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CERN RF Group
RF Amplifiers and Couplers

CAS course on "RF for Accelerators",
18 June - 01 July 2023, Berlin Germany

RF for Accelerators

RF power generation

1983
—2023
years

The CERN Accelerator School

HZB Helmholtz
Zentrum Berlin

The CERN Accelerator School

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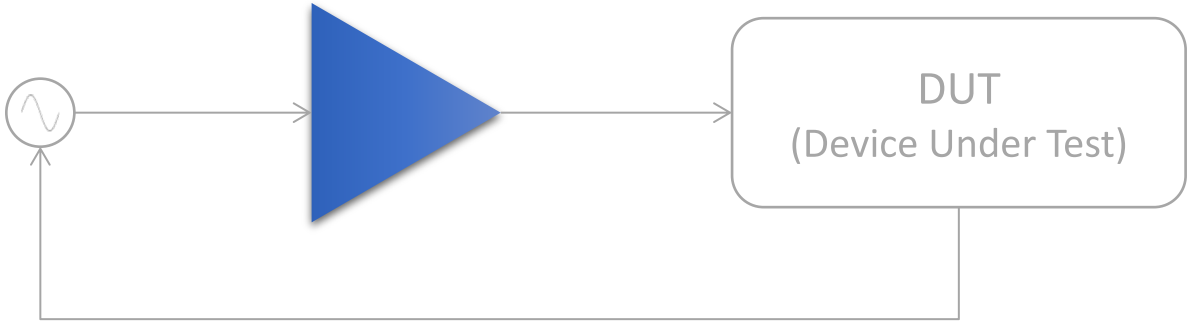
RF Power - preamble



W → kW → MW

€ → k€ → M€

Very important for all projects

Rule of thumbs, HPRF acquisition costs

From 5 € / W (MW amplifiers)

to 10 € / W (kW amplifiers)

RF Power - preamble

Class of operation	A	B	C
Advantage	Linear	Almost linear	Non linear
DC to RF efficiency	30 %	78.5 %	90 %
Wall plug efficiency	20 %	40 %	50 %
Cost per 10 year [k€] **100 kW RF CW < 800 MHz** **5000 hours/year**	**3750**	**1870**	**1500**

W → kW → MW

€ → k€ → M€

Very important for all projects

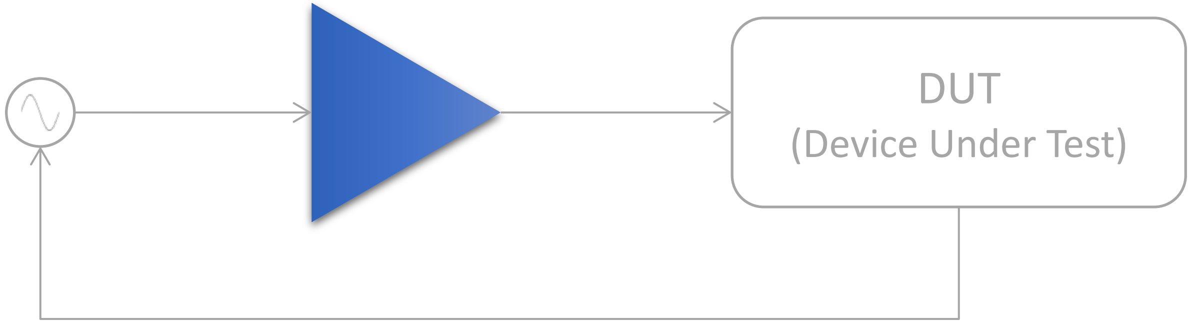
Rule of thumbs, HPRF operational costs

$$\frac{0.20\ € \ /\ kWh}{Wall\ plug\ efficiency}$$

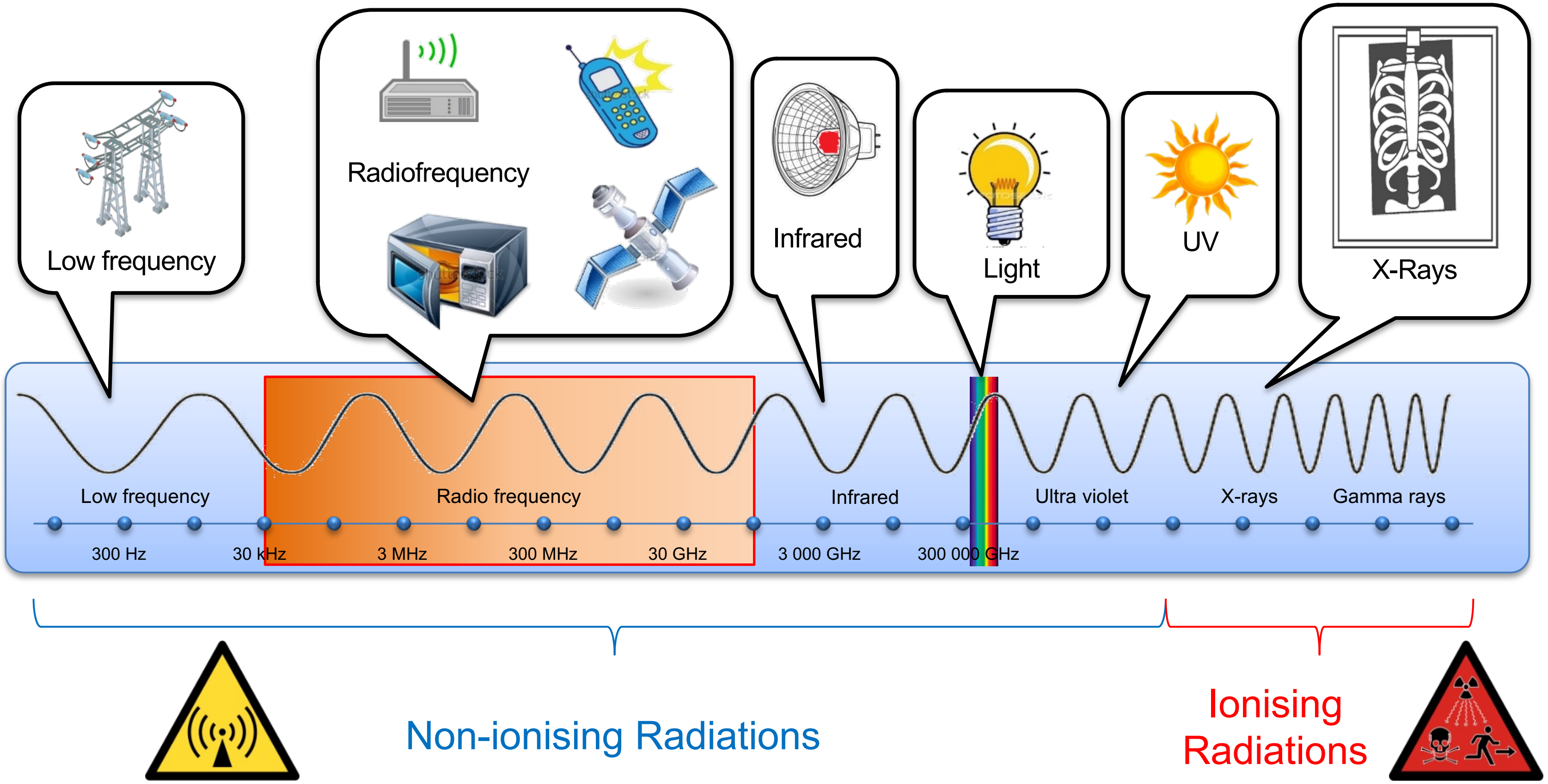
Outlook

- RF power basics
- Vacuum Tubes
  - Vacuum
  - Cathodes
  - Triodes
  - Tetrodes
  - Klystrons
  - IOTs
- Transistors
  - LDMOS
- Combining
- Efficiency
- Conclusion

RF Power basics

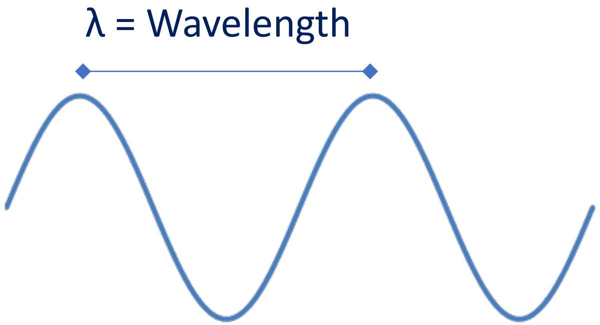


Electromagnetic waves



Wavelength, frequency

$$\lambda = \frac{c}{f\,\sqrt{\varepsilon}} \quad \leftrightarrow \quad f = \frac{c}{\lambda\,\sqrt{\varepsilon}}$$



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)*

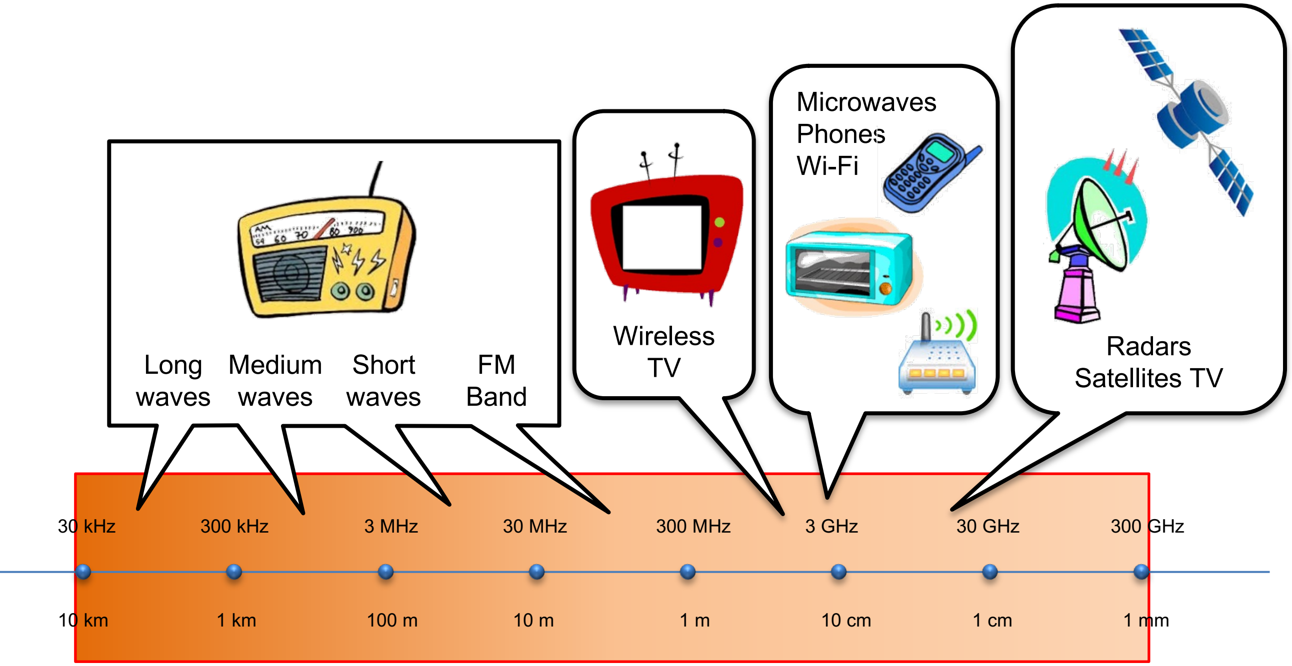
Depends on the medium we are talking about

ε *air*	= 1
ε *vacuum*	= 1
ε *'plastic'*	= 3-5
ε *'ceramic'*	= ~ 9

Radiofrequency waves

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

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



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

Decibel (dB)

$$dBm = 10\ Log_{10}\,(P_{mW})$$

$$dB = 10\ Log_{10}\left(\frac{P_1}{P_2}\right)$$

$$dB = 20\ Log_{10}\,(V_1/V_2)$$
$$dBV = 20\ Log_{10}\,(V_{Vrms})$$
$$dB\mu V = 20\ Log_{10}\,(V_{\mu Vrms})$$
$$dBc = 10\ Log_{10}\,(P_{carrier}/P_{signal})$$

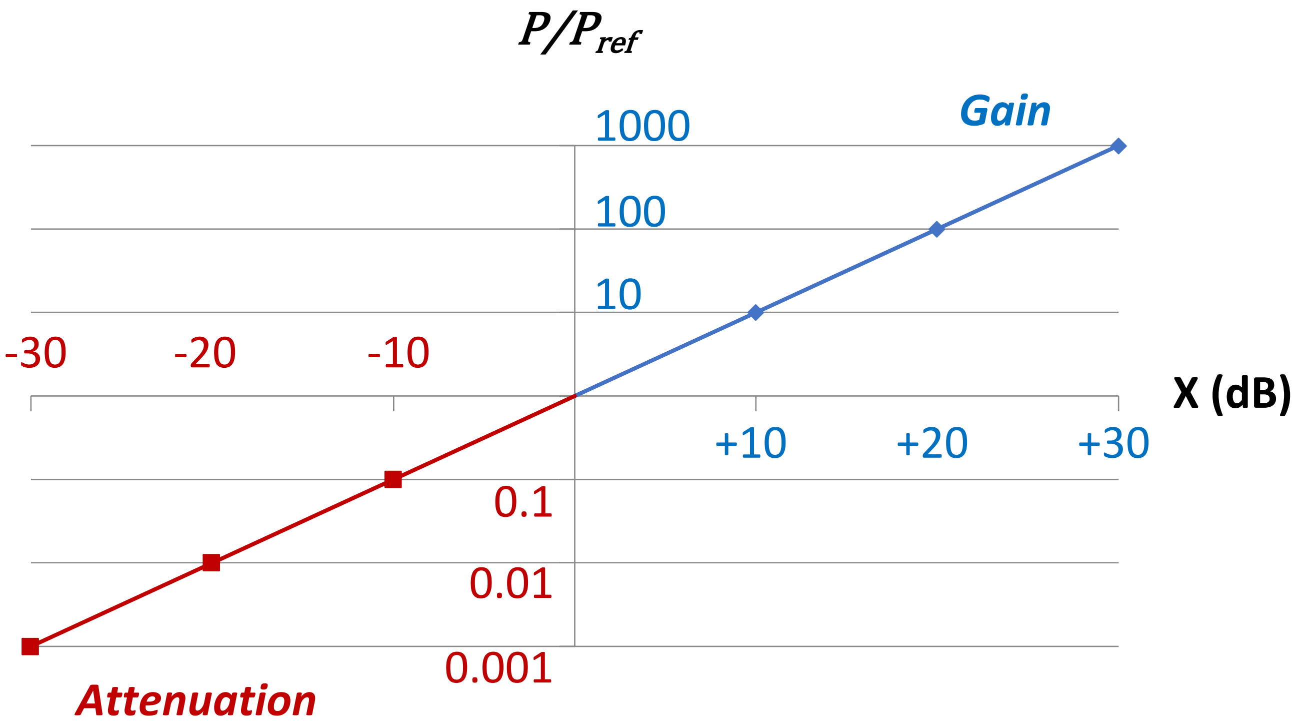
dBm, W

$$x_{dBm} = 10\,Log_{10}\,(PmW) \quad \leftrightarrow \quad P_{mW} = 10^{\,(x_{dBm}/10)}$$

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

dB, Power ratio

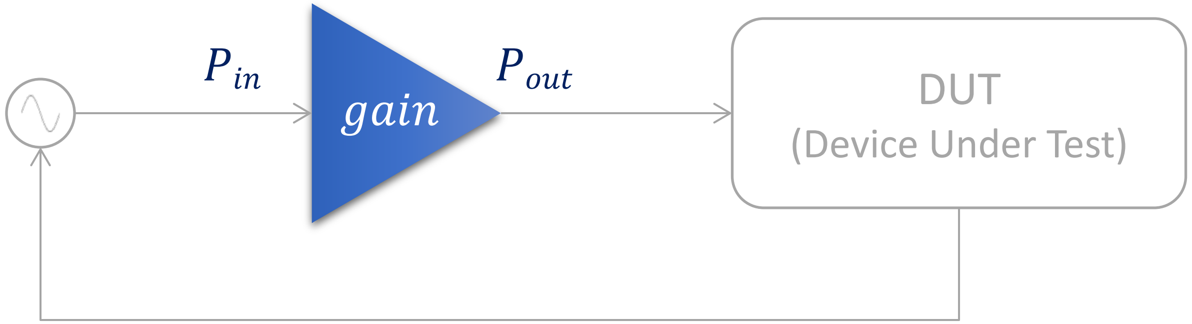
$$x_{dB} = 10\,Log_{10}\,(P/P_{ref}) \quad \leftrightarrow \quad P/P_{ref} = 10^{\,(x_{dB}/10)}$$



dB, Power ratio

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



Basically, it is about amplifying with a gain

$$P_{out} = gain\,.\,Pin$$

The ideal power amplifier

- Large bandwidth amplifying all frequencies equally
- No saturation
- Infinite power
- Zero delay
- No added noise
- Unconditionally stable
- Resistant to reverse power
- Radiation hard
- Efficient to transform AC input into RF output

Unfortunately, such a device does not exist (yet?)

RF power source classification

Vacuum Tubes

Grid Tubes

Triodes
Tetrodes
Pentodes
Diacrodes

Linear Beam Tubes

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

Crossed-field Tubes

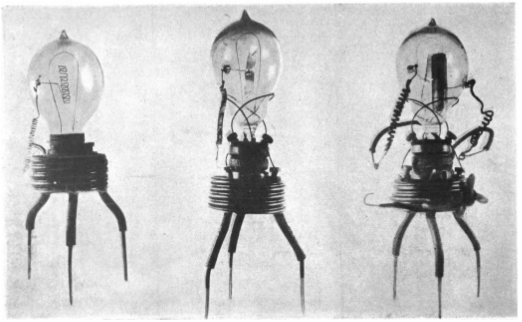
Magnetrons

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)
Silicon Germanium (SiGe)
Gallium Arsenide (GaAs)
Gallium Nitride (GaN)

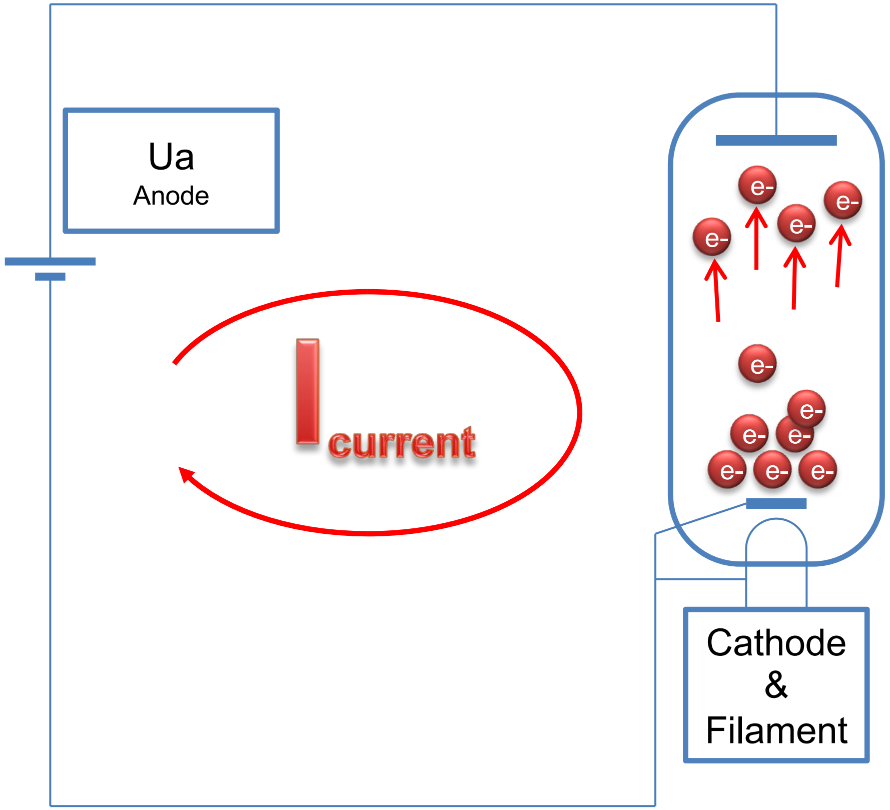
Grid tubes

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

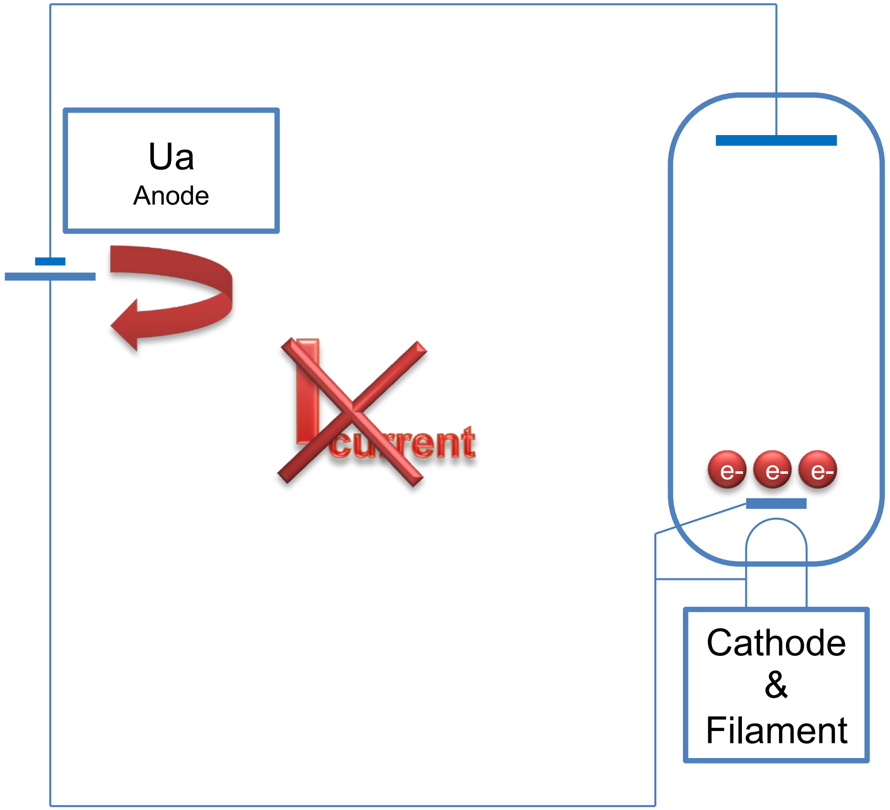
Heater + Cathode

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

Anode

Diode

Essentials of grid tube



Vacuum tube

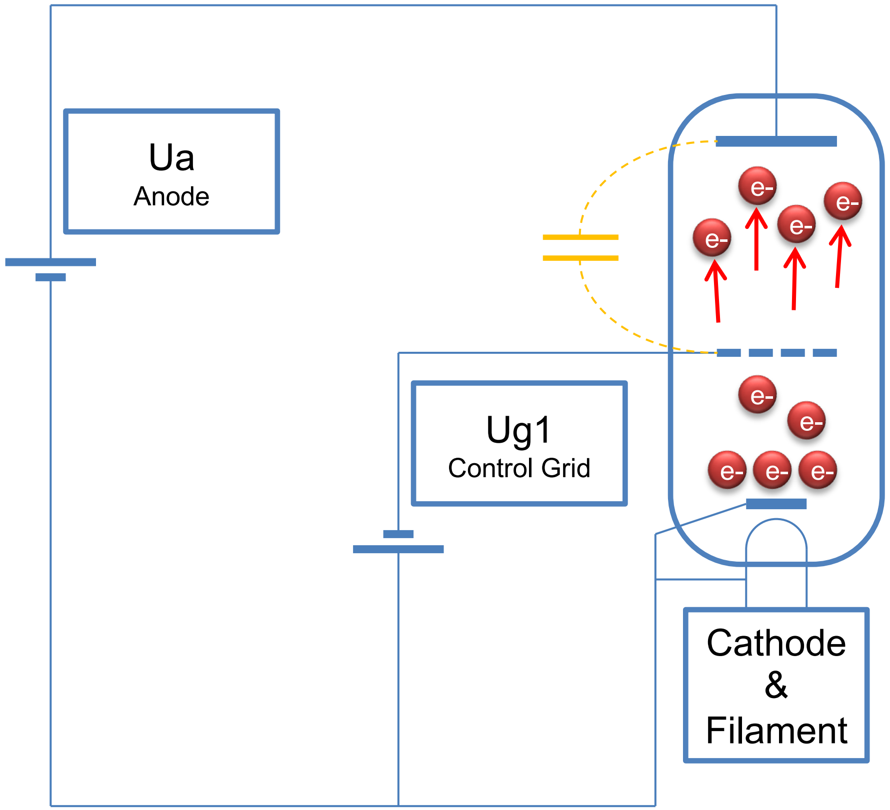
Heater + Cathode

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

Anode

Diode

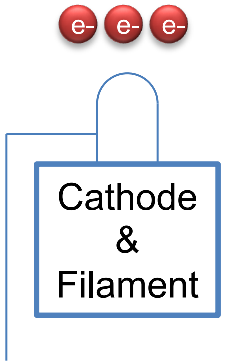
Essentials of grid tube



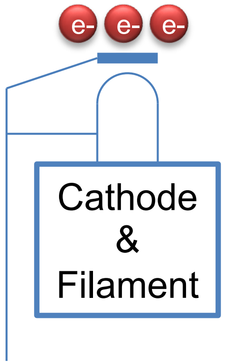
Triode

- 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

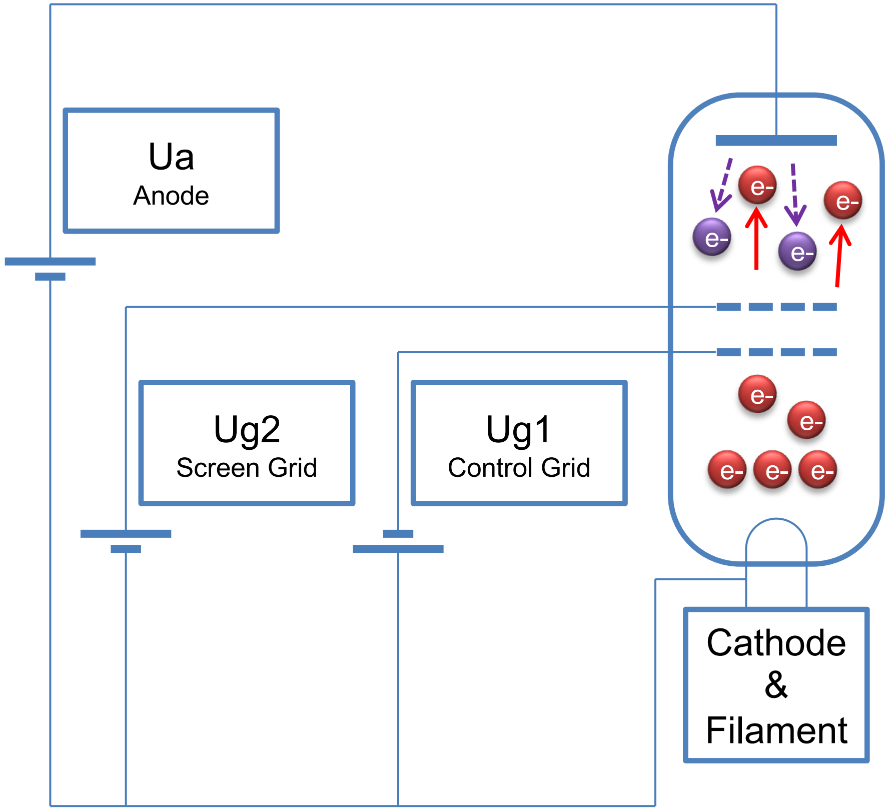


Direct heating cathode, Thoriated Tungsten



Indirect heating cathode, Oxide

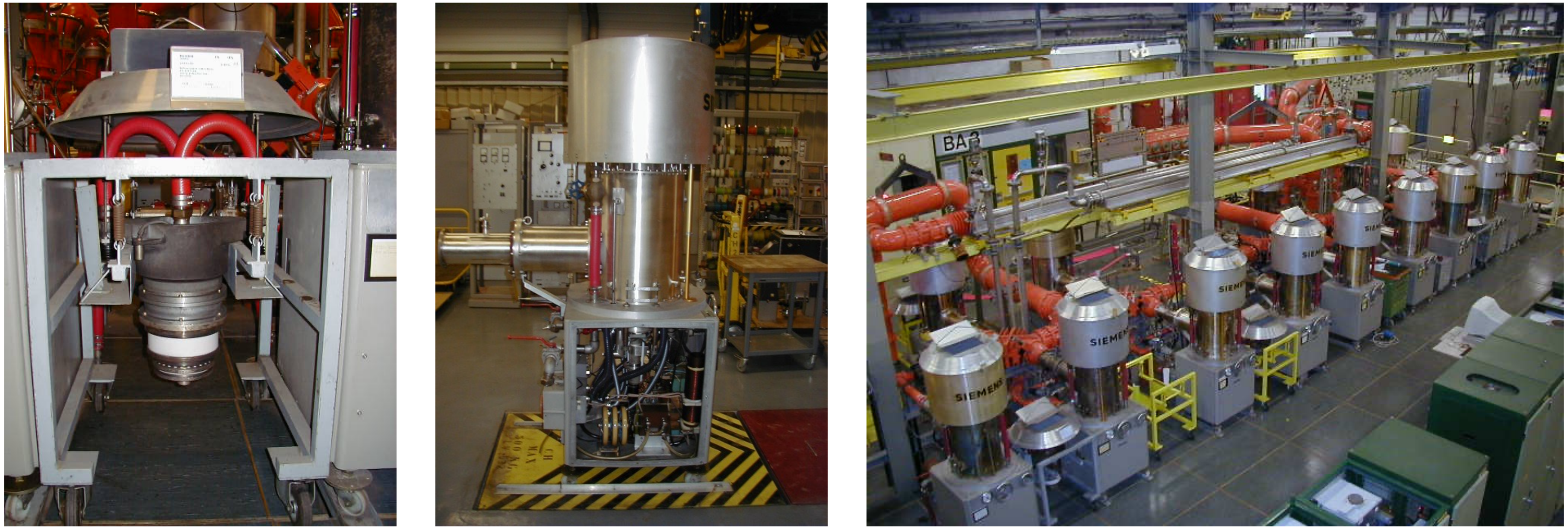
Essentials of grid tube



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 amplifier

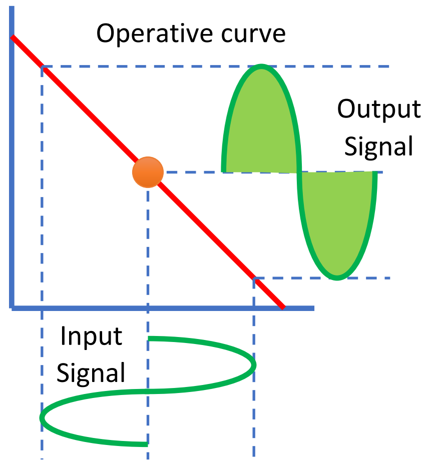


CERN SPS, RS 2004 Tetrode, Trolley (single amplifier), and transmitter (combination of amplifiers)
Two transmitters of eight tubes delivering 2 x 1 MW @ 200 MHz, into operation since 1976

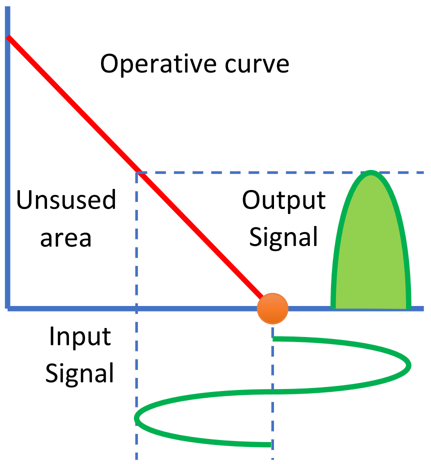
Amplifier class

* Class B and Class C need resonant circuitry for output sine therefore narrow band amplifiers

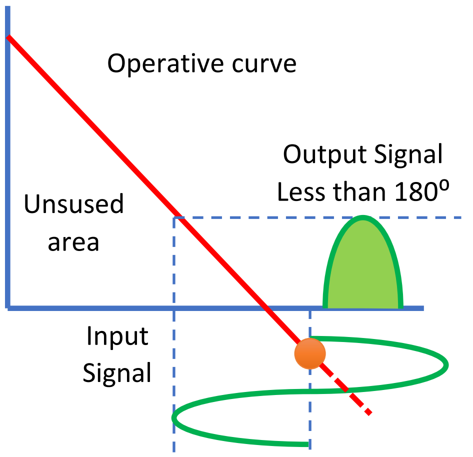
Class A (max theoretical eff 50%)

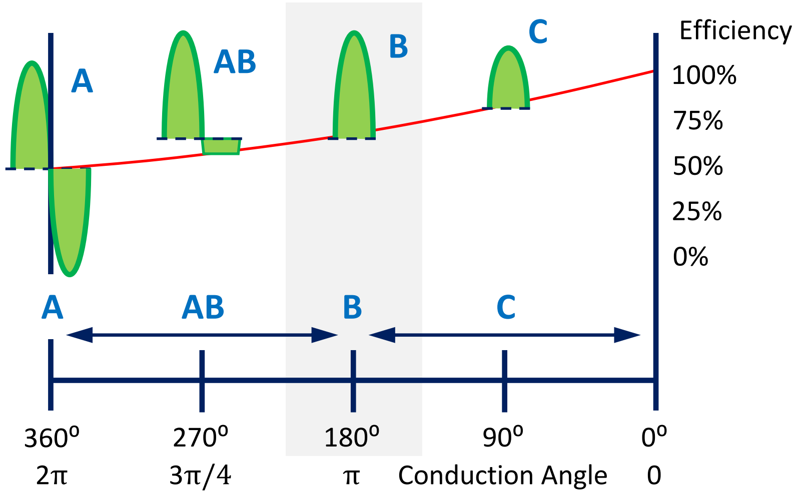


Class B (max theoretical eff 78%) *



Class C (max theoretical eff > 78%) *





Amplifier Class	Description
Class-A	High linearity required, low power amplifiers
Class-B	Regularly used in dual push-pull configuration, so as to restore full sine anode current and cancel even harmonics
Class-C	High efficiency Efficiency depends on conduction angle More the efficiency, less the gain

Theoretical Class B efficiency

DC power is Pdc = Vdc Idc

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

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

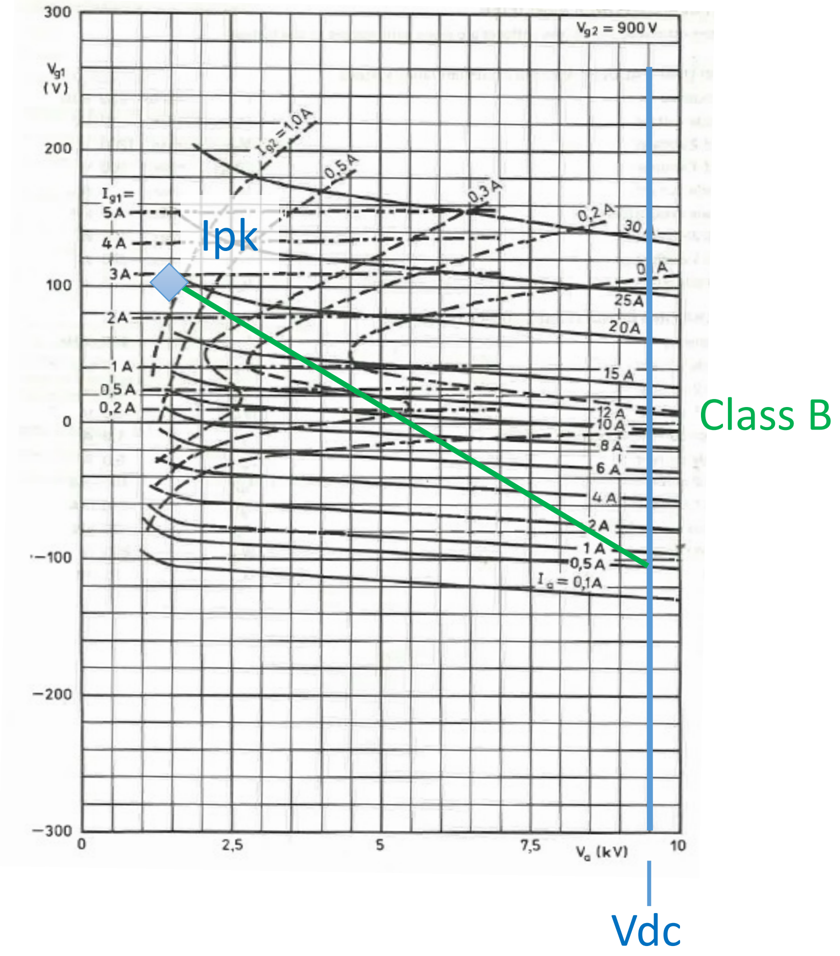
So, RF power is Prf = ½ Vrf Irf

Prf = ½ Vdc Idc π/2 = π/4 Vdc Idc

Theoretical efficiency

η = Prf/Pdc = ¼ Vdc Ipk / Vdc Idc

η = 78.5 %



Class B efficiency in practice

Two reasons for not achieving this impressive number

1. tube is not fully linear whilst it is conducting
2. Anode voltage must be higher than G2 voltage, VG2 being ~ 10% Vdc

