8th Internationally Participated Congress On Particle Accelerators And Applications (UPHUK VIII)

RF powering for accelerators

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RF Powering

W → kW → MW

€ → k€ → M€

(Very important for all projects)

Outlook

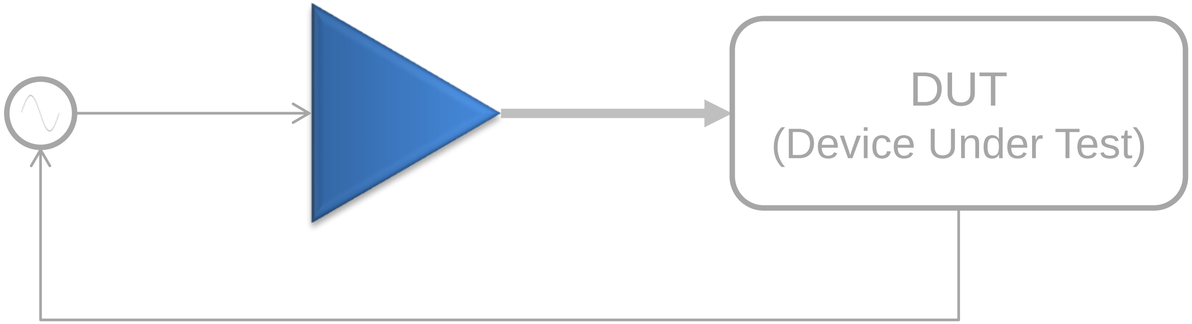
- RF power amplifiers for accelerators
  - Grid Tubes
  - Klystrons
  - Inductive Output Tubes (IOT)
  - Transistors (LDMOS)
  - Combiners

- RF power lines
  - Wave Guides
  - Coaxial lines
  - Circulators

- FPC

- Efficiency

RF Power Amplifier



DUT
(Device Under Test)

RF power source classification

Vacuum Tubes

Grid Tubes

Triodes
Tetrodes
Pentodes
Diacrodes

Linear Beam Tubes

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

Crossed-field Tubes

Magnetrons

Transistors

Bipolar Junction Transistor (BJT)
Field Effect Transistor (FET)
Junction Gate FET (JFET)
Metal Oxide Semiconductor FET (MOSFET)
power MOSFET
Vertically Diffused Metal Oxide Semiconductor (VDMOS)
Laterally Diffused Metal Oxide Semiconductor (LDMOS)
Gallium Nitride (GaN)
Silicon Carbide MOSFET (SiC)

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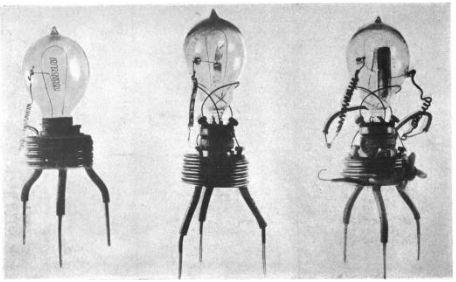
Grid tubes

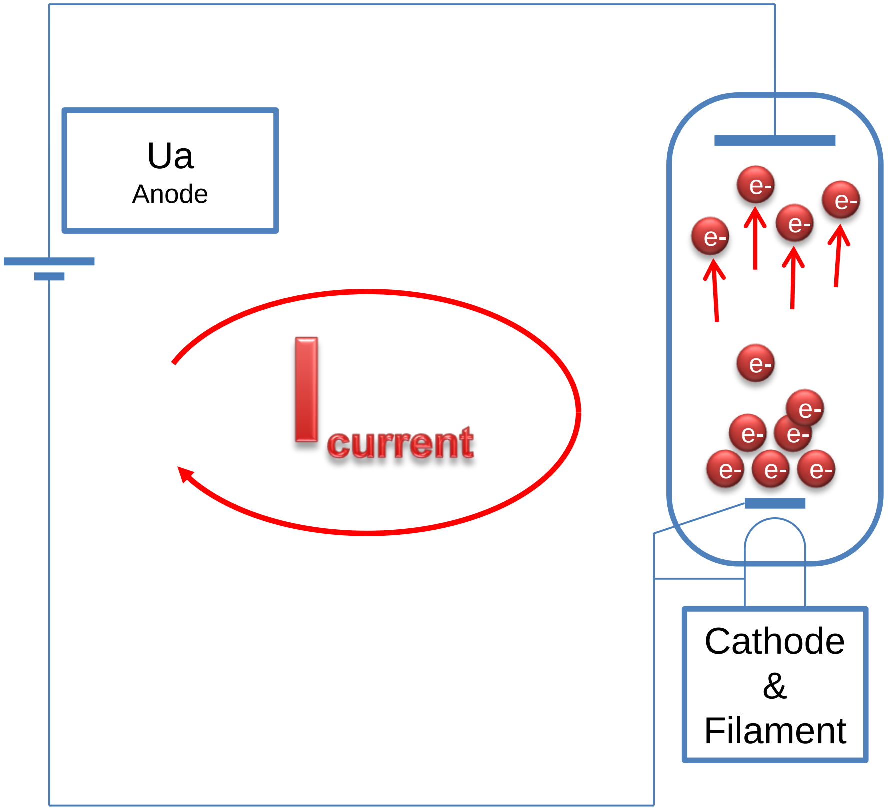
1904	Diode, John Ambrose Fleming
1906	Audion (first triode), Lee de Forest
1912	Triode as amplifier, Fritz Lowenstein
1913	Triode ‘higher vacuum’, Harold Arnold
1915	first transcontinental telephone line, Bell
1916	***Tetrode***, Walter Schottky
1926	Pentode, Bernardus Tellegen
1994	Diacrode, Thales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



The first diode prototype
Fleming Diode, 1904

Thales TH 628 diacrode,
1998

Essentials of grid tube



Vacuum tube

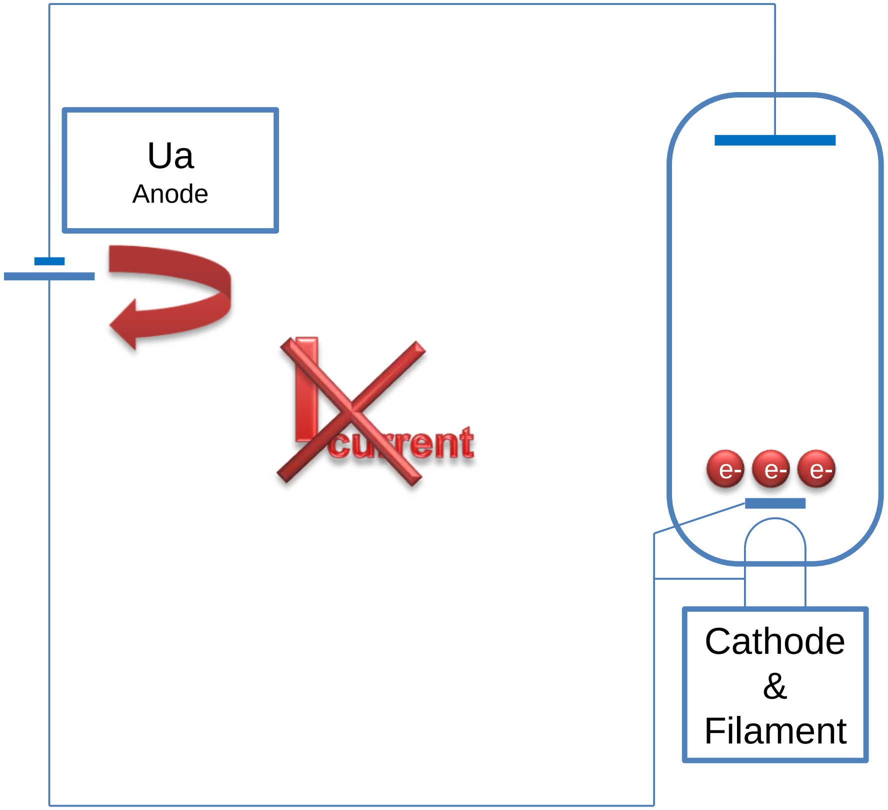
Heater + Cathode

- Heated cathode
  - Coated metal, carbides, borides,…
- thermionic emission
- Electron cloud

Anode

Diode

Essentials of grid tube



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Heater + Cathode

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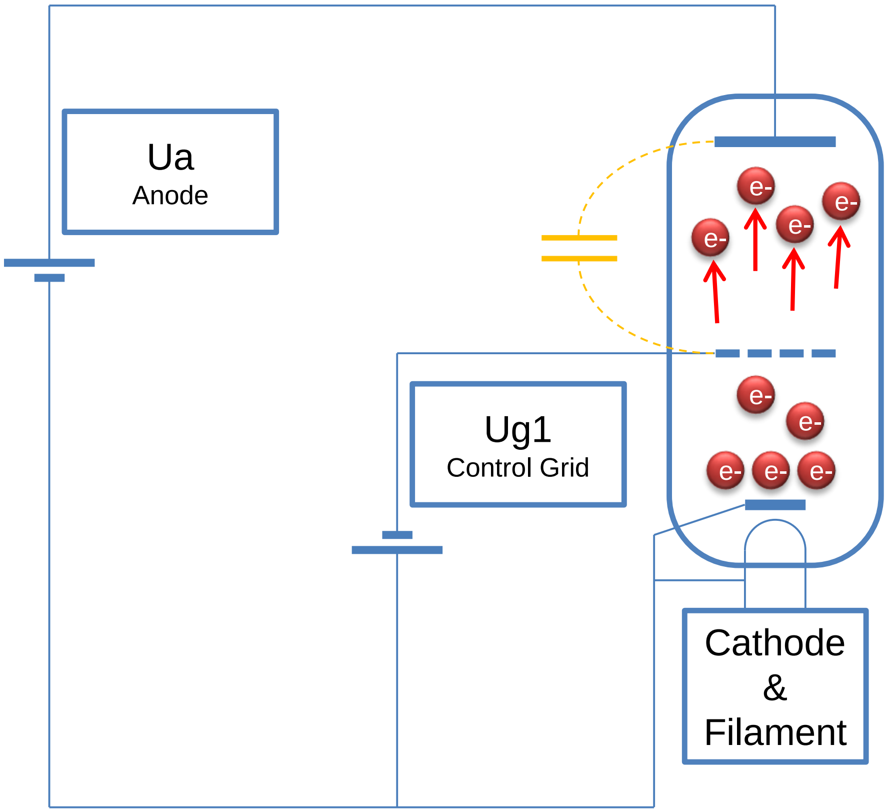
Anode

