RF power & LLRF

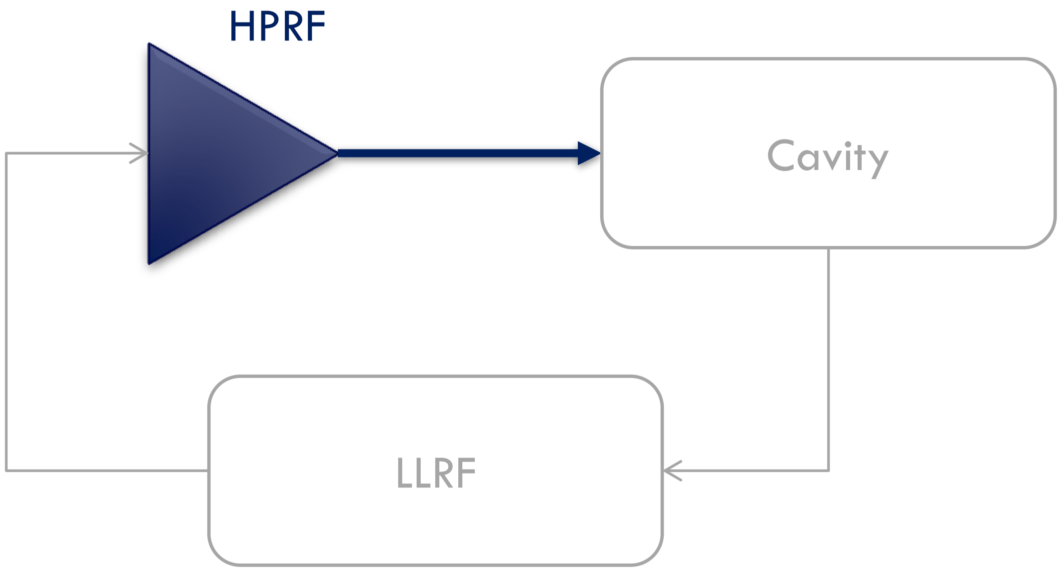
eric.montesinos@cern.ch

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)

eric.montesinos@cern.ch

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

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

eric.montesinos@cern.ch

RF power sources 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)

eric.montesinos@cern.ch

Grid tubes

1904 Diode, John Ambrose Fleming

1906 Audion (first triode), Lee de Forest

1912 Triode as amplifier, Fritz Lowenstein

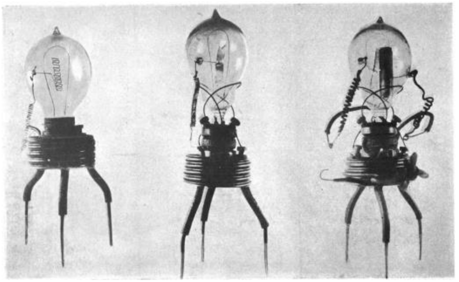
1913 Triode ‘higher vacuum’, Harold Arnold

1915 first transcontinental telephone line, Bell

1916 ***Tetrode***, Walter Schottky

1926 Pentode, Bernardus Tellegen

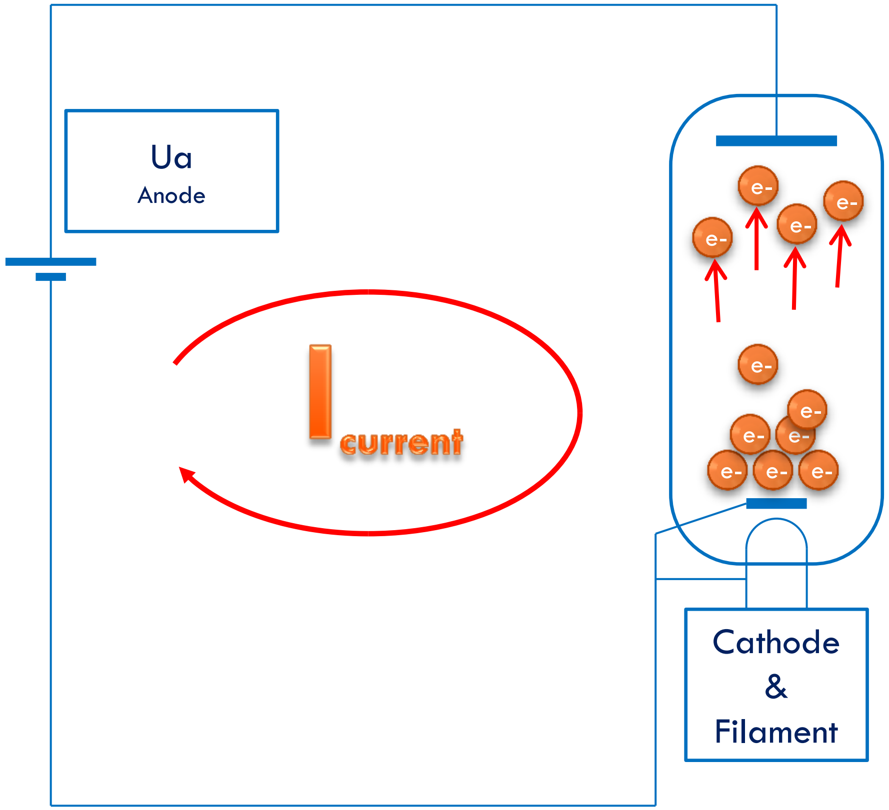
1994 Diacrode, Thales Electron Devices



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,…

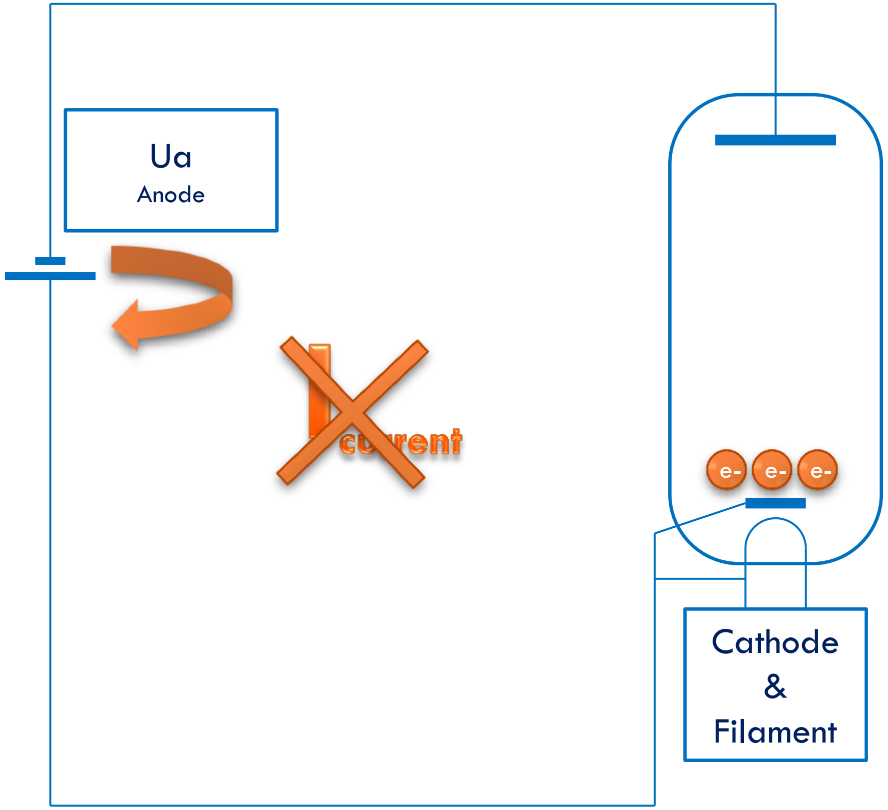
  thermionic emission

  Electron cloud

Anode

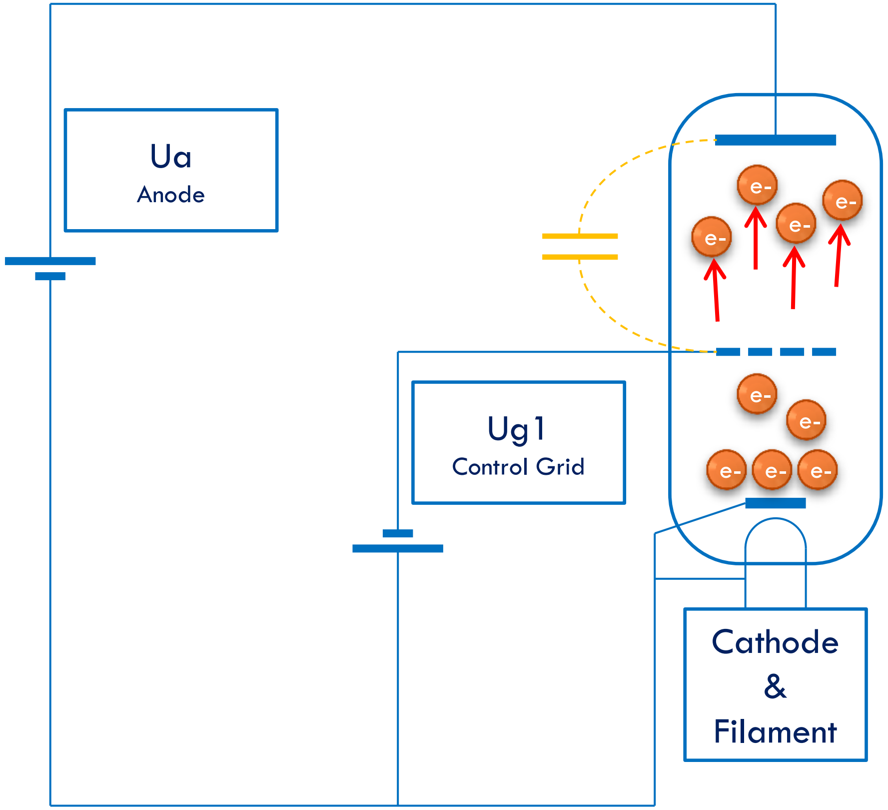
Diode

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

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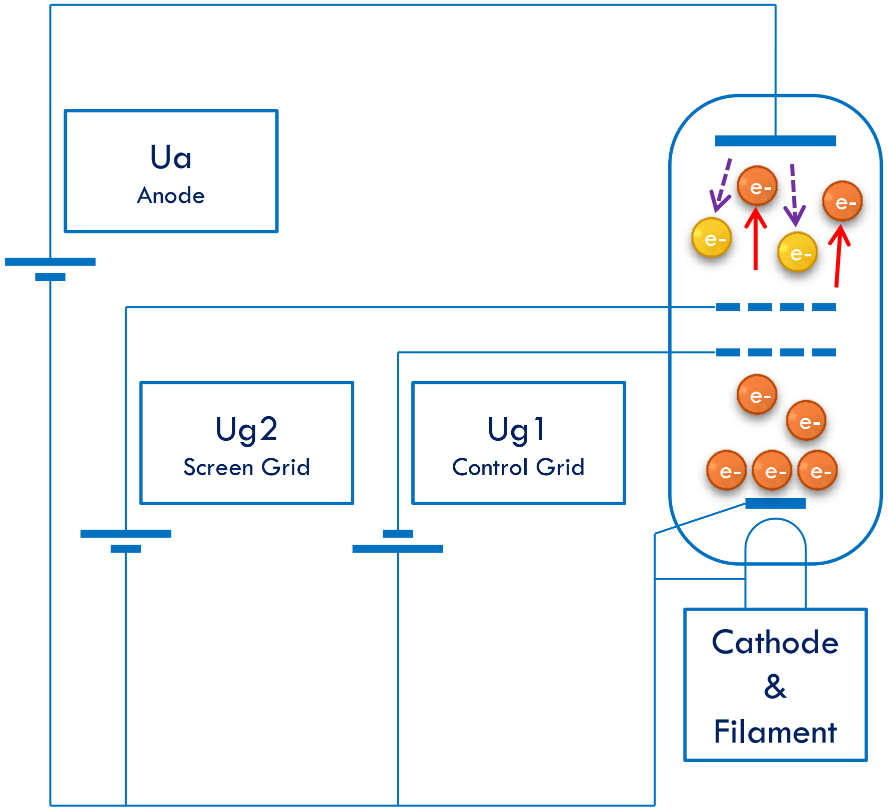
Essentials of grid tube



Tetrode

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

Essentials of grid tube

DC power is Pdc = Vdc Idc

Assuming the tube is linear whilst it is conducting, the dc anode current is found by Fourier analysis of the current waveform and is Idc = Ipk/π

Irf = Ipk/2 = Idc π/2, and ideal class B, Vrf = Vdc

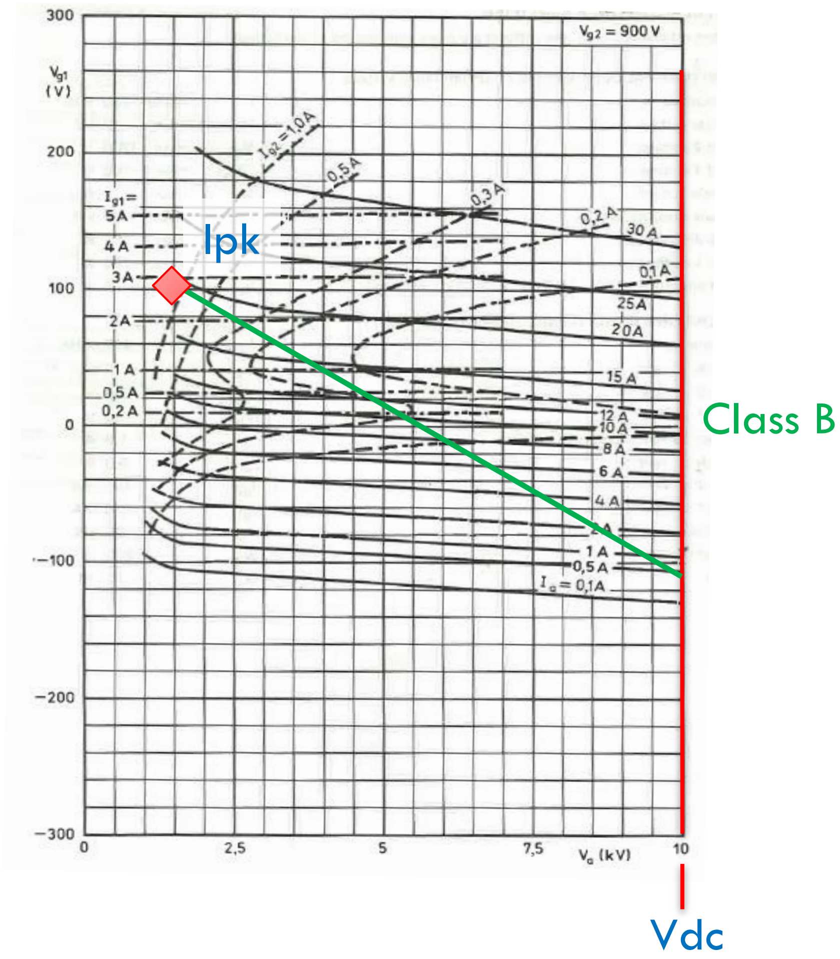
So, RF power is Prf = ½ Vrf Irf

Prf = ½ Vdc Idc π/2 = π/4 Vdc Idc

Theoretical efficiency

η = Prf/Pdc = ¼ Vdc Ipk / Vdc Idc

η = 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

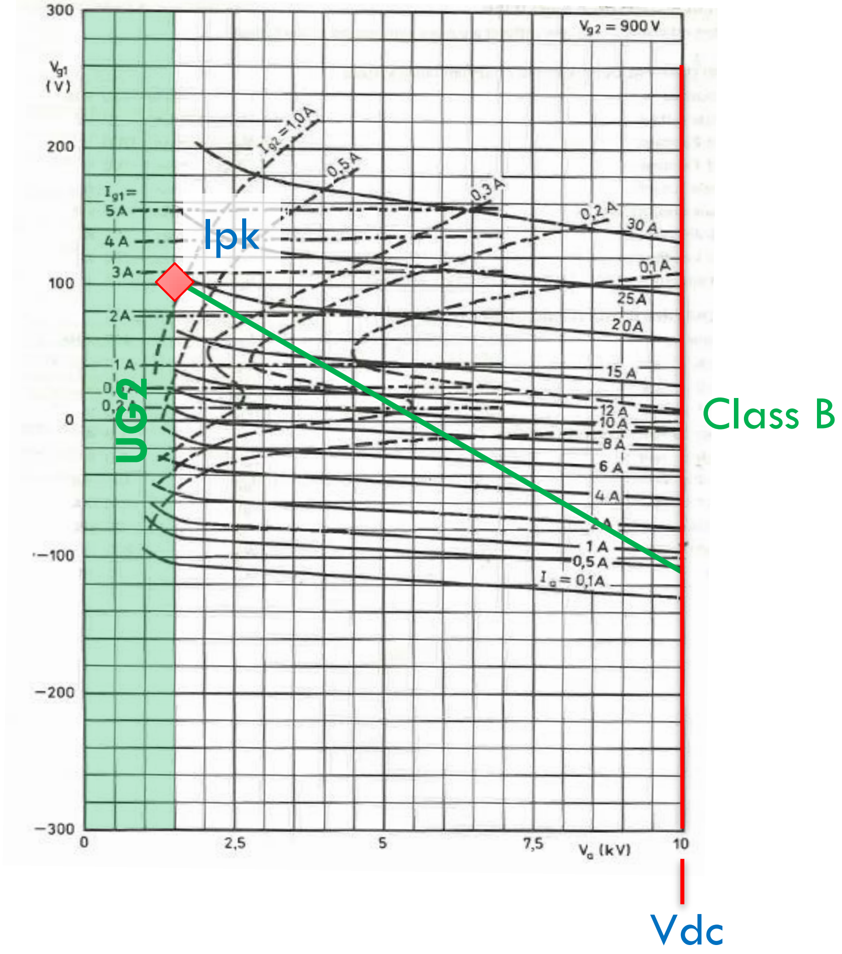
Pdc = Vdc Idc = Vdc 1.05 Ipk/π

Prf = ½ Vrf Irf = ¼ 0.9 Vdc Ipk

Theoretical efficiency in practice

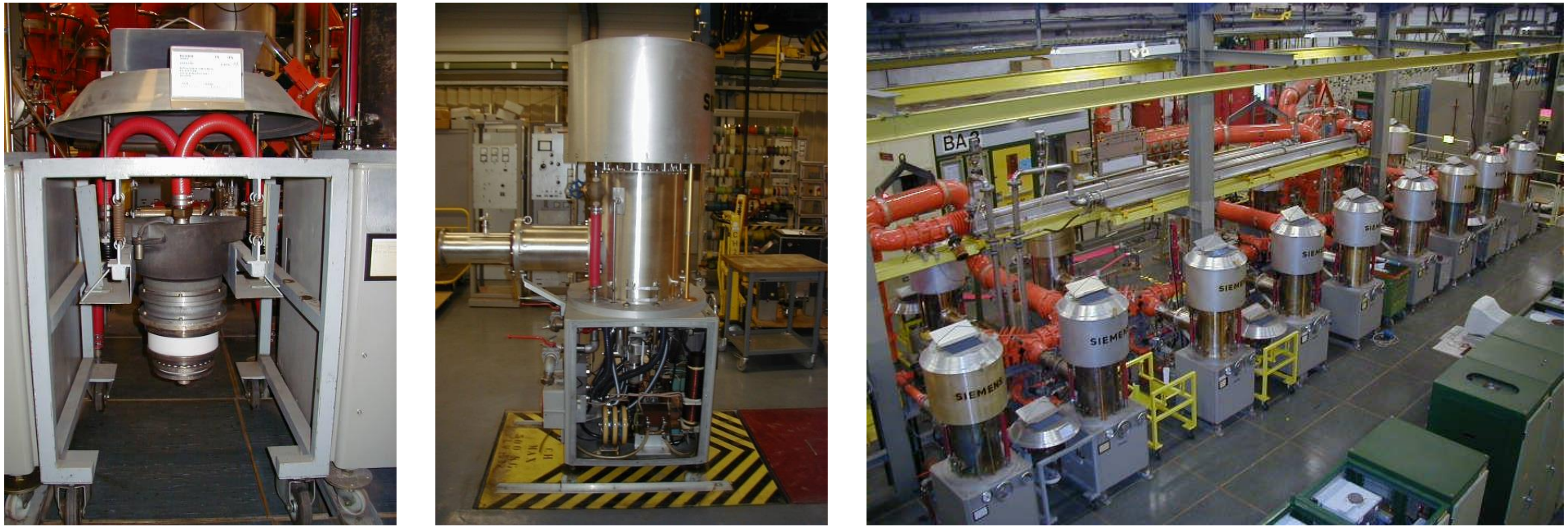
η = Prf/Pdc = ¼ 0.9 Vdc Ipk / 1.05 Vdc Ipk/π

