RF Power Generation II

Klystrons, Magnetrons and Gyrotrons

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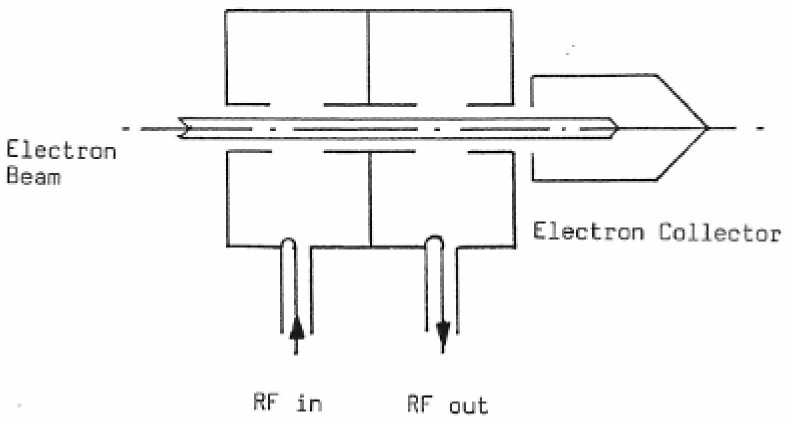
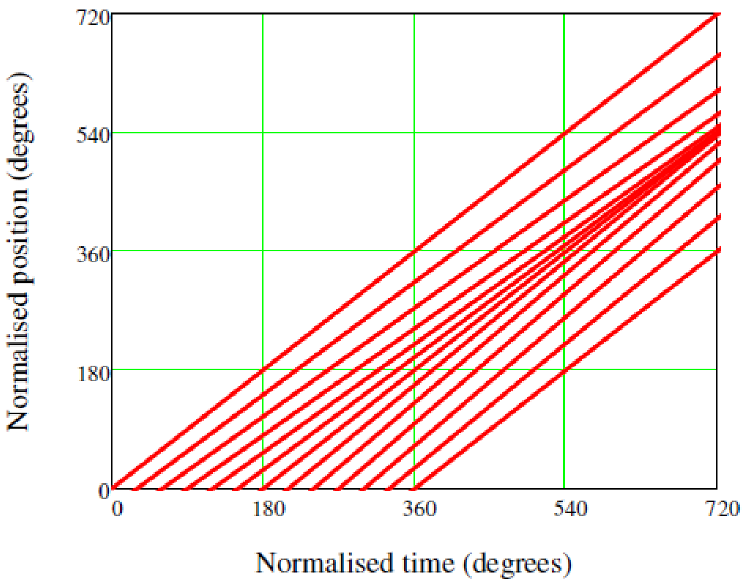
Scope of the lecture:

- The output of an IOT is limited to around 30 kW at 1.3 GHz by the need to use a control grid
- At higher frequencies and higher powers the beam must be bunched in another way
- Klystrons
- Multipactor discharge
- Other high power sources
  - SLAC Energy Doubler
  - Magnetrons
  - Gyrotrons
- State of the art

Velocity modulation

- An un-modulated electron beam passes through a cavity resonator with RF input
- Electrons accelerated or retarded according to the phase of the gap voltage: Beam is velocity modulated:
- As the beam drifts downstream bunches of electrons are formed as shown in the Applegate diagram
- An output cavity placed downstream extracts RF power just as in an IOT
- This is a simple 2-cavity klystron



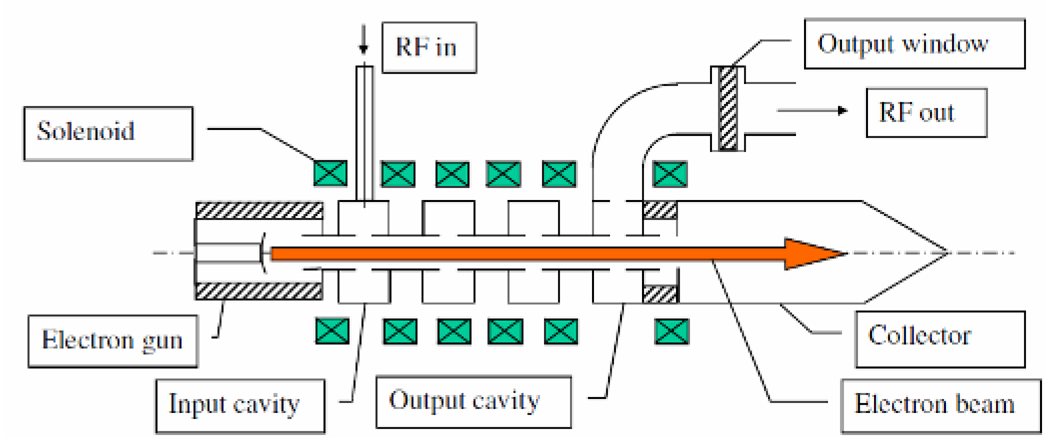


Multi-cavity klystron

- Additional cavities are used to increase gain, efficiency and bandwith
- Bunches are formed by the first (N-1) cavities
- Power is extracted by the N^{th} cavity
- Electron gun is a space-charge limited diode with perveance given by

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

- $K \times 10^6$ is typically 0.5 - 2.0
- Beam is confined by an axial magnetic field