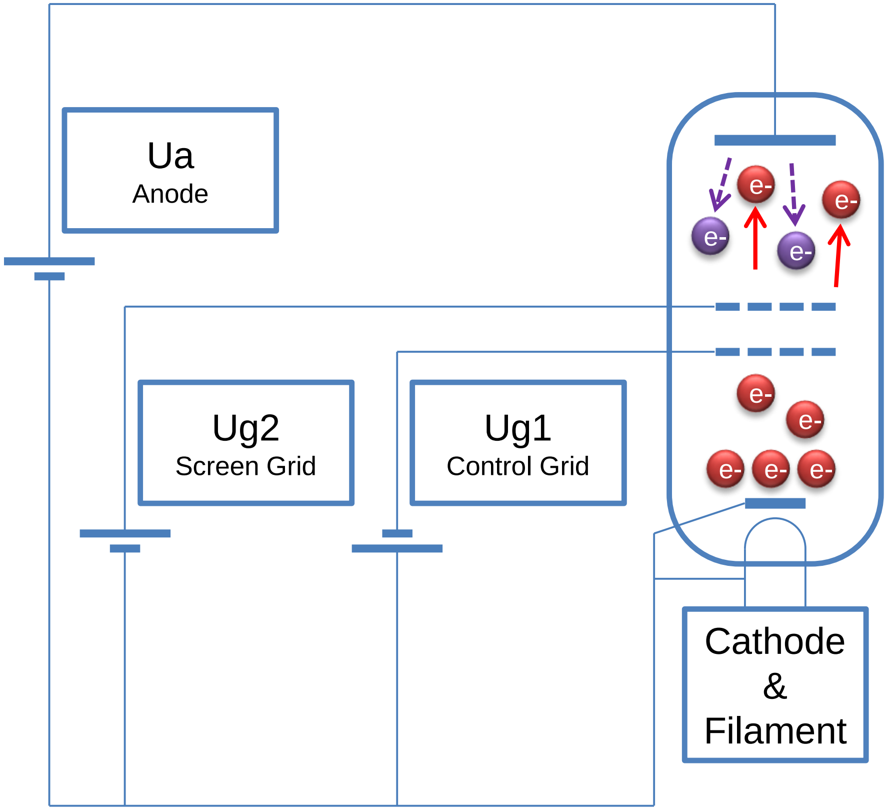
Diode

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

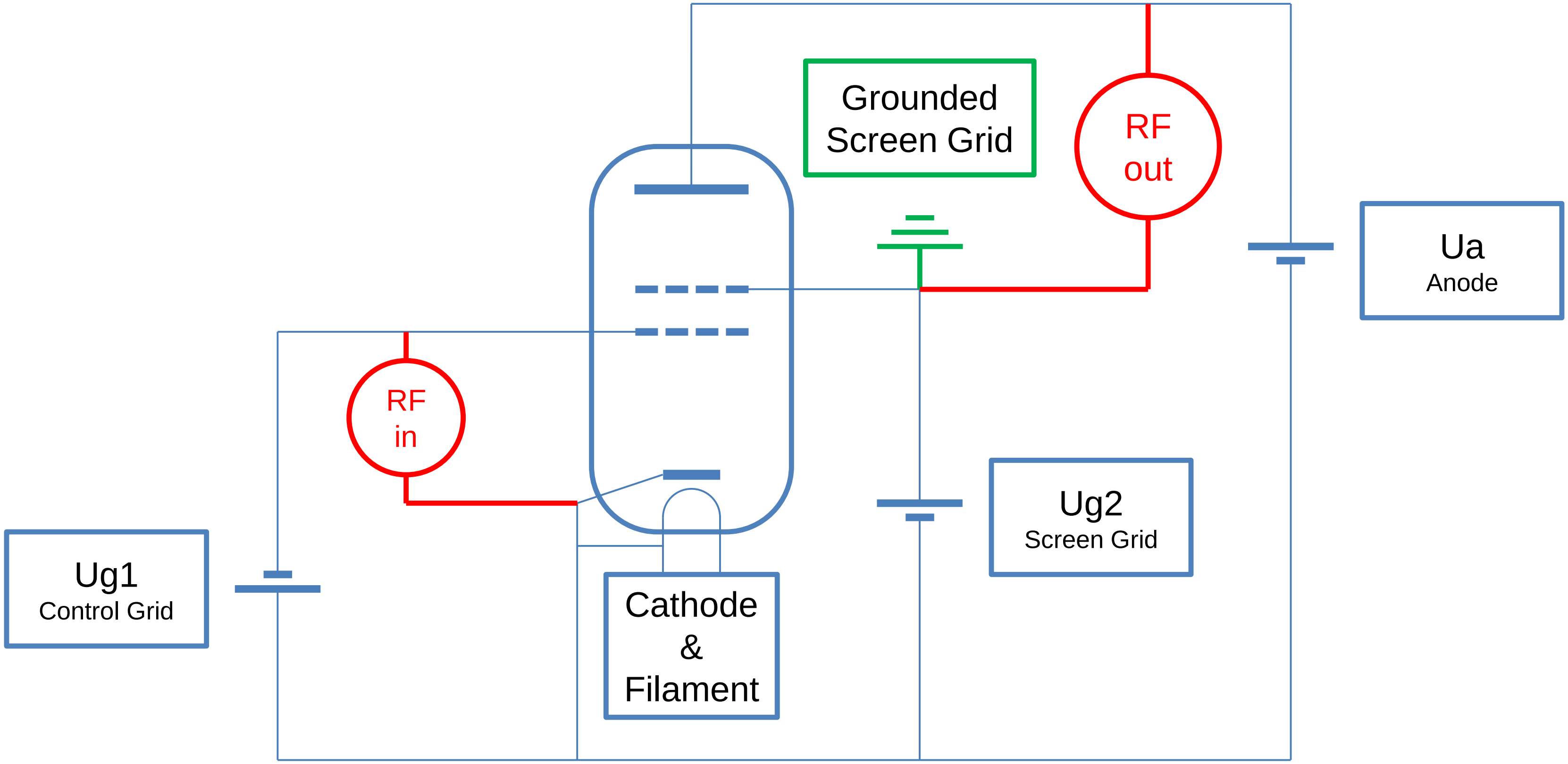
Essentials of grid tube



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

Tetrode

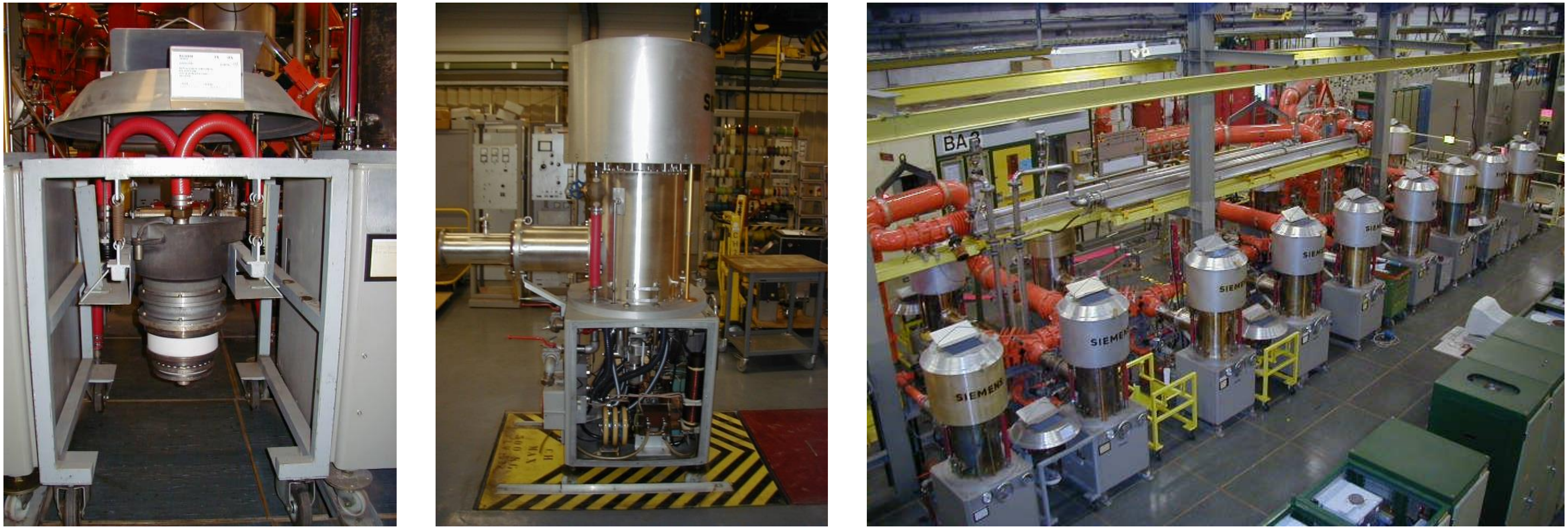
RS 2004 CERN SPS example



CERN SPS, RS 2004 Tetrode (very) simplified bloc diagram

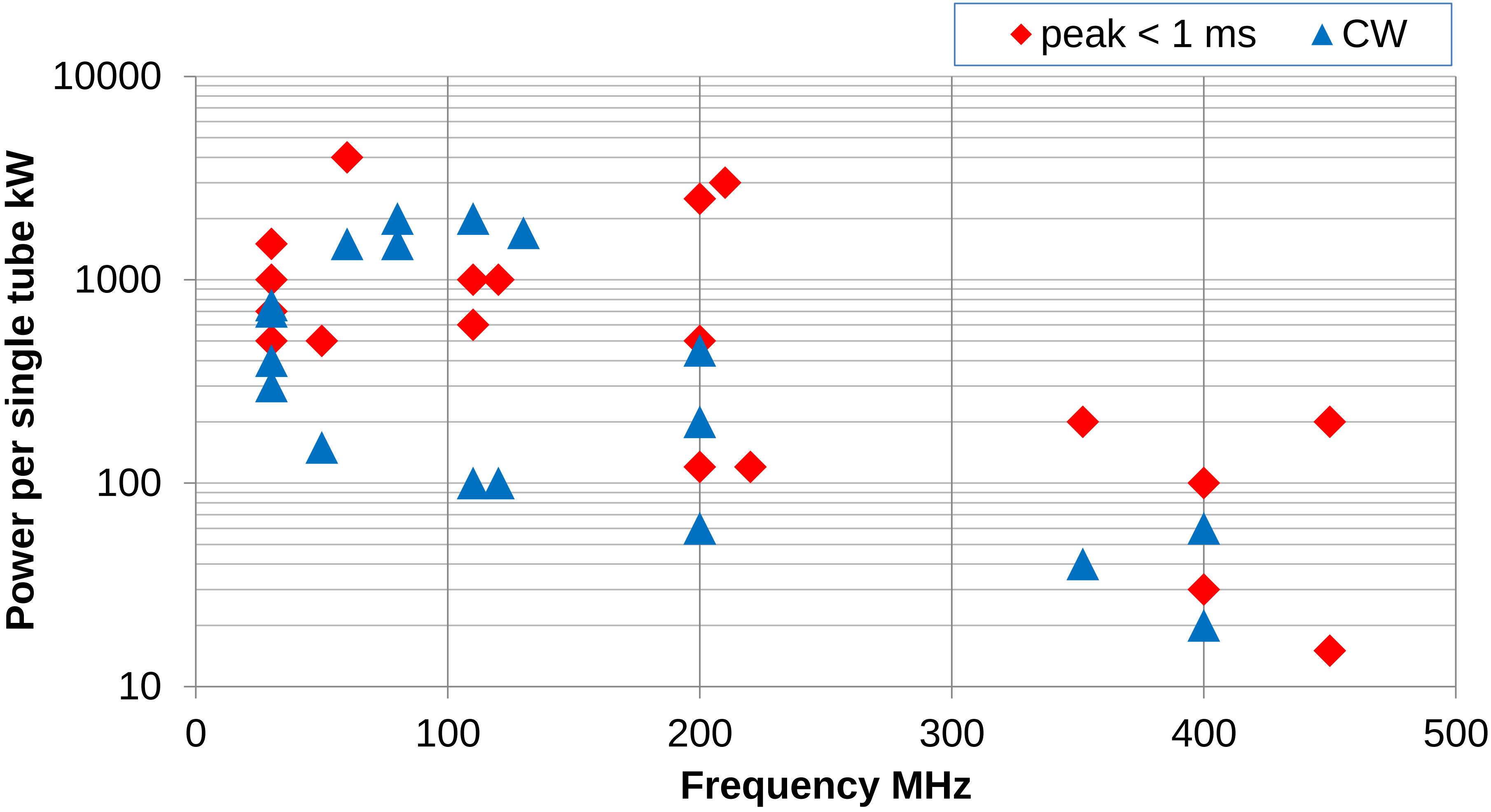
Tetrode

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

Tetrodes & Diacrodes available from industry



RF power source classification

Vacuum Tubes

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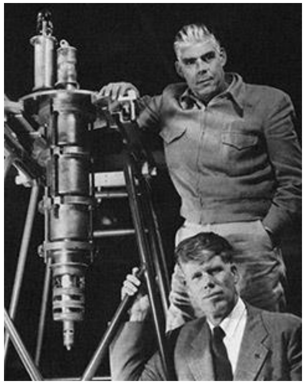
Linear beam tubes

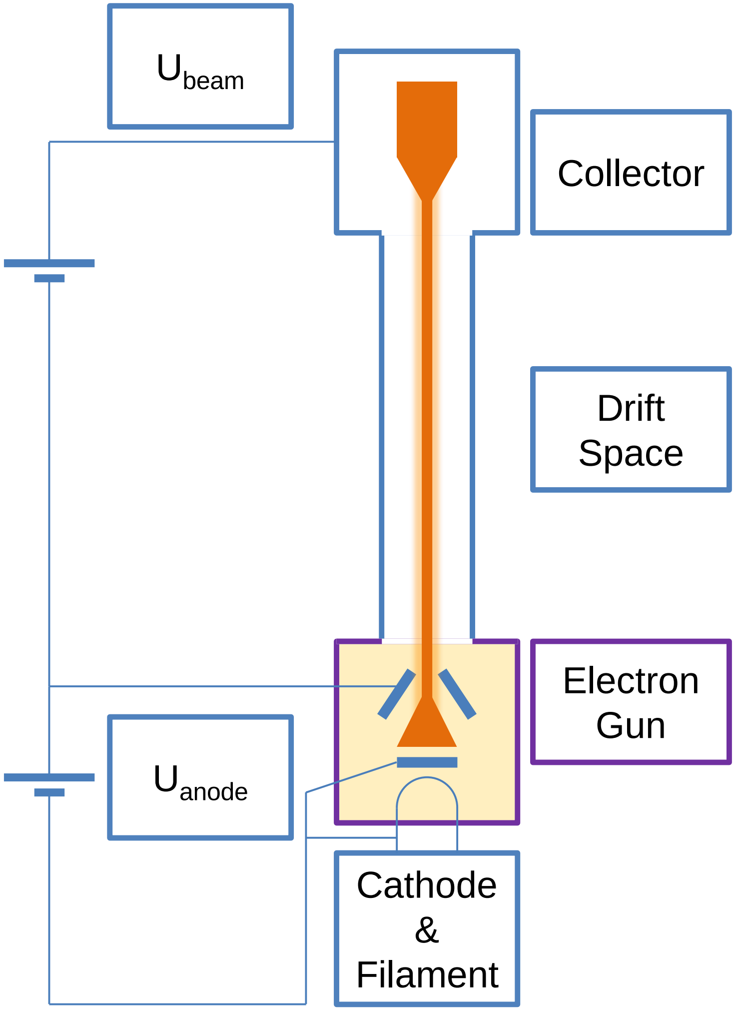
1937	Klystron, Russell & Sigurd Variant
1938	IOT, Andrew V. Haeff
1939	Reflex klystron, Robert Sutton
1940	Few commercial IOT
1941	Magnetron, Randall & Boot
1945	Helix Travelling Wave Tube (TWT), Kompfner
1948	***Multi MW klystron***
1959	Gyrotron, Twiss & Schneider
1963	Multi Beam Klystron, Zusmanovsky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

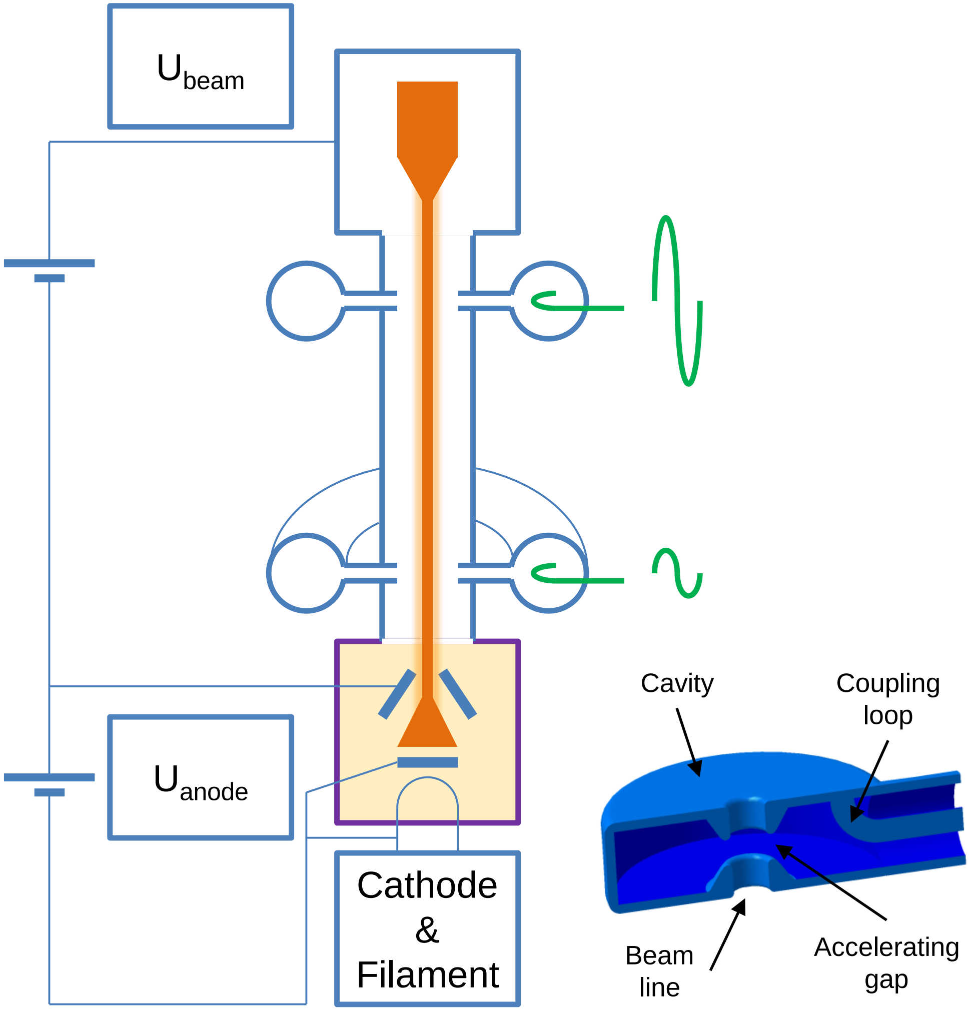
Electron beam

Drift space

Collector

e- constant speed until the collector

Essentials of klystron



Cavity resonators

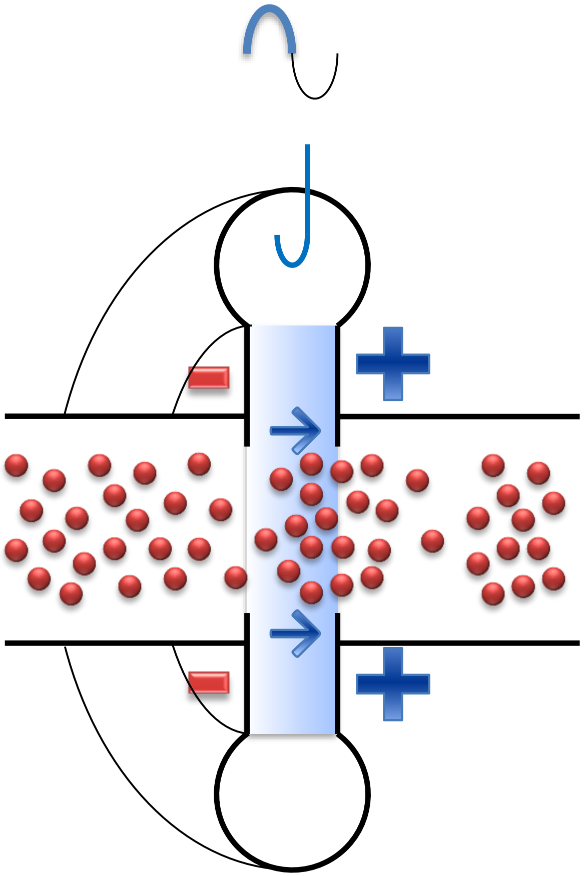
RF input cavity (Buncher)

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

RF output cavity (Catcher)

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

Essentials of klystron



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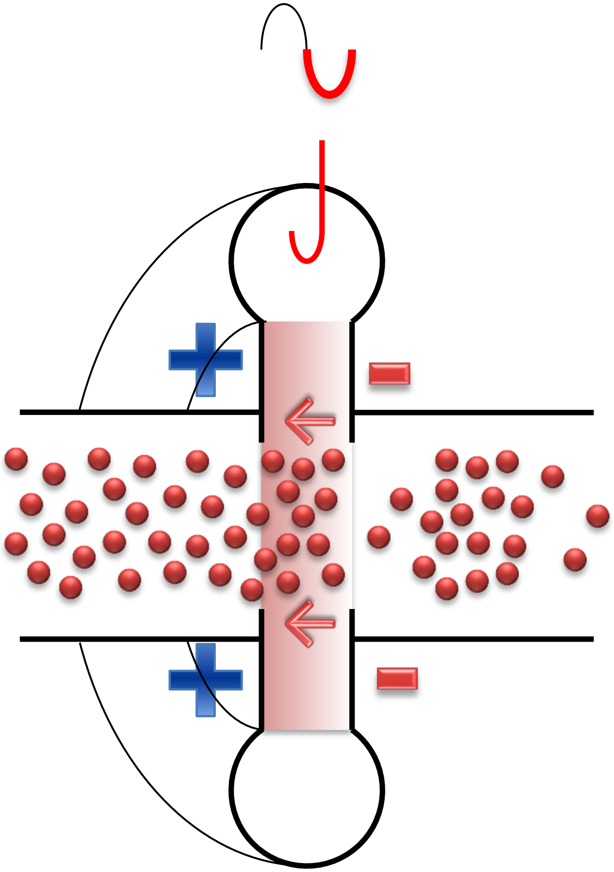