η = 67 %



Tetrode

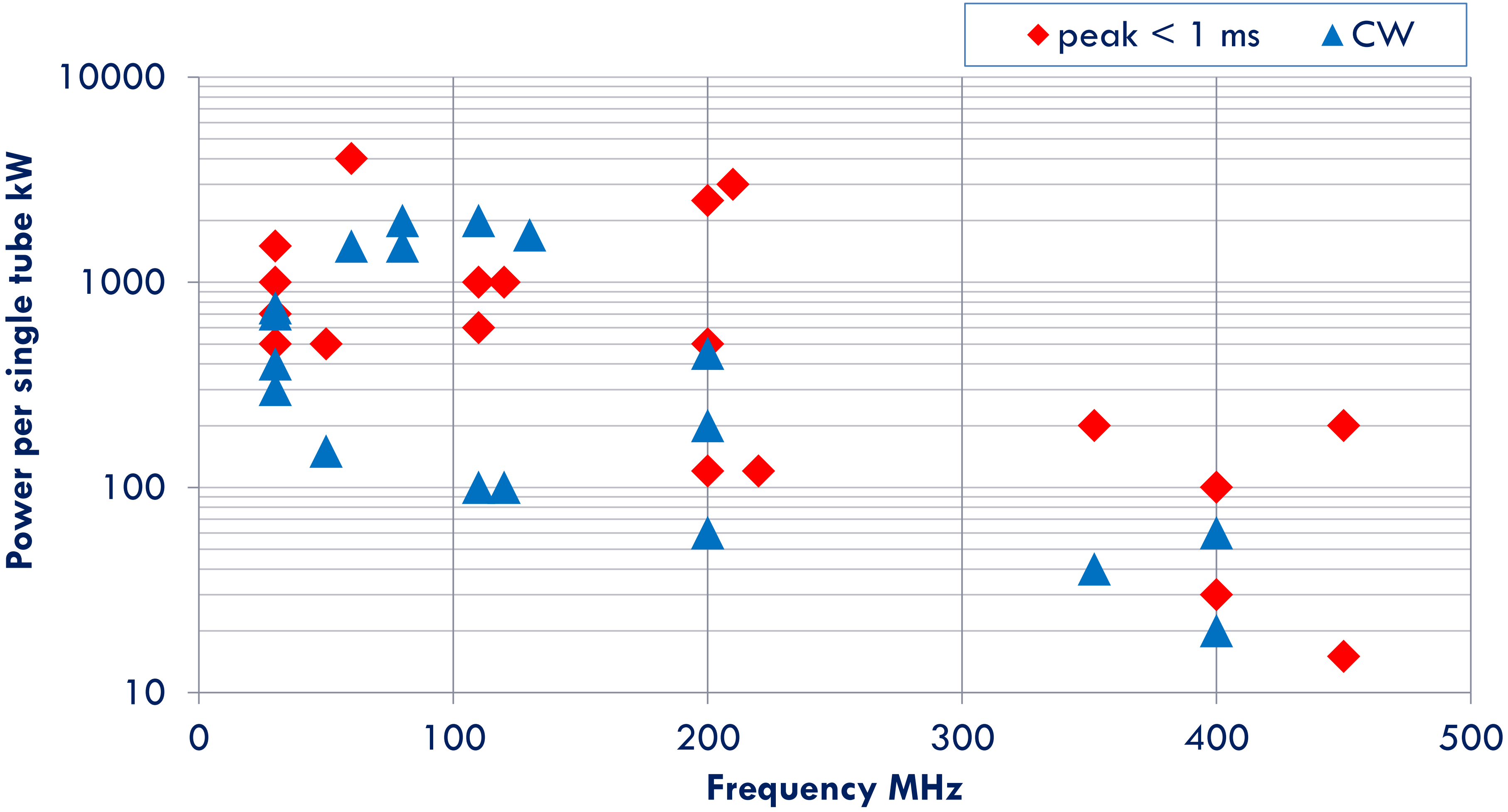
RS 2004 CERN SPS amplifier @ 200 MHz



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

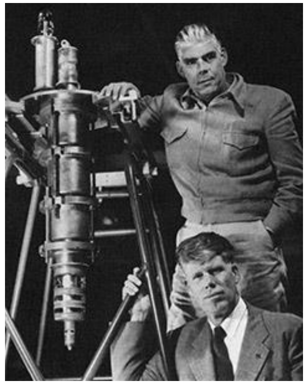
eric.montesinos@cern.ch

Tetrodes & Diacrodes available from industry



Linear beam tubes

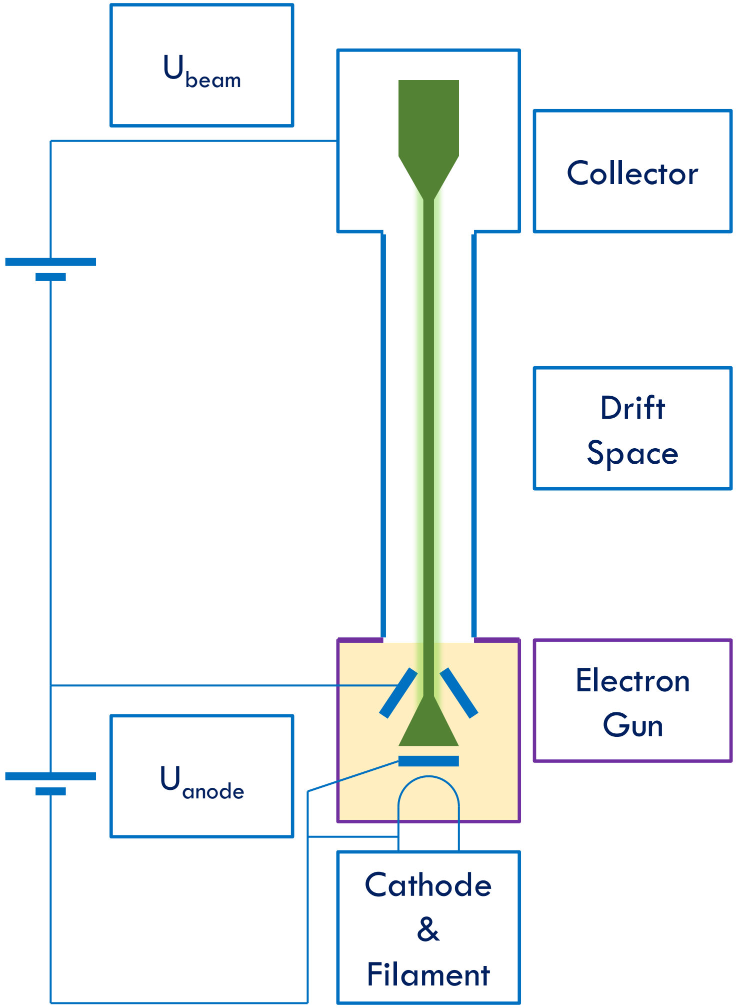
1937	Klystron, Russell & Sigurd Variant
1938	IOT, Andrew V. Haeff
1939	Reflex klystron, Robert Sutton
1940	Few commercial IOT
1941	Magnetron, Randall & Boot
1945	Helix Travelling Wave Tube (TWT), Kompfner
1948	Multi MW klystron
1959	Gyrotron, Twiss & Schneider
1963	Multi Beam Klystron, Zusmanovsky and Korolyov
1980	High efficiency IOT



Russell & Sigurd Varian klystron, 1937

Thales TH 1802, 2002

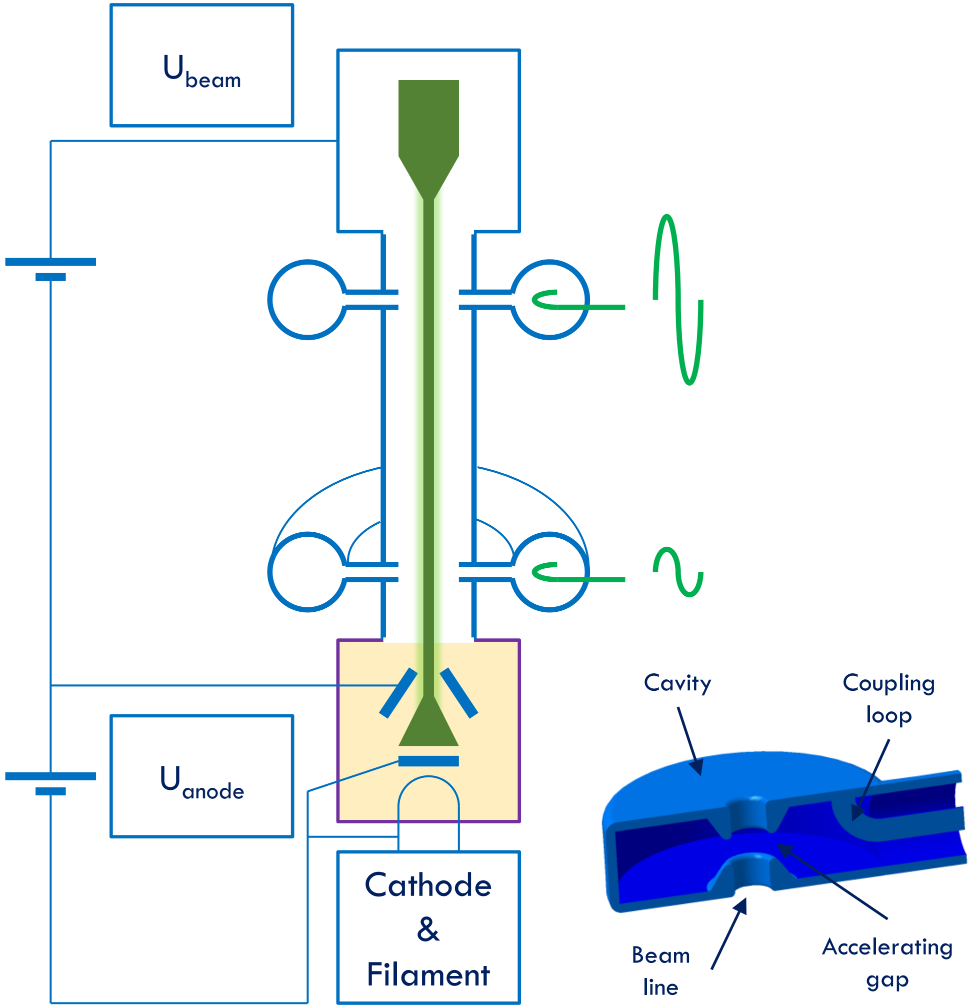
Essentials of klystron



- 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

eric.montesinos@cern.ch

Essentials of klystron



Cavity resonators

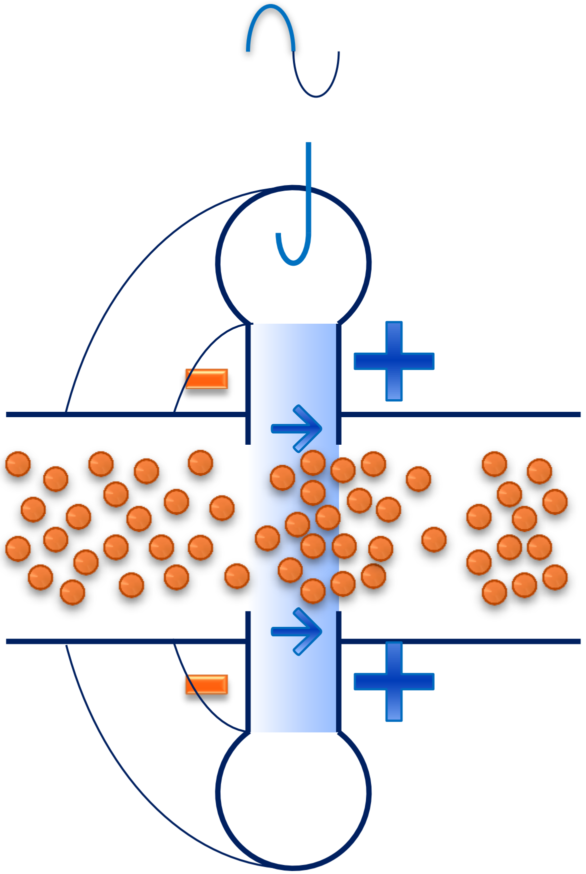
RF input cavity (Buncher)

- 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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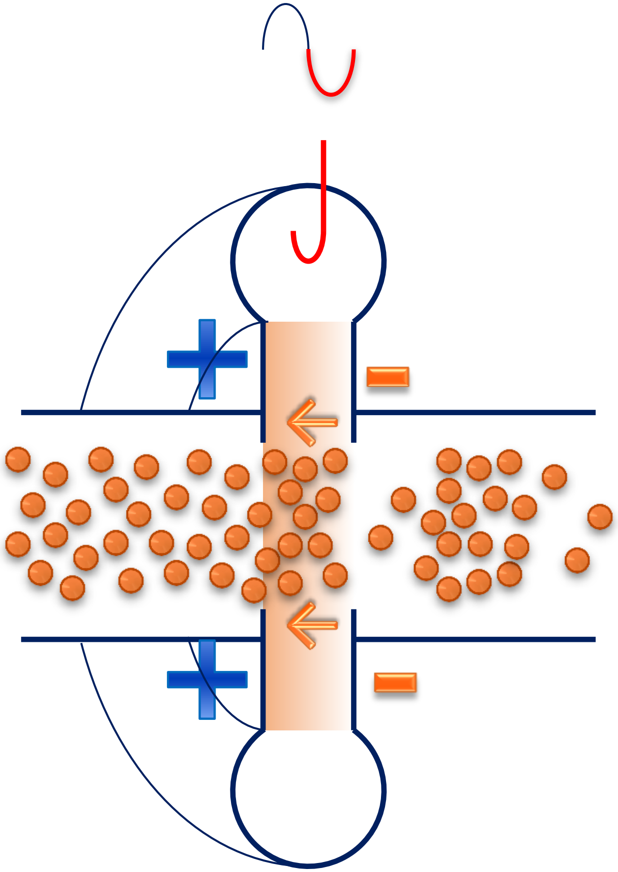