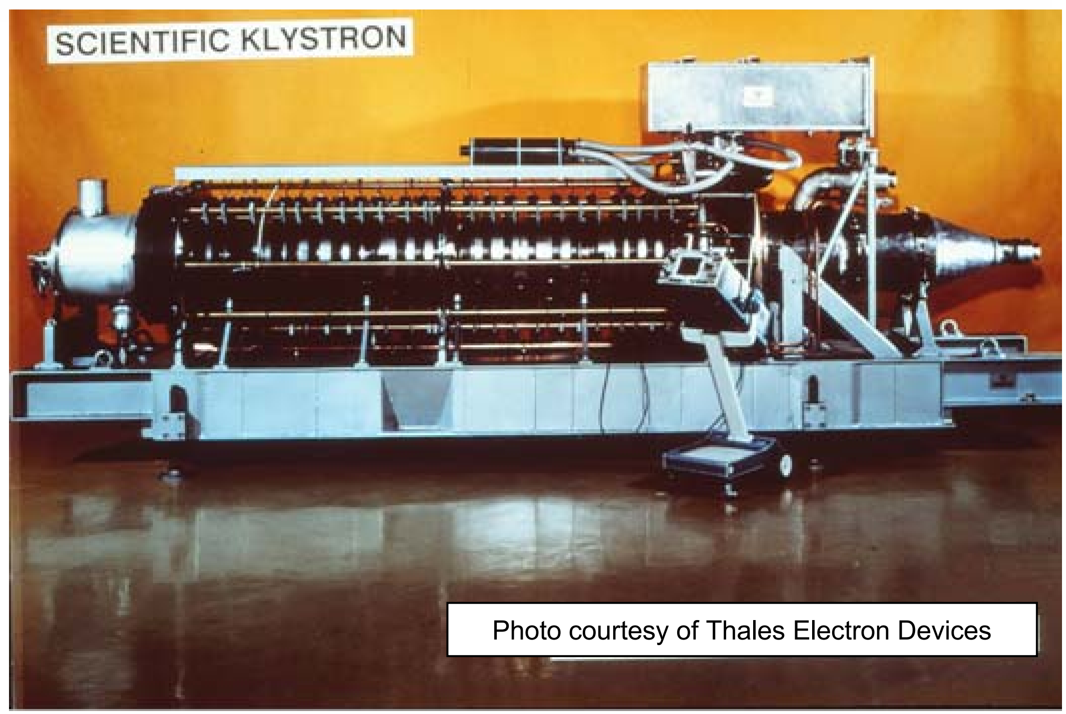
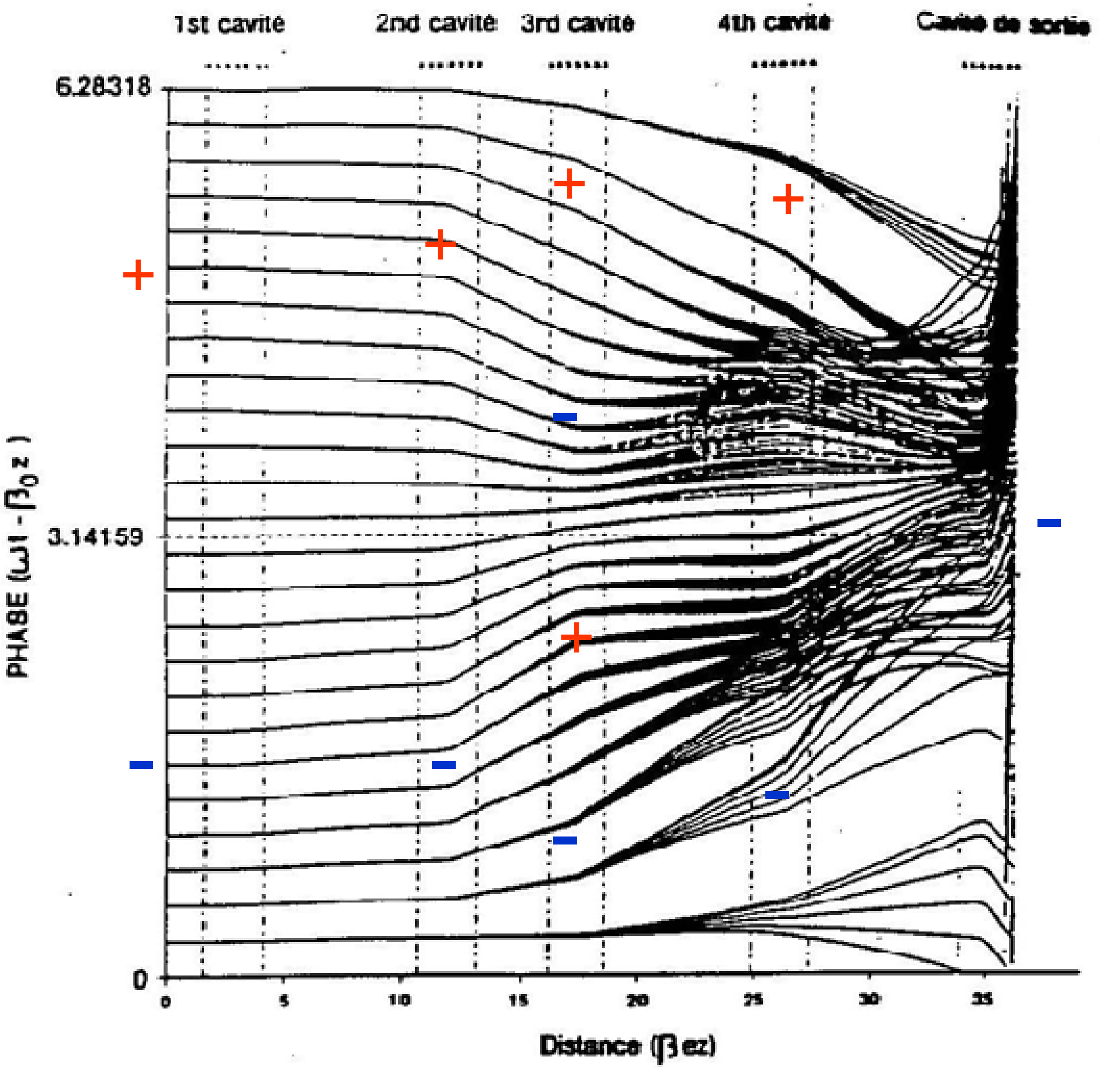


