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CERN RF Group
RF Amplifiers and Couplers

Mechanical & Materials Engineering
for Particle Accelerators and Detectors
2-15 June 2024, Sint-Michielsgestel, Netherlands

RF for Accelerators

RF power generation
RF power transport
RF power couplers

The CERN Accelerator School

Nikhef

The CERN Accelerator School

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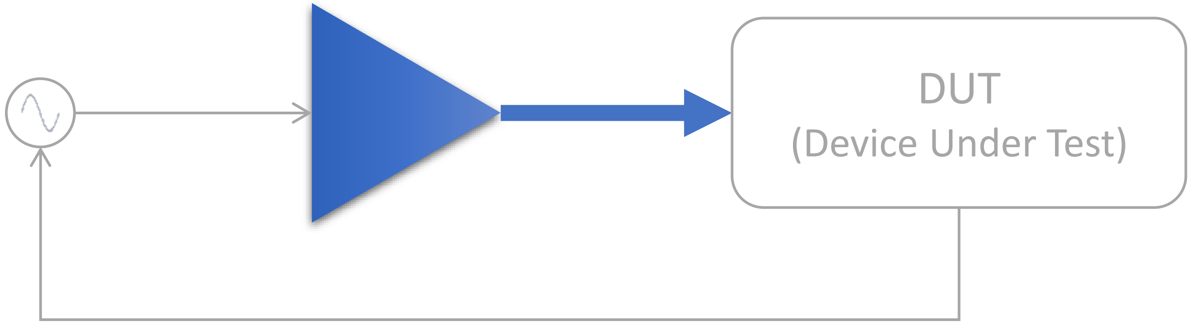
RF Power generation
RF power transport
Fundamental Power Couplers (FPC)



Purpose

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

Requirements

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

Outlook

- RF power generation
  - Vacuum Tubes
    - Vacuum
    - Cathodes
    - Triodes
    - Tetrodes
    - Klystrons
    - IOTs
  - Transistors
    - LDMOS
  - Combining
- RF power transport basics
  - Waveguides
  - Coaxial lines
  - Circulator
- Fundamental Power Couplers
- Conclusion

CERN SPS 'Siemens' Power plant
2 x 600kW continuous wave @ 200MHz
Based on RS2004 water cooled tetrodes
In operation since 1976 (almost 50 years ago)

Outlook

- RF power generation
  - Vacuum Tubes
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CERN LHC Power plant
16 x 330kW continuous wave @ 400MHz
Based on klystron
In operation since 2005 (20 years ago)

Outlook

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CERN SPS ‘Electrosys’ Power plant
2 x 160kW continuous wave @ 800MHz
Based on IOTs
In operation since 2013 (more than 10 years ago)

Outlook

- RF power generation
  - Vacuum Tubes
    - Vacuum
    - Cathodes
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CERN SPS ‘Thales’ Power plant
2 x 800kW continuous wave @ 200MHz
Based on Transistors
In operation since 2021 (a few years ago)

Outlook

- RF power generation
  - Vacuum Tubes
    - Vacuum
    - Cathodes
    - Triodes
    - Tetrodes
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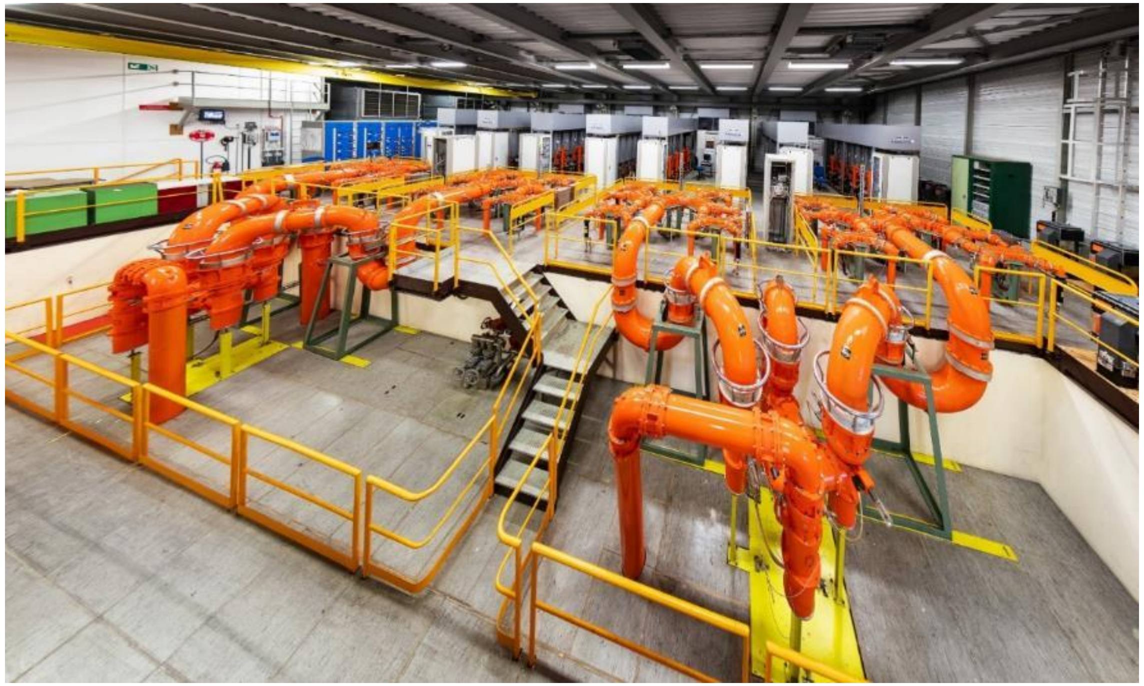

CERN SPS 'Philips' Power plant
2 x 600kW continuous wave @ 200MHz
Large 3dB combiners
In operation since 1981 (more than 45 years ago)

Outlook

- RF power generation
  - Vacuum Tubes
    - Vacuum
    - Cathodes
    - Triodes
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    - Klystrons
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CERN SPS 'Electrosys' Power plant
WR1150 waveguides operating @ 800MHz
3dB combiner, rotative switch, elbows and straight lines
In operation since 1989

Outlook

- RF power generation
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CERN SPS 345mm coaxial lines
6 x 125m lines
In operation since 1976 (more than 45 years ago)
Modified in 2019

Outlook

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CERN LHC circulator
330 kW @ 400 MHz
Here used for a Coupler RF processing
Input power from the top, with a coaxial to WG transition,
FPC on the right, and power load on the left

Outlook

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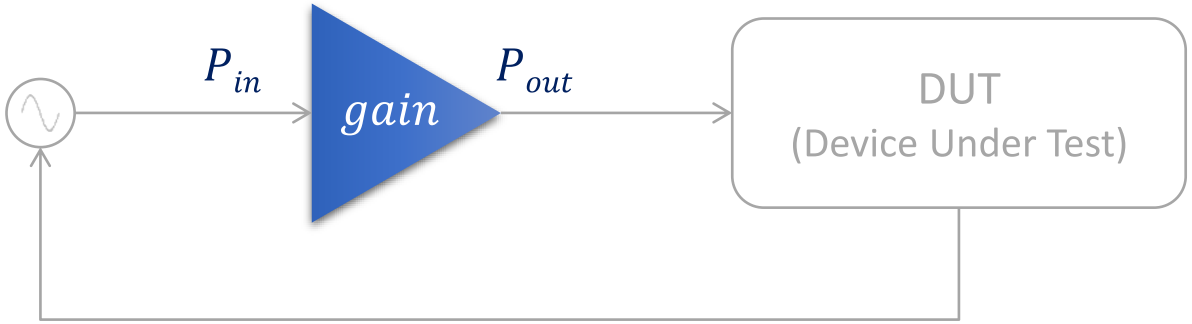
CERN Ceramic window in use with several FPCs
(LHC, SOLEIL, ESRF, ANL-APS)
In operation in the LHC since 2008

RF Power Amplifier



Basically, it is about amplifying with a gain

$$P_{out} = gain \,.\, Pin$$

The ideal power amplifier
- Large bandwidth amplifying all frequencies equally
- No saturation
- Infinite power
- Zero delay
- No added noise
- Unconditionally stable
- Resistant to reverse power
- Radiation hard
- Efficient to transform AC input into RF output

Unfortunately, such a device does not exist (yet?)

RF power source classification

Vacuum Tubes

Grid Tubes

Triodes
Tetrodes
Pentodes
Diacrodes

Linear Beam Tubes

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

Crossed-field Tubes

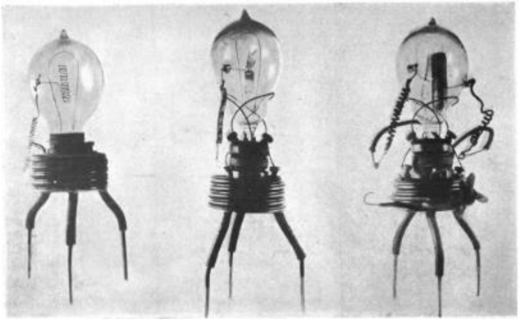
Magnetrons

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)
Silicon Germanium (SiGe)
Gallium Arsenide (GaAs)
Gallium Nitride (GaN)

Grid tubes

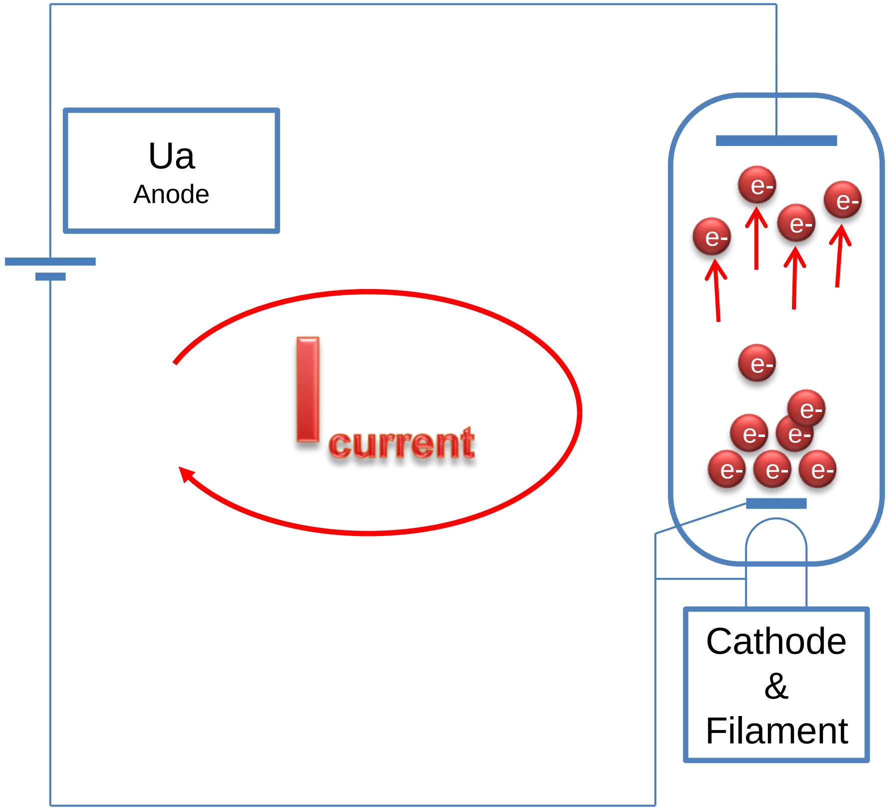
1904	Diode, John Ambrose Fleming
1906	Audion (first triode), Lee de Forest
1912	Triode as amplifier, Fritz Lowenstein
1913	Triode ‘higher vacuum’, Harold Arnold
1915	First transcontinental telephone line, Bell
1916	***Tetrode***, Walter Schottky
1926	Pentode, Bernardus Tellegen
1994	Diacrode, Thales Electron Devices



The first diode prototype
Fleming Diode, 1904

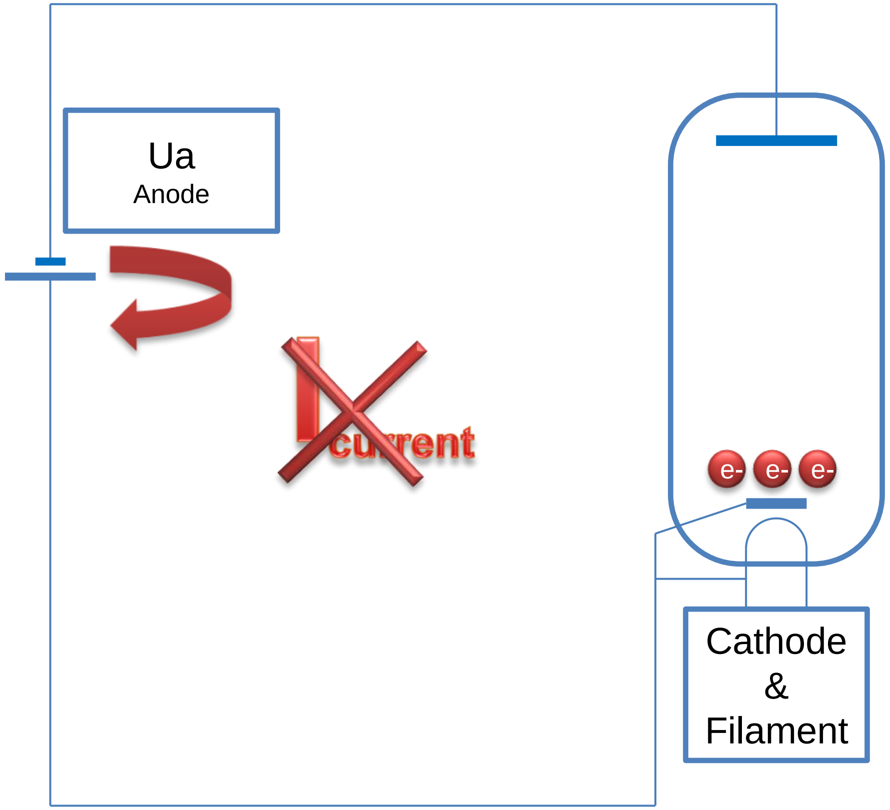
Thales TH 628 diacrode, 1998

Essentials of grid tube



- Vacuum tube
- Heater + Cathode
  - Heated cathode
    - Coated metal, carbides, borides,…
  - thermionic emission
  - Electron cloud
- Anode
- Diode

Essentials of grid tube



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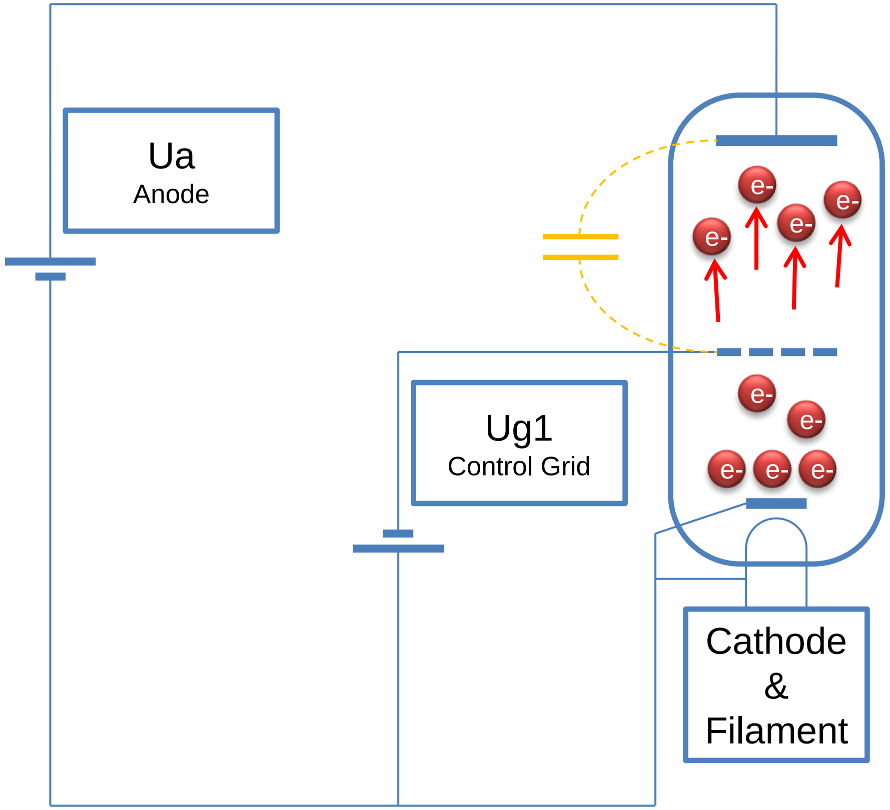
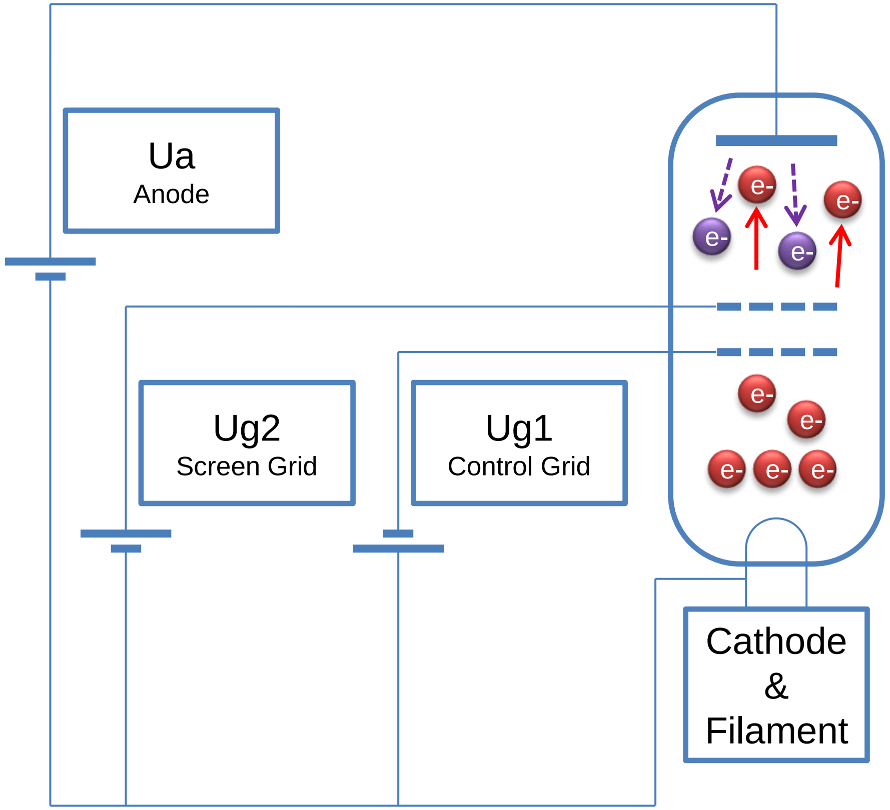


Triode

- Modulating the grid voltage proportionally modulates the anode current
- Transconductance
  - Voltage at the grid
  - Current at the anode
- Limitations
  - Parasitic capacitor Anode/g1
  - Tendency to oscillate

Essentials of grid tube



Tetrode

- Screen grid
  - Positive (lower anode)
  - Decouple anode and g1
  - Higher gain
- Limitations
  - Secondary electron
  - Anode treated to reduce secondary emission

Tetrode RS 2004 CERN SPS amplifier

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

Construction limitations

The main limitations faced by grid-base devices are the following

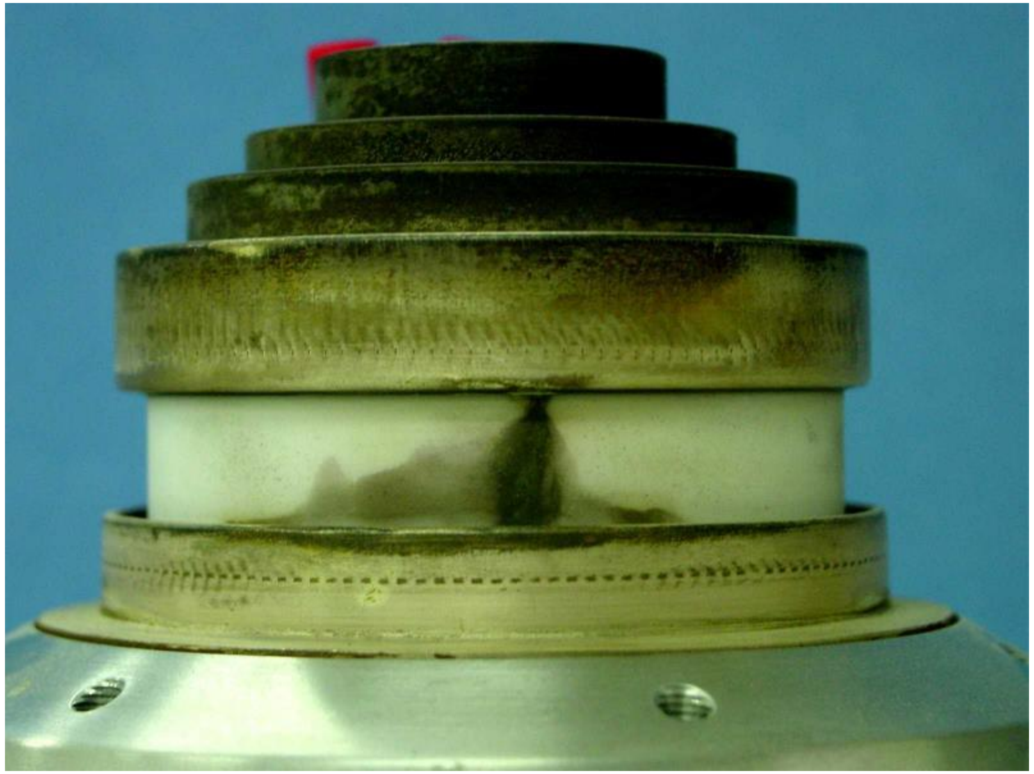
Physical size, ideally RF voltages between electrodes should be uniform, but this condition cannot be achieved unless the major electrode dimensions are significantly smaller than 1/4 wavelength at the operating frequency, this is achievable at lower frequencies than 400 MHz, but at higher frequencies, this becomes a difficulty

Electron transit time, electrode spacing, principally between the grid and the cathode must be scaled inversely with frequency to avoid excessive loading of the drive source, reduction in power gain, back heating of the cathode and reduced conversion efficiency

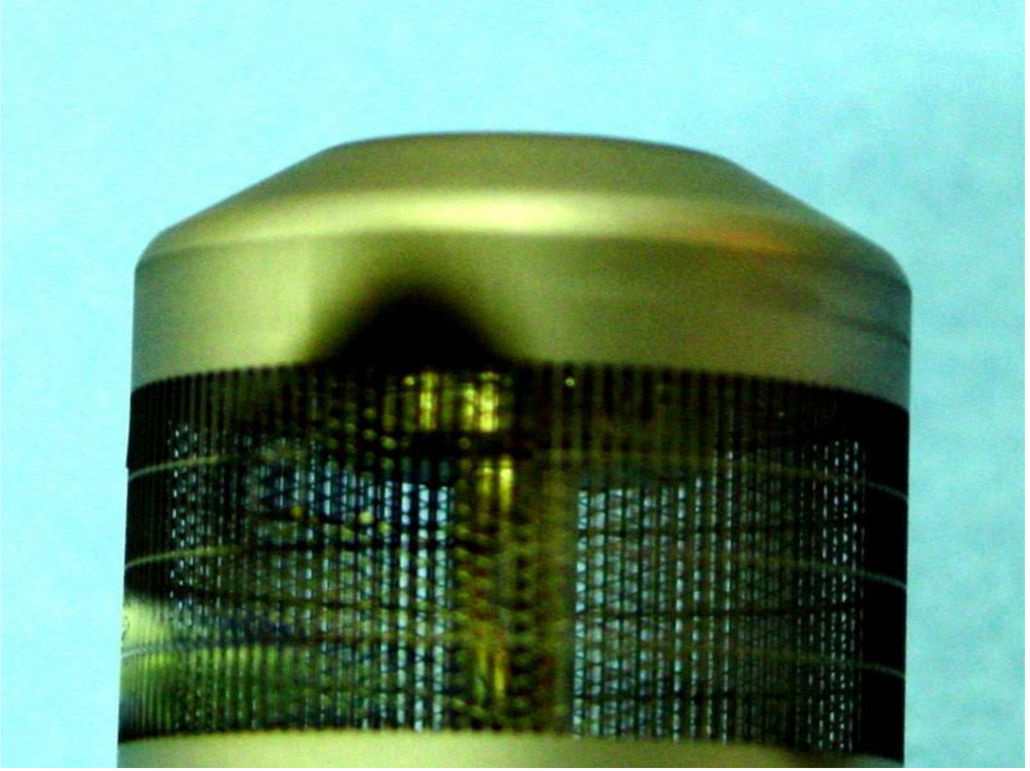
Voltage breakdown, high power tubes operate at high voltages that presents significant problems placing restrictions on the operating voltages that may be applied to the individual elements

Circulating currents, important RF currents may develop as a result of inherent inter electrode capacitances and inductances of the device, causing significant heating of the grid, the connections and the vacuum seals

Heat dissipation, as the element must be kept small with respect to the required power, power dissipation is accordingly consequently limited

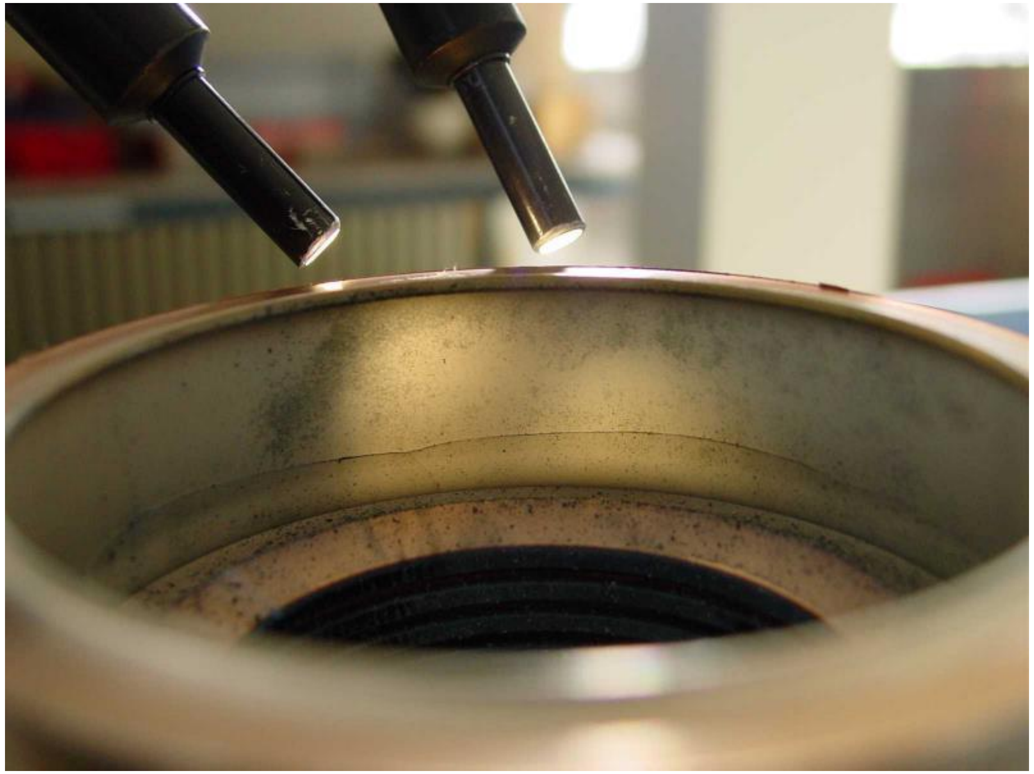


External arcing between Anode and G2



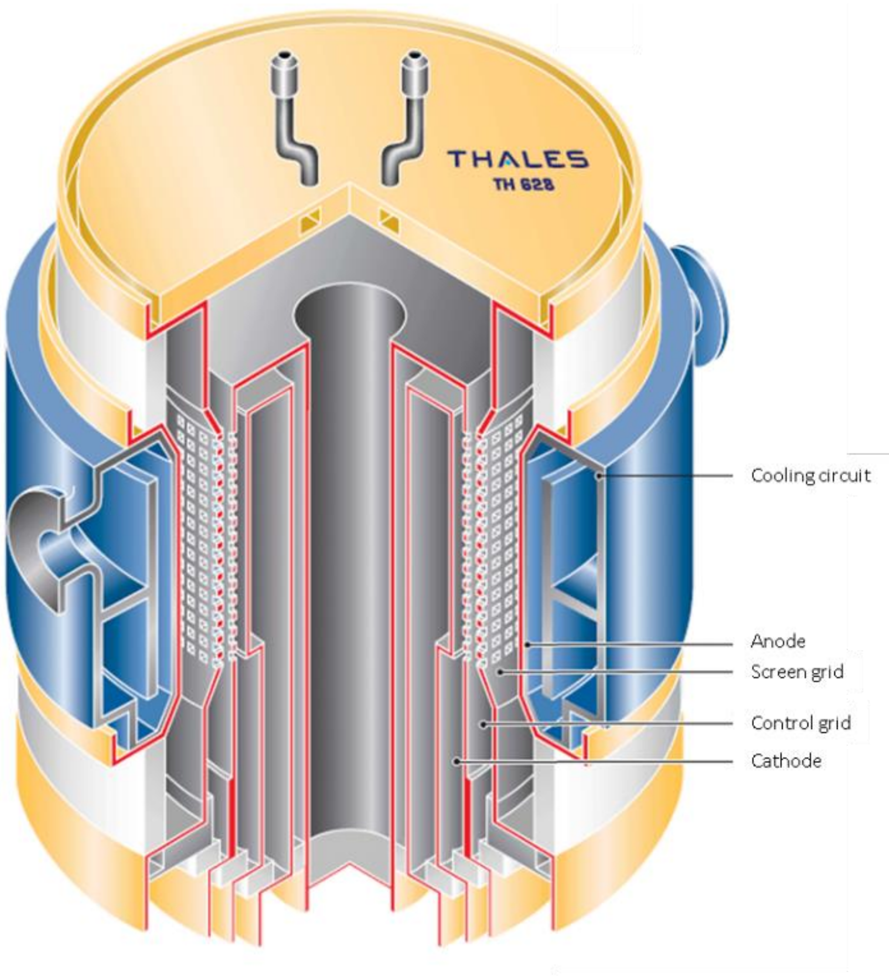
Internal arcing on G2

Overheating due to lack of air cooling

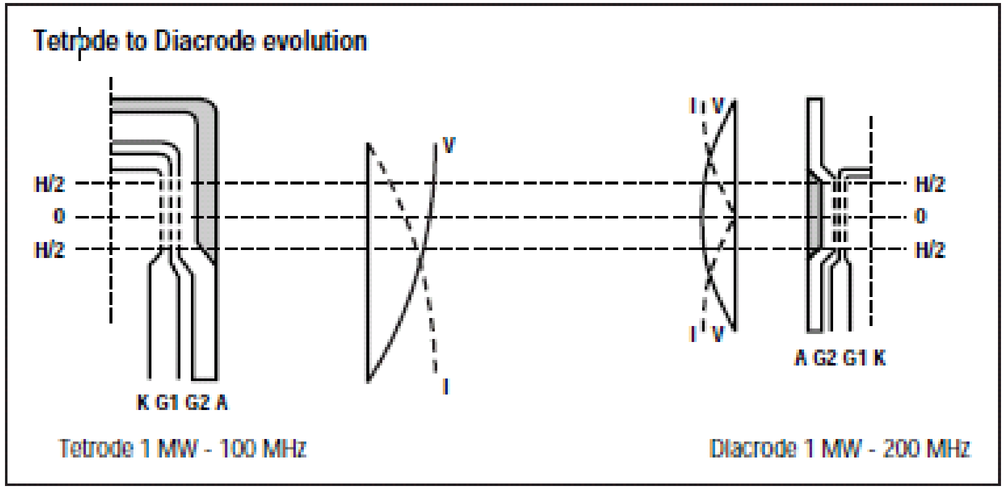


Ceramic crack due to internal metallization of the ceramic, perhaps due to over filament

