C4 – RF sources and related technologies

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www.europeanspallationsource.se

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Summary

1. **The function of a RF source on a particle accelerator**
   - General schematics
   - Main components and their functionality
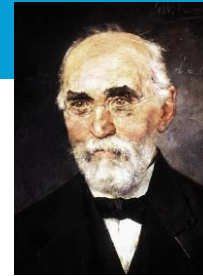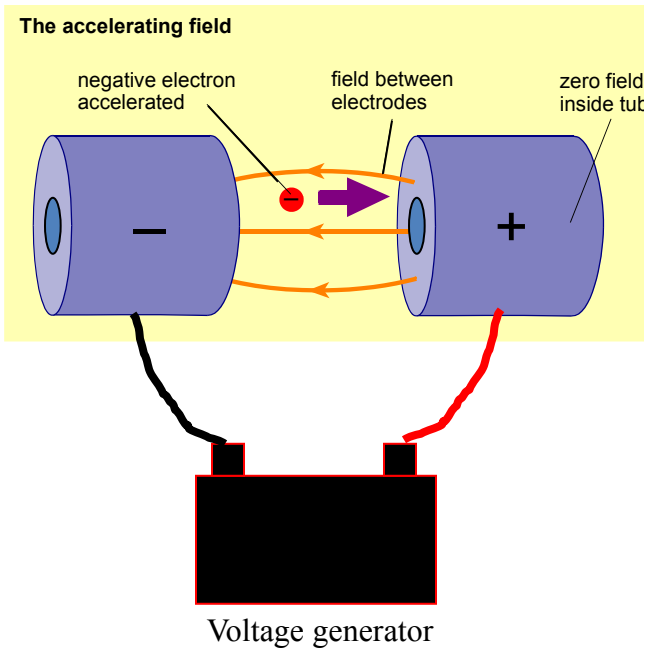2. **Main components of a RF source**
   - The RF amplifiers / generators
     - Klystrons
     - Tetrodes
     - Solid State Amplifiers
   - The modulator
     - CW modulators
     - Pulsed modulators for klystrons and tetrodes
   - RF distribution
     - Waveguides, combiners and splitters
     - Circulators and RF dummy loads
     - RF power couplers
3. **LLRF, controls and interlock systems**
4. **Example: The RF source for the ESS Medium Beta LINAC**

The function of a RF source on a particle accelerator

EUROPEAN SPALLATION SOURCE

1st part of Lorentz's Law

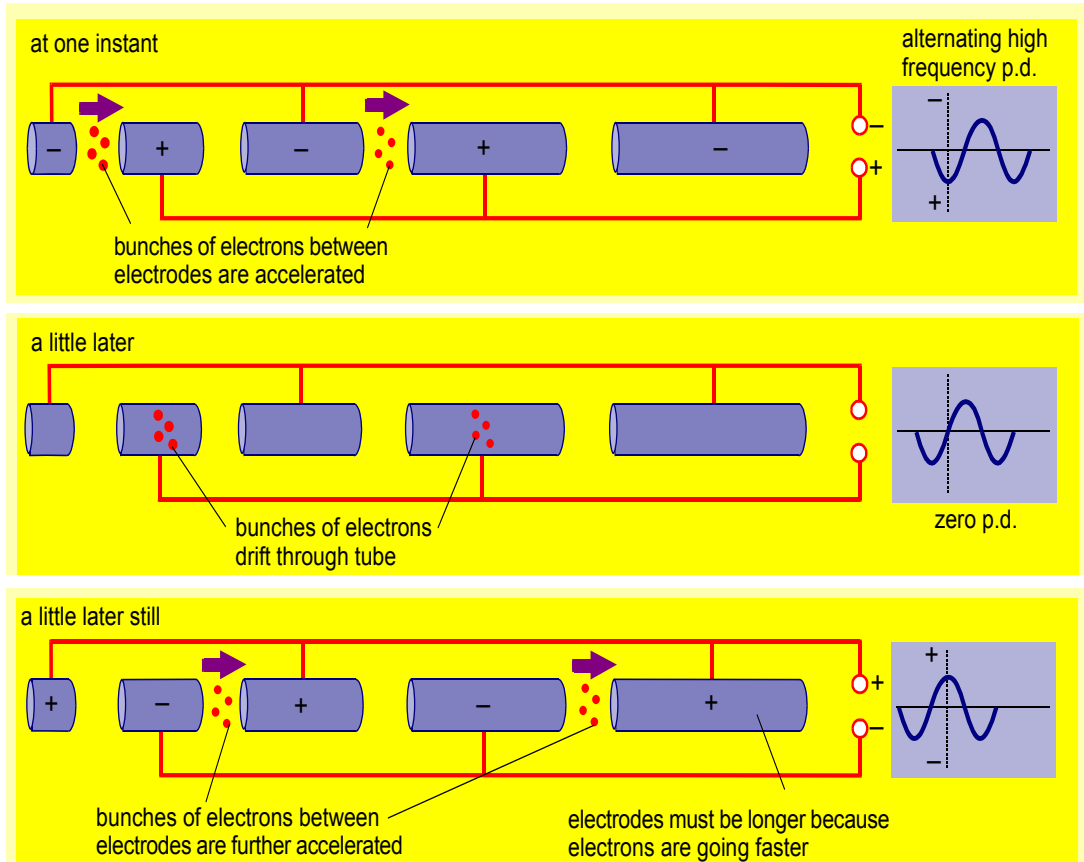$$\vec{F} = q\vec{E} + q(\vec{v} \times \vec{B})$$

Hendrik Lorentz (1853-1928)

The electrical field applied between both electrode plates by the voltage generator accelerates the charged particle in the direction of the field lines
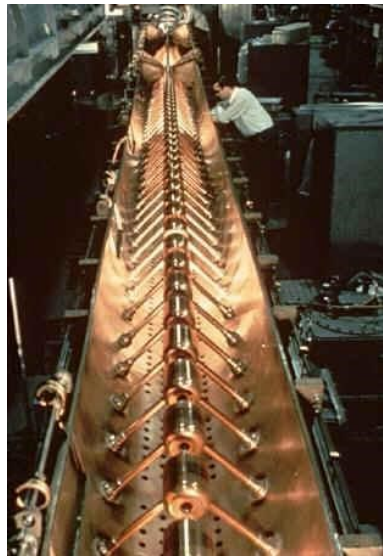
The accelerating field

negative electron accelerated

field between electrodes

zero field inside tube

$-$ $+$

Voltage generator

at one instant

$-$ $+$ $-$ $+$ $-$

bunches of electrons between electrodes are accelerated

alternating high frequency p.d.

a little later

bunches of electrons drift through tube

zero p.d.

a little later still

$+$ $-$ $+$ $-$ $+$

bunches of electrons between electrodes are further accelerated

electrodes must be longer because electrons are going faster

The function of a RF source on a particle accelerator

Drift Tube Linac (DTL)

Bunch of particles

electric field lines

voltage

0 volts

time

gap

drift tube

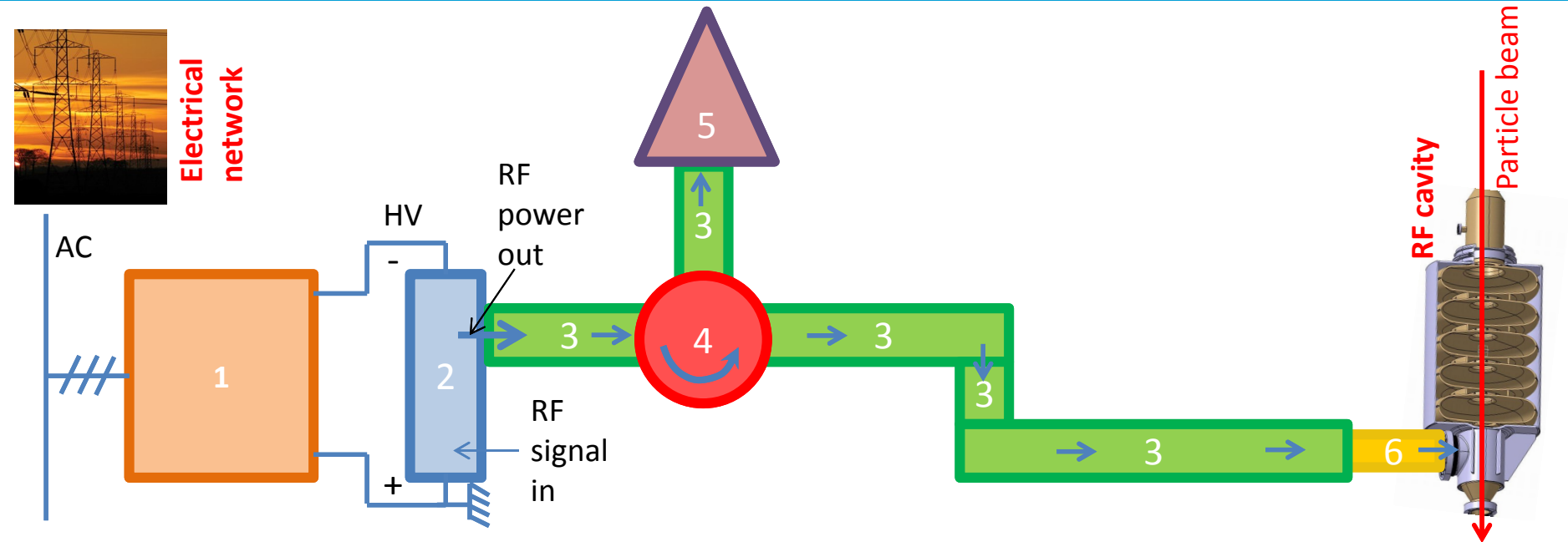**Elliptical RF cavities**
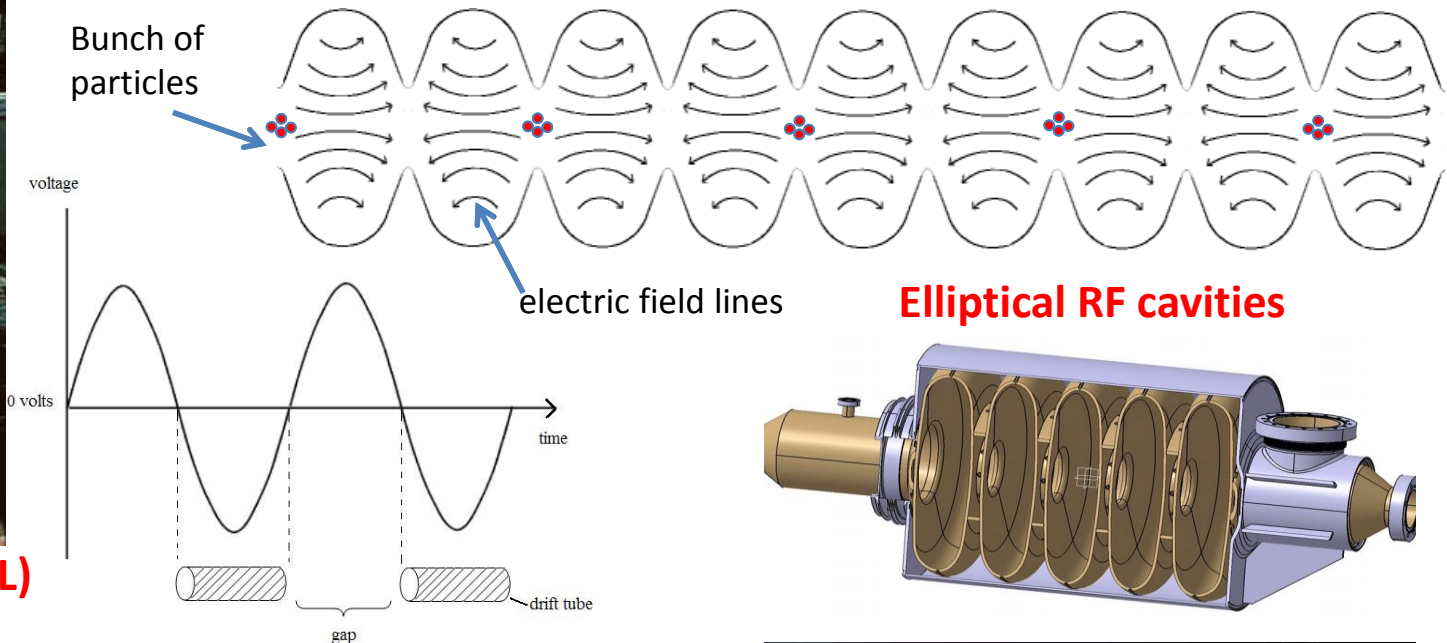
- Radio Frequency (RF) cavities, once excited by RF power, produce high intensity AC electric fields that accelerate the particle beam bunches longitudinally