This leads into

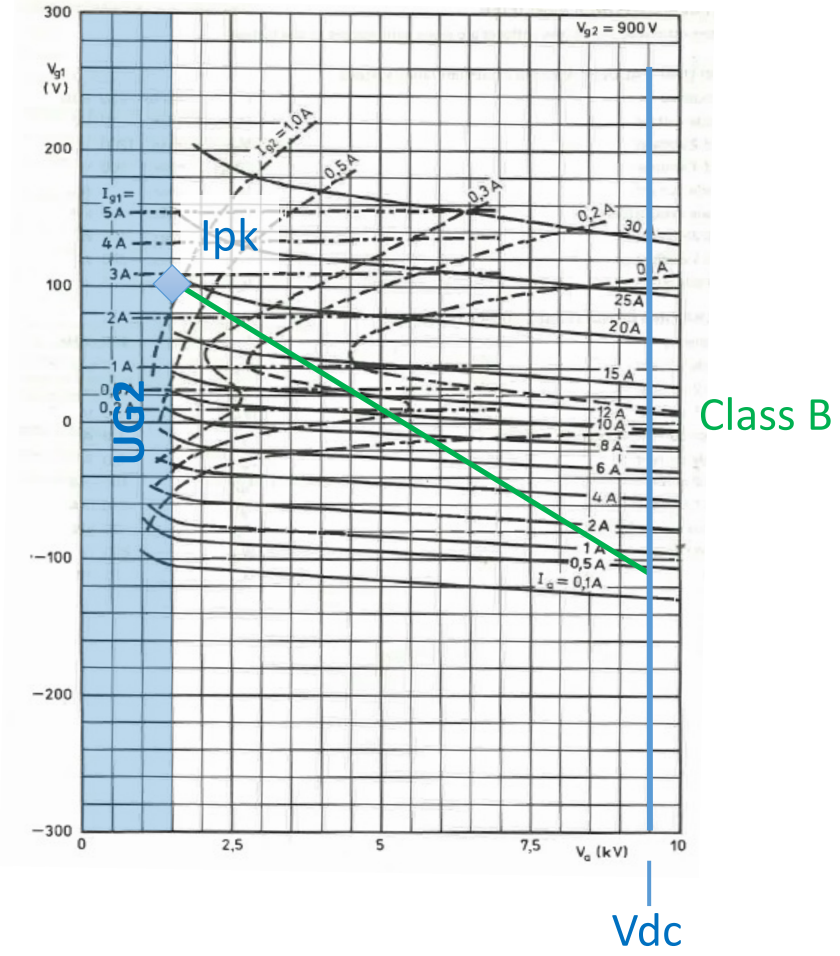
Pdc = Vdc Idc = Vdc 1.05 Ipk/π

Prf = ½ Vrf Irf = ¼ 0.9 Vdc Ipk

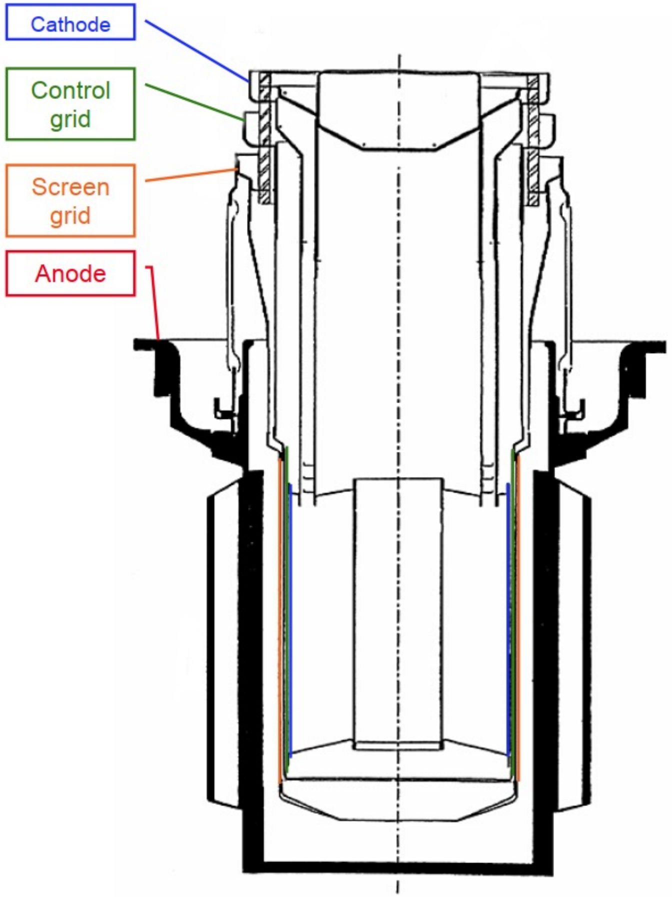
Theoretical efficiency in practice

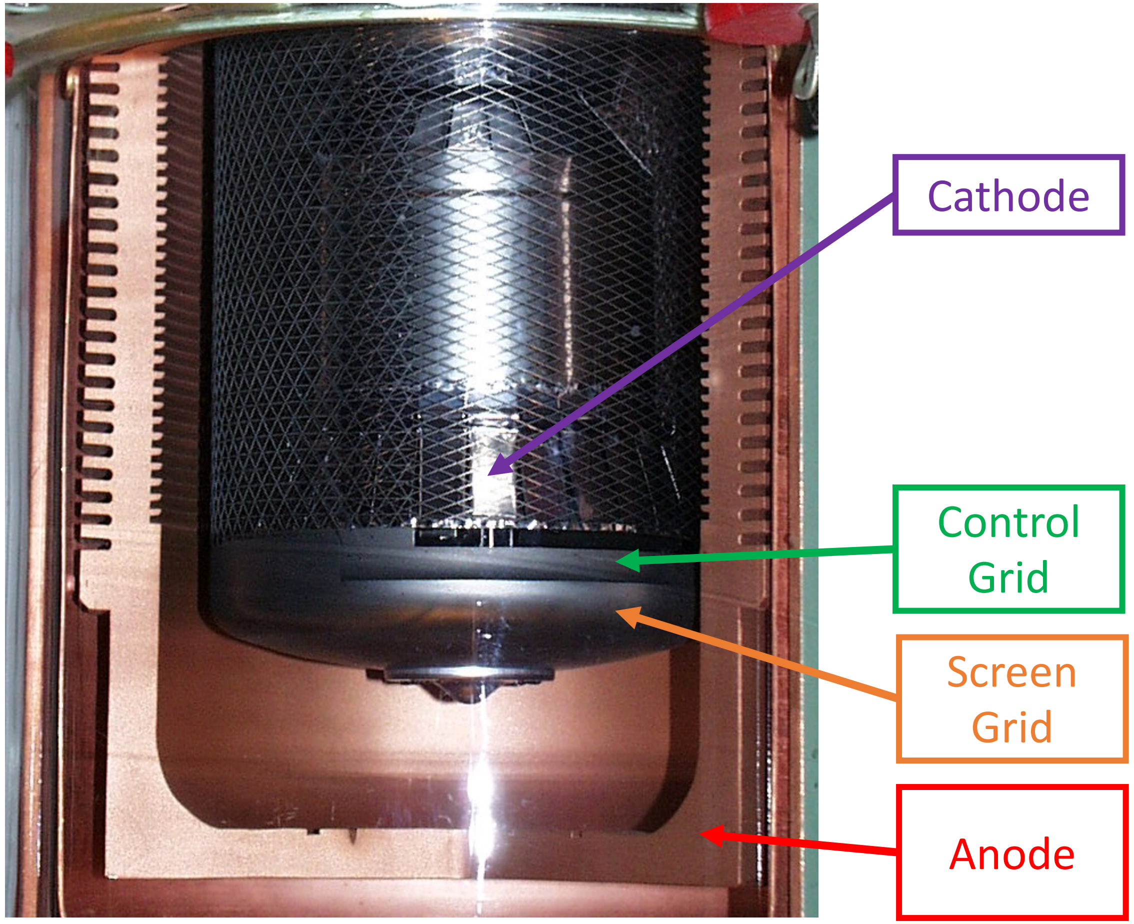
η = Prf/Pdc = ¼ 0.9 Vdc Ipk / 1.05 Vdc Ipk/π

η = 67 %



Construction





Construction limitations

The main limitations faced by grid-base devices are the following

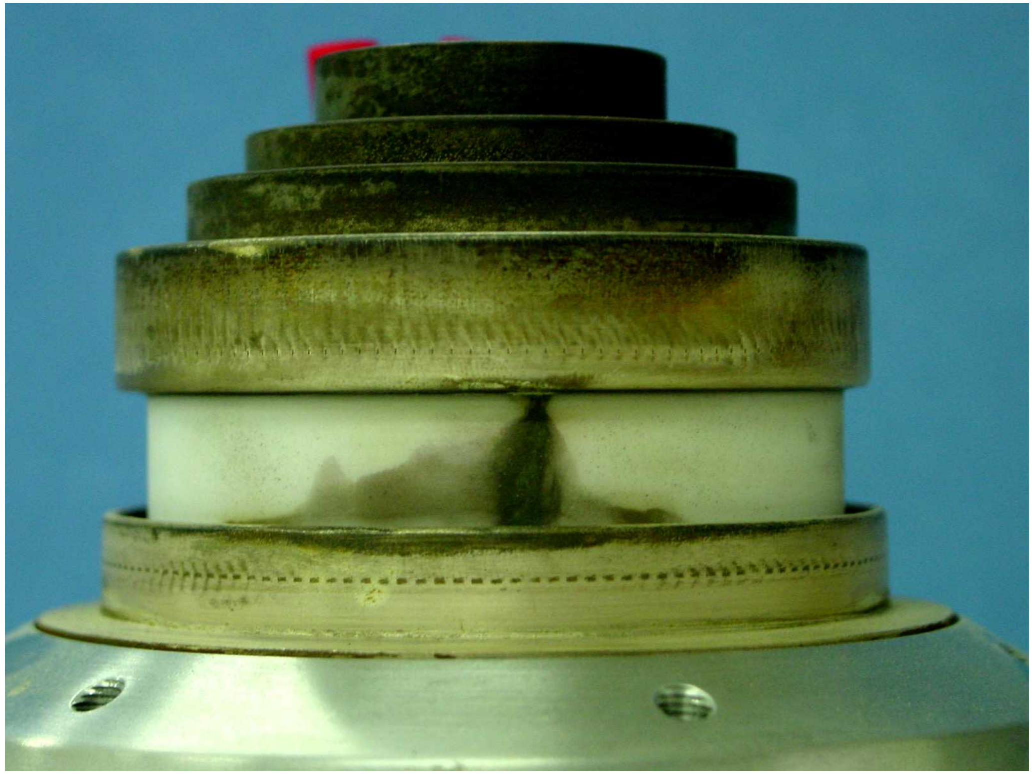
Physical size, ideally RF voltages between electrodes should be uniform, but this condition cannot be achieved unless the major electrode dimensions are significantly smaller than 1/4 wavelength at the operating frequency, this is achievable at lower frequencies than 400 MHz, but at higher frequencies, this becomes a difficulty

Electron transit time, electrode spacing, principally between the grid and the cathode must be scaled inversely with frequency to avoid excessive loading of the drive source, reduction in power gain, back heating of the cathode and reduced conversion efficiency

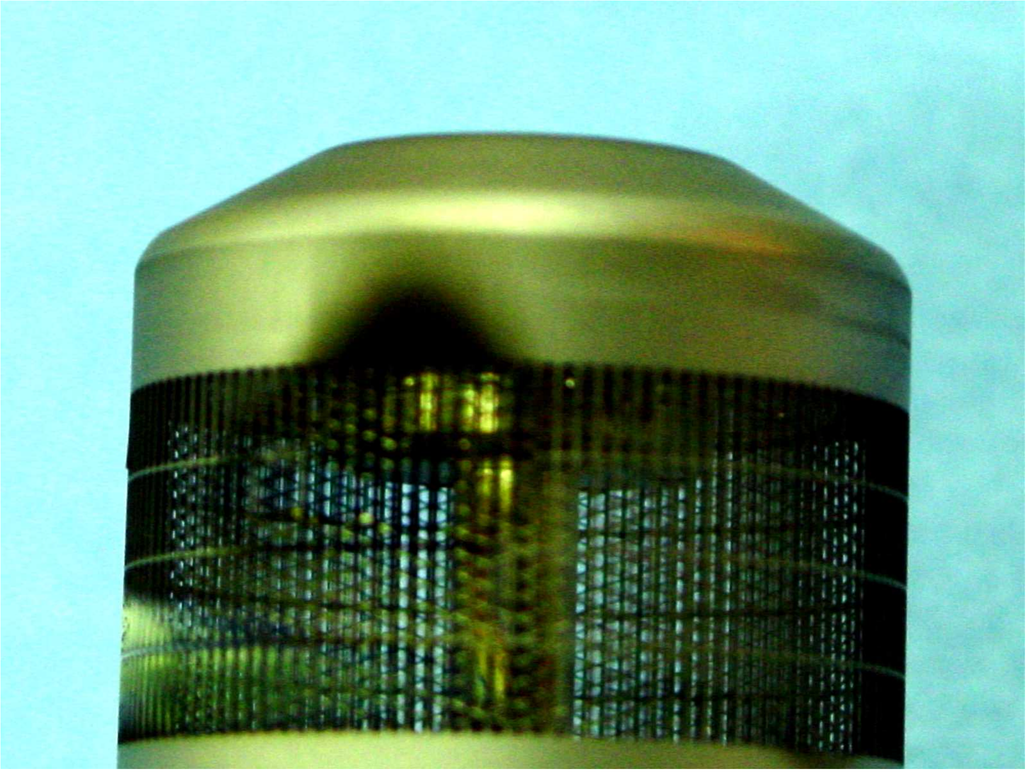
Voltage breakdown, high power tubes operate at high voltages that presents significant problems placing restrictions on the operating voltages that may be applied to the individual elements

Circulating currents, important RF currents may develop as a result of inherent inter electrode capacitances and inductances of the device, causing significant heating of the grid, the connections and the vacuum seals

Heat dissipation, as the element must be kept small with respect to the required power, power dissipation is accordingly consequently limited

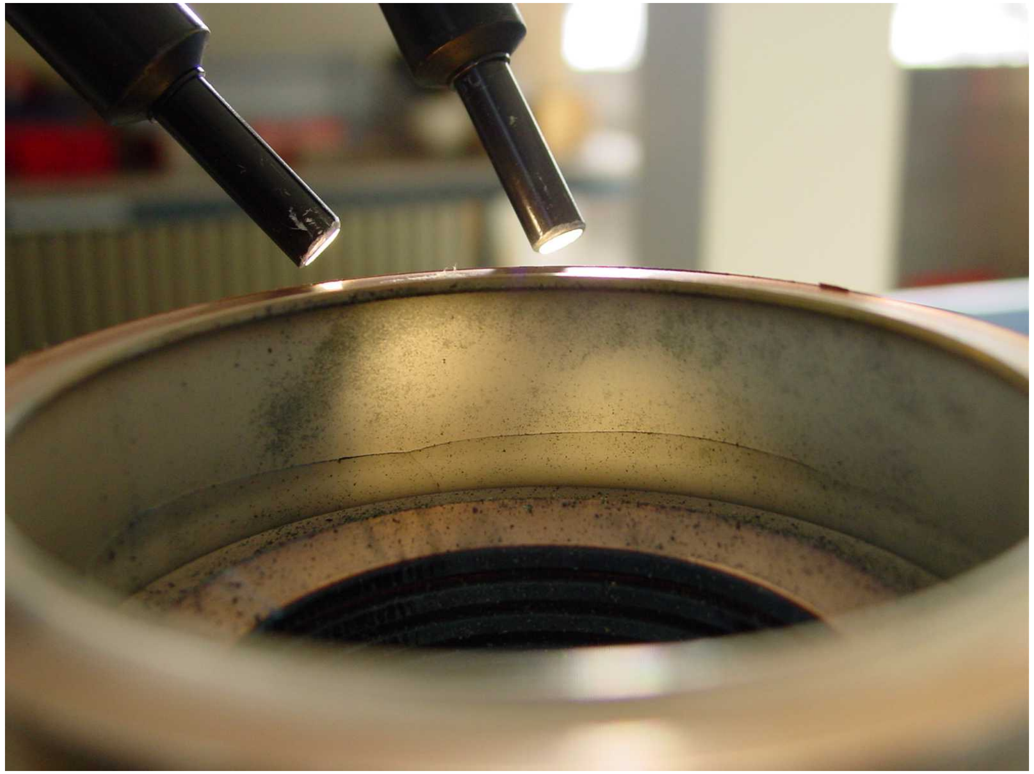


External arcing between Anode and G2



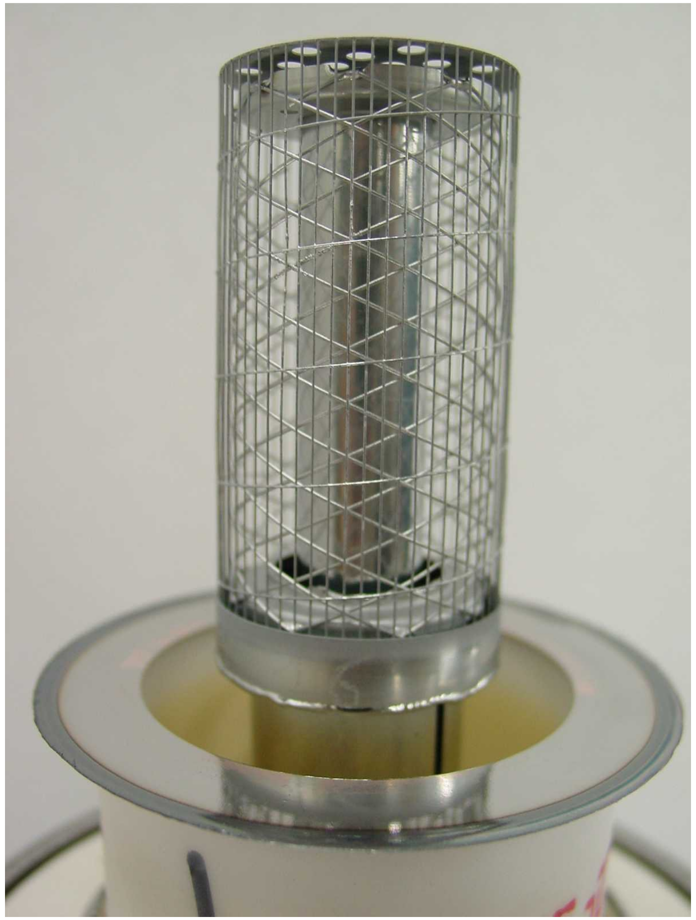
Internal arcing on G2

Overheating due to lack of air cooling



Ceramic crack due to internal metallization of the ceramic, perhaps due to over filament

Cathode



The cathodes we are interested in here emit electrons in the vacuum envelop

Almost all tubes use thermoelectronic cathodes

A metal is heated to a very high temperature

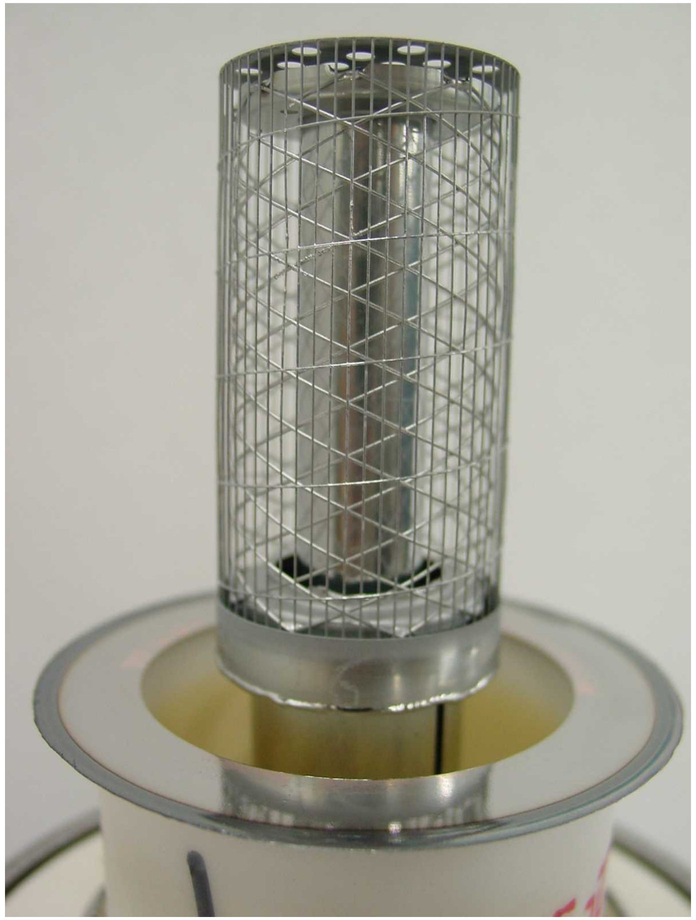
The kinetic energy of the electrons is such that some leave the metal spontaneously and are emitted into the vacuum

They do not go far away because electronic neutrality keeps them in the immediate vicinity of the cathode

However, all that needs to be done is to apply an electric field to form a beam from this 'space charge'

Cathode

$$J_c = A\,.S.T^2.e^{-\frac{W_0}{kT}}$$



J_c = $Maximum\ Cathode\ current\ density$
A = $Constant$
S = $Surface$

W_0 = $output\ Work\ function$ *(kinetic energy to provide to an electron to extract it from the metal)*
T = $operating\ Temperature$
K = $Boltzmann\ constant\ (1.38\ 10^{-23})$

Lower the output Work function W_0, greater the current

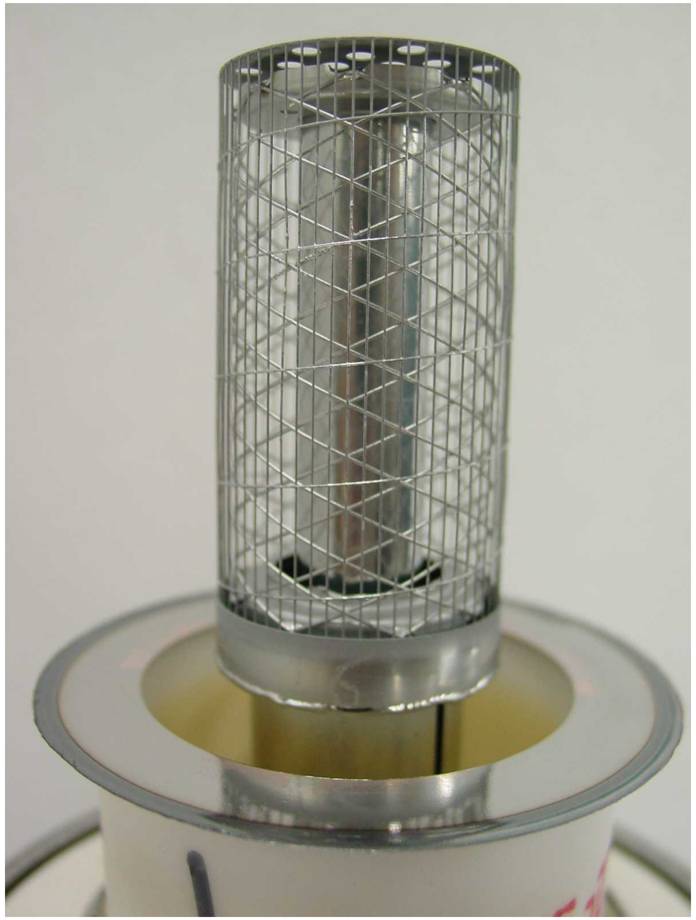
Greater the cathode temperature T, strictly linked to filament voltage, less the cathode lifetime

As a rule of thumb, - 5 % Filament Voltage → + 25 % lifetime

Cathode

Type of Cathode	Output Work function W_0	Operating Temperature T	Current density J_c	Application
Pure Tungsten	4.6 eV	2 200 °C	0.3 A/cm^2	Old generation of radio tubes. (not used anymore)
Oxide Cathode	1 eV	800 °C	0.3 A/cm^2 Up to 40 A/cm^2 up to 2 µs	Triodes and old klystrons
Thorium Tungsten	2.6 eV	1 700 °C	1 to 3 A/cm^2	Triodes and Tetrodes Magnetrons for microwave oven
Impregnated Cathodes (type S: W-Ba; type M and MM: W-Ba-Os)	1.8 eV	1 000 °C	1 to 10 A/cm^2	Klystrons and IOTs

Cathode



Thorium Tungsten is the one used in our high power tubes (could also be Barium or Osmium)

1.5 % of Thorium oxide is added to the Tungsten

Thorium Tungsten is carburized with an hydrocarbon gas, as a result, a layer of Tungsten carbide is formed

All along the lifetime of the cathode, the Thorium evaporates ageing the cathode

At the end of the tube life, the tungsten carbide layer disappears and emission level drops

Too high cathode temperature

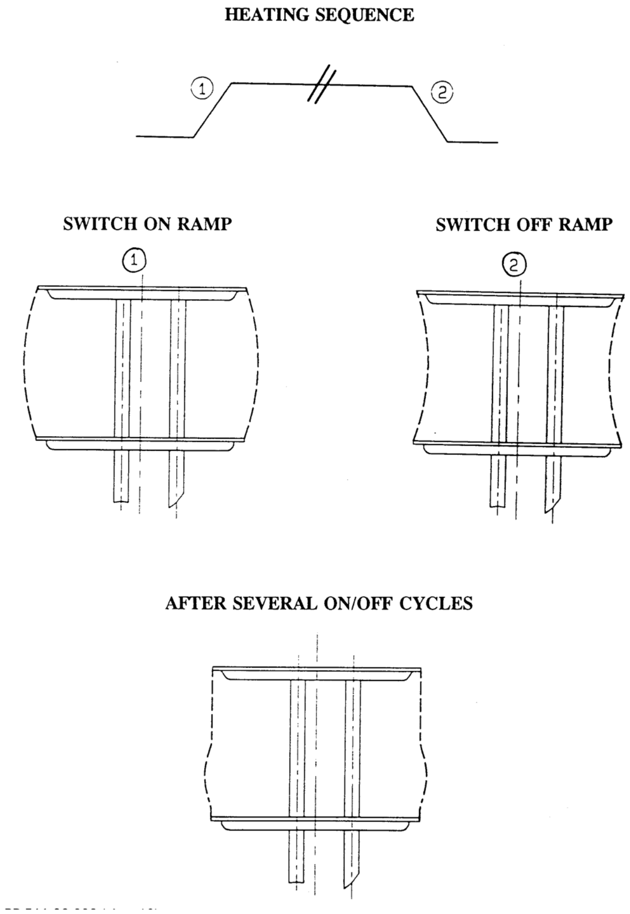
- Accelerate decarburization process
- Tends to deform cathode shape

Too low cathode temperature

- Reduce thermal electrons flow
- Slow down the process of thorium diffusion to the surface

As a rule of thumb, - 5 % Filament Voltage → + 25 % lifetime

Cathode



Heater voltage, always with gradual application and gradual shutdown

The ramp allows cathode assembly, cathode and its support, to absorb differences caused by thermal expansion

Tube lifetime depends on the duration of the ramp, and on the on/off cycling frequency as well

It is advised to keep heater voltage to nominal, during short transmitter interruptions

One cycle per day must be considered as a maximum

Grids

Control grid (G1) controls the electrons flow from the cathode

Screen grid (G2) accelerates the electrons flow and absorb the secondary electrons coming back from the anode

They are almost the same size, only a fraction of mm separate them

Traditional Grids materials are

- Molybdenum
- Tantalum
- Tungsten

Various coating materials are used to reduce secondary emission, among them Zirconium, Platinum…, involving various processes

Thermal emission

- Grids become electrons sources due to the high emissivity of the normal grid materials (Mo [Molybdenum], Ta [Tantalum] and W [Tungsten])

Secondary emission is directly related to

- grid material
- surface regularity
- velocity of impinging electrons

Mechanical rigidity

- Ordinary grids are made by using spot welding techniques, which can cause grid deformation in hard operating conditions

Grids

Pyrobloc® grids by Thales

Pyrolytic graphite is a form of crystal carbon produced by cracking an hydrocarbon gas under high temperature

The useful properties of Pyrobloc® grids

high temperature stability,no thermal expansion

high toughness against thermal shock, no grid deformation

low thermal emission, since actually close to black body material

lower secondary emission than traditional grids

electric conductivity as high as coated metallic grids

excellent mechanical stability, even better under high temperature

Anode

Anode collects the flow of electrons

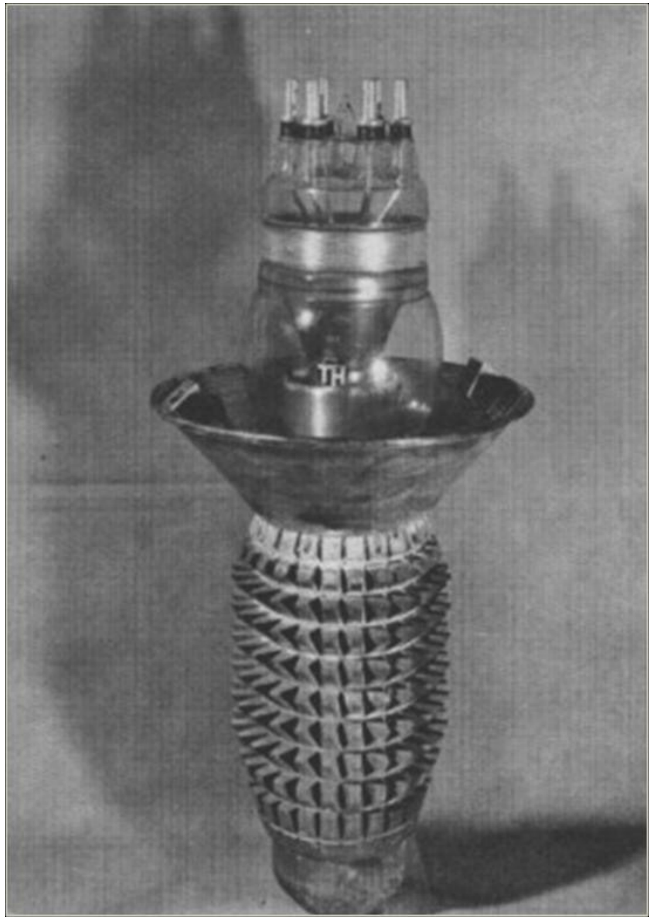
Anode is made of massive oxygen-free copper

The design depends on aimed power dissipation, and on anode cooling system

Anode acts as
  - electrons collector
  - vacuum enclosure
  - heat sink

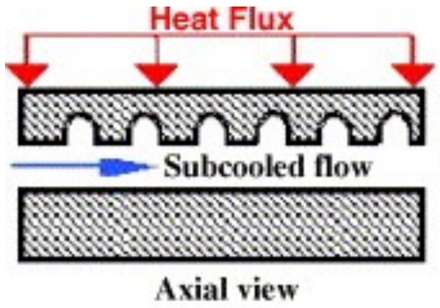
Secondary emission of electrons take place in the collector and special treatment are applied to reduce them

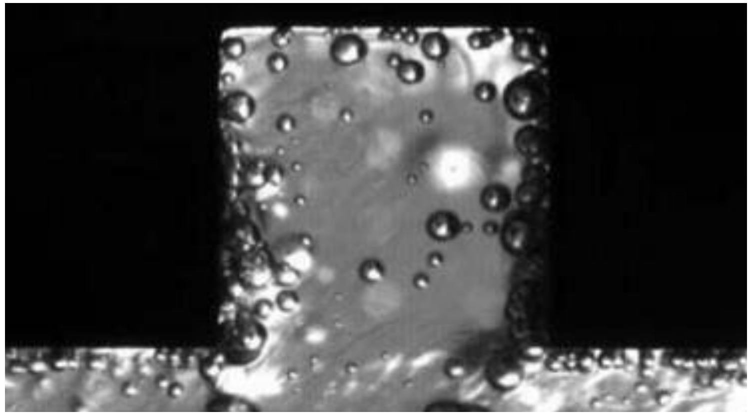
Anode cooling



Anode cooling efficiency

Forced air cooling	100 W/cm²

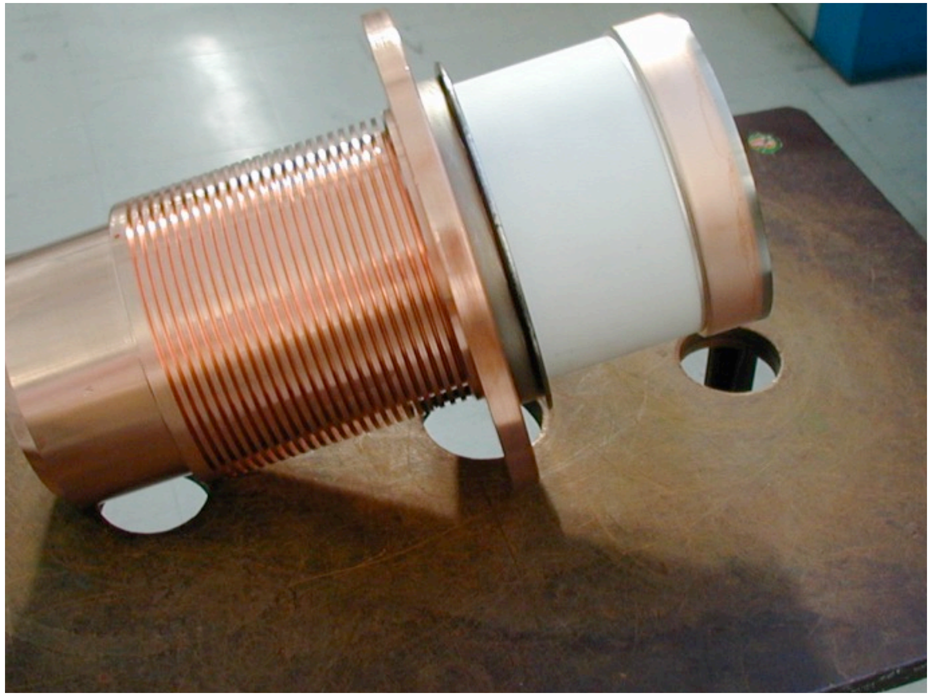




Water cooling

vapotron	350 W/cm²
supervapotron	500 W/cm²
Hypervapotron	2000 W/cm²

Tube assembly



Ceramics are used to join the grids and the anode in order to provide the vacuum leak tightness inside the tube, and to provide the needed insulation material between them

Kovar rings are brazed to the ceramics, as their thermal property are as close as possible to the ceramic for a metal

Final welding are performed to assemble the various elements

Tube assembly

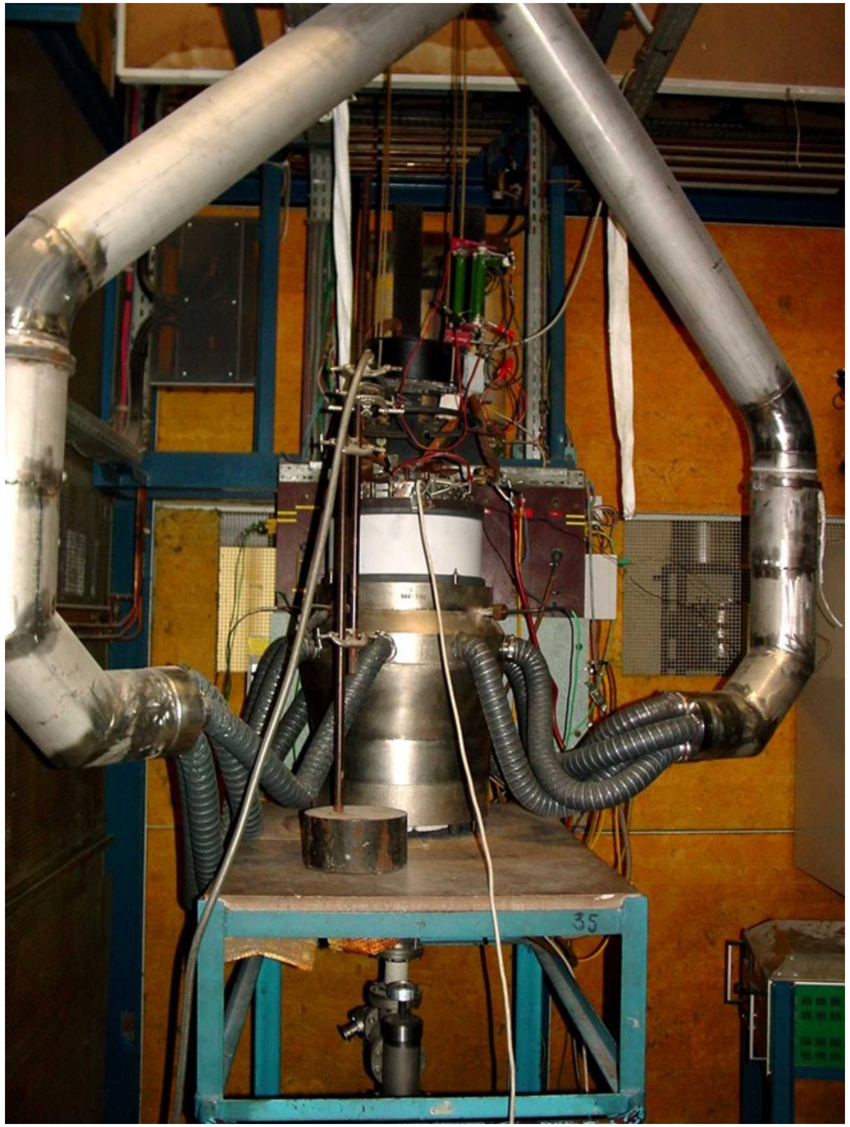
Every raw materials, parts and subassemblies are assessed along the manufacturing process

After final assembly and before pumping, cold measurements, such as capacitances and voltage insulation, are performed on each tube

During the tube being under vacuum pumping, it is baked out at 450˚C for 10 hours, a second step, that can last several days, is to activate the cathode by heating it at a much higher temperature than in normal operation

Vacuum is monitored at each step of the process and must remain within 10^{-7} to 10^{-8} mbar
Insufficient vacuum would cause arcing, early cathode decarburization, metallization of isolators

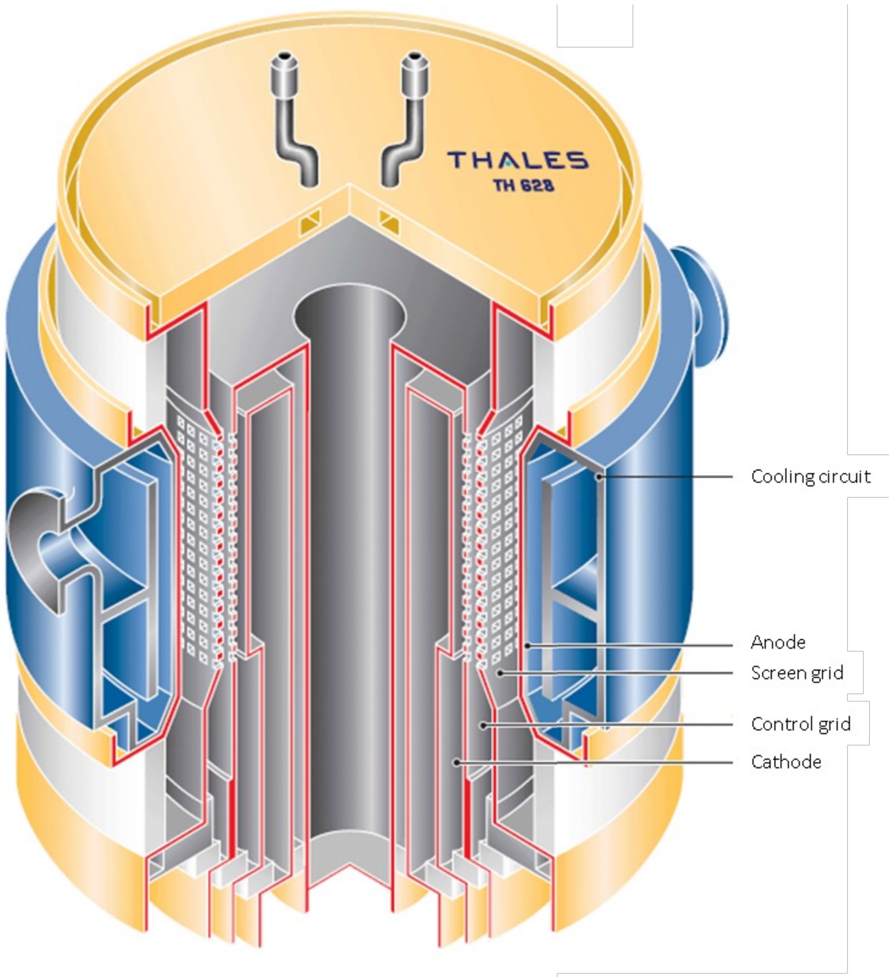
A final tests is performed with all the tubes on specific test benches simulating their working conditions



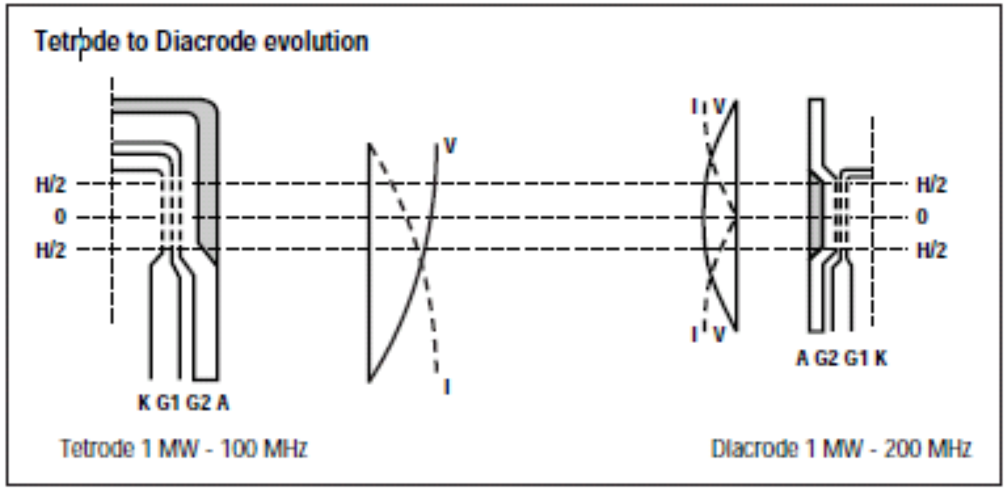
Operation & Possible failures

Factors of influence	Damage in the tube	Limiting factors
Cathode temperature	Cathode deformation Cathode decarburization	Filament voltage too high Dissipated power on the grids RF losses due to harmonics
Cathode cycling	Cathode deformation	More than one on/off cycle per day Mains failure
Overvoltage and overcurrent	Grids damaged due to flashes between KG1 or G1G2	Bad tuning Accidental circuit mismatch Defective protective devices Defective damping circuits
Overheating	Outgassing or even melting of the anode or of the base of the tube	Bad cooling Bad tuning Accidental circuit mismatch
Vacuum	Drop of emission	Bad contacts Corrosion Overheating
Handling	Broken cathode or grids	

Diacrode



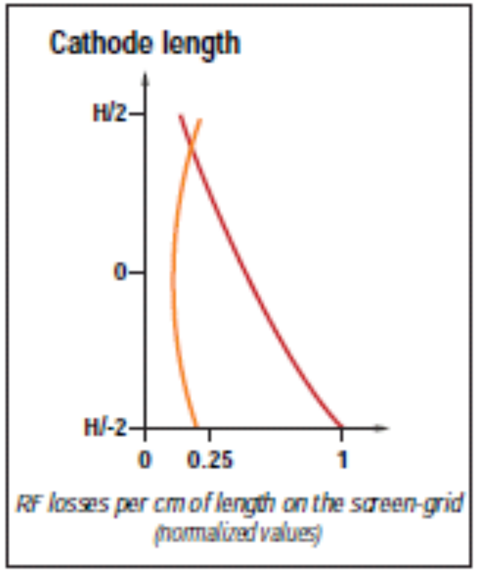
The basic Diacrode design limits electrical losses and electrodes heating by minimizing the reactive currents in the cathode and grids meshes. This means that compared with conventional tetrodes, Diacrodes can either double the output power at a given operating frequency or double the frequency for a given power output. Diacrodes provide the same gain and efficiency as conventional tetrodes - but at frequencies which are out of reach for tetrodes at an equivalent output power