Diacrode



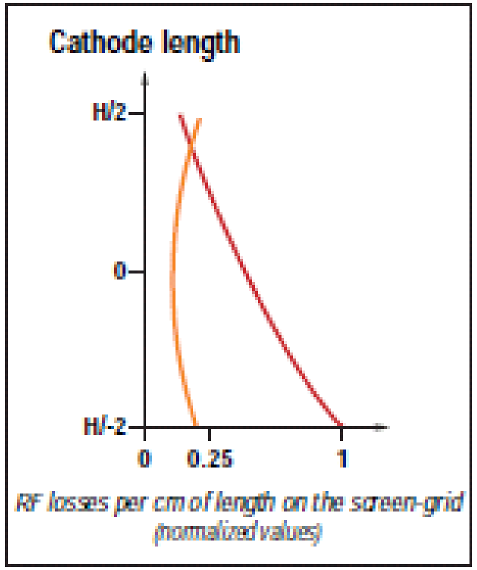
The basic Diacrode design limits electrical losses and electrodes heating by minimizing the reactive currents in the cathode and grids meshes. This means that compared with conventional tetrodes, Diacrodes can either double the output power at a given operating frequency or double the frequency for a given power output. Diacrodes provide the same gain and efficiency as conventional tetrodes - but at frequencies which are out of reach for tetrodes at an equivalent output power



The main difference is in the position of the active zones of the tubes in the resonant coaxial circuits, resulting in improved reactive current distributing in the tube’s electrodes

Example of calculated RF losses on the screen grid for the same cathode length at an output power of 1.4 MW cw @ 120 MHz

— Diacrode — Tetrode



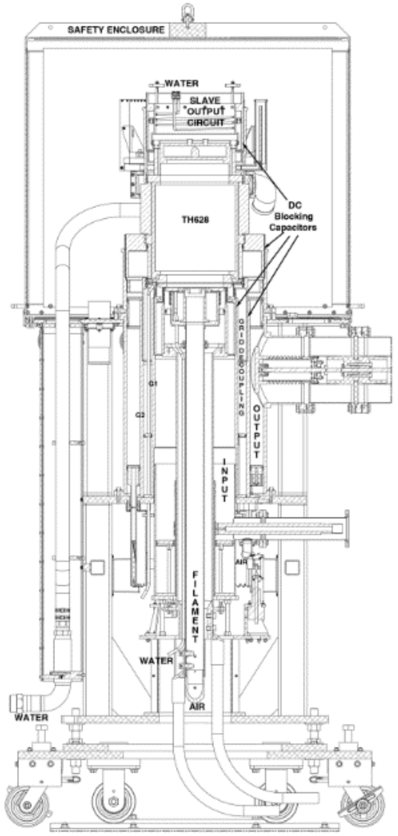
Diacrode

Los Alamos already successfully operate several Diacrodes since 2015

Within the Test Infrastructure and Accelerator Research Area (TIARA) program, CERN and Los Alamos tested a Diacorde for the Ionisation Cooling Test Facility at the Rutherford Appleton Laboratory

Novel pulsed RF power amplifier design, Milestone MS28
https://cds.cern.ch/record/1510945/files/TIARA-REP-WP7-2013-002.pdf

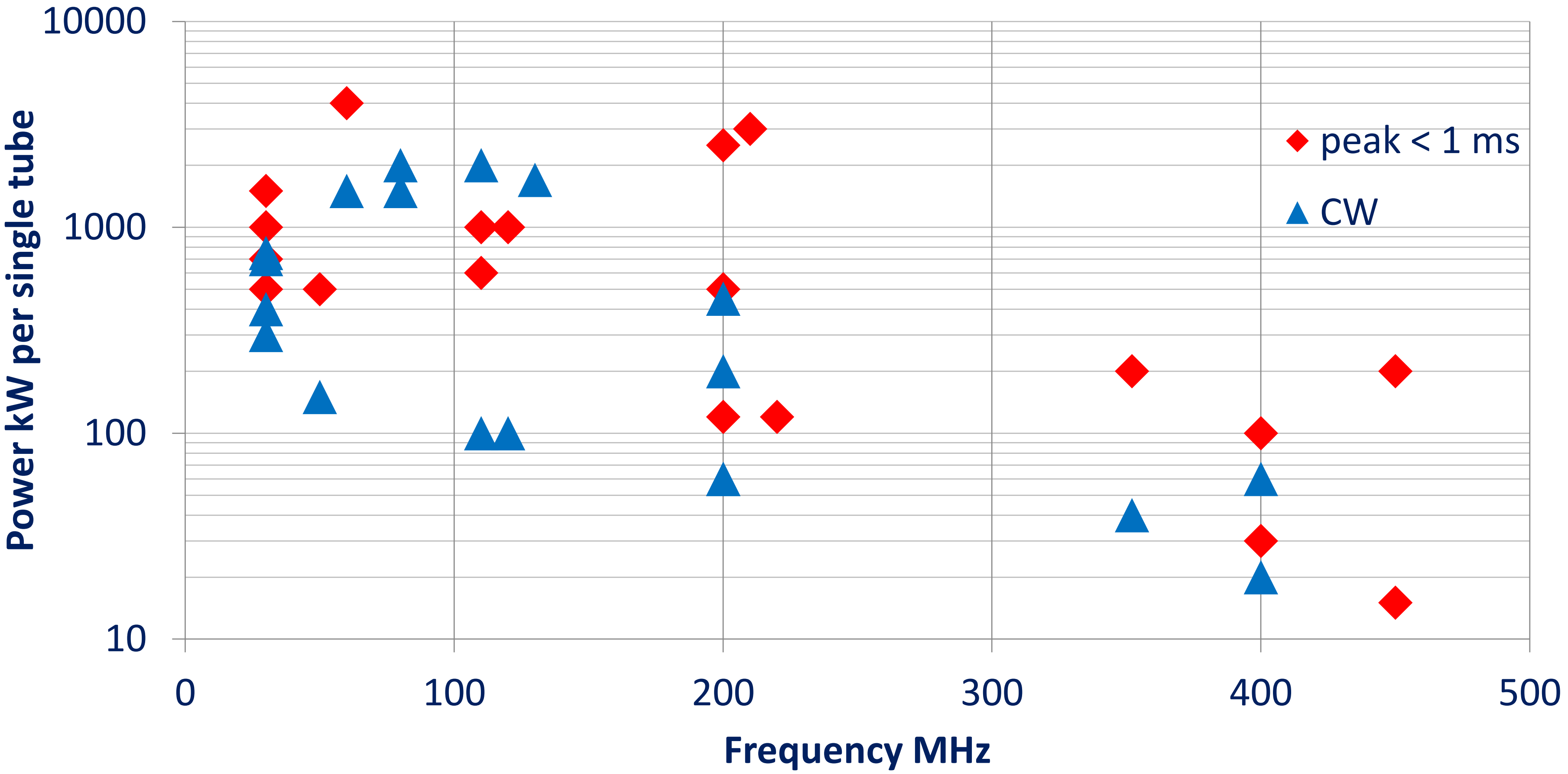
Design report of a 3 MW power amplifier, Deliverable 7.4
https://cds.cern.ch/record/1647574/files/TIARA-REP-WP7-2014-005.pdf



Pulse duration [µs]	Repetition rate [pps]	Anode Voltage [kV]	Anode current [A]	Grid2 voltage [kV]	Pout [MW]	$\eta_{RF/DC}$ [%]
1000	120	26.1	108	1.5	2.0	69.5
300	30	29.4	153	1.6	3.0	65.3

John Lyles, Los Alamos National Laboratory, Design, test and implementation of new 201.25 MHz RF power amplifier for LANSCE Linac* LA-UR-12-20983

Frequency & Power range of tetrodes



RF power source classification

Vacuum Tubes

Grid Tubes

Triodes
Tetrodes
Pentodes
Diacrodes

Linear Beam Tubes

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

Crossed-field Tubes

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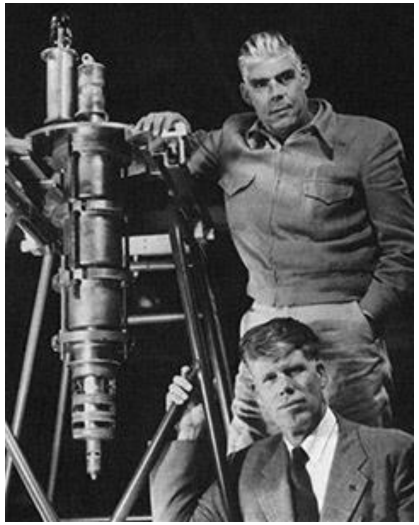
Laterally Diffused Metal Oxide Semiconductor (LDMOS)
Silicon Germanium (SiGe)
Gallium Arsenide (GaAs)
Gallium Nitride (GaN)

Linear beam tubes

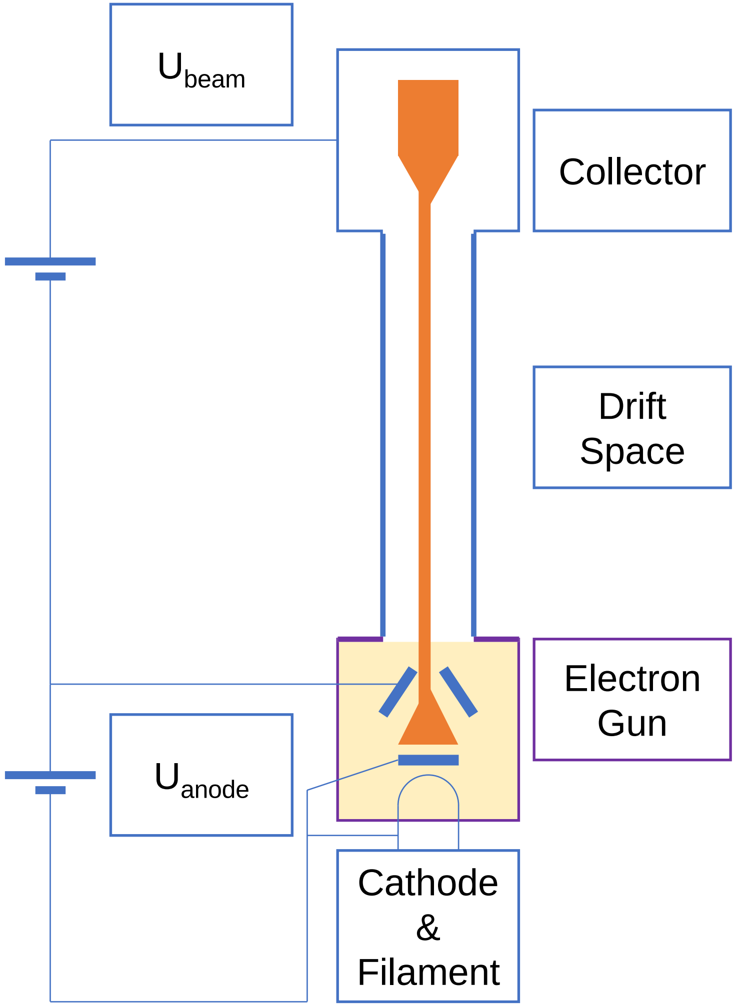
1937	Klystron, Russell & Sigurd Variant
1938	IOT, Andrew V. Haeff
1939	Reflex klystron, Robert Sutton
1940	Few commercial IOT
1945	Helix Travelling Wave Tube (TWT), Kompfner
1948	***Multi MW klystron***
1959	Gyrotron, Twiss & Schneider
1963	Multi Beam Klystron, Zusmanovsky and Korolyov
1980	High efficiency IOT
2022	High Efficiency Klystron



Russell & Sigurd Varian klystron, 1937

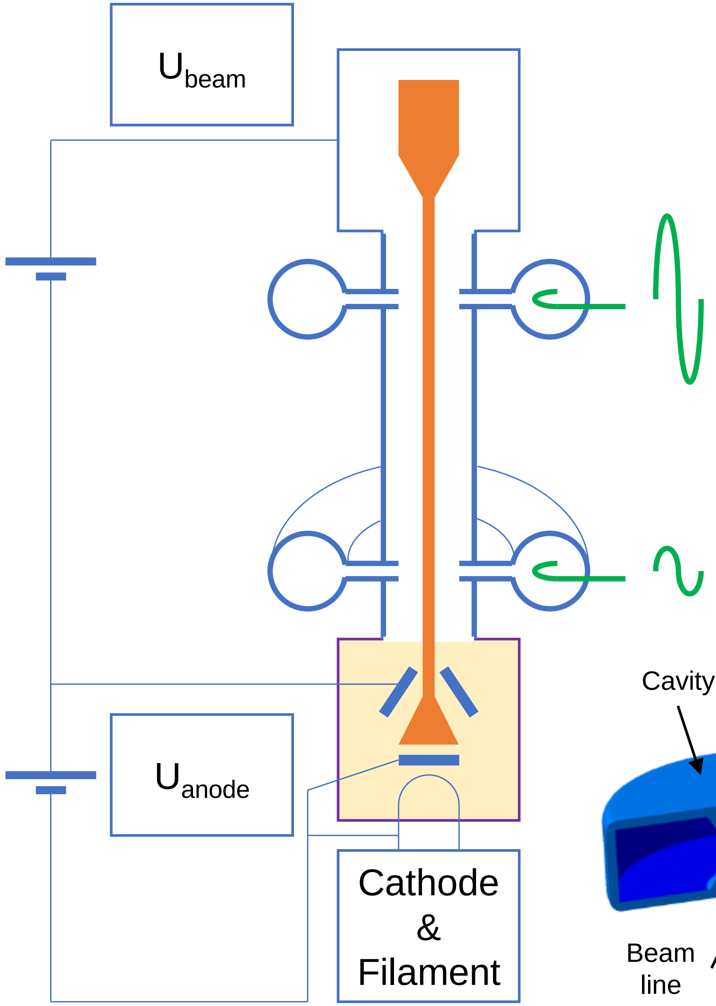
Thales TH 1802, 2002

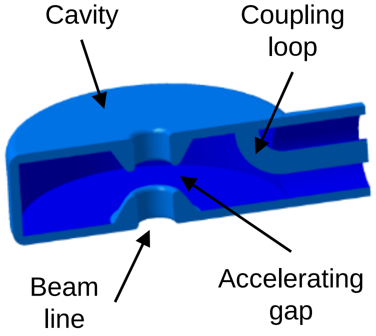
Essentials of klystron



- Klystrons velocity modulation
  - converts the kinetic energy into radio frequency power
- Vacuum tube
- Electron gun
  - Thermionic cathode
  - Anode
- Electron beam
- Drift space
- Collector
- e- constant speed until the collector

Essentials of klystron





Cavity resonators

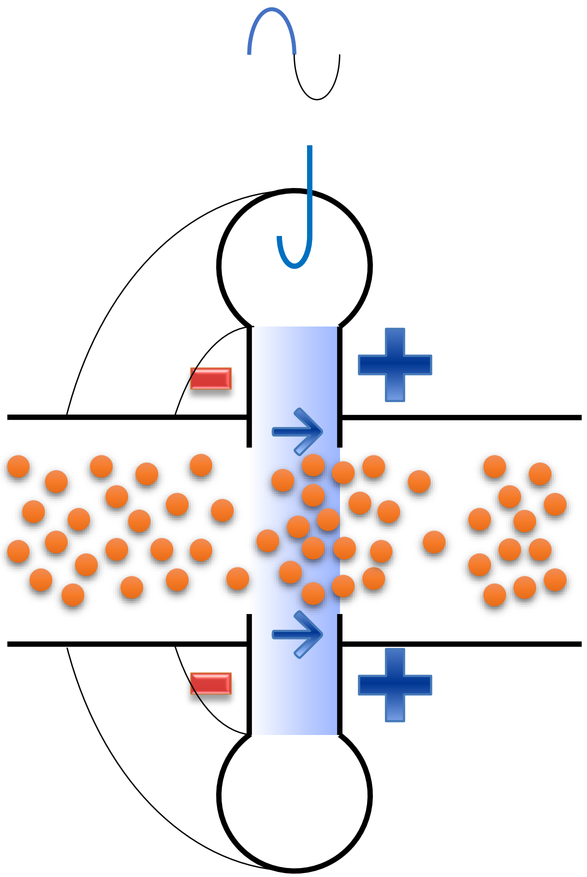
RF input cavity (Buncher)

- modulates e- velocity
- Some are accelerated
- Some are neutral
- Some are decelerated
- Bunching the e-

RF output cavity (Catcher)

- Resonating at the same frequency as the input cavity
- At the place with the numerous number of e-
- Kinetic energy converted into voltage and extracted

Essentials of klystron



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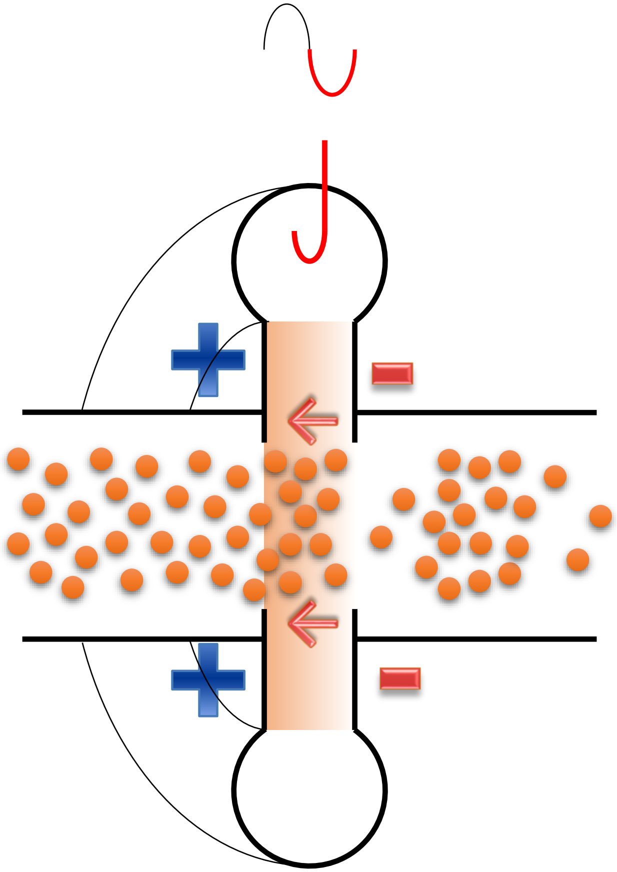

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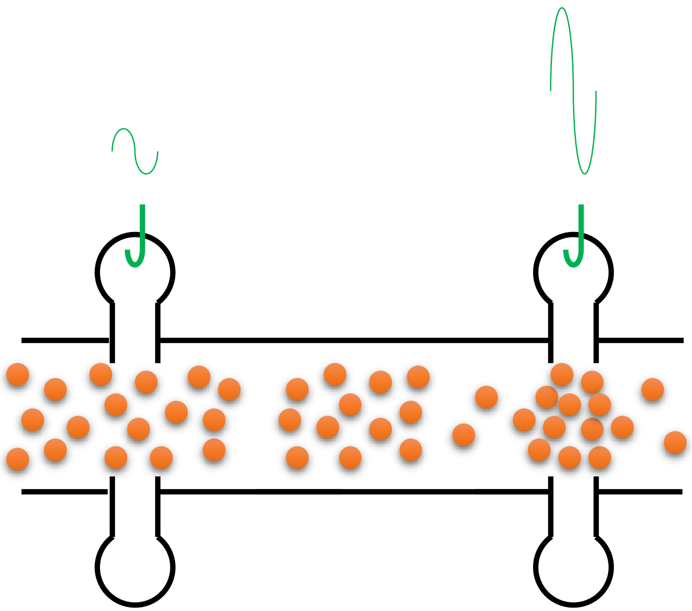

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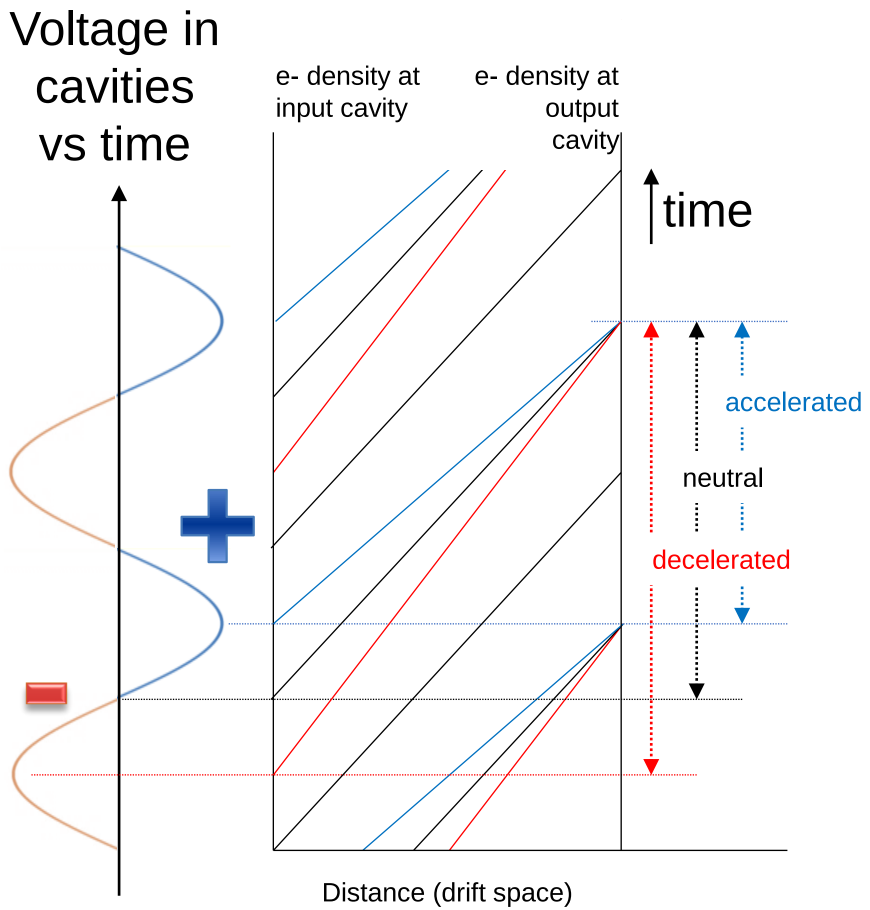

Bunching of e- beam in a klystron

Cavity resonators

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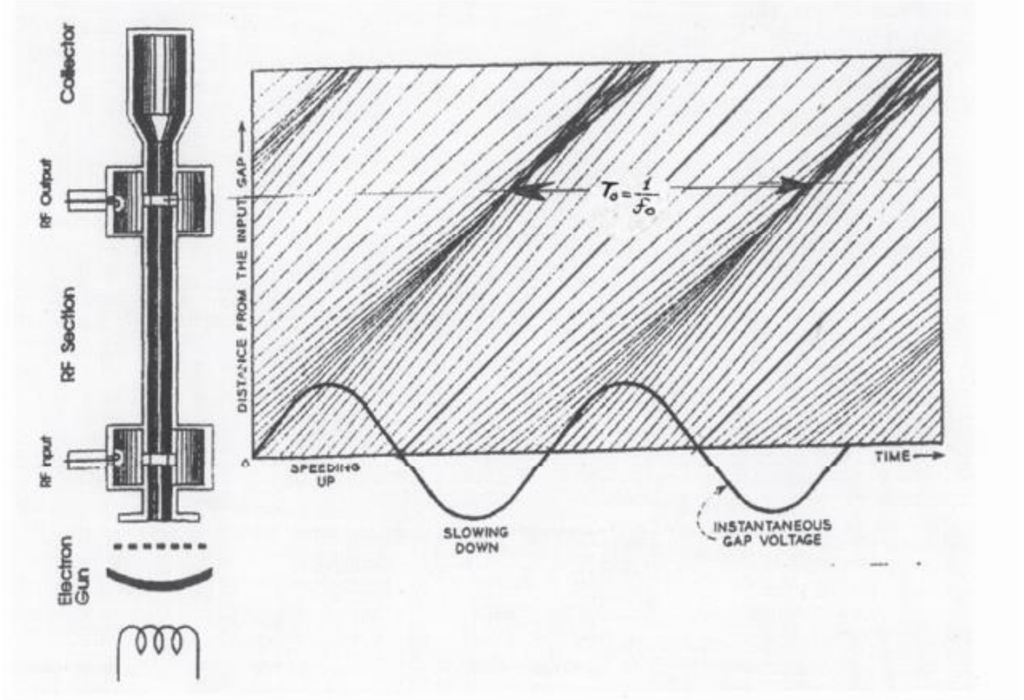
Essentials of klystron

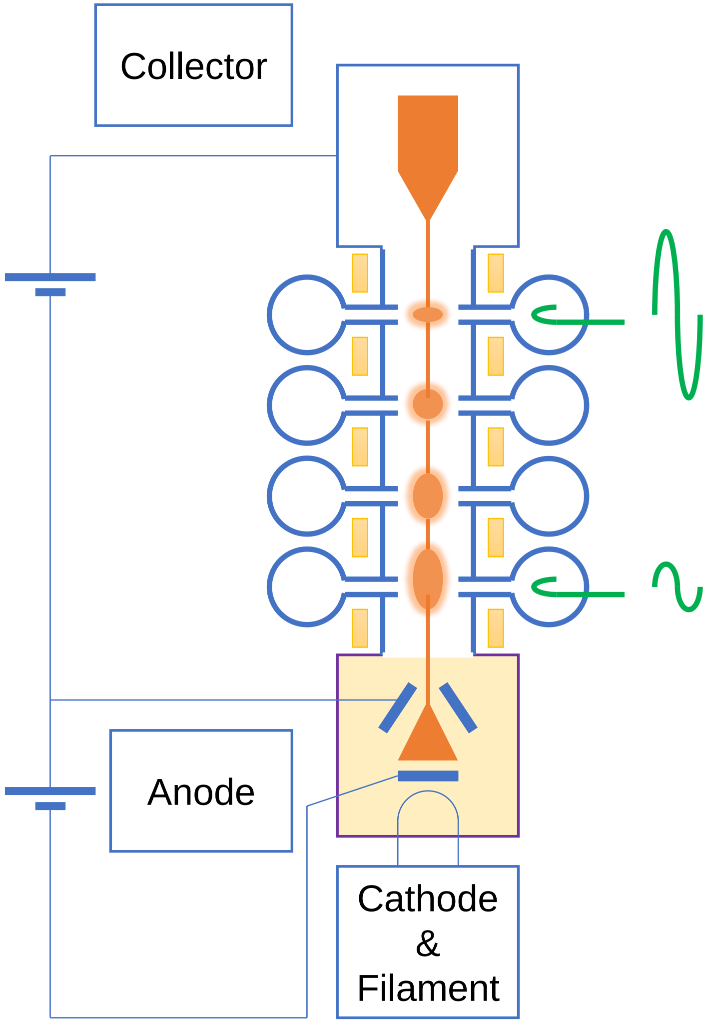


The Applegate diagram

The velocity modulation principle, which made klystrons possible, was explained by Russell Variant as follows, in a book written by his wife, Dorothy: ‘Just picture a steady steam of cars from San Francisco to Palo Alto, if the cars left San Francisco at equal increments and at the same velocity, then even in Palo Alto they would be evenly spaced and you would call this a direct flow of cars. But suppose somehow the speed of some cars, as they left San Francisco, was increased a bit and others retarted. Then, with time, the fast cars would tend to catch up with the slow ones and they would bunch into groups. Thus, if the velocity of the cars was sufficiently different or the time long enough, the steady stream of cars would be broken and, under ideal conditions, would arrive in Palo Alto in clearly defined groups. In the same way an electron tube can built in which the control of the e-beam is produced by the principle of bunching, rather than the direct control of a grid in a triode…’

This is illustrated by the ‘Applegate’ diagram, showing electrons from an electron gun traversing a gap in a first cavity, and having their velocity modulated by the voltage across that gap. As a result, they arrive in bunches at the second, or output cavity. Bunches form around the electrons crossing the first gap when the sinusoidal voltage there crosses from negative to positive (from decelerating to accelerating). Bunches arrive at the second cavity with a period T0, which corresponds to the period of the sinusoidal power input to the first cavity. The bunching action shown in the Applegate diagram is entirely ballistic, or kinematic, i.e. the charge of the electrons does not come into play as their trajectories come very close and actually cross. In an average klystron, space charge will modify these trajectories and the interaction between cavities and beam will be better described by ‘space-charge wave theory’, which treats space charge as an elastic medium and describes electron motion in term of wave.