- RF sources are systems that generate the required RF power and transmit this power down into the RF cavities where the particle beam circulates and will be accelerated

General architecture of a RF source
## - Schematics and main components

1- Modulator (HV power supply)

- Converts the electric power from a standard AC network into High Voltage (HV), either DC (Direct Current) or pulsed, depending on the accelerator duty-cycle (i.e. beam "on" versus beam "off" time) ;

2- RF amplifier (generator)

- Converts electrical power into RF power, by amplifying a low power input RF signal (RF signal in) into a large power electromagnetic wave (RF power out);
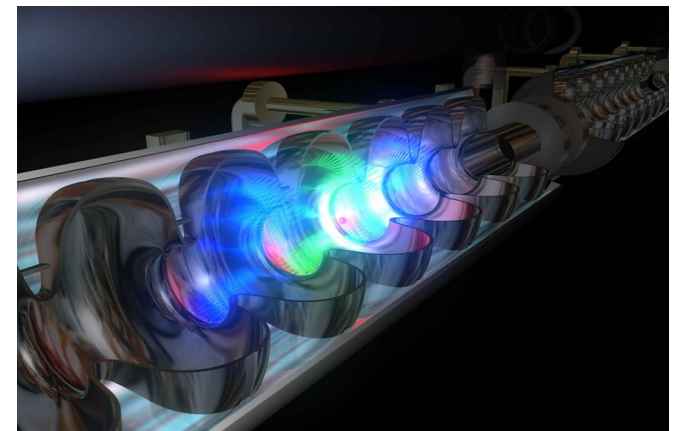
3- Waveguides (Transmission lines)

- Transmit and conduit the RF power from a point A (transmission point) to a point B (receiving point). In terms of function, waveguides are similar to electrical cables transmitting electrical power in a circuit;

4- Circulator

- Prevents any RF reflected power that might come back from the RF cavity to go back to the RF amplifier, harming it. Using a circulator, the impedance seen by the RF amplifier is always matched;

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General architecture of a RF source
- Schematics and main components
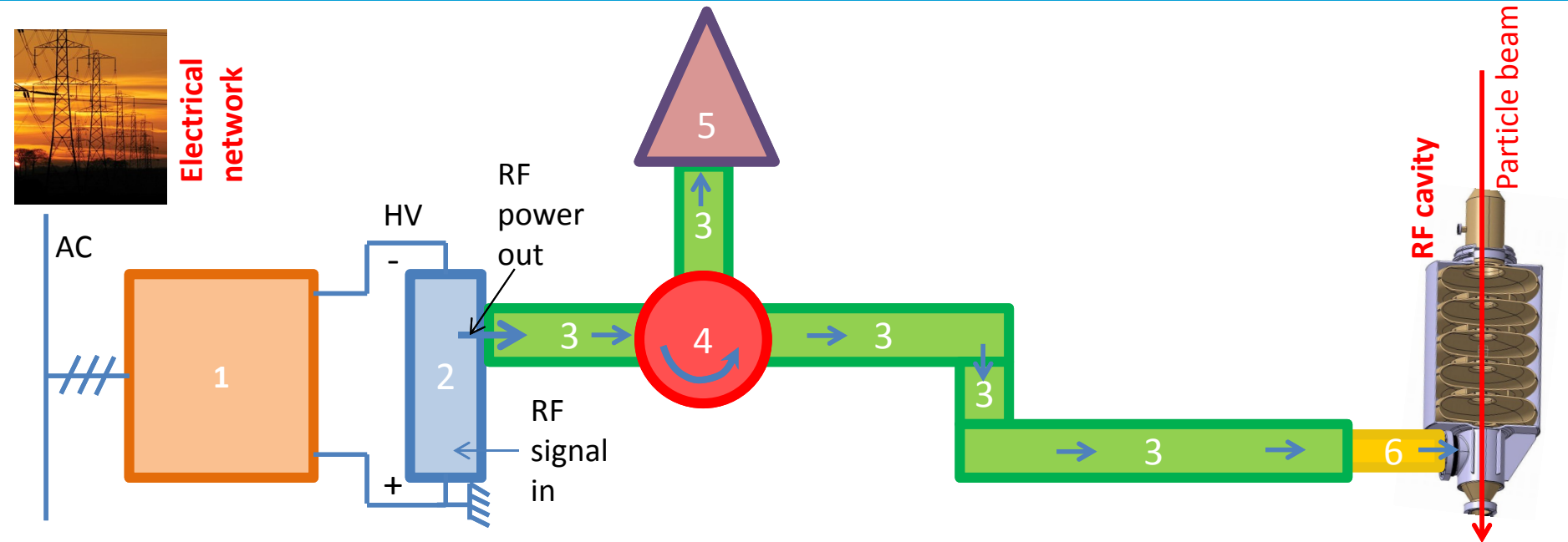
5- RF dummy load
- Absorbs the RF power that might be reflected by the RF cavity, after passing through the circulator;
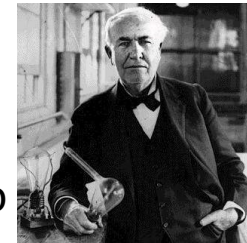
6- Power coupler
- Injects/couples the RF power into the cavity. Matches the impedance of the RF cavity to the characteristic impedance of the RF source, therefore avoiding unnecessary reflections;
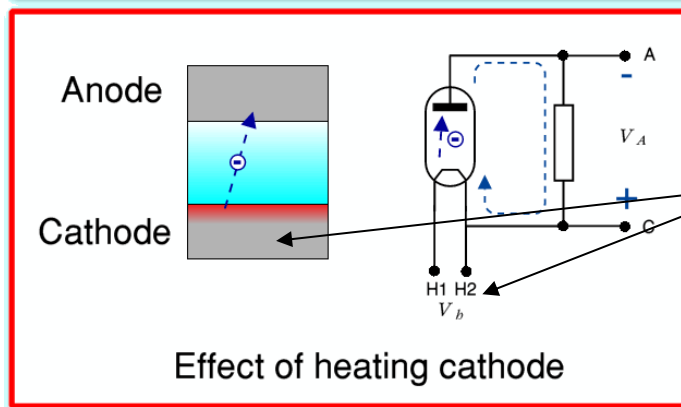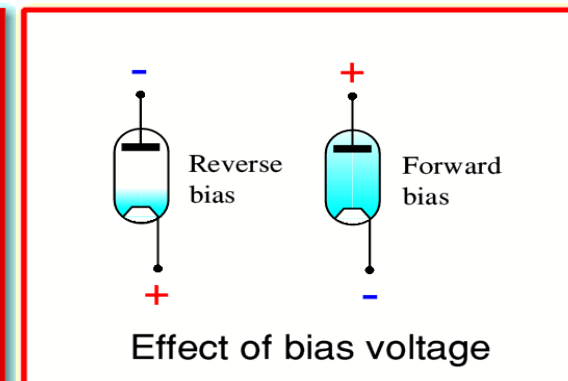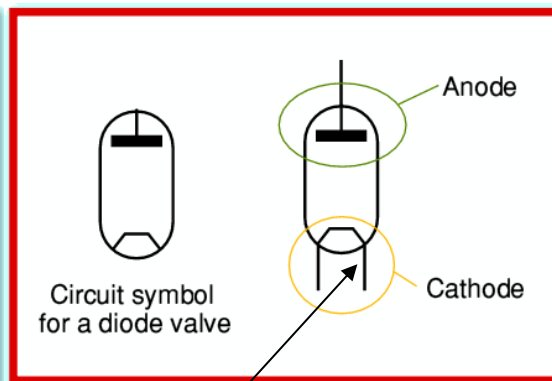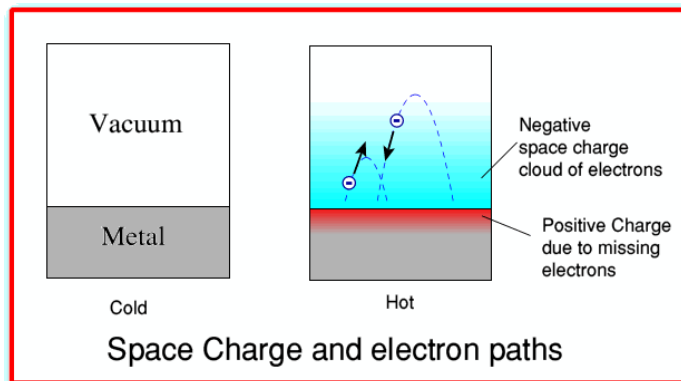
RF Amplifier fundamentals:
- The thermionic effect and the diode valve

- The phenomenon was initially reported in 1873 by [Frederick Guthrie](#) in Britain. While doing work on charged objects, Guthrie discovered that a red-hot iron sphere with a negative charge would lose its charge (by somehow discharging it into air). He also found that this did not happen if the sphere had a positive charge

Thermionic effect

Thomas Edison (1847-1931)

Space Charge and electron paths

Circuit symbol for a diode valve

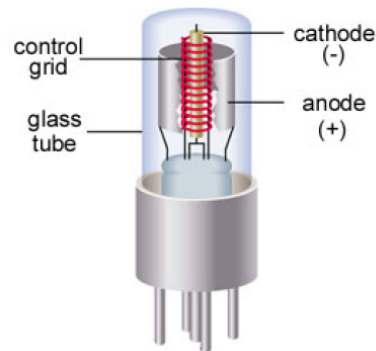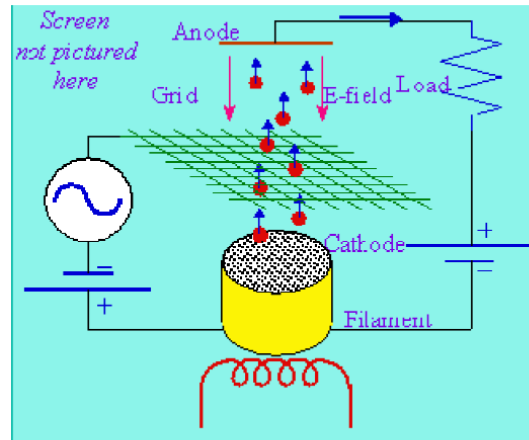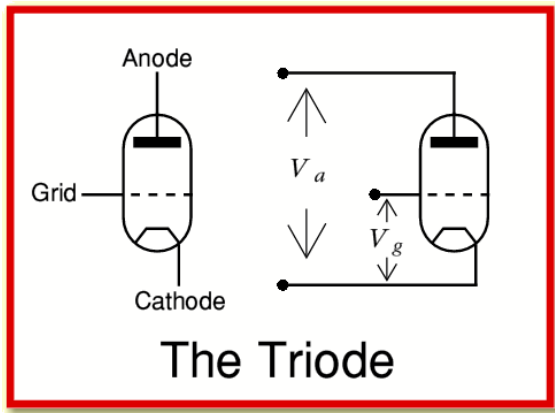Effect of bias voltage