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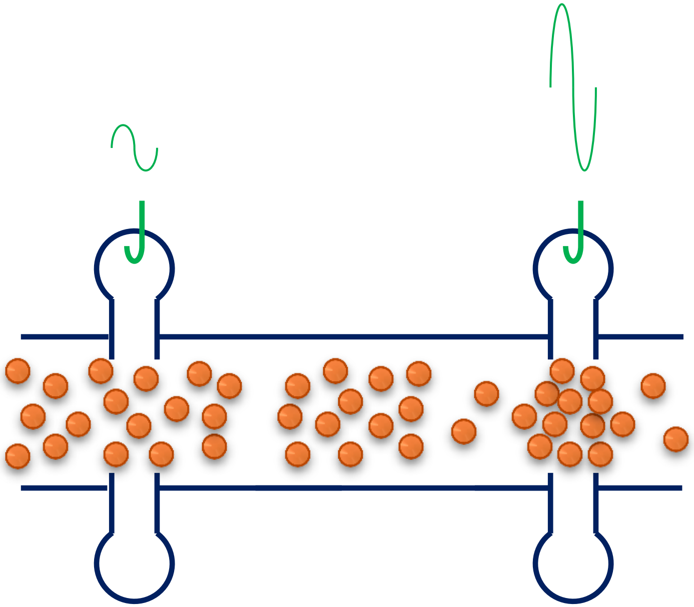
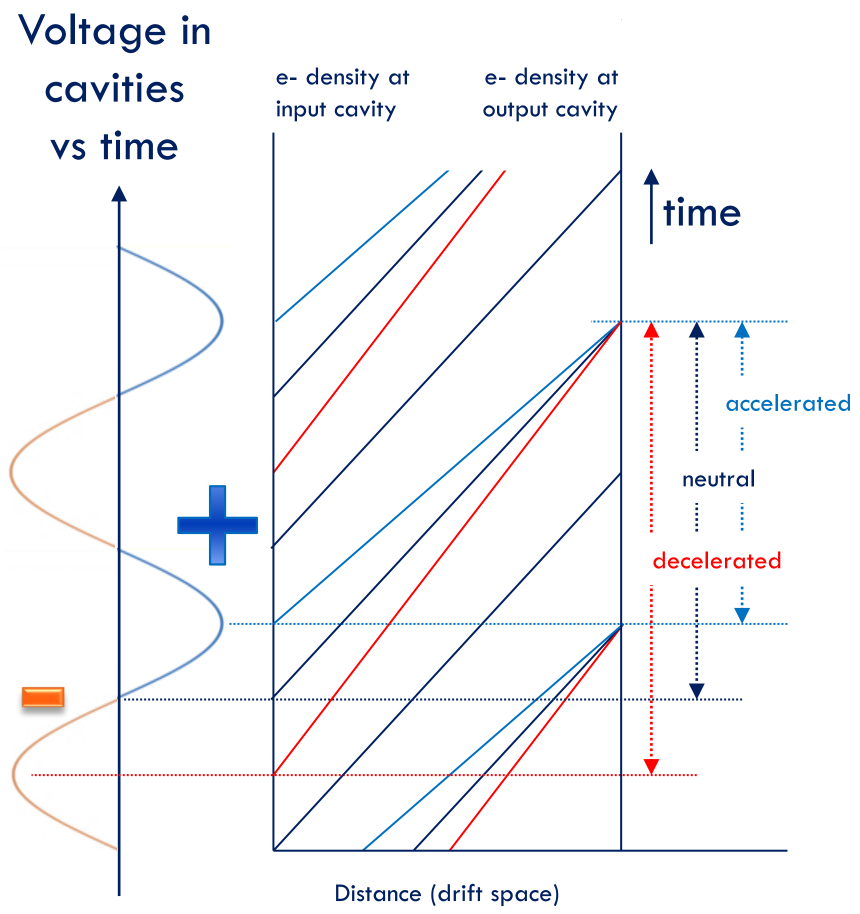
Essentials of klystron



- 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

eric.montesinos@cern.ch

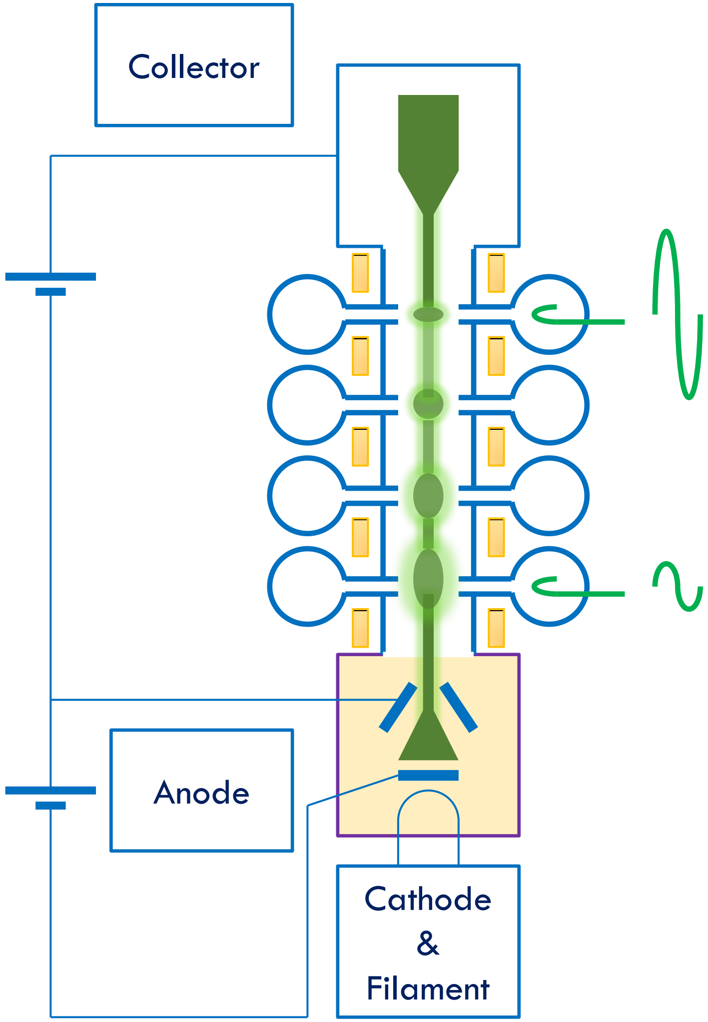
Essentials of klystron



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

eric.montesinos@cern.ch

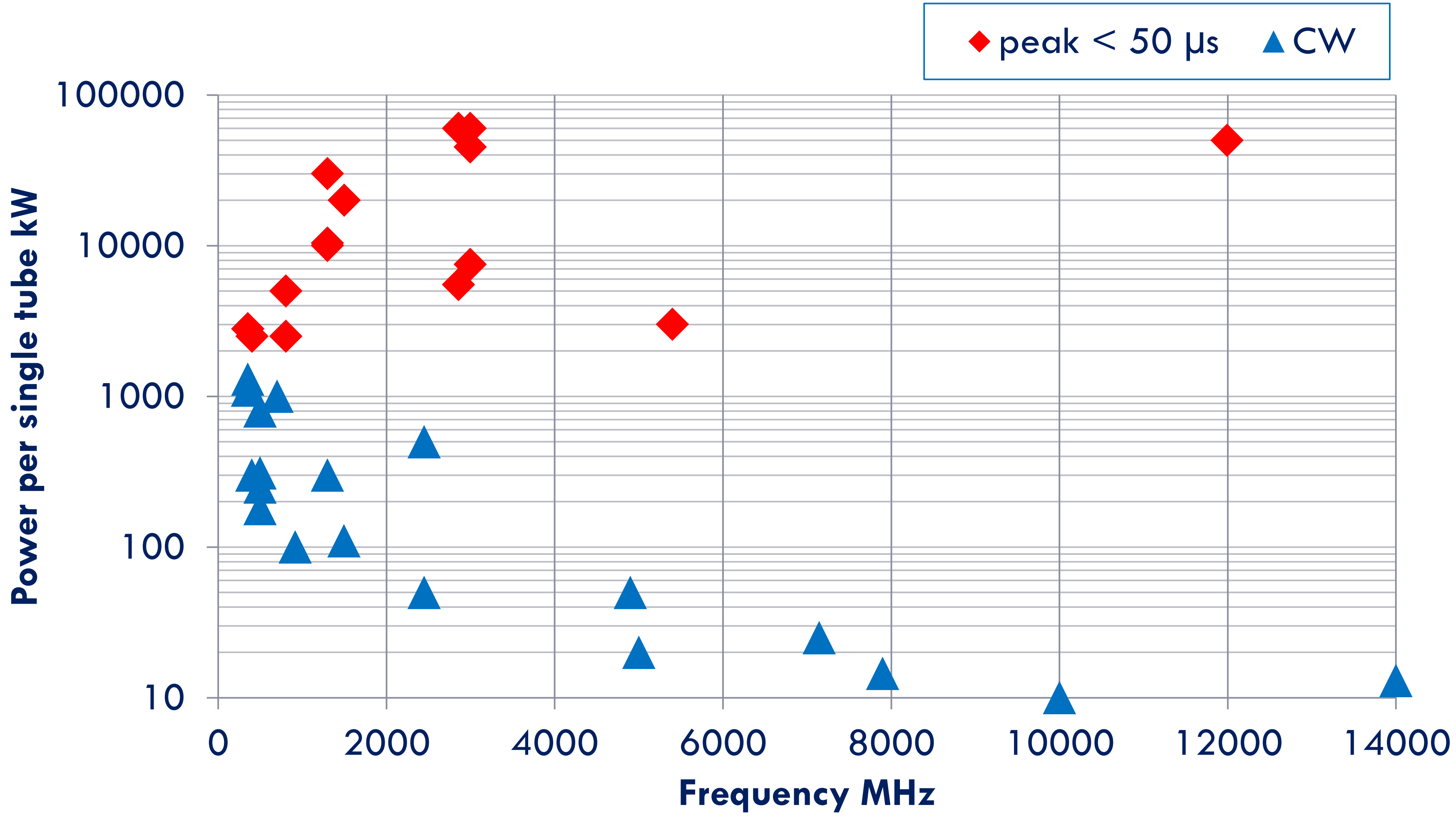
Klystron

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

eric.montesinos@cern.ch

Klystrons available from industry



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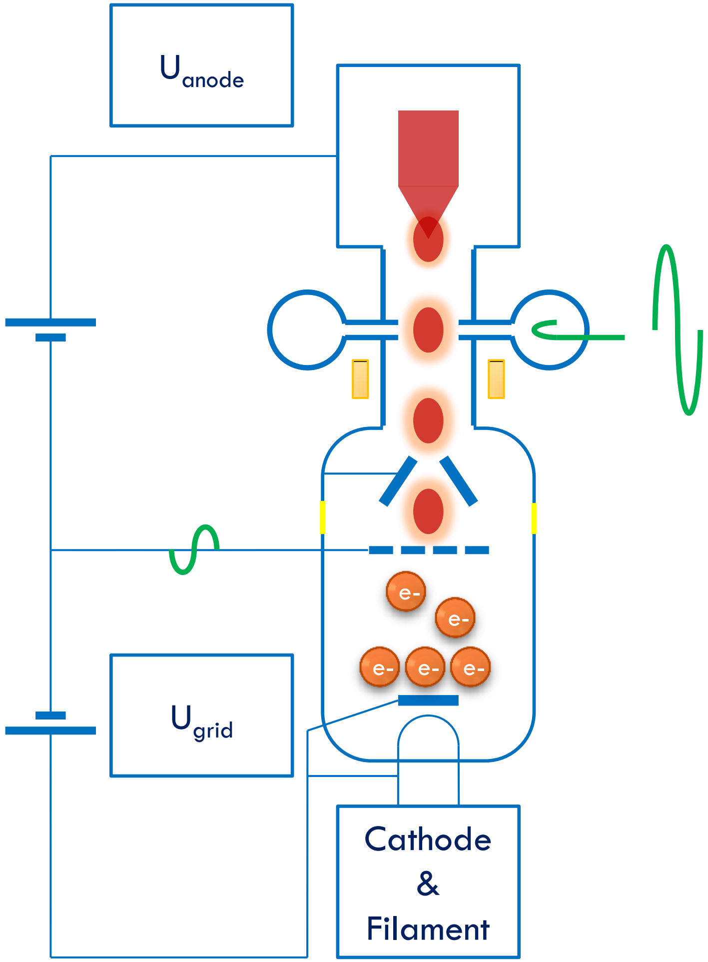
Essentials of IOT



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

eric.montesinos@cern.ch

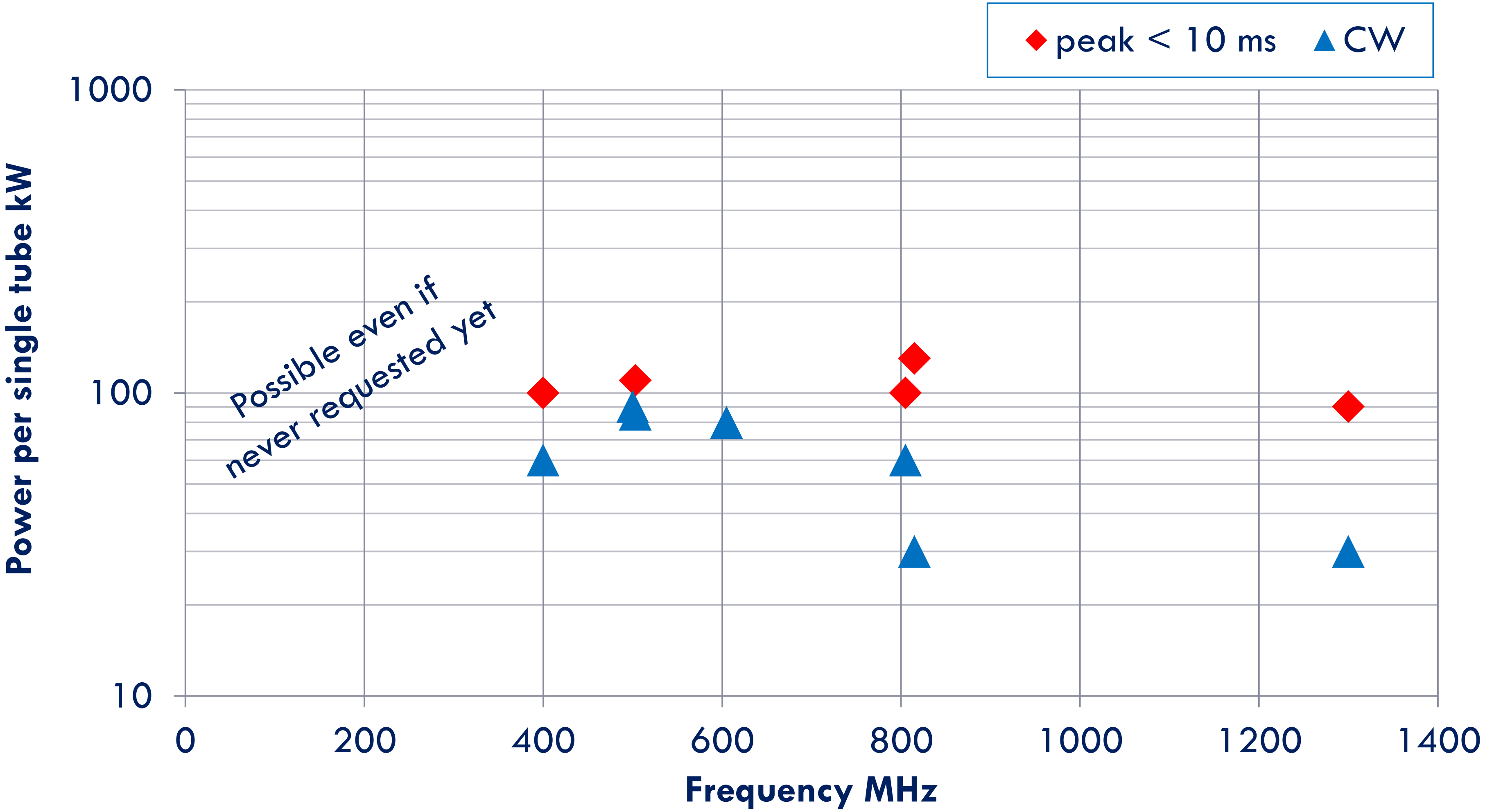
IOT

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

eric.montesinos@cern.ch

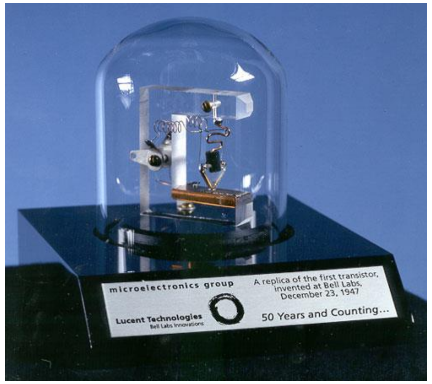
IOT available from industry



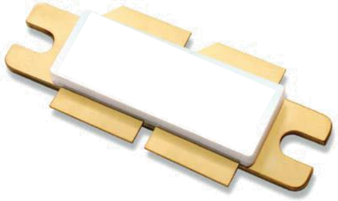
eric.montesinos@cern.ch

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



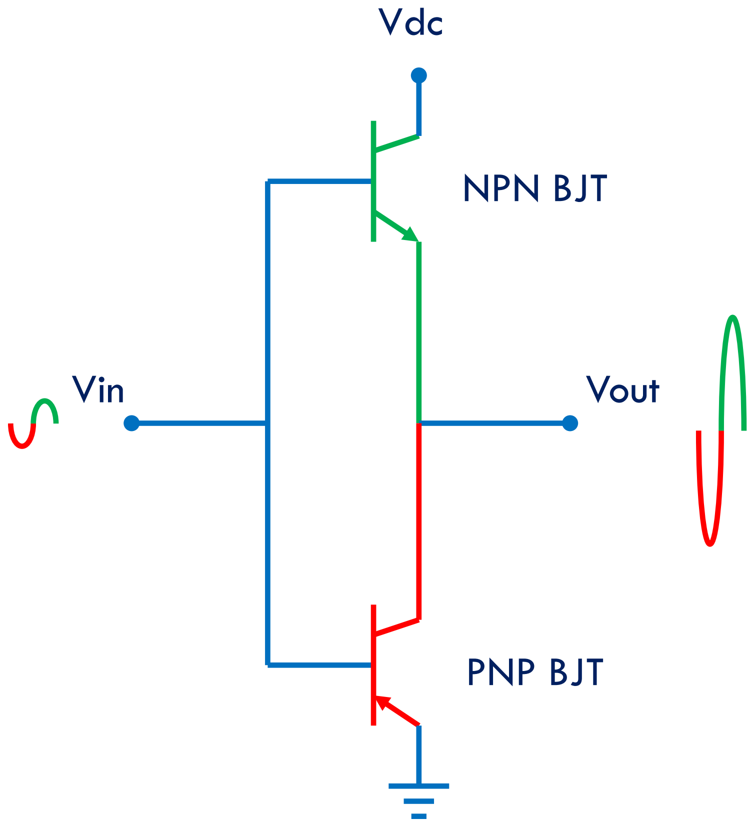
First transistor invented at BELL labs in 1947



