



# Accelerators for Medical applications

**RF powering**  
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Applications, Vösendorf, Austria

# RF Powering

W → kW → MW  
€ → k€ → M€

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

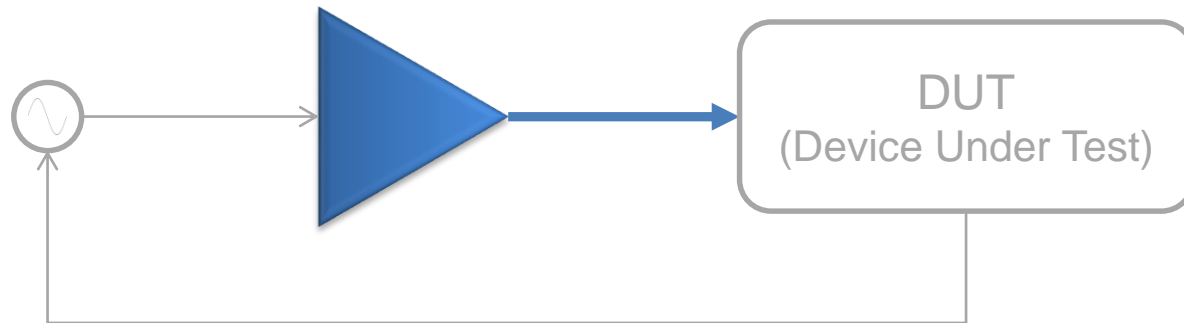
# Outlook

RF power basics

RF power amplifiers

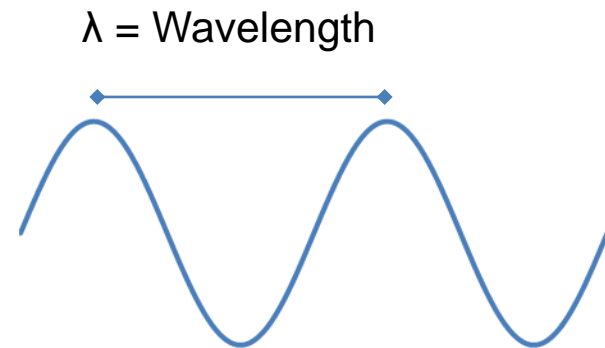
RF power lines

# RF Power basics



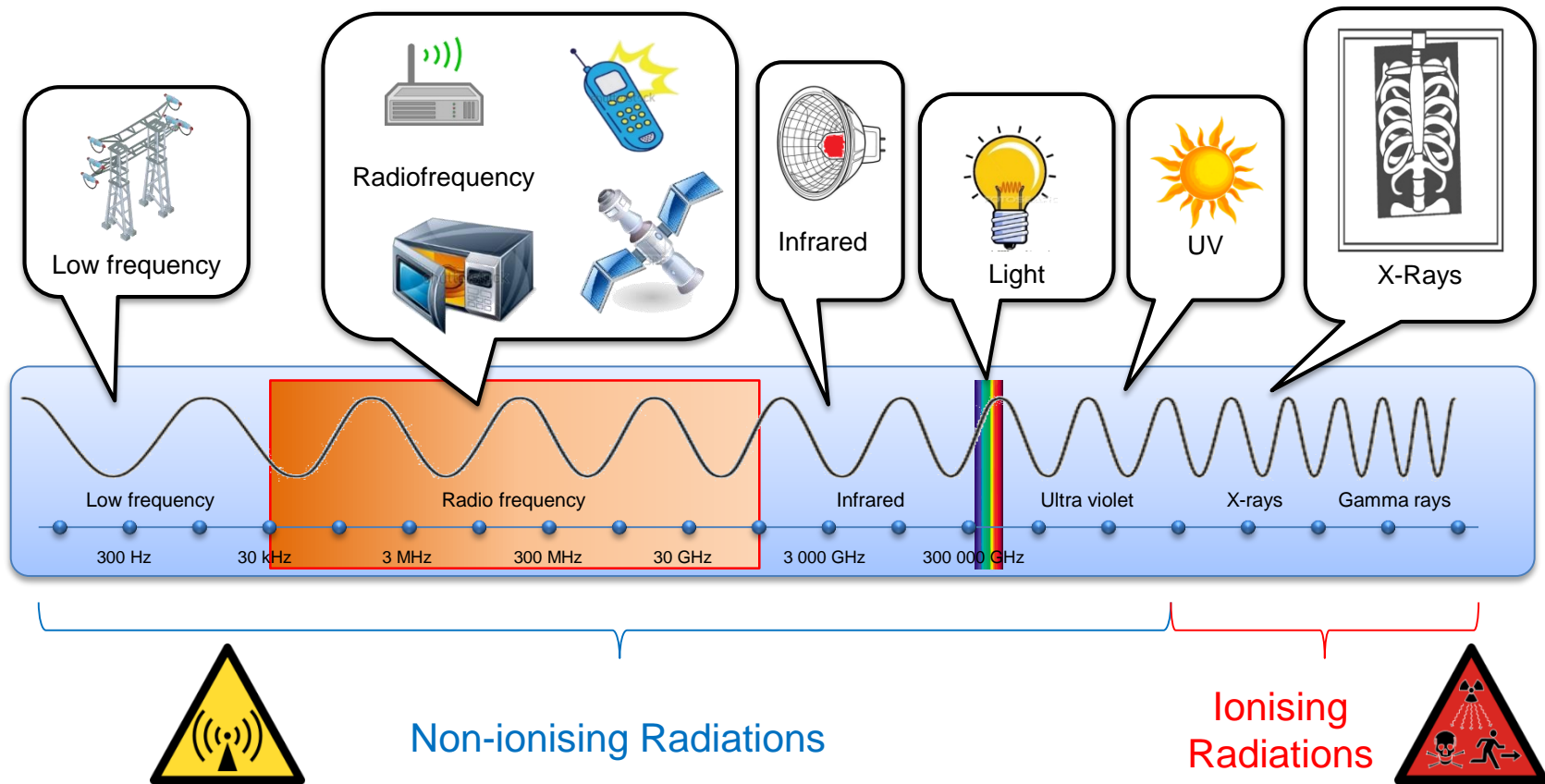
# Wavelength, frequency

$$\lambda = \frac{c}{f \sqrt{\epsilon}} \quad \Leftrightarrow \quad f = \frac{c}{\lambda \sqrt{\epsilon}}$$

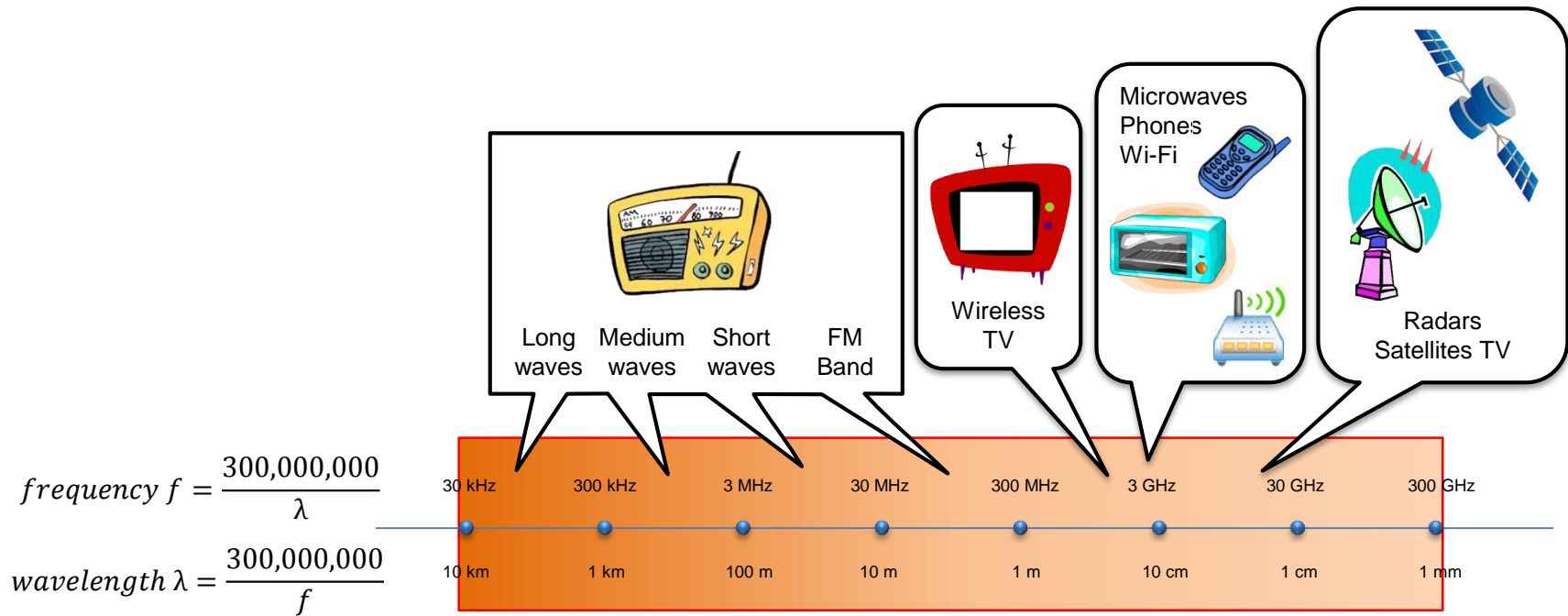


- $\lambda$  = wavelength in meters (m)
- $c$  = velocity of light (m/s) - ( $\sim 300,000,000$  m/s)
- $f$  = frequency in hertz (Hz)
- $\epsilon$  = dielectric constant of the propagation medium ( $\sim 1.0$  in air at  $20^{\circ}\text{C}$ )

# Electromagnetic waves



# Radiofrequency waves



$$\text{frequency } f = \frac{300,000,000}{\lambda}$$

$$\text{wavelength } \lambda = \frac{300,000,000}{f}$$

*With  $\epsilon = \sim 1.0$  (dielectric constant of air at  $20^{\circ}C$ )*

# Decibel (dB)

$$dBm = 10 \text{ Log}_{10} (P_{mW})$$

$$dB = 10 \text{ Log}_{10} (P_1/P_2)$$

$$dB = 20 \text{ Log}_{10} (V_1/V_2)$$

$$dBV = 20 \text{ Log}_{10} (V_{Vrms})$$

$$dB\mu V = 20 \text{ Log}_{10} (V_{\mu Vrms})$$

$$dBc = 10 \text{ Log}_{10} (P_{carrier}/P_{signal})$$



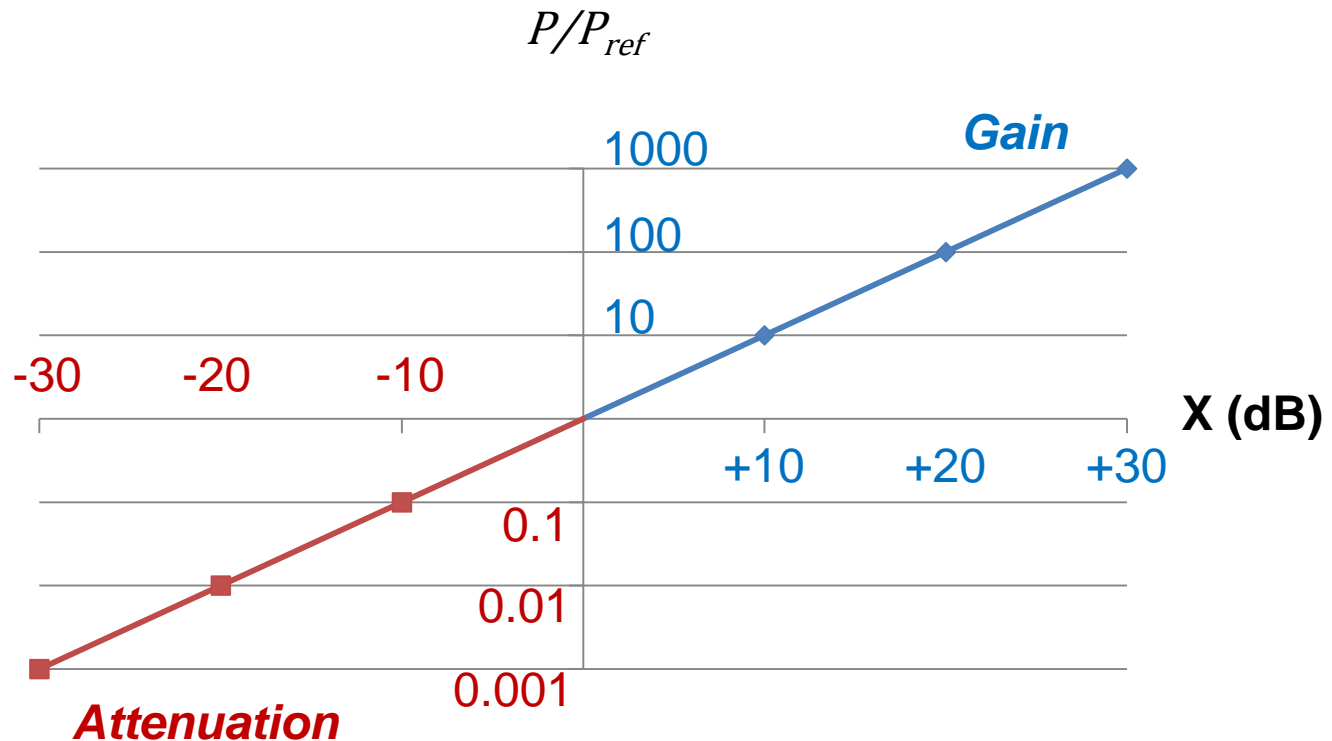
# dBm, W

$$x_{dBm} = 10 \operatorname{Log}_{10} (P_{mW}) \quad \Leftrightarrow \quad P_{mW} = 10^{(x_{dBm}/10)}$$

0	dBm	=	1	mW
30	dBm	=	1	W
60	dBm	=	1	kW
90	dBm	=	1	MW

# dB, Power ratio

$$x_{dB} = 10 \text{ Log}_{10} (P/P_{ref}) \quad \Leftrightarrow \quad P/P_{ref} = 10^{(x_{dB}/10)}$$

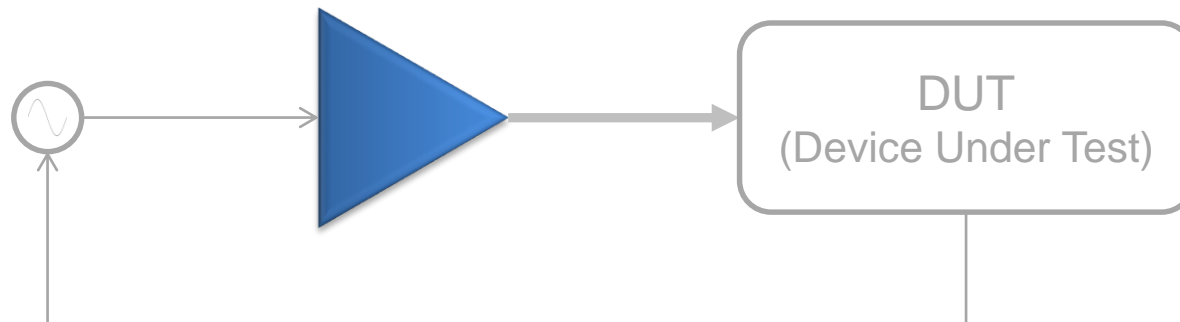


# dB, Power ratio

$$x_{dB} = 10 \operatorname{Log}_{10} (P/P_{ref}) \quad \Leftrightarrow \quad P/P_{ref} = 10^{(x_{dB}/10)}$$

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



# RF power source classification

## Vacuum Tubes

### Grid Tubes

Triodes  
*Tetrodes*  
Pentodes  
Diodes

### Linear Beam Tubes

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

### Crossed-field Tubes

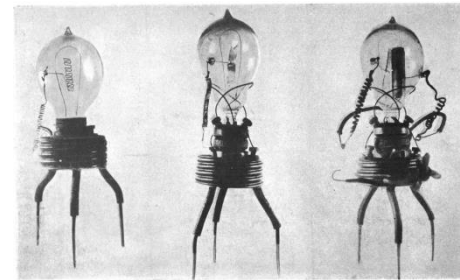
Magnetrons

## 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

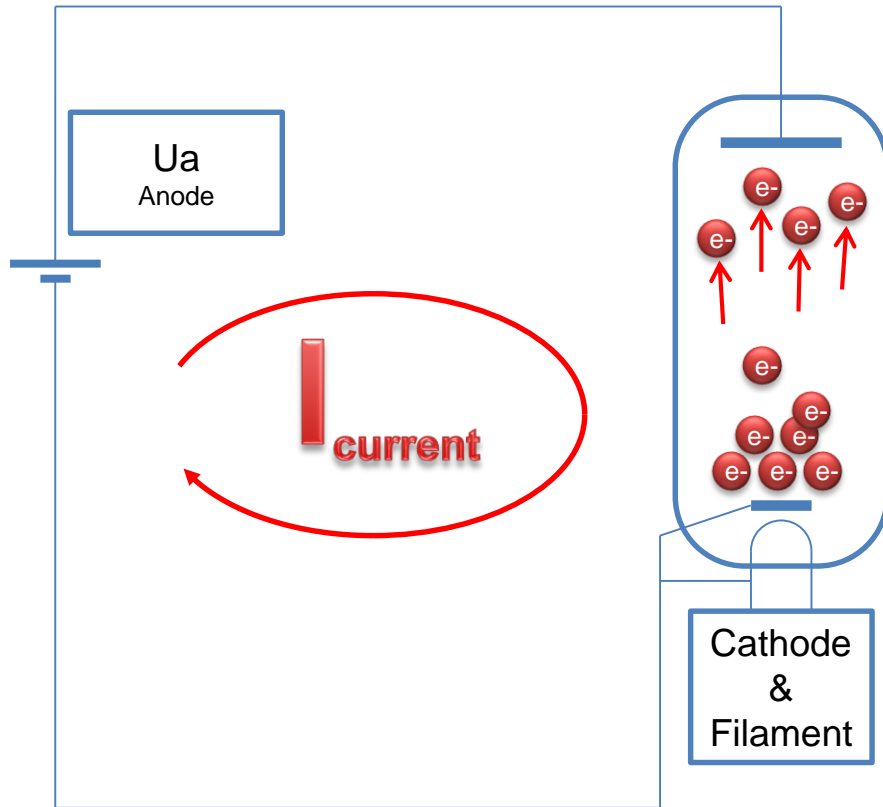


The first diode prototype  
Fleming Diode, 1904



Thales TH 628 diacrode,  
1998

# Essentials of grid tube



Vacuum tube

Heater + Cathode

Heated cathode

Coated metal, carbides,  
borides,...