Effect of heating cathode

A filament resistor connected to a power supply heats the cathode

With the cathode hot:
- Reverse bias: no thermionic emission. The electrons are repelled back to the cathode surface by the reverse electric field;
- Forward bias: the thermionic electrons are accelerated by the electric field and flow from the cathode to the anode
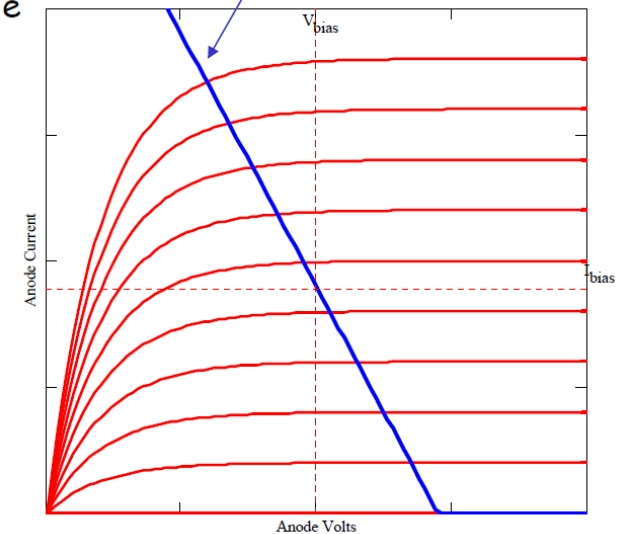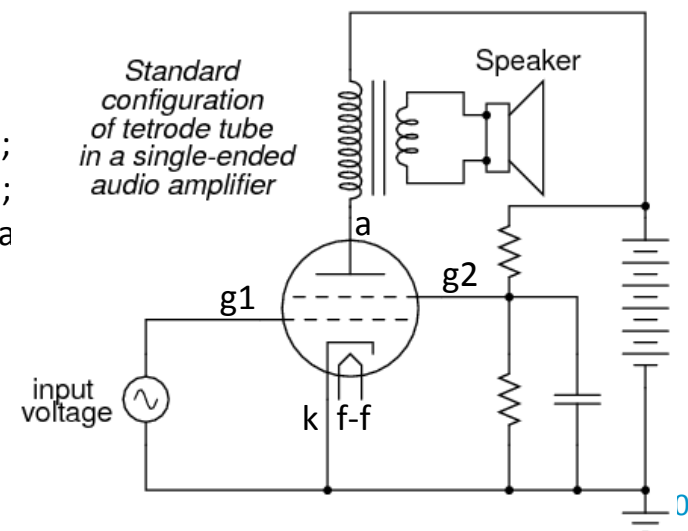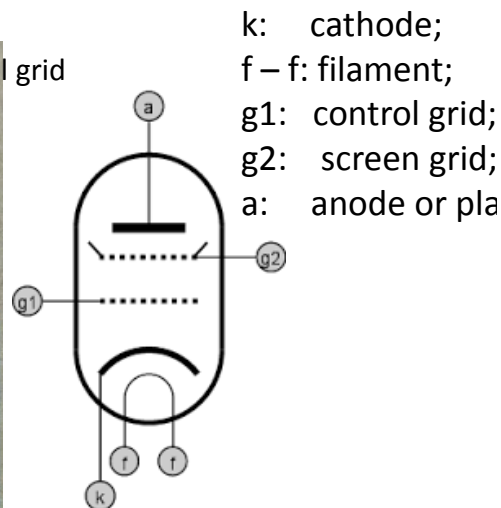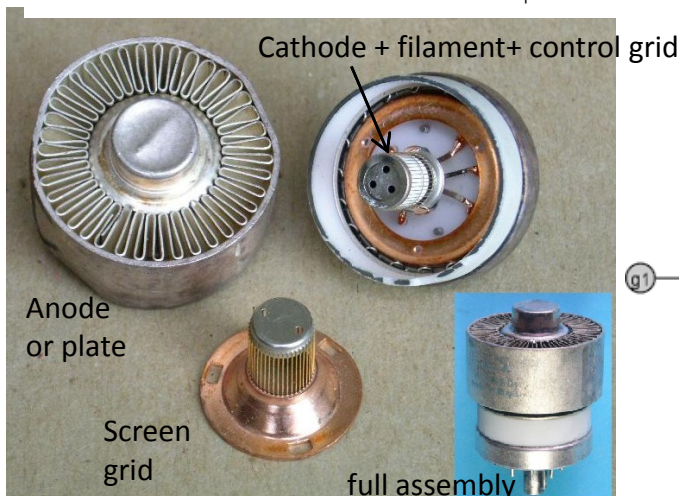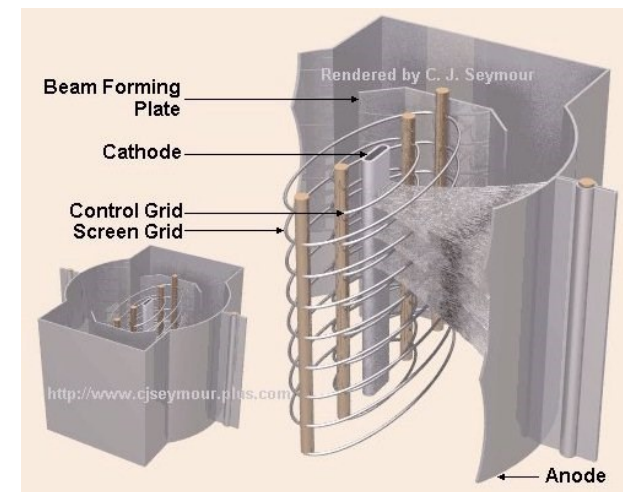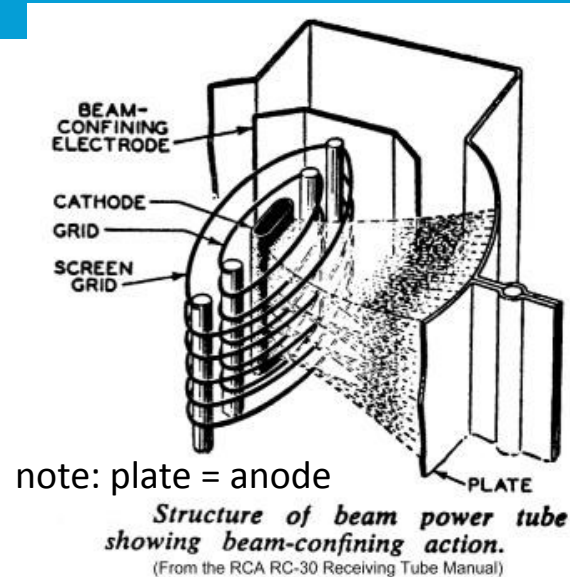
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The Triode

$$I_A = \frac{V_{A_O} - V_A}{R} + I_{A_O}$$

RF Amplifiers:
- The Tetrode

Tetrode

the anode/plate works as an antenna

RF power out

Plaque/Plate

Cathode

Grille-écran/Screen grid

Grille commande/Control grid

heater filament

BEAM-CONFINING ELECTRODE

CATHODE

GRID

SCREEN GRID

PLATE

note: plate = anode

Structure of beam power tube showing beam-confining action.
(From the RCA RC-30 Receiving Tube Manual)

Beam Forming Plate

Cathode

Control Grid
Screen Grid

Rendered by C. J. Seymour

http://www.cjseymour.plus.com

Anode

Cathode + filament+ control grid

Anode or plate

Screen grid

full assembly

k: cathode;
f – f: filament;
g1:   control grid;
g2:   screen grid;
a: anode or plate

a

g2

g1

f   f

k

Standard configuration of tetrode tube in a single-ended audio amplifier

Speaker

a

g2

g1

k   f-f

input voltage

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RF Amplifiers:
- The Tetrode as a RF amplifier

waveguide
RF power out

RF output cavity

tetrode

a

g2

g1

RF signal in

Anode power supply

Filament power supply

U_B k   f   f

Grid bias power suply
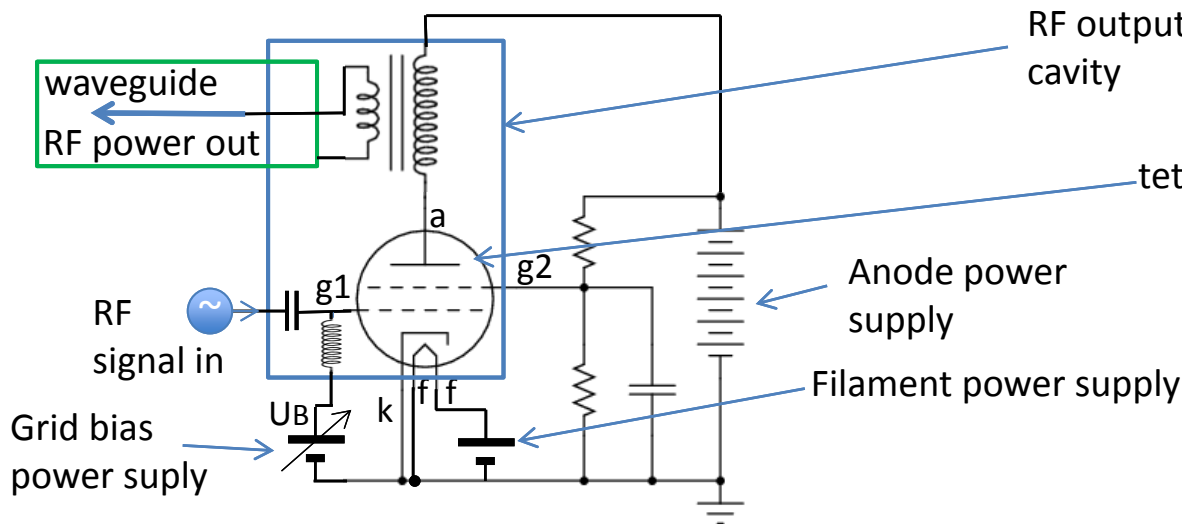
- The anode-plate serves as an antena that radiates RF power into the RF output cavity
- The waveguide collects and transmits the RF power to the load (accelerator RF cavities)
- The control grid g1 is polarised with a DC voltage equal to U_B. The RF input signal is coupled to the control grid via the capacitor

Grid voltage

Electron bunches

U_{B1} U_{B2}

RF in

t(s)

