HiLumi
HL-LHC PROJECT

RF power system IOTs & challenges

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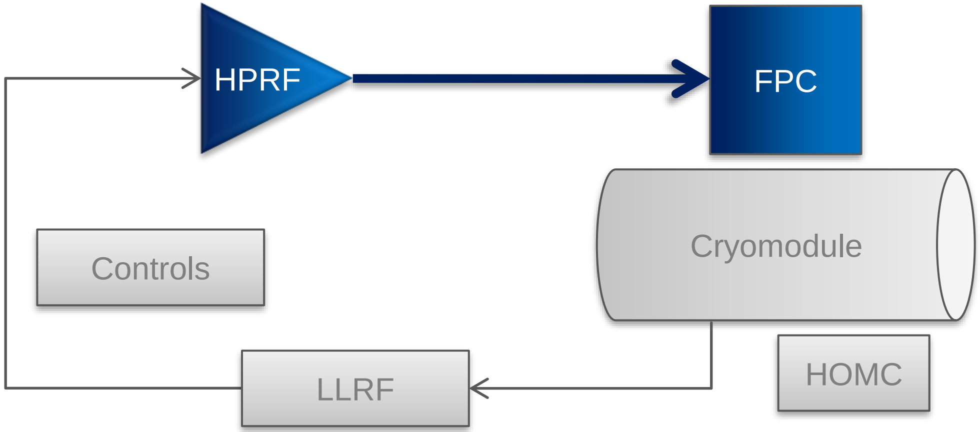
CERN

RF system

HPRF ***H**igh **P**ower **RF** station (including power transmission lines)*
FPC ***F**undamental **P**ower **C**oupler*
HOMC High Order Mode Coupler
LLRF Low Level RF



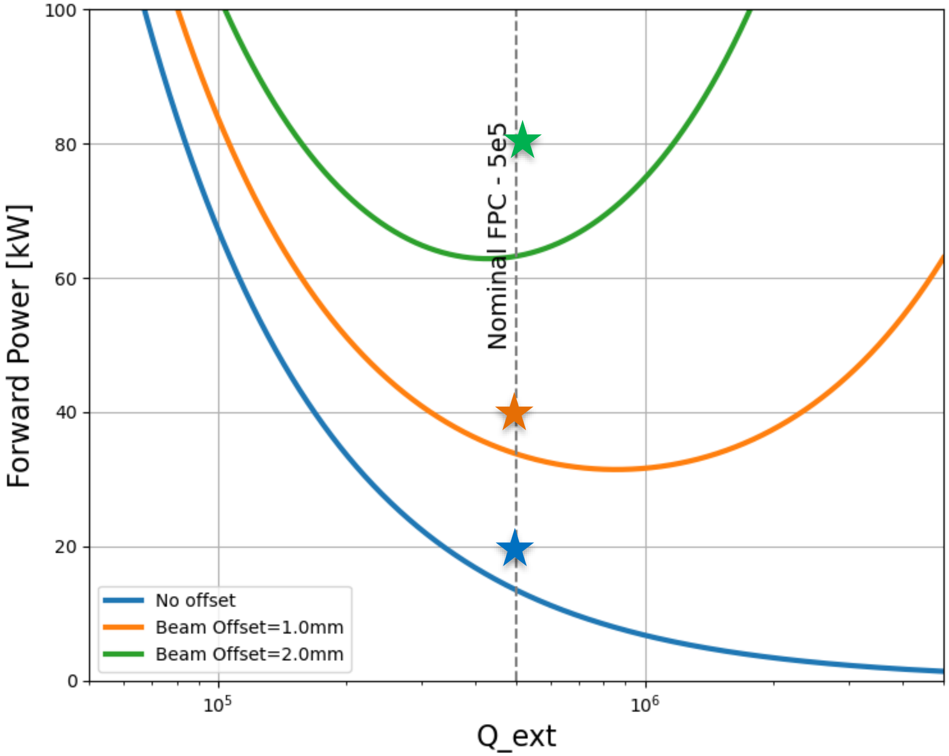
HPRF stations Technical Specification

With a no offset beam, HPRF will have to provide 20 kW

HPRF has been defined such to deliver up to **40 kW**, about 1 mm+ offset

In case of a too large offset, HPRF must provide up to **80 kW** during almost 1 ms, allowing for a clean beam dump

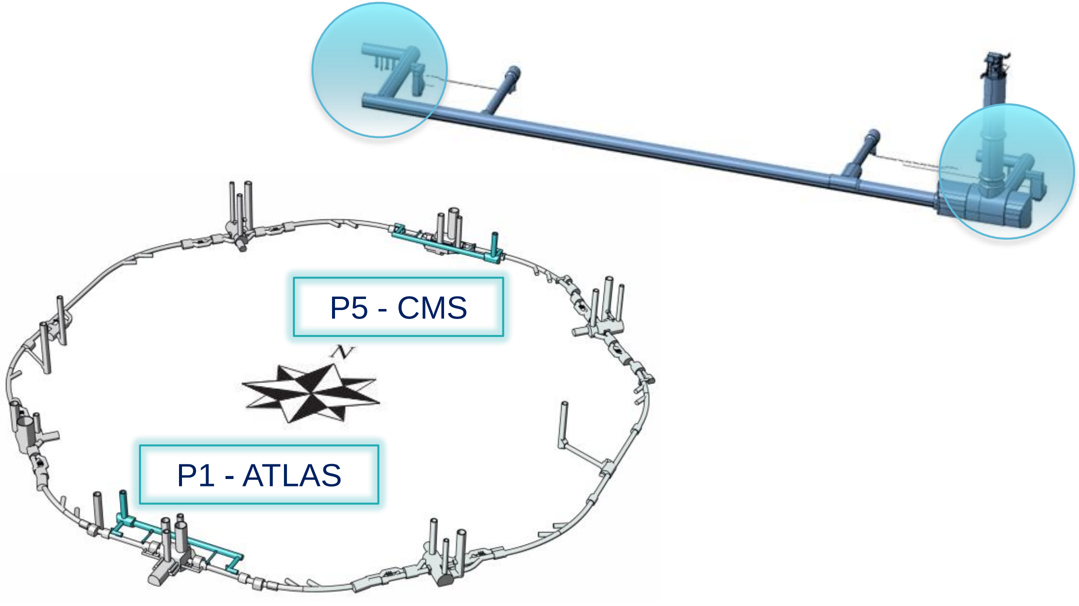
Courtesy Rama Calaga

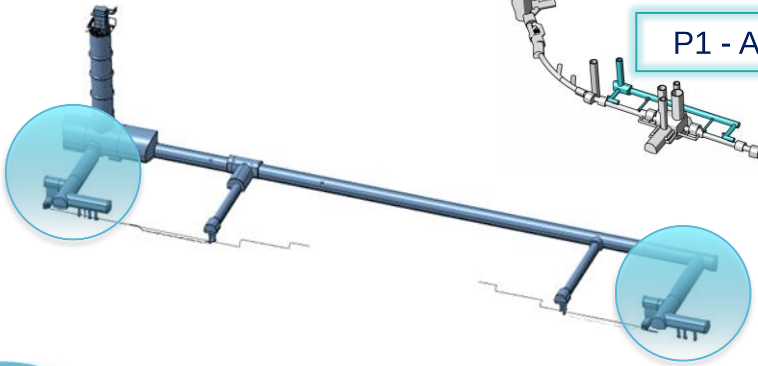


Integration of the HPRF in the galleries

Four different places
with four HPRF stations each

Total 16 HPRF stations



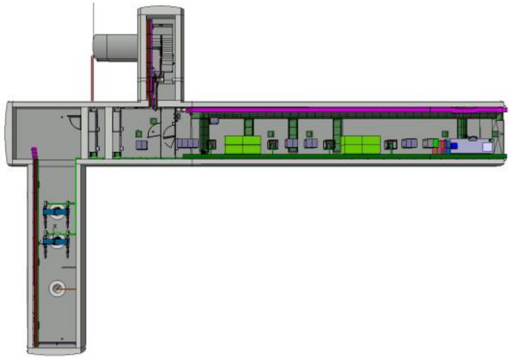


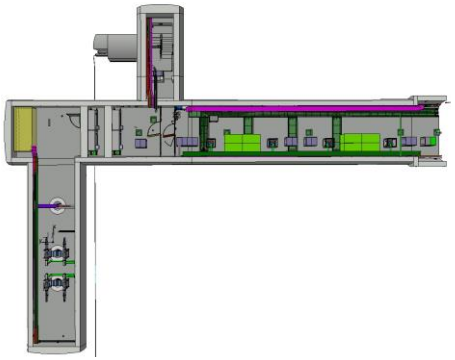
Integration of the HPRF in the galleries

Left side

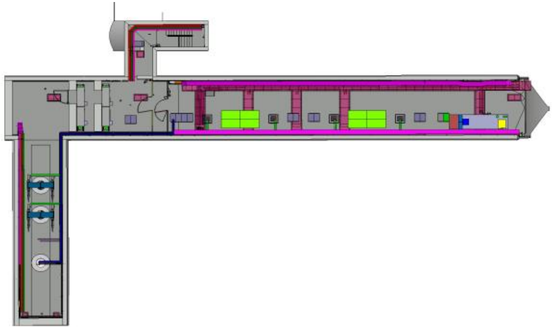
Right side

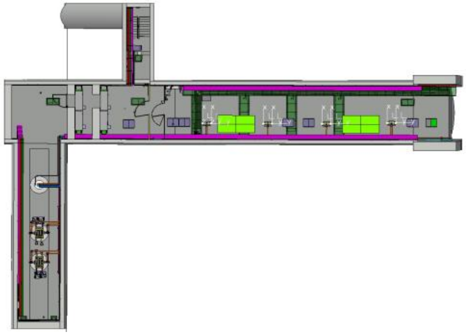
Point 1





Point 5





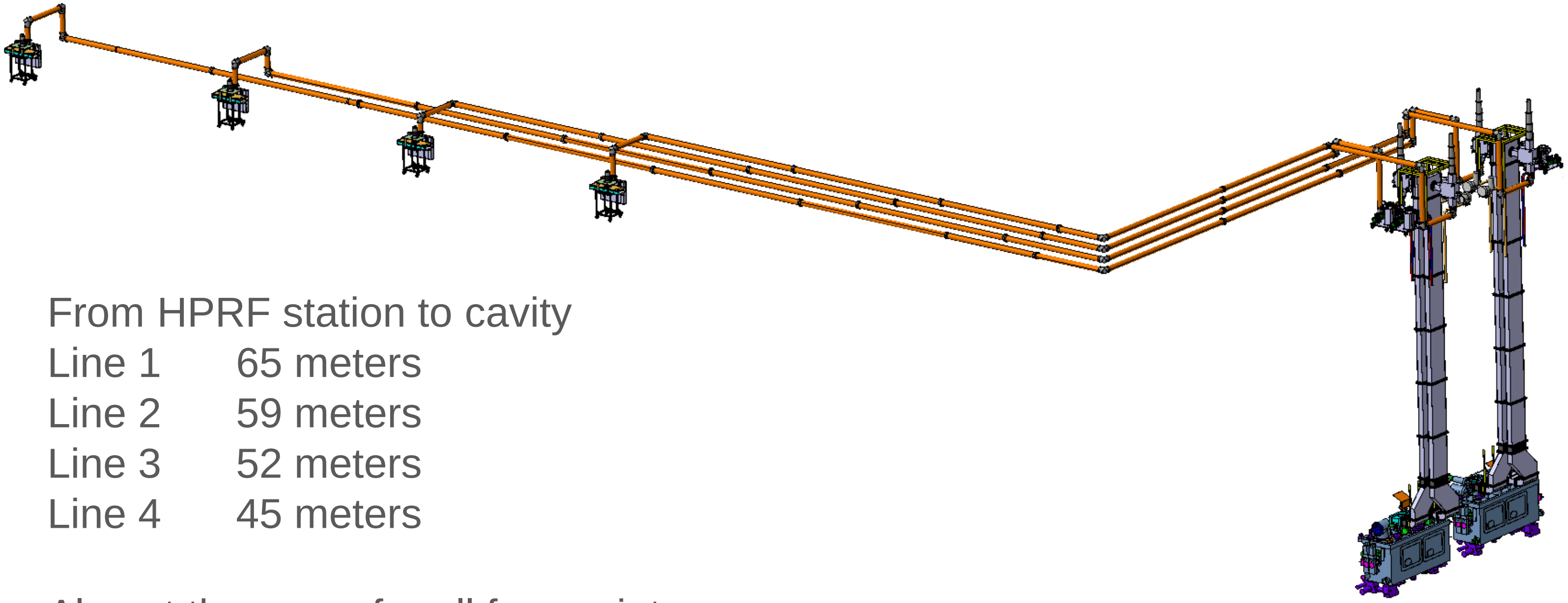
Integration of the HPRF in the galleries

Volume L x l x h

each HPRF station must be maximum 2 x 2 x 2 meters all inclusive

In a gallery so no possibility to increase the size

Integration of the HPRF in the galleries

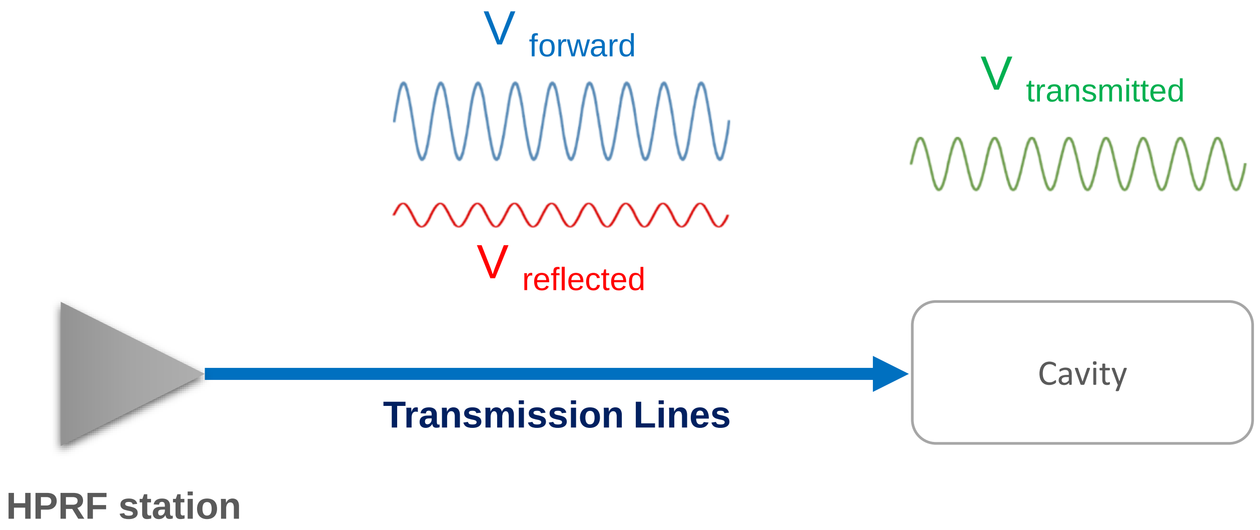


From HPRF station to cavity

Line 1	65 meters
Line 2	59 meters
Line 3	52 meters
Line 4	45 meters

Almost the same for all four points

Mismatch


V forward
V reflected
V transmitted
Cavity
Transmission Lines
HPRF station

Reflection from cavity

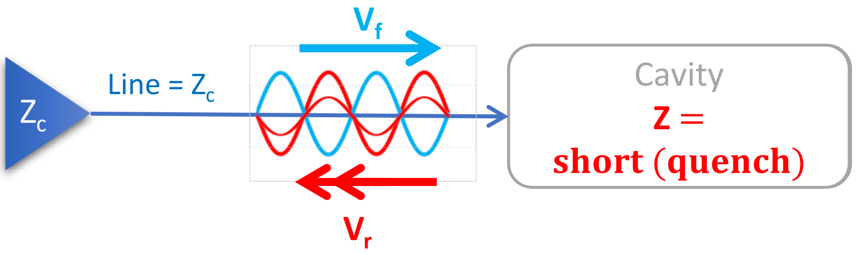
Standing Wave Ration SWR is a measure of impedance matching of the cavity

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
Γ = 0	when the line is perfectly matched, no reflection
Γ = 1	when the line is open-circuited complete positive reflection



Reflection from cavity

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

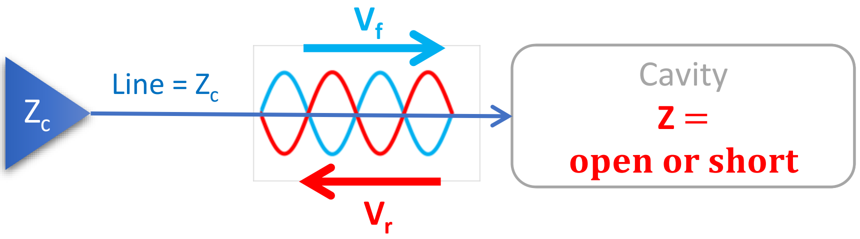
$$|\mathbf{V}_{max}| \quad = \mathbf{2}\ |\mathbf{V}_f|$$