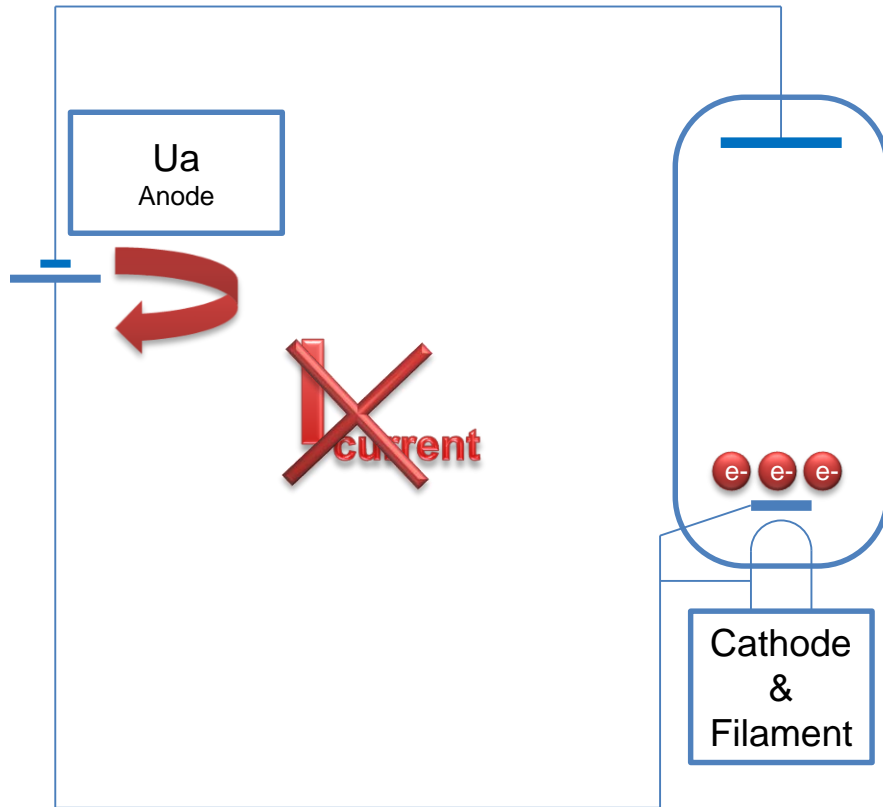
thermionic emission

Electron cloud

Anode

Diode

# Essentials of grid tube



Vacuum tube

Heater + Cathode

Heated cathode

Coated metal, carbides,  
borides,...

thermionic emission

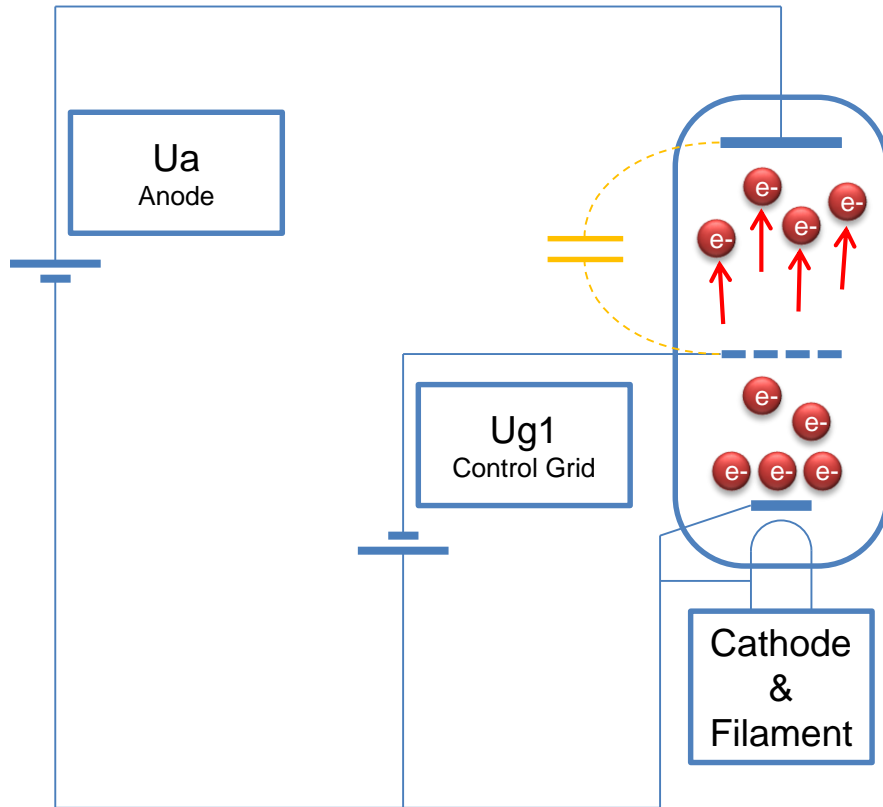
Electron cloud

Anode

Diode



# Essentials of grid tube



## Triode

Modulating the grid voltage proportionally modulates the anode current

## Transconductance

Voltage at the grid

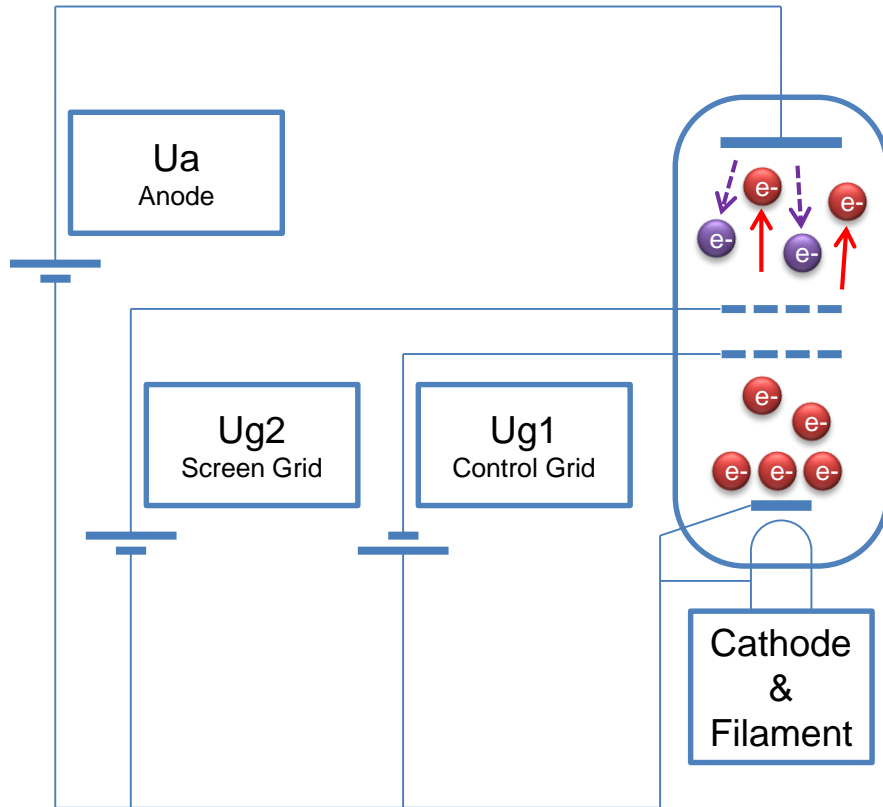
Current at the anode

## Limitations

Parasitic capacitor Anode/g1

Tendency to oscillate

# Essentials of grid tube



## Tetrode

### Screen grid

Positive (lower anode)

Decouple anode and g1

Higher gain

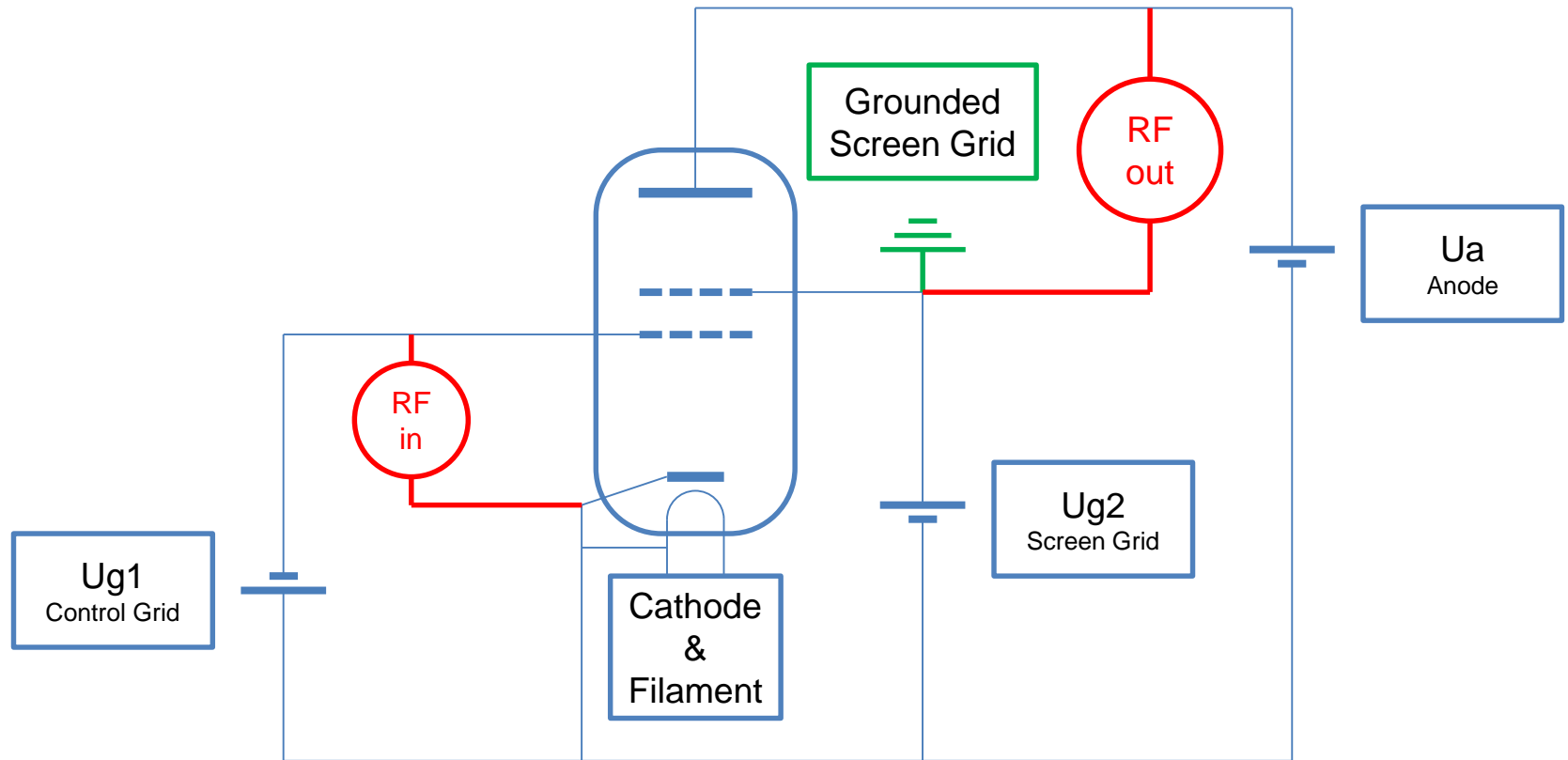
### Limitations

Secondary electron

Anode treated to reduce secondary emission

# Tetrode

## RS 2004 CERN SPS example



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

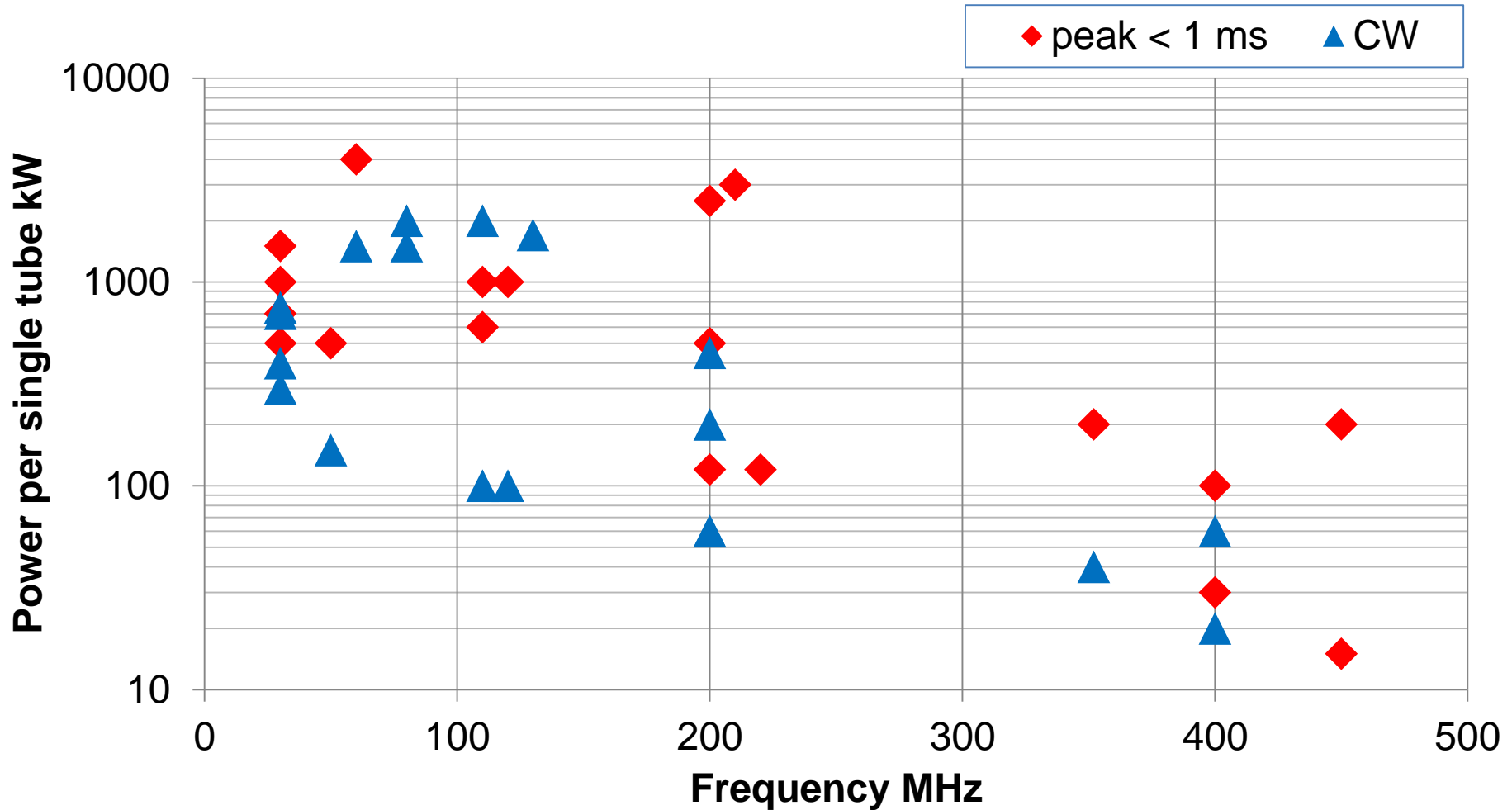
# Tetrode

RS 2004 CERN SPS amplifier @ 200 MHz



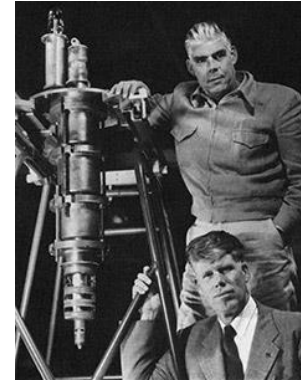
CERN SPS, RS 2004 Tetrode, Trolley (single amplifier), and transmitter (combination of amplifiers)  
Two transmitters of eight tubes delivering 2 x 1 MW @ 200 MHz, into operation since 1976