XXI century LDMOS

eric.montesinos@cern.ch

Essentials of RF transistor



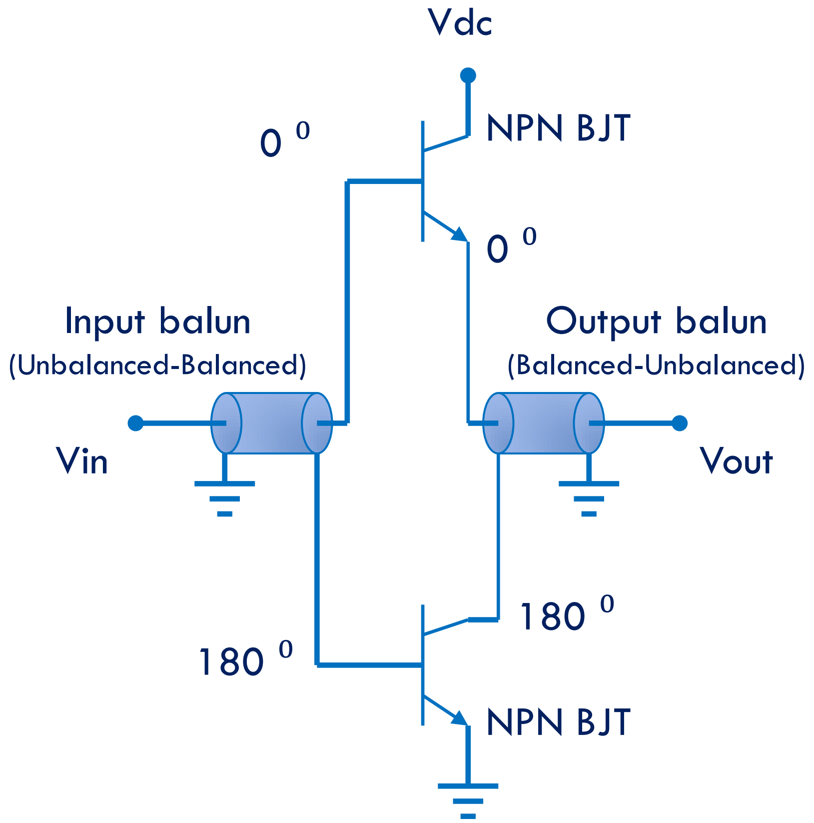
In a push-pull circuit the RF signal is applied to two devices

- 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

eric.montesinos@cern.ch

Essentials of RF transistor



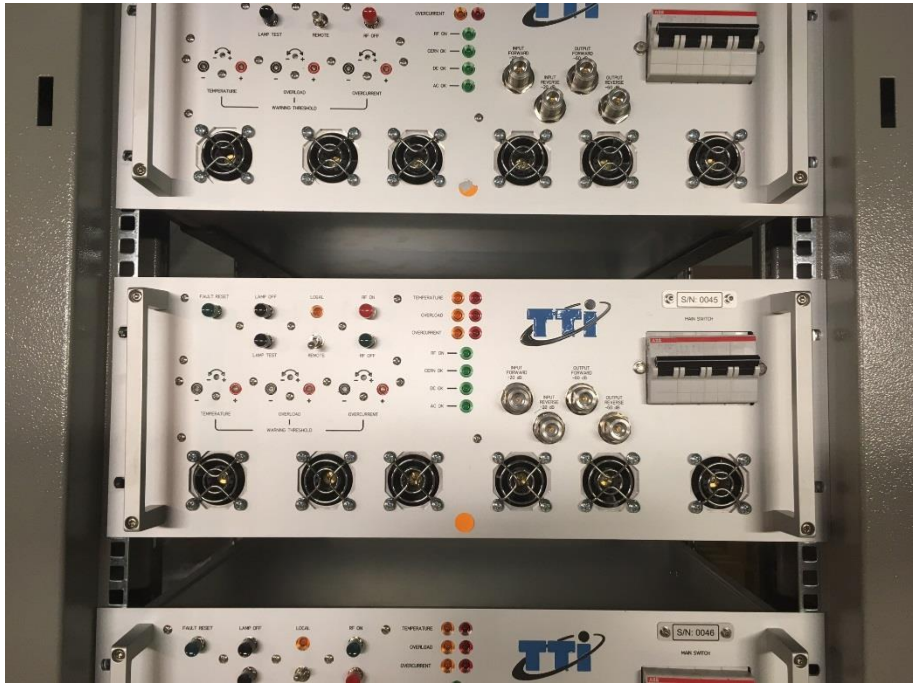
Another push-pull configuration is to use a balun (balanced-unbalanced)

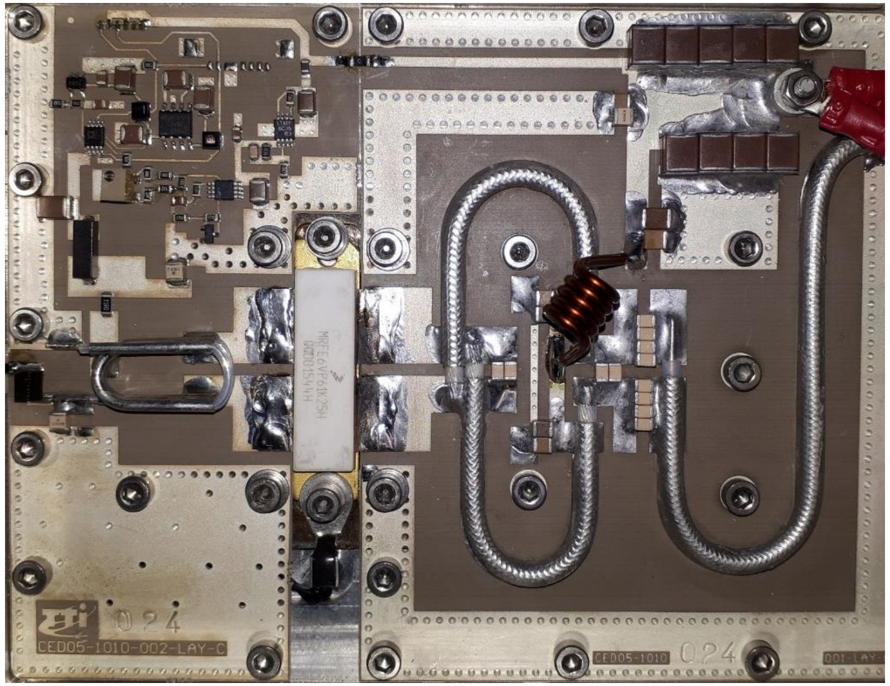
- it acts as a power splitter, equally dividing the input power between the two transistors
- the balun keeps one port in phase and inverts the second port in phase

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 Wp – 700 W CW
solid state amplifiers from TTi Norte (Spain)
that replace discontinued YL 1440 tube

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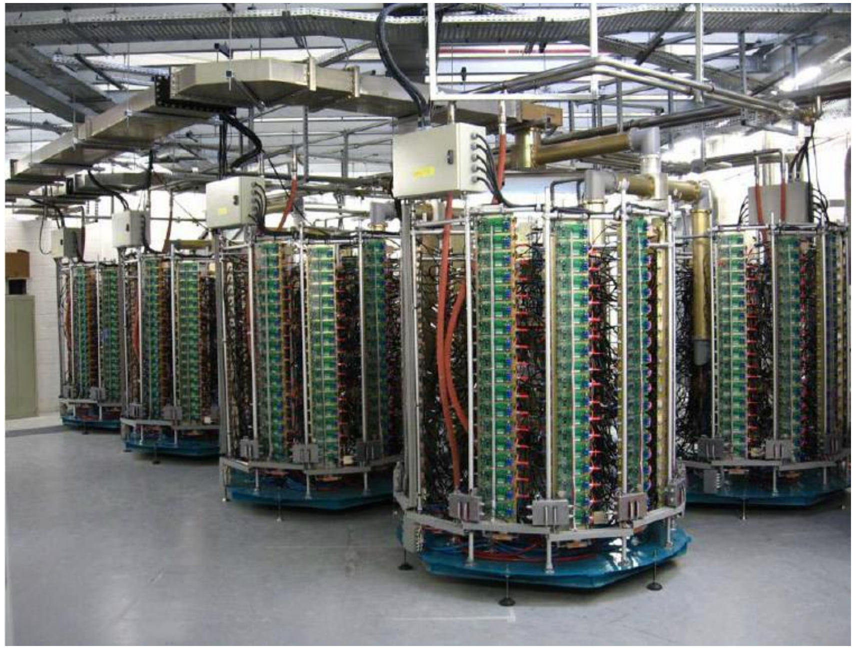
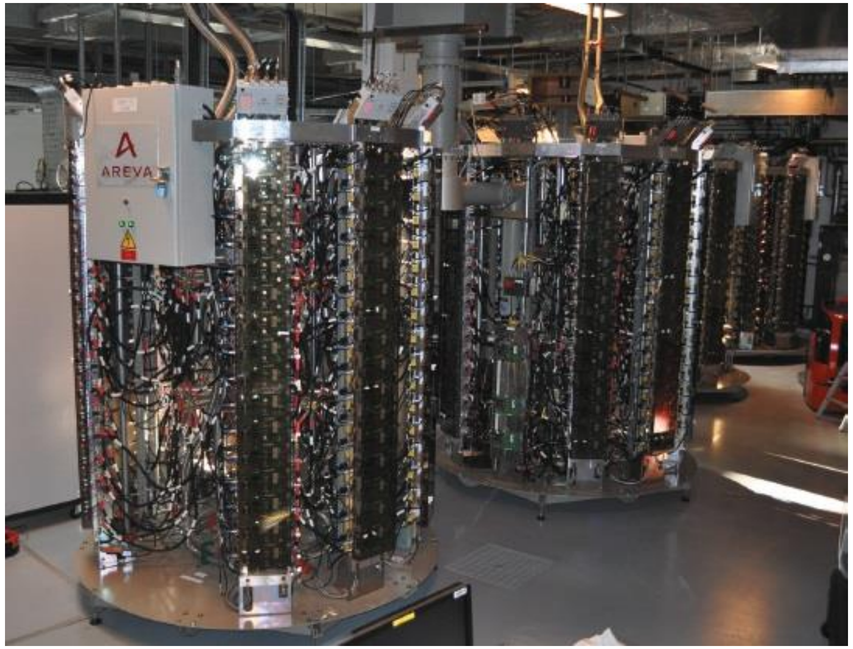
Transistors

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)

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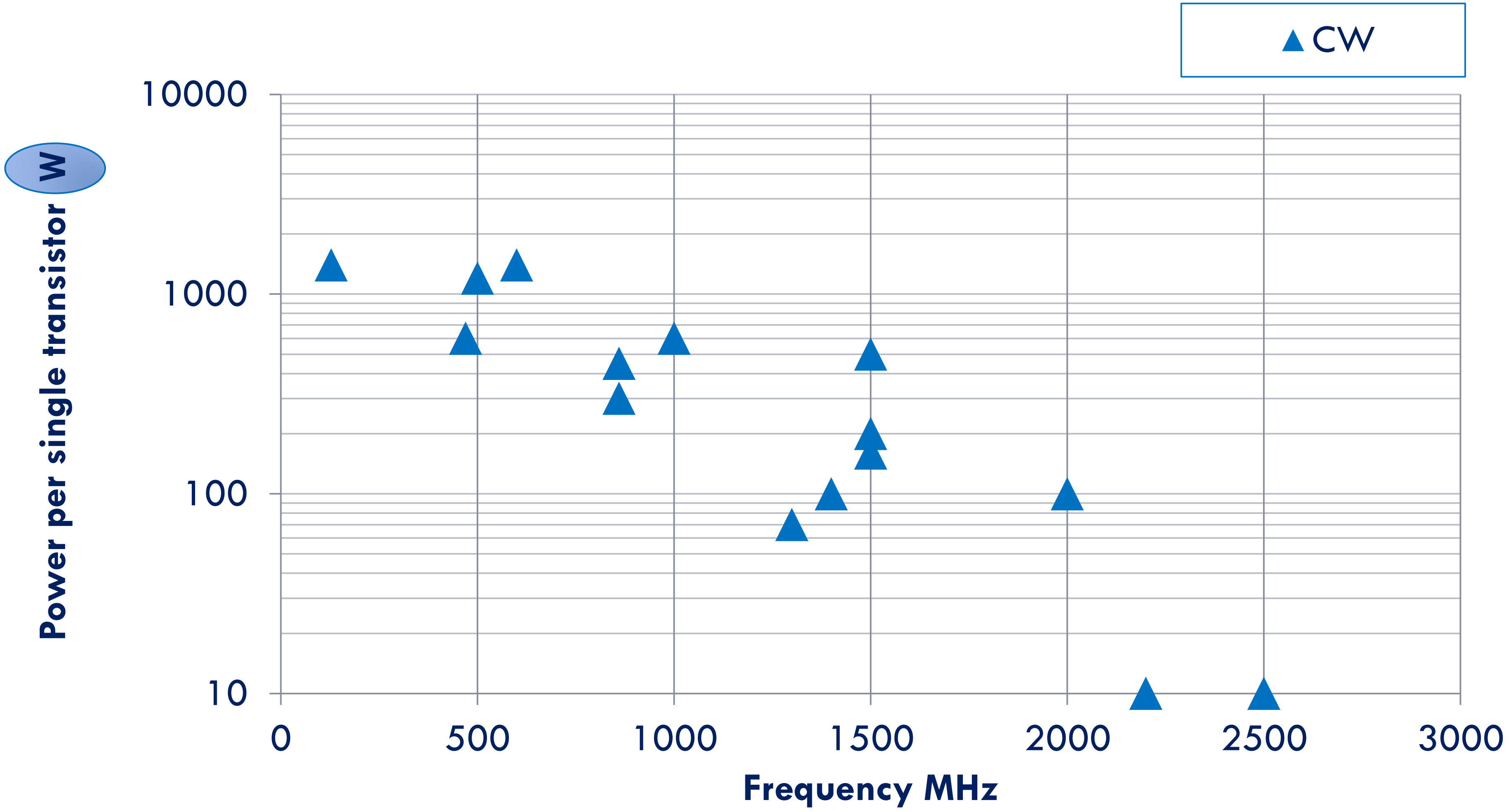
Transistors available from industry



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

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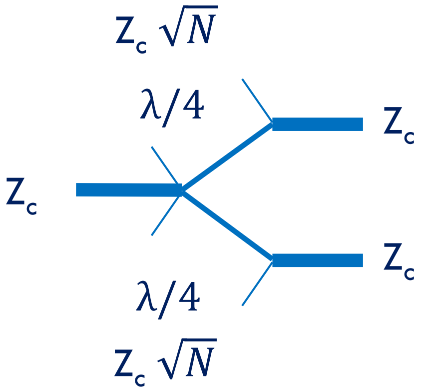
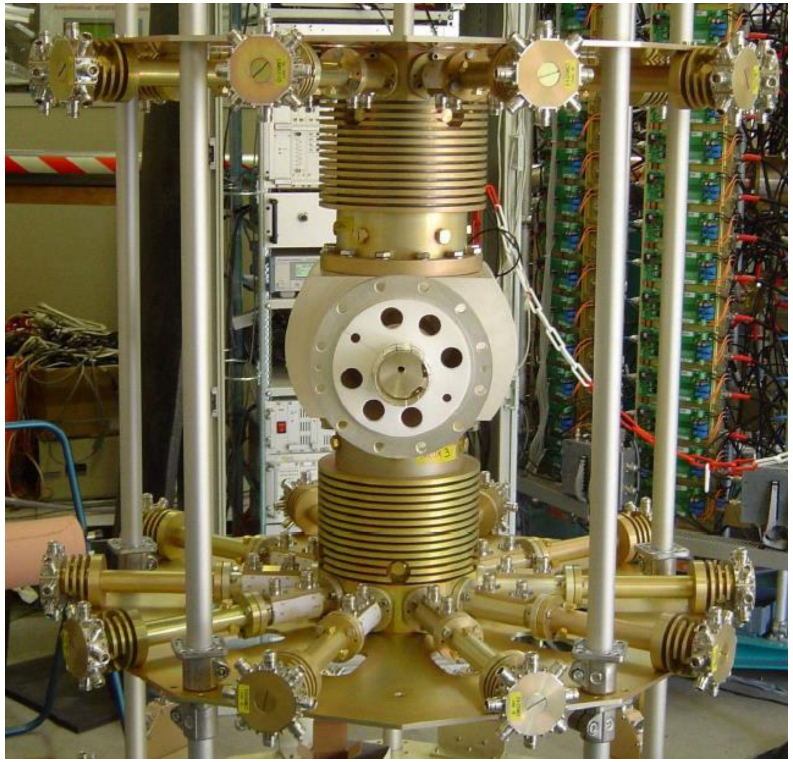
Combiners

Low loss T-Junction



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

We have a N-ways combiner



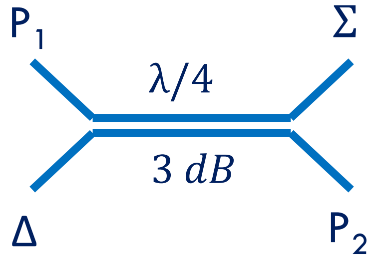
SOLEIL SYNCHROTRON

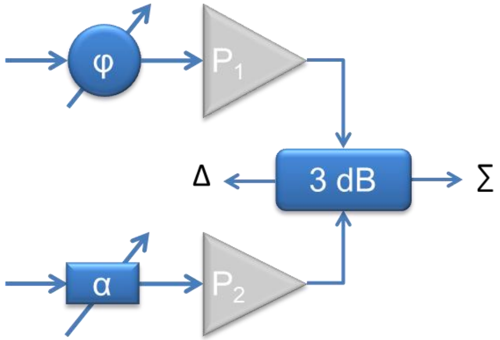
160 to 1 @ 352 MHz

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, P1 = P2 = P

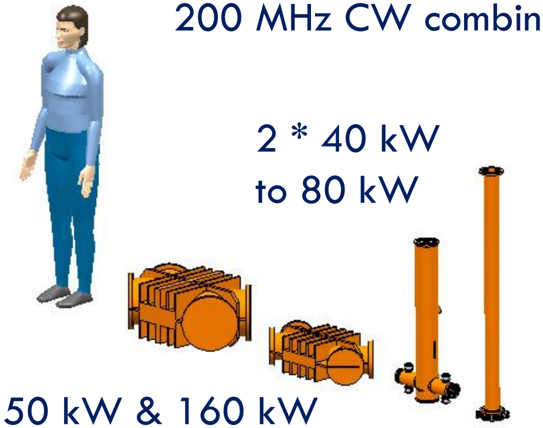
$$\Sigma = \frac{P + P}{2} + \sqrt{PP} = 2\,P$$