Photo courtesy of Thales Electron Devices

Typical Applegate diagram



- Distance and time axes exchanged
- Average beam velocity subtracted
- Intermediate cavities detuned to maximise bunching
- Cavity 3 is a second harmonic cavity
- Space-charge repulsion in last drift section limits bunching
- Electrons enter output gap with energy ~ V_0

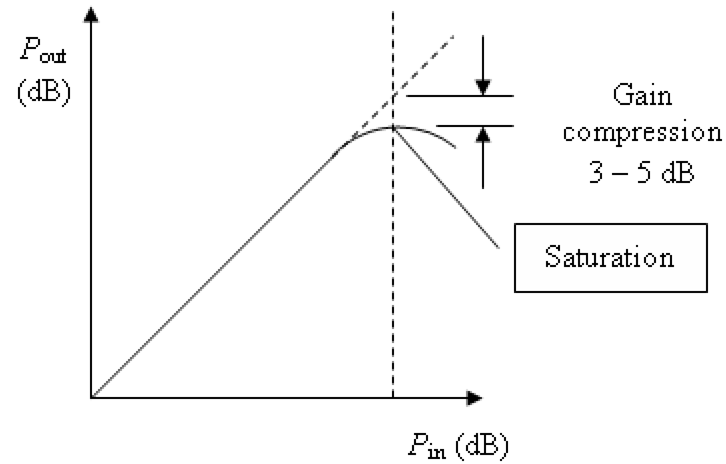
Image courtesy of Thales Electron Devices

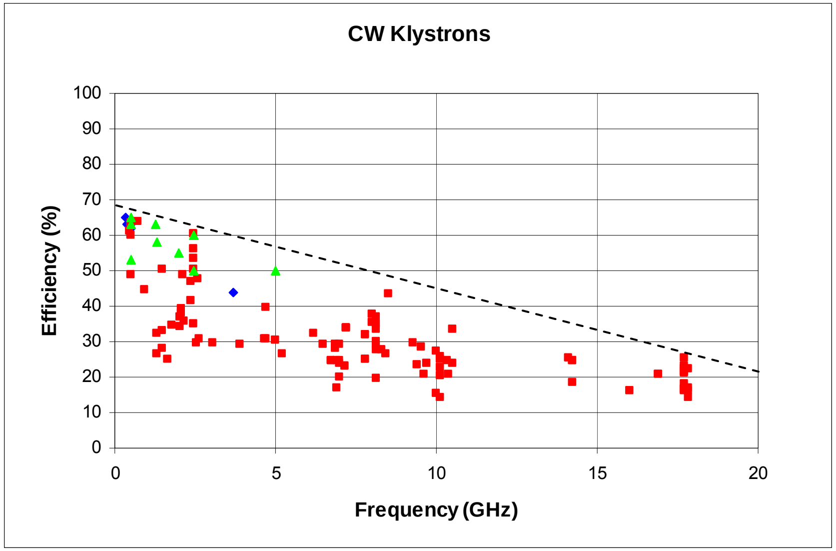
Output saturation

- Non-linear effects limit the power at high drive levels and the output power saturates
- Electrons must have residual energy > $0.1V_0$ to drift clear of the output gap and avoid reflection
- RF beam current increases as bunch length decreases.
  - Theoretical maximum $I_1 = 2I_0$ when space-charge is low
  - Maximum I_1 decreases with increasing space-charge
- Second harmonic cavity may be used to increase bunching
- Maximum possible efficiency with second harmonic cavity is approximately

$$\eta_e = 0.85 - 0.2 \times 10^{-6} K$$

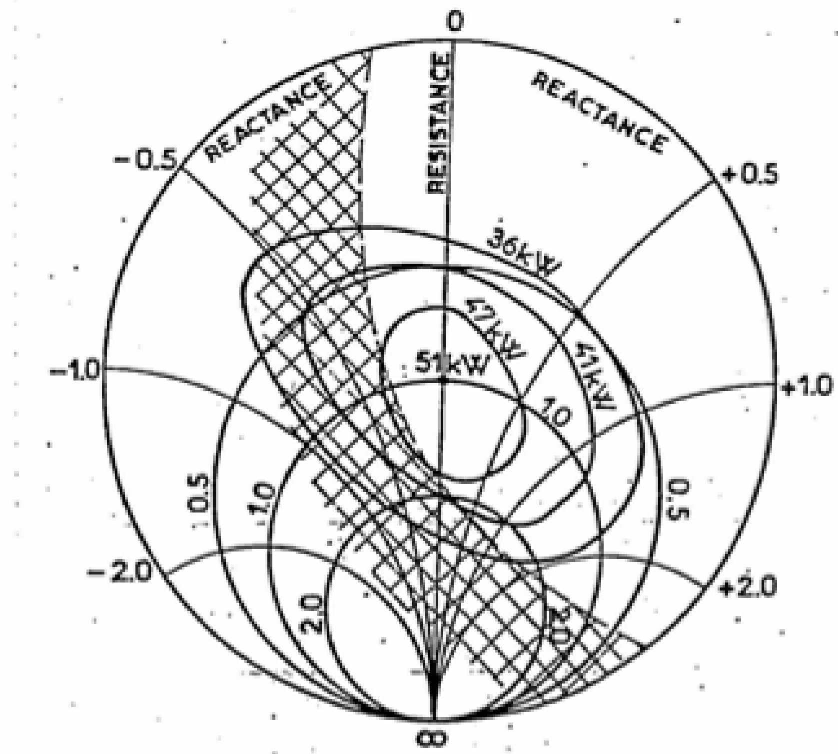
- Efficiency decreases with increasing frequency because of increased losses and design trade-offs