The main difference is in the position of the active zones of the tubes in the resonant coaxial circuits, resulting in improved reactive current distributing in the tube's electrodes

Example of calculated RF losses on the screen grid for the same cathode length at an output power of 1.4 MW cw @ 120 MHz

— Diacrode — Tetrode



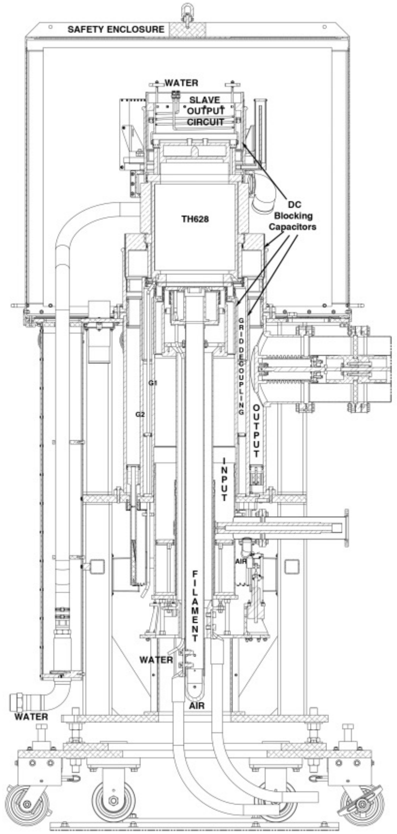
Diacrode

Los Alamos already successfully operate several Diacrodes since 2015

Within the Test Infrastructure and Accelerator Research Area (TIARA) program, CERN and Los Alamos tested a Diacorde for the Ionisation Cooling Test Facility at the Rutherford Appleton Laboratory

Novel pulsed RF power amplifier design, Milestone MS28
https://cds.cern.ch/record/1510945/files/TIARA-REP-WP7-2013-002.pdf

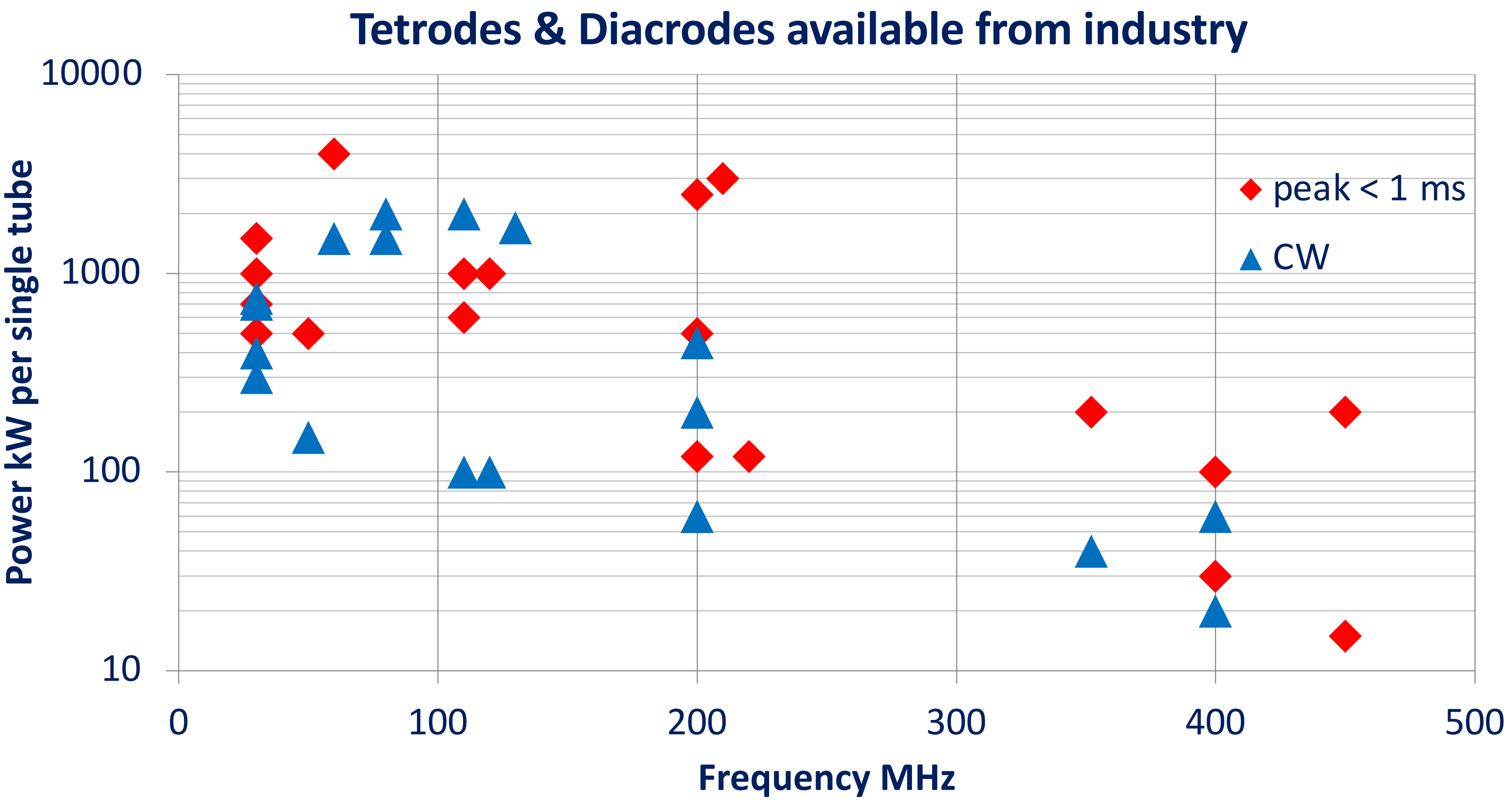
Design report of a 3 MW power amplifier, Deliverable 7.4
https://cds.cern.ch/record/1647574/files/TIARA-REP-WP7-2014-005.pdf



Pulse duration [µs]	Repetition rate [pps]	Anode Voltage [kV]	Anode current [A]	Grid2 voltage [kV]	Pout [MW]	$\eta_{RF/DC}$ [%]
1000	120	26.1	108	1.5	2.0	69.5
300	30	29.4	153	1.6	3.0	65.3

John Lyles, Los Alamos National Laboratory, Design, test and implementation of new 201.25 MHz RF power amplifier for LANSCE Linac* LA-UR-12-20983

Frequency & Power range of tetrodes



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

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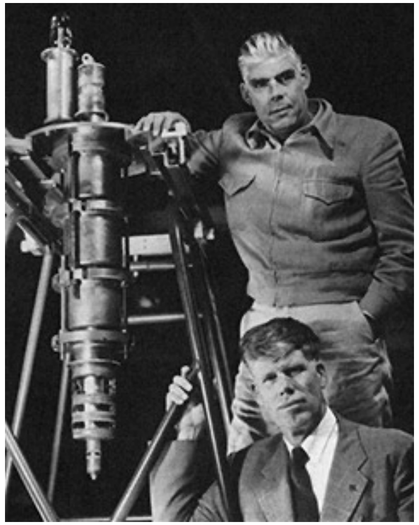
Field Effect Transistor (FET)
Junction Gate FET (JFET)
Metal Oxide Semiconductor FET (MOSFET)
power MOSFET
Vertically Diffused Metal Oxide Semiconductor (VDMOS)
Laterally Diffused Metal Oxide Semiconductor (LDMOS)
Silicon Germanium (SiGe)
Gallium Arsenide (GaAs)
Gallium Nitride (GaN)

Linear beam tubes

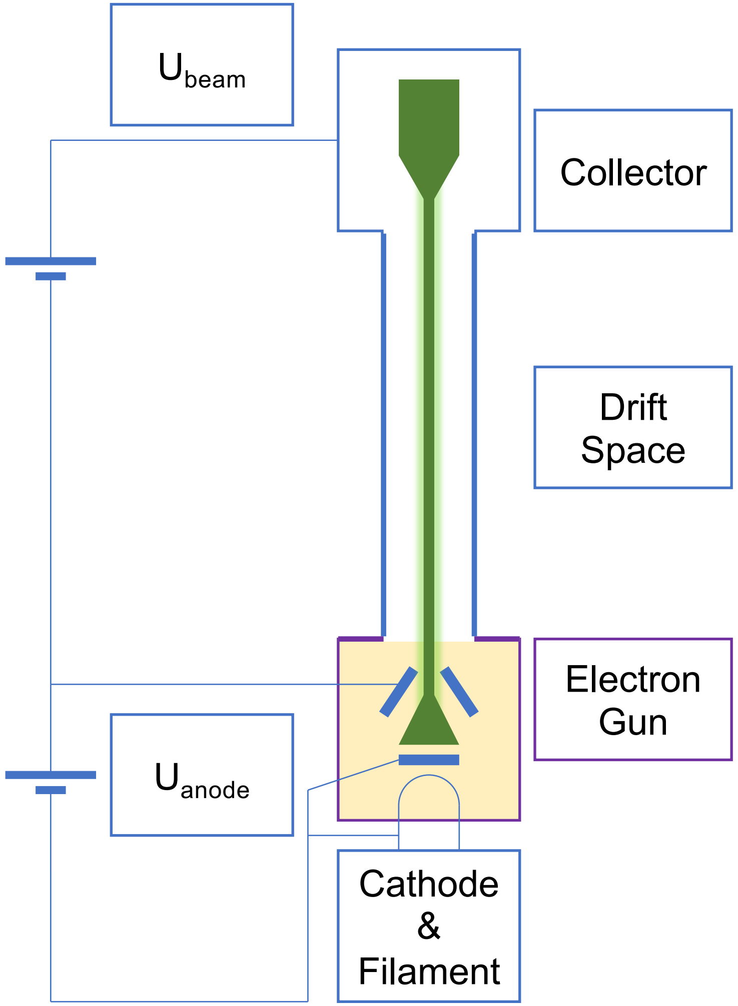
1937	Klystron, Russell & Sigurd Variant
1938	IOT, Andrew V. Haeff
1939	Reflex klystron, Robert Sutton
1940	Few commercial IOT
1945	Helix Travelling Wave Tube (TWT), Kompfner
1948	***Multi MW klystron***
1959	Gyrotron, Twiss & Schneider
1963	Multi Beam Klystron, Zusmanovsky and Korolyov
1980	High efficiency IOT
2022	High Efficiency Klystron



Russell & Sigurd Varian klystron, 1937

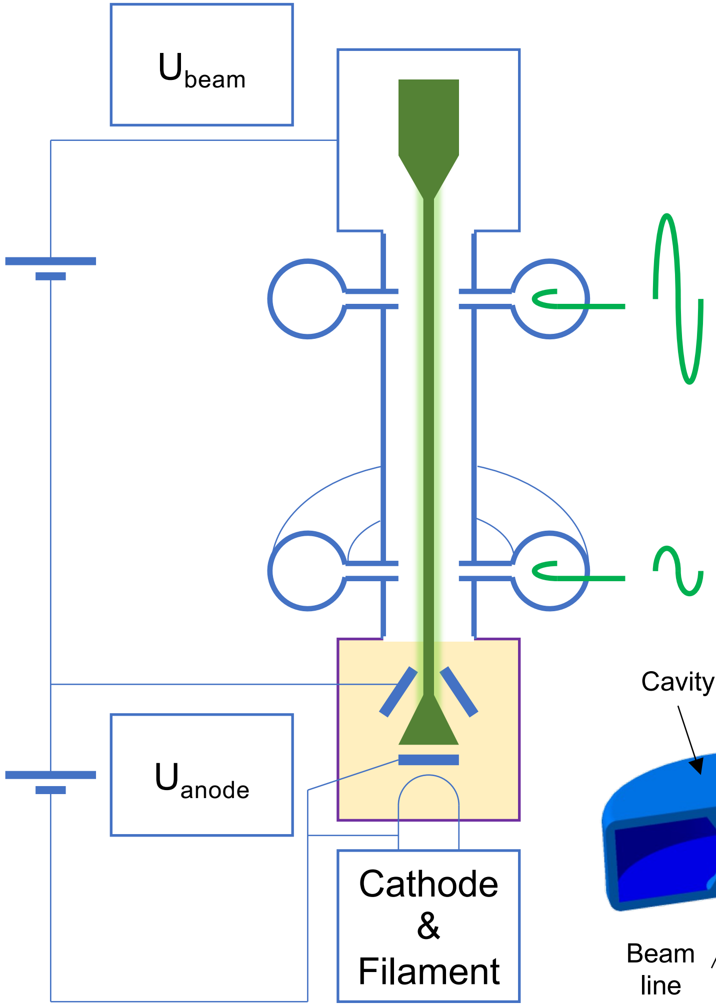
Thales TH 1802, 2002

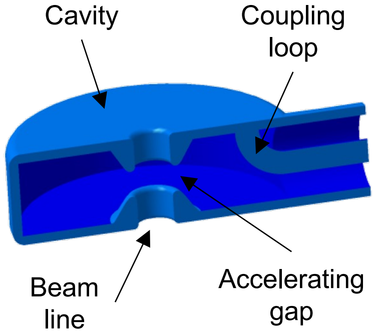
Essentials of klystron



- 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

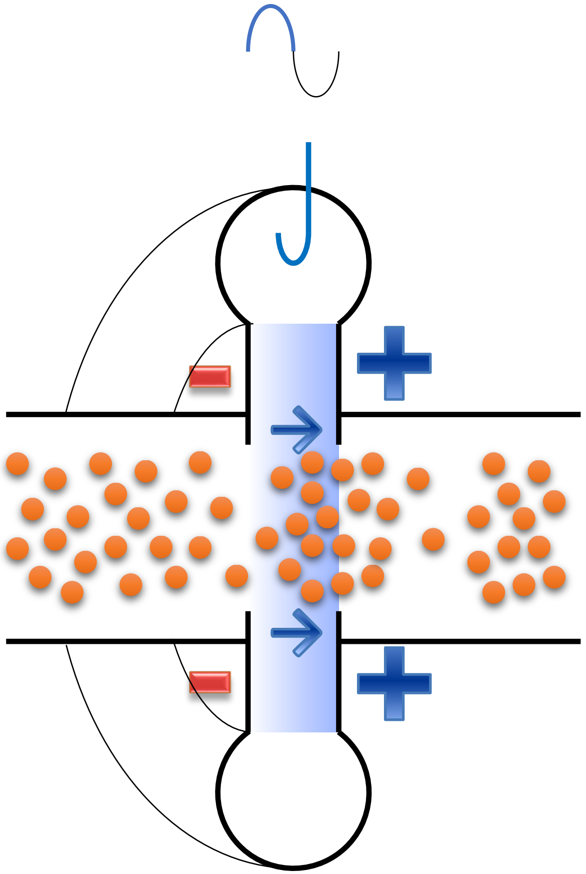
RF input cavity (Buncher)

- 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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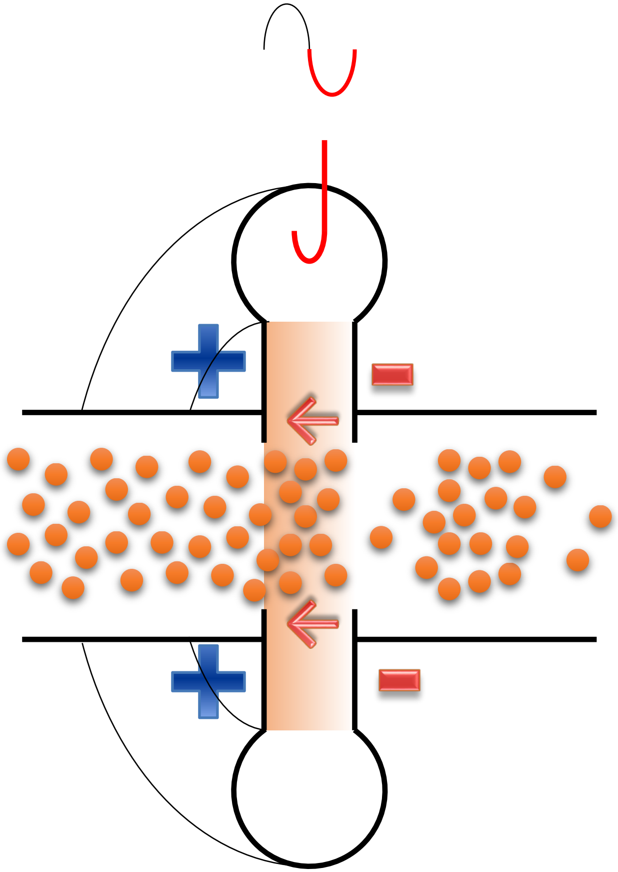

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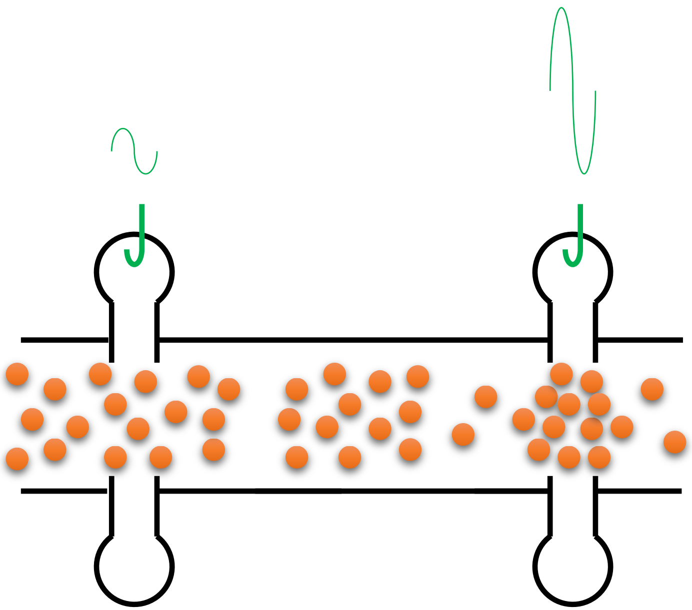

Cavity resonators

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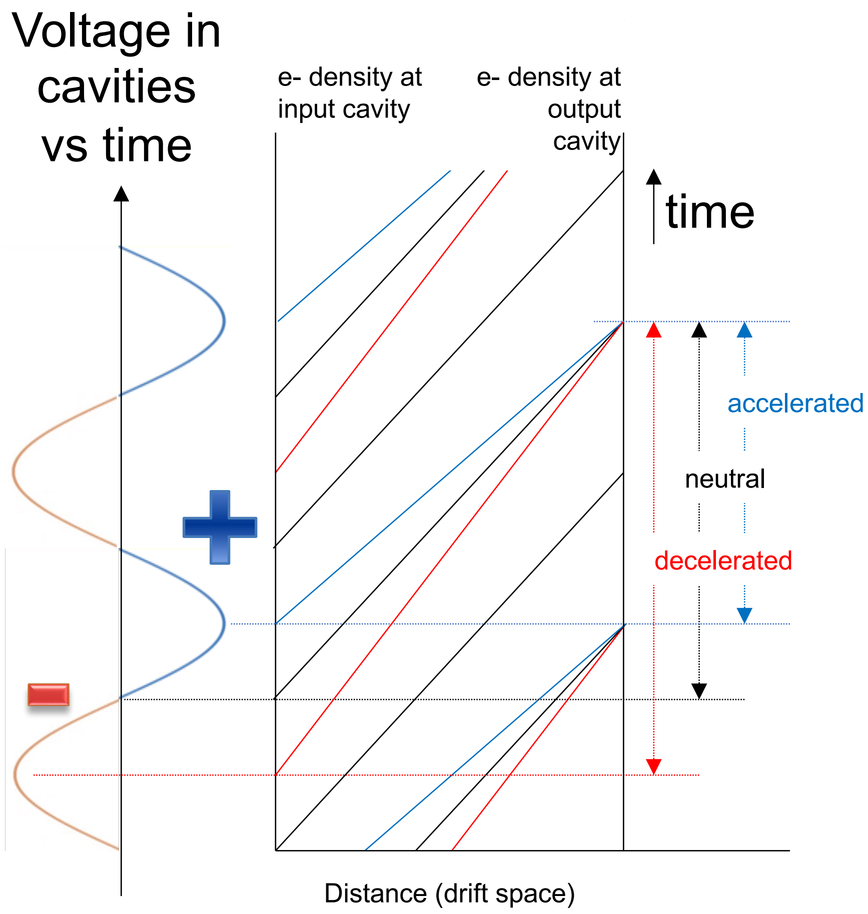
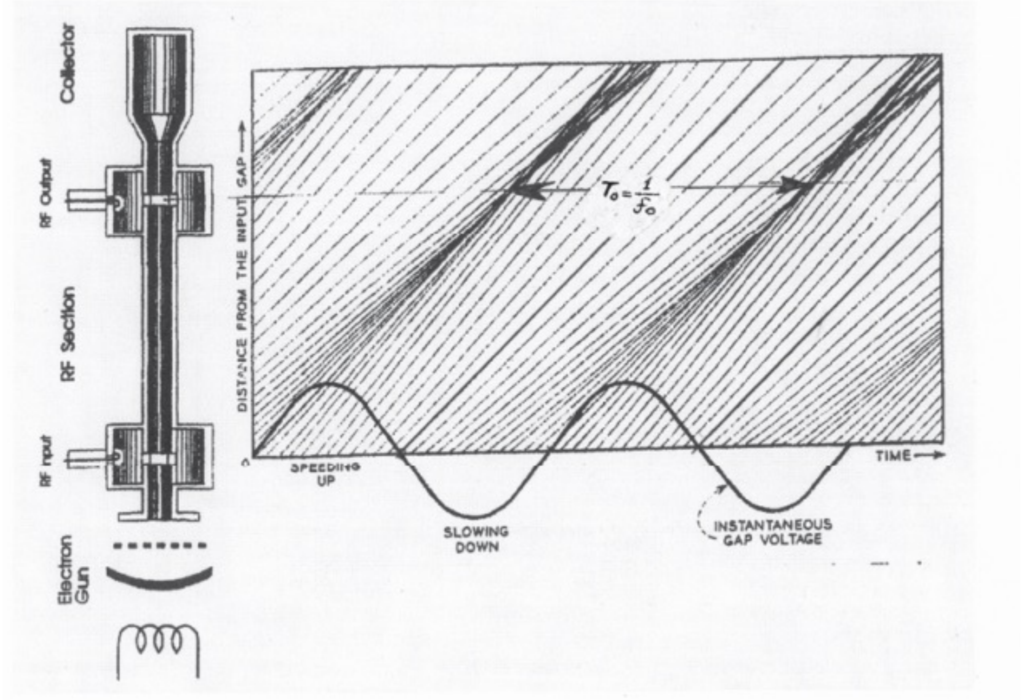


Bunching of e- beam in a klystron

- 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

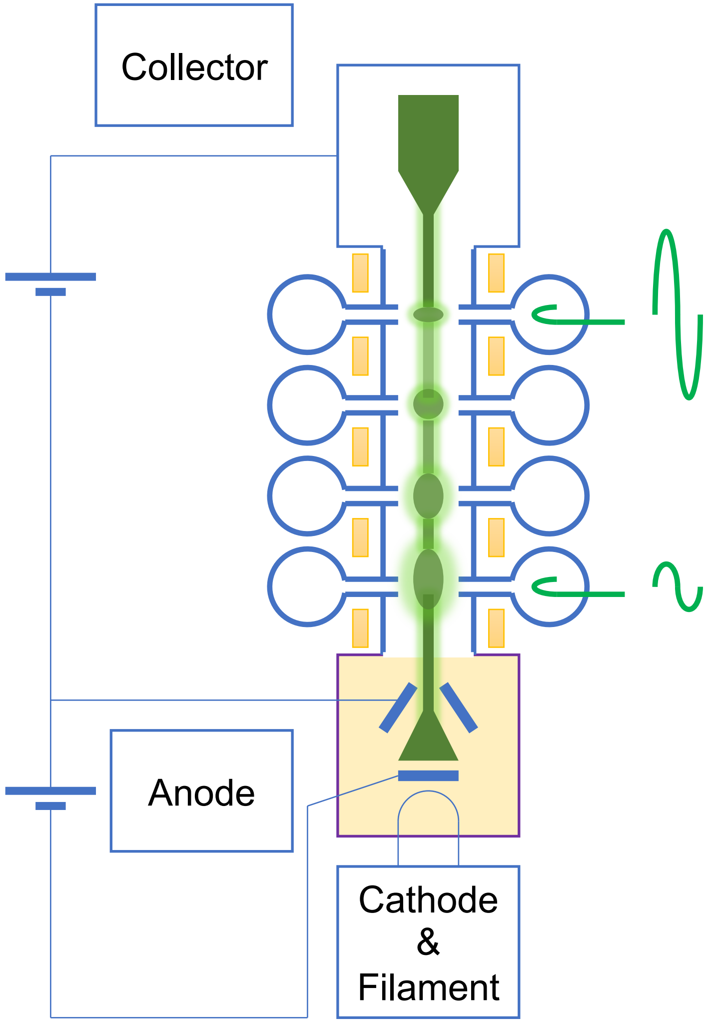


The Applegate diagram

The velocity modulation principle, which made klystrons possible, was explained by Russell Variant as follows, in a book written by his wife, Dorothy: 'Just picture a steady steam of cars from San Francisco to Palo Alto, if the cars left San Francisco at equal increments and at the same velocity, then even in Palo Alto they would be evenly spaced and you would call this a direct flow of cars. But suppose somehow the speed of some cars, as they left San Francisco, was increased a bit and others retarted. Then, with time, the fast cars would tend to catch up with the slow ones and they would bunch into groups. Thus, if the velocity of the cars was sufficiently different or the time long enough, the steady stream of cars would be broken and, under ideal conditions, would arrive in Palo Alto in clearly defined groups. In the same way an electron tube can built in which the control of the e-beam is produced by the principle of bunching, rather than the direct control of a grid in a triode…'

This is illustrated by the 'Applegate' diagram, showing electrons from an electron gun traversing a gap in a first cavity, and having their velocity modulated by the voltage across that gap. As a result, they arrive in bunches at the second, or output cavity. Bunches form around the electrons crossing the first gap when the sinusoidal voltage there crosses from negative to positive (from decelerating to accelerating). Bunches arrive at the second cavity with a period T0, which corresponds to the period of the sinusoidal power input to the first cavity. The bunching action shown in the Applegate diagram is entirely ballistic, or kinematic, i.e. the charge of the electrons does not come into play as their trajectories come very close and actually cross. In an average klystron, space charge will modify these trajectories and the interaction between cavities and beam will be better described by 'space-charge wave theory', which treats space charge as an elastic medium and describes electron motion in term of wave.

Essentials of klystron



Additional bunching cavities

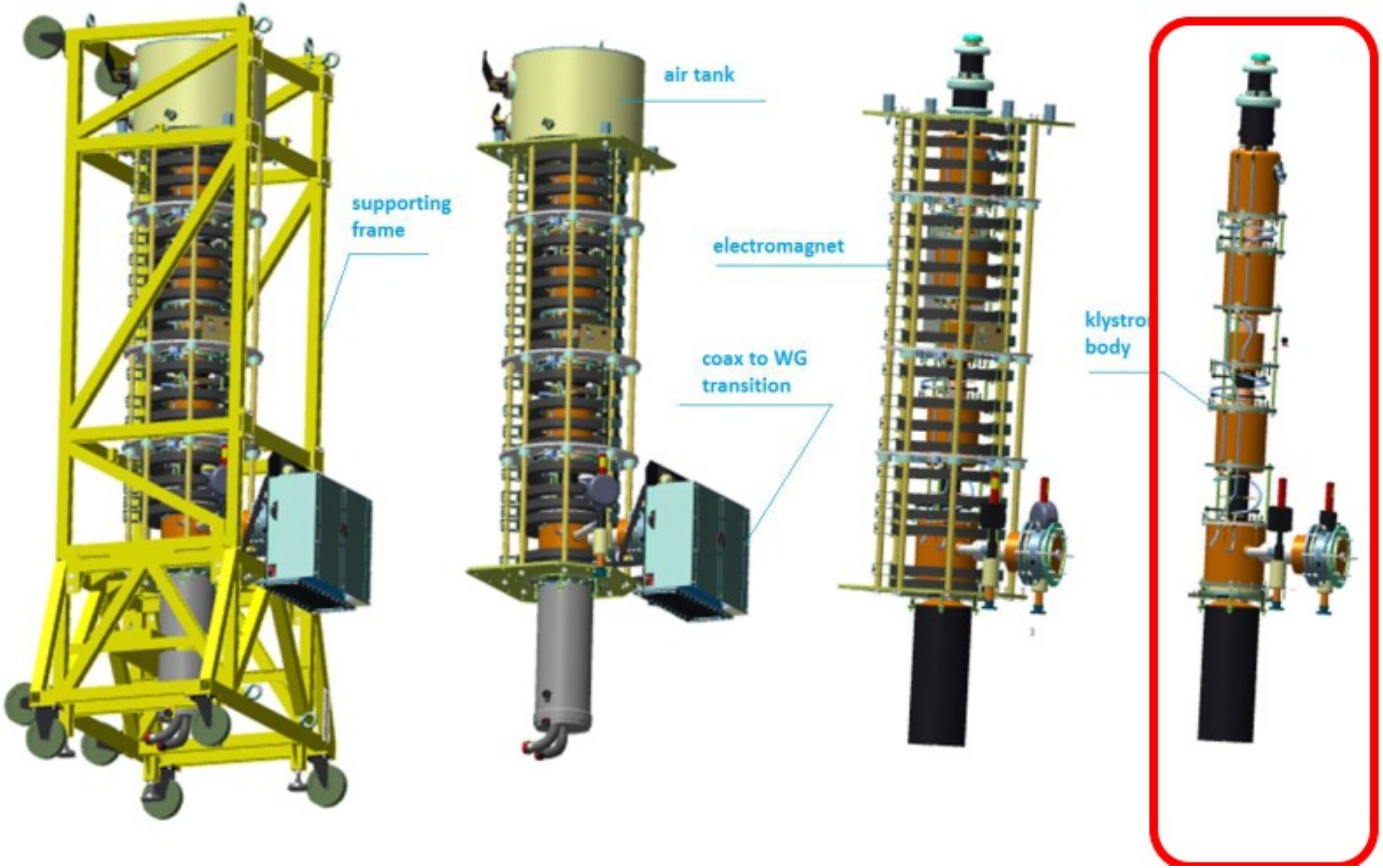
- Resonate with the pre-bunched electrons beam
- Generate an additional accelerating/decelerating field
- Better bunching
- Gain 10 dB per cavity

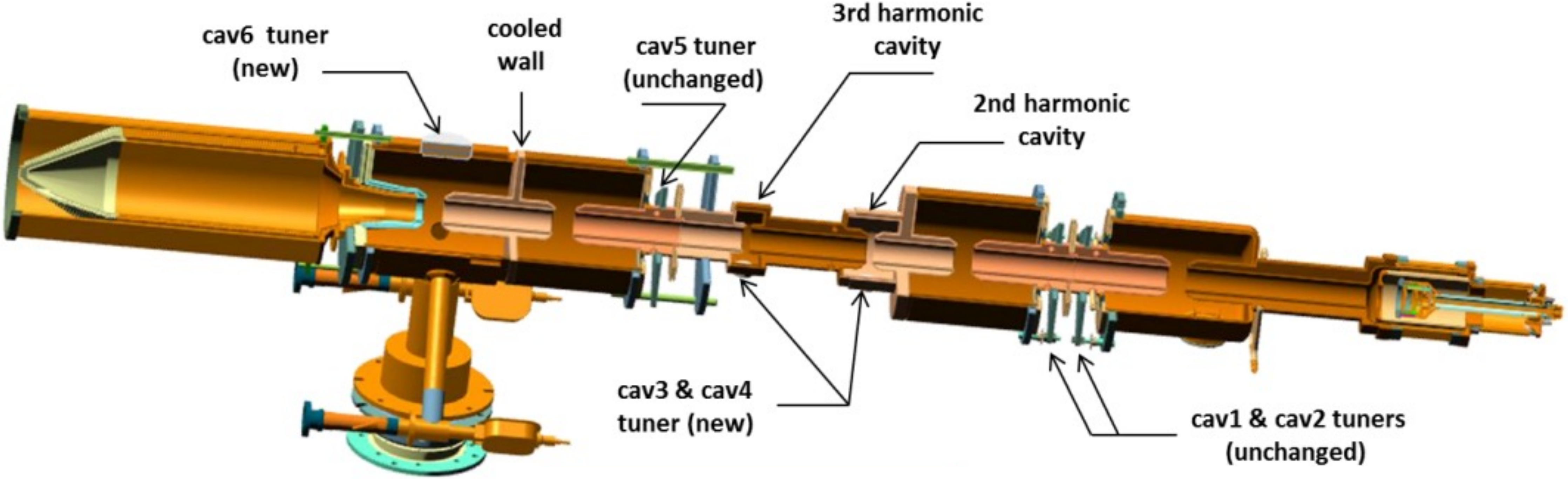
Focusing magnets

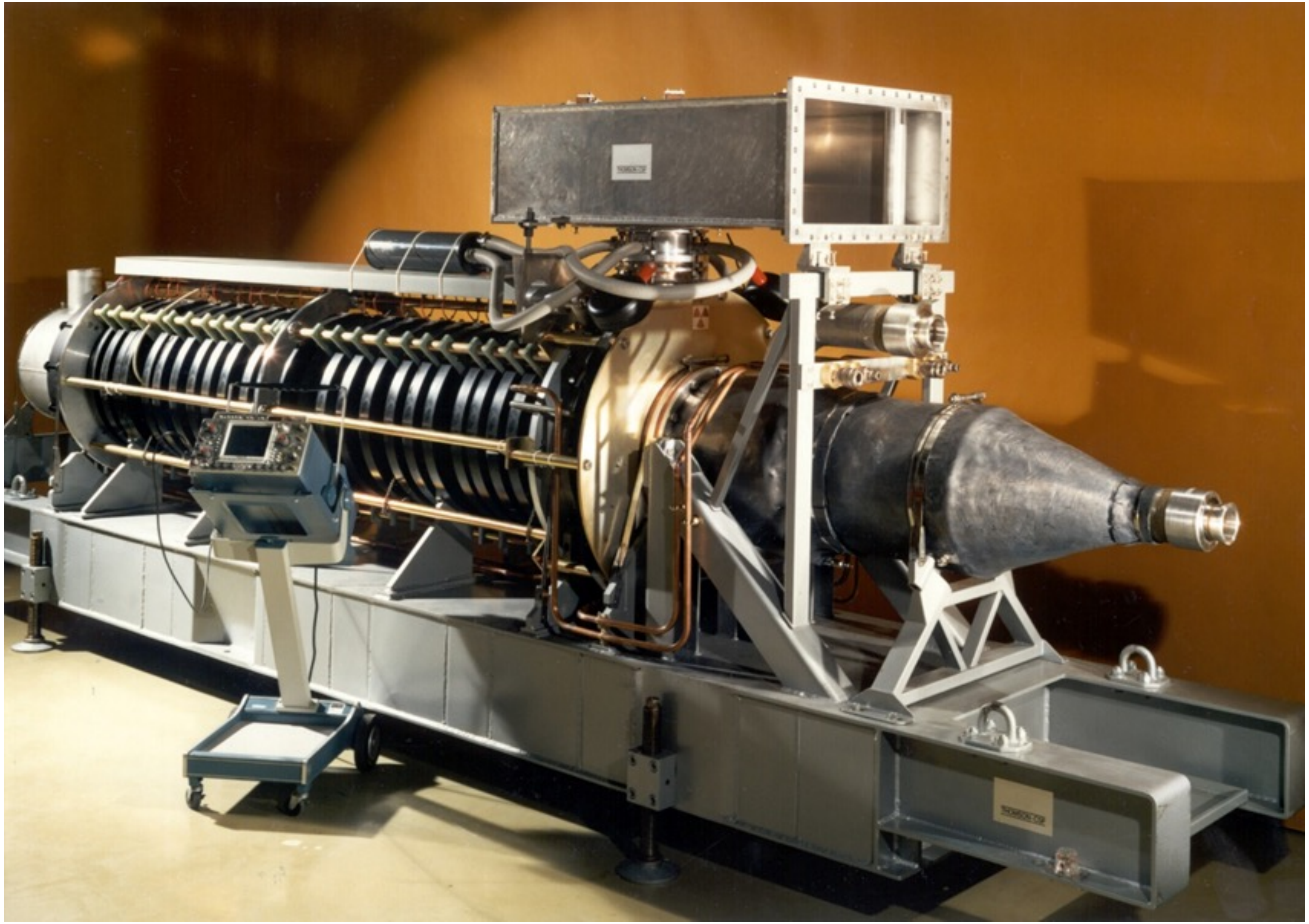
- To maintain the e- beam as expected and where expected

27.11.2006

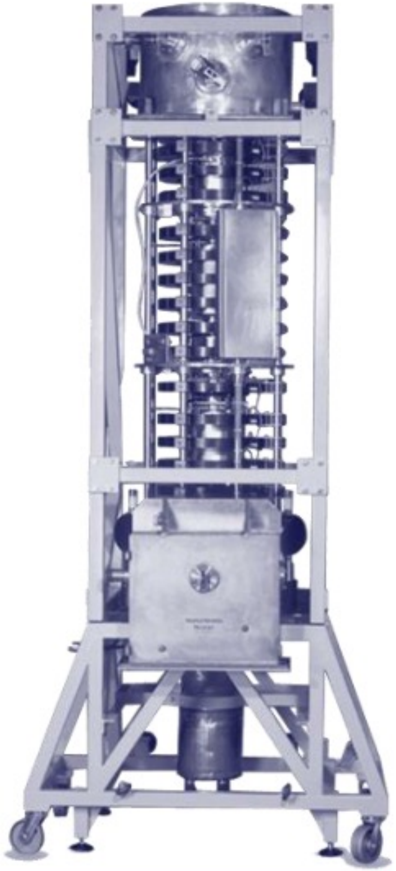
CERN LHC, TH 2167 klystron and in UX45 cavern
16 klystrons delivering 330 kW @ 400 MHz, into operation since 2008


air tank
supporting
frame
electromagnet
coax to WG
transition
klystro
body


cav6 tuner
(new)
cooled
wall
cav5 tuner
(unchanged)
3rd harmonic
cavity
2nd harmonic
cavity
cav3 & cav4
tuner (new)
cav1 & cav2 tuners
(unchanged)


THOMSON-CSF
THOMSON-CSF

LHC TH2167 high efficiency project

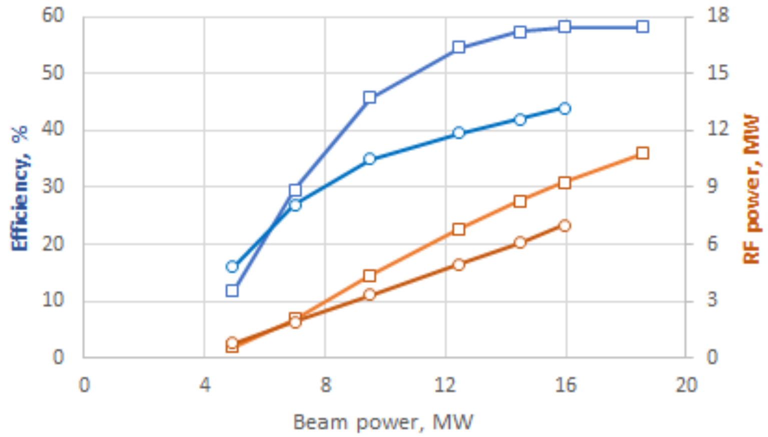


Commonly with CERN, be the first team to develop, manufacture and operate a high efficiency (CSM based) klystrons set in reliable conditions

Integrating the major improvements held over the last four years on klystron modeling within HEIKA, compatible with industrial manufacturing margin

High Efficiency Klystron

	E37113 at factory	E37117 design
Voltage, kV	154	154
Current, A	93	94
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.16
Sat. gain, dB	49	58
Efficiency, %	42	57/ FCI
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.4
RF circuit length, m	**0.127**	**0.127**

