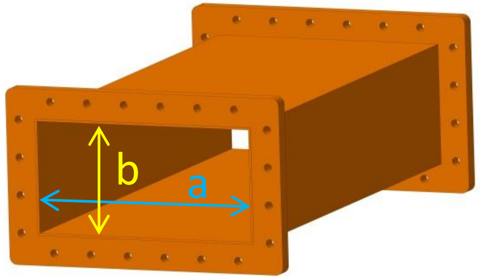


Wavelength	$\lambda_g = \frac{\lambda}{\sqrt{1-(\frac{\lambda}{2a})^2}}$
Cutoff frequency dominant mode	$f_c = \frac{c}{2a}$
Cutoff frequency next higher mode	$f_{c2} = \frac{c}{4a}$
Usable frequency range	**1.3 f_c to 0.9 f_{c2}**

Rectangular waveguides

Waveguides are usable over certain frequency ranges

- For very lower frequencies the waveguide dimensions become impractically large
- For very high frequencies the dimensions become impractically small & the manufacturing tolerance becomes a significant portion of the waveguide size



Waveguide name			Recommended frequency band of operation (GHz)	Cutoff frequency of lowest order mode (GHz)	Cutoff frequency of next mode (GHz)	Inner dimensions of waveguide opening (inch)	Inner dimensions of waveguide opening (mm)
EIA	RCSC	IEC					
WR2300	WG0.0	R3	0.32 — 0.45	0.257	0.513	23.000 × 11.500	584.2 x 292.1
WR1150	WG3	R8	0.63 — 0.97	0.513	1.026	11.500 × 5.750	292.1 x 146
WR340	WG9A	R26	2.20 — 3.30	1.736	3.471	3.400 × 1.700	86.1 x 43.2
WR75	WG17	R120	10.00 — 15.00	7.869	15.737	0.750 × 0.375	19.05 x 9.52
WR10	WG27	R900	75.00 — 110.00	59.015	118.03	0.100 × 0.050	2.54 x 1.27
WR3	WG32	R2600	220.00 — 330.00	173.571	347.143	0.0340 × 0.0170	0.86 x 0.43

Rectangular waveguides, Maximum Power handling

$$P_{peak} = 6.63\ 10^{-4}\ Emax^2\ b\sqrt{(a^2 - \frac{\lambda^2}{4})}$$

With

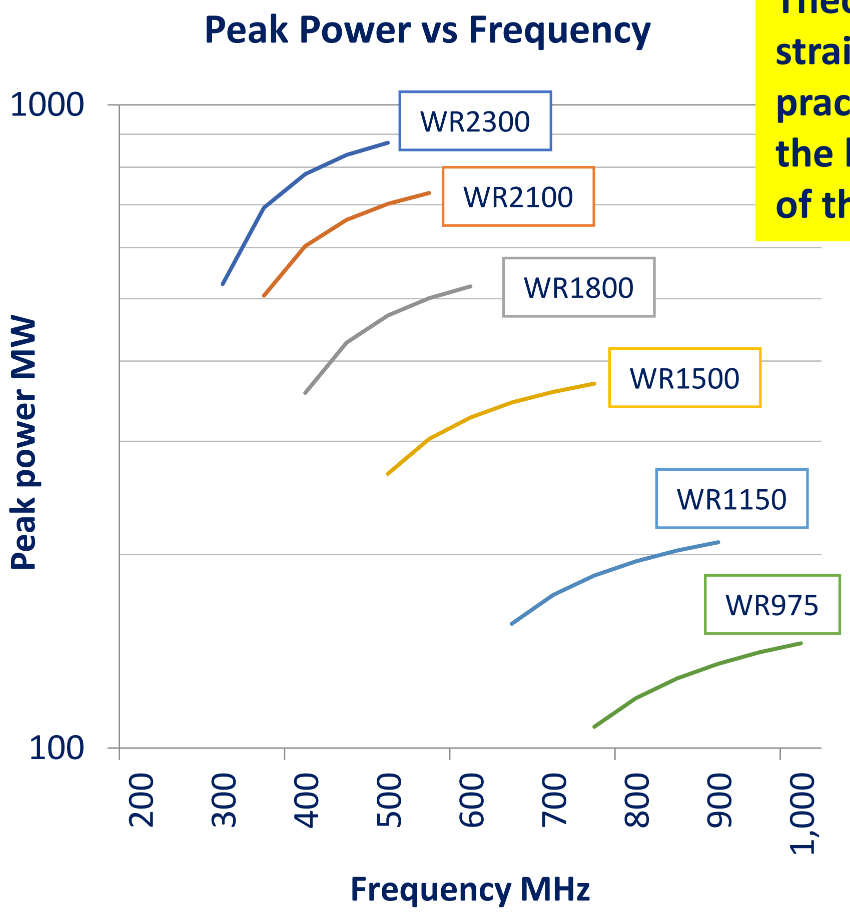
P_{peak} = Power in watts

a = width of waveguide in cm

b = height of waveguide in cm

λ = free space wavelength in cm

Emax = breakdown voltage gradient of the dielectric filling the waveguide in Volt/cm (for dry air 30 kV/cm, for ambient air 10 kV/cm)



Theoretical for straight WG, in in practice consider the limit being 10 % of this value

Rectangular waveguides, Attenuation

The walls of the waveguides are not perfect conductors, they have finite conductivity resulting in skin depth effect

Due to current in the wall of the waveguides, losses appear following the rule

$$\boldsymbol{\alpha} = \frac{4a0}{a}\frac{\sqrt{c/\lambda}}{\sqrt{1-(\lambda/2a)^2}}\left(\frac{a}{2b}+\frac{\lambda^2}{4a^2}\right)$$

With

α = attenuation constant, dB/m

a0 = 3 10-7 [dB/m] for copper

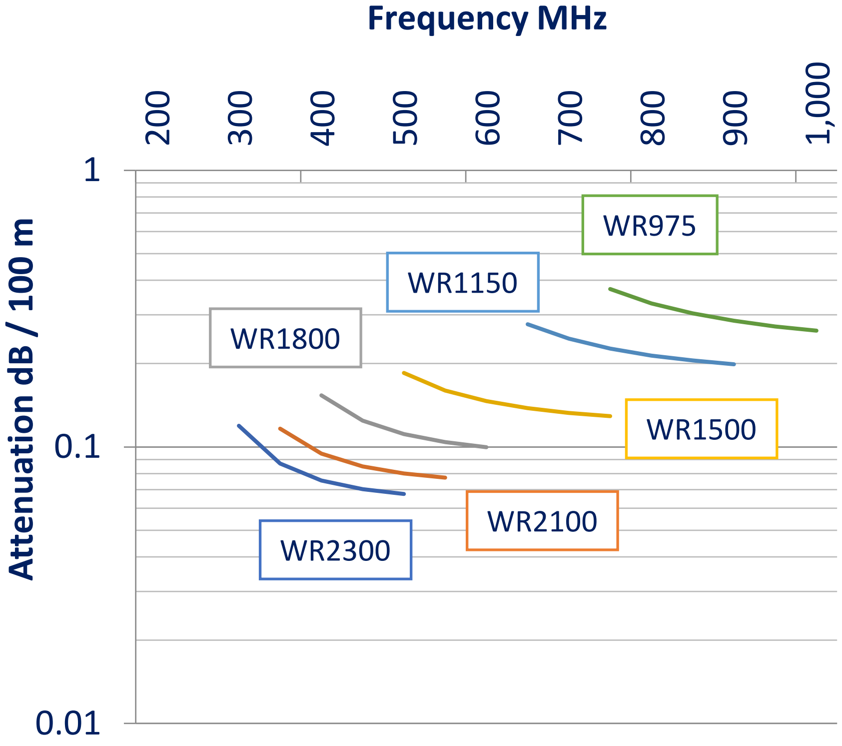
a = width of waveguide in m

b = height of waveguide in m

λ = free space wavelength in m

Attenuation factors of waveguides made from different material normalized to a waveguide of same size made of copper	
Copper	1.00
Silver	0.98
Aluminium	1.30
Brass	2.05