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

Combiners

CERN SPS 64 to 1 combiner @ 200 MHz

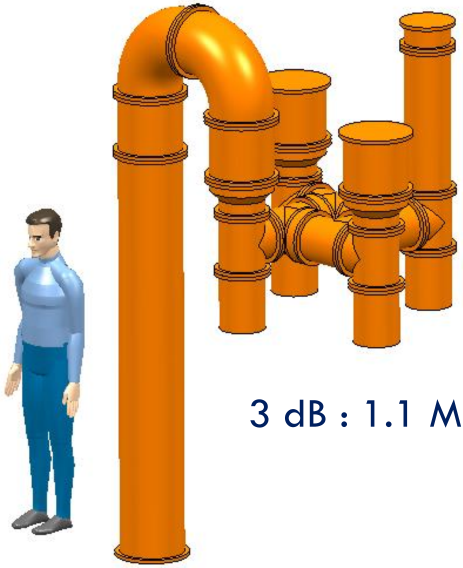
200 MHz CW combiners



2 * 40 kW
to 80 kW

10 * 4 kW
to 40 kW

3 dB : 550 kW & 160 kW



3 dB : 1.1 MW

Combiners

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

The CaCo from Alba is one of the first example

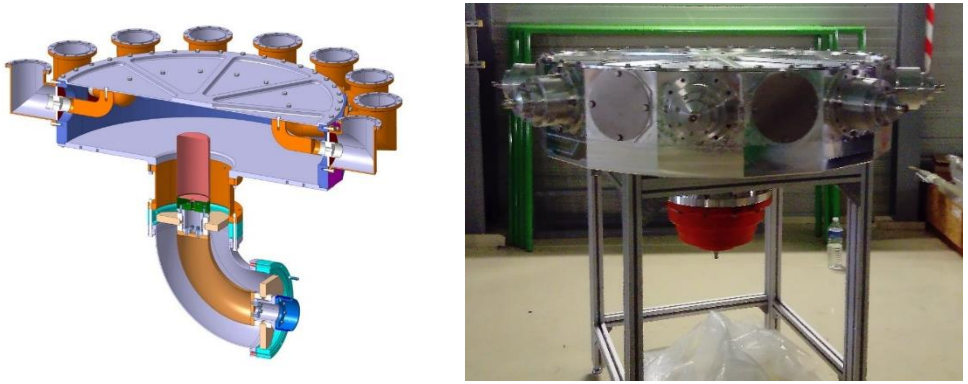
Then with ESRF with funding from the EU as WP7 in the framework of the FP7/ESFRI/CRISP program we launched a first Cavity Combiner (I invite you to read the mopc005 IPAC 11 and wepfi004 IPAC13 reports from ESRF)

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

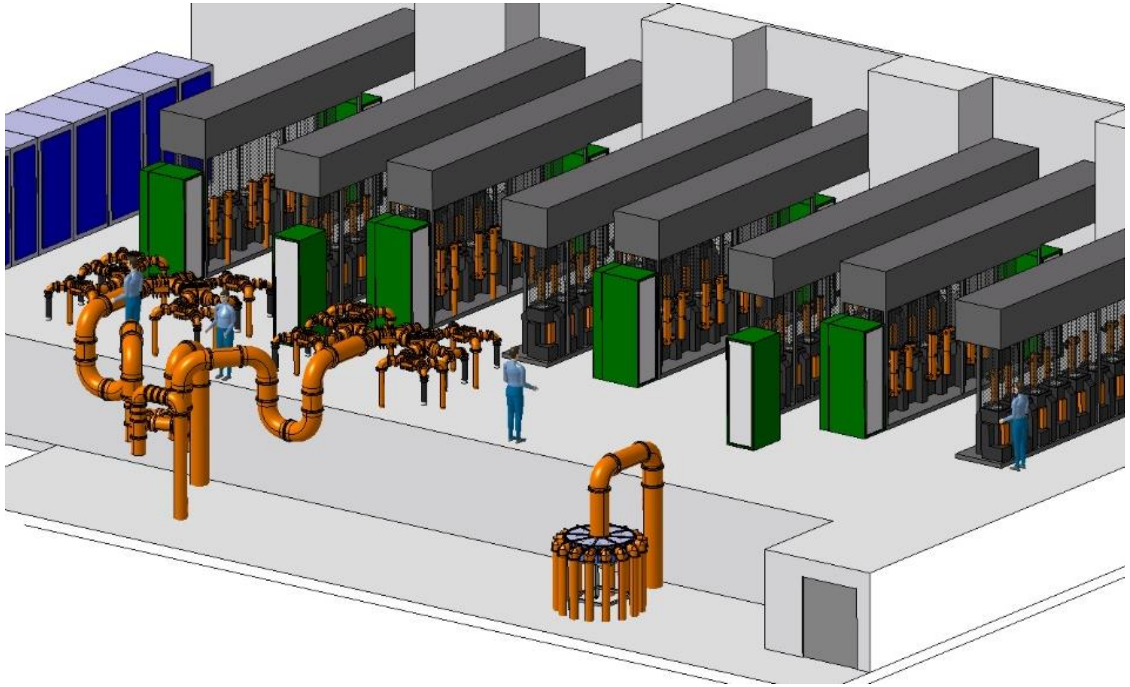


eric.montesinos@cern.ch

Combiners

Advantages of Cavity Combiners

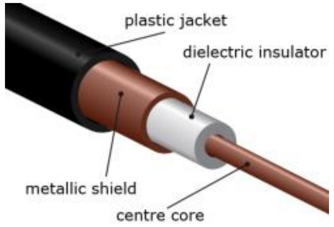
- Compact
- No dummy load
- Less losses



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

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

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

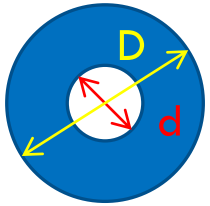
Size	Outer conductor		Inner conductor	
	Outer diameter	Inner diameter	Outer diameter	Inner diameter
7/8"	22.2 mm	20 mm	8.7 mm	7.4 mm
1 5/8"	41.3 mm	38.8 mm	16.9 mm	15.0 mm
3 1/8"	79.4 mm	76.9 mm	33.4 mm	31.3 mm
4 1/2"	106 mm	103 mm	44.8 mm	42.8 mm
6 1/8"	155.6 mm	151.9 mm	66.0 mm	64.0 mm

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

eric.montesinos@cern.ch

Coaxial lines Maximum Power handling

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



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

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

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

With

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

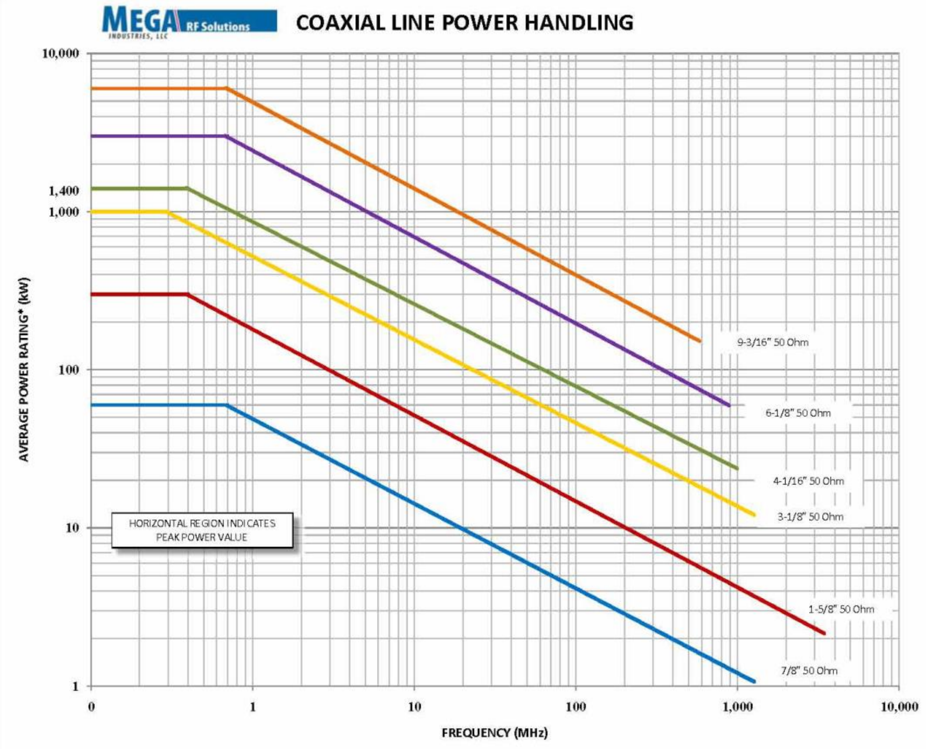
D = inside electrical diameter of outer conductor in mm

d = outside electrical diameter of inner conductor in mm

Zc= characteristic impedance in Ω

ε_r = relative permittivity of dielectric

f = frequency in MHz



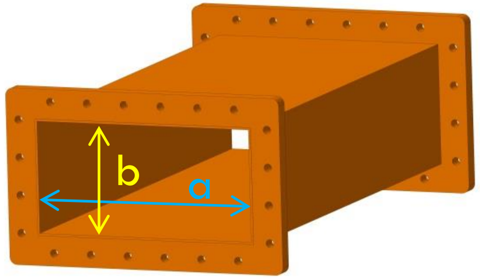
Curves valid for straight lines, in case of elbow, reduce it by 30 %

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



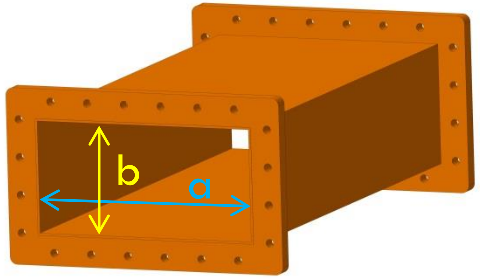
Wavelength	$\lambda_g = \frac{\lambda}{\sqrt{1-(\frac{\lambda}{2a})^2}}$
Cutoff frequency dominant mode	$f_c = \frac{c}{2a}$
Cutoff frequency next higher mode	$f_{c2} = \frac{c}{4a}$
Usable frequency range	1.3 f_c to 0.9 f_{c2}

eric.montesinos@cern.ch

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

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

With

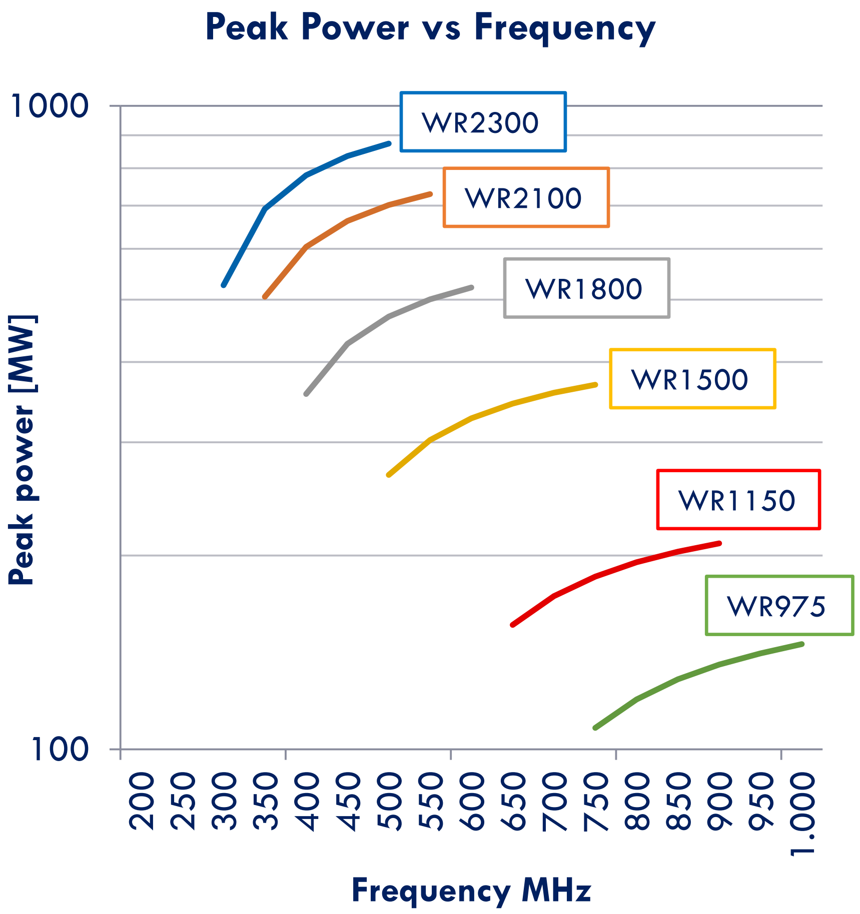
P = Power in watts

a = width of waveguide in cm

b = height of waveguide in cm

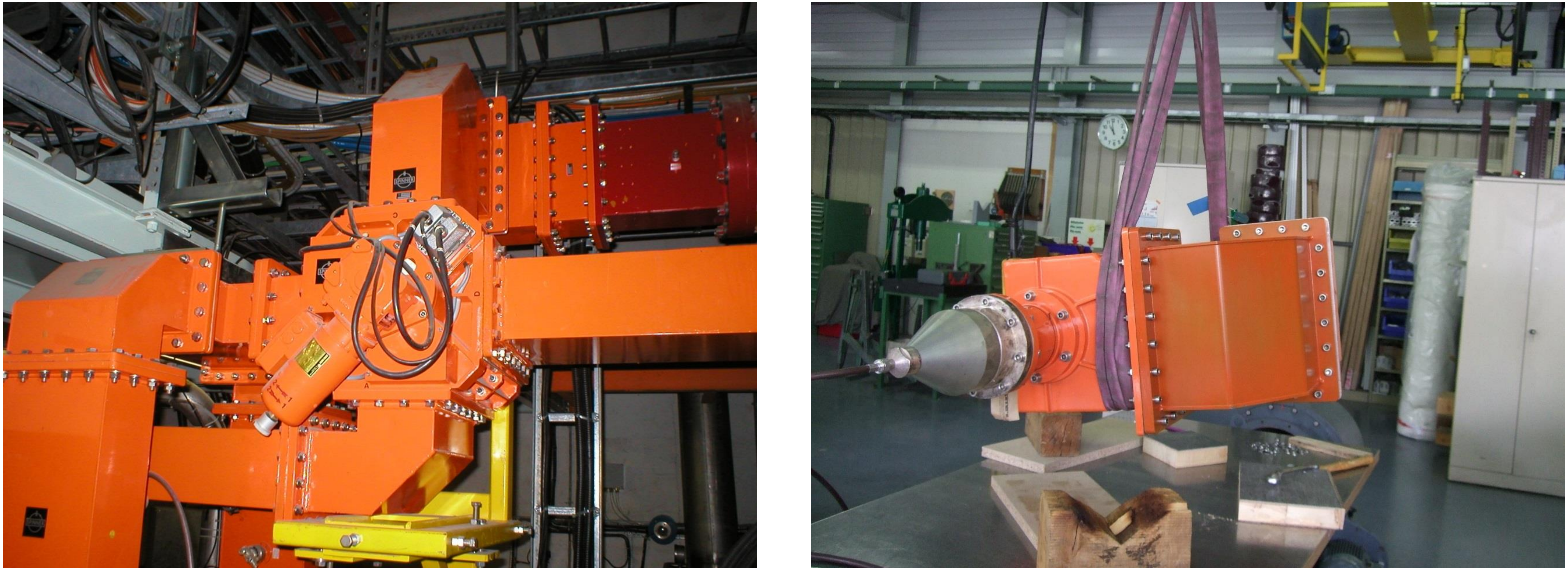
λ = free space wavelength in cm

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)



eric.montesinos@cern.ch

Rectangular waveguides



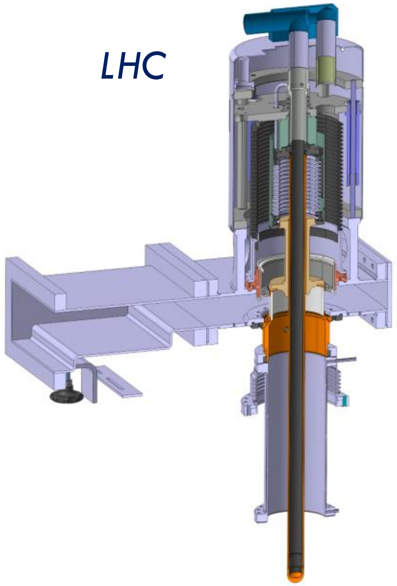
CERN SPS 800 MHz, 2 * 150 meters of WR1150 waveguides from the surface building to the cavities

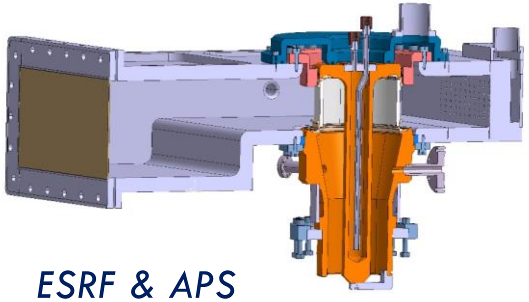
eric.montesinos@cern.ch

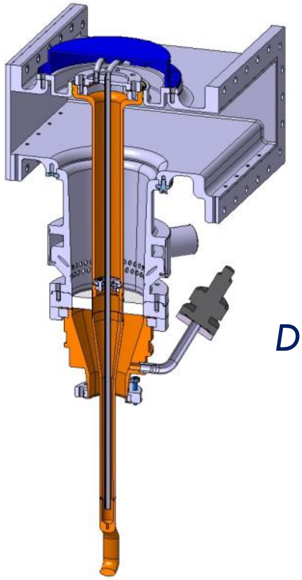
Fundamental Power Couplers (FPC)