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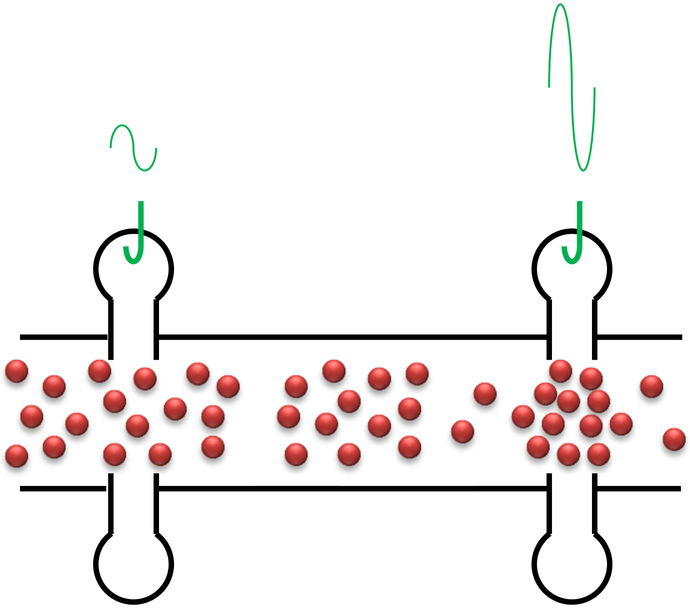

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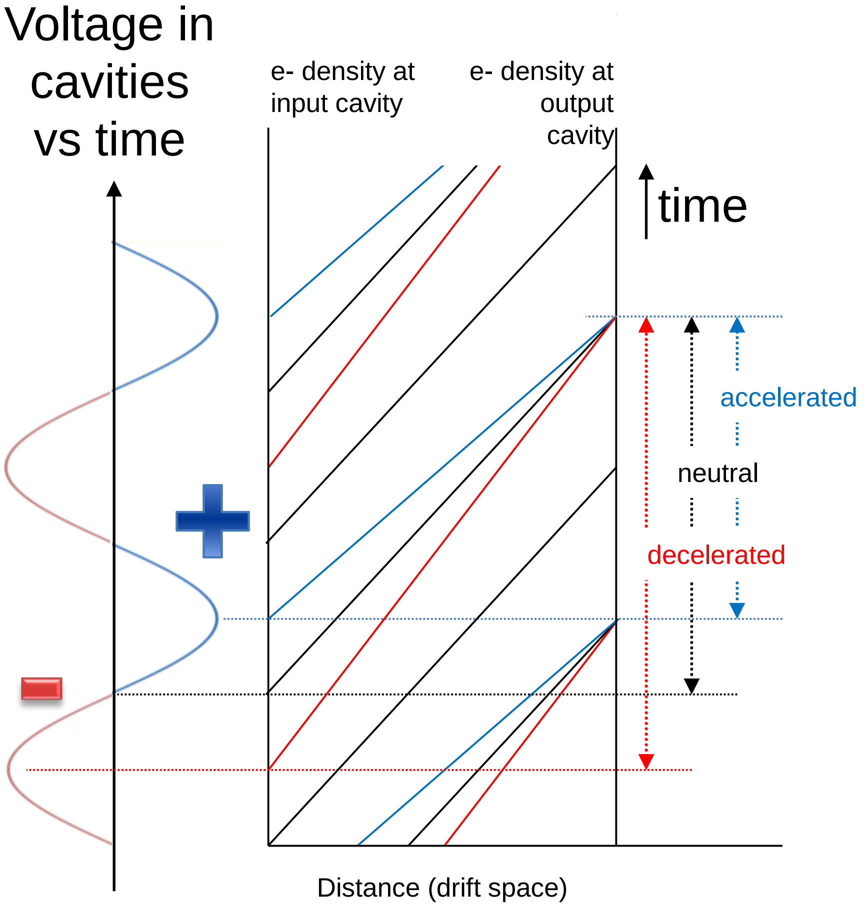
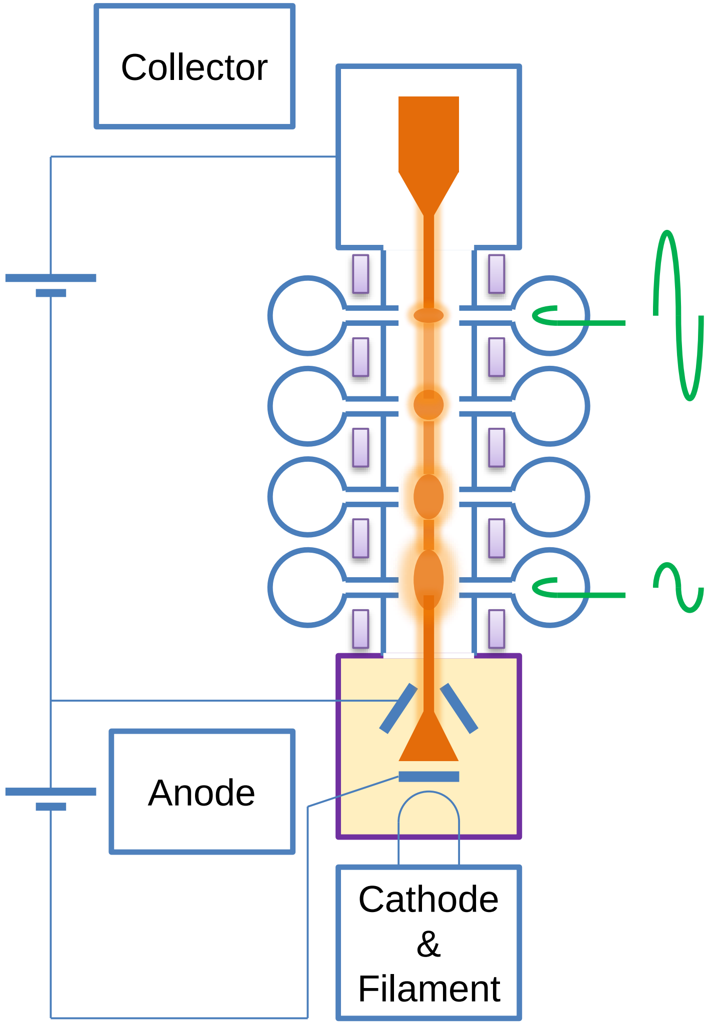


Bunching of e- beam in a klystron

- Cavity resonators
- 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

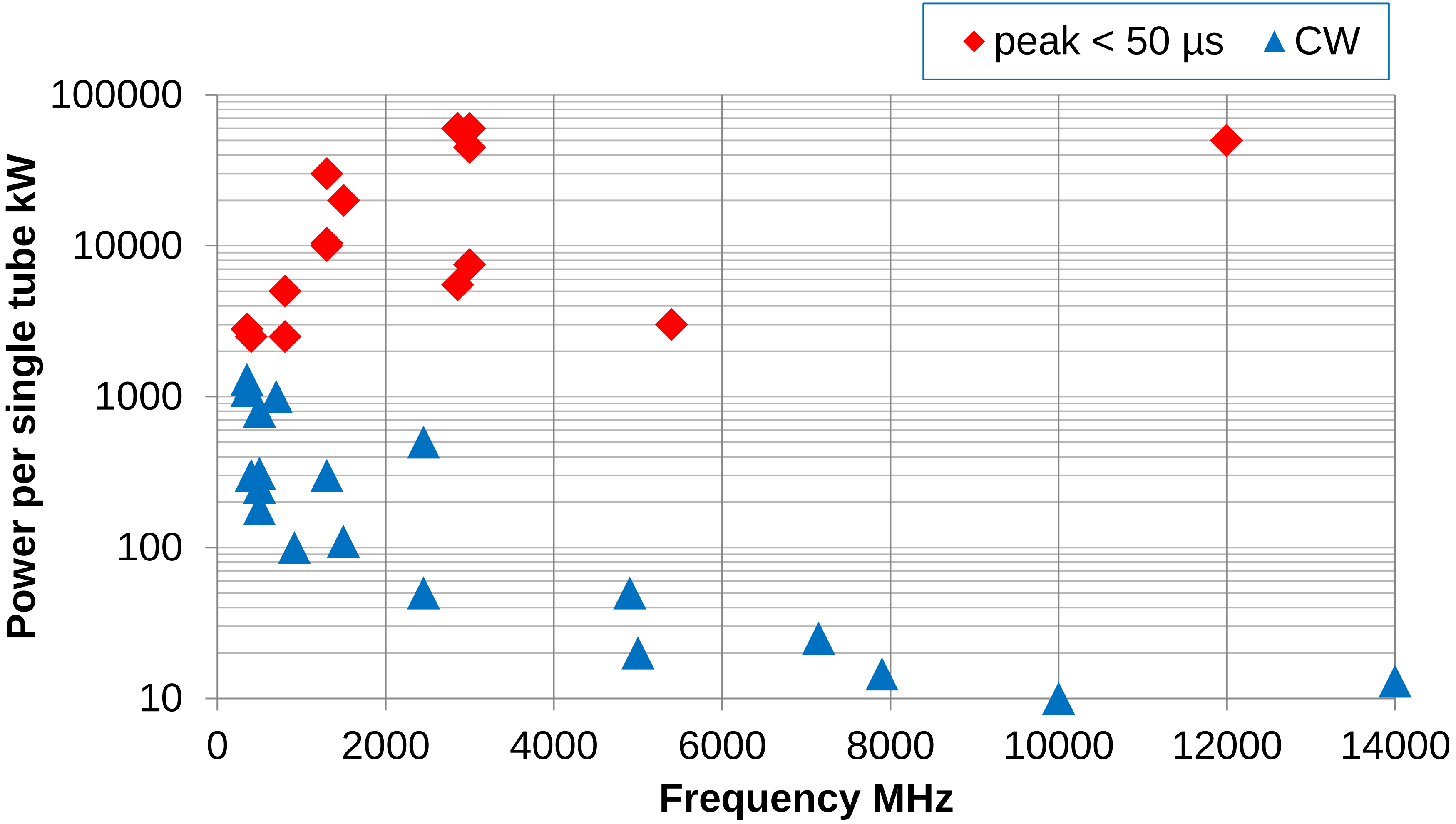
- To maintain the e- beam as expected and where expected

Klystron

TH 2167 CERN LHC @ 400 MHz

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

Klystrons available from industry



RF power source classification

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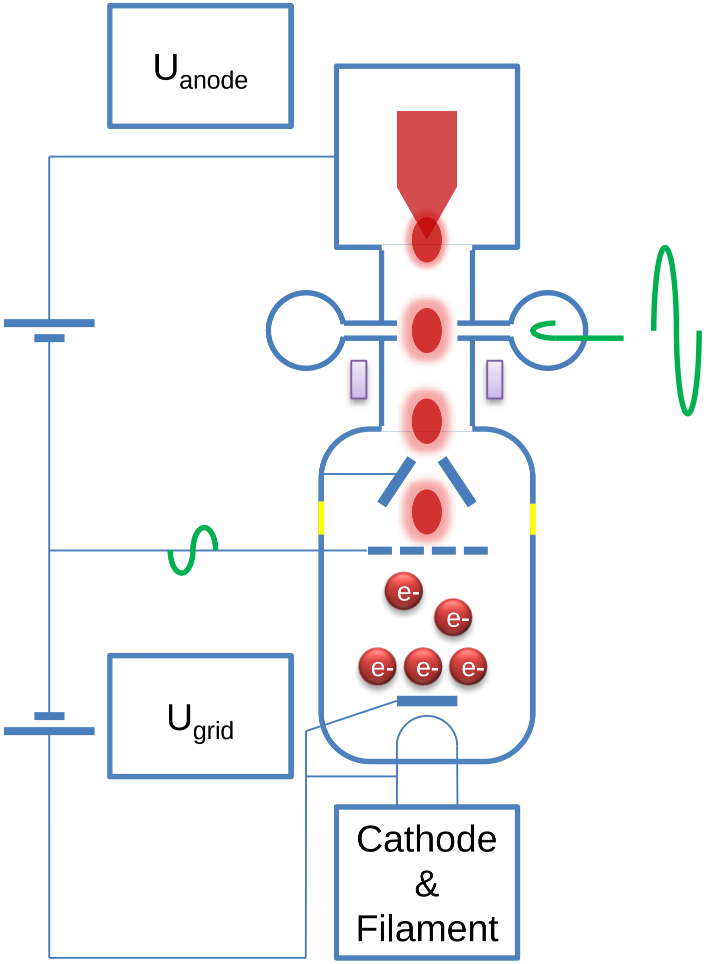
Essentials of IOT



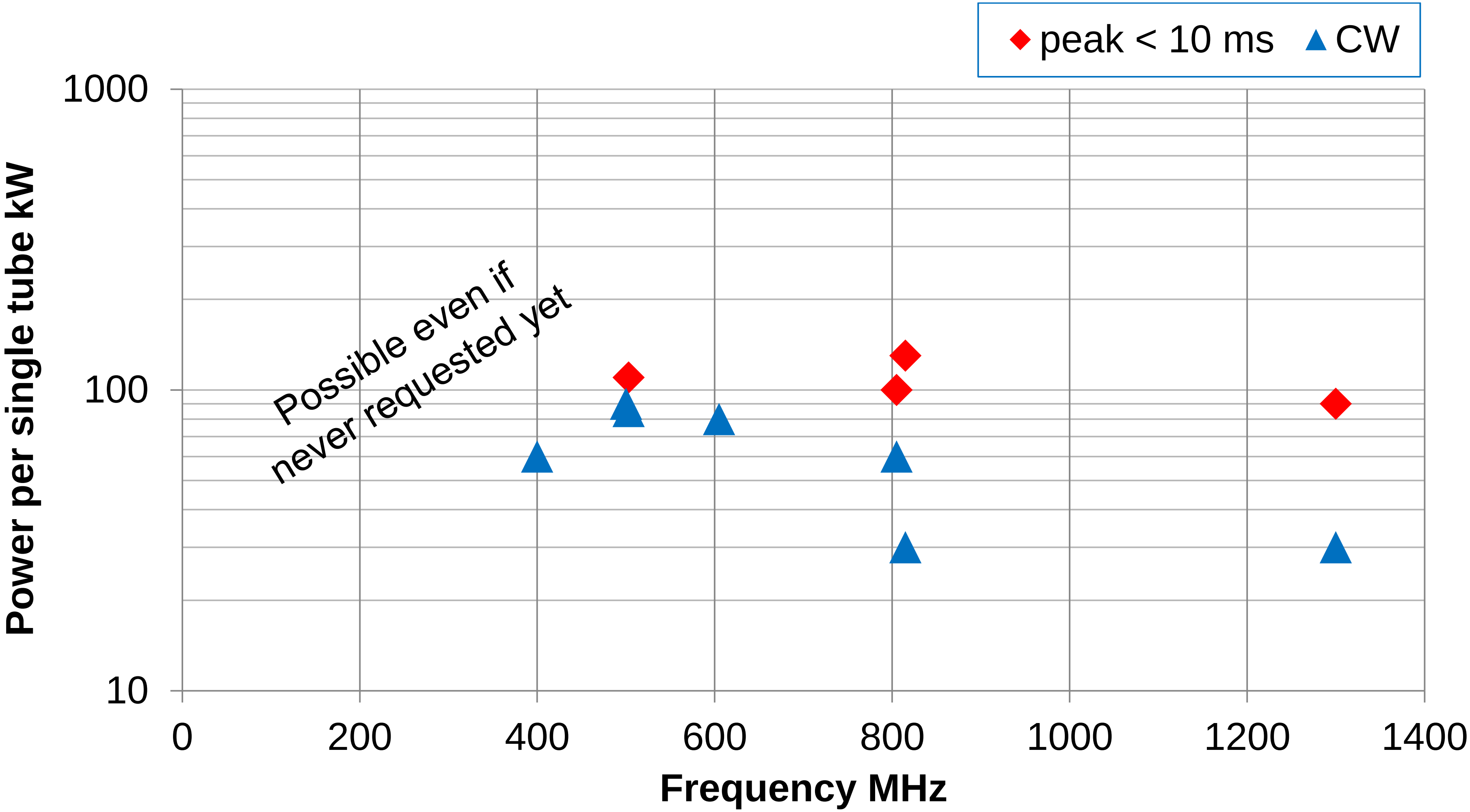
- IOT density modulation
  - converts the kinetic energy into radio frequency power
- Vacuum tube
- Triode input
  - Thermionic cathode
  - Grid modulates e- emission
- Klystron output
  - Anode accelerates e- buckets
  - Short drift tube & magnets
  - Catcher cavity
  - Collector