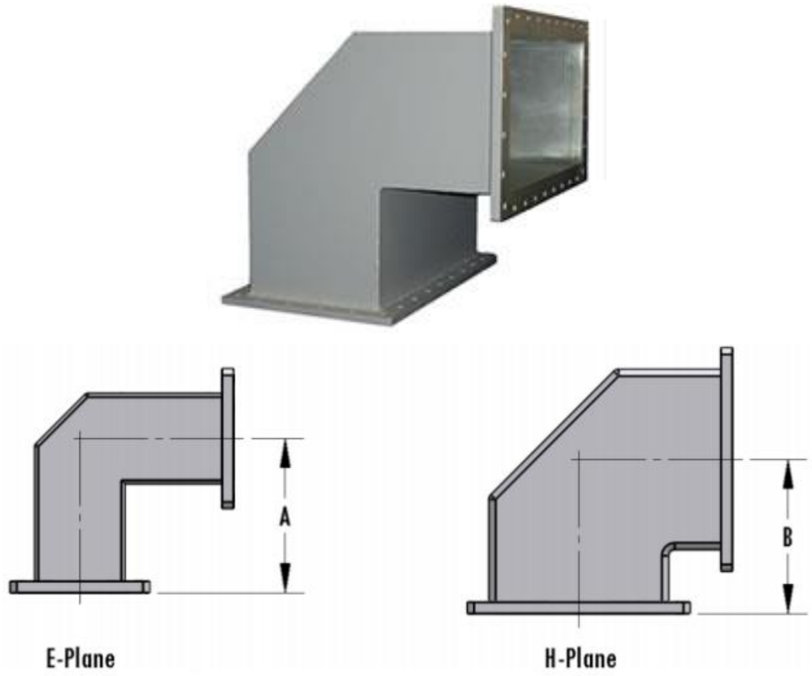
Peak Power vs Frequency



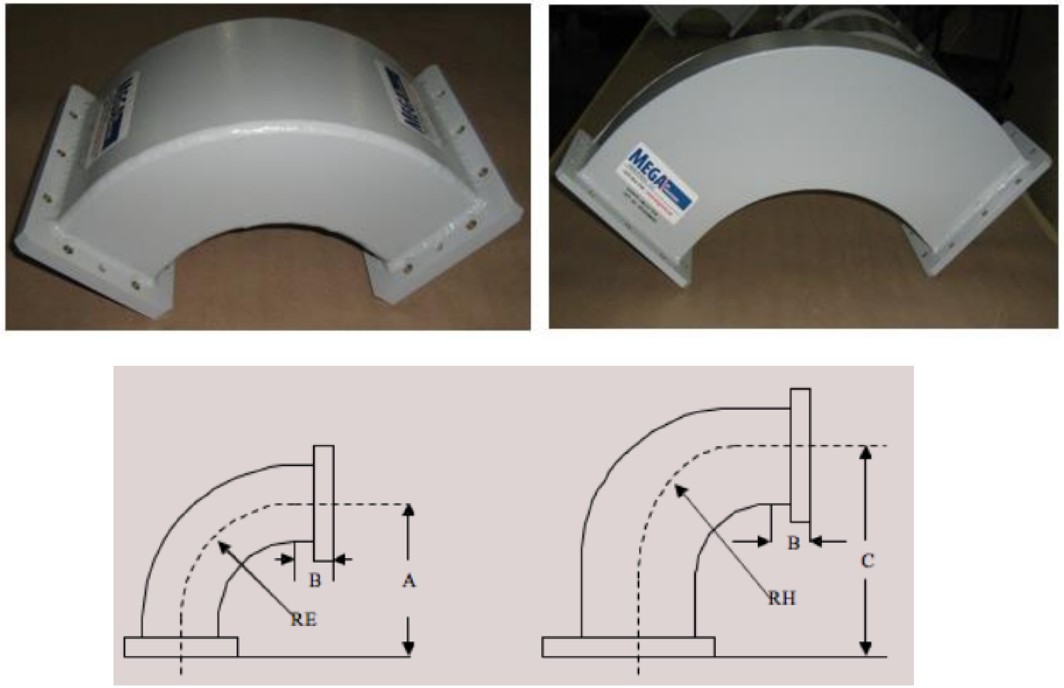
Rectangular waveguides

MEGA industries, straight waveguides

Rectangular waveguides

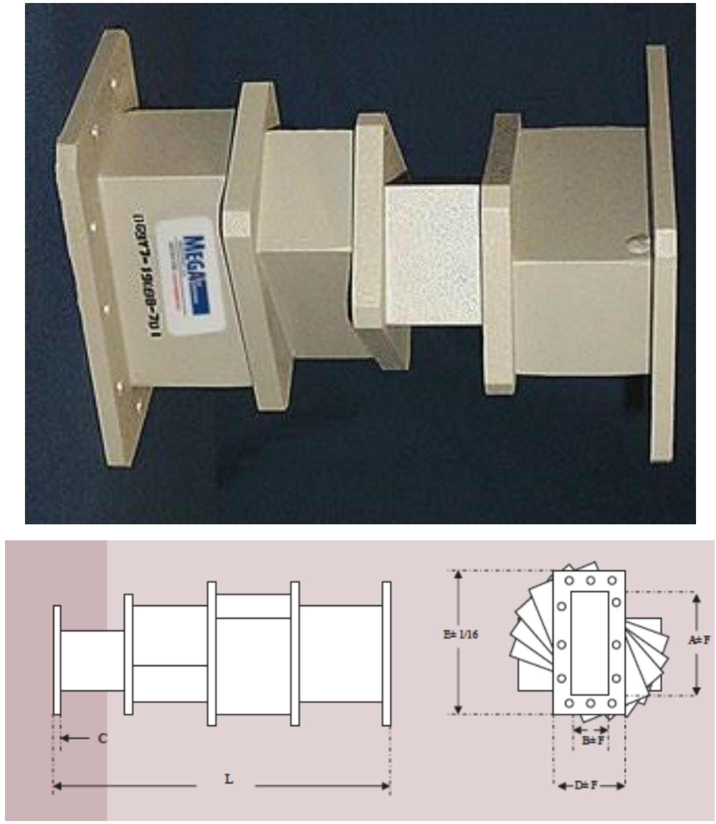


Mega Industries Miter Bends



Mega Industries Sweep Bends

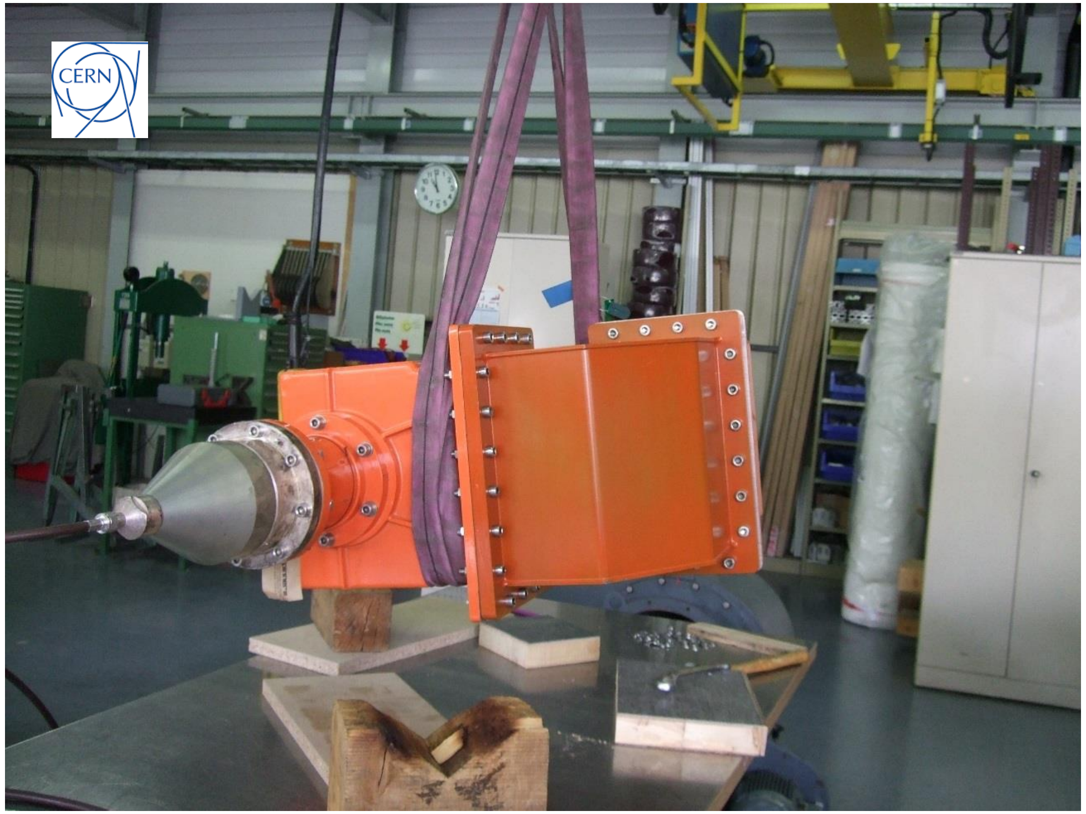
Rectangular waveguides



Mega Industries Step Twist waveguide

Mega Industries Flexible and Flexible twist waveguide

Rectangular waveguides



Adaptor from WR 1150 to N

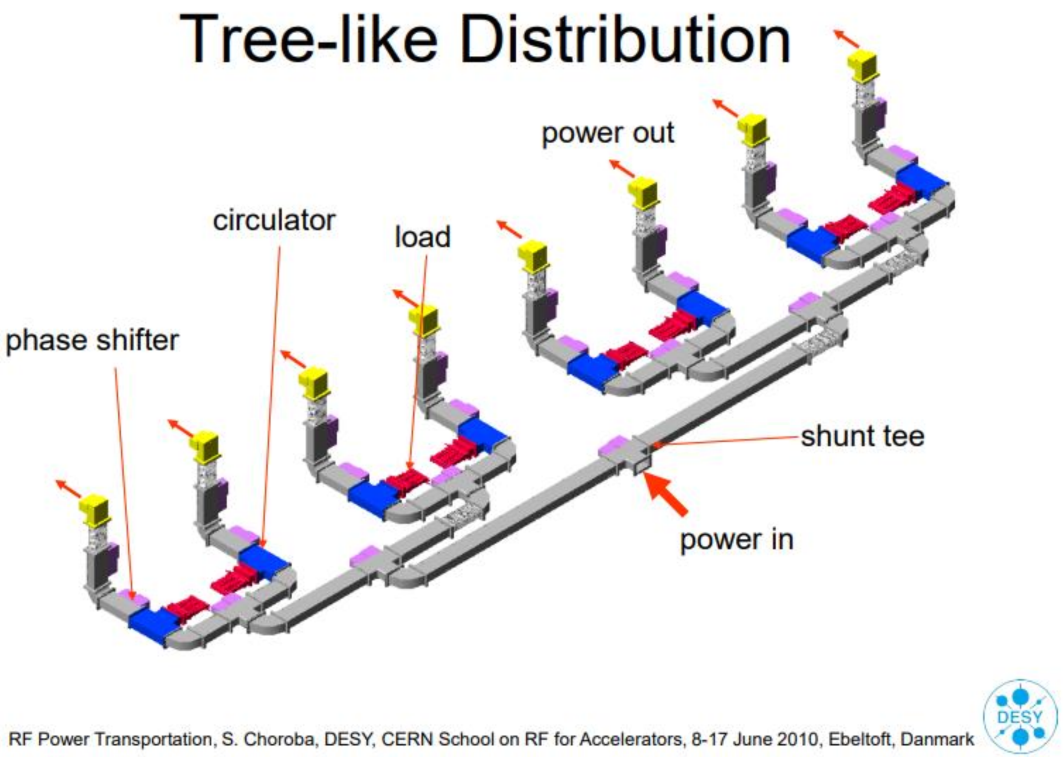
Distribution with rectangular waveguides

If you wish to use a high-power klystron to drive several cavities, you will need to distribute the power

There are two main distribution schemes with rectangular waveguides, linear distribution and tree like distribution

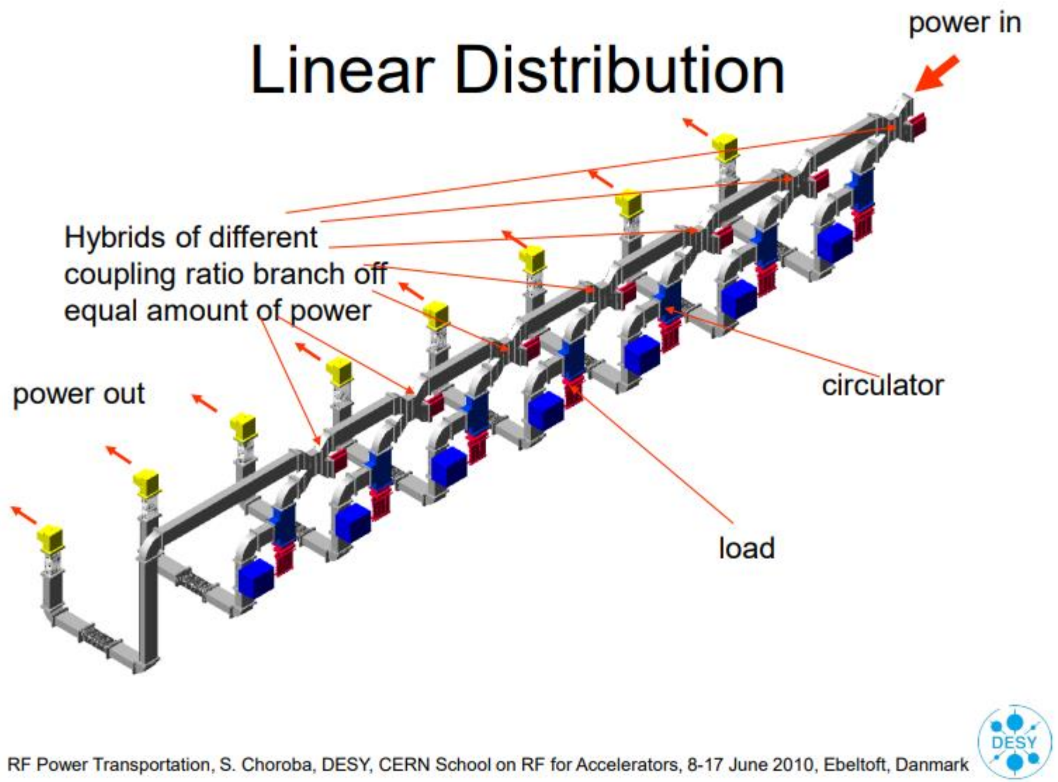
Combination of both are possible, the layout depending on the requirements, such as power capability, isolation between cavities, weight, available space, assembly processes, etc…

Distribution with rectangular waveguides



Tree-like Distribution

RF Power Transportation, S. Choroba, DESY, CERN School on RF for Accelerators, 8-17 June 2010, Ebeltoft, Danmark

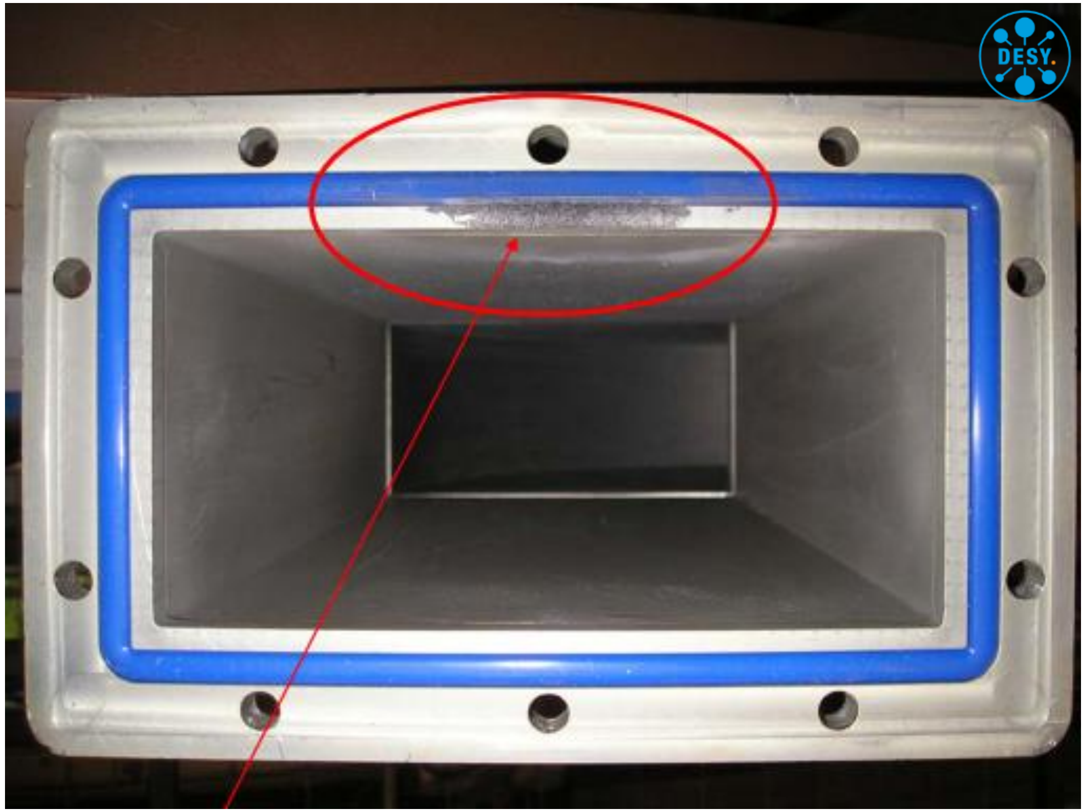


Linear Distribution

RF Power Transportation, S. Choroba, DESY, CERN School on RF for Accelerators, 8-17 June 2010, Ebeltoft, Danmark

Rectangular waveguides

Staff for opening and cleaning SF6 filled waveguide must use protection clothes



Damaged Waveguide due to bad Connection of two Waveguide Flanges

Outlook

RF power transport basics

Waveguides

Coaxial lines

Circulator

Fundamental Power Couplers

Coaxial Lines

Characteristic impedance is

$$Zc = \frac{60}{\sqrt{\varepsilon r}} ln\left(\frac{D}{d}\right)$$

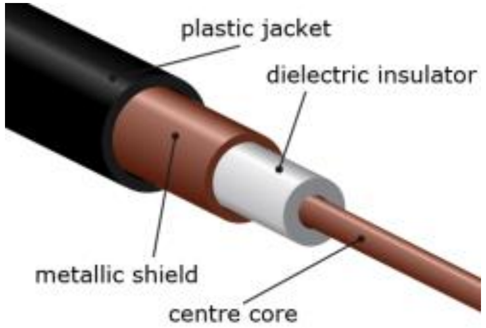
With

D = inner dimension of the outer conductor

d = outer dimension of the inner conductor

εr = dielectric characteristic of the medium

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



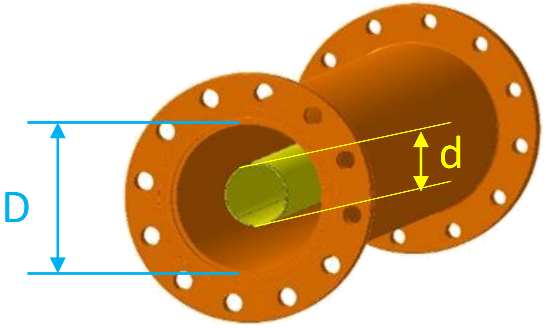
Coaxial cables are often with PTFE foam to keep concentricity

Flexible lines have spacer helicoidally placed all along the line

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

Coaxial lines Maximum Power handling

Power handling of an air coaxial line is related to breakdown field E



$$\boldsymbol{Vpeakmax = E\frac{d}{2}ln\left(\frac{D}{d}\right)}$$

$$\boldsymbol{Ppeakmax = \frac{Vpeakmax^2}{2Zc}}$$

$$\boldsymbol{Ppeakmax = \frac{E^2\,d^2\sqrt{\varepsilon r}}{480}ln\left(\frac{D}{d}\right)}$$

with

E = breakdown strength of air (‘dry air’ E = 3 kV/mm, commonly used value is E = 1 kV/mm for ambient air)