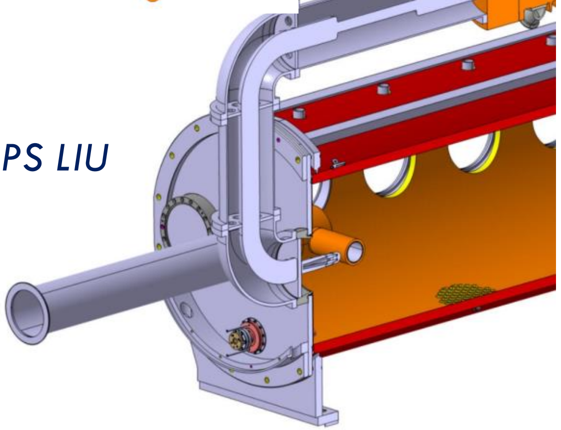
SRF2017 – Tutorial on FPC
http://ddl.escience.cn/f/M2wh

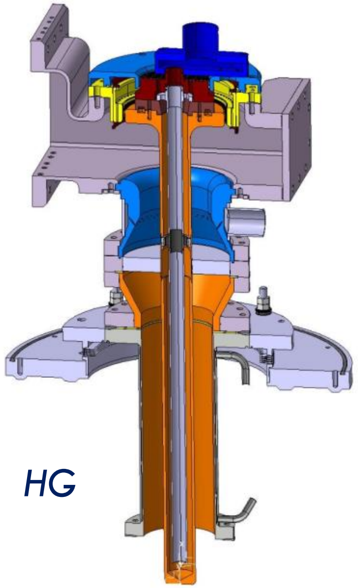
LHC	400 MHz, 500 kW
SPS 2.0	200 MHz, 750 kW
SPL 1.0	704 MHz, 900 kWp
SPL 2.0	704 MHz, 1000 kWp
Linac4	352 MHz, 1000 kWp
Crab DQW	400 MHz, 100 kW
Crab RFD	400 MHz, 100 kW
ESRF	352 MHz, 250 kW
SOLEIL	352 MHz, 250 kW
APS 1.0	352 MHz, 250 kW
SPS LIU	200 MHz, 800 kW
HG (SPL 3.0)	704 MHz, 1200 kWp
LHC 2.0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

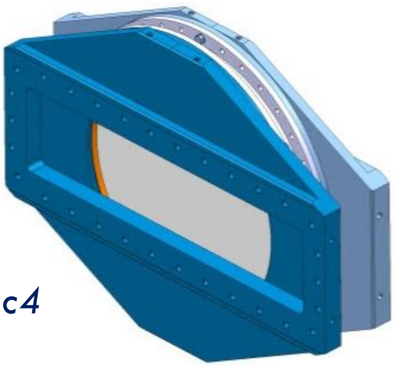

LHC


ESRF & APS


Crab DQW & RFD


SPS LIU


HG


Linac4

Fundamental Power Couplers (FPC)

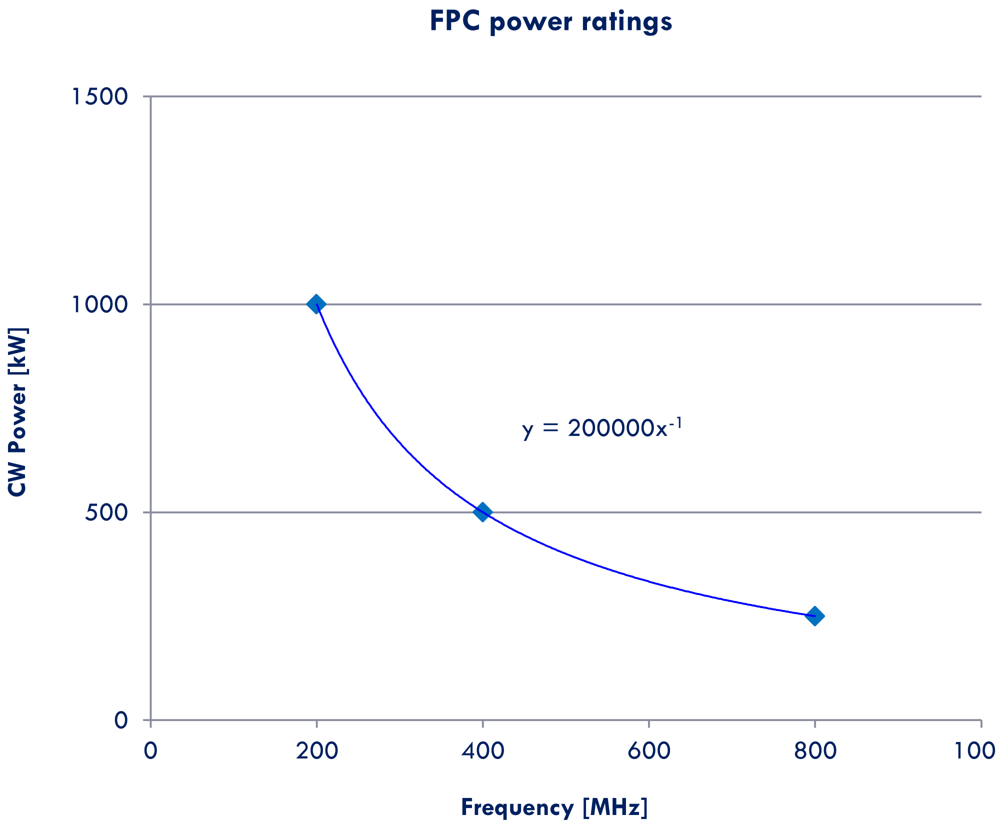
Even if we can imagine cavities able to receive a large amount of power

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)

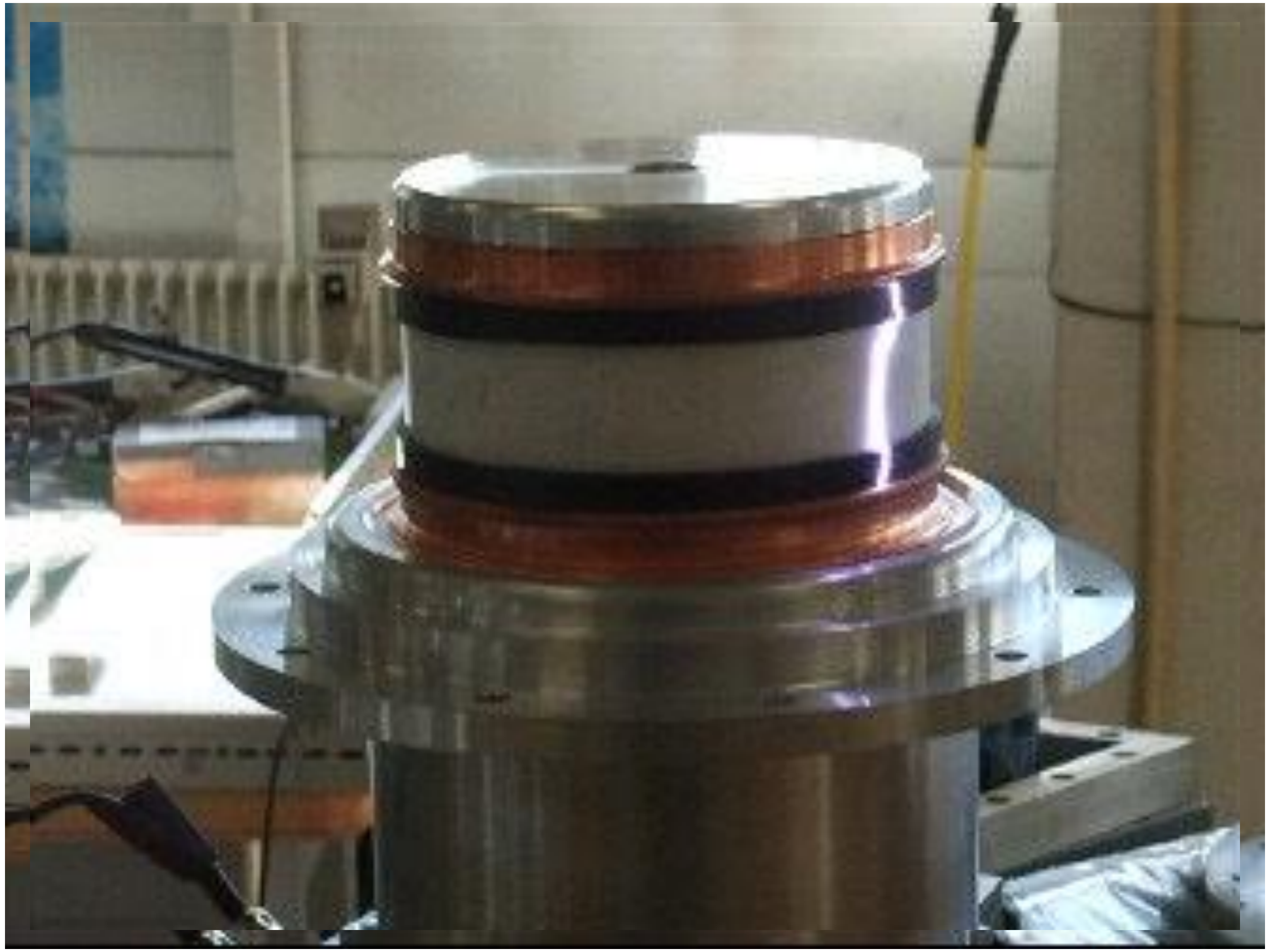


eric.montesinos@cern.ch

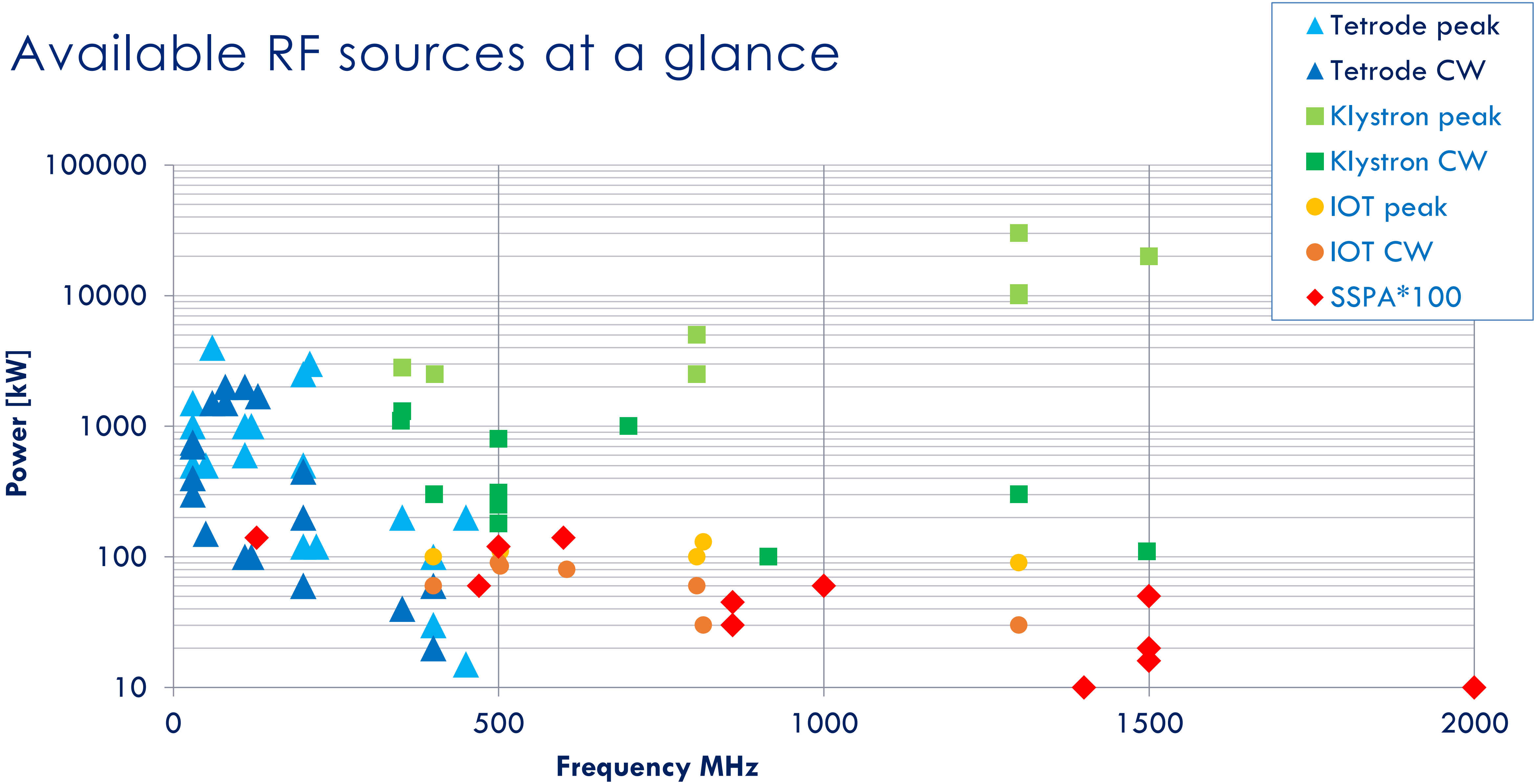
Fundamental Power Couplers (FPC)

