RF POWER GENERATION AND TRANSMISSION FOR PARTICLE ACCELERATORS

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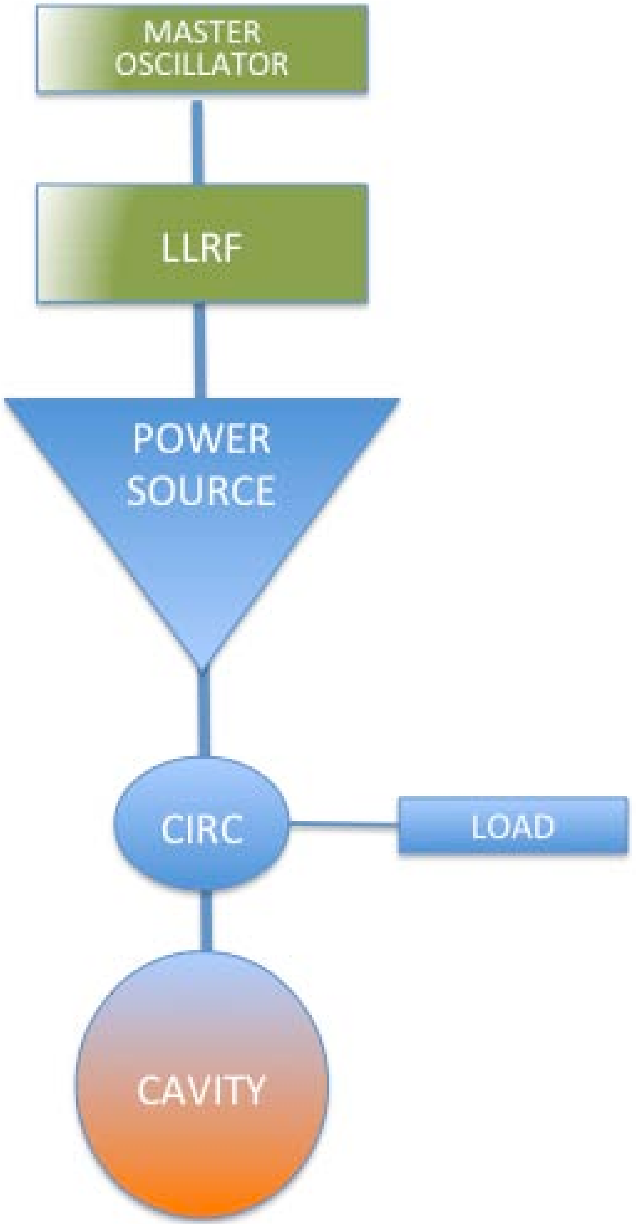
OVERVIEW

- ✓ Introduction
- ✓ Power generation
  - ✓ Tubes
  - ✓ Solid state
- ✓ Power transmission
  - ✓ Coaxial
  - ✓ Waveguide
- ✓ Summary
- ✓ References

INTRODUCTION

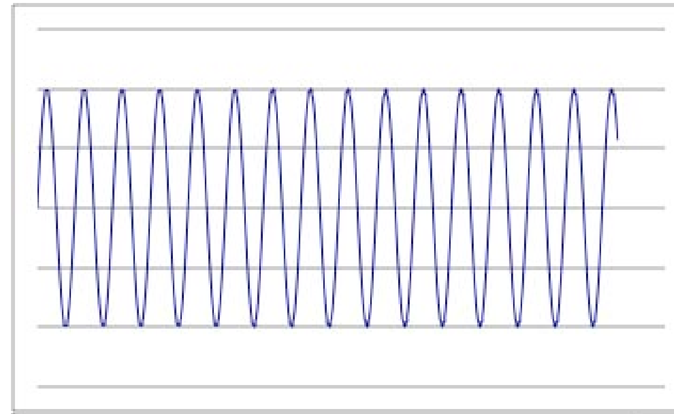
INTRODUCTION

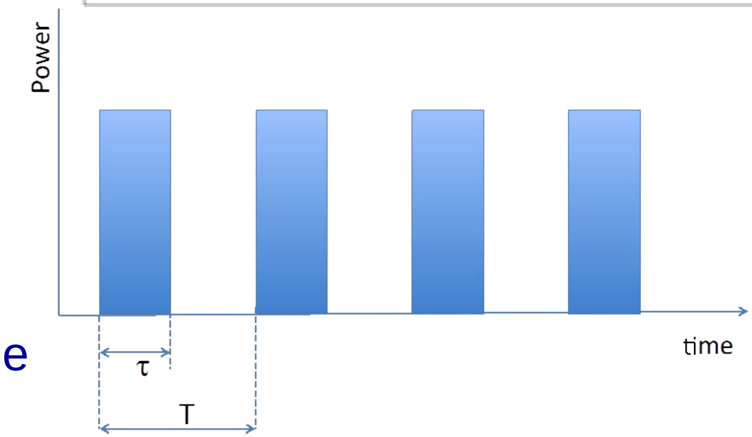
- ✓ **High power RF is needed for particle accelerators**
- ✓ Typical frequency ranges span from tens of MHz to tens of GHz or higher.
- ✓ Power requirements vary from few kW to few MW in cw (continuous wave) mode operation and to up to 150 MW for pulsed sources.
- ✓ ***A power amplifier is the equipment which transforms d.c. electrical input power to RF power amplifying the driving signal provided by the low level RF electronics.***
- ✓ ***The power transmission system is the assembly of components that performs the tasks to transport the RF power from the RF power source to the cavities.***



BASIC CONCEPTS

- ✓ **Continuous wave (CW) RF System.**
  - ✓ CW means that RF is uninterrupted.
  - ✓ In this context amplitude modulated (AM), frequency modulated (FM) and phase modulated (PM) RF are considered cw since RF is continuously present.
- ✓ **Pulsed RF system**
  - ✓ The RF is produced in bursts (pulse) with no RF present between the bursts.
- ✓ **Duty cycle (d.c.)**
  - ✓ Measure of the fraction of the time the RF is produced.
  - ✓ If τ is the pulse width and T is the period of the repetition of the pulses, the duty cycle is:
    - ✓ *d.c. (%) =* $\tau/T * 100$
    - ✓ *For a cw system the d.c. = 100 %.*
  - ✓ The duty cycle is also the ratio between average and peak RF power.





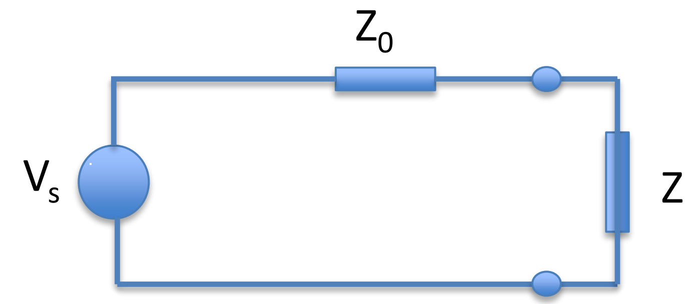
BASIC CONCEPTS

- **Gain**
  - For an amplifier, it is the ratio between output and input power
  - Gain= $P_{rf\text{-}out}/P_{in\text{-}out}$
  - Usually it is measured in dB
  - Gain(dB)=10 $Log_{10}(P_{rf\text{-}out}/P_{in\text{-}out)}$

- **Efficiency**
  - For an amplifier, it is the ratio between the RF output power and the DC input power
  - $\eta= P_{rf\text{-}out}/P_{dc}$
  - Usually it is measured in %

- **Attenuation (α)**
  - For a coaxial line or a waveguide represents the loss in the transmission system
  - Usually it is measured in dB per unit length
  - α(dB)=(10 $Log_{10}(P_{rf\text{-}out}/P_{in\text{-}out)})/L$

BASIC CONCEPTS



- ## Reflection coefficient (ρ)
  - It is the ratio of the amplitude of the reflected wave to the amplitude of the incident wave, for example when crossing a discontinuity or a change in the impedance.
  - $\rho = V_{ref}/V_{in}$
  - For a matched line the reflection current is 0.
- ## Standing wave ratio (SWR)
  - It is the ratio of a partial standing wave at an antinode (maximum) to the amplitude at a adjacent node (minimum).
  - $SWR = V_{max} / V_{min}$
  - For a matched line, SWR=1
- ## Return loss (RL)
  - It is the ratio between incident and reflected power.
  - It is normally measured in dB.
  - $RL = 10 \, Log_{10} \, (P_{in}/P_{ref})$

Reflection Coefficient

$$\rho = \frac{V_{reflected}}{V_{incident}} = \frac{Z - Z_0}{Z + Z_0} \; ; \; Z_0 = Z_{transmission\ line}$$

Characteristic Impedance

Voltage Standing Wave Ratio

$$VSWR = \frac{V_{max}}{V_{min}} = \frac{V_{incident} + V_{reflected}}{V_{incident} - V_{reflected}} = \frac{1+\rho}{1-\rho}$$

$$\rho = \frac{VSWR - 1}{VSWR + 1}$$

Return Loss

$$\text{Return Loss} = 10 \, log_{10} \frac{P_{incident}}{P_{reflected}} = 20 \, log_{10} \frac{1}{\rho}$$

$$= 20 \, log_{10} \left(\frac{VSWR + 1}{VSWR - 1} \right)$$

POWER GENERATION

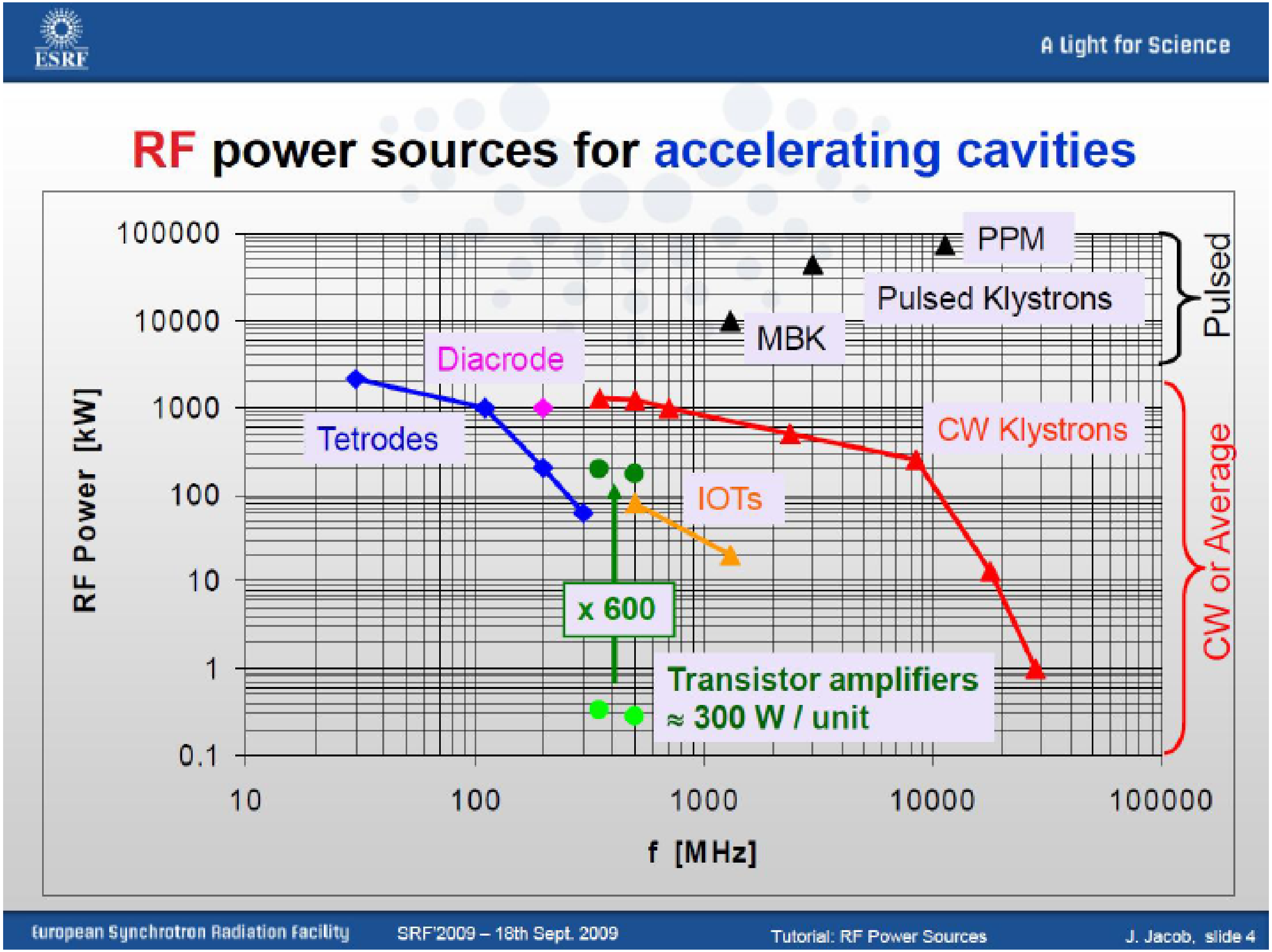
GENERAL

- **A power amplifier is the equipment which transforms d.c. electrical input power to RF power amplifying the driving signal provided by the low level RF electronics.**
- If needed, power amplifier can be combined to achieve higher power level.
- **The high power sources represent one of the main capital costs both in construction and in operations.**
- **Technologies**
  - Vacuum tubes
    - *Tetrodes*
    - *Klystron*
    - *IOT*
    - *Magnetron*
    - *Travelling tubes*
    - *Gyratrons*
  - Solid state

CHOICE

- ✓ The choice of the technology depends on several considerations:
  - ✓ Frequency
  - ✓ Power level required
  - ✓ Efficiency
  - ✓ Gain
  - ✓ Installation costs
  - ✓ Running costs
  - ✓ Maintenance costs
  - ✓ Size
  - ✓ Weight

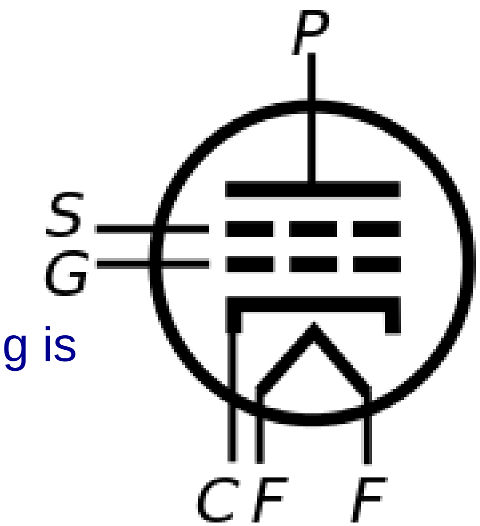
TECHNOLOGY



ESRF
A Light for Science
RF power sources for accelerating cavities
RF Power [kW]
f [MHz]
100000
10000
1000
100
10
1
0.1
10
100
1000
10000
100000
PPM
Pulsed Klystrons
MBK
Diacrode
Tetrodes
CW Klystrons
IOTs
x 600
Transistor amplifiers
≈ 300 W / unit
Pulsed
CW or Average
European Synchrotron Radiation Facility
SRF'2009 – 18th Sept. 2009
Tutorial: RF Power Sources
J. Jacob, slide 4

TETRODE - PRINCIPLE

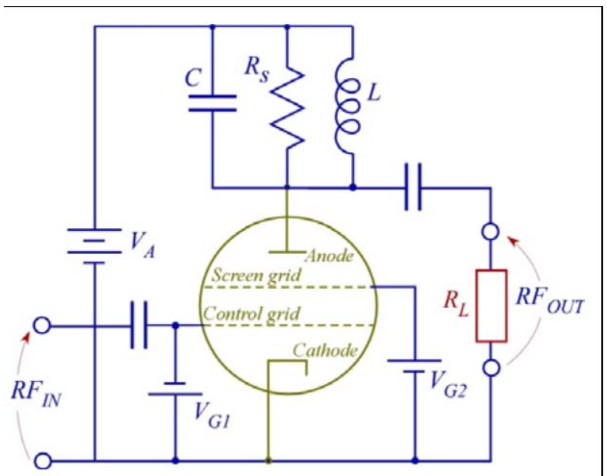
THE TETRODE IS A FOUR ELEMENT TUBE.



