The CERN Accelerator School

Accelerators for Medical applications

RF powering

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RF Powering

W → kW → MW

€ → k€ → M€

(Very important for all projects, particularly true for medical applications)

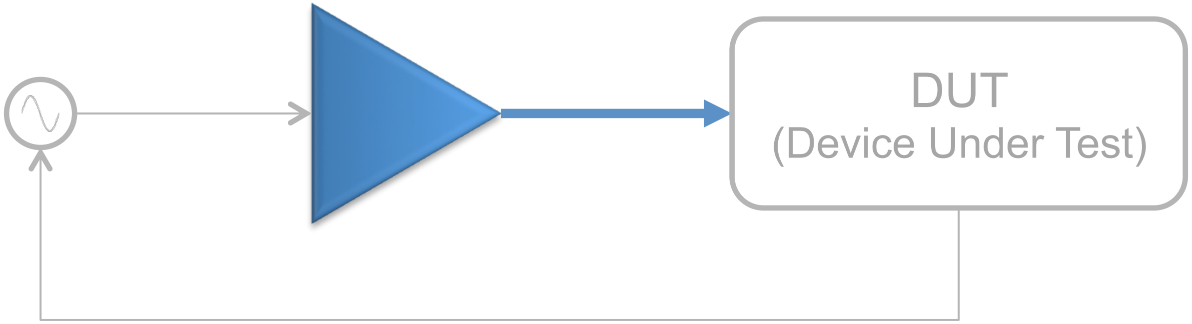
Outlook

RF power basics

RF power amplifiers

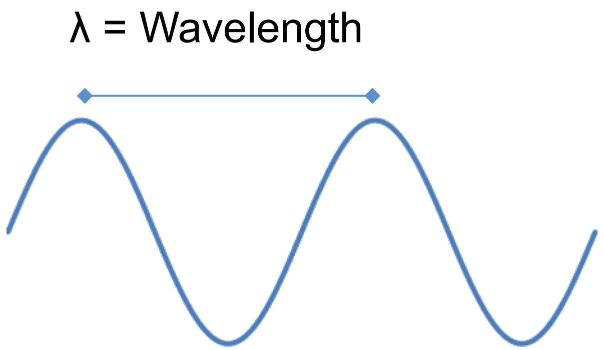
RF power lines

RF Power basics



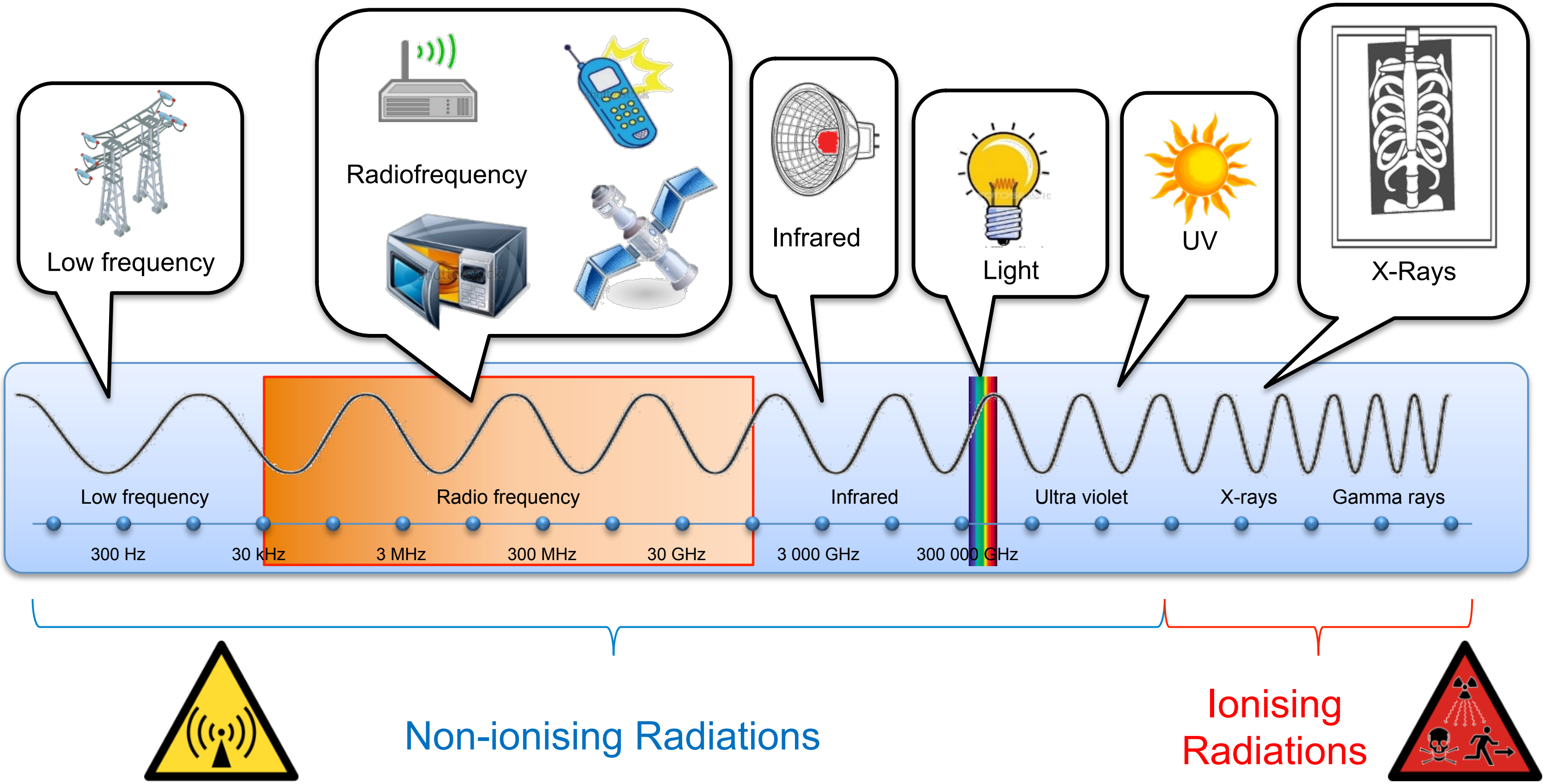
Wavelength, frequency

$\lambda = c/f\,\sqrt{\varepsilon}$ ↔ $f = c/\lambda\,\sqrt{\varepsilon}$



λ = *wavelength in meters (m)*
c = *velocity of light (m/s) – (~ 300,000,000 m/s)*
f = *frequency in hertz (Hz)*
ε = *dielectric constant of the propagation medium (~ 1.0 in air at 20^{0} C)*

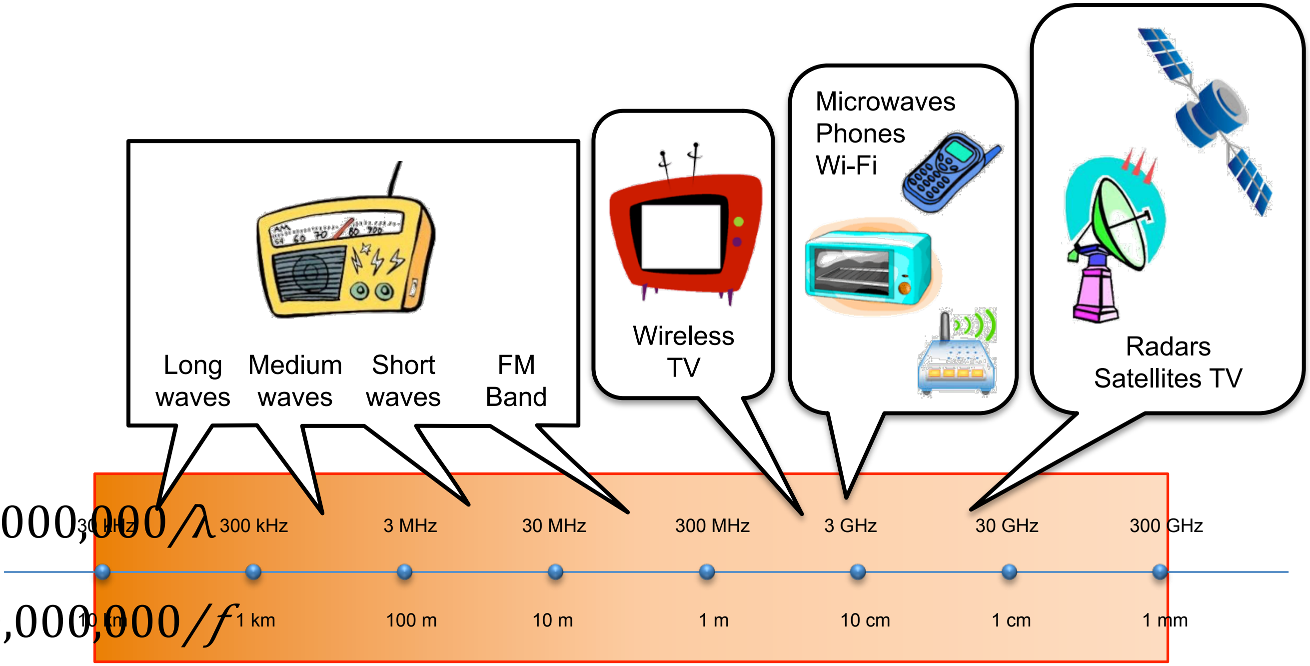
Electromagnetic waves



Non-ionising Radiations

Ionising
Radiations

Radiofrequency waves



$frequency\ f = 300{,}000{,}000 / \lambda$

$wavelength\ \lambda = 300{,}000{,}000 / f$

With $\varepsilon = \sim 1.0$ *(dielectric constant of air at* $20^{0}\,C$*)*

Decibel (dB)

$$dBm = 10\ Log10\ (PmW)$$

$$dB = 10\ Log10\ (P1/P2)$$

$$dB = 20\ Log10\ (V1/V2)$$

$$dBV = 20\ Log10\ (VVrms)$$

$$dB\mu V = 20\ Log10\ (V\mu Vrms)$$

$$dBc = 10\ Log10\ (Pcarrier/Psignal)$$

dBm, W

$xdBm = 10\ Log10\ (PmW) \quad \leftrightarrow \quad PmW = 10\ (xdBm/10)$

0 dBm = 1 mW

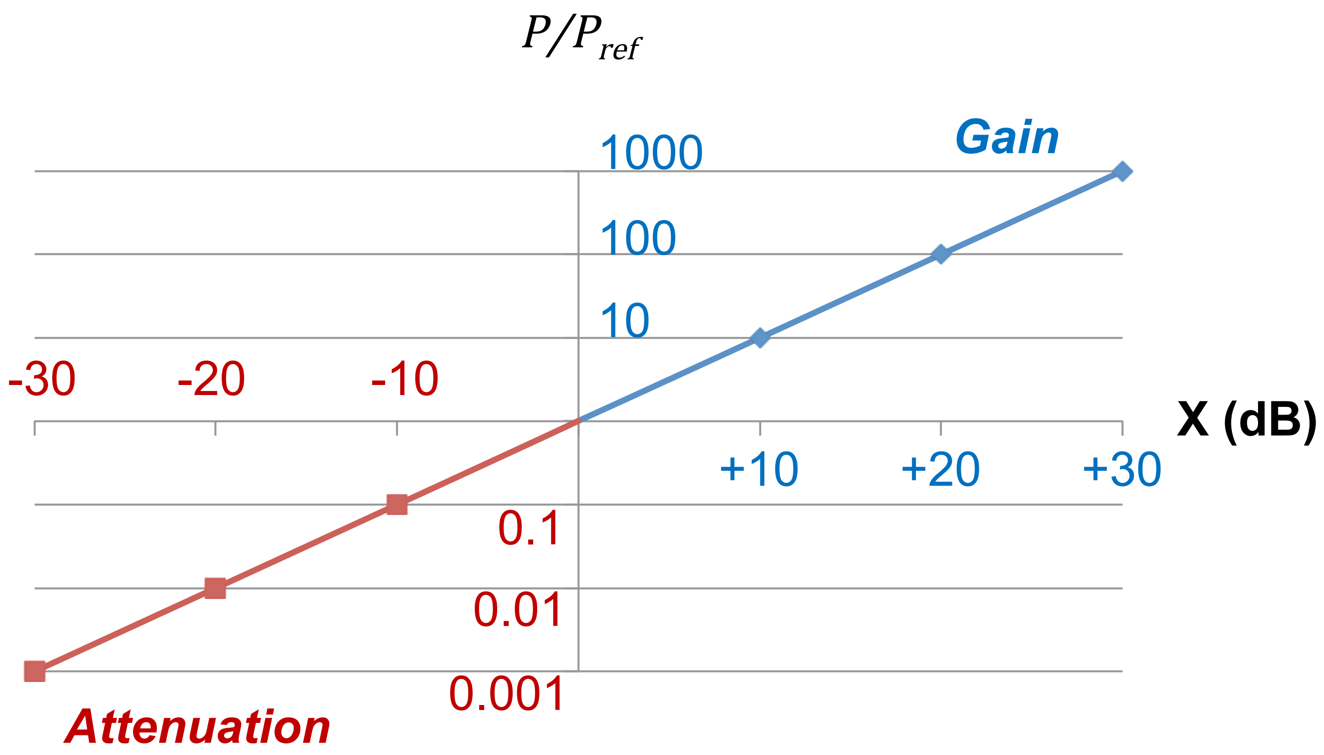
30 dBm = 1 W

60 dBm = 1 kW

90 dBm = 1 MW

dB, Power ratio

$$xdB = 10\ Log10\ (P/Pref) \quad \leftrightarrow \quad P/Pref = 10\ (xdB/10)$$

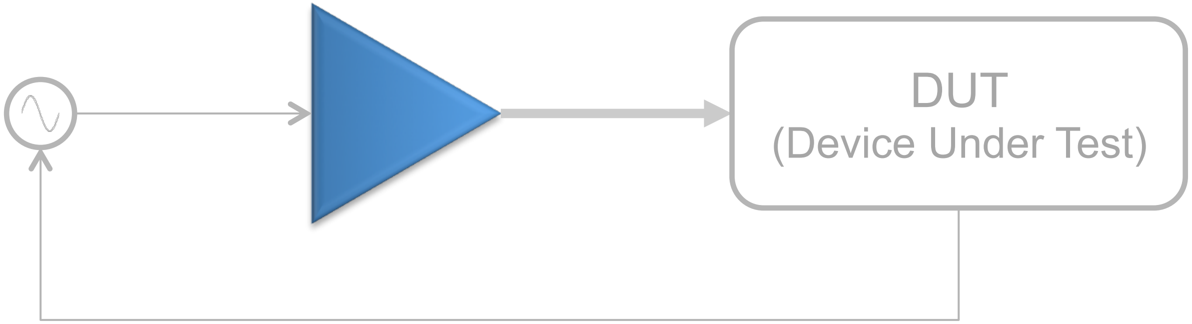


dB, Power ratio

$$xdB = 10\ Log10\ (P/Pref) \quad \leftrightarrow \quad P/Pref = 10\ (xdB/10)$$

x (dB)	P/P_{ref}	
+ 0.1	1.023	+ 2.5%
+ 0.5	1.122	+ 12%
+ 1	1.259	+ 25%
+ 3	1.995	2
- 0.1	0.977	- 2.5%
- 0.5	0.891	- 11%
- 1	0.794	- 20%
- 3	0.501	0.5

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

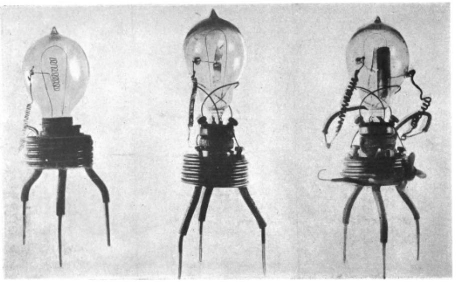
Magnetrons

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)