V_{bias}

Anode Current

U_{B1}

V_{bias}

U_{B2}

Anode Volts
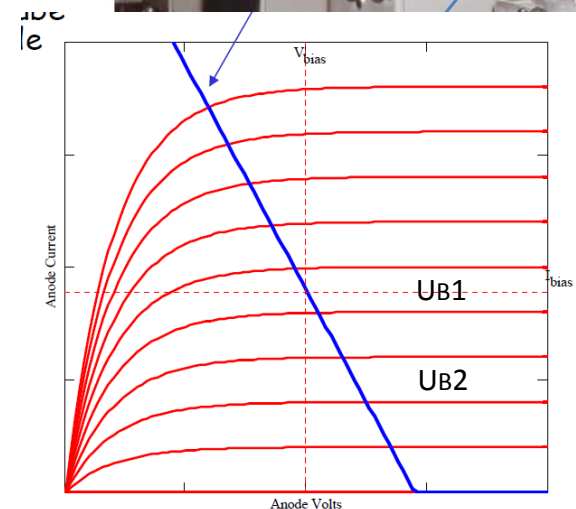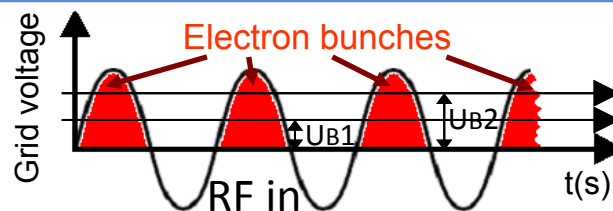
RF Amplifier fundamentals:
- Cavity resonances and principle of RF generation

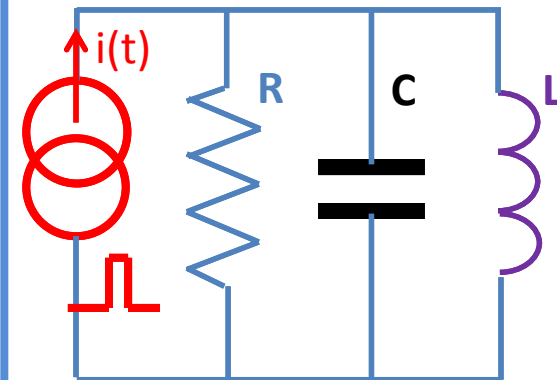$|E|_{axis}(t)$

$i(t)$

→ Electric field lines
↻ Magnetic field lines
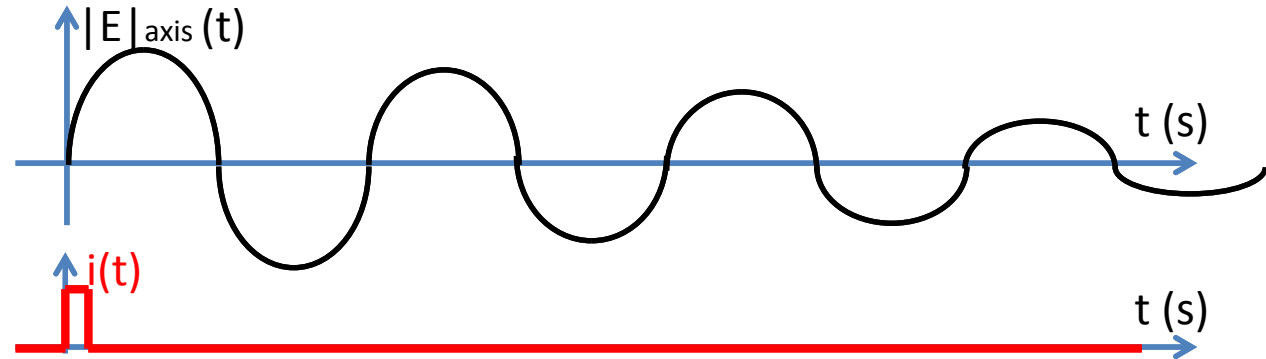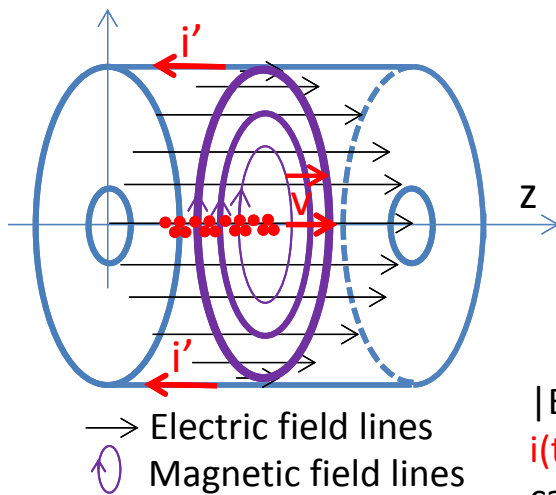
$|E|_{axis}(t)$: amplitude of electric field at the axis/center of the cavity
i(t): current due to the movement of the bunch of particles inside the cavity, along the z axis

- A bunch of particles travel at constant speed, v, along the z axis of the cavity;
- This movement of charged particles generates a current flowing along the z axis in the center of the cavity (i) and induces an image current flowing in the metallic walls of the cavity (i': eddy currents);
- When the particles have completely left the cavity through the output hole, the eddy currents i' remain captured in the cavity and will oscillate at the resonant frequency of the cavity which depends on its geometry;
- As a result, the eddy currents will maintain the magnetic field and electric field lines oscillating over time at the same frequency;
- Due to the non-zero resistivity of the metallic walls, the energy will be lost over time and all these quantities will decay down-to zero;
- The energy lost due to the heat generated by the eddy currents flowing in the cavity walls has been transmitted by the movement of the bunch of particles, therefore the bunch will be slowed down when exiting the cavity
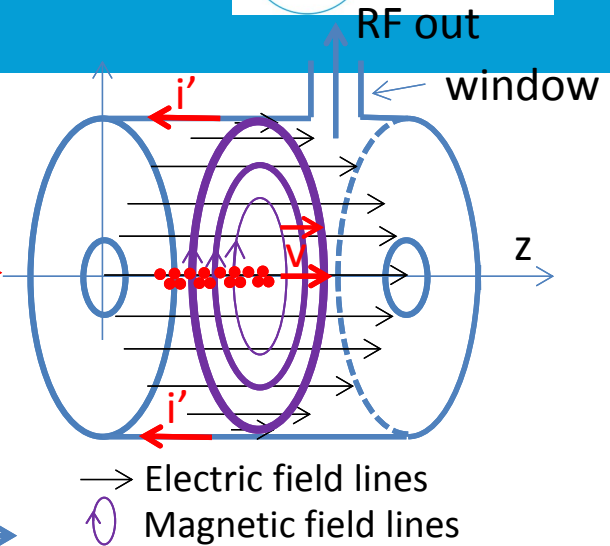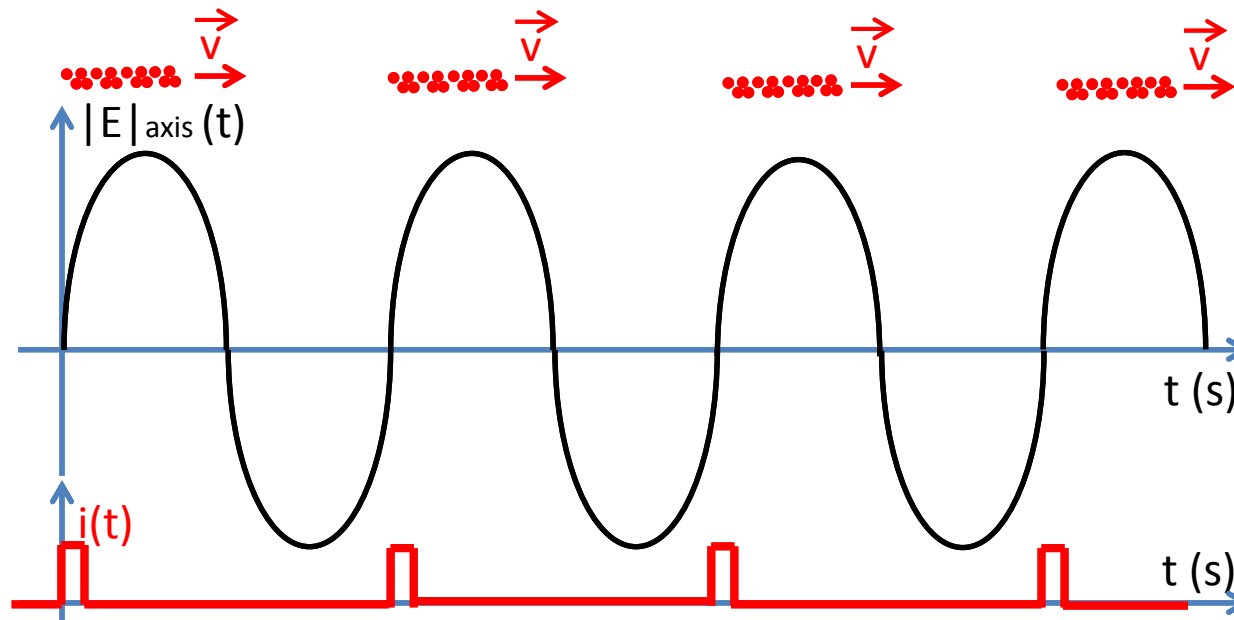
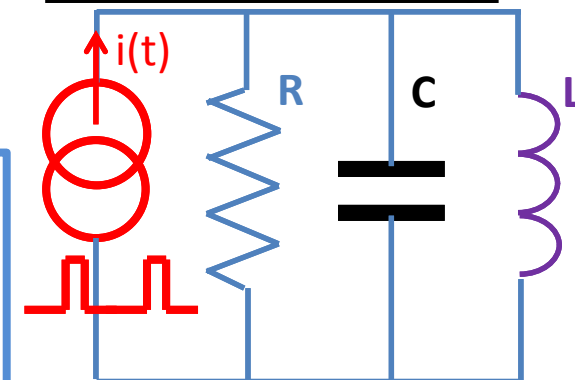## Equivalent electrical model (RLC model of a cavity)

i(t)

R   C   L

Resonant frequency:
$f_0 = 1/(2\pi * \sqrt{LC})$ [12]

EUROPEAN
SPALLATION
SOURCE

RF out

window

$\longrightarrow$ Electric field lines
$\curvearrowleft$ Magnetic field lines

Equivalent electrical model (RLC model of a cavity)

Quality factor:
$$Q = R * \sqrt{C/L})$$

- A continuous bunched beam of particles generates a Continuous Wave (CW) inside the RF cavity that can be collected by an antenna and sent out to a waveguide through a RF window;
- The distance between bunches must be matched with the cavity resonant frequency;
- The generated RF wave can be coupled to an output window and transmitted to an external waveguide;
- This phenomenon is reversible:- if RF wave is coupled in via the window, an electric field is created inside the cavity which can accelerate a bunched beam;

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Velocity modulation resulting in density modulation (bunched beam)

- The filament boils electrons off the cathode;
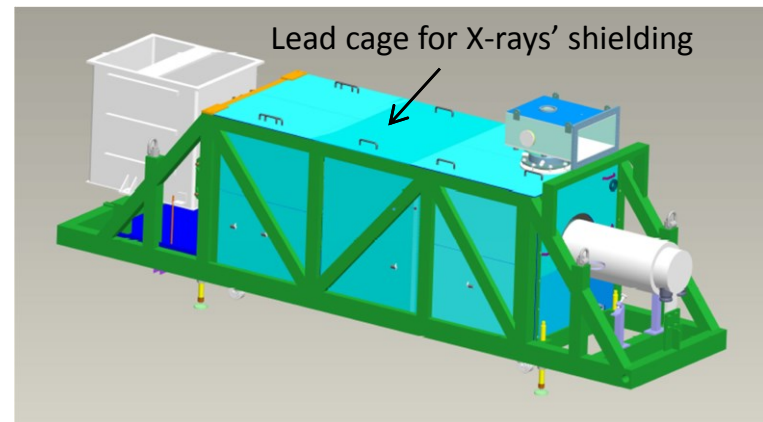- The velocity (or energy) of the electrons is modulated by the input RF in the first cavity;
- The electrons drift to the cathode;
- Because of the velocity modulation, some electrons are slowed down, some are sped up in the 1st cavity;
- If the output (2nd) cavity is placed at the right place, the electrons will bunch up at the output cavity, which will create a high intensity RF field in the output cavity;
- Klystrons need a minimum of two cavities but can have more for larger gain;
- A Klystron size is determined by the size of the bunching cavities;
- Klystrons are used at high frequencies (>500 MHz)