- ✓ **Cathode**
  - ✓ Emitting surface
  - ✓ Heated by the filament (thermionic emission)
  - ✓ Direct or indirect heating. For high power tubes direct heating is normally used.
  - ✓ The most common type is the thoriated tungsten filament
- ✓ **Plate**
  - ✓ When positive voltage is applied, electrons emitted from the cathode flow to the plate through the two girds
- ✓ **Control grid**
  - ✓ Varying voltage, applied to the control grid, controls the current to the plate.
- ✓ **Screen grid**
  - ✓ Isolates control grid with respect to the plate, reducing parasitic capacitance.
  - ✓ Normally it is connected to a positive DC voltage.

THE BEAM IN A TETRODE IS DENSITY MODULATED.

TETRODE



- ✓ The construction of a high power tetrode is coaxial with the cathode inside and the anode outside.
- ✓ This arrangement allows cooling of the cathode.
- ✓ Output power is limited by the maximum current density available from the cathode and the maximum power density that can be dissipated on the plate.
- ✓ Transit time between cathode and anode should be much less than the RF period, so spacing between the electrodes must be small enough. This limits the frequency range of operation.

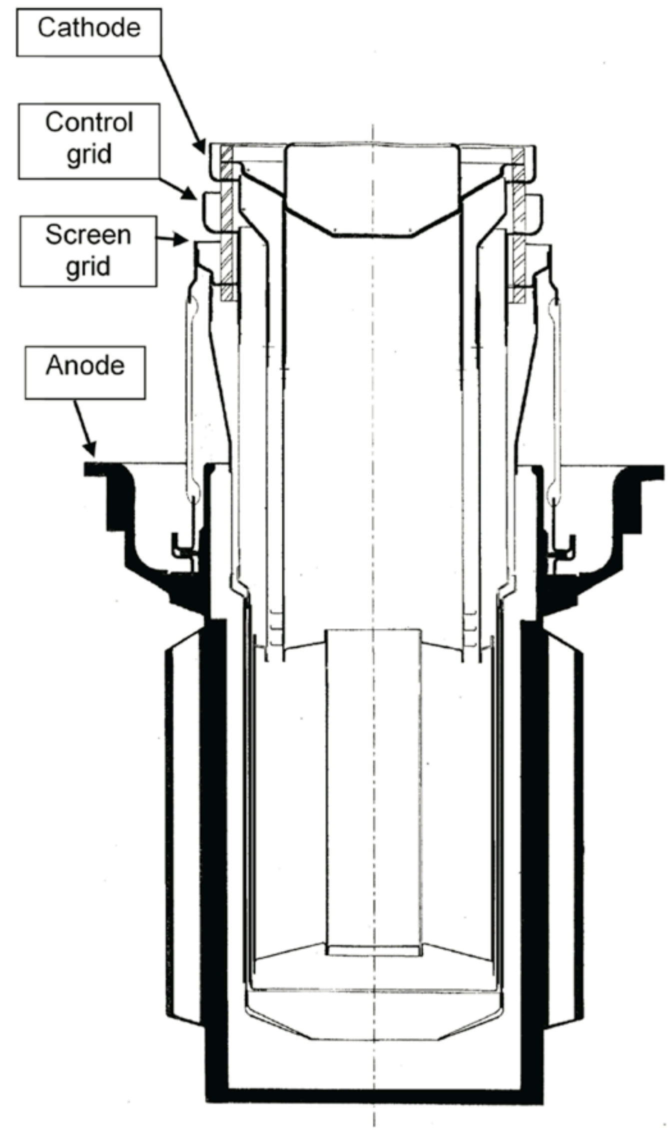
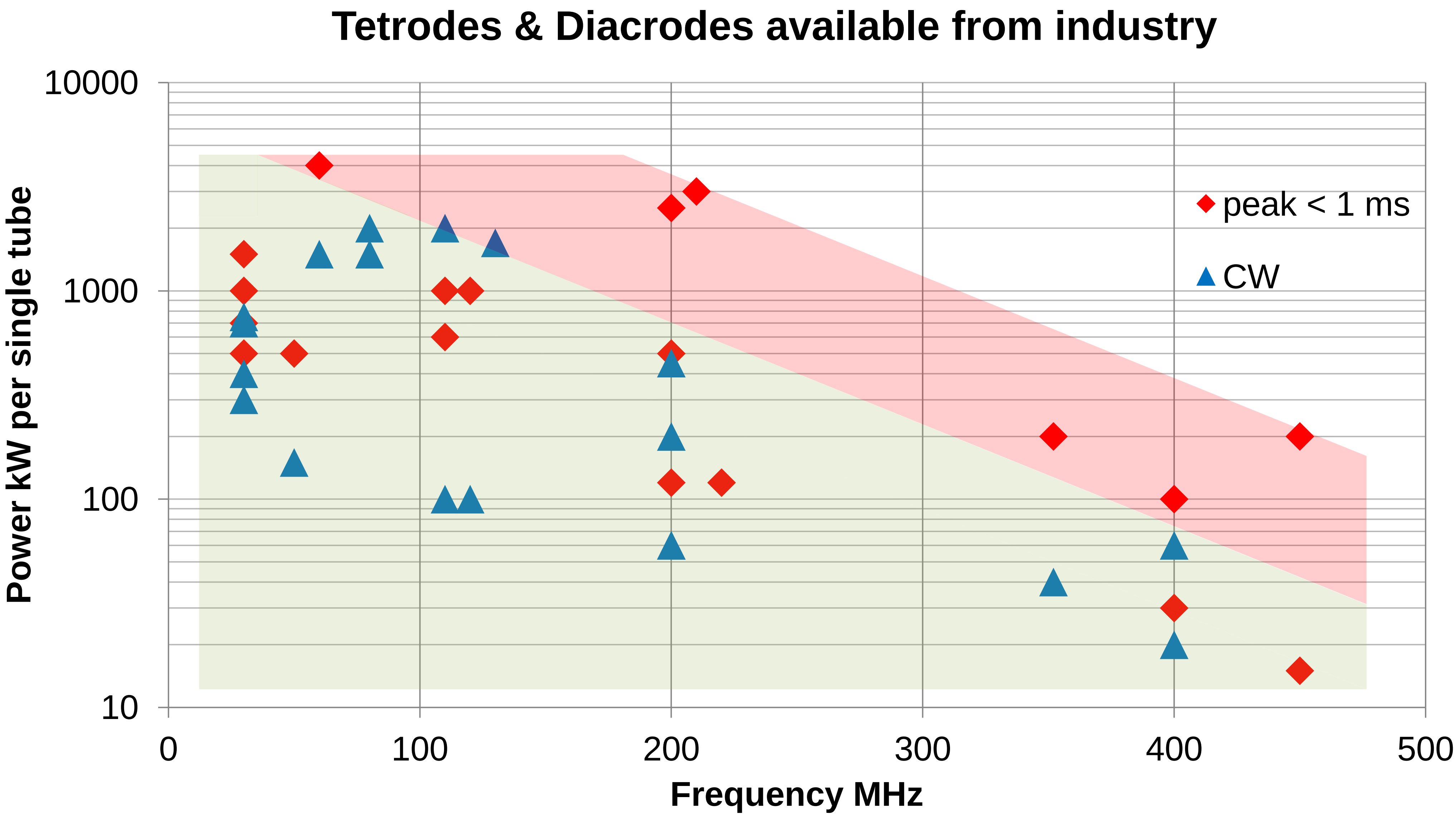


Fig. 3: Cross-sectional view of a high-power tetrode (Courtesy of e2v technologies)

TETRODE -SUMMARY

FREQUENCY RANGE	tens to 500 MHz
BANDWIDTH	few %
MAXIMUM POWER EXAMPLES	CW 1 MW up to 30 MHz 200 KW @ 350 MHz pulsed up to 4 MW @ 200 MHz
CLASS OF OPERATION	A, AB, B, C
EFFICIENCY	UP TO 70 %
GAIN	High gain at low frequencies Low gain at high frequencies Typical values between 14 and 20 dB
RELIABILITY	Medium Cathode lifetime limited to 5000-40000 hours
FEATURES	Simplicity Relatively robust Low cost
	High voltage Low current Transit time limited

TETRODES-EXAMPLES



Eric Montesinos, TIARA Workshop, 2013

TETRODES-EXAMPLES

RF performance

	CW		Short pulses			
Frequency	110	200	200	200	200	MHz
Output power	280	200	300	400	500	kW
Anode voltage	16	11	16	17	19	kV
Anode current	27	28	30	40	45	A
Screen-grid voltage	1 300	1 250	1 200	1 200	1 200	V
Control-grid voltage	- 320	- 350	- 300	- 300	- 300	V
Heater voltage (1)	10	10	10	10	10	V
Heater current	360	360	360	360	360	A
Pulse duration	-	-	1	1	0.5	msec
	-	-	10	10	1	%

TH 595

CW operation	60 kW @ 150 MHZ
	30 kW@250 MHz
Short pulse	up to 200 kW up to 450 MHz

YL1530

Output Power	35 kW
Maximum Frequency	250 MHz
Cooling	Forced Air
Filament Voltage	7.5 V
Filament Current	180 A
Peak Anode Voltage	12 kV

TETRODES AMPLIFIERS EXAMPLES

YL1530

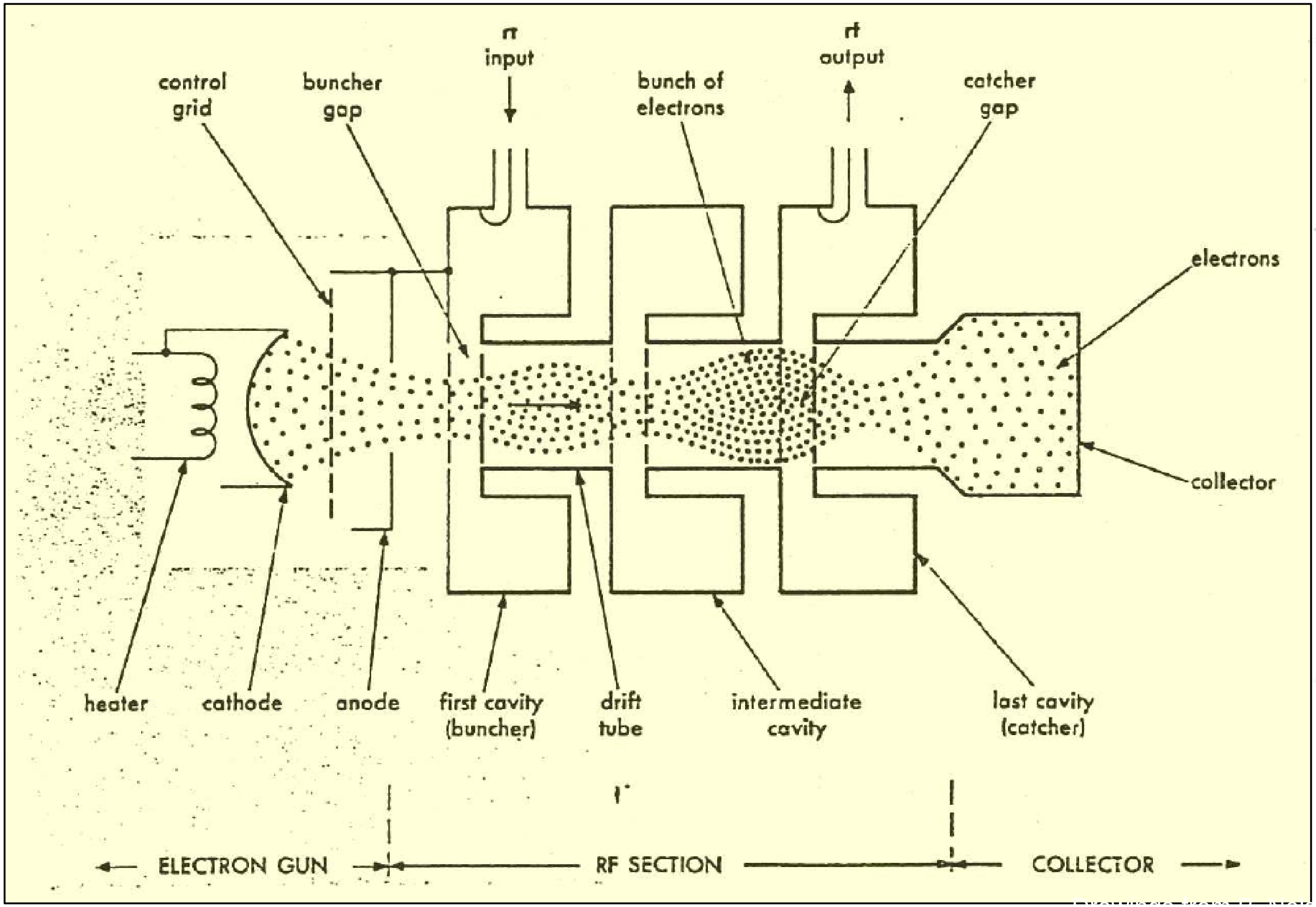
Key Attributes	**Value**
Output Power	35 kW
Maximum Frequency	250 MHz
Cooling	Forced Air
Filament Voltage	7.5 V
Filament Current	180 A
Peak Anode Voltage	12 kV