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

$$|V_{min}| \quad = \mathbf{0}$$



The Voltage Standing Wave Ratio is equal to

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

Full reflection

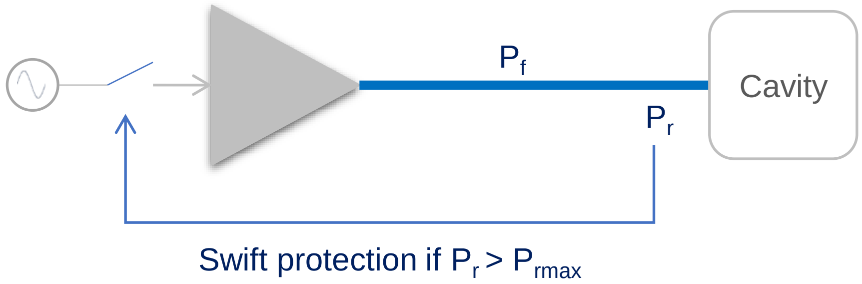
In case of full reflection $V_{max} = 2\ V_f$

(Pmax equivalent to 4 P_f)

RF power amplifiers based on Klystron and SSPA will not like this reflected wave

If correctly designed, Grid tube and IOT can sustain it

Swift protection if $P_r > P_{rmax}$, but then the system is NOT operational (not always possible)



Circulator

The circulator helps the system to remain operational and to protect our lines and our amplifiers from the reflected power

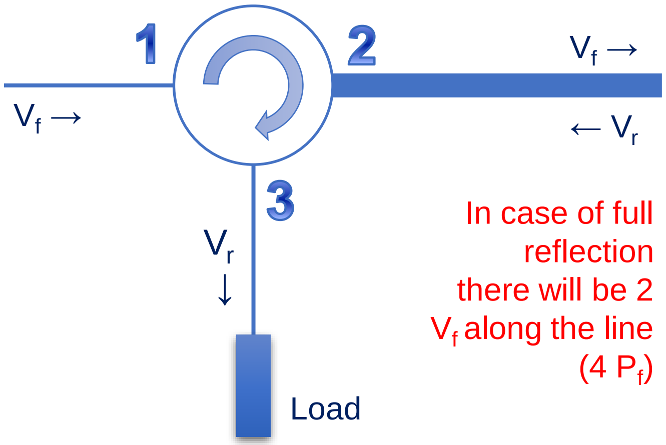
It is a passive non-reciprocal three-port device

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

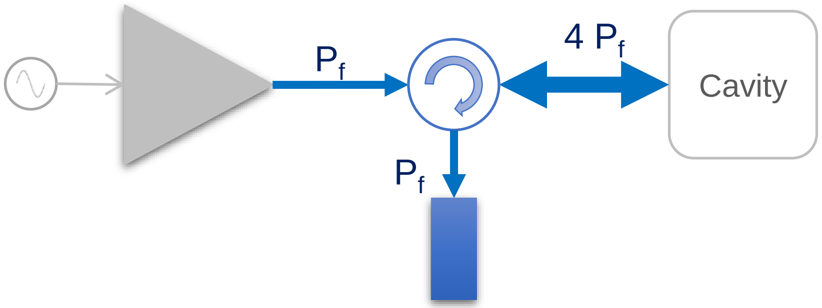
The best place to insert it is close to the reflection source

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

A load of P_f is needed on port 3 at all time

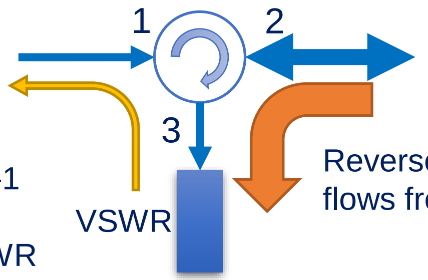


In case of full reflection there will be 2 V_f along the line (4 P_f)



Circulator

Reflected signal from 3 is circulated back to 1



Isolation from 2-1 depends on 3 termination VSWR

Reverse power flows from 2 to 3

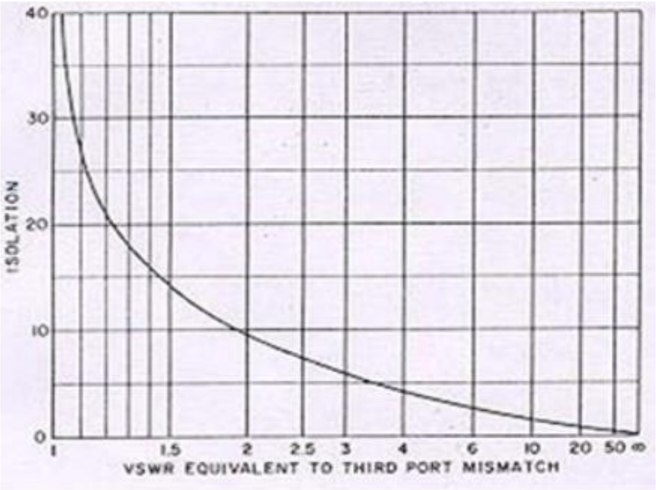
Load on 3 absorb most of the signal coming from 2

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



Coaxial Lines

Characteristic impedance is

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

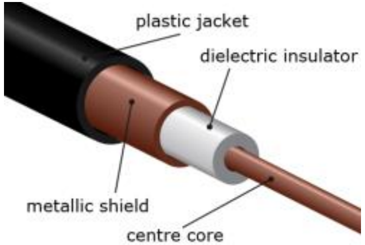
with

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**



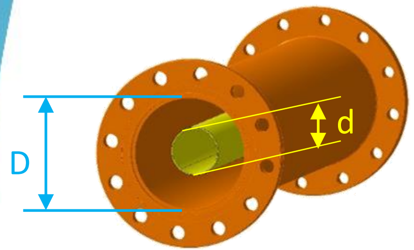
Coaxial cables are often with PTFE foam to keep concentricity

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

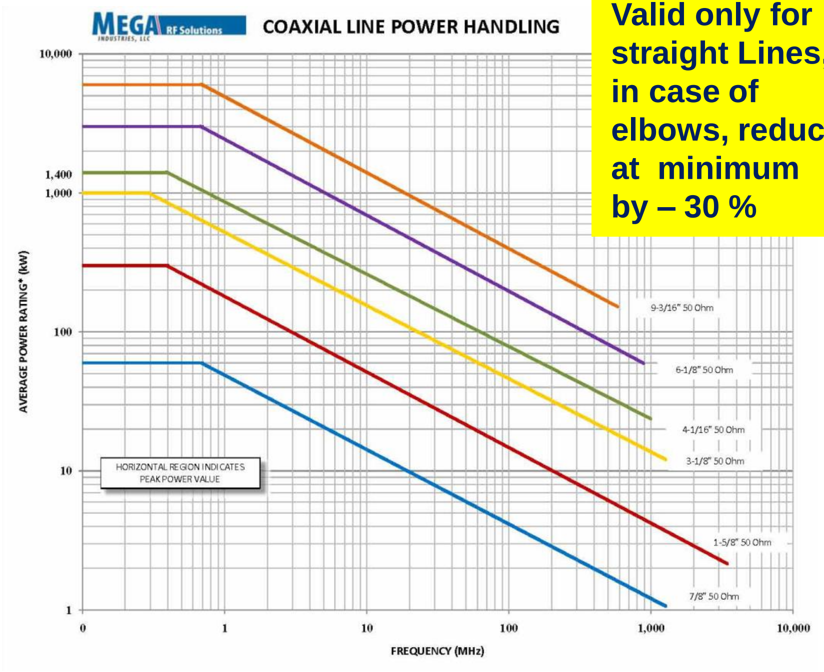


$$Vpeakmax = E\frac{d}{2}ln\left(\frac{D}{d}\right)$$

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

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

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 %

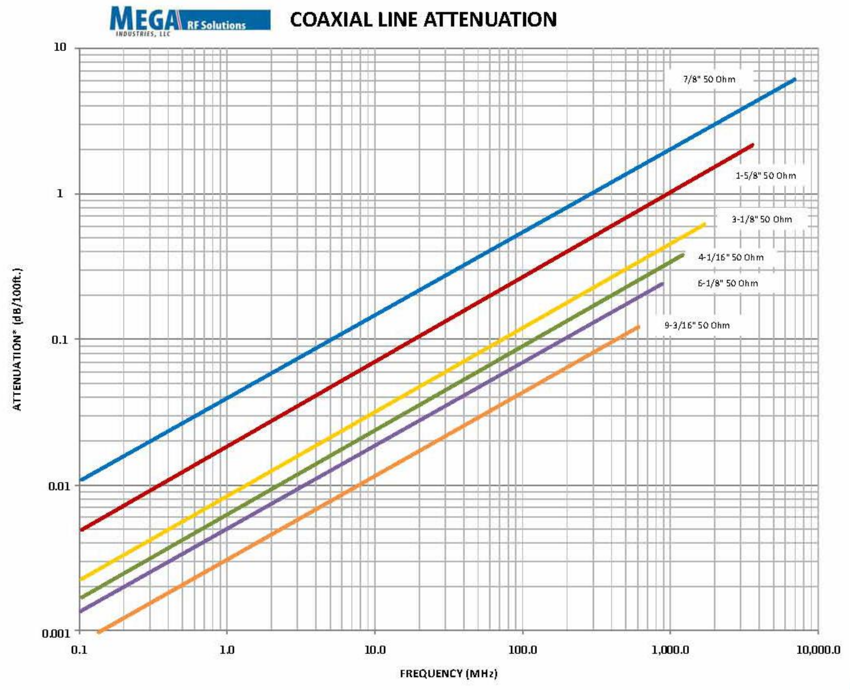
Coaxial lines Attenuation

The attenuation of a coaxial line is expressed as

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

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 formulas together

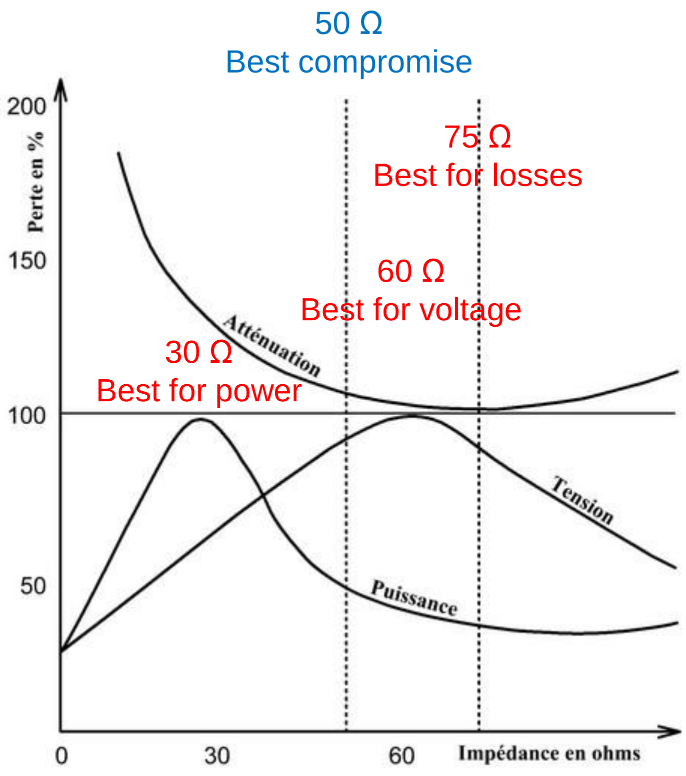
$$Zc = \frac{60}{\sqrt{\varepsilon r}} ln\left(\frac{D}{d}\right)$$

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

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

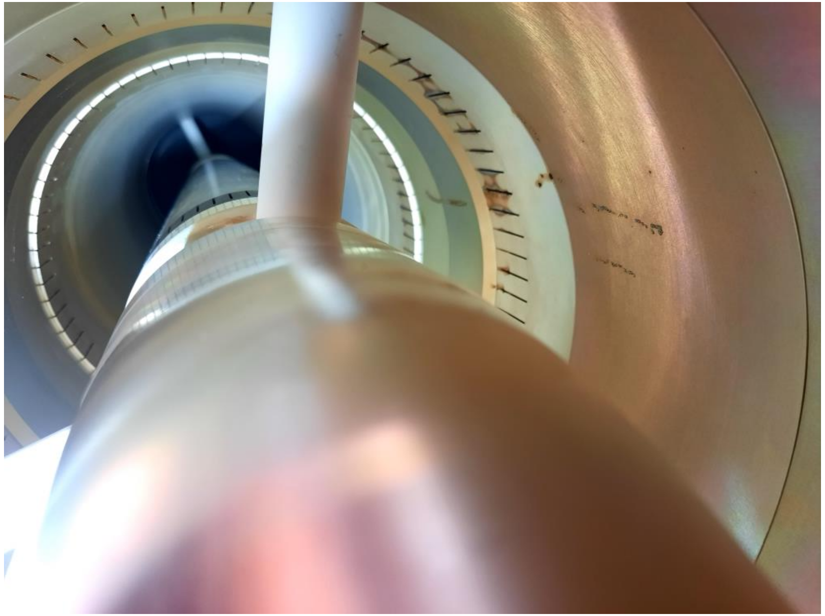
$$Ppeakmax = \frac{E^2\ d^2\sqrt{\varepsilon r}}{480} ln\left(\frac{D}{d}\right)$$

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



Impédance et pertes dans un câble coaxial

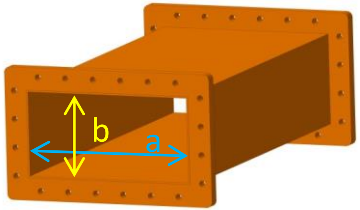
Possible damages



Damages to internal conductor of a coaxial line in case of excess of power

Rectangular waveguides

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



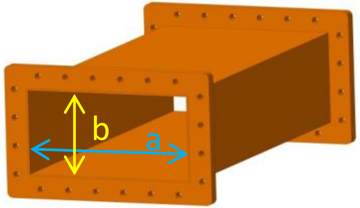
Wavelength	$\lambda_g = \frac{\lambda}{\sqrt{1-(\frac{\lambda}{2a})^2}}$
Cutoff frequency dominant mode	$f_c = \frac{c}{2a}$
Cutoff frequency next higher mode	$f_{c2} = \frac{c}{4a}$
Usable frequency range	**1.3 f_c to 0.9 f_{c2}**