Effect of output match

- Reflected power changes the amplitude and/or phase of the output gap voltage
- Rieke diagram shows output power as a function of match at the output flange
- Shaded region forbidden because of voltage breakdown and/or electron reflection
- Output mismatch can also cause:
  - Output window failure
  - Output waveguide arcs
- A Circulator is needed to protect against reflected power



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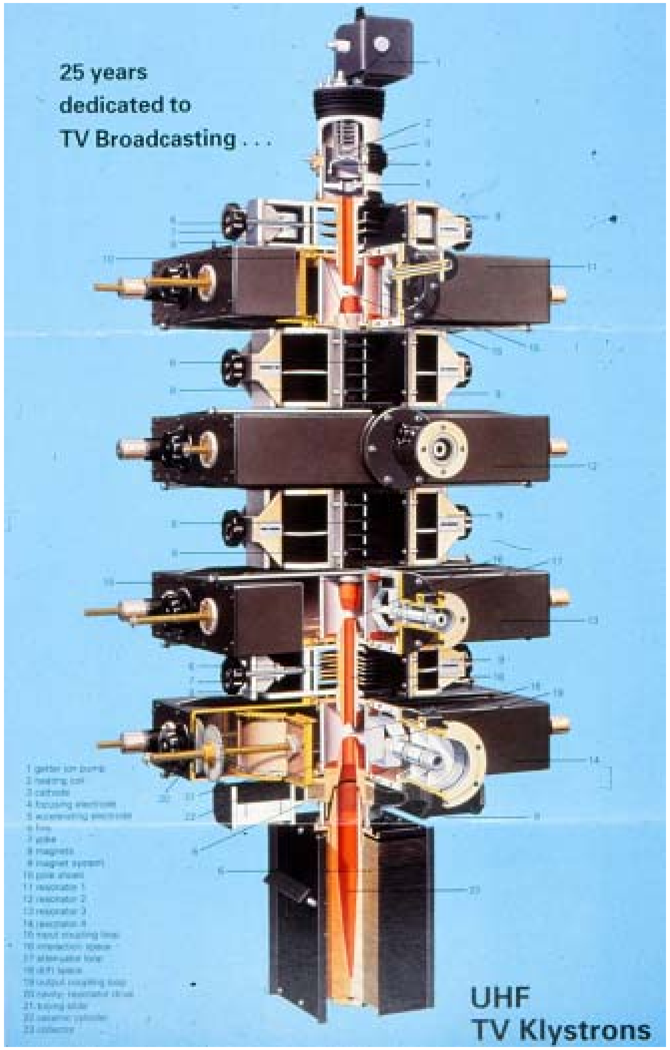
UHF TV klystrons

