



LLRF2017

Low Level Radio
Frequency
Workshop



BARCELONA
16-19 October

RF power & LLRF

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20171017

Outlook

Preamble

Power sources

Tetrodes

Klystrons

IOT

Solid State Power Amplifiers (SSPA)

Combiners

Transmission Lines

Fundamental Power Couplers

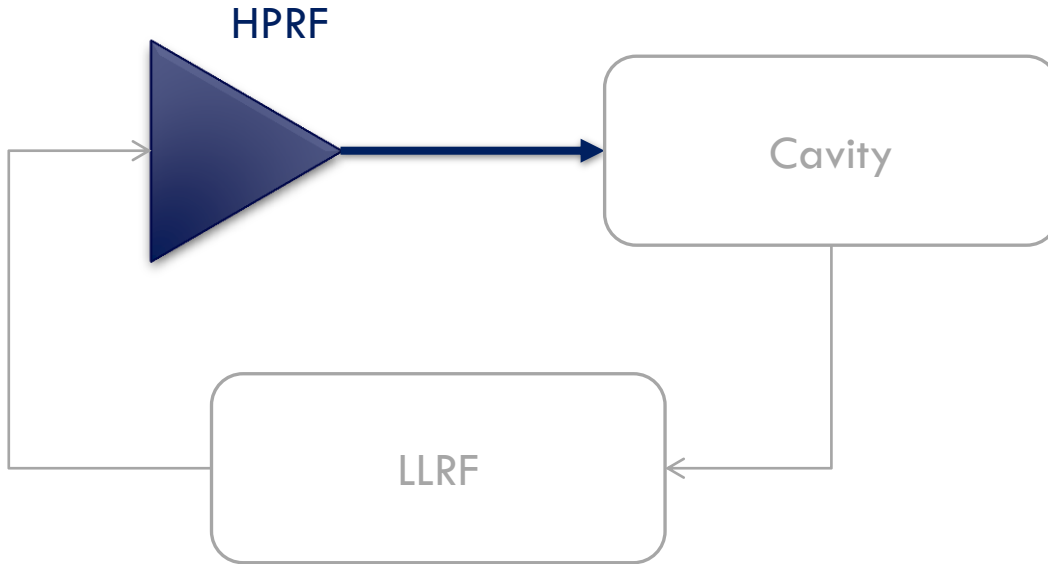
Range of HPRF at a glance

Overhead

True life for HPRF and LLRF

Conclusion

Preamble



W → **kW** → **MW**

€ → **k€** → **M€**

Very important for all projects

Rule of thumbs, HPRF

acquisition costs

5 € / W (MW amplifiers)

to 10 € / W (kW amplifiers)

Preamble

Class of operation	A	B	C
Advantage	Linear	Almost linear	Non linear
DC to RF efficiency	30 %	78.5 %	90 %
Wall plug efficiency	20 %	40 %	50 %
Cost per 10 year [k€] 100 kW RF CW 5000 hours	3750	1870	1500
Acquisition	500	500	500

W → **kW** → **MW**
€ → **k€** → **M€**

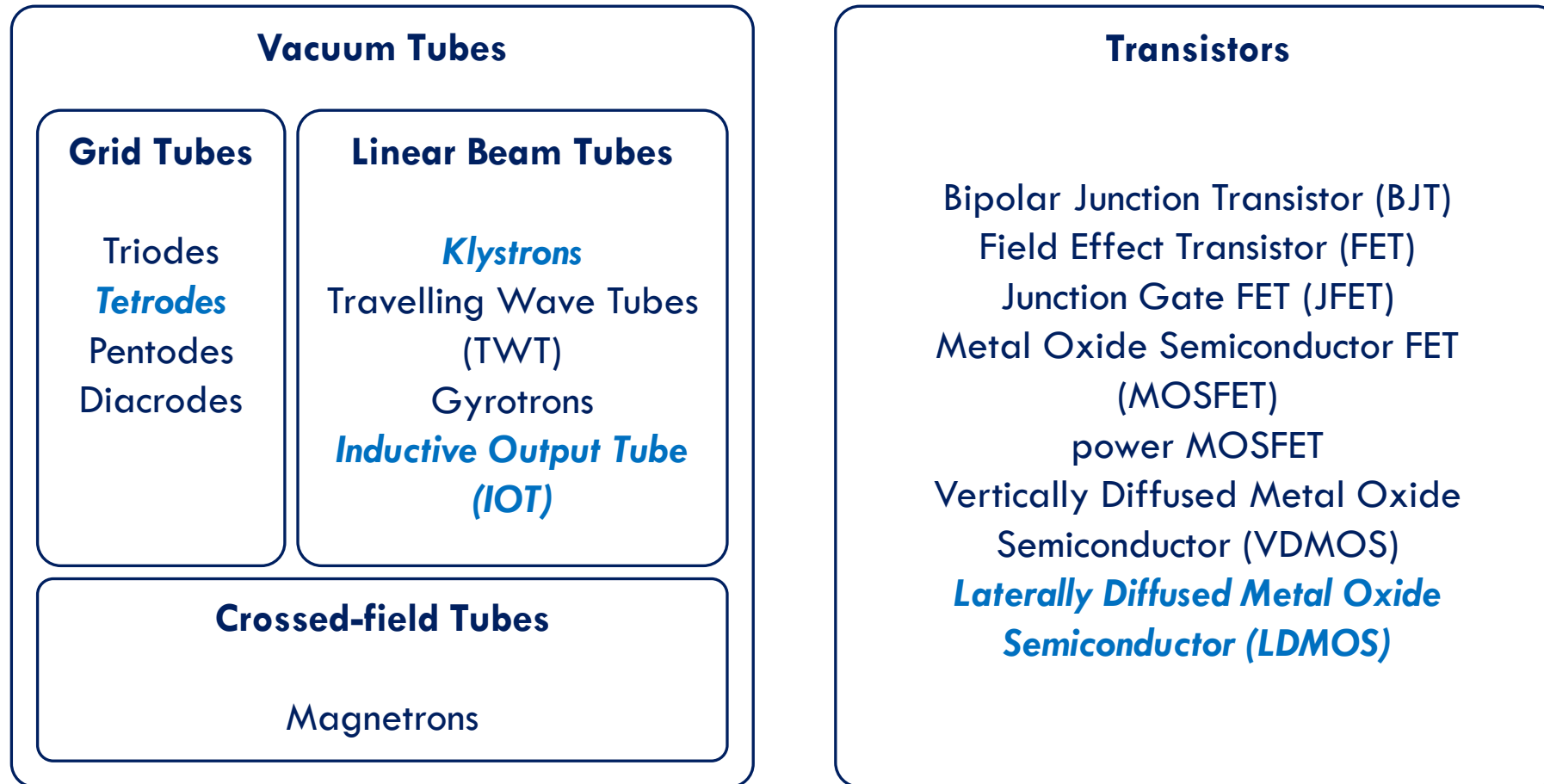
Very important for all projects

Rule of thumbs, HPRF

operational costs

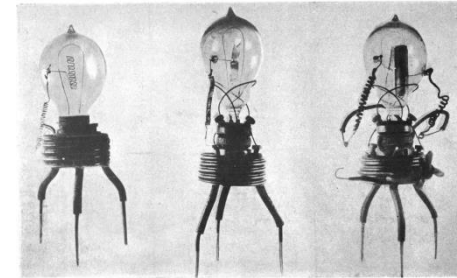
$$\frac{0.15 \text{ €} / kWh}{\text{efficiency}}$$

RF power sources classification



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

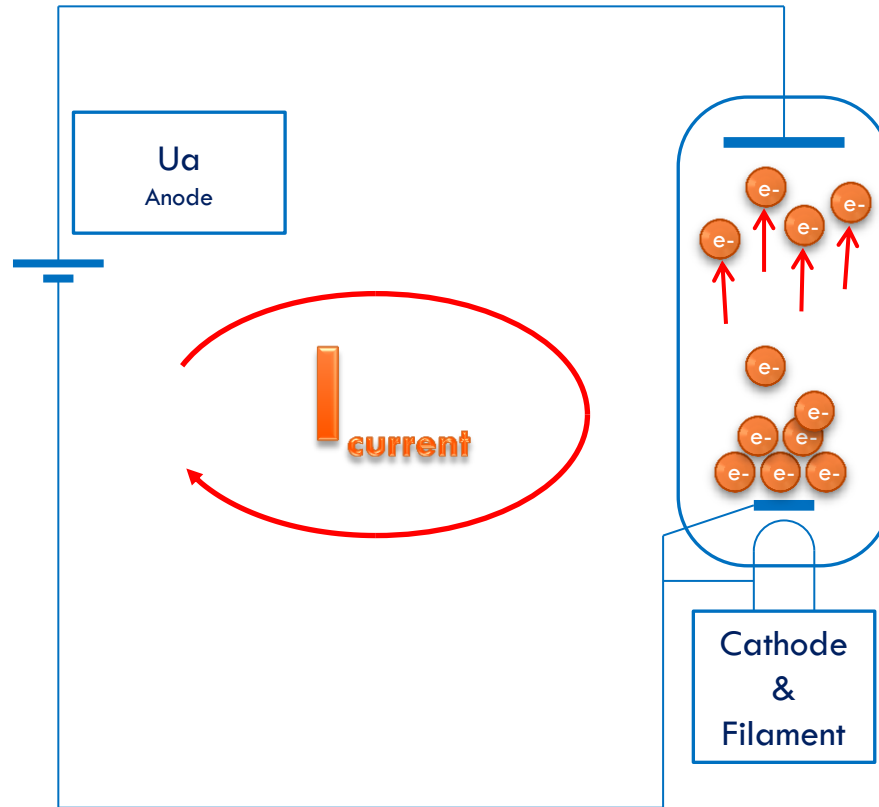


The first diode prototype
Fleming Diode, 1904



Thales TH 628 diacrode, 1998

Essentials of grid tube



Vacuum tube

Heater + Cathode

Heated cathode

Coated metal, carbides, borides,...

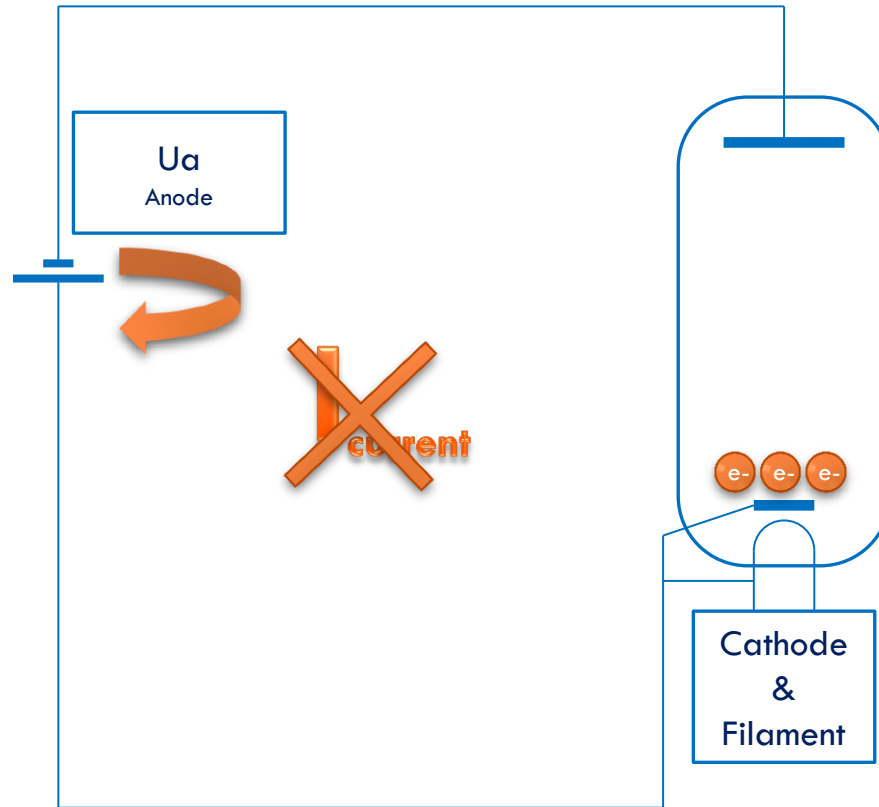
thermionic emission

Electron cloud

Anode

Diode

Essentials of grid tube



Vacuum tube

Heater + Cathode

Heated cathode

Coated metal, carbides, borides,...

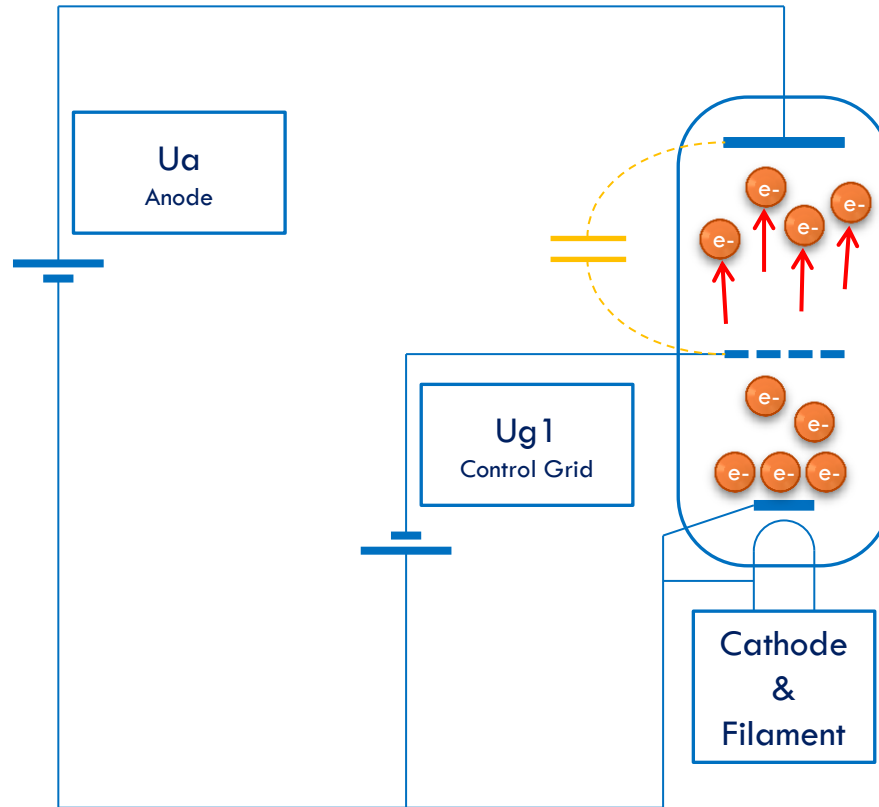
thermionic emission

Electron cloud

Anode

Diode

Essentials of grid tube



Triode

Modulating the grid voltage proportionally modulates the anode current

Transconductance

Voltage at the grid

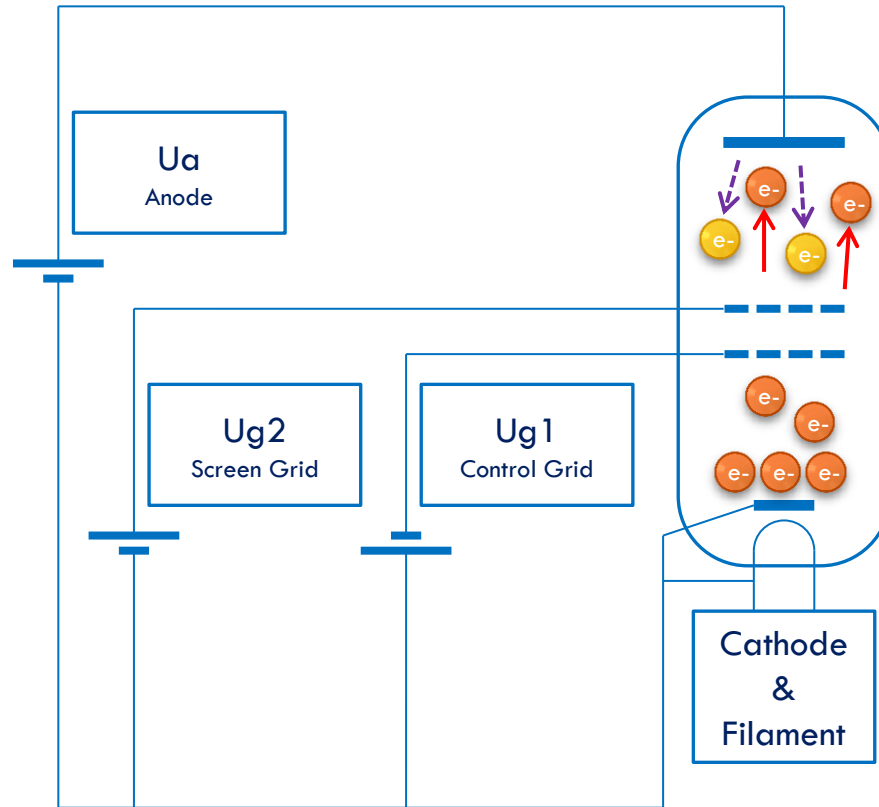
Current at the anode

Limitations

Parasitic capacitor Anode/g1

Tendency to oscillate

Essentials of grid tube



Tetrode

Screen grid

Positive (lower anode)

Decouple anode and g_1

Higher gain

Limitations

Secondary electrons

Anode treated to reduce secondary emission

Essentials of grid tube

DC power is $P_{dc} = V_{dc} I_{dc}$

Assuming the tube is linear whilst it is conducting, the dc anode current is found by Fourier analysis of the current waveform and is $I_{dc} = I_{pk}/\pi$

$I_{rf} = I_{pk}/2 = I_{dc} \pi/2$, and ideal class B, $V_{rf} = V_{dc}$

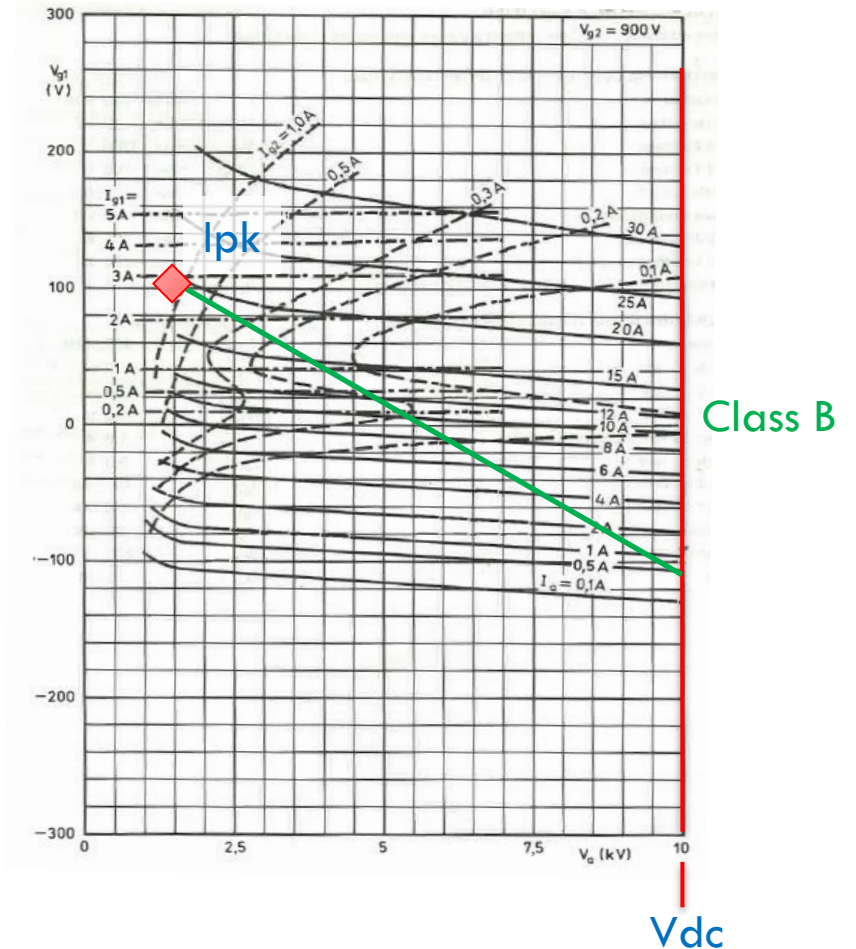
So, RF power is $P_{rf} = \frac{1}{2} V_{rf} I_{rf}$