SPS (CERN) Philips
4x550kW 72 tetrode amplifiers

KLYSTRON - PRINCIPLE

ELECTRON BEAM IS VELOCITY MODULATED

✓ Overcomes tetrode limitations due to the transit time of the electrons



Three main parts

- ✓ Electron gun
- ✓ RF section
- ✓ collector

Drawings from B. Nelson, Introduction to Klystron Amplifiers and Travelling Tube Fundamentals, Varian Palo Alto Microwave Tube Division ,1978

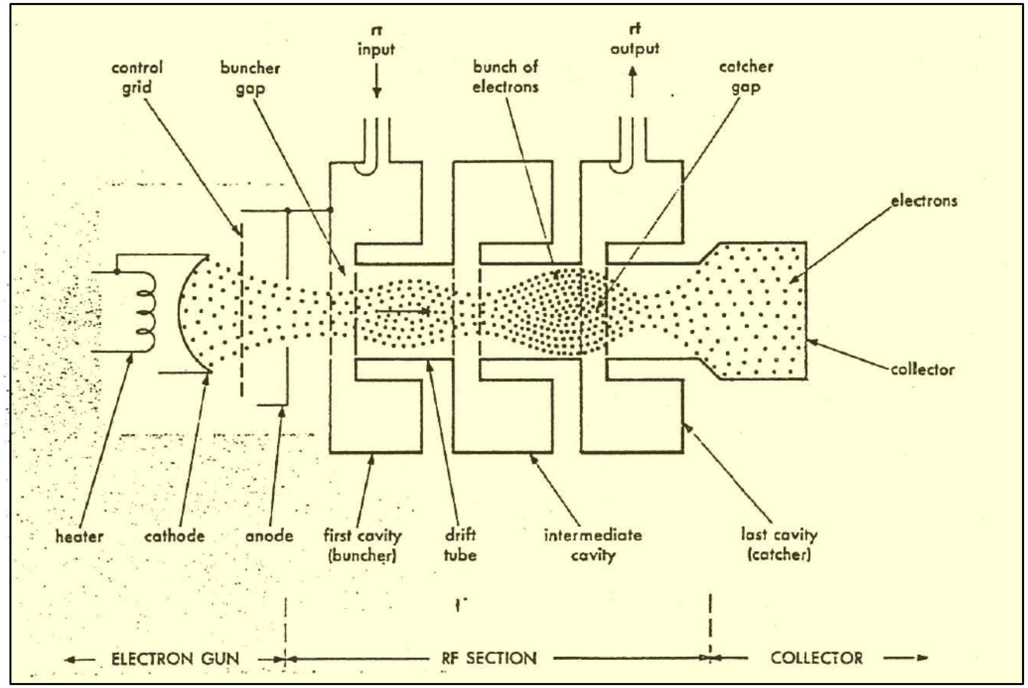
KLYSTRON - PRINCIPLE

Electron Gun

- ✓ Heater
- ✓ Cathode
- ✓ Control grid (sometimes)
- ✓ Anode

✓ Electrons emitted by the cathode are accelerated to the anode by the positive voltage applied.

✓ A grid may be used to control the flow of electrons to the anode region. This may be also used to switch off the beam completely in some pulsed applications.

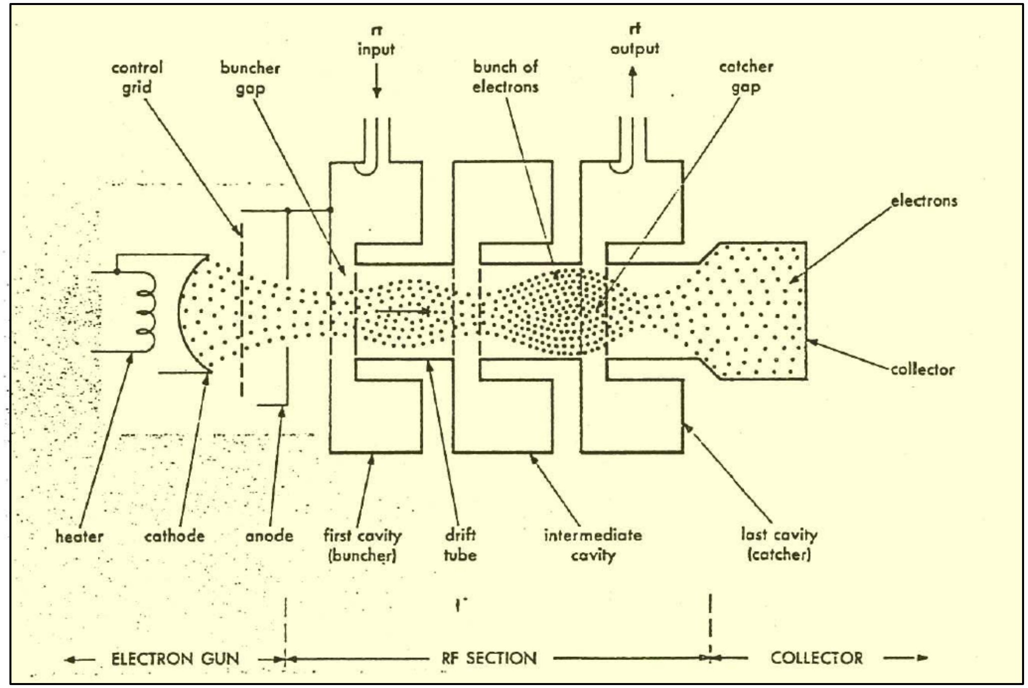


Collector

- ✓ Collects the electrons, that from the anode have passed through the RF sections.
- ✓ The collector is not connected to the RF circuitry at all.

KLYSTRON - PRINCIPLE

RF SECTION



- ✓ Composed of cavities separated by drift tubes.
- ✓ Cavities are tuned according to the required operating frequency and bandwidth.
- ✓ Input RF signal is applied to the first cavity (the buncher) where it excites an electromagnetic RF field.
- ✓ The RF field in the buncher modulates the velocity of the electron beam.
- ✓ In the drift tube region the electrons are bunched.
- ✓ The bunched electron beam arrives at the output cavity (the catcher) where it induces an alternating field at the RF frequency as they pass through the catcher gap.
- ✓ The RF fields can be coupled from the cavity to the output line.

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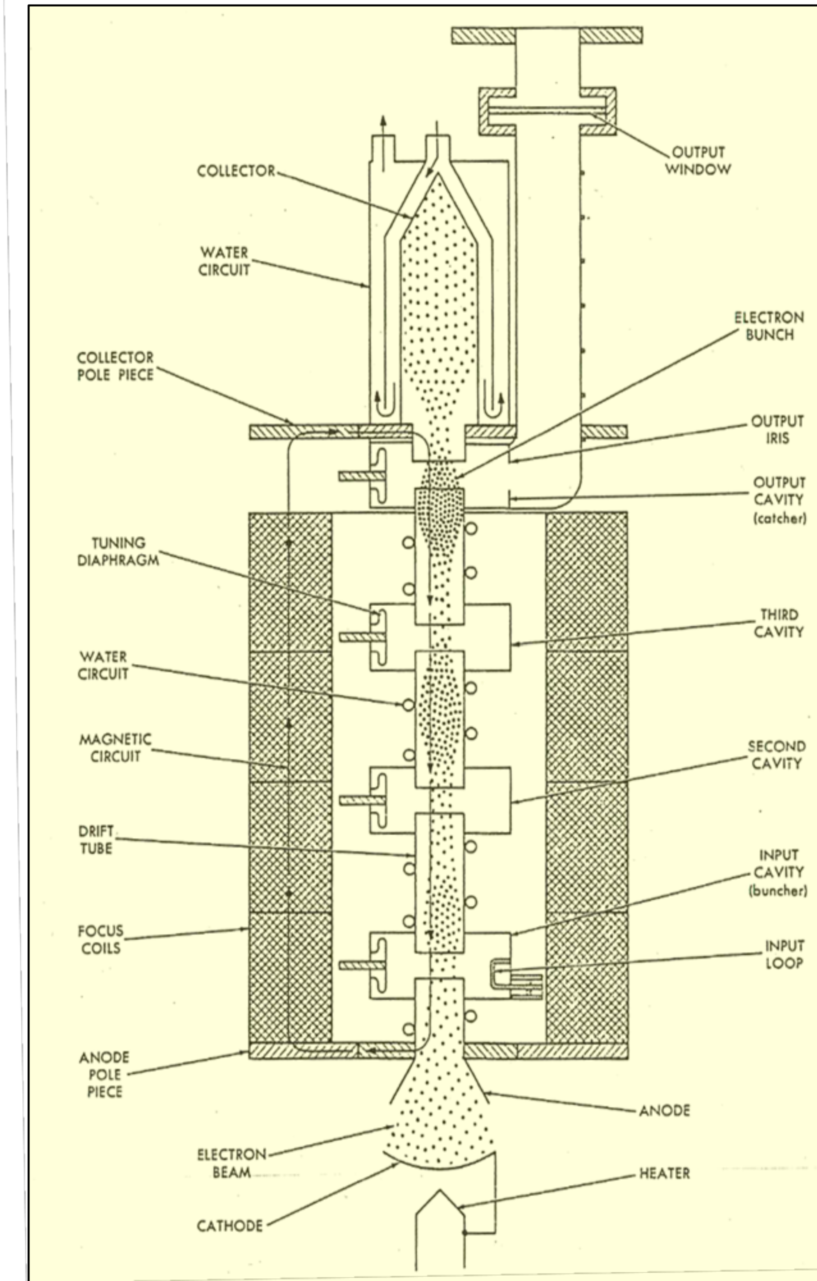
KLYSTRON - PRINCIPLE

- ✓ If the process is working properly, the oscillating currents in the catcher cavity will be considerably higher than in the buncher cavity, i.e. amplification has taken place.
- ✓ Electron beam delivers energy to the cavity, therefore the beam arrives to the collector with less energy than it had when crossing the input cavity. The difference is roughly the RF power delivered.
- ✓ Intermediate cavities improve the bunching process, i.e.:
  - ✓ Increase amplifier gain and efficiency.
  - ✓ Increase bandwdith
- ✓ Effect is similar to adding more stages to an amplifier
- ✓ To keep the electron beam formed properly, an axial magnetic field is used to confine it. Magnet coils are used.



KLYSTRON - SUMMARY

FREQUENCY RANGE	300 MHz to 30 GHz
BANDWIDTH	few %
MAXIMUM POWER EXAMPLES	Few MW in cw Up to 100 MW in pulsed operation
CLASS OF OPERATION	A
EFFICIENCY	40 to 60 %
GAIN	High gain Typical values around 40 dB
RELIABILITY	Medium Cathode lifetime limited
FEATURES	High power High gain Controlled output
	High voltage Efficiency Needs expert care

NOTE: Multi beam klystrons may represent an option to deliver higher power with high efficiency not increasing the high voltage

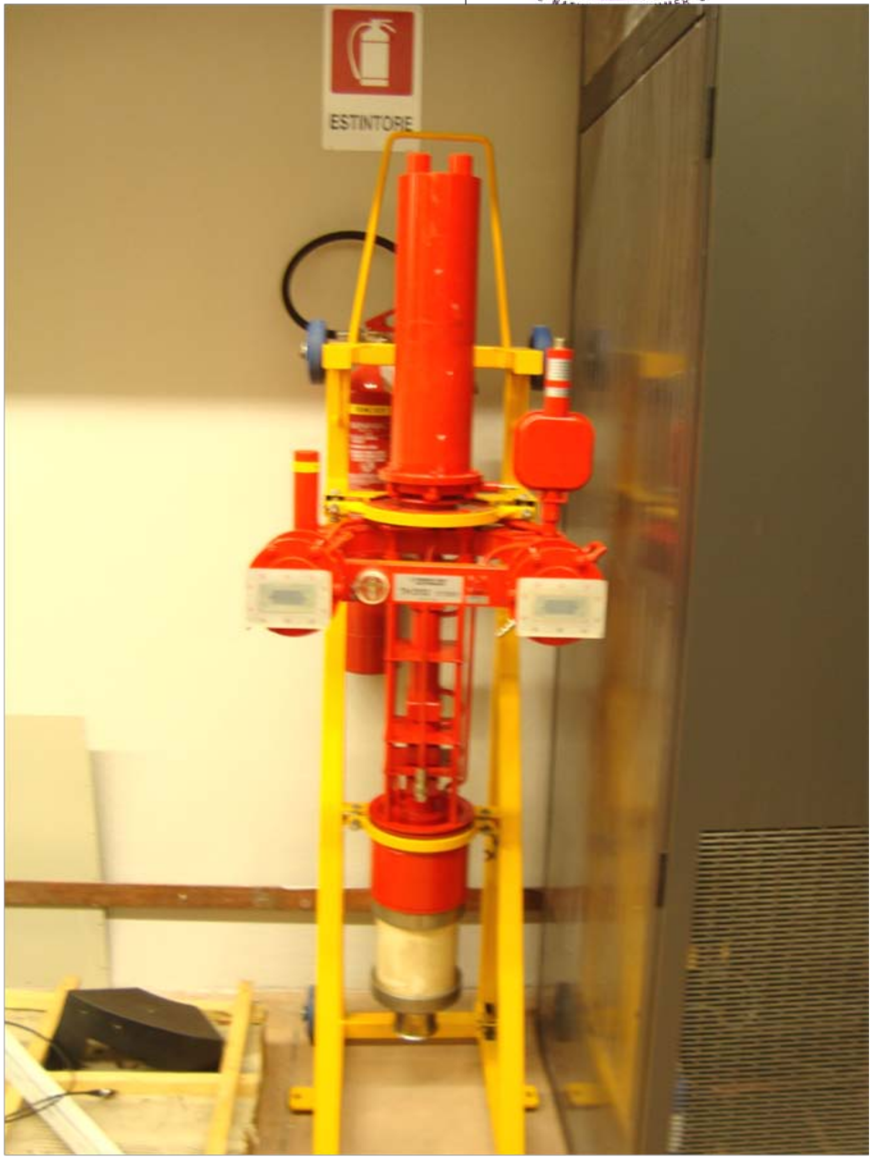
KLYSTRON - EXAMPLES

External cavities UHF Klystron used at Elettra 60 kW cw 500 MHz (E2v 2672BCD))