# 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*

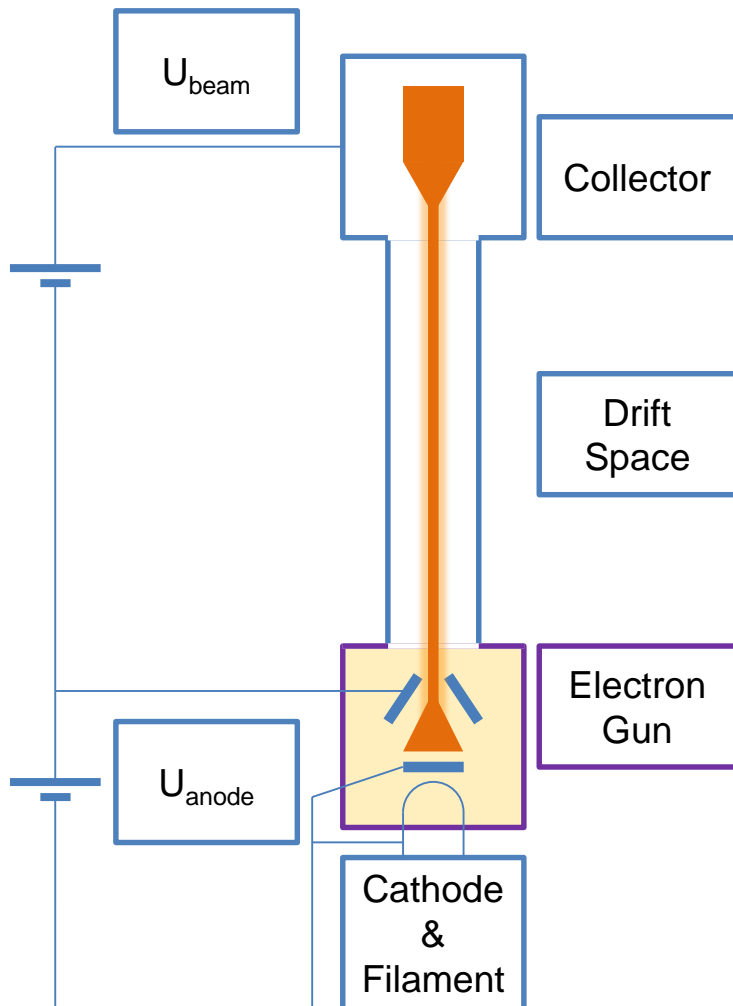


Russell & Sigurd Varian klystron, 1937



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

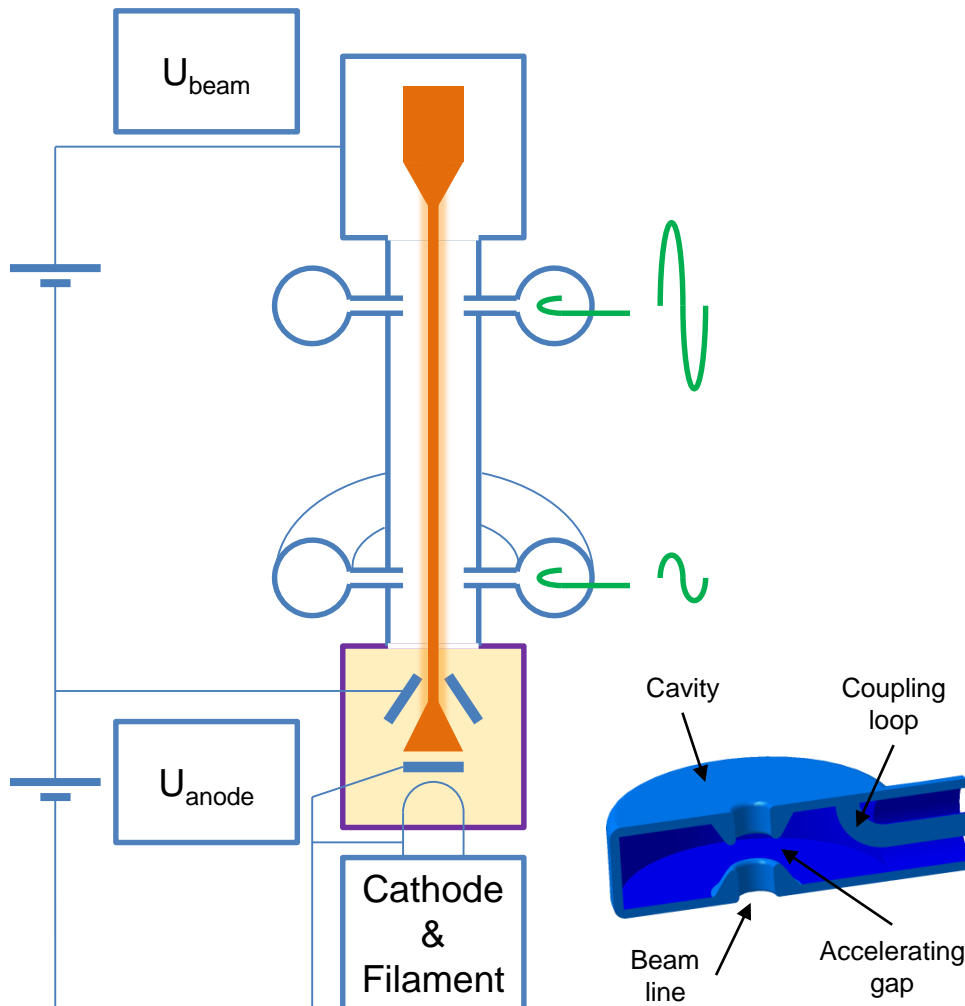
Electron beam

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)

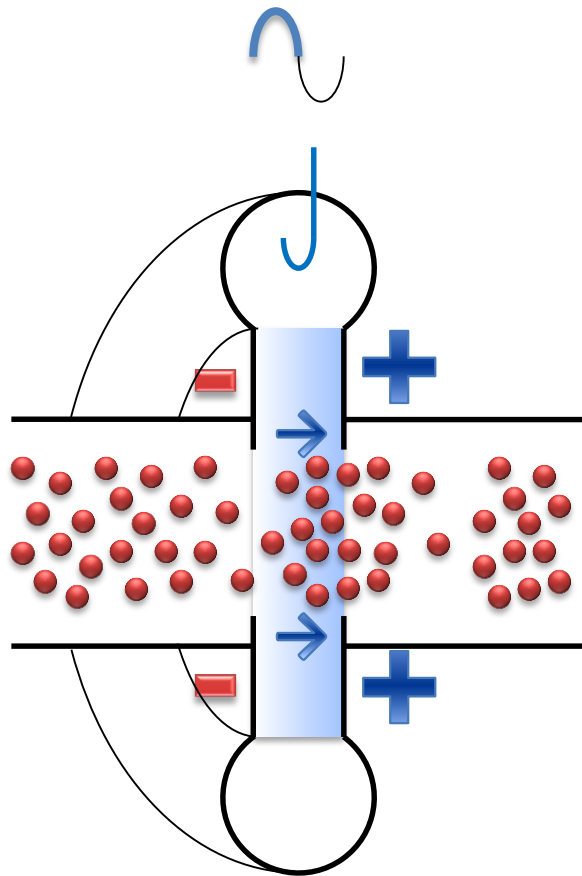
Resonating at the same frequency as the input cavity

At the place with the numerous number of e-

Kinetic energy converted into voltage and extracted



# Essentials of klystron



Cavity resonators

RF input cavity (Buncher)

modulates e- velocity

Some are accelerated

Some are neutral

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Bunching the e-

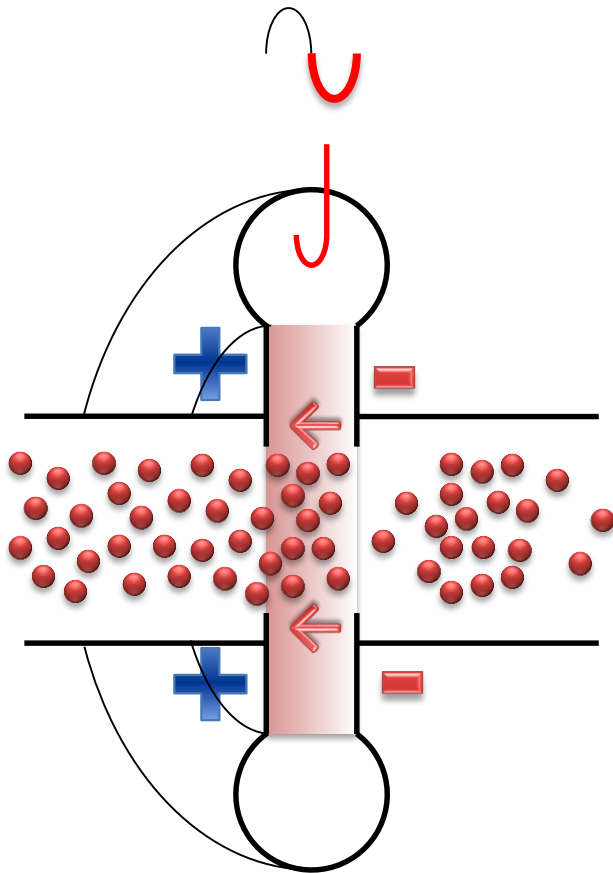
RF output cavity (Catcher)

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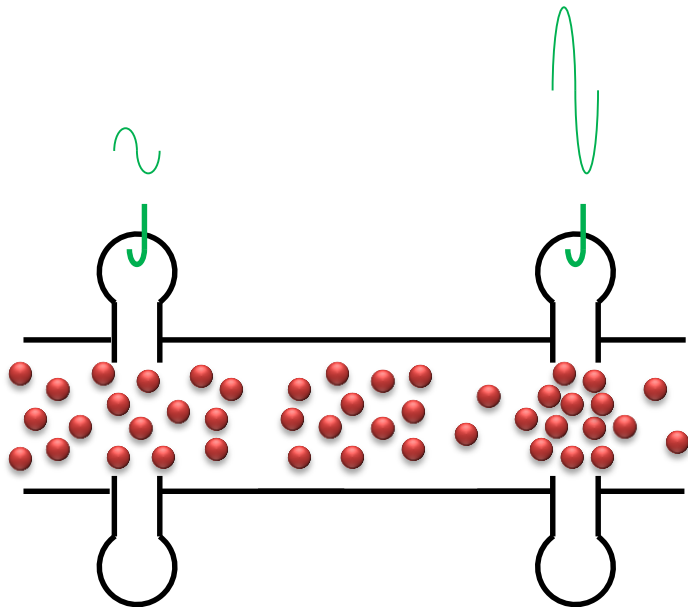
RF output cavity (Catcher)

Resonating at the same frequency as the input cavity

At the place with the numerous number of e-

Kinetic energy converted into voltage and extracted

# Essentials of klystron



Cavity resonators

RF input cavity (Buncher)

modulates e- velocity

Some are accelerated

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Bunching the e-

RF output cavity (Catcher)

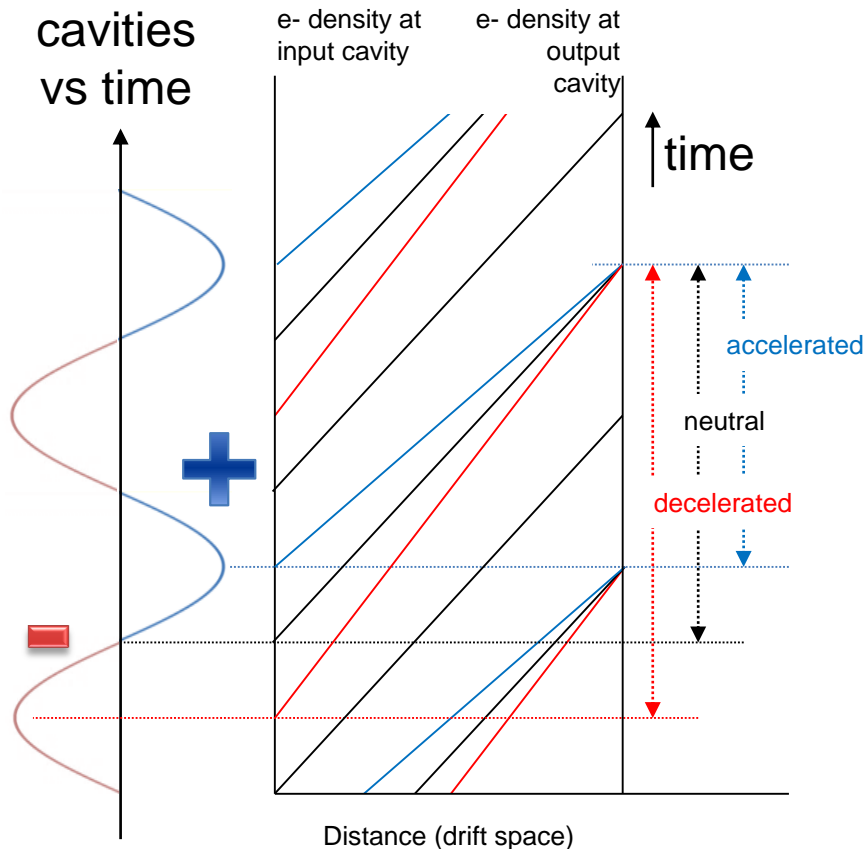
Resonating at the same frequency as the input cavity

At the place with the numerous number of e-

Kinetic energy converted into voltage and extracted

# Essentials of klystron

Voltage in cavities vs time



Cavity resonators

RF input cavity (Buncher)

modulates e- velocity

Some are accelerated

Some are neutral

Some are decelerated

Bunching the e-

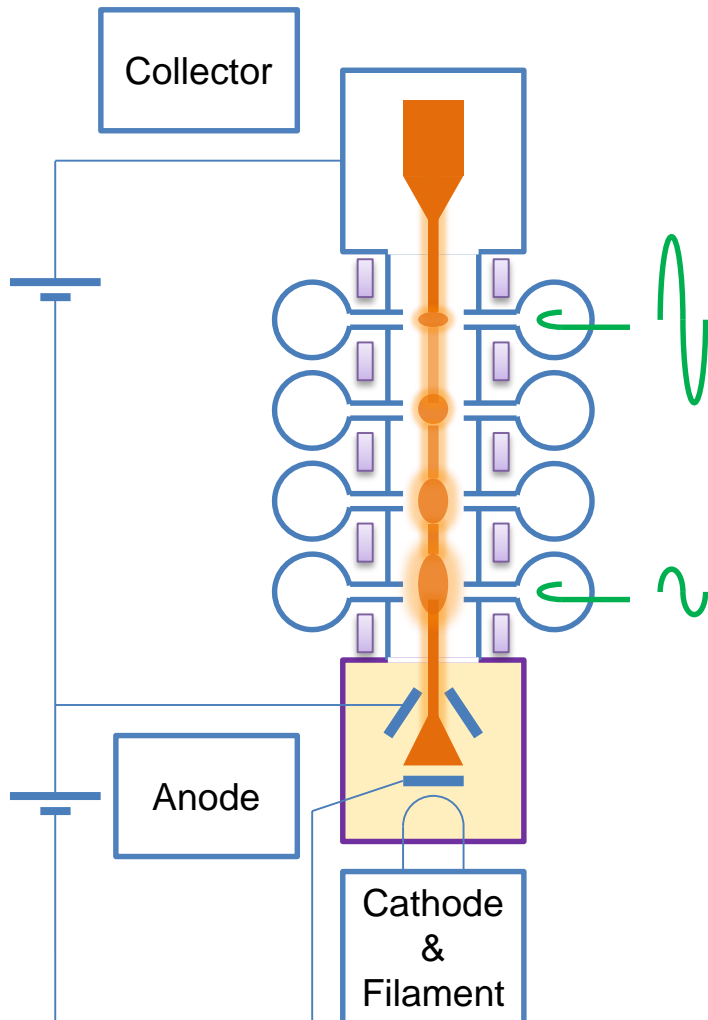
RF output cavity (Catcher)