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



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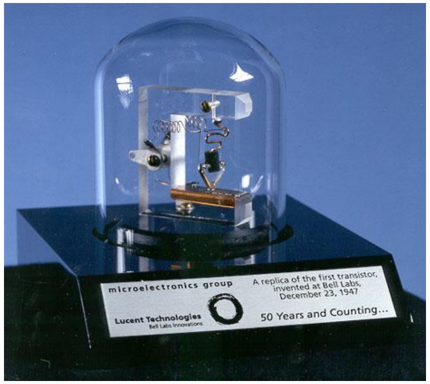
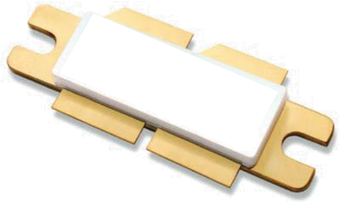
Transistor for RF power

1925	theory, Julius Edgar Lilienfeld
1947	Germanium US first transistor, John Bardeen, Walter Brattain, William Shockley
1948	Germanium European first transistor, Herbert Mataré and Heinrich Welker
1953	first high-frequency transistor, Philco
1954	Silicon transistor, Morris Tanenbaum
1960	MOS, Kahng and Atalla
1966	Gallium arsenide (GaAs)
1980	VDMOS
1989	Silicon-Germanium (SiGe)
1990	Gallium Nitrade (GaN)
1997	Silicon carbide (SiC)
2004	Graphene (GFET)
20xx	…

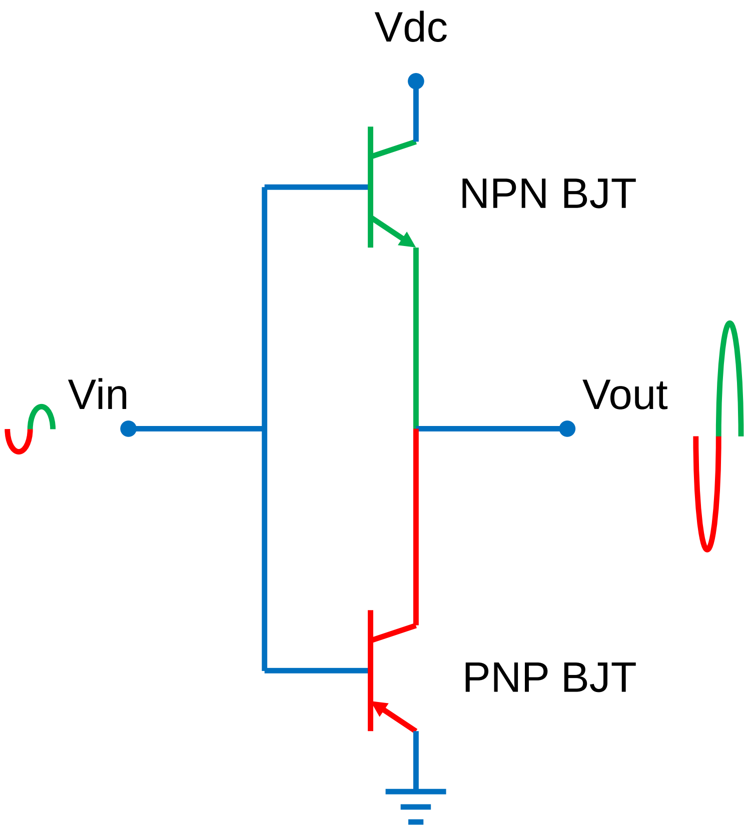


First transistor invented at BELL labs in 1947



XXI century LDMOS

Essentials of RF transistor

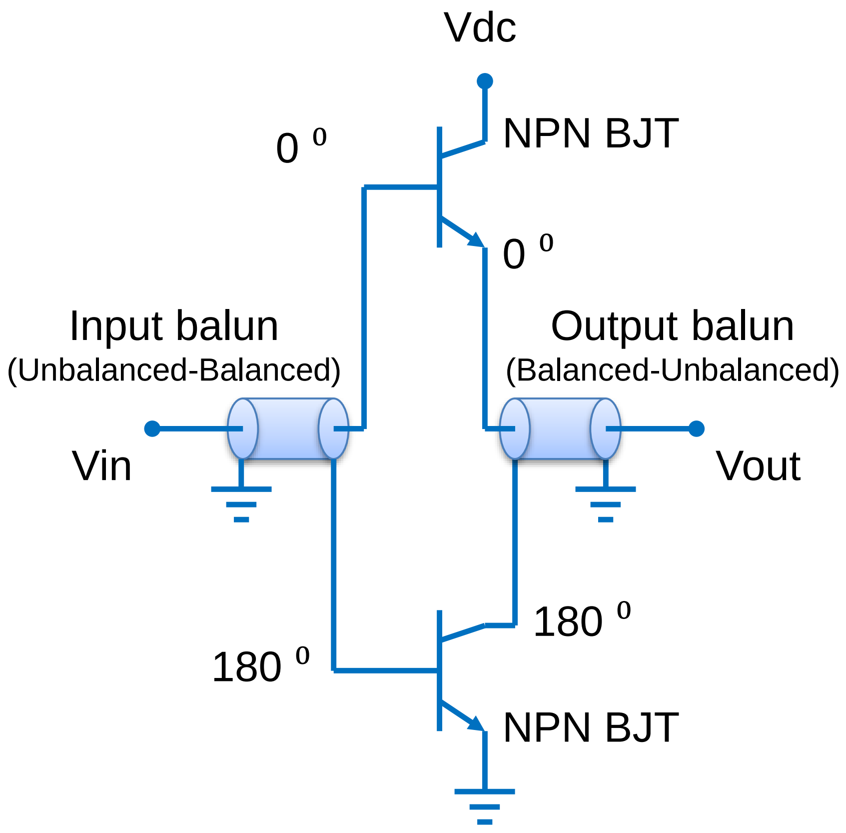


In a push-pull circuit the RF signal is applied to two devices

- 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



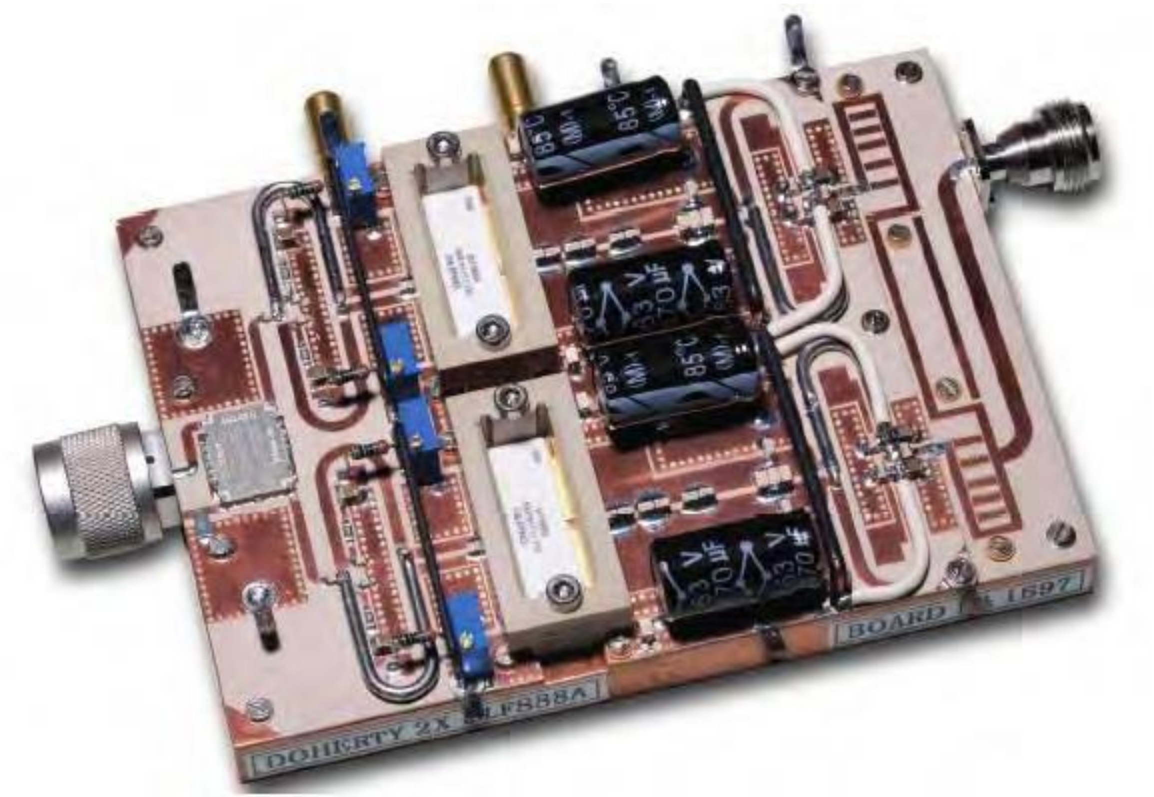
Another push-pull configuration is to use a balun (balanced-unbalanced)

- 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

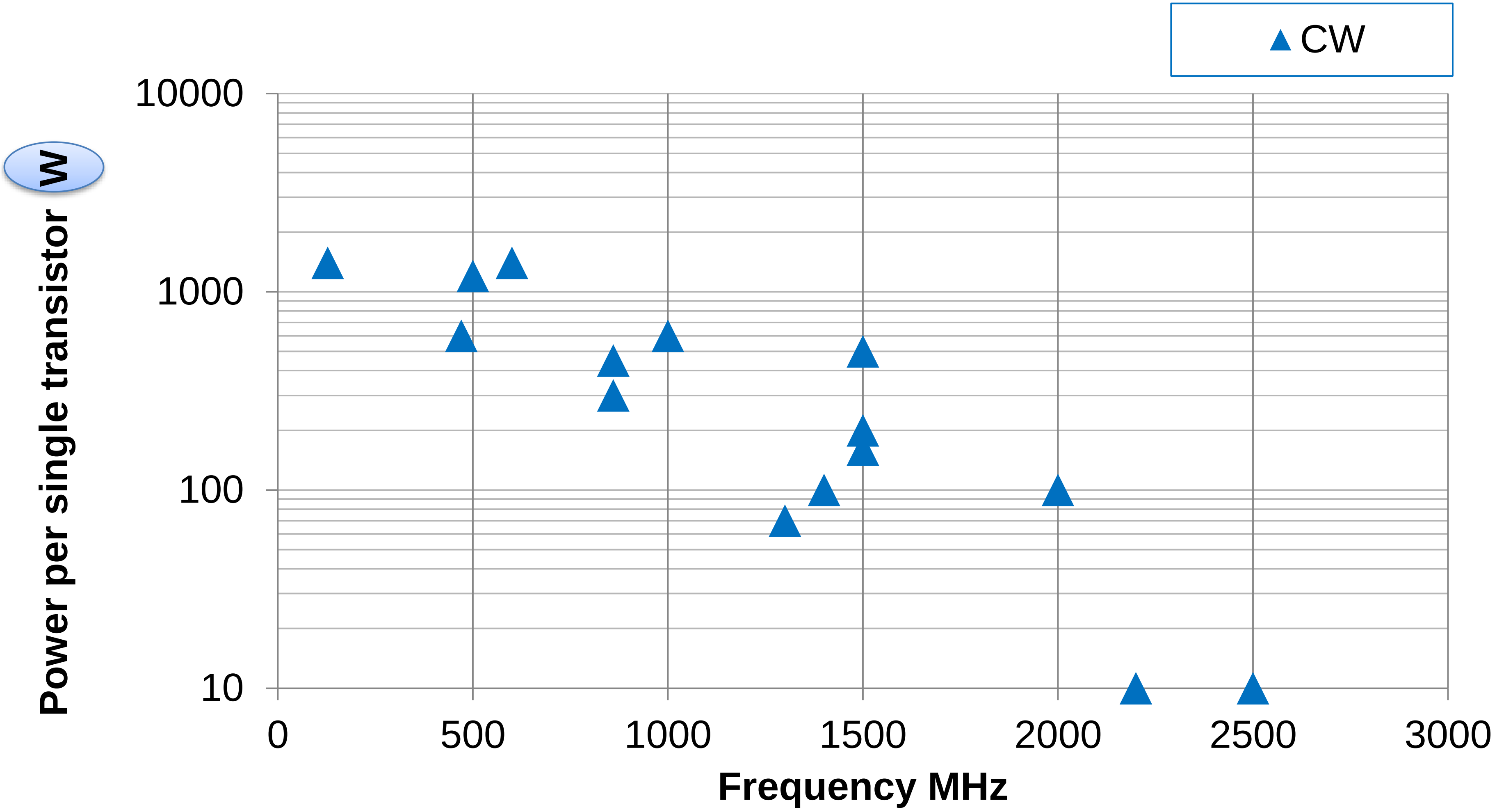
This configuration is easier to manufacture since only one type of device is required

Essentials of RF transistor



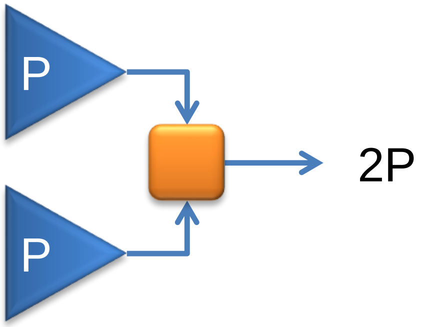
NXP Semiconductors AN11325
2-way Doherty amplifier with BLF888A

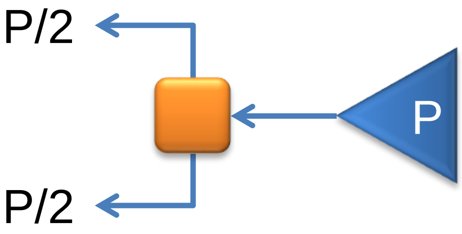
Transistors available from industry



Combiners & Splitters

RF power combiners and RF power splitters are the same items





Resistive power splitters & Combiners

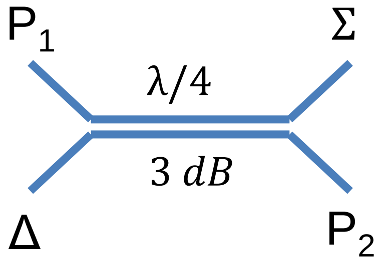
- Cheap and easy to build
- Use of resistor to maintain the impedance
- Power limitation and losses induces by the resistors (→ not used in high power)

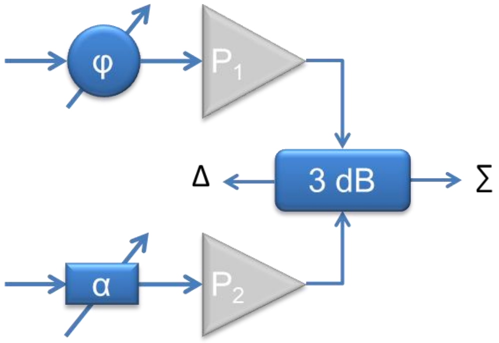
Hybrid power splitters & Combiners

- Use RF lines
- Low levels of loss
- Limitation by the size of the lines

Combiners & Splitters

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

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

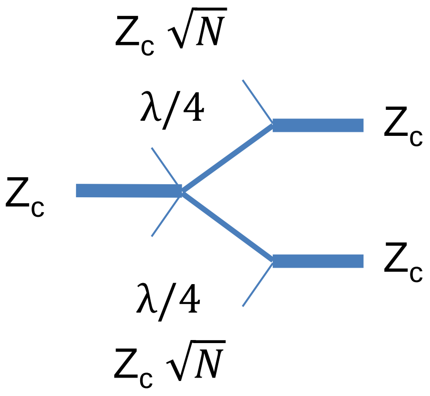
$$\Delta = \frac{P + P}{2} - \sqrt{PP} = 0$$