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

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

with

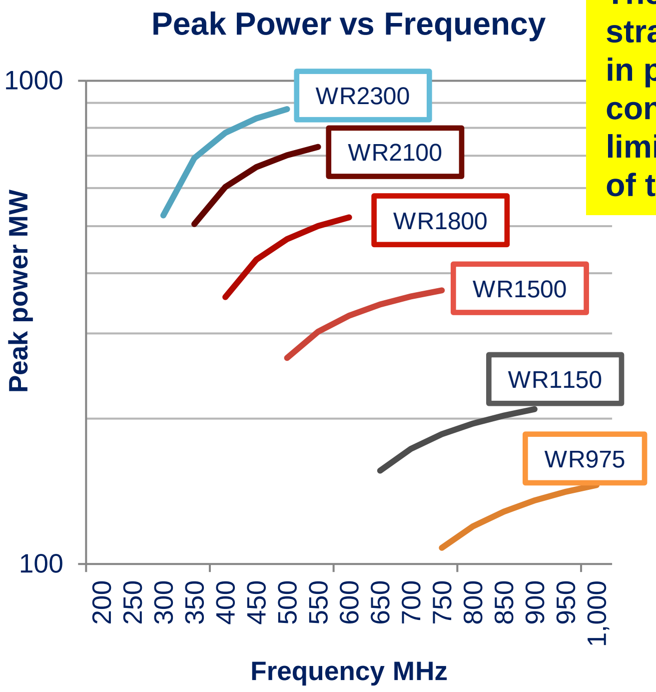
P_{peak} = Peak power in watts

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

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

with

α = attenuation constant, dB/m

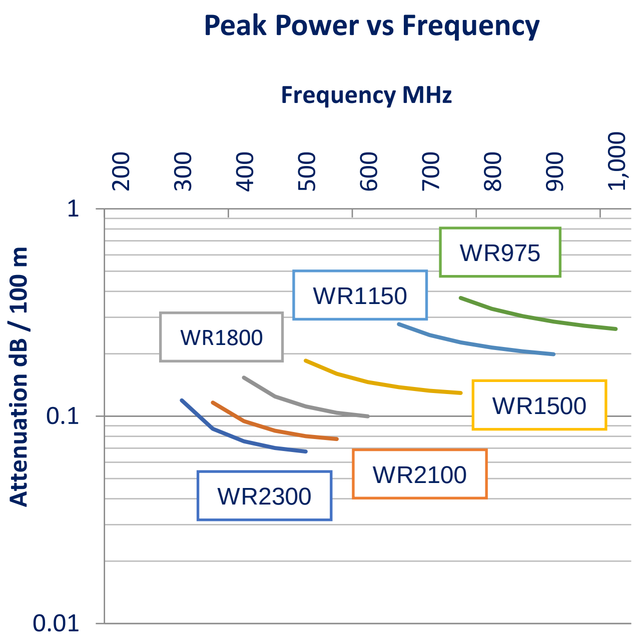
a0 = 3 10^{-7} [dB/m] for copper

a = width of waveguide in m

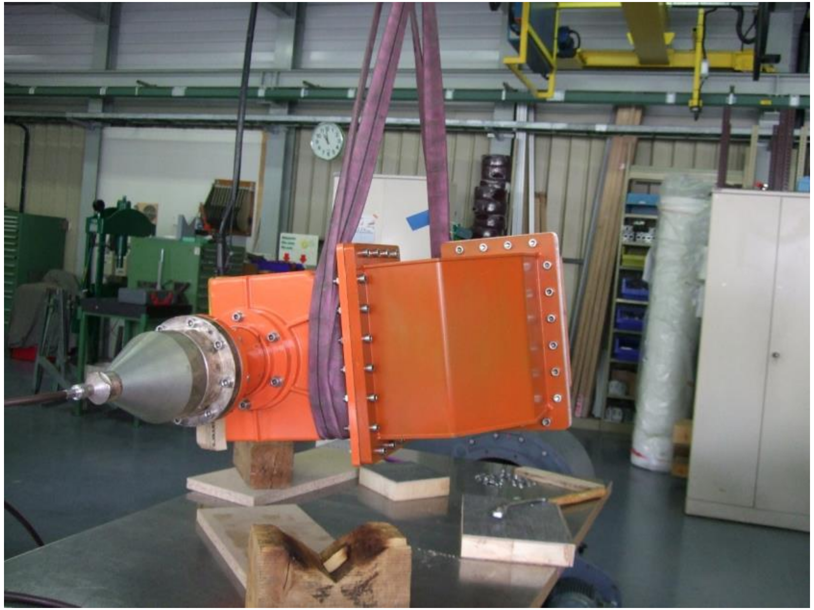
b = height of waveguide in m

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

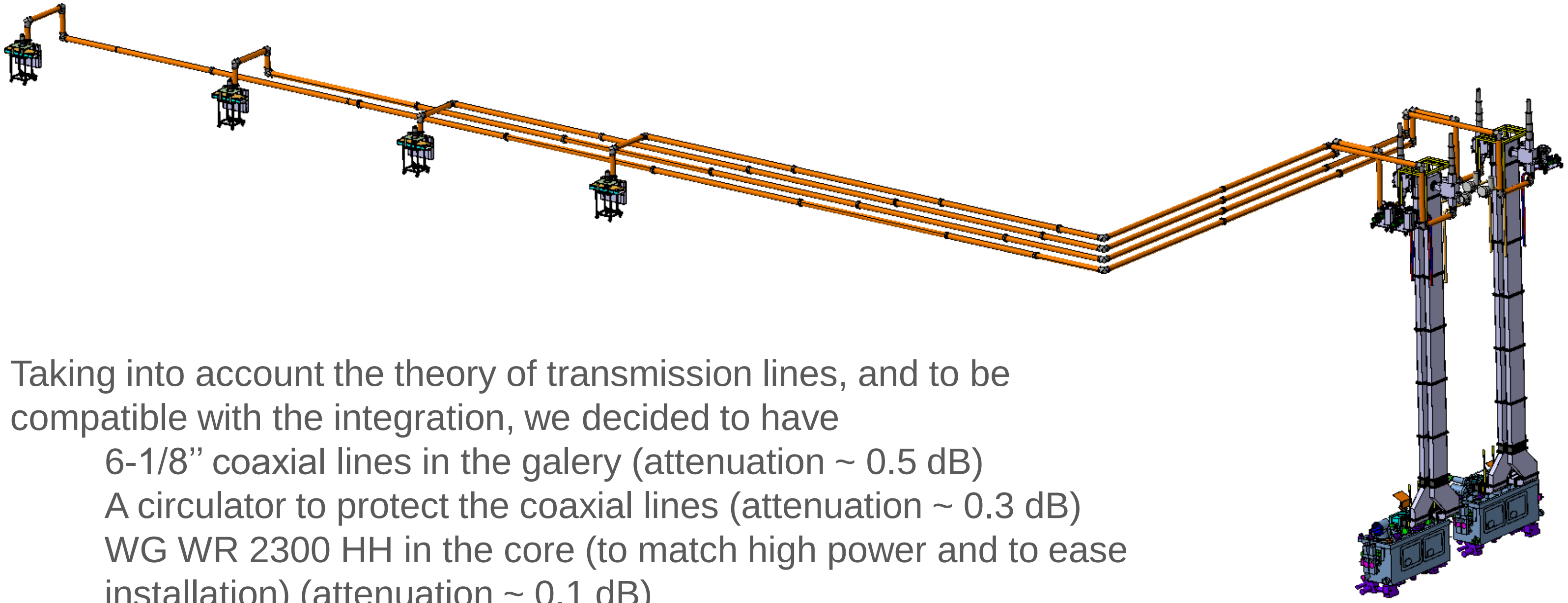


Rectangular waveguides



Adaptor from WR 1150 to N

Integration of the HPRF in the galleries

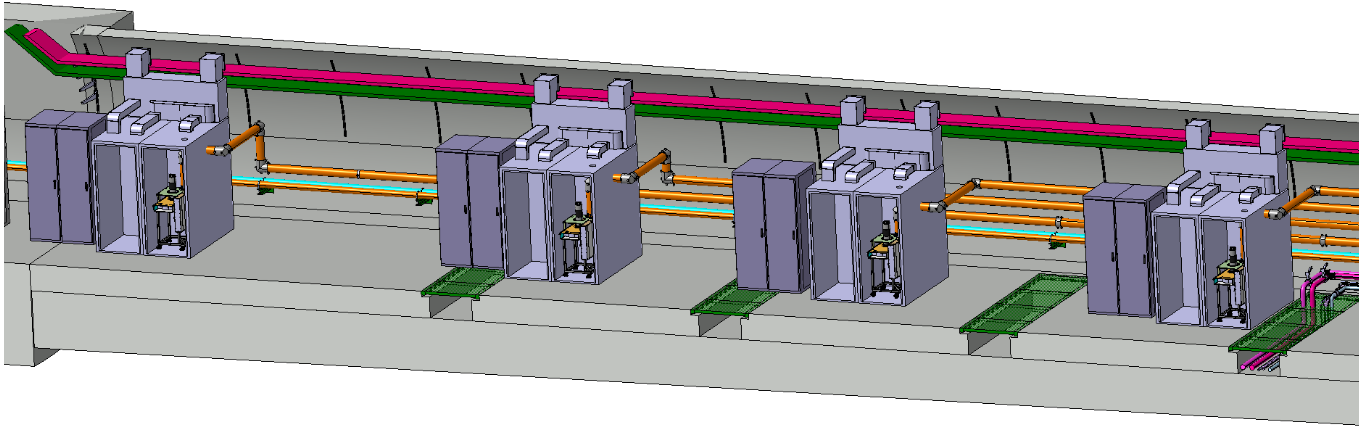


Taking into account the theory of transmission lines, and to be compatible with the integration, we decided to have

- 6-1/8’’ coaxial lines in the galery (attenuation ~ 0.5 dB)
- A circulator to protect the coaxial lines (attenuation ~ 0.3 dB)
- WG WR 2300 HH in the core (to match high power and to ease installation) (attenuation ~ 0.1 dB)

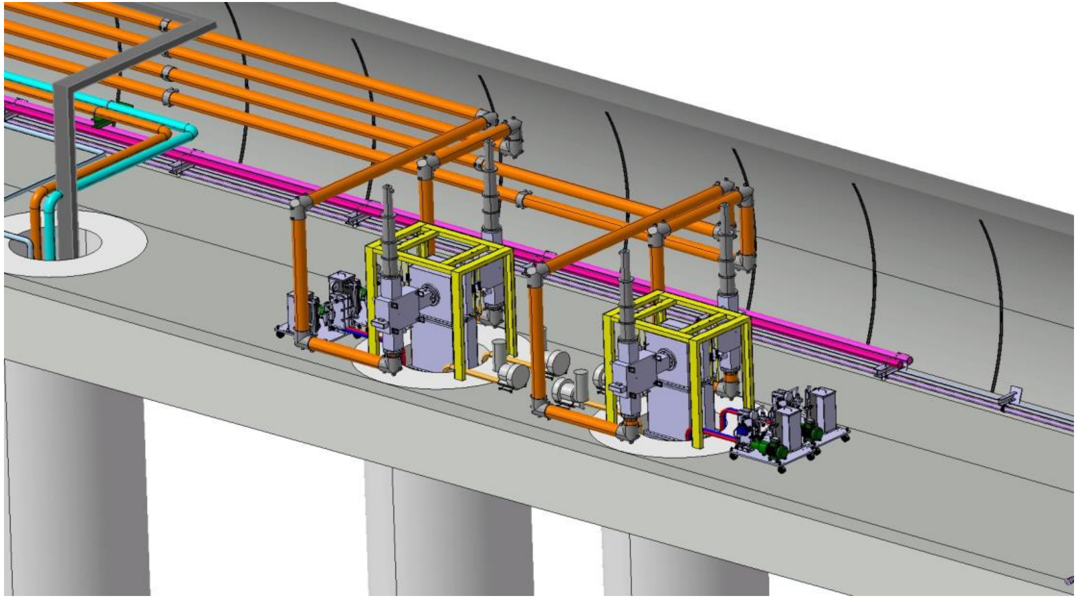
Total attenuation ~ 1 dB

HPRF stations in galery



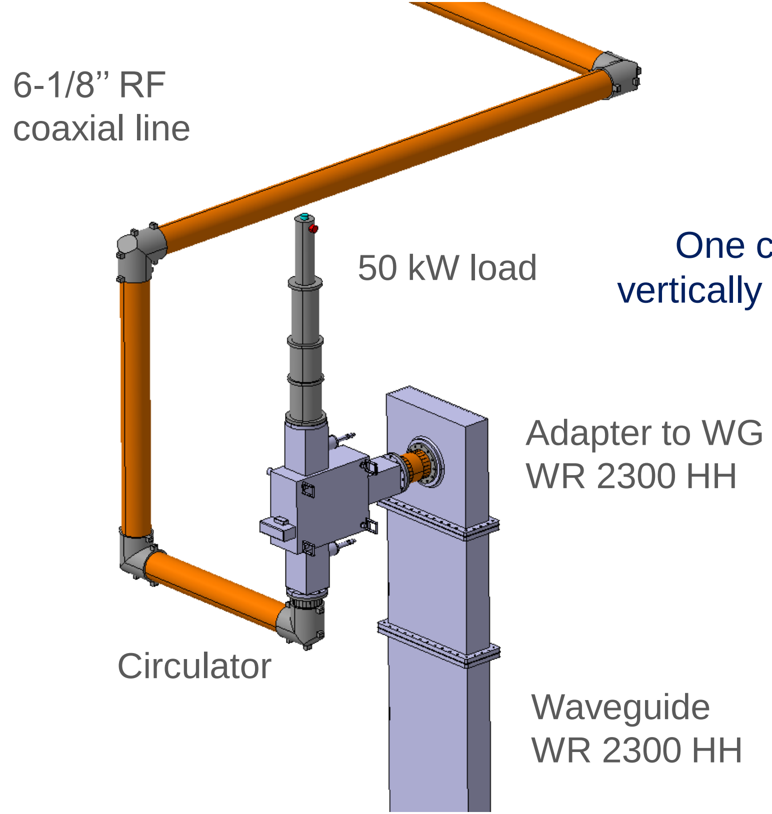
One HPRF station per cavity, delivering power through 6-1/8’’ coaxial lines

Circulators



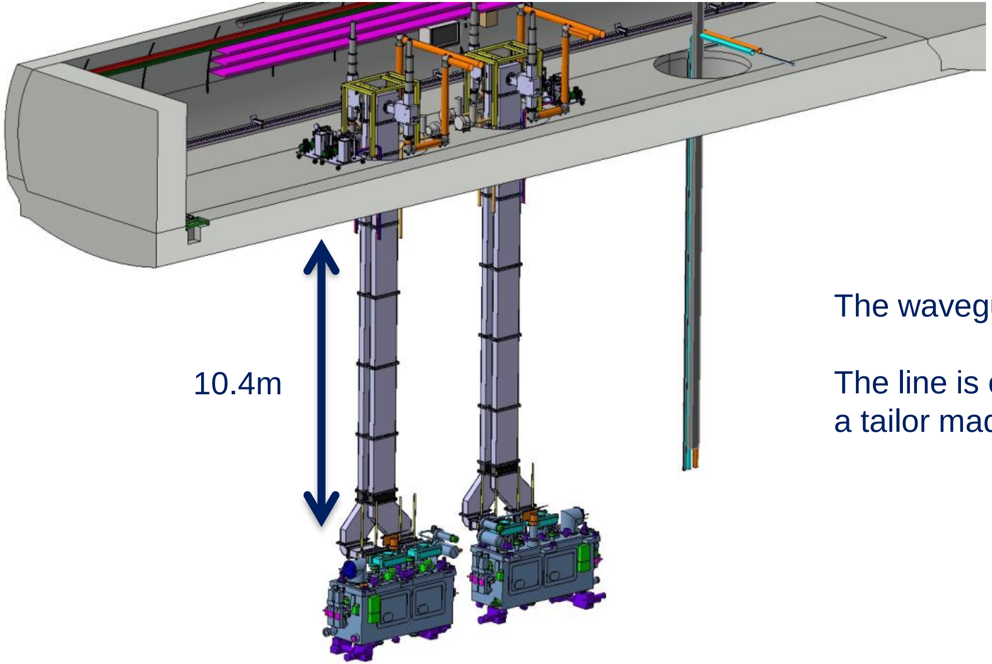
6-1/8'' coaxial lines connected to a circulator, with its port 2 connected to a WG WR 2300 HH

Detailed view of circulators



One can notice that the load is vertically oriented to avoid trapped air

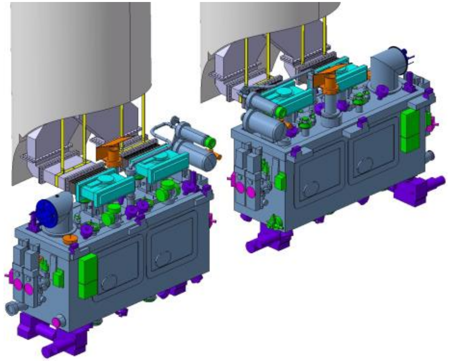
WG in the cores



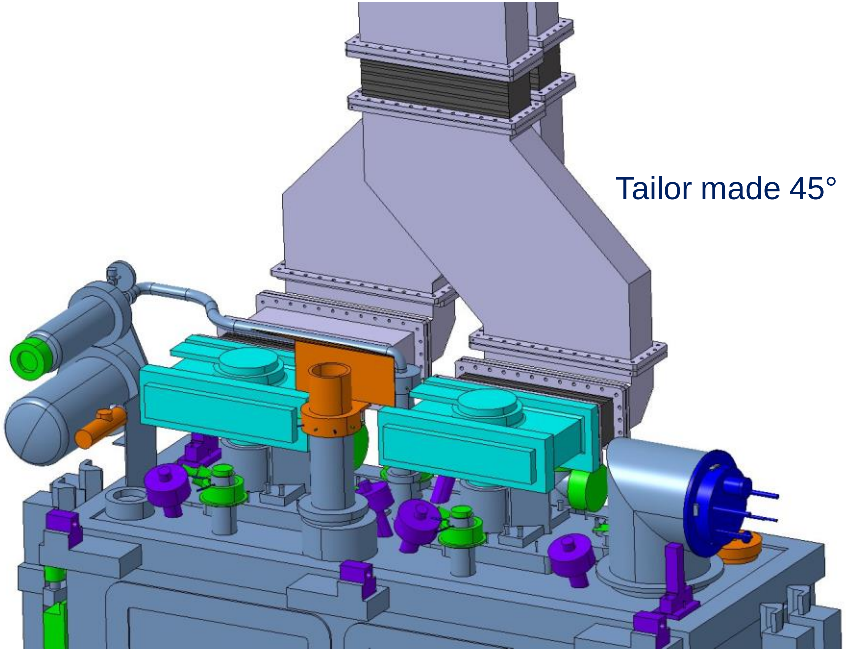
The waveguide WR 2300 lenght is 10.4 metre

The line is composed of an adpter, 7 straight parts, a tailor made 45°, a 90° elbow and 2 belows

WG connection to FPC

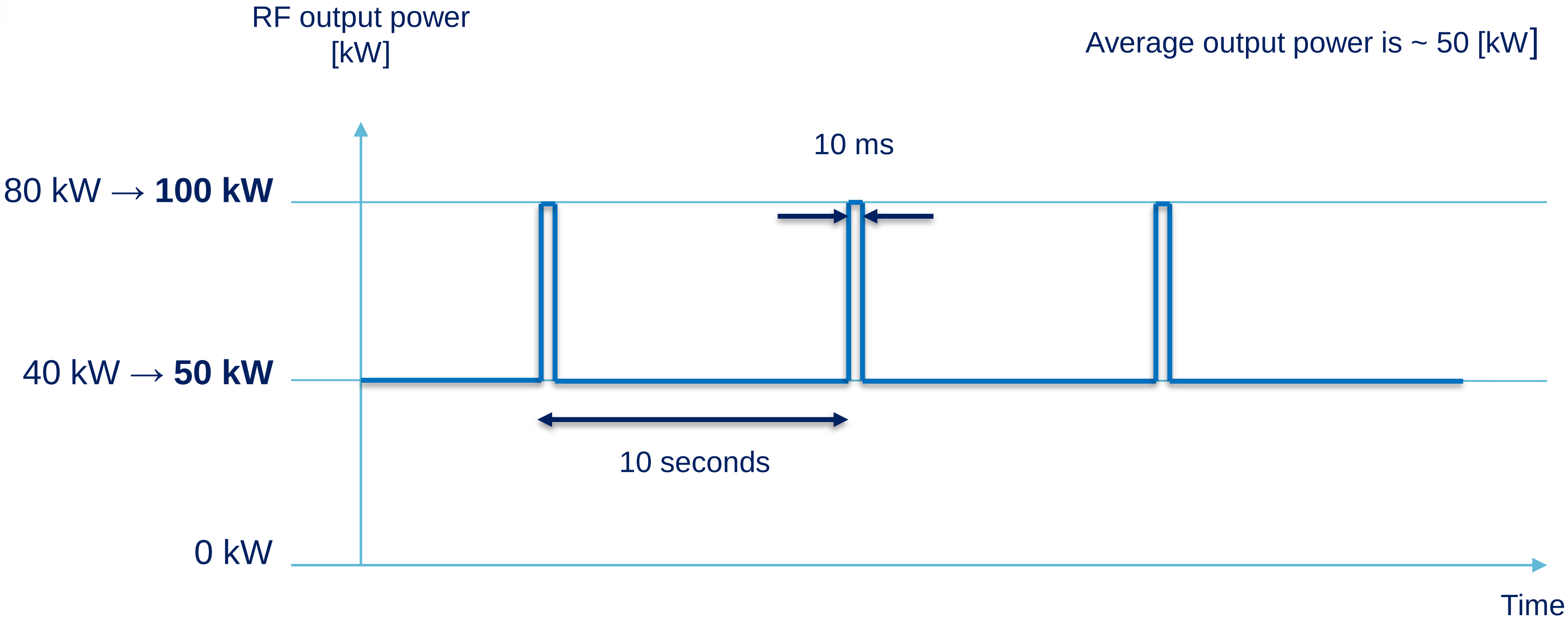


Due to the opening of the cores, we have to design a tailor made 45° waveguide with an inclination of 0.7 degrees