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

Bunching of e- beam in a klystron

# Essentials of klystron



## Additional bunching cavities

Resonate with the pre-bunched electrons beam

Generate an additional accelerating/decelerating field

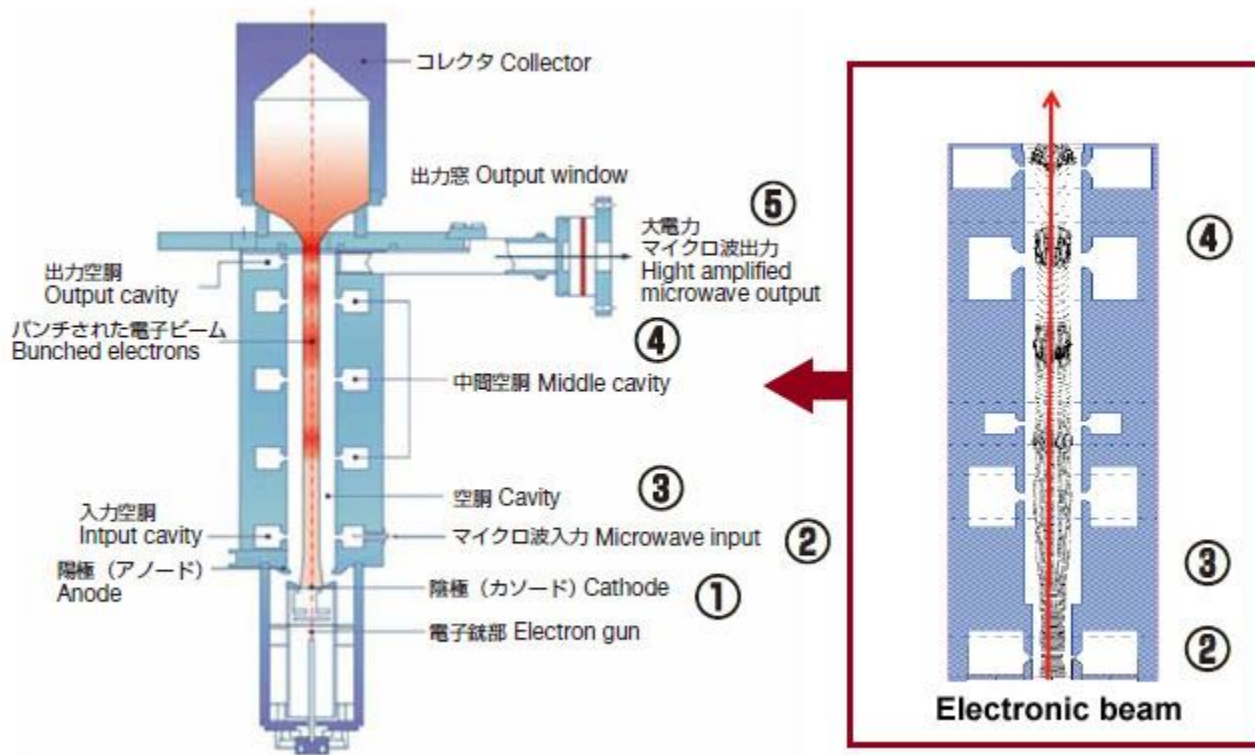
Better bunching

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>

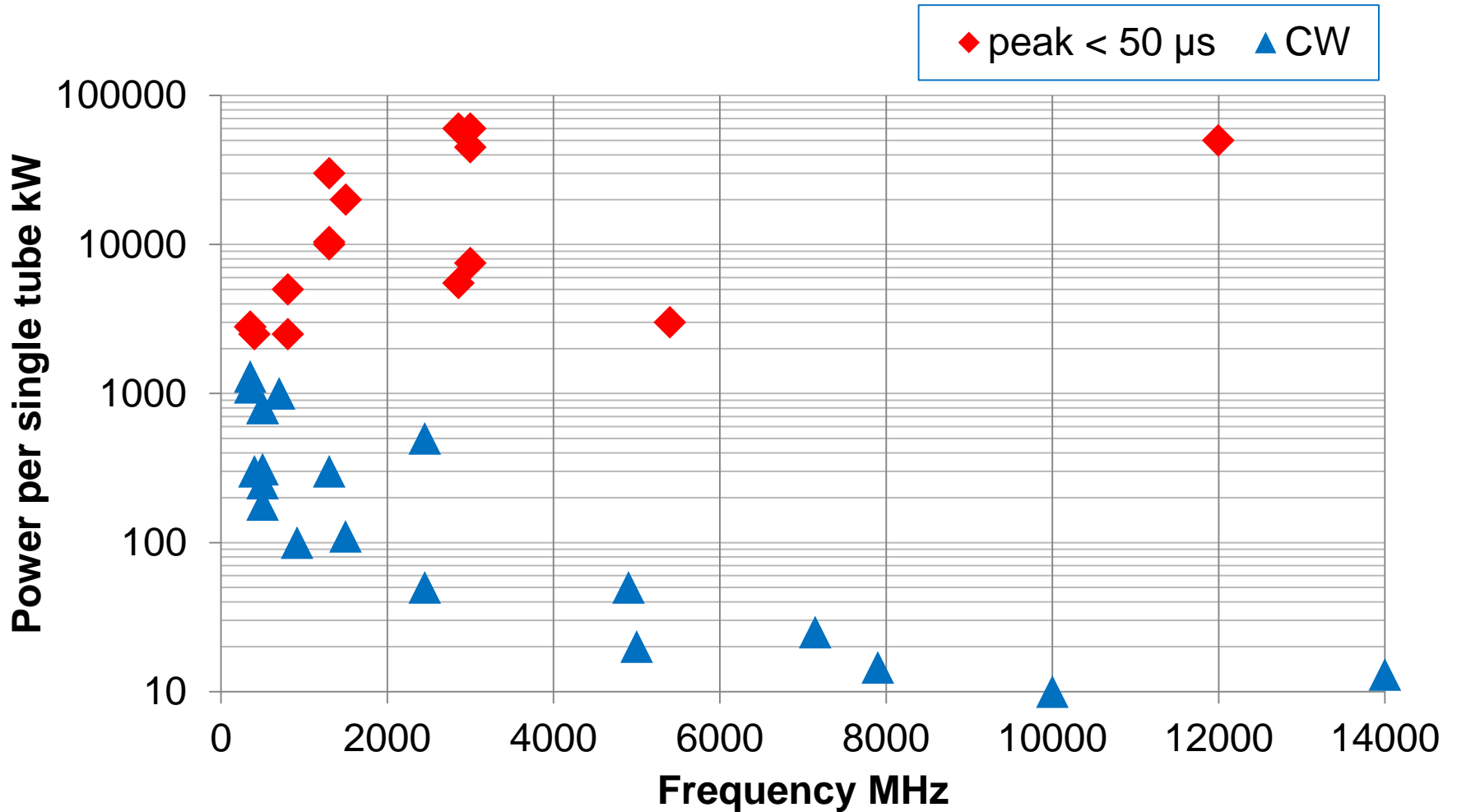
# Klystron

TH 2167 CERN LHC @ 400 MHz



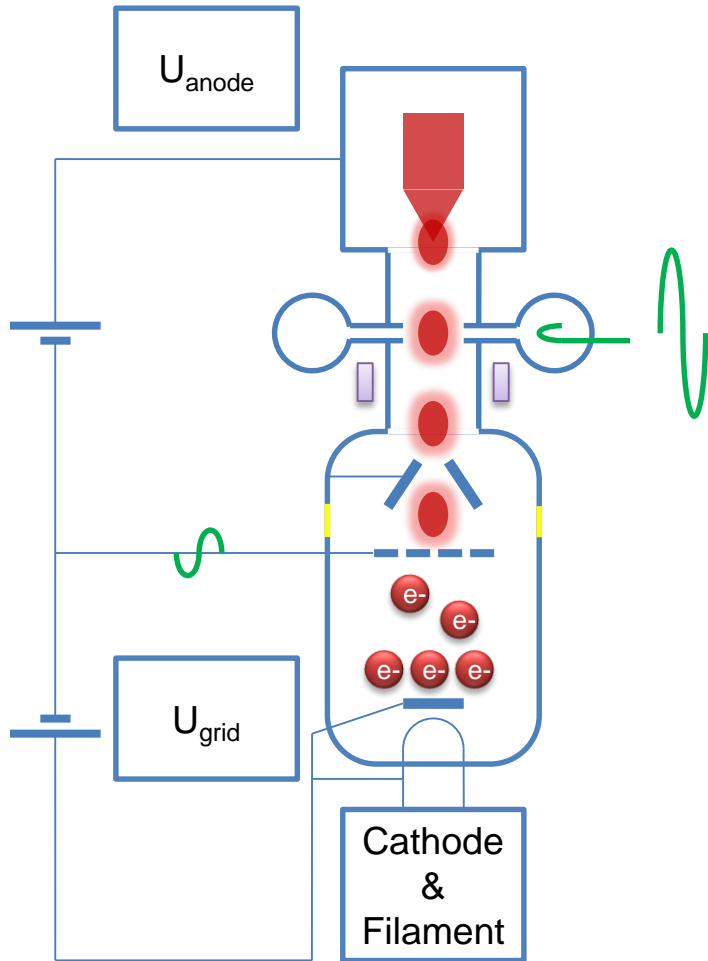
CERN LHC, TH 2167 klystron in lab and in UX45 cavern  
16 klystrons delivering 330 kW @ 400 MHz, into operation since 2008