Note: Dimensions not equivalent

300 kW cw 500 MHz klystron (Thales TH22161)

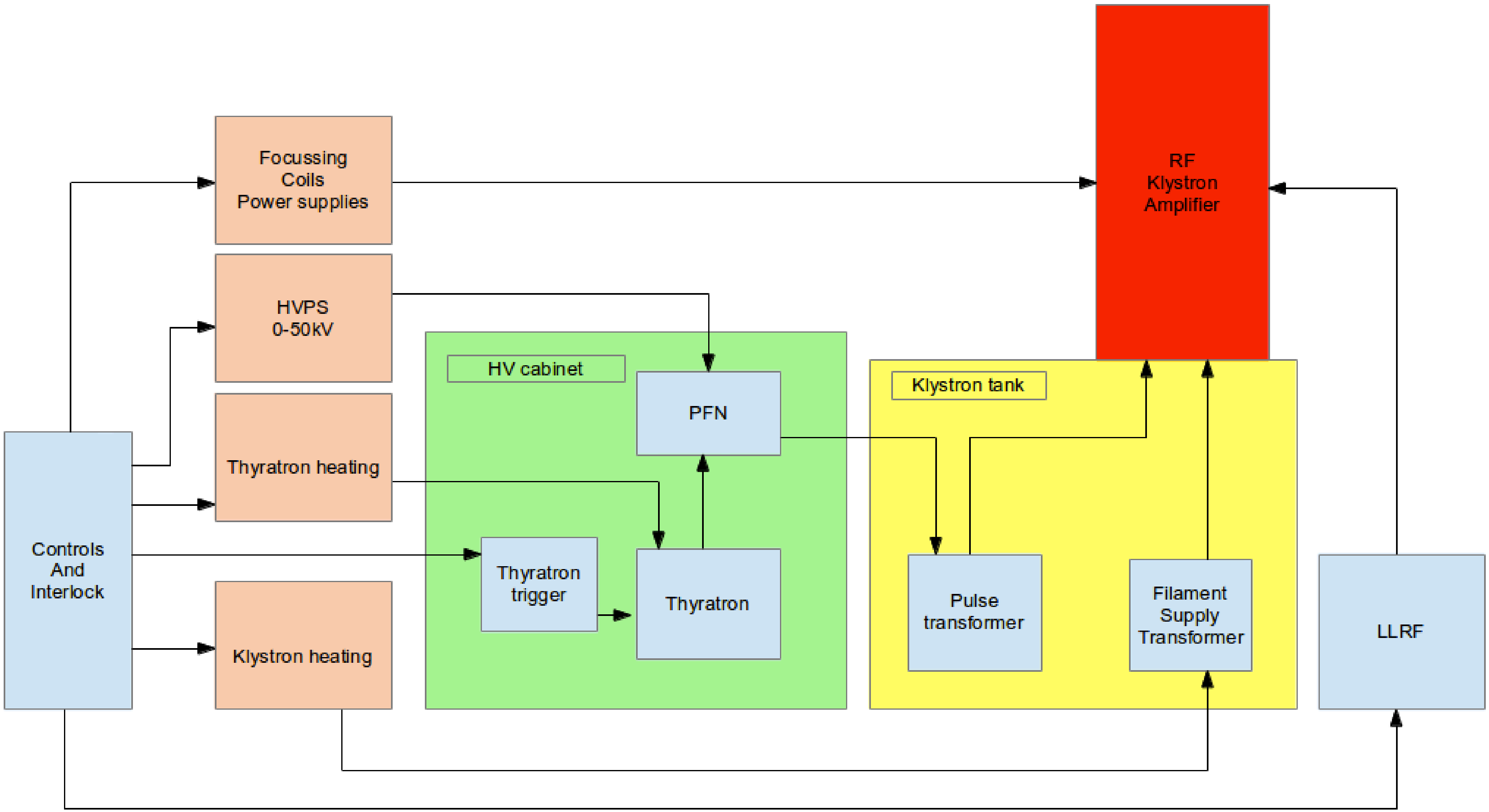
KLYSTRON - EXAMPLES



45 MW pulsed S-band
klystron (Thales TH2132A)

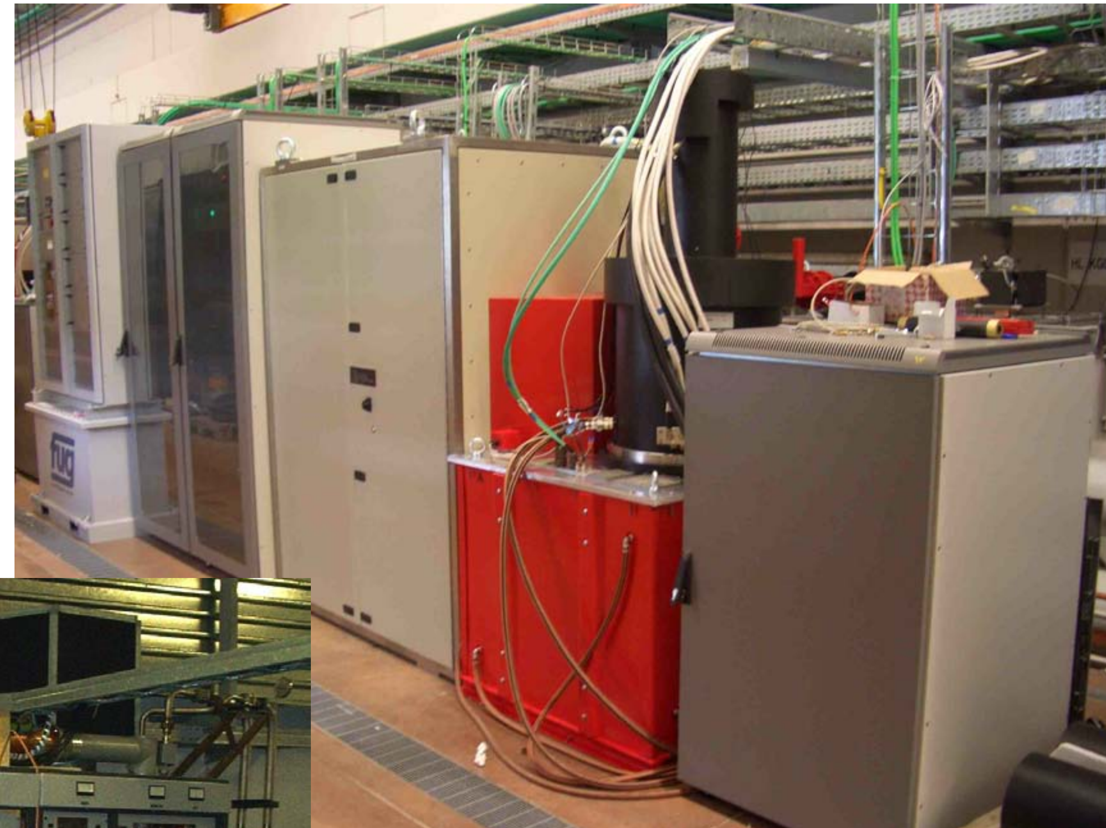
50 MW pulsed X-band
klystron (SLAC XL5)

KLYSTRON PFN MODULATOR



KLYSTRON BASED POWER PLANTS - EXAMPLES

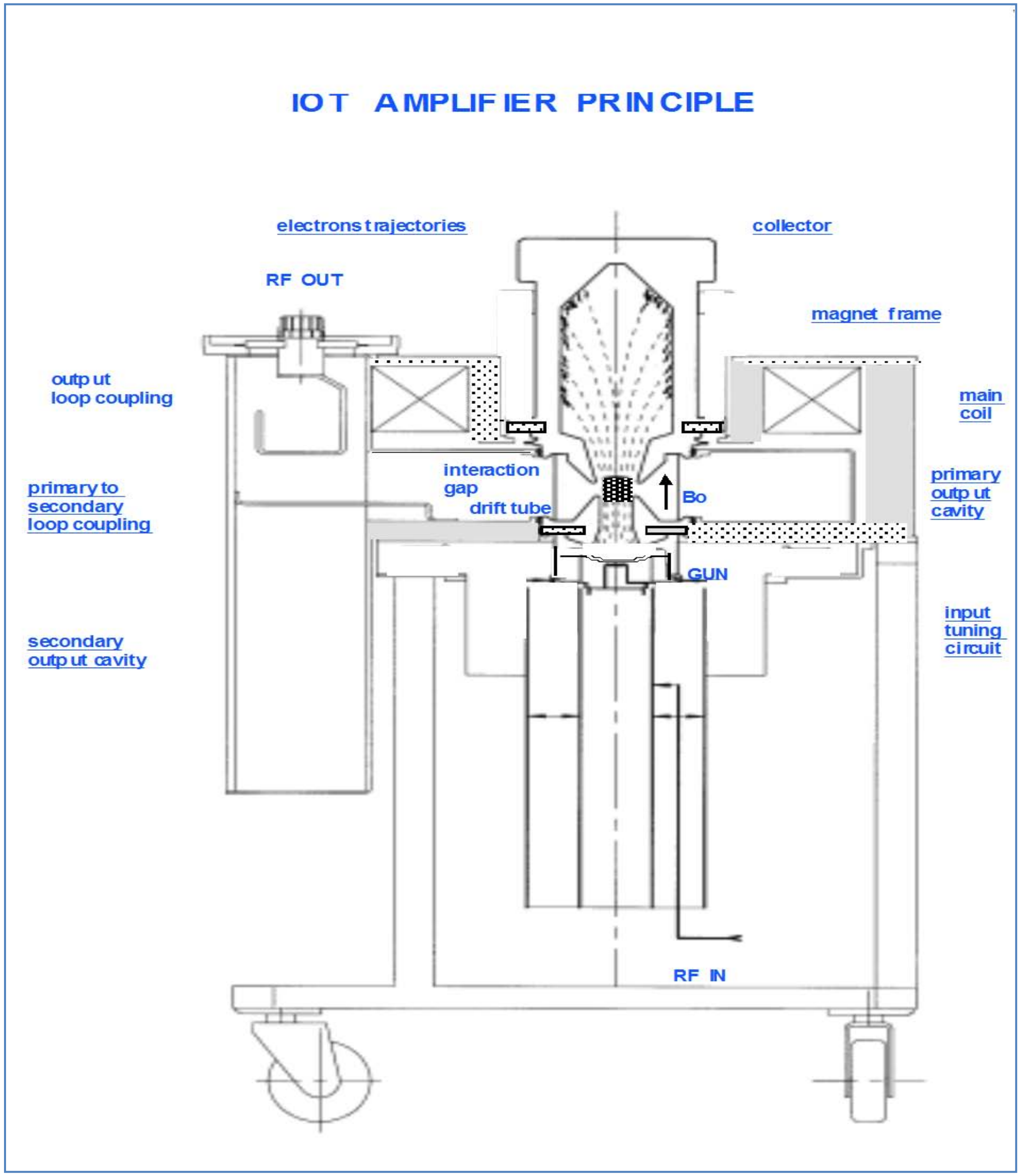
45 MW peak S-band klystron and modulator at FERMI



60 kW cw 500MHz at Elettra

IOT

- **The IOT combines aspects of gridded tube and klystron technology.**
- The main difference is that while in a klystron the electron beam is velocity modulated, in an IOT it is density modulated.
- The input signal is applied between cathode and a grid (closed and in front of the cathode) through a coaxial resonant circuit.
- Electron beam is density modulated in the gun region itself.
- The beam is accelerated through an aperture in the anode (at ground potential) to the output region.
- Here the power is extracted via a conventional klystron system. A double tuned output cavity system may be used to give a wider bandwidth.
- Anode grounded and separated from collector



IOT -SUMMARY

FREQUENCY RANGE	100 MHz to 2 GHz
BANDWIDTH	few %
MAXIMUM POWER EXAMPLES	100 KW
CLASS OF OPERATION	B, C
EFFICIENCY	Up to 80 %
GAIN	Medium gain (around 23 dB)
RELIABILITY	Medium Cathode lifetime limited, grid
FEATURES	Efficient cheap
	High voltage Power limited at high frequency

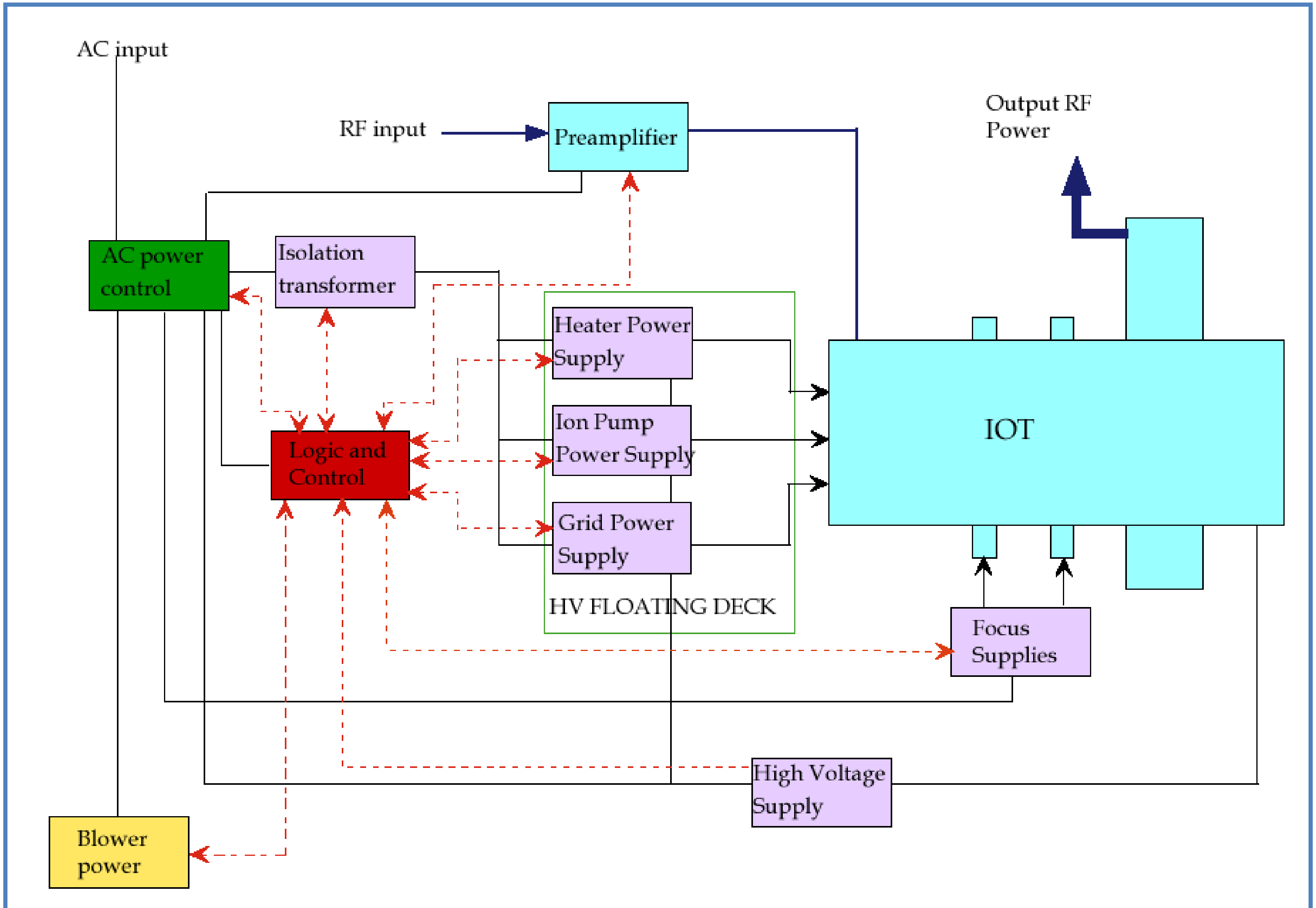
- ✓ Widely used in digital broadcasting
- ✓ For higher power they are combined
- ✓ To increase the maximum power multi-beam IOTs are presently being studied for ESS.