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

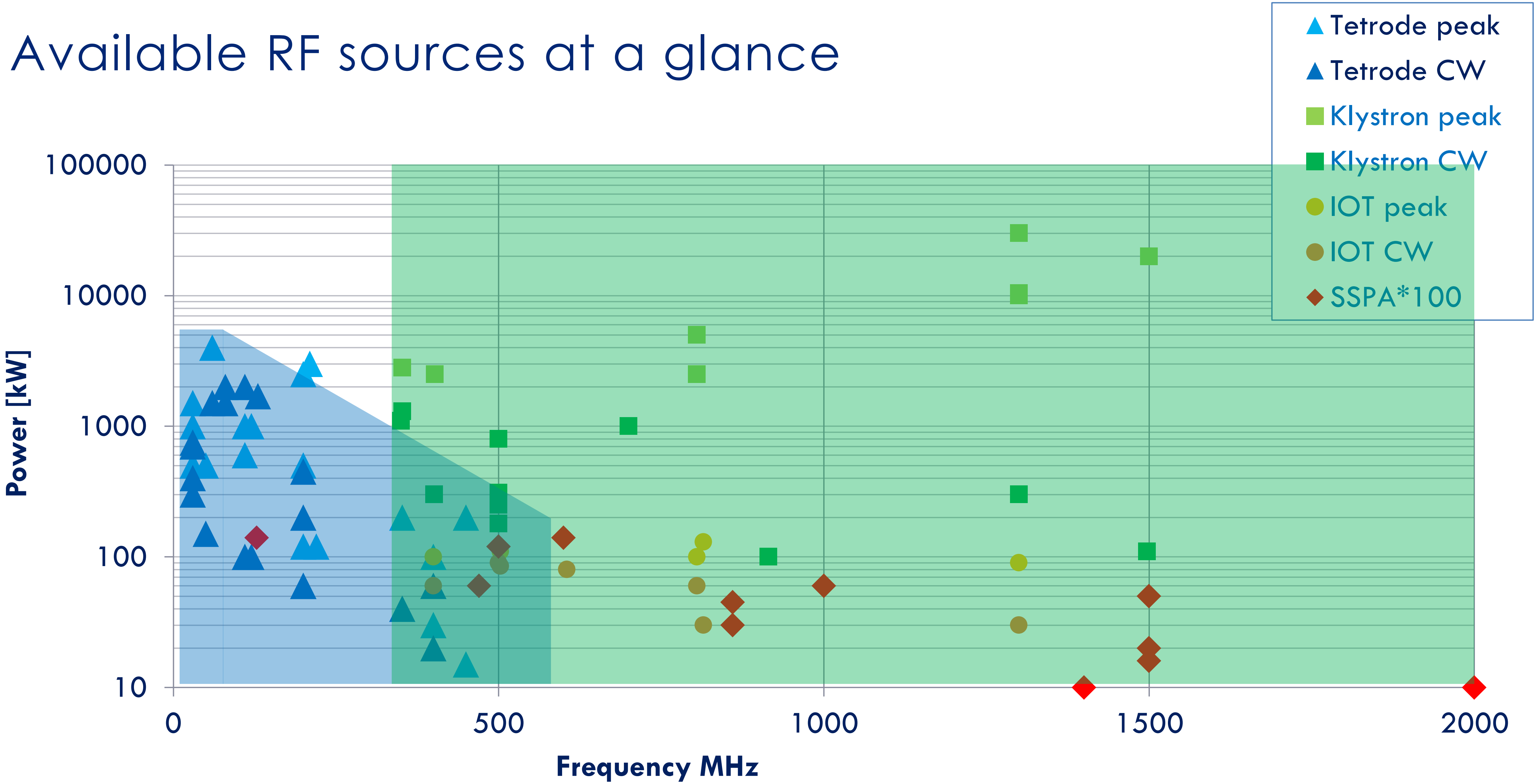


Available RF sources at a glance

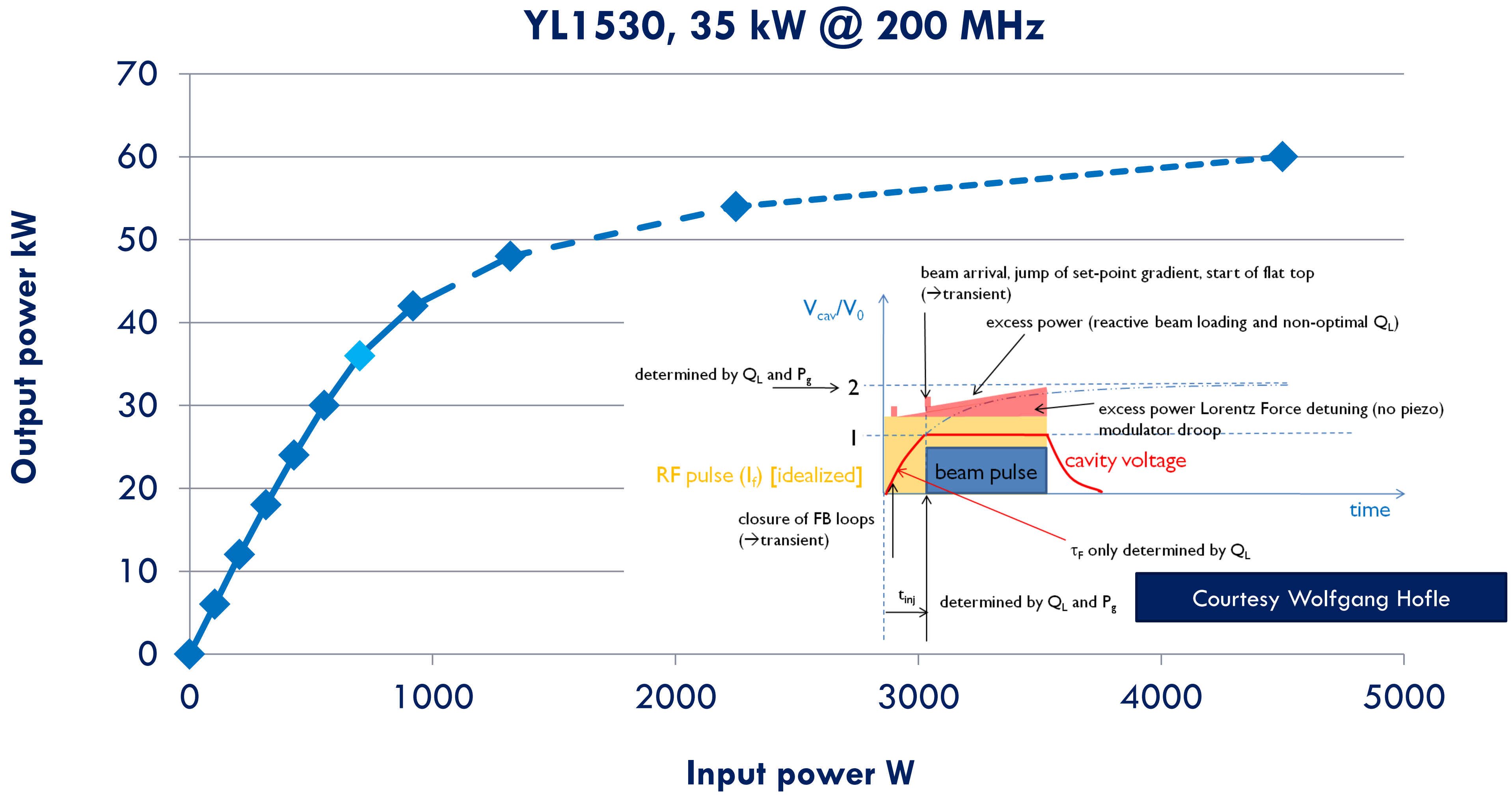


eric.montesinos@cern.ch

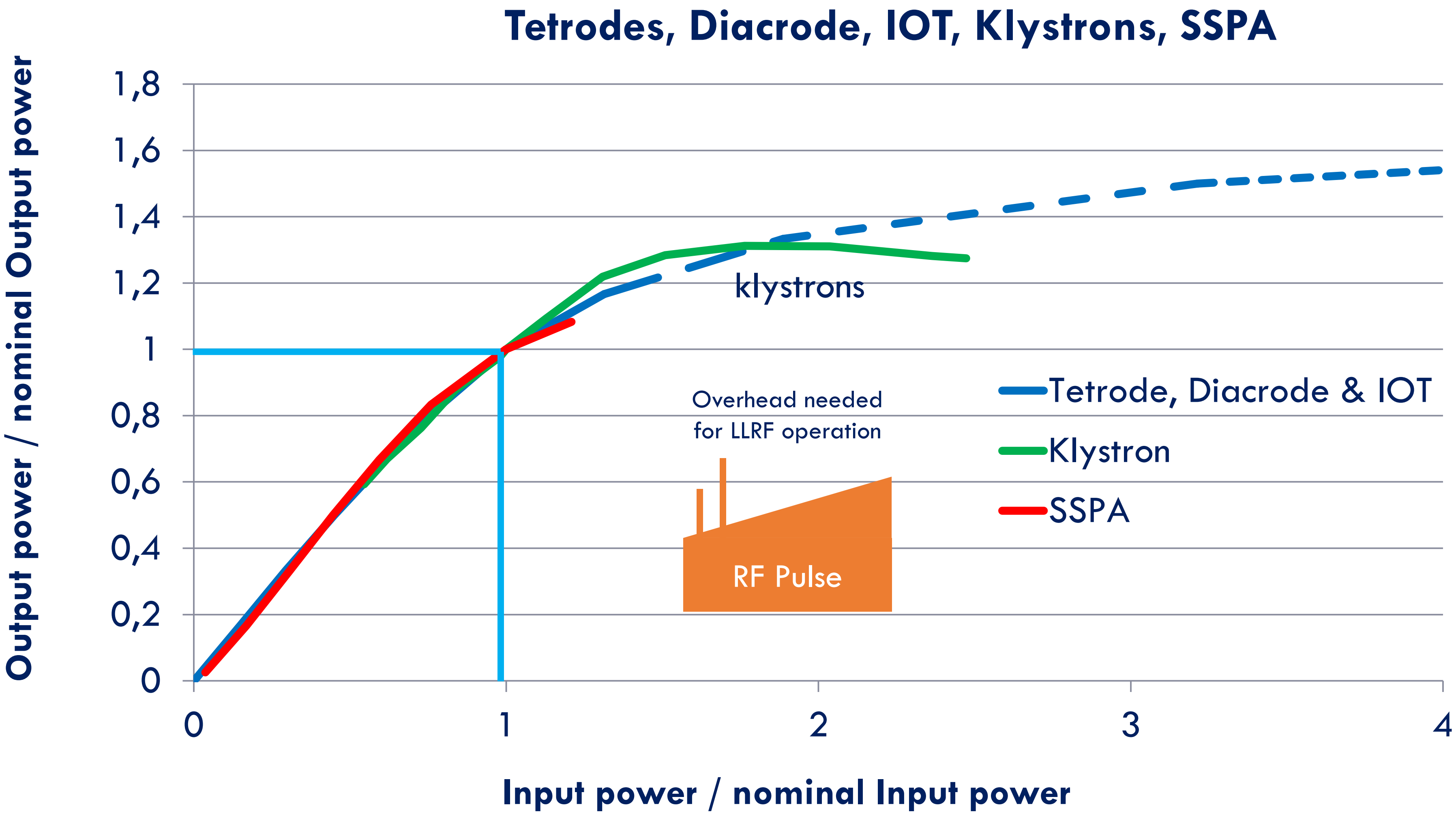
Available RF sources at a glance



Overhead


YL1530, 35 kW @ 200 MHz
Output power kW
Input power W
0
10
20
30
40
50
60
70
0
1000
2000
3000
4000
5000
beam arrival, jump of set-point gradient, start of flat top (→transient)
V_{cav}/V_0
excess power (reactive beam loading and non-optimal Q_L)
determined by Q_L and P_g
2
excess power Lorentz Force detuning (no piezo)
modulator droop
1
cavity voltage
RF pulse (I_f) [idealized]
beam pulse
time
closure of FB loops (→transient)
τ_F only determined by Q_L
t_{inj}
determined by Q_L and P_g
Courtesy Wolfgang Hofle

Overhead



eric.montesinos@cern.ch

Klystrons

Output power reduces if we go over saturation (nominal) point of operation

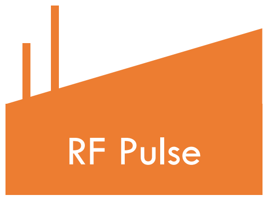
Need to operate lower than nominal point of operation

Loss of efficiency

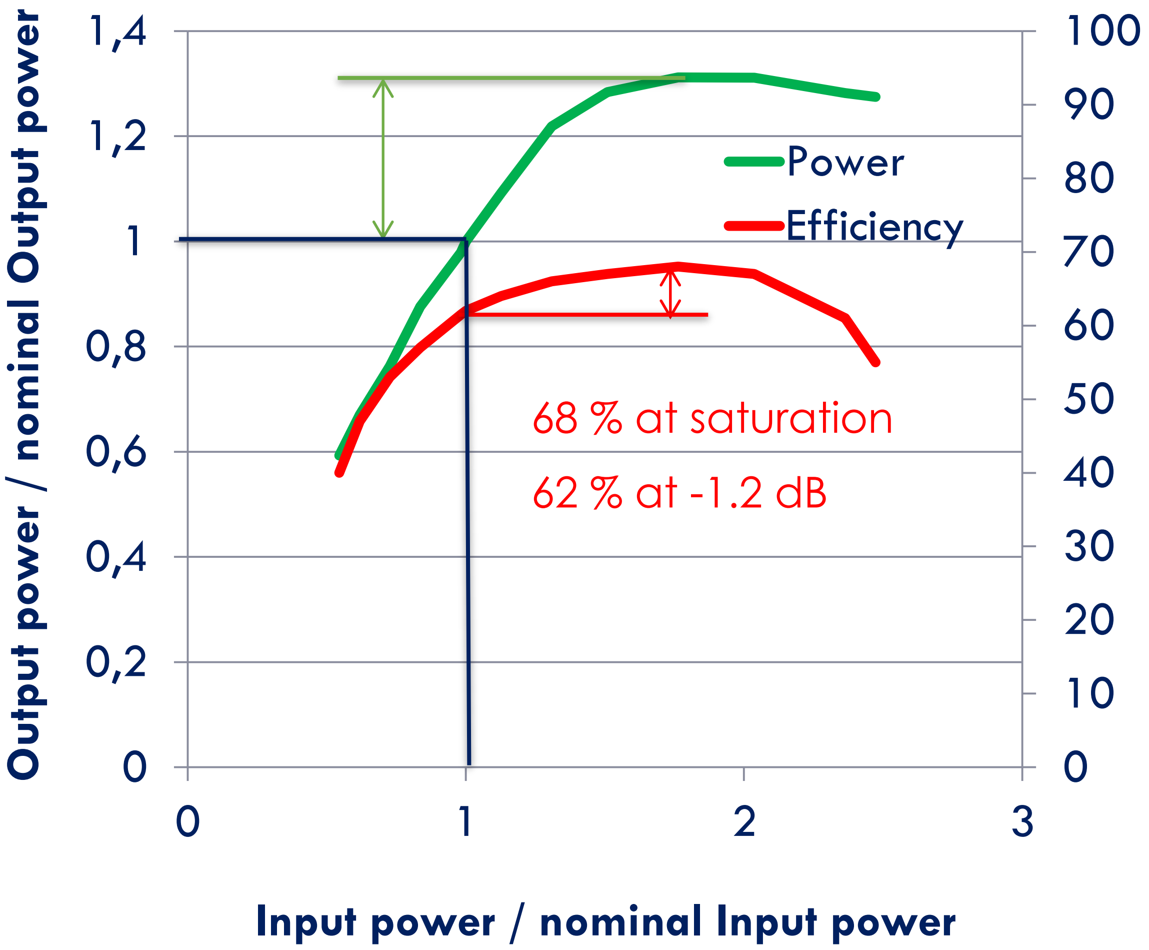
Double cost (acquisition + operation)

Phase stability is given by construction from HV stability (very expensive)