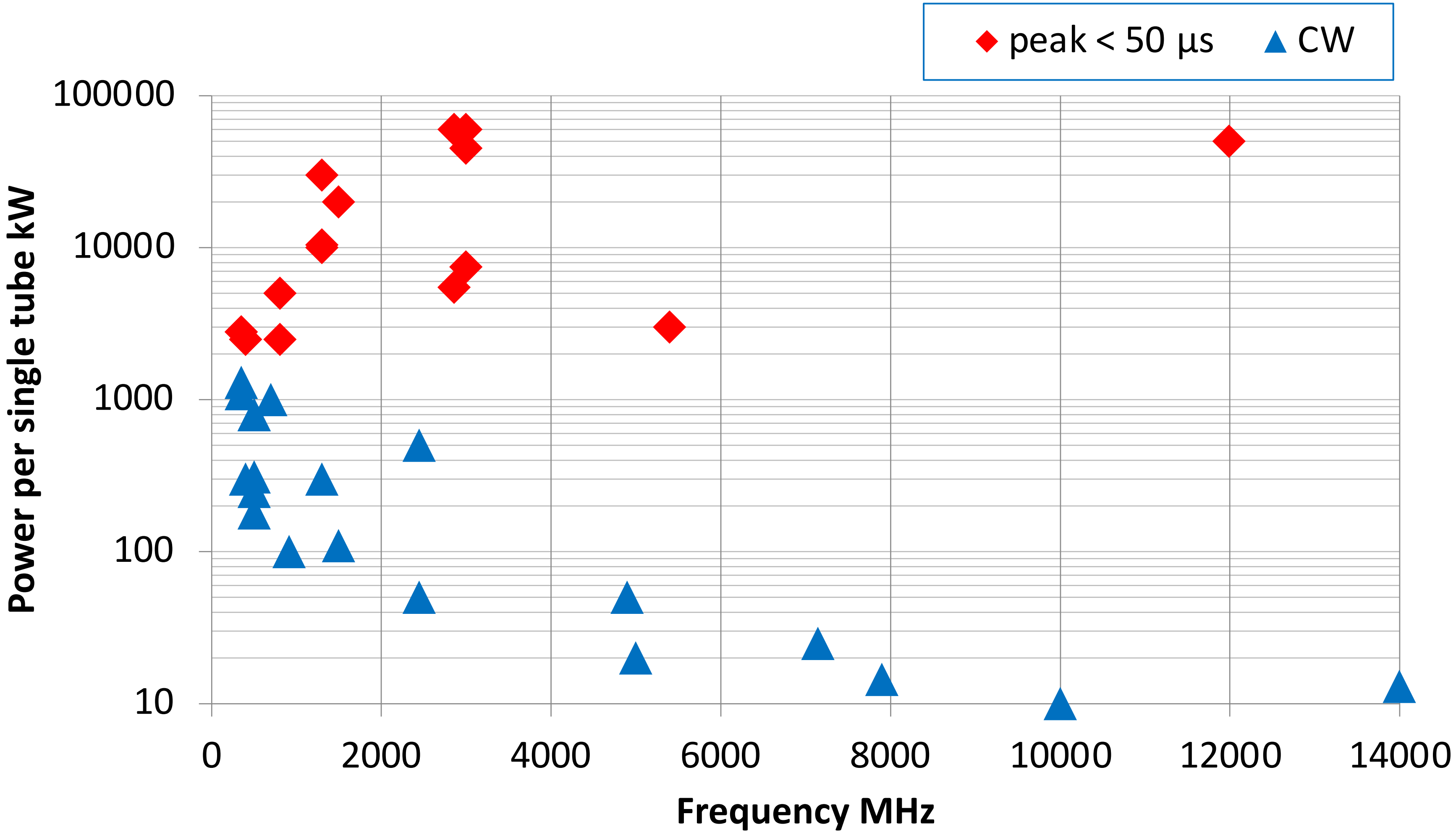


High Efficiency solution allowed to increase peak RF power available for the high gradient X-band test facility at CERN by 35% within original environment (re-used modulator and solenoid)

Tube is now commercially available, prototype successfully tested in December 2022

Technology(ies) developed at CERN allow to improve significantly efficiency/RF power of any existing commercial klystron (based on retrofit approach if necessary)

Klystrons available from industry



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)
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Junction Gate FET (JFET)
Metal Oxide Semiconductor FET (MOSFET)
power MOSFET
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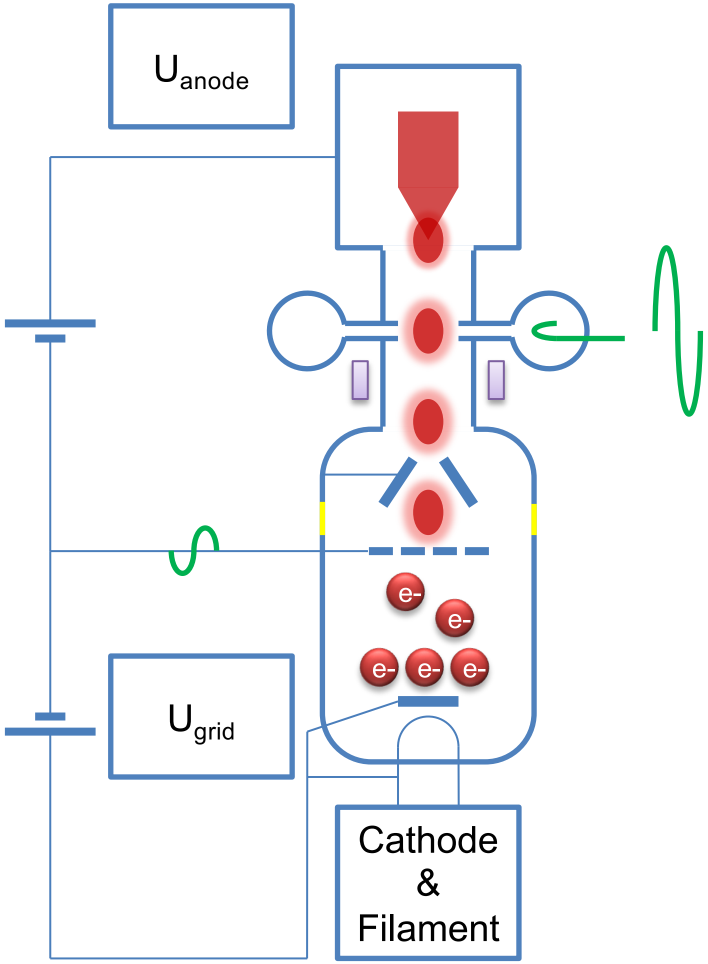
Laterally Diffused Metal Oxide Semiconductor (LDMOS)
Silicon Germanium (SiGe)
Gallium Arsenide (GaAs)
Gallium Nitride (GaN)

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

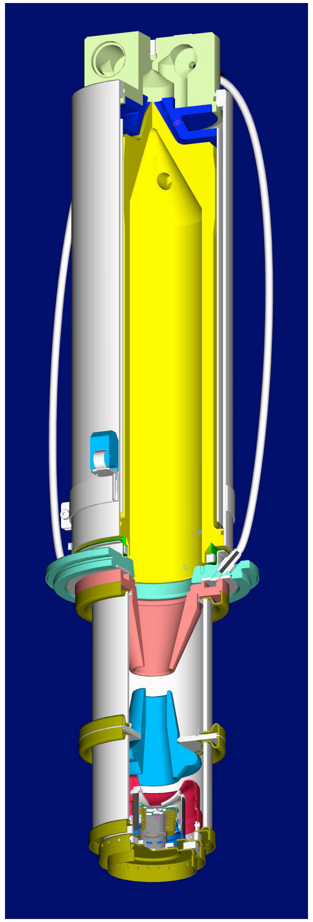
  Anode accelerates e- buckets

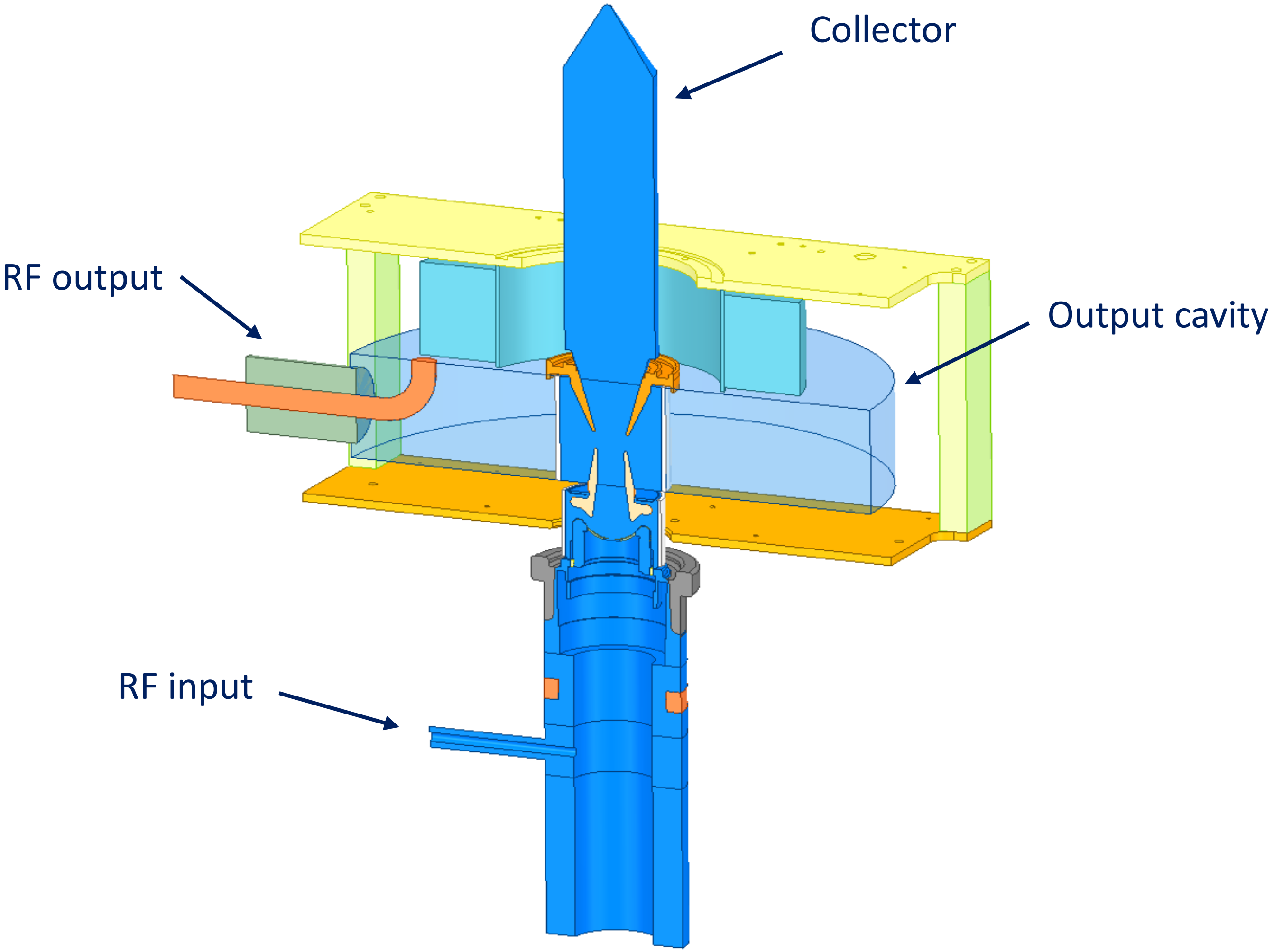
  Short drift tube & magnets

  Catcher cavity

  Collector

THALES
ELECTRON DEVICES





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


THALES
THALES
795
THALES
795

R&D program, MB-IOT

EUROPEAN SPALLATION SOURCE

CERN

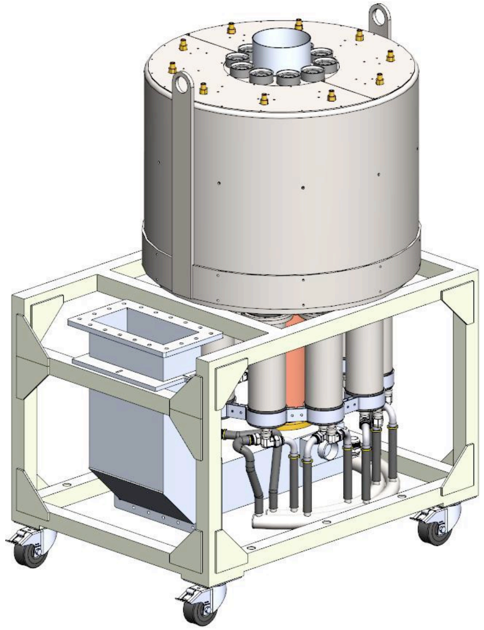
In order to provide an alternative to klystrons, ESS launched a R&D program for Multi Beam IOT

Two prototypes will be delivered in 2016

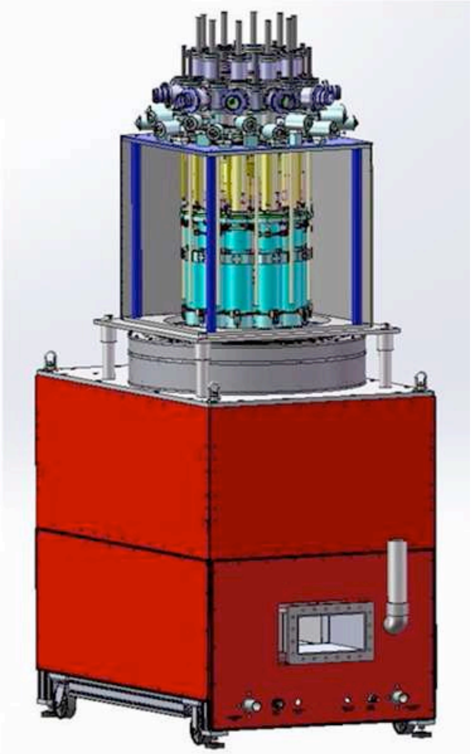
The goal was to reach 1.3 MW @ 704 MHz pulsing up to 3.5 ms – 14 Hz

Each tubes were composed of 10 guns, combined into a single output cavity

Both tubes successfully achieved the required performances

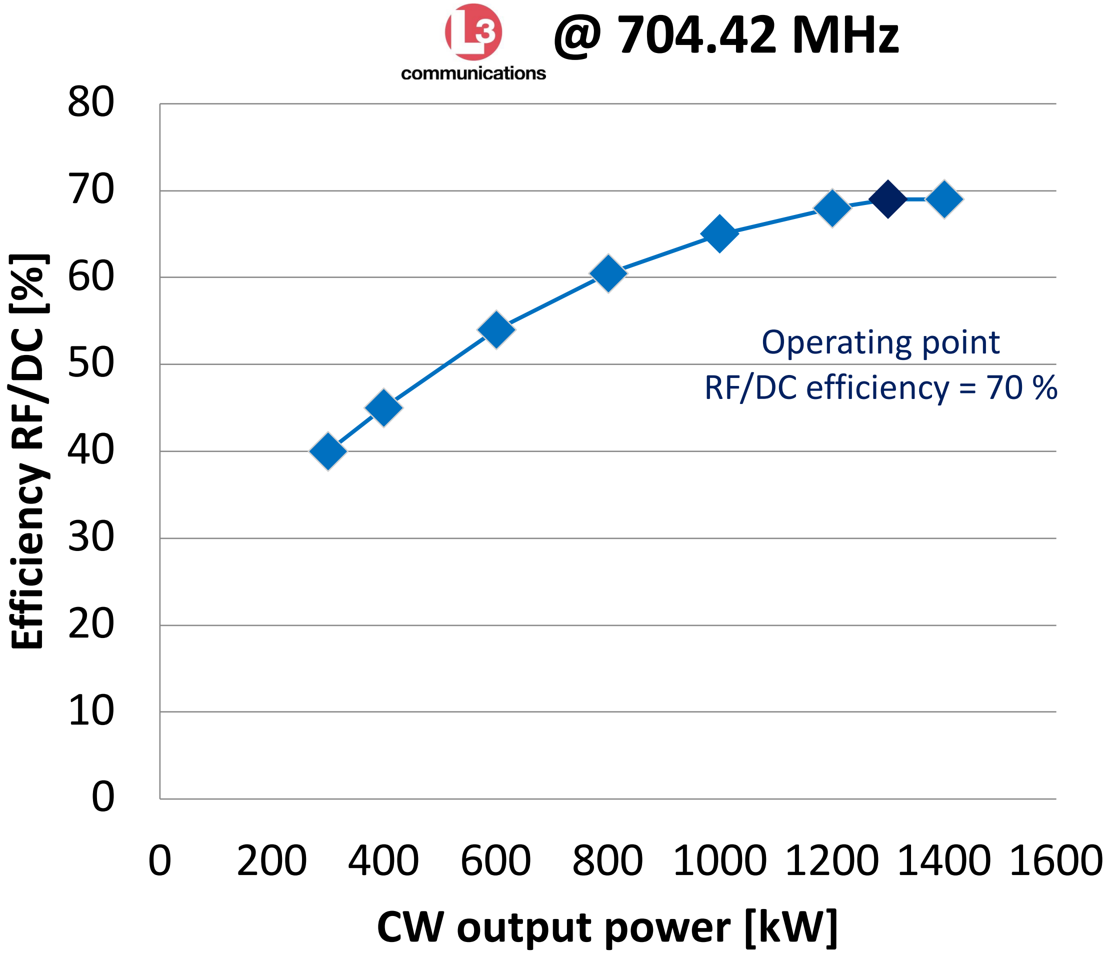


L3 communications

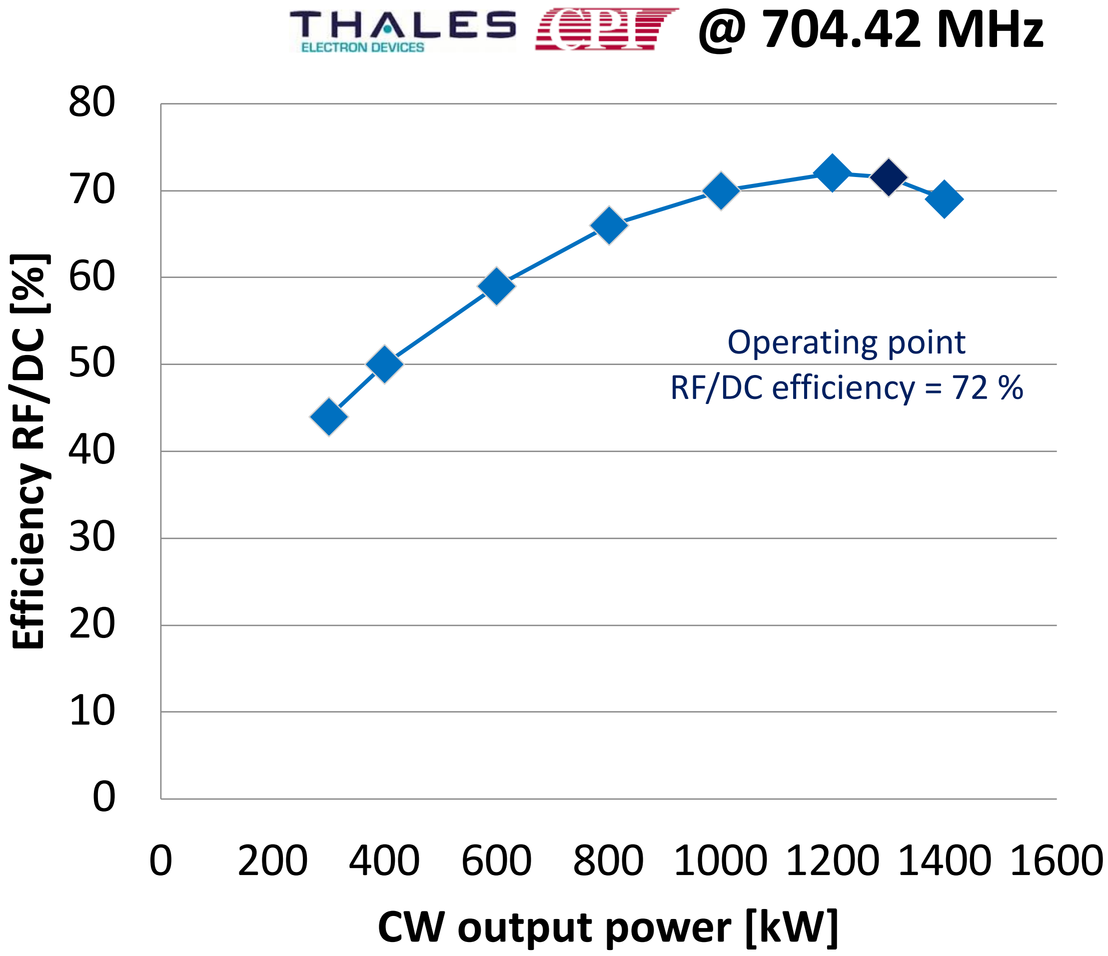


THALES ELECTRON DEVICES CPI

R&D program, MB-IOT



Operating point
RF/DC efficiency = 70 %



Operating point
RF/DC efficiency = 72 %

R&D, MB-IOT

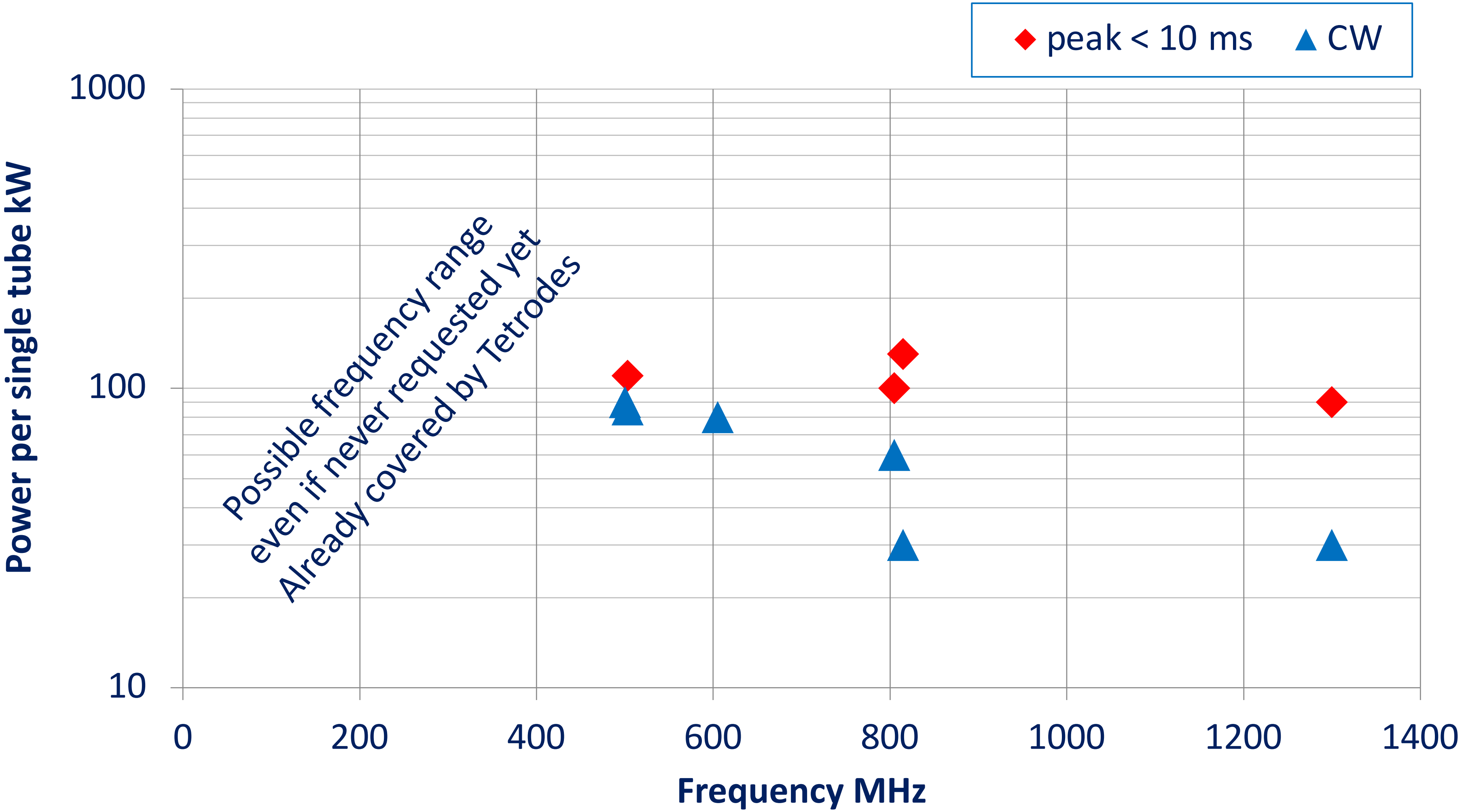
L3 MB-IOT, 750 MHz, 5 % duty cycle

```
Aav
Gate 1
Av    1.350 MW
Pk    1.357 MW
P/A   0.022 dB

Bav
Gate 1
Av    9.352 kW
Pk    9.802 kW
P/A   0.204 dB
```

Thales-CPI MB-IOT, 750 MHz, 5 % duty cycle

IOT available from industry



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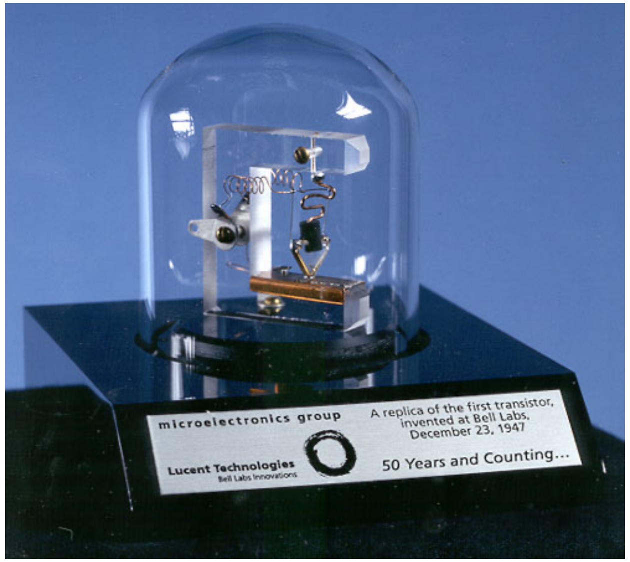
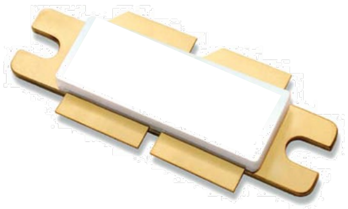
Transistor for RF power

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)
1997	Silicon carbide (SiC)
2004	Carbon graphene

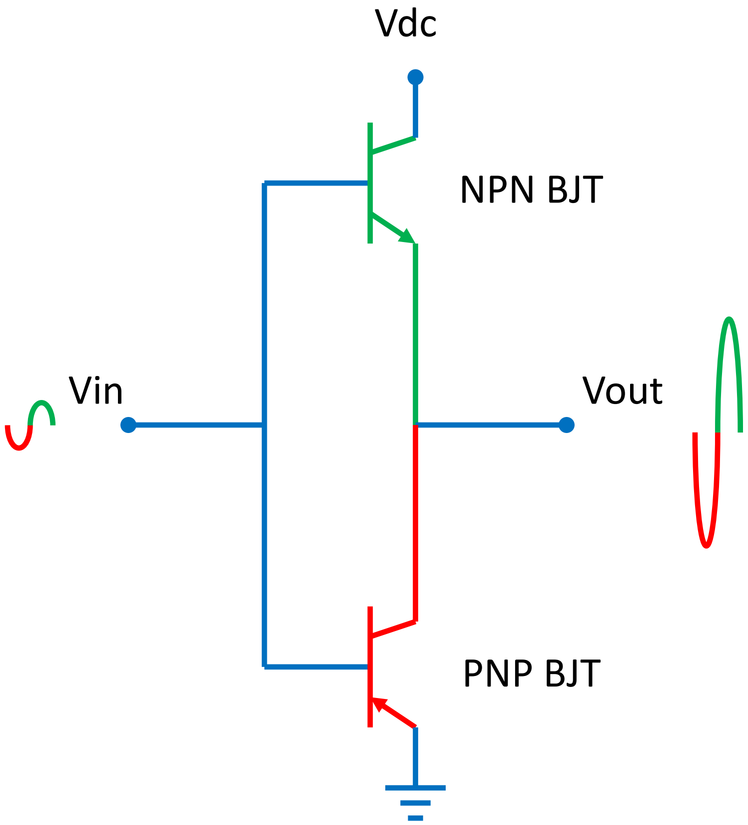


First transistor invented at BELL labs in 1947



XXI century LDMOS

Essentials of RF transistor

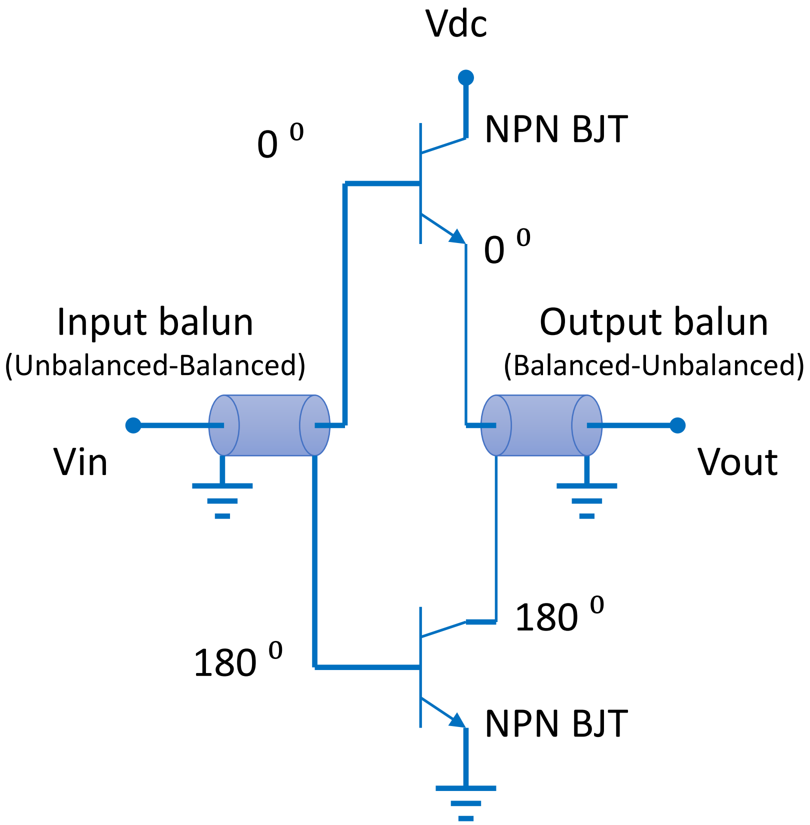


In a push-pull circuit the RF signal is applied to two devices

- 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



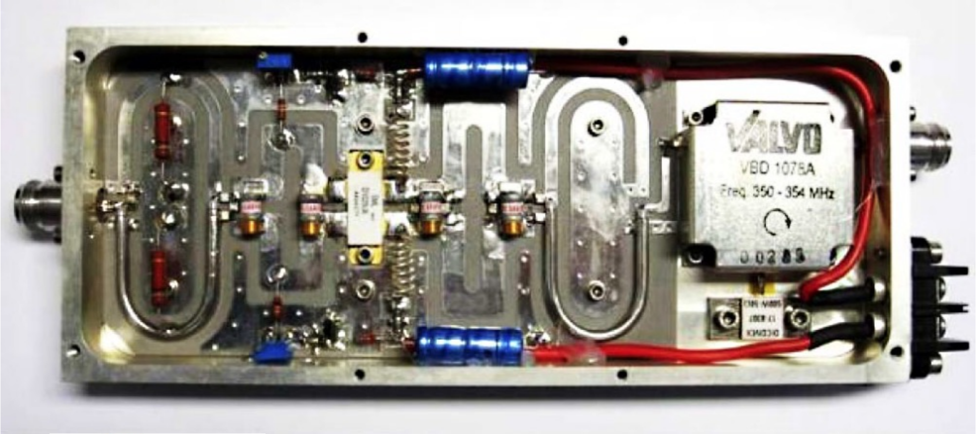
Another push-pull configuration is to use a balun (balanced-unbalanced)

- 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

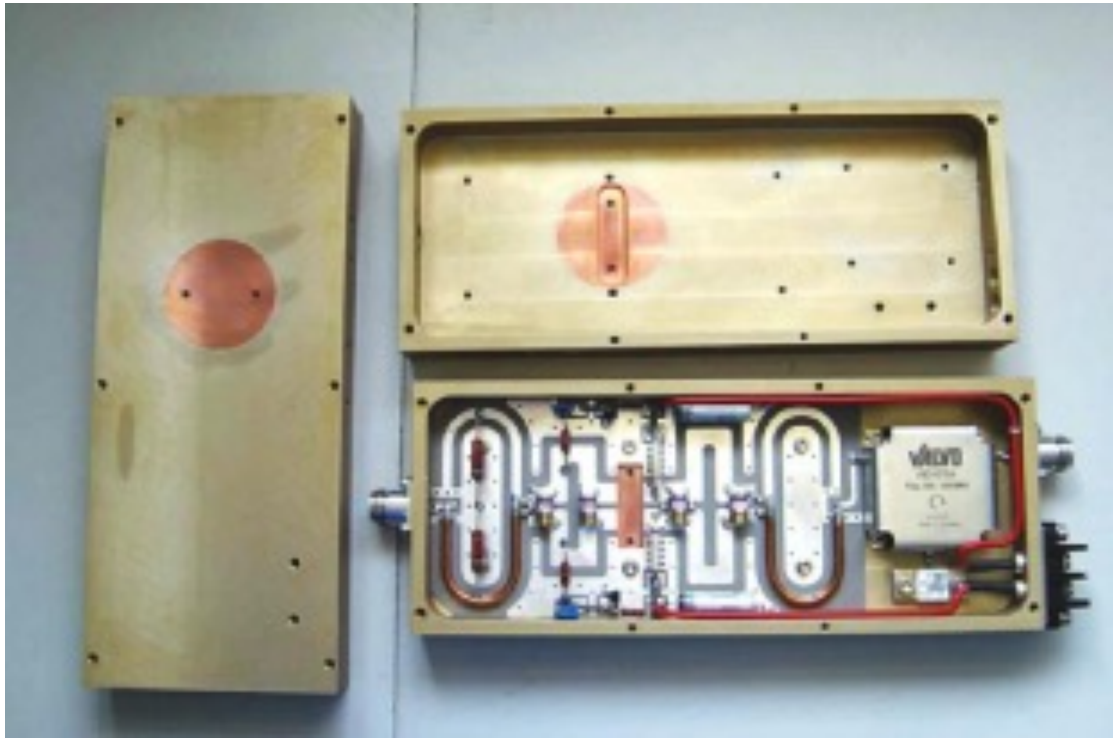


SOLEIL SYNCHROTRON elementary amplifier module
VDMOS-D1029UK05 operated at 330 W at 352 MHz
under 30 Vdc with a gain of 11 dB
Each module is with a Valvo 500 W circulator to protect
the transistors from excess of reflected power

Essential of transistors

An important aspect of high-power transistors is the heat transfer to the cooling system

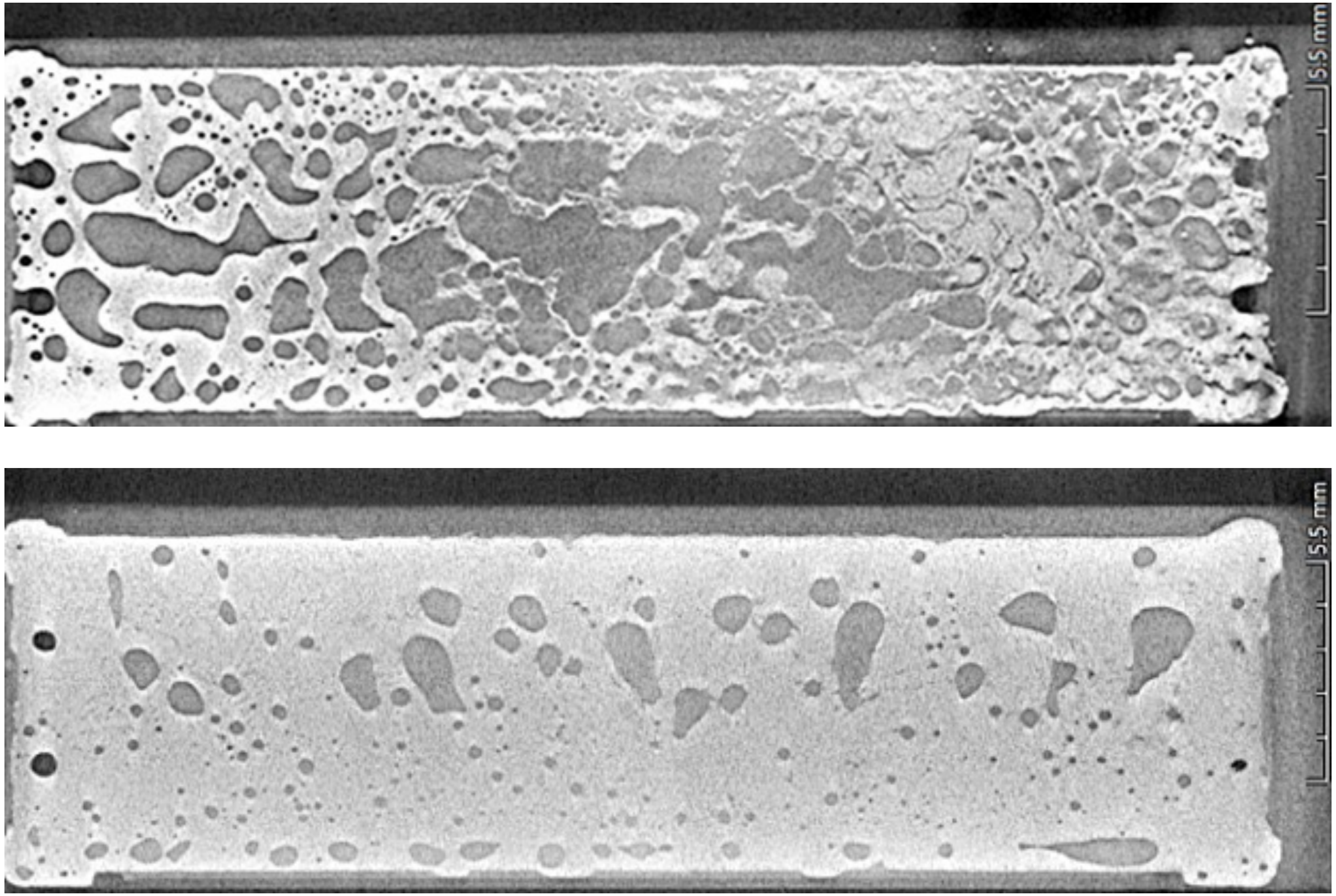
An upgrade of the SOLEIL system was the insertion of a copper slug through the aluminium case of the amplifier modules, at the transistor location, significantly improving the heat transfer, computer simulations shown a 15˚C temperature drop



SOLEIL SYNCHROTRON amplifier module with copper slug through the aluminium case

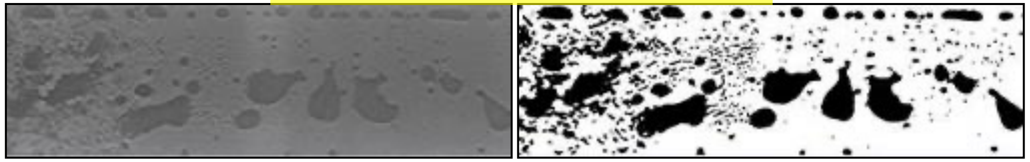
VOIDS

Thermal effect are closely linked to the way the transistors are brazed to their cold plate