$P_{rf} = \frac{1}{2} V_{dc} I_{dc} \pi/2 = \pi/4 V_{dc} I_{dc}$

Theoretical efficiency

$\eta = P_{rf}/P_{dc} = \frac{1}{4} V_{dc} I_{pk} / V_{dc} I_{dc}$

$\eta = 78.5 \%$



Essentials of grid tube

Two reasons for not achieving this impressive number

- tube is not fully linear whilst it is conducting

- Anode voltage must be higher than G2 voltage, VG2 being ~ 10% Vdc

This leads into

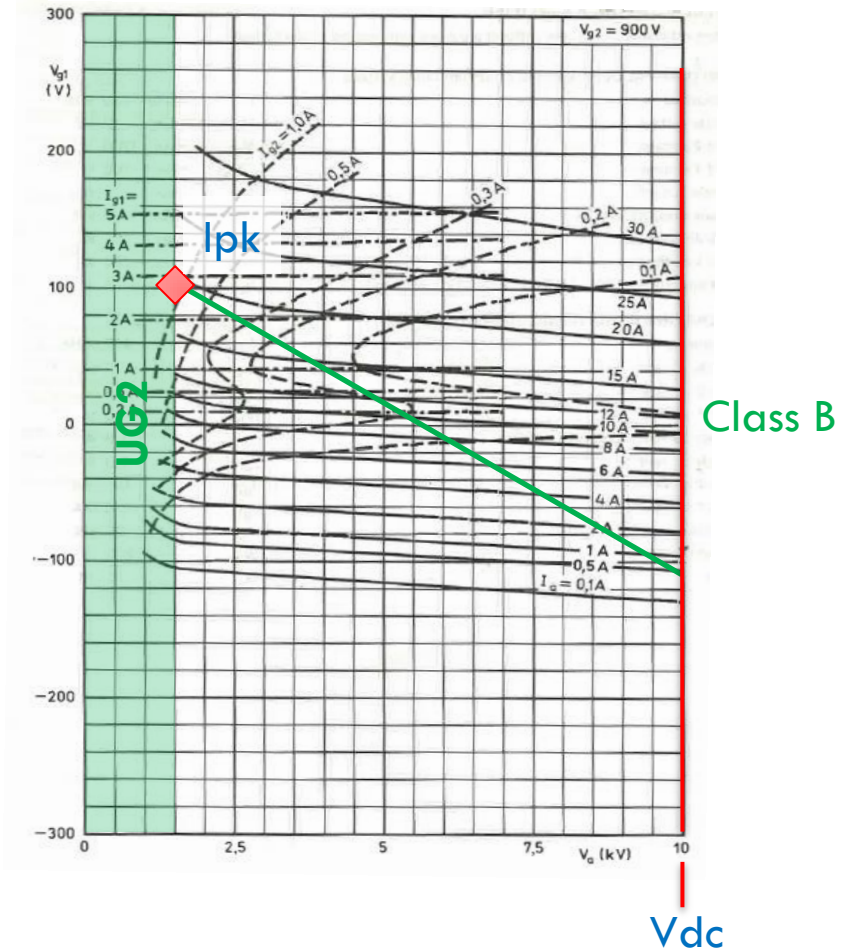
$$P_{dc} = V_{dc} I_{dc} = V_{dc} 1.05 I_{pk}/\pi$$

$$P_{rf} = \frac{1}{2} V_{rf} I_{rf} = \frac{1}{4} 0.9 V_{dc} I_{pk}$$

Theoretical efficiency in practice

$$\eta = P_{rf}/P_{dc} = \frac{1}{4} 0.9 V_{dc} I_{pk} / 1.05 V_{dc} I_{pk}/\pi$$

$$\eta = 67 \%$$



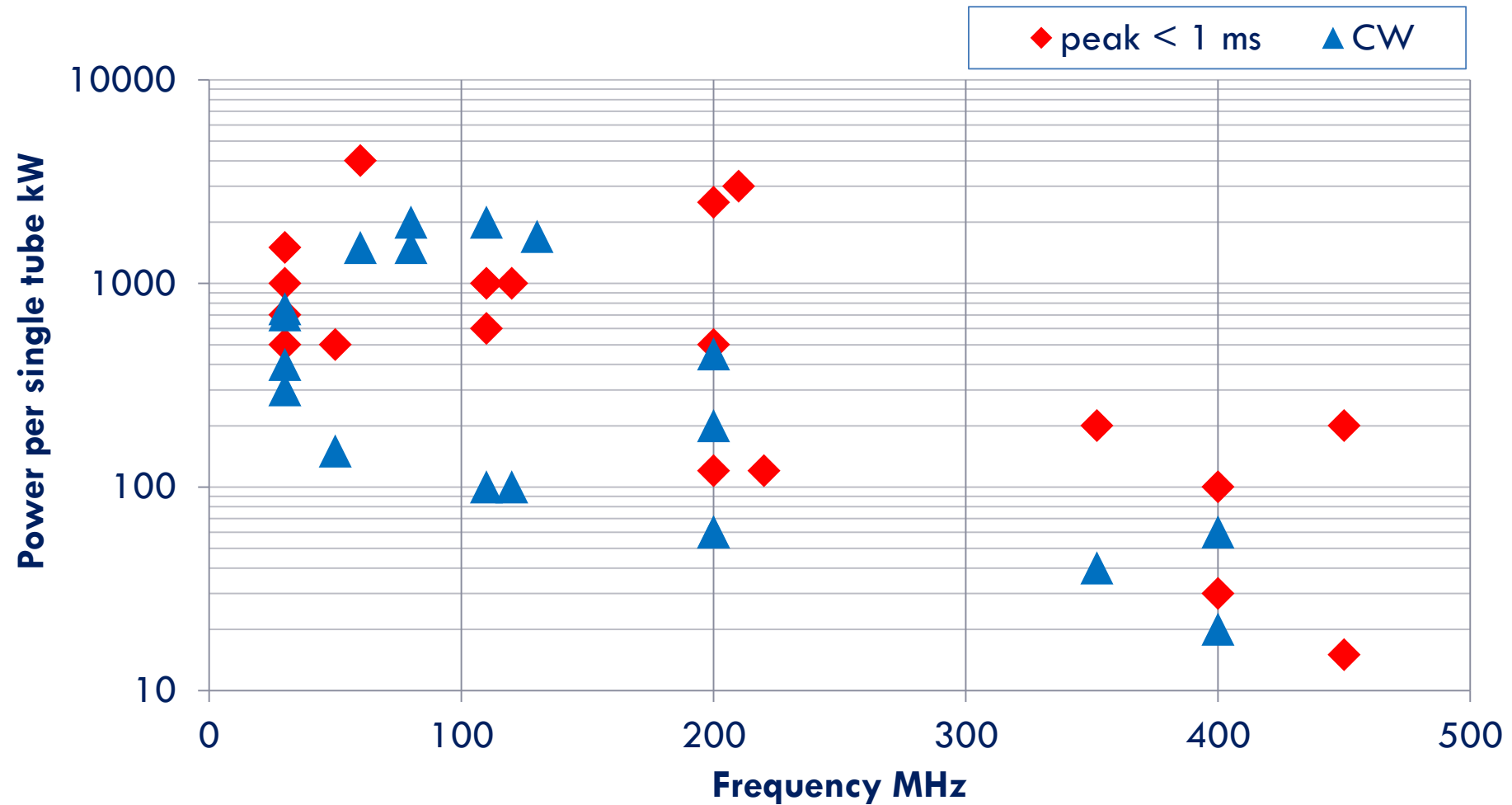
Tetrode

RS 2004 CERN SPS amplifier @ 200 MHz



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

Tetrodes & Diacrodes available from industry



Linear beam tubes

- 1937 Klystron, Russell & Sigurd Varian
- 1938 IOT, Andrew V. Haeff
- 1939 Reflex klystron, Robert Sutton
- 1940 Few commercial IOT
- 1941 Magnetron, Randall & Boot
- 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

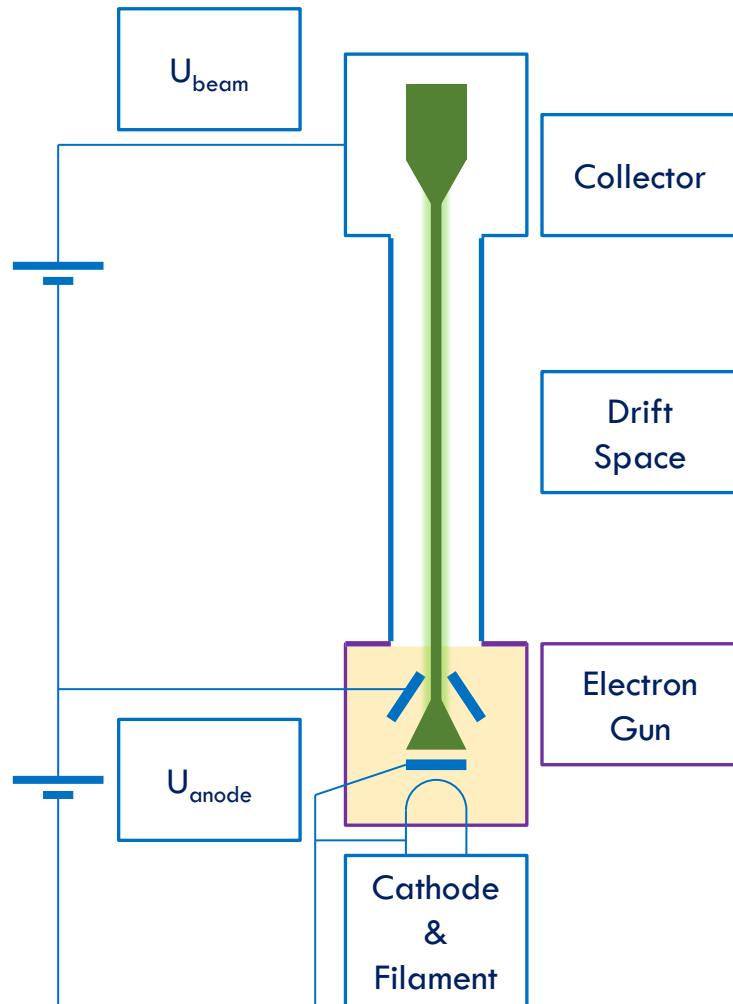


Russell & Sigurd Varian klystron, 1937



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

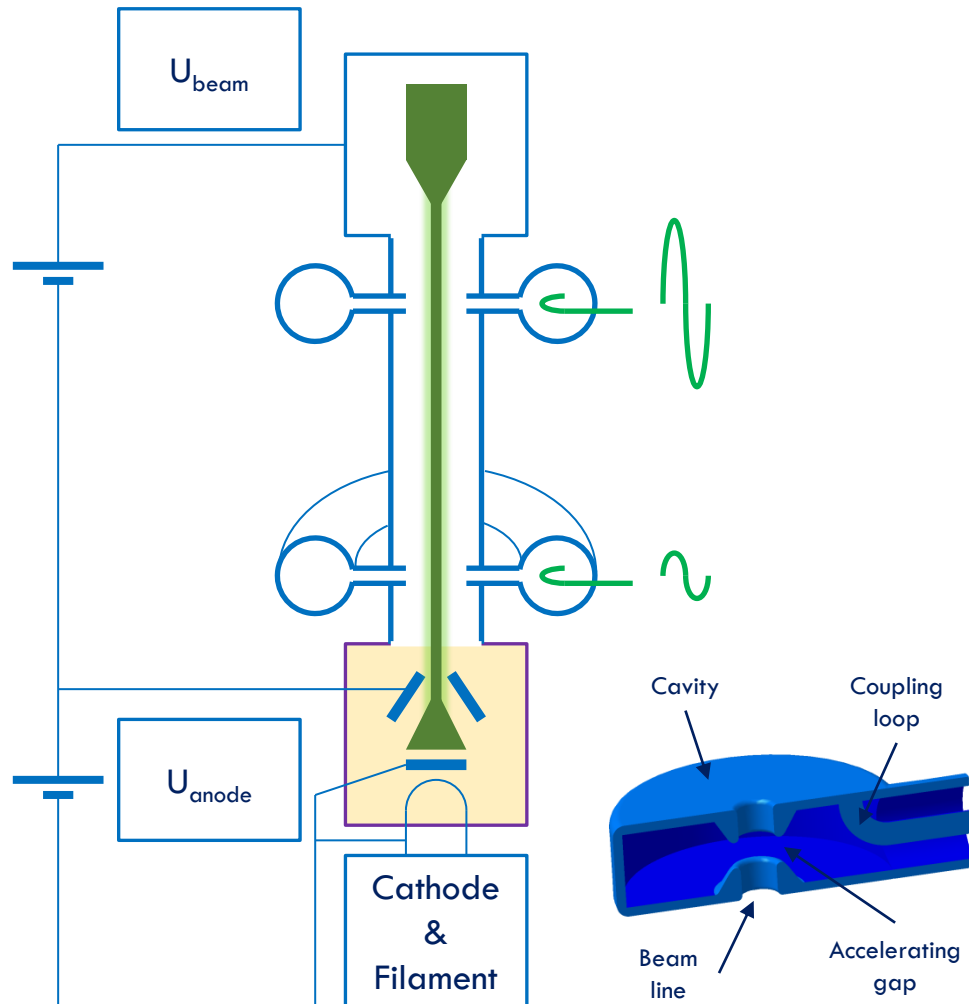
Electron beam

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

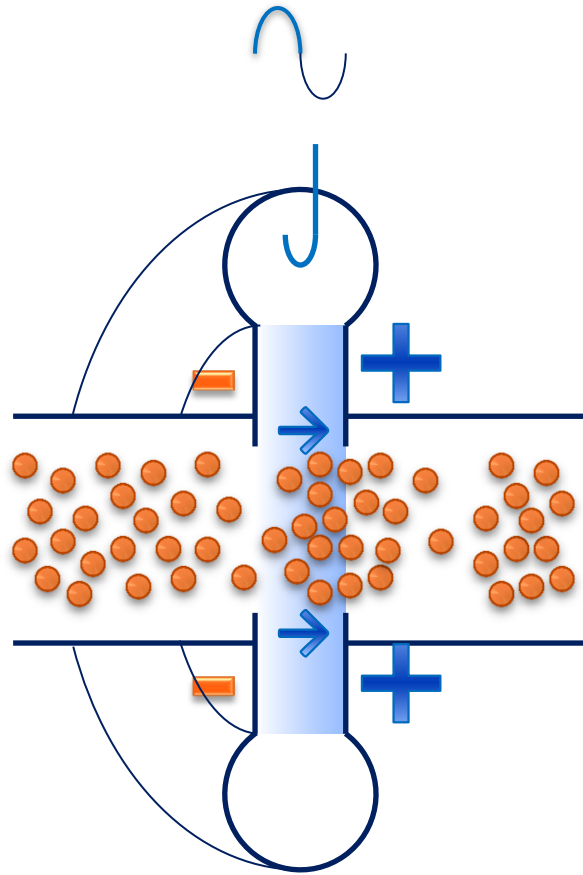
Bunching the e-

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



Cavity resonators

RF input cavity (Buncher)

modulates e- velocity

Some are accelerated

Some are neutral

Some are decelerated

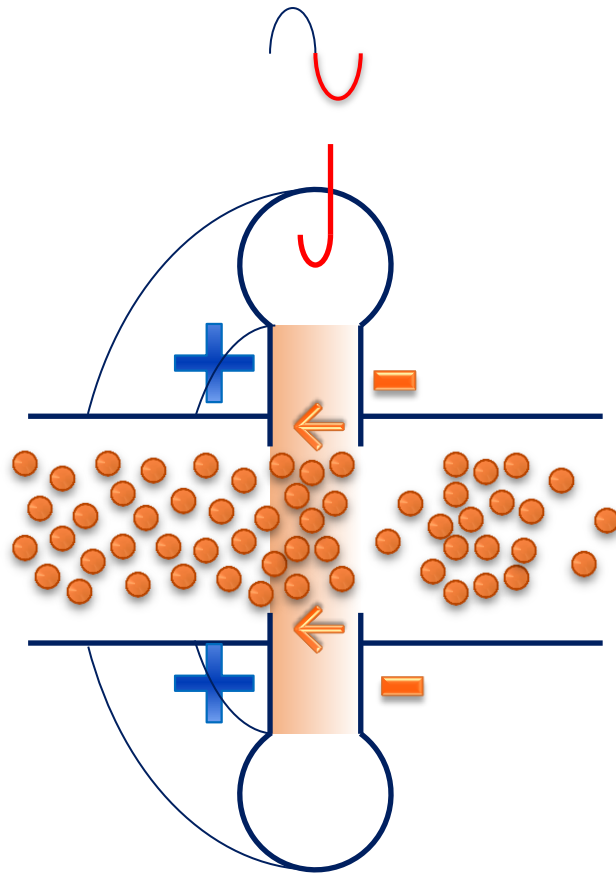
Bunching the e-

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Essentials of klystron



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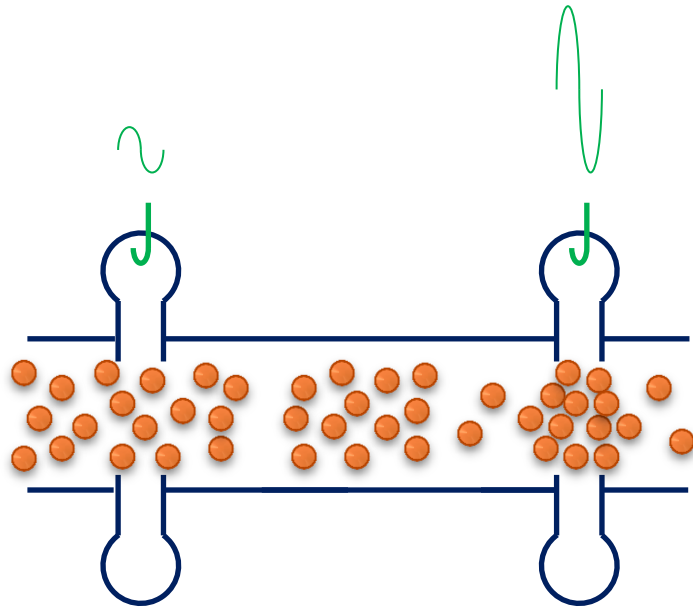
Bunching the e-