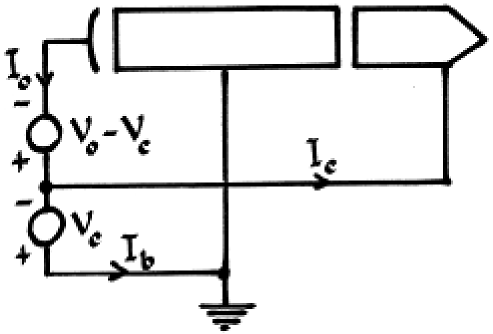


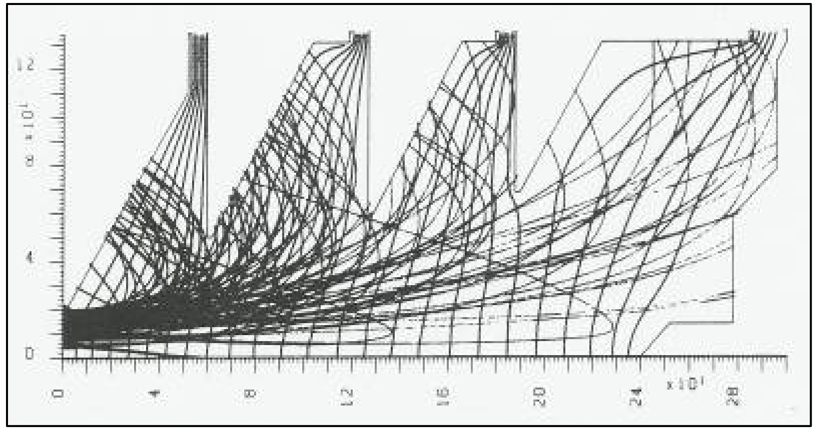
Photos courtesy of Phillips

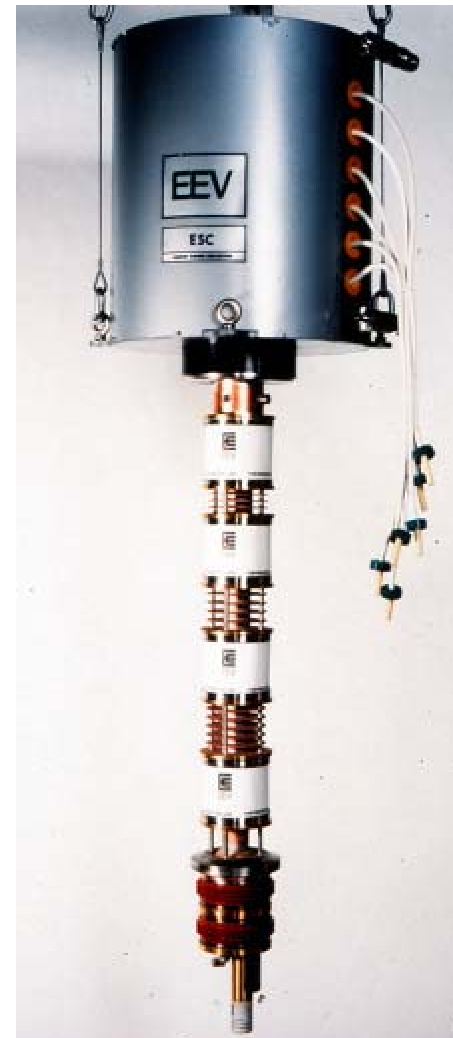
- Frequency 470 - 860 MHz
- Power 10 - 70 kW
- Gain 30 - 40 dB
- Efficiency 40 – 50%
- Beam control by modulating anode
- 4 or 5 tunable internal or external cavities

CERN SPS 450kW 800MHz amplifier

Collector depression







$$P_{DC} = I_C\left(V_0 - V_C\right) + I_b V_0 = I_0 V_0 - I_C V_C$$

$$\eta = \frac{P_{RF}}{I_0 V_0 - I_C V_C}$$

- Efficiency increases with number of stages: realistic maximum is 4 – 5
- Adds to the complexity and cost of the tube
- High voltage electrodes are difficult to cool
- Can also be used with IOTs

Accelerator klystrons

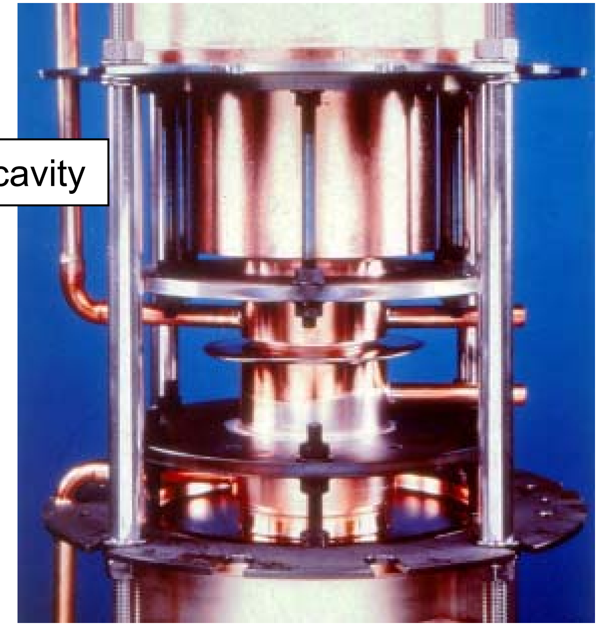
Frequency	508 MHz
Beam	90 kV; 18.2A
Power	1 MW c.w.
Efficiency	61%
Gain	41 dB

Photos courtesy of Phillips

Accelerator klystrons

Output cavity and coupler

Second harmonic cavity



Window components

Photos courtesy of Phillips

Klystrons: State of the art

CW Klystrons

Frequency	352	700	3700	MHz
Beam voltage	100	92	60	kV
Beam current	19	17	20	A
RF output power	1.3	1.0	0.7	MW
Efficiency	67	65	44	%

Pulsed Klystrons

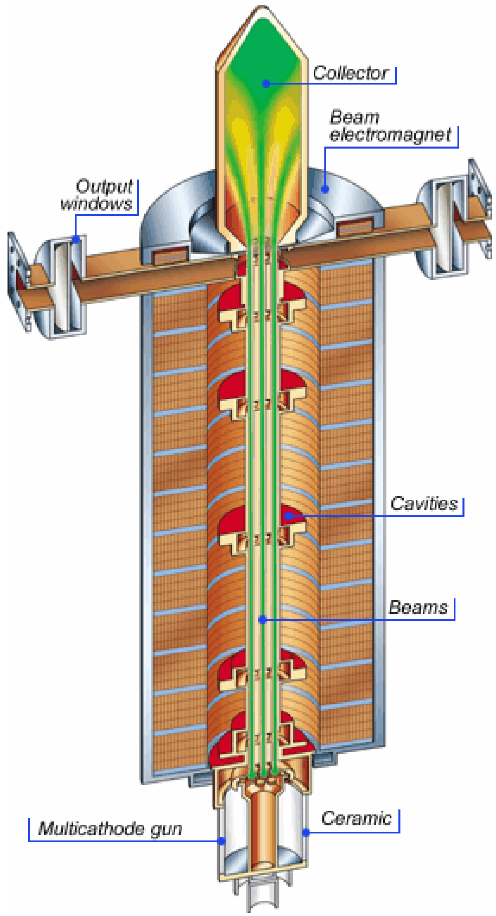
Frequency	2.87	3.0	11.4	GHz
Beam voltage	475	590	506	kV
Beam current	620	610	296	A
RF output power	150	150	75	MW
Efficiency	51	42	50	%