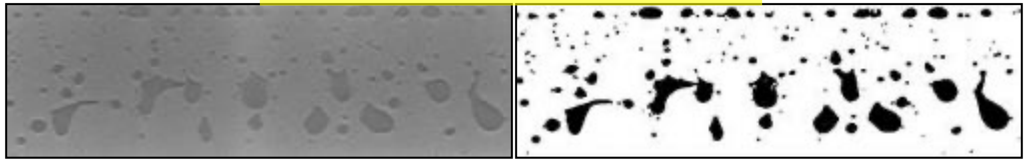


Voids

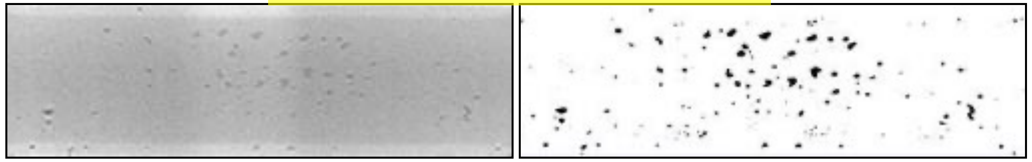
Very bad 25 % voids

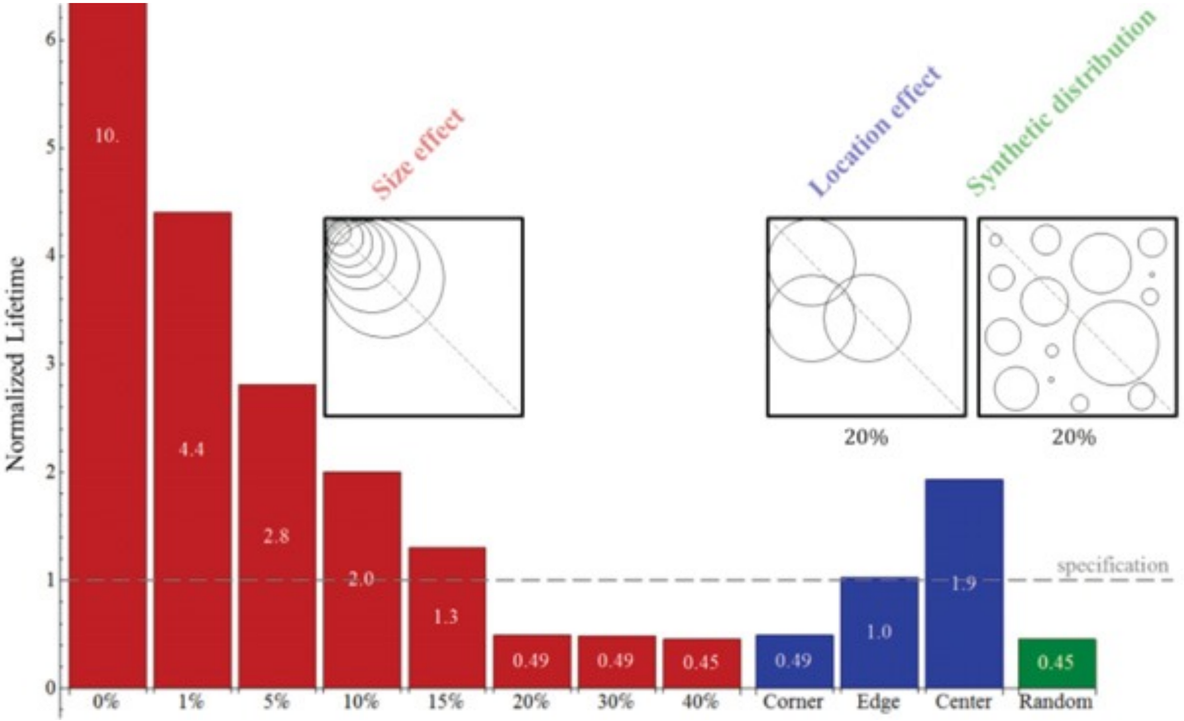


Bad 15 % voids



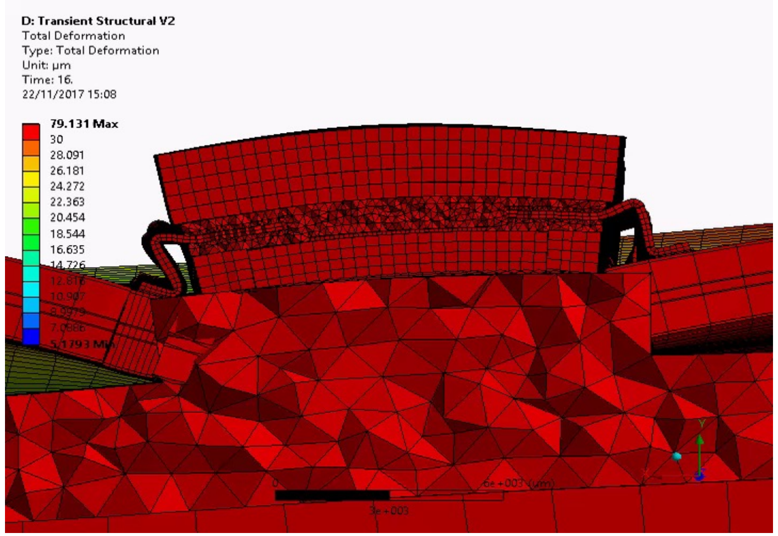
Very good 2 % voids

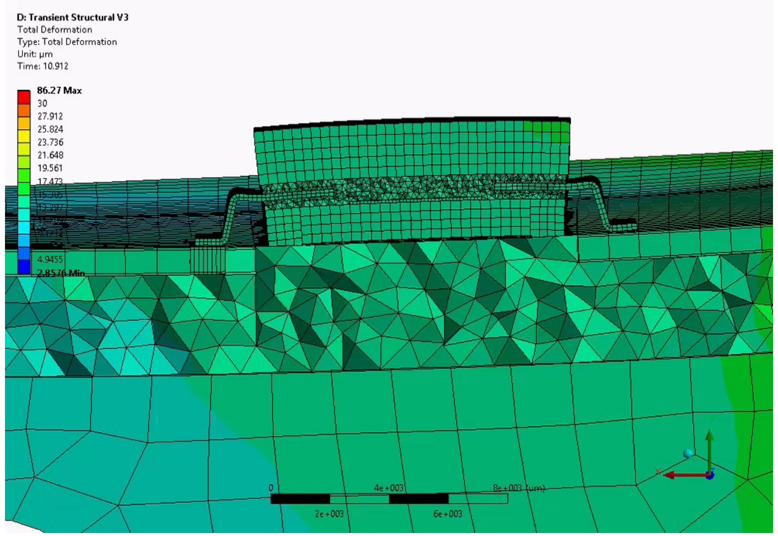


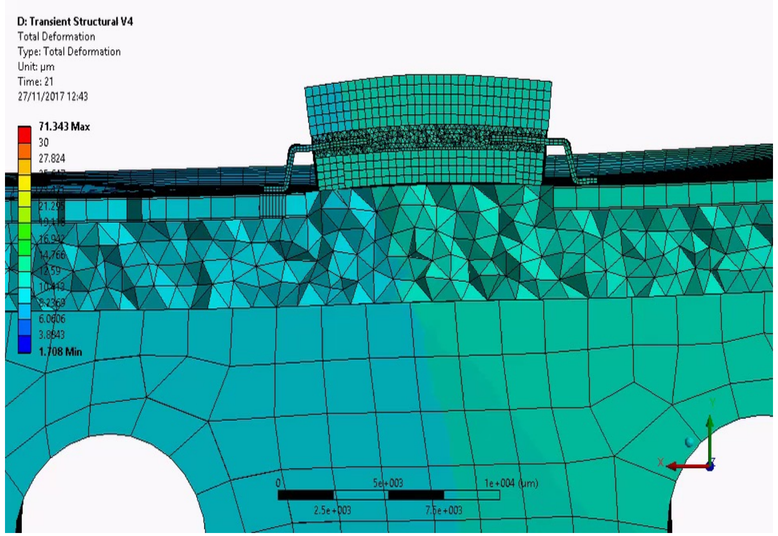


One must develop a very specific way to proceed with the brazing, under vacuum, with a special deposition of the brazing pate, and a specific thermal ramp up and ramp down in order to minimize the number and the shape of voids

Thermal stress on PCB & transistors







Regarding the cycling of your machine, thermal stress can damage your transistor to PCB link
Careful simulations are mandatory to define the best design

Lifetime thermal improvement

Applying some LESIT or Coffin-Manson formula, and defining a stress thermal cycle, with a 10 seconds ON / 10 seconds OFF cycle, one can predict the expected lifetime of a transistor

Design 1 (with 83 modules)

Nb cycles = 4E14*36^(-5) = 6.6E6

Tcase = 66

Delta T = 36

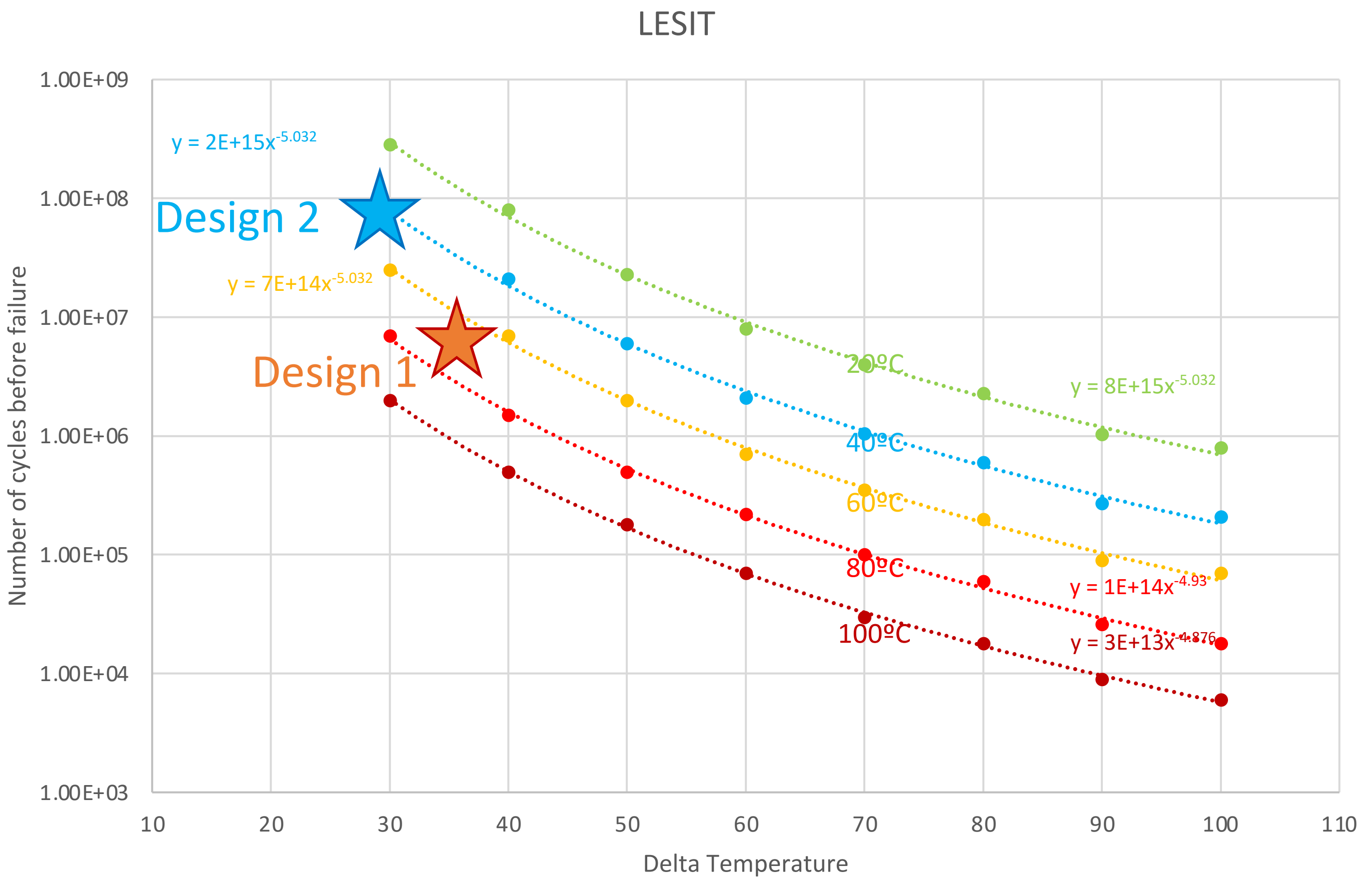
Design 2 (with 67 modules)

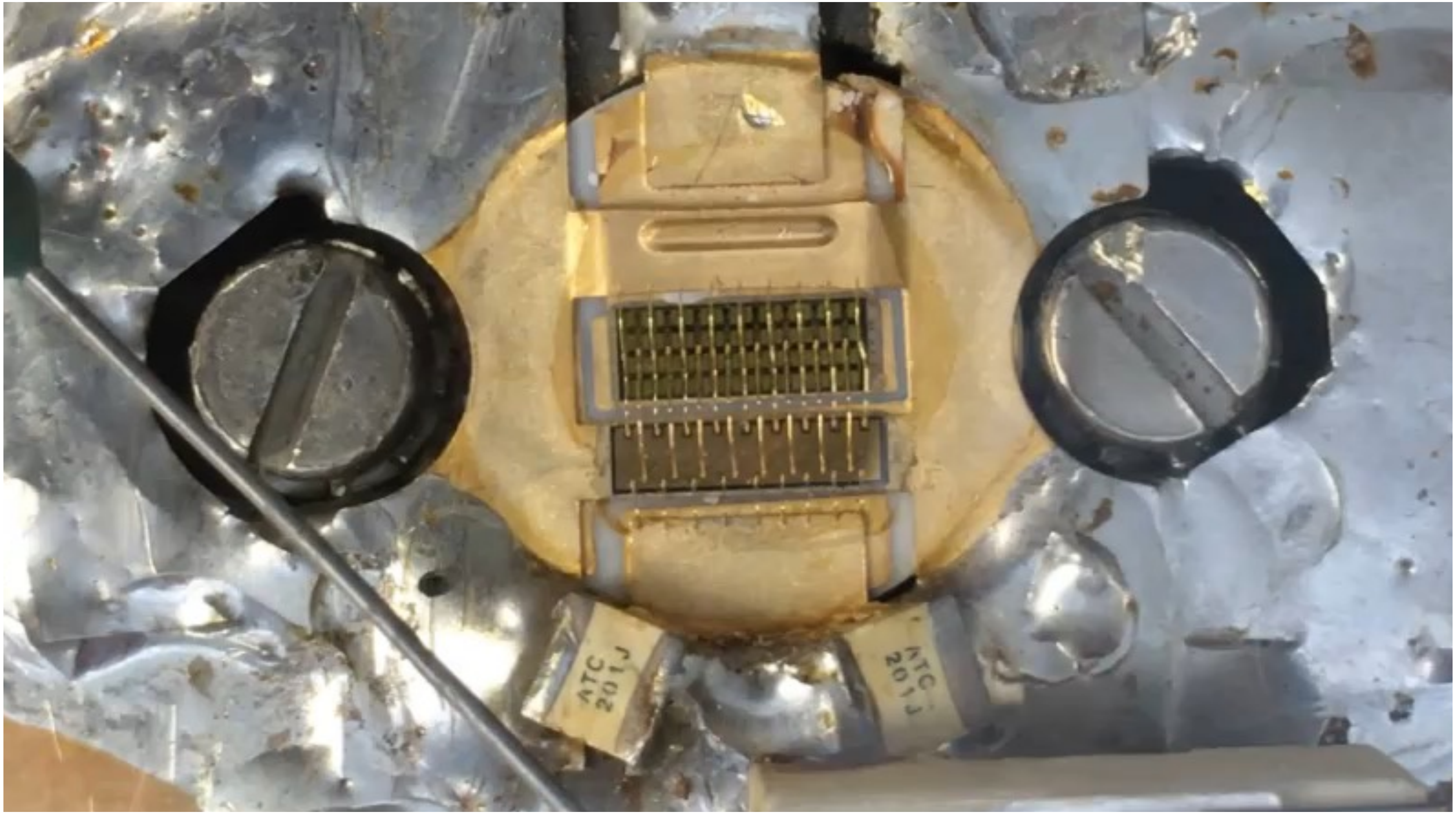
Nb cycles = 2E15*29^(-5) = 9.8E7

Tcase = 40

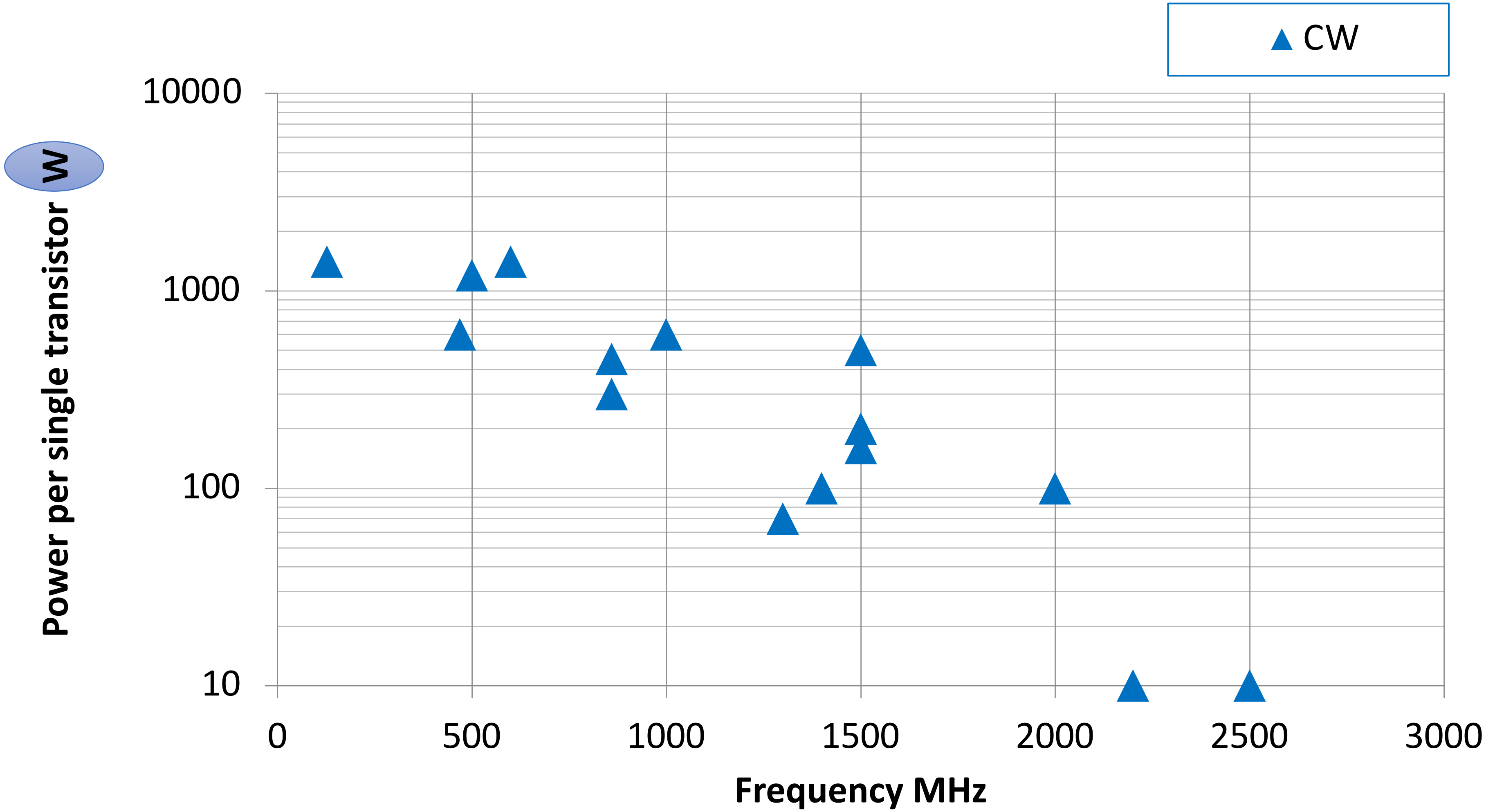
Delta T = 29

Improvement factor =8.2E7/7.5E6 = **15**




ATC
201J
ATC
201J

Transistors available from industry



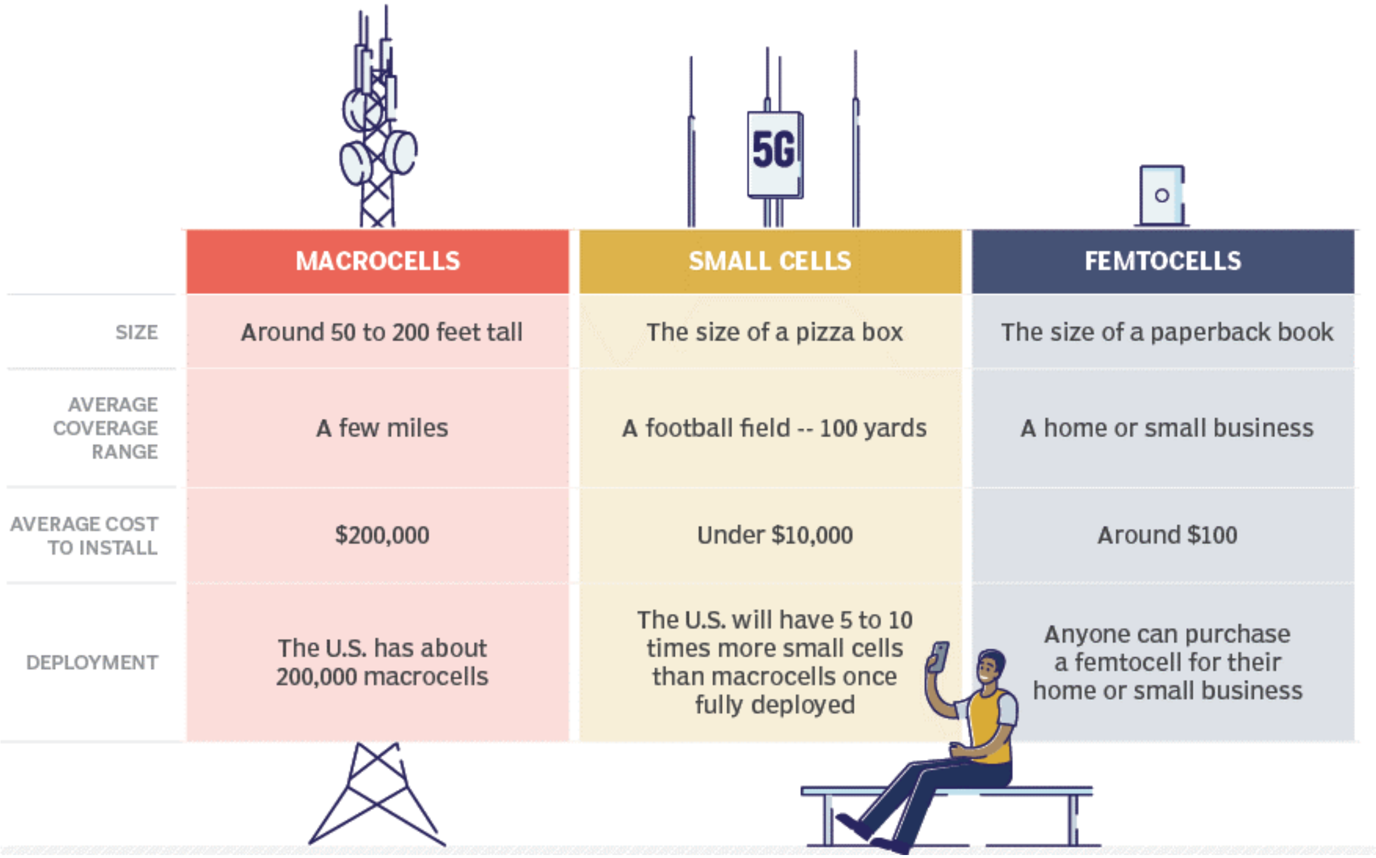
Transistor power ratings

Device	Distance	Power
Phone	20 km	2 W
Microcell	2 km	10 W
Macrocell	20 km	50 W

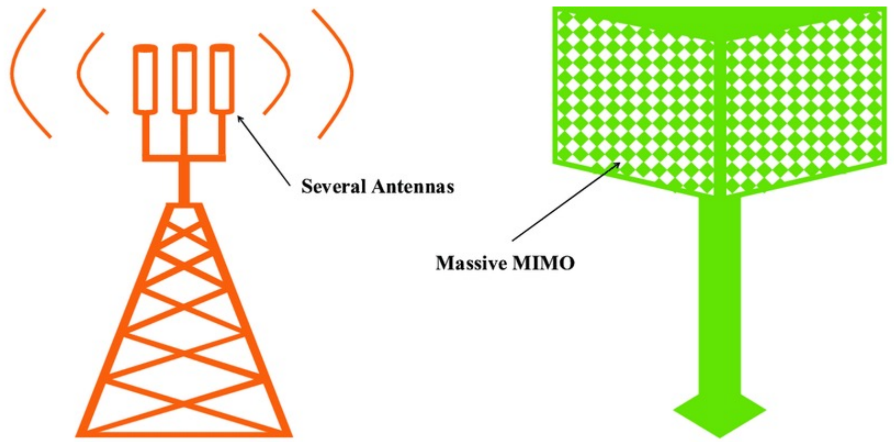
Voltage limits		
	2002	Since 2006
900 MHz	41 V/m	3 V/m
1800 MHz	58 V/m	
2100 MHz	61 V/m	

The tendency is to increase the number of smaller cells in order to keep the phone battery autonomy, increase the data bandwidth, and reduce the exposition of population to too high electromagnetic fields

Macro cells vs Small cells vs femtocells

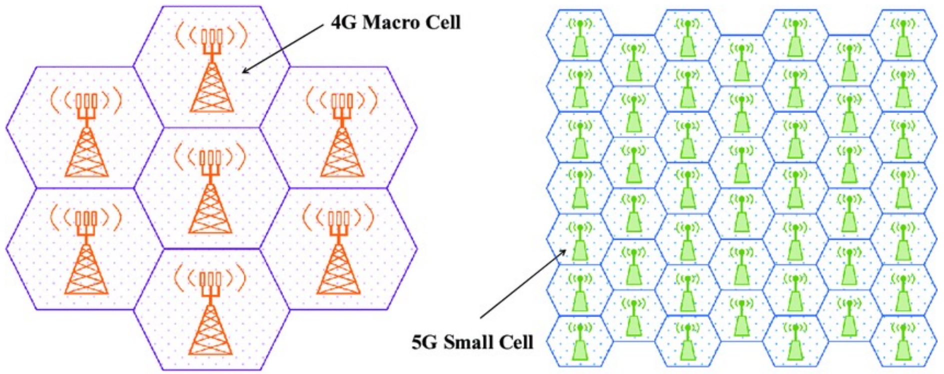


	MACROCELLS	SMALL CELLS	FEMTOCELLS
SIZE	Around 50 to 200 feet tall	The size of a pizza box	The size of a paperback book
AVERAGE COVERAGE RANGE	A few miles	A football field -- 100 yards	A home or small business
AVERAGE COST TO INSTALL	$200,000	Under $10,000	Around $100
DEPLOYMENT	The U.S. has about 200,000 macrocells	The U.S. will have 5 to 10 times more small cells than macrocells once fully deployed	Anyone can purchase a femtocell for their home or small business



(a) 4G Macro Base Station

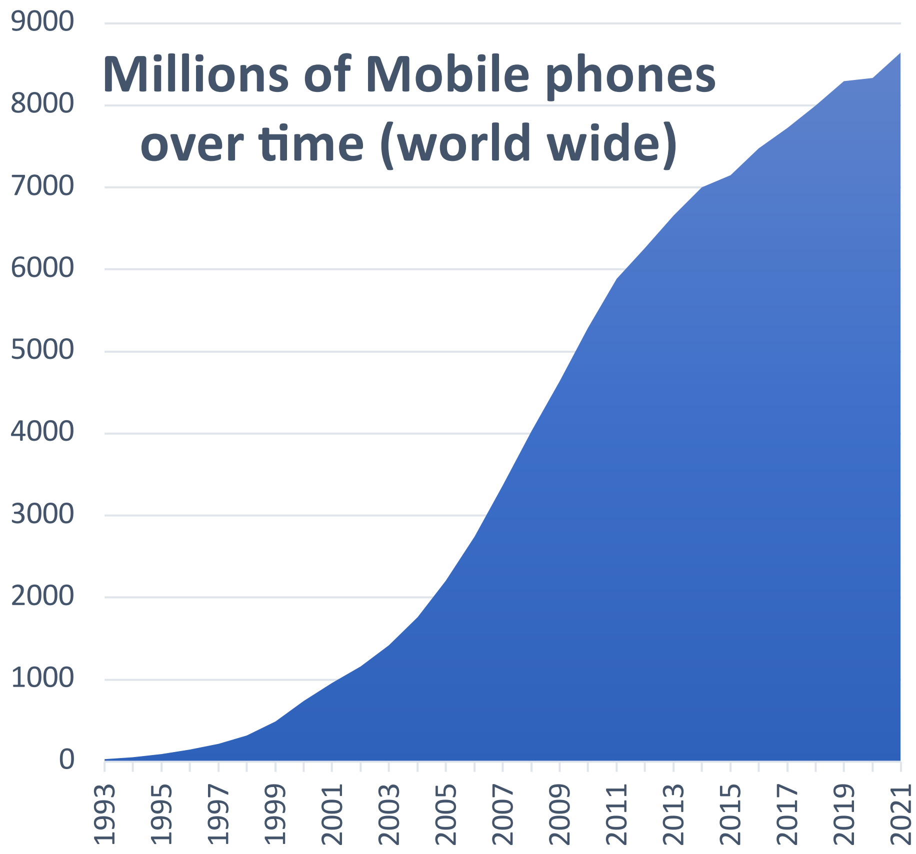
(b) 5G Macro Base Station

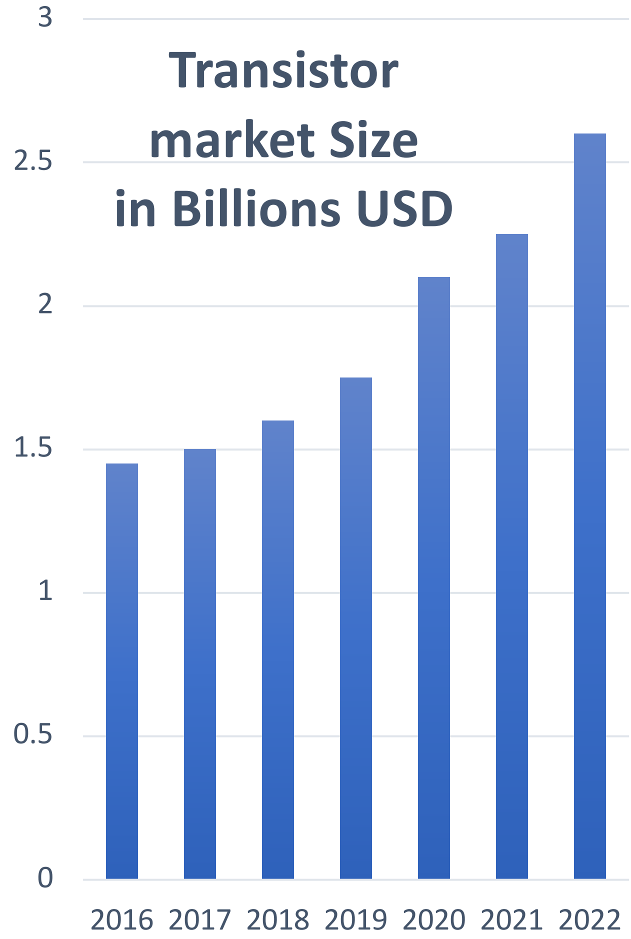


(c) 4G Communication Network

(d) 5G Communication Network

A few numbers to situate RF transistors in accelerators

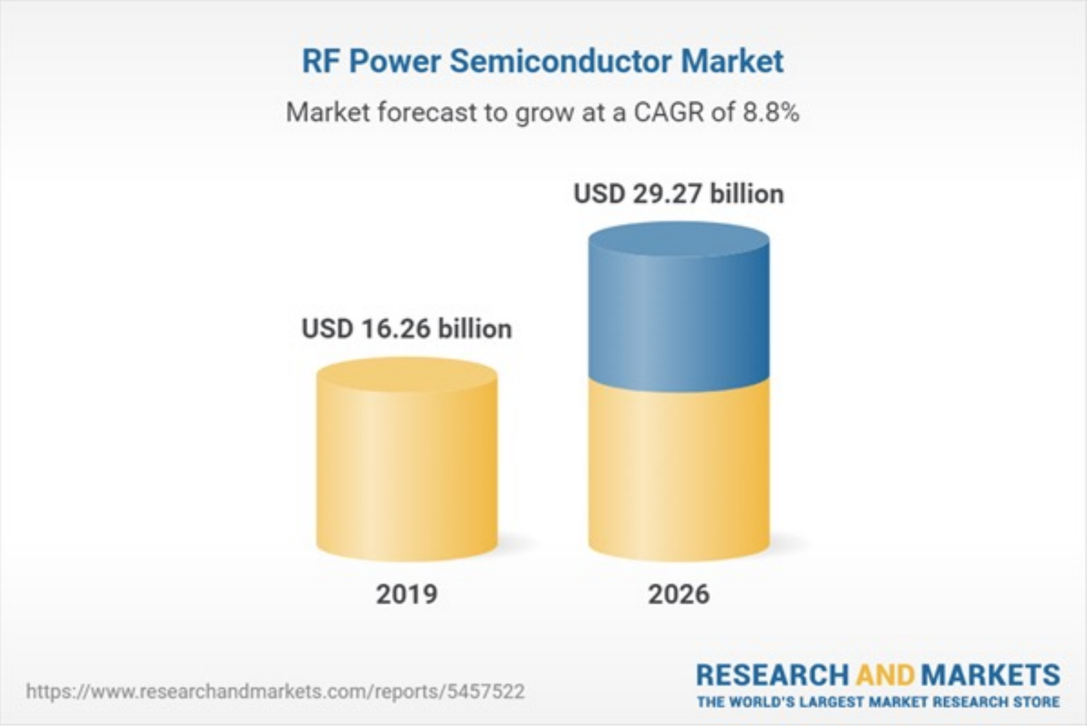


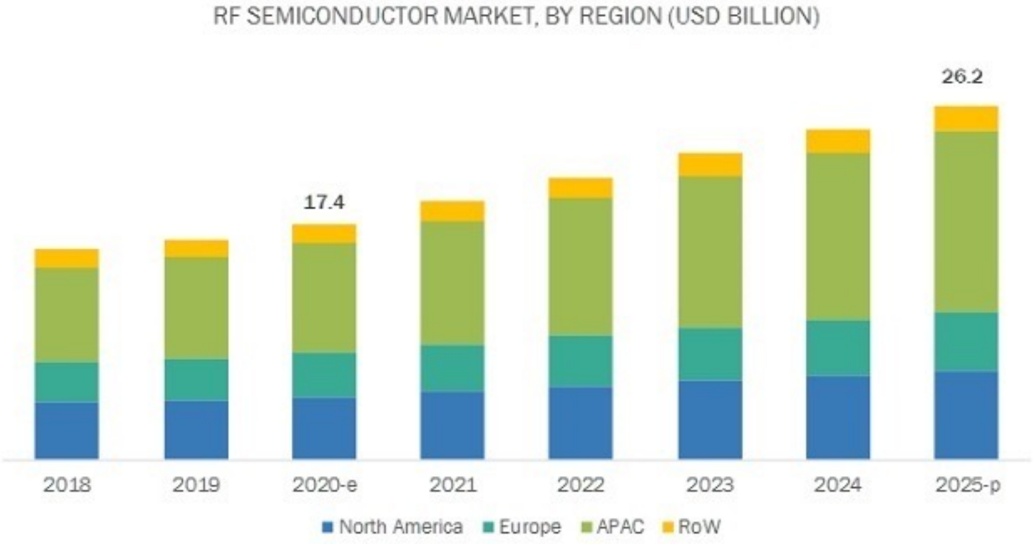


Some of the Key Players

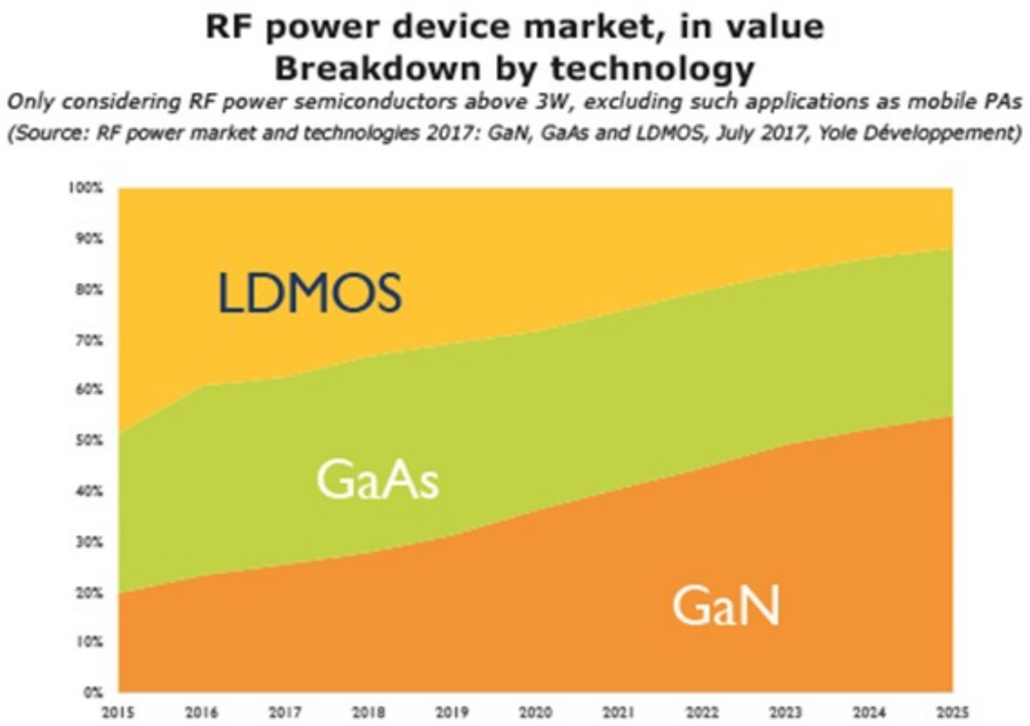
Ampleon
Analog Devices
BONN Elecktronik
Broadcom Pte.
Cree
General Dynamics
Infineon
Integra
MACOM
Maxim Integrated
Mitsubishi
NoleTec
NXP Semiconductors
Qorvo
Qualcomm
Skyworks Solutions
STMicroelectronics
Tagore Technology
Thales Alenia Space
Toshiba

A few numbers to situate RF transistors in accelerators



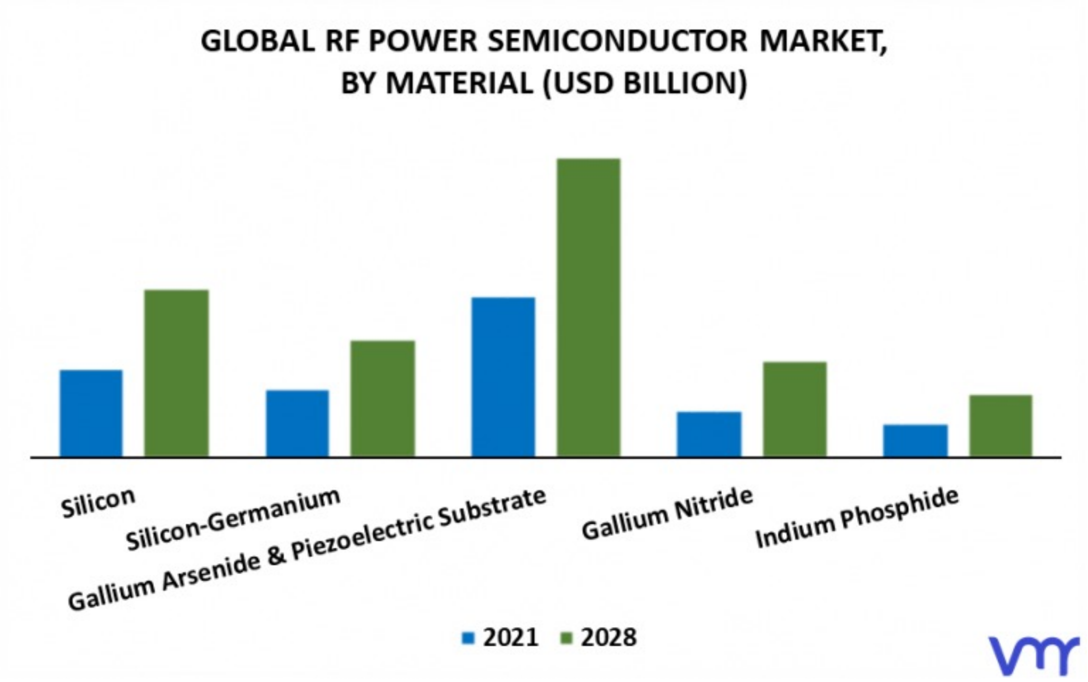


A few numbers to situate RF transistors in accelerators



RF power device market, in value
Breakdown by technology

Only considering RF power semiconductors above 3W, excluding such applications as mobile PAs
(Source: RF power market and technologies 2017: GaN, GaAs and LDMOS, July 2017, Yole Développement)