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Essentials of klystron



Cavity resonators

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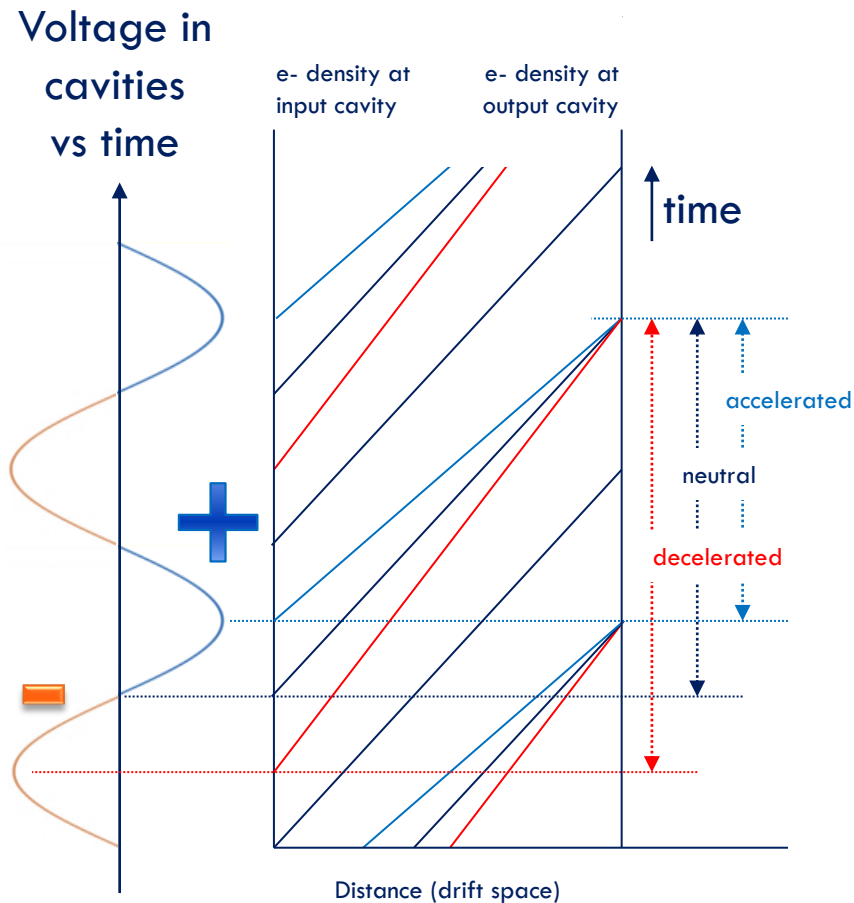
- Bunching the e-

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



Bunching of e- beam in a klystron

Cavity resonators

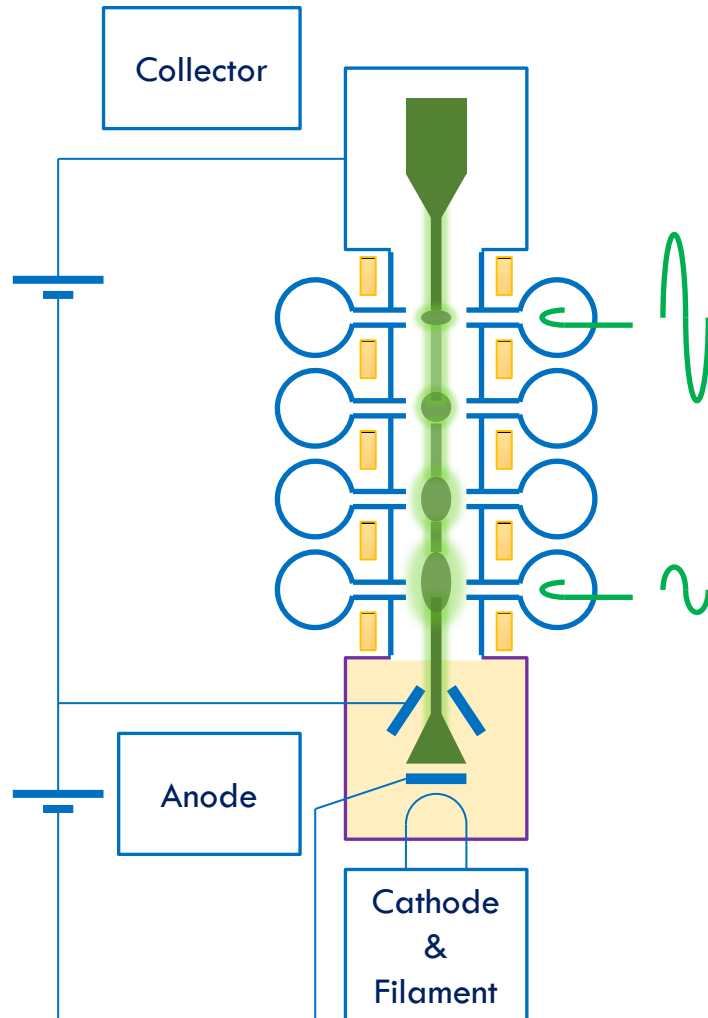
RF input cavity (Buncher)

- 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



Additional bunching cavities

Resonate with the pre-bunched electrons beam

Generate an additional accelerating/decelerating field

Better bunching

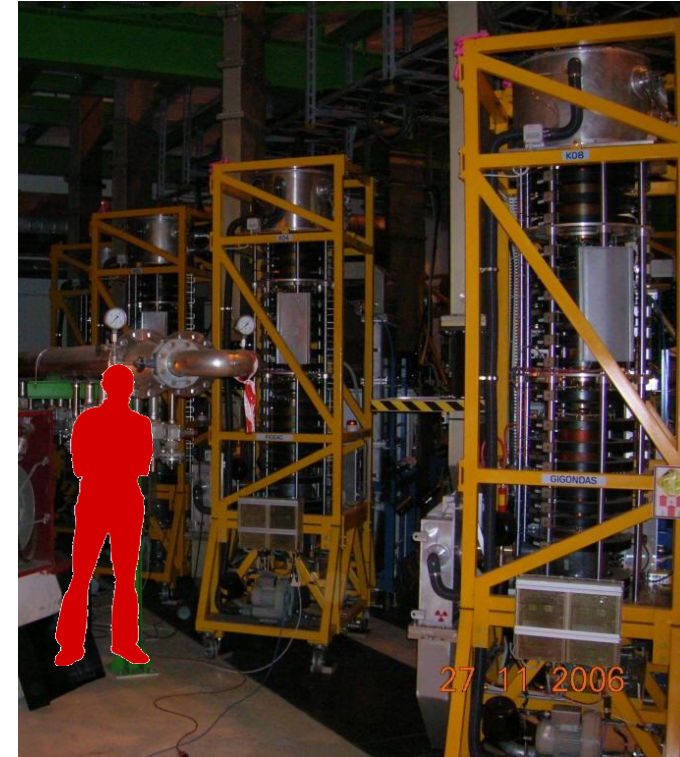
Gain 10 dB per cavity

Focusing magnets

To maintain the e- beam as expected and where expected

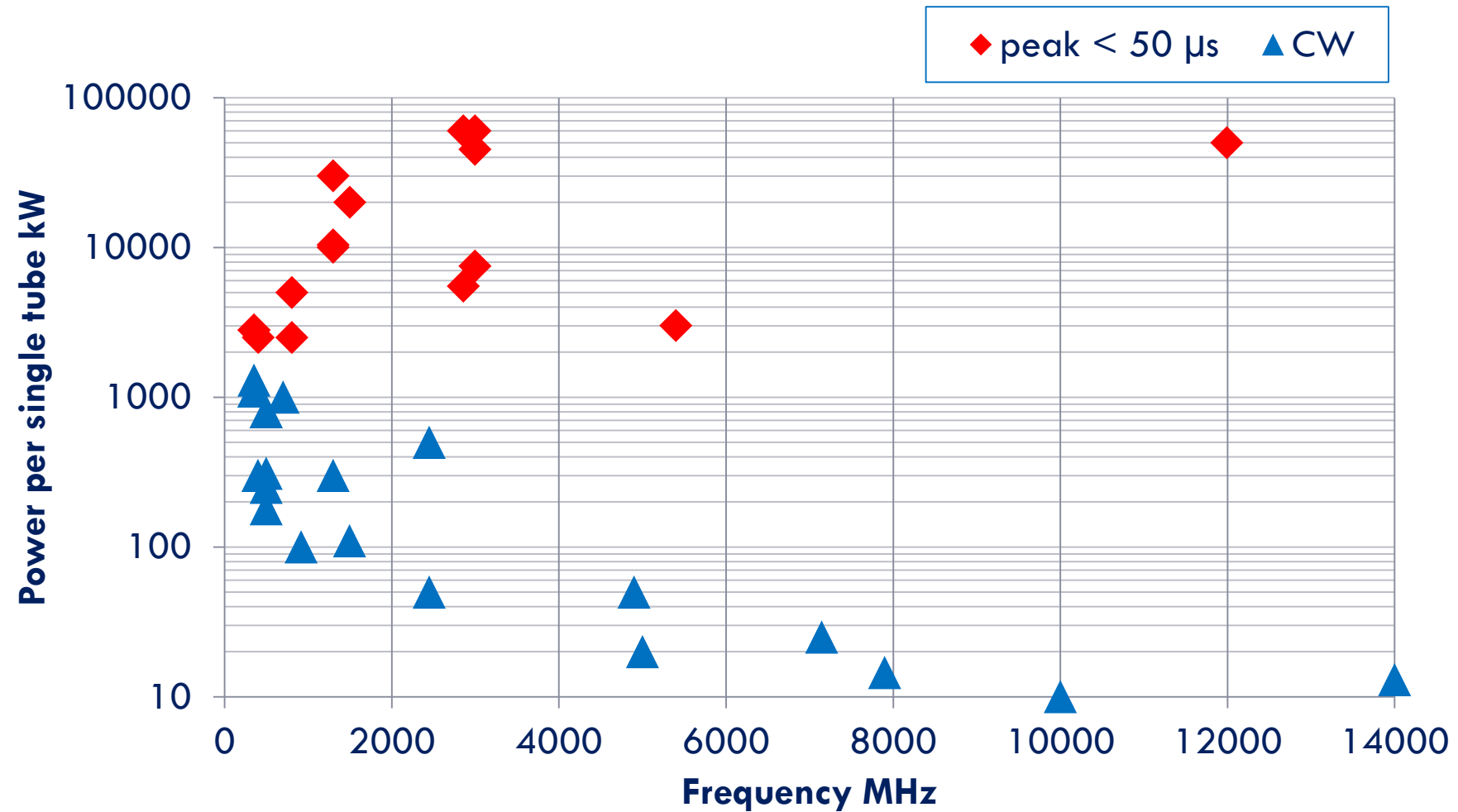
Klystron

TH 2167 CERN LHC @ 400 MHz

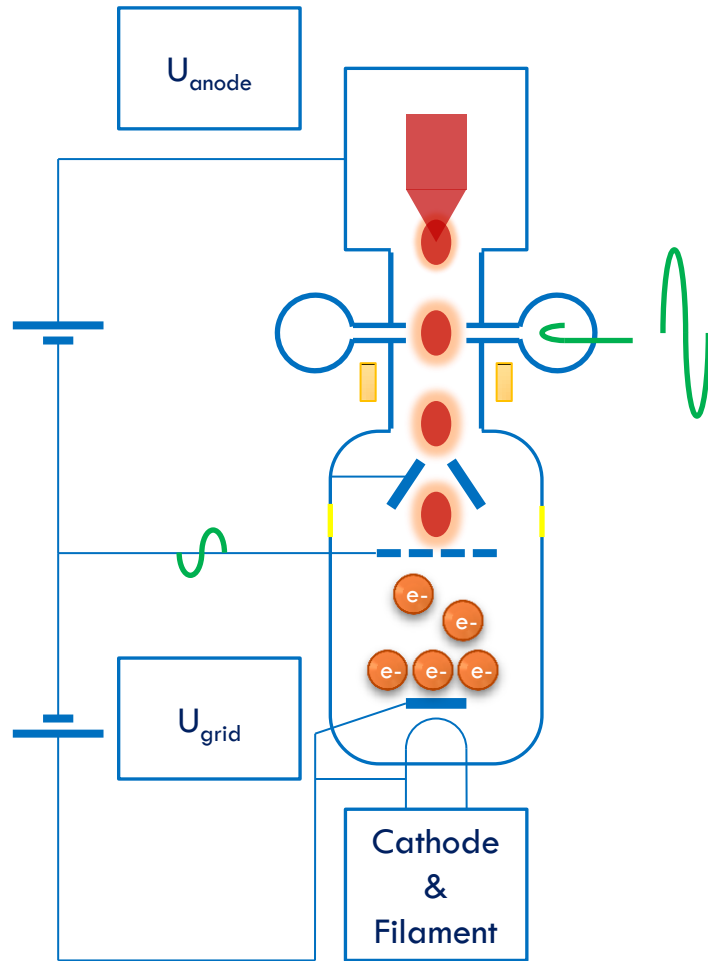


CERN LHC, TH 2167 klystron in lab and in UX45 cavern
16 klystrons delivering 330 kW CW @ 400 MHz, into operation since 2008

Klystrons available from industry



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

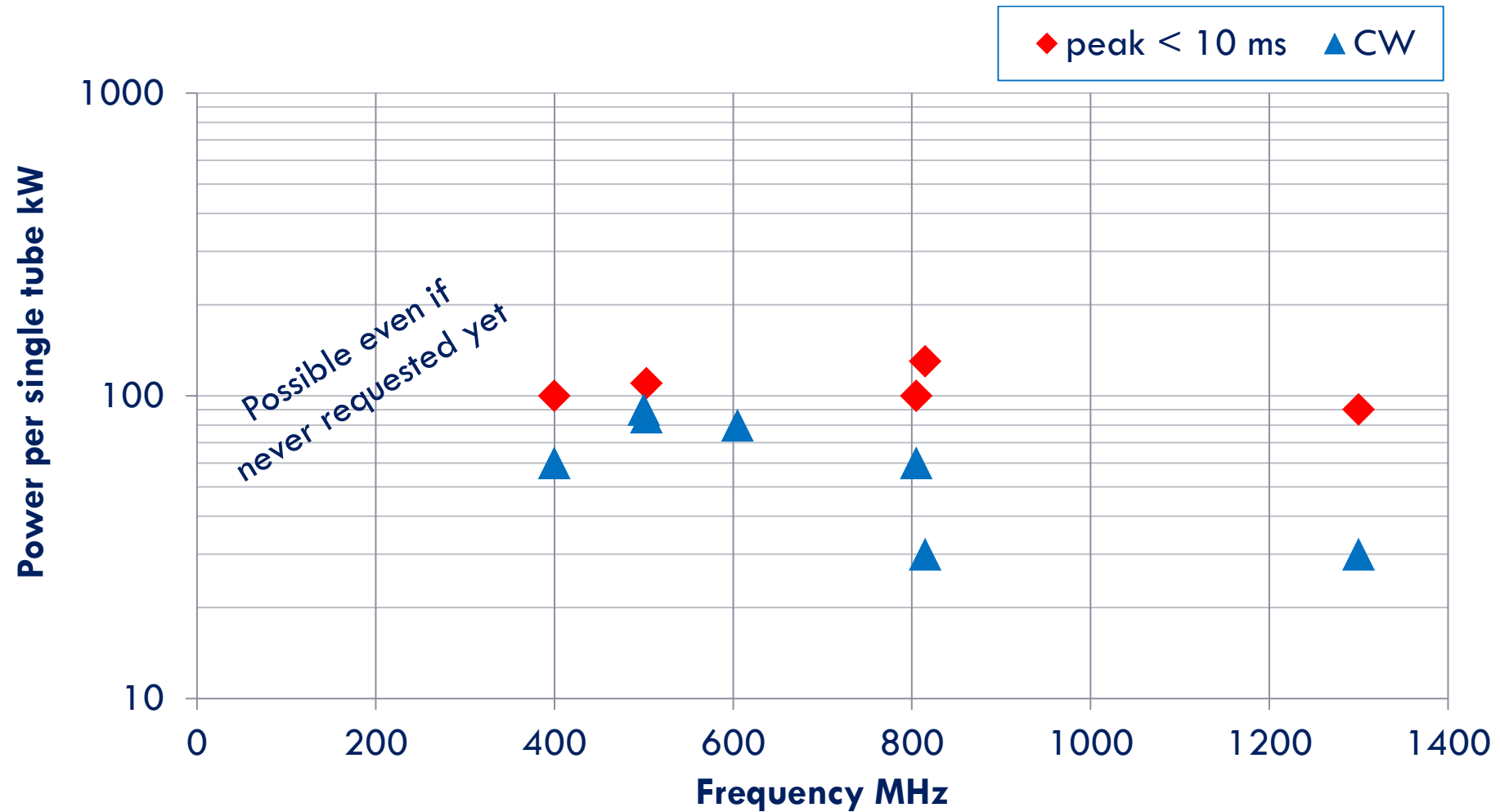
IOT

TH 795 CERN SPS @ 800 MHz



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

IOT available from industry

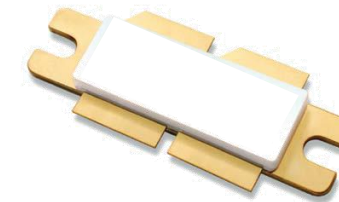


Transistor for RF power

- 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

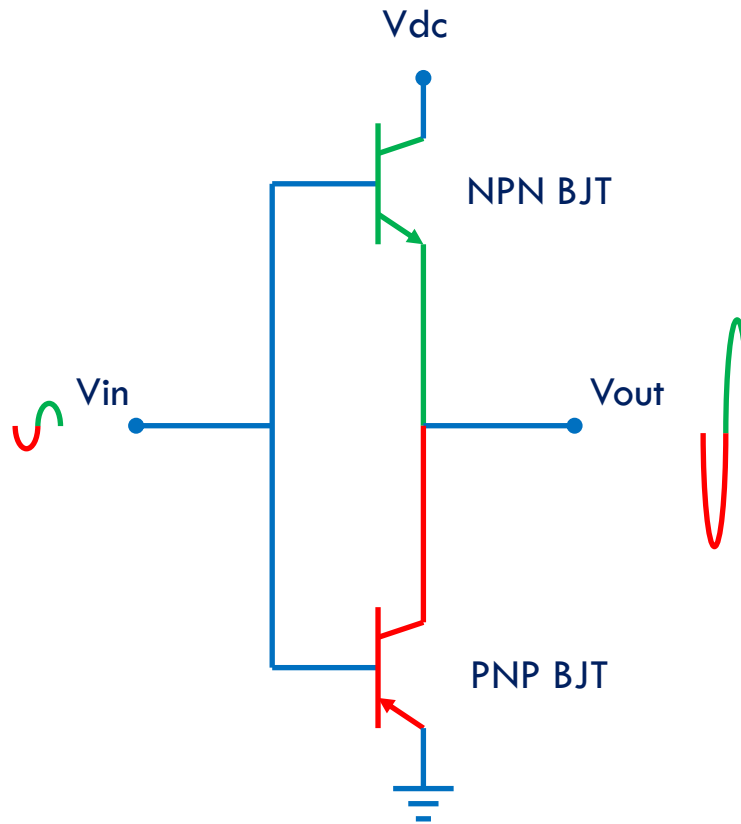


First transistor invented at
BELL labs in 1947



XXI century LDMOS

Essentials of RF transistor



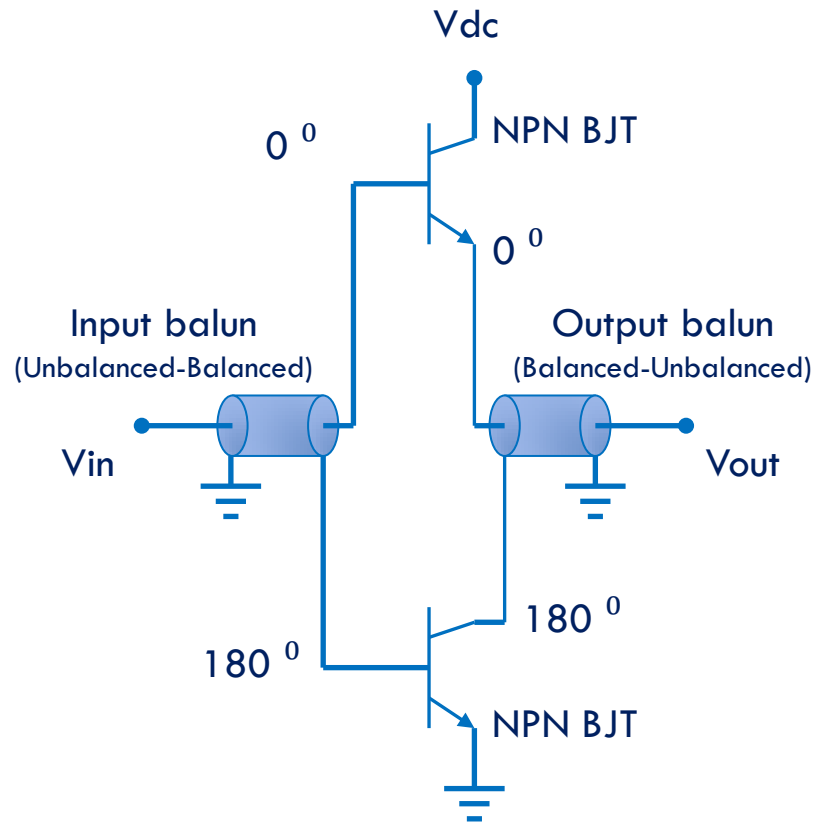
In a push-pull circuit the RF signal is applied to two devices