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RF Amplifiers:
- The klystron

Cathode + filament
(= electron gun)

collector

bunching cavities

output RF cavity

gun oil tank (contains filament power supply)

collector jacket
(water cooled)

support frame

RF output waveguide

Lead cage for X-rays' shielding

Solenoid magnet focalizes the beam all along
the klystron tube
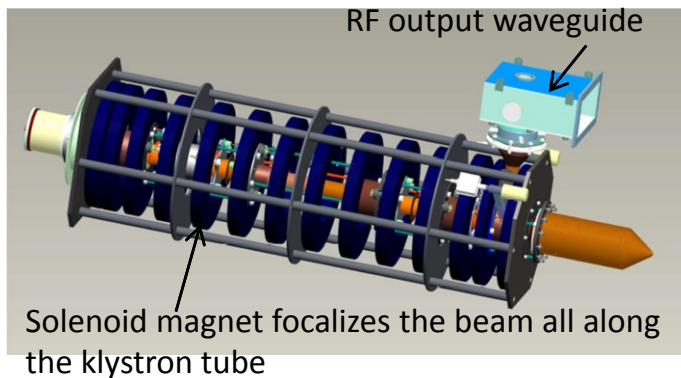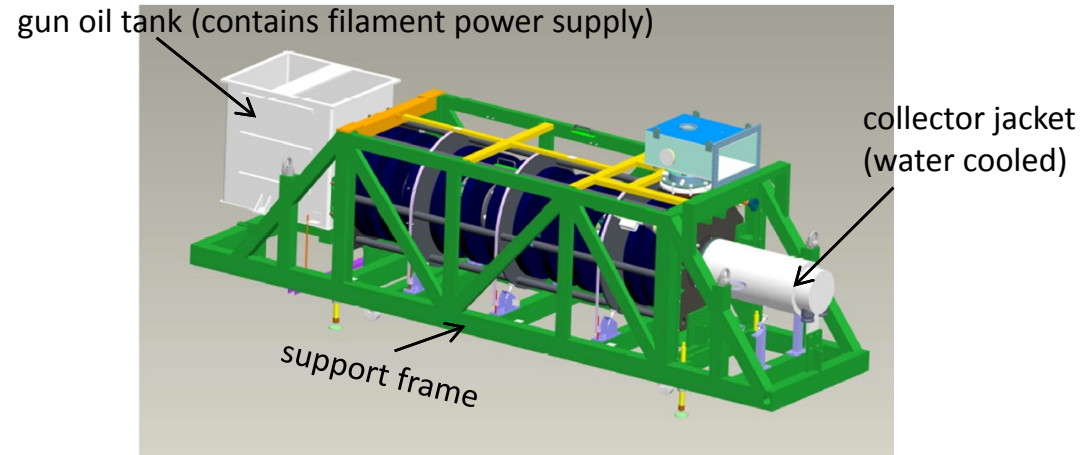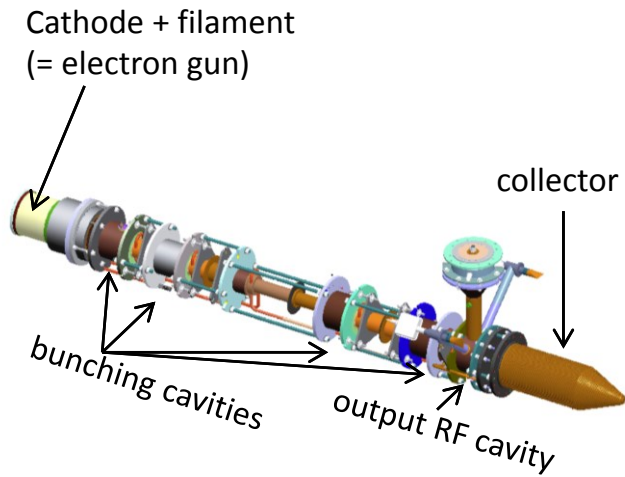
Courtesy Thales Electron Devices

$$I_k = P_v\, U_k{}^{3/2}$$

U_k – Cathode voltage; I_k - beam current; P_v – klystron perveance (const.)
P_k – Electrical power absorbed by the cathode

$$P_k = U_k * I_k = P_v\, U_k{}^{5/2}$$

- The beam current only depends on the cathode voltage;
- The electrical power only depends on the cathode voltage;

Gain as a function of cathode voltage

RF power out (MW)

nominal operating point

saturation point

Uk = -110kV
Uk = -106kV
Uk = -103kV
Uk = -96kV
Uk = -90kV

1.5
1
0.5

RF drive in (W)

10   20   30
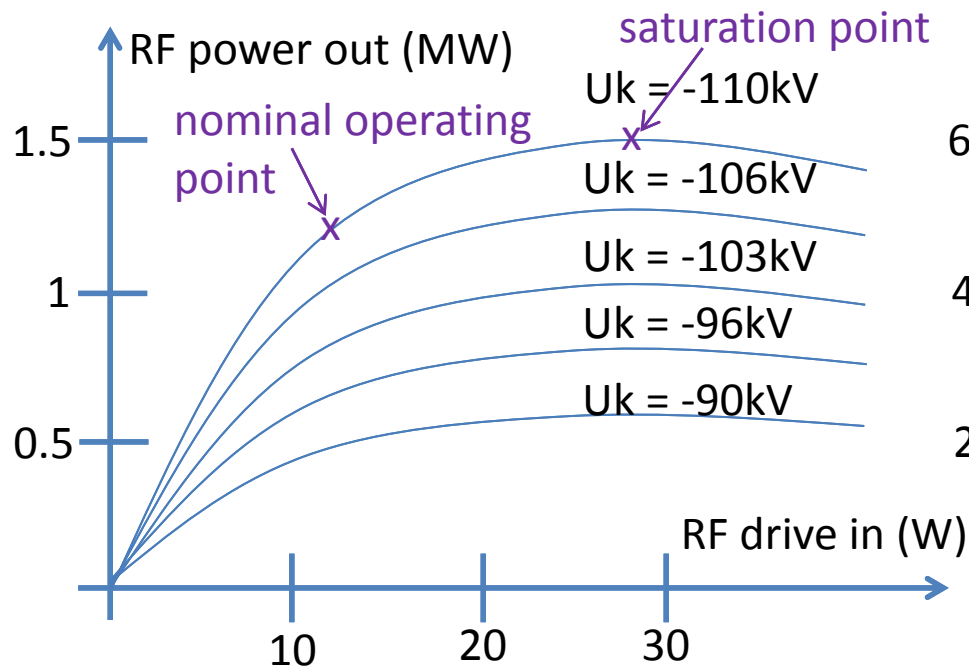
Efficiency as a function of RF power

Efficiency (%)

Uk = -110kV

66
44
22

saturation point

nominal operating point

RF drive in (W)

10   20   30
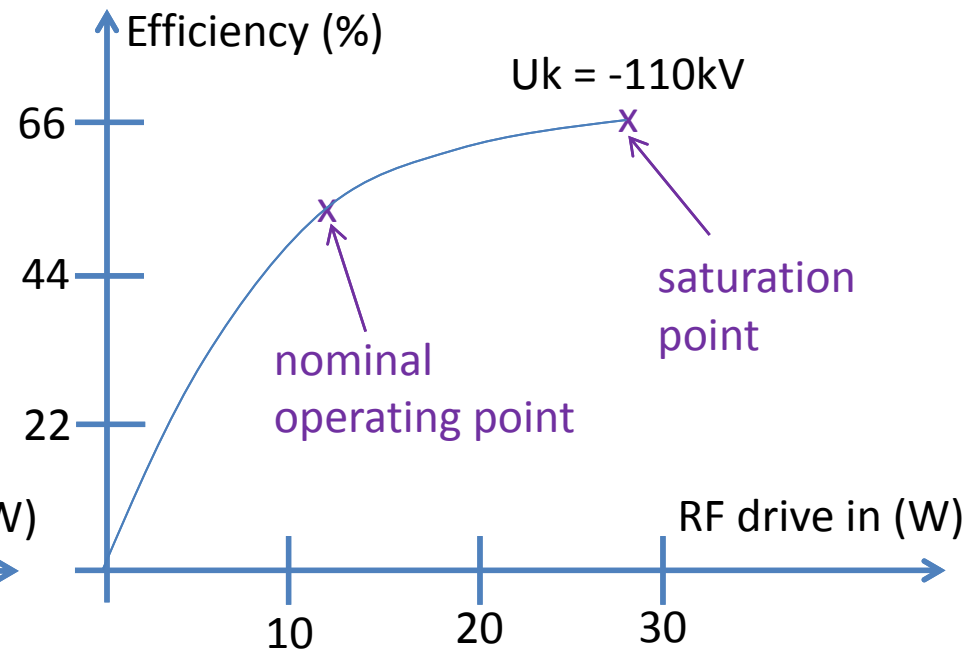
Efficiency = RF power out / Electrical power in
(drops when operating below saturation point) 16

RF Amplifiers:
- Solid State Amplifiers (SSA's)

- One RF MOSFET is used in a module to form a RF amplifier cell;
- RF MOSFET's are presently limited to 1kW per device, therefore combination of several modules is required for larger power sources;
- Each module is fed by a low voltage (50V) power supply, Vcc, therefore no need for high voltage power supplies;
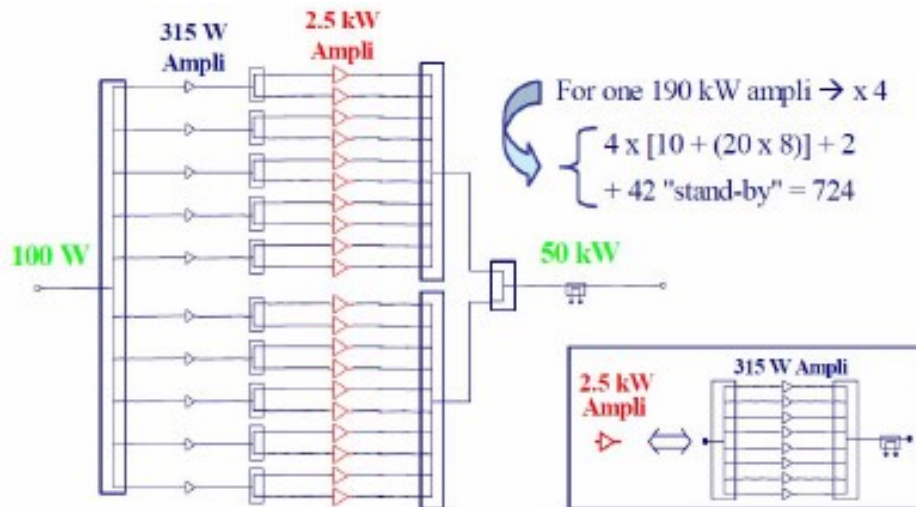- The auxiliary power supplies used in vacuum tubes are not required;
- The efficiency is typically in the order of 60%