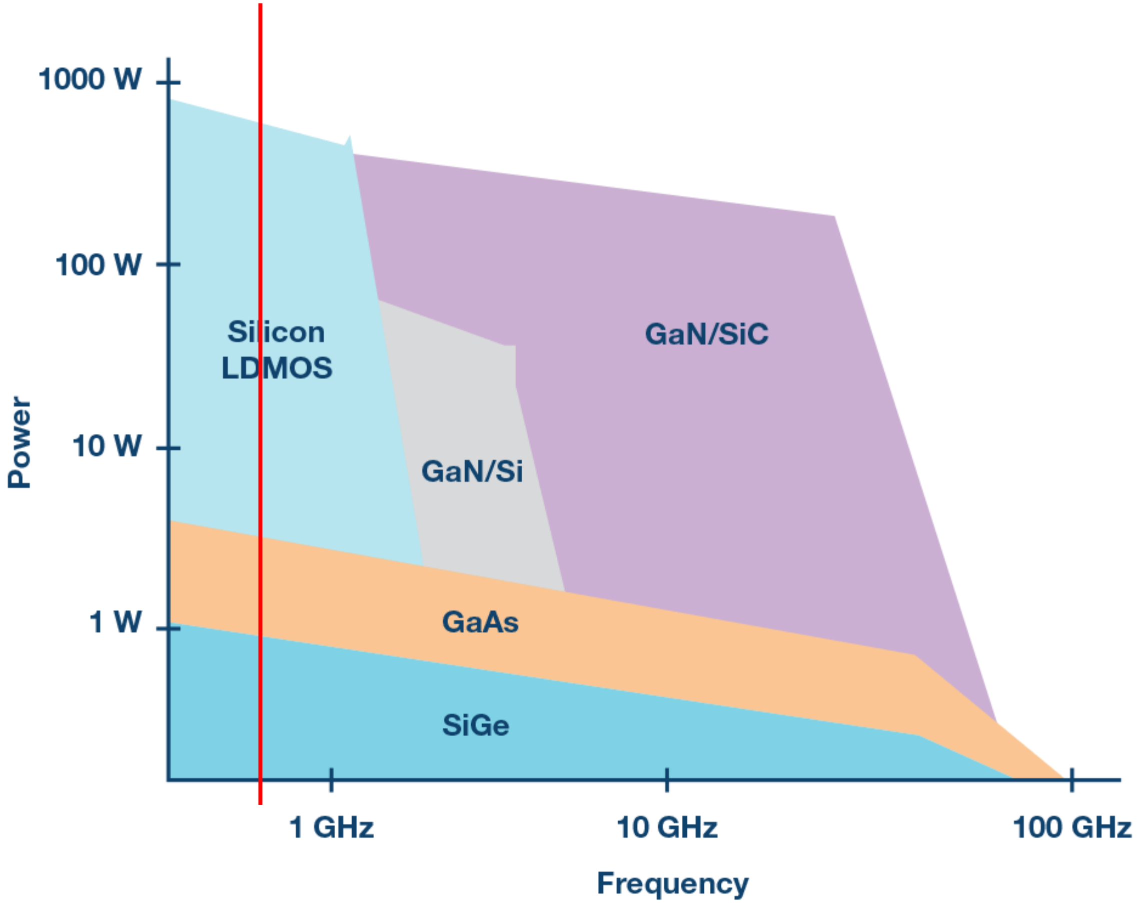


GLOBAL RF POWER SEMICONDUCTOR MARKET, BY MATERIAL (USD BILLION)

Source: RF Power Semiconductor Market Trends
From Yole Développement
Patrick Hindle - Editor, Microwave Journal July 11, 2017

A few numbers to situate RF transistors in accelerators

HL-LHC (400 MHz) due in ~ 5 years
FCC (400 MHz to 800 MHz) due in ~ 15 years



Transistor power ratings – *personal view* of future perspective

(CWRF 2016, updated 2022)

Transistor supplier main business will not be higher power per transistor

Conclusion: below a GHz, 1 kW per transistor (LDMOS) seems *(to me)* a very good goal

8.5 Billions Smartphones in 2021

90 Millions Femtocell stations 2016

7 Millions Macrocell stations 2017

NXP Semiconductors revenue in 2020 was $8’600 Millions

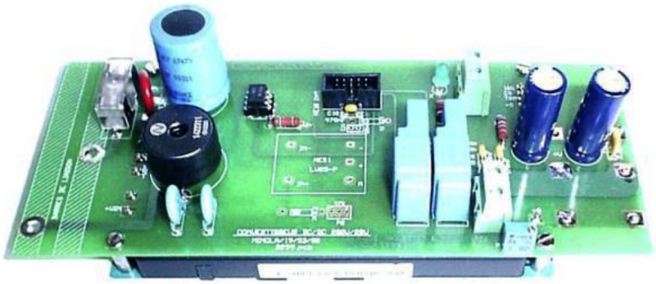
Assumption (with a lot of simplifications)

Machine	**# RF stations**	**Power**	**# 1 kW LDMOS**
FCC	1’000	1 MW	1’000’000

Cost of a LDMOS	~ $100
Total cost of FCC	~ $100 Million
Over minimum 5 years of construction	~ $20 Million per year

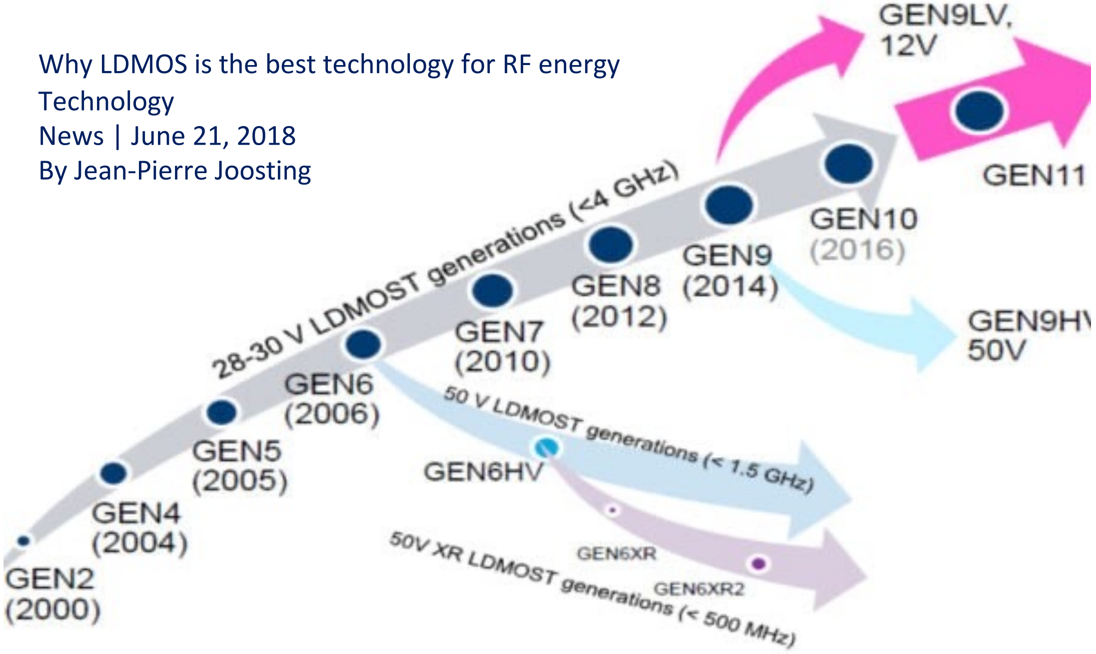
RF for accelerators could be
20 / 8600 = 0.2 % of main suppliers revenue

Drain voltage



SOLEIL SYNCHROTRON elementary 600 W 300 Vdc / 30 Vdc converter board

Why LDMOS is the best technology for RF energy
Technology
News | June 21, 2018
By Jean-Pierre Joosting



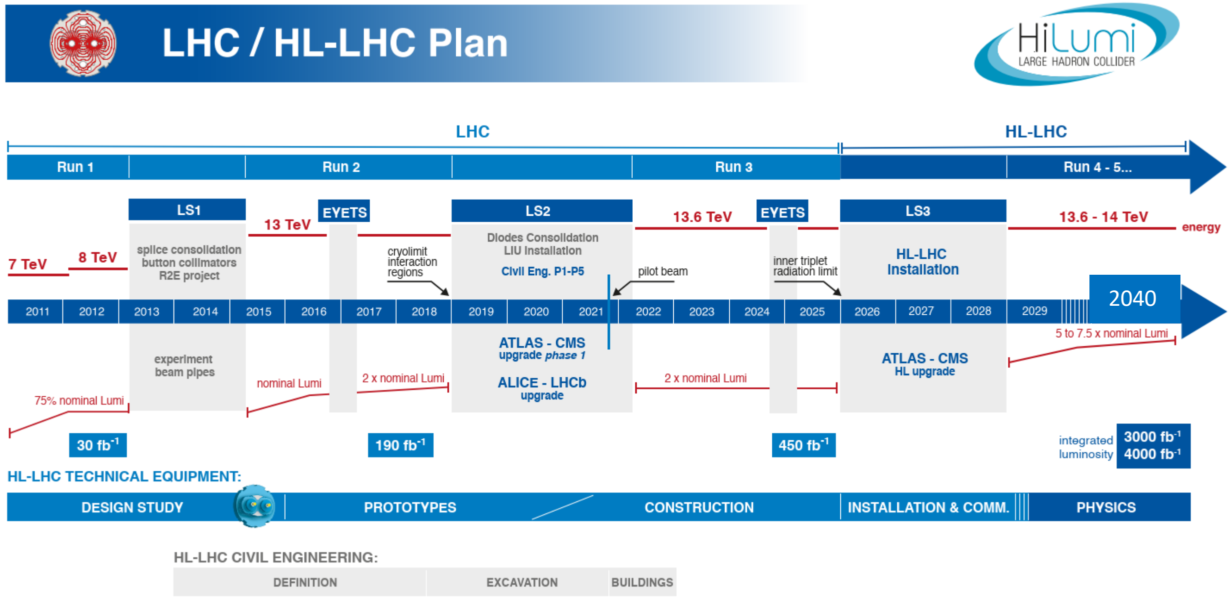
Evolution of the transistors market is quick

This is still a volatile market (as tubes have been a century ago)

Drain voltage is increasing with the development of transistors, and the Drain supply used with a generation of device could not suit the next generation
(moving from 12V to 24 V to 30 V to 36 V to 48 V to 50 V to 60 V to 80 V to 100 V)

Changing the transistor will not be the only challenge, either it will be under used as keeping the previous power supply, or power supply voltage will have to be upgraded

Obsolescence



When we started SPS SSPA in 2017, the chosen transistor was the 'best for new design' quoted by the transistor supplier

Beginning 2022, we received a 'Last Buy Order' email…

(the same with other labs, within 3-5 years, 'best to use' transistors turn to be 'do not use for new design', and to 'obsolete' item…)

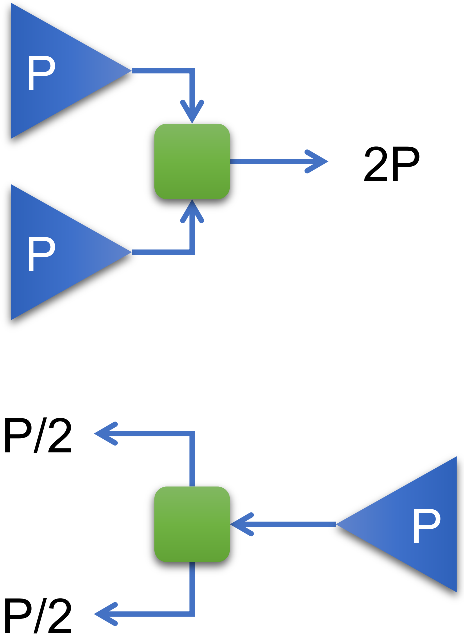
Changing the transistor generation is often linked to changing the operating voltage, this makes that change out of budget

The difficulty with Accelerators is that when we buy a new amplifier, it has to last 20-25 years

The amplifier architecture should then be designed such that the amplifier will last the 20 years without major upgrade

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)

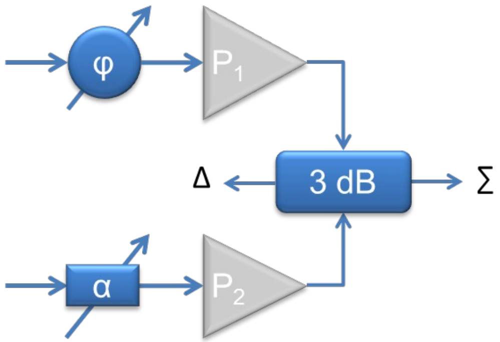
Hybrid power splitters & Combiners

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

Combination

$$\Sigma = \frac{PA1 + PA2}{2} + \sqrt{PA1\,PA2}$$

$$\Delta = \frac{PA1 + PA2}{2} - \sqrt{PA1\,PA2}$$



3 dB combiner is very common for RF power combination at these frequencies since the 70’s

If one correctly adjusts the phases and the amplitudes, equations show that

With PA1 = PA2 = PA3 = PA4 = P then

Pout = 4 P

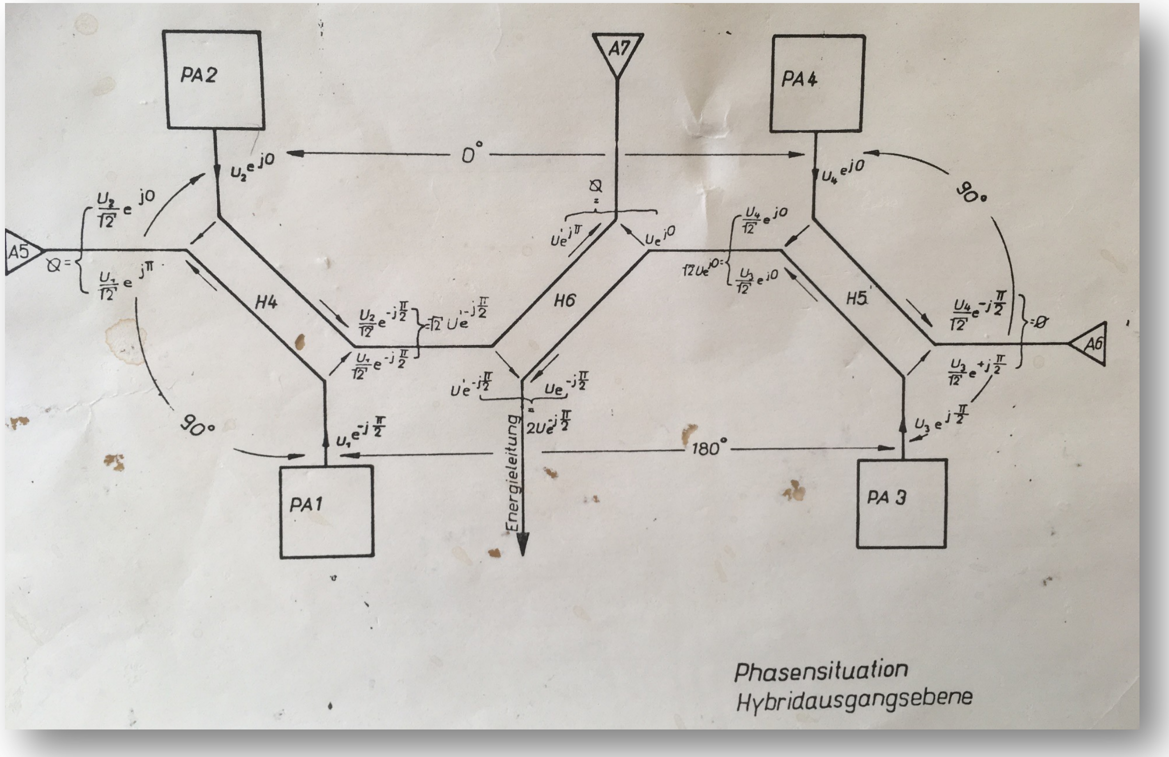
Load A5 = A6 = A7 = 0

In case **one** amplifier is **stopped** (PA1 for example), then

Pout = (9/16) 4P = **2,25 P**

Load A5 = 0,5 P

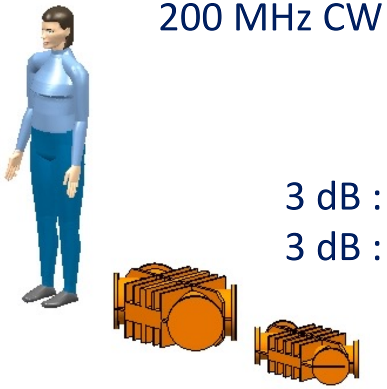
Load A7 = 0,25 P



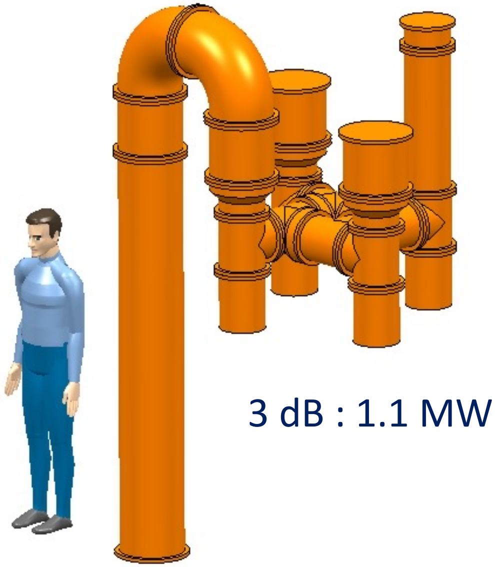
Combination

CERN SPS 16:1 combiner @ 200 MHz

200 MHz CW combiners



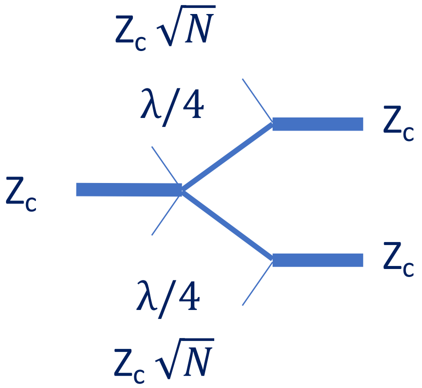
3 dB : 550 kW
3 dB : 160 kW



3 dB : 1.1 MWp

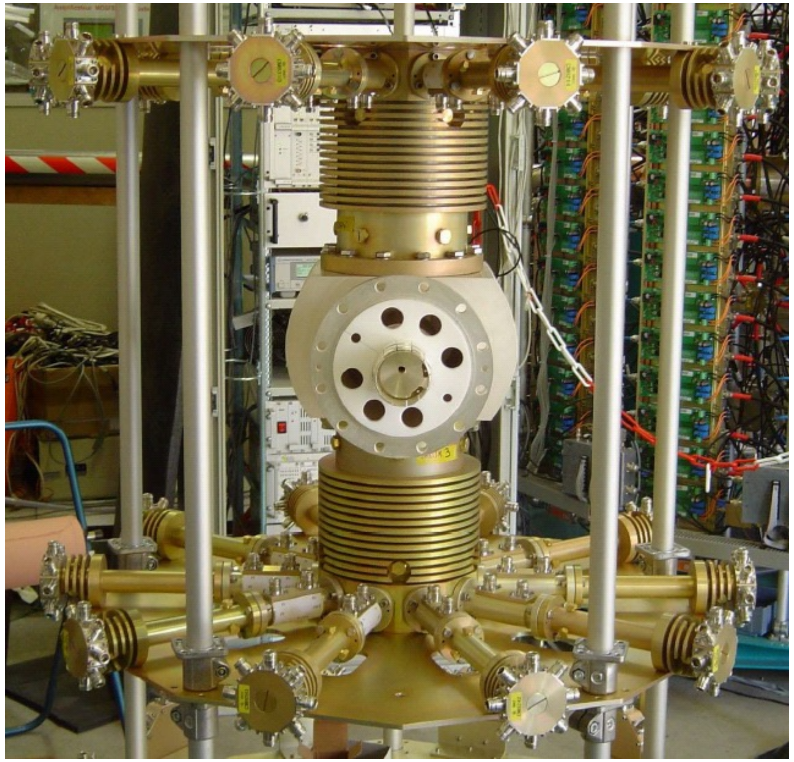
Combiners & Splitters

Low loss T-Junction



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

We have a N-ways splitter

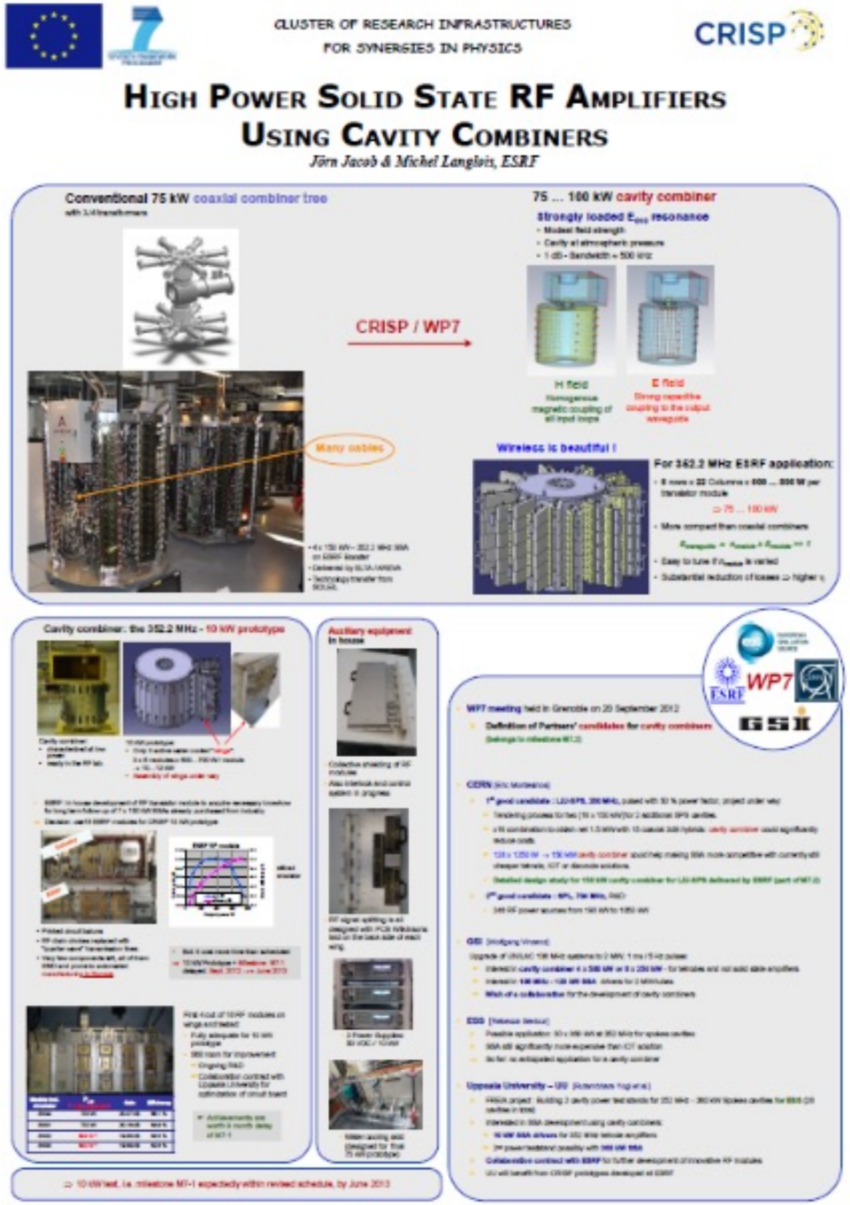


SOLEIL SYNCHROTRON

160 to 1 @ 352 MHz
T-junction combiner

Cavity combiner

- CRISP (Sept 2010)
  - Jörn Jacob (ESRF) asked for support to the development of cavity combiners receiving funding from the EU as work package WP7 in the framework of the FP7/ESFRI/CRISP program
  - CERN immediately supported it
- CRISP, 2nd yearly meeting, PSI 18-19 March 2013
  - ESRF cavity combiner
  - 144:1 Cavity combiner for CERN-LIU-SPS
- In addition, please refer to two excellent papers from ESRF at IPAC
  - MOPC005-IPAC11, 352.2 MHZ – 150 kW Solid State Amplifiers at the ESRF
  - WEPFI004-IPAC13, Commissioning of first 352.2 MHz - 150 kW Solid state amplifiers at the ESRF and status of R&D



CLUSTER OF RESEARCH INFRASTRUCTURES
FOR SYNERGIES IN PHYSICS

CRISP

HIGH POWER SOLID STATE RF AMPLIFIERS
USING CAVITY COMBINERS

Jörn Jacob & Michel Langlois, ESRF

Conventional 75 kW coaxial combiner tree

75 … 100 kW cavity combiner

Strongly loaded E_{010} resonance

- Cavity at atmospheric pressure

CRISP / WP7

H field

E field

Many cables

Wireless is beautiful !

For 352.2 MHz ESRF application:

- More compact than coaxial combiners

Cavity combiner: the 352.2 MHz - 10 kW prototype

Auxiliary equipment in house

WP7

Cavity combiner

The radius of a cylindrical resonator is set so that the E010 mode frequency is 200 MHz

A fine tuning is provided by a piston located at the bottom of the resonator

The electrical field is vertical and maximum at the resonator symmetry axis

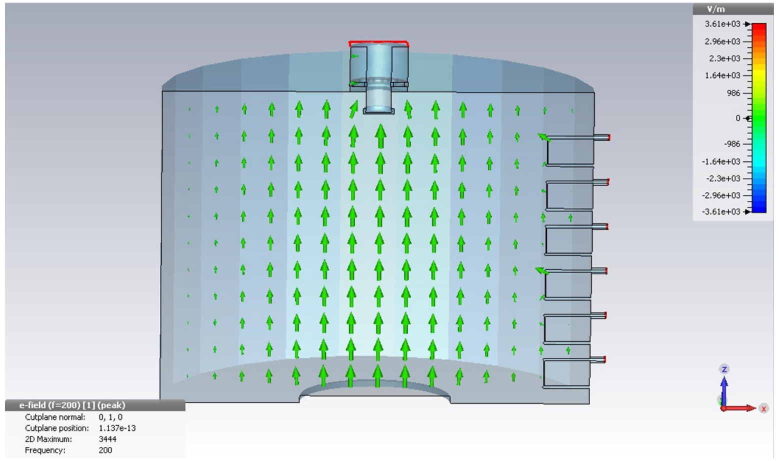
The magnetic field is circular and maximum close to the resonator wall

These field patterns are perfectly suited for coupling many inputs loops protruding through the cavity wall and coupling out the power with a capacitive plate

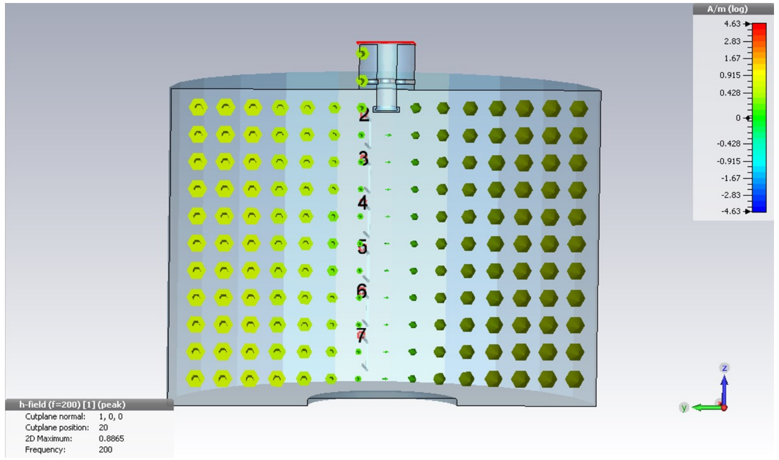
All input signals must have the same amplitude and phase

Attention should be paid to several issues

- There is a possibility of resonance on another mode for the same frequency, the best suspect being H111, it can be controlled with the height of the resonator
- At high power, the electric field in the vicinity of the output coupling may be high and cause breakdowns
- There may be crosstalk between adjacent loops
- Input and output coupling must be determined so that βout=n*βin, n being the number of inputs
- Behaviour of the combiner for harmonics



e-field (f=200) [1] (peak)
Cutplane normal: 0, 1, 0
Cutplane position: 1.137e-13
2D Maximum: 3444
Frequency: 200



h-field (f=200) [1] (peak)
Cutplane normal: 1, 0, 0
Cutplane position: 20
2D Maximum: 0.8865
Frequency: 200

Cavity combiner

EUROPEAN SYNCHROTRON RADIATION FACILITY

ESRF

Accelerator & Source

Technical Note

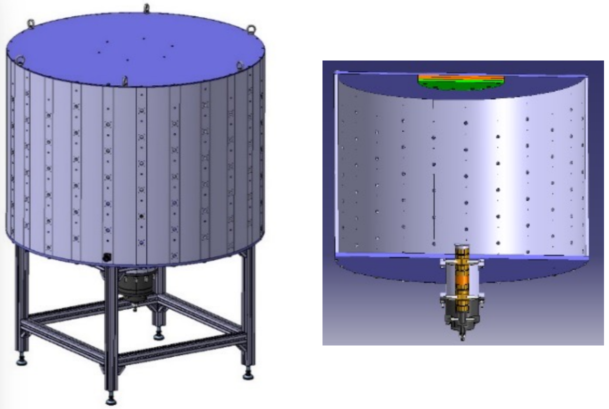
01-13/RF

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

Author(s): Michel LANGLOIS

Date: February11th, 2013

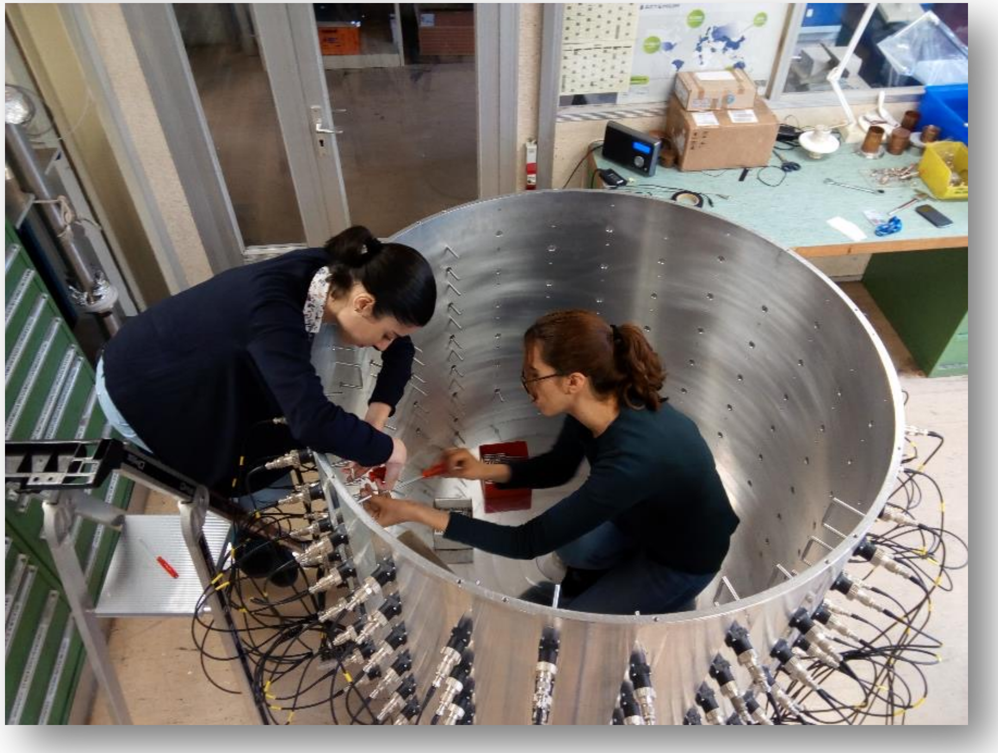
Distribution: Jörn JACOB, Eric MONTESINOS



Feb 2013, within the CRISP programme, we received a report from ESRF, describing how to build our LIU-SPS 200 MHz 144:1 cavity combiner

We completed the calculations and build a first prototype

We also completed the coupling loop design, the tuning design, and the output coupling element and we finally obtained at fantastic 144:1 cavity combiner with only 0,1 dB insertion loss, as calculated



VHPCC (Very High Power Cavity Combiner)

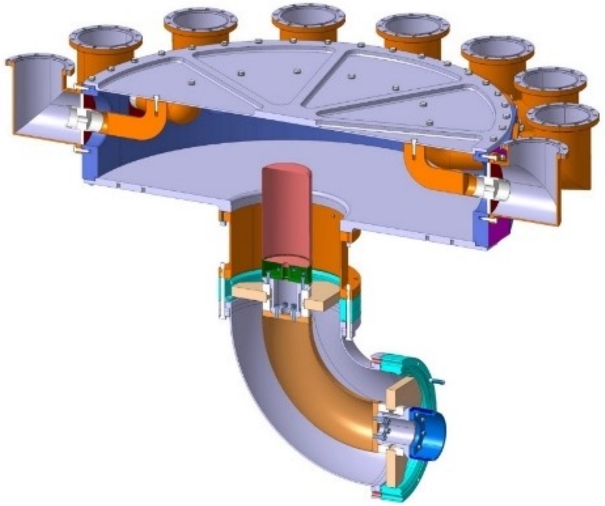
We also designed a VHPCC (Very High Power Cavity Combiner)

The goal was to have 16:1 combiner with inputs in the hundred of kW range and an output in the MW range

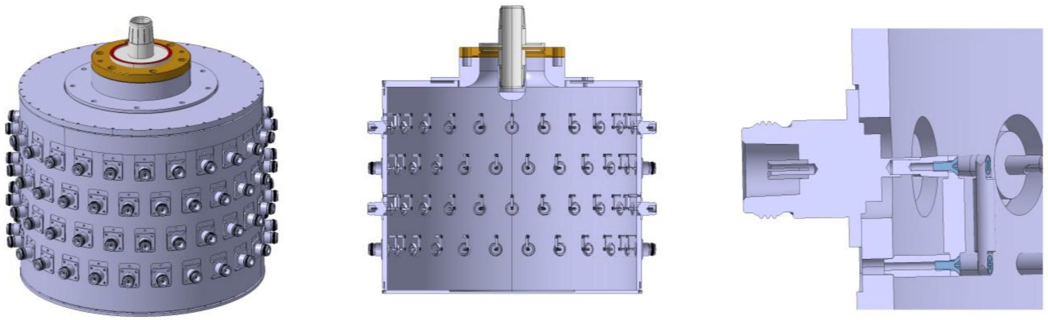
The ‘cavity’ has been machined from a single piece of metal

We tested it in reverse mode, as we had no hundred kW class amplifiers to test it in forward mode, and we checked that we had a perfect distribution between the test loads

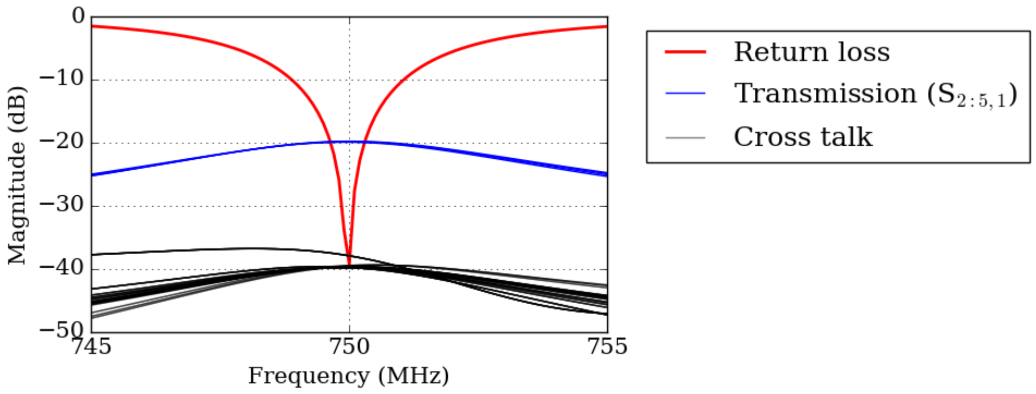
With 1.26 MWp input, we obtained
78 kW +/- 1 kW and the losses were less than 10 kW



Cavity combiner



(a) (b) (c)



With our latest combiner, the body is comprised of four main pieces

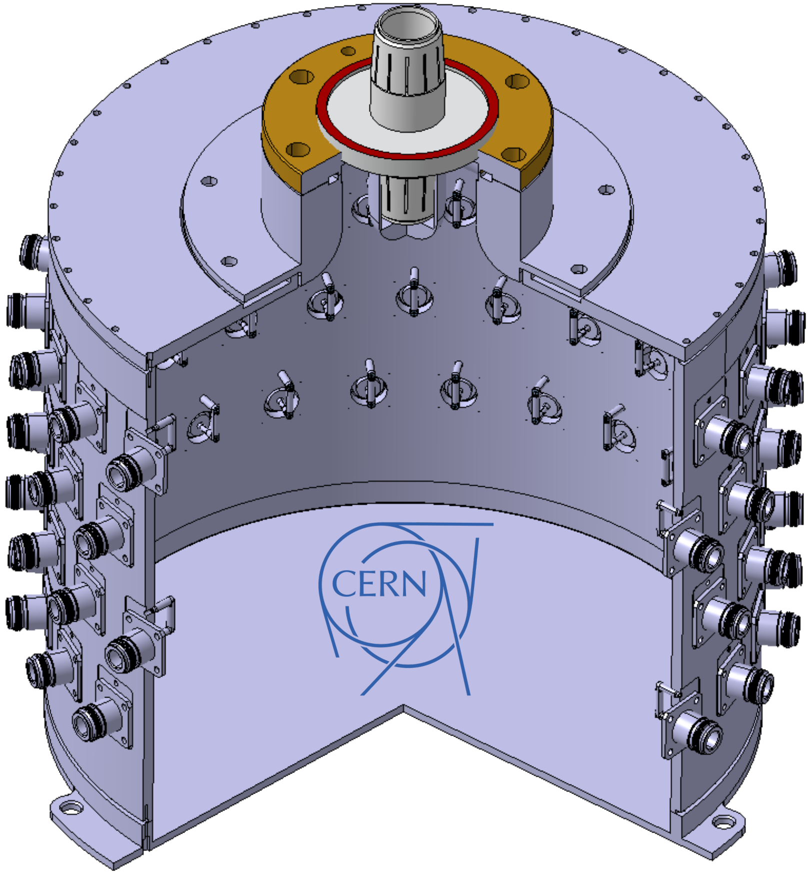
- a tube
- a bottom plate
- a top plat
- an output probe housing

The tube has machined holes compatible with N-type solder cups, the bottom plate has an indentation for disc tuning and the output probe housing is compatible with a standard EIA 3-1/8” flange.