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



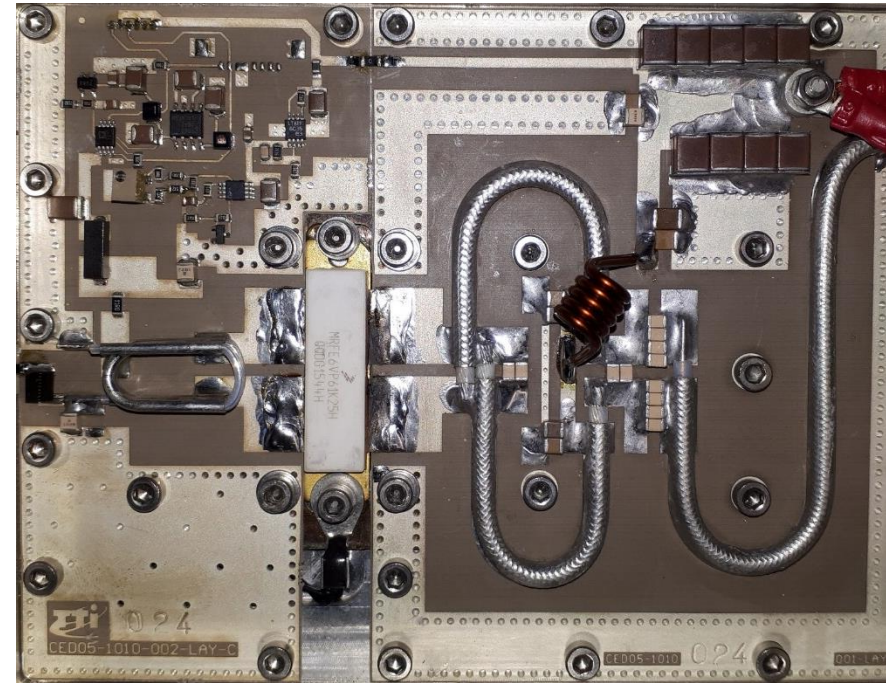
Another push-pull configuration is to use a balun (balanced-unbalanced)

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



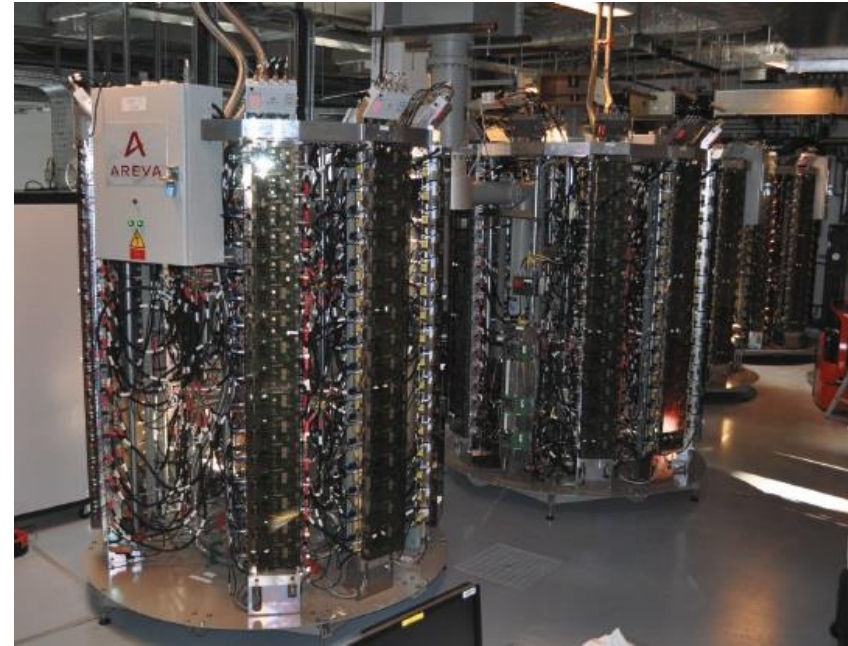
CERN SPS 200 MHz, 1250 W_p – 700 W CW
solid state amplifiers from TTI Norte (Spain)
that replace discontinued YL 1440 tube

Transistors

SOLEIL @ 352 MHz and ESRF @ 352 MHz

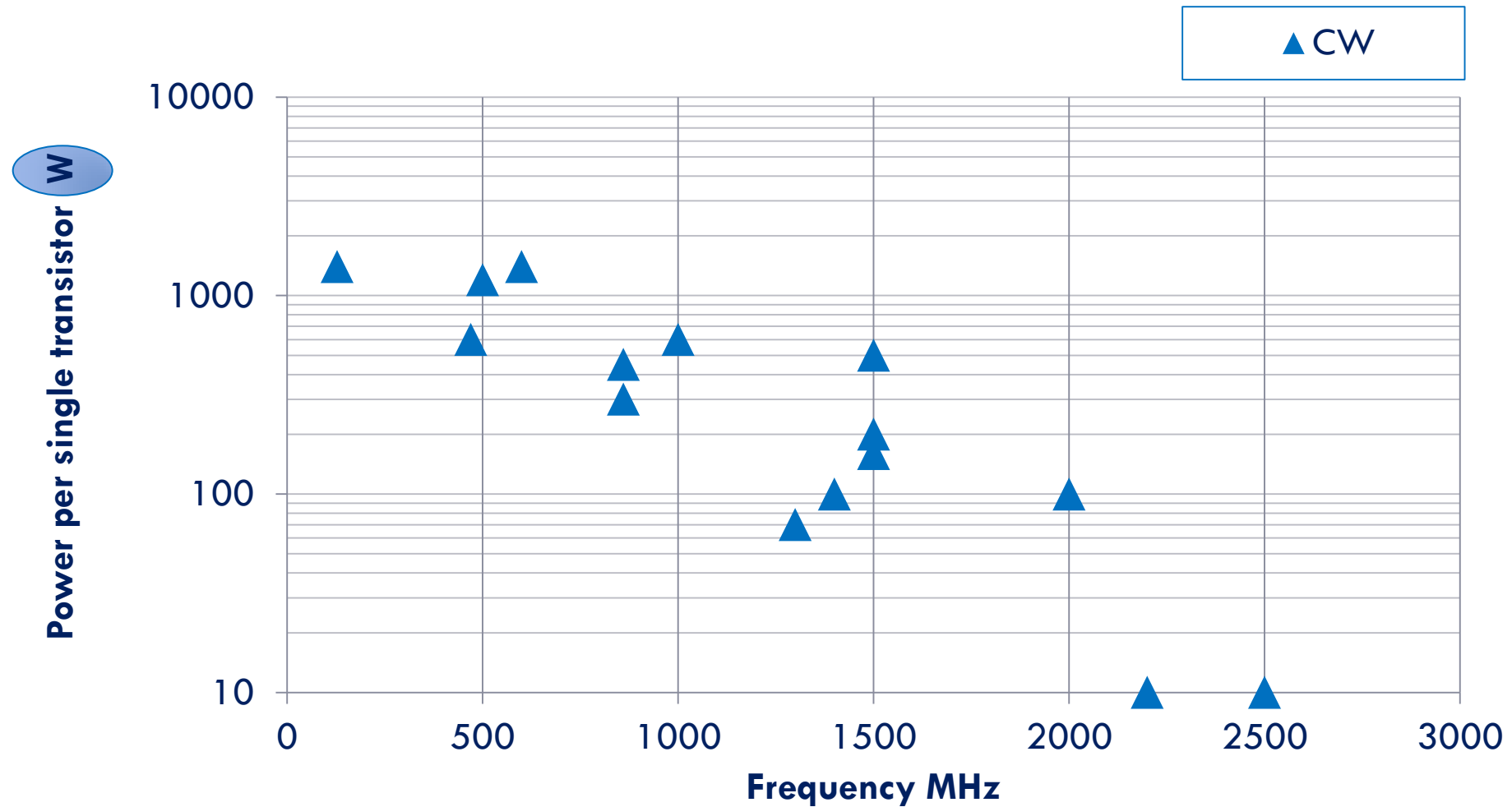


SOLEIL 45 kW @ 352 MHz tower
solid state amplifiers (2004 & 2007)



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

Transistors available from industry



Combiners

Resistive power Combiners

- Cheap and easy to build

- Use of resistors to maintain the impedance

- Power limitation and losses induce by the resistors (→ not used in high power)

Hybrid power Combiners

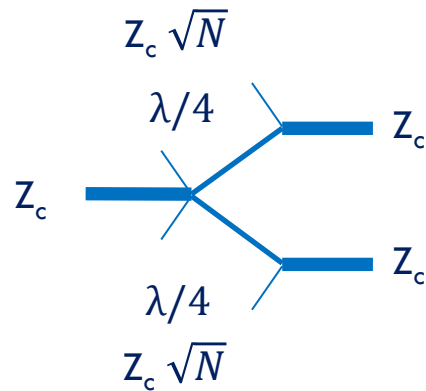
- Use RF lines

- Low level of loss

- Limitation by the size of the lines

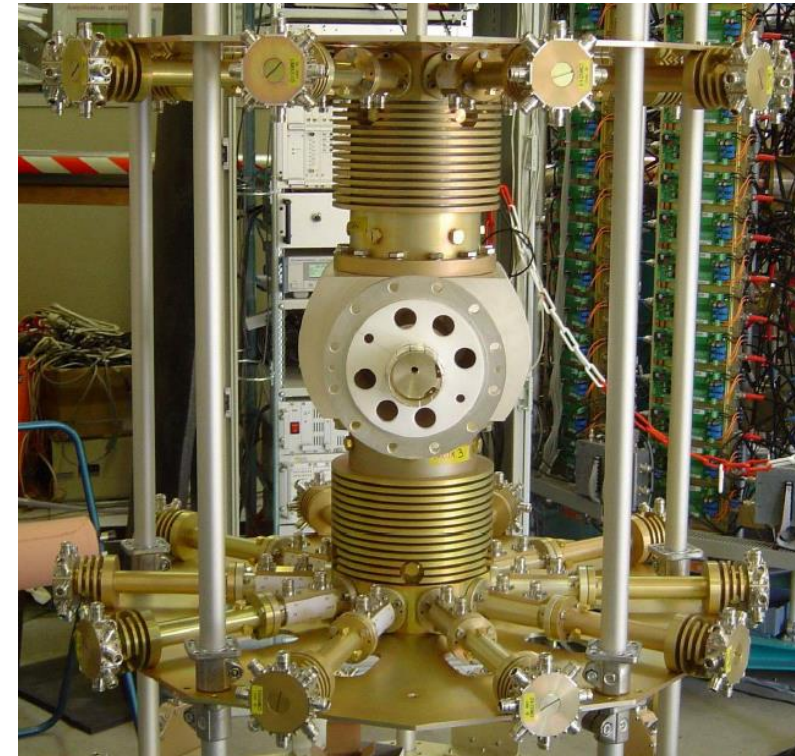
Combiners

Low loss T-Junction



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

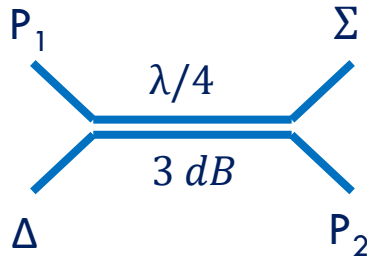
We have a N-ways combiner



160 to 1 @ 352 MHz
T-junction combiner

Combiners

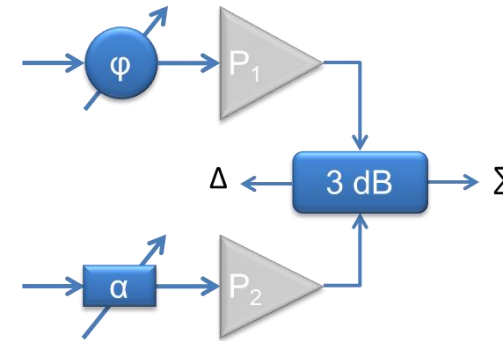
3 dB phase combiner



With correct input phases

$$\Sigma = \frac{P_1 + P_2}{2} + \sqrt{P_1 P_2}$$

$$\Delta = \frac{P_1 + P_2}{2} - \sqrt{P_1 P_2}$$



Correctly adjusting the phase and the gain,
 $P_1 = P_2 = P$

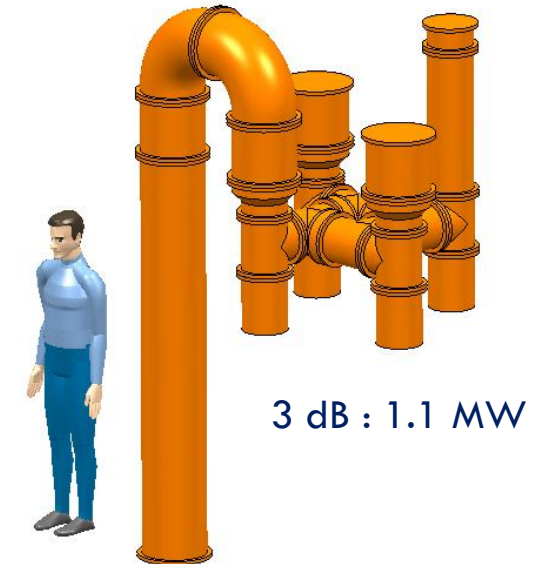
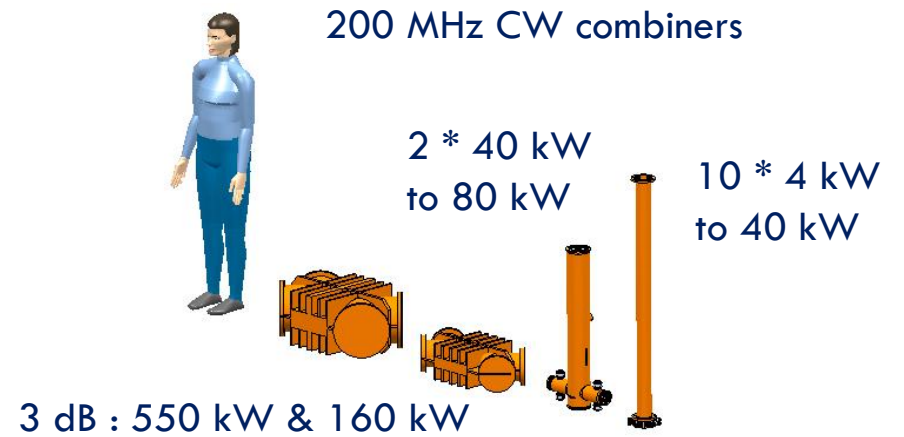
$$\Sigma = \frac{P + P}{2} + \sqrt{PP} = 2P$$

$$\Delta = \frac{P + P}{2} - \sqrt{PP} = 0$$

Combiners



CERN SPS 64 to 1 combiner @ 200 MHz



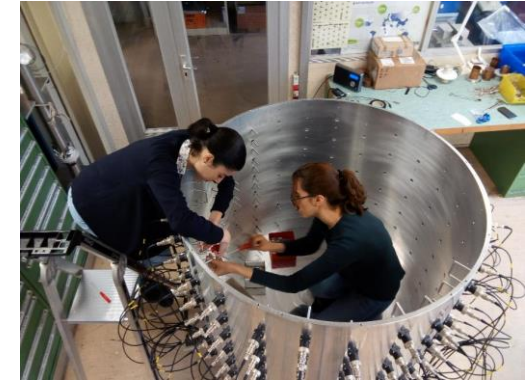
Combiners

Since some years now we are moving to Cavity combiners and Radial combiners

The CaCo from Alba is one of the first example
Then with ESRF with funding from the EU as WP7 in the framework of the FP7/ESFRI/CRISP program we launched a first Cavity Combiner (I invite you to read the mopc005 IPAC 11 and wepfi004 IPAC13 reports from ESRF)

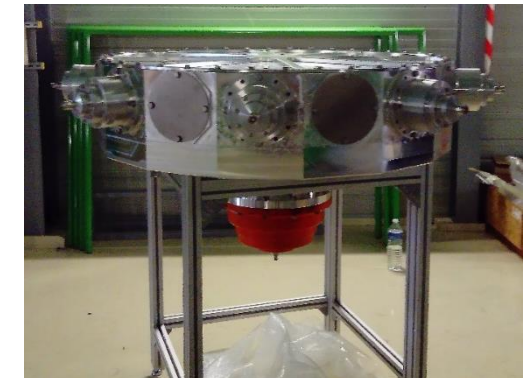
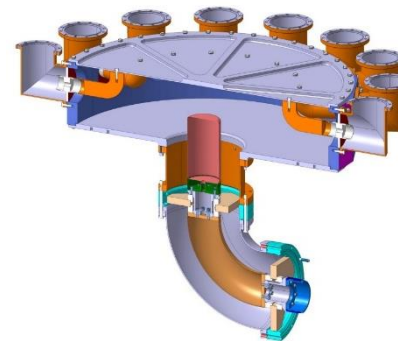
Recently CERN developed a new VHPCC (Very High Power Cavity Combiner)