Note: Breakdown voltage is higher for short pulses than for DC

Multiple beam klystrons

- To deliver high power with high efficiency requires low perveance
- High beam voltage is not desirable
- Several low perveance klystrons combined in one vacuum envelope as a multiple-beam klystron

Frequency	1300 MHz
Beam	115 kV; 133 A
Power	9.8 MW peak
Efficiency	64 %
Gain	47 dB
Pulse	1.5 msec



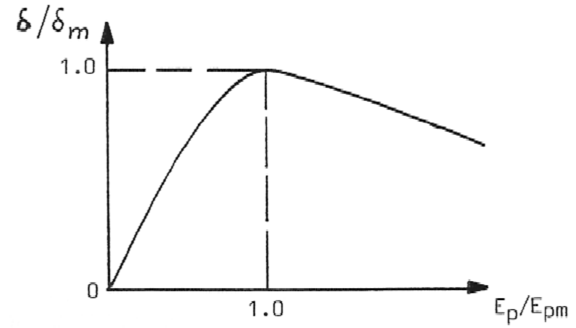
Images courtesy of Thales Electron Devices

Klystron performance limited by:

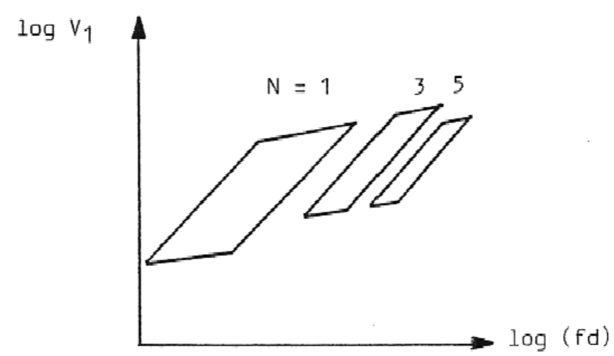
- Voltage breakdown
  - Electron gun
  - Output gap
- Cathode current density
- Output window failure caused by
  - Reflected power
  - Vacuum arcs
  - Multipactor discharge
  - X-ray damage
- Heat dissipation

Multipactor discharge

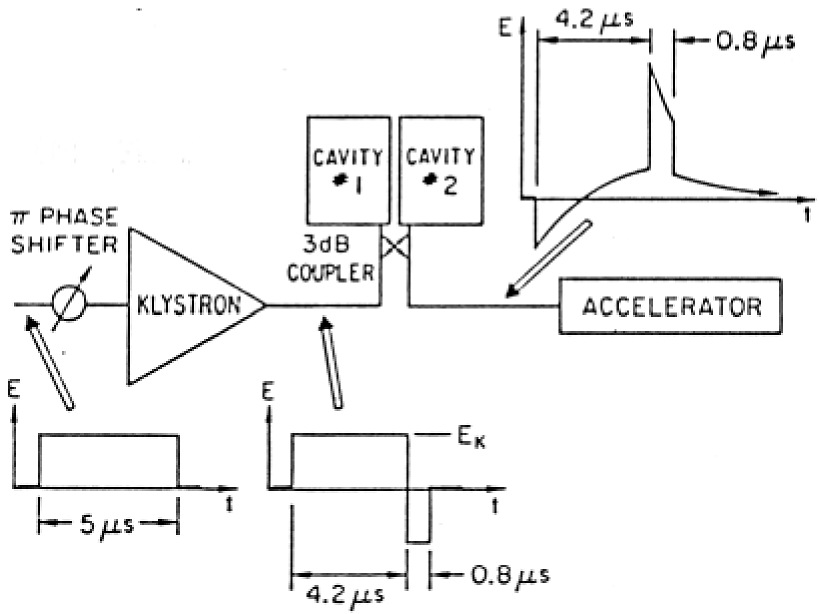
- Resonant RF vacuum discharge sustained by secondary electron emission
- One or two surfaces involved
- Multiple modes
- Signs of multipactor:
  - Heating
  - Changed r.f. performance
  - Window failure
  - Light and X-ray emission
- Multipactor on dielectric surfaces does not require RF field
- Multipactor can sometimes be suppressed by
  - Changing shape of surface
  - Surface coatings
  - Static electric and magnetic fields