Grid tubes

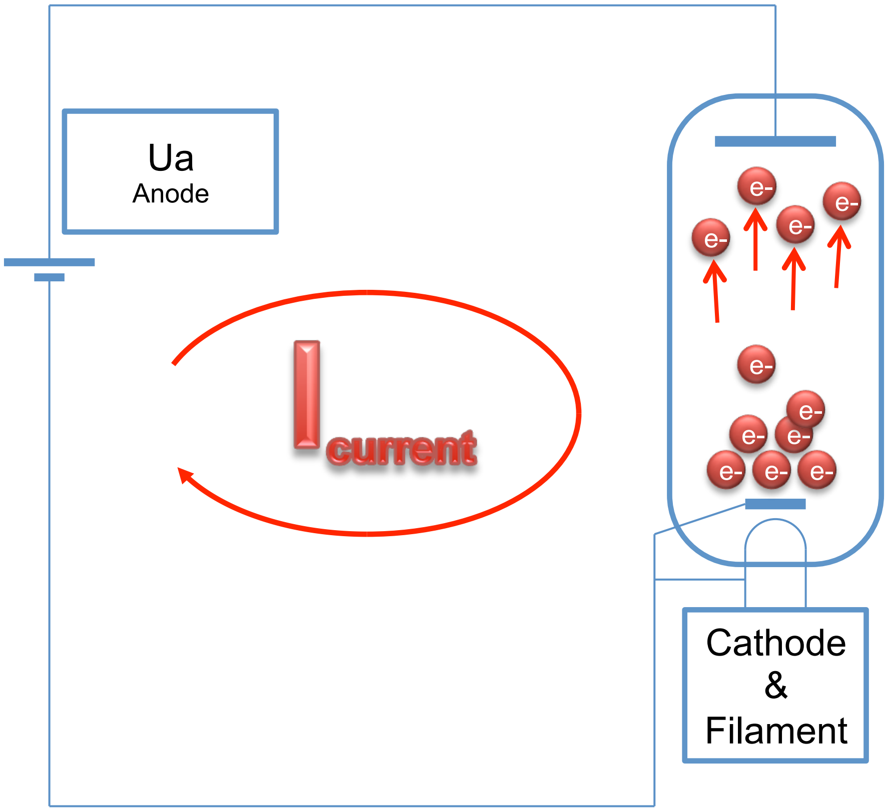
1904	Diode, John Ambrose Fleming
1906	Audion (first triode), Lee de Forest
1912	Triode as amplifier, Fritz Lowenstein
1913	Triode ‘higher vacuum’, Harold Arnold
1915	first transcontinental telephone line, Bell
1916	***Tetrode***, Walter Schottky
1926	Pentode, Bernardus Tellegen
1994	Diacrode, Thales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



The first diode prototype
Fleming Diode, 1904

Thales TH 628 diacrode,
1998

Essentials of grid tube



Vacuum tube

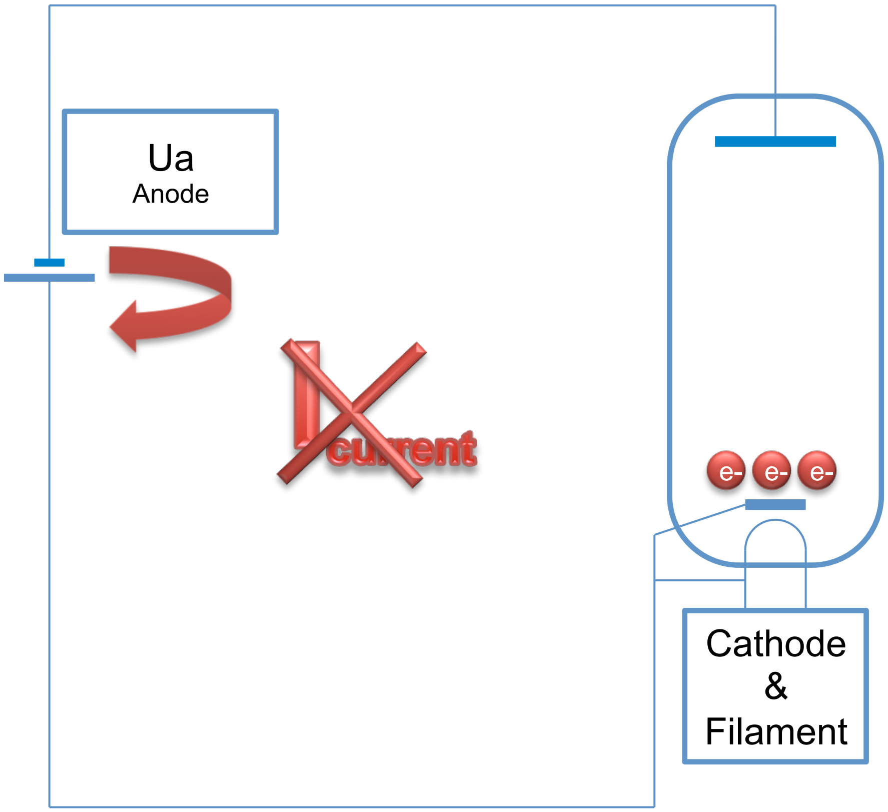
Heater + Cathode

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

Anode

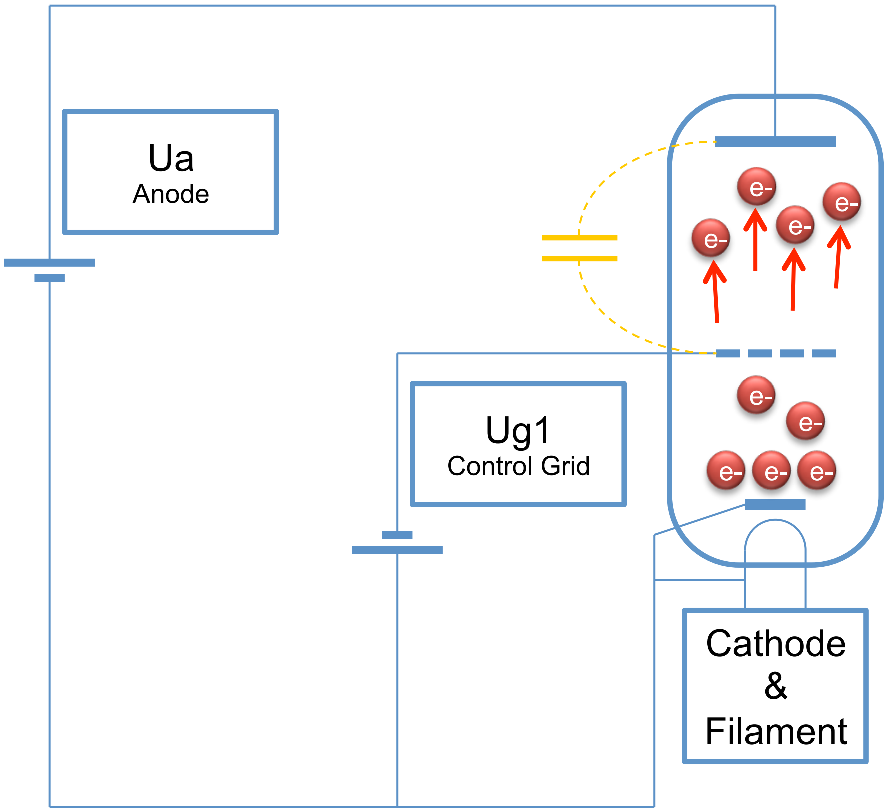
Diode

Essentials of grid tube



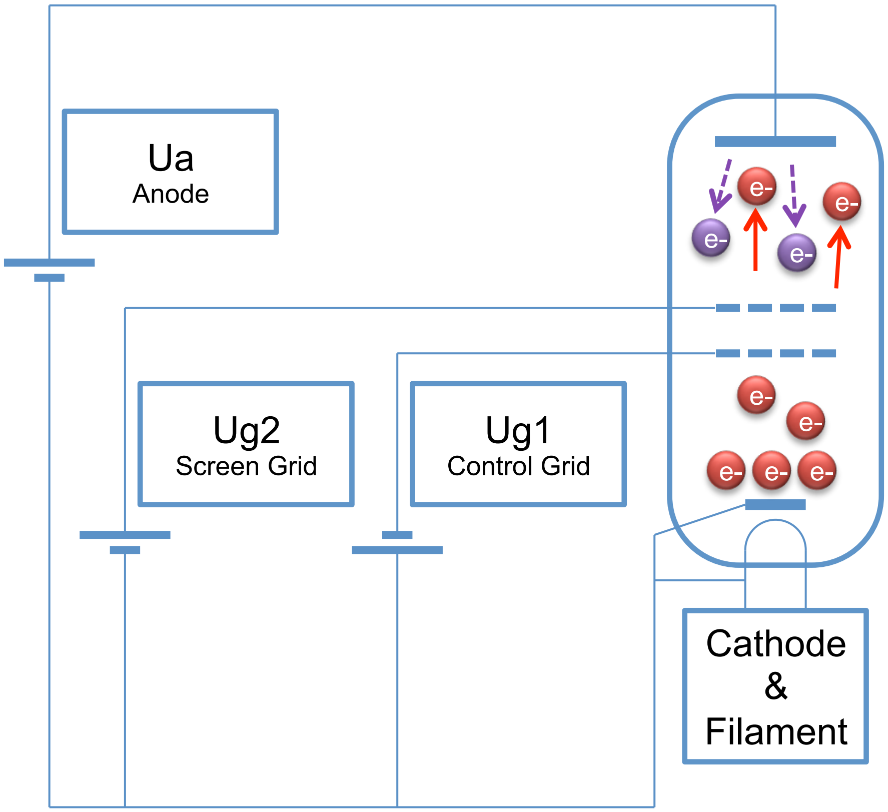
- Vacuum tube
- Heater + Cathode
  - Heated cathode
    - Coated metal, carbides, borides,…
  - thermionic emission
  - Electron cloud
- Anode
- Diode