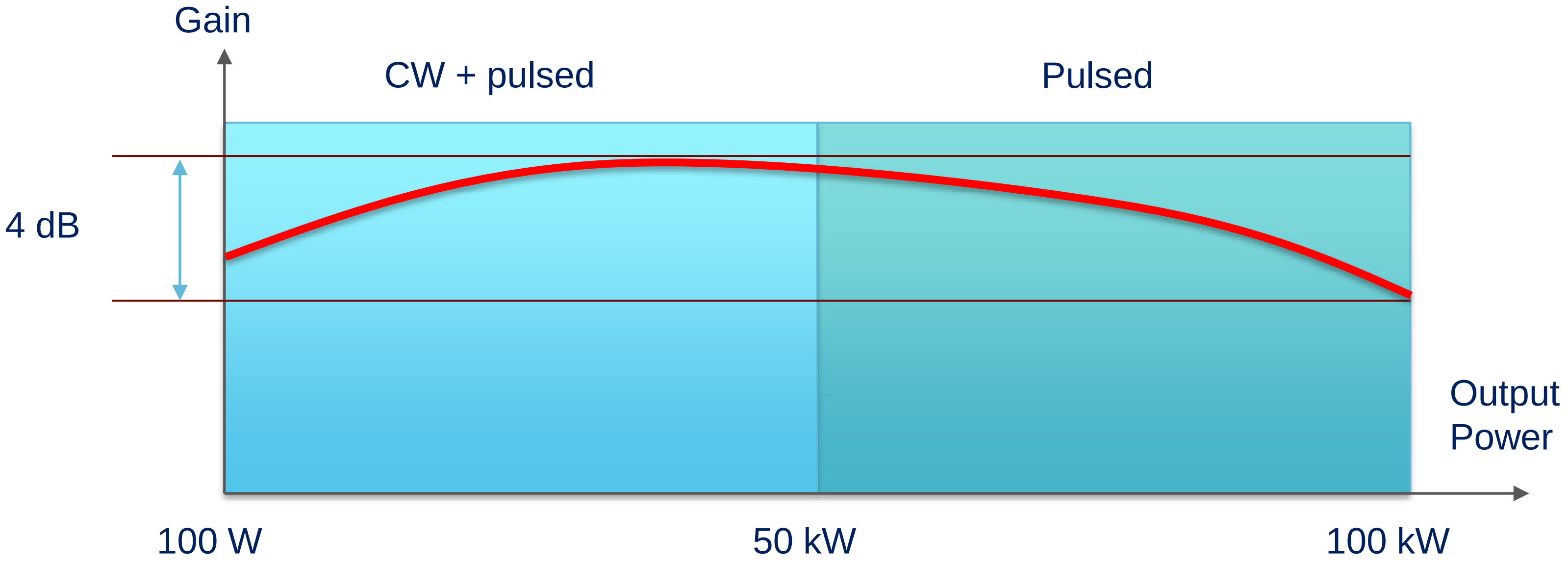


Tailor made 45° waveguide

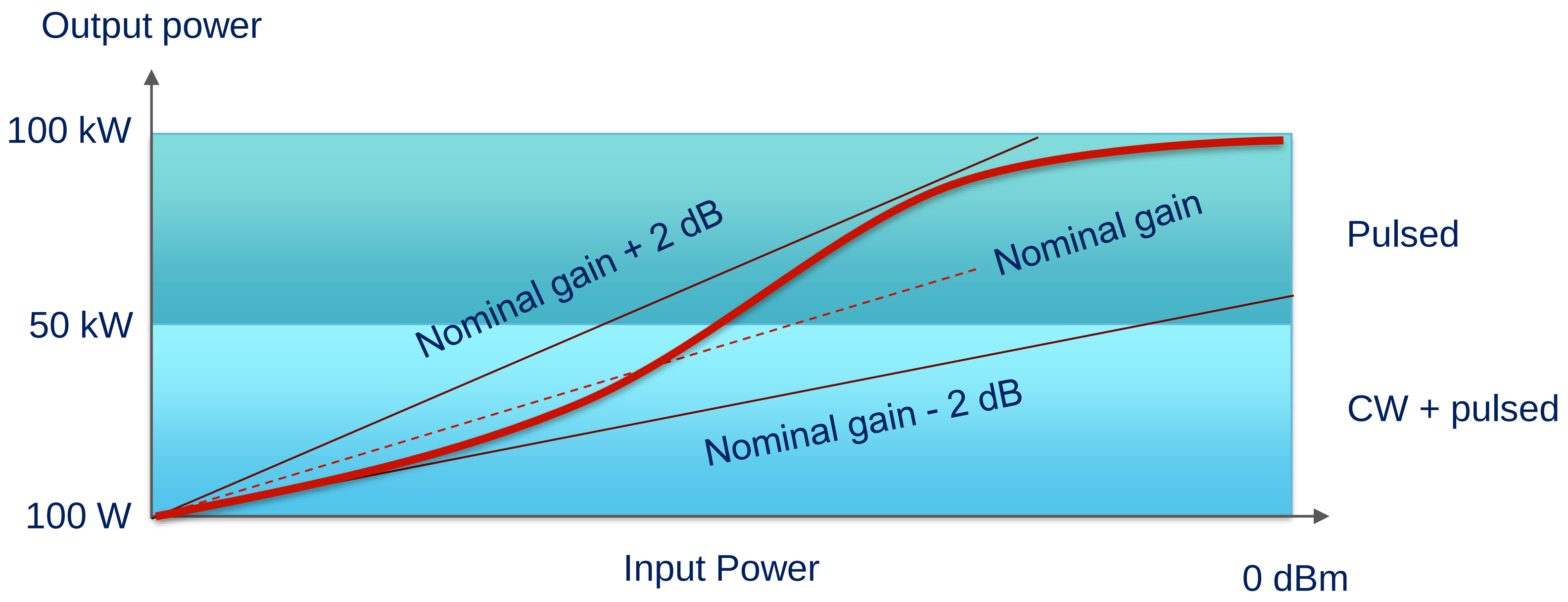
Power requirements from HPRF system



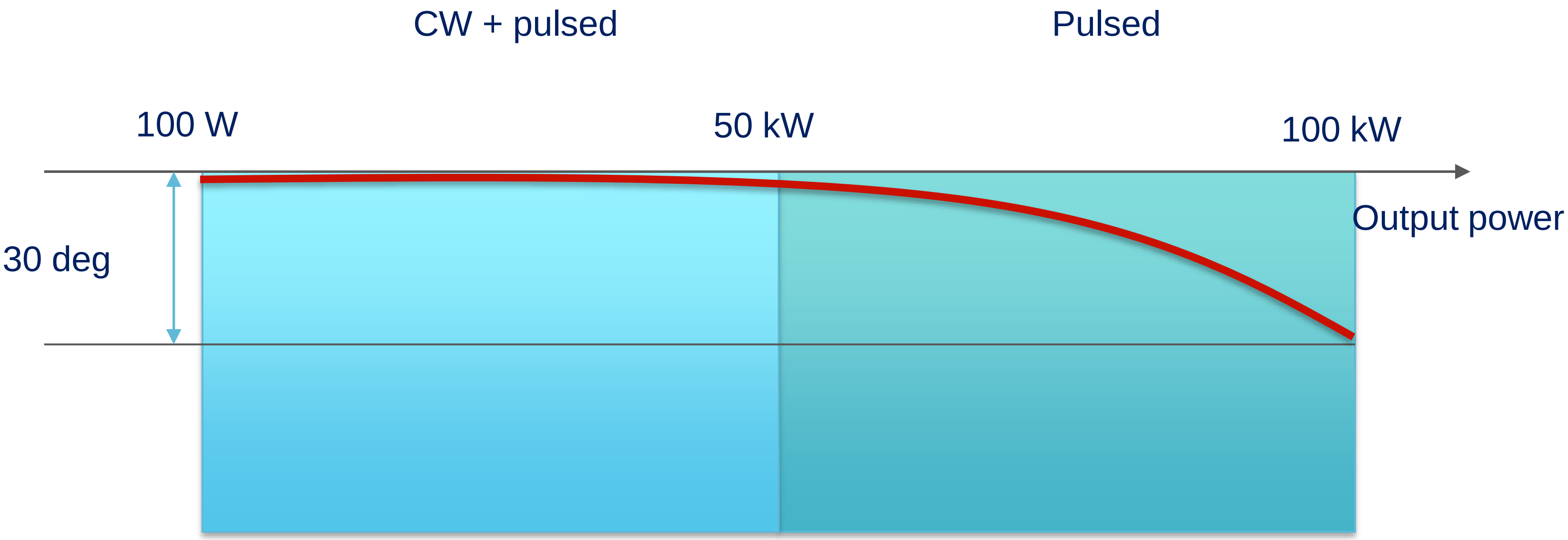
Gain flatness & monotonous



Gain flatness & monotonous



Phase flatness & monotonous



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)

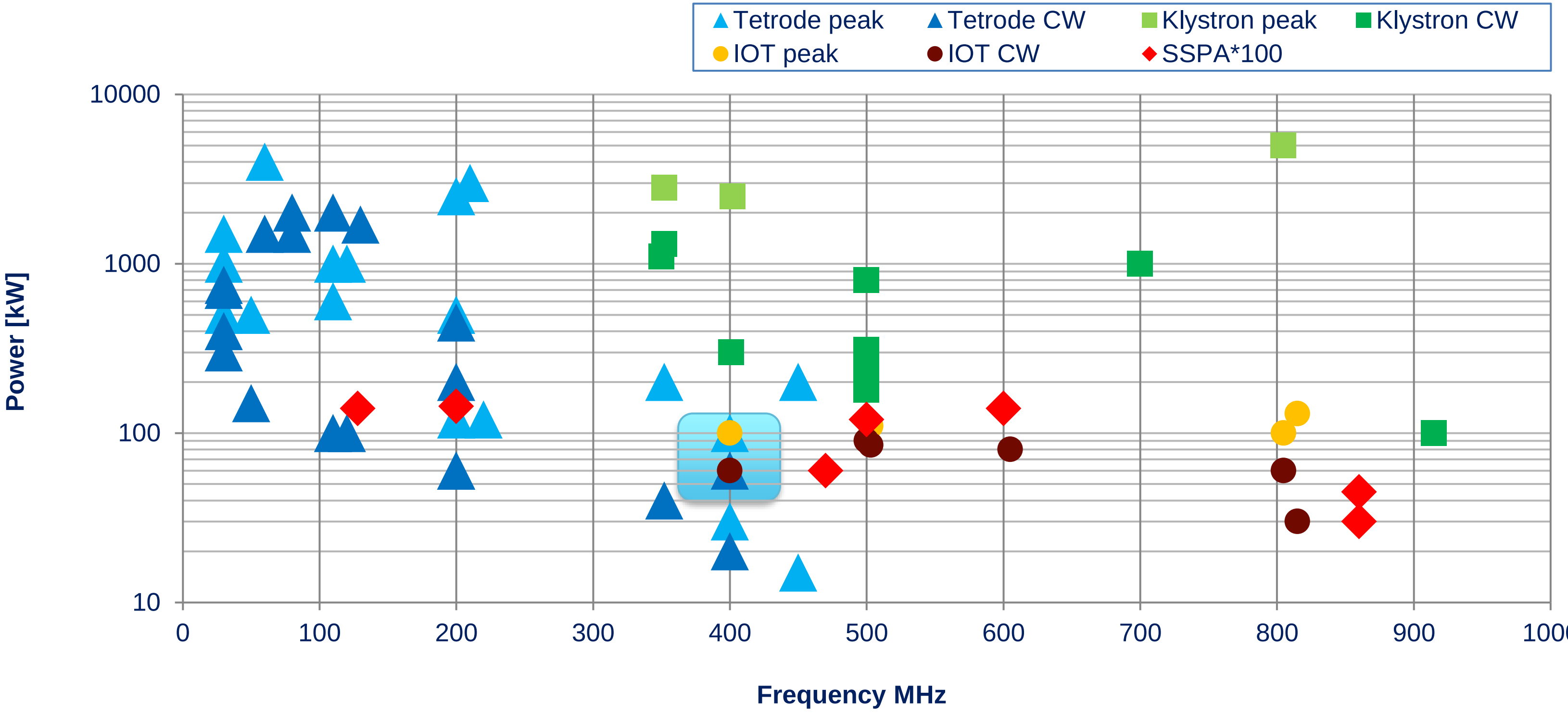
Crossed-field Tubes

Magnetrons

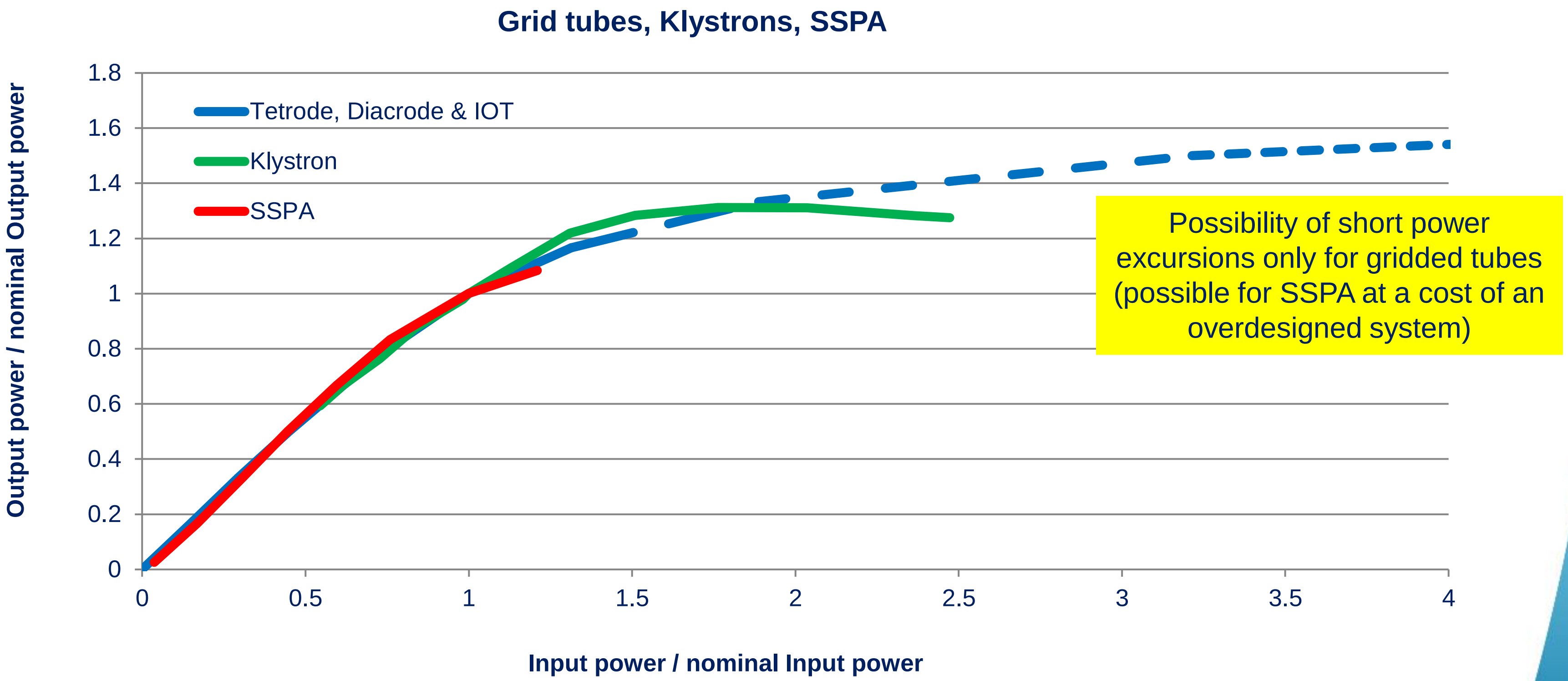
Transistors

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)

Available RF sources at a glance



Overhead and maximum power



No klystron at that ‘little power’ available

Klystron of such small power does not exist on the market

The ones that exist provide too much power and are not possible to integrate in our ‘small’ galleries

In addition, for such specific power requirements, as output power reduces if we go over saturation (nominal) point of operation, we would need to operate lower than nominal point of operation

This would induce loss of efficiency, almost doubling the cost (acquisition + operation)

Finally, phase stability is given by construction from HV stability (very expensive)

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

SSPA, an option but at high cost

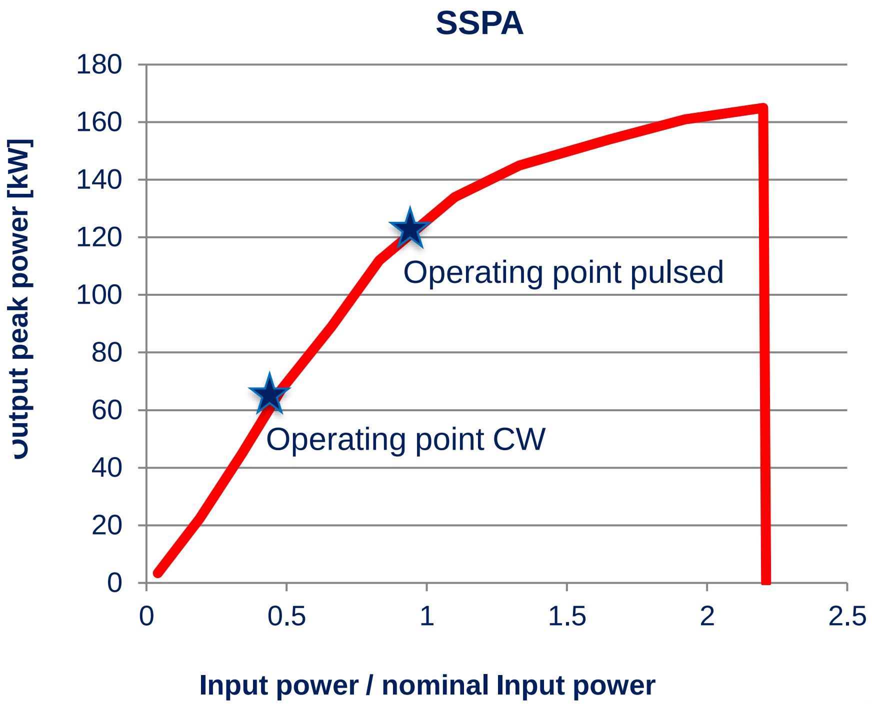
Transistors are destroyed in case of large overdrive (+ 3 dB = x 2) longer than ~ 100 µs

Hard protection limit are needed, could be built in, but then it is complex to manage for LLRF, so we try to have a good LLRF protection system

To avoid destruction, overhead must be perfectly and ...