Combiners & Splitters

CERN SPS 64 to 1 combiner @ 200 MHz

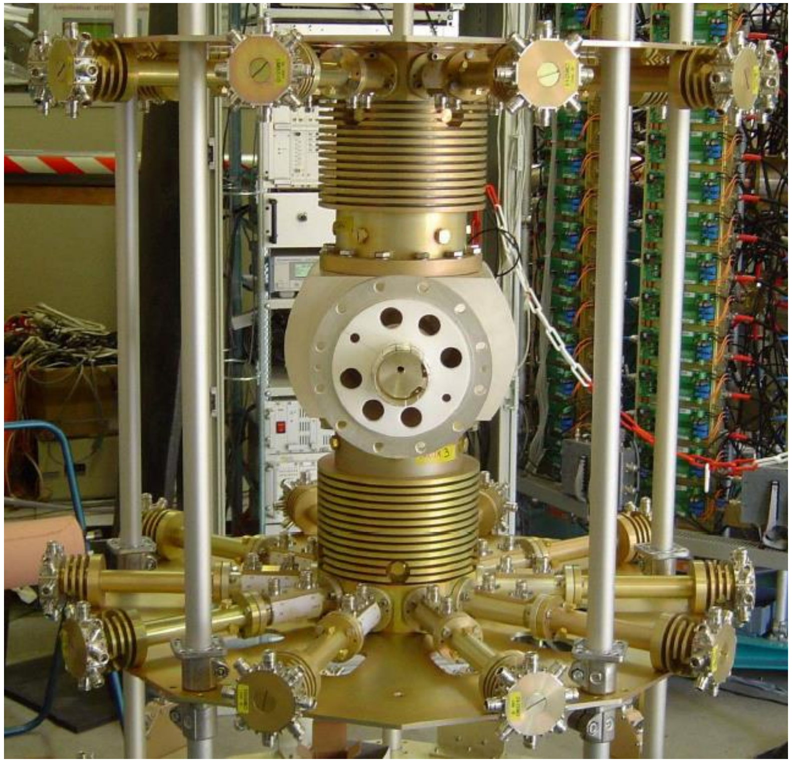
Combiners & Splitters

Low loss T-Junction



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

We have a N-ways splitter

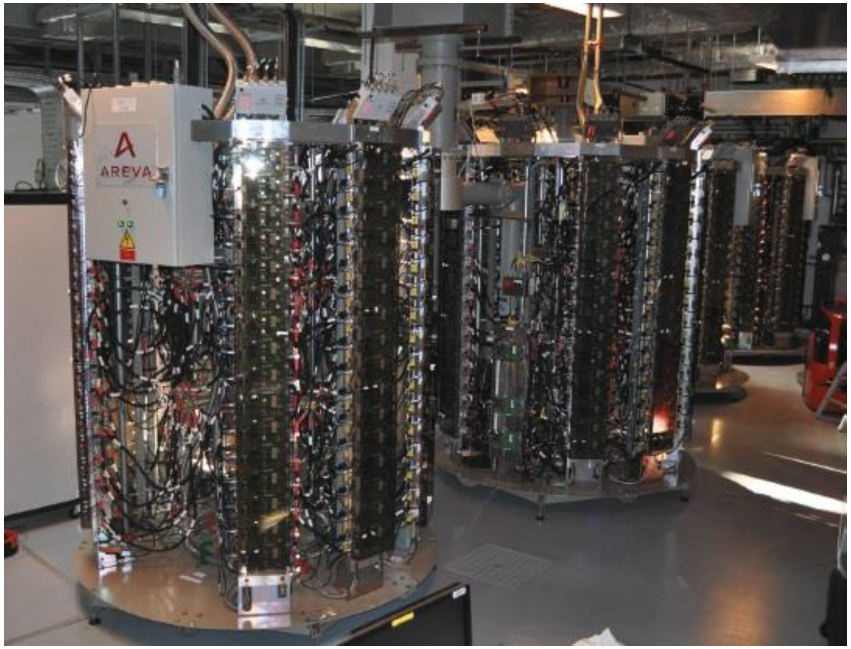


160 to 1 @ 352 MHz
T-junction combiner

Transistors

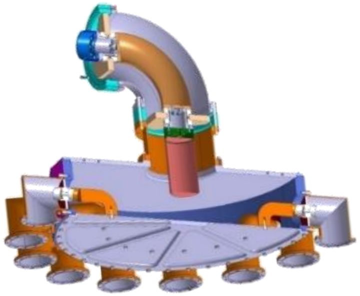
SOLEIL @ 352 MHz and ESRF @ 352 MHz

SOLEIL 45 kW @ 352 MHz
solid state amplifier towers (2004 & 2007)



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

Combining system



3 dB combiner
32 x 35 kW to 1 x 1 MW
(~ 50 m²)

EUROPEAN SYNCHROTRON RADIATION FACILITY

ESRF

Accelerator & Source

Technical Note

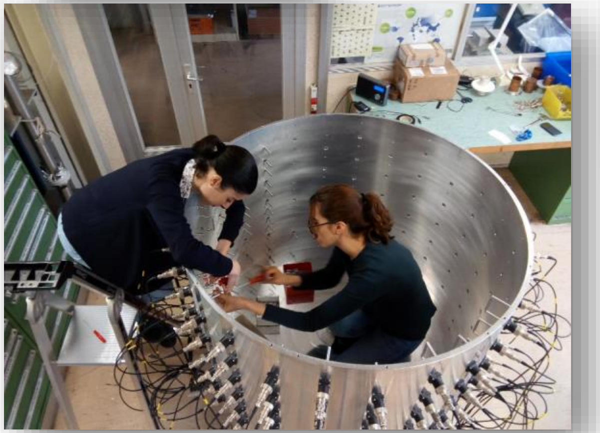
01-13/RF

150 kW Cavity combiner for CERN-LIU-SPS[1]

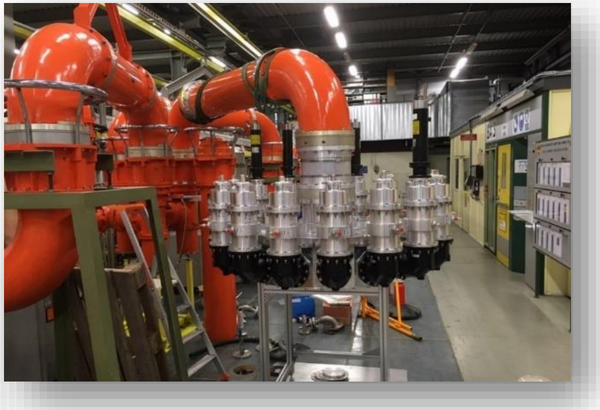
Author(s): Michel LANGLOIS

Date: February11th, 2013

Distribution: Jörn JACOB, Eric MONTESINOS



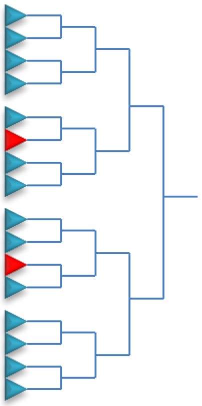
CC (Cavity Combiner)
144 x 1 kW to 1 x 144 kW



VHPCC (Very High Power Cavity Combiner)
16 x 70 kW to 1 x 1 MW
(~ 3 m²)

Combining system

In order to ensure 100 % availability, your combining system will define the number ‘Base units’



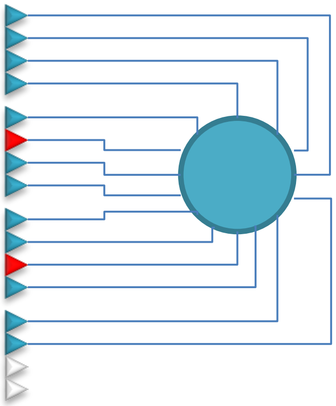
Base unit = 1

Nominal Output = 16
Wish to have full performance with 2 ‘Off Line’
Degraded Output = 12.25

So, in order to be 100 % available, this system composed of 16 x Base Units, is in fact a **12 x Base Unit**

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

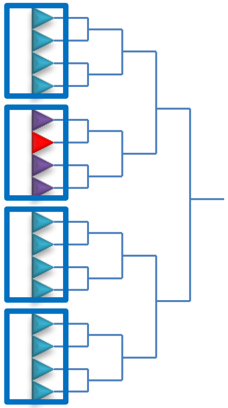
In order to perform the same **12 x Base Unit**, with the same 2 Base unit tolerance, with a cavity combiner, you need only **14 x Base Unit instead of 16**



$$Pout = n\,A1$$

Combining system granularity

- In order to ensure 100 % availability, your *Granularity* will define the number ‘Module units’ and ‘Base units’

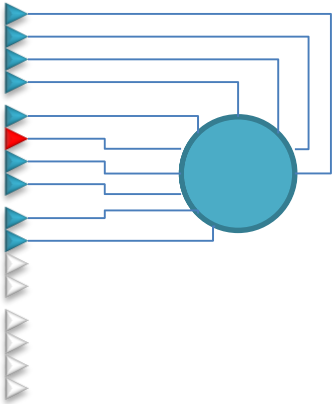


1 Module =
4 x Base unit

Nominal Output = 16
If because of your ‘pre-grouping’, several transistors are not available, granularity is then not enough
Degraded Output = 9

So, in order to be 100 % available, this system composed of 16 x Base Units, is in fact a **9 x Base Unit**

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



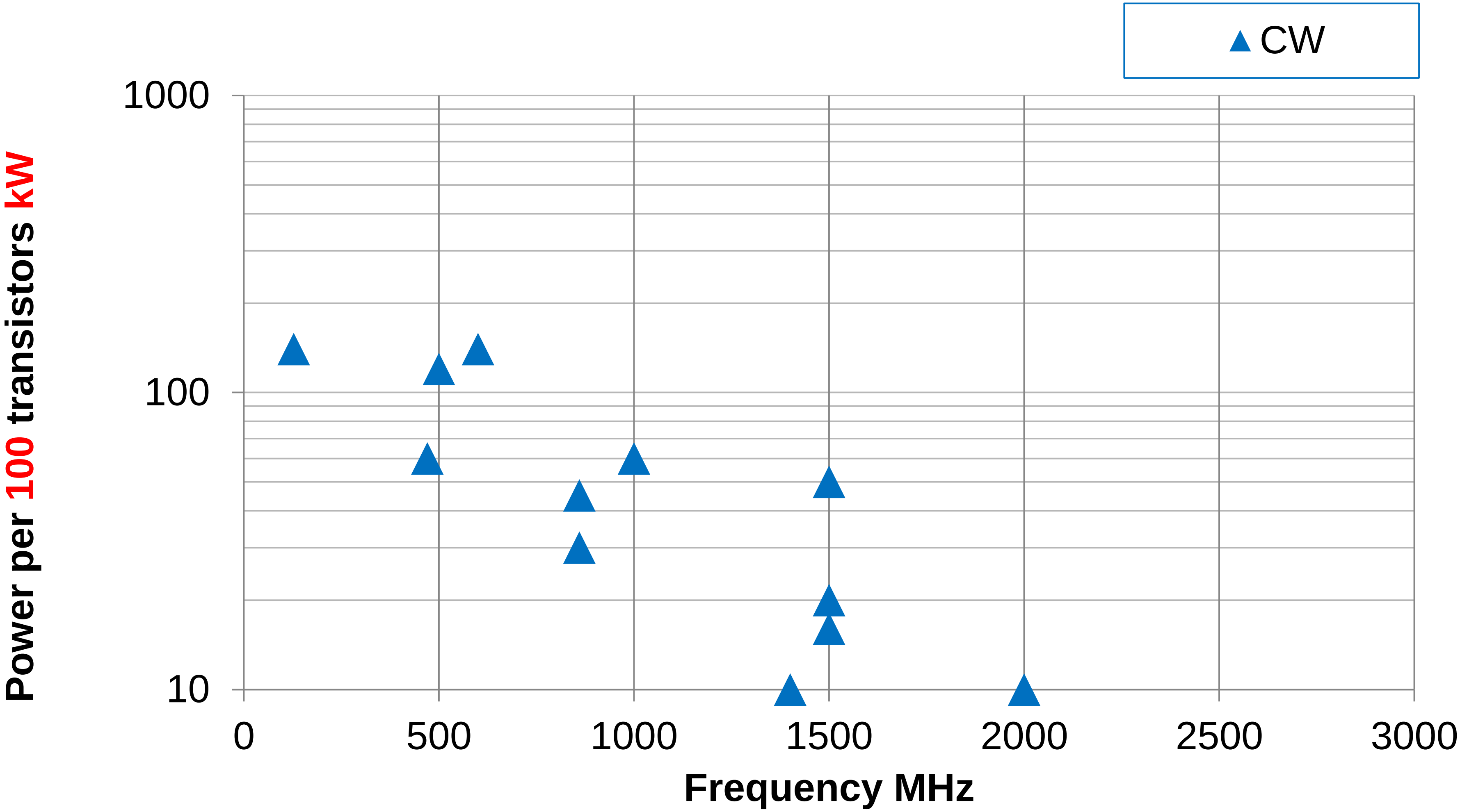
In order to perform the same **9 x Base Unit**, with the same 1 Module unit tolerance, with a cavity combiner and keeping the Base unit granularity, you need only **10 x Base Unit instead of 16**

$$\boldsymbol{Pout = n\,A1}$$

‘Young’ technology for HPRF in 100 kW to MW range

CERN SPS Thales Solid State Power Amplifiers,
32 towers x 144 kW @ 200 MHz, combined into 2 x 2 MW amplifiers,
into operation since 2021

Transistors available from industry



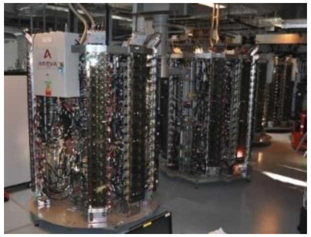
Power density

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

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

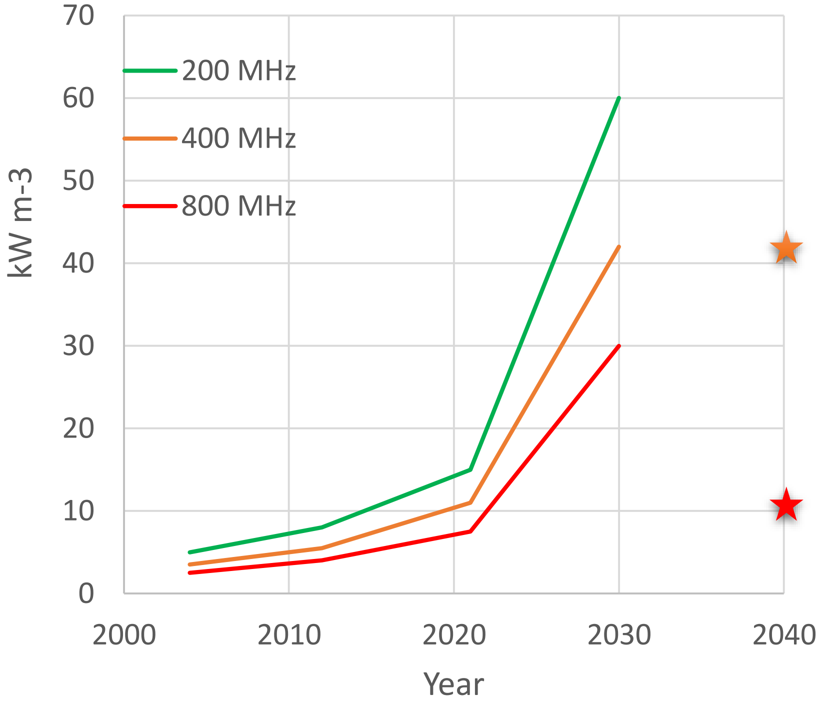
including power supplies and combining systems
AND granularity providing **100 % availability !**