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

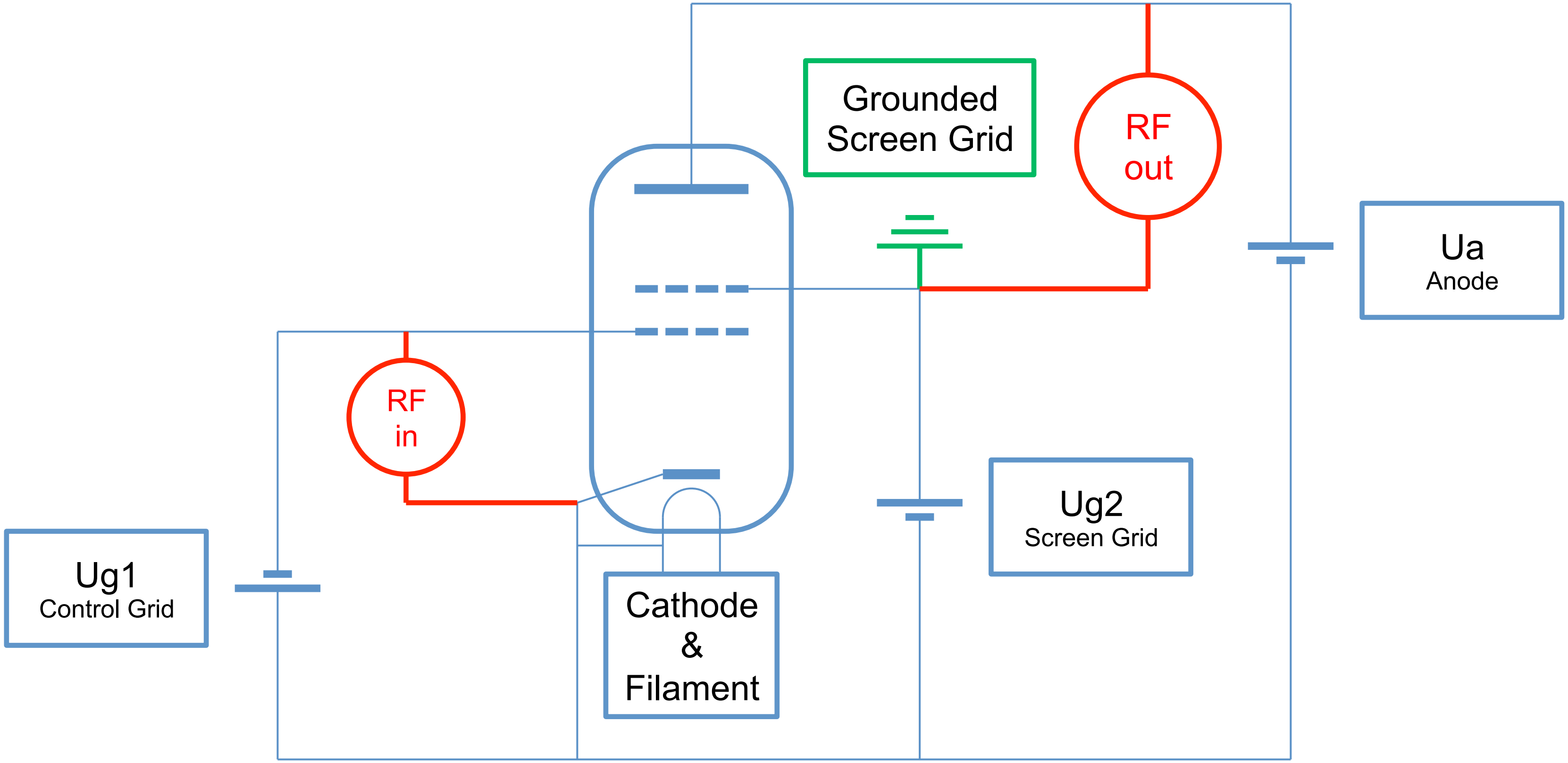


Tetrode

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

Tetrode

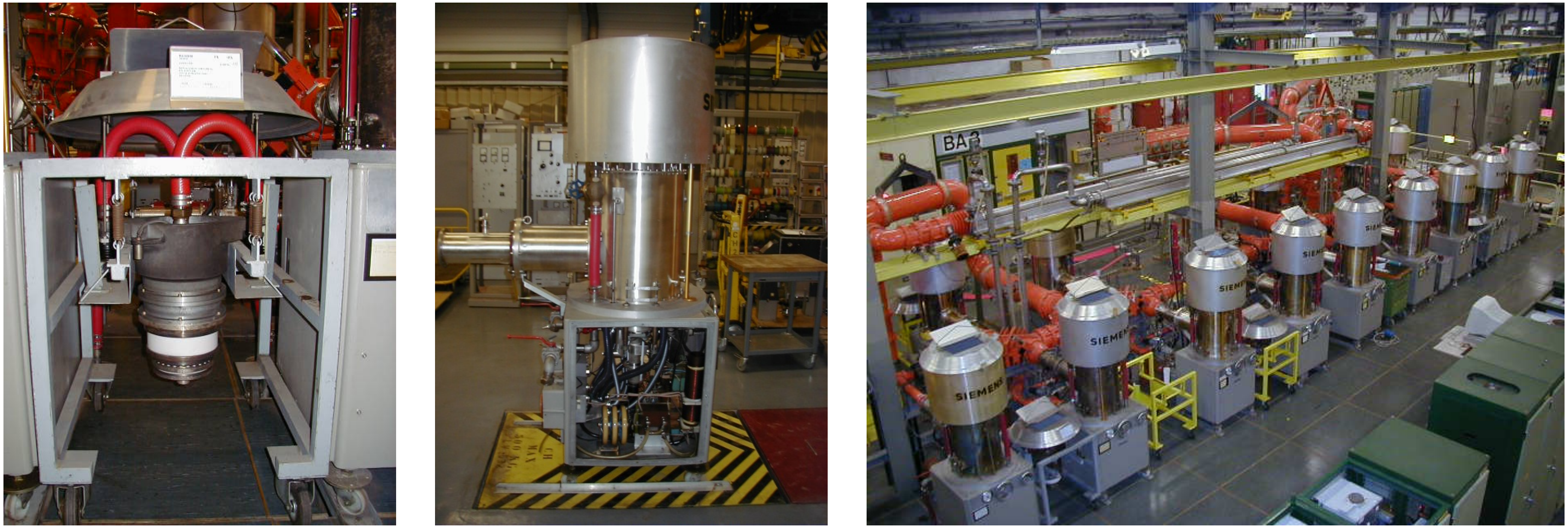
RS 2004 CERN SPS example



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

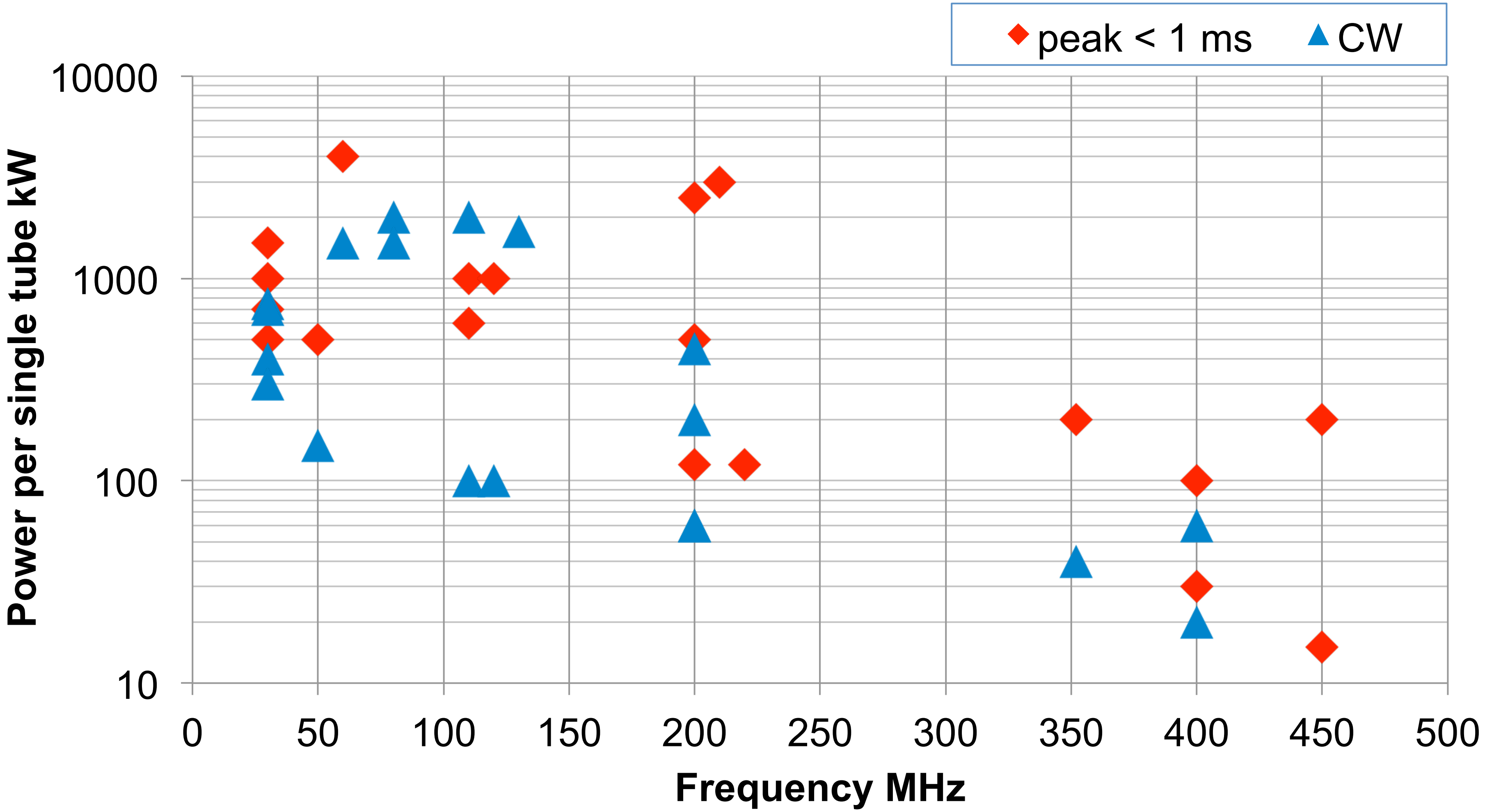
Tetrode

RS 2004 CERN SPS amplifier @ 200 MHz



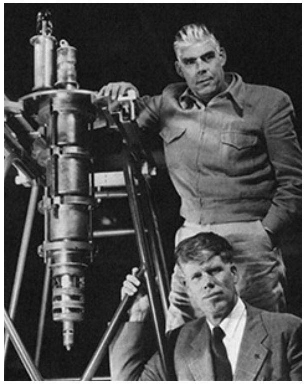
CERN SPS, RS 2004 Tetrode, Trolley (single amplifier), and transmitter (combination of amplifiers)
Two transmitters of eight tubes delivering 2 x 1 MW @ 200 MHz, into operation since 1976

Tetrodes & Diacrodes available from industry



Linear beam tubes

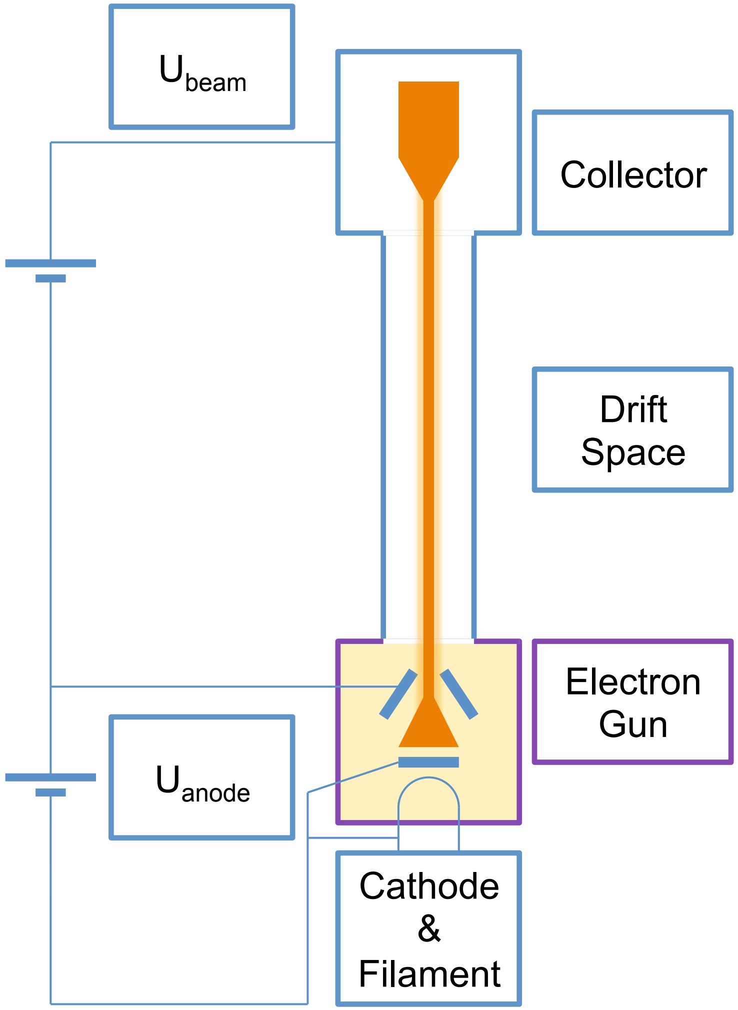
1937	Klystron, Russell & Sigurd Variant
1938	IOT, Andrew V. Haeff
1939	Reflex klystron, Robert Sutton
1940	Few commercial IOT
1941	Magnetron, Randall & Boot
1945	Helix Travelling Wave Tube (TWT), Kompfner
1948	***Multi MW klystron***
1959	Gyrotron, Twiss & Schneider
1963	Multi Beam Klystron, Zusmanovsky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

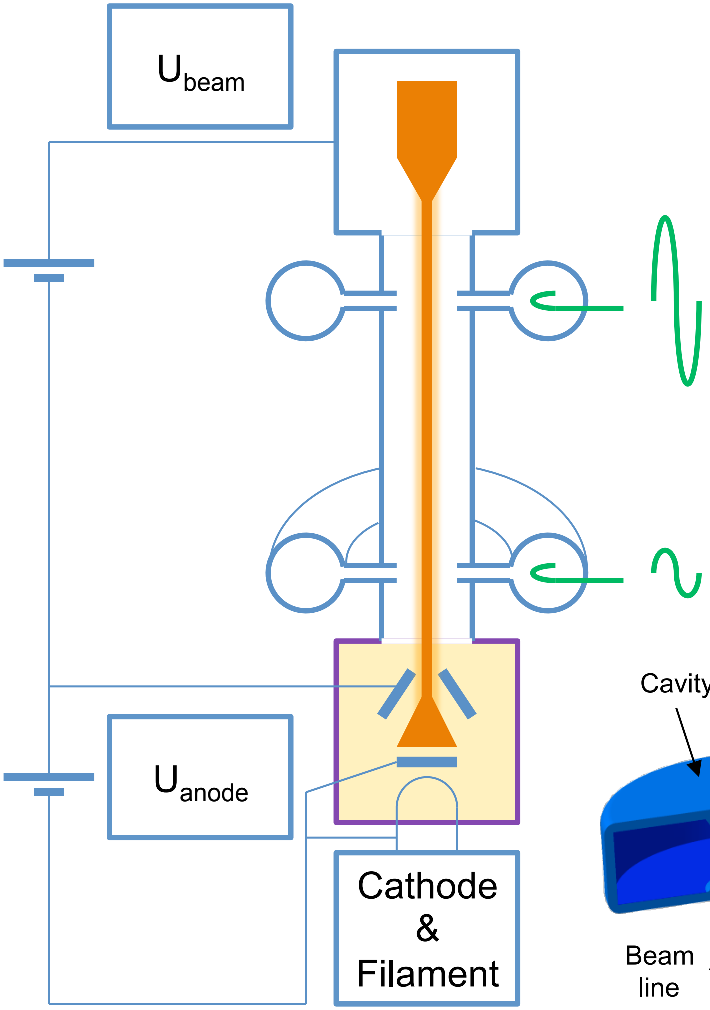
Electron beam

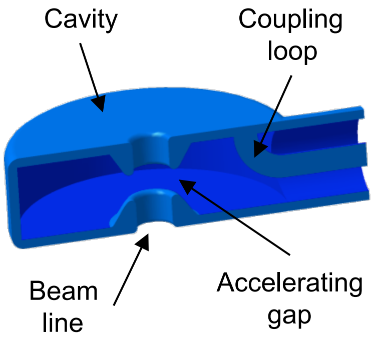
Drift space

Collector

e- constant speed until the collector

Essentials of klystron





Cavity resonators

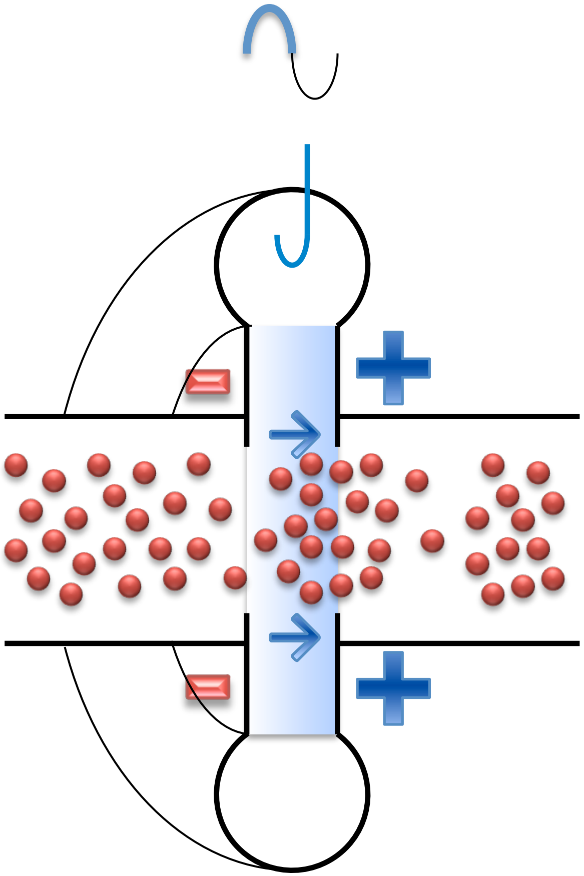
RF input cavity (Buncher)

- 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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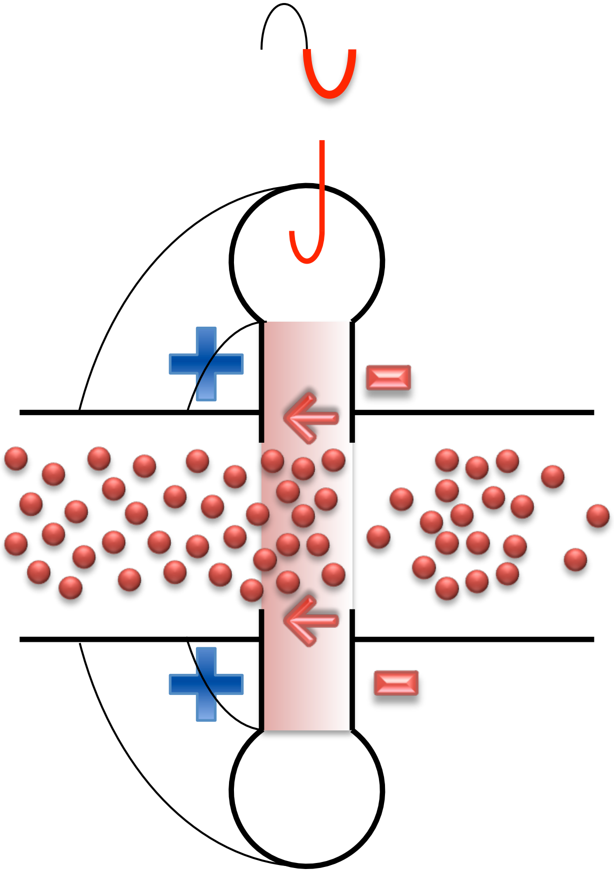

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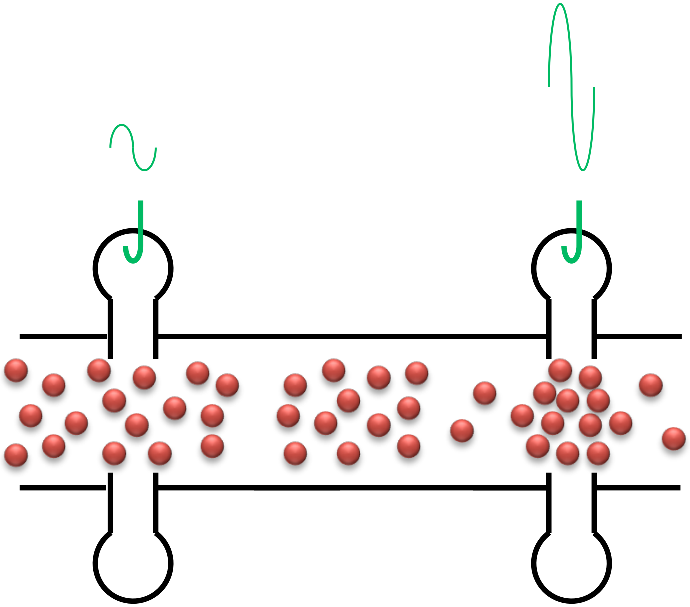

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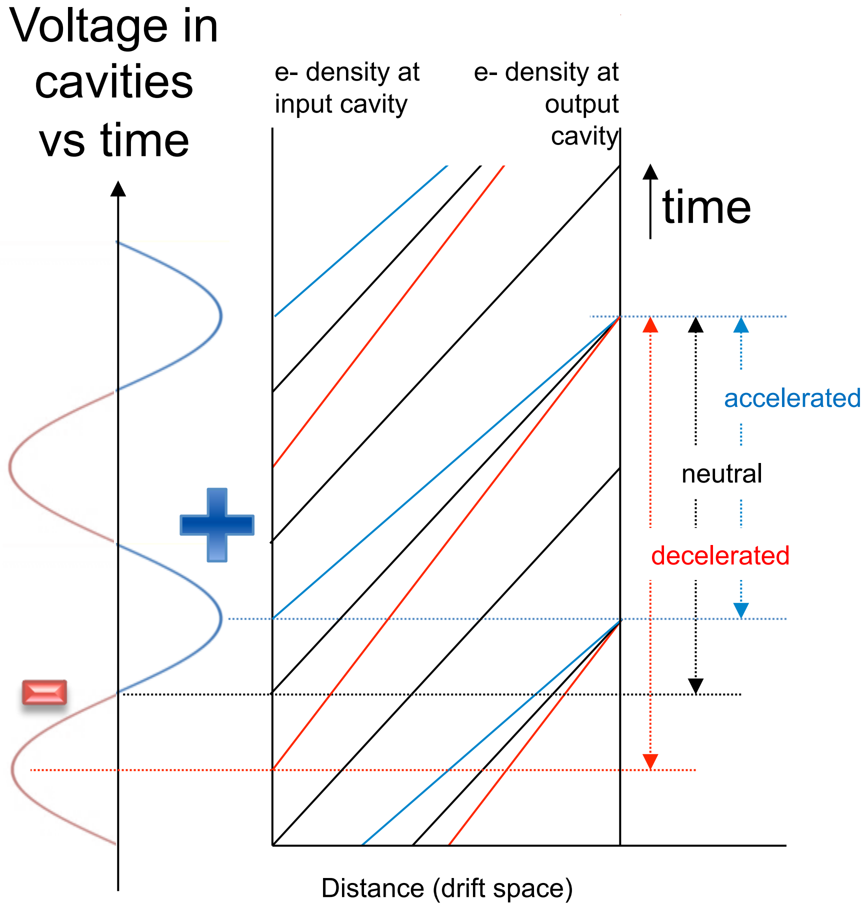
  - Kinetic energy converted into voltage and extracted

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)