16 * 150 kW : 1 * 2.4 MW CW @ 200 MHz



CERN 144:1 cavity combiner 144 kW CW @ 200 MHz
calculations by ESRF within CRISP, construction by CERN

CERN 16:1 radial cavity combiner 2.4 MW CW @ 200 MHz



Combiners

Advantages of Cavity Combiners

- Compact

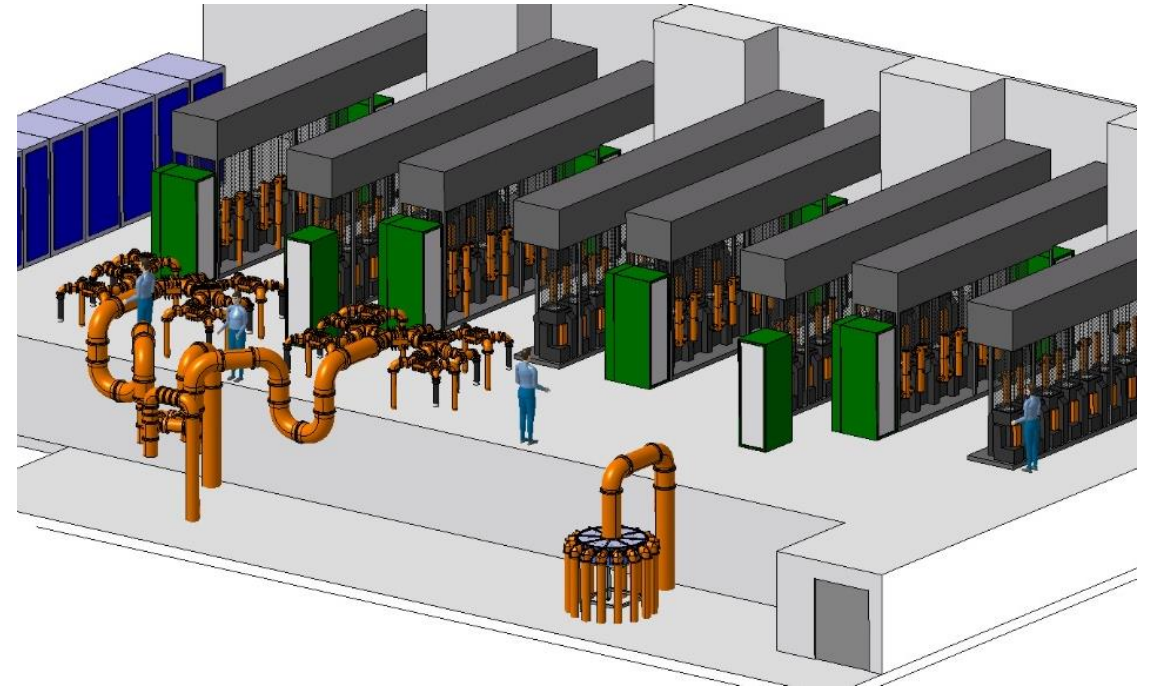
- No dummy load

- Less losses

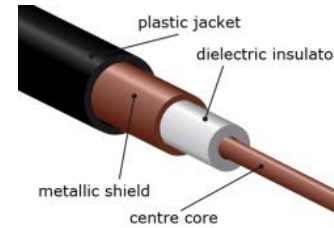
Drawbacks

- Reduced bandwidth (still large enough)

- Reflection in case of wrong phase



Coaxial Lines



Coaxial cables are often with PTFE foam to keep concentricity

Characteristic impedance is

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

With

D = inner dimension of the outer conductor

d = outer dimension of the inner conductor

ϵ_r = dielectric characteristic of the medium

Flexible lines have spacer helicoidally placed all along the line



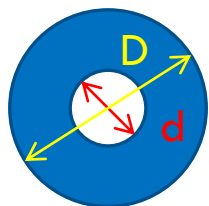
Size	Outer conductor		Inner conductor	
	Outer diameter	Inner diameter	Outer diameter	Inner diameter
7/8"	22.2 mm	20 mm	8.7 mm	7.4 mm
1 5/8"	41.3 mm	38.8 mm	16.9 mm	15.0 mm
3 1/8"	79.4 mm	76.9 mm	33.4 mm	31.3 mm
4 1/2"	106 mm	103 mm	44.8 mm	42.8 mm
6 1/8"	155.6 mm	151.9 mm	66.0 mm	64.0 mm



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



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

$$P_{peakmax} = \frac{V_{peakmax}^2}{2Z_c}$$

$$P_{peakmax} = \frac{E^2 d^2 \sqrt{\epsilon_r}}{480} \ln\left(\frac{D}{d}\right)$$

With

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

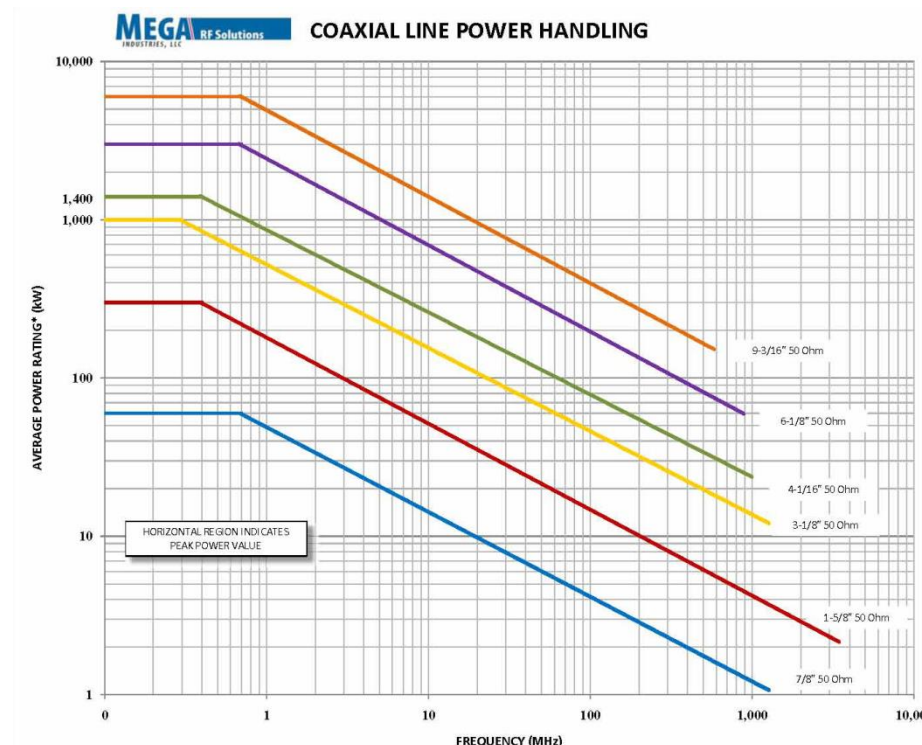
D = inside electrical diameter of outer conductor in mm

d = outside electrical diameter of inner conductor in mm

Z_c = characteristic impedance in Ω

ε_r = relative permittivity of dielectric

f = frequency in MHz



Curves valid for straight lines, in case of elbow, reduce it by 30 %

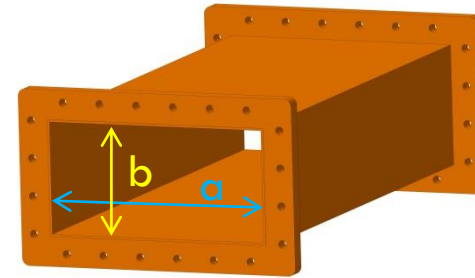
Coaxial lines



CERN SPS 200 MHz, 4 * 150 meters of 345 mm coaxial lines from the surface building to the cavities

Rectangular waveguides

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



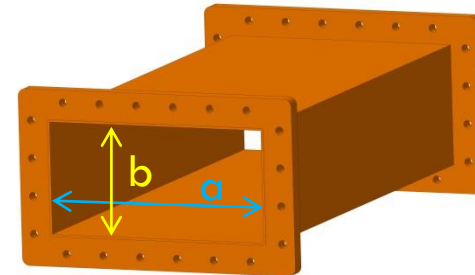
Wavelength	$\lambda_g = \frac{\lambda}{\sqrt{1 - (\frac{\lambda}{2a})^2}}$
Cutoff frequency dominant mode	$f_c = \frac{c}{2a}$
Cutoff frequency next higher mode	$f_{c2} = \frac{c}{4a}$
Usable frequency range	$1.3 f_c \text{ to } 0.9 f_{c2}$

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)
EIA	RCSC	IEC				
WR2300	WG0.0	R3	0.32 — 0.45	0.257	0.513	23.000 × 11.500
WR1150	WG3	R8	0.63 — 0.97	0.513	1.026	11.500 × 5.750
WR340	WG9A	R26	2.20 — 3.30	1.736	3.471	3.400 × 1.700
WR75	WG17	R120	10.00 — 15.00	7.869	15.737	0.750 × 0.375
WR10	WG27	R900	75.00 — 110.00	59.015	118.03	0.100 × 0.050
WR3	WG32	R2600	220.00 — 330.00	173.571	347.143	0.0340 × 0.0170

Rectangular waveguides Maximum Power handling

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

With

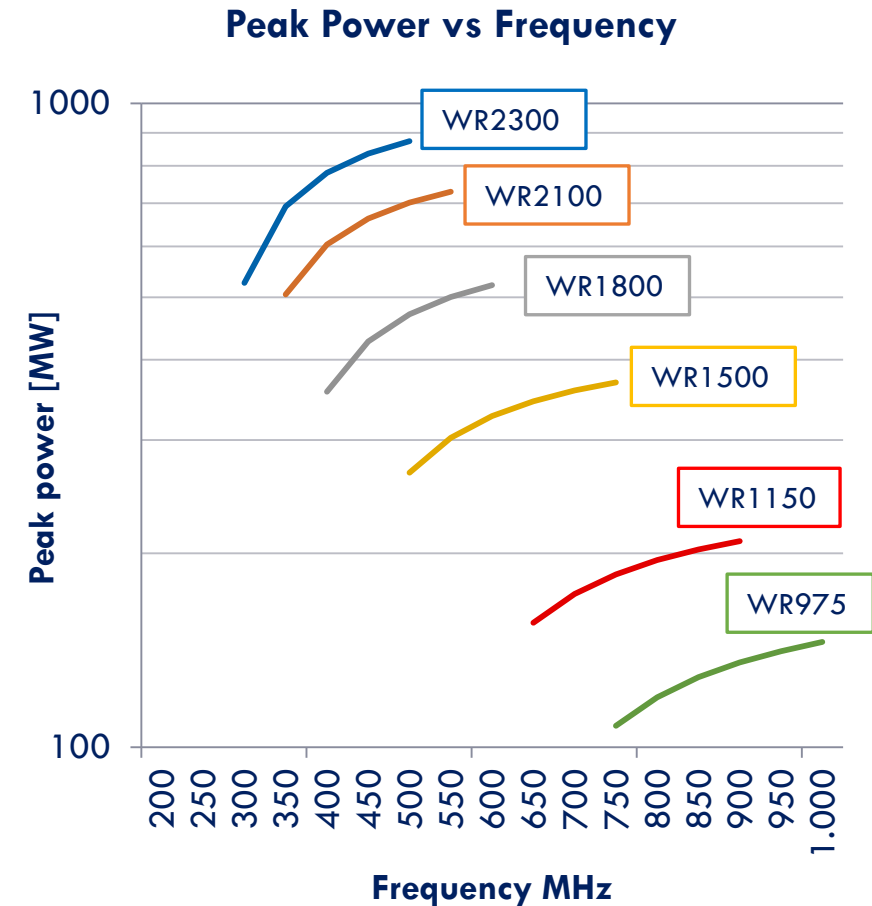
P = Power in watts

a = width of waveguide in cm

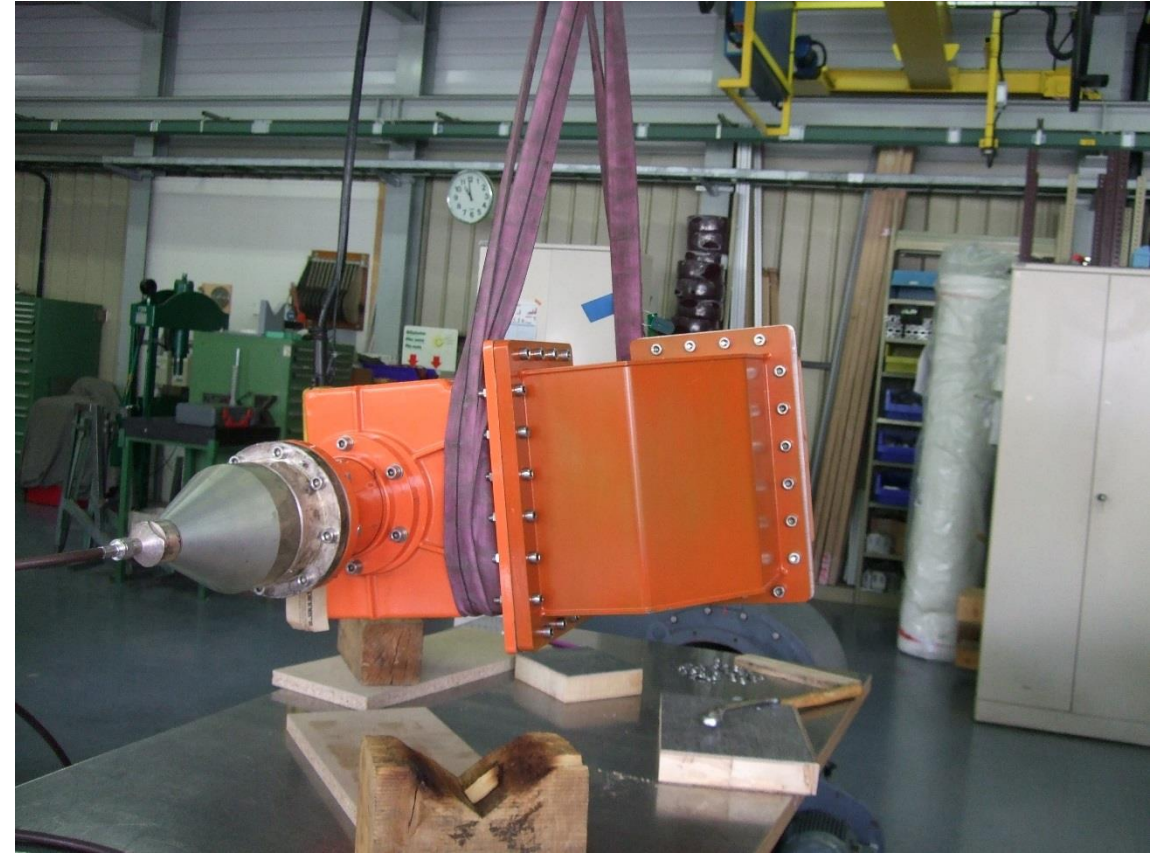
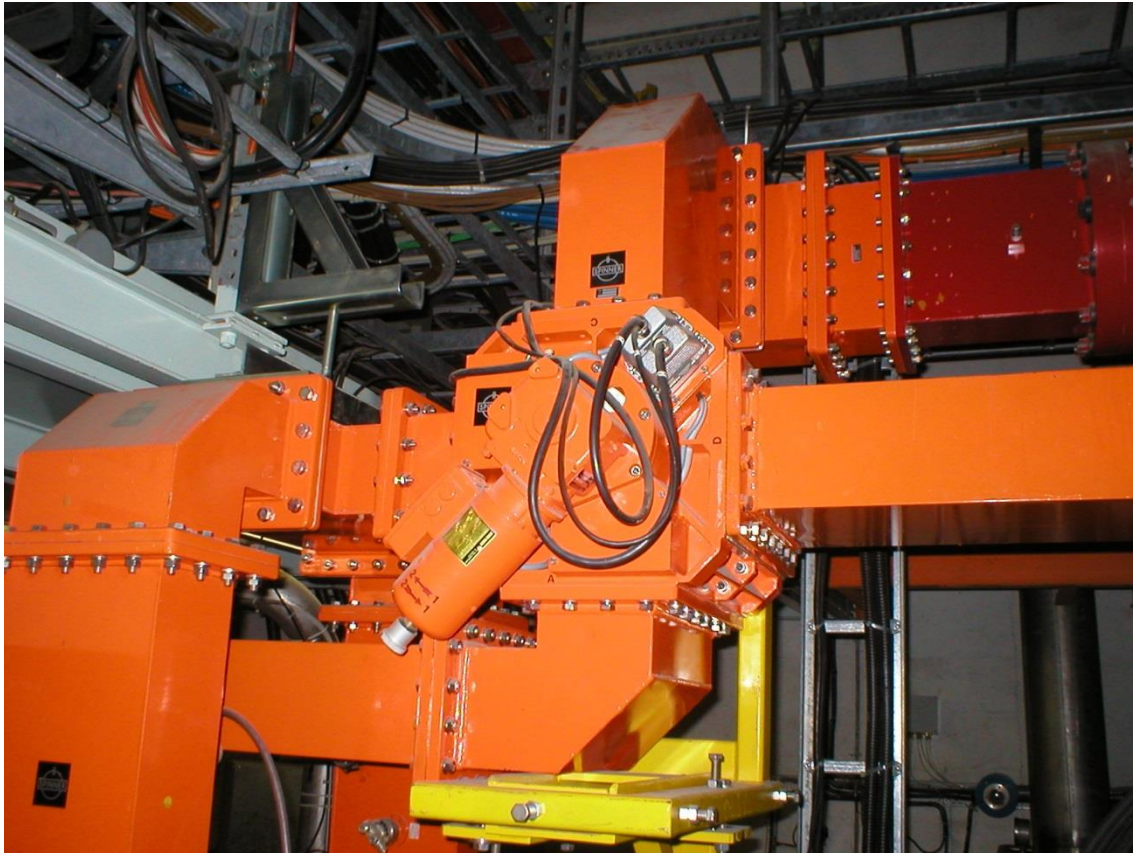
b = height of waveguide in cm