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



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

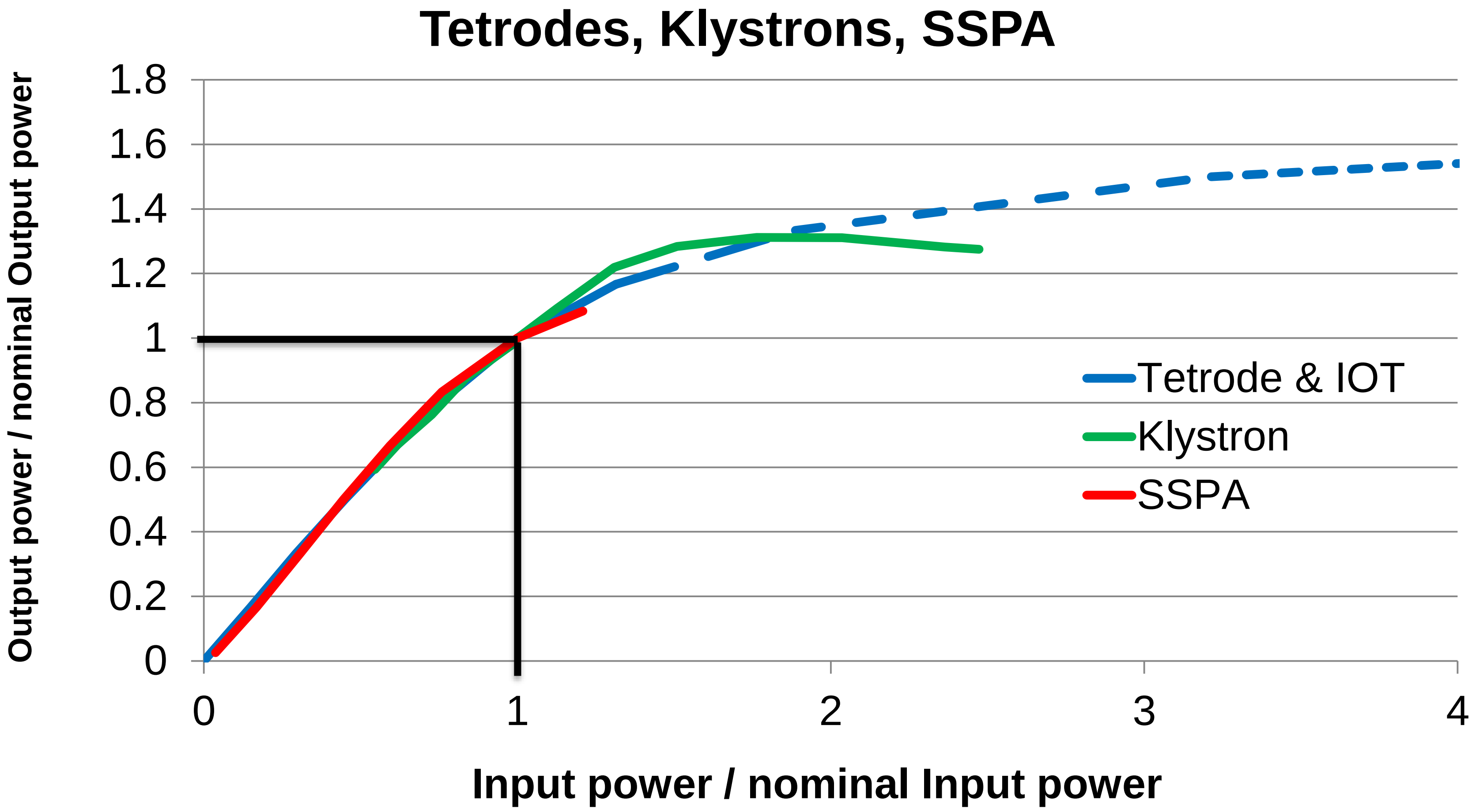
CERN 160 kW @ 200 MHz
2021
Power density
15 kW m^{-3}



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

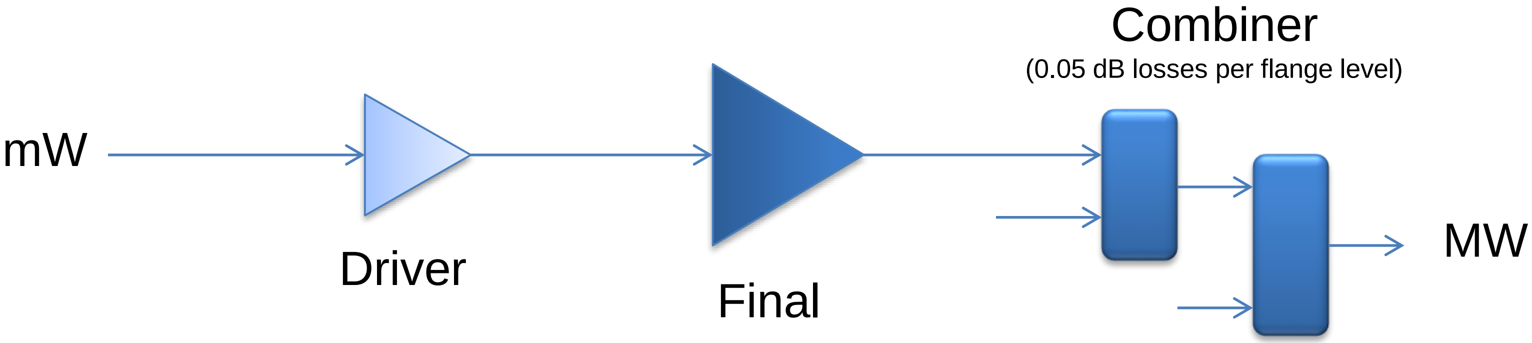
FCC 200 kW @ 800 MHz
Power density
10 kW m^{-3}

Overhead comparison

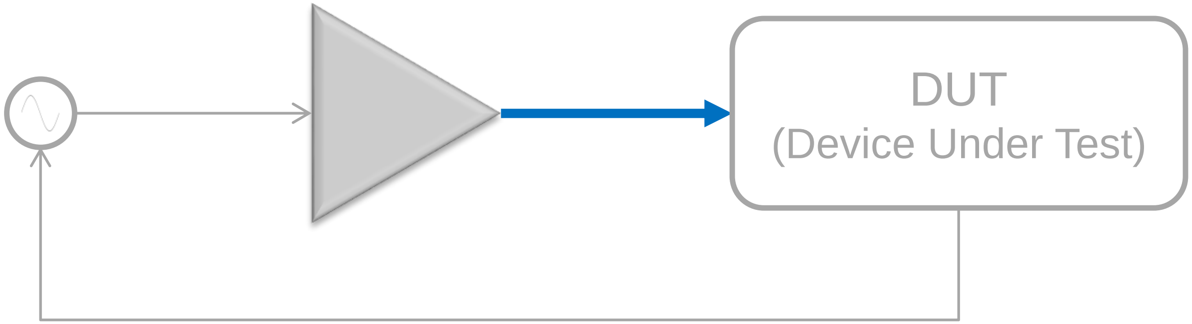


High Power options

Final stage	DC Voltage	Driver	Gain	Power per unit	Combiner (for 1 MW)
Tetrode	15 kV	6.2 kW	13 dB	135 kW	8:1
Klystron	100 kV	10 W	50 dB	1 MW	-
IOT	40 kV	320 W	23 dB	65 kW	16:1
SSPA	50 V	5 W	23 dB	1100 W	1024:1



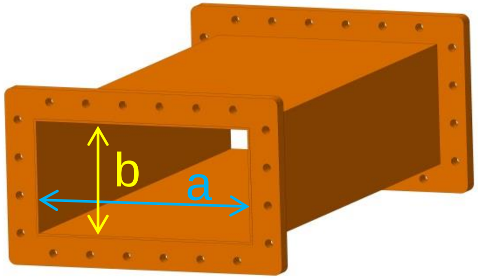
RF Power Lines



DUT
(Device Under Test)

Rectangular waveguides

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

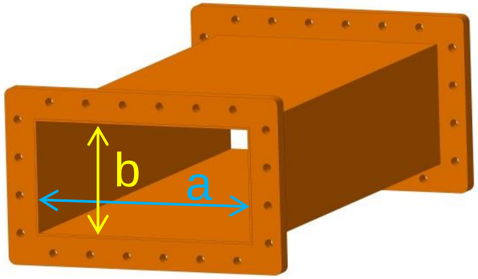


Wavelength	$\lambda_g = \dfrac{\lambda}{\sqrt{1-(\frac{\lambda}{2a})^2}}$
Cutoff frequency dominant mode	$\mathrm{f_c} = \dfrac{\mathrm{c}}{2a}$
Cutoff frequency next higher mode	$\mathrm{f_{c2}} = \dfrac{\mathrm{c}}{4a}$
Usable frequency range	1.3 $\mathrm{f_c}$ to 0.9 $\mathrm{f_{c2}}$

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

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

With

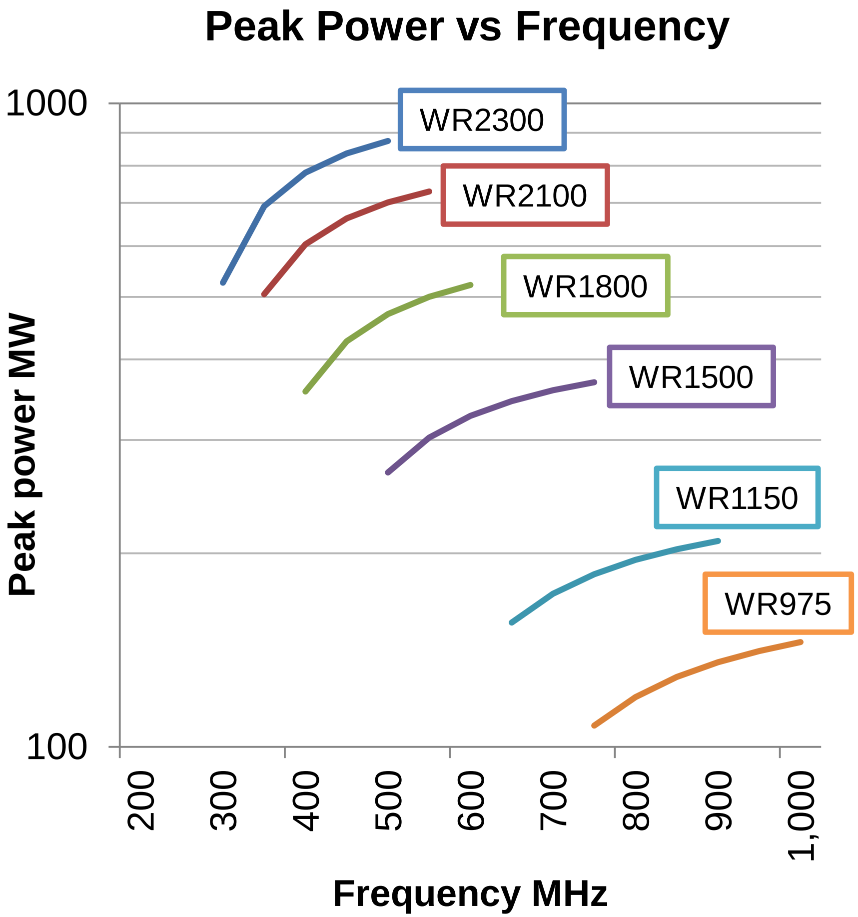
P = Power in watts

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)

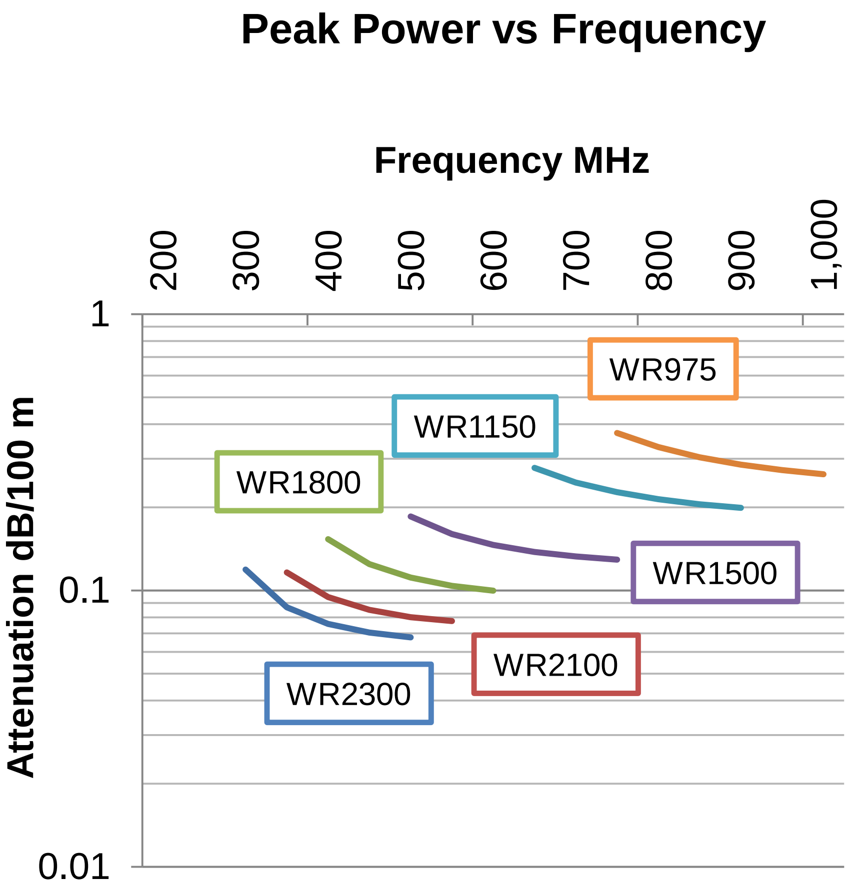


Rectangular waveguides Attenuation

$$Attenuation = \frac{4a_0}{a}\frac{\sqrt{c/\lambda}}{\sqrt{1-(\lambda/2a)^2}}\left(\frac{a}{2b}+\frac{\lambda^2}{4a^2}\right)$$

With
$a_0 = 3\ 10^{-7}$ [dB/m] for copper
a = width of waveguide in m
b = height of waveguide in m
λ = free space wavelength in m

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


Peak Power vs Frequency

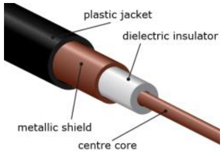
Coaxial Lines

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

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

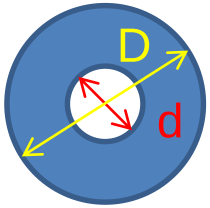
Flexible lines have spacer helicoidally placed all along the line

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

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



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

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

With

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

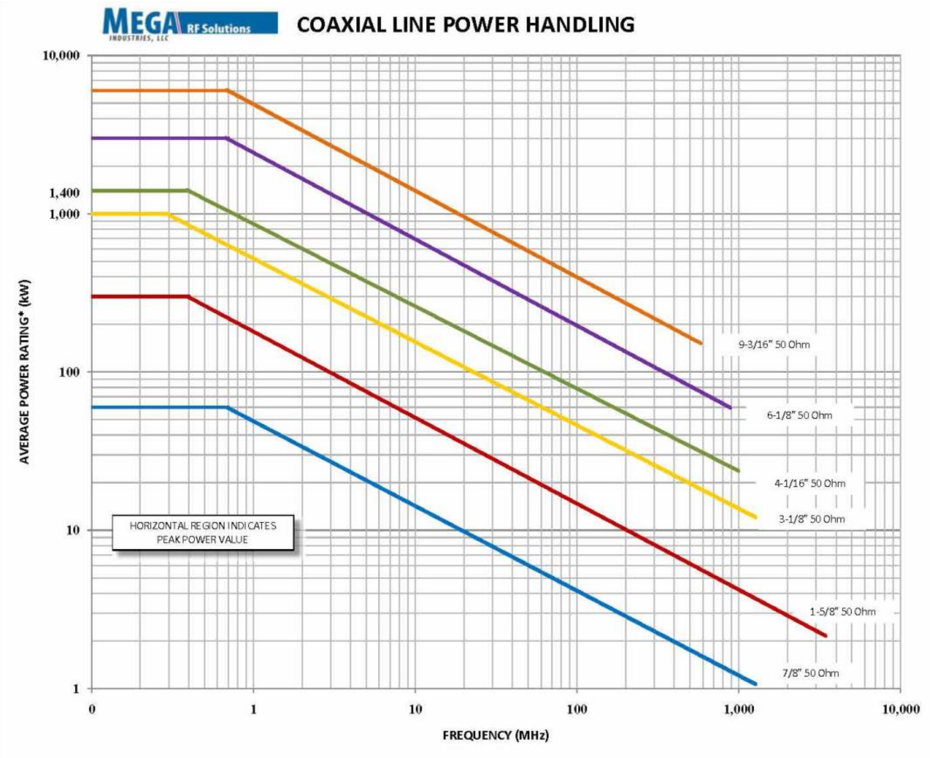
D = inside electrical diameter of outer conductor in mm

d = outside electrical diameter of inner conductor in mm

Zc= characteristic impedance in Ω

ε_r = relative permittivity of dielectric

f = frequency in MHz



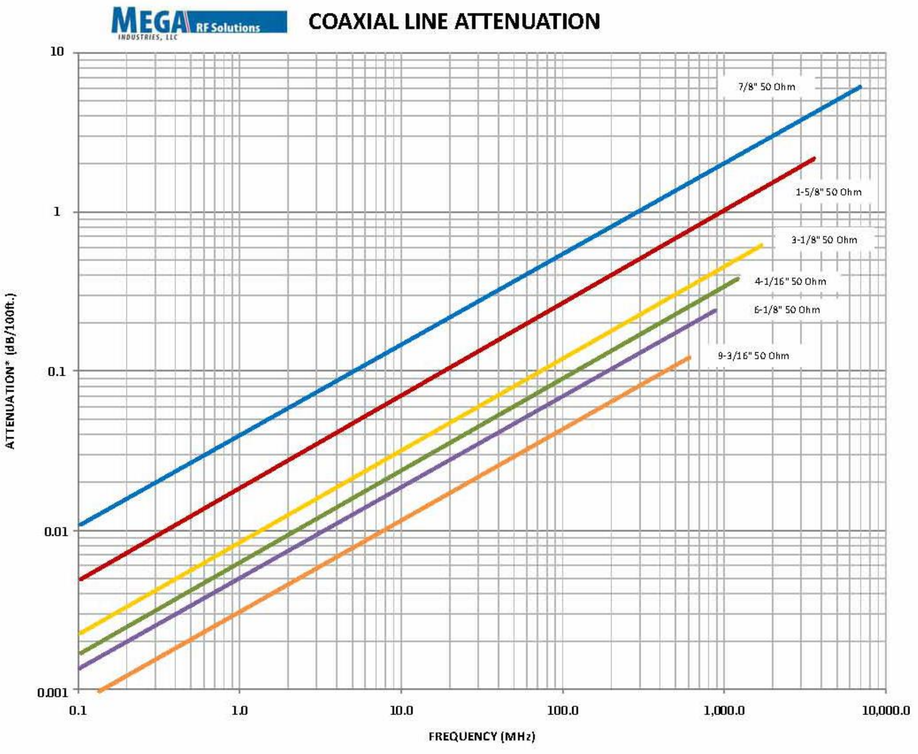
Coaxial lines Attenuation

The attenuation of a coaxial line is expressed as

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

where
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
ε_r = 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