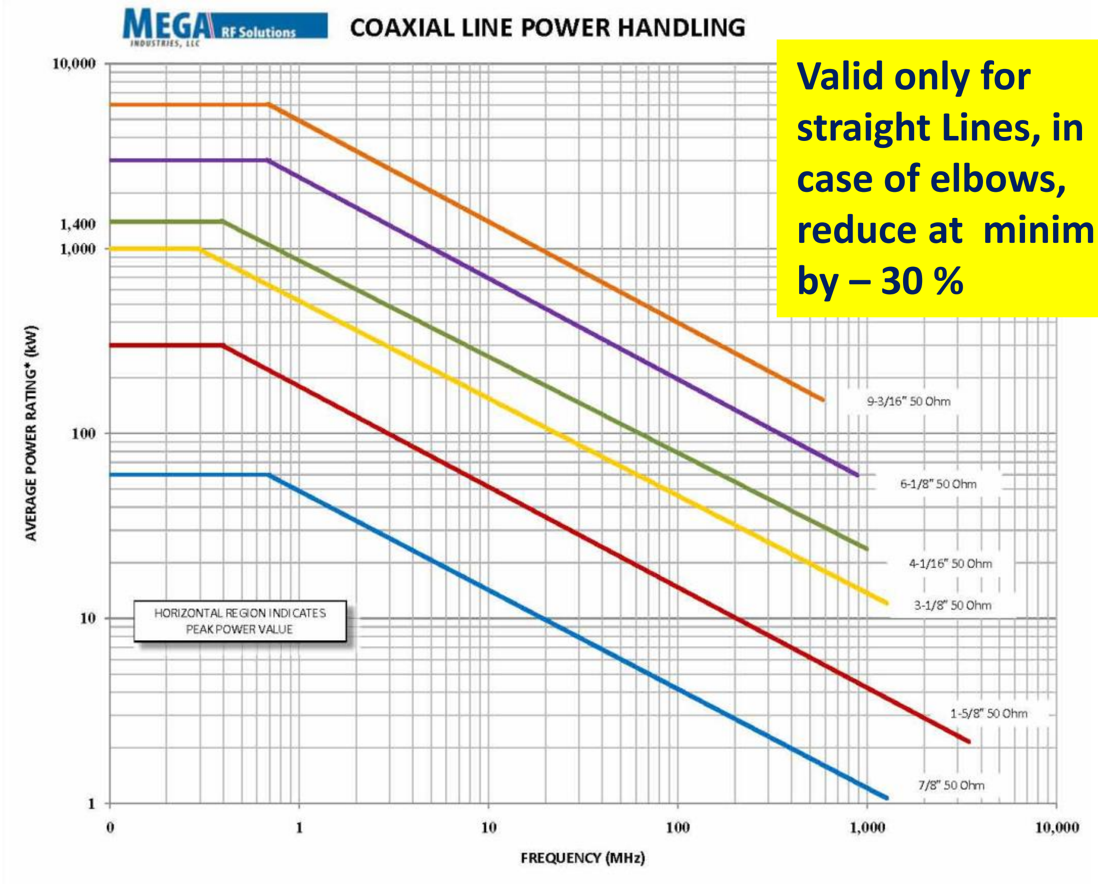
D = inside electrical diameter of outer conductor in mm

d = outside electrical diameter of inner conductor in mm

Zc= characteristic impedance in Ω

εr = relative permittivity of dielectric

f = frequency in MHz



Valid only for straight Lines, in case of elbows, reduce at minimum by – 30 %

Coaxial lines Attenuation

The attenuation of a coaxial line is expressed as

$$\boldsymbol{\alpha = \left(\frac{36.1}{Zc}\right)\left(\frac{1}{D}+\frac{1}{d}\right)\sqrt{f} + 9.1\ \sqrt{\varepsilon r}\,\tan\delta\ f}$$

with

α = attenuation constant, dB/m

Zc= characteristic impedance in Ω

f = frequency in MHz

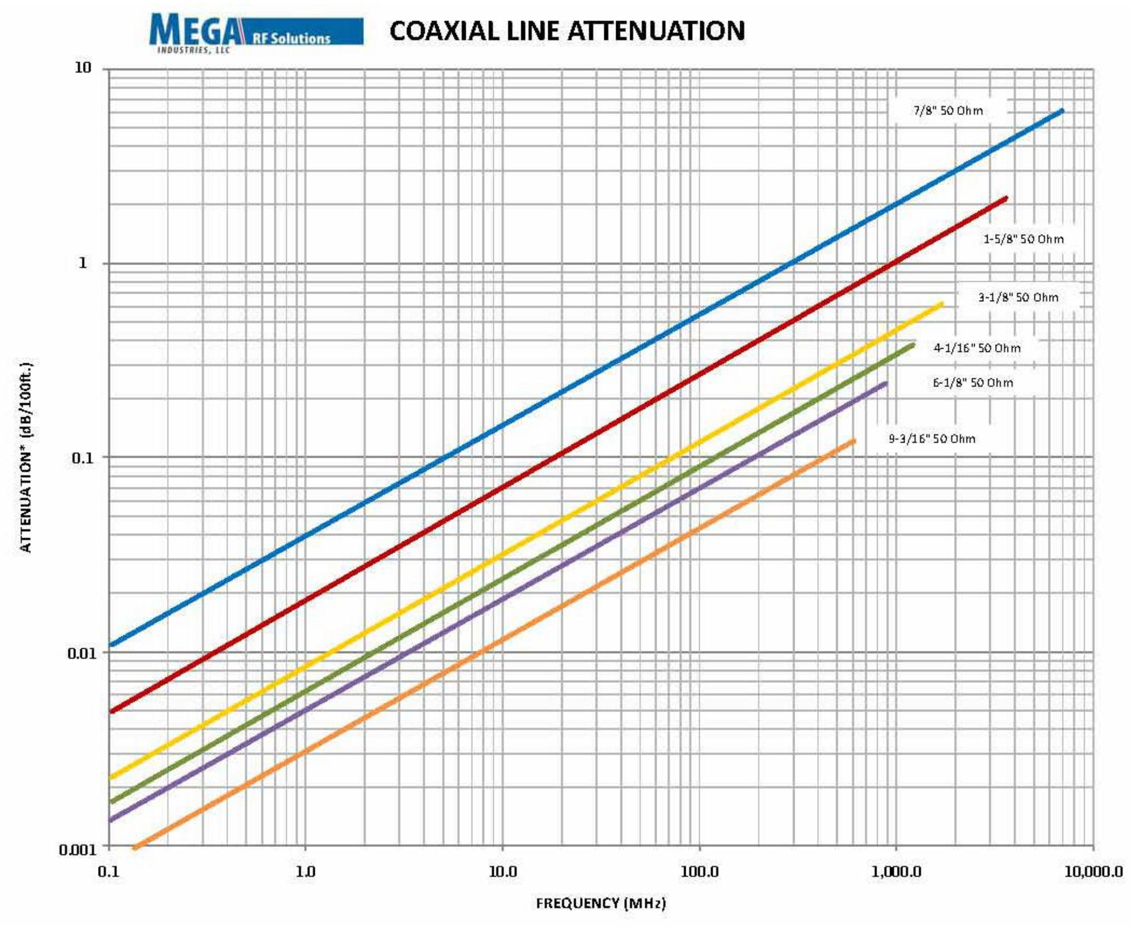
D = inside electrical diameter of outer conductor in mm

d = outside electrical diameter of inner conductor in mm

εr = relative permittivity of dielectric

tan δ = loss factor of dielectric

Material	ε_r	tan δ	Breakdown MV/m
Air	1.00006	0	3
Alumina 99.5%	9.5	0.00033	12
PTFE	2.1	0.00028	100



Why 50 Ohms lines ?

Taking all the coaxial line formulae together

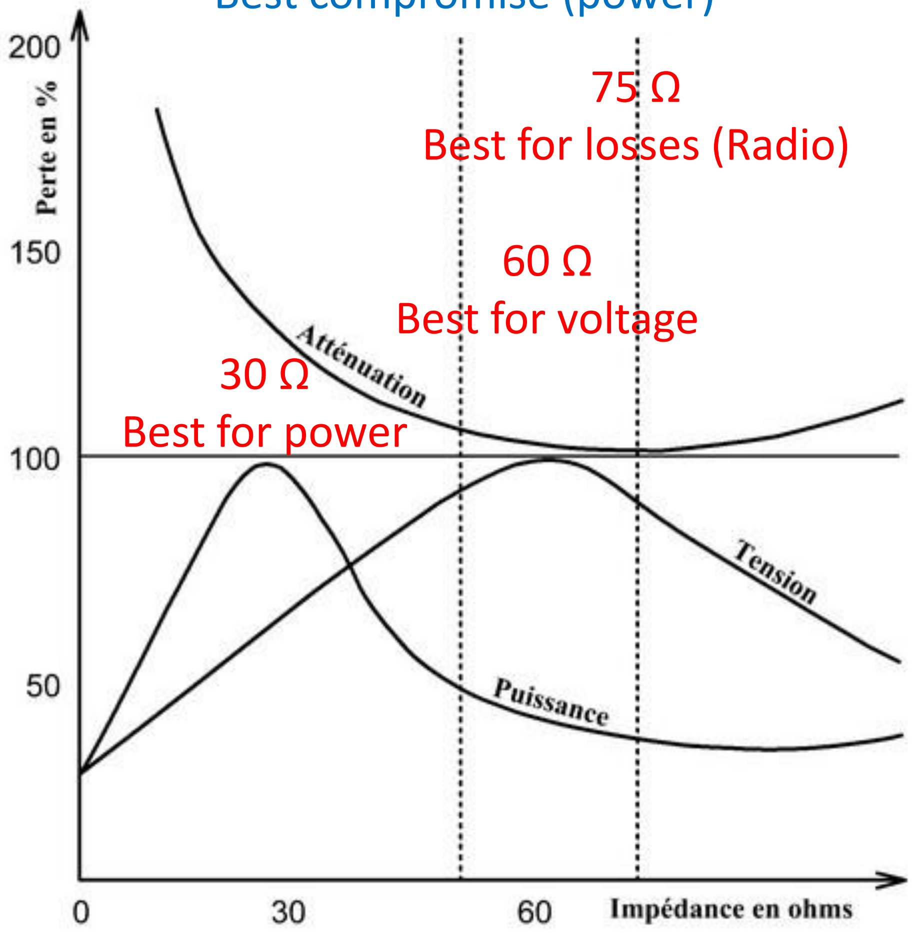
$$\mathbf{Zc} = \frac{60}{\sqrt{\varepsilon r}} ln\left(\frac{D}{d}\right)$$

$$\alpha = \left(\frac{36.1}{Zc}\right)\left(\frac{1}{D} + \frac{1}{d}\right)\sqrt{f} + 9.1\ \sqrt{\varepsilon r}\ \tan\delta\ f$$

$$\mathbf{Vpeakmax} = E\frac{d}{2} ln\left(\frac{D}{d}\right)$$

$$\mathbf{Ppeakmax} = \frac{E^2\ d^2\sqrt{\varepsilon r}}{480} ln\left(\frac{D}{d}\right)$$

A compromise to normalize line construction and instrumentation was chosen at 50 Ω



50 Ω
Best compromise (power)

75 Ω
Best for losses (Radio)

60 Ω
Best for voltage

30 Ω
Best for power

Impédance et pertes dans un câble coaxial

Coaxial Lines

Transporting a piece of 5 meters
of a 345 mm Coaxial Line

Using a crane to join two 345 mm Coaxial Line

Coaxial Lines

345 mm Coaxial Line
Installed suspended from the ceiling

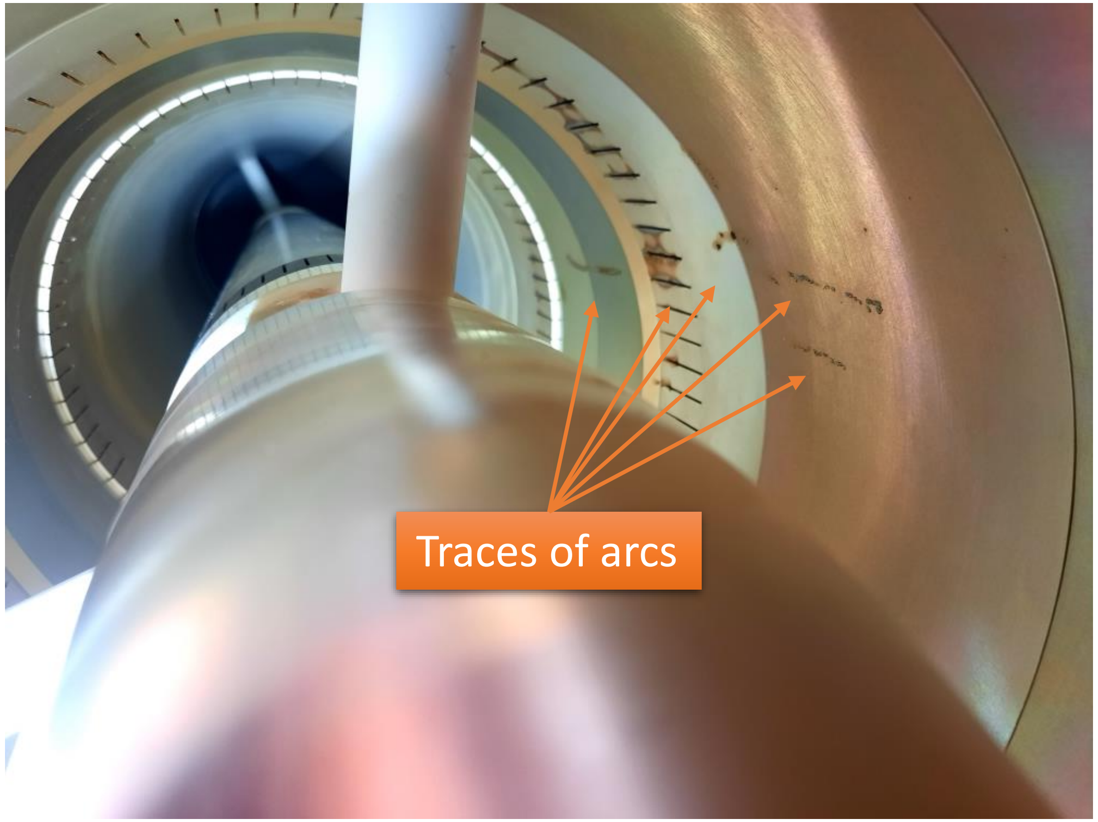
The supporting system is made to allow for movements due to thermal expansion

Coaxial Lines

Installation of 500 meters of 345 mm Coaxial Line during the LHC Injector Upgrade project