# 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

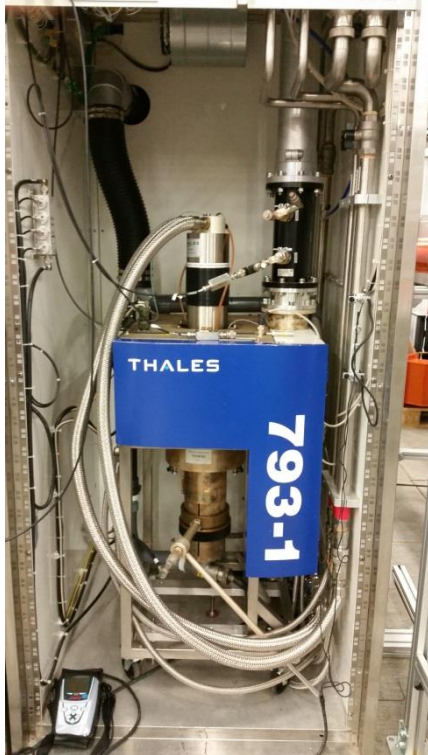
Short drift tube & magnets

Catcher cavity

Collector

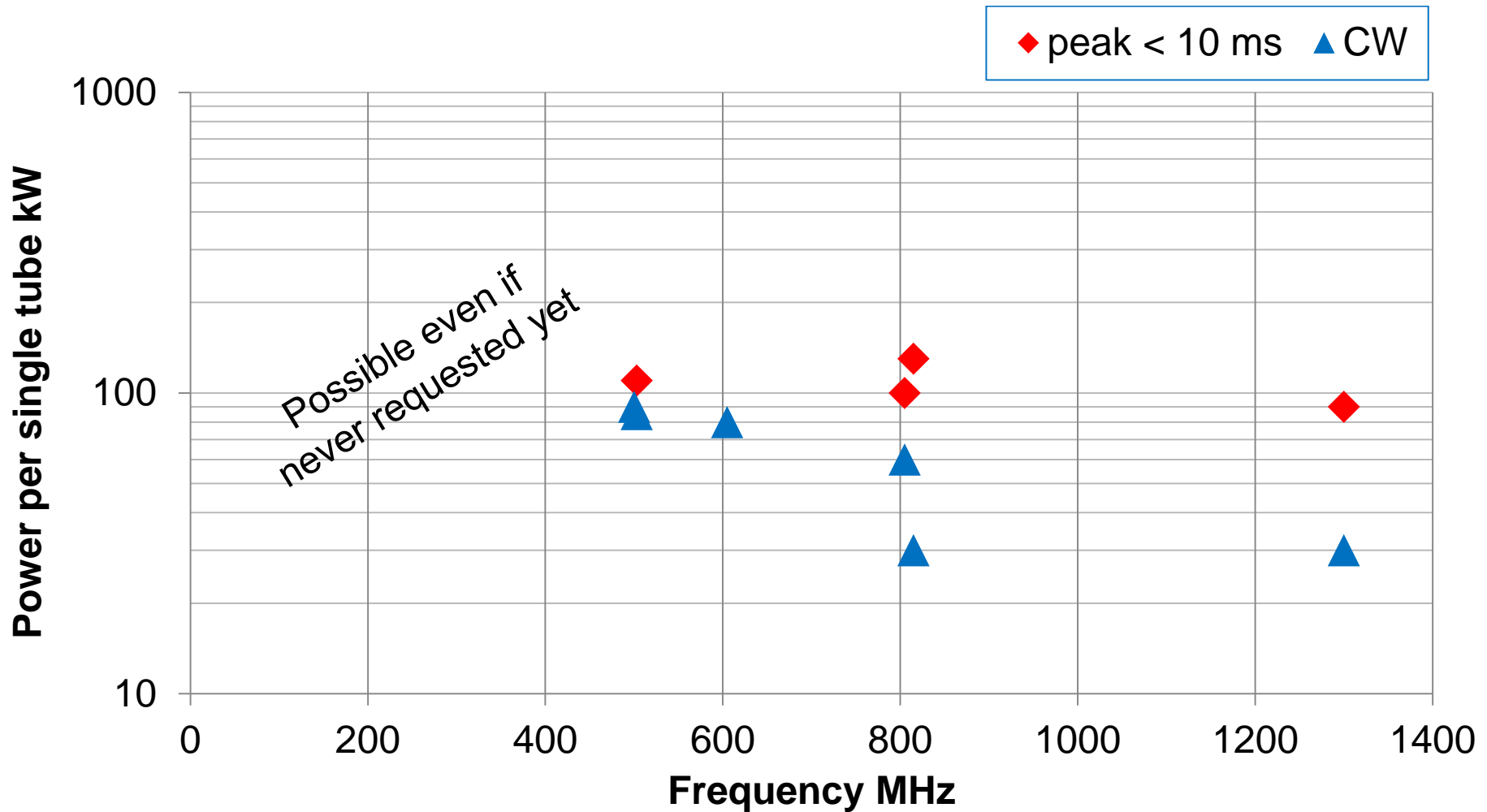
# IOT

## 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

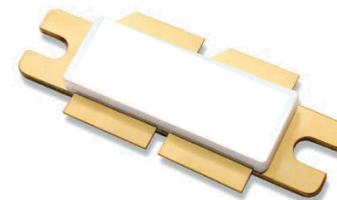


# Transistor for RF power

- 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

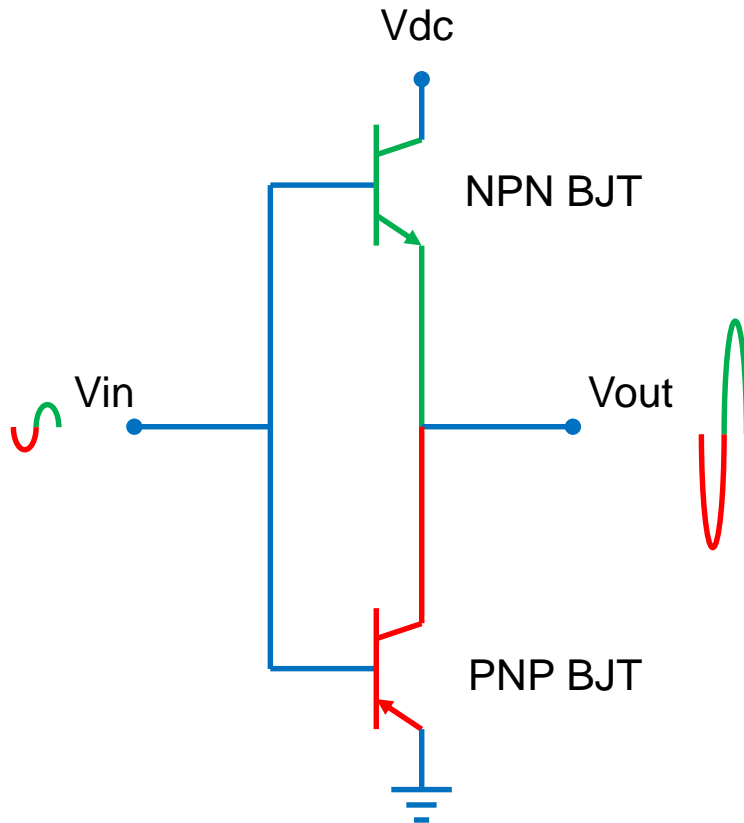


First transistor  
invented at BELL labs  
in 1947



XXI century LDMOS

# Essentials of RF transistor



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

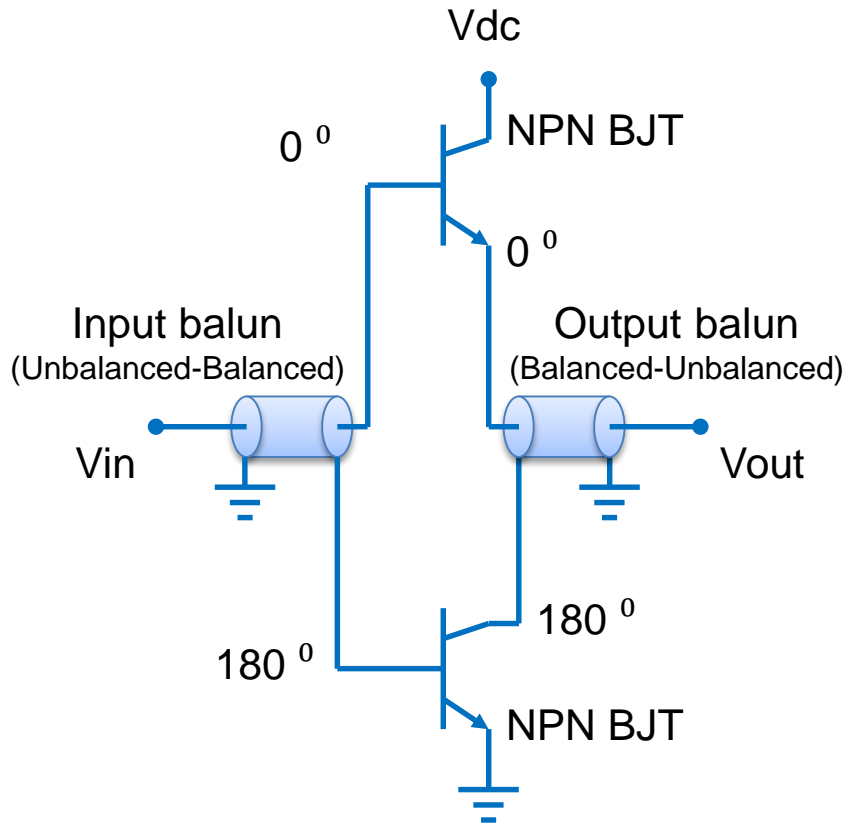
One of the devices is active on the positive voltage swing and off during the negative voltage swing

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)

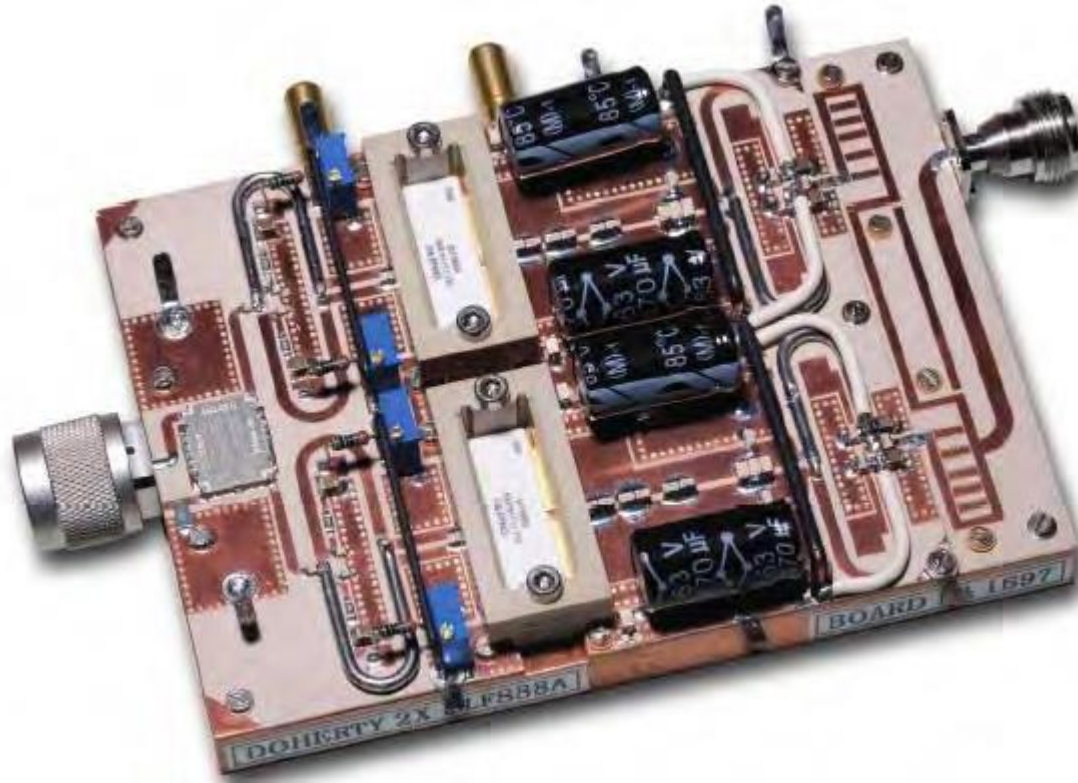
it acts as a power splitter, equally dividing the input power between the two transistors

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

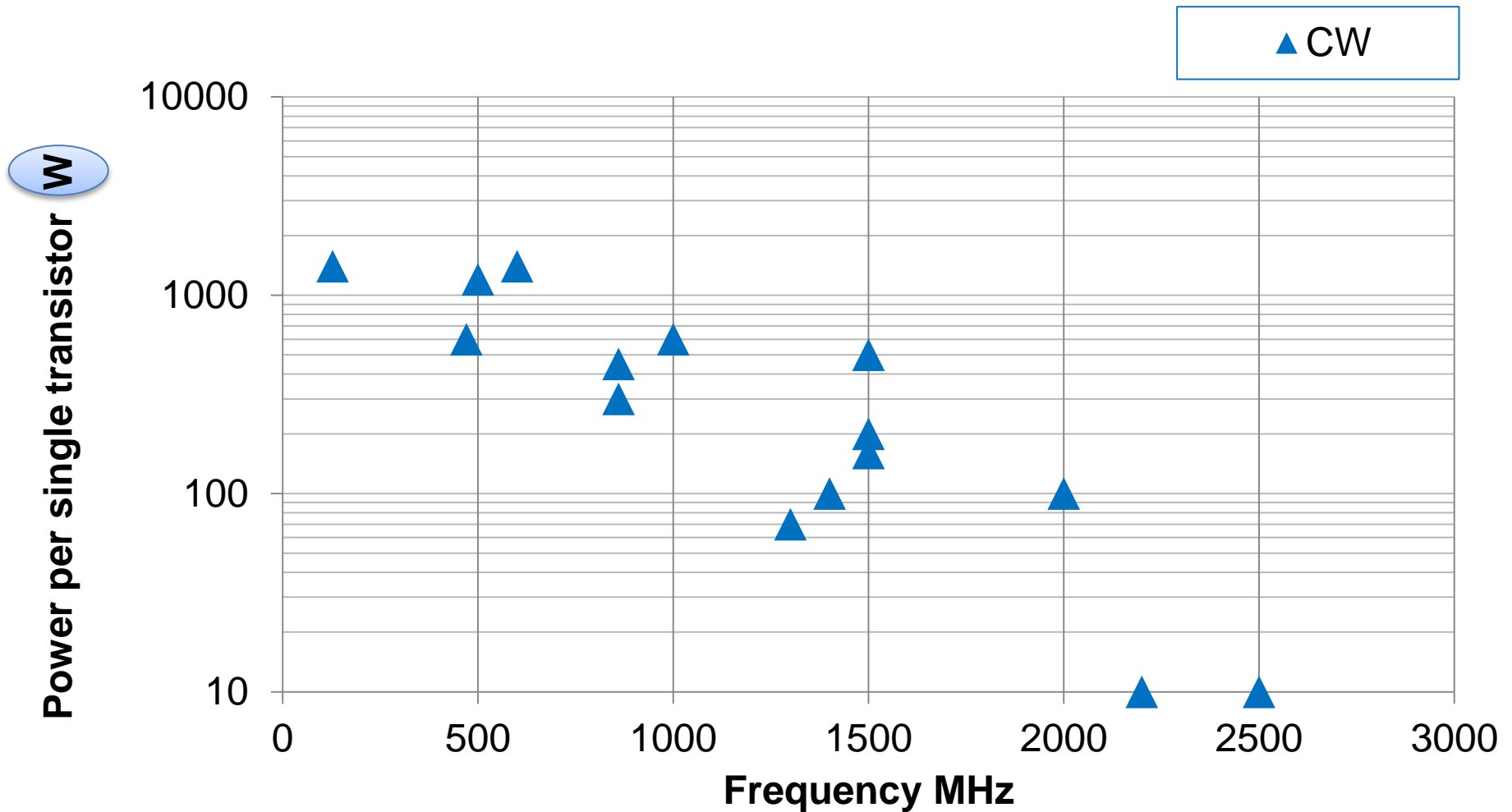
This configuration is easier to manufacture since only one type of device is required

# Essentials of RF transistor



NXP Semiconductors AN11325  
2-way Doherty amplifier with BLF888A

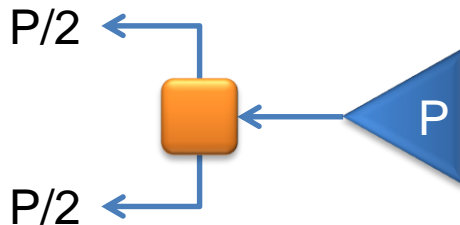
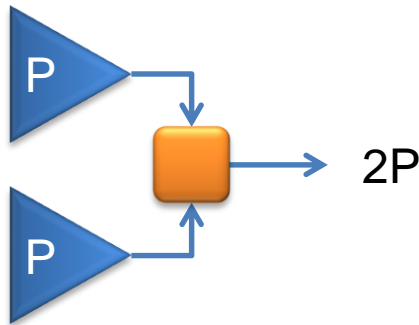
# Transistors available from industry





# 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 induced by the resistors (→ not used in high power)

## Hybrid power splitters & Combiners

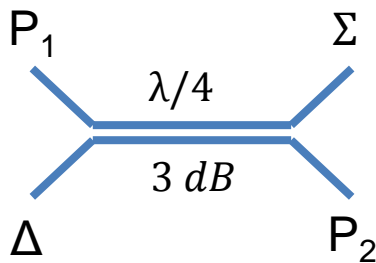
Use RF lines

Low levels of loss

Limitation by the size of the lines

# Combiners & Splitters

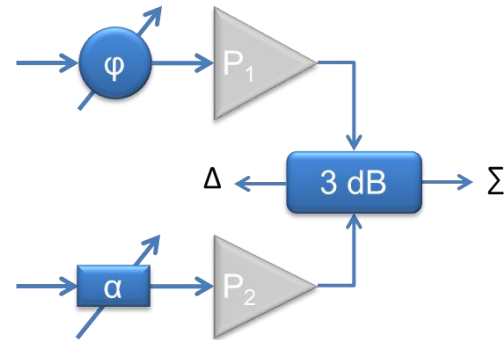
3 dB phase combiner



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,  $P_1 = P_2 = P$

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

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

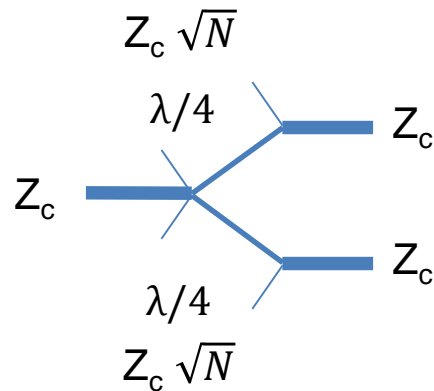
# Combiners & Splitters



CERN SPS 64 to 1 combiner @ 200 MHz

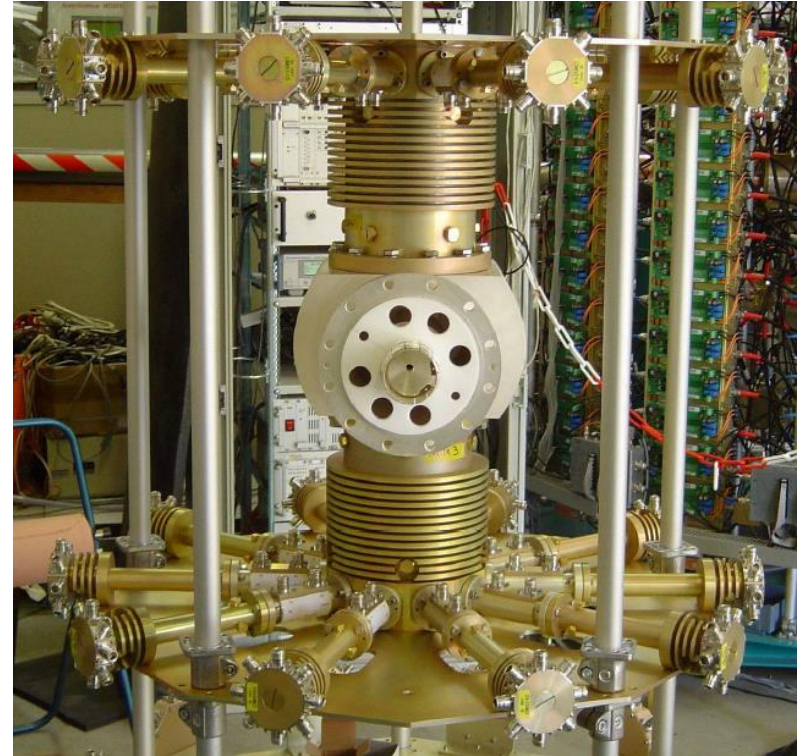
# Combiners & Splitters

Low loss T-Junction



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

We have a N-ways splitter



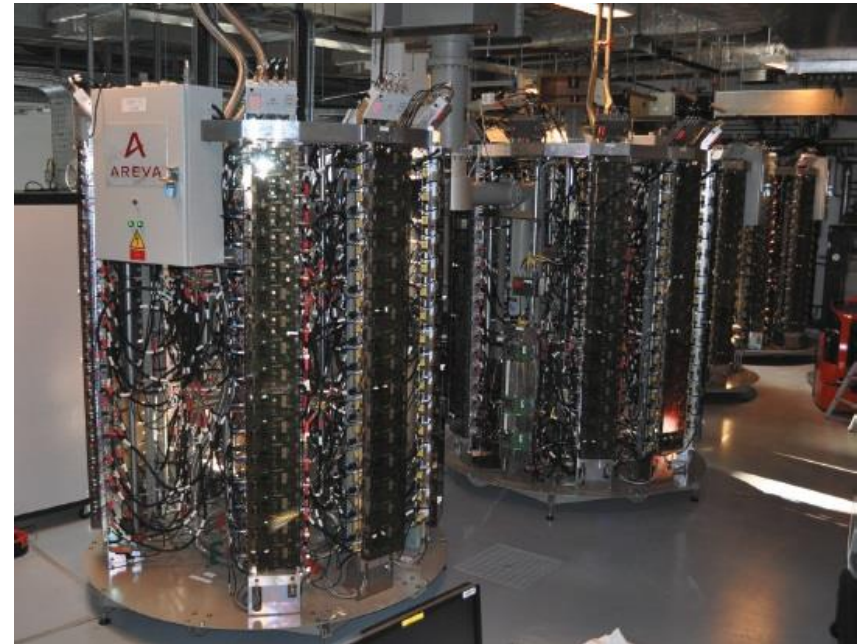
160 to 1 @ 352 MHz  
T-junction combiner