λ = free space wavelength in cm

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



Rectangular waveguides



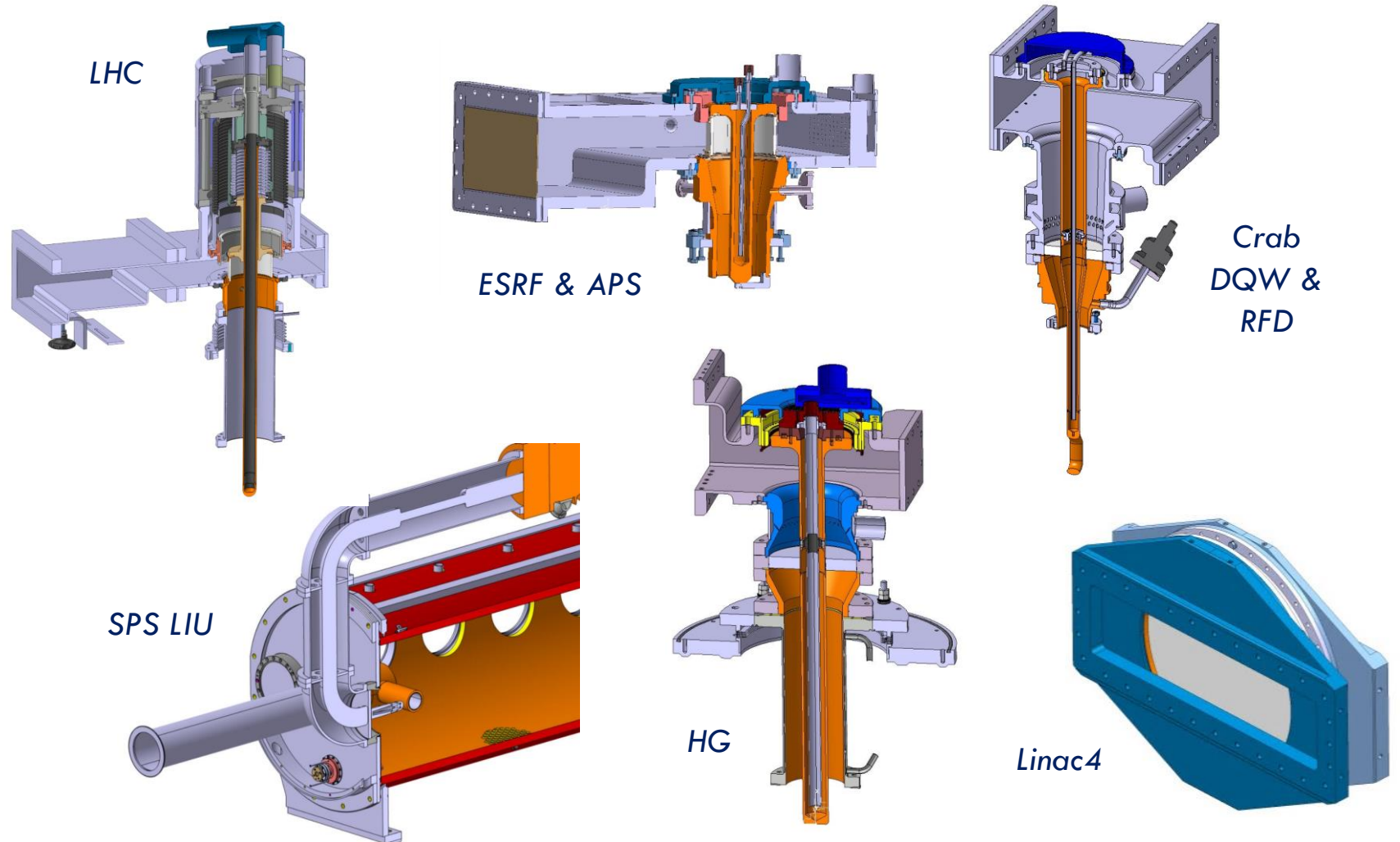
CERN SPS 800 MHz, 2 * 150 meters of WR1150 waveguides from the surface building to the cavities

Fundamental Power Couplers (FPC)

SRF2017 – Tutorial on FPC

<http://ddl.esience.cn/f/M2wh>

LHC	400 MHz, 500 kW
SPS 2.0	200 MHz, 750 kW
SPL 1.0	704 MHz, 900 kWp
SPL 2.0	704 MHz, 1000 kWp
Linac4	352 MHz, 1000 kWp
Crab DQW	400 MHz, 100 kW
Crab RFD	400 MHz, 100 kW
ESRF	352 MHz, 250 kW
SOLEIL	352 MHz, 250 kW
APS 1.0	352 MHz, 250 kW
SPS LIU	200 MHz, 800 kW
HG (SPL 3.0)	704 MHz, 1200 kWp
LHC 2.0	400 MHz, 500 kW
APS 2.0	352 MHz, 250 kW
Crab 2.0	400 MHz, 100 kW



Fundamental Power Couplers (FPC)

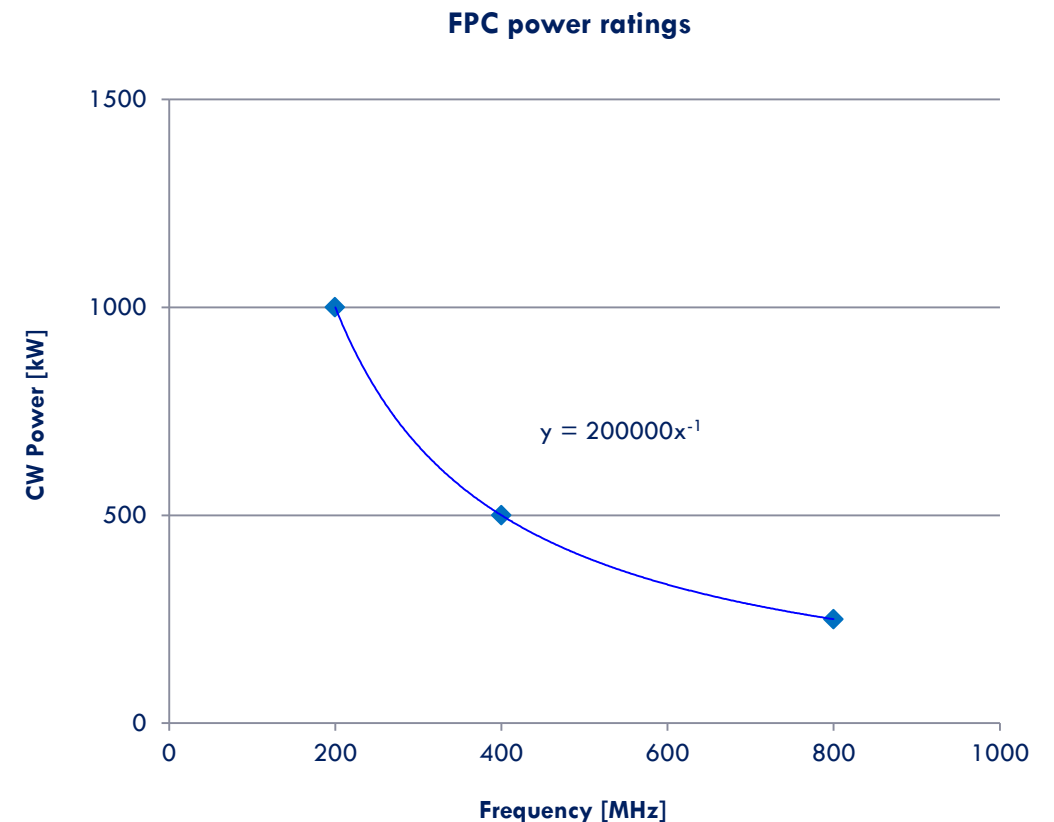
Even if we can imagine cavities able to receive a large amount of power

In the frequency range, Fundamental Power Coupler will limit the maximum power that can be delivered to the cavity

Currently the limit is around

$$P_{max} [kW] = \frac{200000}{f [MHz]}$$

(for a stable operation 10-20 years lifetime of a Fundamental Power Coupler)



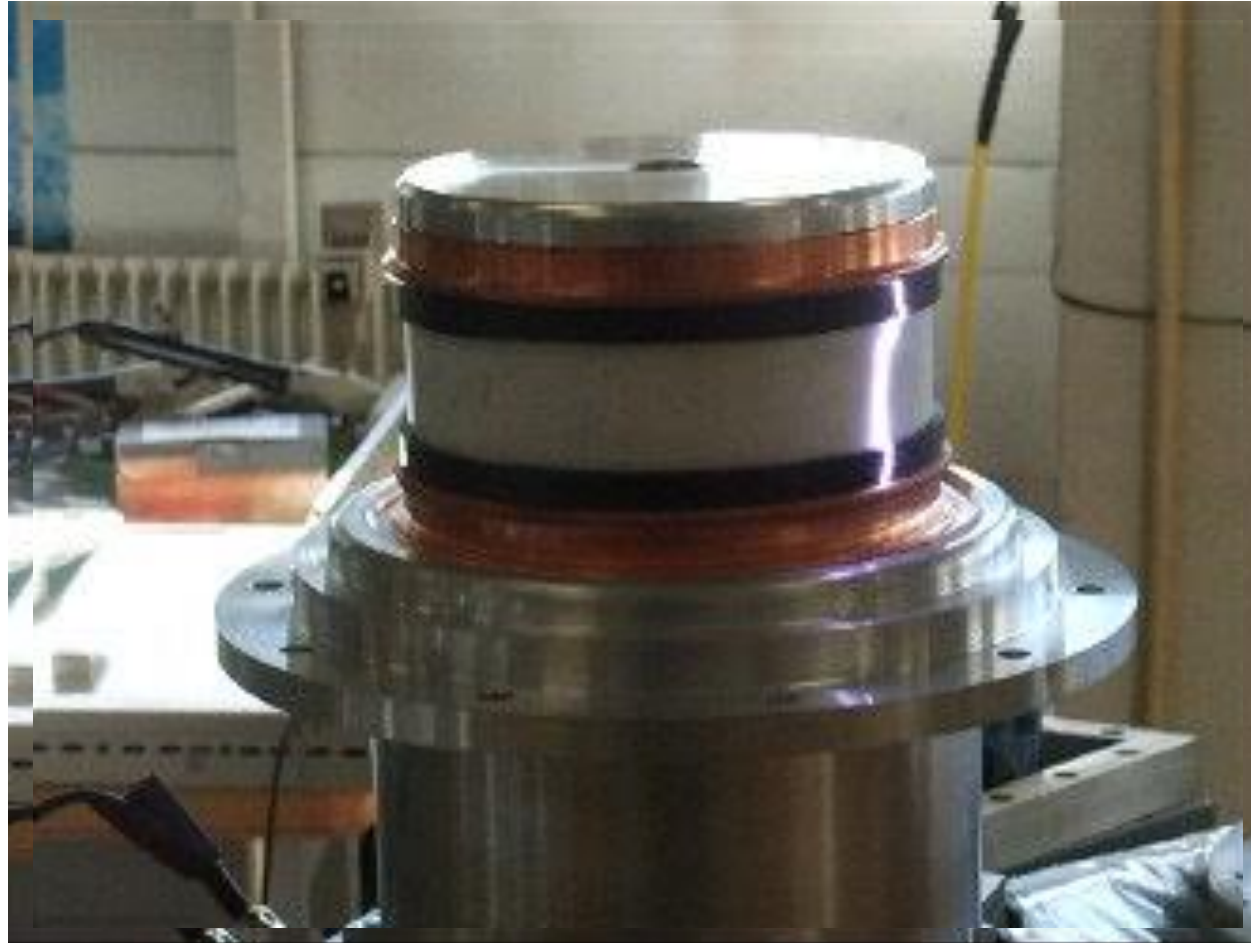
Fundamental Power Couplers (FPC)

LLRF07

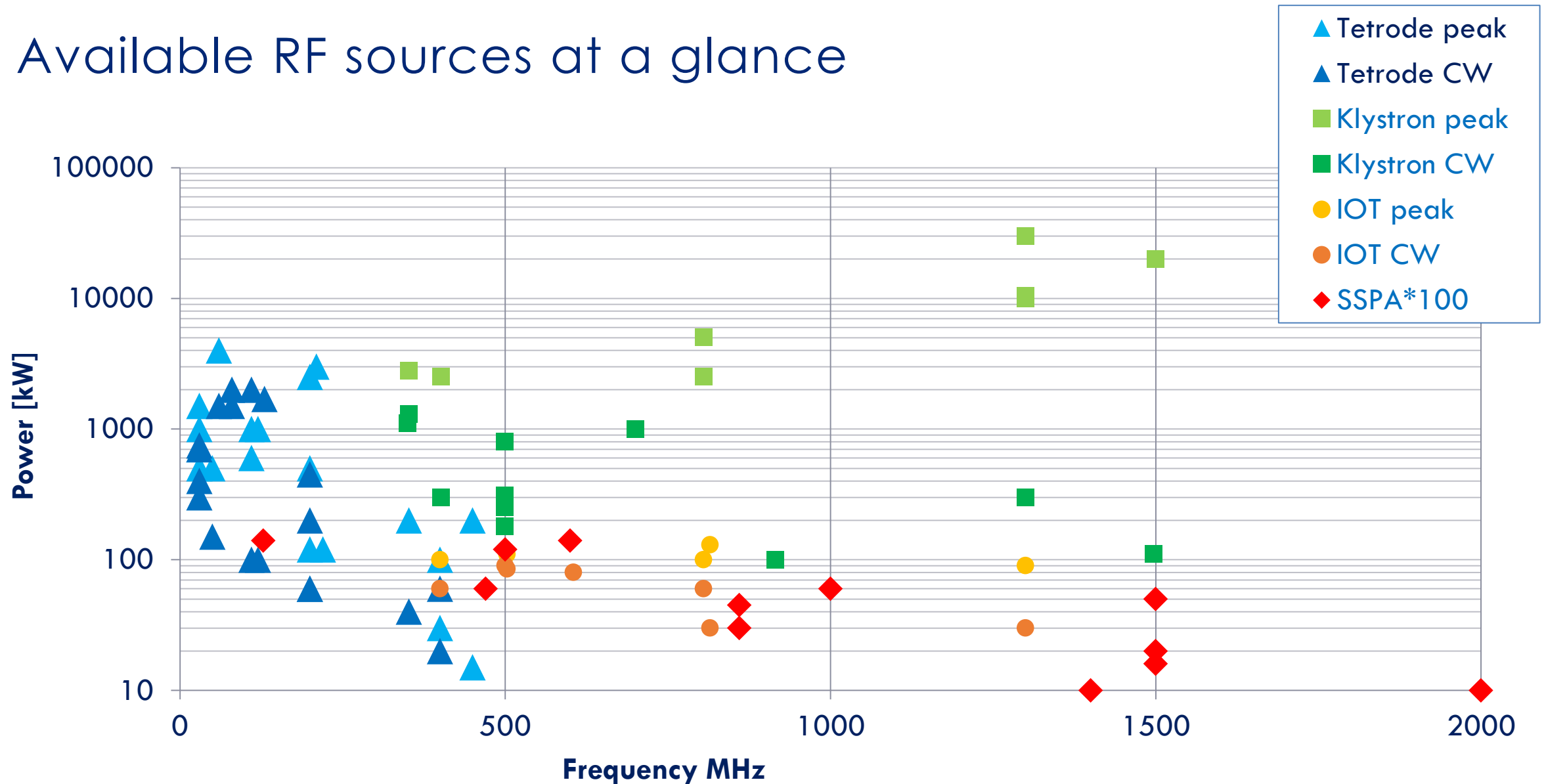
A Fully Integrated
Controller for RF
Conditioning of the
LHC Superconducting
cavities, John C.
Molendijk

CWRF08

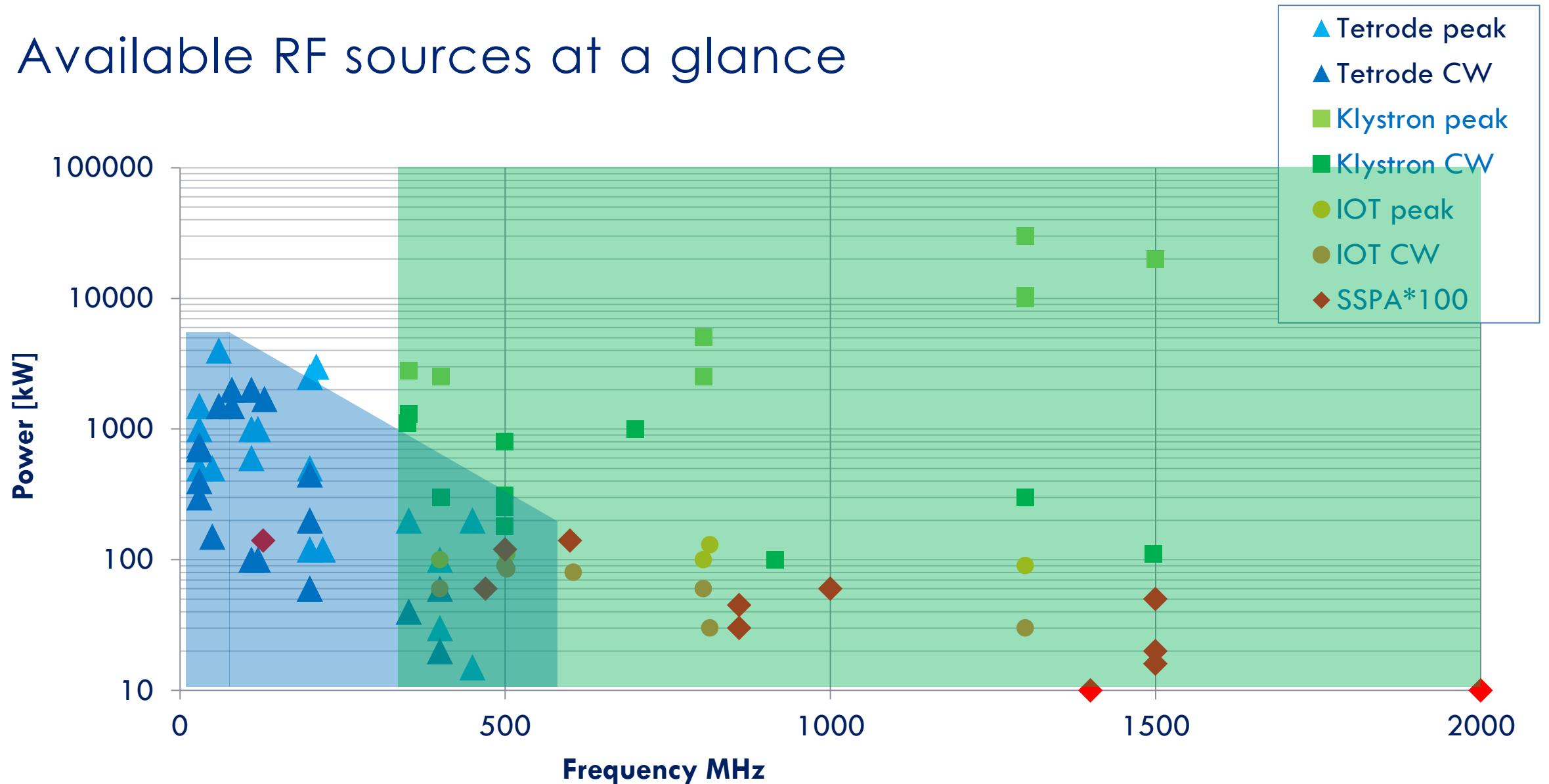
LHC RF Embedded SC
Cavity Conditioning
System, John C.
Molendijk