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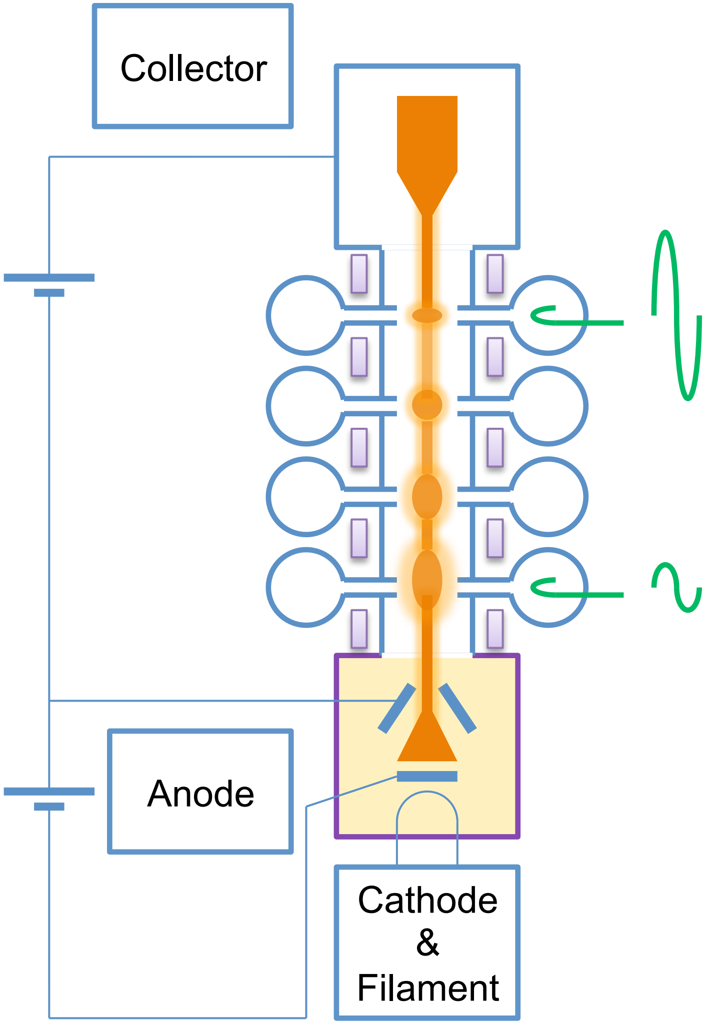
Essentials of klystron



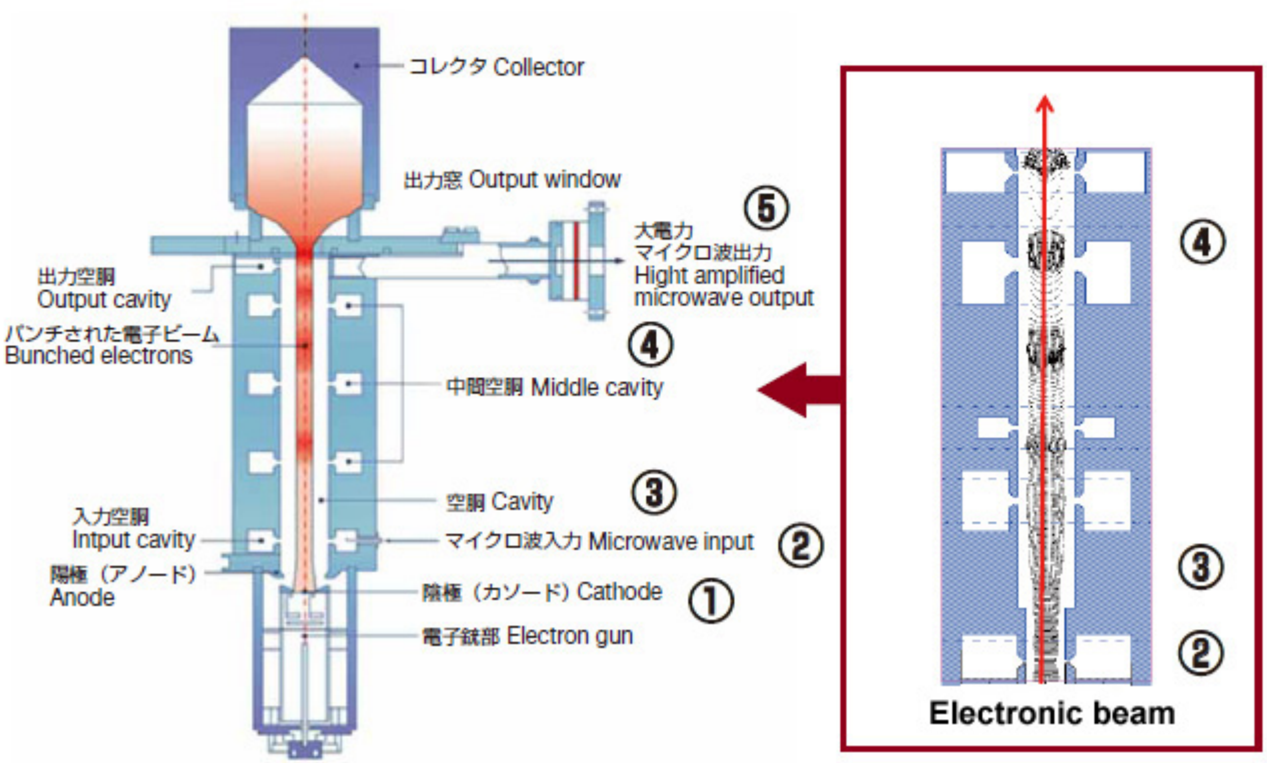
Additional bunching cavities

- 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

Essentials of klystron



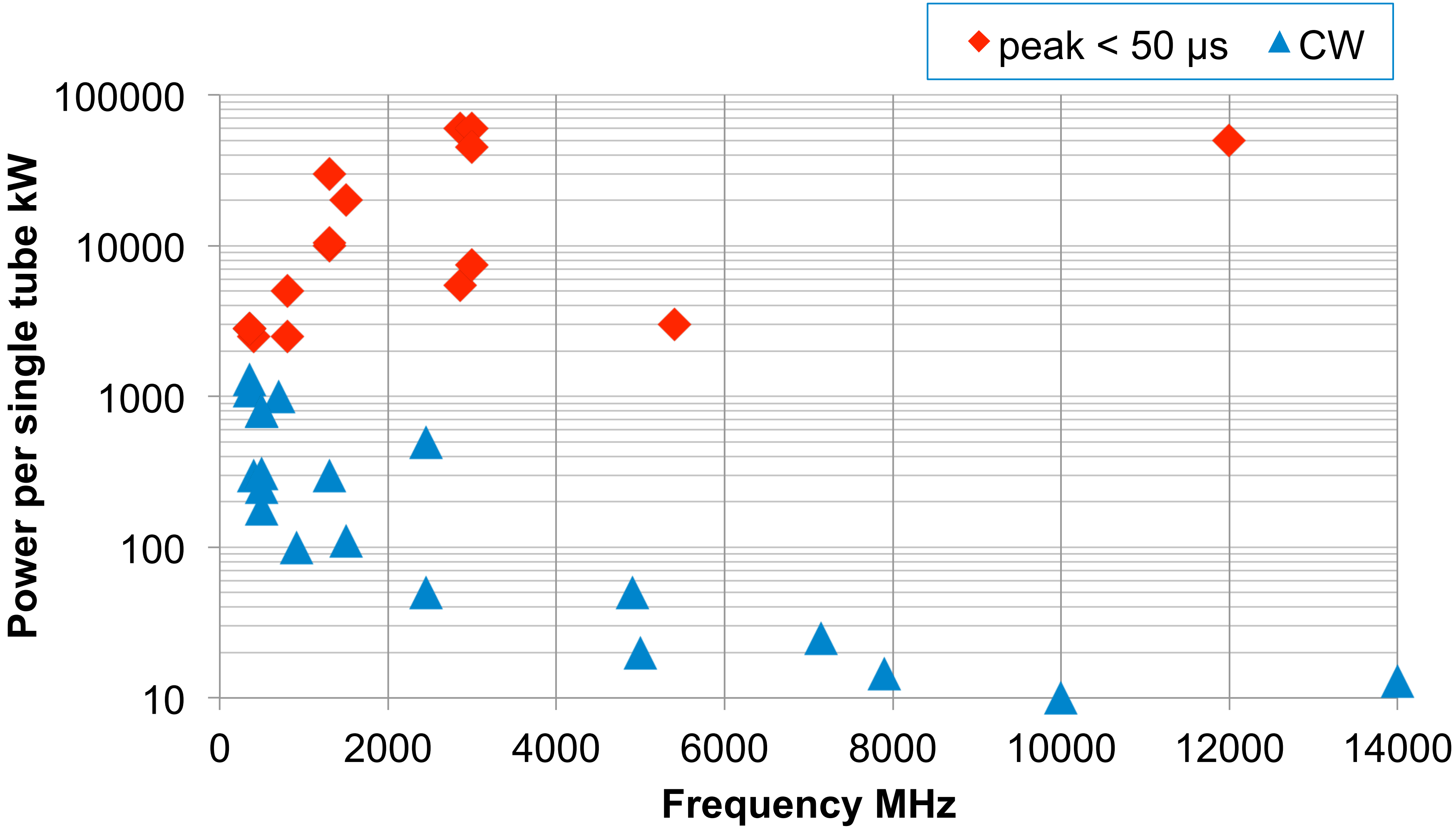
http://www.toshiba-tetd.co.jp/eng/tech/klystron.htm

Klystron

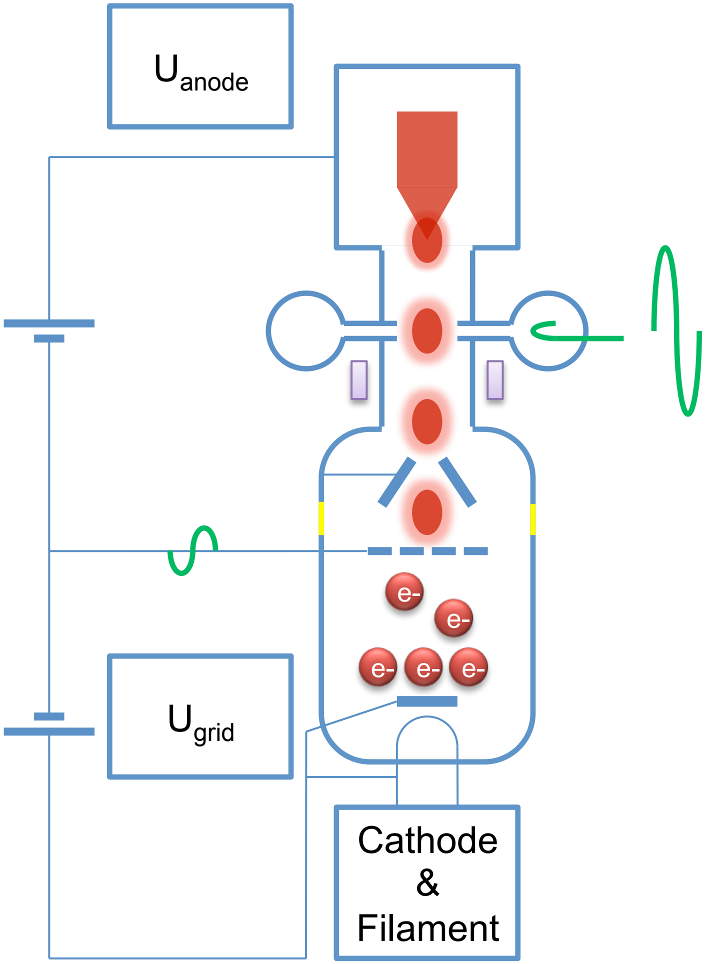
TH 2167 CERN LHC @ 400 MHz

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



Essentials of IOT



IOT density modulation
  - converts the kinetic energy into radio frequency power

Vacuum tube

Triode input
  - Thermionic cathode
  - Grid modulates e- emission

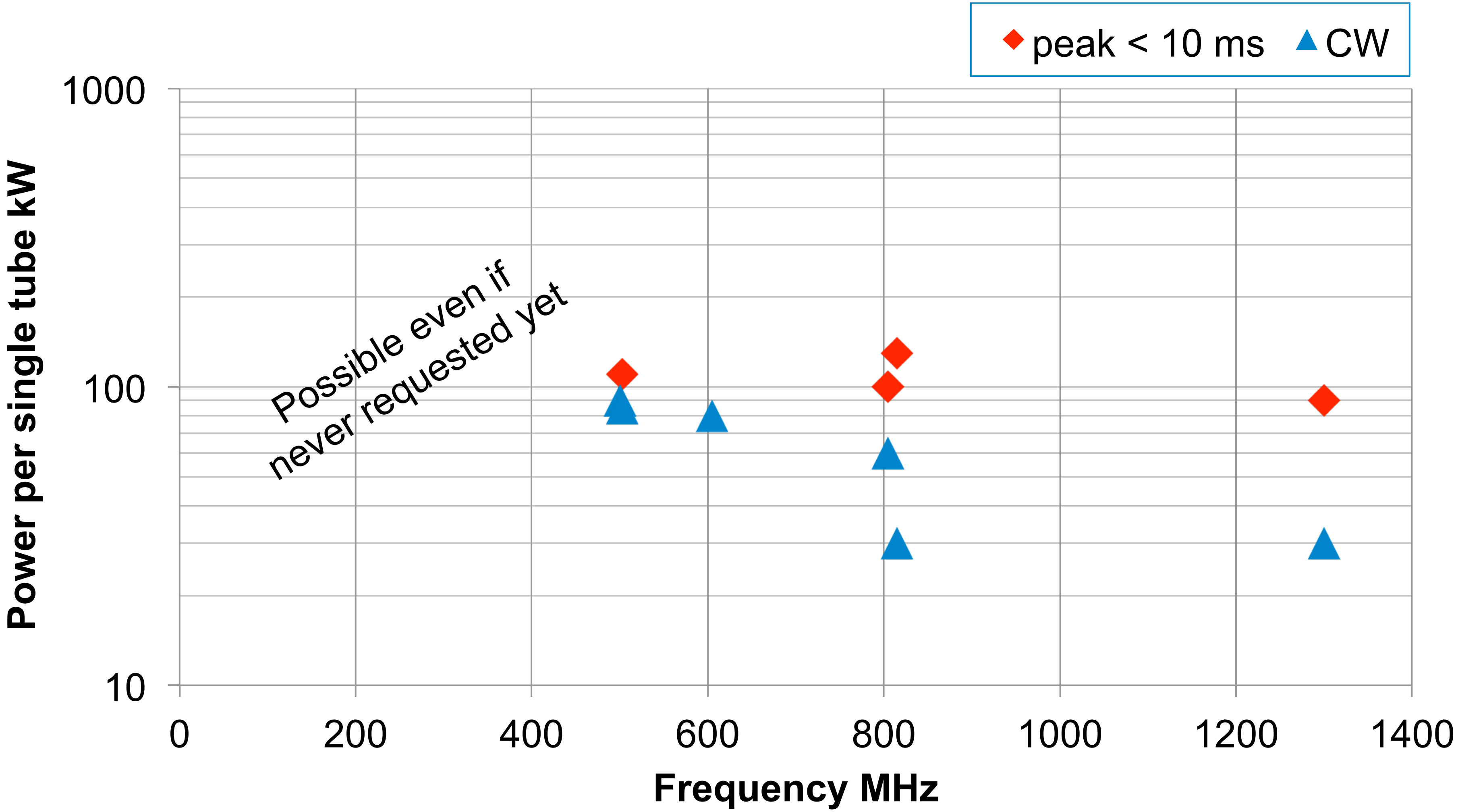
Klystron output
  - Anode accelerates e- buckets
  - Short drift tube & magnets
  - Catcher cavity
  - Collector

IOT

TH 795 CERN SPS @ 800 MHz

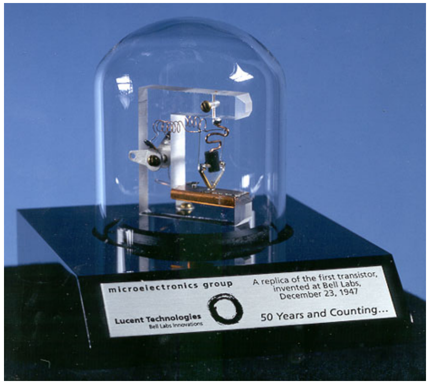
CERN SPS, TH 795 IOT, Trolley (single amplifier), and transmitter (combination of amplifiers)
Two transmitters of four tubes delivering 2 x 240 kW @ 801 MHz, into operation since 2014