Reflection from Load

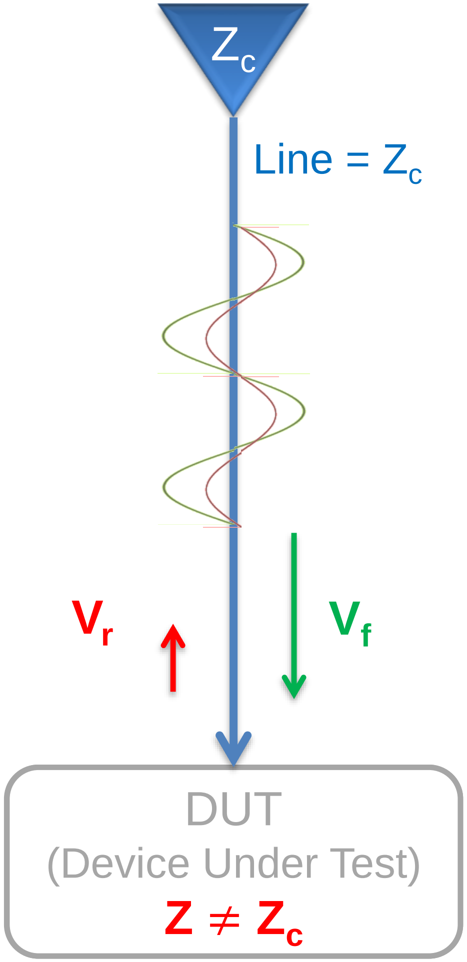
Standing Wave Ration SWR is a measure of impedance matching of DUT

A wave is partly reflected when a transmission line is terminated with other than a pure resistance equal to its characteristic impedance

The reflection coefficient is defined by

$$\Gamma = \frac{V_r}{V_f}$$

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 Load

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

$$\begin{aligned}|Vmax| &= |Vf| + |Vr| \\ &= |Vf| + |\Gamma Vf| \\ &= (1 + |\Gamma|)\ |Vf|\end{aligned}$$

full reflection

$$|Vmax| = 2\ |Vf|$$

At other points they are 180° out of phase

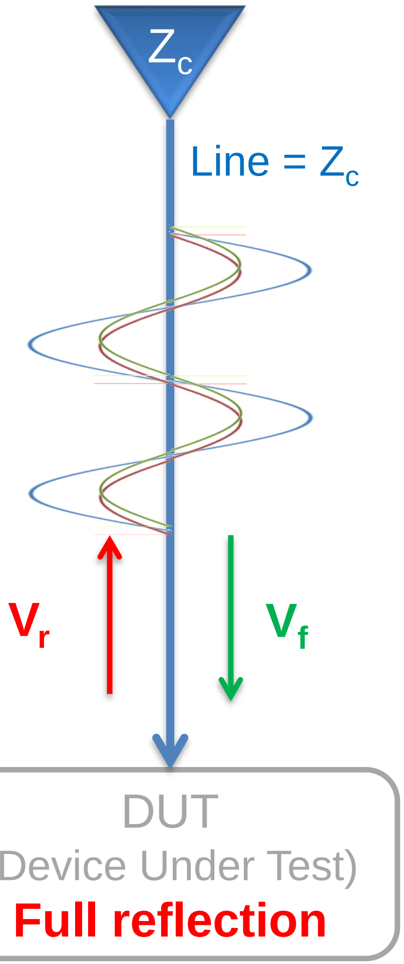
$$\begin{aligned}|Vmin| &= |Vf| - |Vr| \\ &= |Vf| - |\Gamma Vf| \\ &= (1 - |\Gamma|)\ |Vf|\end{aligned}$$

full reflection

$$|Vmin| = 0$$

The Voltage Standing Wave Ratio is equal to

$$VSWR = \frac{|Vmax|}{|Vmin|} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$



Reflection from Load

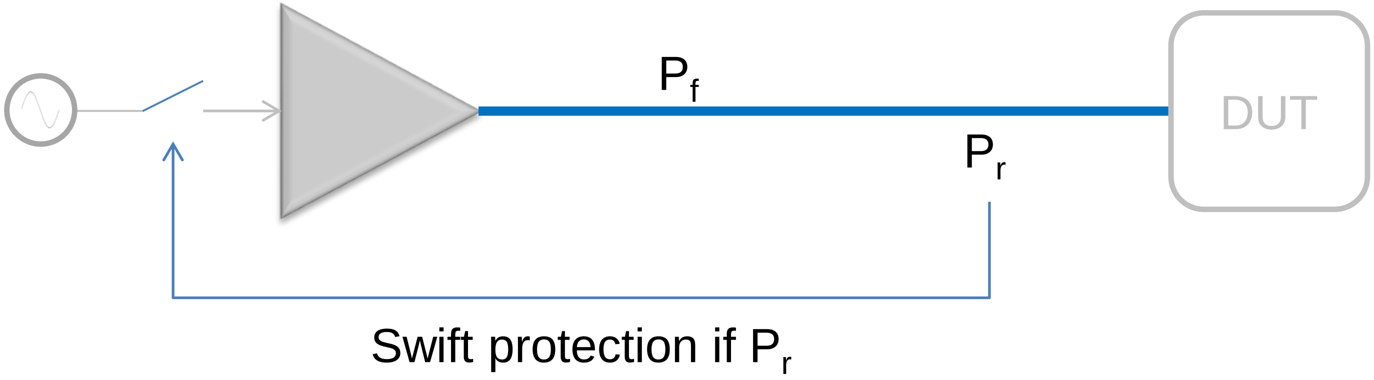
In case of full reflection $V_{max} = 2\ V_f$ (P_{max} equivalent to 4 P_f)

RF power amplifiers will not like this reflected wave

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

Swift protection if $P_r > P_{rmax}$

- system NOT operational (not always possible)



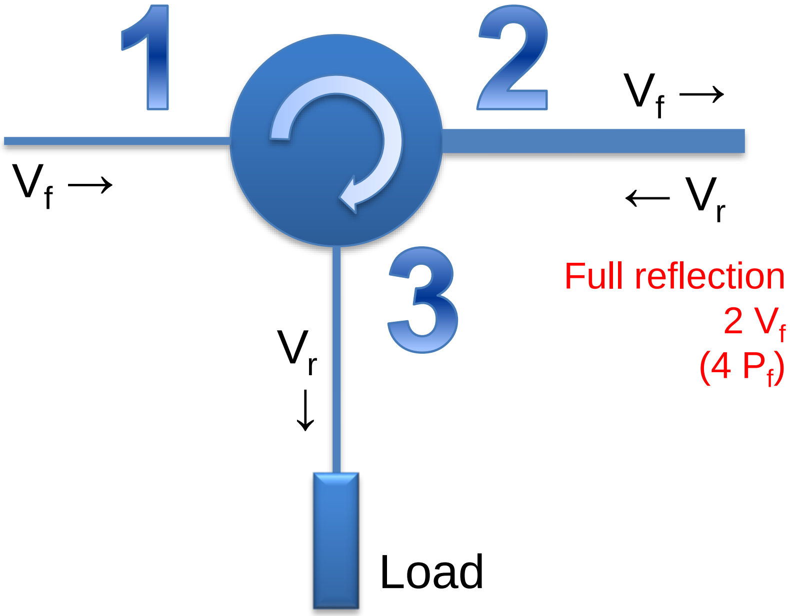
Circulator

In order to protect our lines and our amplifiers from this reflected power: Circulator

- passive non-reciprocal three-port device
- signal entering any port is transmitted only to the next port in rotation

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

- Lines between circulator and DUT shall sustain 4 P_f if full reflection
- A load of P_f is needed on port 3 to absorb P_r



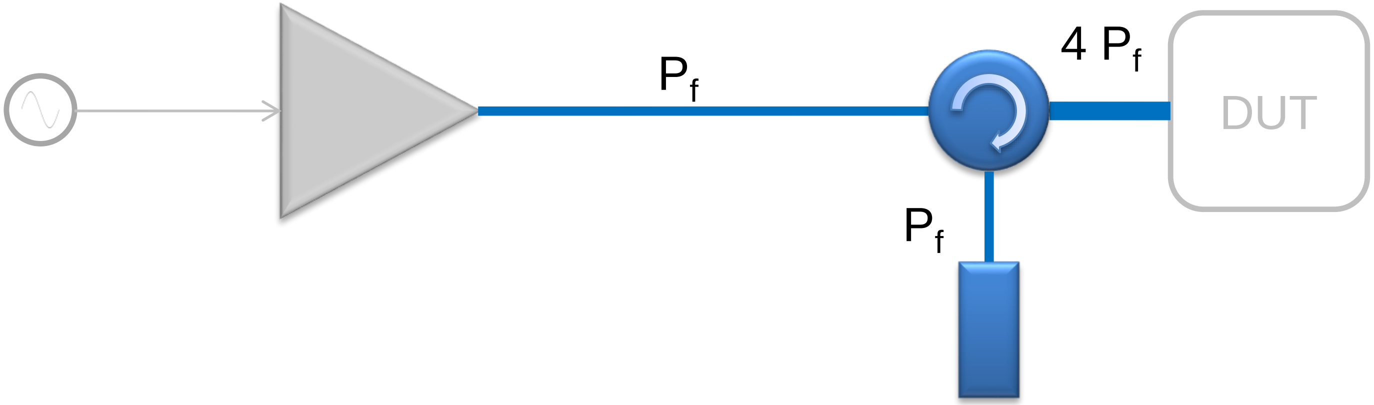
Full reflection
2 V_f
(4 P_f)

Circulator

Even in case of full reflection $V_{max} = 2\ V_f$ (P_{max} equivalent to $4\ P_f$)

RF power amplifiers will not see reflected power and will not be affected
Lines between circulator and DUT MUST at least be designed for $4\ P_f$
Loads must be designed for P_f

System remains always operational at any time



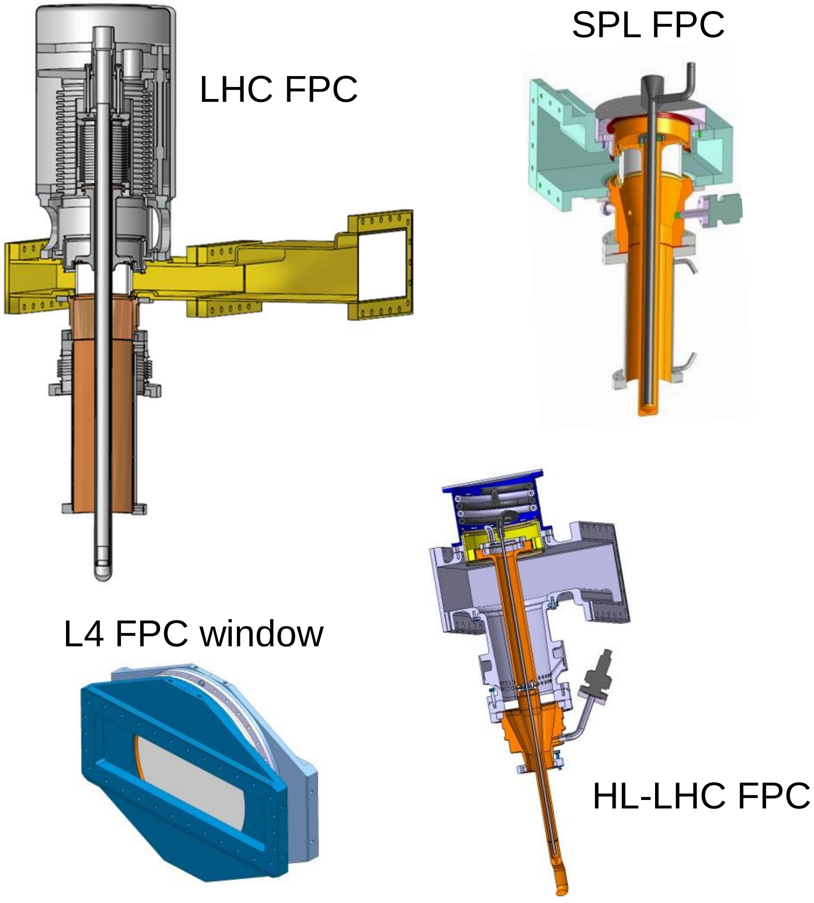
Fundamental Power Coupler FPC

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

It is a specific piece of transmission line that also has to provide the vacuum barrier for the beam vacuum

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

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



LHC FPC

SPL FPC

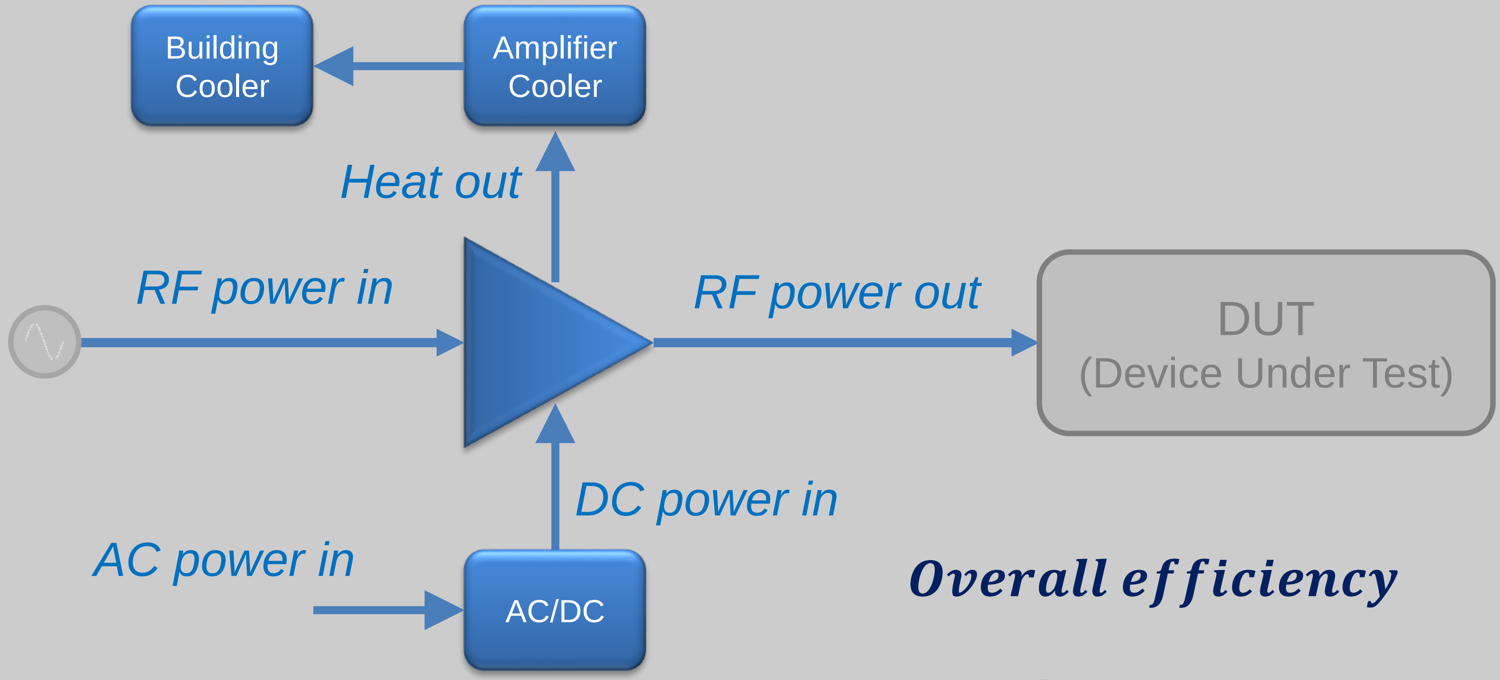
L4 FPC window

HL-LHC FPC

Various FPC at CERN

Overall Efficiency = Electrical bill

Building HVAC (Heating, Ventilation, Air Conditioning)