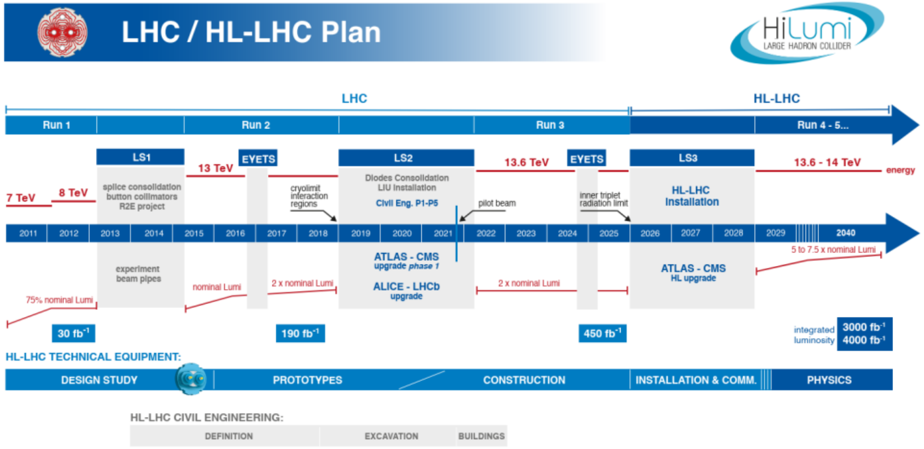
Overhead v... gridded tube...

Spare slides if you wish to better understand the constraints




ATC
201J
ATC
201J

SSPA obsolescence



When we started SPS SSPA in 2017, the chosen transistor was the 'best for new design' quoted by the transistor supplier

Beginning 2022, we received a 'Last Buy Order' email…

(the same with other labs, within 3-5 years, 'best to use' transistors turn to be 'do not use for new design', and to 'obsolete' item…)

Changing the transistor generation is often linked to changing the operating voltage, this mak… at change out of budget

The difficulty with Acce… buy a new amplifier, it …

…ier architecture should then be … uch that the amplifier will last the 20 years without major upgrade

Spare slides if you wish to better understand the constraints

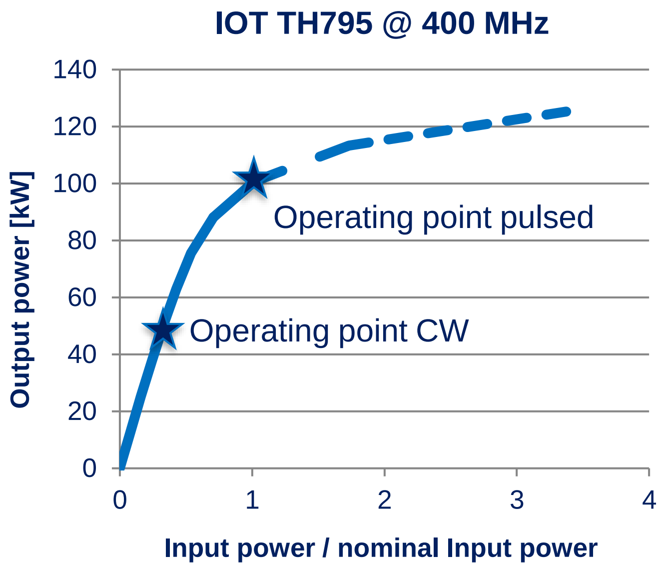
IOT, 'like if designed' for the Crab

A great advantage of gridded tubes is that they allow overdrive without damage

Tetrodes & Diacrodes are limited in frequency (max ~ 400 MHz)

IOT can operate from low (100 MHz) to high frequencies (1.3 GHz), including 400 MHz

The gain of an IOT is around 23 dB, so to reach 100 kW, an only 500 W driver is needed



IOT, Already tested in the SPS

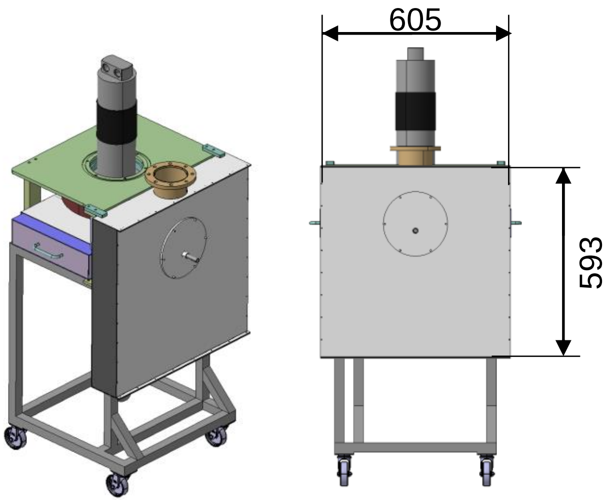
CERN SPS, TH 793 IOT, Trolley (single amplifier), and transmitter (combination of amplifiers)
Two transmitters of four tubes delivering 2 x 160 kW @ 801 MHz, into operation since 2014

IOT, Already tested in the SPS

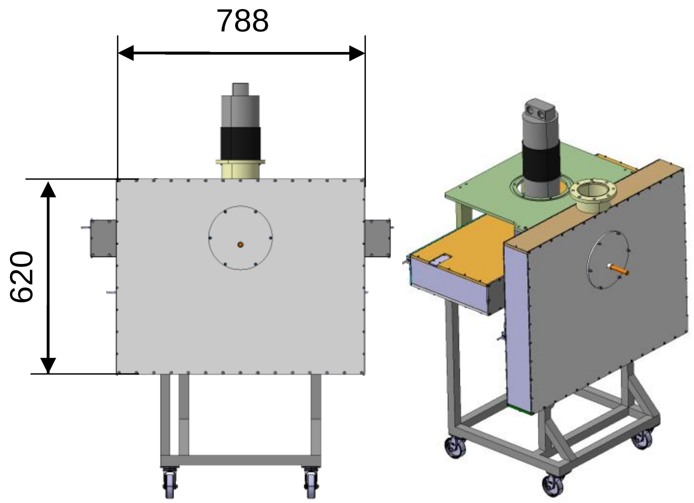
CERN SPS, TH 795 IOT upgrade to deliver full power at 801 MHz

The tube is an evolution of the TH793, providing even more reliability than the TH793

IOT trolley designed by CERN for SPS tests



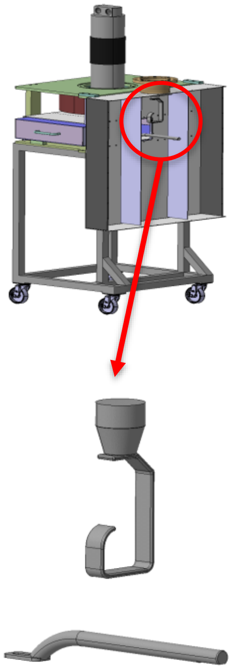
TH18795 800 MHz trolley



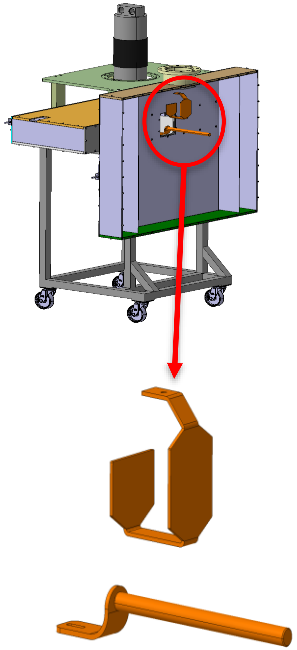
TH18795 modified by CERN 400 MHz trolley

IOT trolley designed by CERN for SPS tests

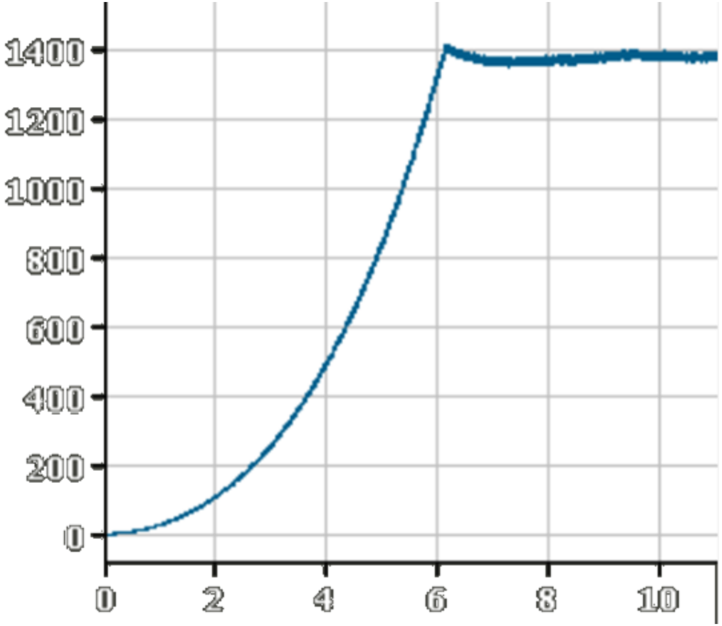
TH18795
800 MHz
trolley and
800 MHz
coupling
elements



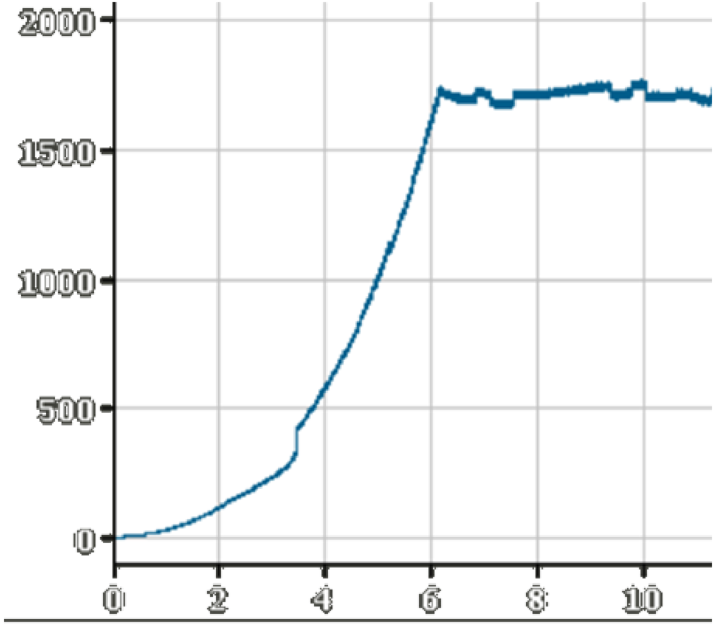
TH18795m
odified by
CERN
400 MHz
trolley and
400 MHz
coupling
elements



Still difficult linearisation at very low power



Following a careful adjustment of all parameters (Fc, BW, HV, Focus, Heater), correct transfer curve



If some parameters are not correct (Fc, BW, HV, Focus, Heater), step in transfer curve at low power

The difficulty is that this never occurs on a 50 Ω load

Still difficult linearisation at very low power

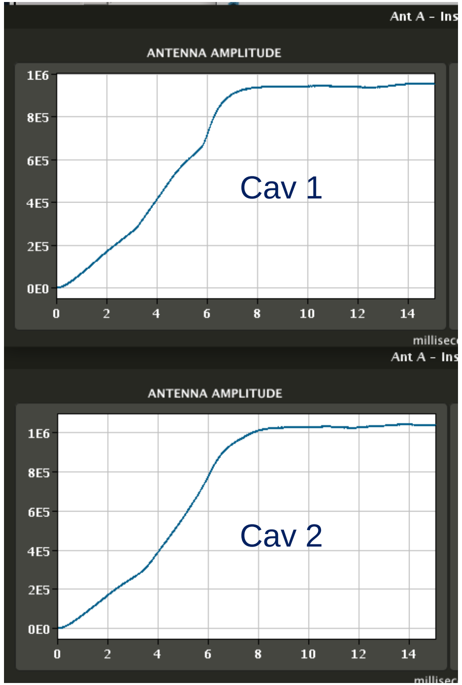
During MD, we noticed a problem with a tube that needed a replacement of this tube

After exchange, as retuning all parameters, we were able to remove the nonlinearity

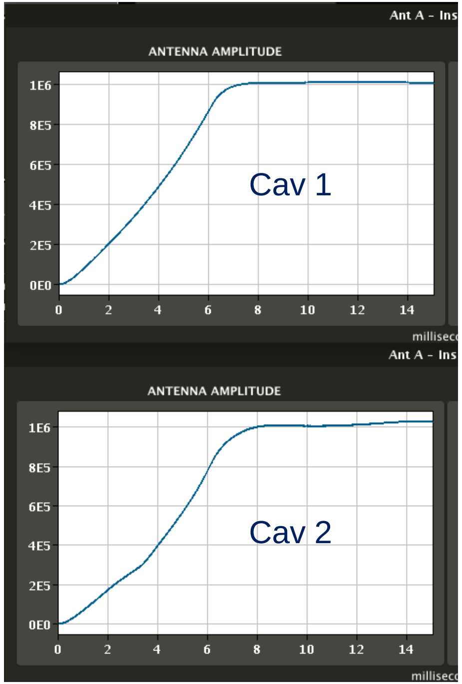
The difficulty is that this phenomena does not appear when the amplifier is connected onto a 50 Ω load