330 W amplifier module

600 W, 300 Vdc / 30 Vdc converter

315 W Ampli   2.5 kW Ampli

For one 190 kW ampli → x 4

4 x [10 + (20 x 8)] + 2
+ 42 "stand-by" = 724

100 W   50 kW

2.5 kW Ampli   315 W Ampli
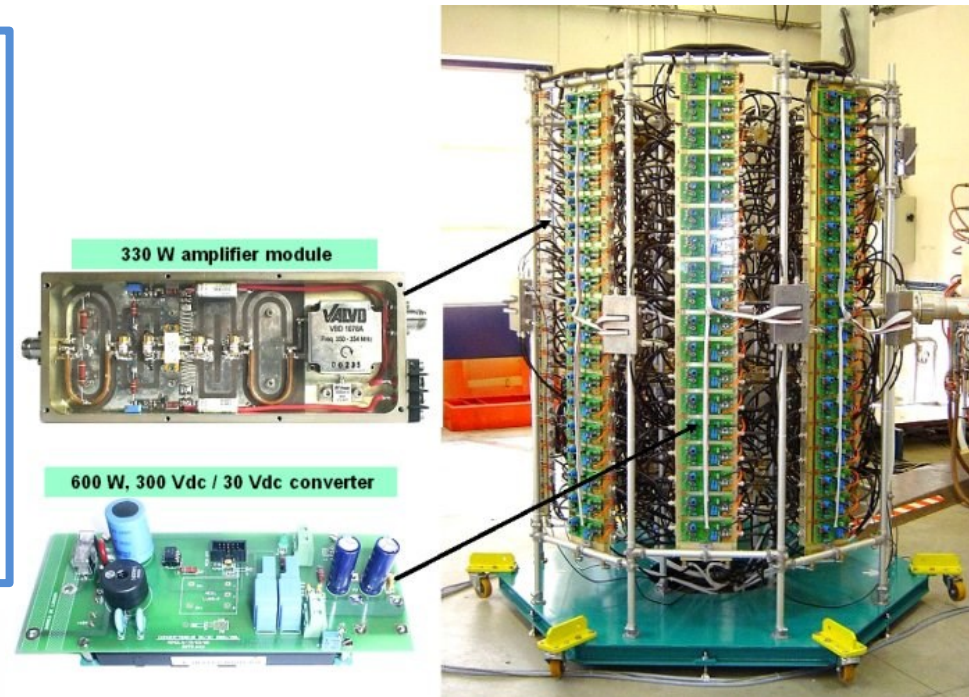
Schematics of one RF Mosfet amplifier

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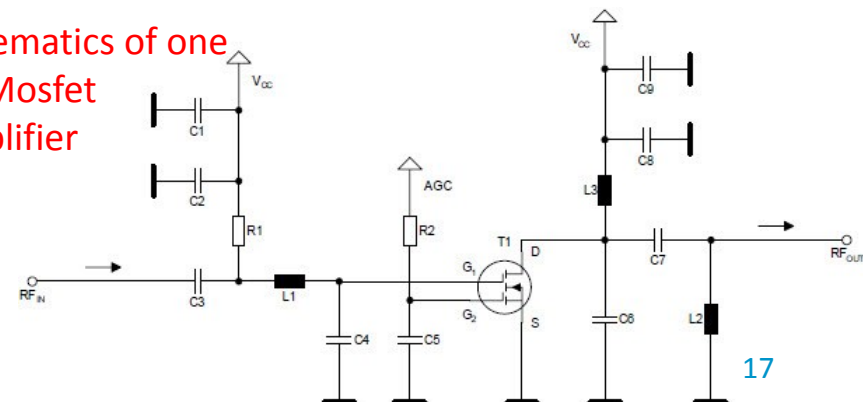
RF Amplifiers:
- Technology comparison

Tetrodes:

- Gridded tube. The grid is fragile; limits lifetime to ~20'000 h;

- Power below 2MW; Frequency below 300MHz;

- Efficiency ~65%, independent of operating power level;

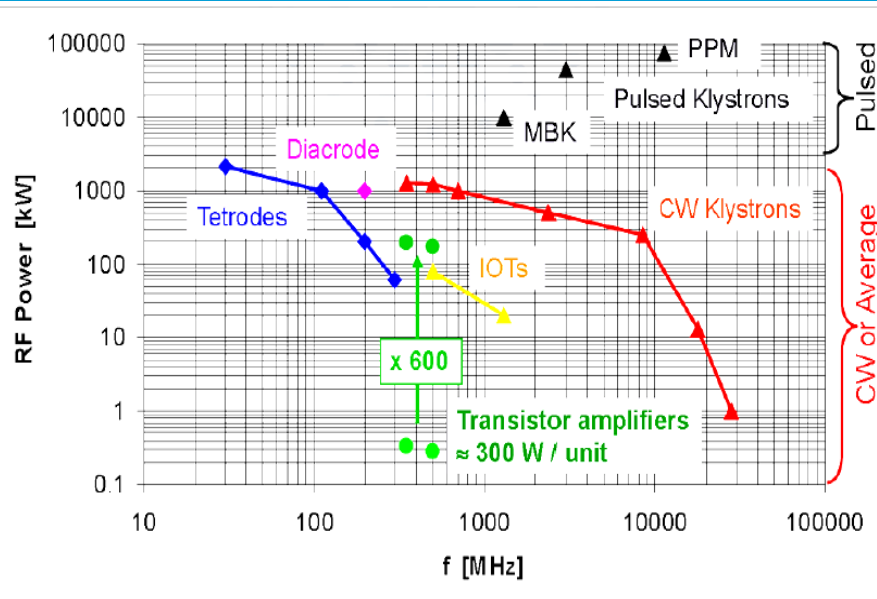- Short/compact tube;

Klystrons:

- Grid free tube. Increased robustness and lifetimes >~50'000 h;

- Power up-to 1.5MW; Frequency up-to 30GHz;

- Limited efficiency ~60%, strongly reduced when reducing the operating power level;

- Long/heavy tube due to the need for the bunching drift tube;

Variants: Diacrode, IOT, Multi Beam Klystron (MBK)

Solid State (Transistor) amplifiers:

- No need for: vacuum, HV power supplies, auxiliaries (filament heater);

- Power below 100kW; Frequency below 1GHz;

- Good efficiency ~60%, independent from the operating power level;

- Reliability/lifetime is a concern (recent technology, not well proven yet);

• A CW modulator is generally just a High Voltage power supply that feeds:- the Anode of tetrodes or the Cathode of klystrons, etc;
• Depending on the type of HV power supply a CROWBAR might be needed to bypass the current in case an arc occurs in the RF amplifier tube

AC electrical network

100 kV crowbar (Thyratron)

Klystron

A - Anode;
C - Collector;
K - Cathode;
F - Filament
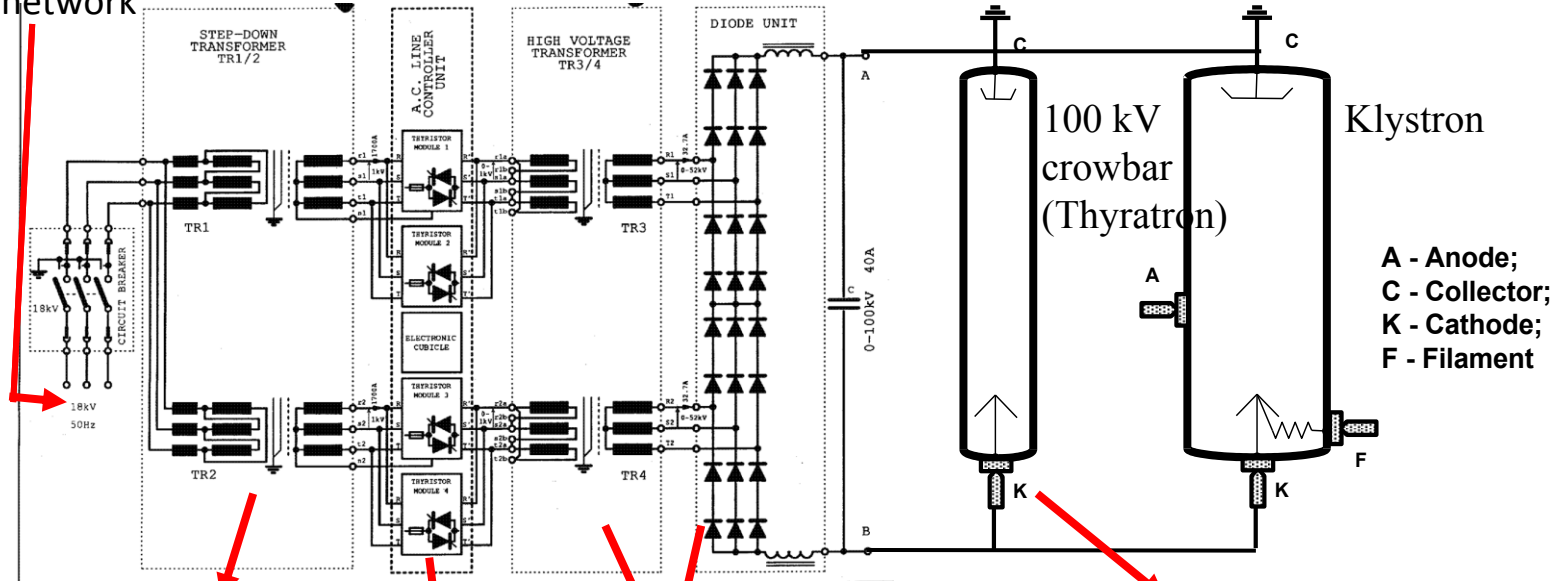
Thyratron CROWBAR

Modulators:
- Pulsed modulators for klystrons

PS1, PS3, PS4 - Commercial
PS2 - CERN made
——— **120 kV High voltage cables**
▯ **120 kV High voltage connectors**

Simplified schematics

Anode power converter, PS3

Filament power converter, PS4

Hign Frequency ISOLATION TRANSFORMER

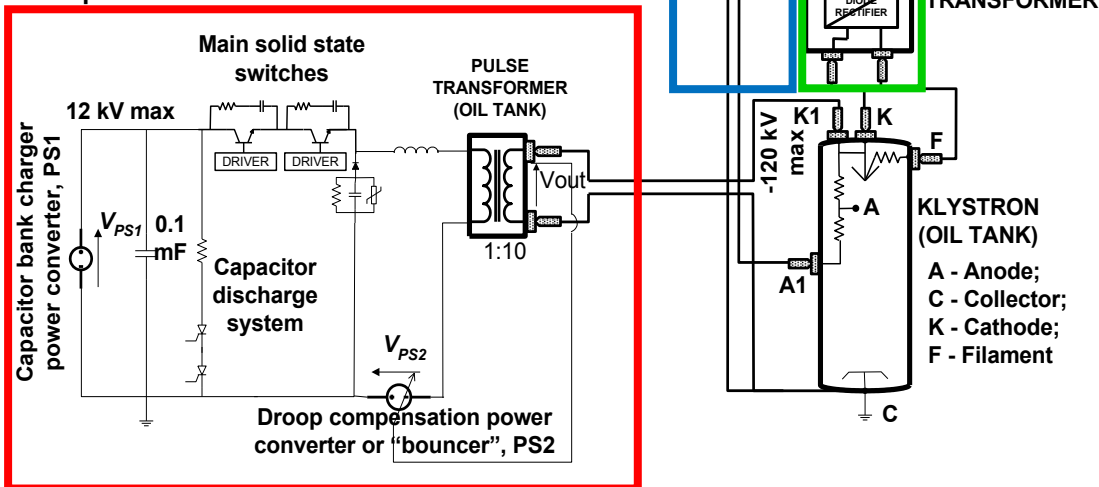**Main solid state switches**

PULSE TRANSFORMER (OIL TANK)