# Transistors

SOLEIL @ 352 MHz and ESRF @ 352 MHz

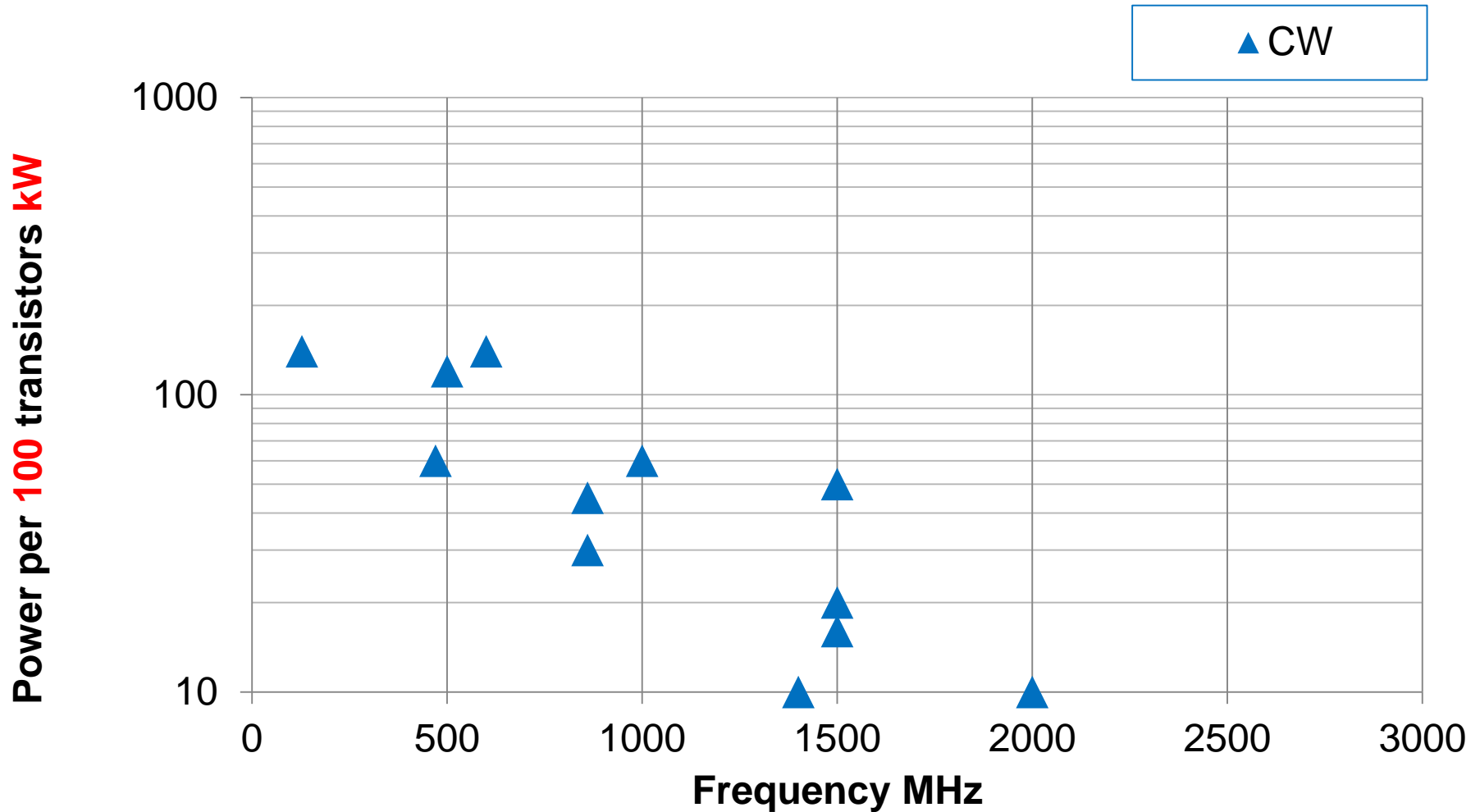


SOLEIL 45 kW @ 352 MHz  
solid state amplifier towers (2004 & 2007)



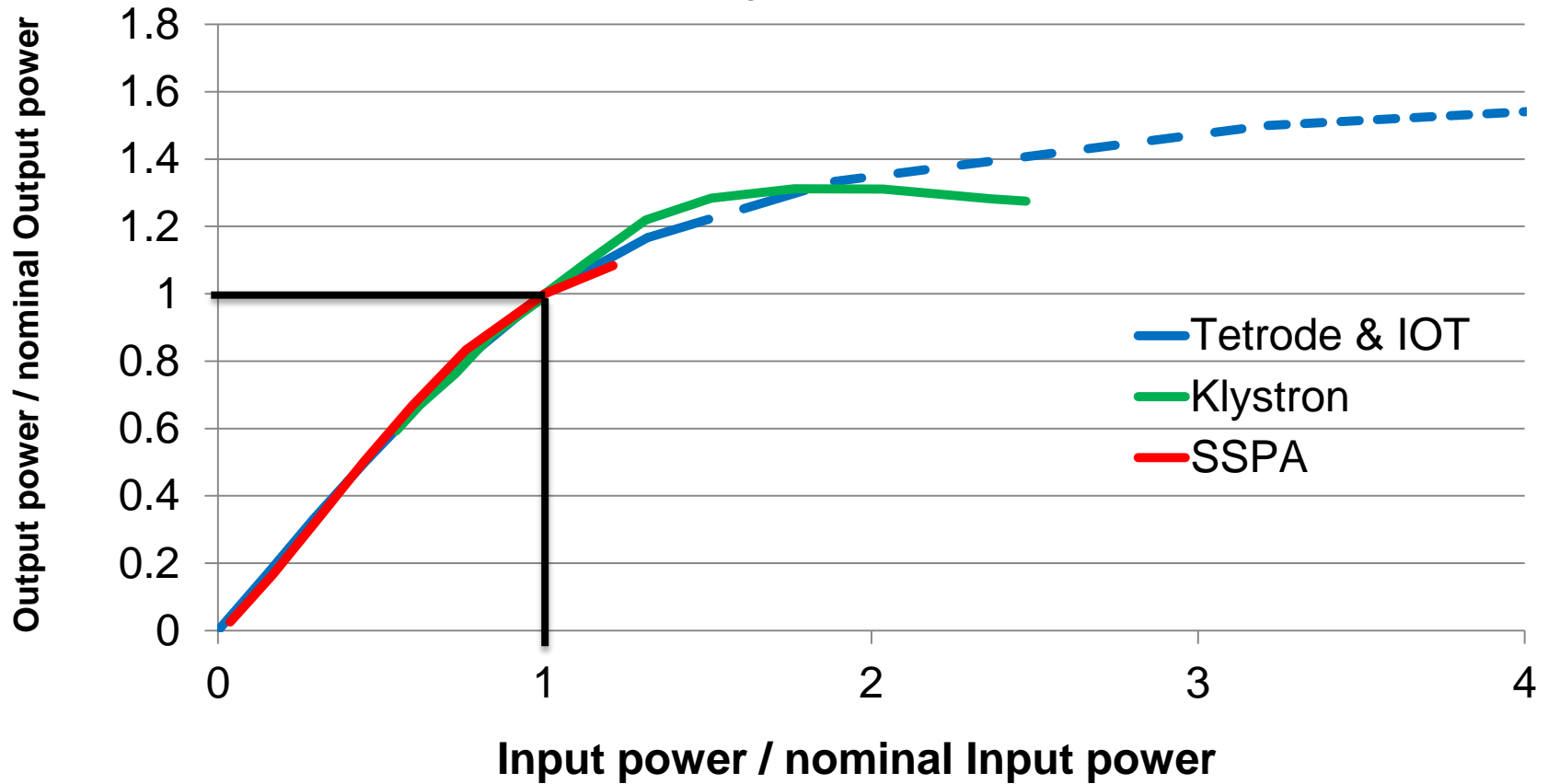
ESRF four 150 kW @ 352 MHz  
solid state amplifiers (2012)

# Transistors available from industry



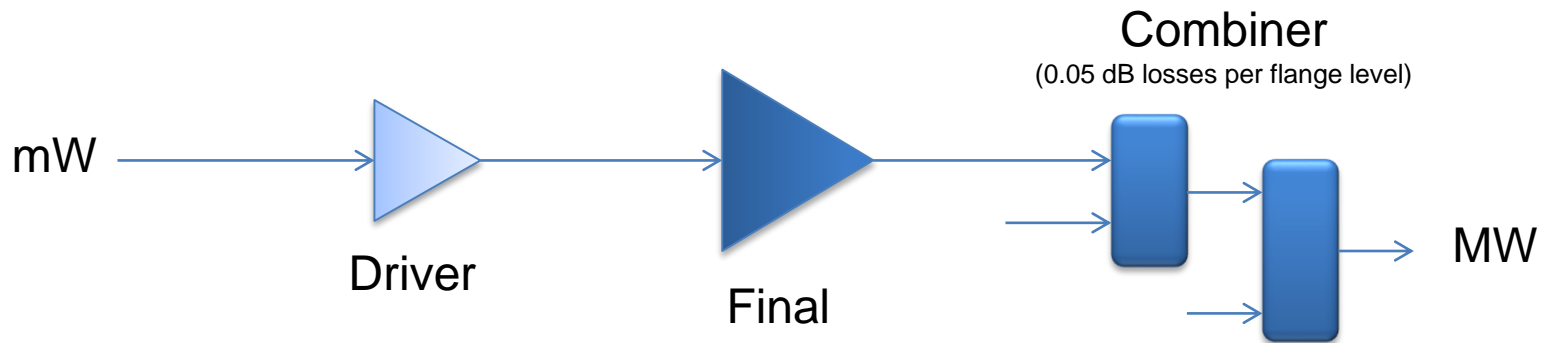
# Overhead

## Tetrodes, Klystrons, SSPA



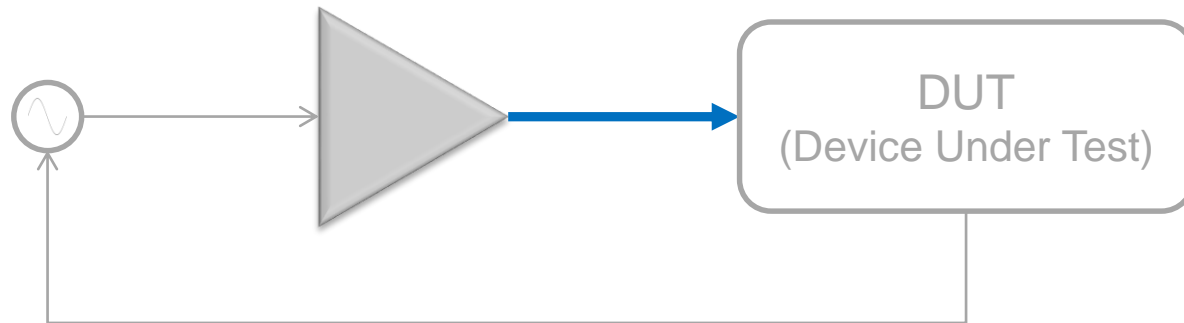
# High Power options

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



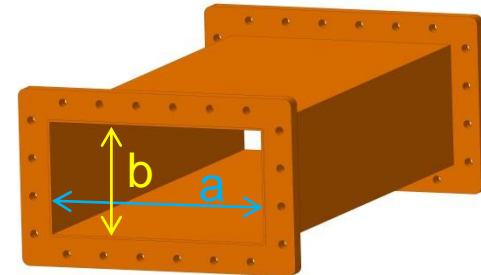


# RF Power Lines



# Rectangular waveguides

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



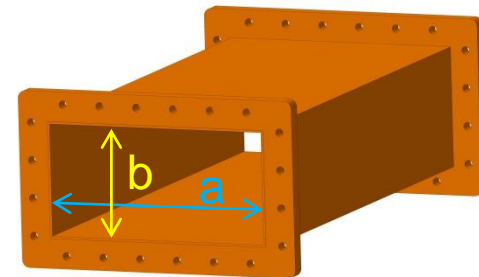
Wavelength	$\lambda_g = \frac{\lambda}{\sqrt{1 - \left(\frac{\lambda}{2a}\right)^2}}$
Cutoff frequency dominant mode	$f_c = \frac{c}{2a}$
Cutoff frequency next higher mode	$f_{c2} = \frac{c}{4a}$
Usable frequency range	$1.3 f_c \text{ to } 0.9 f_{c2}$

# Rectangular waveguides

Waveguides are usable over certain frequency ranges

For very lower frequencies the waveguide dimensions become impractically large

For very high frequencies the dimensions become impractically small & the manufacturing tolerance becomes a significant portion of the waveguide size



Waveguide name			Recommended frequency band of operation (GHz)	Cutoff frequency of lowest order mode (GHz)	Cutoff frequency of next mode (GHz)	Inner dimensions of waveguide opening (inch)
EIA	RCSC	IEC				
WR2300	WG0.0	R3	0.32 — 0.45	0.257	0.513	23.000 × 11.500
WR1150	WG3	R8	0.63 — 0.97	0.513	1.026	11.500 × 5.750
WR340	WG9A	R26	2.20 — 3.30	1.736	3.471	3.400 × 1.700
WR75	WG17	R120	10.00 — 15.00	7.869	15.737	0.750 × 0.375
WR10	WG27	R900	75.00 — 110.00	59.015	118.03	0.100 × 0.050
WR3	WG32	R2600	220.00 — 330.00	173.571	347.143	0.0340 × 0.0170

# Rectangular waveguides

## Maximum Power handling

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

With

P = Power in watts

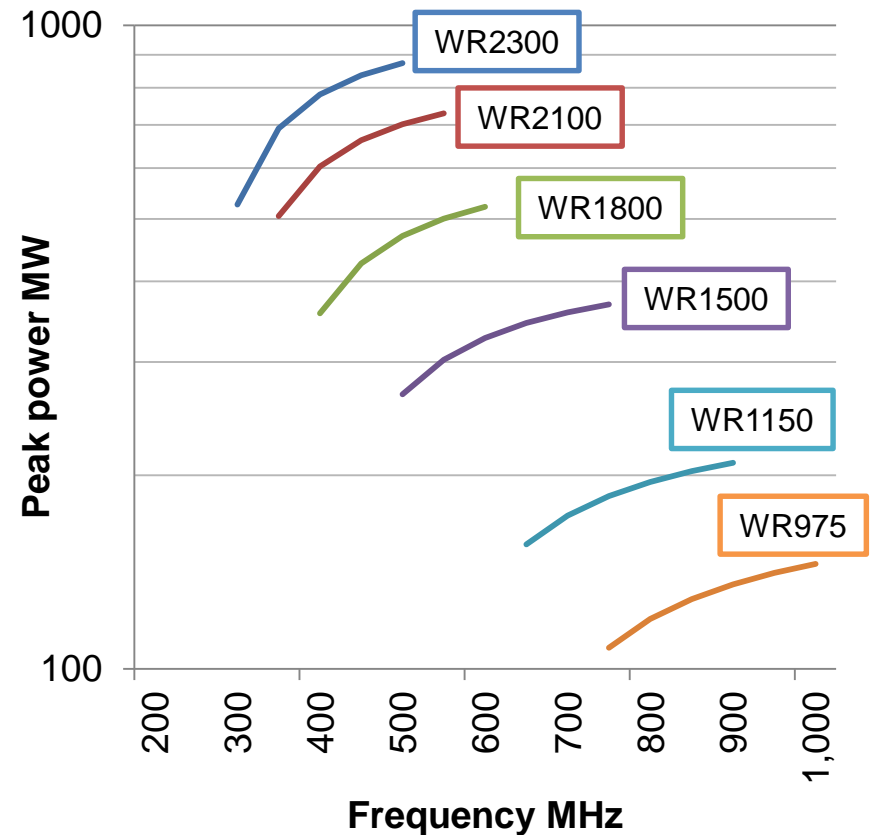
a = width of waveguide in cm

b = height of waveguide in cm

$\lambda$  = 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)

Peak Power vs Frequency



# 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

$a_0 = 3 \cdot 10^{-7}$  [dB/m] for copper

$a$  = width of waveguide in m

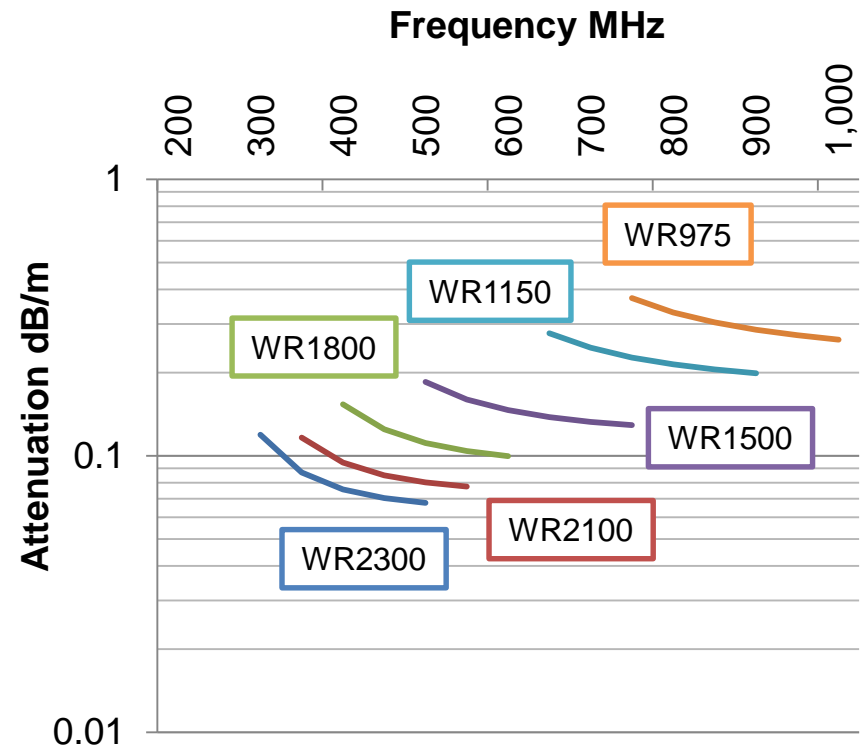
$b$  = height of waveguide in m

$\lambda$  = 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

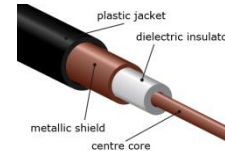
$$Z_c = \frac{60}{\sqrt{\epsilon_r}} \ln \left( \frac{D}{d} \right)$$