BA 3 ASCENSEUR ET
MONTE CHARGES
HORS SERVICE
DATE DE A
DANGER
RADIATION
YDPZ01.302
=
PA3

Coaxial Lines



Arcs in the vicinity of the rod of ceramic

Arcs in the vicinity of the triangular ceramic

Outlook

RF power transport basics

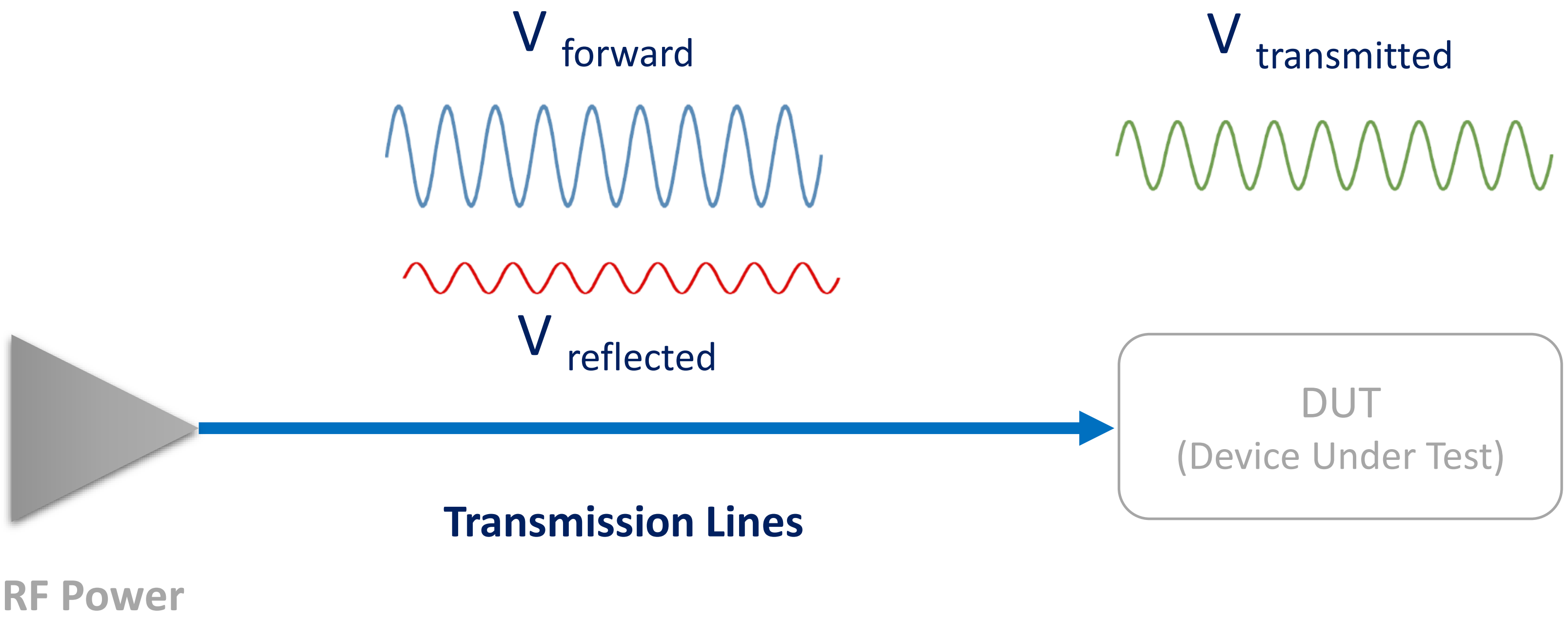
Waveguides

Coaxial lines

Circulator

Fundamental Power Couplers

Mismatch


V forward
V transmitted
V reflected
DUT
(Device Under Test)
Transmission Lines
RF Power

Reflection from Device Under Test (DUT)

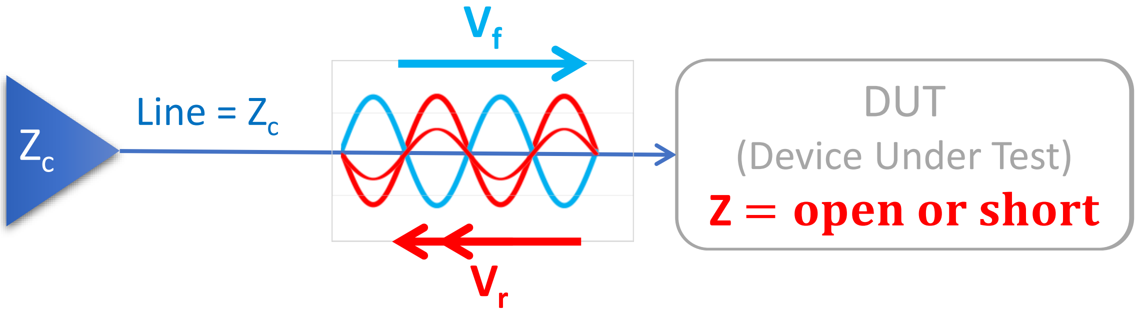
Standing Wave Ration SWR is a measure of impedance matching of DUT

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

$$\Gamma = \frac{\mathbf{Vr}}{\mathbf{Vf}}$$

$\Gamma = -1$	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



Reflection from Device Under Test (DUT)

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

$$|\mathbf{V}_{max}| \quad = |\mathbf{V}_f| + |\mathbf{V}_r| = |\mathbf{V}_f| + |\Gamma \mathbf{V}_f| = (\mathbf{1} + |\Gamma|)\ |\mathbf{V}_f|$$

full reflection

$$|\mathbf{V}_{max}| \quad = \mathbf{2}\ |\mathbf{V}_f|$$

At other points they are 180° out of phase

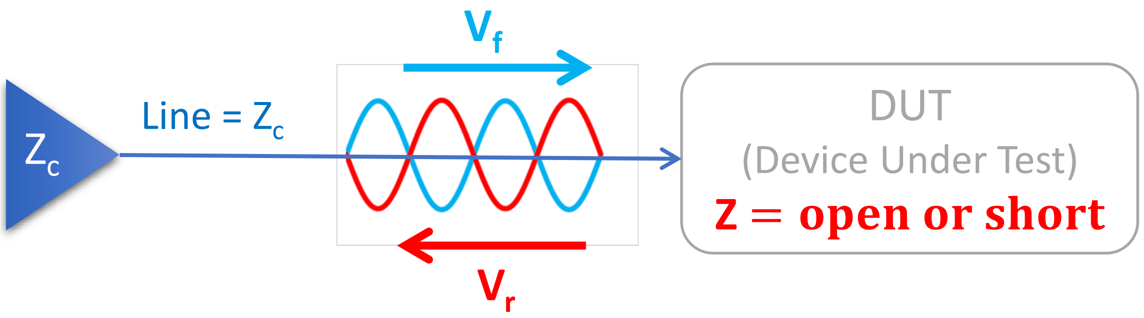
$$|\mathbf{V}_{min}| \quad = |\mathbf{V}_f| - |\mathbf{V}_r| = |\mathbf{V}_f| - |\Gamma \mathbf{V}_f| = (\mathbf{1} - |\Gamma|)\ |\mathbf{V}_f|$$

full reflection

$$|\boldsymbol{V}_{min}| \quad = \mathbf{0}$$

The Voltage Standing Wave Ratio is equal to

$$\mathbf{VSWR} = \frac{|\mathbf{V}_{max}|}{|\mathbf{V}_{min}|} = \frac{\mathbf{1} + |\Gamma|}{\mathbf{1} - |\Gamma|}$$

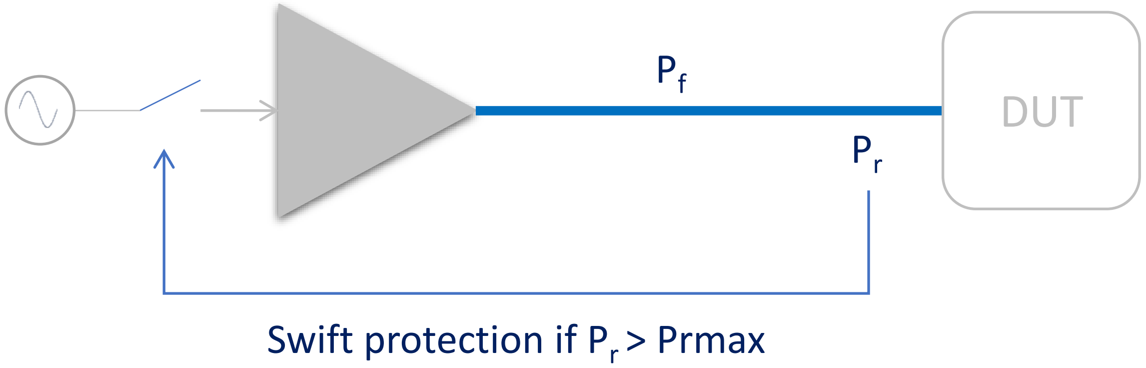


Reflection from Load

In case of full reflection Vmax = 2 Vf (Pmax equivalent to 4 Pf)

RF power amplifiers will not like this reflected wave
  - Klystron output cavity disturbed
  - Grid tube, IOT and Transistor voltage capability

Swift protection if Pr > Prmax
  - system NOT operational (not always possible)



Circulator

In order to protect our lines and our amplifiers from the reflected power a possible device is a Circulator

It is a passive non-reciprocal three-port device

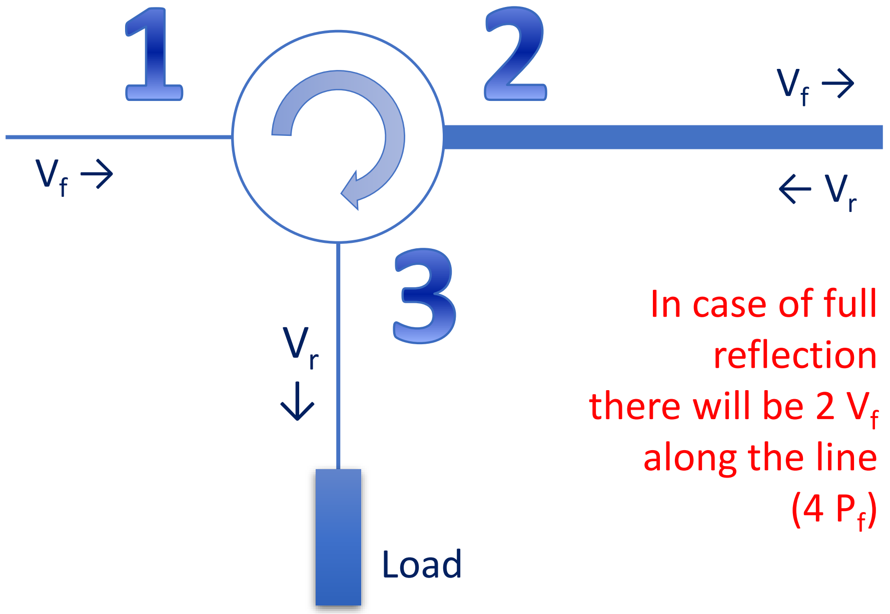
The signal entering any port is transmitted only to the next port in rotation, an RF signal experiences a low loss in the direction of the arrow and high loss in reverse direction while propagating through the Circulator

The best place to insert it is close to the reflection source

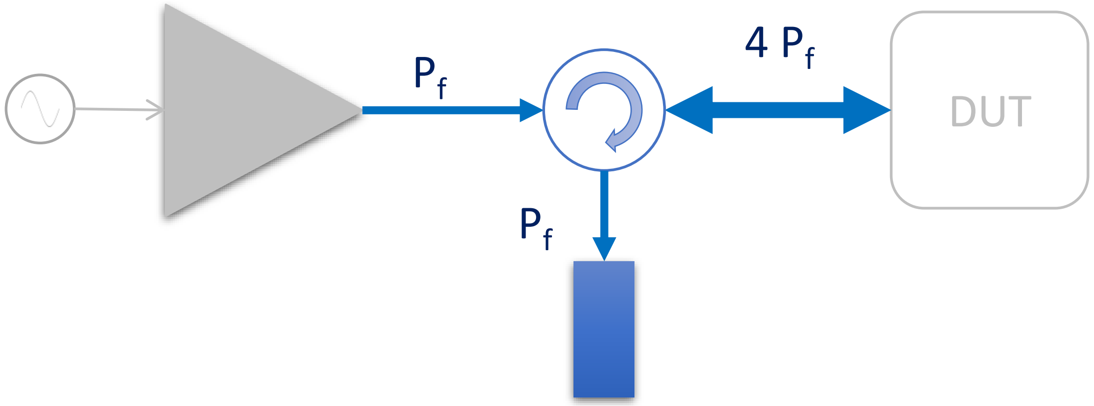
If full reflection lines between circulator and DUT shall sustain $\mathbf{V_{max} = 2\ V_f}$ (P_{max} equivalent to 4 P_f)

A load of P_f is needed on port 3 to absorb P_r

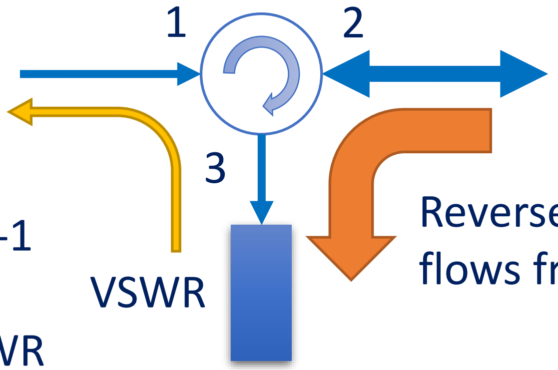
System remains operational at all time



In case of full reflection there will be 2 V_f along the line (4 P_f)



Circulator



Reflected signal from 3 is circulated back to 1

Isolation from 2-1 depends on 3 termination VSWR

VSWR

Reverse power flows from 2 to 3

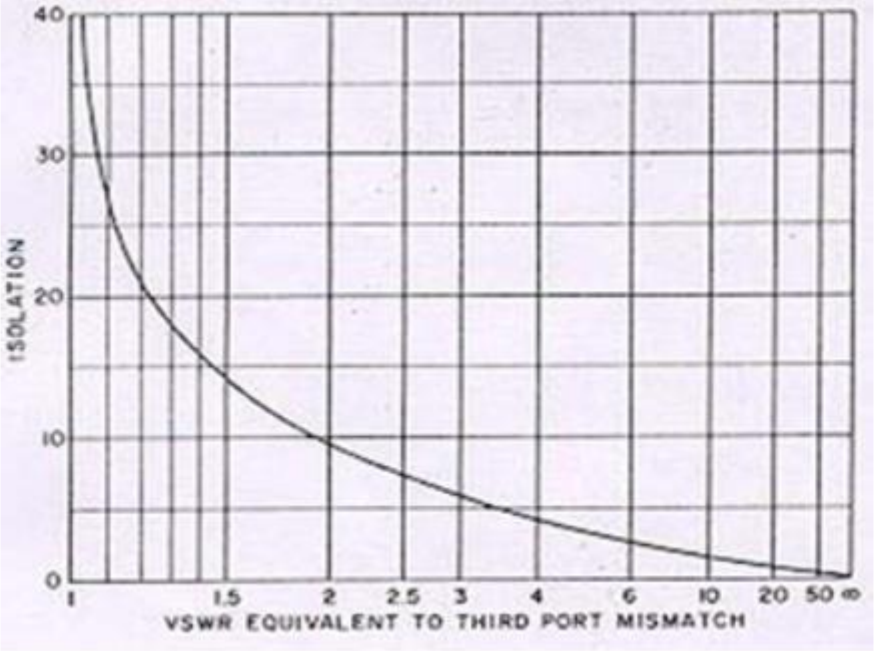
Load on 3 absorb most of the signal coming from 2

The most misunderstood concept of circulators is that of isolation

Circulators do not provide isolation until one of the ports is terminated

Then the isolation between the other two ports (in the direction opposing the direction of circulation) is approximately equal to the return loss due to any mismatch on the terminated port

So, a very good load is needed on port 3 in order to guaranty a good isolation at port 1