Overhead needed for LLRF operation



Klystrons



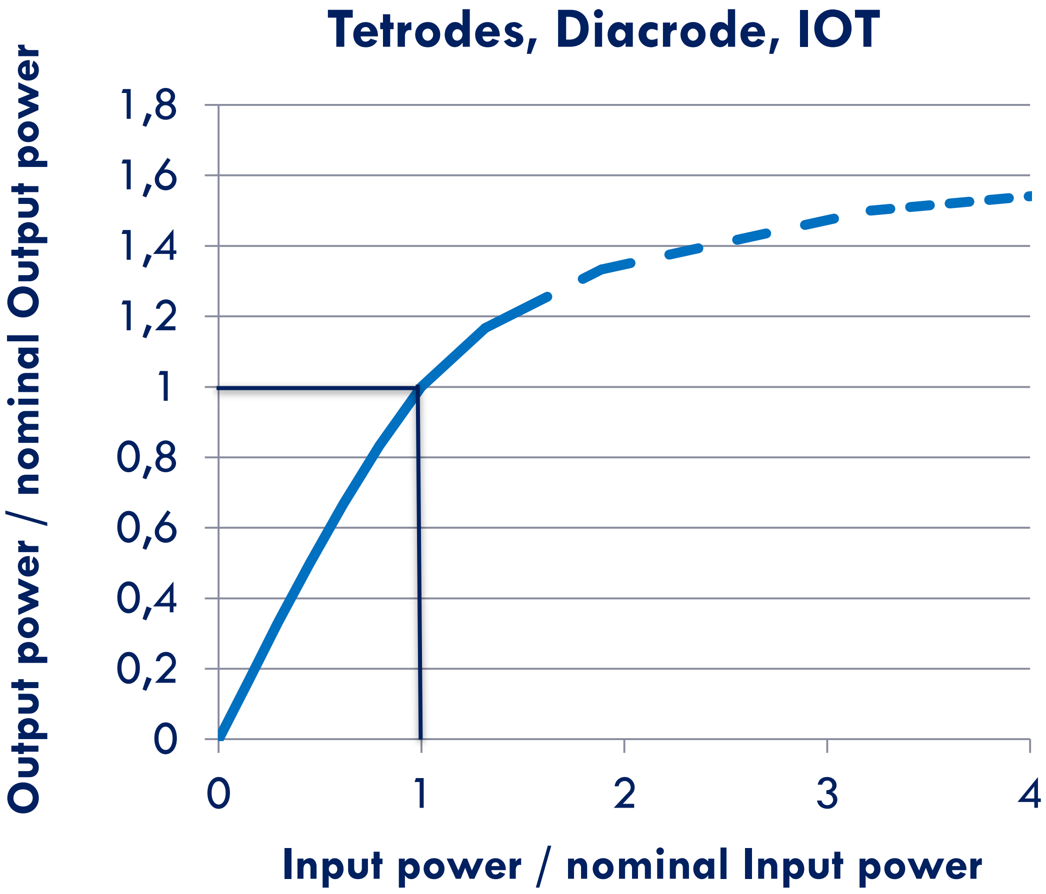
Tetrodes, Diacrodes, IOT

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



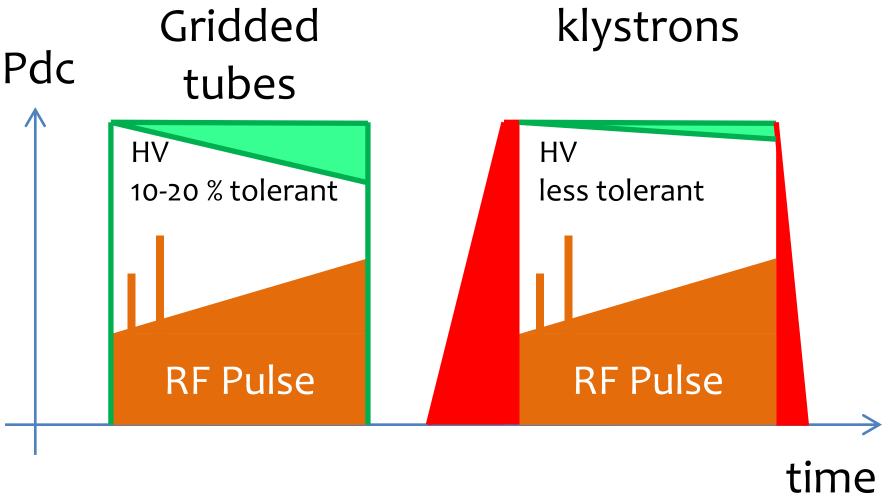
HVPS

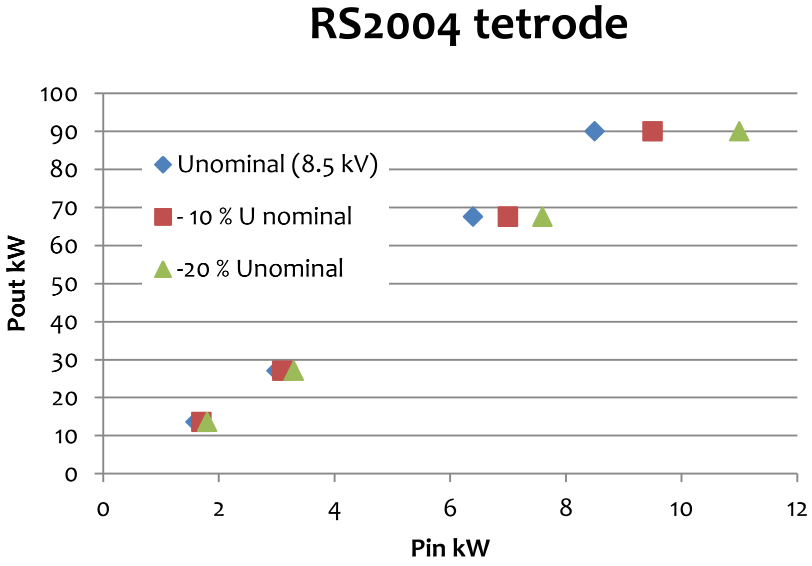
For gridded tubes HVPS is very simple

No RF -> 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





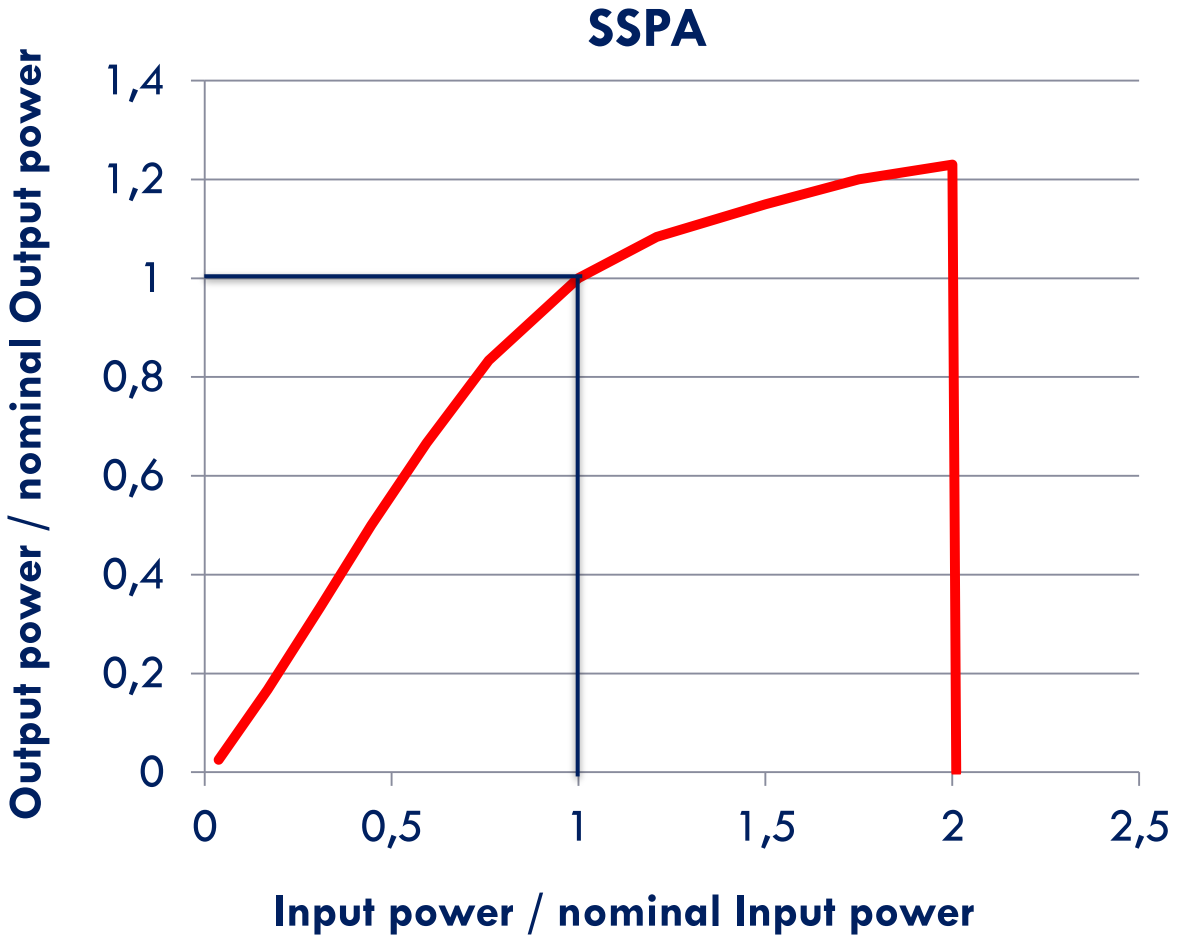
SSPA

Destruction in case of large overdrive (+ 3 dB) longer than ~ 100 µs

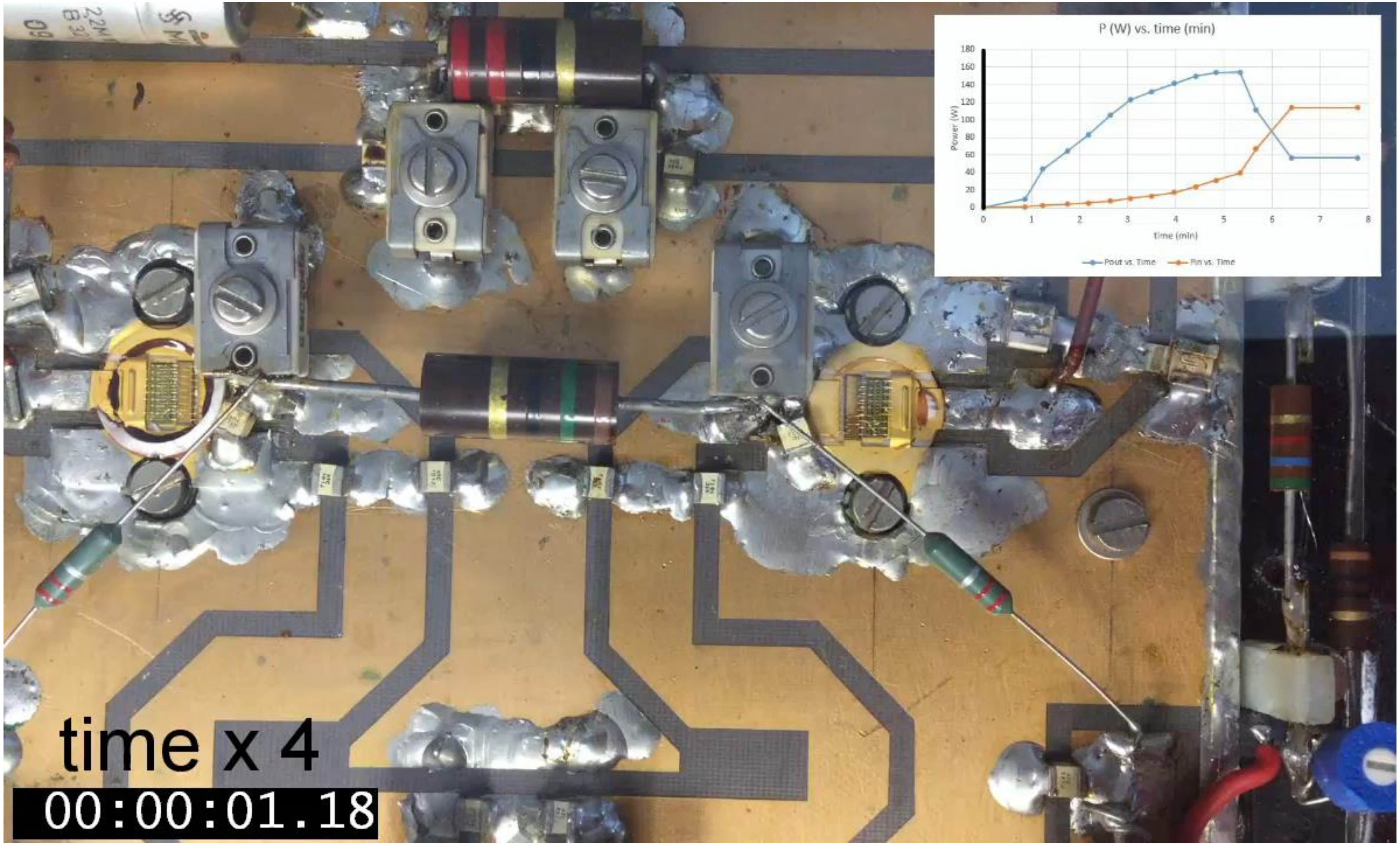
Hard protection limit are needed, could be built in, but then it is complex to manage for LLRF, so we try to have a good LLRF protection system

Overhead must be perfectly and correctly defined

Overhead very costly (compare to gridded tubes)




ATC 201J
ATC 201J



eric.montesinos@cern.ch

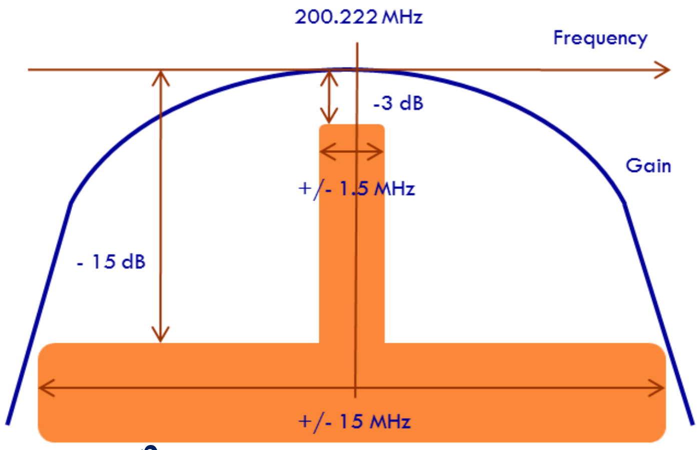
True life for LLRF & HPRF

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

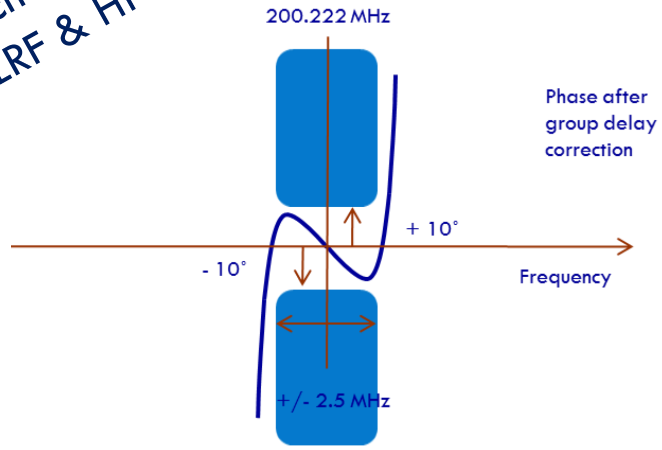
Be aware that HPRF is very expensive

and that we will have, what we will have…

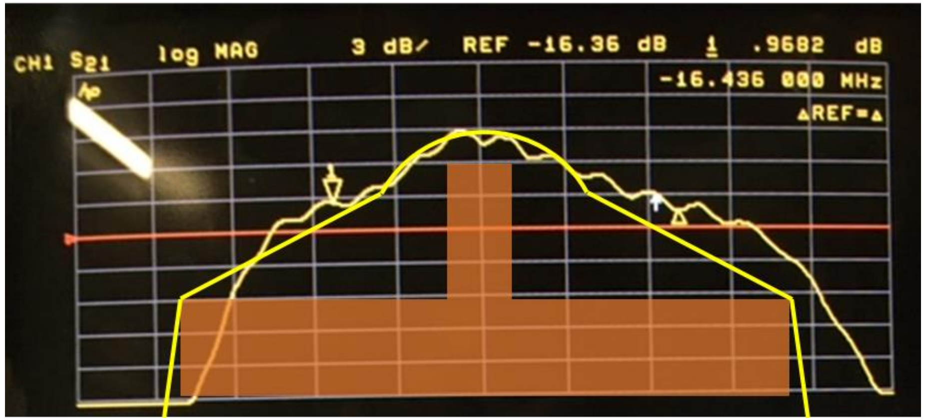
True life for LLRF & HPRF

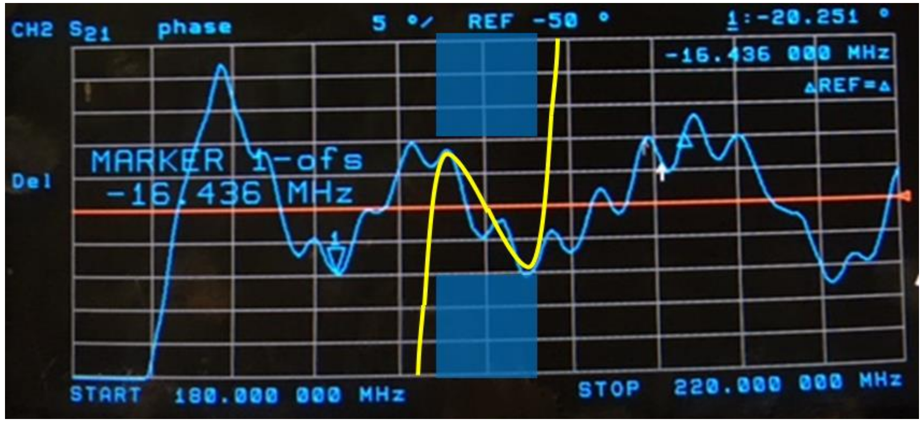


Technical Specification made with LLRF & HPRF

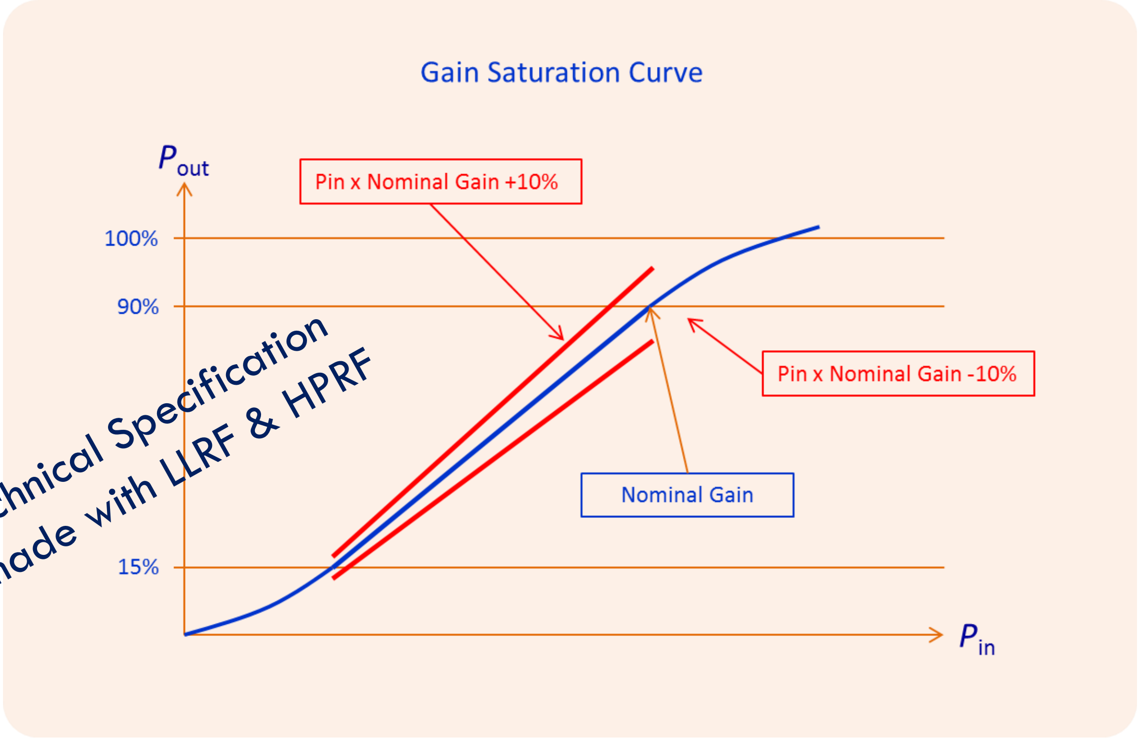


Two years of work from the HPRF company



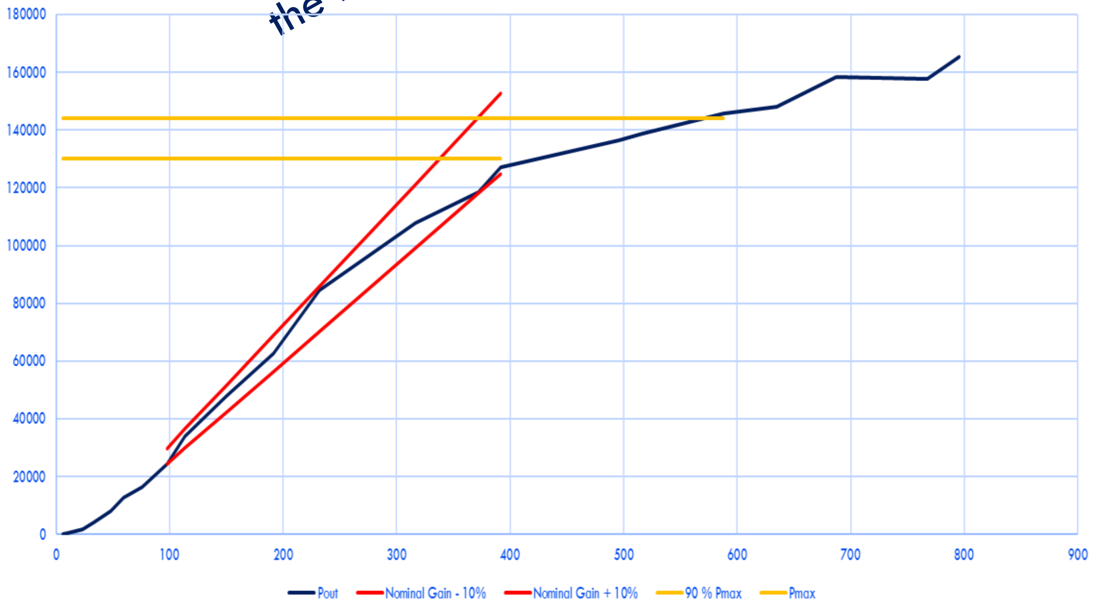


True life for LLRF & HPRF



Technical Specification made with LLRF & HPRF

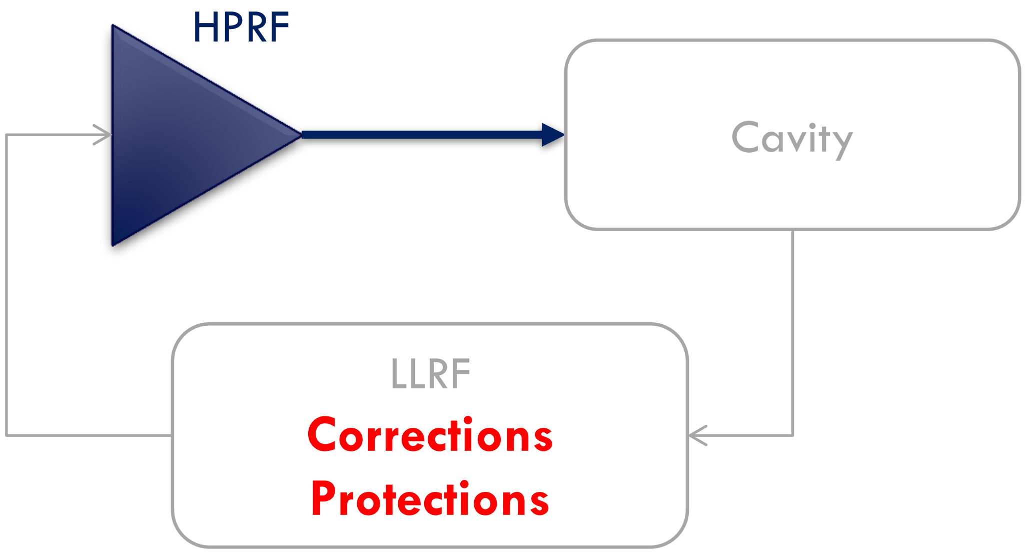
Two years of work from the HPRF company



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



eric.montesinos@cern.ch

Thank you very much

eric.montesinos@cern.ch

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