With

D = inner dimension of the outer conductor

d = outer dimension of the inner conductor

$\epsilon_r$  = dielectric characteristic of the medium



Coaxial cables are often with PTFE foam to keep concentricity

Flexible lines have spacer helicoidally placed all along the line



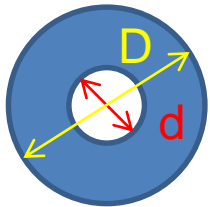
Size	Outer conductor		Inner conductor	
	Outer diameter	Inner diameter	Outer diameter	Inner diameter
7/8"	22.2 mm	20 mm	8.7 mm	7.4 mm
1 5/8"	41.3 mm	38.8 mm	16.9 mm	15.0 mm
3 1/8"	79.4 mm	76.9 mm	33.4 mm	31.3 mm
4 1/2"	106 mm	103 mm	44.8 mm	42.8 mm
6 1/8"	155.6 mm	151.9 mm	66.0 mm	64.0 mm



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

# Coaxial lines Maximum Power handling

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



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

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

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

With

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

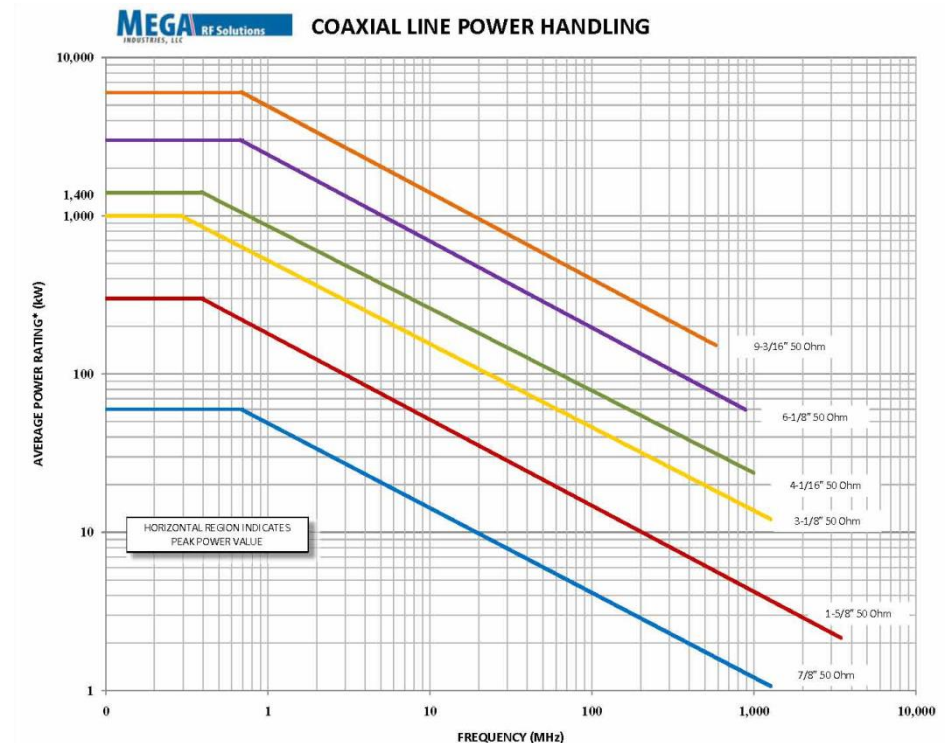
D = inside electrical diameter of outer conductor in mm

d = outside electrical diameter of inner conductor in mm

Zc = characteristic impedance in Ω

ε<sub>r</sub> = relative permittivity of dielectric

f = frequency in MHz



# Coaxial lines Attenuation

The attenuation of a coaxial line is expressed as

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

where

$\alpha$  = attenuation constant, dB/m

$Z_c$  = characteristic impedance in  $\Omega$

$f$  = frequency in MHz

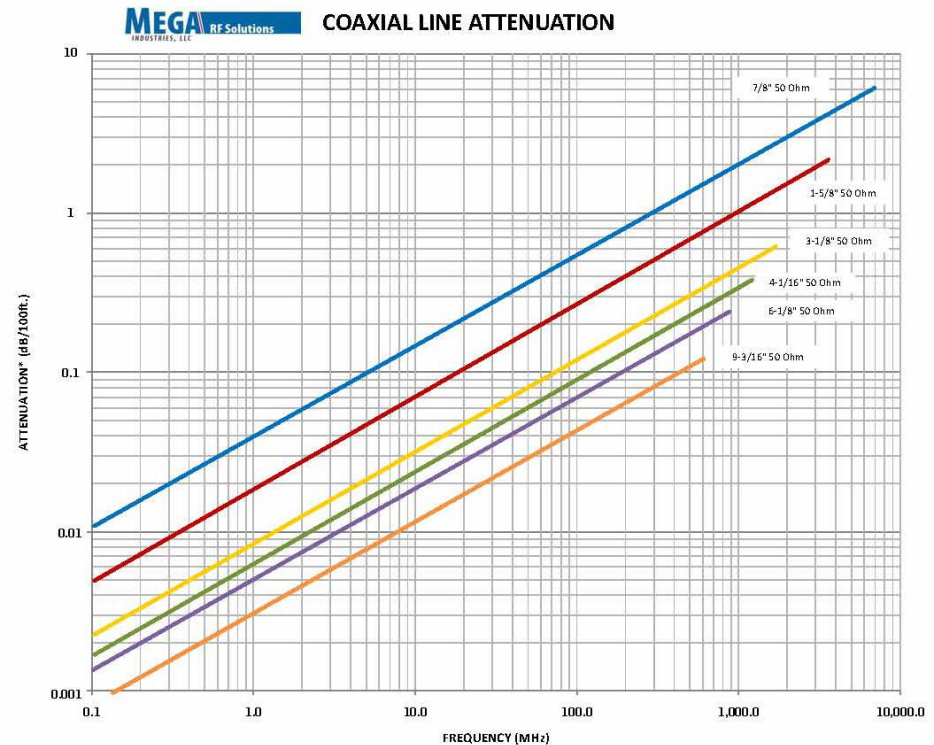
$D$  = inside electrical diameter of outer conductor in mm

$d$  = outside electrical diameter of inner conductor in mm

$\epsilon_r$  = relative permittivity of dielectric

$\tan \delta$  = loss factor of dielectric

Material	$\epsilon_r$	$\tan \delta$	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

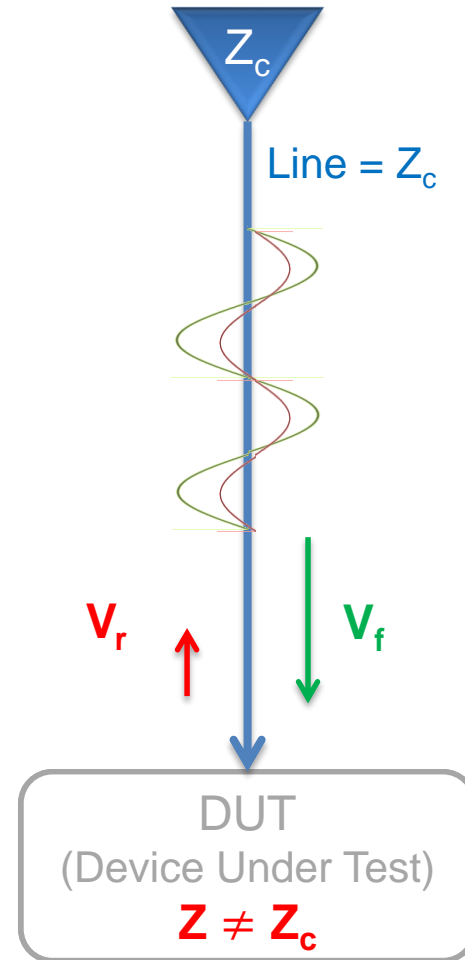
Standing Wave Ratio SWR is a measure of impedance matching of DUT

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

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

$\Gamma = -1$	when the line is short-circuited complete negative reflection
$\Gamma = 0$	when the line is perfectly matched, no reflection
$\Gamma = 1$	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

$$\begin{aligned}|V_{max}| &= |V_f| + |V_r| \\ &= |V_f| + |\Gamma V_f| \\ &= (1 + |\Gamma|) |V_f|\end{aligned}$$

full reflection

$$|V_{max}| = 2 |V_f|$$

At other points they are 180° out of phase

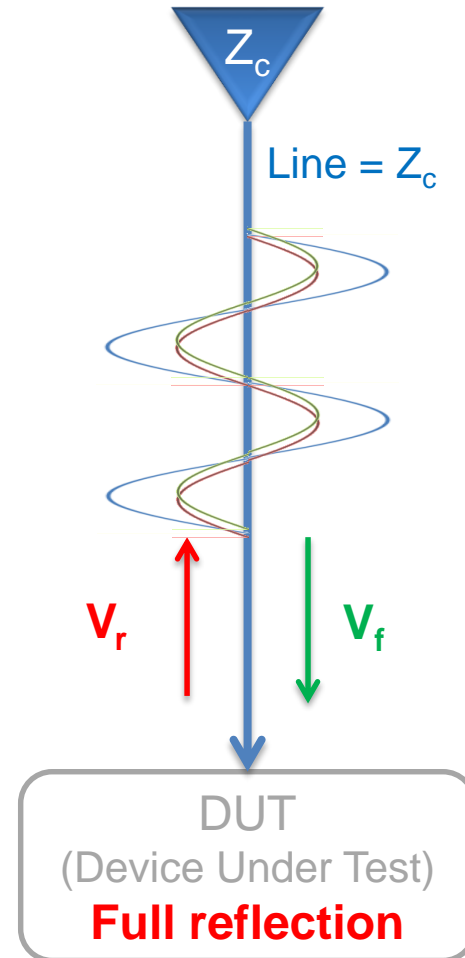
$$\begin{aligned}|V_{min}| &= |V_f| - |V_r| \\ &= |V_f| - |\Gamma V_f| \\ &= (1 - |\Gamma|) |V_f|\end{aligned}$$

full reflection

$$|V_{min}| = 0$$

The Voltage Standing Wave Ratio is equal to

$$VSWR = \frac{|V_{max}|}{|V_{min}|} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$



# Reflection from Load

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

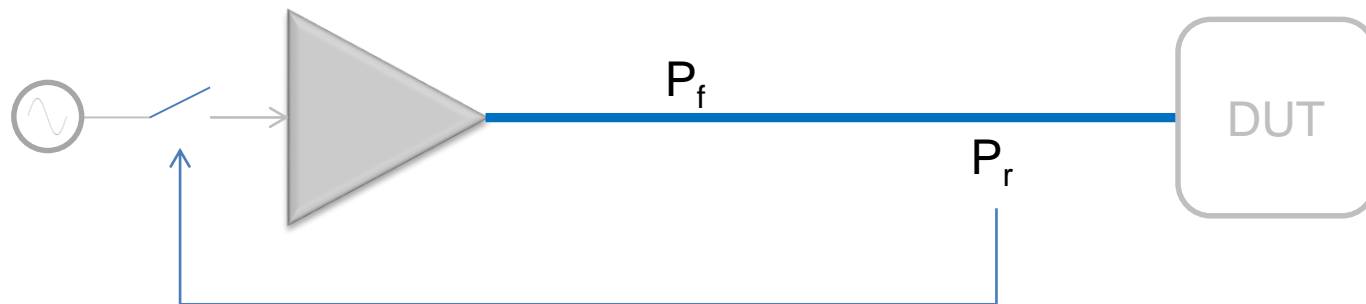
RF power amplifiers will not like this reflected wave

Klystron output cavity disturbed

Grid tube, IOT and Transistor voltage capability

Swift protection if  $P_r > P_{r\max}$

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

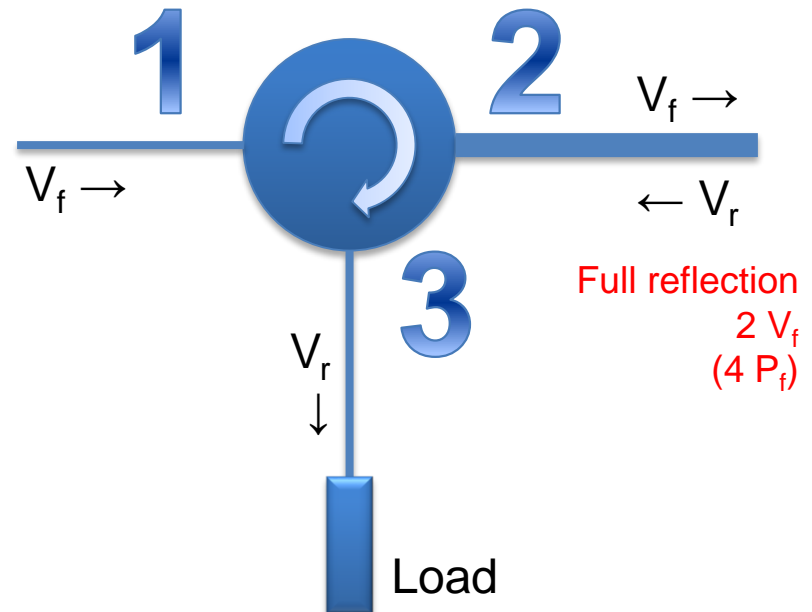
passive non-reciprocal three-port device