The return loss of the output port is ≤ -20 dB between over a 1 MHz bandwidth

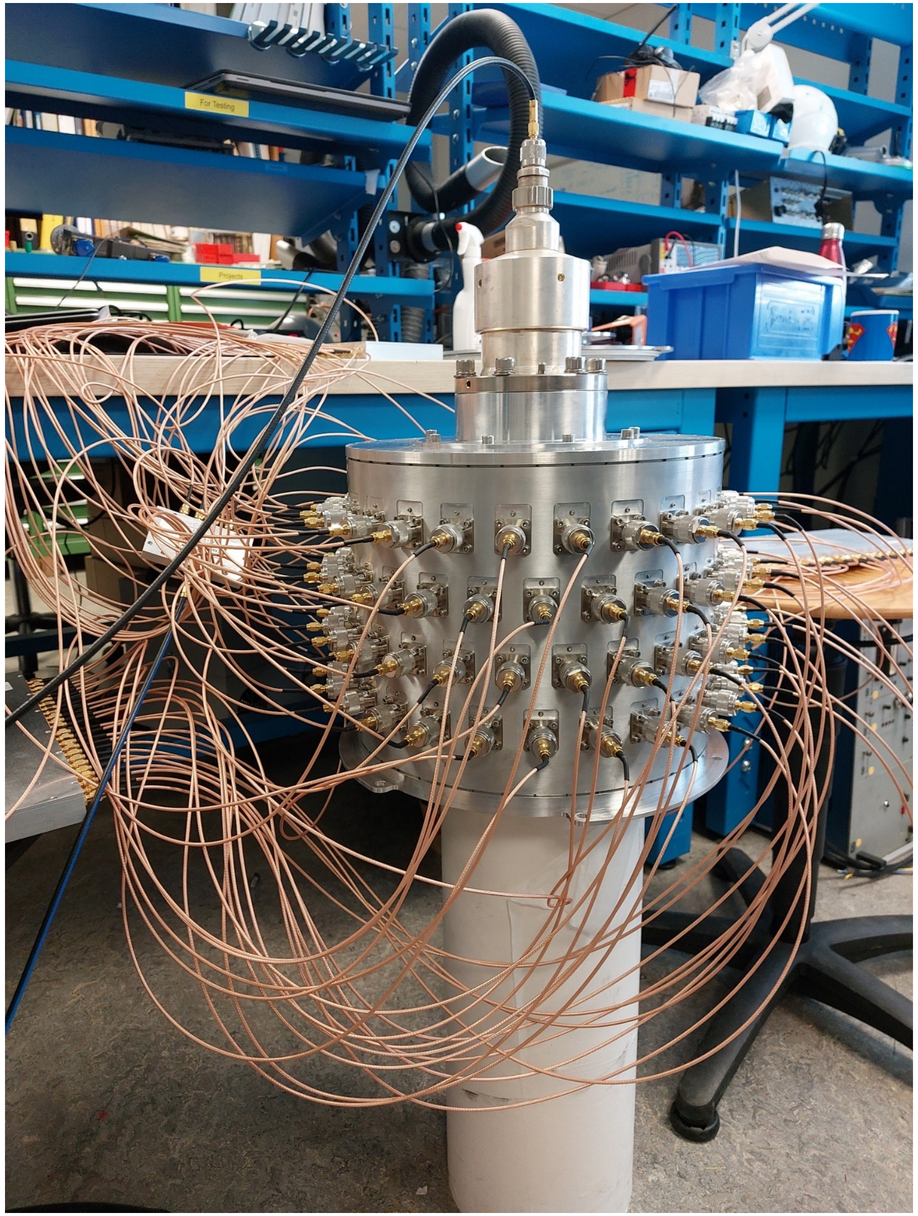
The transmission between the 96 individual inputs and output is -19.84 ± 0.05 and the cross talk between the inputs is < -35 dB

Cavity combiner



We measured it with only – 0.15 dB insertion losses

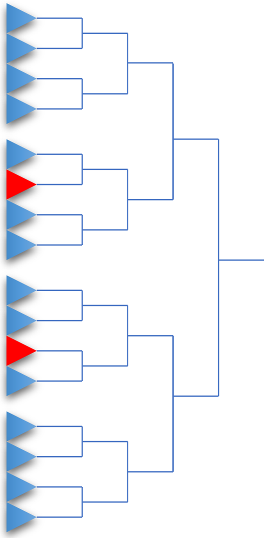
(even being made in aluminium)



Redundancy

In order to ensure 100 % availability, given a *Redundancy*, the technology of the combining system will define the number of **Units**

Power per **Unit** = 1



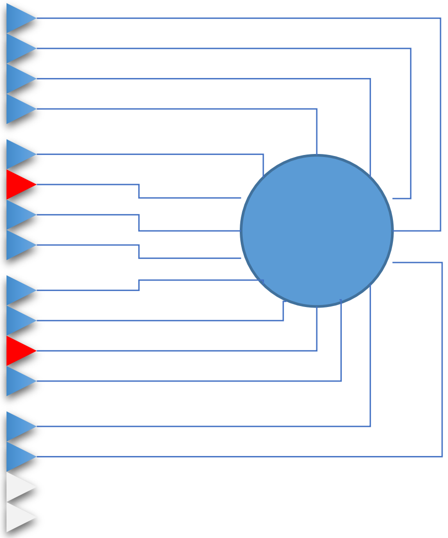
P_{out} must be 12 x P
at all time, even with
2 Units 'off-line'

In order to be 100 %
available a 3 dB combiner
requires **16 Units**

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

P_{out} must be 12 x P
at all time, even with
2 Units 'off-line'

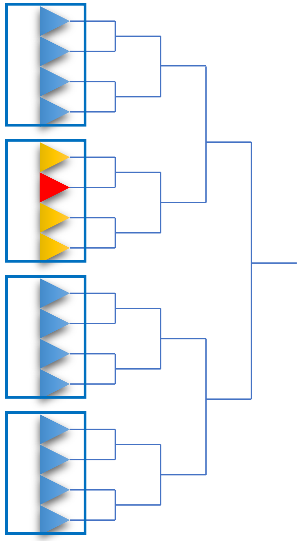
In order to be 100 %
available a cavity
combiner only requires
14 Units



$$Pout = n \, A1$$

Granularity

In order to ensure 100 % availability, given a *Granularity,* the technology of the combining system will define the number of **Modules**



1 Module =
4 x Units

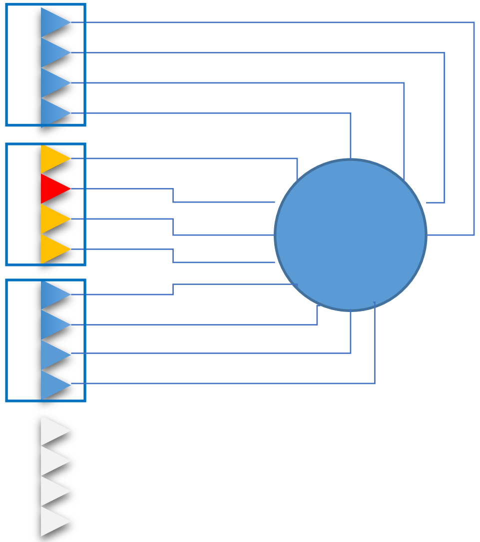
P_{out} must be 8 x P
at all time, even with
1 Unit 'off-line'

In order to be 100 %
available a 3 dB combiner
requires **16 Units**

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

P_{out} must be 8 x P
at all time, even with
1 **Unit 'off-line'**

In order to be 100 %
available a cavity
combiner only requires
12 Units



$$Pout = n\,A1$$

Redundancy & Granularity

3 dB Combiner (given the phases and amplitudes are correct)

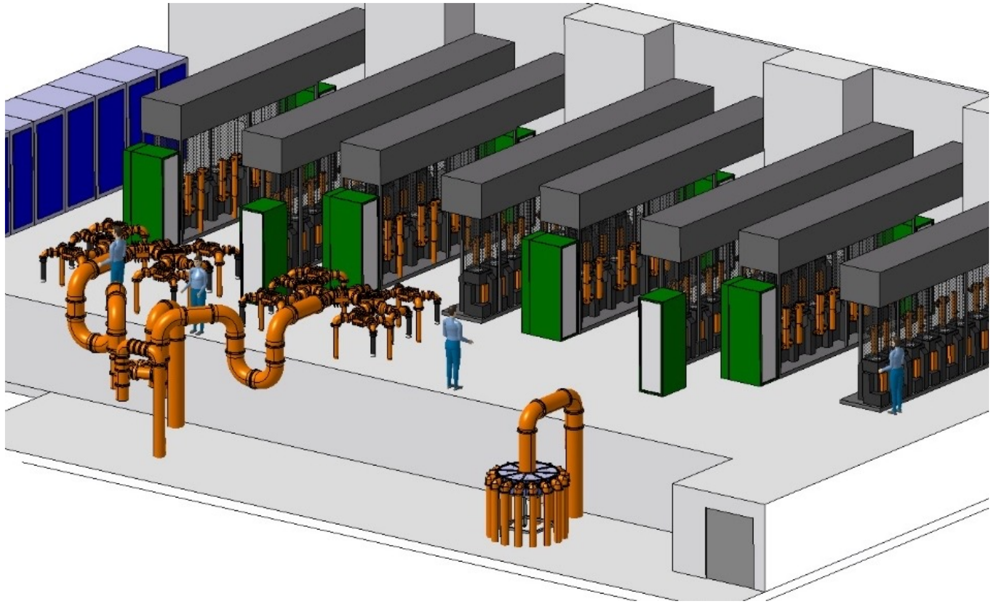
$$\text{Pout} = \frac{\text{PA1} + \text{PA2}}{2} + \sqrt{\text{PA1 PA2}}$$

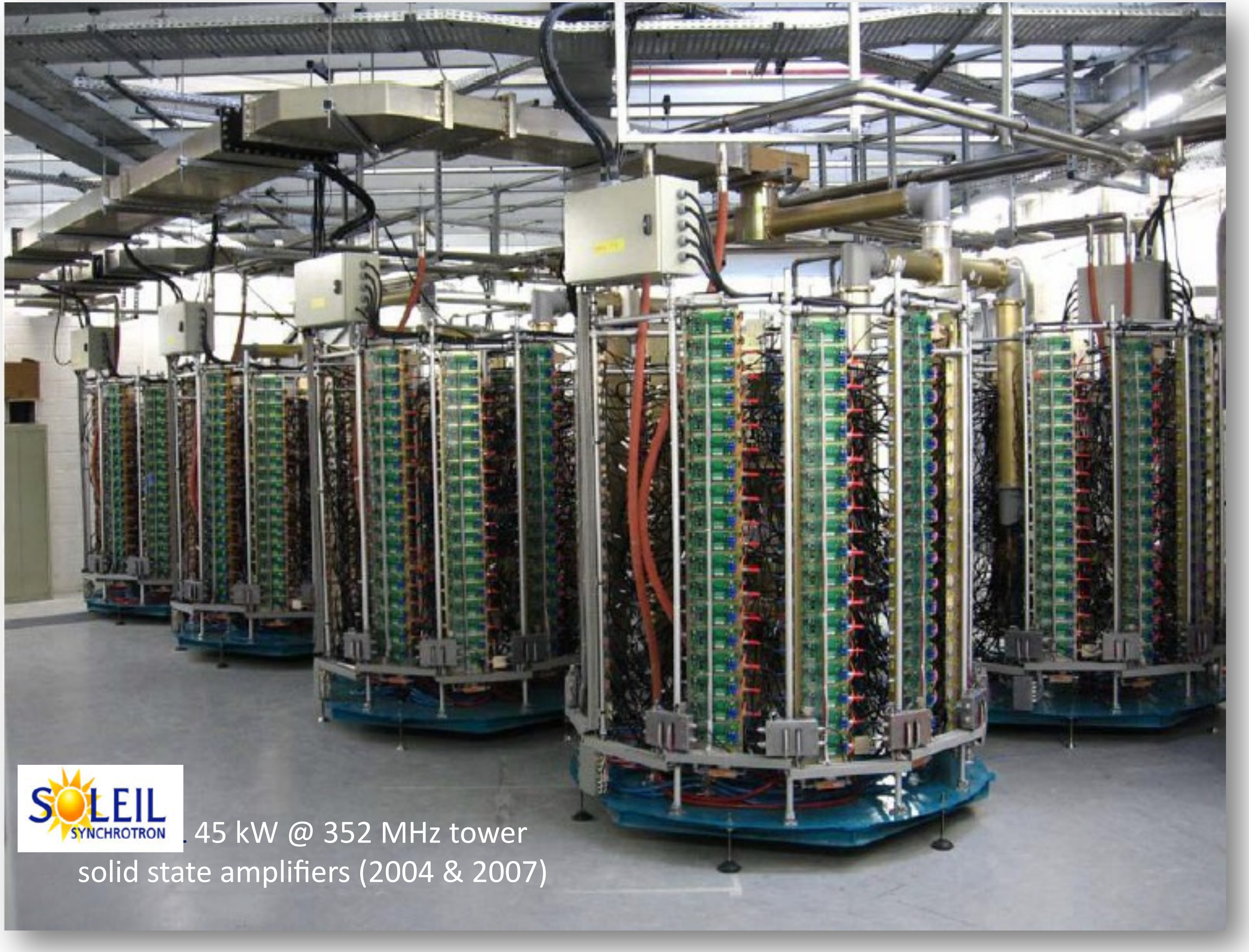
$$\text{Pload} = \frac{\text{PA1} + \text{PA2}}{2} - \sqrt{\text{PA1 PA2}}$$

Cavity combiner is one of the best way to achieve power density with multiple sources

A fantastic intrinsic characteristic of a cavity combiner is that if you present a short circuit at a missing input, the output is the exact sum of all remaining inputs

16:1 combiner with	3 dB combiner Pout	Cavity combiner Pout
0 missing input	16 P	16 P
1 missing input	14 P	15 P
4 missing inputs	9 P	12 P





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

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

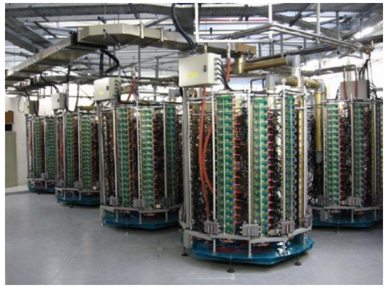
CERN 2 x 16 x 160 kWp @ 200 MHz tower
solid state amplifiers (2022)

Power density

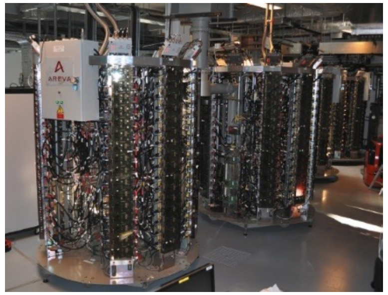
$$\boldsymbol{Power\ density\ (f) = Power\ density_{200\ MHz}\sqrt{200/f}}$$

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 !**

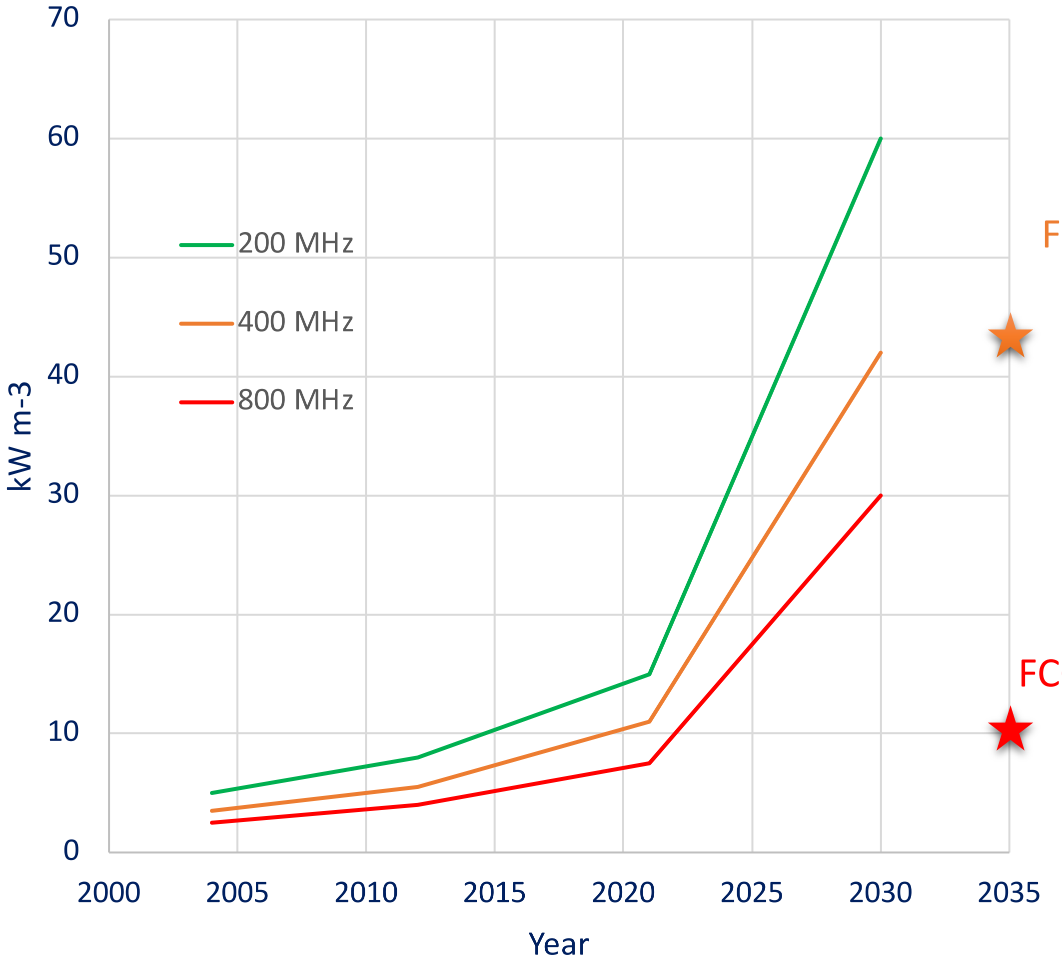


SOLEIL 45 kW @ 352 MHz
2004
Power density
3.5 kW m^{-3}



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

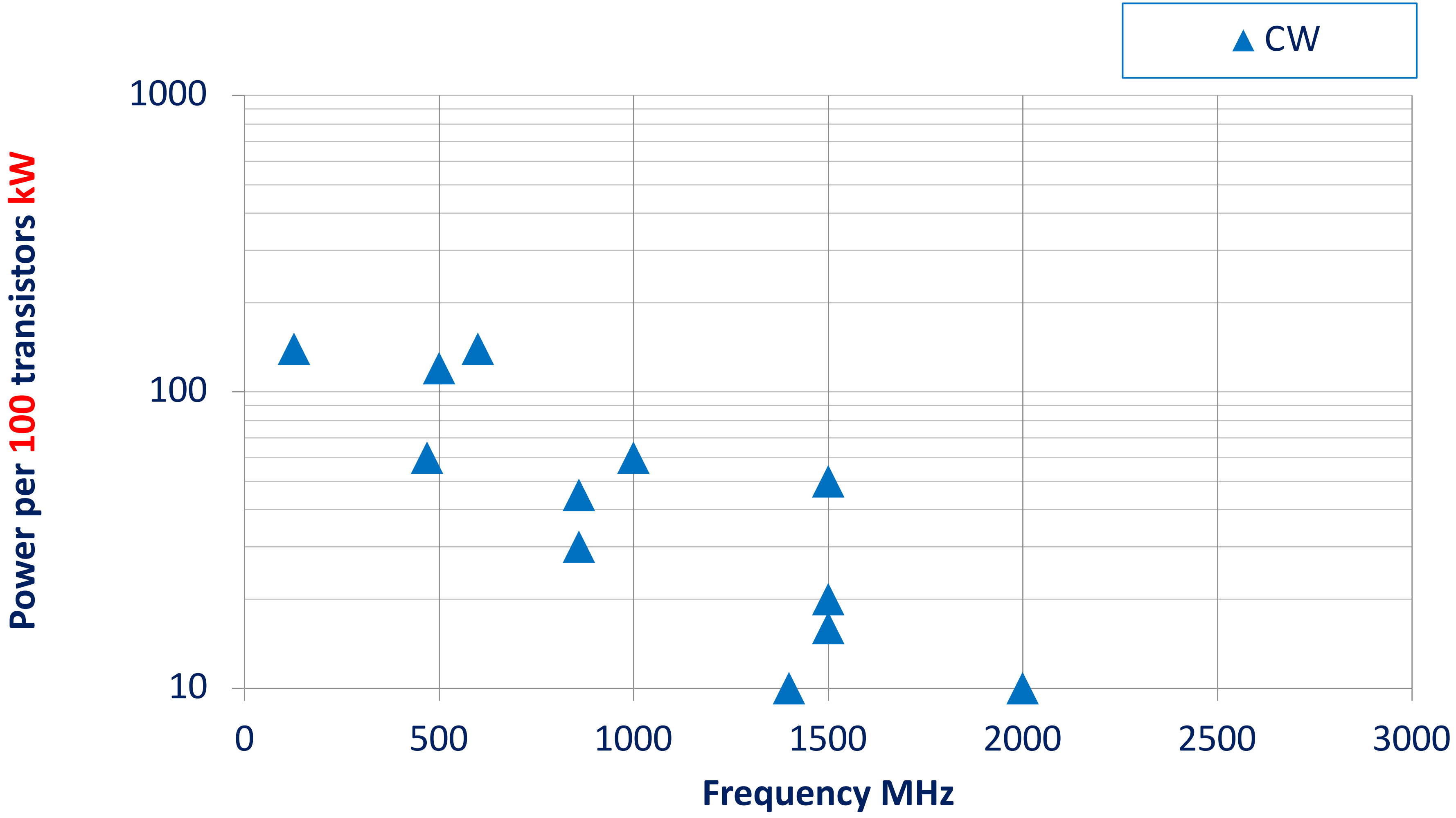
CERN 160 kW @ 200 MHz
2021
Power density
15 kW m^{-3}



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

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

Transistors available from industry



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)

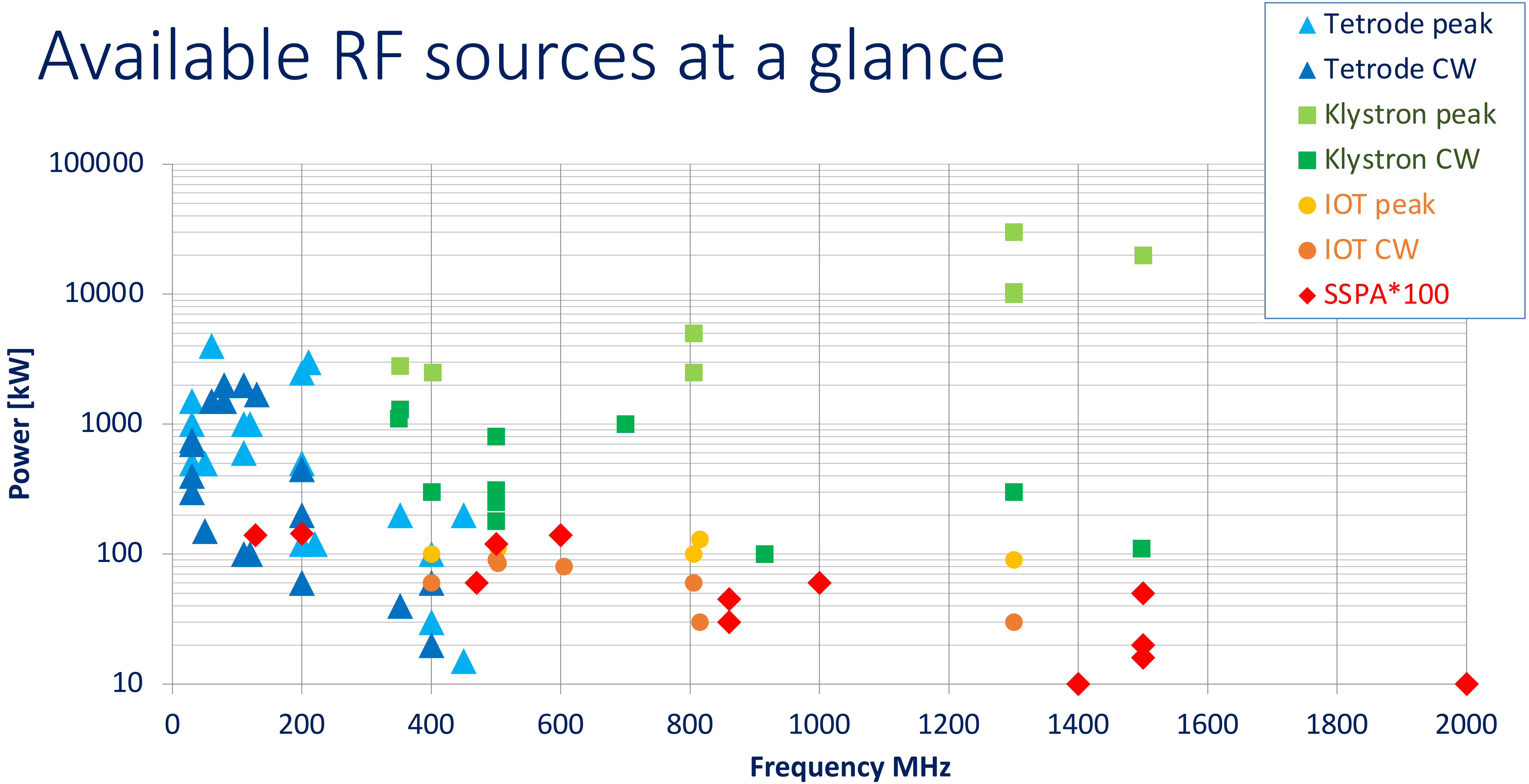
Crossed-field Tubes

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)
Silicon Germanium (SiGe)
Gallium Arsenide (GaAs)
Gallium Nitride (GaN)

Available RF sources at a glance

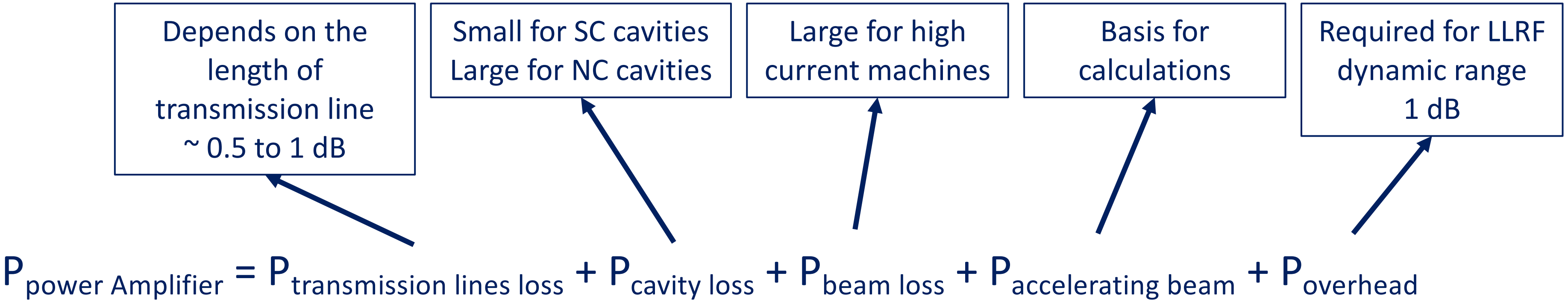


Good Machine =

(when my boss does not hear about it)

Efficiency	*	Reliability	*	AVAILABILITY	*	Experienced team	*	***k***
RF/DC efficiency		Oversize		Overhead		Manpower management		Everything
Overall efficiency		Acquisition cost		Preventive Maintenance		Age profile		Else
Including peripherals		Quantity of spares		Operation costs		Training		I missed
& building HVAC		Obsolescence						

RF Power Amplifier



Depends on the length of transmission line ~ 0.5 to 1 dB

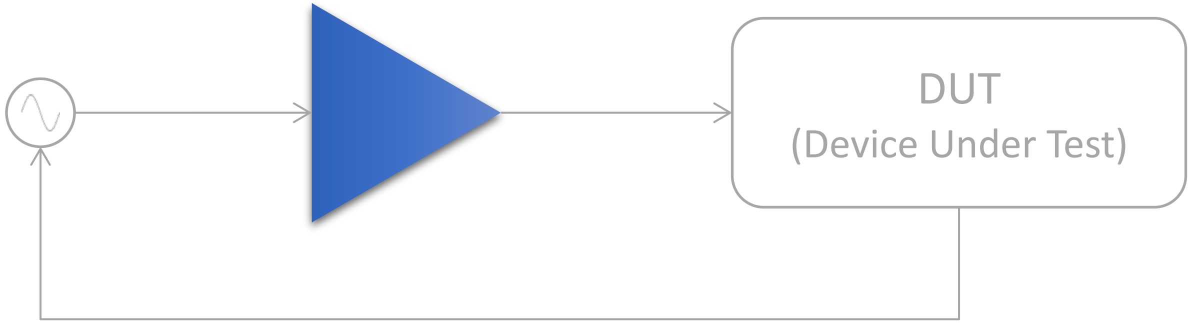
Small for SC cavities
Large for NC cavities

Large for high current machines

Basis for calculations

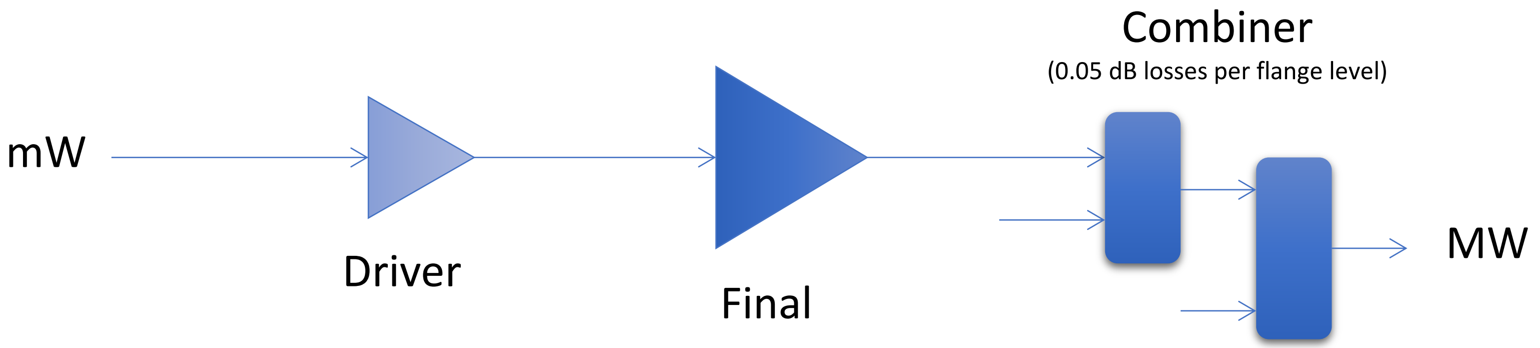
Required for LLRF dynamic range 1 dB

$$P_{\text{power Amplifier}} = P_{\text{transmission lines loss}} + P_{\text{cavity loss}} + P_{\text{beam loss}} + P_{\text{accelerating beam}} + P_{\text{overhead}}$$

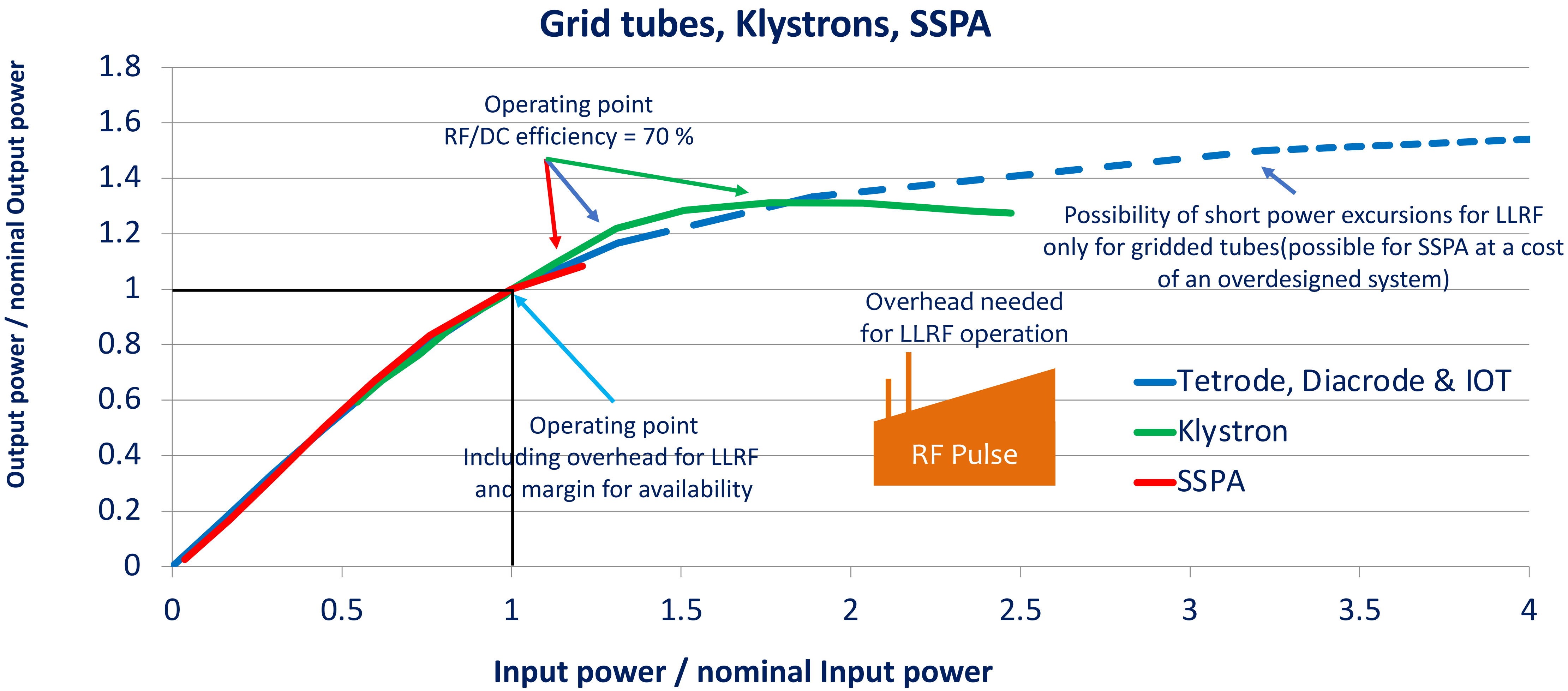


High Power options

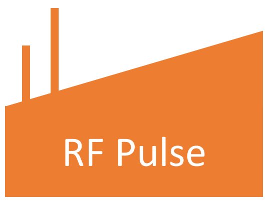
Final	Voltage	Driver	Gain	Power per unit	Combiner (for 1 MW)
Tetrode	15 kV	6.2 kW	13 dB	135 kW	8:1
Klystron	100 kV	10 W	50 dB	1 MW	-
IOT	40 kV	320 W	23 dB	65 kW	16:1
SSPA	50 V	5 W	23 dB	1100 W	1024:1



Overhead and maximum power



Tetrodes, Diacrodes, IOT



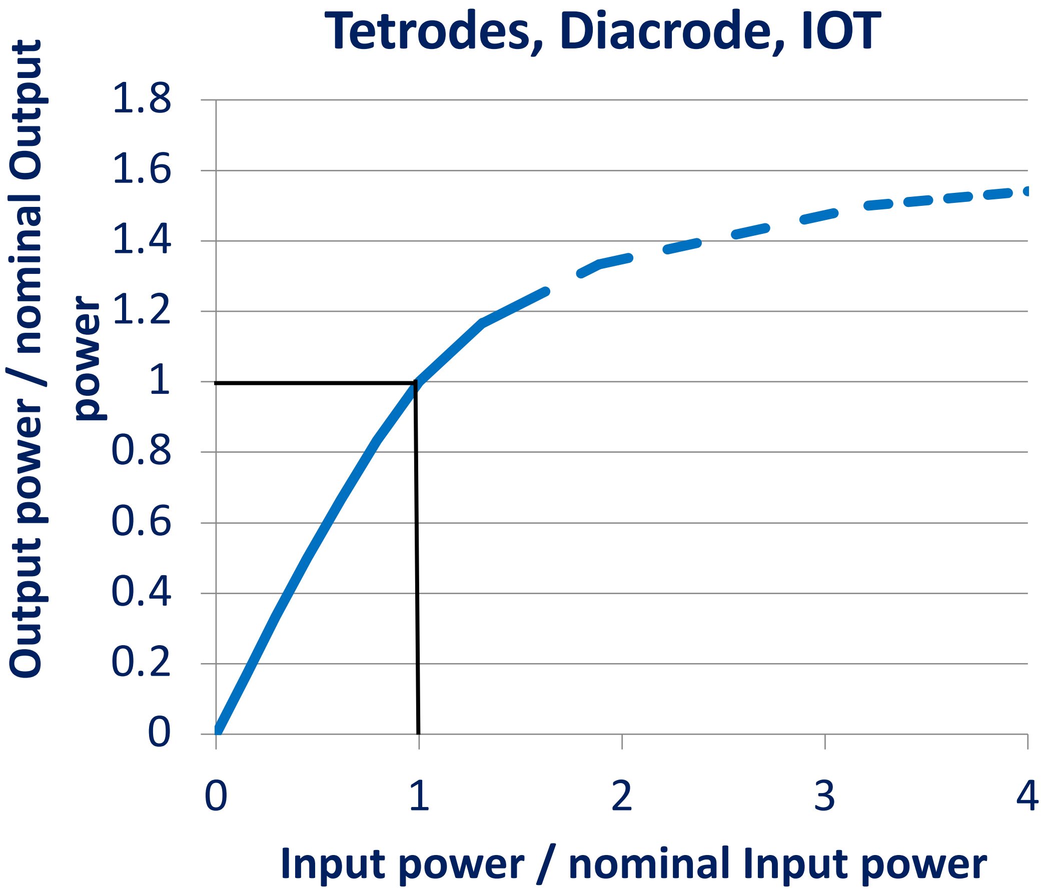
Overhead needed for
LLRF operation

A great advantage of gridded tubes is that they allow overdrive without damage

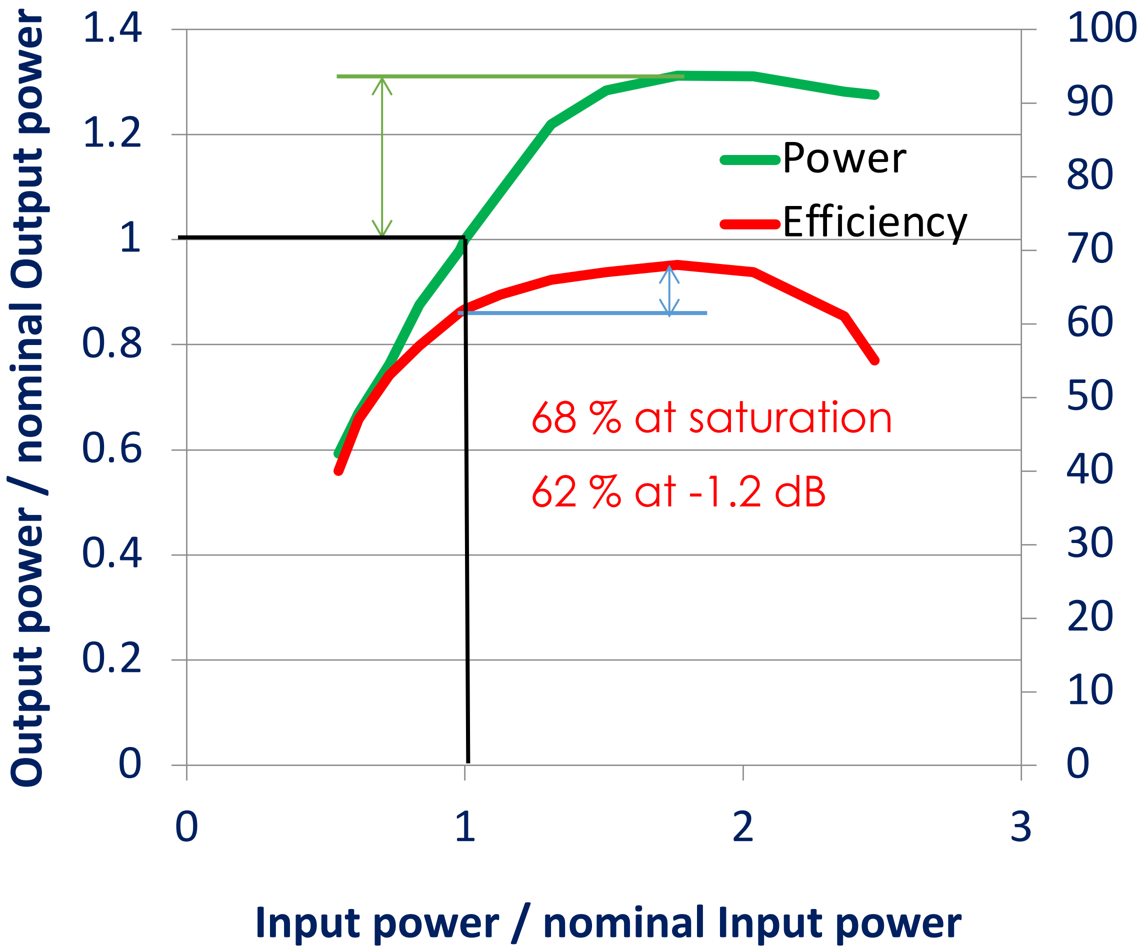
Thanks to that, they can be operated very close to their nominal point

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

Lower gain, some more stages, addition of limiting parameters



Klystrons



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

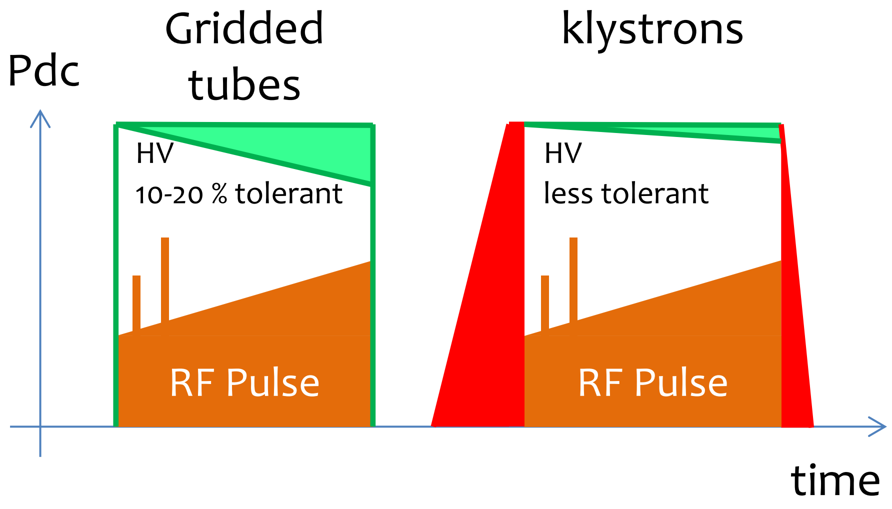
Need to operate lower than nominal point of operation