IOT EXAMPLES

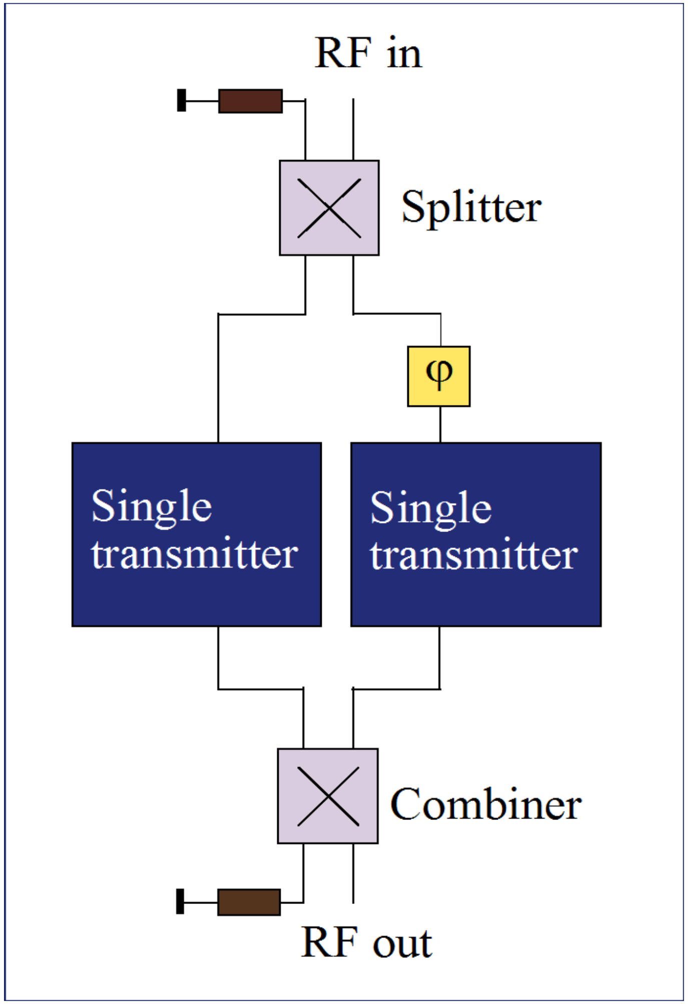
IOTD2130 (E2V) in Elettra

TH 793LS (Thales) in Elettra

IOT AMPLIFIER



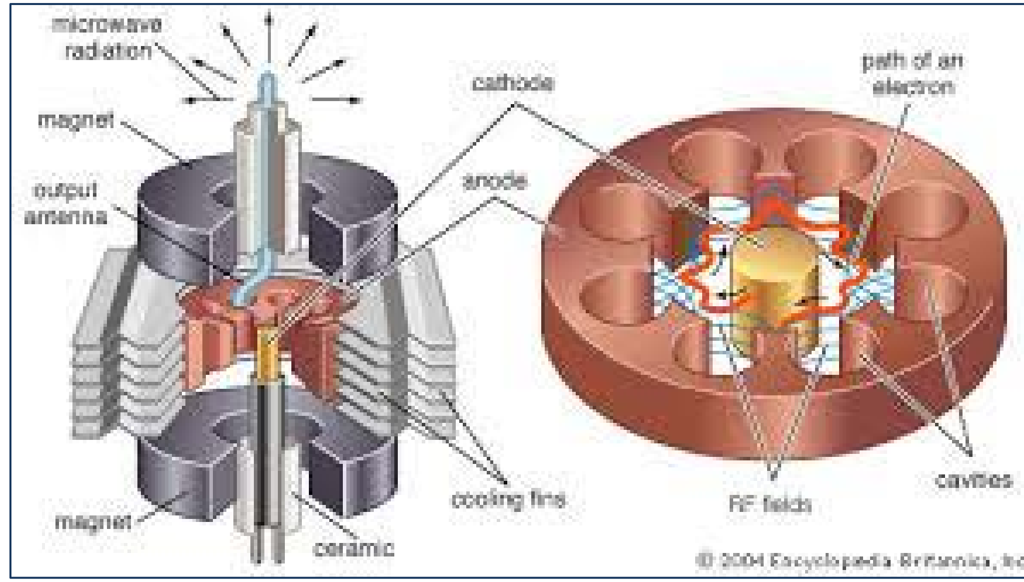
IOT BASED AMPLIFIERS



150 kW amplifier combining 2 x 80 kW IOTs in Elettra

MAGNETRON

- ✓ High power vacuum tube where the RF power is generated using the interactions of the electrons with a magnetic field while crossing a series of open metal cavities.
- ✓ The magnetron is an oscillator not an amplifier

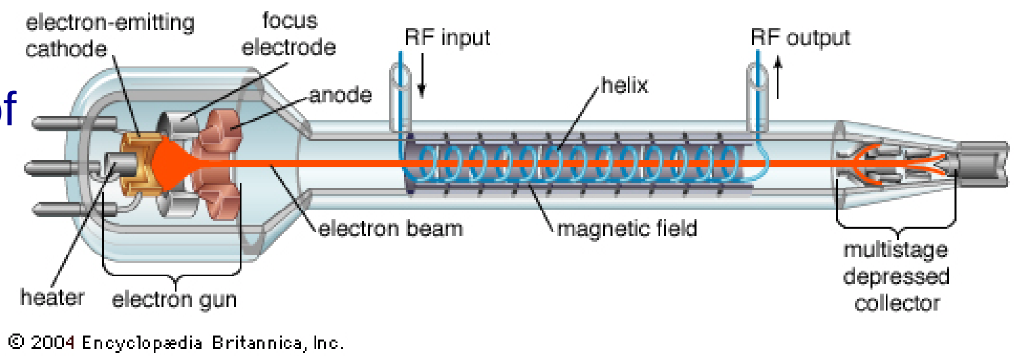


- ✓ Principle of operation:
  - ✓ Coaxial cathode and anode structure.
  - ✓ Anode contains a number of equally spaced cavities
  - ✓ Longitudinal static magnetic field modifies the electron flow
  - ✓ Electrons excite the cavities.
  - ✓ Output power is coupled from one of the cavities.
  - ✓ If needed, frequency locking can be achieved injecting some RF power (around 0.1 %)
- ✓ In accelerators applications, magnetrons are used especially in medical linacs.
- ✓ Peak power level can reach some MW in C, S and X band

OTHER VACUUM TUBES

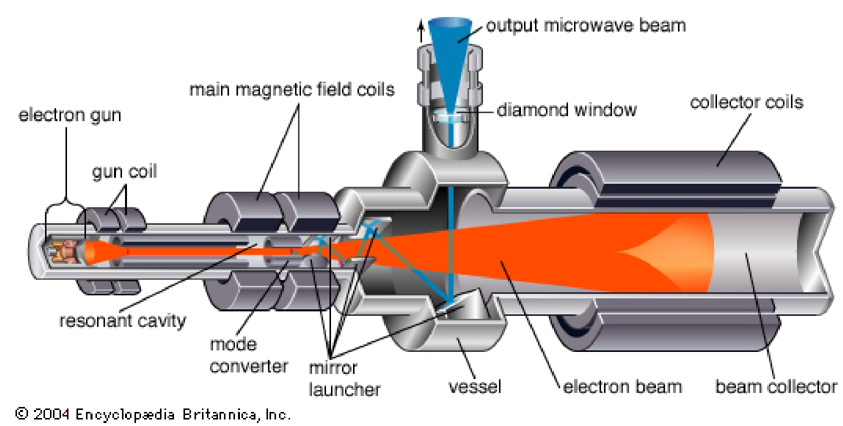
Travelling wave tube

- ✓ High power linear vacuum tube
- ✓ Helix TWT: bunching of the electron beam by the interaction with the RF field travelling along an helix line which allows the energy transfer from the beam to the line
- ✓ Wideband amplifier
- ✓ Operating from hundreds of MHz to tens of GHz
- ✓ Output power up to few MW



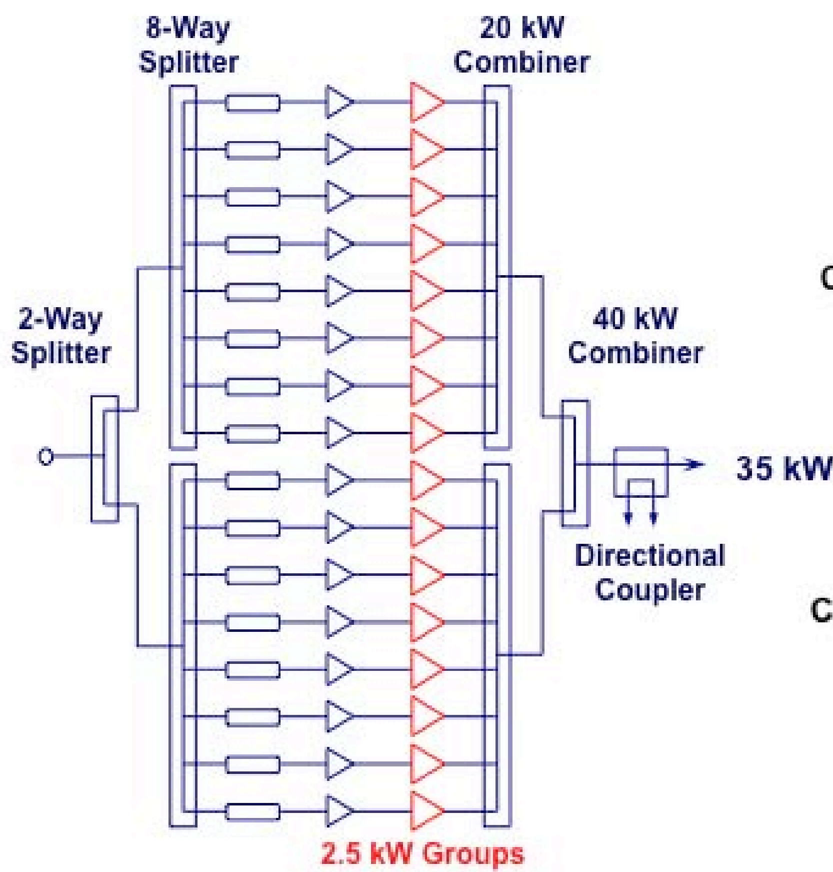
Gyrotron

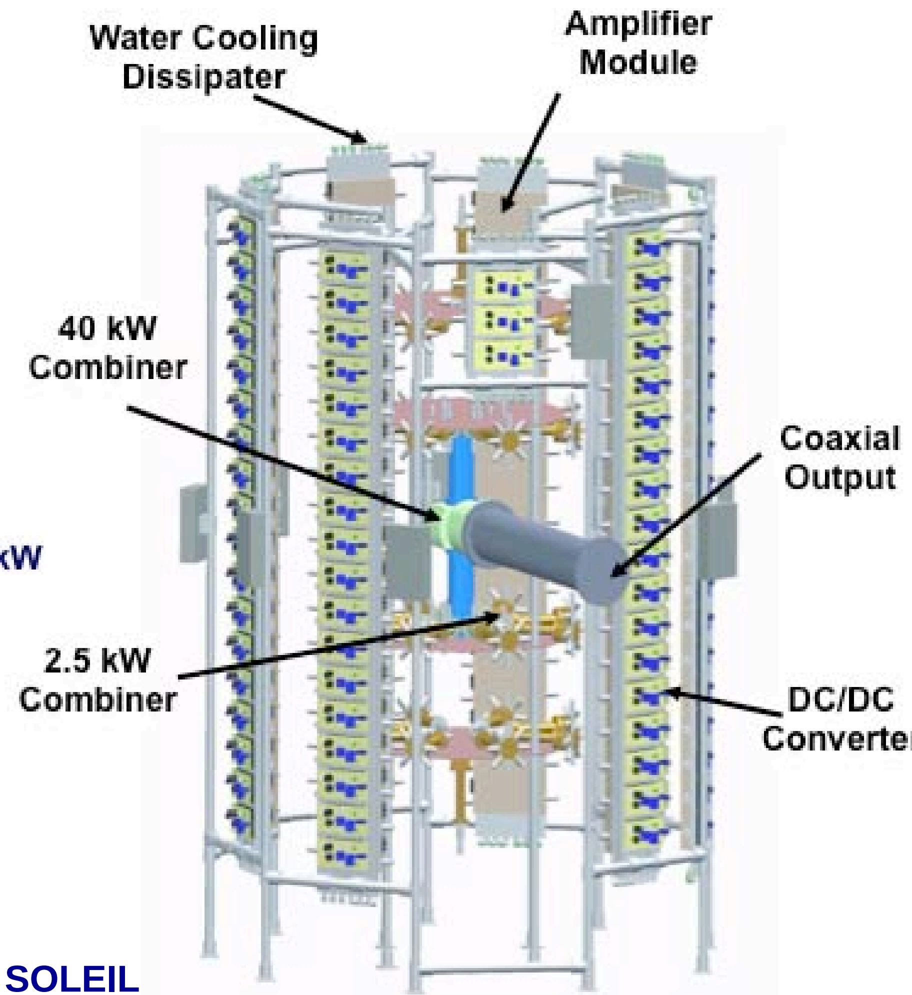
- ✓ High powered linear beam vacuum tube which generates millimiter wave electromagnetic waves exploiting the cyclotron resonance of electrons in a strong magnetic fields.
- ✓ CW or pulse operation
- ✓ Output frequencies from 20 to 25 0 GHz
- ✓ Output power up to 1-2 MW