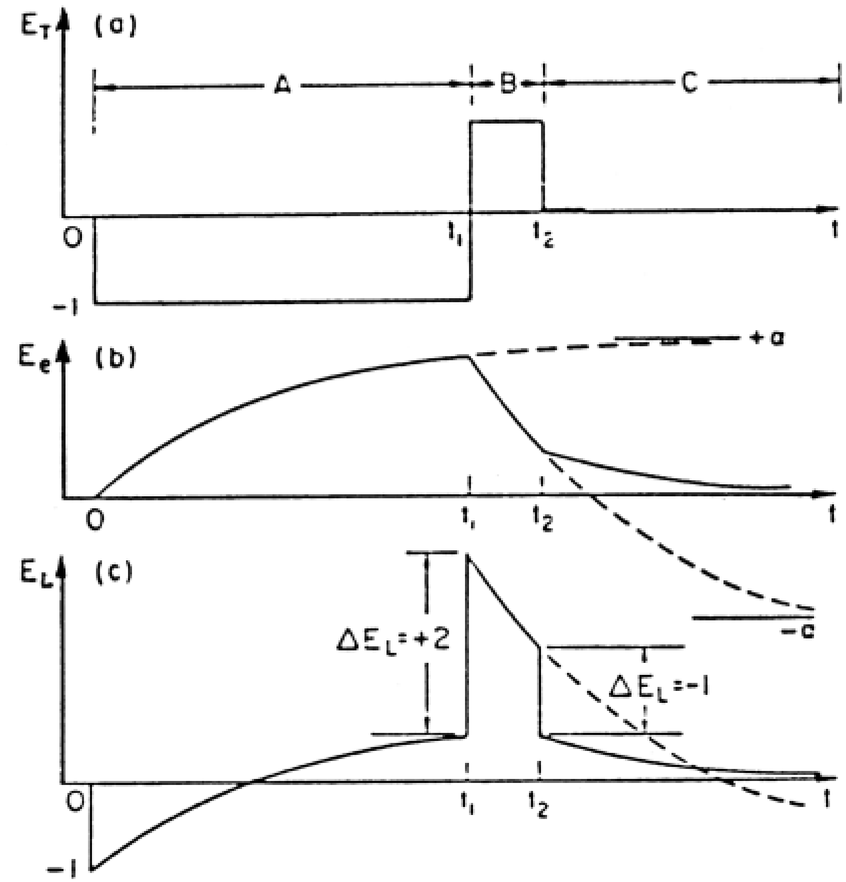


Secondary electron emission constants		
	δ_m	E_{pm} (Volts)
Copper	1.3	600
Platinum	1.8	800
Carbon black	0.45	500
Aluminium Oxide	2.35	500



The SLAC Energy Doubler (SLED)





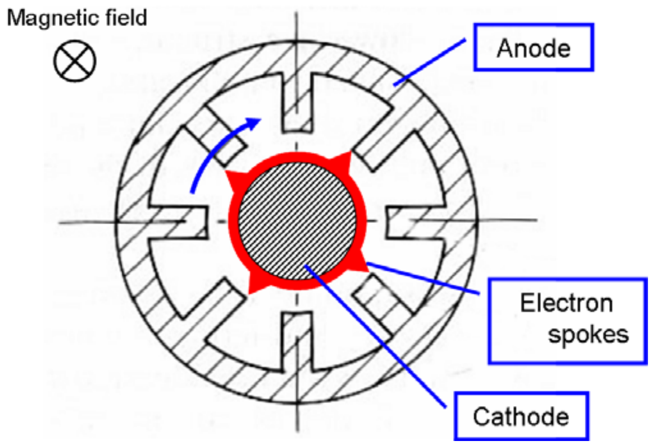
a) Power transmitted by the cavities (E_T)

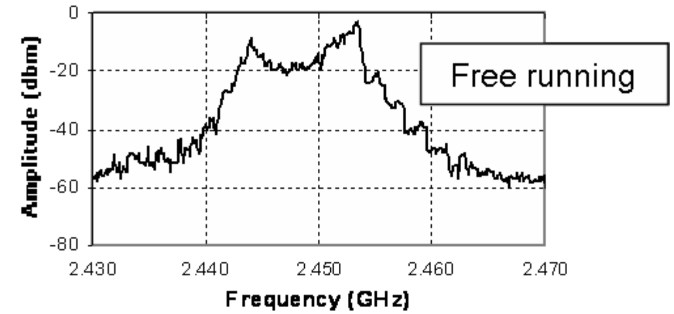
b) Power re-radiated by the cavities (E_e) (antiphase)

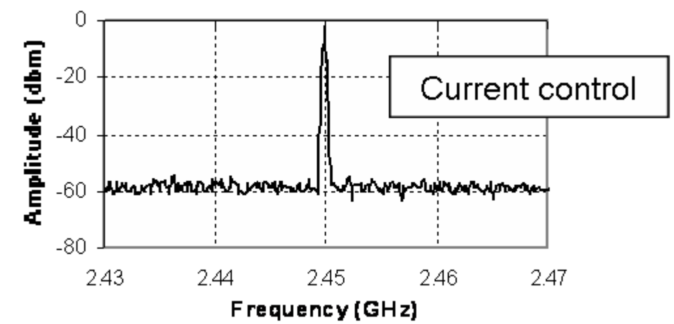
c) Sum of transmitted and radiated power

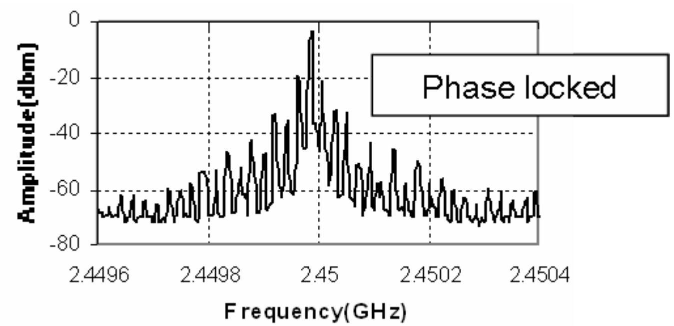
Note: No power is reflected to the klystron