Next MD, we will retune all parameters of the second amplifier

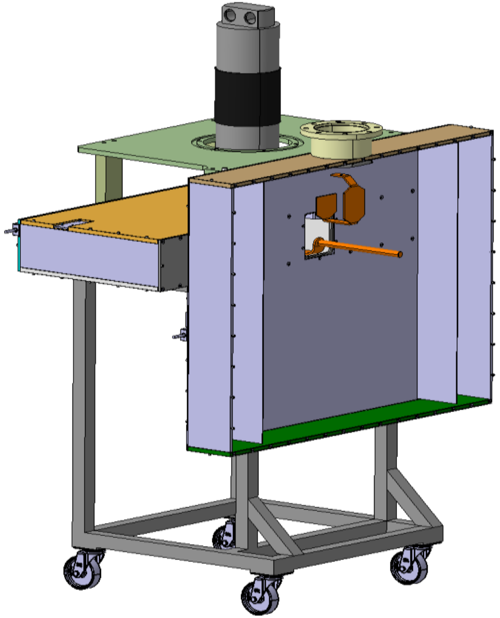
Jun 2023, MD



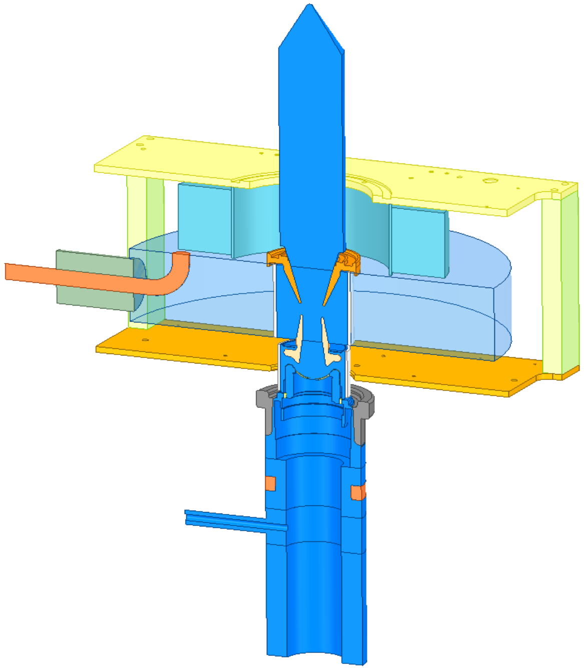
Jul 2023, MD



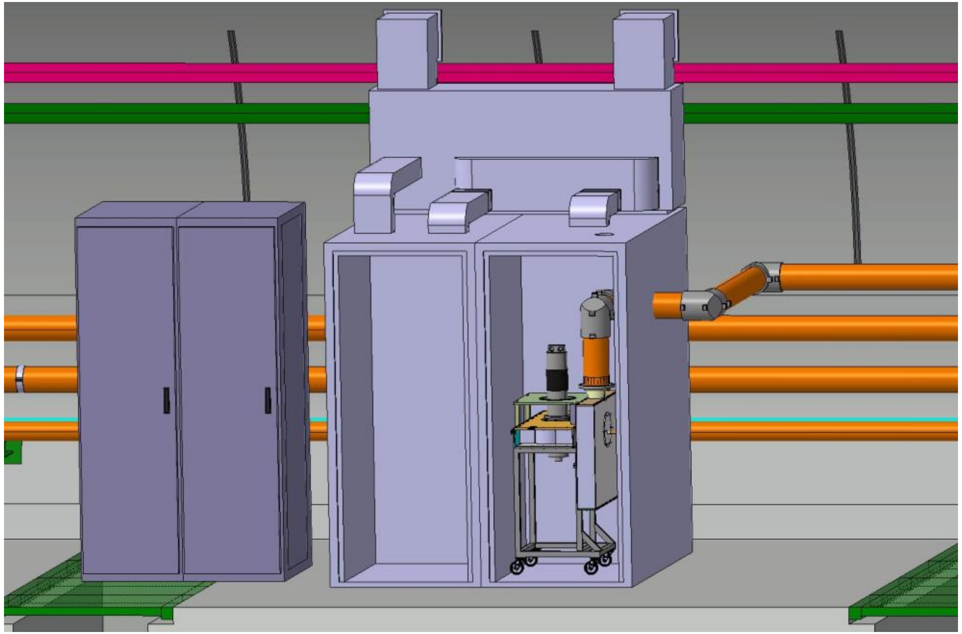
New trolley as a collaboration CERN/Thales



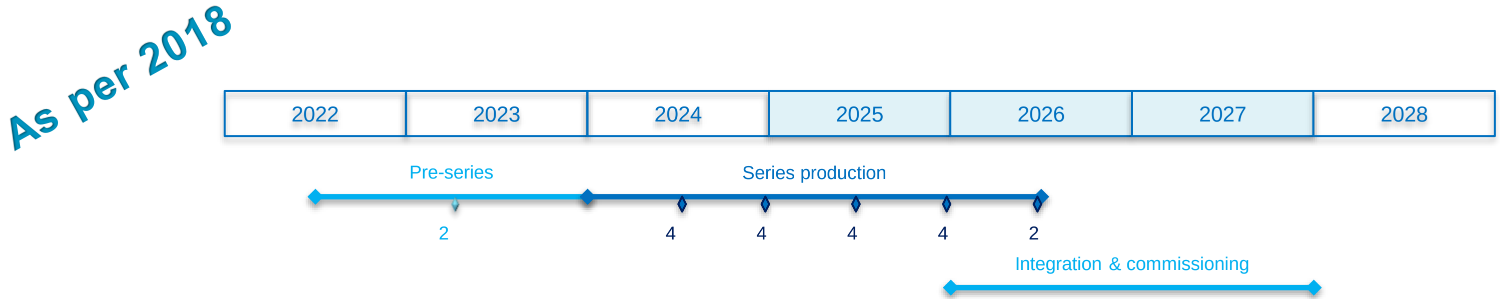
Two output cavities
will become
one single output
cavity with a radial
coupling element

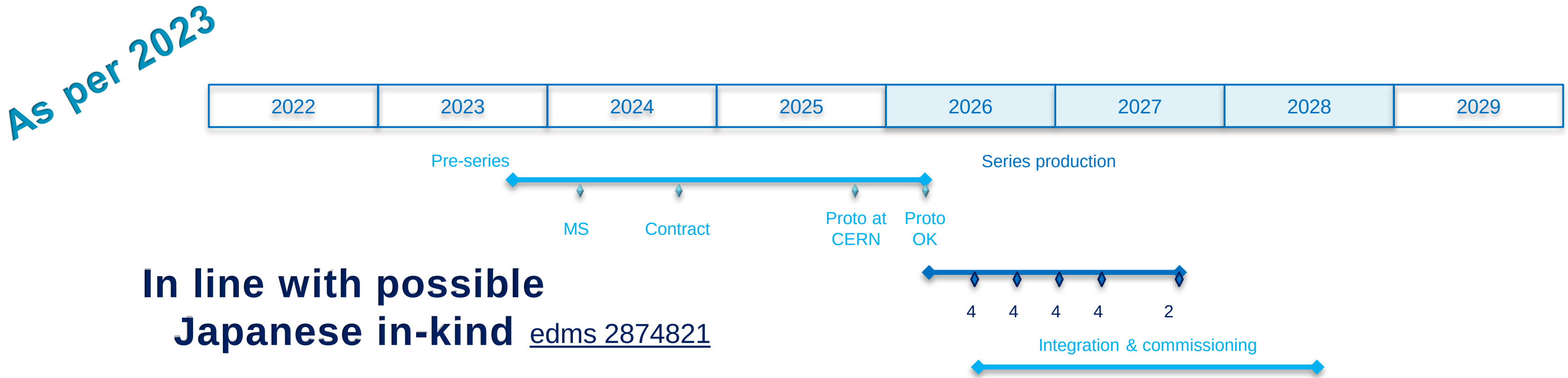


New HPRF as a collaboration station CERN/Thales



IOT HPRF schedule





In line with possible Japanese in-kind edms 2874821

HPRF stations, where?, when?

2023	2024

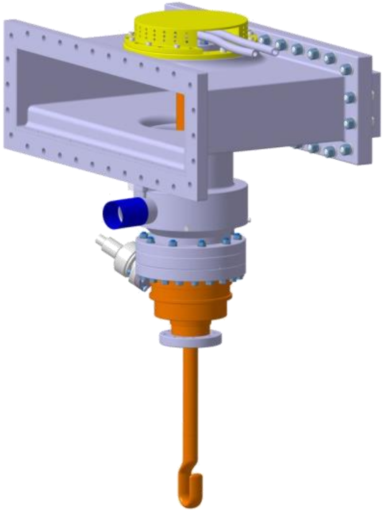
HPRF1 ◆ BB3 (FPC processing) — Canada on request ◆