Essentials of klystron

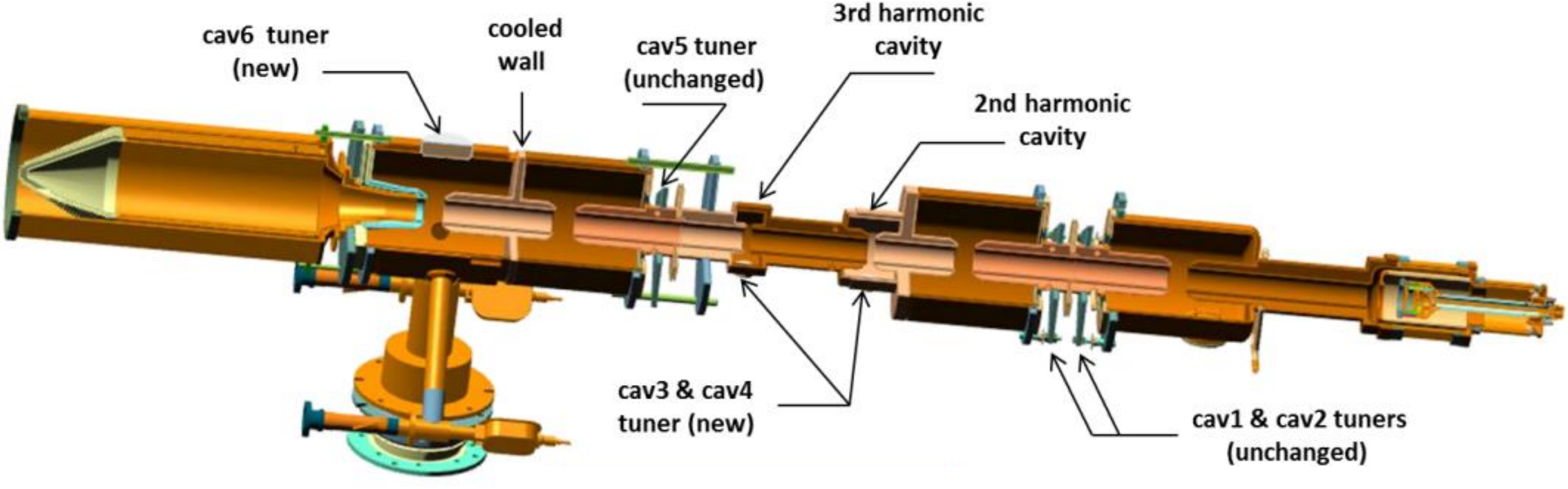


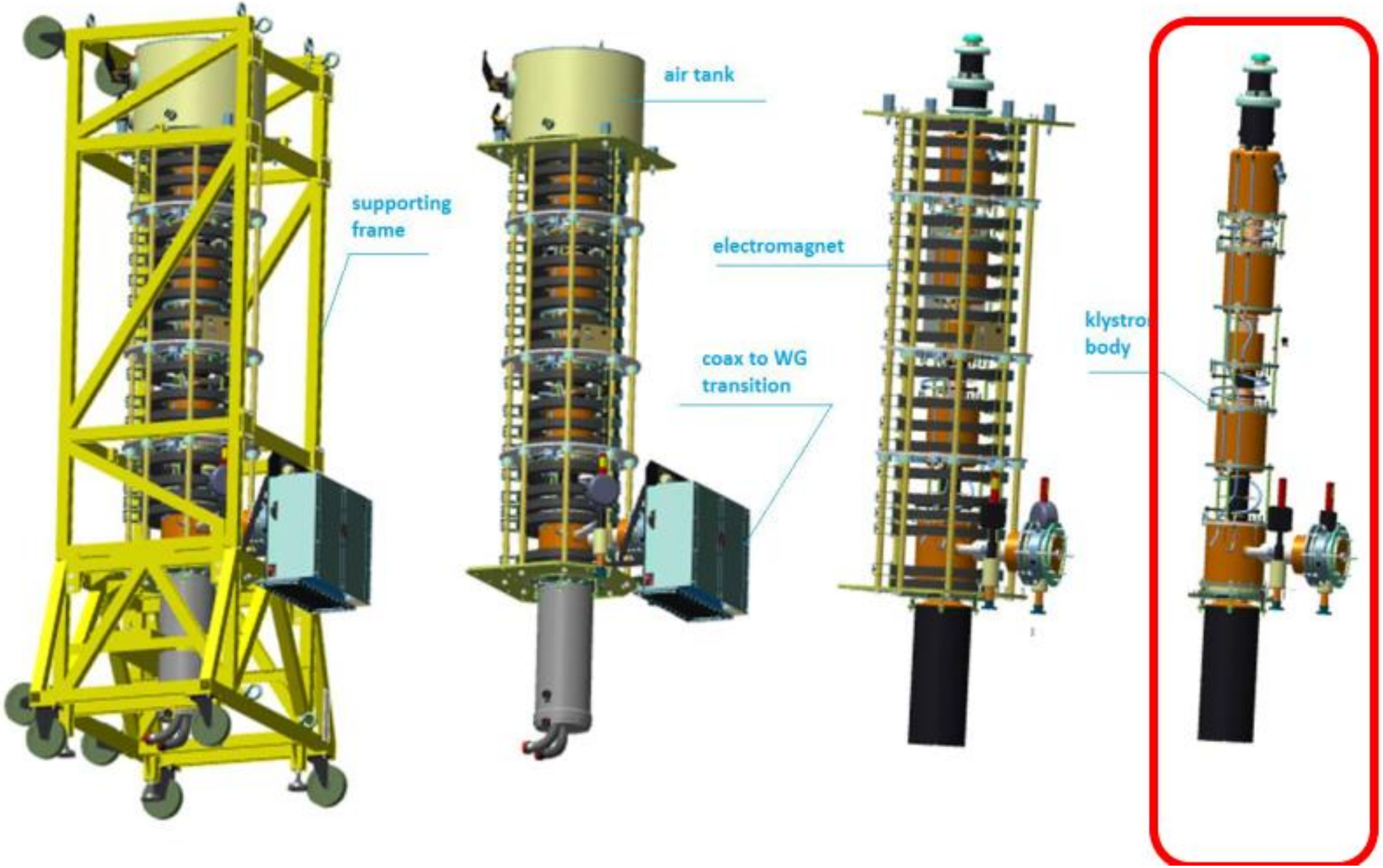
Additional bunching cavities

- Resonate with the pre-bunched electrons beam
- Generate an additional accelerating/decelerating field
- Better bunching
- Gain 10 dB per cavity

Focusing magnets

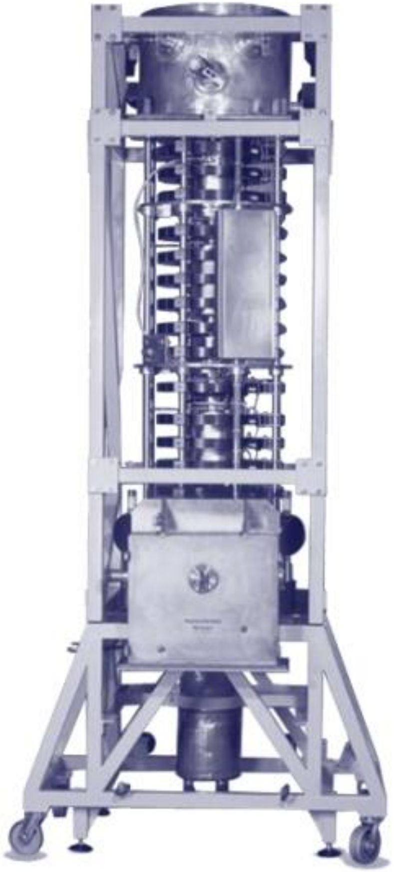
- To maintain the e- beam as expected and where expected


cav6 tuner (new)
cooled wall
cav5 tuner (unchanged)
3rd harmonic cavity
2nd harmonic cavity
cav3 & cav4 tuner (new)
cav1 & cav2 tuners (unchanged)


air tank
supporting frame
electromagnet
coax to WG transition
klystro
body

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

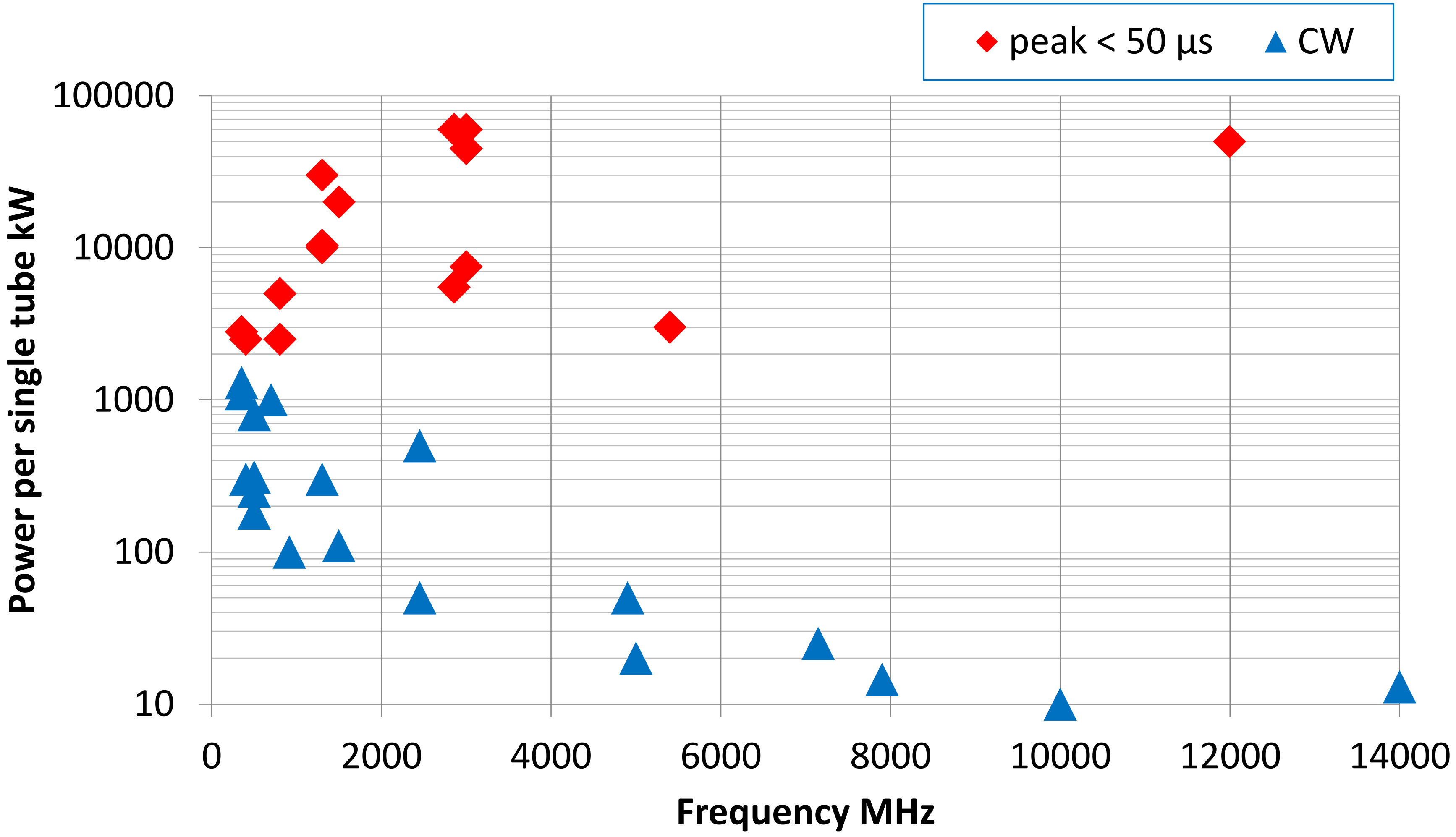
LHC TH2167 high efficiency project



Commonly with CERN, be the first team to develop, manufacture and operate a high efficiency (CSM based) klystrons set in reliable conditions

Integrating the major improvements held over the last four years on klystron modeling within HEIKA, compatible with industrial manufacturing margin

Klystrons available from industry



RF power source classification

Vacuum Tubes

Grid Tubes

Triodes
Tetrodes
Pentodes
Diacrodes

Linear Beam Tubes

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

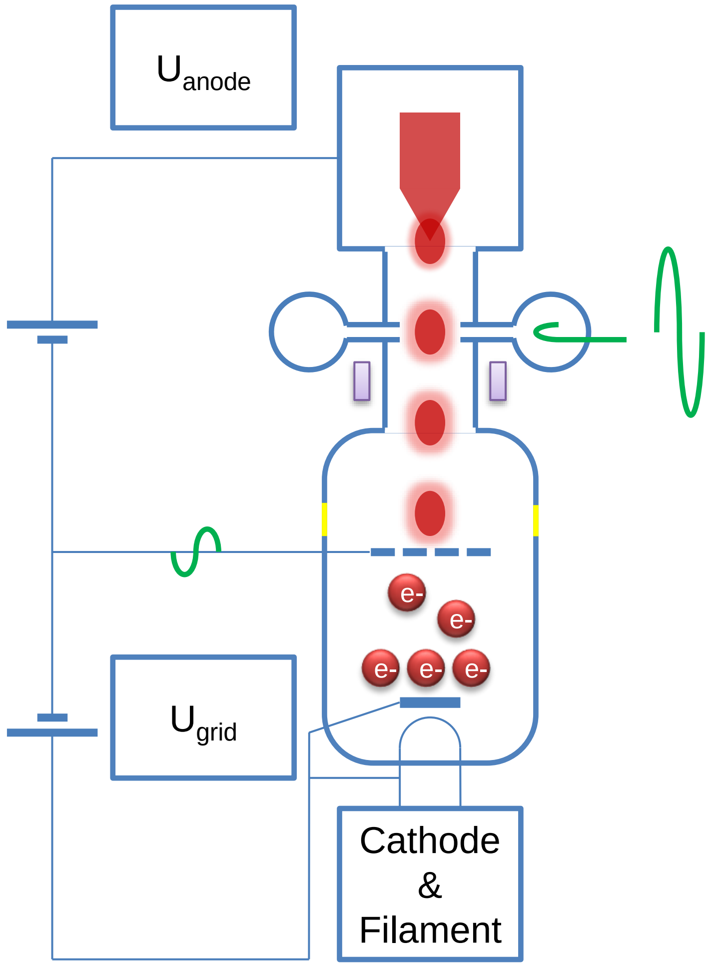
Crossed-field Tubes

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)
Silicon Germanium (SiGe)
Gallium Arsenide (GaAs)
Gallium Nitride (GaN)

Essentials of IOT



IOT density modulation

- converts the kinetic energy into radio frequency power

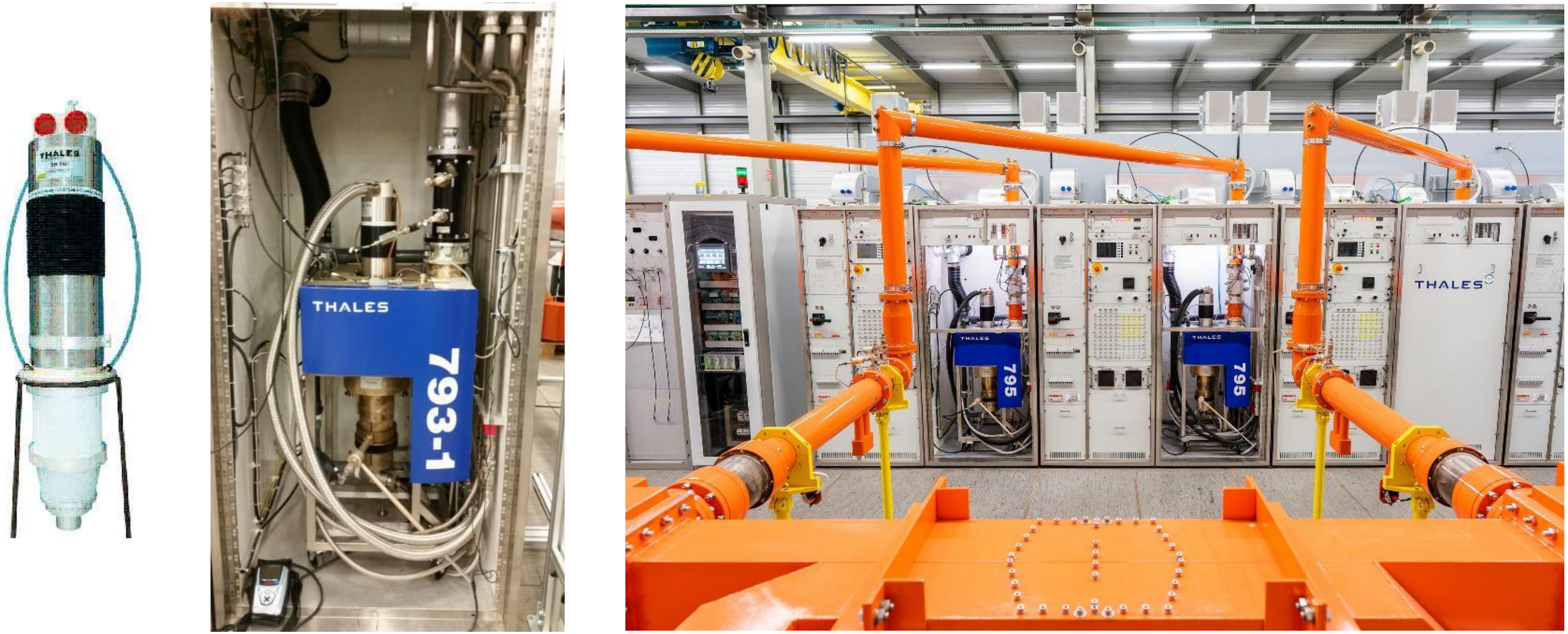
Vacuum tube

Triode input

- Thermionic cathode
- Grid modulates e- emission

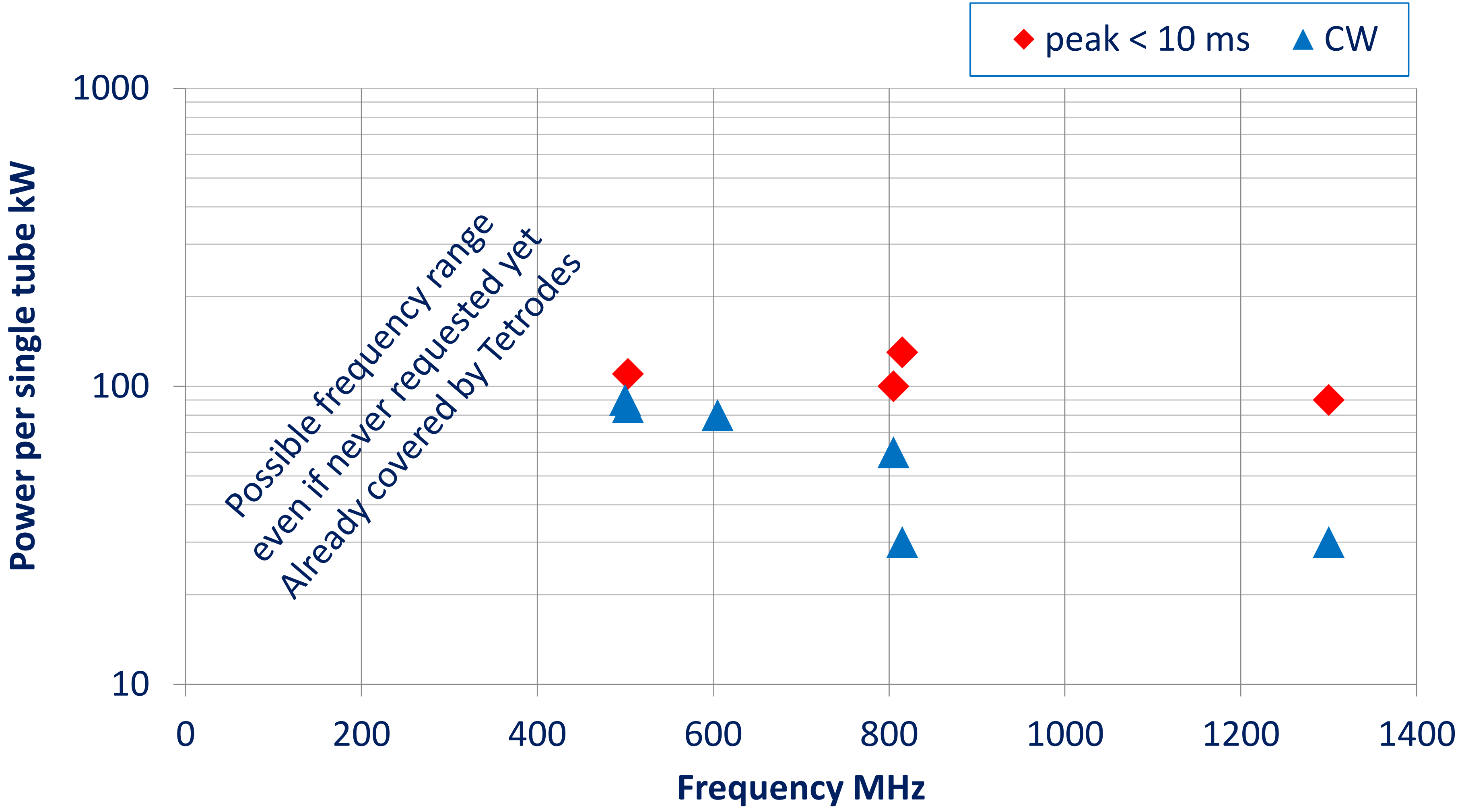
Klystron output

- Anode accelerates e- buckets
- Short drift tube & magnets
- Catcher cavity
- Collector



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

IOT available from industry



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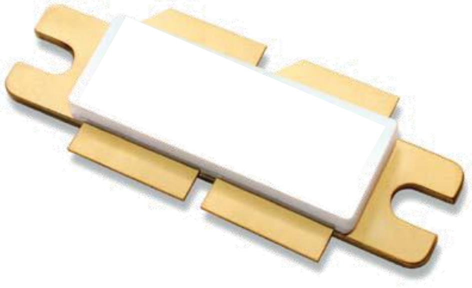
Transistor for RF power

1925	theory, Julius Edgar Lilienfeld
1947	Germanium US first transistor, John Bardeen, Walter Brattain, William Shockley
1948	Germanium European first transistor, Herbert Mataré and Heinrich Welker
1953	first high-frequency transistor, Philco
1954	Silicon transistor, Morris Tanenbaum
1960	MOS, Kahng and Atalla
1966	Gallium arsenide (GaAs)
1980	VDMOS
1989	Silicon-Germanium (SiGe)
1997	Silicon carbide (SiC)
2004	Carbon graphene

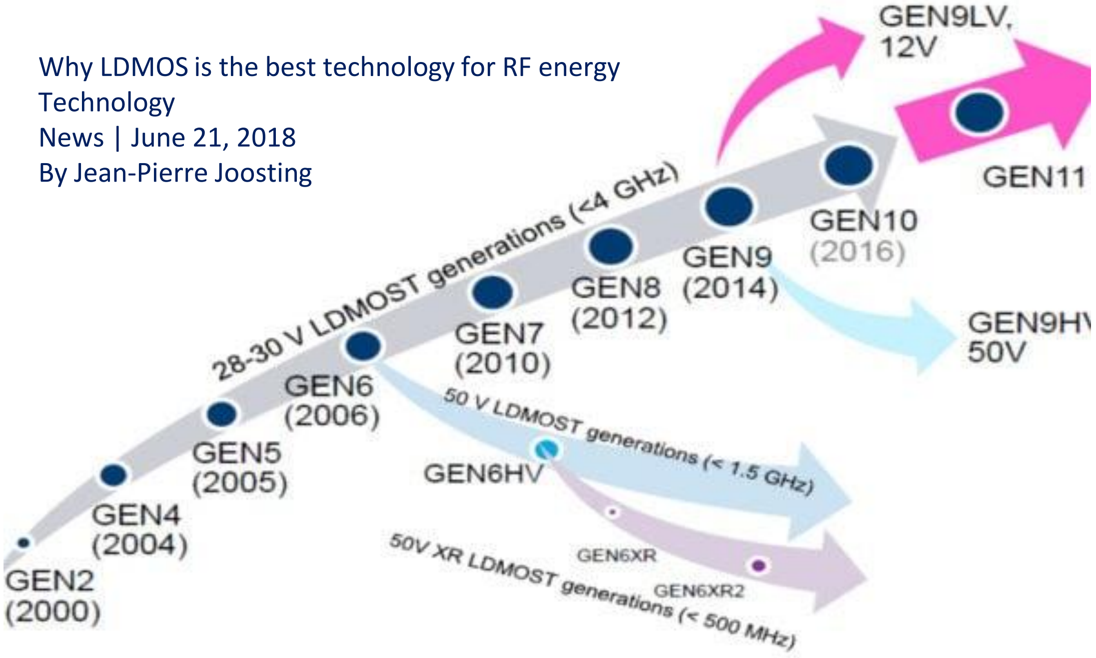
First transistor invented at BELL labs in 1947



XXI century LDMOS

Drain voltage

Why LDMOS is the best technology for RF energy
Technology
News | June 21, 2018
By Jean-Pierre Joosting



SOLEIL SYNCHROTRON elementary 600 W 300 Vdc / 30 Vdc converter board

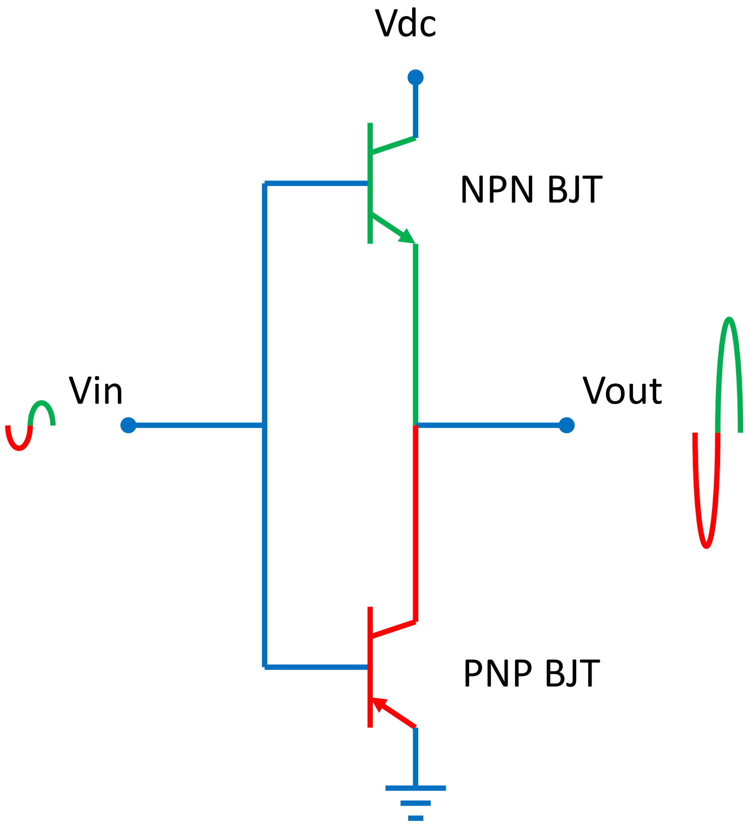
Evolution of the transistors market is quick

This is still a volatile market (as tubes have been a century ago)

Drain voltage is increasing with the development of transistors, and the Drain supply used with a generation of device could not suit the next generation
(moving from 12V to 24 V to 30 V to 36 V to 48 V to 50 V to 60 V to 80 V to 100 V)

Changing the transistor will not be the only challenge, either it will be under used as keeping the previous power supply, or power supply voltage will have to be upgraded

Essentials of RF transistor

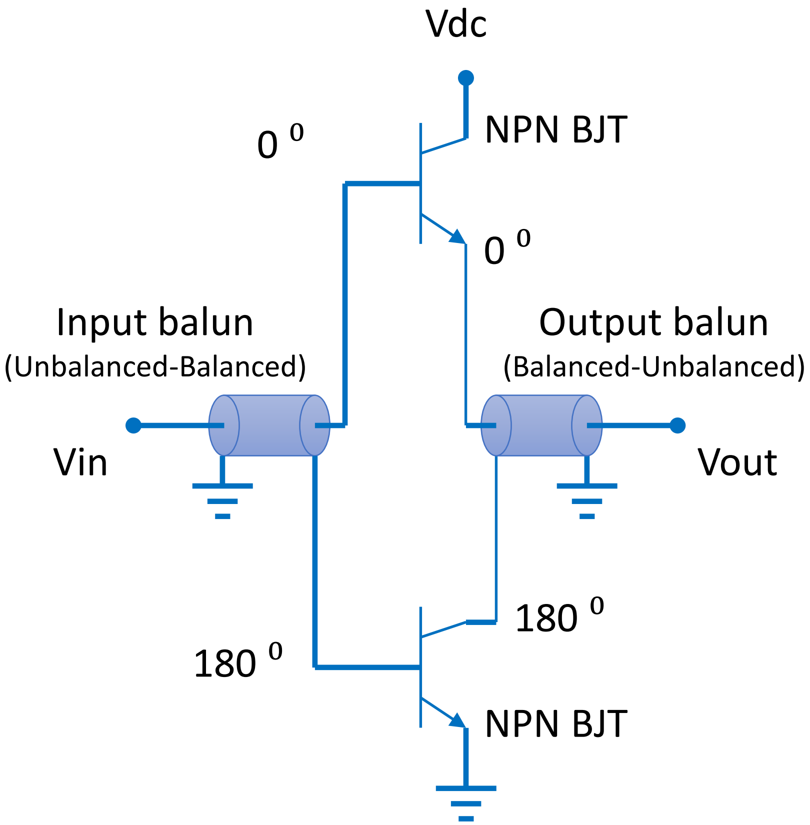


In a push-pull circuit the RF signal is applied to two devices

- One of the devices is active on the positive voltage swing and off during the negative voltage swing
- The other device works in the opposite manner so that the two devices conduct half the time
- The full RF signal is then amplified

Two different type of devices

Essentials of RF transistor



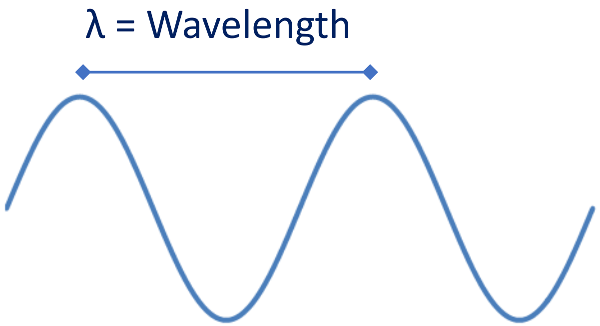
Another push-pull configuration is to use a balun (balanced-unbalanced)