Building Cooler

Amplifier Cooler

Heat out

RF power in

RF power out

DUT
(Device Under Test)

DC power in

AC power in

AC/DC

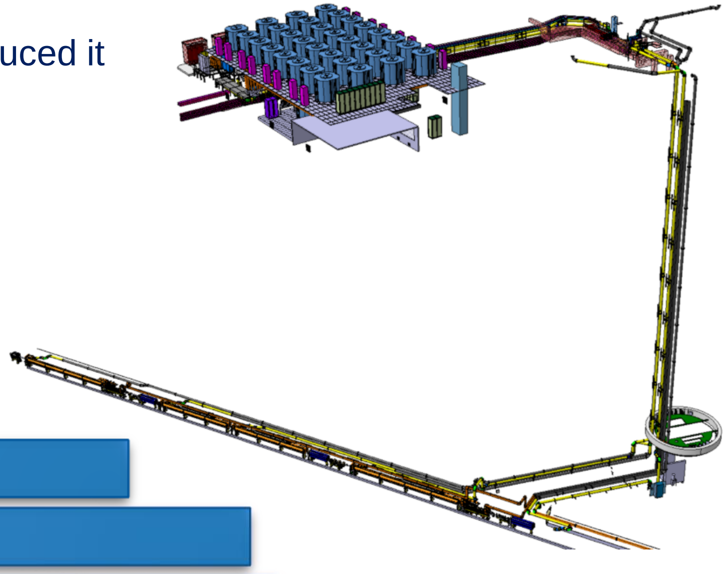
Overall efficiency

$$\simeq \frac{P_{RFout}}{P_{ACin} + P_{RFin} + P_{coolers}} \simeq 45\ \%$$

Efficiency

Thales design report: ‘Le rendement des blocs RF avec les MRFE6VP61K25N est de l’ordre de 66 % (valeur conservative)’

This was before linearity and bandwidth adjustments, I reduced it to 60 % for this exercise



Cavity = 1 MW

150 m coaxial line = + 0.2 dB = + 5 % = 1.050 MW

Circulator = + 0.2 dB = + 5 % = 1.103 MW

Hybrid combiner 16:1 = + 0.3 dB = + 7 % = 1.175 MW

DC to RF (efficiency ~ **60** %) = 1.960 MW

AC to DC (efficiency ~ 90 %) = 2.175 MW (1’000 kW to be dissipated)

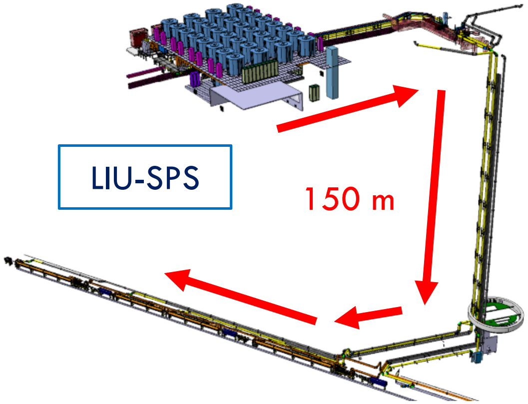
Air cooling station (10 % of 1’000 kW = 100 kW) ~ + 50 kW = 2.225 MW

Water cooling station (90 % of 1’000 kW = 900 kW) ~ + 45 kW = 2,270 MW

Electrical distribution (5 % of 2.270 MW) ~ + 50 kW = **2,4 MW** taken from the grid

Overall efficiency **41,9 %**

Efficiency



Cavity = 1 MW

20 m coaxial line = ~~+ 5 %~~ + 1 % = 1.010 MW

Circulator = + 0.2 dB = + 5 % = 1.060 MW

Hybrid combiner 16:1 = + 0.3 dB = + 7 % = 1.130 MW

DC to RF (efficiency ~ 60 %) = 1.890 MW

AC to DC (efficiency ~ 90 %) = 2,100 MW (970 kW to be dissipated)

Air cooling station (10 % of 970 kW = 97 kW) ~ + 49 kW = 2,149 MW

Water cooling station (90 % of 970 kW = 873 kW) ~ + 44 kW = 2,190 MW

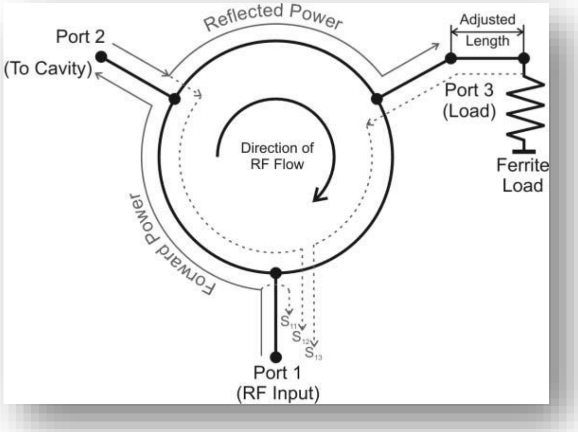
Electrical distribution (5 % of 2,190 MW) ~ + 99 kW = **2,3 MW** taken from the grid

Overall efficiency **43,5 %** **41,9 %**

Having the amplifiers very close to the cavity, will reduce all other losses

A gallery is very expensive, as an acquisition cost, but can help to reduce acquisition cost of transmission lines and to reduce cost of operation

Efficiency



Cavity = 1 MW

20 m coaxial line = + 1 % = 1.010 MW

NO Circulator = ~~+ 5 %~~ + 0 % = 1.010 MW

Hybrid combiner 16:1 = + 0.3 dB = + 7 % = 1.080 MW

DC to RF (efficiency ~ 60 %) = 1.800 MW

AC to DC (efficiency ~ 90 %) = 2,000 MW (920 kW to be dissipated)

Air cooling station (10 % of 920 kW = 92 kW) ~ + 46 kW = 2,046 MW

Water cooling station (90 % of 920 kW = 828 kW) ~ + 42 kW = 2,088 MW

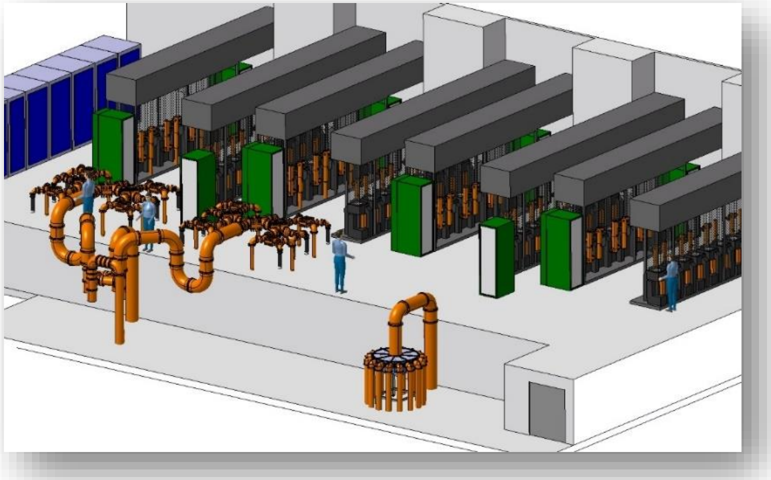
Electrical distribution (5 % of 2,088 MW) ~ + 104 kW = **2,2 MW** taken from the grid

Overall efficiency **45,5 %** **41,9 %**

As said, we are now able to build Power Amplifiers **without** circulator (Tetrodes and IOT can also do it)

The 'cost' is a (very) good protection system on the LLRF side

Efficiency



Cavity = 1 MW

20 m coaxial line = + 1 % = 1.010 MW

NO Circulator = 1.010 MW

VHPCC 16:1 = + 0.1 dB = ~~+ 7 %~~ + 2,5 % = 1.035 MW

DC to RF (efficiency ~ 60 %) = 1.725 MW

AC to DC (efficiency ~ 90 %) = 1,920 MW (882 kW to be dissipated)

Air cooling station (10 % of 882 kW ~ 88 kW) ~ + 44 kW = 1,964 MW

Water cooling station (90 % of 882 kW ~ 794 kW) ~ + 39 kW = 2,003 MW

Electrical distribution (5 % of 2,003 MW) ~ + 100 kW = **2,1 MW** taken from the grid

Overall efficiency **47,6 %**

41,9 %

Using cavity combiners instead of 3 dB combiners will also reduce maintenance cost as no more power loads to maintain

Efficiency

Cavity = 1 MW

20 m coaxial line = + 1 % = 1.010 MW

NO Circulator = 1.010 MW

VHPCC 16:1 = + 0.1 dB = + 2,5 % = 1.035 MW

DC to RF (efficiency ~~~ 60 %~~ ~ 66 %) = 1.570 MW

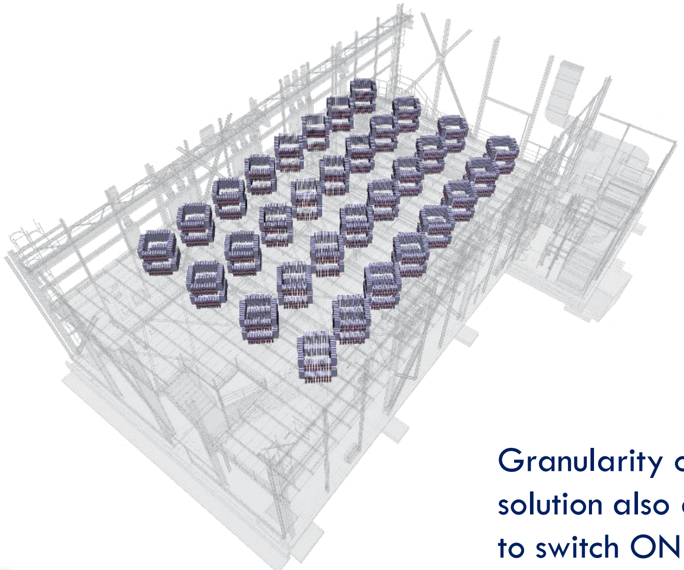
AC to DC (efficiency ~~~ 90 %~~ ~ 95 %) = 1,650 MW (615 kW to be dissipated)

Air cooling station (10 % of 615 kW ~ 62 kW) ~ + 31 kW = 1,681 MW

Water cooling station (90 % of 615 kW ~ 553 kW) ~ + 28 kW = 1,709 MW

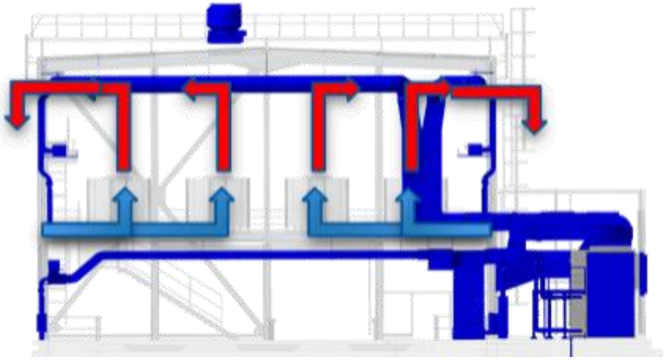
El. distribution (5 % of 1,709 MW) ~ + 86 kW = **1,8 MW** taken from the grid

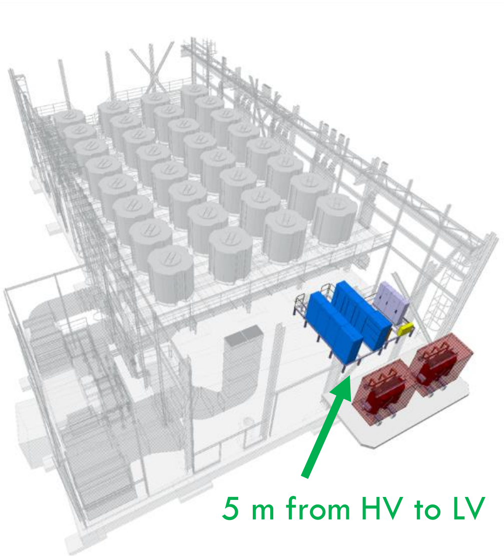
Overall efficiency **55,5 %** 41,9 %



Granularity of the SSPA solution also allows to switch ON the exact correct number of modules such that we operate as close as possible to the nominal point

Efficiency





Cavity = 1 MW

20 m coaxial line = + 1 % = 1.010 MW

NO Circulator = 1.010 MW

VHPCC 16:1 = + 0.1 dB = + 2,5 % = 1.035 MW

DC to RF (efficiency ~ 66 %) = 1.590 MW

AC to DC (efficiency ~ 95 %) = 1,625 MW (590 kW to be dissipated)

Air cooling station (10 % of ~~615 kW~~ 590 kW ~ 60 kW) ~ + 27 kW = 1,652 MW

Water cooling station (90 % of ~~615 kW~~ 590 kW ~ 530 kW) ~ + 24 kW = 1,676 MW

El. distribution (~~5 % of 1,709 MW~~ 3 % 1,676 MW) ~ + 50 kW =
1,7 MW taken from the grid

Overall efficiency **58,8 %**

41,9 %

Taking advantage of the natural chimney effect of the tower, having a well defined water station (variable speed), and shortening the LV cables will help reducing the remaining losses

Acquisition & operation costs

Technology * Including SSPA driver	Very rough estimates for a 100 kW CW 352 MHz RF system including RF power + Power Supplies + circulators + cooling + controls (lines not included)	Lifetime ** x 1000 hours	20 years Maintenance Tubes, HVPS, workshop	20 years Electrical bill 3000 hours / year 10 hours/day 6/7 days 50 weeks/year 0.15 € / kWh η = 45 %	Total 20 years
Tetrode	500 k€	20	350 k€	200 k€	1050 k€
IOT	600 k€	50	200 k€	200 k€	1000 k€
Klystron	750 k€	100	100 k€	200 k€	1050 k€
SSPA	850 k€	200	50 k€	200 k€	1100 k€
Circulator	75 k€	-	-		75 k€
Lines	1 k€/m	-	-		1 k€/m

* Construction of the infrastructure not included
SSPA option requires more volume

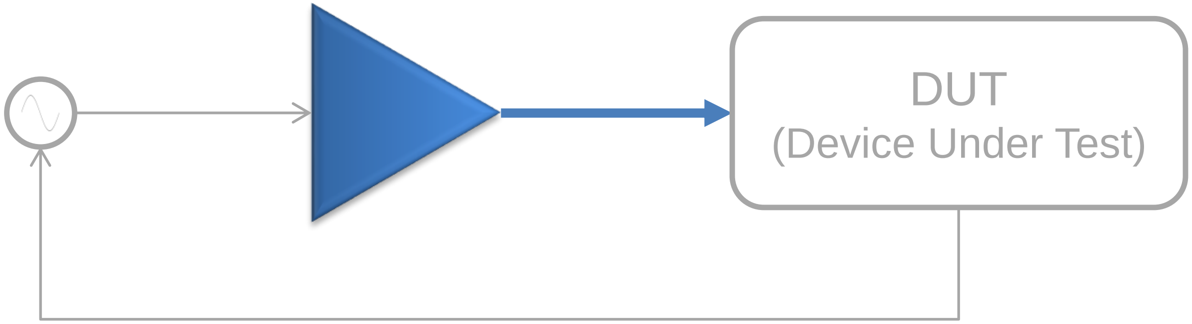
** Tubes need highly qualified HV specialists for maintenance

Conclusion

We plan to launch (or we even already launched) R&D on

- **Combining systems**, this will reduce foot print and increase power density; plenty of ideas, cavity combiners, waveguide progressive combiners, RF transmission combiners, Gysel combiners, multi layers waveguides combiners)
- **Availability**, including granularity, hot swappable modules, embedded spares
- **Efficiency**, next key parameter, must be grid AC to RF for fair comparison
- **Low cost circulators**, at small power level ~kW and high power level ~MW
- **Cost optimization**, asking the correct architecture
- **Mass production optimization**, asking for the correct parameters
- **Close follow-up** of new technologies available in large series production (SiC, GaN, 2D transistors…).

RF powering



This was a quick overview of the RF powering, for detailed explanations, please refer to specialized CAS on RF

2010 (468 pages) https://cas.web.cern.ch/schools/ebeltoft-2010
2000 (486 pages) CERN-2005-003
1992 (596 pages) http://cds.cern.ch/record/211448/files/CERN-92-03-V-2.pdf

References

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

HÜTTE des ingenieurs taschenbuch (Berlin 1955 edition)

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

Online

- Thales, e2v, CPI, L-3 communications, Toshiba
- NXP, Freescale

They did not know it was impossible,
so they did it !

Mark Twain