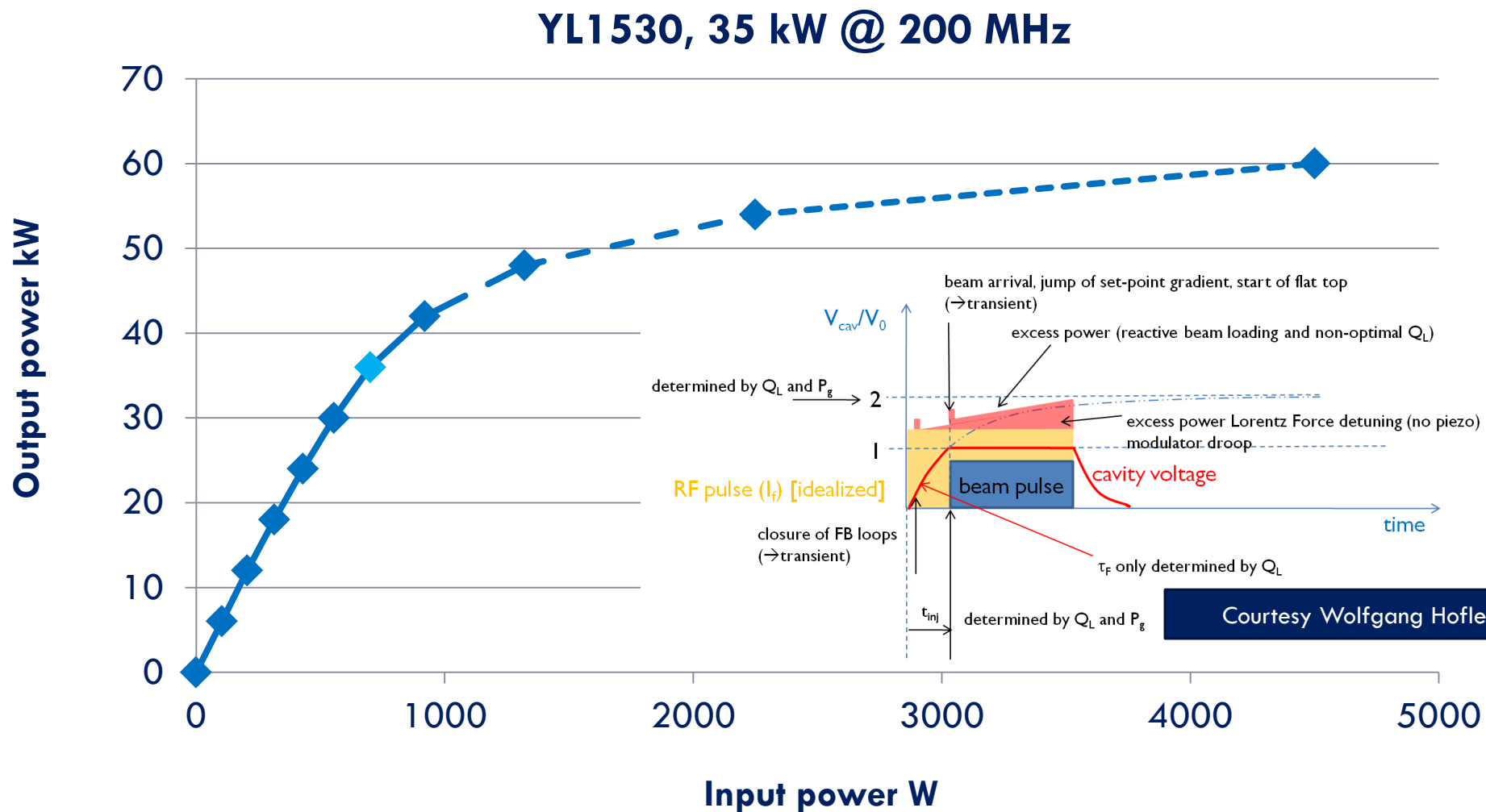
Available RF sources at a glance



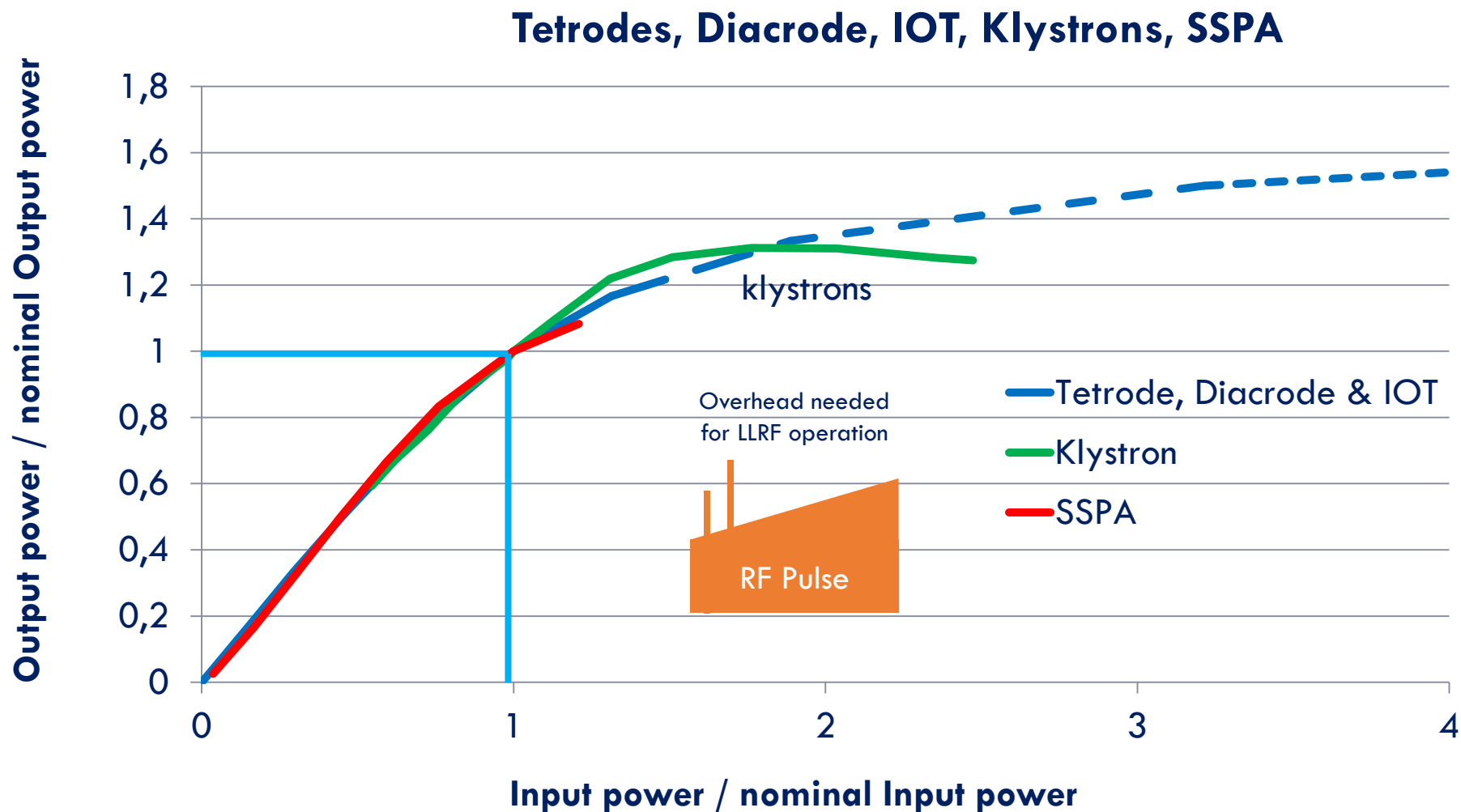
Available RF sources at a glance



Overhead

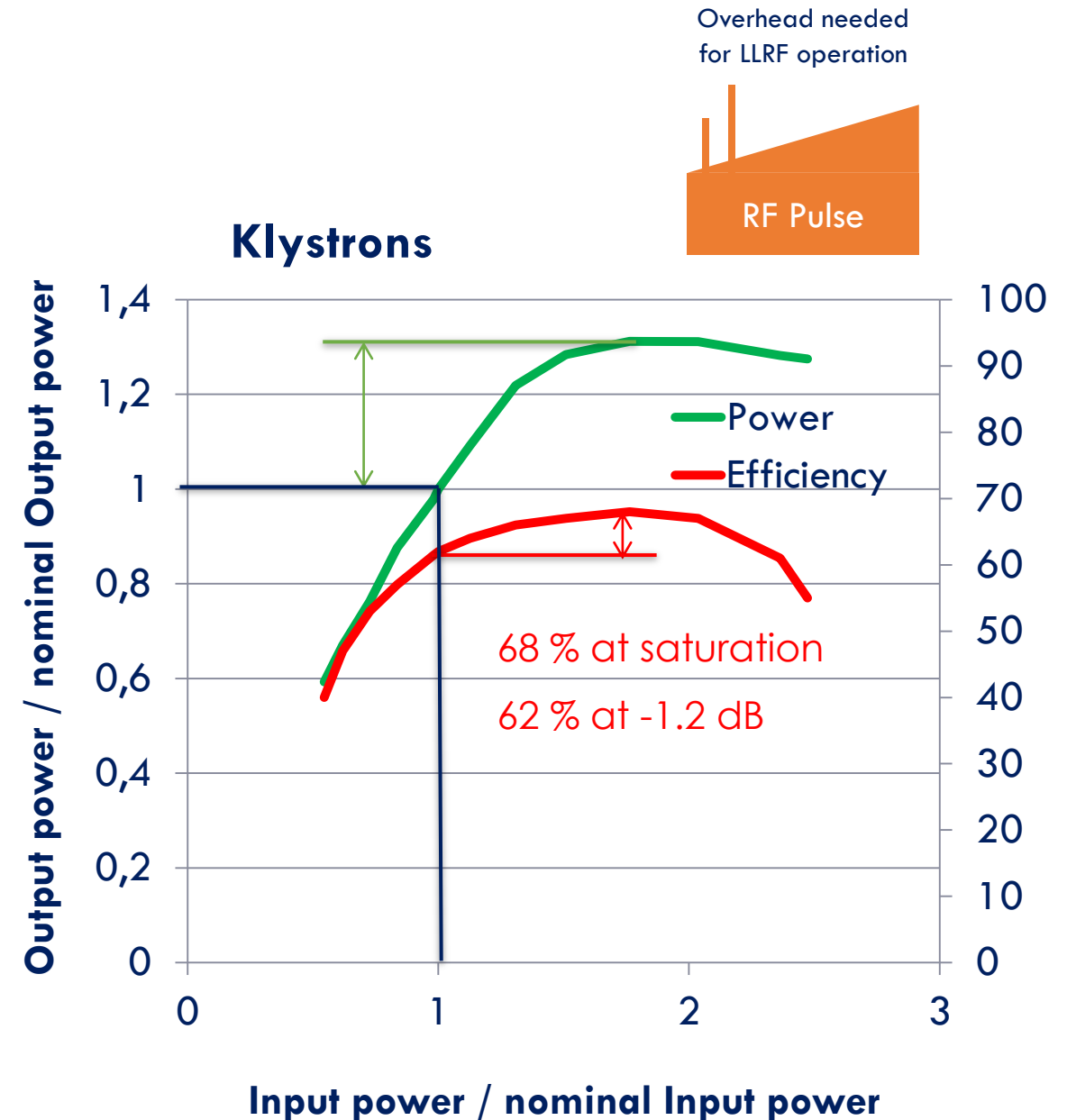


Overhead



Klystrons

Output power reduces if we go over saturation (nominal) point of operation
Need to operate lower than nominal point of operation
Loss of efficiency
Double cost (acquisition + operation)
Phase stability is given by construction
from HV stability (very expensive)



Tetrodes, Diacrodes, IOT

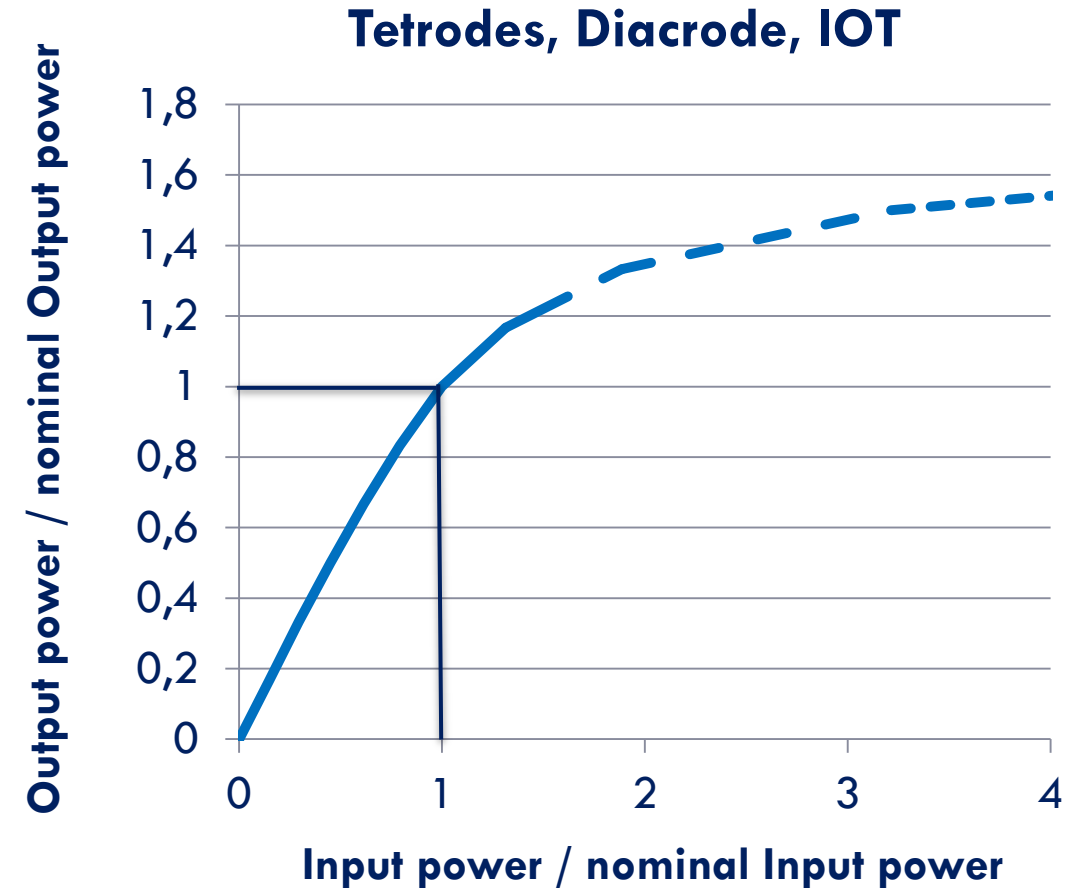
Overhead needed
for LLRF operation



A great advantage of gridded tubes is that they allow overdrive without damage
Thanks to that, they can be operated very close to their nominal point

Tetrodes & Diacrodes are limited in frequency (max ~ 400 MHz), not IOT

Lower gain, some more stages, addition of limiting parameters

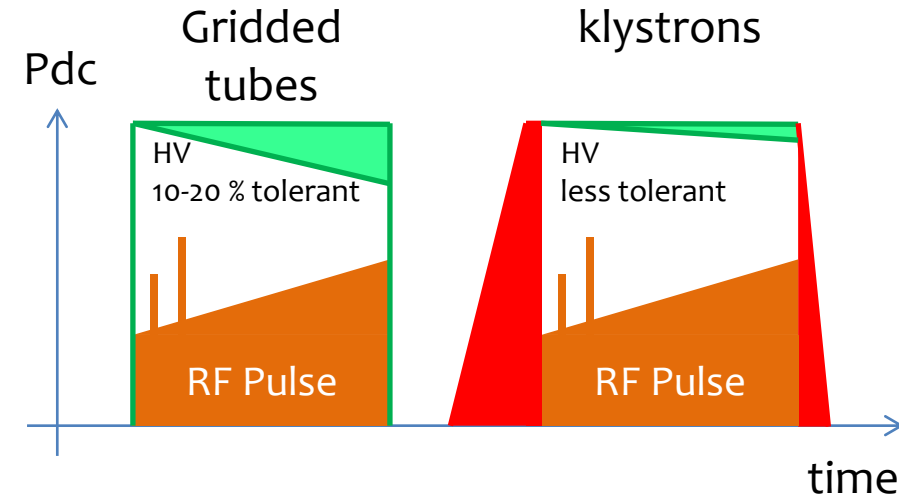


HVPS

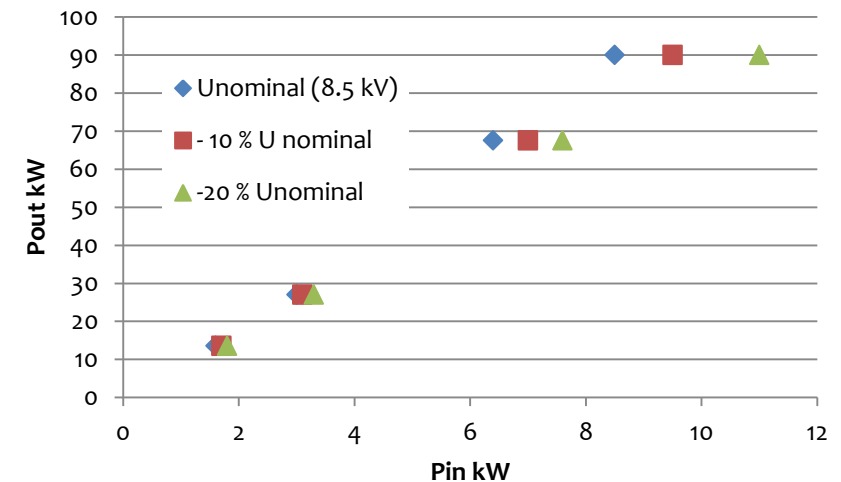
For gridded tubes HVPS is very simple
No RF \rightarrow idle current (can be zero in class B or class C)

Even if HV is drooping, the LLRF will impose output power, and tetrode remains able to deliver requested Power

Stability of the klystron is much more dependant on stability of the HVPS as any drop will result on different acceleration, and length of drift tube remains the same, it means a phase variation