- it acts as a power splitter, equally dividing the input power between the two transistors
- the balun keeps one port in phase and inverts the second port in phase

Since the signals are out of phase only one device is on at a time

This configuration is easier to manufacture since only one type of device is required

Essentials of RF transistor



$$\lambda = \frac{c}{f\,\sqrt{\varepsilon}} \quad \leftrightarrow \quad f = \frac{c}{\lambda\,\sqrt{\varepsilon}}$$

SOLEIL SYNCHROTRON

λ = *wavelength in meters (m)*
c = *velocity of light (m/s) – (~ 300,000,000 m/s)*
f = *frequency in hertz (Hz)*
ε = *dielectric constant of the propagation medium (~ 1.0 in air at 20 °C)*

Depends on the medium we are talking about

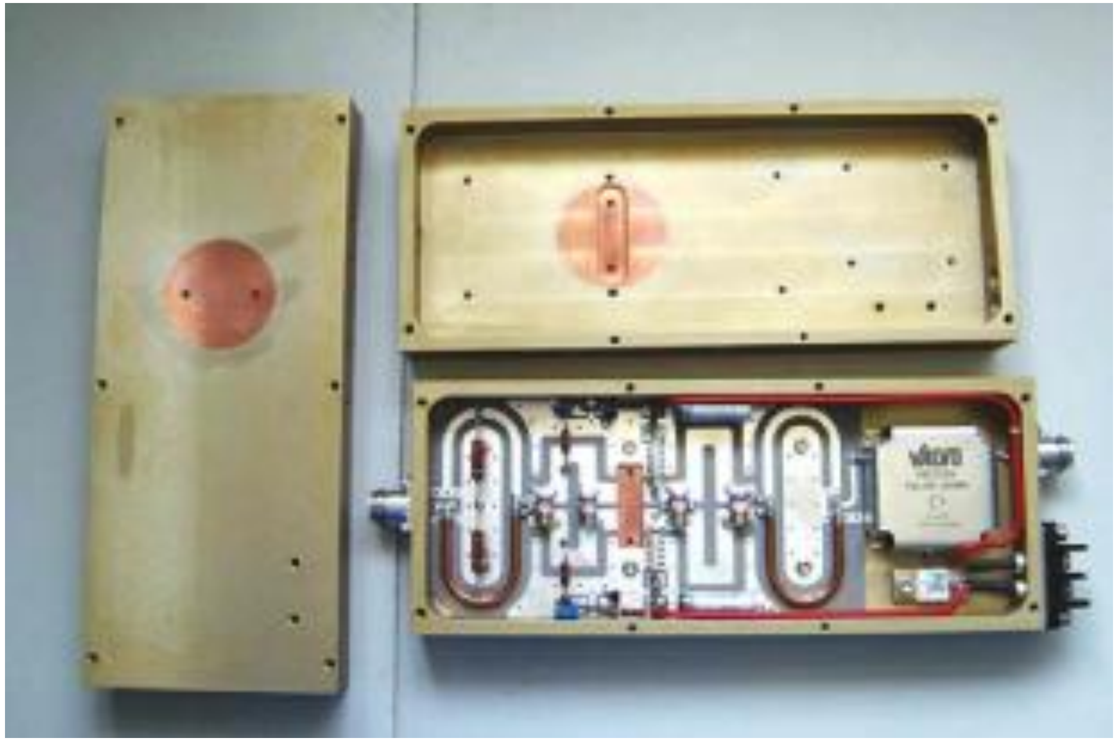
ε air = 1
ε vacuum = 1
ε 'plastic' = 3-5
ε 'ceramic' = ~ 9

SOLEIL elementary amplifier module
VDMOS-D1029UK05 operated at 330 W at 352 MHz
under 30 Vdc with a gain of 11 dB
Each module is with a Valvo 500 W circulator to protect
the transistors from excess of reflected power

Essential of transistors

An important aspect of high-power transistors is the heat transfer to the cooling system

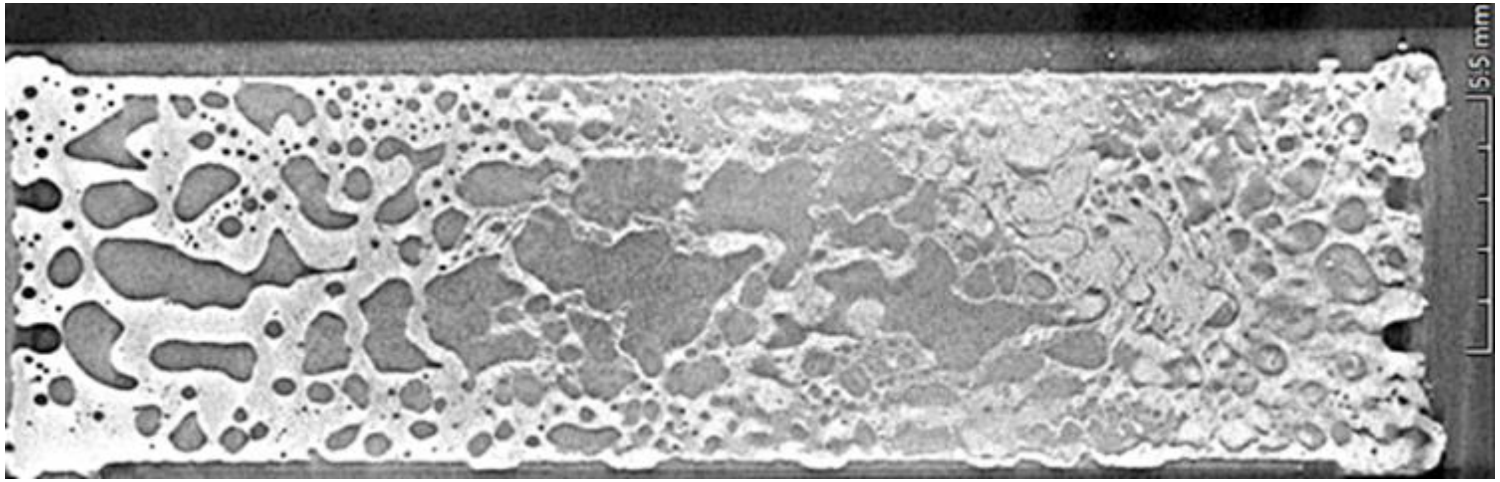
An upgrade of the SOLEIL system was the insertion of a copper slug through the aluminium case of the amplifier modules, at the transistor location, significantly improving the heat transfer, computer simulations shown a 15˚C temperature drop

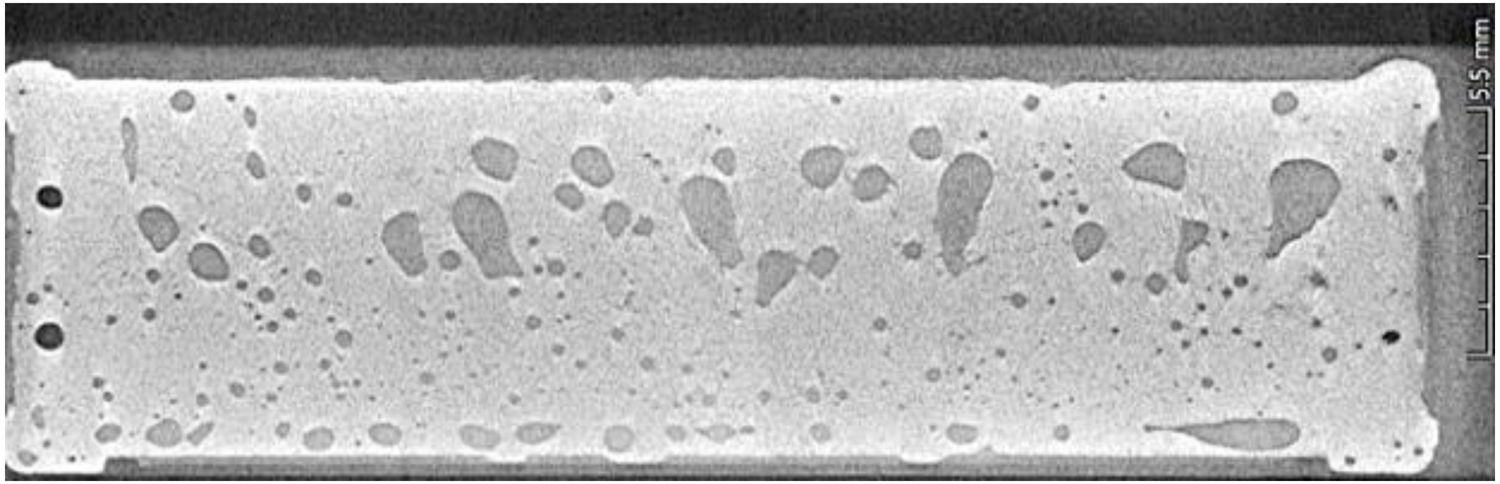


SOLEIL SYNCHROTRON amplifier module with copper slug through the aluminium case

VOIDS

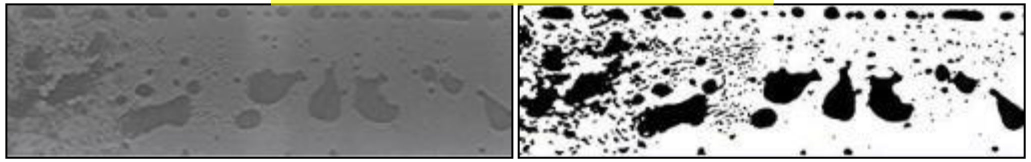
Thermal effect are closely linked to the way the transistors are brazed to their cold plate



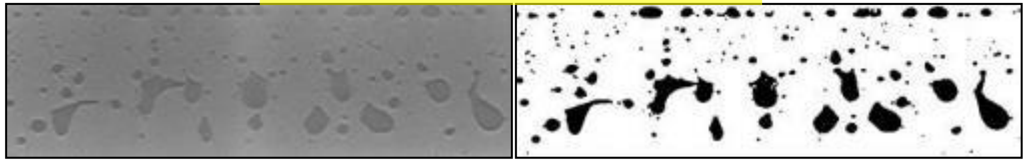


Voids

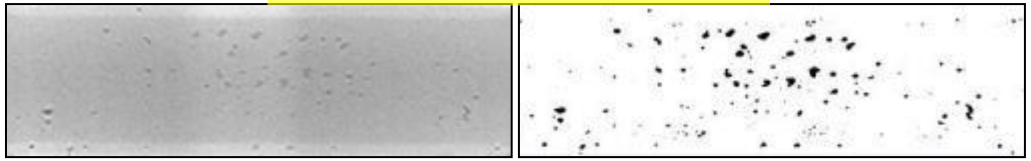
Very bad 25 % voids

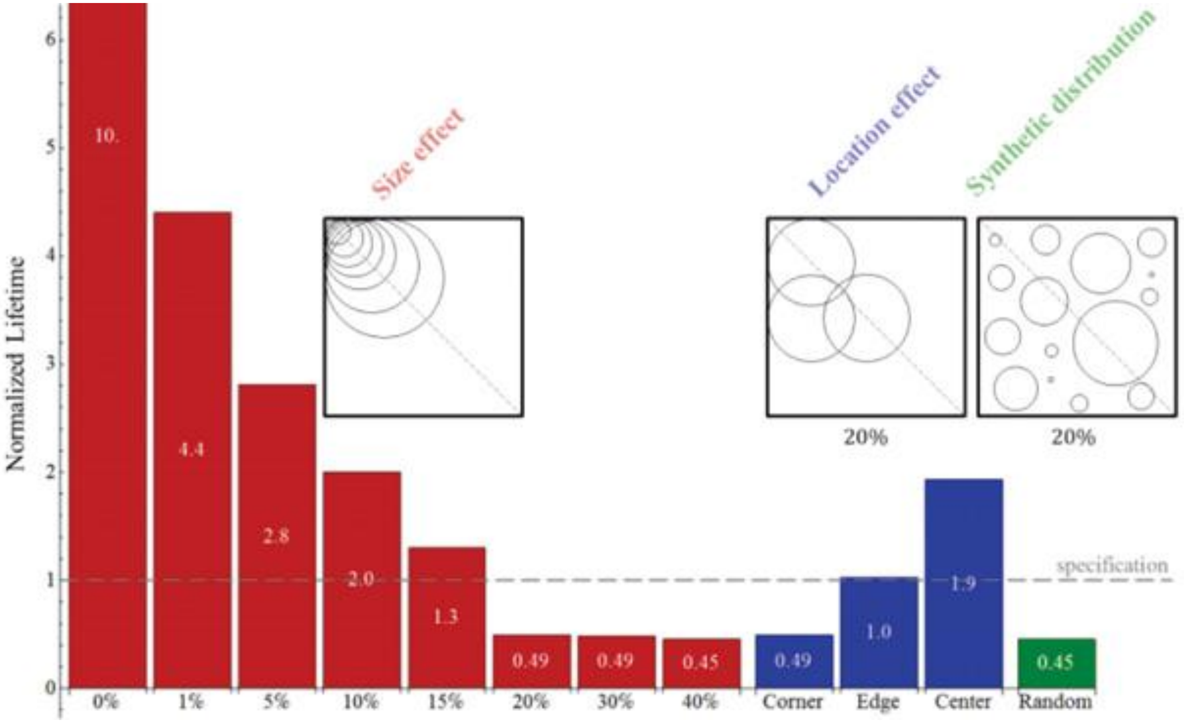


Bad 15 % voids



Very good 2 % voids

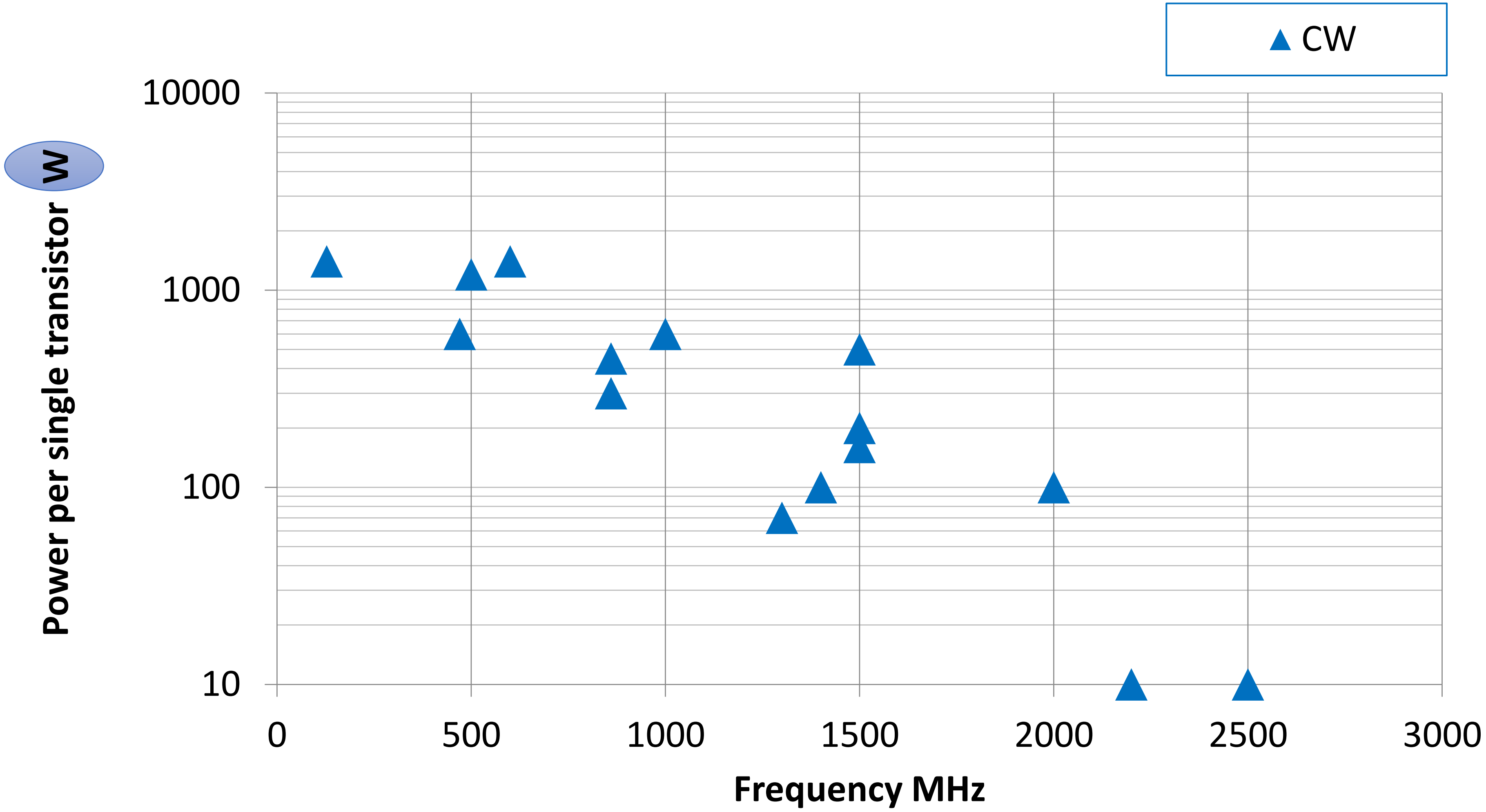




One must develop a very specific way to proceed with the brazing, under vacuum, with a special deposition of the brazing pate, and a specific thermal ramp up and ramp down in order to minimize the number and the shape of voids


ATC
201J
ATC
201J

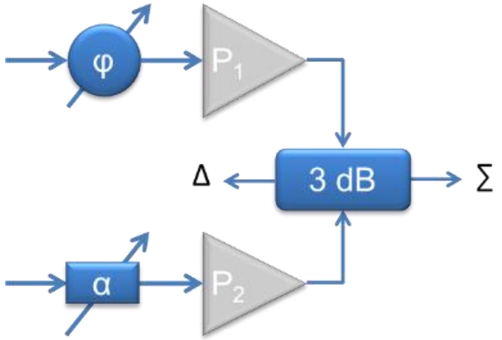
Transistors available from industry



Combination

$$\Sigma = \frac{PA1 + PA2}{2} + \sqrt{PA1\,PA2}$$

$$\Delta = \frac{PA1 + PA2}{2} - \sqrt{PA1\,PA2}$$



3 dB combiner is very common for RF power combination at these frequencies since the 70's

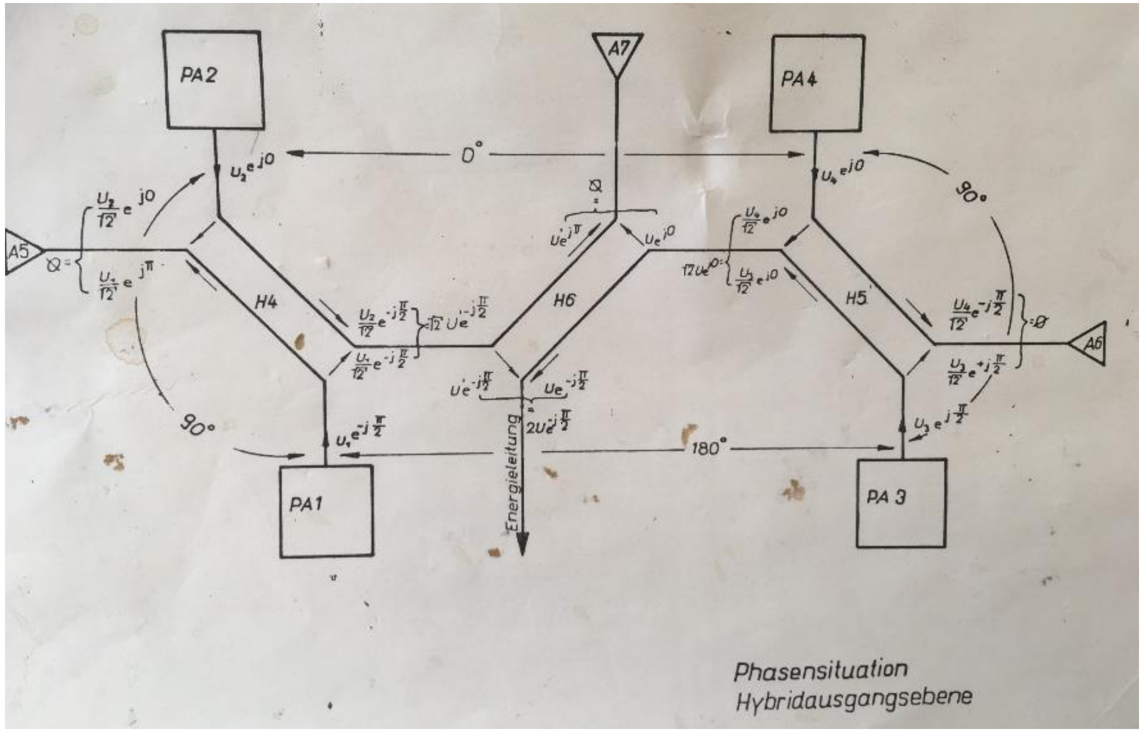
If one correctly adjusts the phases and the amplitudes, equations show that

With PA1 = PA2 = PA3 = PA4 = P then

- **Pout = 4 P**
- Load A5 = A6 = A7 = 0

In case **one** amplifier is **stopped** (PA1 for example), then

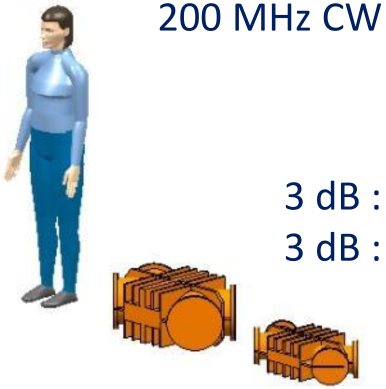
- Pout = (9/16) 4P = **2,25 P**
- Load A5 = 0,5 P
- Load A7 = 0,25 P



Combination

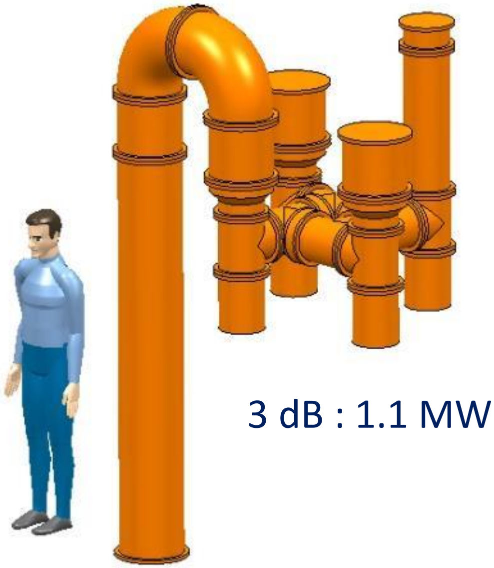
CERN SPS 16:1 combiner @ 200 MHz

200 MHz CW combiners



3 dB : 550 kW

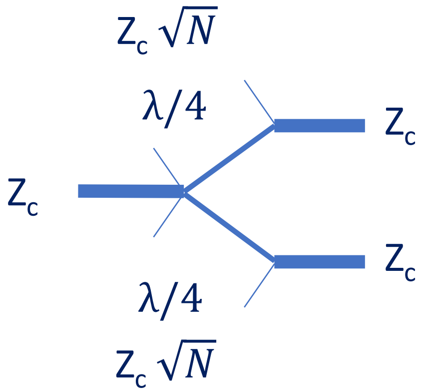
3 dB : 160 kW



3 dB : 1.1 MWp

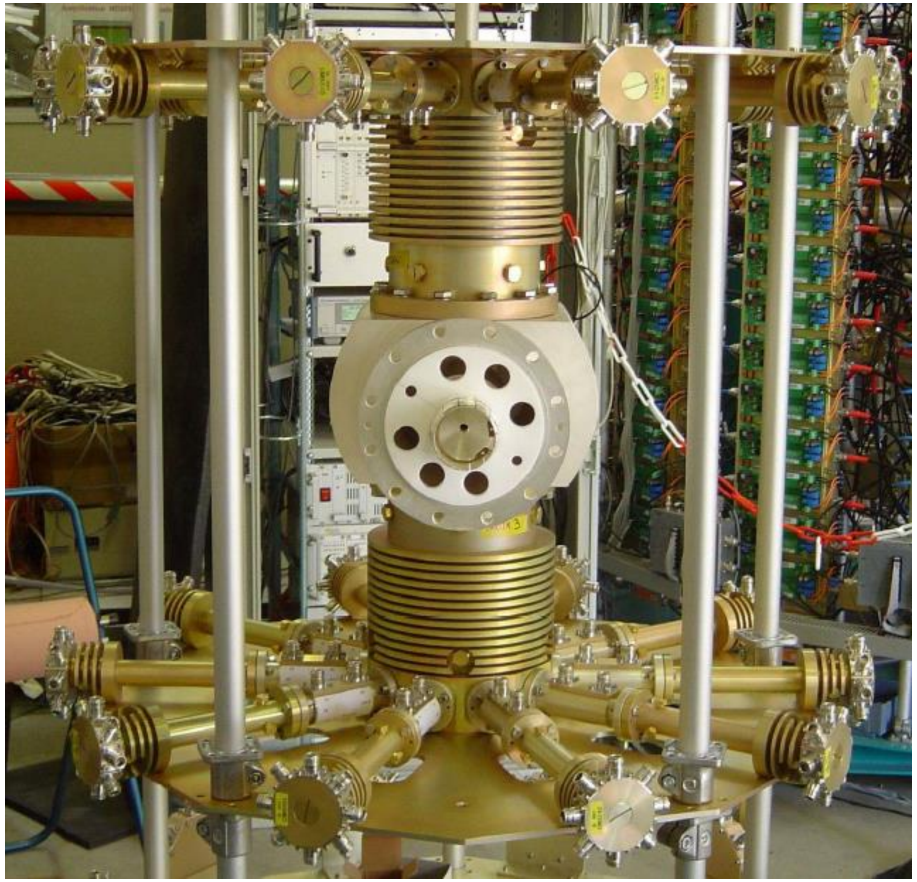
Combiners & Splitters

Low loss T-Junction



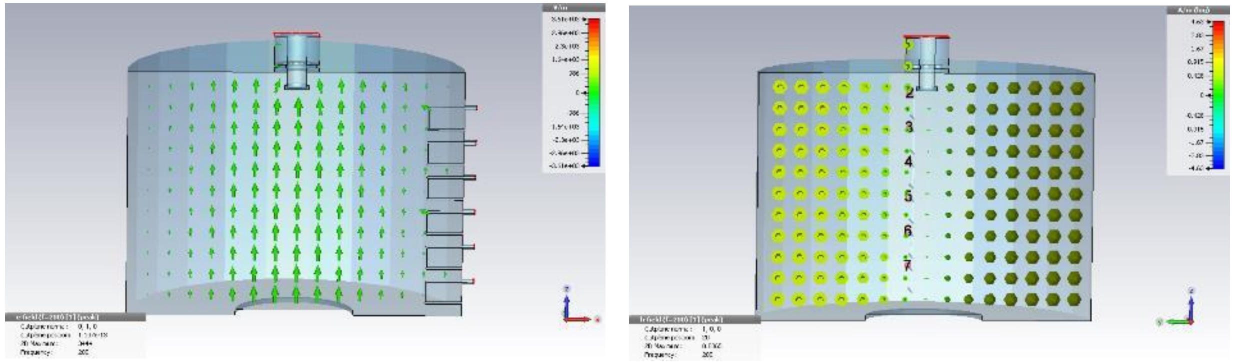
With $Z_{\lambda/4} = Zc\sqrt{N}$

We have a N-ways splitter



160 to 1 @ 352 MHz
T-junction combiner

Cavity combiner



- CRISP (Sept 2010)
  - Jörn Jacob (ESRF) asked for support to the development of cavity combiners
  - CERN immediately supported it
  - please refer to two excellent papers from ESRF at IPAC
    - MOPC005-IPAC11, 352.2 MHZ – 150 kW Solid State Amplifiers at the ESRF
    - WEPFI004-IPAC13, Commissioning of first 352.2 MHz - 150 kW Solid state amplifiers at the ESRF and status of R&D
- The radius of a cylindrical resonator is set so that the E010 mode frequency is 200 MHz
- A fine tuning is provided by a piston located at the bottom of the resonator
- The electrical field is vertical and maximum at the resonator symmetry axis
- The magnetic field is circular and maximum close to the resonator wall
- These field patterns are perfectly suited for coupling many inputs loops protruding through the cavity wall and coupling out the power with a capacitive plate
- All input signals must have the same amplitude and phase

VHPCC (Very High Power Cavity Combiner)

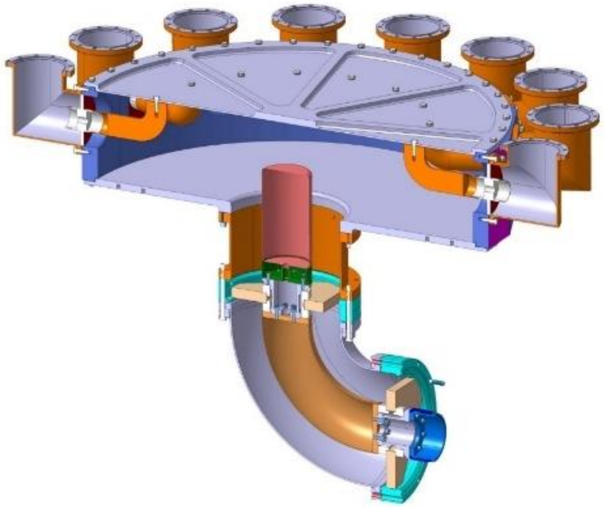
We also designed a VHPCC (Very High Power Cavity Combiner)