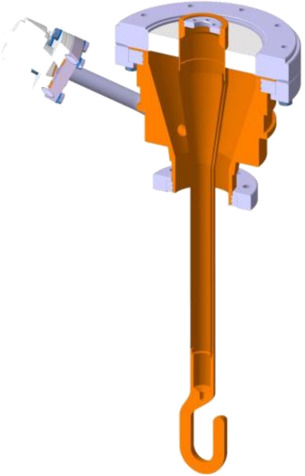
HPRF2 ◆ BA6 — ◆ BA6 + FPC processing

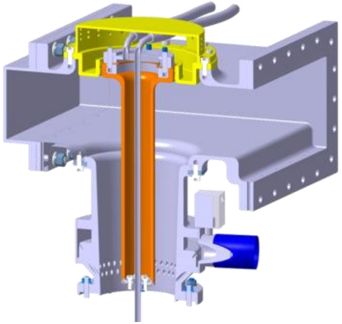
HPRF3 ◆ BA6

Collaboration with Thales ◆ SM18

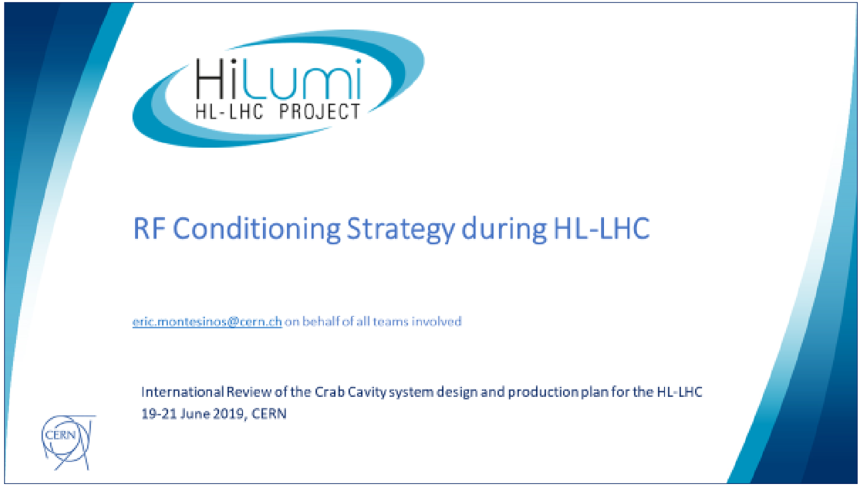
FPC

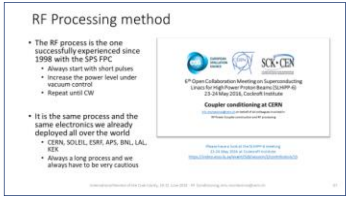


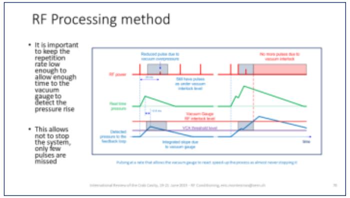


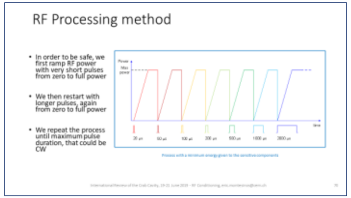


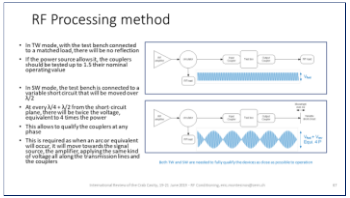
RF Processing

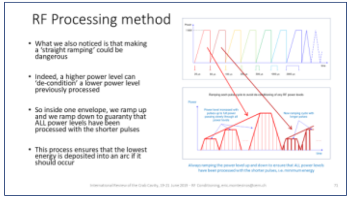


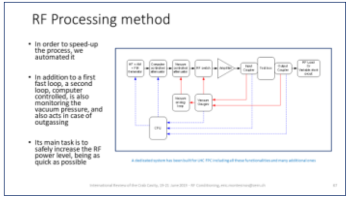




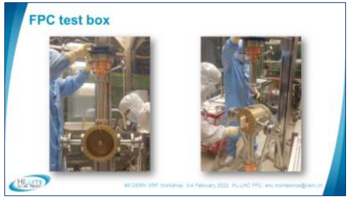


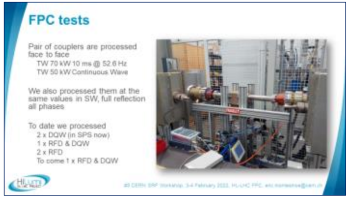




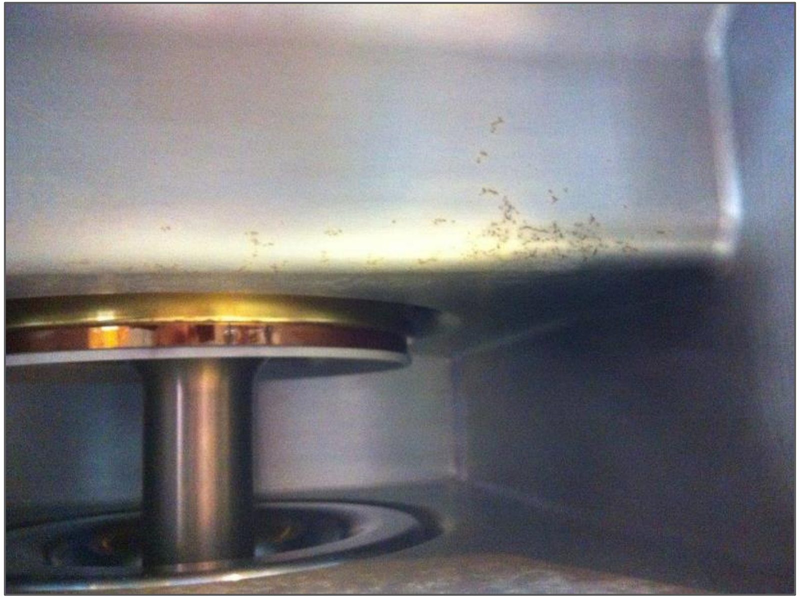


Clean room preparation of FPC

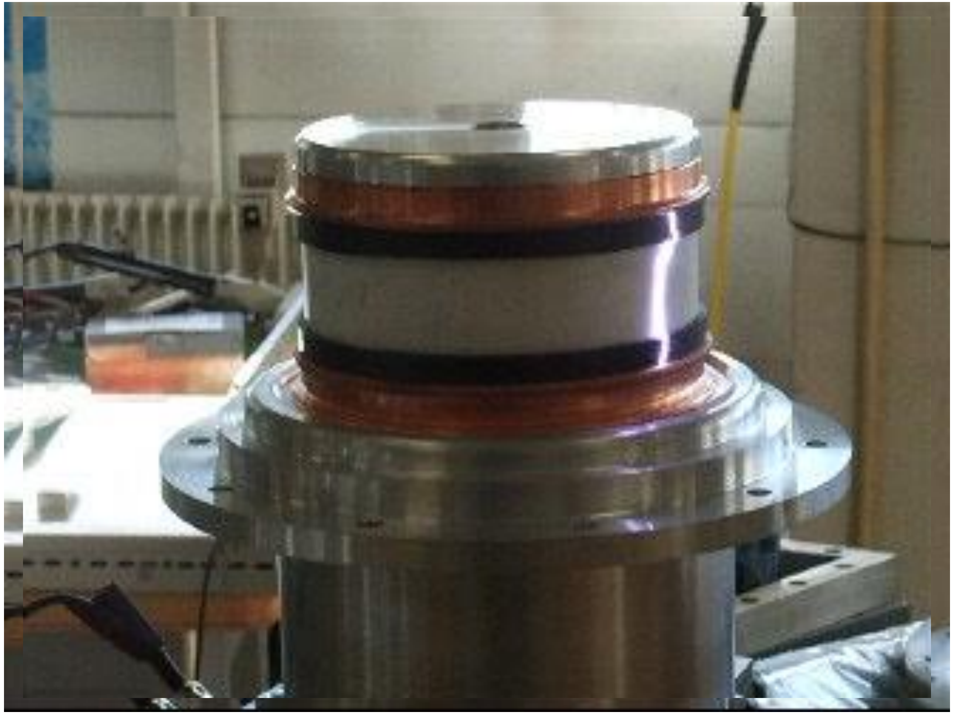




Arcing in FPC

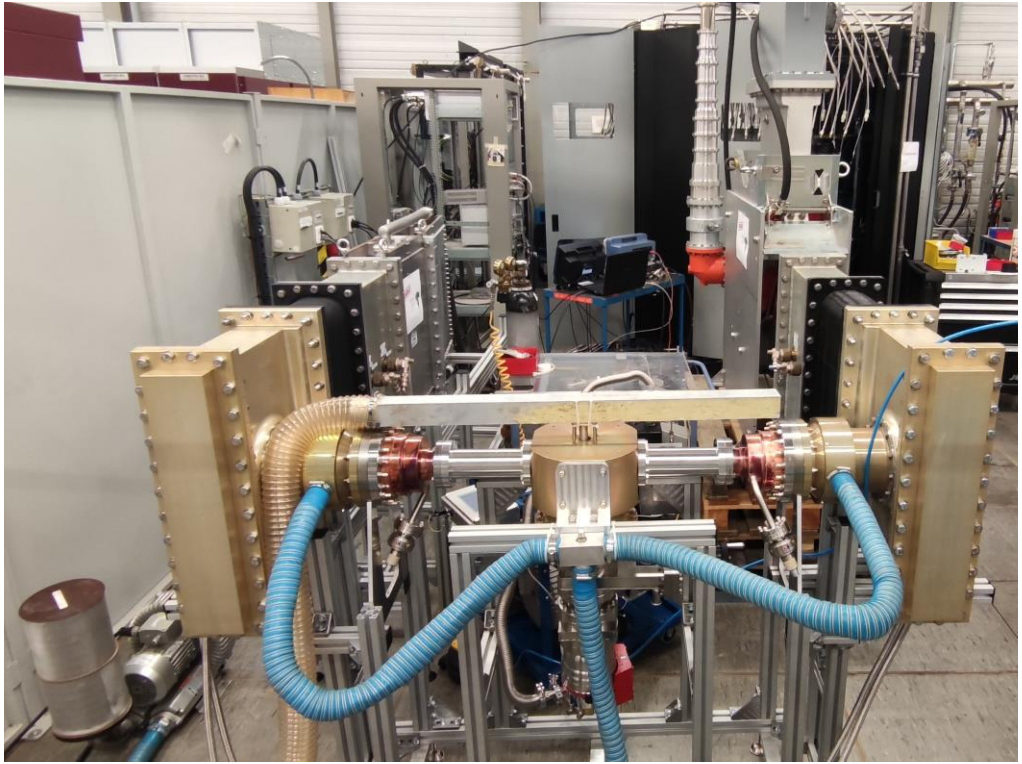


Arcing in FPC



RF processing to avoid failures

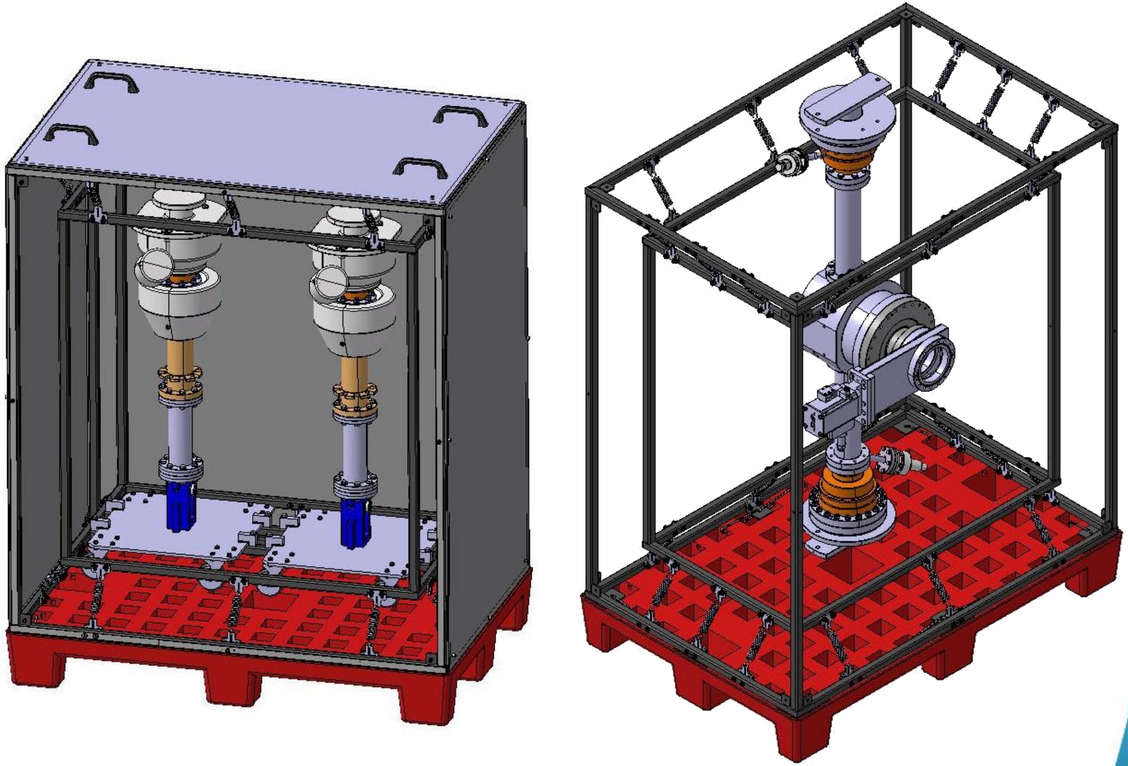
FPC RF processing



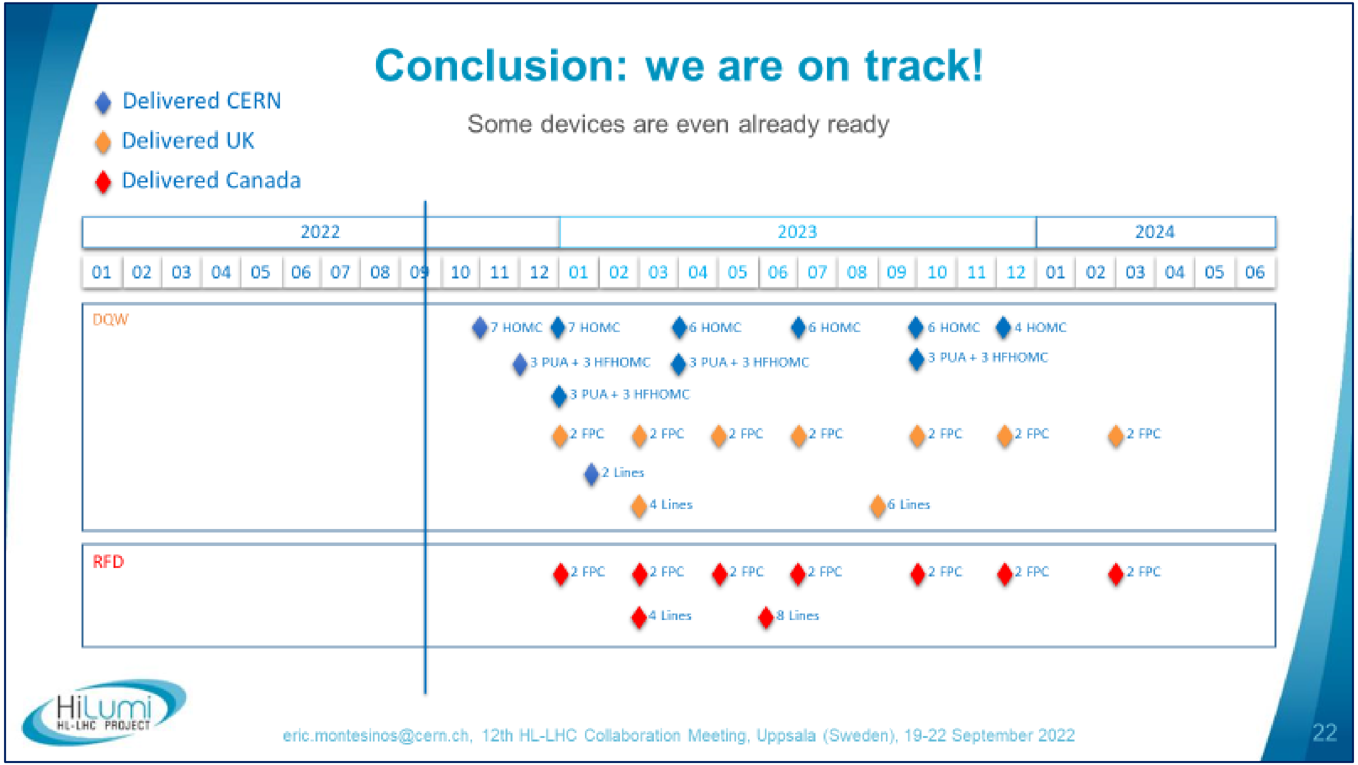
FPC transport to Canada and UK

Initially, we intended to disassemble the two couplers from their test box, and to transport them individually

However, this would remove all the RF processing work we did, so we now prefer to send them still assembled onto their test box, under vacuum

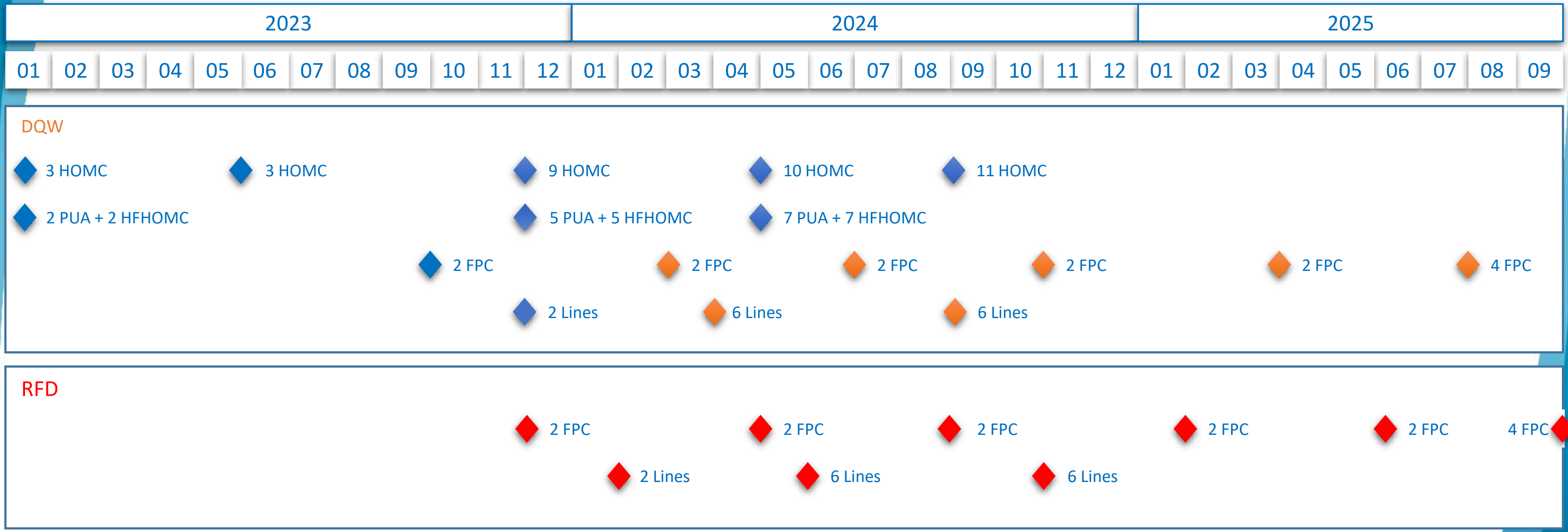


Last year at Uppsala



Couplers Master Schedule

Delivered CERN
Delivered UK
Delivered Canada



Conclusion

IOT is really THE solution for Crab

We really hope that in-kind with Japan will happen

Our schedule is in-line with proposals made by our colleagues

Production of FPC (and HOMC and RF lines for cryomodule) is on good way

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

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

Thanks to all colleagues involved with this HPRF & couplers projects

Thanks to all colleagues from Japan for trying to make the in-Kind a reality

Thanks to Rama and Ofelia (WP4 leaders), to RF management and to HL-LHC management for supporting us with this very exciting (and very challenging) project

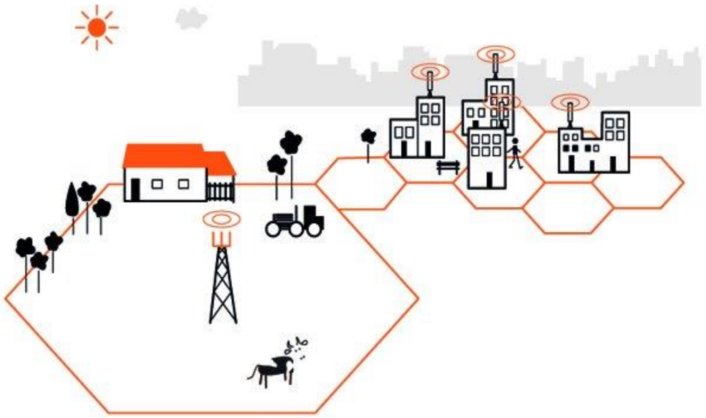
We (SY-RF teams and all associated colleagues from many groups) are devoted to provide HL-LHC with reliable RF systems

SSPA obsolescence spare slides

Transistor power ratings

Device	Distance	Power
Phone	20 km	2 W
Microcell	2 km	10 W
Macrocell	20 km	50 W

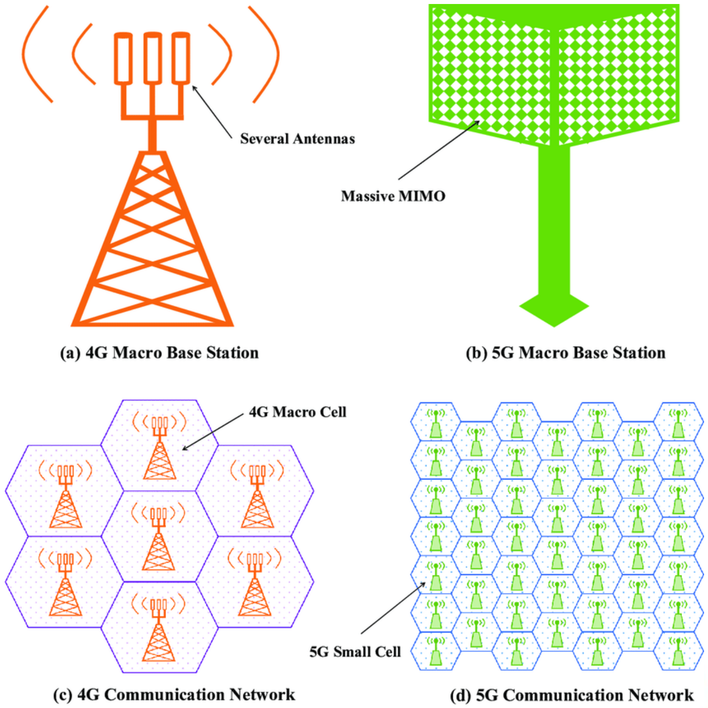
Voltage limits		
	2002	Since 2006
900 MHz	41 V/m	3 V/m
1800 MHz	58 V/m	
2100 MHz	61 V/m	



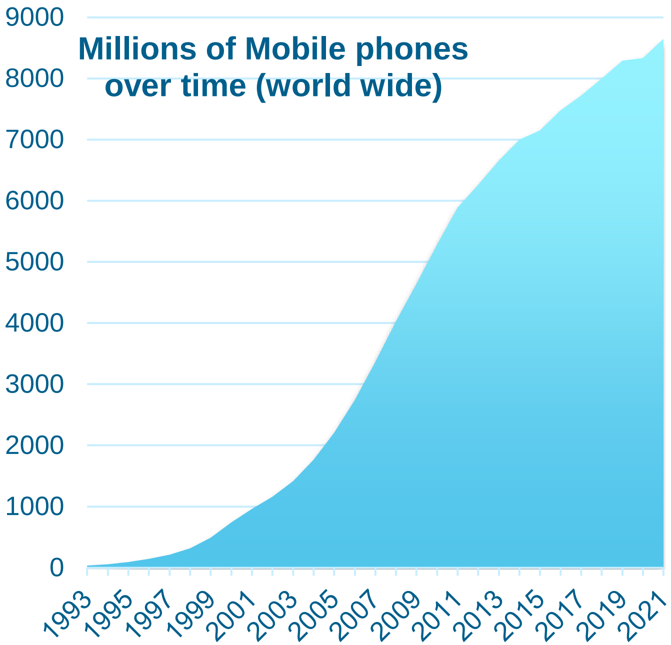
The tendency is to increase the number of smaller cells in order to keep the phone battery autonomy, increase the data bandwidth, and reduce the exposition of population to too high electromagnetic fields

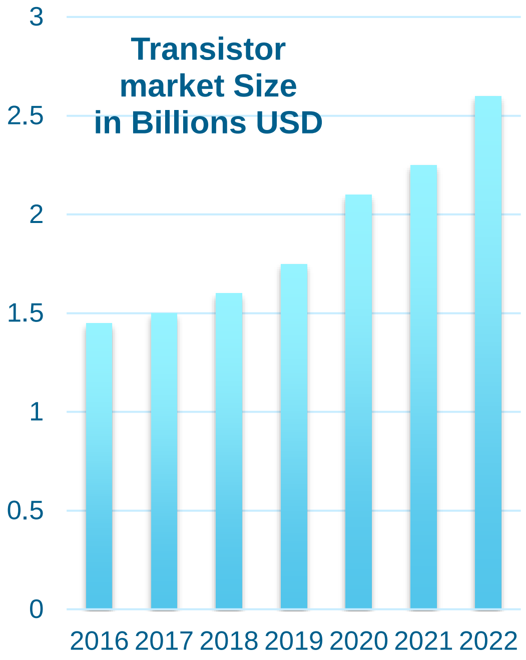
Macro cells vs Small cells vs femtocells

	MACROCELLS	SMALL CELLS	FEMTOCELLS
SIZE	Around 50 to 200 feet tall	The size of a pizza box	The size of a paperback book
AVERAGE COVERAGE RANGE	A few miles	A football field -- 100 yards	A home or small business
AVERAGE COST TO INSTALL	$200,000	Under $10,000	Around $100
DEPLOYMENT	The U.S. has about 200,000 macrocells	The U.S. will have 5 to 10 times more small cells than macrocells once fully deployed	Anyone can purchase a femtocell for their home or small business