Circulator

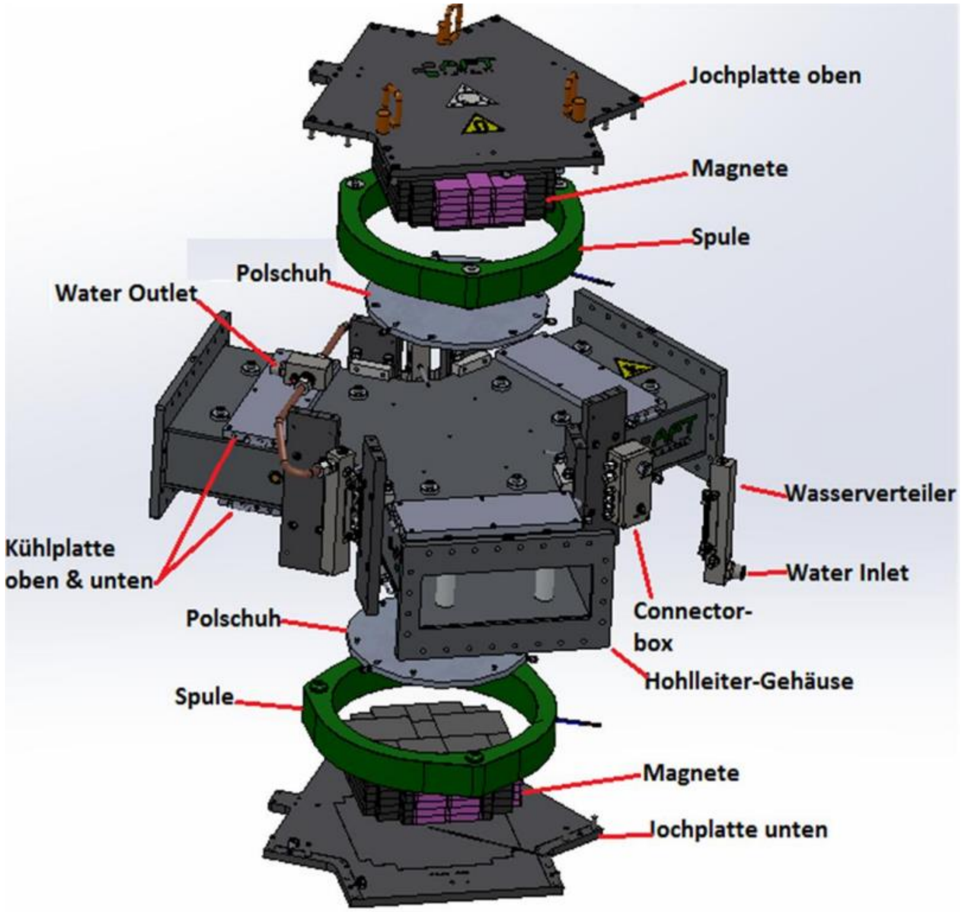
Basically, a circulator shall provide

- low loss
- high isolation
- low reflection

The crucial high-power requirements for a circulator are to

- Handle full peak and average power
- Handle forward power and reverse power up to 100% reflection and at any phase
- Consider worst case operating conditions

AFT microwave



Circulator

AFT microwave

High-Power Design Aspects	Peak Power	Average Power
Characteristic	• high voltage & E field • high current & H field	• Losses in ferrites, dielectrics & conductors → power dissipation → heating
Risk	• Electrical breakdown (arcing) in air gaps between ferrites and at edges & corners • Burning at poor electrical contacts	• Overheating & burning of materials • Reduced el. breakdown capability at overheated surfaces • Thermo-mechanical stress • Thermal drift of ferrite properties
Solution	• Elaborated design by 3D EM sim., covering detailed E field analysis • Proper design margins x avoid sharp edges • Well defined electrical contacts • Gas pressurization, if required	• Careful 3D thermal modeling based on the simulated EM power loss • Low ferrite loss by material and bias • Good el. conductors, low loss dielectrics • Good thermal bonding of ferrites • Adequate cooling of hot spots/areas • Thermal compensation (TCU)

Circulator

High-Power handling requirements	Characteristic Peak Power max. E field	Maximum Power Loss max. H field
Design criterion for power capability	$\boldsymbol{Pc = (\sqrt{Pfwd1} + \sqrt{Prev2} + \sqrt{Prev3})^2}$ $\boldsymbol{\sim 4\,Pfwd1}$ with $Prev2 = Pfwd1$ and $Prev3 = 0$ as Return Loss > 30 dB	$\sim 3\ insertion\ loss\ (1 - way)$ for a 3-port circulator operated into a short
Note	• In the simulation of a circulator with matched terminations, we have to consider 4 times the forward power to calculate max. E field strength • A bad dummy load would increase Pc significantly: factor 4.4 for RL = 20dB factor 9 for RL = 0dB • The circulator is usually not designed to withstand these conditions!	• The maximum ferrite power loss is more than 2 times the insertion loss as expected for the FWD and REV wave, due to the resonant pattern in the 3-port junction • Ferrite power loss varies between 1 and 3 times insertion loss as the short phase is shifted by 180° (2- way)

Outlook

RF power transport basics

Waveguides

Coaxial lines

Circulator

Fundamental Power Couplers

Power Couplers

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

Proceedings of the ***1995*** *Workshop on RF Superconductivity - MARK S. CHAMPION*
… When particle accelerators make use of radiofrequency cavities, either superconducting or normal conducting, it is often the cavities themselves that receive the most attention. However, ***the cavities are of little value without rf input couplers, which are usually more difficult to realize than is foreseen****. There are many, sometimes conflicting, requirements placed on the couplers…*

Fundamental Power Coupler FPC

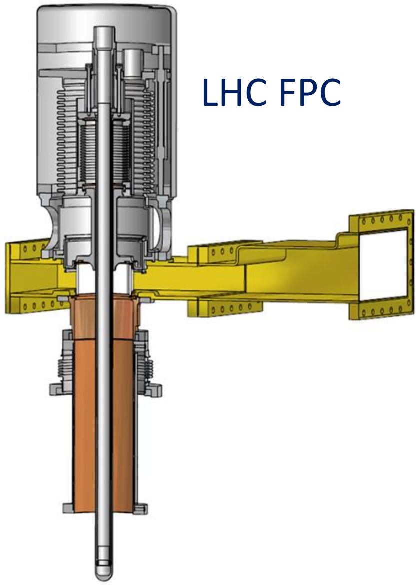
The Fundamental Power Coupler (FPC) is the connecting part between the RF transmission line and the RF cavity

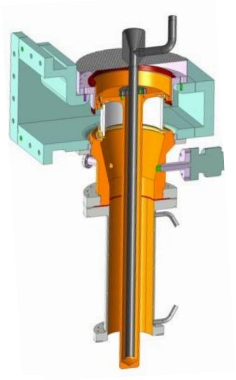
The FPC a ***specific piece of transmission line*** that provides the vacuum barrier for the beam vacuum, with one side at high pressure and the other side under beam vacuum pressure, that also enables RF power to feed the cavity

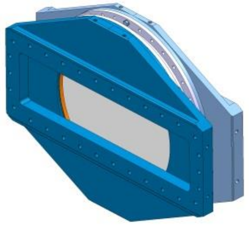
FPC are one of the most critical parts of the RF cavity system in an accelerator

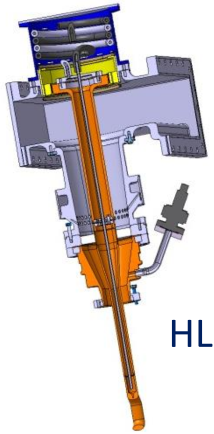
A good RF design, a good mechanical design and a high-quality fabrication are essential for an efficient and reliable operation

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


LHC FPC


SPL FPC

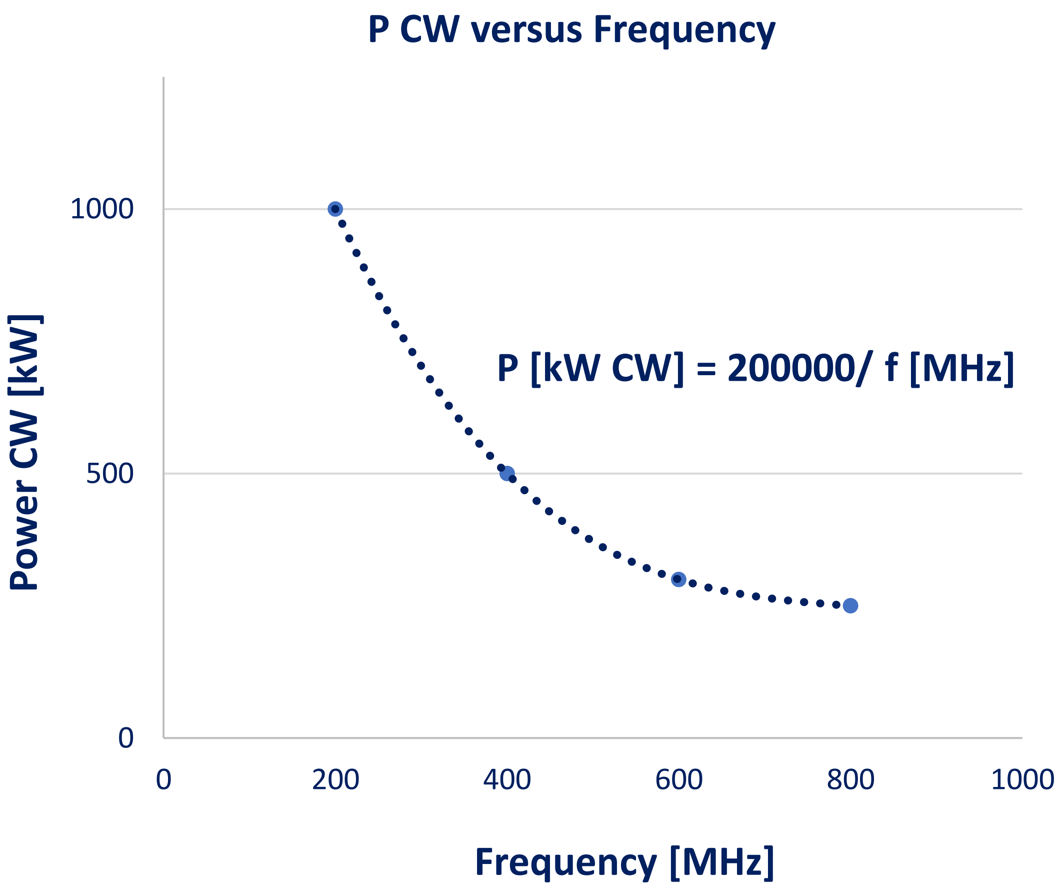

L4 FPC window


HL-LHC FPC

Various CERN FPC

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 2.0	**704 MHz, 900 kWp 10 % SW**
SPL 3.0	**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*

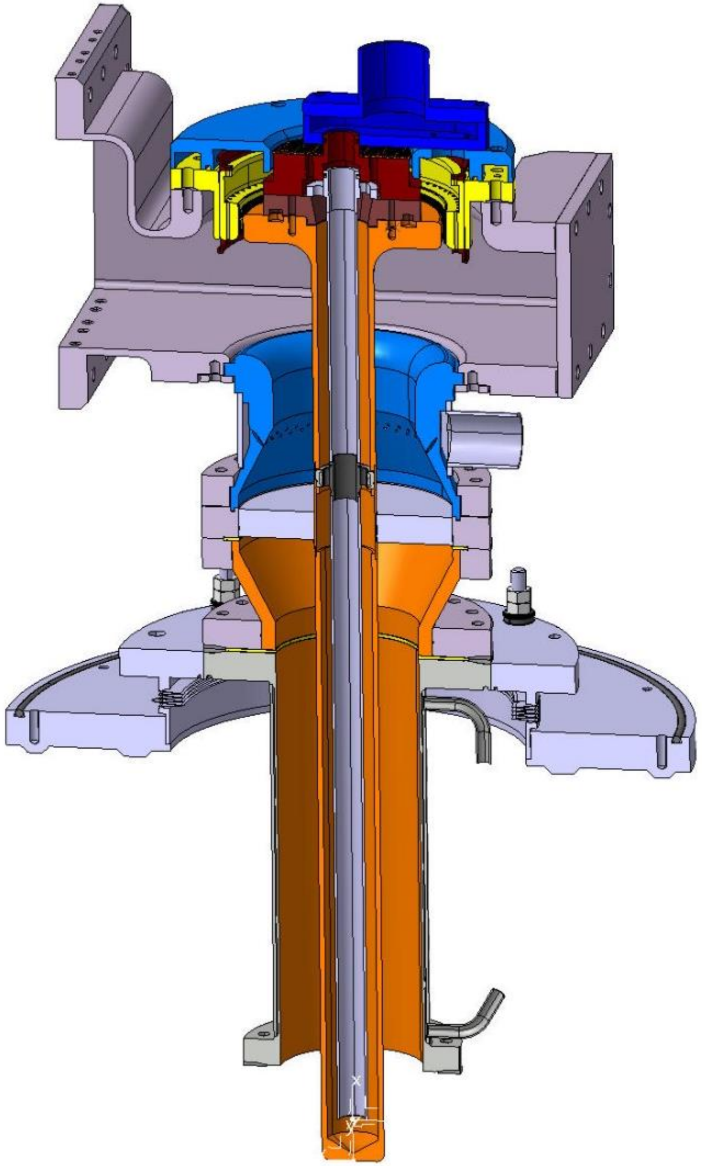


Example of a design

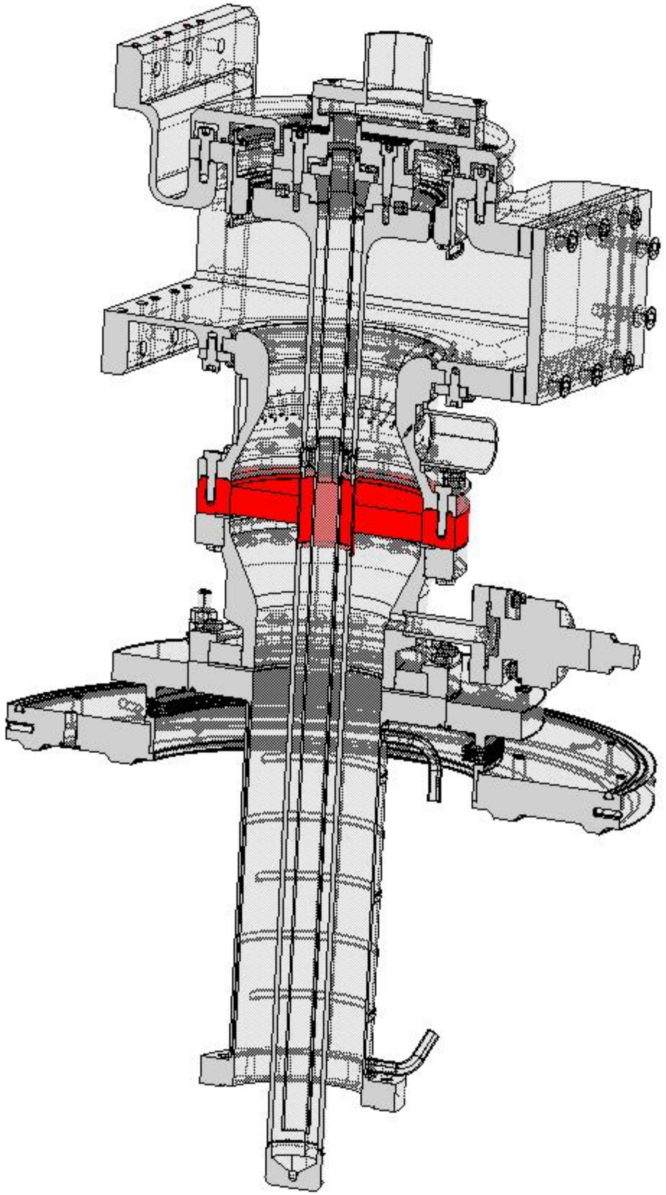
- **Ceramics**
  - Ceramic material
  - Metallization
  - Window families
    - Disk
    - Cylindrical
    - Coaxial disk
  - Two windows
  - Single window
  - Solutions proposed
- Antenna
  - Adjustable coupler
  - Antenna shape
- **Outer Antenna line**
  - Copper for RF
  - Stainless steel
  - Bad coating
  - RF & vacuum seal
- Protection of the FPC
- Cryomodule integration