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  $P_r$

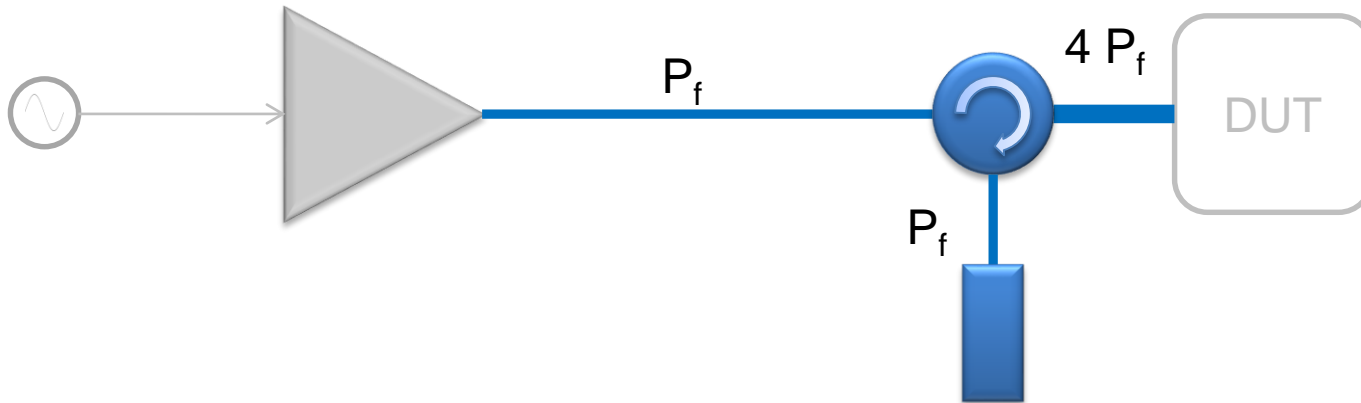


# Circulator

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



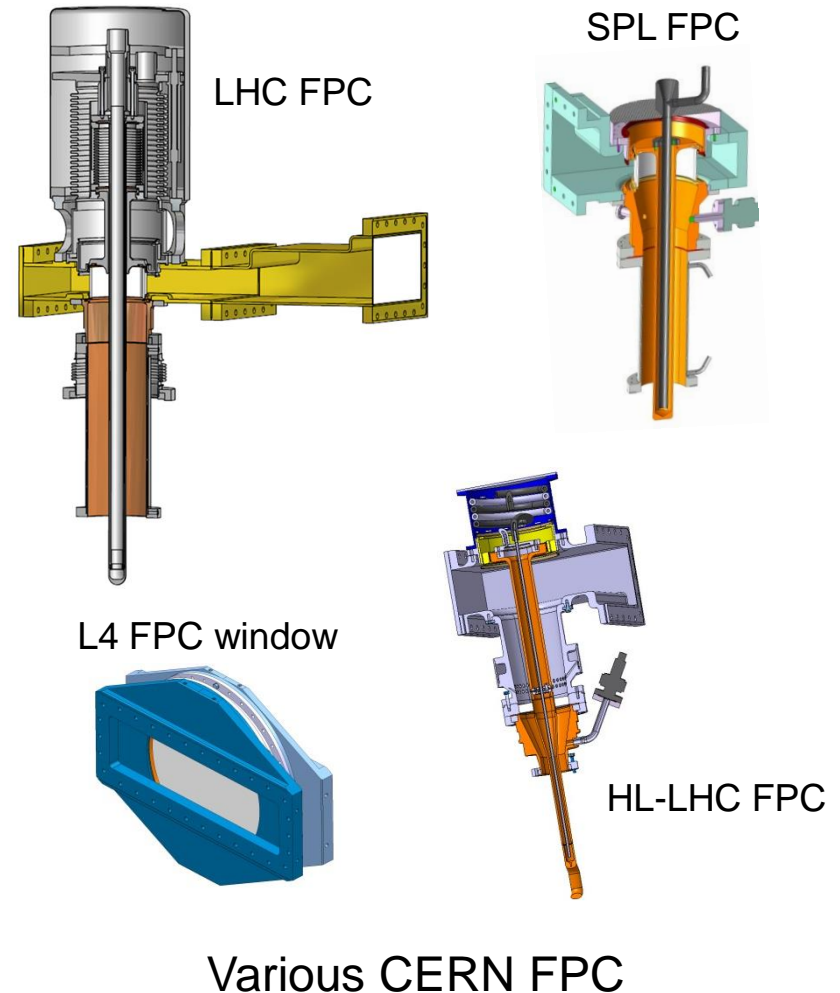
# Fundamental Power Coupler FPC

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



# Case Study

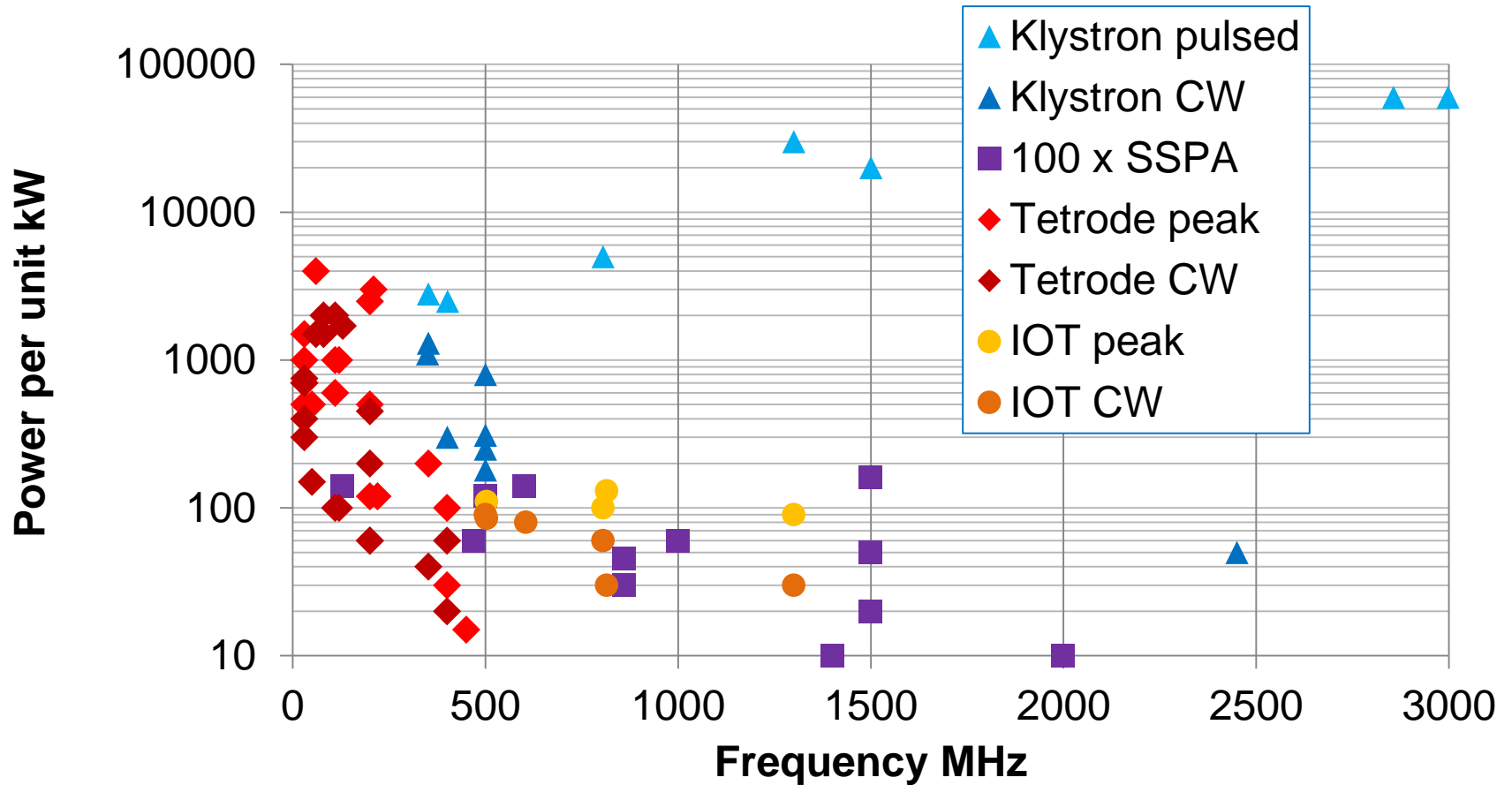
Frequency

Overhead, peak and average power

Efficiency

Rough cost estimate

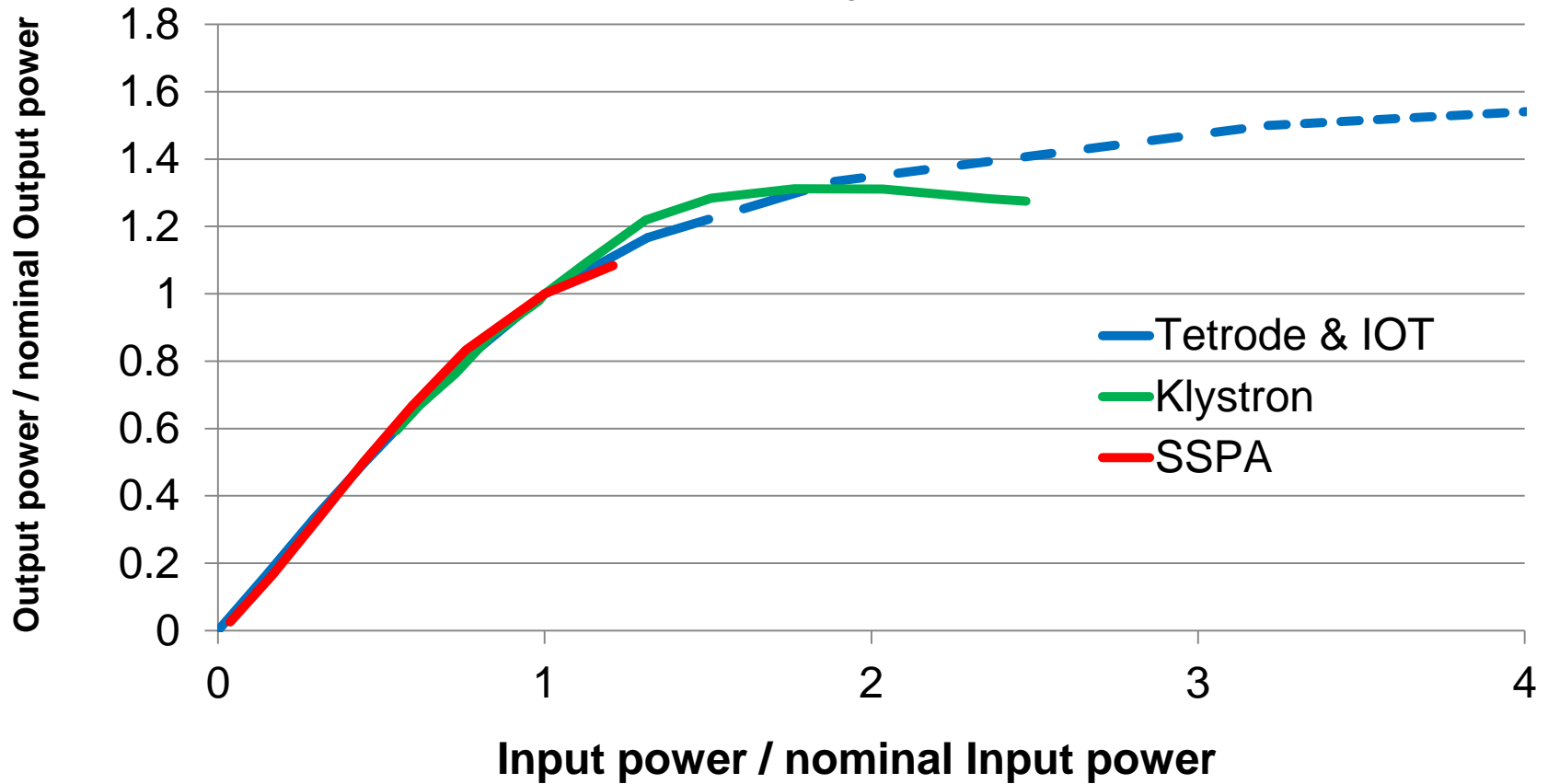
# Frequency



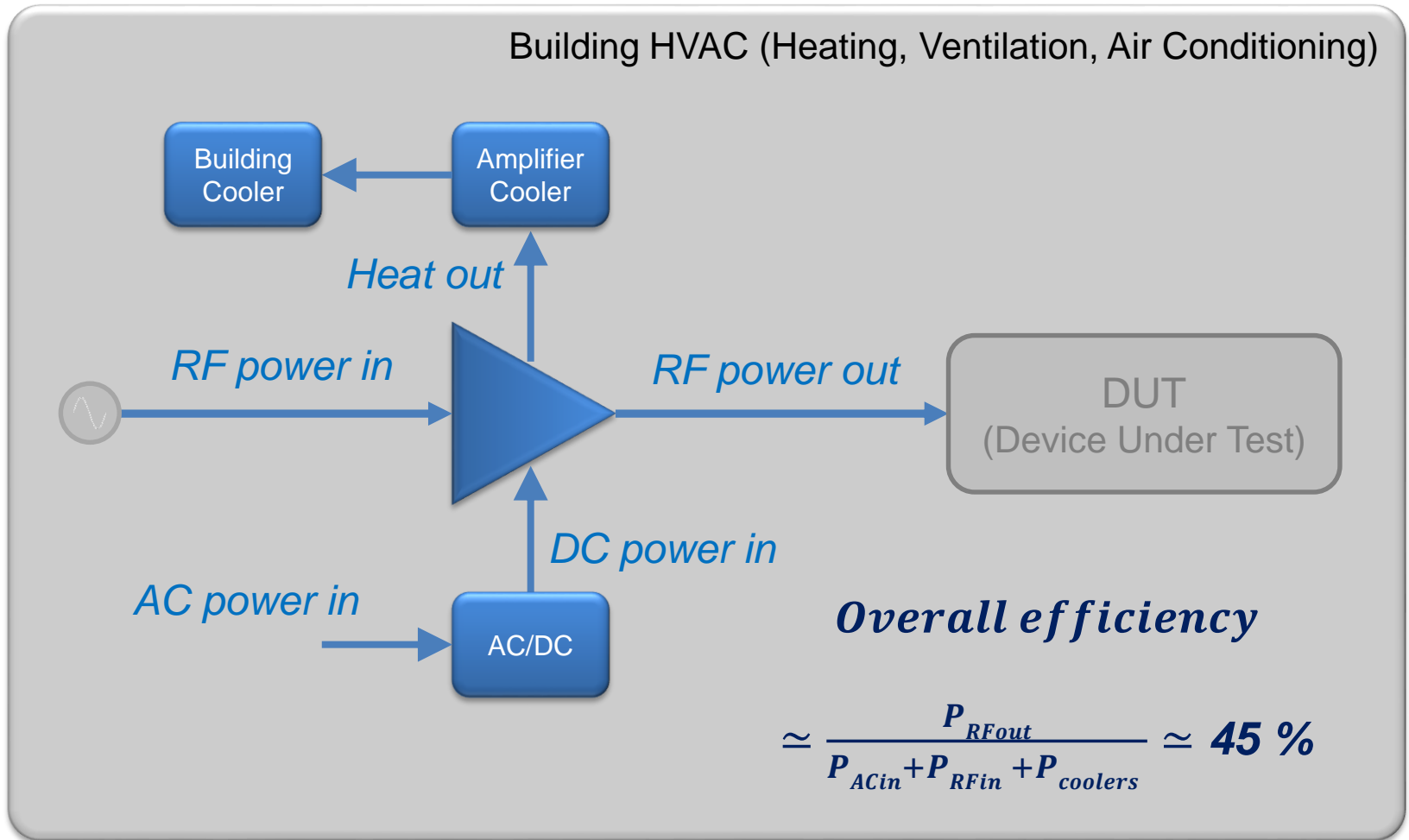


# Overhead, peak and average power

## Tetrodes, Klystrons, SSPA



# Overall Efficiency = Electrical bill



# Overall Efficiency

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

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

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

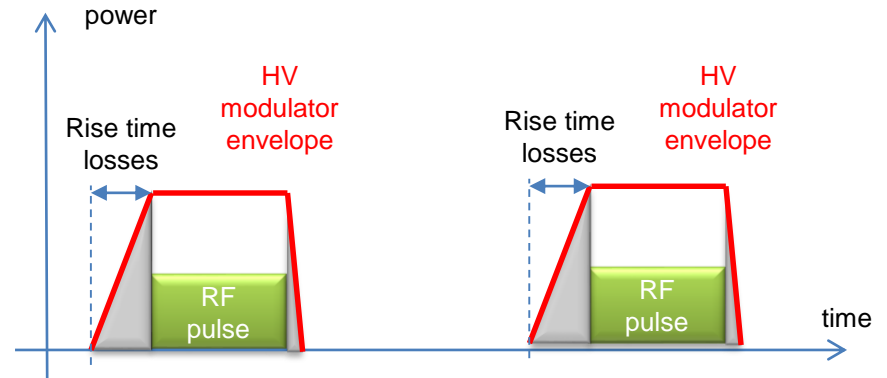
Amplifier cooler  $\approx 15 \% P_{RFout}$

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

$$\text{Overall efficiency} = \frac{P_{RFout}}{P_{RFin} + P_{ACin} + P_{coolers}}$$

$$\approx \frac{P_{RFout}}{P_{RFout} (0.05 + 1.62 + 0.45)}$$

$\approx 45 \%$



HVPS Modulator for klystron -> few additional overall losses



Amplifier and building coolers are not so efficient

# Acquisition & operation costs

Technology *	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 $\eta = 45\%$	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)

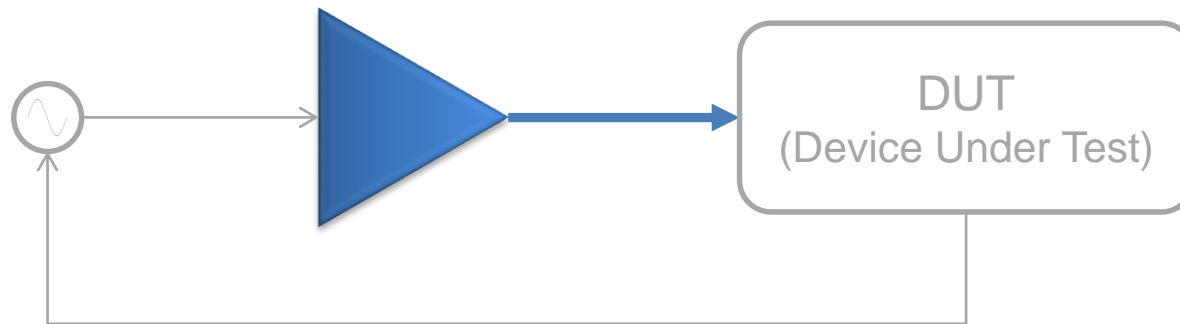
What power specialists are available (technology choice)

To correctly size the transmission lines

The need or not of a circulator

Your HVAC system (this will dominate your wall-plug efficiency ratio)

# 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](http://cds.cern.ch/record/211448/files/CERN-2005-003)

1992 (596 pages) <http://cds.cern.ch/record/211448/files/CERN-92-03-V-2.pdf>

# References

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HÜTTE des ingenieurs taschenbuch (Berlin 1955 edition)

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/](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