A few numbers to situate RF transistors in accelerators

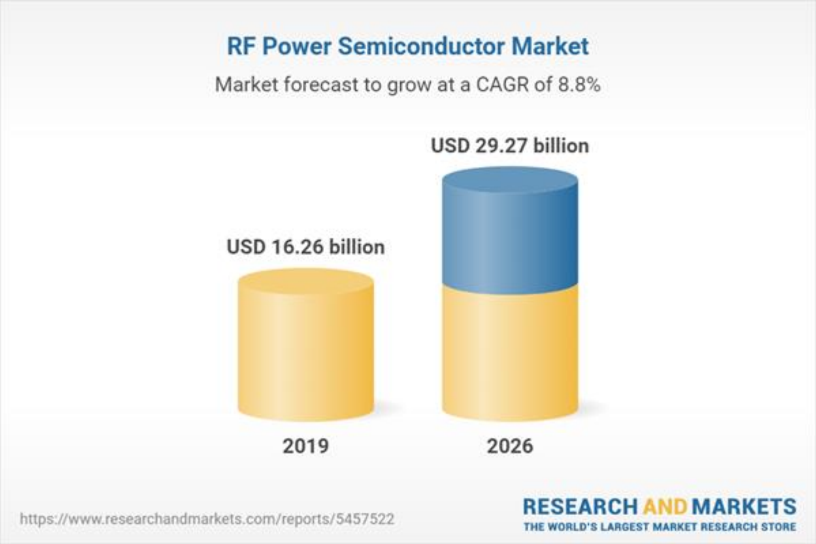


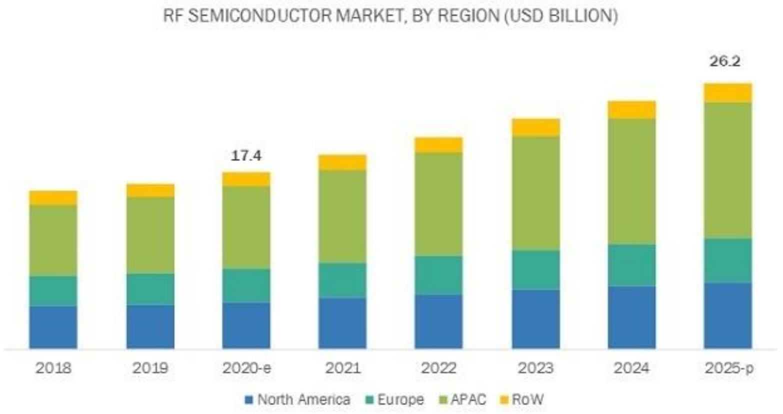


Some of the Key Players

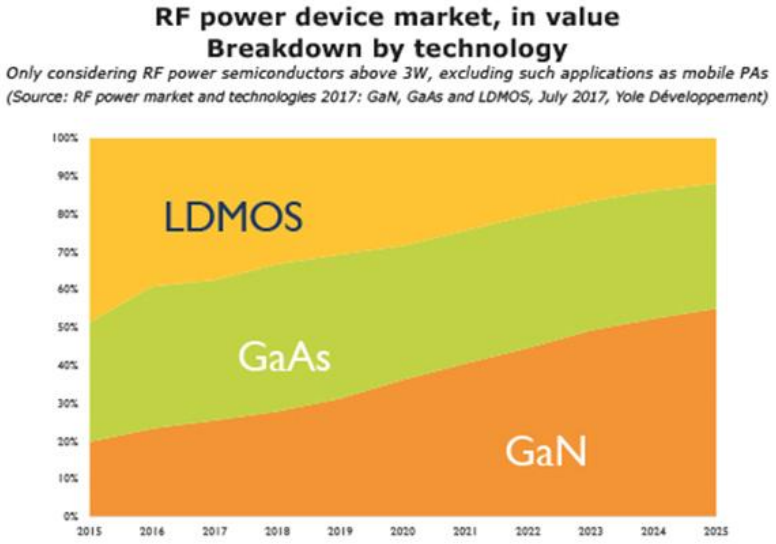
Ampleon
Analog Devices
BONN Elecktronik
Broadcom Pte.
Cree
General Dynamics
Infineon
Integra
MACOM
Maxim Integrated
Mitsubishi
NoleTec
NXP Semiconductors
Qorvo
Qualcomm
Skyworks Solutions
STMicroelectronics
Tagore Technology
Thales Alenia Space
Toshiba

A few numbers to situate RF transistors in accelerators

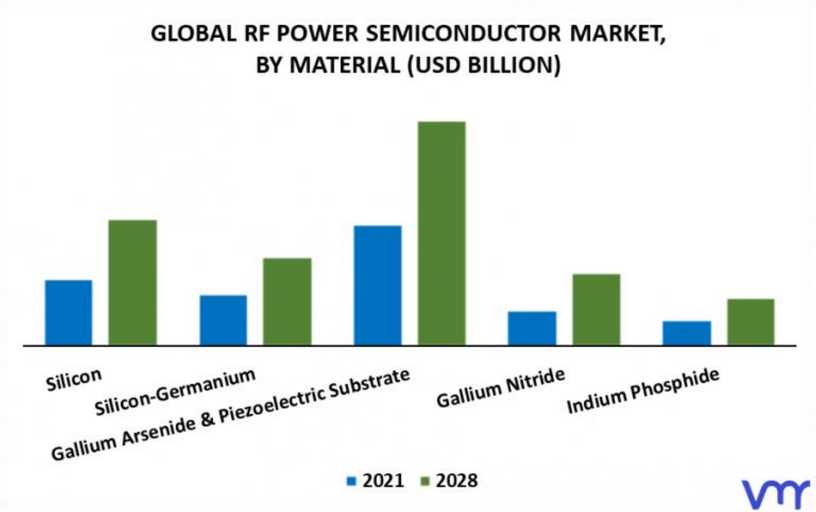




A few numbers to situate RF transistors in accelerators

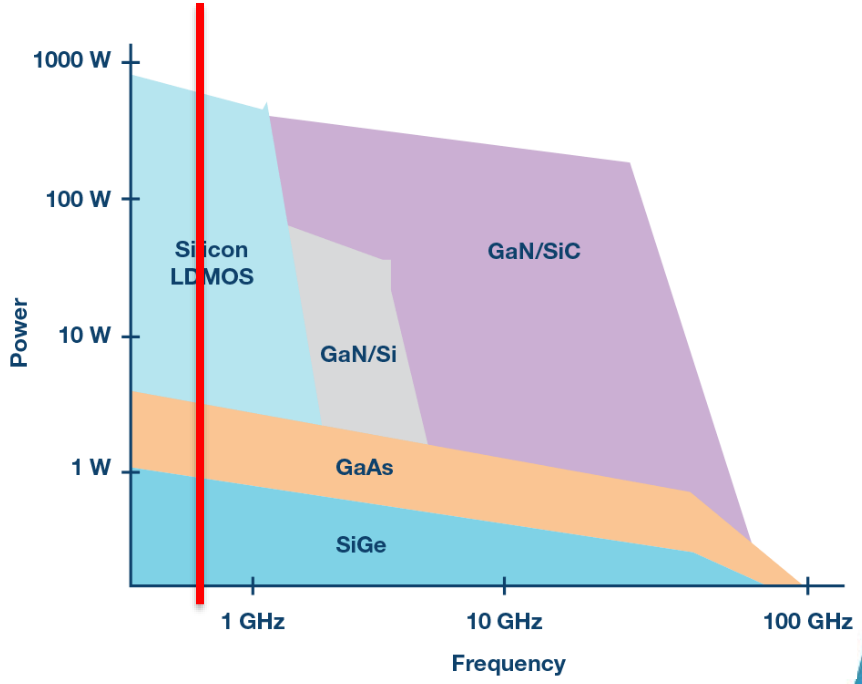


Source: RF Power Semiconductor Market Trends
From Yole Développement
Patrick Hindle - Editor, Microwave Journal July 11, 2017



A few numbers to situate RF transistors in accelerators

FCC (400 MHz to 800 MHz) due in ~ 15 years



Transistor power ratings – *personal view* of future perspective (CWRF 2016, updated 2022)

Transistor supplier main business will not be higher power per transistor

Conclusion: below a GHz, 1 kW per transistor (LDMOS) seems *(to me)* a very good goal

8.5 Billions Smartphones in 2021

90 Millions Femtocell stations 2016

7 Millions Macrocell stations 2017

NXP Semiconductors revenue in 2020 was $8’600 Millions

Assumption (with a lot of simplifications)

Machine	# RF stations	Power	# 1 kW LDMOS
FCC	1’000	1 MW	1’000’000

Cost of a LDMOS ~ $100

Total cost of FCC ~ $100 Million

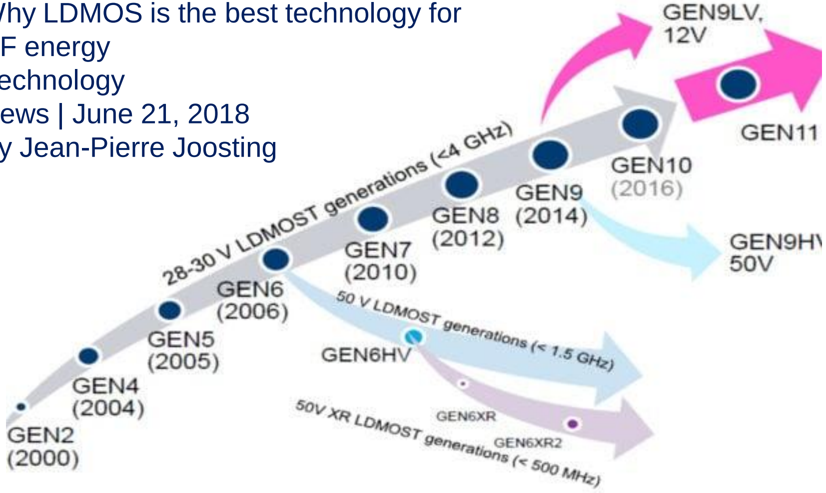
Over minimum 5 years of construction ~ $20 Million per year

RF for accelerators could be 20 / 8600 = 0.2 % of main suppliers' revenue

Drain voltage

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

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



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

SSPA granularity & redundancy

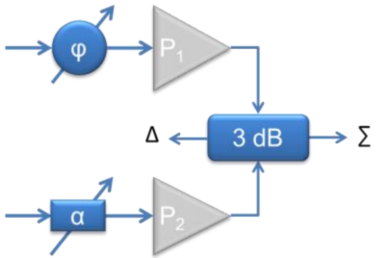
Combination

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

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

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



With PA1 = PA2 = PA3 = PA4 = P then

Pout = 4 P

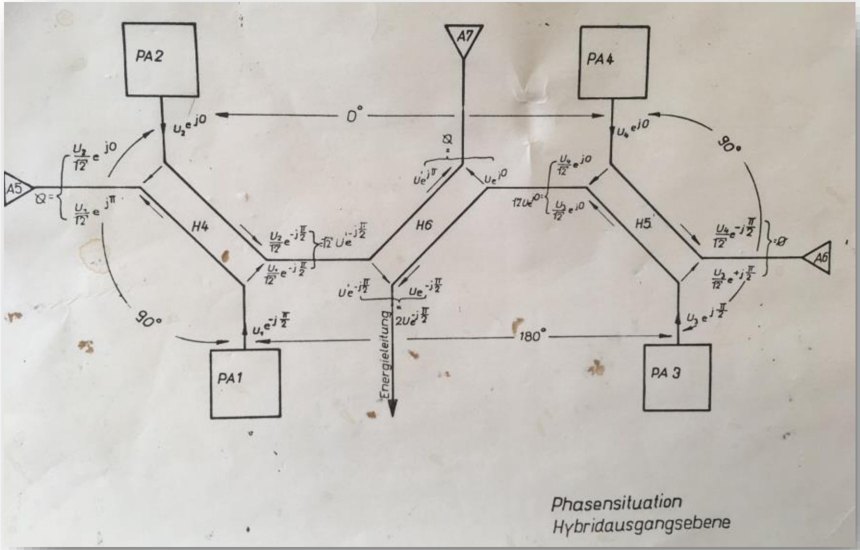
Load A5 = A6 = A7 = 0

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



Cavity Combiner

With our latest combiner, @ 750 MHz, the body is composed of four main pieces

a tube

a bottom plate

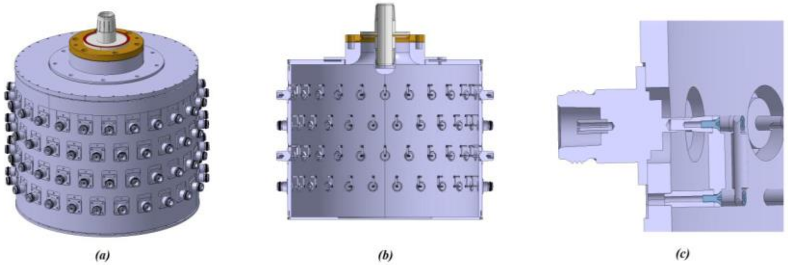
a top plat

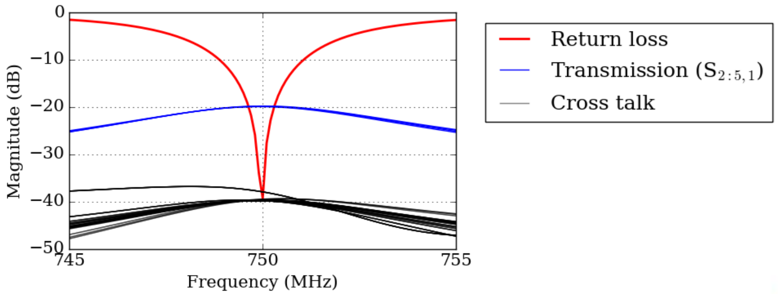
an output probe housing

The tube has machined holes compatible with N-type solder cups, the bottom plate has an indentation for disc tuning and the output probe housing is compatible with a standard EIA 3-1/8” flange

The return loss of the output port is ≤ -20 dB between over a 1 MHz bandwidth

The transmission between the 96 individual inputs and output is -19.84 ± 0.05 and the cross talk between the inputs is < -35 dB

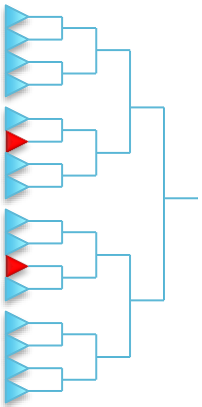




Redundancy

In order to ensure 100 % availability, given a ***Redundancy***, the technology of the combining system will define the number of **Units**

Power per **Unit** = 1



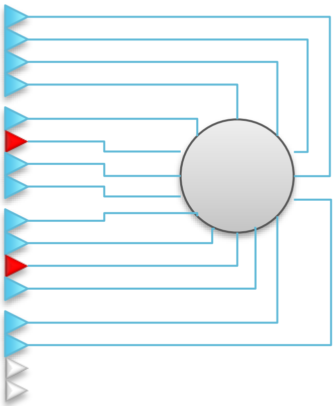
P_{out} must be 12 x P at all time, even with **2 Units 'off-line'**

In order to be 100 % available a 3 dB combiner requires **16 Units**

$$Pout = \frac{A1 + A2}{2} + \sqrt{A1 \, . \, A2}$$

P_{out} must be 12 x P at all time, even with **2 Units 'off-line'**

In order to be 100 % available a cavity combiner only requires **14 Units**

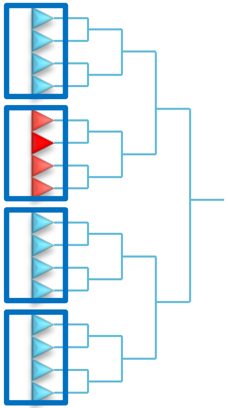


$$Pout = n \, A1$$

Redundancy

In order to ensure 100 % availability, given a ***Granularity***, the technology of the combining system will define the number of **Units**

1 Module =
4 x Units



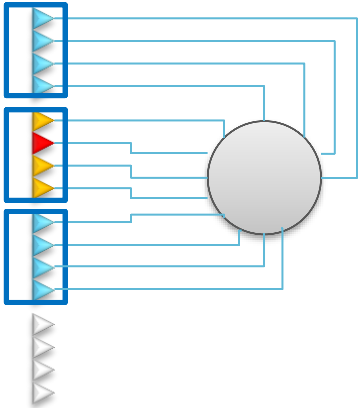
P_{out} must be 8 x P
at all time, even with
1 Unit 'off-line'

In order to be 100 % available a 3 dB combiner requires **16 Units**

$$Pout = \frac{A1 + A2}{2} + \sqrt{A1 \, . A2}$$

P_{out} must be 8 x P
at all time, even with
1 **Unit 'off-line'**

In order to be 100 % available a cavity combiner only requires **12 Units**



$$Pout = n \; A1$$

Redundancy & Granularity for Crab

Let imagine that we go for a SSPA for Crab

We would have to deliver 50 kW CW and 100 kWp

At 400 MHz, power per LDMOS transistor would (safely) be around 500 W, breaking with 2.2 x the 500 W equivalent drive

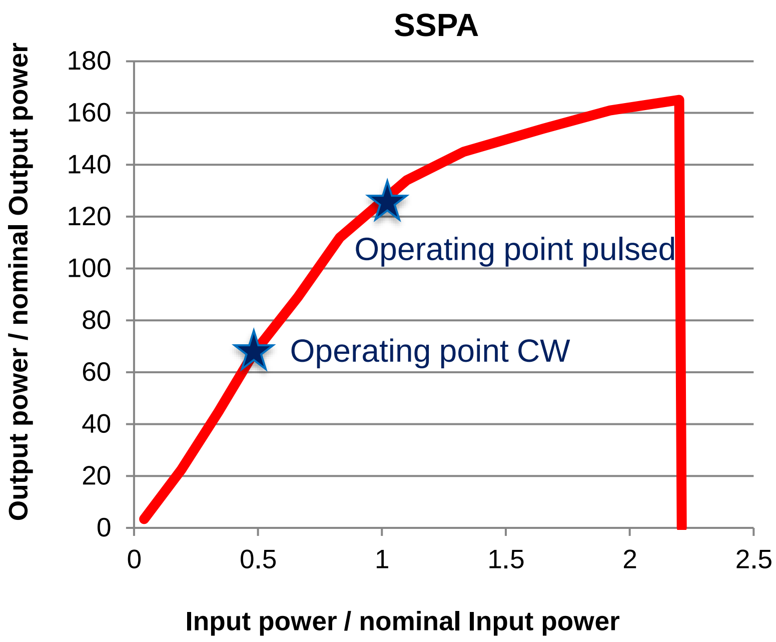
Going with single Power Supply per transistor to keep the granularity, and imposing full characteristics even with 10 % Units off, this would mean

With a 3 dB combiner

- 256 Units
- Full power with 230/256 Units = 103 KWp

With a cavity Combiner

- 220 Units
- Full power with 200/220 Units = 100 kWp



CERN 2 x 16 x 80 = 2560 modules of 2 kWp each @ 200 MHz solid state amplifiers (2021) in the SPS delivering 2 x 1.6 MWp (compared to 2 x 2.5 MW possible)