SOLID STATE

- ✓ High power is achieved by combining a large number of transistor
- ✓ Pioneered at SOLEIL, now also at ESRF and other facilities

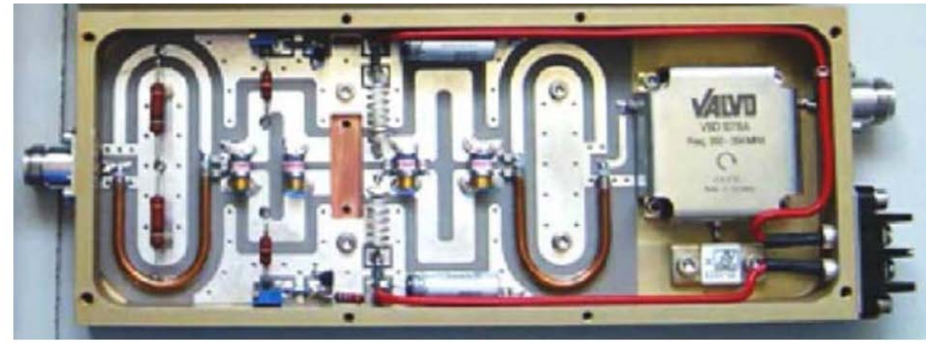




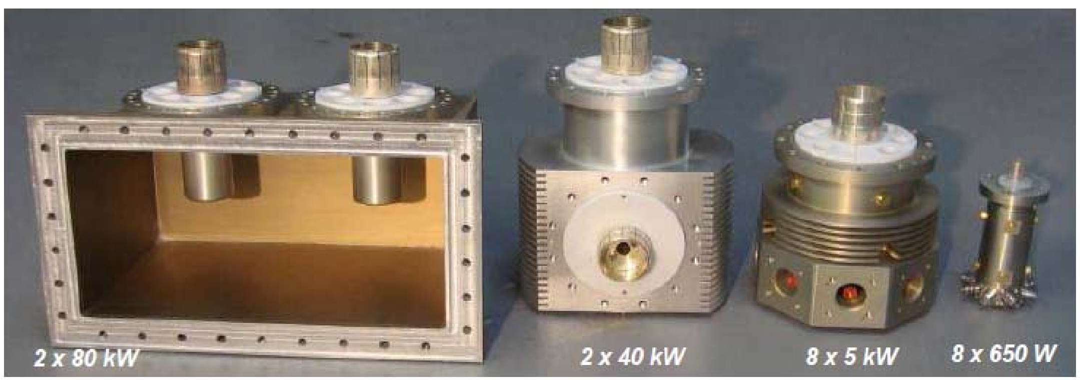
Courtesy of SOLEIL

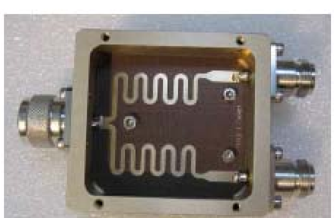
SOLID STATE

- ✓ Different technologies available
  - ✓ Silocon bipolar transistors
  - ✓ Silicon LDMOS
  - ✓ GaAsFET
  - ✓ Static Induction Transistors (SITs)
- ✓ Each module has a circulator
- ✓ Different combination elements are needed



Power combination components





2-way splitter

8-way splitter

P_i - P_r monitoring coupler

- ✓ Pictures from SOLEIL

SOLID STATE

- ✓ High reliability due to redundancy
- ✓ No high voltage
- ✓ Used without high power circulator at the final output
- ✓ Failure of single modules mainly due to thermal fatigue (transistor breakdown, older damage for example)
- ✓ Topology is an important aspect for maintainability and operability, also on long term
- ✓ Considering the fast development of the semiconductors market, already in the design phase, the design should consider carefully how to assure an enduring and long term maintenance.

SOLID STATE -SUMMARY

FREQUENCY RANGE	Up to 2 GHz
BANDWIDTH	large
MAXIMUM POWER EXAMPLES	0.8 kW/module 200 kW/plant
CLASS OF OPERATION	A, AB
EFFICIENCY	40 %
RELIABILITY	Good (redundancy)
FEATURES	Modular approach Maintenance Graceful degradation No high voltage
	Efficiency Combination losses Module isolation

SOLID STATE AMPLIFIERS EXAMPLES

SOLEIL SSA:
Frequency: 352 MHz
Output power: 180 kW
726 × 315 modules in 4 towers.
2 × Si LDMOS transistors per module.

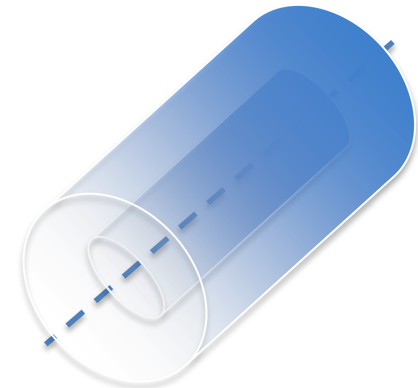
ELBE
Frequency: 1.3 GHz
20 kW
2 x 10 kW
9 power modules

POWER TRANSMISSION

GENERAL

- **The power transmission system is the assembly of components that perform the tasks to transport the RF power from the RF power source to the cavities.**
- This is accomplished by a network of coaxial lines or rigid rectangular waveguides.
- The choice of the system depends on the frequency and power levels involved
- Coaxial lines
  - No cut-off
  - Higher attenuation
  - Difficult to cool
  - Typical ranges in use: frequency dc to 10 GHz, power rating example 1 MW at 200 MHz
- Waveguides
  - Cut-off
  - Lower attenuation
  - Easier to cool
  - Higher frequency
  - Higher power
  - Typical ranges in use: frequency 0.32 to 352 GHz, power rating example 150 MW peak at 310 MHz
- In addition to standard components, also special components are needed, like bends, directional couplers, circulators, loads, etc.

COAXIAL LINES



- ✓ TEM mode
- ✓ No cut-off, i.e. can be used down to d.c.
- ✓ Upper frequency limited by moding
- ✓ Higher attenuation than waveguides
- ✓ Difficult to cool
- ✓ Easier to handle than waveguides
- ✓ Characteristic impedance Z_0
- ✓ Phase velocity v
- ✓ For high power applications:
  - ✓ Air spaced lines, so dielectric is limited to support the inner conductor.
  - ✓ Rigid lines, either copper or aluminum
  - ✓ Characteristic impedance is 50 ohm (ratio between diameters is 2.3)
  - ✓ Compromise between power handling capabilities and attenuation.