IOT available from industry

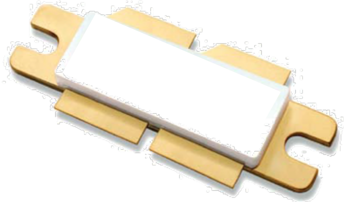


Transistor for RF power

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

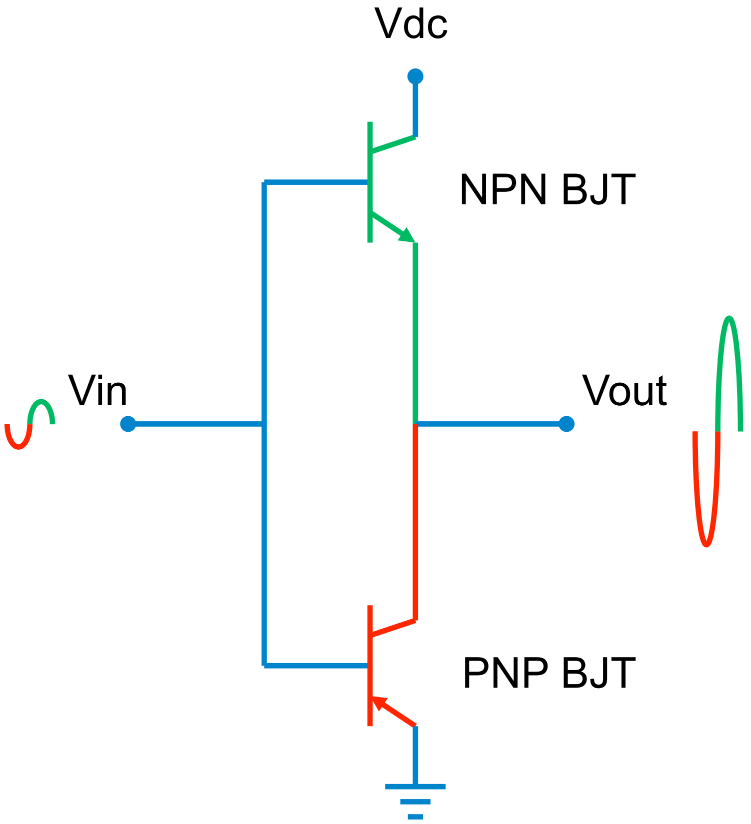


First transistor invented at BELL labs in 1947



XXI century LDMOS

Essentials of RF transistor

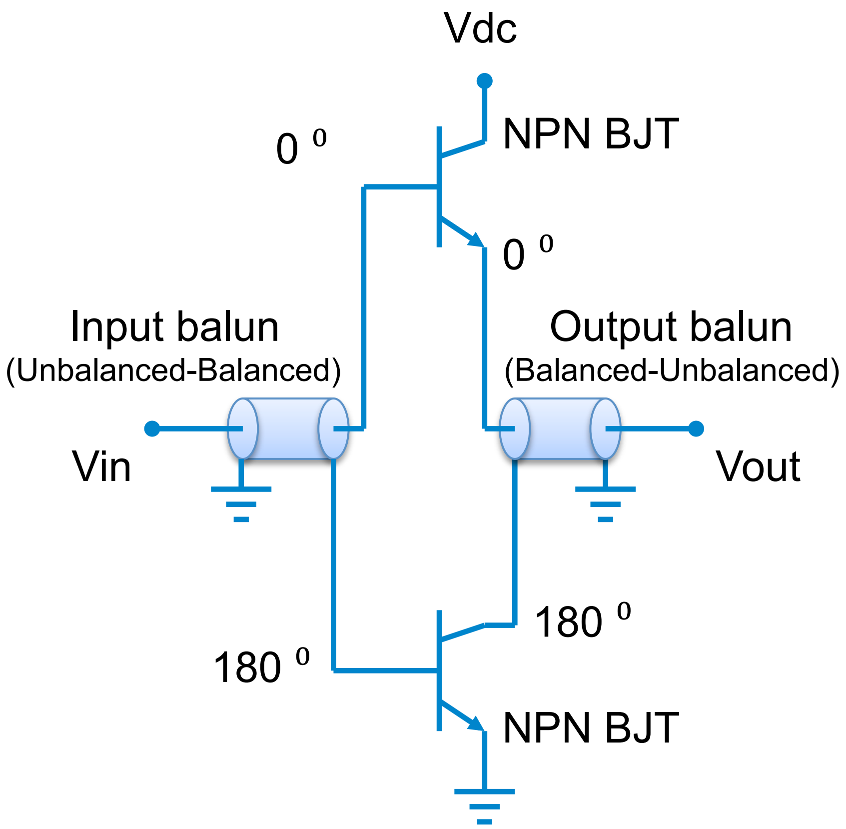


In a push-pull circuit the RF signal is applied to two devices

- 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



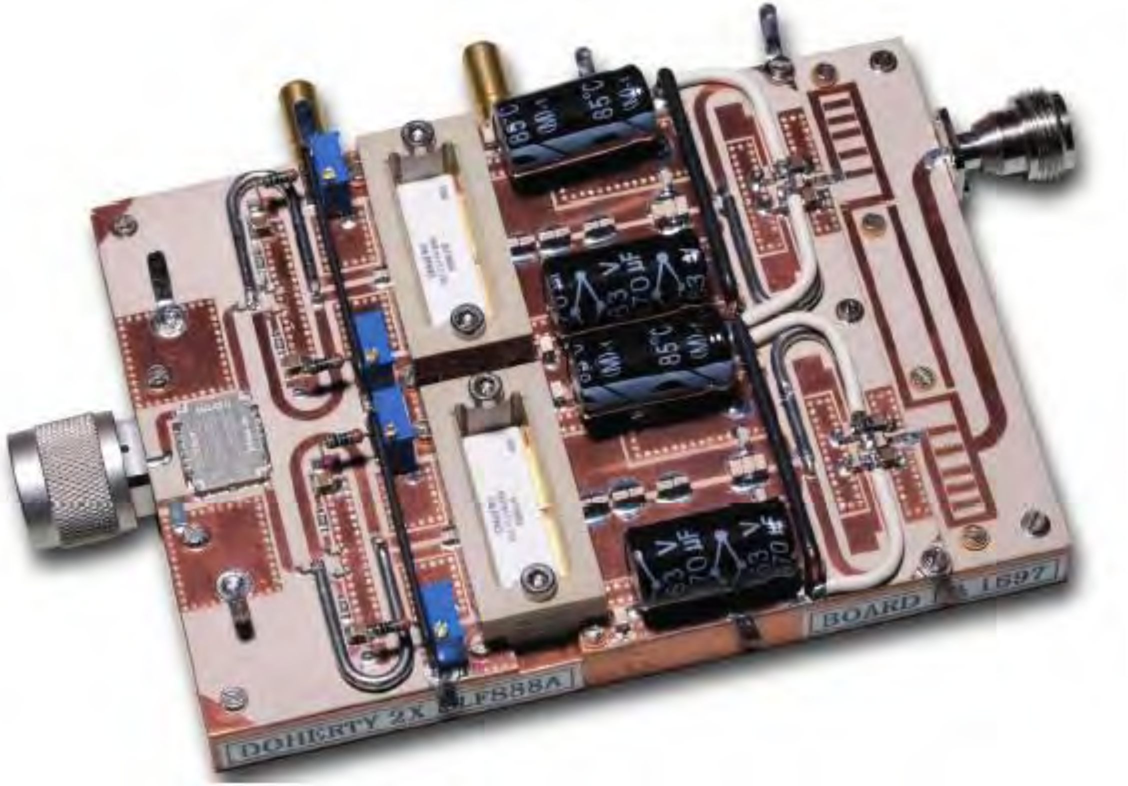
Another push-pull configuration is to use a balun (balanced-unbalanced)

- 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

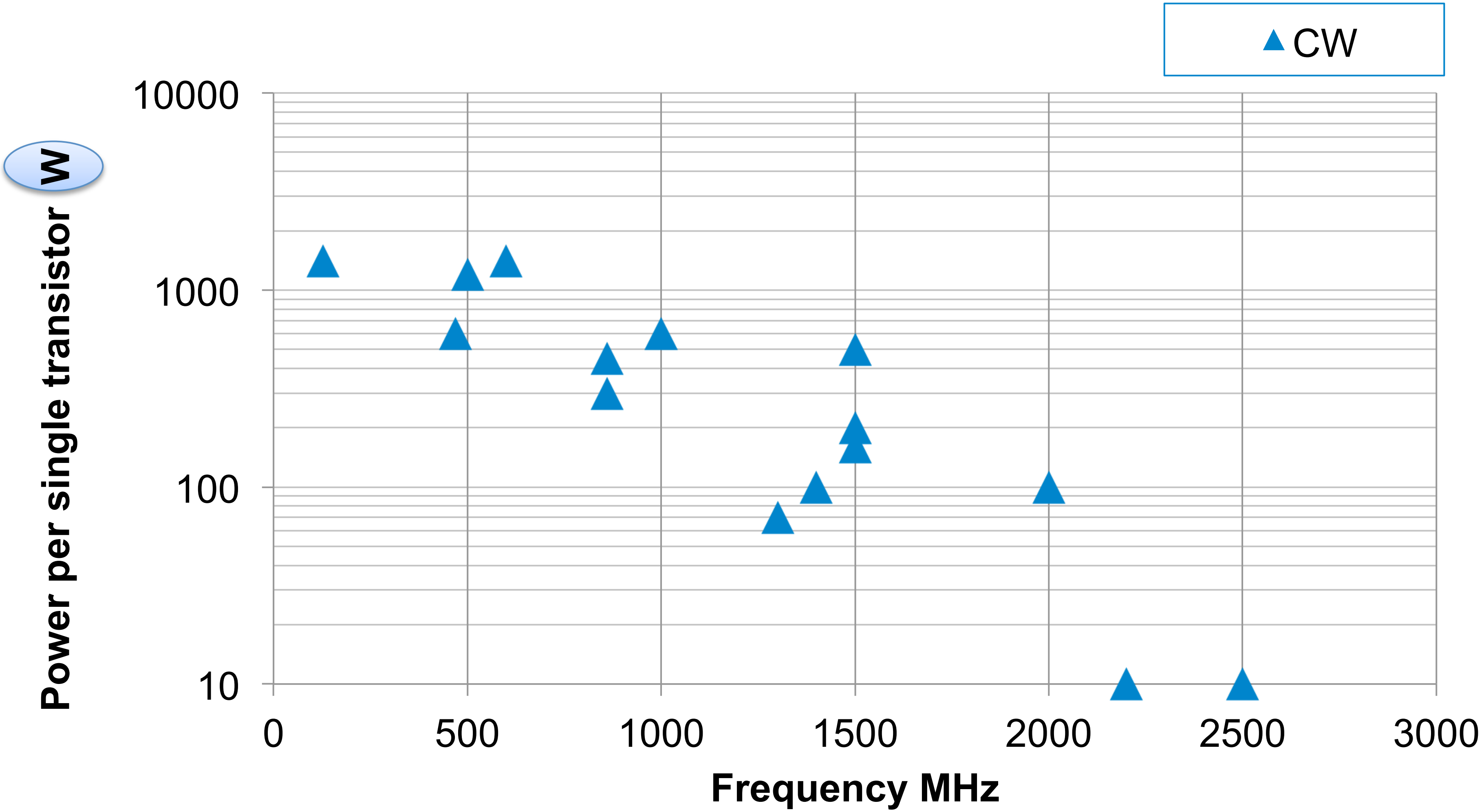
This configuration is easier to manufacture since only one type of device is required

Essentials of RF transistor



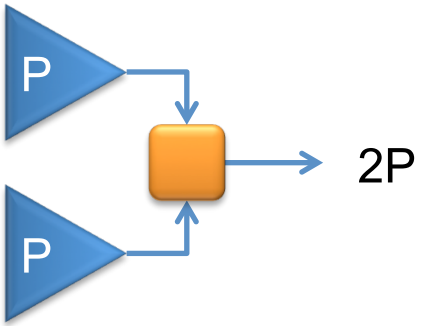
NXP Semiconductors AN11325
2-way Doherty amplifier with BLF888A

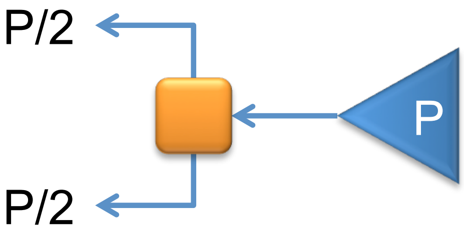
Transistors available from industry



Combiners & Splitters

RF power combiners and RF power splitters are the same items





Resistive power splitters & Combiners

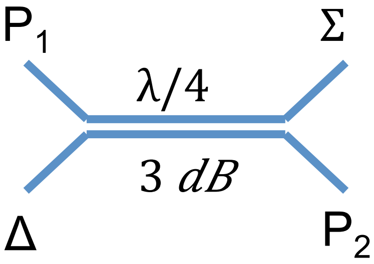
- Cheap and easy to build
- Use of resistor to maintain the impedance
- Power limitation and losses induces by the resistors (→ not used in high power)