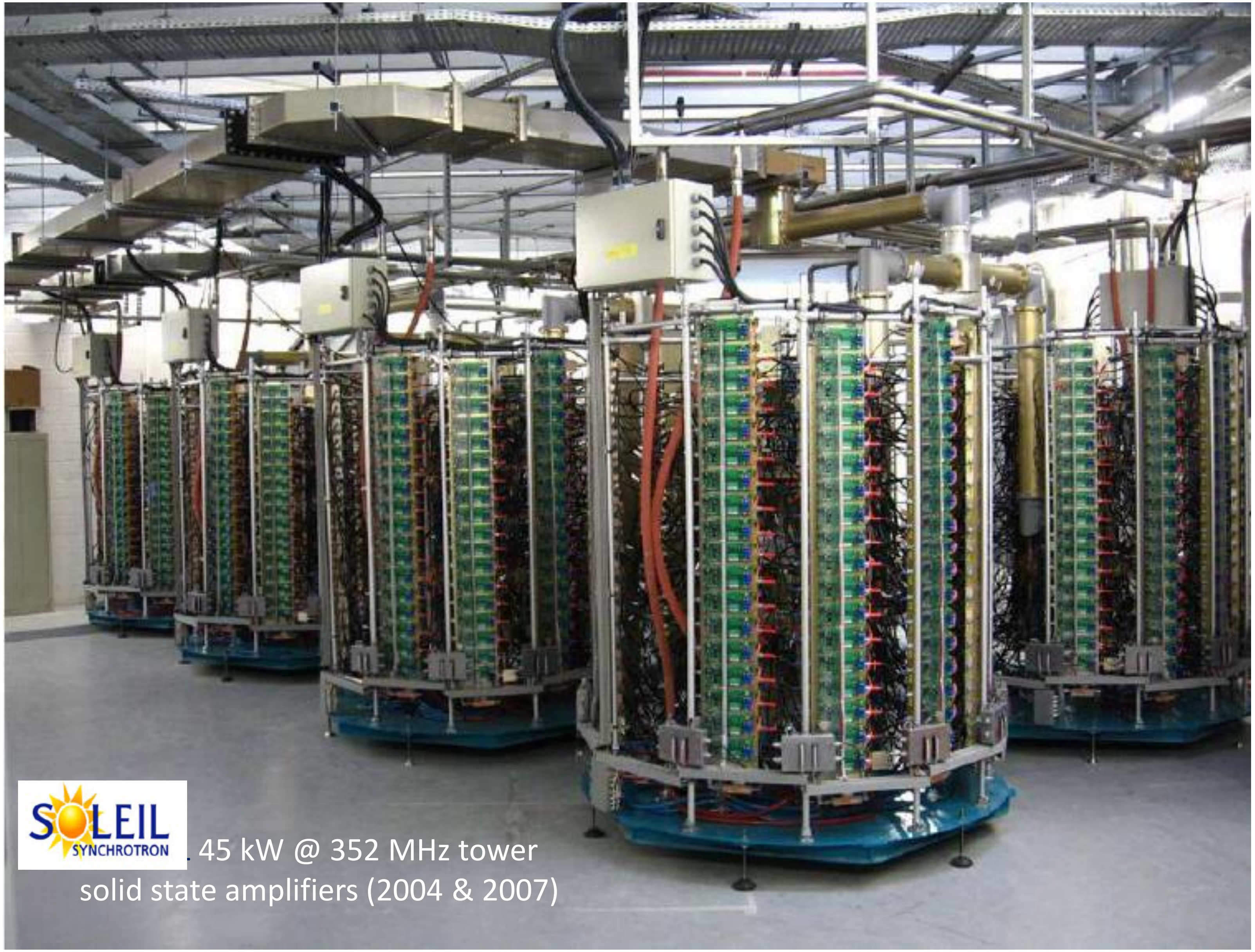
The goal was to have 16:1 combiner with inputs in the hundred of kW range and an output in the MW range

The ‘cavity’ has been machined from a single piece of metal

We tested it in reverse mode, as we had no hundred kW class amplifiers to test it in forward mode, and we checked that we had a perfect distribution between the test loads

With 1.26 MWp input, we obtained
78 kW +/- 1 kW and the losses were less than 10 kW





SOLEIL SYNCHROTRON

45 kW @ 352 MHz tower solid state amplifiers (2004 & 2007)

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

CERN 2 x 16 x 160 kWp @ 200 MHz tower
solid state amplifiers (2021)

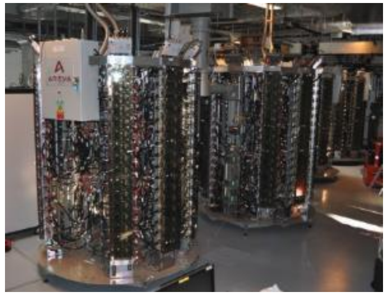
Power density

$$Power\ density\,(f) = Power\ density_{200\ MHz}\sqrt{200/f}$$

Approximation, given the fact that transistors deliver less with respect to frequency, and taking into account a smaller combining system size

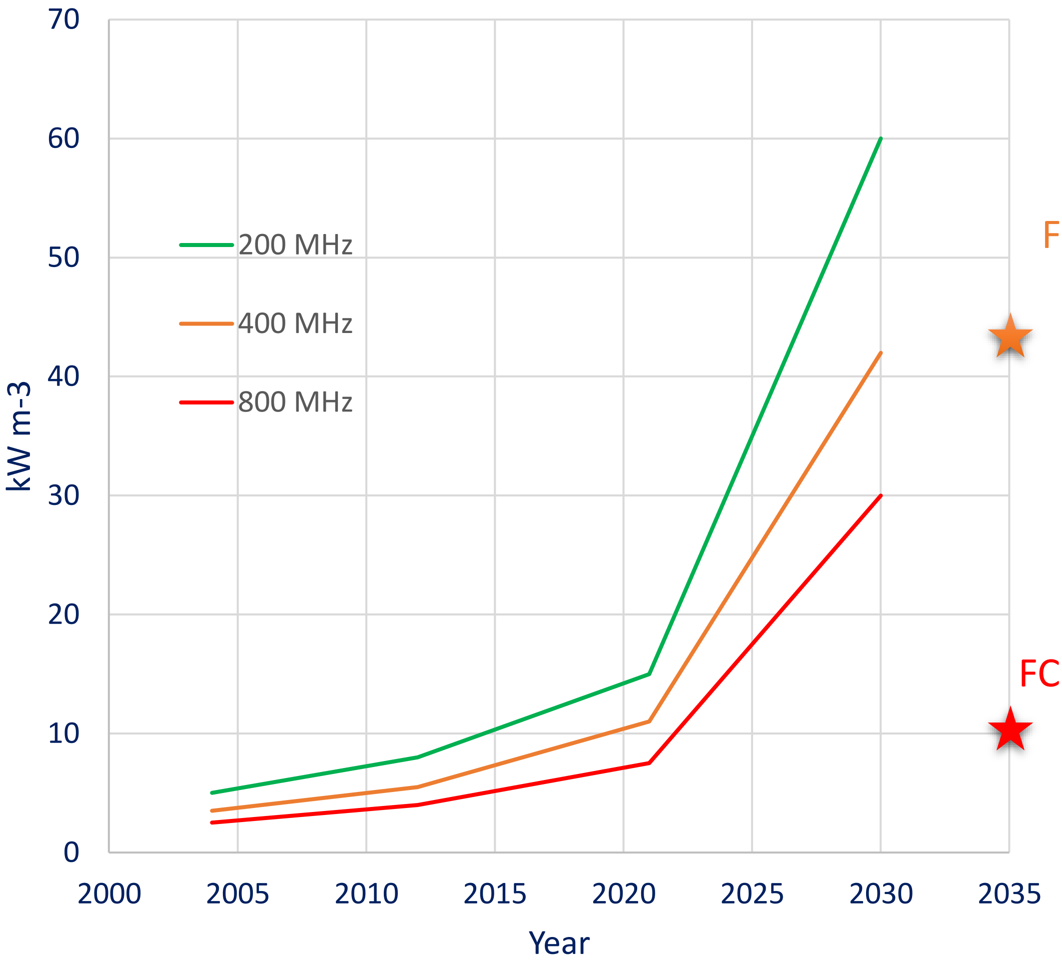
including power supplies and combining systems AND granularity providing **100 % availability !**

SOLEIL 45 kW @ 352 MHz
2004
Power density
3.5 kW m^{-3}



ESRF 150 kW @ 352 MHz
2012
Power density
6.5 kW m^{-3}

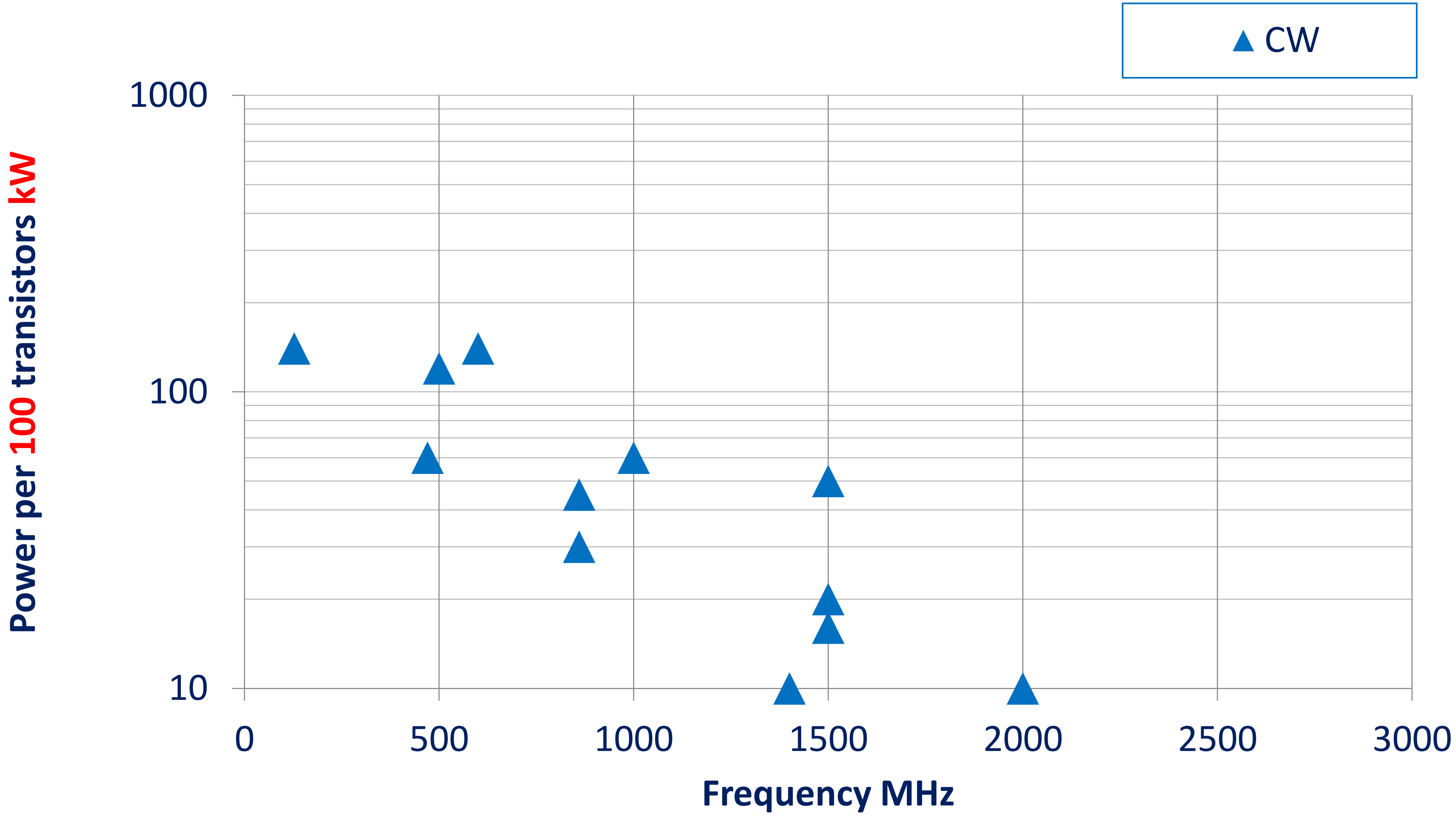
CERN 160 kW @ 200 MHz
2021
Power density
15 kW m^{-3}



FCC 1 MW @ 400 MHz
Power density
43 kW m^{-3}

FCC 200 kW @ 800 MHz
Power density
10 kW m^{-3}

Transistors available from industry



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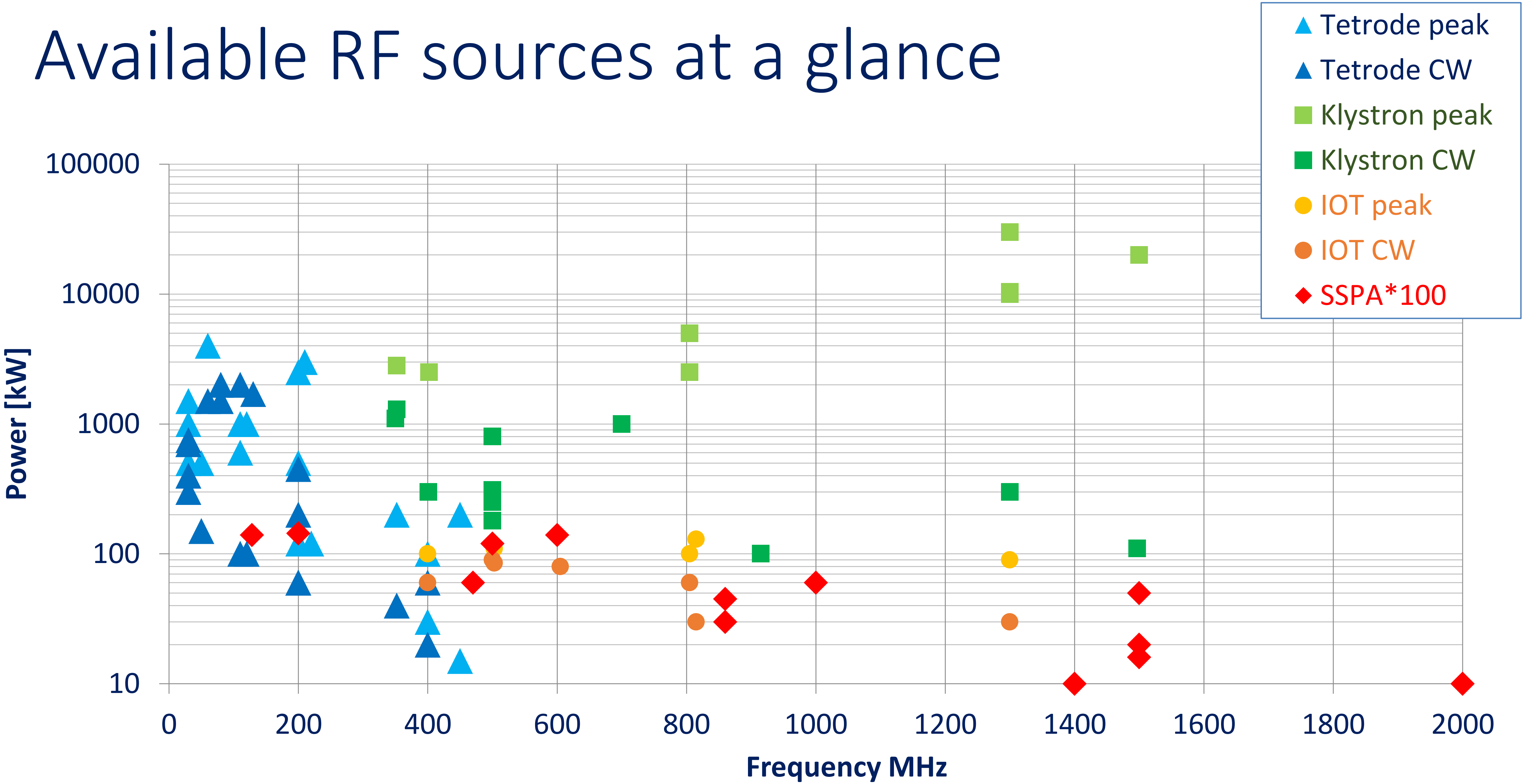
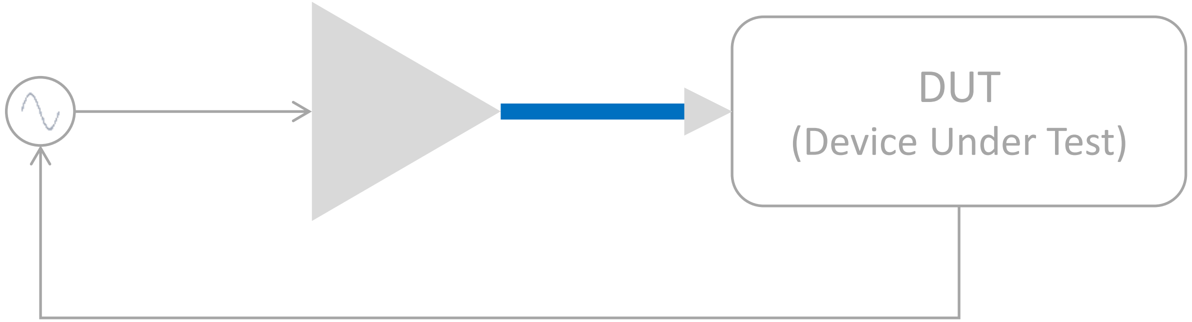
Available RF sources at a glance



RF Power Transport (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

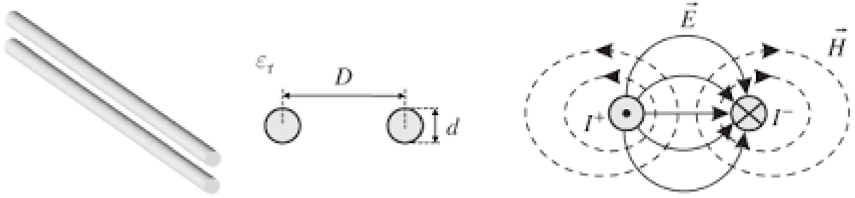
low loss, high reliability,…

Transmission line families

Two-wire lines

often used for indoor antenna, radio or TV

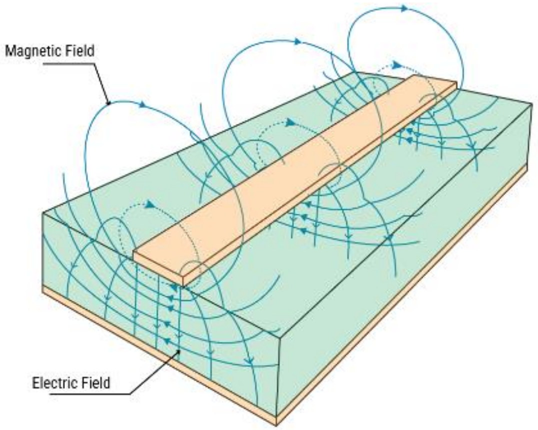
Radiation to the environment, cannot be used for high power Transportation



Strip-lines

often used for microwave integrated circuits

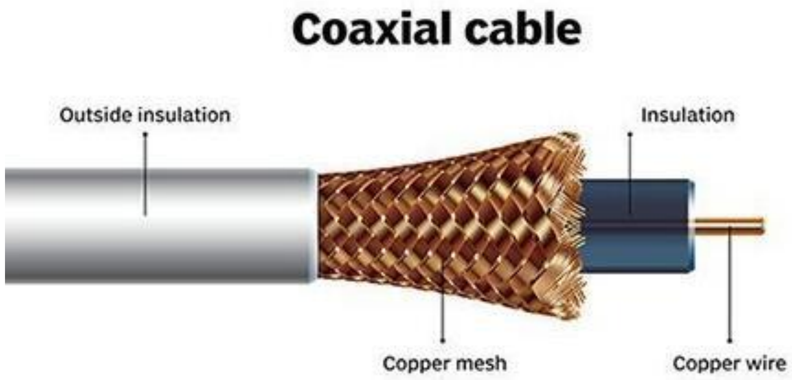
Radiation to the environment and limited power capability, cannot be used for high power transportation

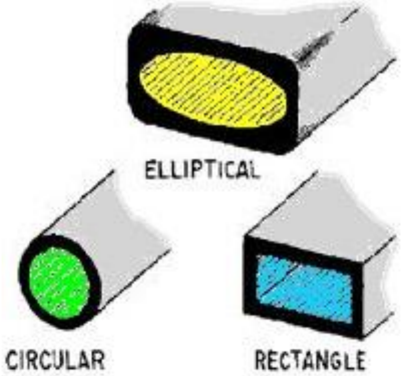


Transmission line families

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%

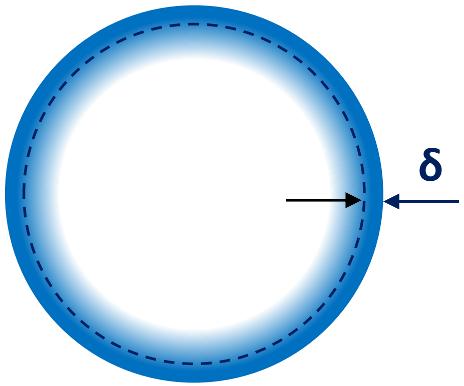
at two skin depths, 13.5%

at three skin depths, 5.0%

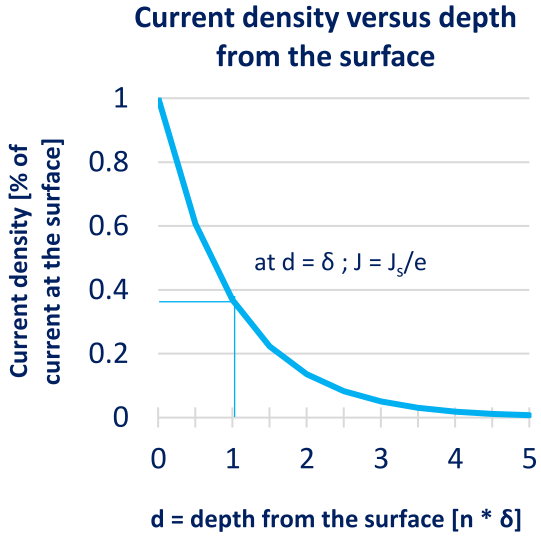
at four, 1.8%

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



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

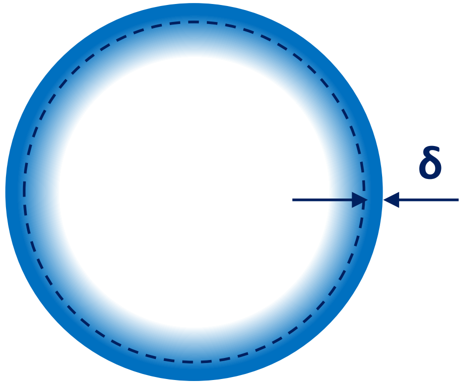
$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}$$

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

$\mu = \mu_r * \mu_0$

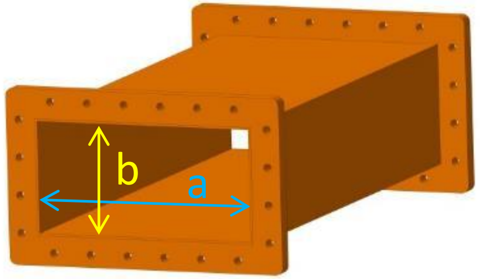
μ_r = relative magnetic permeability of the conductor

μ_0 = permeability of free space

material	ρ [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

Rectangular waveguides

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

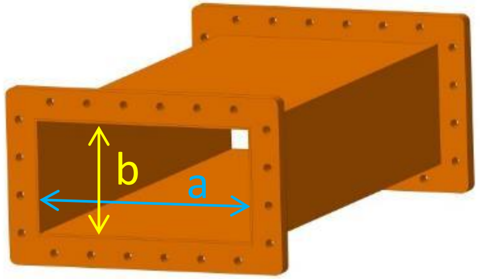


Wavelength	$\lambda_g = \frac{\lambda}{\sqrt{1-(\frac{\lambda}{2a})^2}}$
Cutoff frequency dominant mode	$f_c = \frac{c}{2a}$
Cutoff frequency next higher mode	$f_{c2} = \frac{c}{4a}$
Usable frequency range	**1.3 f_c to 0.9 f_{c2}**

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

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

With

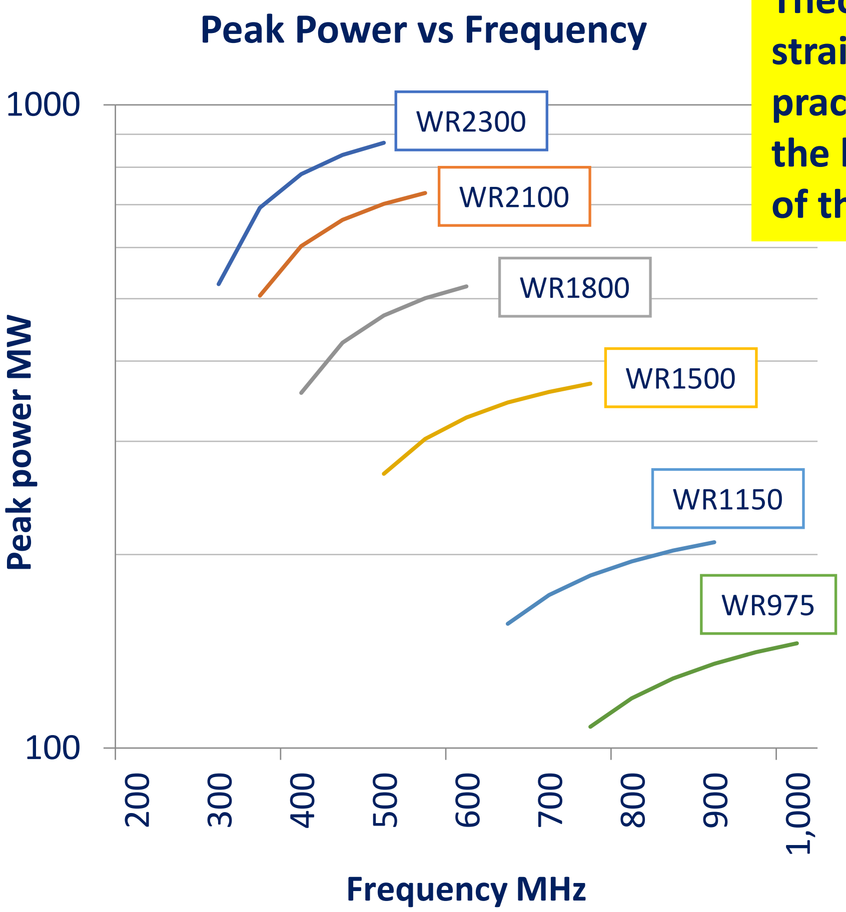
P_{peak} = Power in watts

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

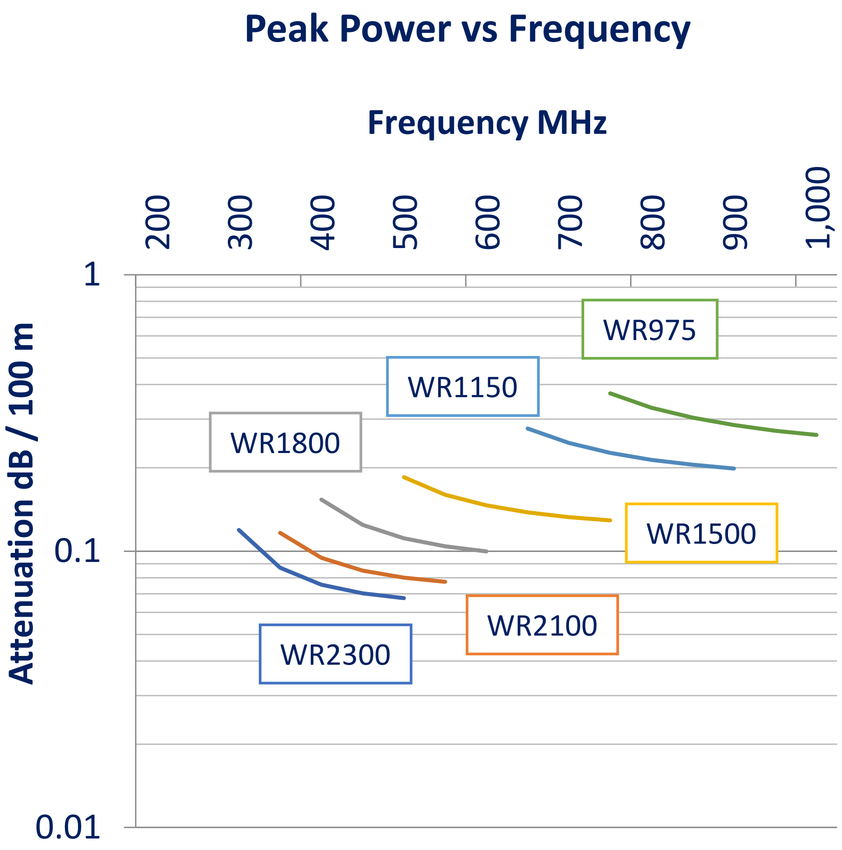
a0 = 3 10-7 [dB/m] for copper

a = width of waveguide in m

b = height of waveguide in m

λ = free space wavelength in m

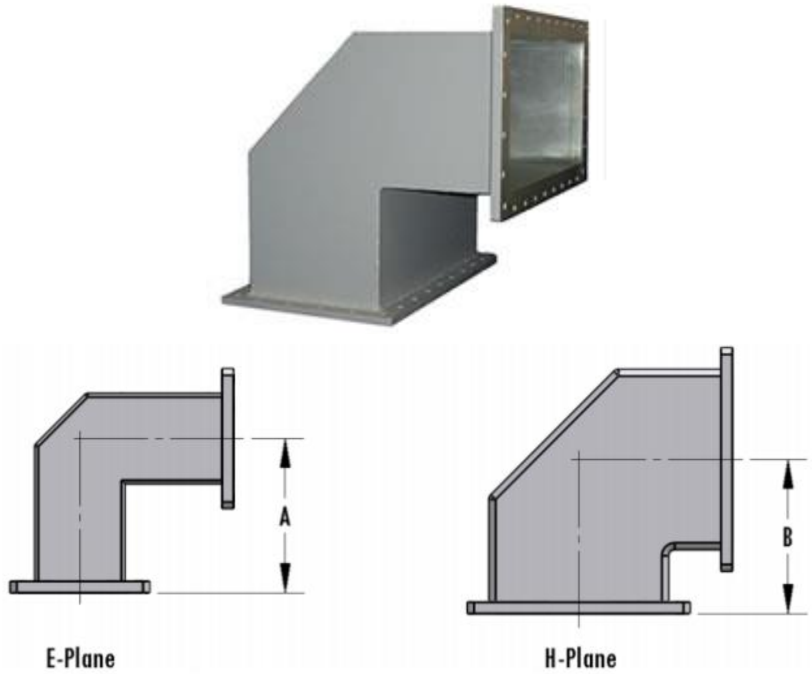
Attenuation factors of waveguides made from different material normalized to a waveguide of same size made of copper	
Copper	1.00
Silver	0.98
Aluminium	1.30
Brass	2.05