- Orientation of the FPC
- Inner antenna cooling
- WG to coax
- Multipacting
  - Ti sputtering
  - DC polarisation
- Simulation and proposed solution
  - Cylindrical Design
  - Coaxial disk
  - Disk
- Construction
- **Clean room**
  - Clean process study
  - Mock-ups
  - Preparation for assembly
  - Assembly in ISO 5
  - Assembly in ISO 4

- FPC test boxes
- FPC test benches
  - In clean room
  - Resonant ring
- RF conditioning
  - Ceramic cracks
  - Conditioning process
  - VCA
  - Pulses
  - Ramping
  - Repetition rate
  - TW and SW mode
  - Automated process
  - Processing time
  - Summary
- First test results
  - Arcing
- Restart from step #1



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

Ceramic material

	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

Most of the windows are built with an Al2O3 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

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 Al2O3 - 97.6 % purity ones

In view of future machine, we push R&D to move to 99.9 % purity, having less losses, allowing for more power

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

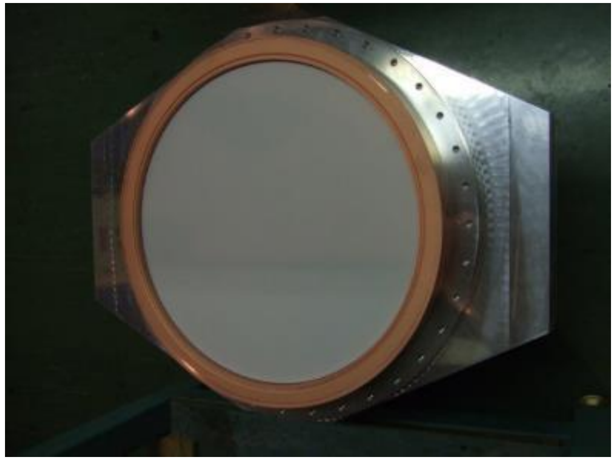
It is often painted by hands

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

Window families



Disk windows

SPS, 800 MHz
150 KW CW

Linac4, 352 MHz
1 MW 10 % duty

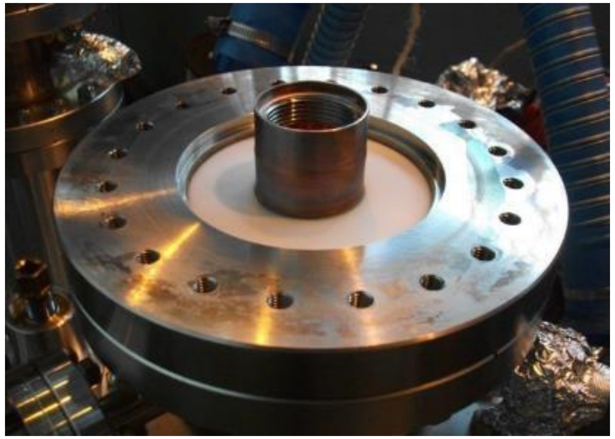
LHC 2, 400 MHz
1 MW (expected) CW

Cylindrical windows

LHC, 400 MHz
500 kW CW

ESRF/SOLEIL/APS, 352 MHz
250 kW CW

SPL, 704 MHz
1 MW 5 % duty



Coaxial disk windows

HL-LHC Crab, 400 MHz
100 KW CW

SPL 2.0, 704 MHz
1 MW 5 % duty

SPL 3.0, 704 MHz
2 MW (expected) 5 % duty

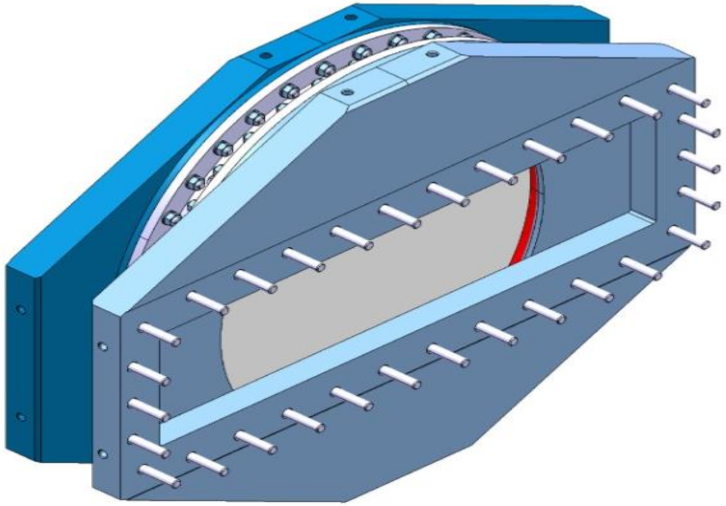
Disk windows

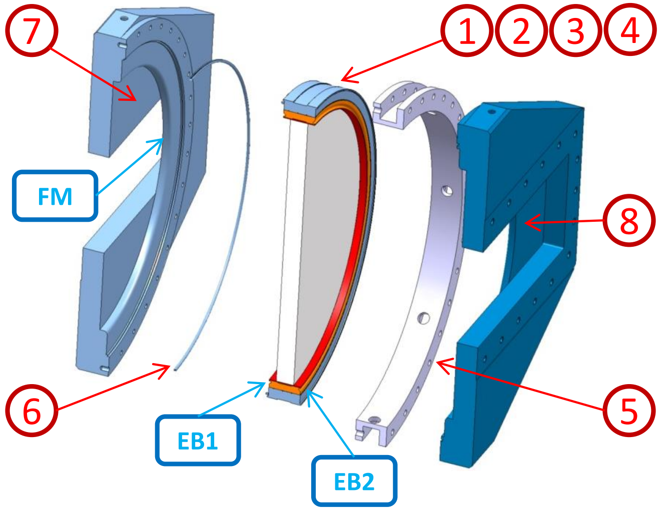
Robust and compact (in length) design
- 12 kg ceramic
- 400 mm diameter
- 25 mm thickness

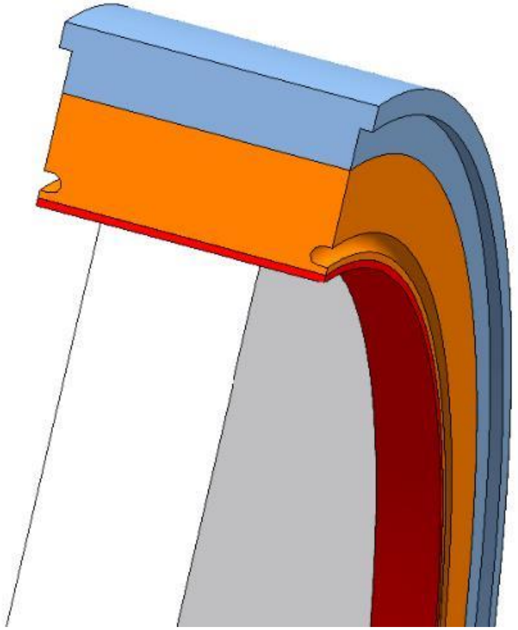
As simple as possible
- 1-2-3-4 : Ceramic assembly
- 5 : spacer
- 6 : Helicoflex seal
- 7-8 : Stainless Steel flanges

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







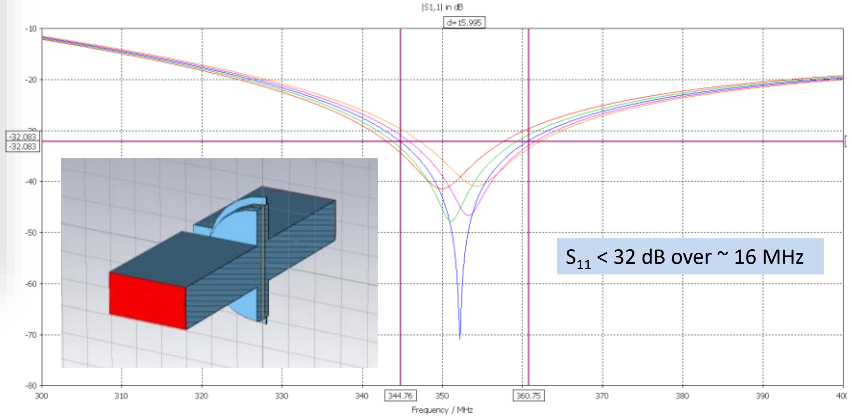
Disk windows

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

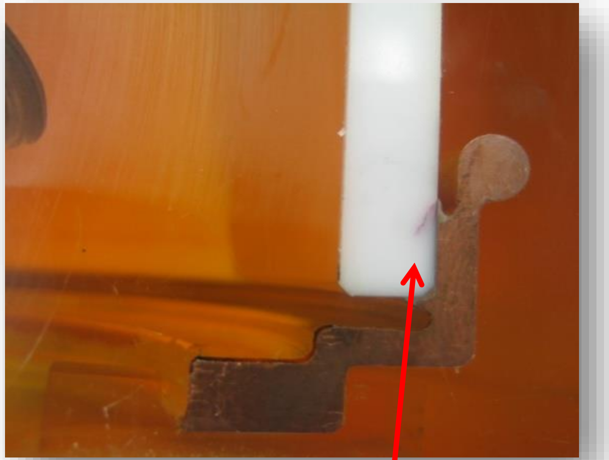
Massive stainless Steel flanges, not copper plated

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



S_{11} < 32 dB over ~ 16 MHz

Cylindrical window



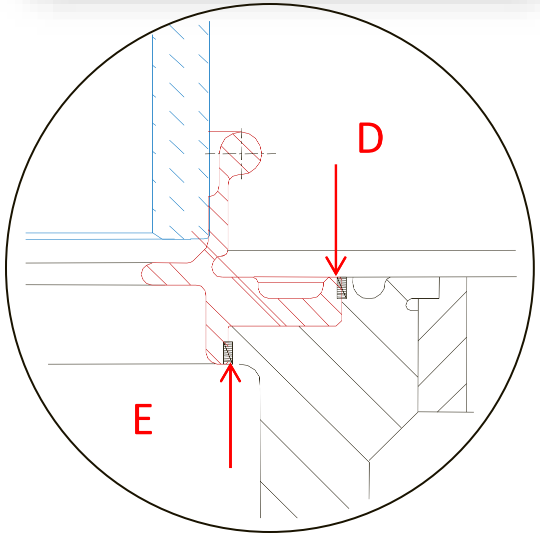
Solid copper rings directly brazed to the ceramic to lower the RF losses and increase the thermal capability

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

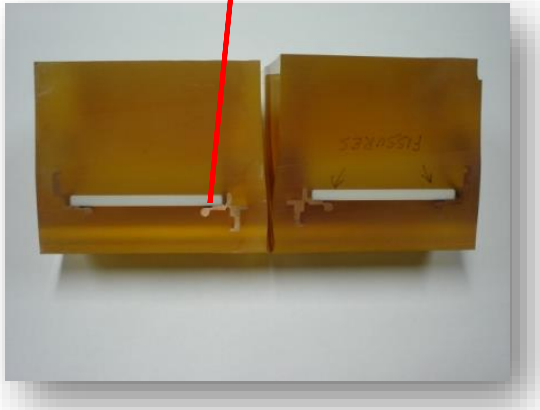
we had to fight against semi-cracks developing with time

Finally, powers up to 575 kW cw @ 400 MHz full reflection all phases were achieved for some hours, local peak power of 2.3 MW SW

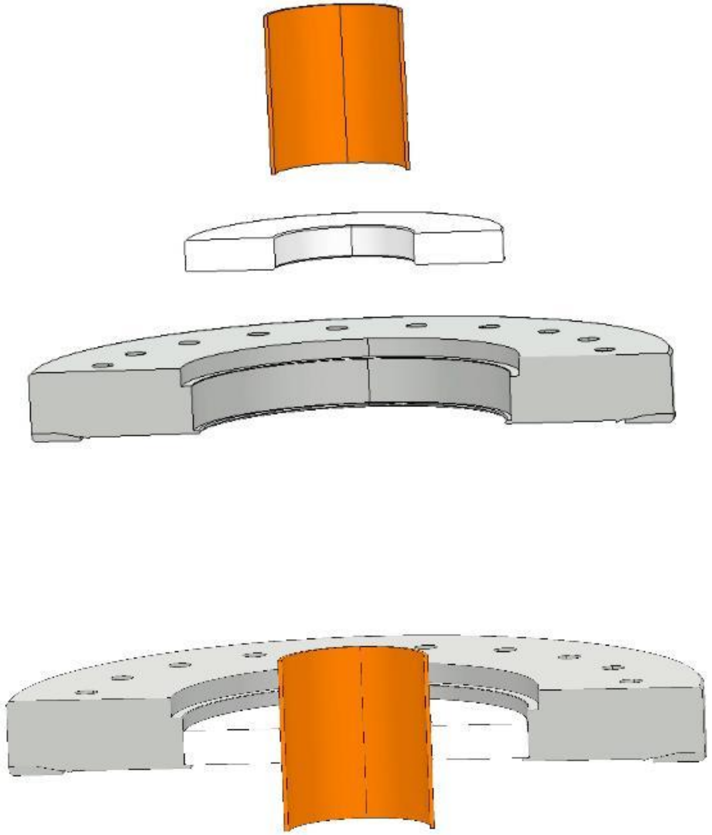


LHC process

1) Braze a solid copper collar to the metallised ceramic
2) Two EB welding (D+E) for metallic continuity