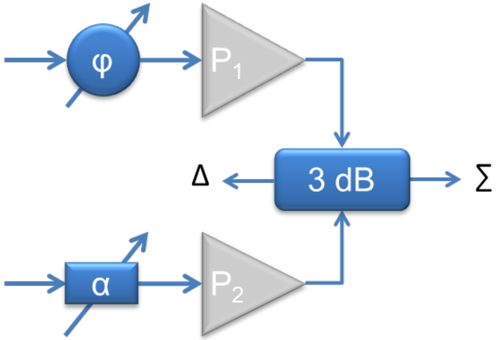
Hybrid power splitters & Combiners

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

Combiners & Splitters

3 dB phase combiner





With correct input phases

$$\Sigma = P1 + P2/2 + \sqrt{P1P2}$$

$$\Delta = P1 + P2/2 - \sqrt{P1P2}$$

Correctly adjusting the phase and the gain, P1 = P2 = P

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

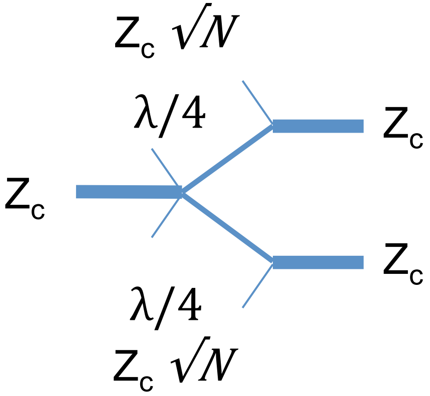
$$\Delta = P + P/2 - \sqrt{PP} = 0$$

Combiners & Splitters

CERN SPS 64 to 1 combiner @ 200 MHz

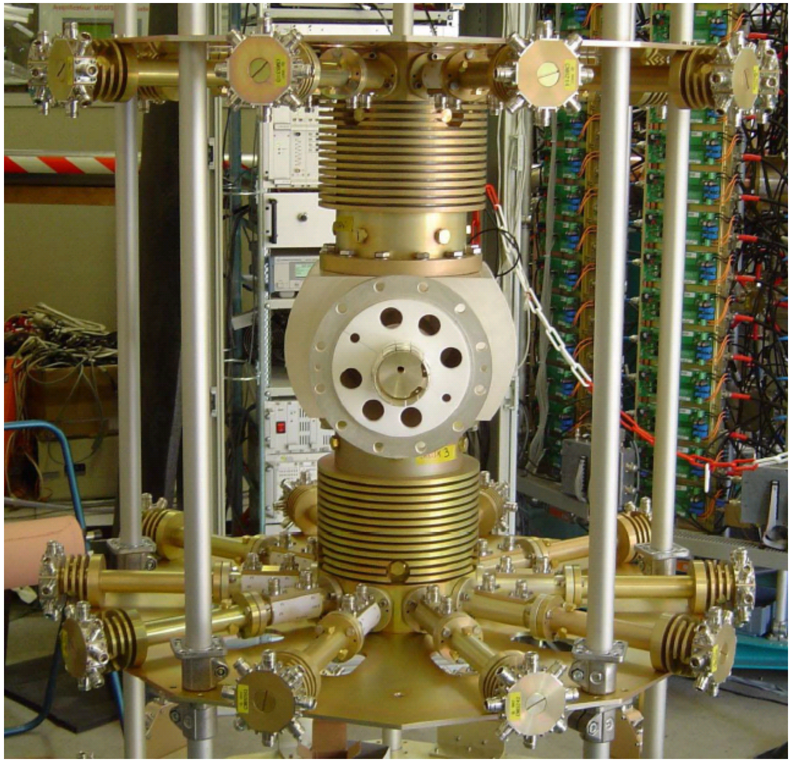
Combiners & Splitters

Low loss T-Junction



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

We have a N-ways splitter



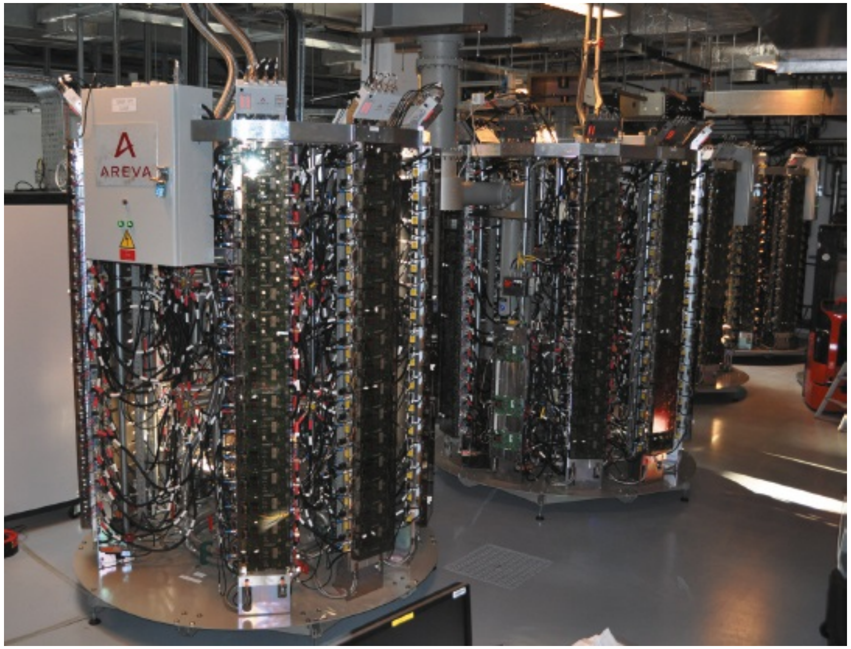
SOLEIL SYNCHROTRON

160 to 1 @ 352 MHz
T-junction combiner

Transistors

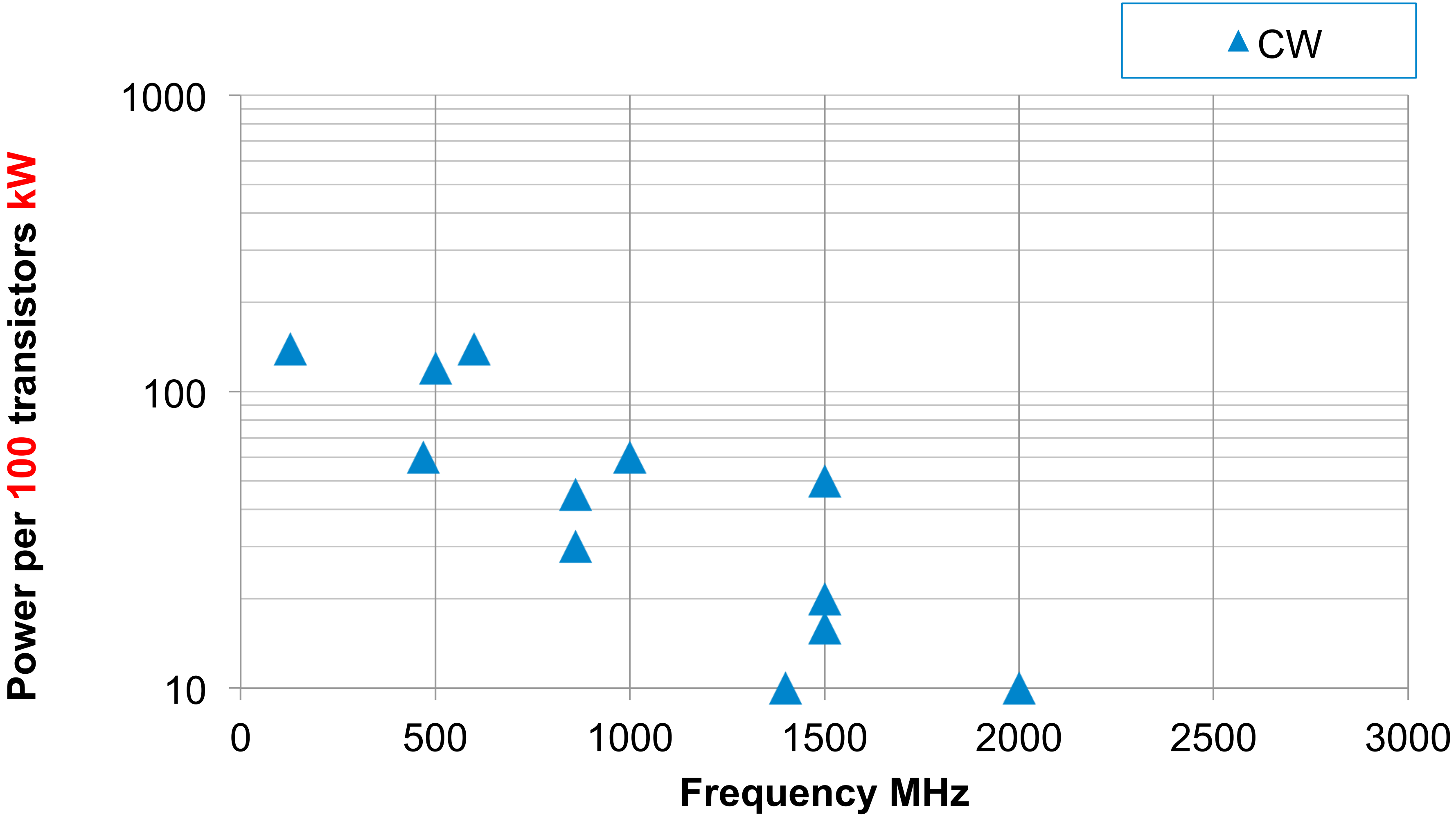
SOLEIL @ 352 MHz and ESRF @ 352 MHz

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

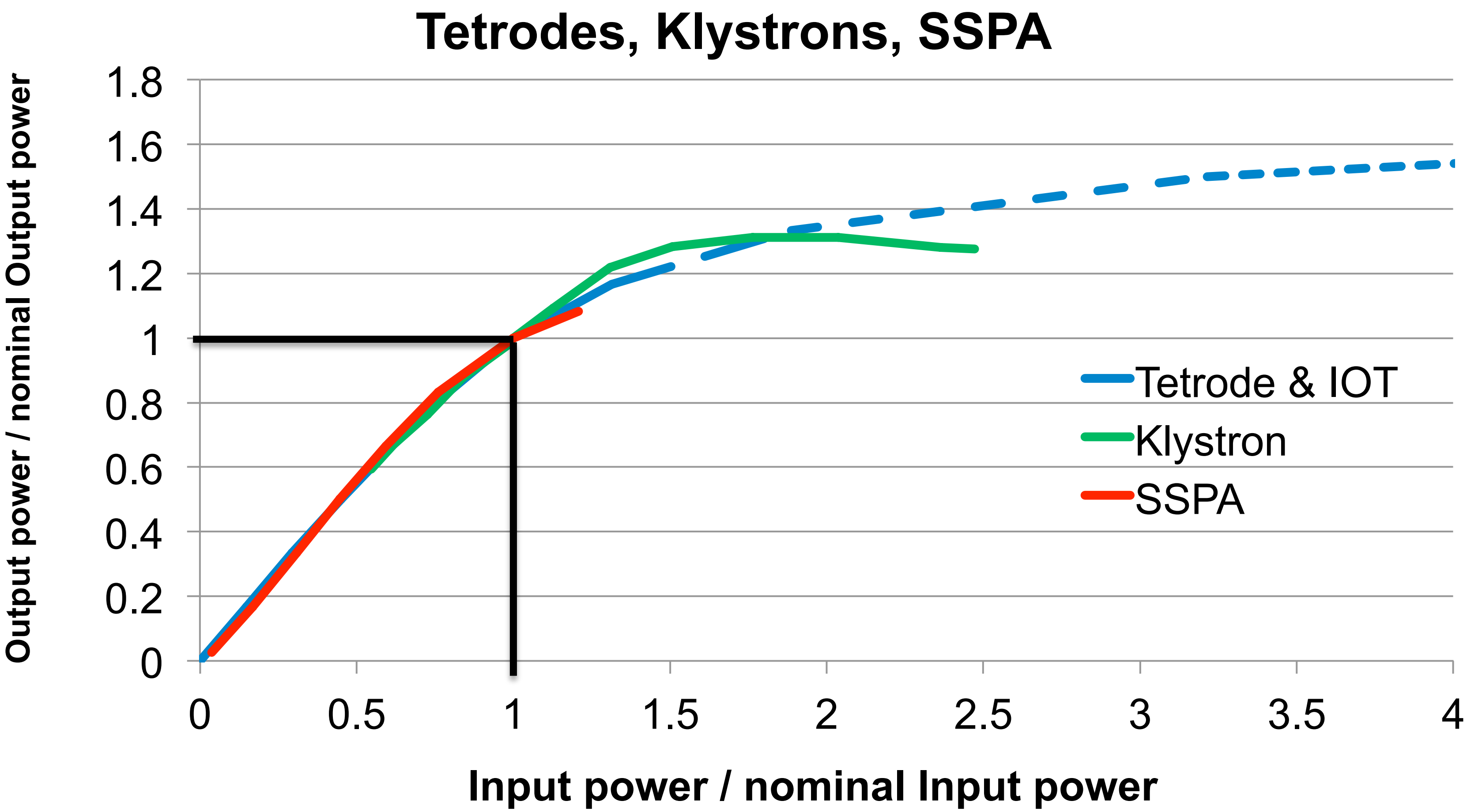


ESRF four 150 kW @ 352 MHz
solid state amplifiers (2012)

Transistors available from industry

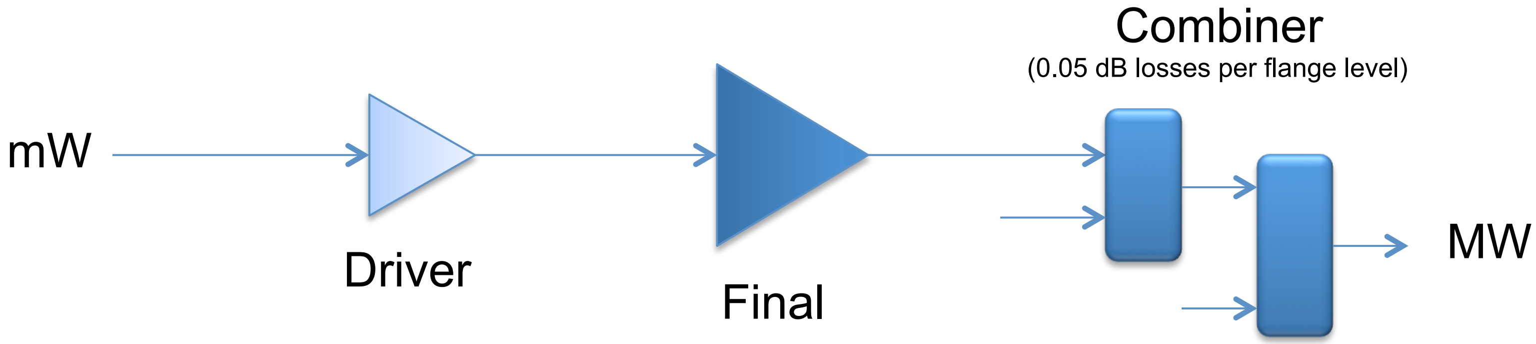


Overhead

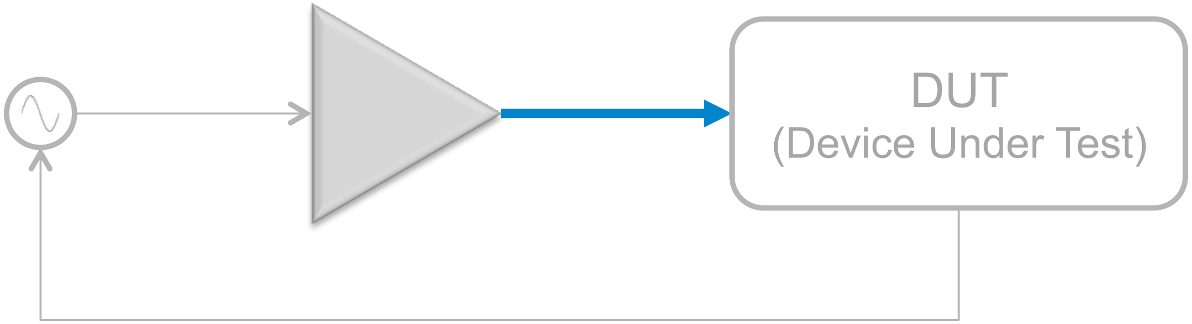

Tetrodes, Klystrons, SSPA
Output power / nominal Output power
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Input power / nominal Input power
Tetrode & IOT
Klystron
SSPA

High Power options

Final	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

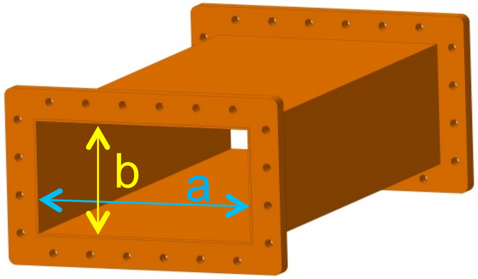


RF Power Lines


DUT
(Device Under Test)

Rectangular waveguides

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

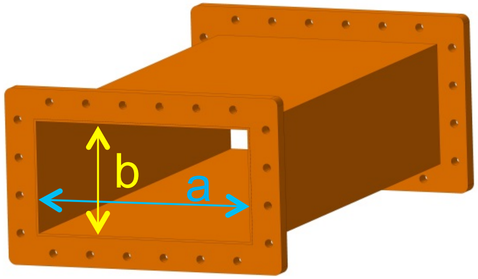


Wavelength	$\lambda g=\lambda/\surd 1-(\lambda/2a)\uparrow 2$
Cutoff frequency dominant mode	$\mathrm{fc}=\mathrm{c}/2a$
Cutoff frequency next higher mode	$\mathrm{fc2}=\mathrm{c}/4a$
Usable frequency range	1.3 fc to 0.9 fc2

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

$$P=6.63\ 10^{-4}\ Emax^{2}\ \sqrt{b^{2}}\ (a^{2}-\lambda^{2}/4)$$

With

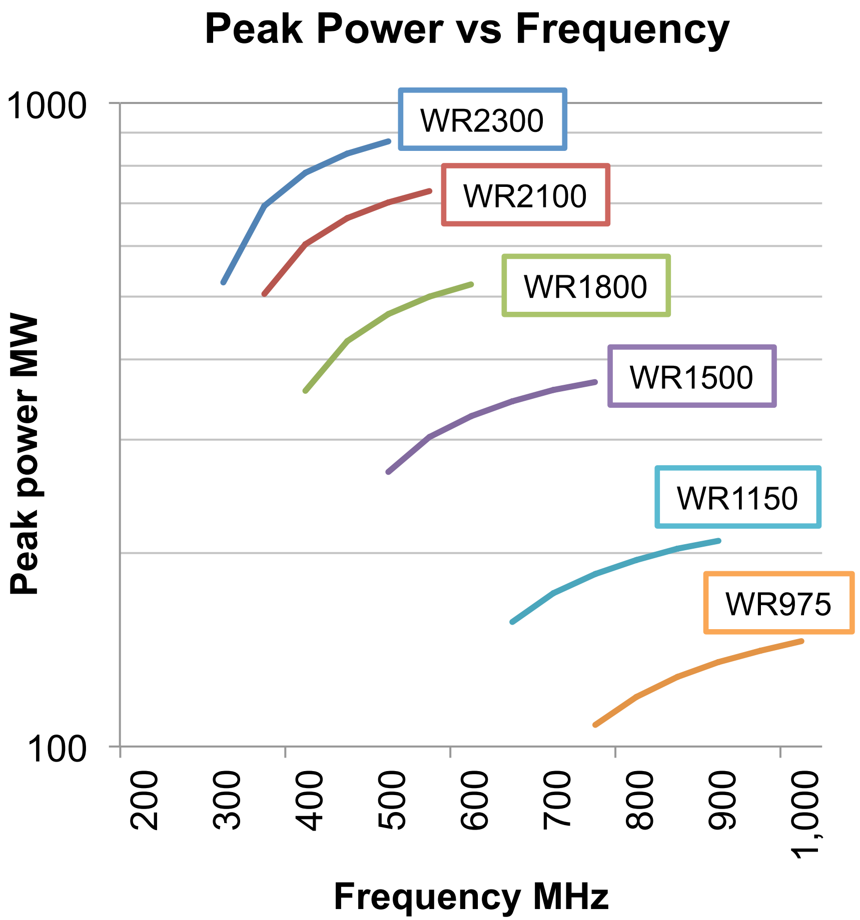
P = Power in watts

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)