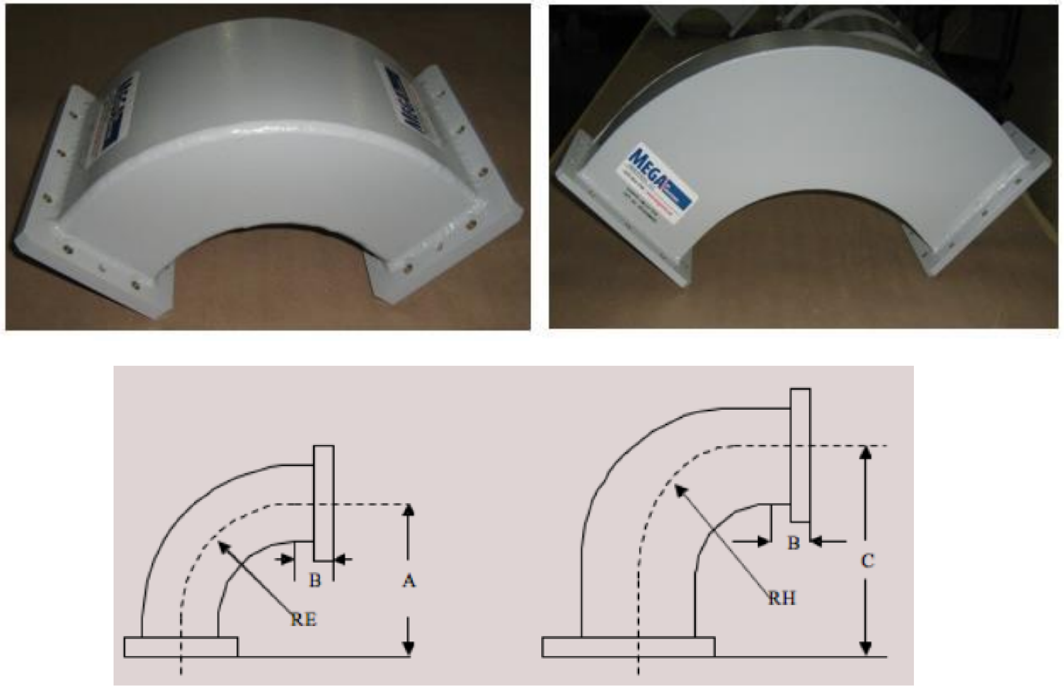
Rectangular waveguides

MEGA industries, straight waveguides

Rectangular waveguides

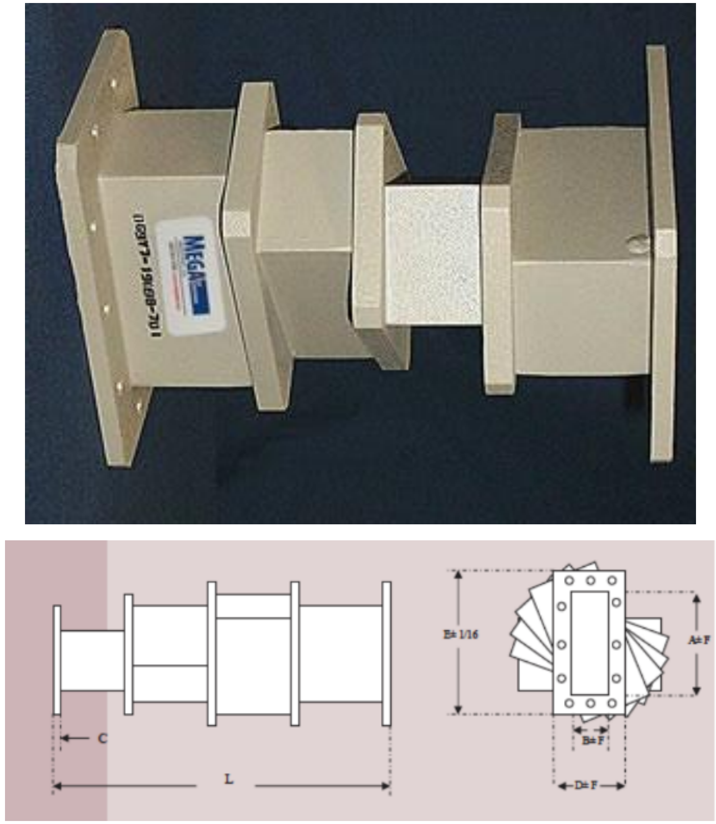


Mega Industries Miter Bends



Mega Industries Sweep Bends

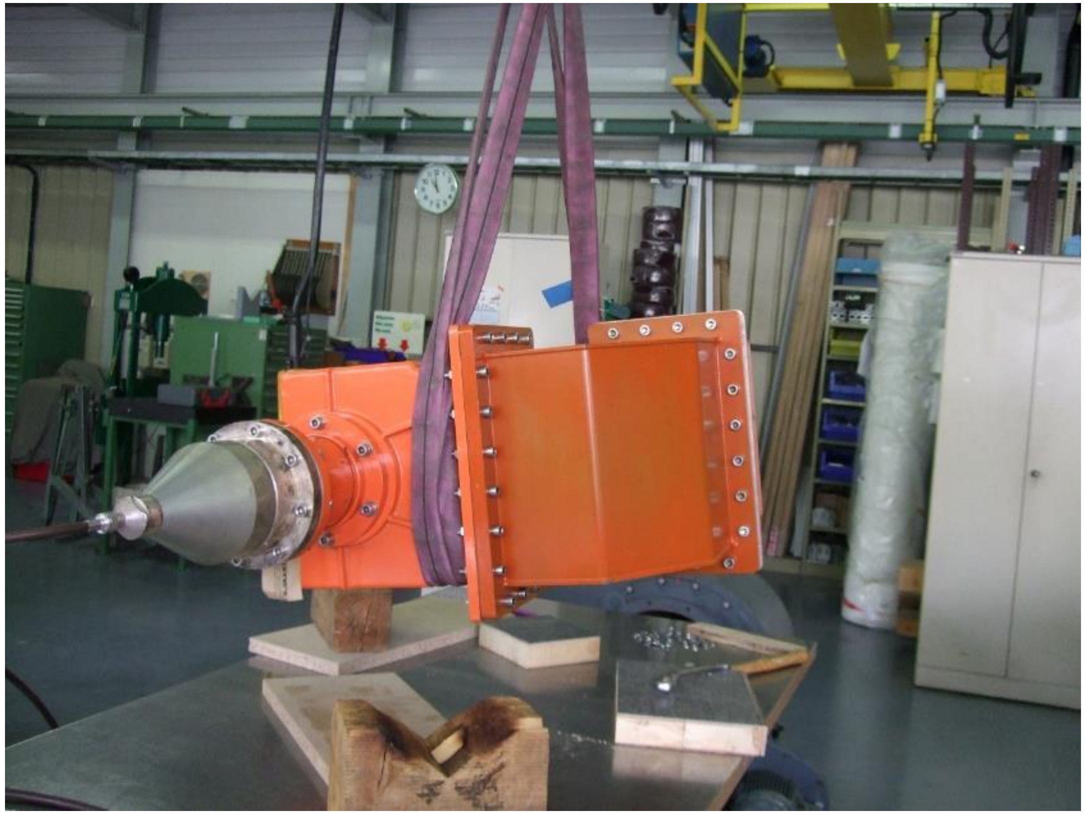
Rectangular waveguides



Mega Industries Step Twist waveguide

Mega Industries Flexible and Flexible twist waveguide

Rectangular waveguides



Adaptor from WR 1150 to N, not a light item…

Coaxial Lines

Characteristic impedance is

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

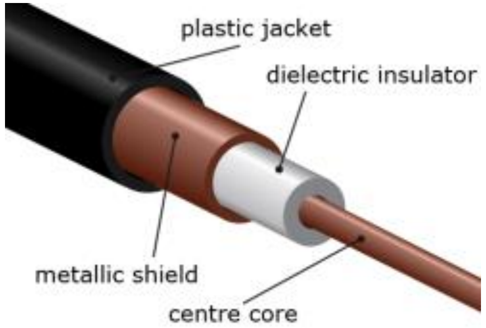
With

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



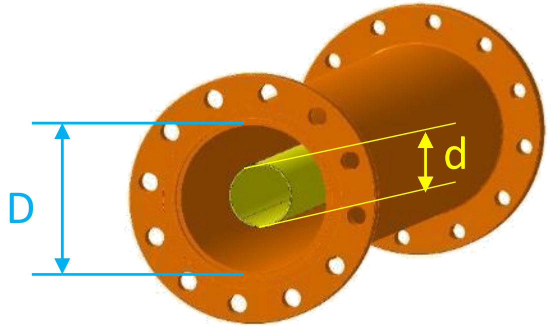
Coaxial cables are often with PTFE foam to keep concentricity

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



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

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

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

with

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

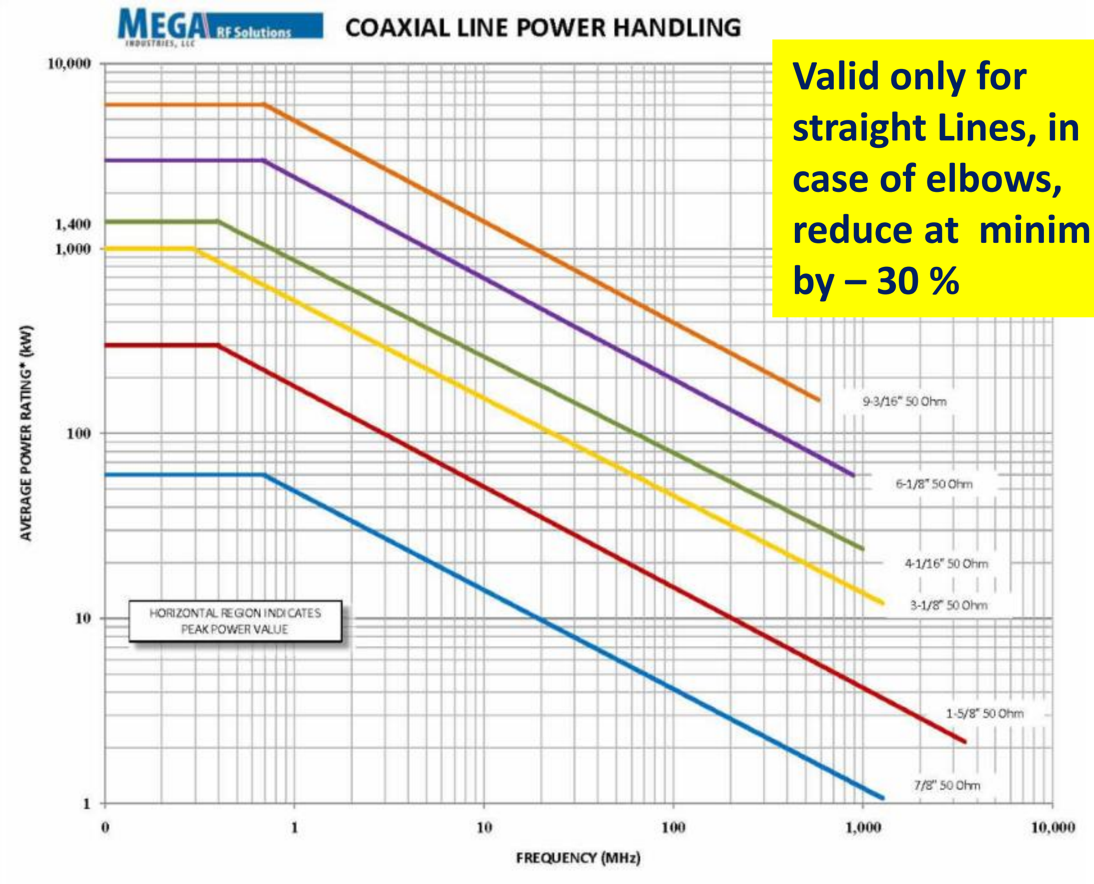
D = inside electrical diameter of outer conductor in mm

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

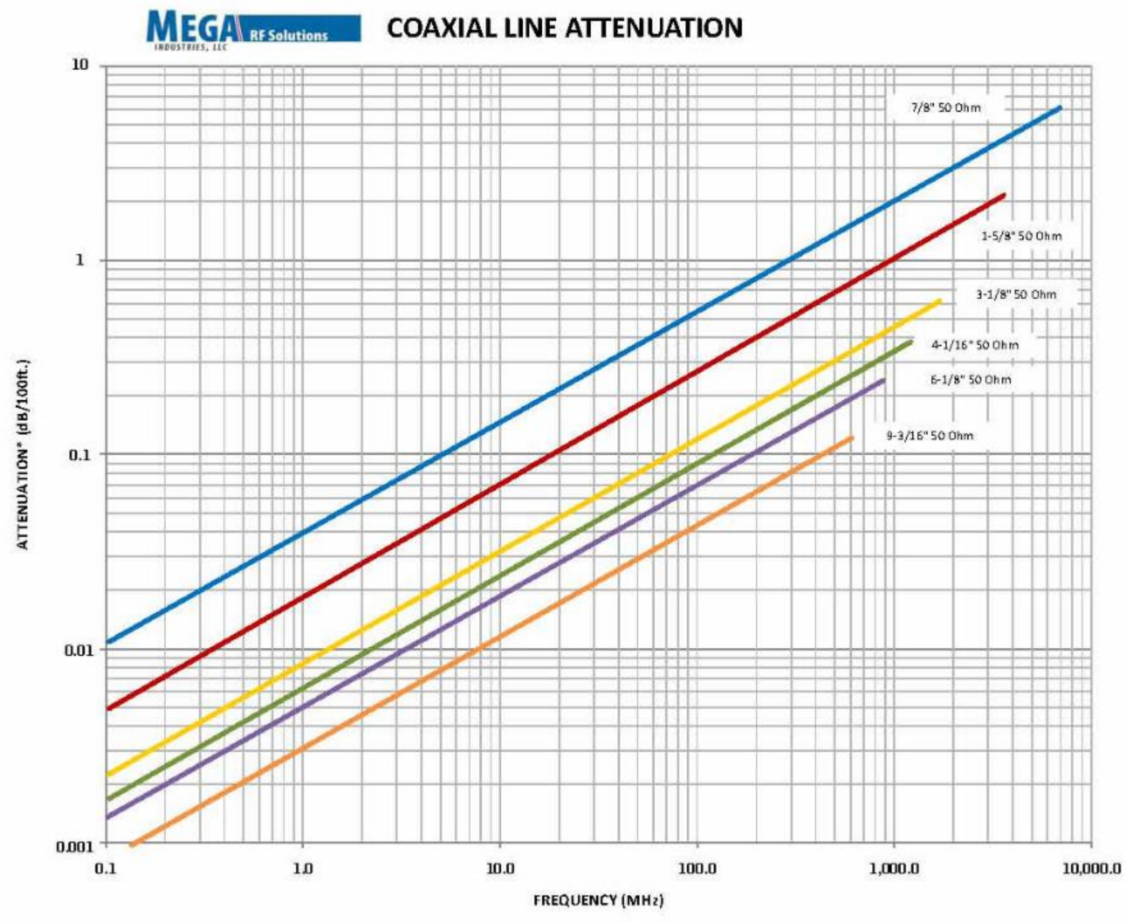
D = inside electrical diameter of outer conductor in mm

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

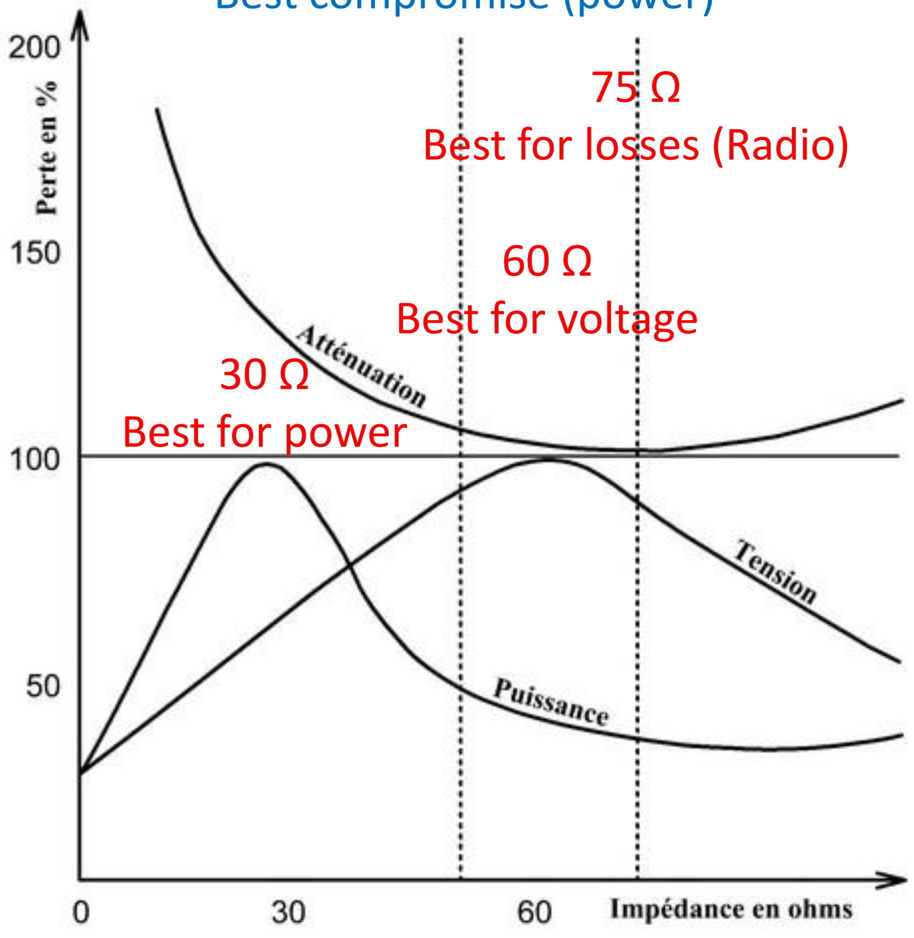
$$\mathbf{Zc} = \frac{60}{\sqrt{\varepsilon r}} \ln\left(\frac{D}{d}\right)$$

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

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

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

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

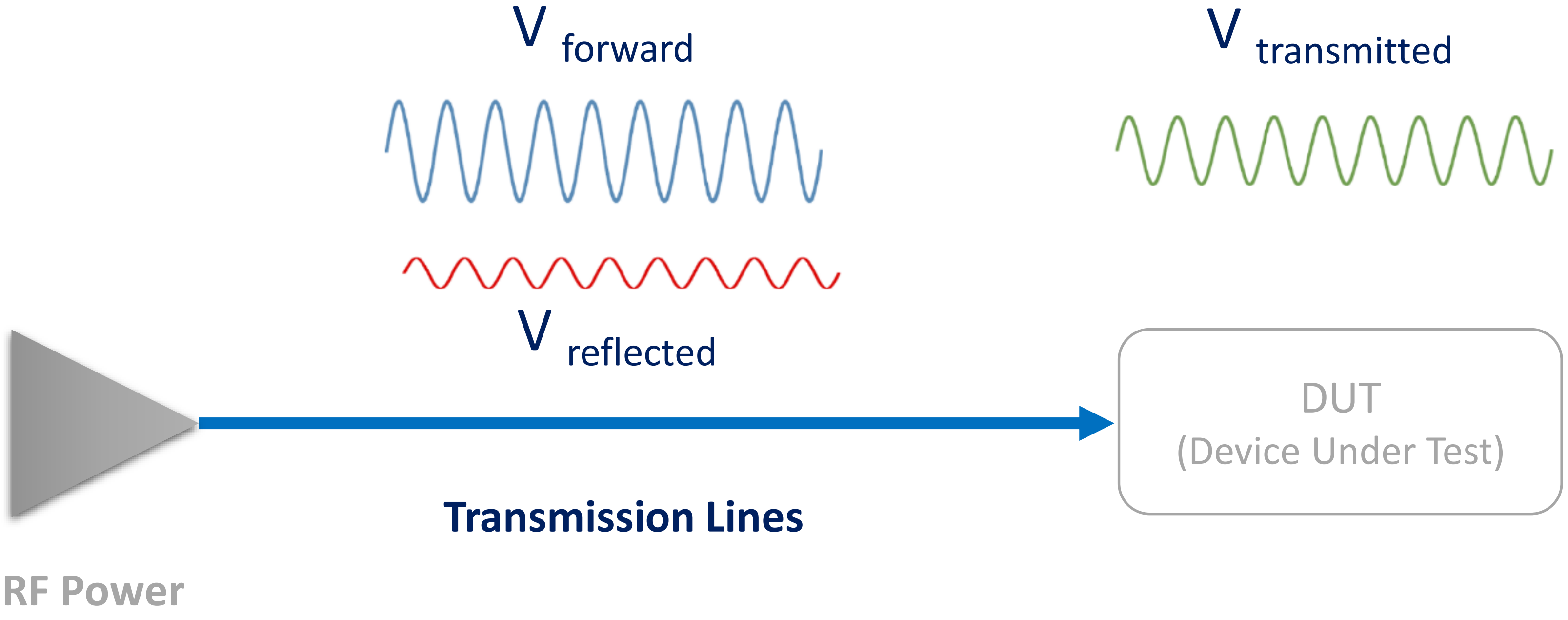
345 mm Coaxial Line
Installed suspended from the ceiling

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

Mismatch


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

Reflection from Device Under Test (DUT)

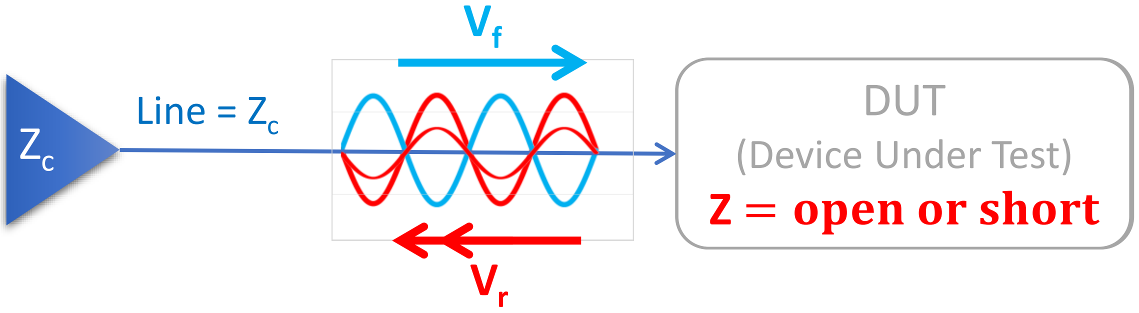
Standing Wave Ration SWR is a measure of impedance matching of DUT

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

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

Γ = -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

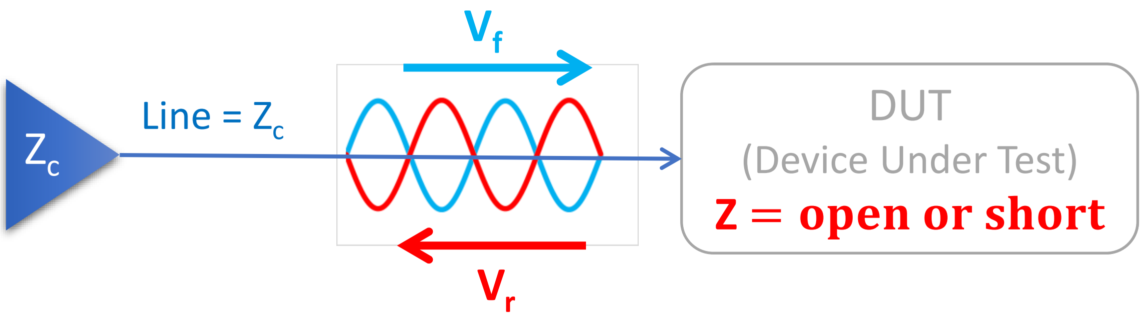
$$|\mathbf{V}_{min}| \quad = |\mathbf{V}_f| - |\mathbf{V}_r| = |\mathbf{V}_f| - |\Gamma \mathbf{V}_f| = (\mathbf{1} - |\Gamma|)\, |\mathbf{V}_f|$$

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

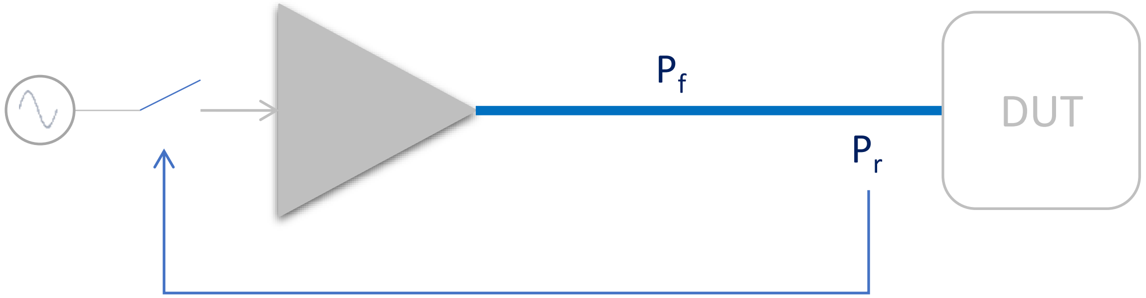
(Pmax equivalent to 4 Pf)

RF power amplifiers will not like this reflected wave

- Klystron output cavity disturbed
- Grid tube, IOT and Transistor voltage capability

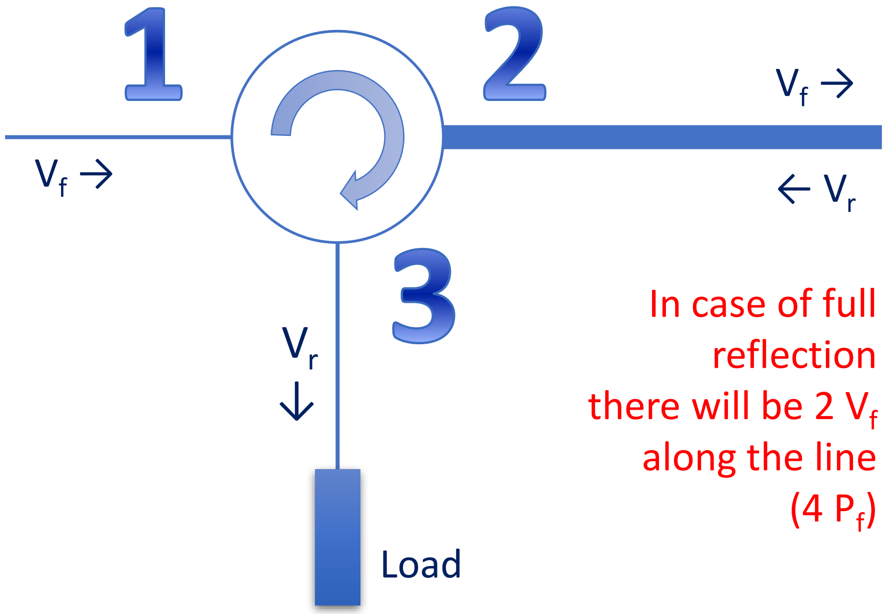
Swift protection if Pr > Prmax

- system NOT operational (not always possible)



Swift protection if P_r > Prmax

Circulator



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

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

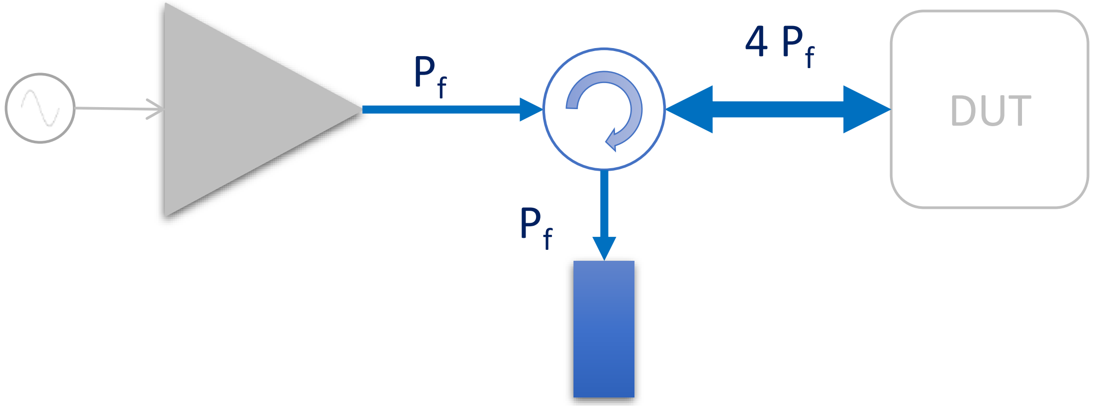
The signal entering any port is transmitted only to the next port in rotation, an RF signal experiences a low loss in the direction of the arrow and high loss in reverse direction while propagating through the Circulator

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

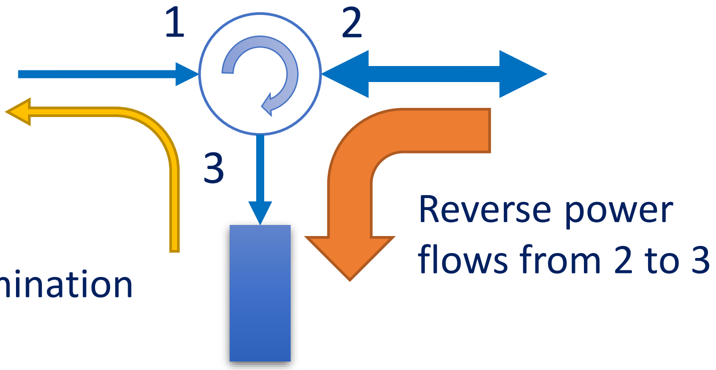
If full reflection lines between circulator and DUT shall sustain $\mathbf{V_{max} = 2\ V_f}$ (P_{max} equivalent to $4\ P_f$)