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

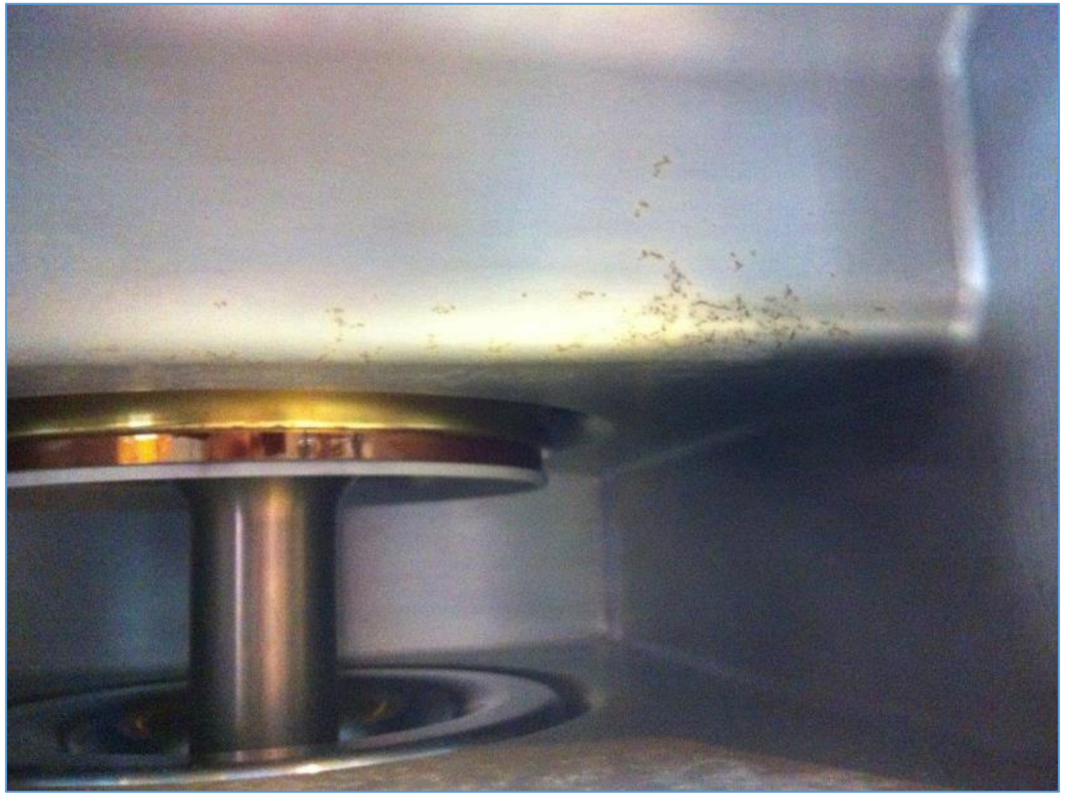
Coaxial disk

Simplest way to make a window with

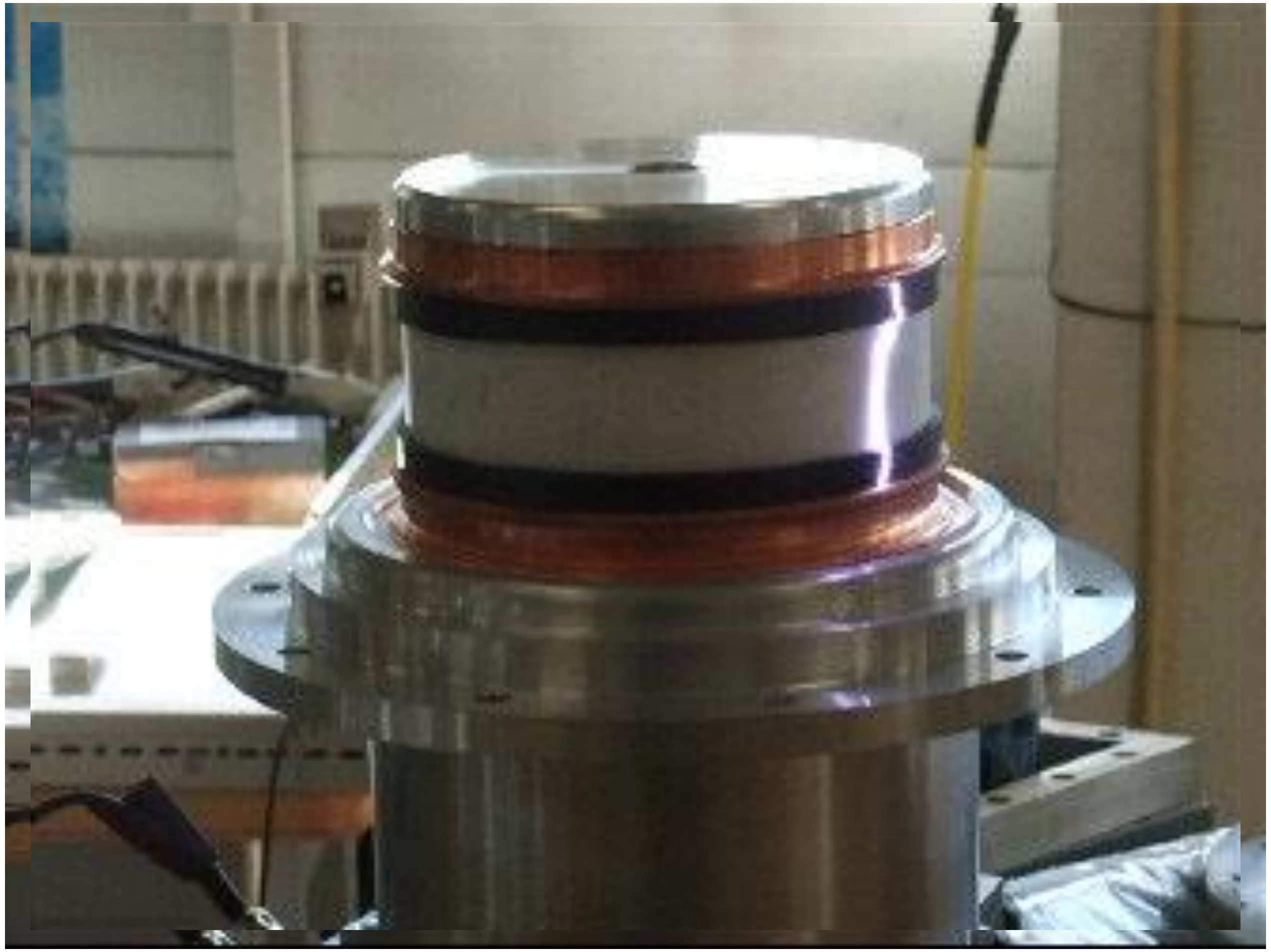
- An inner tube of copper, maximum 1.5 mm thickness due to brazing limitation
- A coaxial disk ceramic
- A titanium flange

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

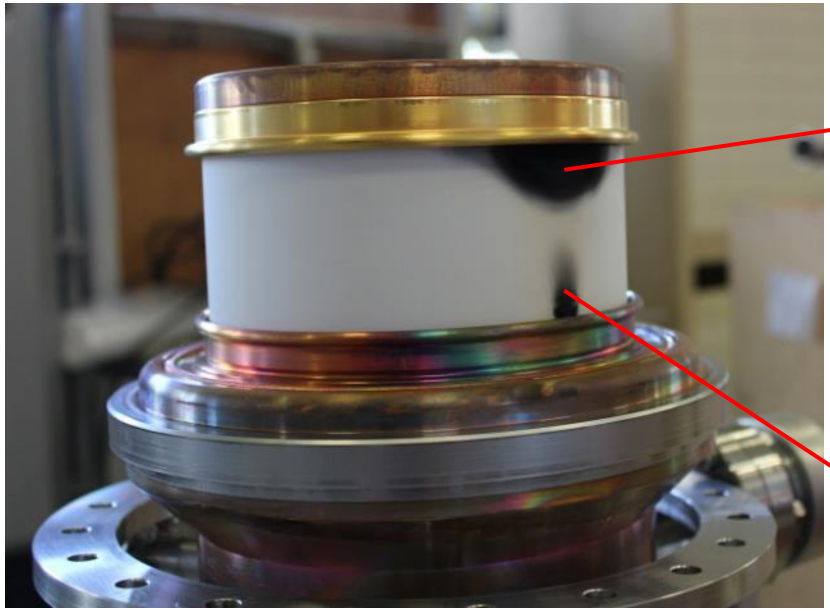
Arcing in FPC



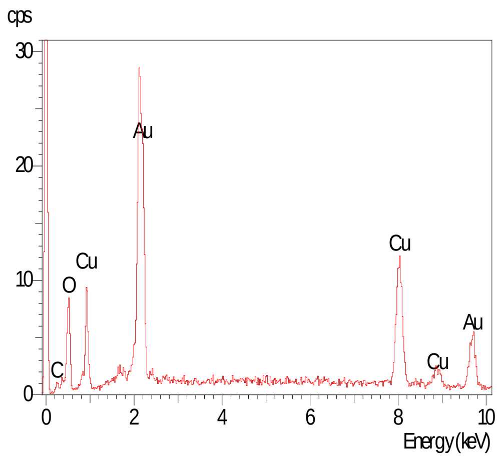
Arcing along ceramic on the air side

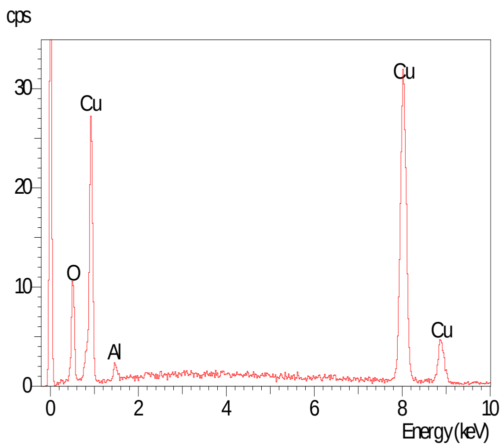


Arcing along ceramic on the air side



Black deposit
Gold & Copper from upper collar
Copper from lower collar

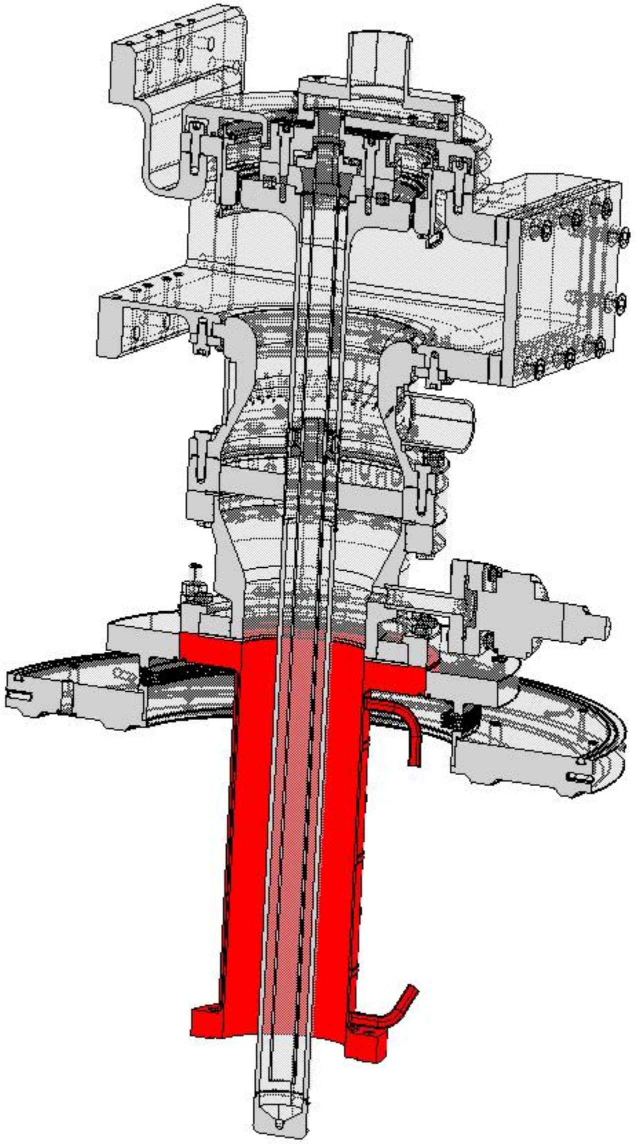




FPC ceramic crack

RF processing or FPC conditioning

Outer antenna line

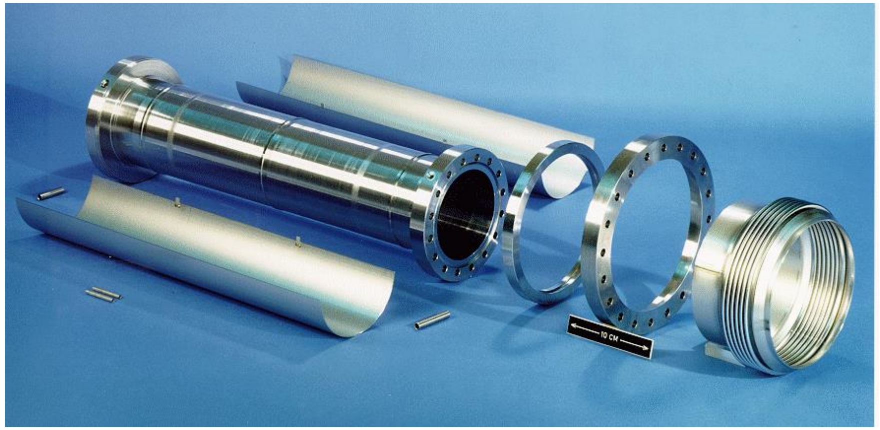


In order to ensure thermal shielding between the FPC and the cavity the outer antenna can be with thermal anchor(s) or with a Double walled Tube

From an RF point a view, it is a simple outer conductor tube of the coaxial line

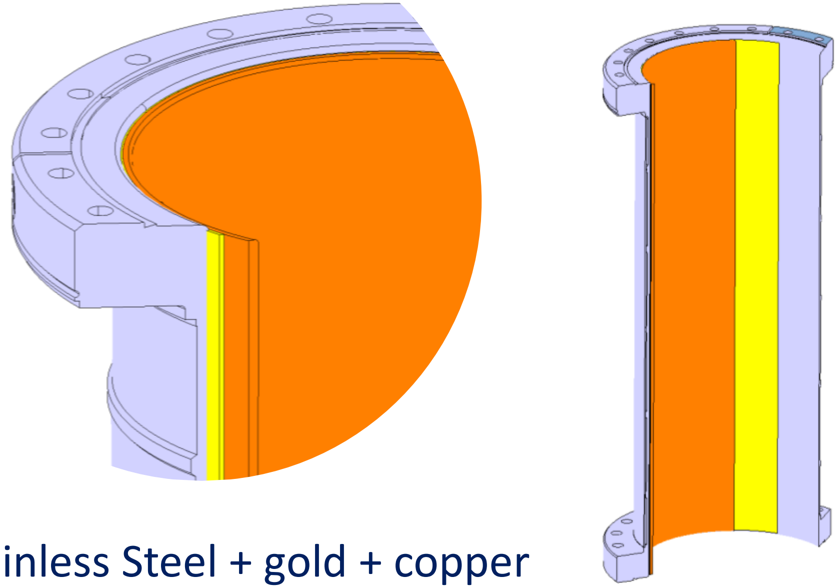
Its mechanical contraction must be perfectly pre-calculated, because this will give the coupling value (Q_{ext})