$$Z_0 = \frac{60\Omega}{\sqrt{\varepsilon_r}} \ln(D/d)$$

$$v = \frac{c}{\sqrt{\mu_r \varepsilon_r}}$$

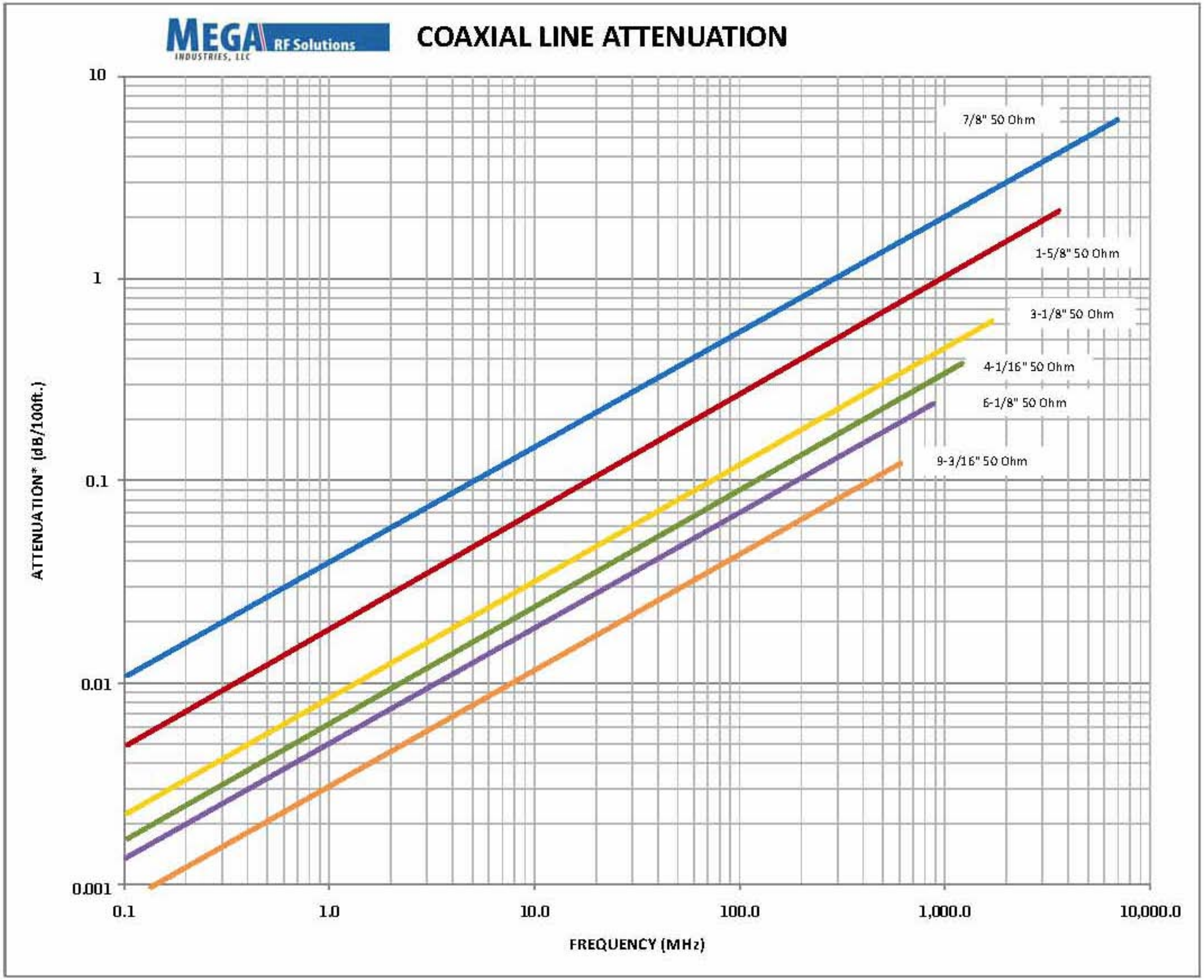
D=outer diameter

d=inner diameter

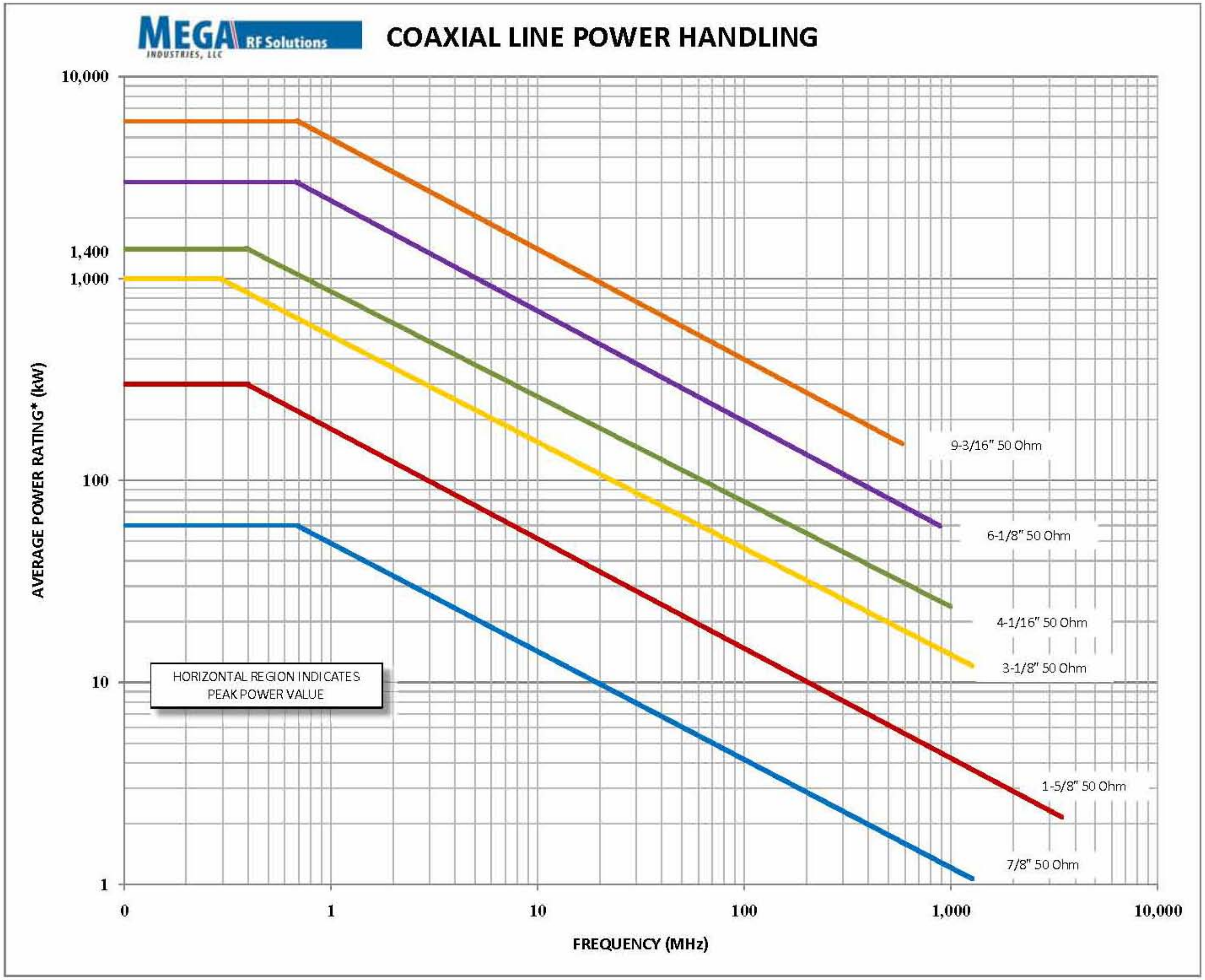
e_r=relative permittvity

m_r=relative permeability

COAXIAL LINES



COAXIAL LINES



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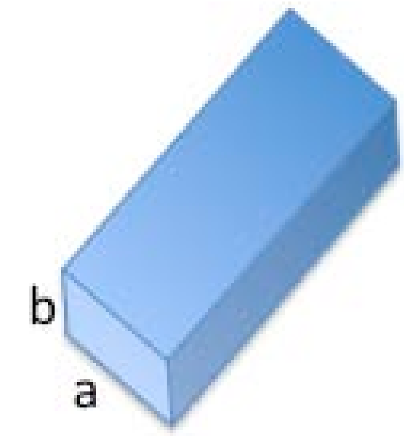
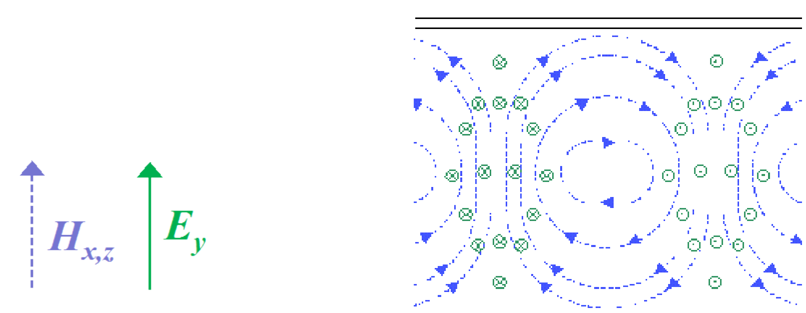
WAVEGUIDES

- ✓ TE_{10} mode
- ✓ Most used rectangular waveguides with aspect ratio 2:1, but reduced height are also used.
- ✓ Cut-off frequency
- ✓ Roughly used approximately between 1.25 and 1.9 f_c
- ✓ Lower attenuation
- ✓ Easier to cool
- ✓ Higher frequency than coaxial lines
- ✓ Higher power than coaxial line
- ✓ Pressurized waveguide to increase the breakdown field strength
- ✓ In-vacuum waveguides
- ✓ Typically made in copper or aluminum.



$$f_c = \frac{c}{2a}$$

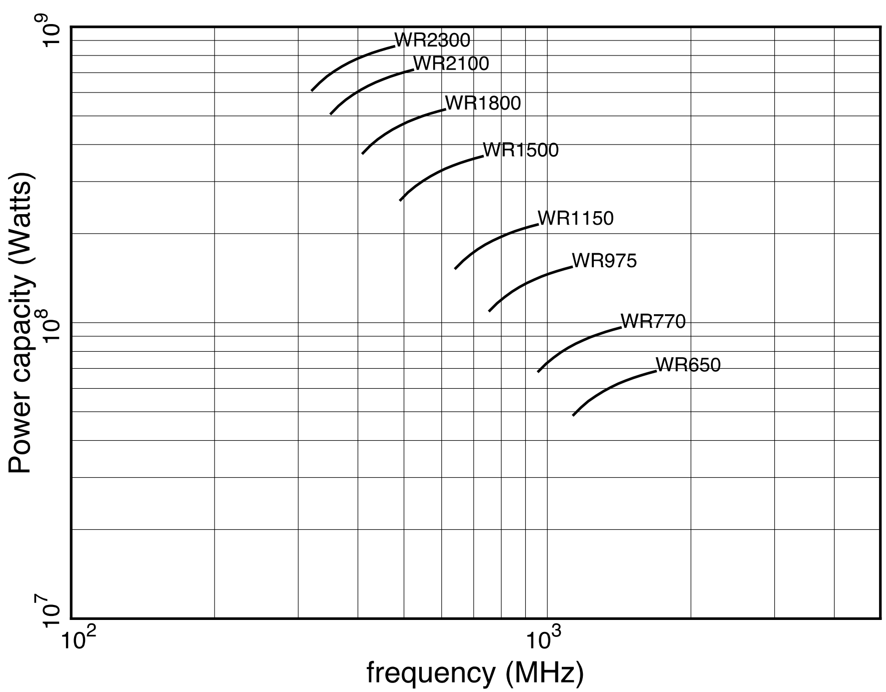
$$f_c = cutoff\ frequency$$



WAVEGUIDES

Table 1: Standard waveguide characteristics

Waveguide designation	Inside dimensions (inches)	TE_{10} mode operating Range (MHz)	Cut-off frequency (MHz)	Cut-off wavelength (cm)
WR2300	23.0 × 11.5	320–490	256	116.84
WR2100	21.0 × 10.5	350–530	281	106.68
WR1800	18.0 × 9.0	410–625	328	91.44
WR1500	15.0 × 7.5	490–750	393	76.20
WR1150	11.5 × 5.75	640–960	513	58.42
WR975	9.75 × 4.875	750–1120	605	49.53
WR770	7.7 × 3.85	960–1450	766	39.12
WR650	6.5 × 3.25	1200–1700	908	33.02



er handling capacity at a beakdown voltage of 3 MV/m

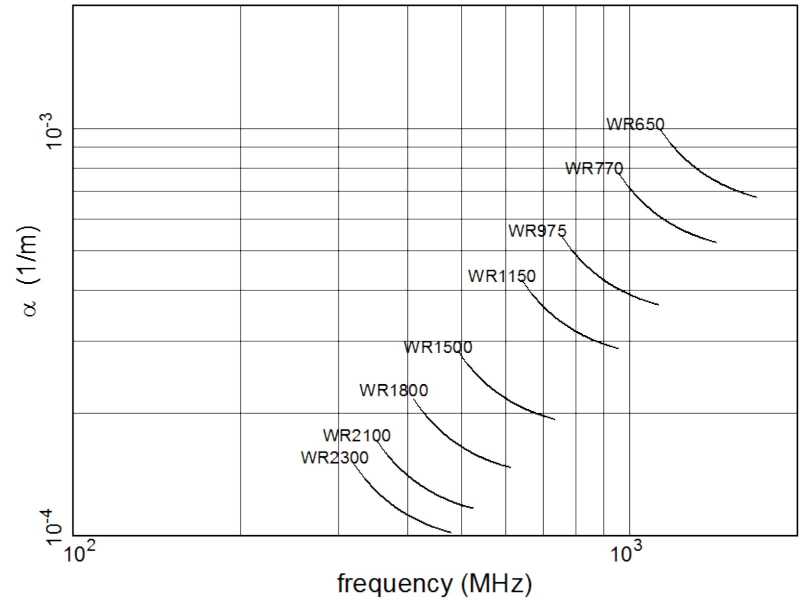


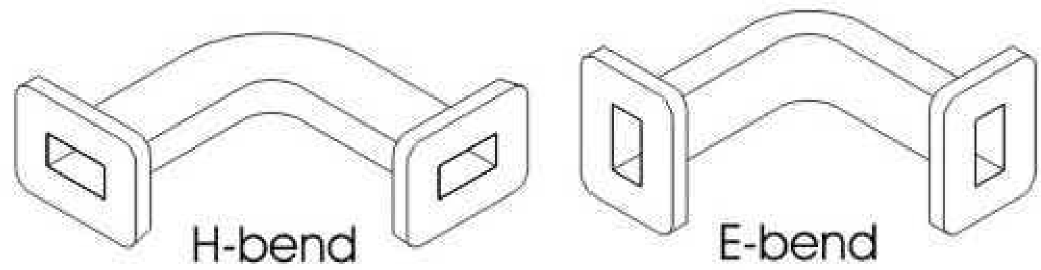
Fig. 4: Attenuation constant vs frequency for standard waveguides

R.K.Cooper, R.G. Carter,
“ High Power RF Transmission”
CAS 2000

COMPONENTS

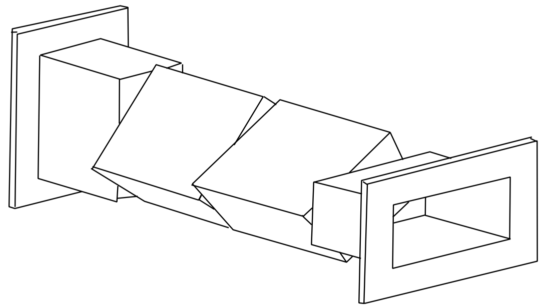
- **2 port devices**
  - Bends
    - *Coaxial bends*
    - *Waveguide bends (E plane, H plane)*
  - Twists
  - Windows
  - ………….
- **Three and four port devices**
  - Directional couplers
  - Hybrids
  - Magic Tees
  - Phase shifters
  - Variable attenuators
  - ………..
- **Circulators**
- **Loads**

BENDS



- ✓ Waveguide H-bend
  - ✓ distorts or changes the magentic field to allow the waveguide to bend in the required direction. It creates the bend around the thinner side.
- ✓ Waveguide E-bend
  - ✓ distorts or changes the electric field to allow the waveguide to bend in the required direction)
- ✓ Meter or sweep
- ✓ Typical commercial mitre waveguide bends have VSWR around 1.03:1 over a 10% band
- ✓ Also other angles

TWISTS AND WINDOWS

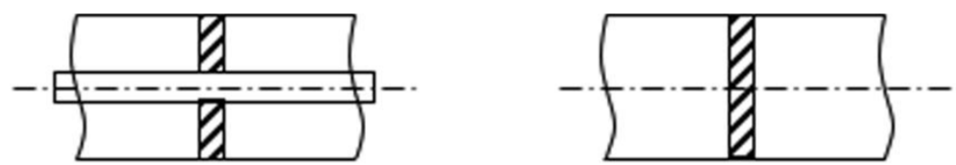


Twists

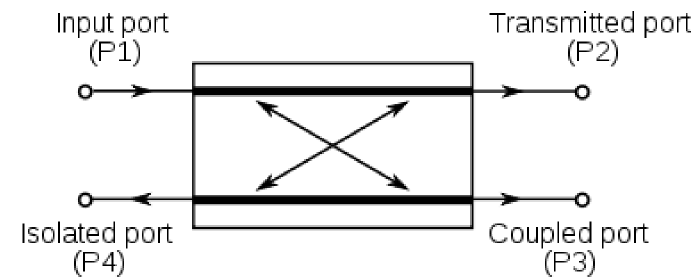
- ✓ Step or continuous
- ✓ Allow rotation of the electric field
- ✓ Typical 90, but also other angles
- ✓ Typical commercial waveguide twists have VSWR around 1.05:1 over a 10% band

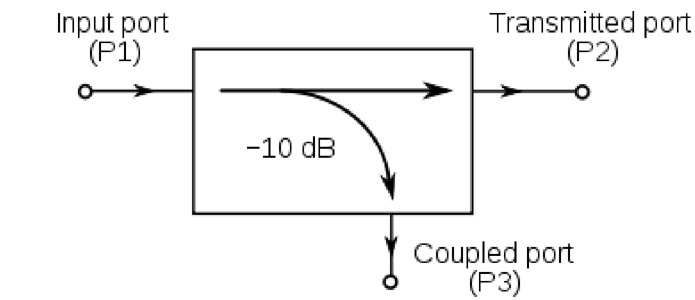
Window

- ✓ Separate parts of the waveguide circuit under vacuum and in atmospheric pressure
- ✓ Very critical component
- ✓ Typically made of high purity alumina ceramic brazed in the transmission line



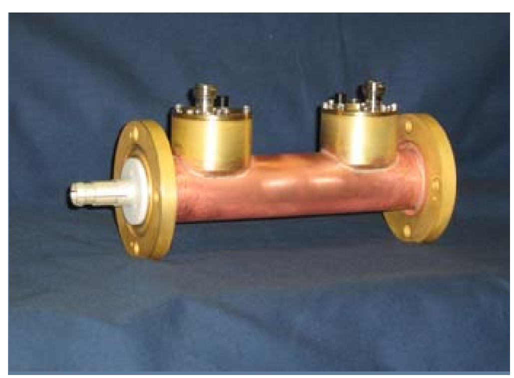
DIRECTIONAL COUPLERS





- ✓ Directional couplers are used to couple energy from the waveguides system to another system
- ✓ They are mainly used to sample the fields in the waveguides for measurements and diagnostic purposes.
- ✓ Typical parameter of commercial components over a 10 % bandwidth:

  VSWR 1.05
  Coupling 6 to 60 dB
  Directivity 30 dB



$$C_{3,1} = -10\log(\frac{P_3}{P_1}) \;\; dB \;\; coupling\ factor$$

$$I_L = -10\log(\frac{P_2}{P_1}) \;\; dB \;\; insertion\ loss$$

$$I_{4,1} = -10\log(\frac{P_4}{P_1}) \;\; dB \;\; isolation$$

$$D_{3,4} = -10\log(\frac{P_4}{P_3}) \;\; dB \;\; directivity$$

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HYBRID AND MAGIC TEE

Hybrid

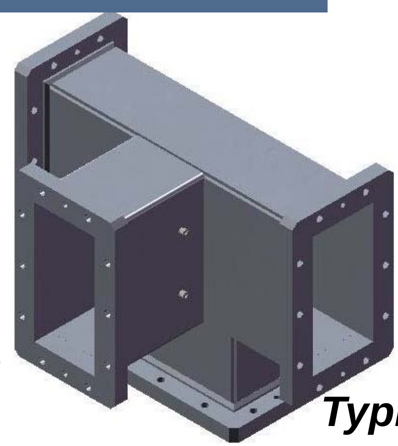
- ✓ 4 port device
- ✓ Power supplied to one terminal is ideally divided between two of the three remaining ports and nothing is coupled to the fourth one.
- ✓ Used for power splitting and combining