Loss of efficiency

Double cost (acquisition + operation)

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

HVPS

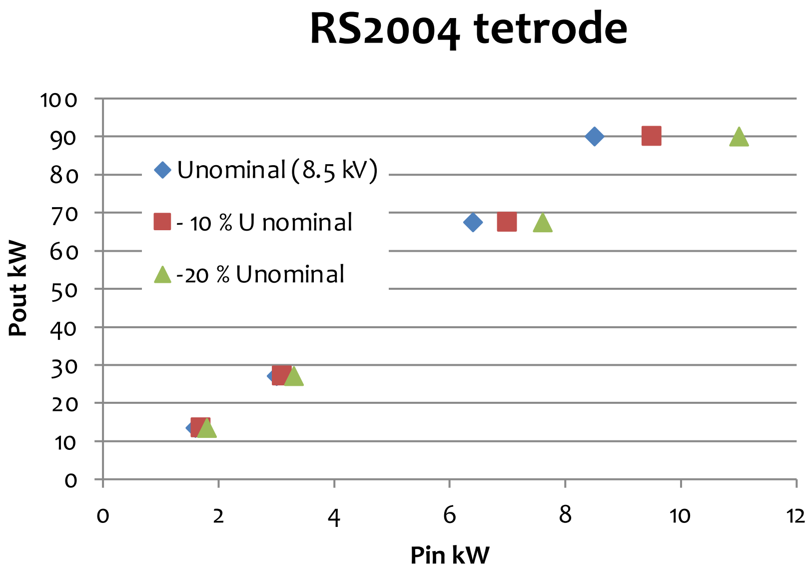


For gridded tubes HVPS is very simple

No RF -> idle current (can be zero in class B or class C)

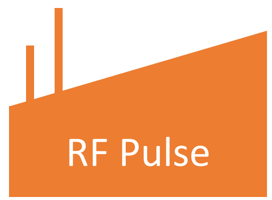
Even if HV is drooping, the LLRF will impose output power, and tetrode remains able to deliver requested Power

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



SSPA

Overhead needed for LLRF operation

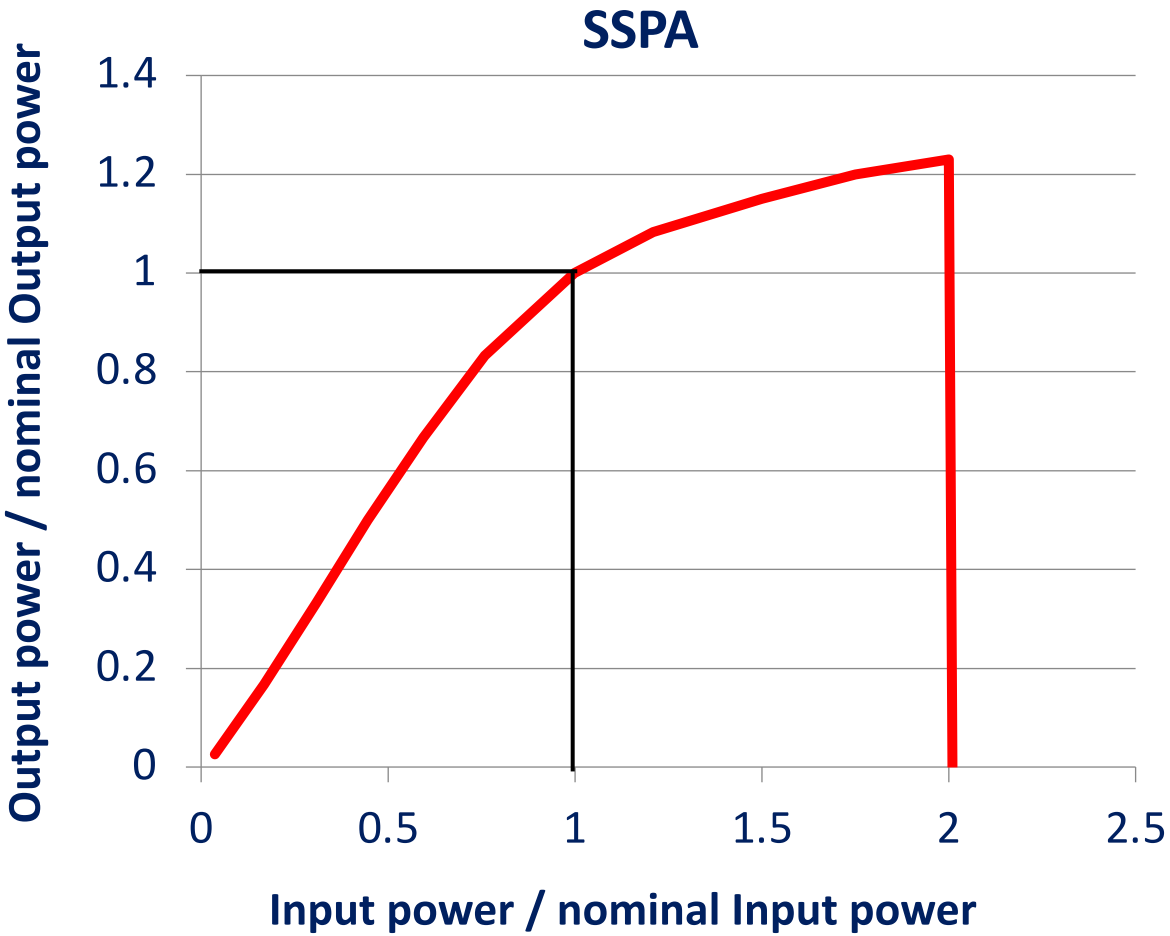


Destruction in case of large overdrive (+ 3 dB) longer than ~ 100 µs

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

Overhead must be perfectly and correctly defined

Overhead very costly (compare to gridded tubes)

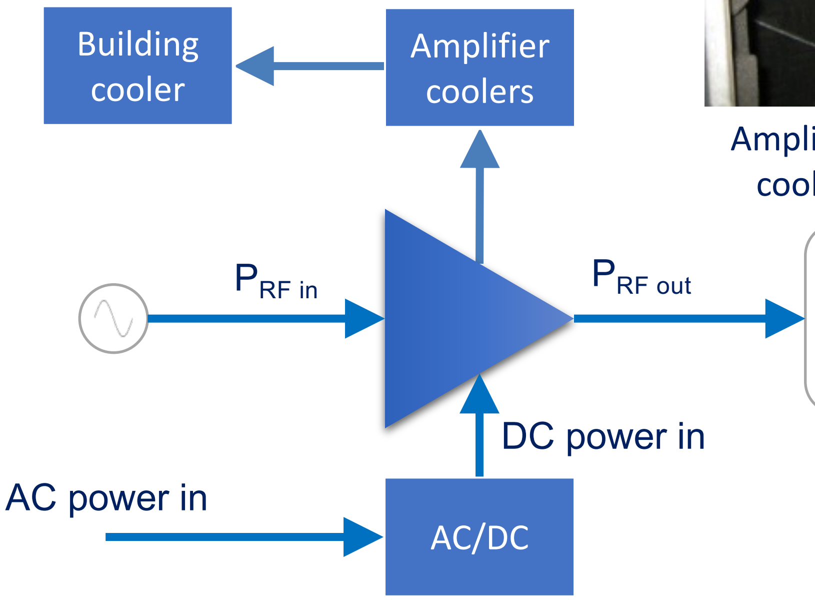


A few values

RF source type Numbers for lower than 0.5 GHz range	Gain range [dB]	Maximum peak output Power per unit [kW]	Rise time	Pulse length range [ms]	Repetition rate range [Hz]	Maximum output power CW [kW]	Efficiency at working point [%]	High voltage needs [kV]
Tetrode	15	4000	ns	Almost whatever requested (depends on HVPS design)		1500	70	10 – 25
Diacrode	15	3000	ns			2000	70	20 – 30
IOT	20	130	ns			85	70	36 – 38
MB-IOT	20	1300	ns			150	70	50
Klystron	>50	3000	ns			1000	60	100
SSPA	20	0.1	ns			0.1	70	0.05

Reminder: Grid modulates RF, No RF means No current, direct impact onto efficiency

Overall Efficiency $\simeq \dfrac{P_{RFout}}{P_{ACin} + PR_{Fin} + Pc_{oolers}} \simeq$ **45 %**



Amplifier coolers and building coolers are not so efficient

$P_{RFin} \simeq$ 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}

$$Overall\ efficiency \simeq \frac{P_{RFout}}{P_{RFout}\,(0.05 + \ 1.62 + 0.45)}$$

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

Availability

Case of an injector

SPS is an injector for LHC

RF is 4.5 MW for 30 % of the time

AC to RF efficiency is 42 %

SPS electrical consumption is then 3 MVA

LHC is consuming 99 MVA for its magnets

Main parameter for SPS is availability

Case of a CW machine

FCC will be 1000 RF power sources of 1 MW each

RF will be CW

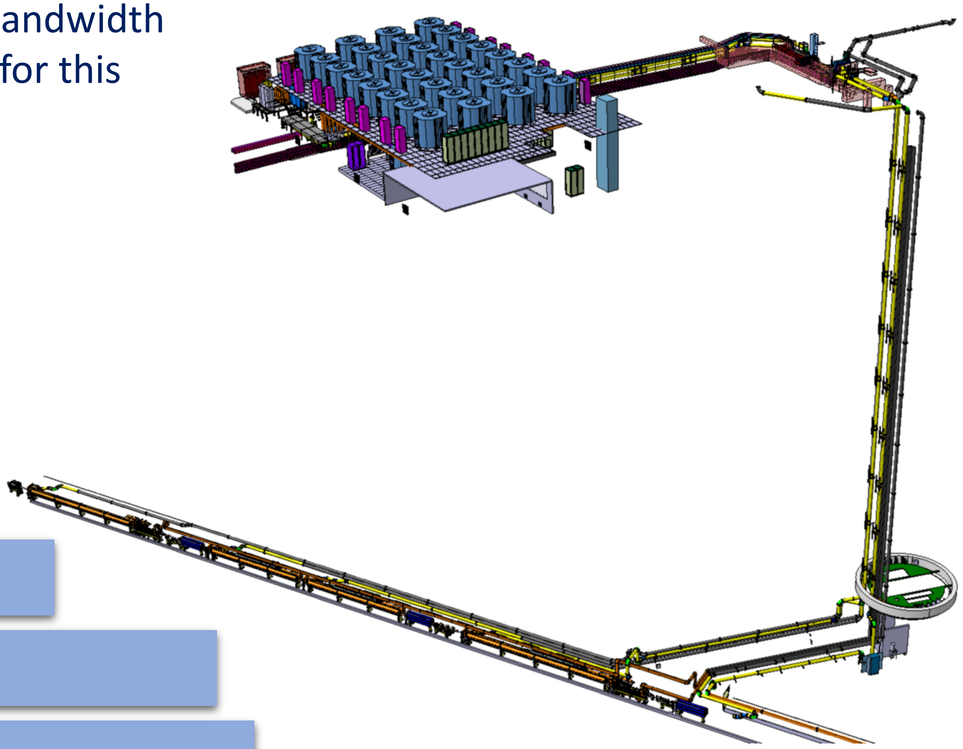
Availability will be thanks to redundancy in the number of cavities and RF power stations

AC to RF will be the main challenge for RF power generation regarding FCC and other big CW machines

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, reduced 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

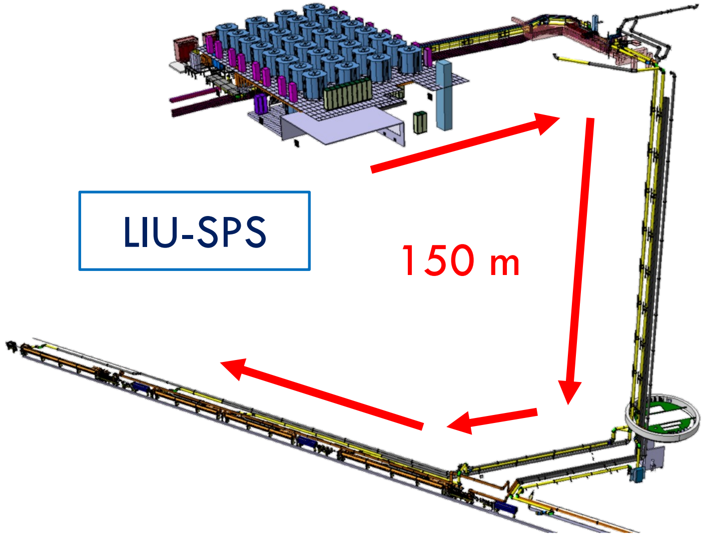
AC to DC (efficiency ~ 90 %) = 2,100 MW (970 kW to be dissipated)

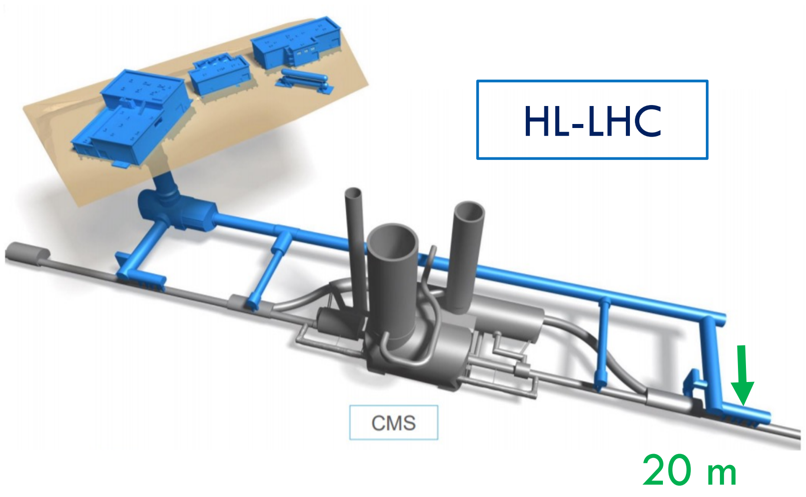
Air cooling station (10 % of 970 kW = 97 kW) ~ + 49 kW = 2,149 MW

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 %**

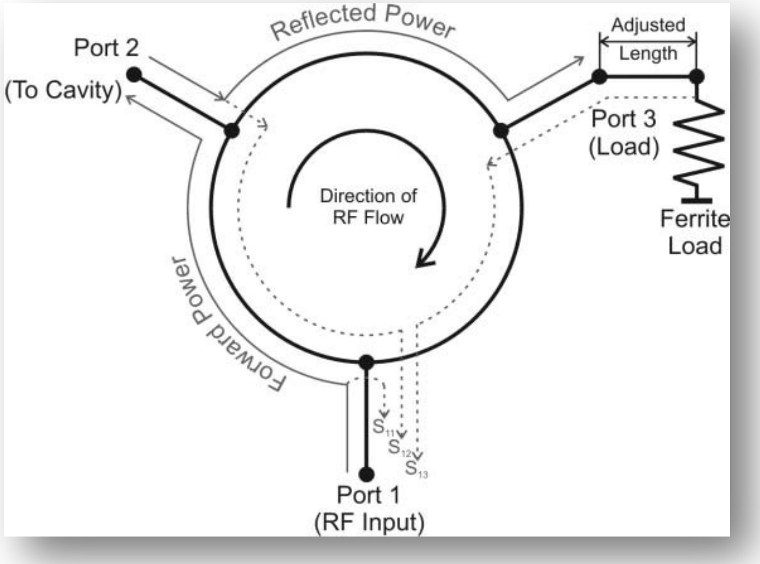




Having the amplifiers very close to the cavity, will reduce all other losses
A gallery is very expensive, as an acquisition cost, but can help to reduce acquisition cost of transmission lines and to reduce cost of operation

Gain in efficiency **1,7 %**

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

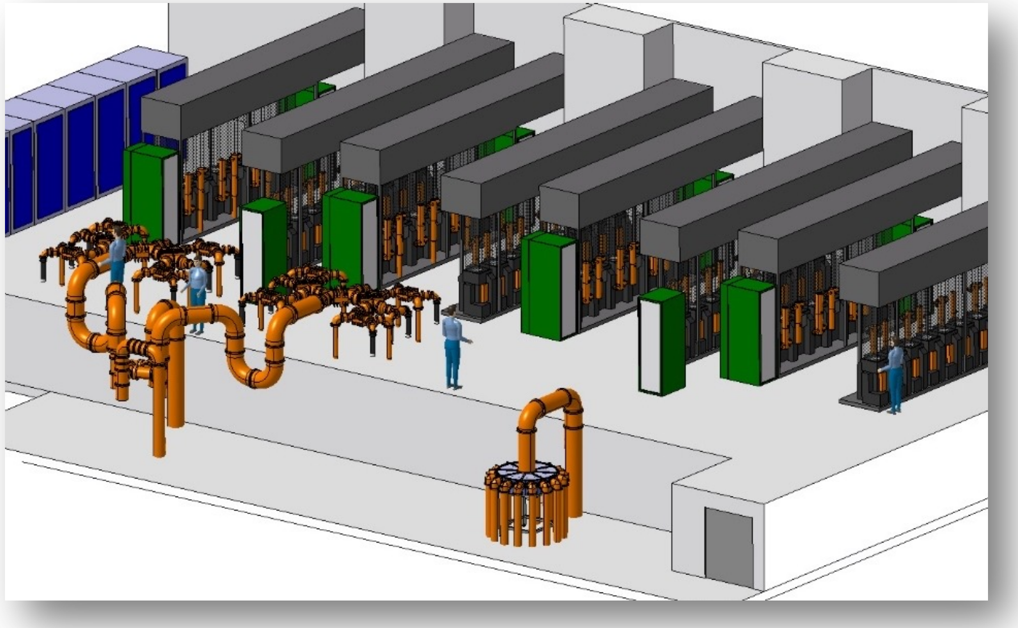
Overall efficiency **45,5 %** **41,9 %**

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

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

Gain in efficiency **4,2 %**

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

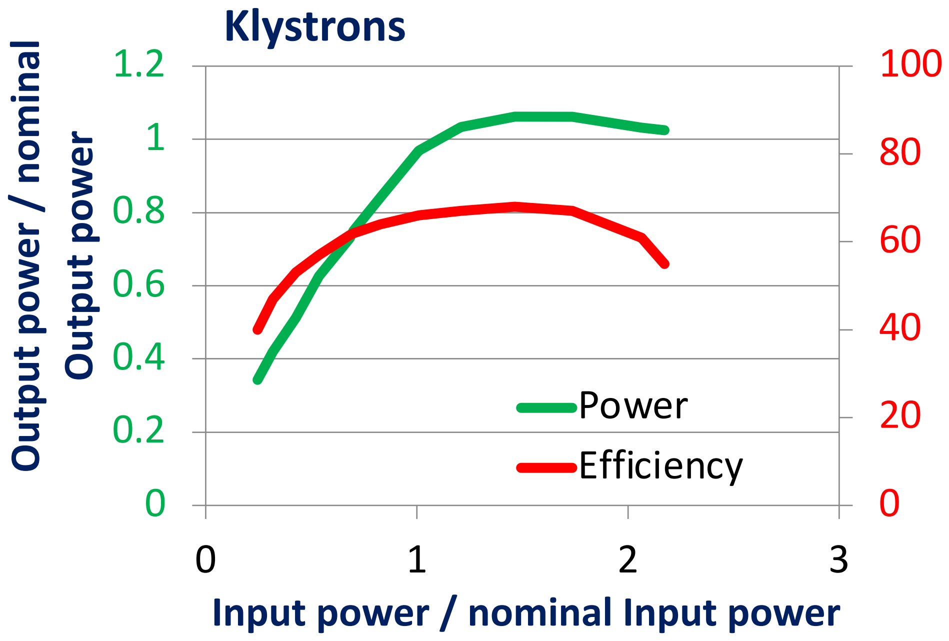
Electrical distribution (5 % of 2,003 MW) ~ + 100 kW = **2,1 MW** taken from the grid

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

Gain in efficiency **6,3 %**

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

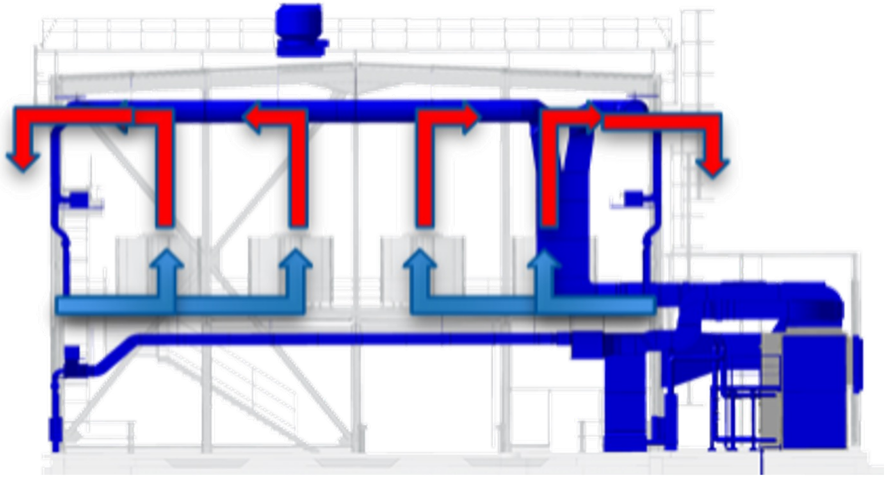
El. distribution (5 % of 1,709 MW) ~ + 86 kW = **1,8 MW** taken from the grid

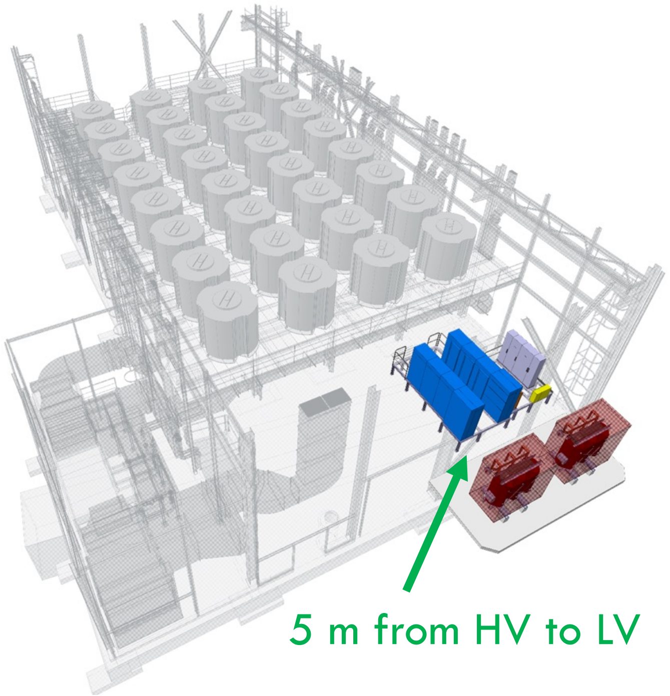
Overall efficiency **55,5 %** **41,9 %**

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

Gain in efficiency **14,2 %**

Efficiency





5 m from HV to LV

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

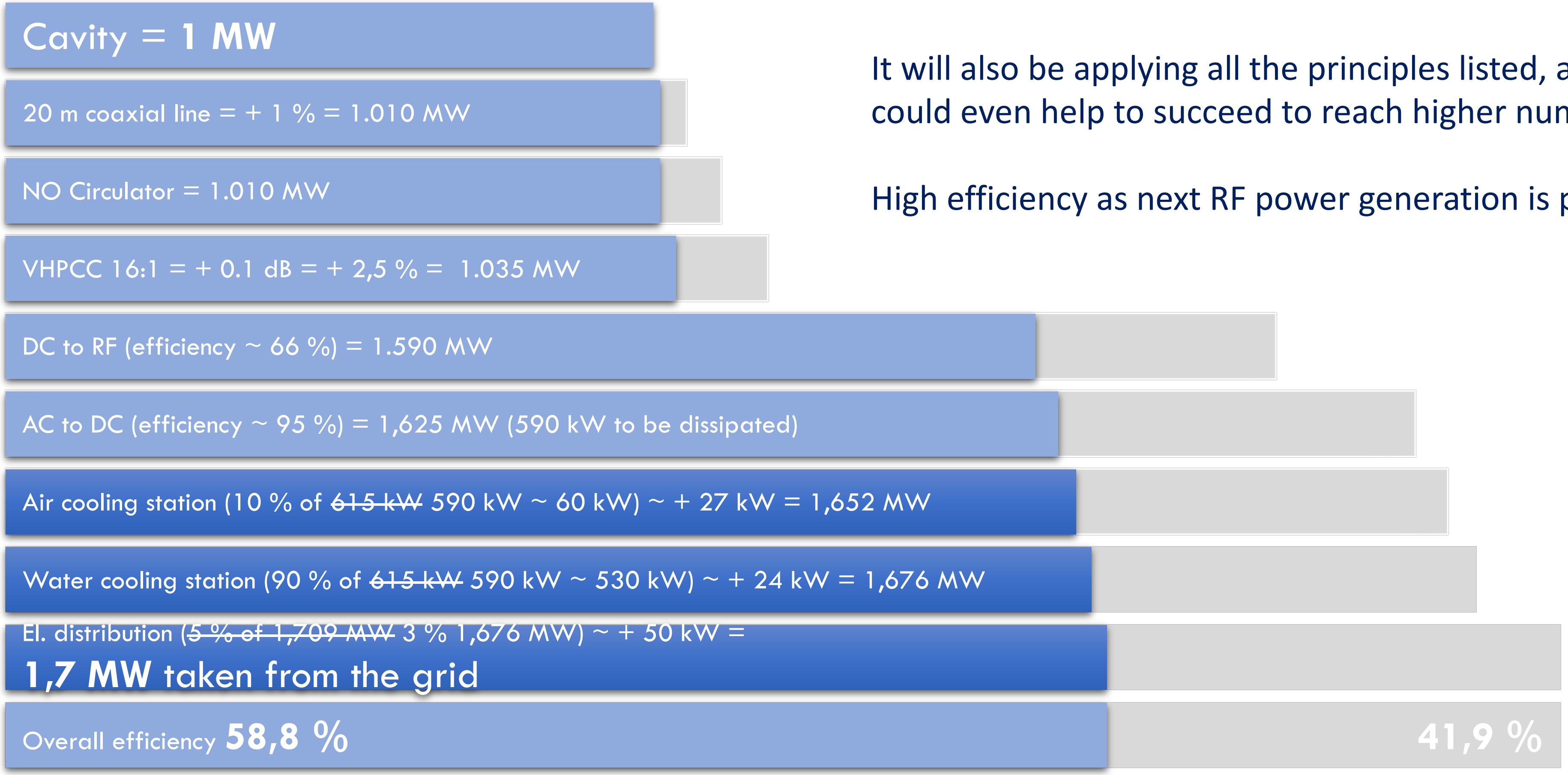
El. distribution (~~5 % of 1,709 MW~~ 3 % 1,676 MW) ~ + 50 kW =
1,7 MW taken from the grid

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

Gain in efficiency **16,9 %**

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

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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 %

Improving the efficiency will of course be improving the DC to RF efficiency (High-Efficient klystrons for example)

It will also be applying all the principles listed, and some additional others that could even help to succeed to reach higher numbers (we are working it out)

High efficiency as next RF power generation is probably the next key challenge

Conclusion 1/2

As Tube market perspectives are decreasing, the community is moving to SSPA
However, keep in mind that Tetrodes, IOTs, MB-IOTs, Klystrons, HE-klystrons are still very interesting

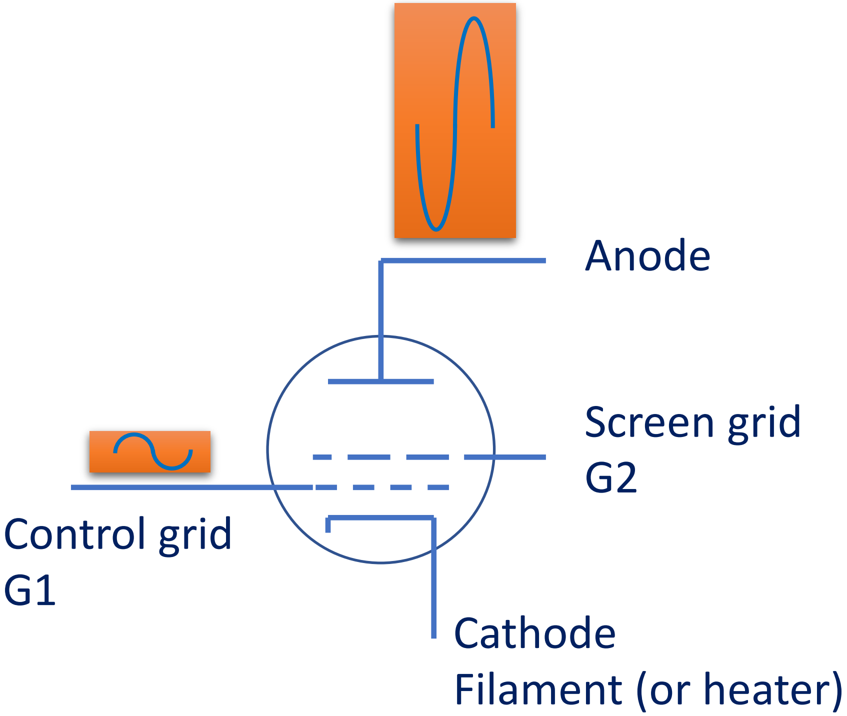
SSPA is a very quickly evolving market, all of us must witness the market evolutions

Labs should focus R&D where industrials need us, with respect to our specific needs

Conclusion 2/2

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

- **Combining systems**, this will reduce footprint and increase power density; plenty of ideas, cavity combiners, DNA waveguide progressive combiners, RF transmission combiners, Gysel combiners, multi layers waveguides combiners
- **Availability**, including granularity, hot swappable modules, oversizing, 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, High Voltage GaN, GaAs, 2D transistors…)



Thank you very much

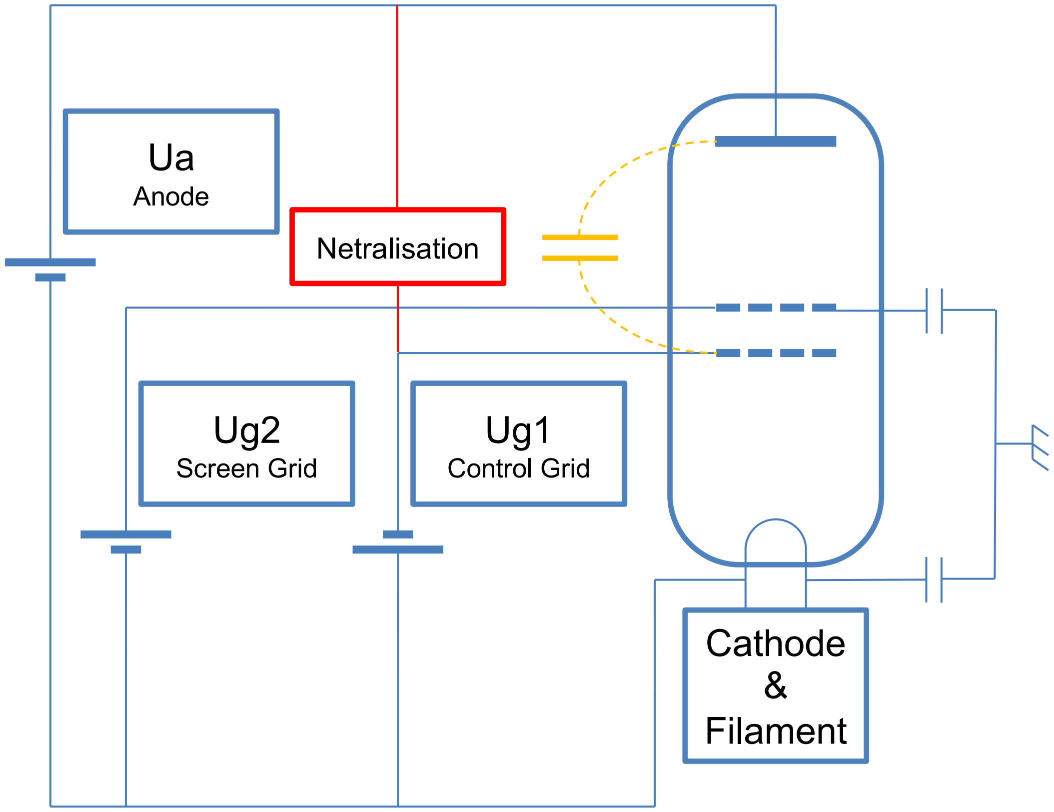
They did not know it was impossible, so they did it
(Mark Twain)

Simplicity is the ultimate sophistication
(Leonardo da Vinci, 500 years ago)

References

Spare slides

How to use tetrodes



Cathode based or Grounded cathode

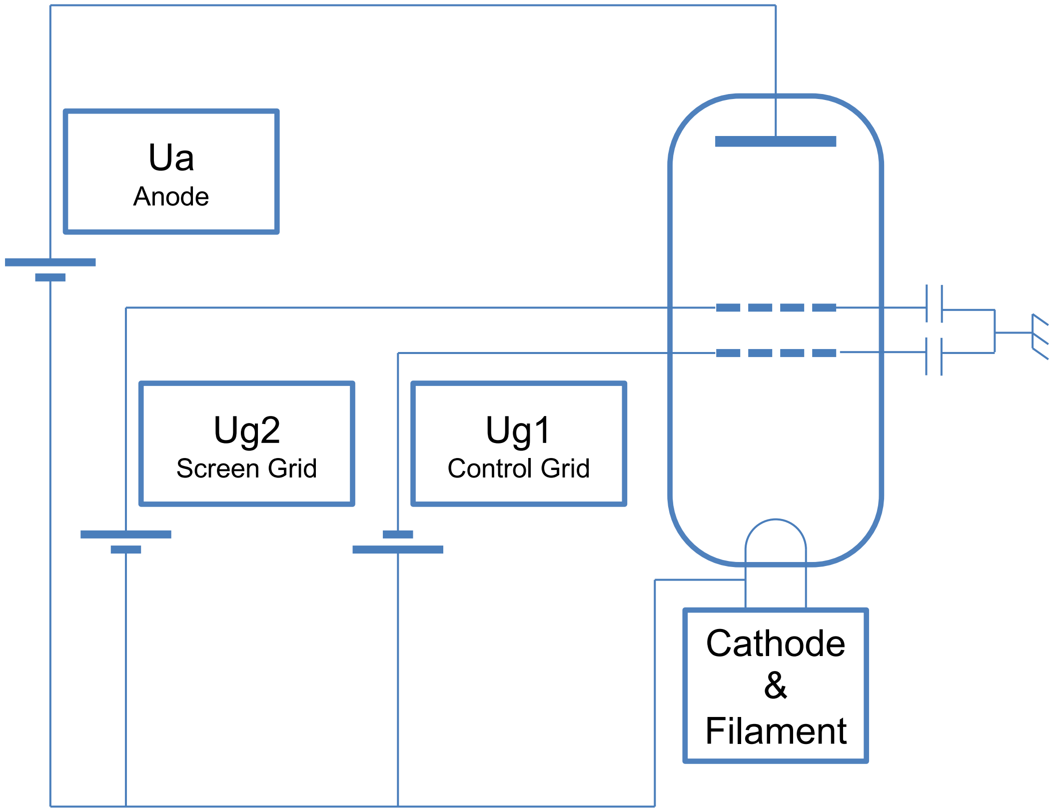
- Main advantage High gain
- Drawback neutralization circuit required

Typically used with tetrodes in MW amplifiers and audio amplifiers

Gain is only limited by RF losses

Neutralization circuit is to be adjusted to cancel G1-Anode capacitance

How to use tetrodes



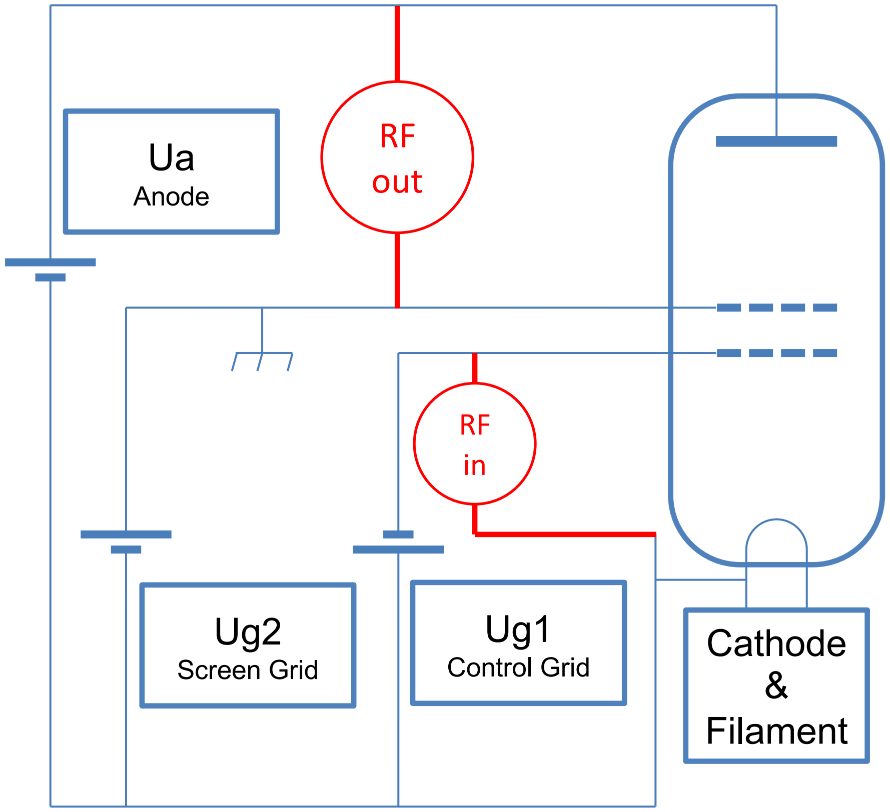
Common Grid or Grounded grids

- Main advantage Stability
- Drawback less amplification

Typically used with triodes amplifiers

Grids held at ground isolate input from output

How to use tetrodes



Grounded screen-grid

- Main advantage reduced control grid power dissipation

Configuration used with the large MW range CERN SPS RF amplifiers

Klystron tutorial SLAC

The Klystron:

A Microwave Source of Surprising Range and Endurance

George Caryotakis

Stanford Linear Accelerator Center, Stanford University, Stanford CA 94309

The rf current produced by the bunched beam, moving from left to right, causes the output cavity (the “extended interaction” circuit to the right of the illustration above) to “ring” at its fundamental frequency. The current induced at the output circuit produces a voltage across it, which slows the beam down, converting its kinetic energy to rf energy in the cavity, and dispersing the bunches. Power is taken out by a waveguide (not shown). The electrons shown between bunches detract from good efficiency. More electrons can be directed toward the bunches by inductively tuned cavities placed before the output circuit (as the single TM01 resonator shown above), or by one or more 2nd harmonic cavities upstream. Space charge forces prevent tighter bunches from being formed. These forces increase with ***beam perveance***, which is defined as:

$$K = \frac{I_0}{{V_0}^{3/2}}$$

Hence, the lower the perveance, the tighter the bunching and the conversion efficiency.

Klystron tutorial SLAC

A ***gap resistance Rg*** must be chosen to optimize the gap voltage for good conversion efficiency. Its value depends on the coupling coefficient M between beam and circuit, and on the ratio of rf to dc current, I1/I0. M and I1/Io are usually determined by simulation. An empirical formula for the gap resistance Rg is:

$$\boldsymbol{Rg = \frac{V0}{I0}\frac{1}{M^2\frac{I_1}{I_0}}}$$

The required gap resistance and the cavity R/Q determine how tightly the output cavity is to be coupled to the output waveguide (or how low the Qe can be). R/Q is proportional to the ratio of the square of the gap voltage to the energy stored in the cavity.

$$\boldsymbol{Q_e = \frac{R_g}{\frac{R}{Q}}}$$

A low Qe implies better circuit efficiency and wider bandwidth for the klystron. Good design calls for a high coupling coefficient and R/Q, either of which results in a low Qe. Low-perveance klystrons have good efficiency, but because of a higher Rg, have narrower bandwidth and lower ***output circuit efficiency***.

$$\boldsymbol{\eta = \frac{Q_0}{Q_0 + Qe}}$$

In pulsed, high-peak power klystrons, it is essential to minimize the surface gradients at the output circuit to avoid ***rf breakdown***. A single cavity is often unsuitable and “extended” circuits must be employed. Their function is to develop the required interaction voltage over a longer distance to reduce surface gradients.