Outer antenna line



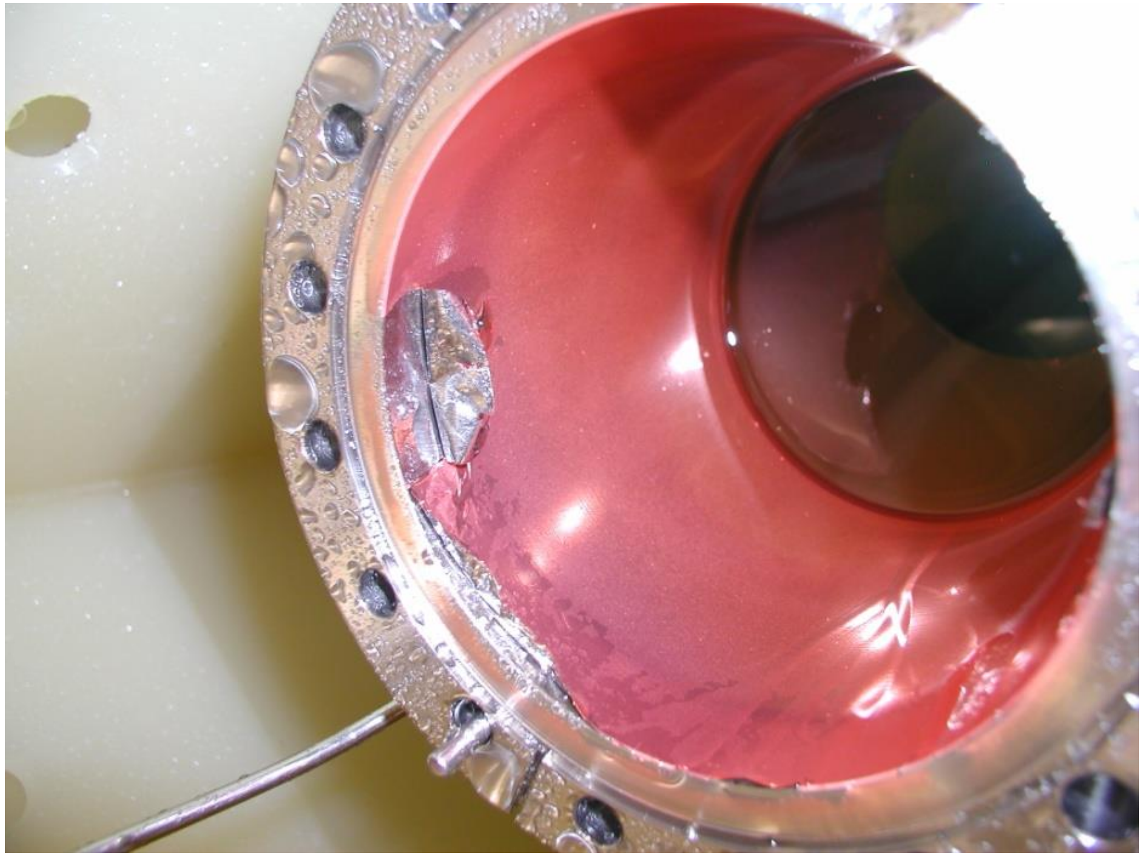
With SRF cavities, we usually have

- A thin Stainless-Steel support, being the good thermal insulator
- Onto which we add a thin layer of few µm of copper, being the RF conductor with minimum RF losses and as being very thin, not transmitting so well the thermal losses to the cryogenic system
- As Copper is not adhering to Stainless-Steel, in between we have an additional layer, that we selected to be gold for both deposition and RF properties



Stainless Steel + gold + copper

Outer antenna line



A FPC 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

Since LEP time, as we experienced a lot of difficulties with this component

This copper coating is one of the key processes for all the couplers over the world, but the fabrication is difficult as the process is very strict

Cryomodule integration requirements

The string of cavities will be connected together

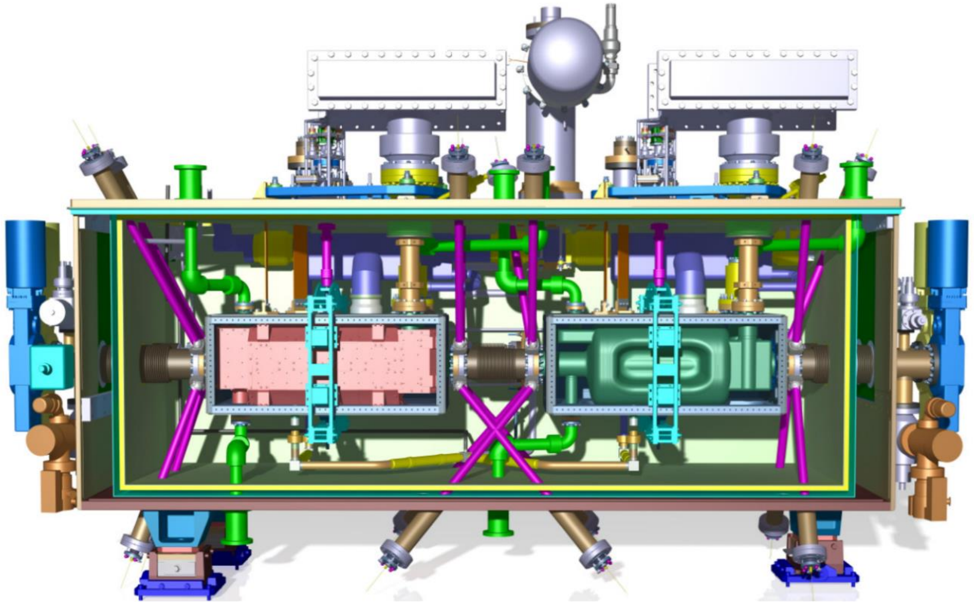
After that, the beam vacuum should remain closed until installation into the machine

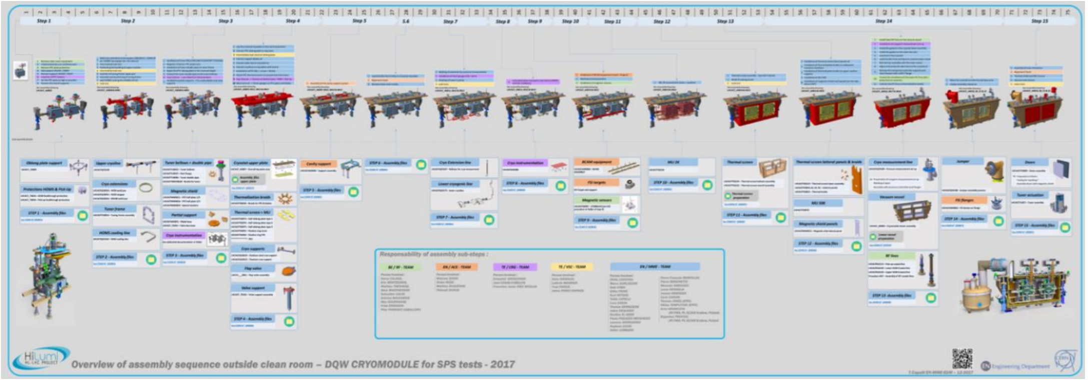
Very important decision for the design of the coupler

→ imposes a short distance from the ceramic to the beam axis …

Cryomodule integration requirements

Cryomodule integration requirements





Overview of assembly sequence outside clean room – DQW CRYOMODULE for SPS tests - 2017

https://youtu.be/eI5M_LAO-xE

Another alternative is to have a box type cryomodule, that enables to close the beam vacuum with ‘other (longer)’ distance from the ceramic to the beam axis

Clean room

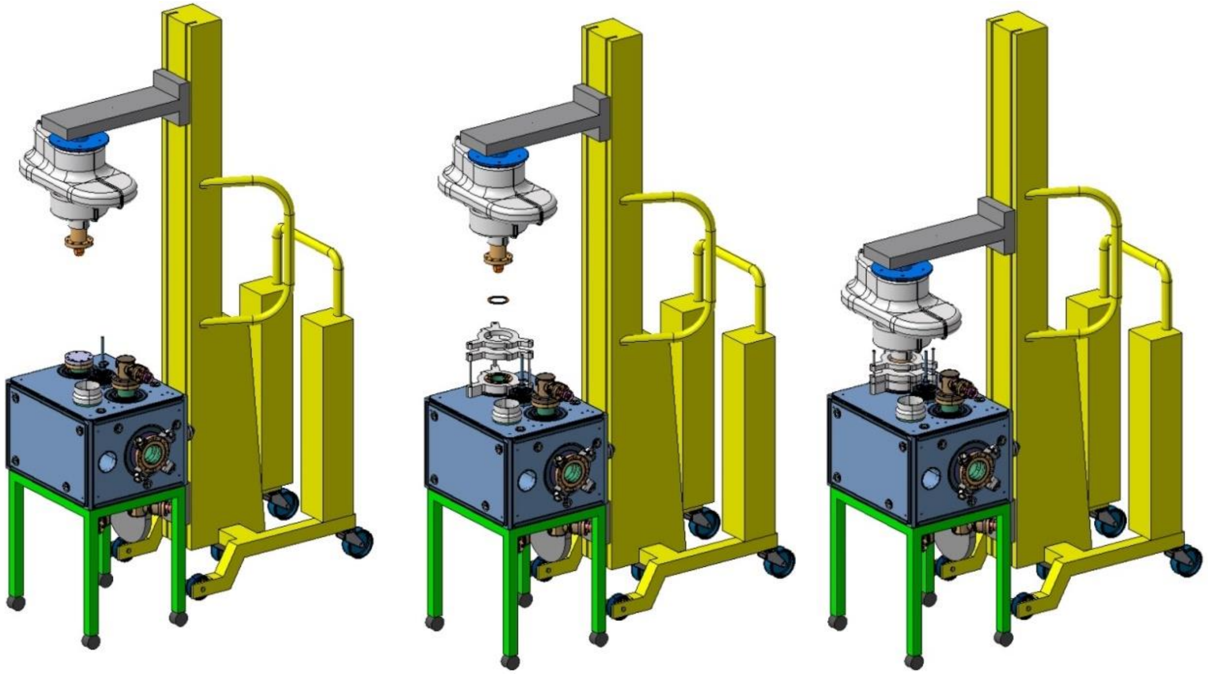
Especially for SRF cavities, none of the peripherals should pollute the cavity

Specific clean room assembly processes must be applied, they have to be carefully studied in order to guaranty the minimum pollution due to FPC or HOM couplers assembly onto the cavity

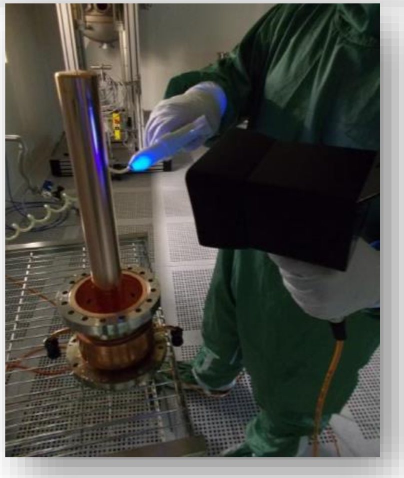
We developed specific tooling, recently 3D printed with accura 25 ® (Polypropylene-like) as being qualified particle free for ISO 4 clean room

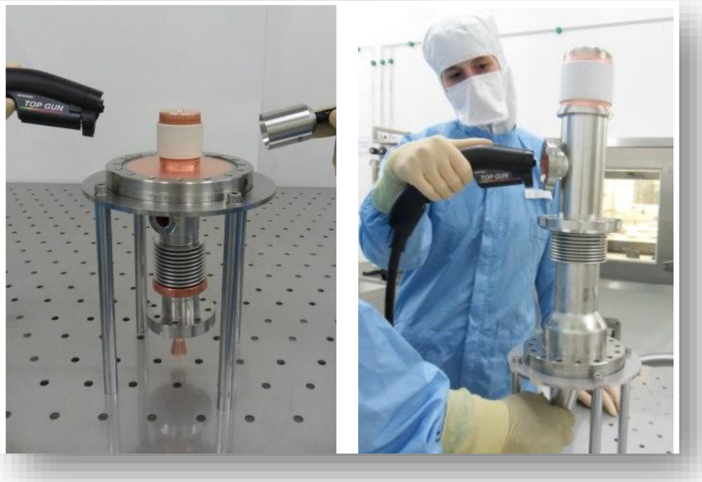
The use of robot is also a key for success

As soon as per the design phase, FPC and HOM couplers also have to take into consideration clean room assembly, this will ease the entire work

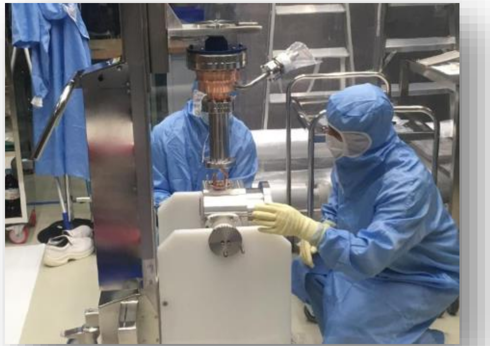


Clean room – preparation prior to assembly





Clean room – assembly in ISO 5



Clean room – assembly in ISO 4

References

Reference Data for Radio Engineers (ISBN 0-672-22753-3)

HÜTTE des ingenieurs taschenbuch (Berlin 1955 edition)

Taschenbuch der Hochfrequenz-technik (Berlin-Heidelberg-New York 1968 edition)

RF power transportation, Stefan Choroba, DESY, CAS 2011
https://cas.web.cern.ch/sites/default/files/lectures/ebeltoft-2010/choroba-1.pdf

Practical power capability of rectangular waveguides, Stefan Doebert, CERN,
https://indico.cern.ch/event/245685/contributions/1565266/attachments/421127/584776/waveguidelimits.pdf

MEGA Industries, Waveguides and Coaxial lines Catalog
https://www.megaind.com/wp-content/uploads/2020/06/Mega-Waveguide-Catalog-15.pdf
https://www.megaind.com/assets/files/catalogs%2FMega-Coaxial-Catalog.pdf

AFT Circulators, CWRF 2022, https://indico.cern.ch/event/1116404/contributions/5003545/

SRF tutorial on FPC and HOMC, Eric Montesinos, CERN, SRF conference 2021
https://indico.frib.msu.edu/event/38/attachments/159/1270/20210624_SRF_tutorial_FPC_Eric_Montesinos.pdf