12 kV max

Capacitor bank charger power converter, PS1

DRIVER DRIVER

V_{PS1} **0.1 mF**

Capacitor discharge system

1:10 Vout

V_{PS2}

Droop compensation power converter or "bouncer", PS2

-120 kV max

KLYSTRON (OIL TANK)

K1 K F
A
A1
C

A - Anode;
C - Collector;
**K - Cathode;**
F - Filament

100 kV, 20A, 0.8ms, 2 Hz

• The power absorbed by the klystron during the pulse cannot be delivered by the electrical network;
• A capacitor bank is required to store the energy that will be given to the klystron during the pulse (buffer);
• A capacitor charger charges the capacitor bank before the pulse is generated. It is fed from the AC network;
• The pulse is formed by switching "on" and "off" the main solid state switch, therefore connecting/disconnecting the capacitor bank to the primary side of the pulse transformer;
• The pulse transformer steps-up the voltage to the value required by the klystron cathode;
• A droop compensation system is required to keep the voltage flat over the entire duration of the pulse despite the fact that the voltage across the capacitor bank droops down by 5 to 15% (discharge during the pulse);
• No HV crowbar is needed. In case of arcing in the klystron, the main solid state switch is opened in less than 10µs

Modulators:
- Pulsed modulators for Tetrodes
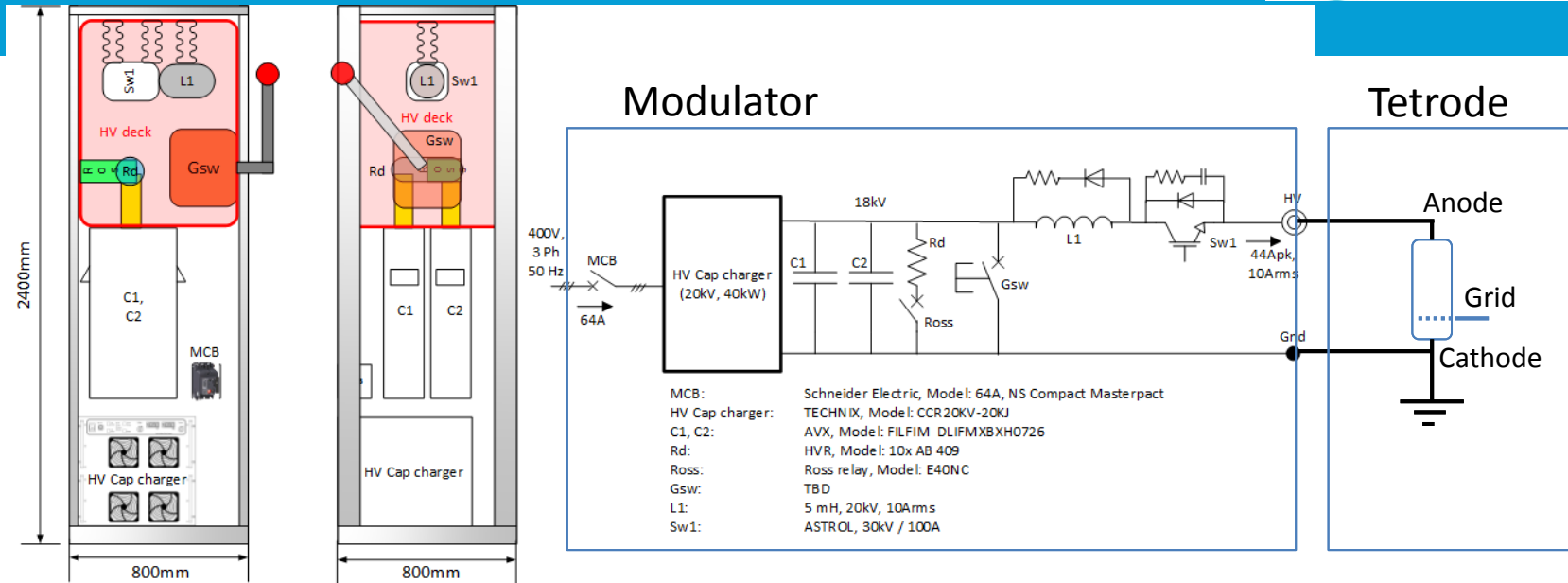
- Tetrodes are gridded tubes, therefore the pulsed power can be generated by pulsing the grid terminal using the RF input driver ;
- In that case, the Anode can be permanently connected to a HV source formed by a HV capacitor charger and a capacitor bank (C1 and C2);
- The series switch, Sw1, is always at "on" state in normal operation. Only in case of an arc in the tetrode, the series switch Sw1 is switched "off", therefore lowering the voltage across the Anode down to zero clearing the arc.
- When the RF input driver is switched "on", the current starts flowing from Anode to Cathode, initiating the pulse;
- During the pulse, the energy flows from the capacitor bank to the tetrode, discharging partially the capacitor bank (by ~5%);
- The capacitor bank is recharged after the pulse has finished and before the next pulse starts;

RF distribution:
- Waveguides

- Waveguides are transmission lines that transmit RF waves from the emitter to the receiver points;
- Propagation of waves
  - **TE waves**: Transverse electric waves, also sometimes called H waves, are characterized by the fact that the electric vector (E) is always perpendicular to the direction of propagation.
  - **TM waves**: Transverse magnetic waves, also called E waves are characterized by the fact that the magnetic vector (H vector) is always perpendicular to the direction of propagation.
- Waveguides can only transmit waves having frequencies above their cut-off frequency, f_c;
- In rectangular waveguides, the height (h) is equal to half of the width (a) (i.e. h=1/2a, full height) or to one quarter of the width (i.e. h=1/4a, half height);
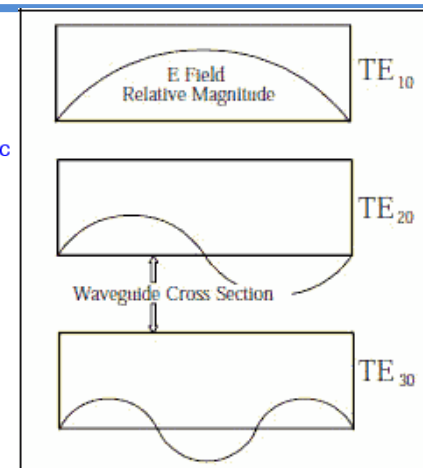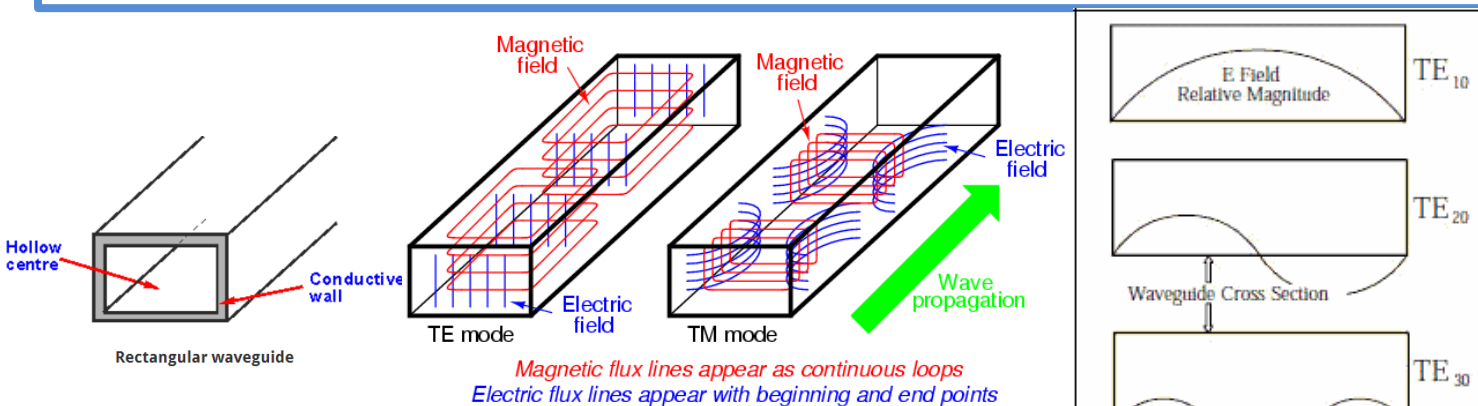- The attenuation per length defines how much RF power is lost per meter of length (in dB)

Magnetic flux lines appear as continuous loops
Electric flux lines appear with beginning and end points

Figure 2. TE modes

- TE_{10} mode: a = λ/2;
- TE_{20} mode: a = λ;
- TE_{30} mode: a = 3/2 λ;

λ is the wavelength
f is the wave frequency
λ = c / f

Cut off frequency of rectangular waveguides:

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

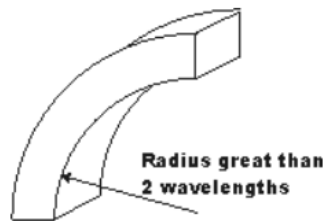*c* is the speed of light; *a* is the width of the rectangular waveguide

For effective transmission in TE$_{10}$ mode:
$$f > {\sim}1.25 * f_c$$
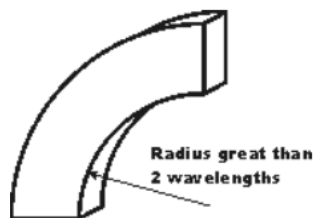
RF distribution:
- Waveguides

Standard waveguides – WG type

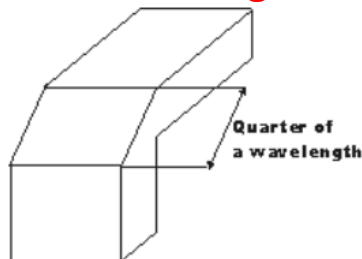| WG DESIGN	FREQ RANGE*	WAVEGUIDE CUT OFF *	THEORETICAL ATTN DB / 30M	MATERIAL	BAND	WAVEGUIDE DIMENSIONS (MM)
WG00	0.32 - 0.49	0.256	0.051 - 0.031	Alum	B	584 x 292
WG0	0.35 - 0.53	0.281	0.054 - 0.034	Alum	B,C	533 x 267
WG1	0.41 - 0.625	0.328	0.056 - 0.038	Alum	B,C	457 x 229
WG2	0.49 - 0.75	0.393	0.069 - 0.050	Alum	C	381 x 191
WG3	0.64 - 0.96	0.513	0.128 - 0.075	Alum	C	292 x 146
WG4	0.75 - 1.12	0.605	0.137 - 0.095	Alum	C,D	248 x 124
WG5	0.96 - 1.45	0.766	0.201 - 0.136	Alum	D	196 x 98
WG6	1.12 - 1.70	0.908	0.317 - 0.212	Brass	D	165 x 83
WG6	1.12 - 1.70	0.908	0.269 - 0.178	Alum	D	165 x 83
WG7	1.45 - 2.20	1.157			D,E	131 x 65
WG8	1.70 - 2.60	1.372	0.588 - 0.385	Brass	E	109 x 55
WG8	1.70 - 2.60	1.372	0.501 - 0.330	Alum	E	109 x 55
WG9A	2.20 - 3.30	1.736	0.877 - 0.572	Brass	E,F	86 x 43
WG9A	2.20 - 3.30	1.736	0.751 - 0.492	Alum	E,F	86 x 43
WG10	2.60 - 3.95	2.078	1.102 - 0.752	Brass	E,F	72 x 34
WG10	2.60 - 3.95	2.078	0.940 - 0.641	Alum	E,F	72 x 34
WG11A	3.30 - 4.90	2.577			F,G	59 x 29
WG12	3.95 x 5.85	3.152	2.08 - 1.44	Brass	F,G	48 x 22
WG12	3.95 x 5.85	3.152	1.77 - 1.12	Alum	F,G	48 x 22
WG13	4.90 - 7.05	3.711			G,H	40 x 20
WG14	5.85 - 8.20	4.301	2.87 - 2.30	Brass	H	35 x 16
WG14	5.85 - 8.20	4.301	2.45 - 1.94	Alum	H	35 x 16
WG15	7.05 - 10.0	5.26	4.12 - 3.21	Brass	I	29 x 13
WG15	7.05 - 10.0	5.26	3.50 - 2.74	Alum	I	29 x 13