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

System remains operational at all time



Circulator

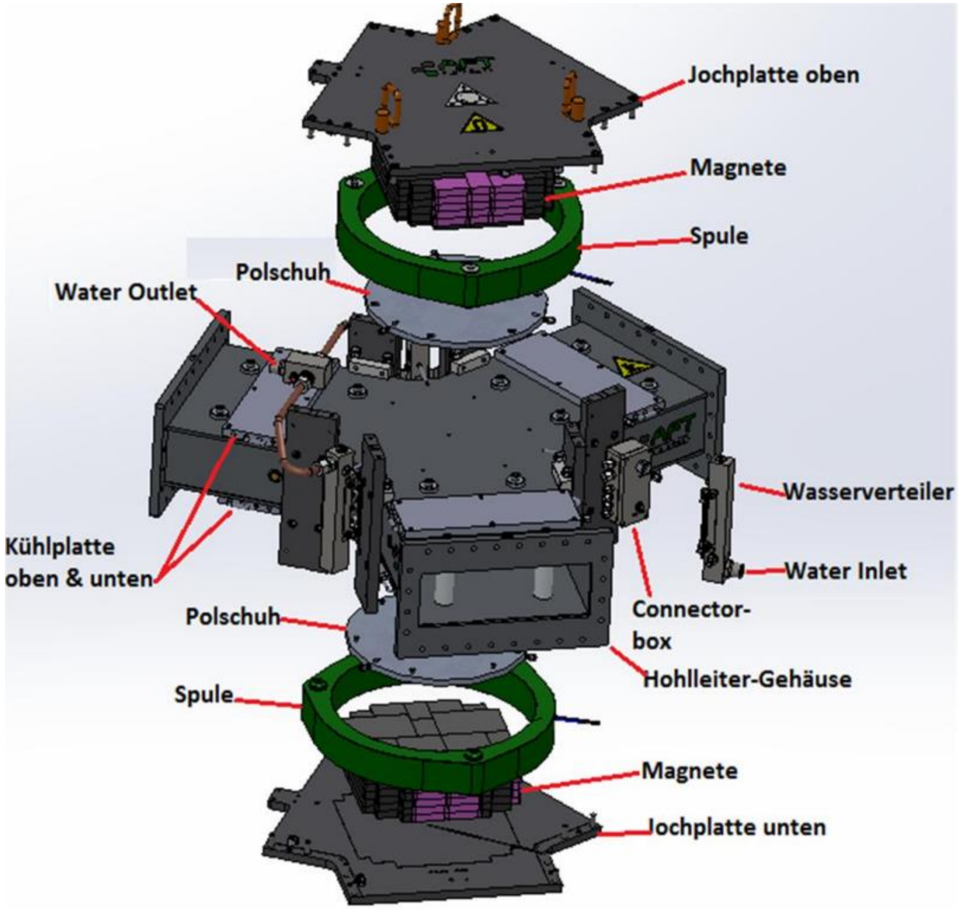


Reflected signal from 3 is circulated back to 1

Isolation from 2-1 depends on 3 termination VSWR

Reverse power flows from 2 to 3

Load on 3 absorb most of the signal coming from 2



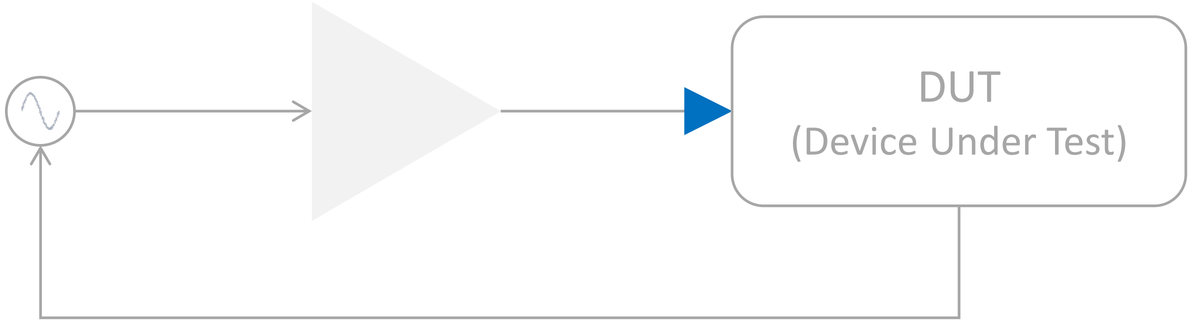
The most misunderstood concept of circulators is that of isolation

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

Fundamental Power Coupler (FPC)



The Power Coupler is to transfer the RF power of the generator into the cavity ensuring the beam vacuum integrity

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

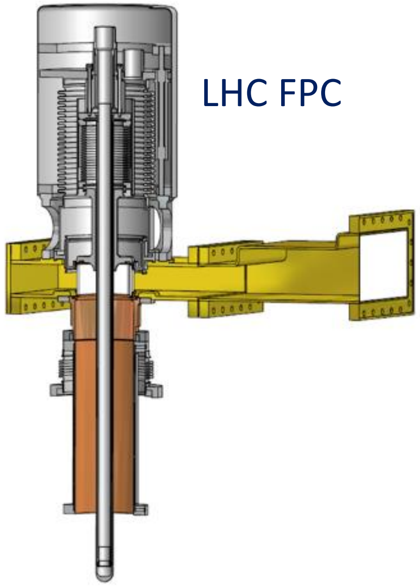
The FPC a ***specific piece of transmission line*** that provides the vacuum barrier for the beam vacuum, with one side at high pressure and the other side under beam vacuum pressure, that also enables RF power to feed the cavity

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

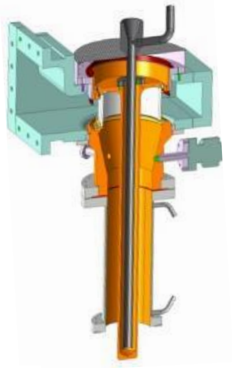
Even if not technical, the cost must be taken into consideration as FPC can easily become very expensive

Construction time is between 1.5 to 2 years, any mistake at a late stage is a lot of lost work

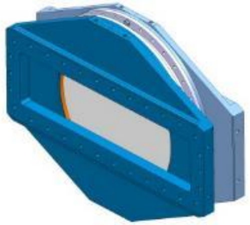


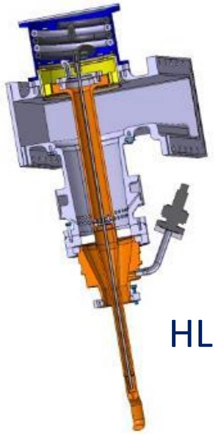
LHC FPC

SPL FPC



L4 FPC window



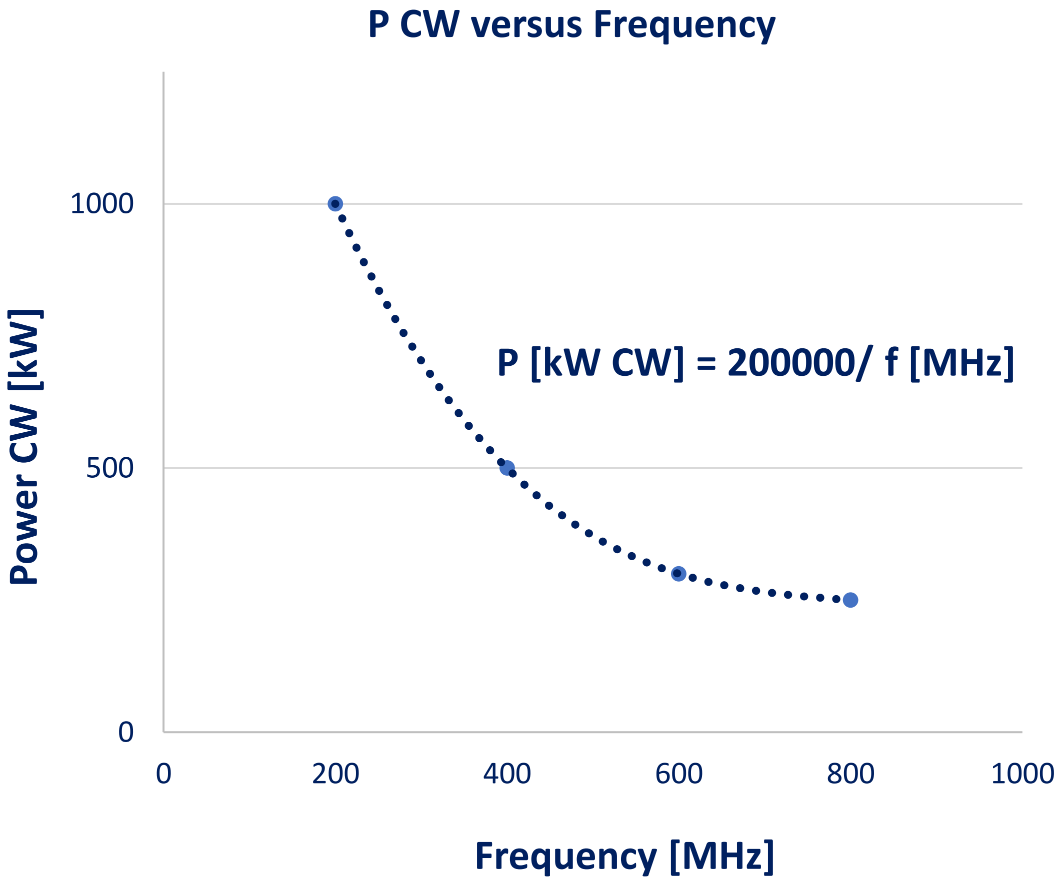


HL-LHC FPC

Various CERN FPCs

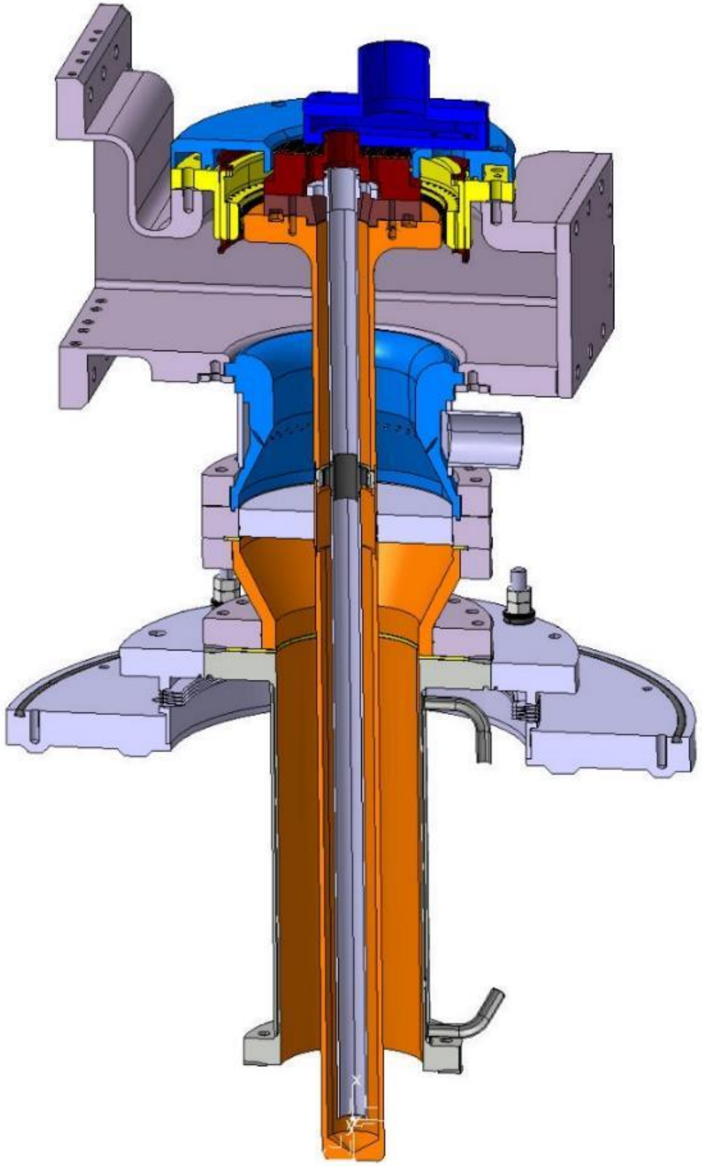
Overview of the CERN power couplers since the 2000's

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*

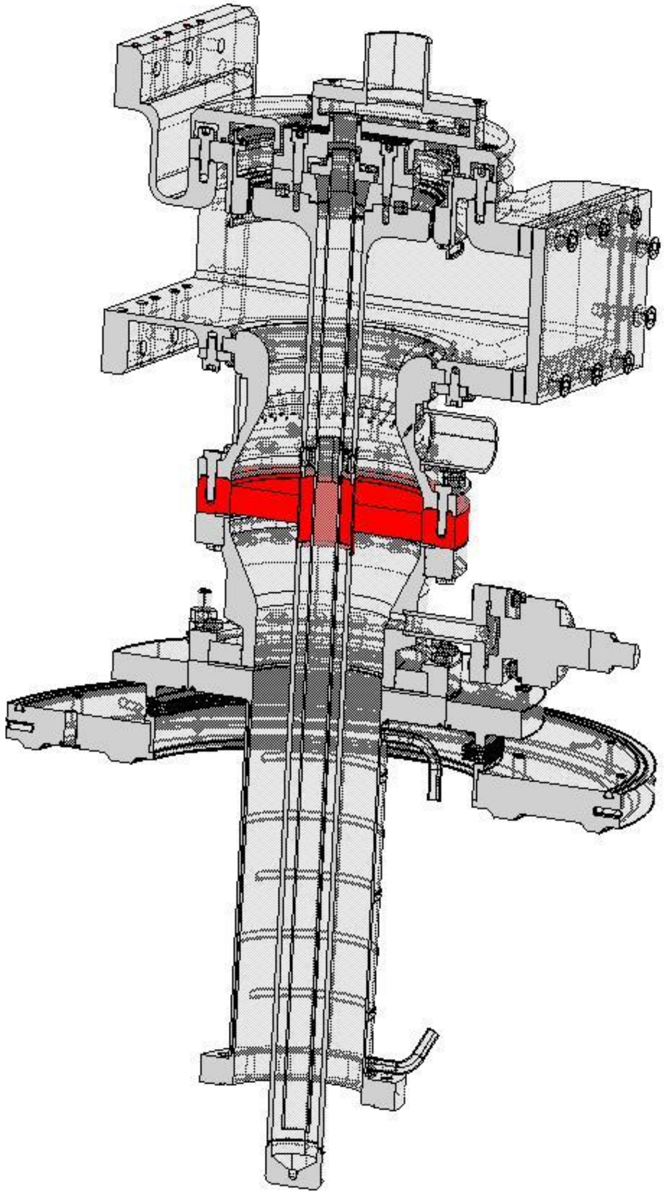


Example of a design

- 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 made 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

Cylindrical window

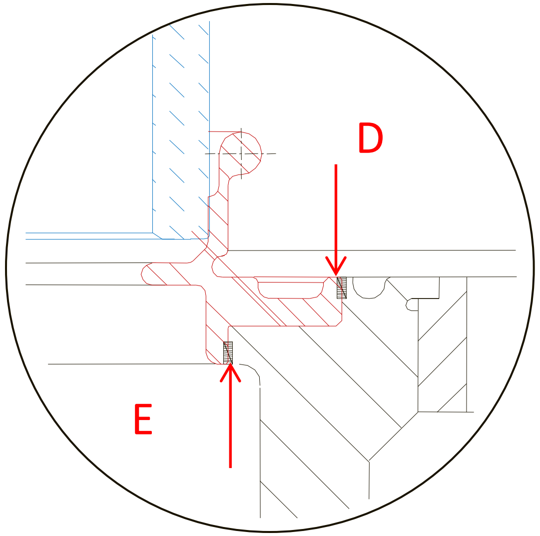
Solid copper rings directly brazed to the ceramic to lower the RF losses and increase the thermal capability

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

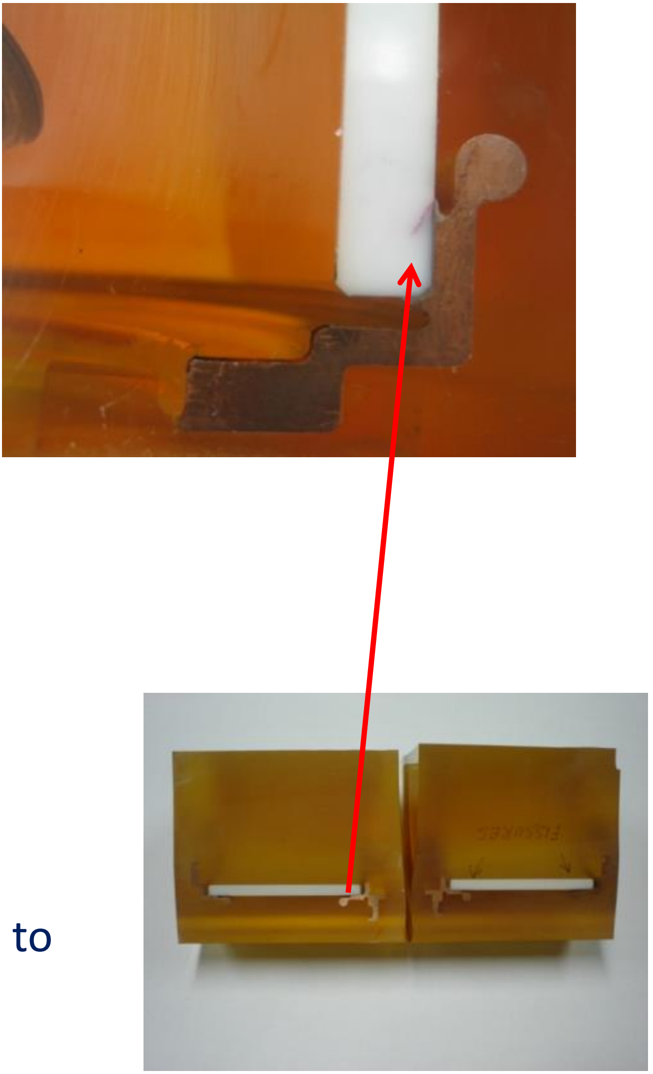
we had to fight against semi-cracks developing with time

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

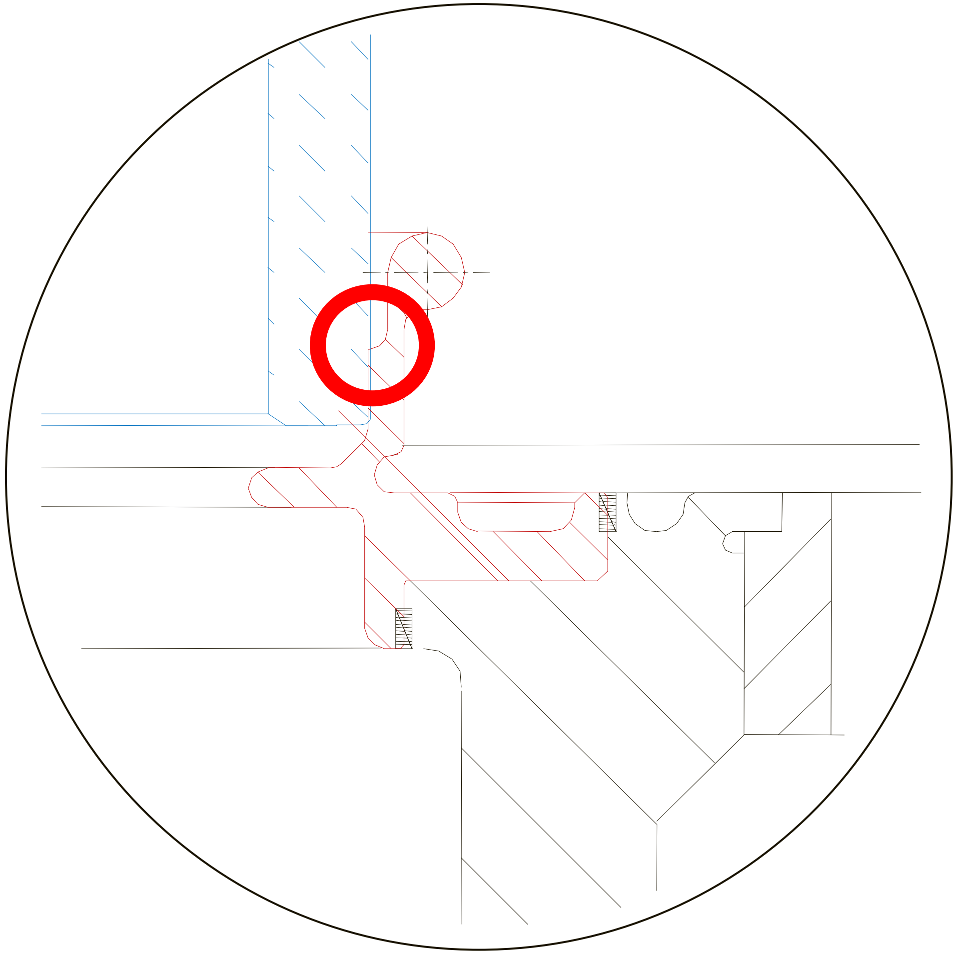


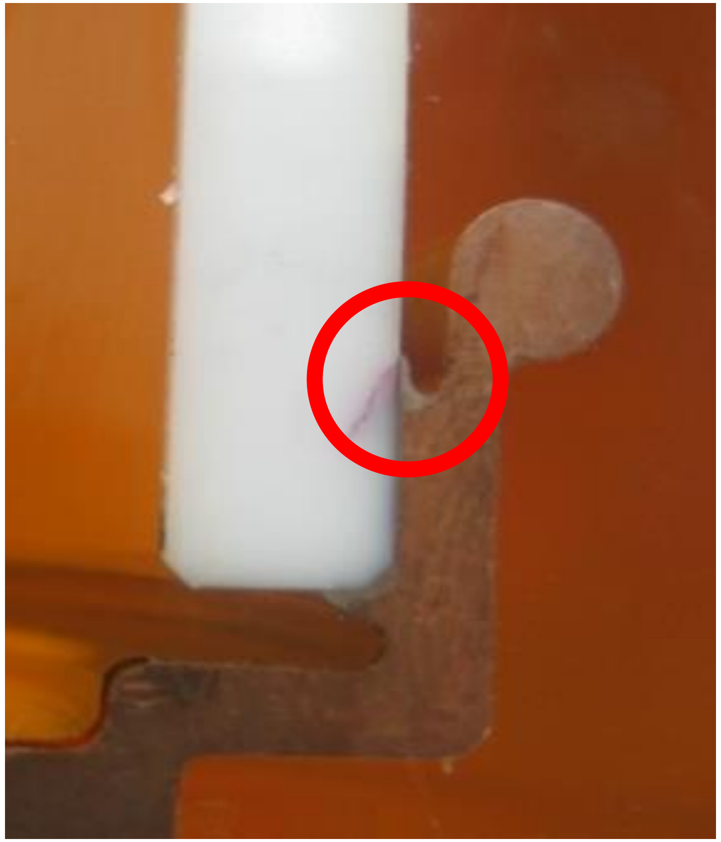
LHC process

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



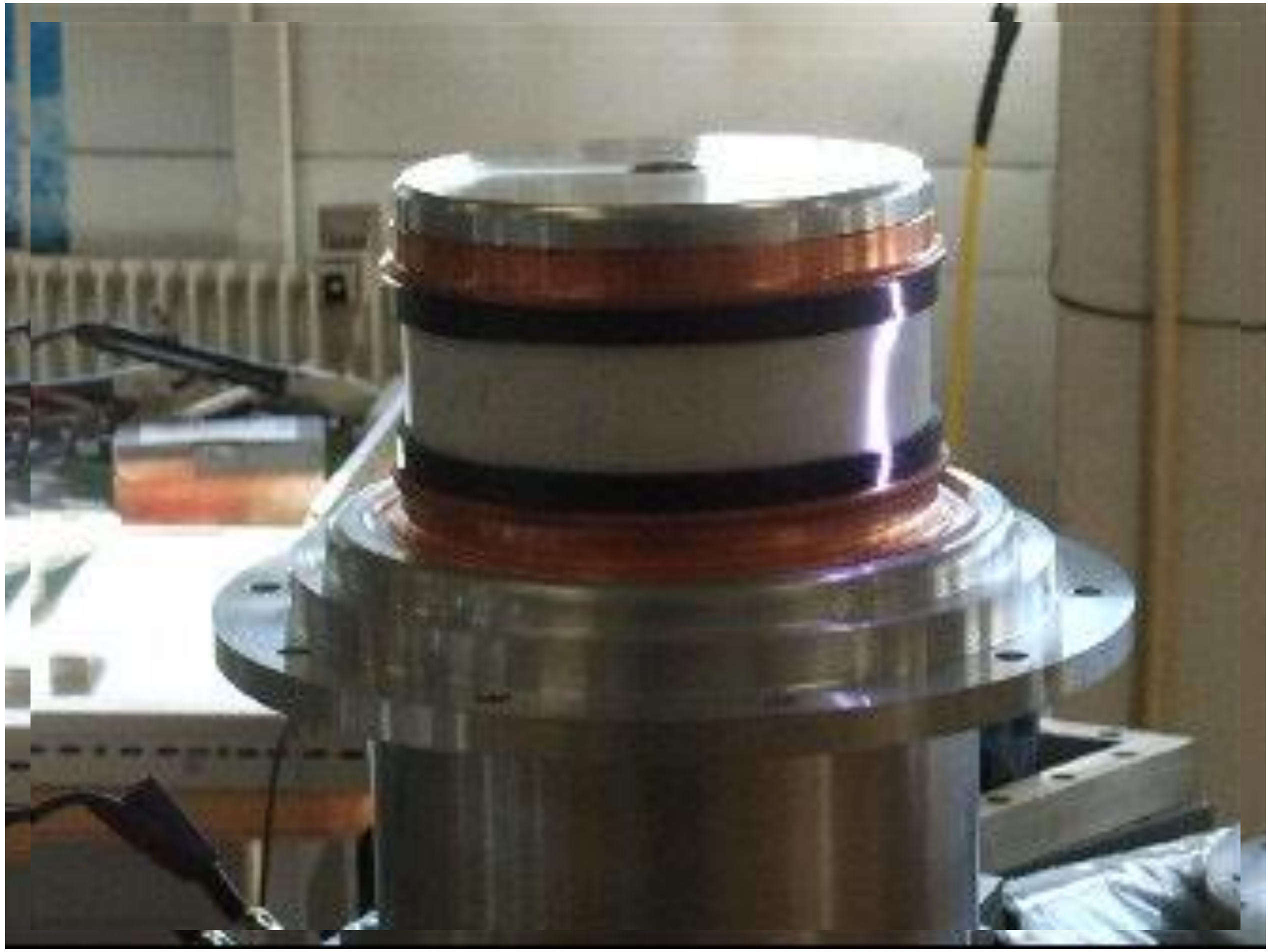
Cylindrical window



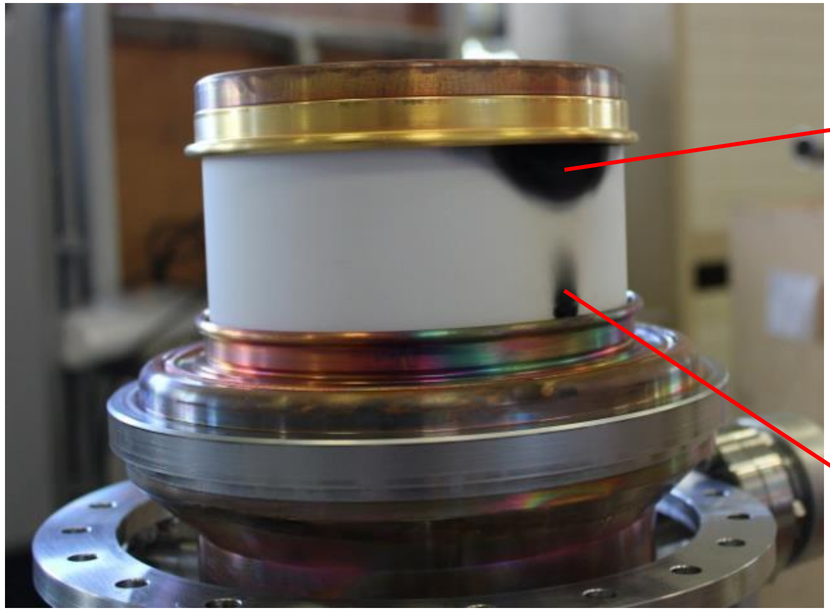


With drawings and simulations, everything is always perfect
In true life, there are details that are different…

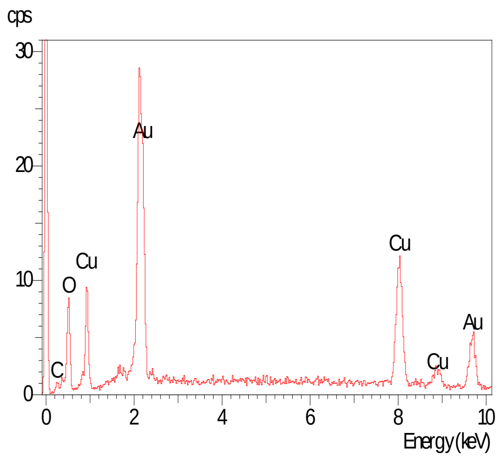
Arcing along ceramic on the air side

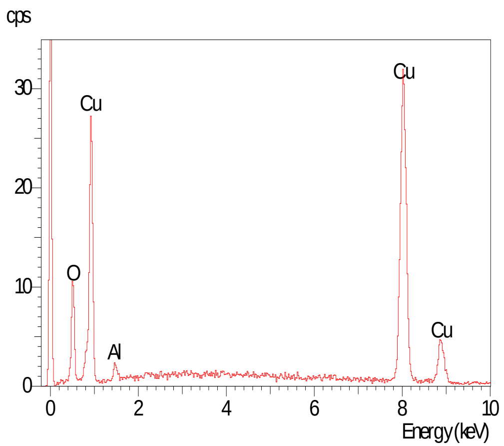


Arcing along ceramic on the air side



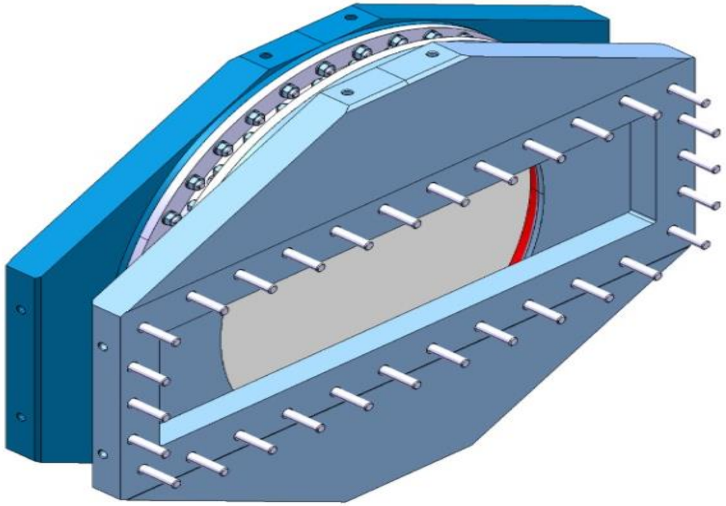
Black deposit
Gold & Copper from upper collar
Copper from lower collar