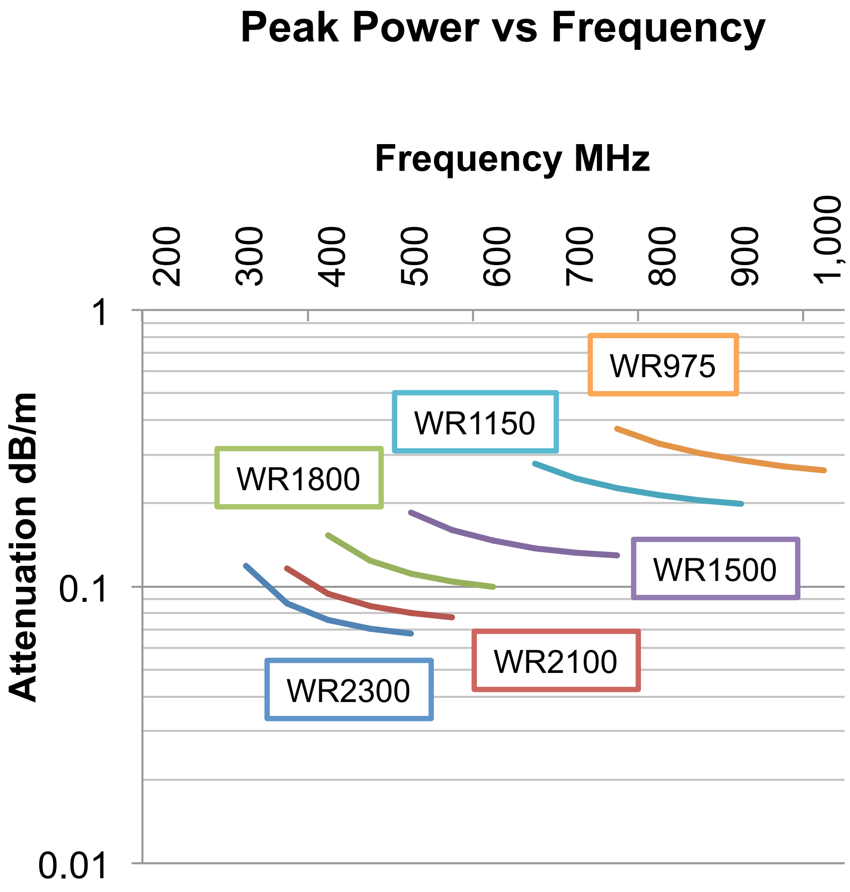


Rectangular waveguides Attenuation

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

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

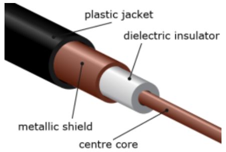
Coaxial Lines

Characteristic impedance is

$$Zc=60/\sqrt{\varepsilon r}\ \ln(D/d)$$

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



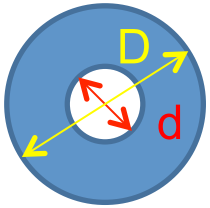
Coaxial cables are often with PTFE foam to keep concentricity

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

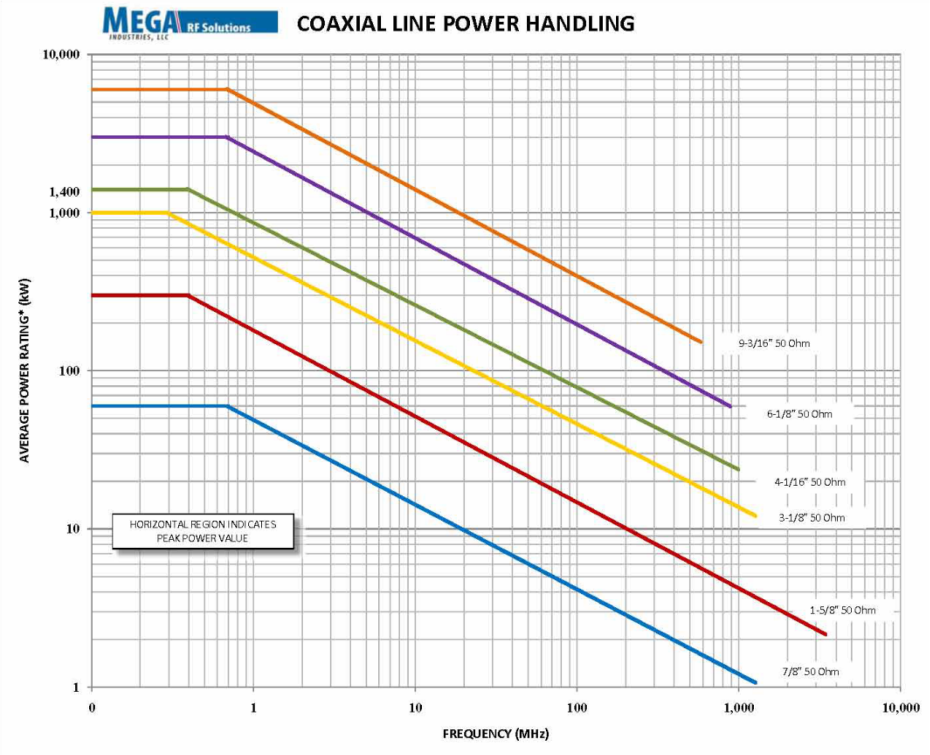
Power handling of an air coaxial line is related to breakdown field E



$$Vpeakmax=Ed/2\ ln(D/d)$$

$$Ppeakmax=Vpeakmax^2/2Zc$$

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



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

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

where

α = attenuation constant, dB/m

Zc= characteristic impedance in Ω

f = frequency in MHz

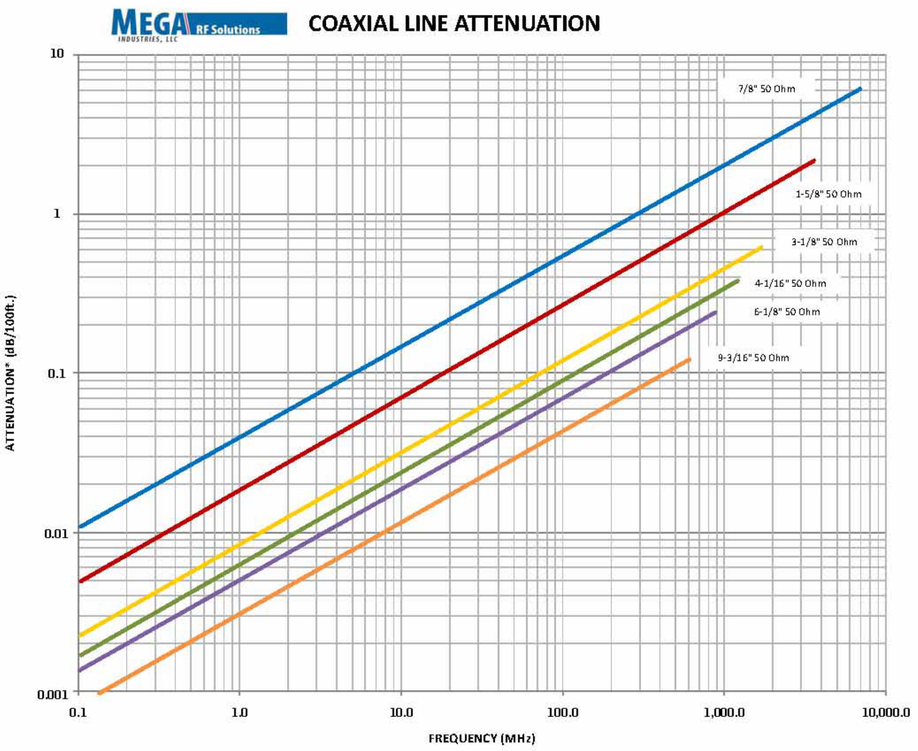
D = inside electrical diameter of outer conductor in mm

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

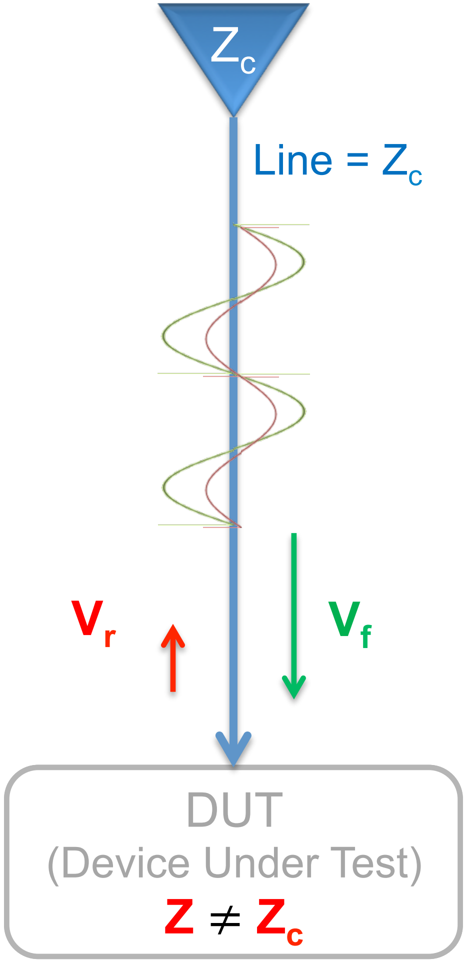
Standing Wave Ration SWR is a measure of impedance matching of DUT

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

$\Gamma = Vr/Vf$

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



Reflection from Load

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

$$|Vmax| = |Vf| + |Vr|$$
$$= |Vf| + |\Gamma Vf|$$
$$= (1 + |\Gamma|)\ |Vf|$$

full reflection

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

At other points they are 180° out of phase

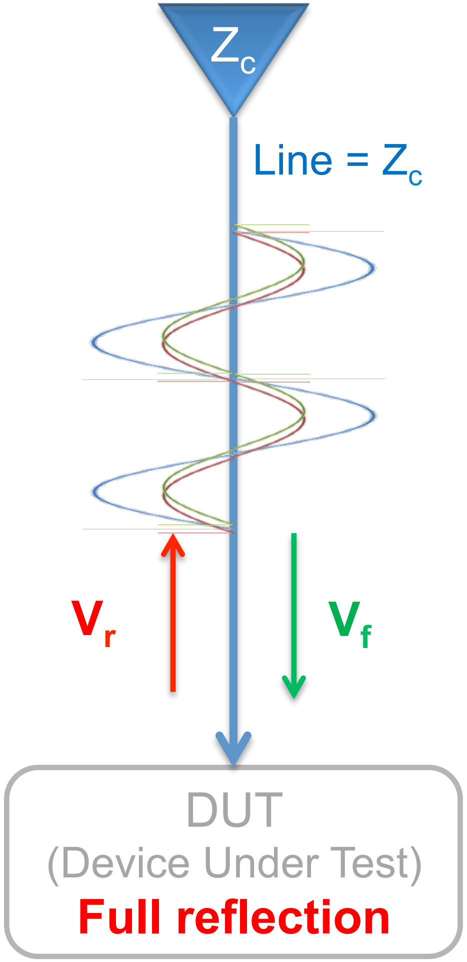
$$|Vmin| = |Vf| - |Vr|$$
$$= |Vf| - |\Gamma Vf|$$
$$= (1 - |\Gamma|)\ |Vf|$$

full reflection

$$|Vmin| = 0$$

The Voltage Standing Wave Ratio is equal to

$$VSWR = |Vmax| / |Vmin| = 1 + |\Gamma| / 1 - |\Gamma|$$



DUT
(Device Under Test)
Full reflection

Reflection from Load

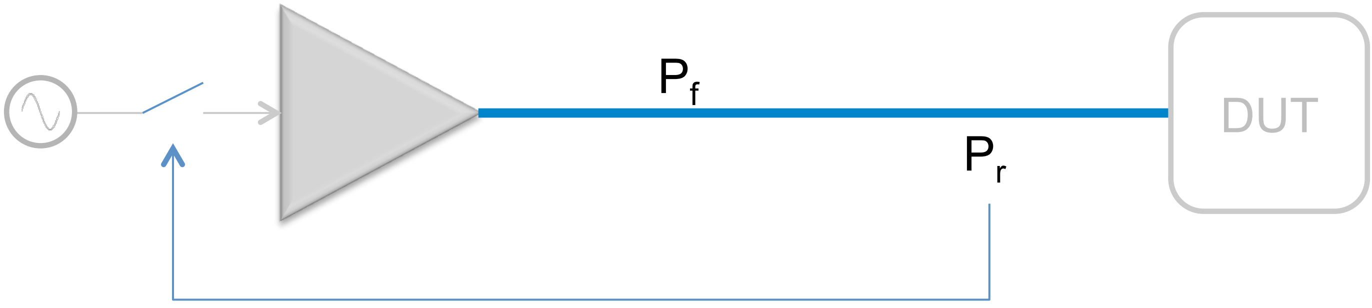
In case of full reflection $V_{max} = 2\ V_f$ (P_{max} equivalent to 4 P_f)

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)



Swift protection if P_r

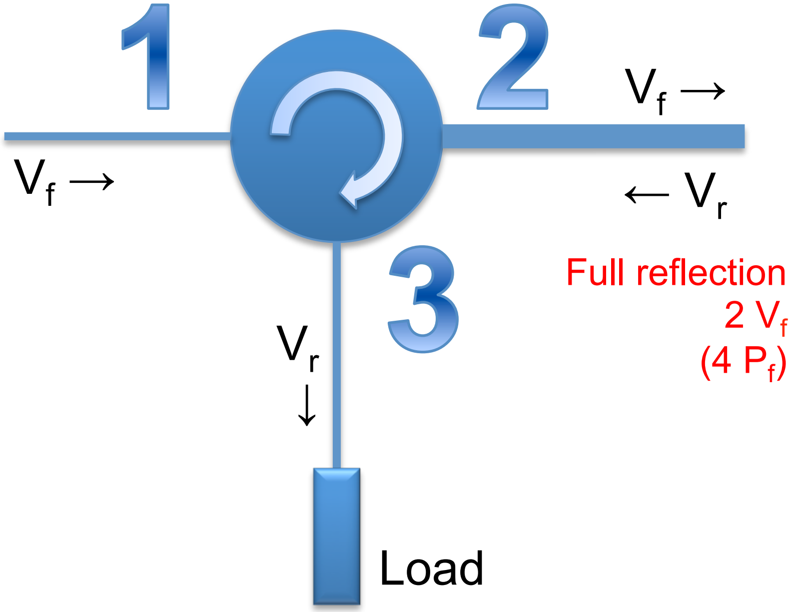
Circulator

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



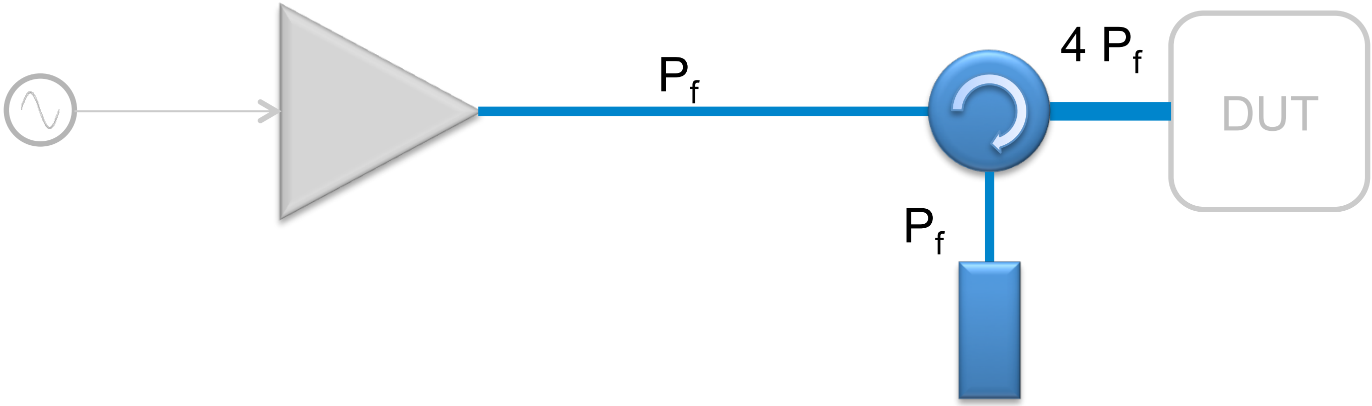
Full reflection
2 V_f
(4 P_f)

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



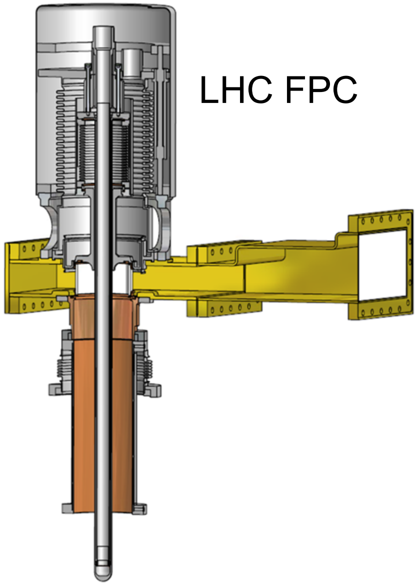
Fundamental Power Coupler FPC

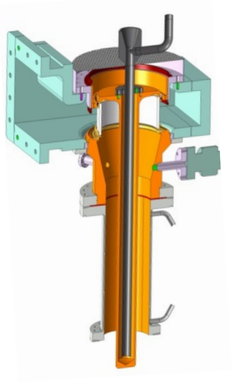
The Fundamental Power Coupler is the connecting part between the RF transmission line and the RF cavity