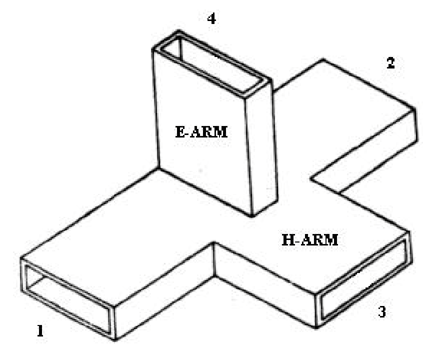
Typical commercial components

- ✓ equal 3 dB or unequal 4.77 and 6 dB
- ✓ 10 % bandwidth
- ✓ VSVR: 1/10:1
- ✓ Amplitude balance: ±0.25 dB,
- ✓ phase balance: 90 ±2°
- ✓ Isolation: higher than 28 dB

Magic Tee

- ✓ 4 port device
- ✓ Combination of E type and H type Tee
- ✓ Used as power combiner or power splitter
- ✓ Signal from H arm is splitted to 1 and 2 in phase
- ✓ Signal from E arm is splitted in 3 and 4 a 180° phase
- ✓ Signals fed from ports 1 and 2 are added in the H pane port and subtracted in the E plane port



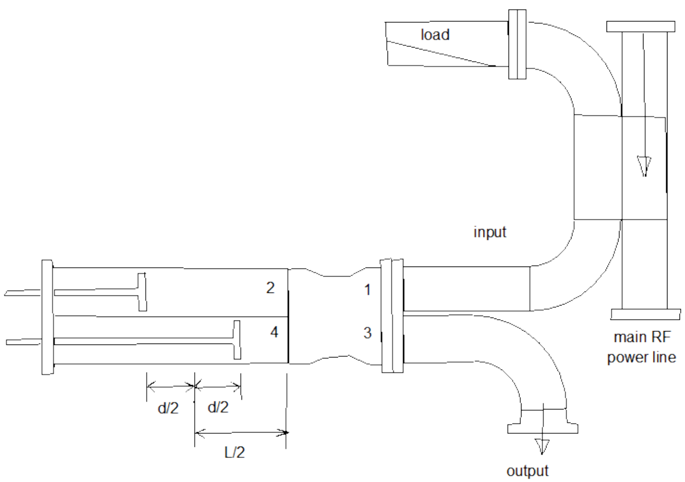


Typical commercial components

- ✓ 10 % bandwidth
- ✓ VSVR: 1/10:1
- ✓ Colinear balance: ± 0.1 dB
- ✓ Inserton loss: less than 0.1 dB
- ✓ E-H isolation: higher than 30 dB

PHASE SHIFTERS AND ATTENUATORS

- ✓ At low power they can be built by placing dielectric or lossy material in the waveguide
- ✓ At high power. Handling of the power could be problematic.
- ✓ Solution: exploit proprieties of hybrid junctions and use movable short circuits instead of loads



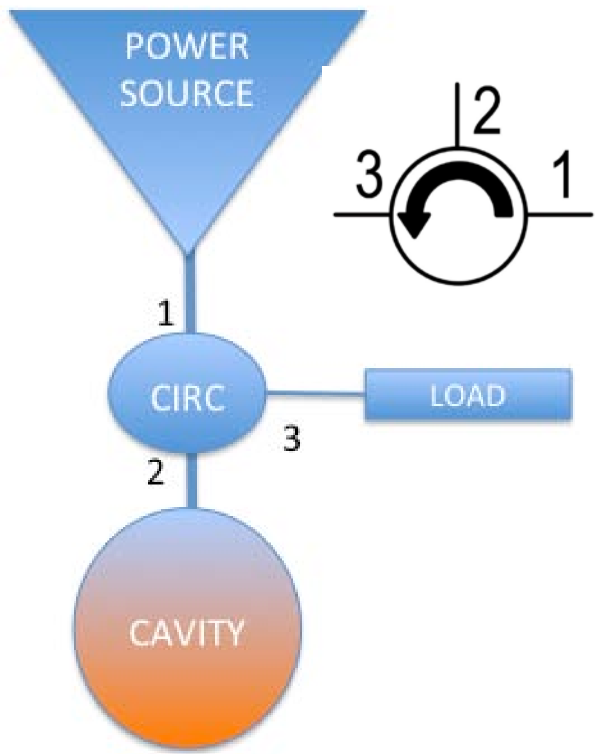
Typical commercial components (phase shifter)

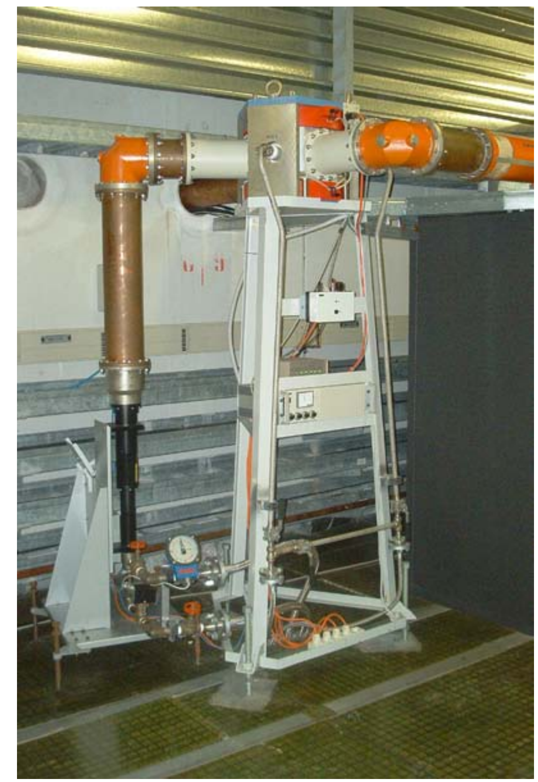
- ✓ 10 % bandwidth
- ✓ VSVR: 1.05:1
- ✓ Insertion loss less than 0.1 dB
- ✓ Phase range higher than 360 °

CIRCULATOR

- ✓ Non reciprocal device.
- ✓ Ferrite material
- ✓ Basically they are used to isolate then power source and the cavity, so that the reflected power is conveyed to a dummy load, where the power is dissipated.

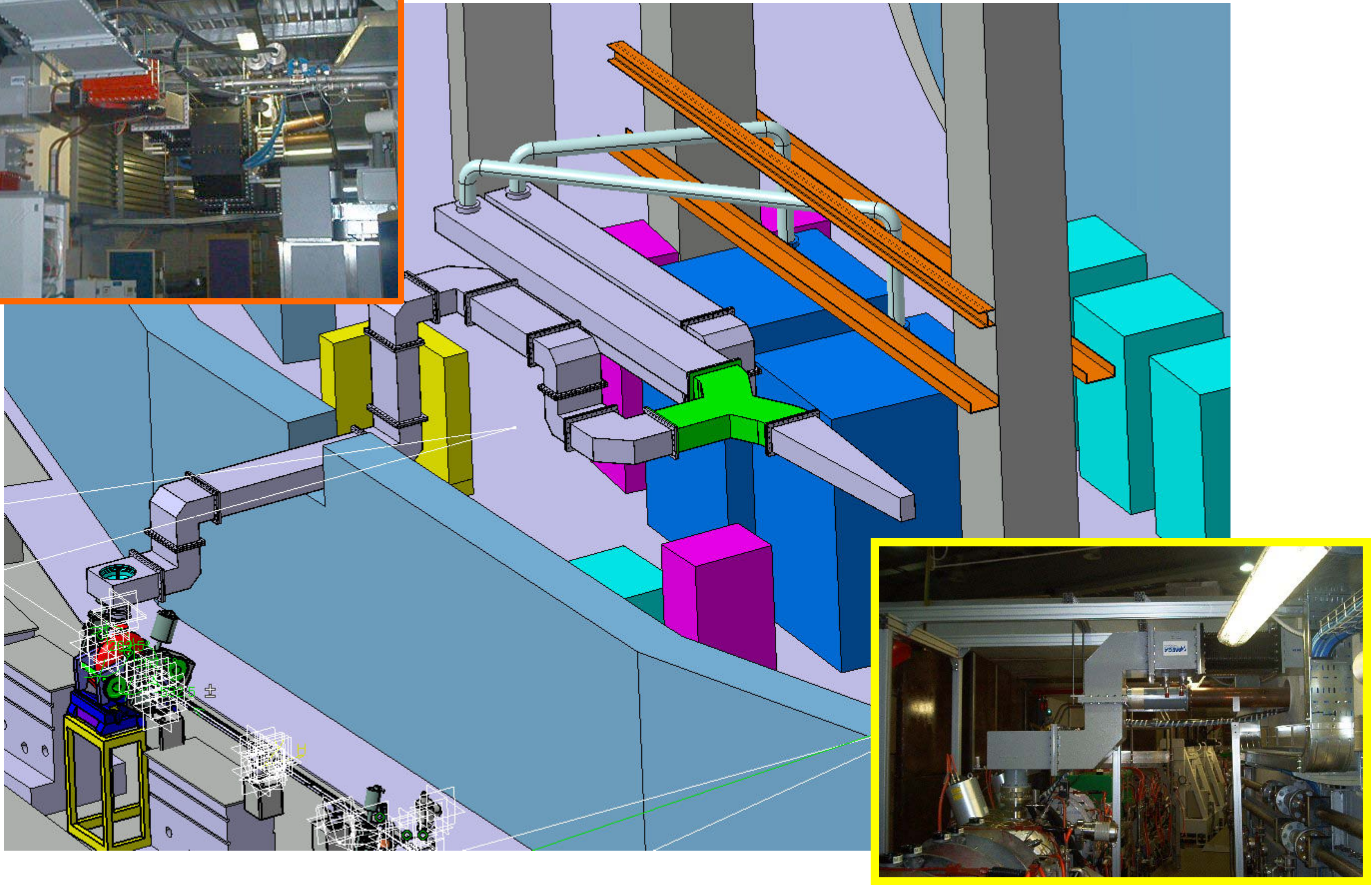
$$S = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$



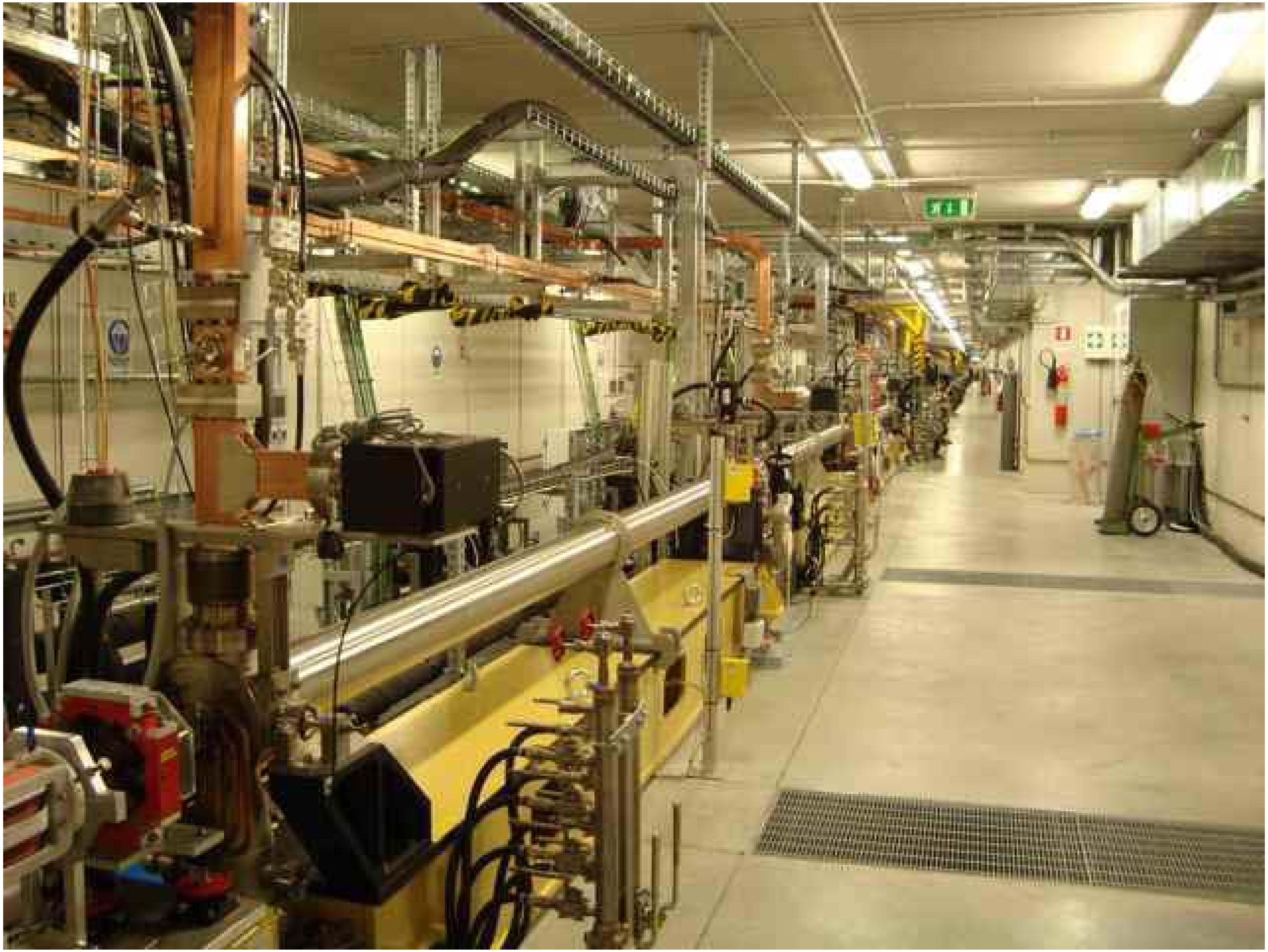


EXAMPLES

Waveguides for the 150 kW 500 MHz cw plant at elettra



EXAMPLES



Waveguides feeding the S-band FERMI linac

SUMMARY

- ✓ Different alternatives are possible for high power generation and transmission.
- ✓ Choice depends on several aspects and there is no unique solutions.
- ✓ Some of the aspects to be considered:
  - Power level
  - Frequency and duty cycle
  - Efficiency
  - Availability of the technology
  - Space
  - ……………..
- ✓ This lecture is just to give a taste of the many technical and scientific aspects involved.
- ✓ Some topics not covered:
  - SLED
  - Power supplies technology
  - Cooling
  - ……….

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Thank you!

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