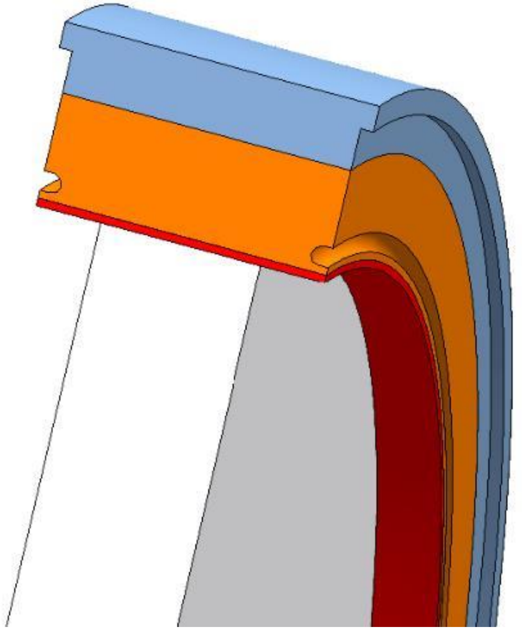




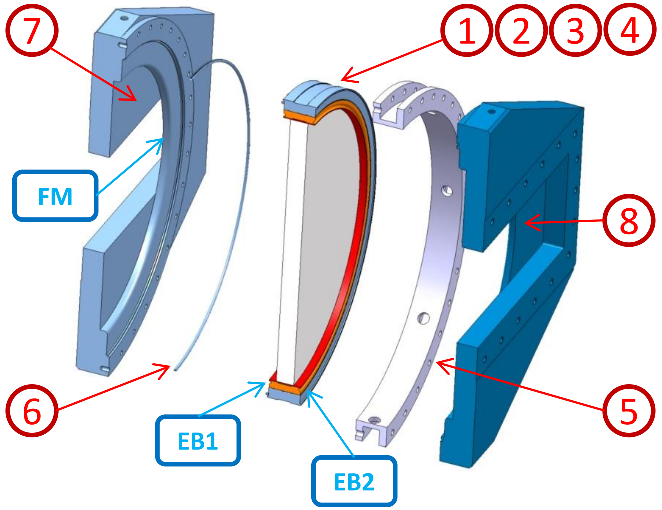
FPC ceramic crack

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



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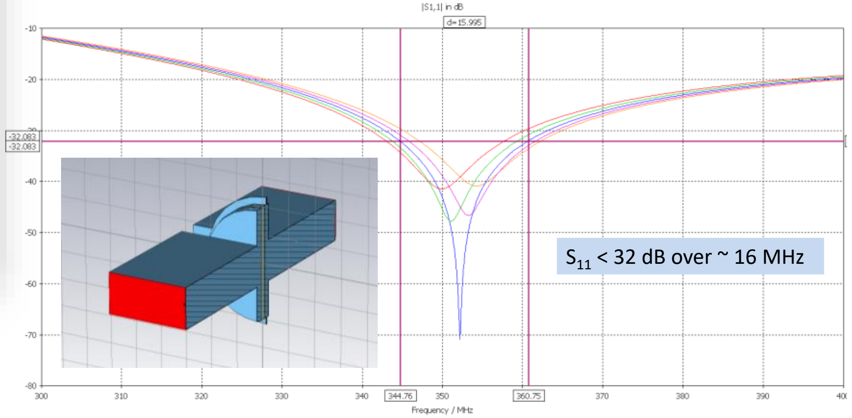


S_{11} < 32 dB over ~ 16 MHz

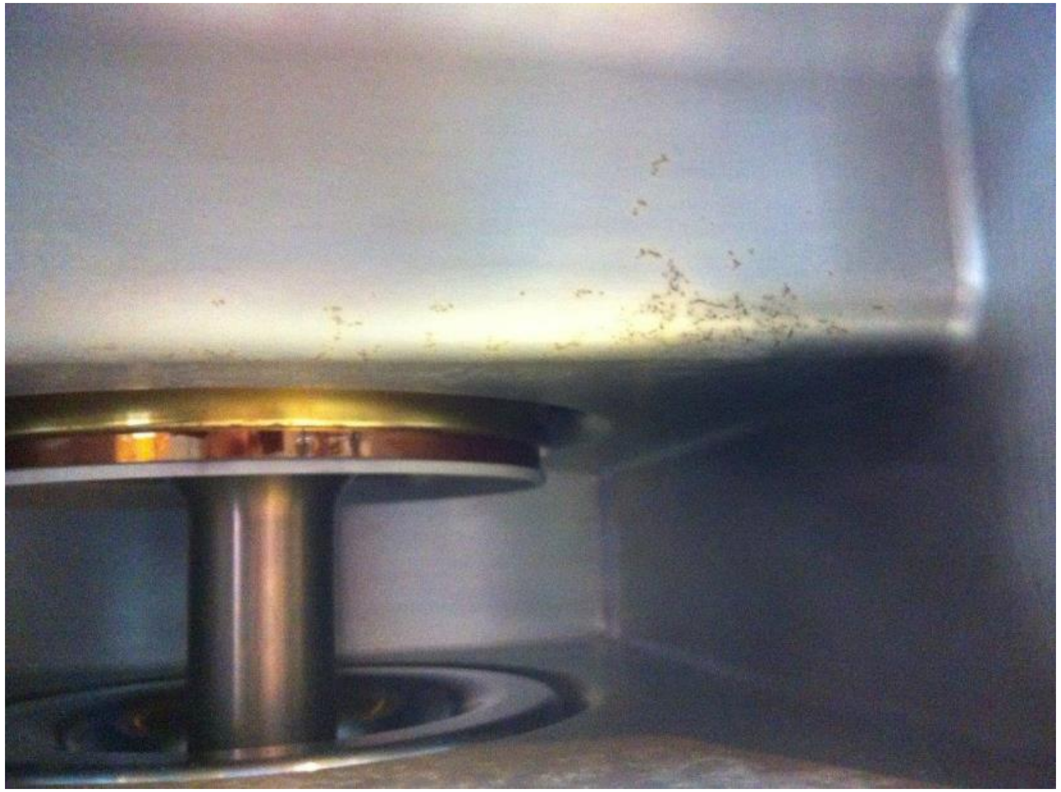
RF processing or FPC conditioning

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

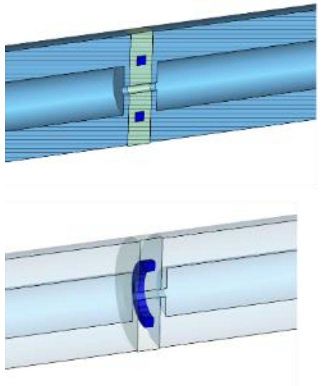
Arcing in FPC

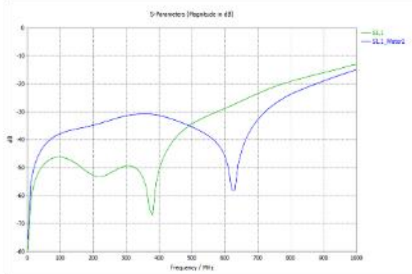


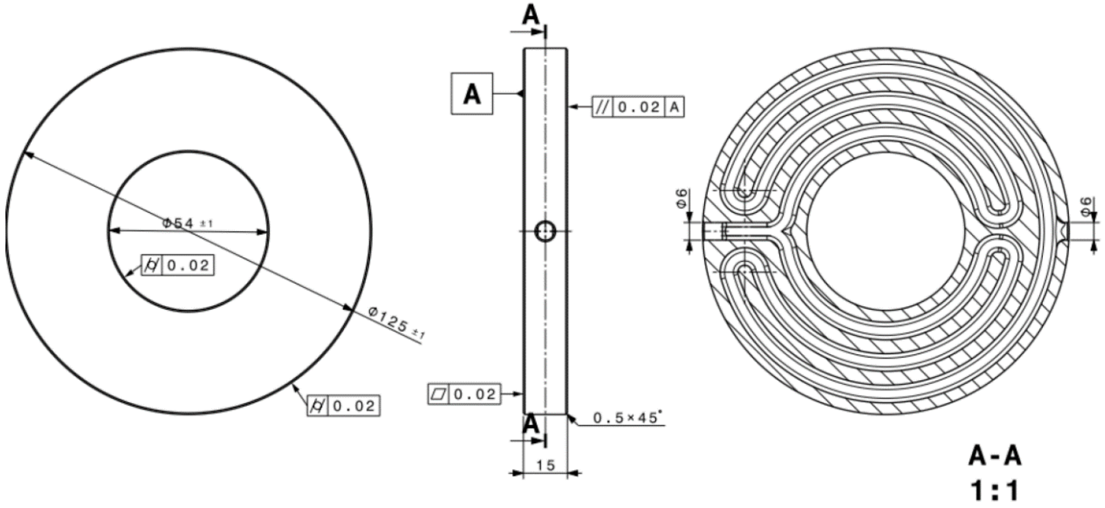
Water cooled from the inside ceramics

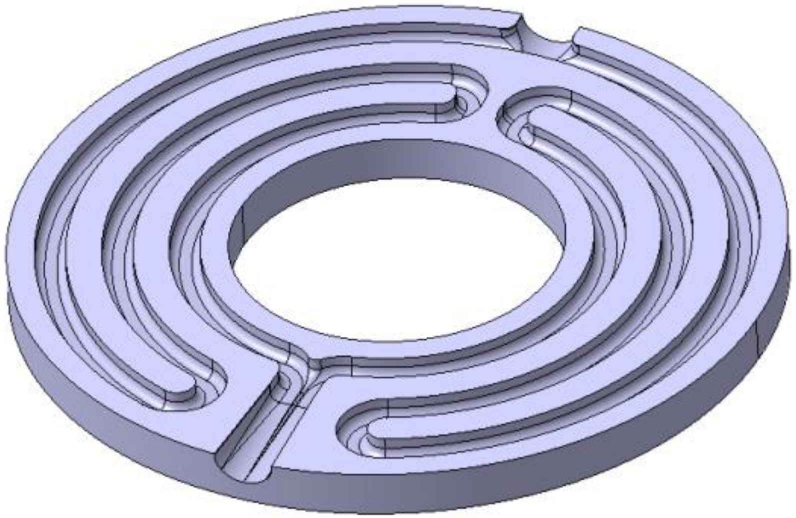
With the help of mechanical experts, we launched a prototyping of a 3D printed ceramic with water channels cooling down the ceramic from the inside

This should help getting to higher power handling









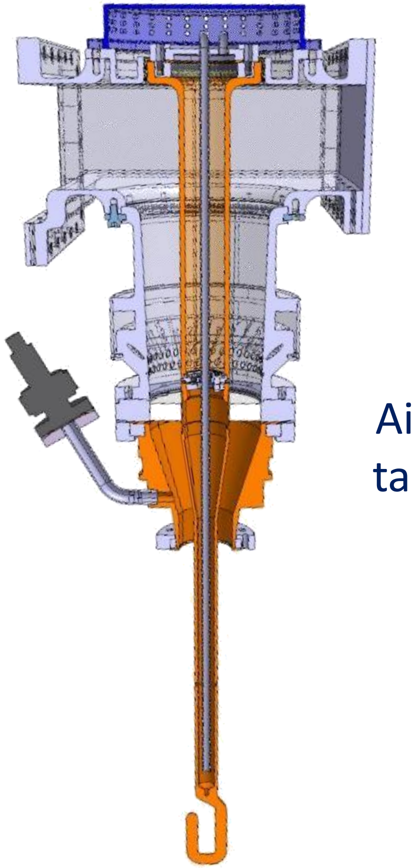
Cyclotronic© air cooling

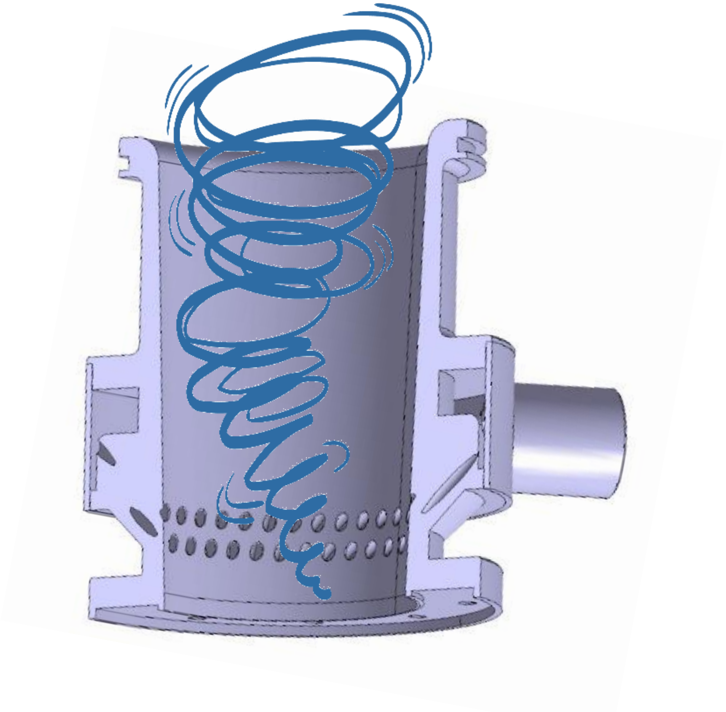
In order to cool down the ceramic from the air side, we invented the cyclotronic air cooling system

The goal is to avoid any ‘no air flow area’ that would generate a hot spot

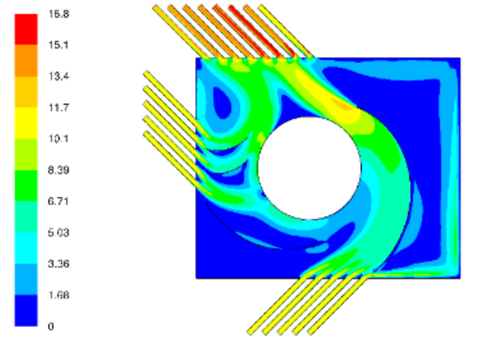
To do so, the air is directed down to the ceramic and with a tangential angle

This was proven very efficient with the SPL couplers





Air inlet directed to the ceramic and with a tangential angle to avoid ‘no air flow areas’
Cyclotronic © air cooling

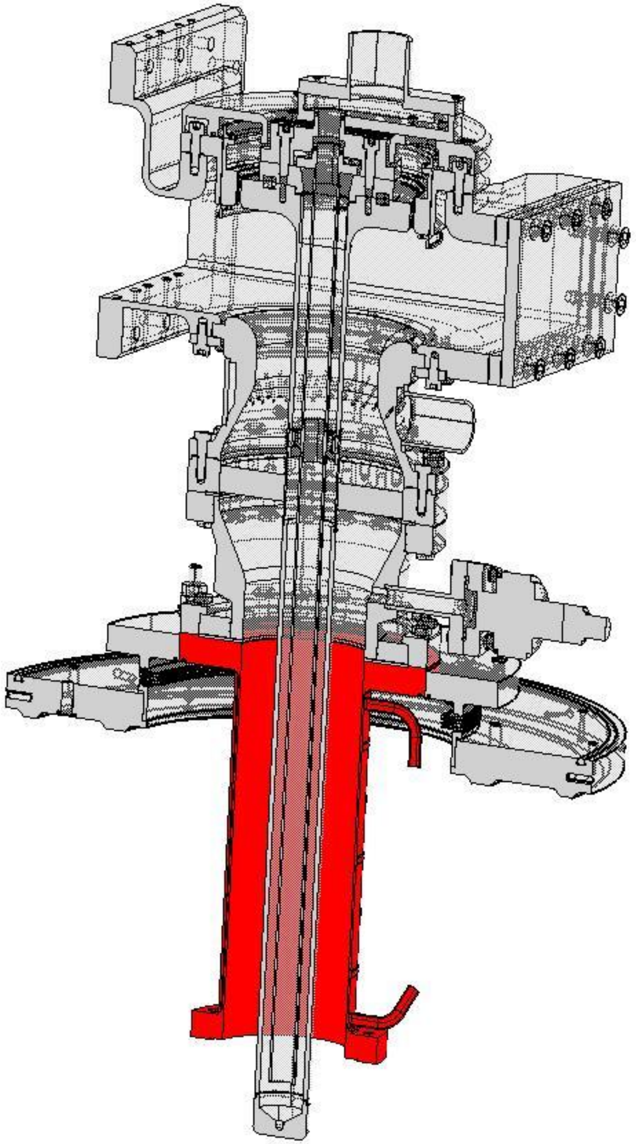


Outer antenna line

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

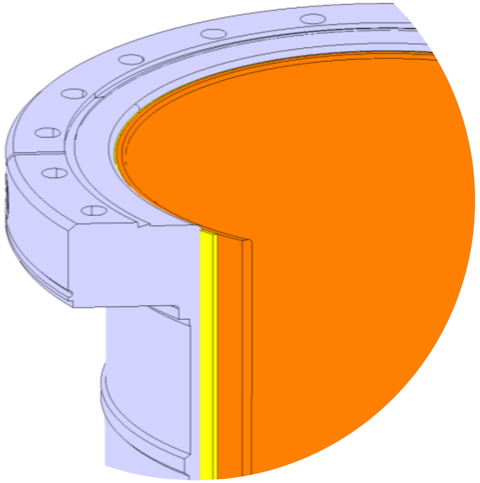
Its mechanical contraction must be perfectly pre-calculated, because this will give the coupling value (Q_{ext})

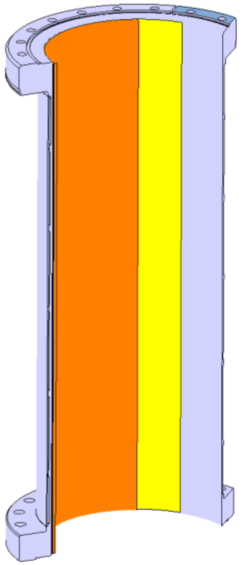


Outer antenna line

With SRF cavities, we usually have

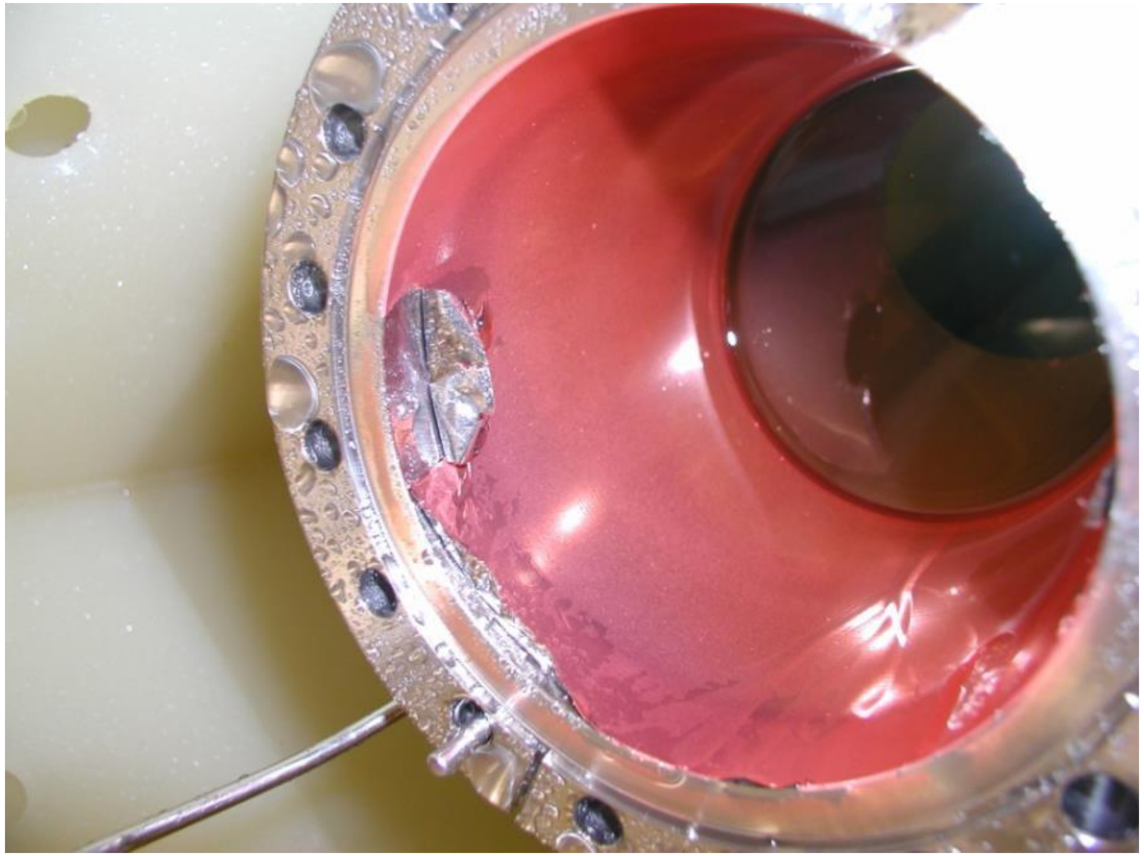
- A thin Stainless-Steel support, being the good thermal insulator
- Onto which we add a thin layer of few µm of copper, being the RF conductor with minimum RF losses and as being very thin, not transmitting so well the thermal losses to the cryogenic system
- As Copper is not adhering to Stainless-Steel, 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

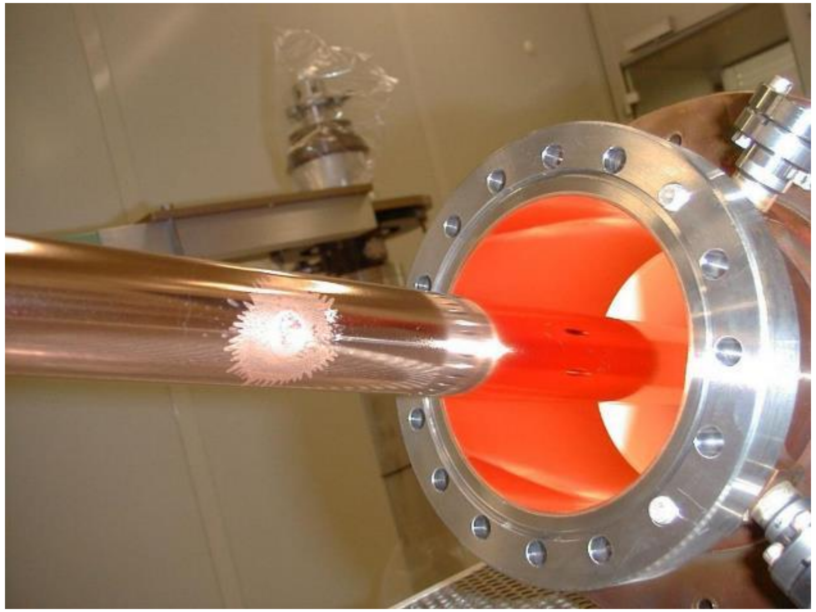


A FPC outer line with its copper layer peeling from the Stainless-Steel support. More than one year of work lost in a few second, more than half a year to repair

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

Multipacting



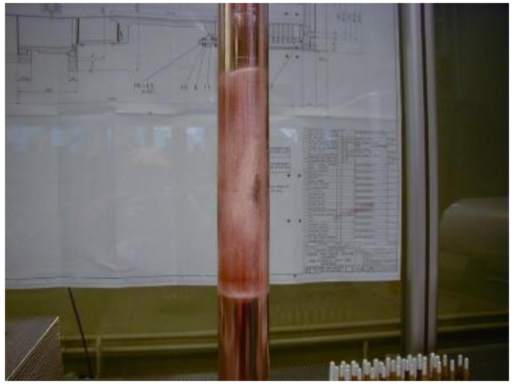
Never neglect the danger of multipacting

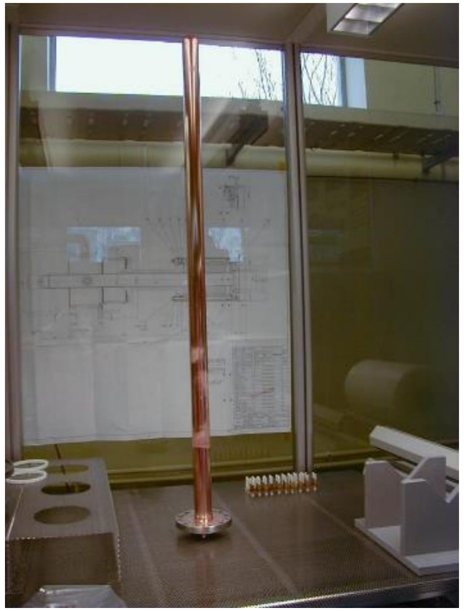
Nowadays there are codes that will allow us to take multipacting into account whilst designing the coupler geometry

However, always keep in mind an advice I received from Joachim Tückmantel ‘when your simulation tool tells you there will be multipacting… there will probably be multipacting. When it does not tell you there will be multipacting… there could nevertheless be multipacting! So always implement a multipacting stopper [DC bias]’

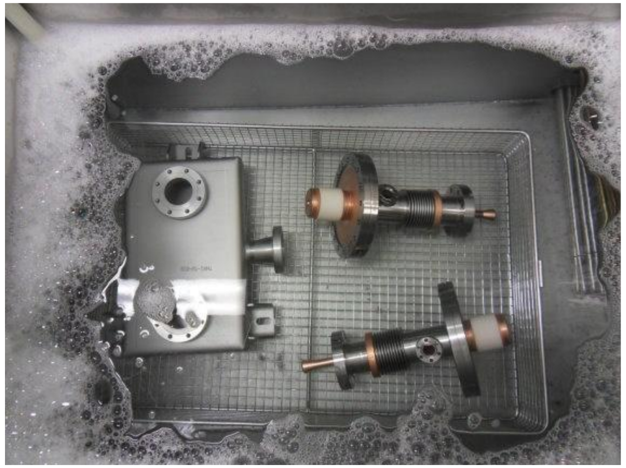
We work on an additive manufacturing pseudo random surface that should reduce the multipacting occurences

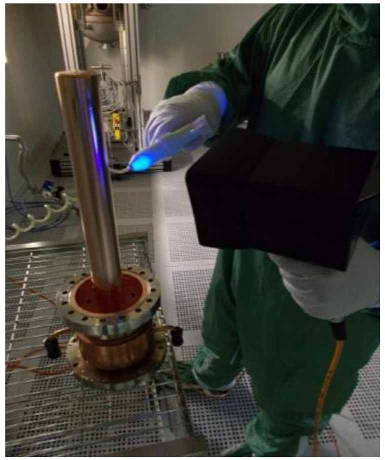
Multipacting could lead into impressive effects that will irreversibly damage the FPC

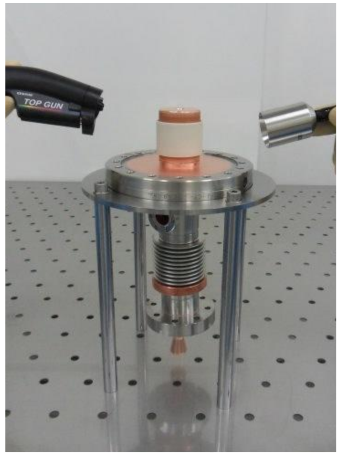




Clean room – preparation prior to assembly

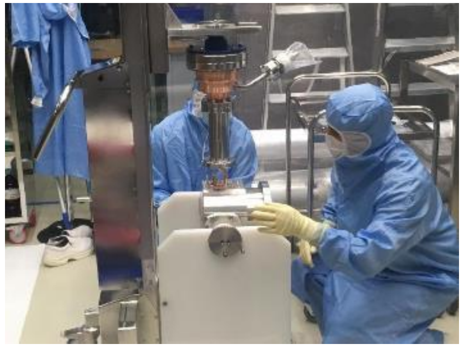






Clean room – assembly in ISO 5



Clean room – assembly in ISO 4

Cryomodule integration requirements

Conclusion

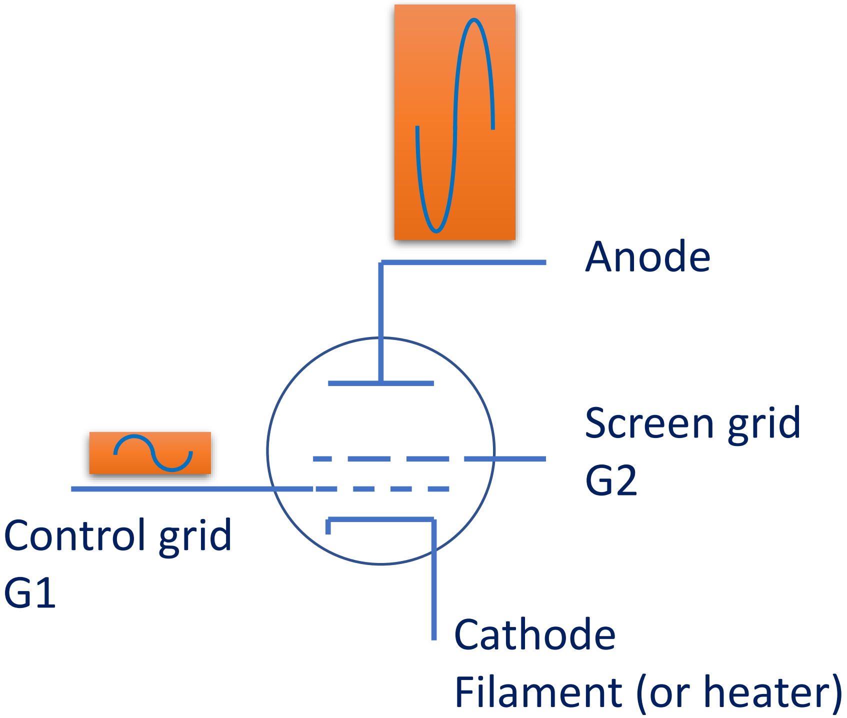
If RF power is of course an RF topic,

its implementation mainly involves a series of mechanical challenges

All in one, RF is only the need of a few µm of good metal…

We are looking towards your creativity to invent the new objects of tomorrow that we will need for future large accelerators

It all depends on… you!



Thank you very much

They did not know it was impossible, so they did it
(Mark Twain)

Simplicity is the ultimate sophistication
(Leonardo da Vinci, 500 years ago)

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