WG waveguide dimensions, sizes and waveguide cut-off frequencies for rigid rectangular RF waveguides
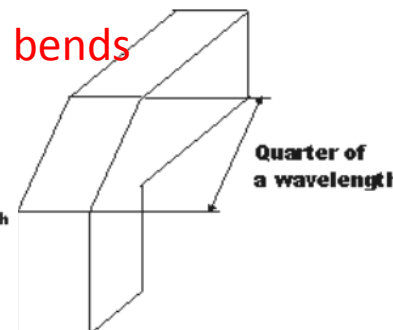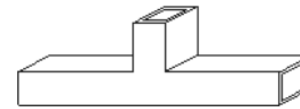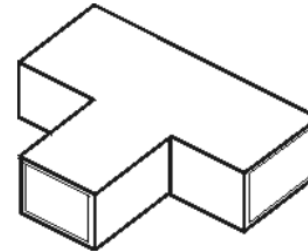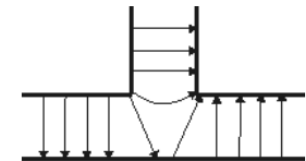
Waveguide junctions

Waveguide E-type junction

Waveguide E-type junction E fields

× Indicates electric field line coming out of screen

Waveguide H-type junction

Waveguide H-type junction electric fields

No signal

Signal in

Magic T waveguide junction signal directions

Waveguide bends

Radius great than 2 wavelengths

Waveguide E bend

Radius great than 2 wavelengths

Waveguide H bend

Quarter of a wavelength

Waveguide sharp E bend

Quarter of a wavelength

Waveguide sharp H bend

Signal in

No signal

RF distribution:
- Circulators and RF dummy loads

Forward power Reflected power

waveguide

RF amplifier

Without circulator / RF dummy load

RF cavity

RF dummy load

Forward power Reflected power

RF amplifier

With circulator / RF dummy load
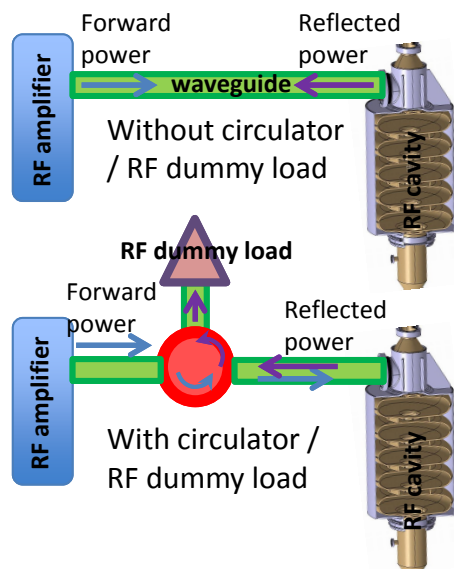
RF cavity

Function:

- Mismatches on the RF cavity impedance might originate reflected power that might damage the RF amplifier;
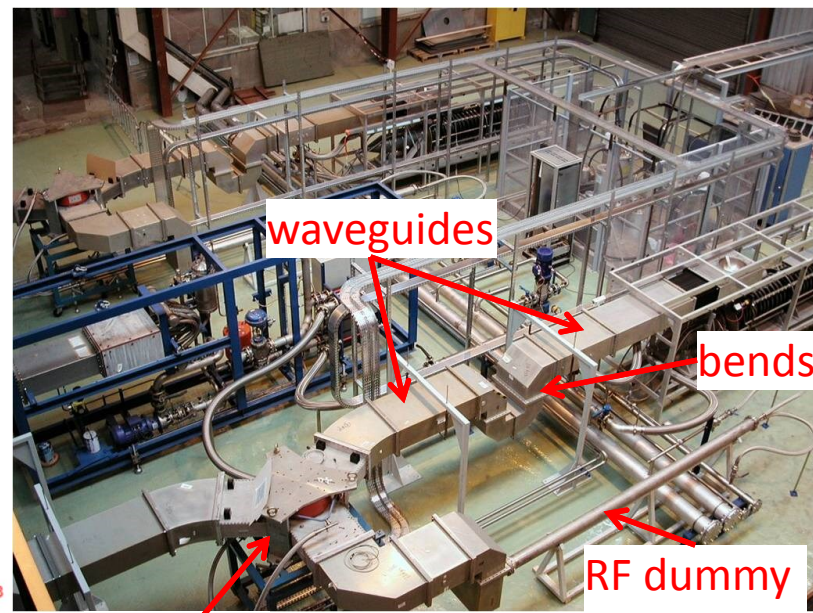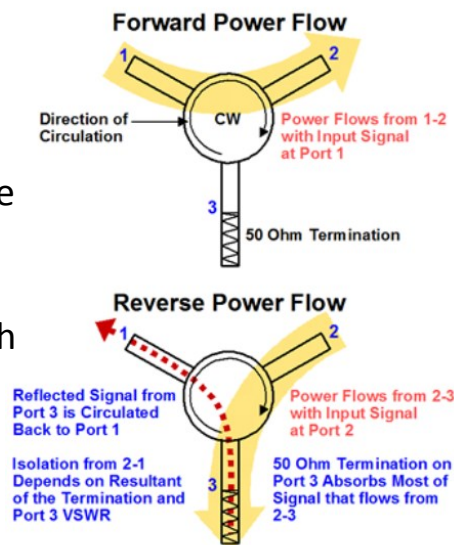- The association of a circulator and a RF dummy load, placed between the amplifier and the RF cavity deviates this reflected power to the dummy load where it will be dissipated;
- The RF dummy load can be a pipe filled with salt water or a ferrite based absorber

- The circulator is formed by a ferrite magnet with anisotropic properties. Once magnetised, the ferrites will provide low impedance in one direction of wave propagation and a very high impedance in the opposite direction (i.e. like a round about in a road)

Forward Power Flow

Direction of Circulation

CW

Power Flows from 1-2 with Input Signal at Port 1

50 Ohm Termination

Reverse Power Flow

Reflected Signal from Port 3 is Circulated Back to Port 1

Power Flows from 2-3 with Input Signal at Port 2

Isolation from 2-1 Depends on Resultant of the Termination and Port 3 VSWR

50 Ohm Termination on Port 3 Absorbs Most of Signal that flows from 2-3

waveguides

bends

circulator

RF dummy load

The RF dummy load is a pipe filled with water+glycol

24

Low Level RF (LLRF)

Function:
The LLRF is a fast regulation system that regulates and stabilizes the amplitude and the phase of the wave in the cavities, therefore compensating for errors in the RF amplifiers RF distribution and cavities;

Principle: Measure the accelerating voltage in the cavity, compare it to the desired voltage and use the error to regulate the driver of the power amplifier:
- it is a real RF feedback, not an amplitude and phase loop;
- but it can be implemented using I/Q Demodulators
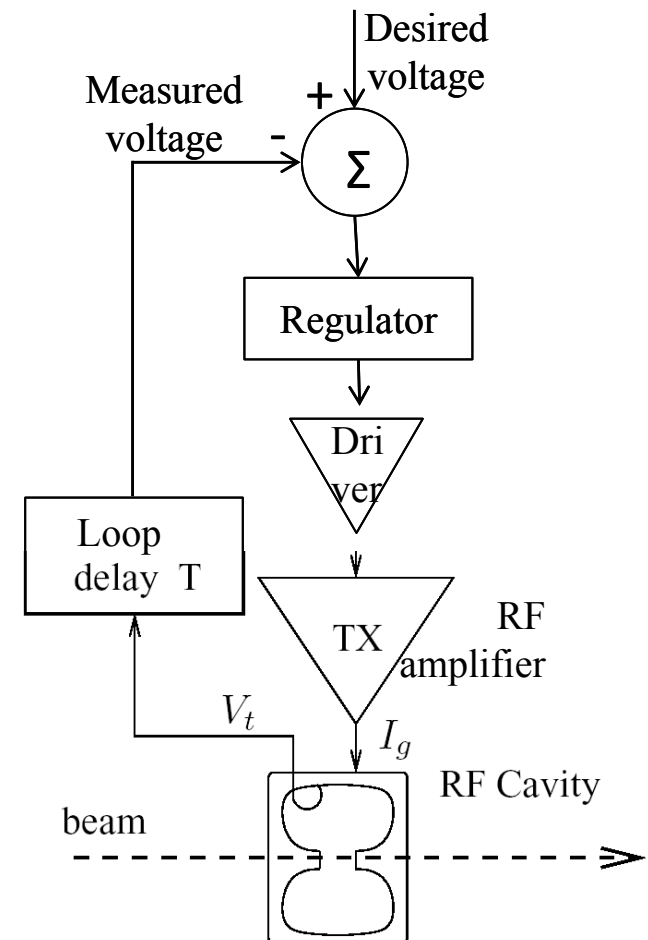
Control and interlock systems

Function:
The complete RF system, formed by…
- Modulator;
- RF amplifier;
- Auxiliary power supplies of the RF amplifier;
- RF distribution (i.e. waveguides, circulators, RF dummy loads, etc.), including arc detectors, forward and reflected power detectors;
- Power couplers and RF cavities;
- Water cooling circuits;

… has many sensors and actuators that need to be continuously verified, activated and interlocked (protection)

Fast signal interlocks
(i.e. arc detectors, forward/reflected power sensors, etc.) can be handled by a FPGA (Field Programmable Gate Array) based interlock board
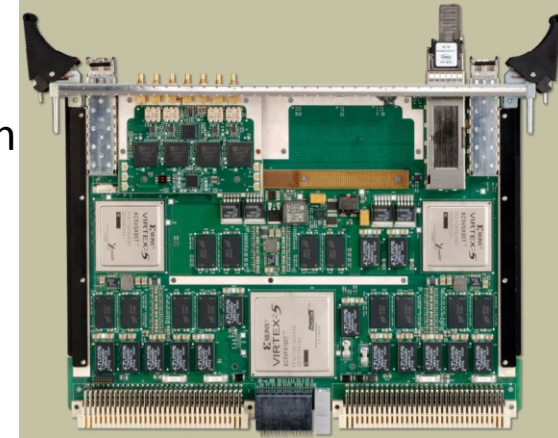
Slow signal interlocks
(i.e. temperature sensors, waterflow meters, etc.) can be handled for instance by a PLC (Programmable Logic Controller)