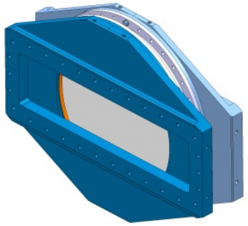
It is a specific piece of transmission line that also has to provide the vacuum barrier for the beam vacuum

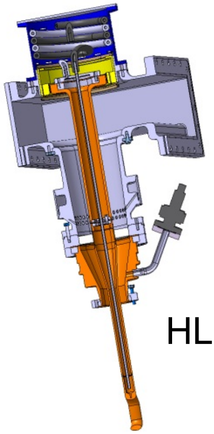
FPC are one of the most critical parts of the RF cavity system in an accelerator

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


LHC FPC

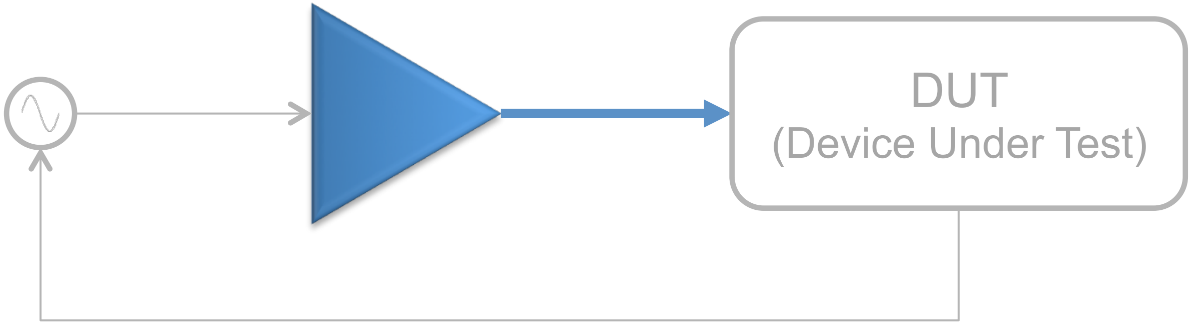

SPL FPC


L4 FPC window


HL-LHC FPC

Various CERN FPC

RF powering



Quick overview of the RF powering, for detailed explanations, please refer to specialized CAS on RF

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

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

Thales https://www.thalesgroup.com/en/worldwide/security/rf-sources-medical-accelerators
e2v http://www.e2v.com/products/rf-power/

CPI http://www.cpii.com/division.cfm/1
L-3 communications http://www2.l-3com.com/edd/
Toshiba http://www.toshiba-tetd.co.jp/eng/tech/index.htm

NXP http://www.nxp.com/products/bipolar_transistors/
Freescale http://www.freescale.com/

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

Mark Twain

Case Study

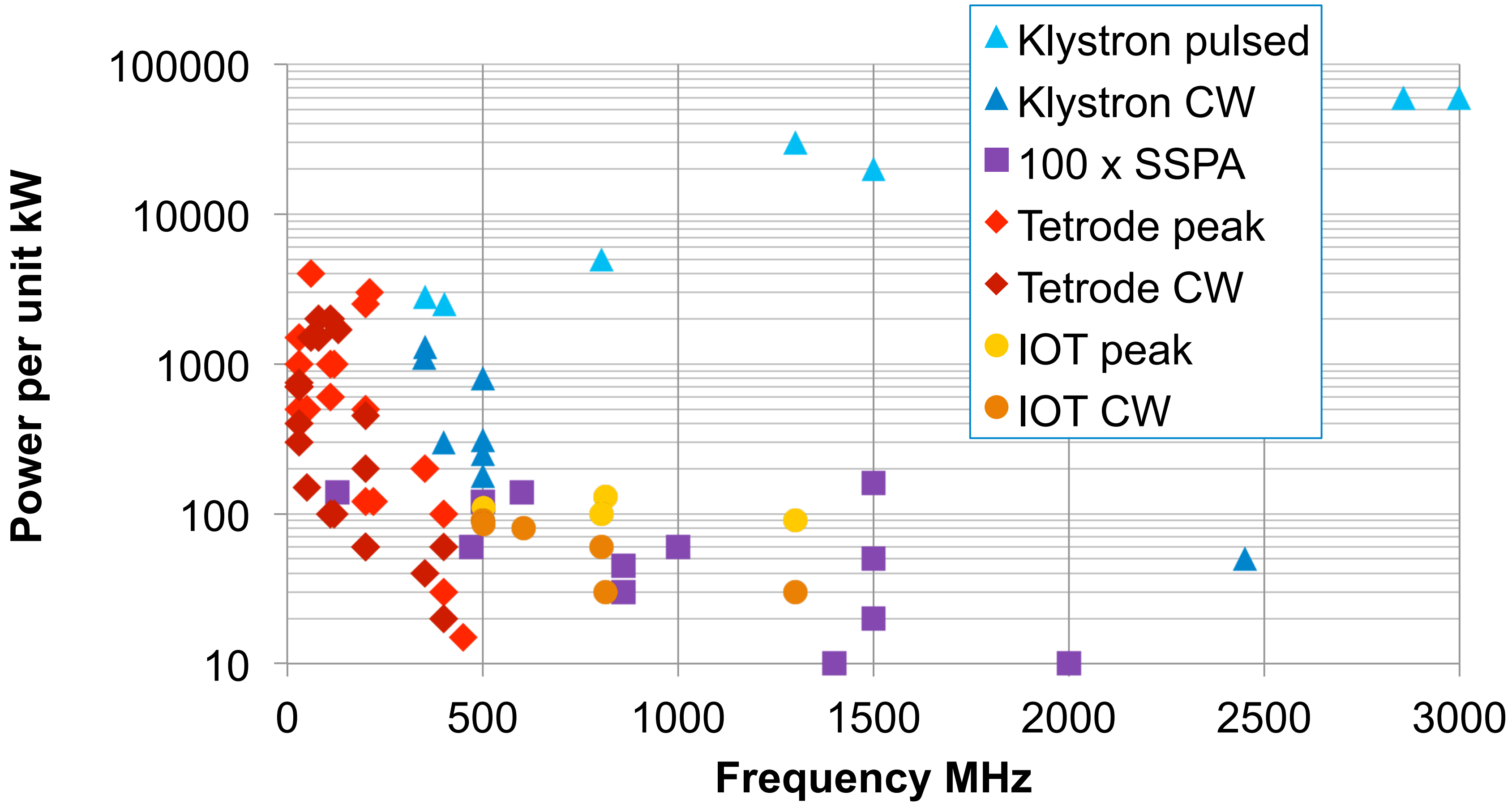
Frequency

Overhead, peak and average power

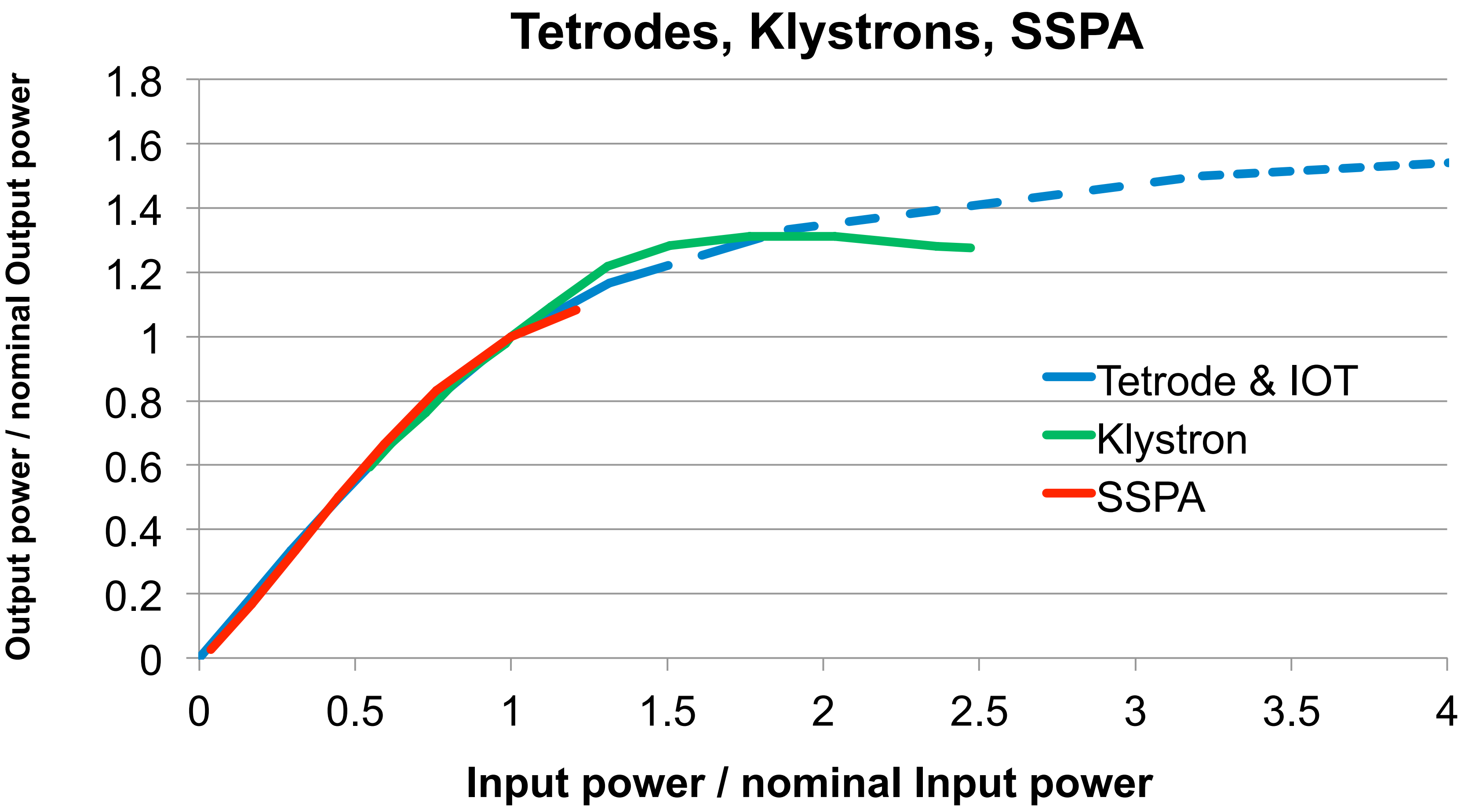
Efficiency

Rough cost estimate

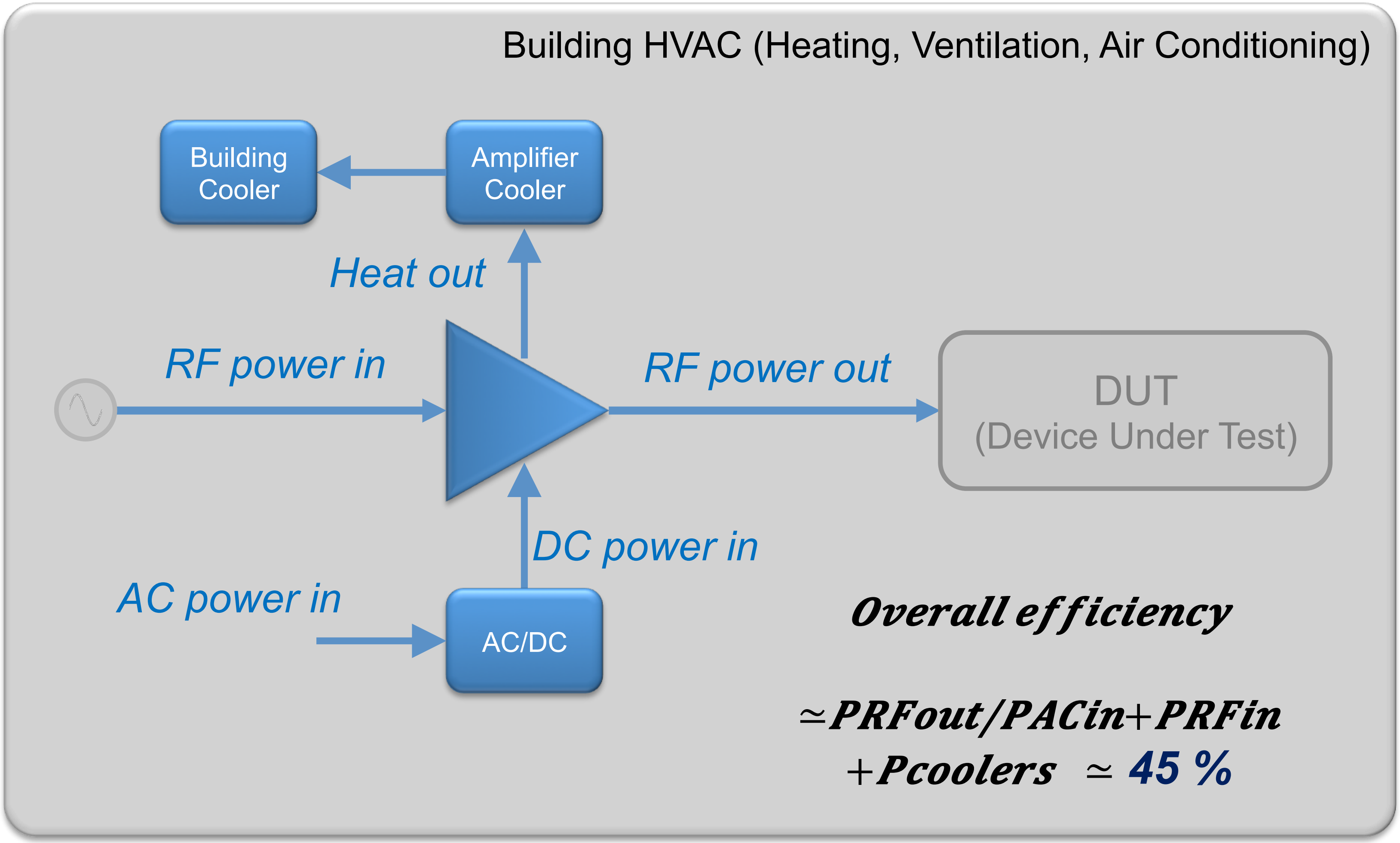
Frequency


Klystron pulsed
Klystron CW
100 x SSPA
Tetrode peak
Tetrode CW
IOT peak
IOT CW
100000
10000
1000
100
10
Power per unit kW
0
500
1000
1500
2000
2500
3000
Frequency MHz

Overhead, peak and average power



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

$$Overall\ efficiency$$

$$\simeq PRFout/PACin+PRFin+Pcoolers \simeq \mathbf{45\ \%}$$

Overall Efficiency

$P_{RFin} \simeq$ 1 to 5 % P_{RFout} (Gain is usually high)

$\eta_{RF/DC} \simeq$ 65 % (including overhead)

$\eta_{PAC/PDC} \simeq$ 95 % to 98 %

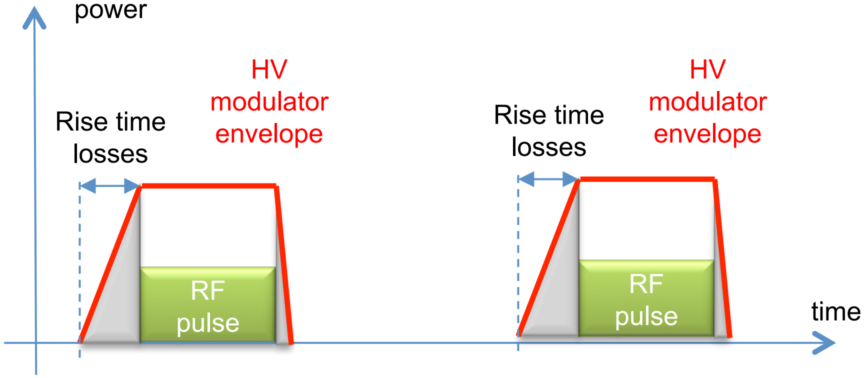
Amplifier cooler $\simeq$ 15 % P_{RFout}

Building cooler $\simeq$ 30 % P_{RFout}

$$Overall\ efficiency = PRFout/PRFin+P\ ACin+P\ coolers$$

$$\simeq PRFout/PRFout\ (0.05+1.62+0.45)$$

$$\simeq \mathbf{45}\ \%$$



HVPS Modulator for klystron -> few additional overall losses

Amplifier and building coolers
are not so efficient

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

Case study

To design your RF power system, carefully consider

- Your infrastructure (additional overall costs)
- What power specialists are available (technology choice)
- To correctly size the transmission lines
- The need or not of a circulator
- Your HVAC system (this will dominate your wall-plug efficiency ratio)

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