RS2004 tetrode



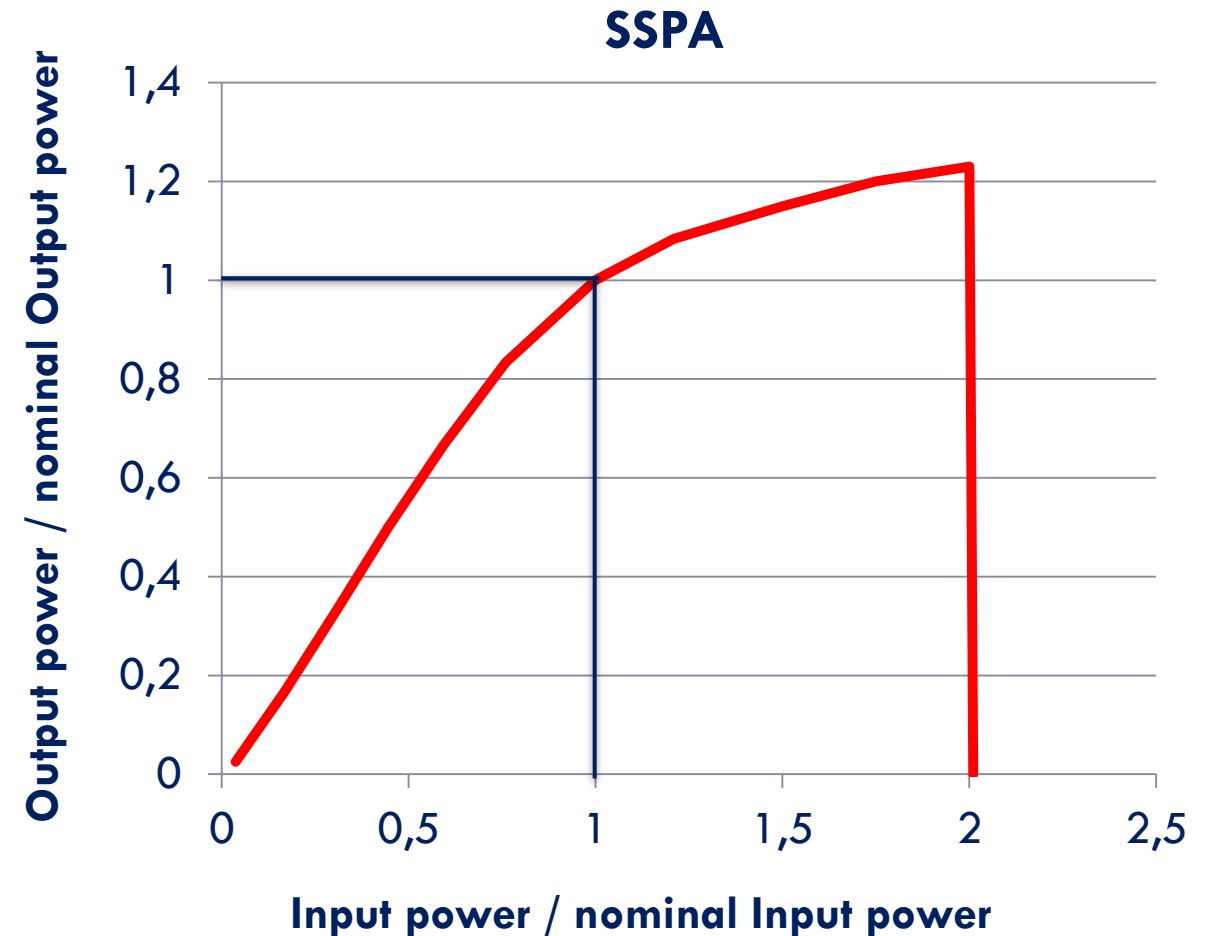
SSPA

Destruction in case of large overdrive
(+ 3 dB) longer than $\sim 100 \mu\text{s}$

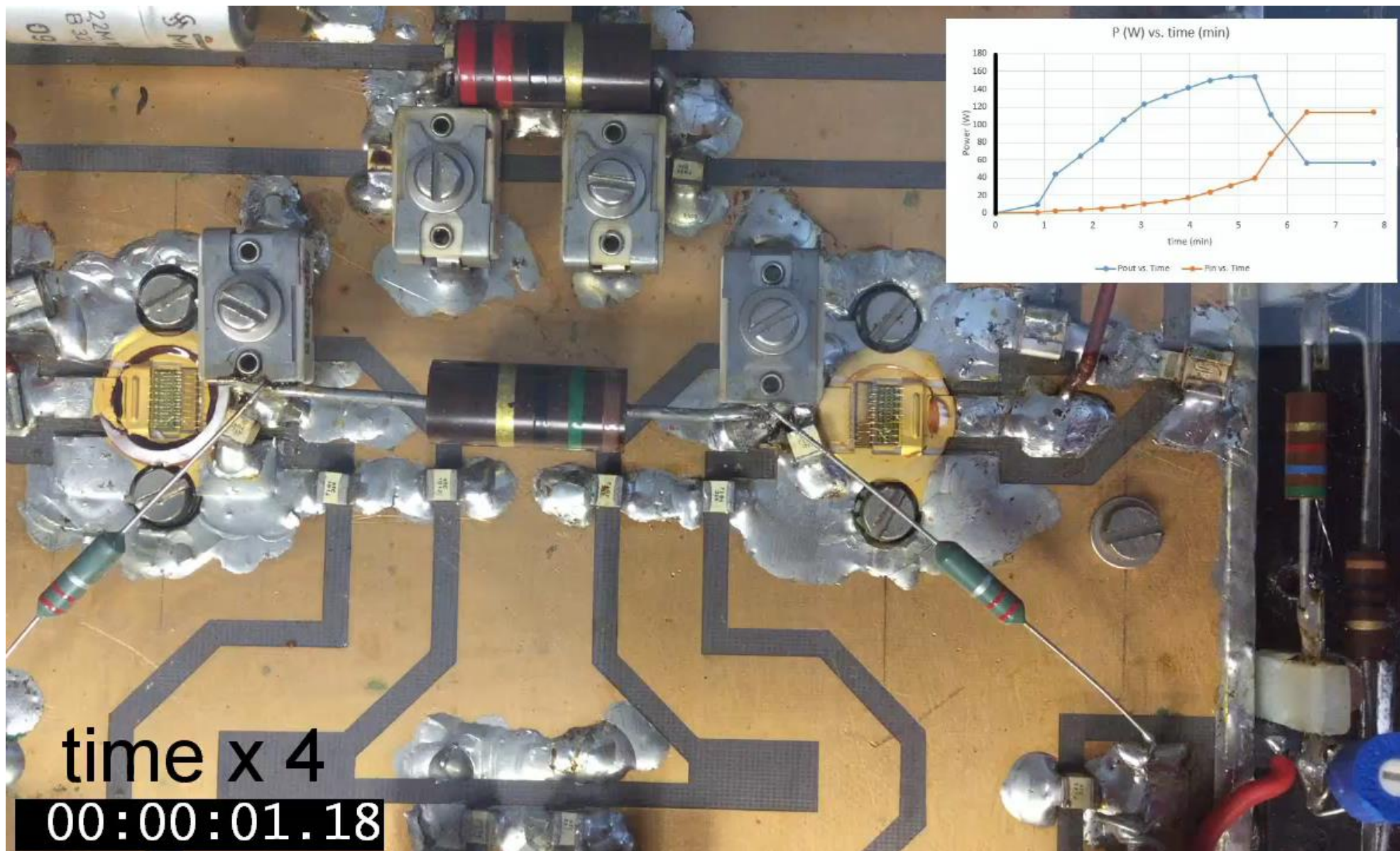
Hard protection limit are needed,
could be built in, but then it is
complex to manage for LLRF, so we
try to have a good LLRF protection
system

Overhead must be perfectly and
correctly defined

Overhead very costly (compare to
gridded tubes)







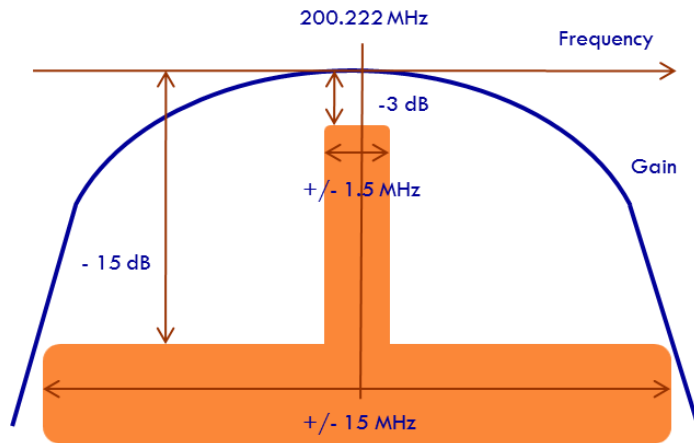
True life for LLRF & HPRF

For any new HPRF system, LLRF colleagues should be involved from the very beginning in order to provide the boundaries needed for operation

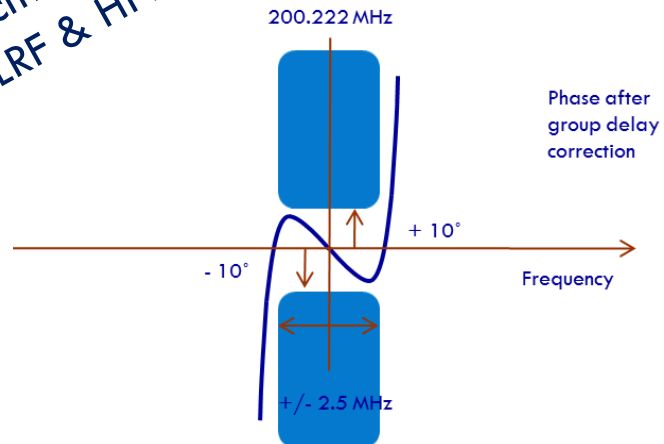
Be aware that HPRF is very expensive

and that we will have, what we will have...

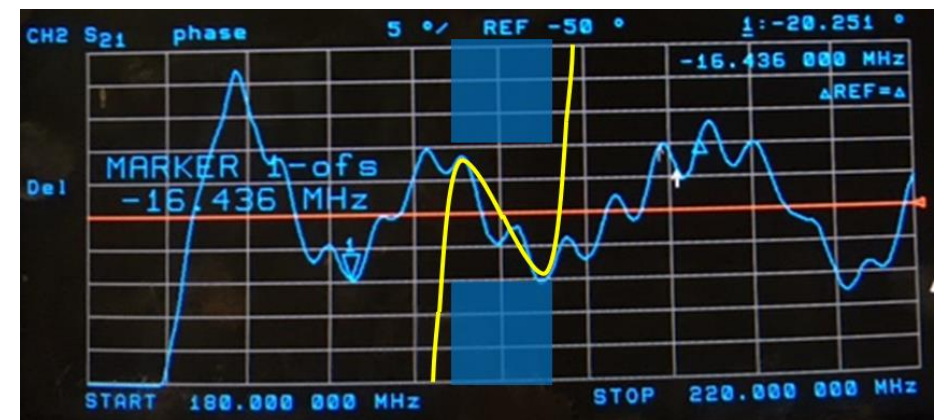
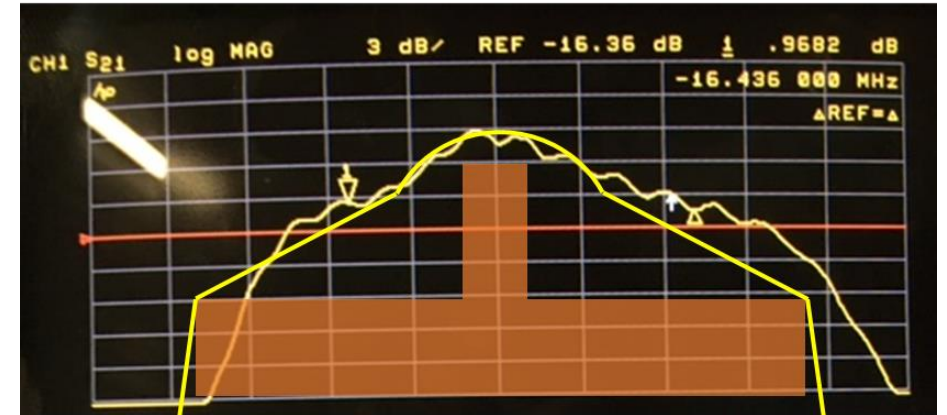
True life for LLRF & HPRF



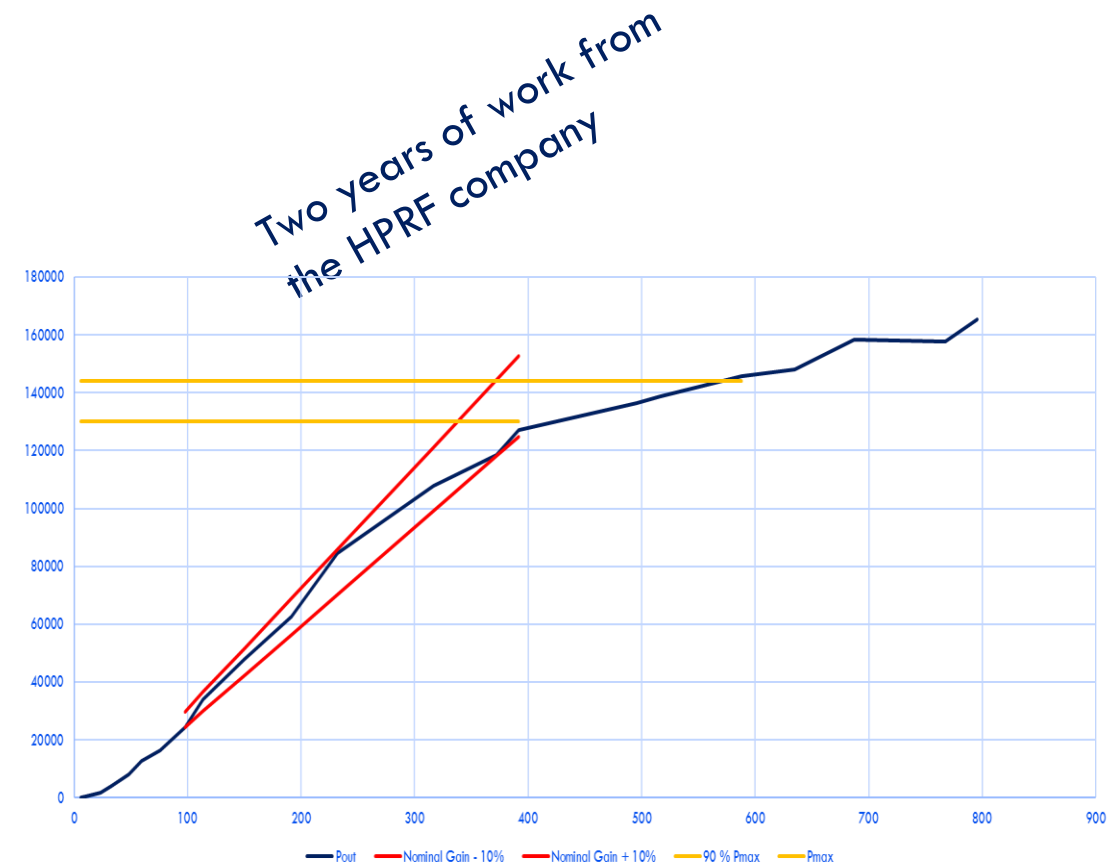
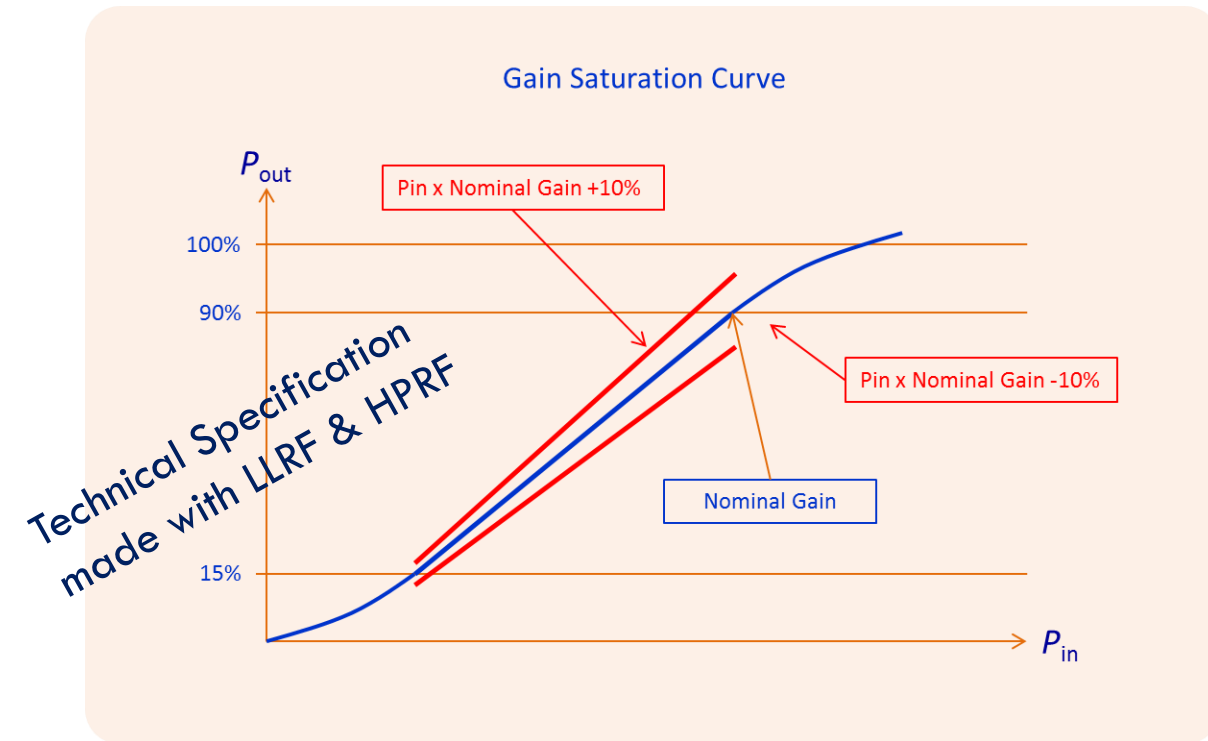
Technical Specification
made with LLRF & HPRF



Two years of work from
the HPRF company



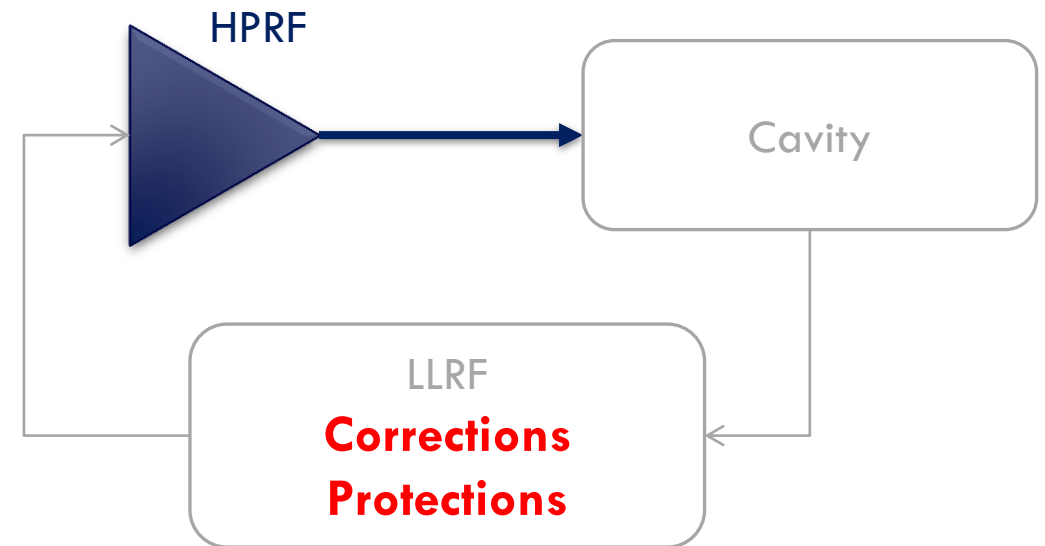
True life for LLRF & HPRF



Conclusion

Whatever characteristics you need, please keep in mind that HPRF is very long to build, is very expensive, and that LLRF will have to compensate all our HPRF systems defaults

You are the ones that will enable our very expensive HPRF systems to be operational and reliable





Thank you very much

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