Magnetrons





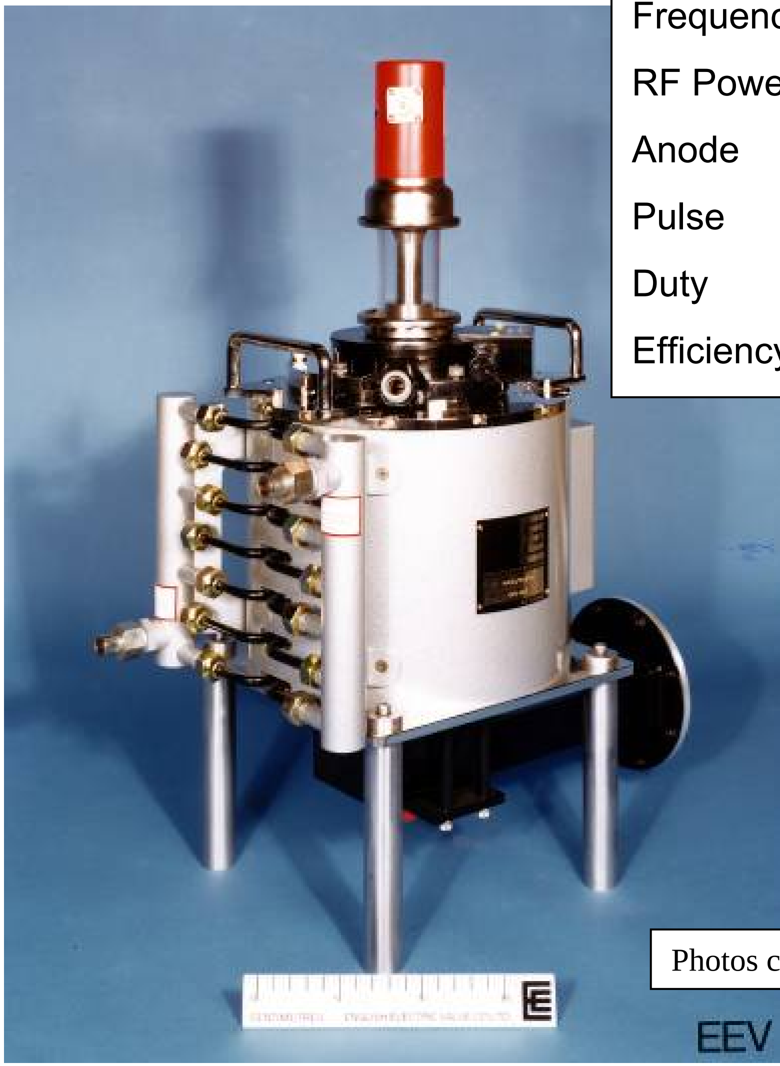




- Interaction in crossed electric and magnetic fields
- Free-running oscillator: Efficiency up to 90%
- Frequency
  - Is not stable enough for use in most accelerators
  - Coarse control of frequency by controlling the current
  - Frequency locked by injecting radio-frequency power ~ 0.1% of output power
- Locked magnetrons could be suitable for use in accelerators

Magnetron for medical linacs

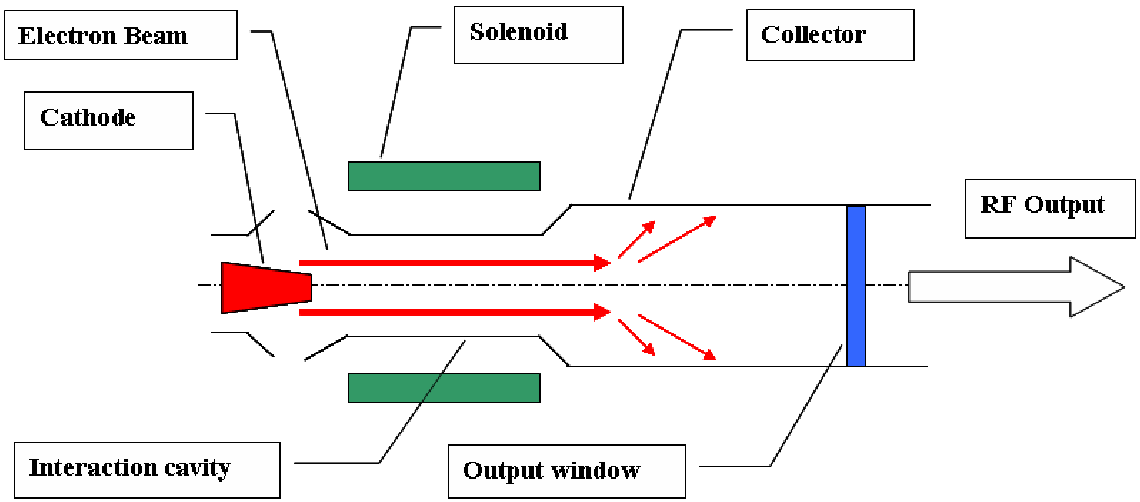
Frequency	2.855 GHz
RF Power	5.5 MW peak
Anode	51 kV; 240 A
Pulse	2.3 μs
Duty	0.00055
Efficiency	45%

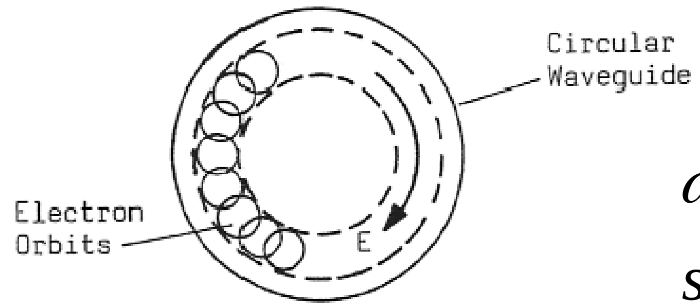


Photos courtesy of e2v technologies

Gyrotrons

- Interaction between a relativistic hollow electron beam and a waveguide TE mode
- Use of fast wave allows electrons to be further from the metal than in a klystron
- Cyclotron resonance requires strong axial magnetic field
- Chiefly developed for heating plasmas for fusion





$$\omega = s\,\omega_c$$

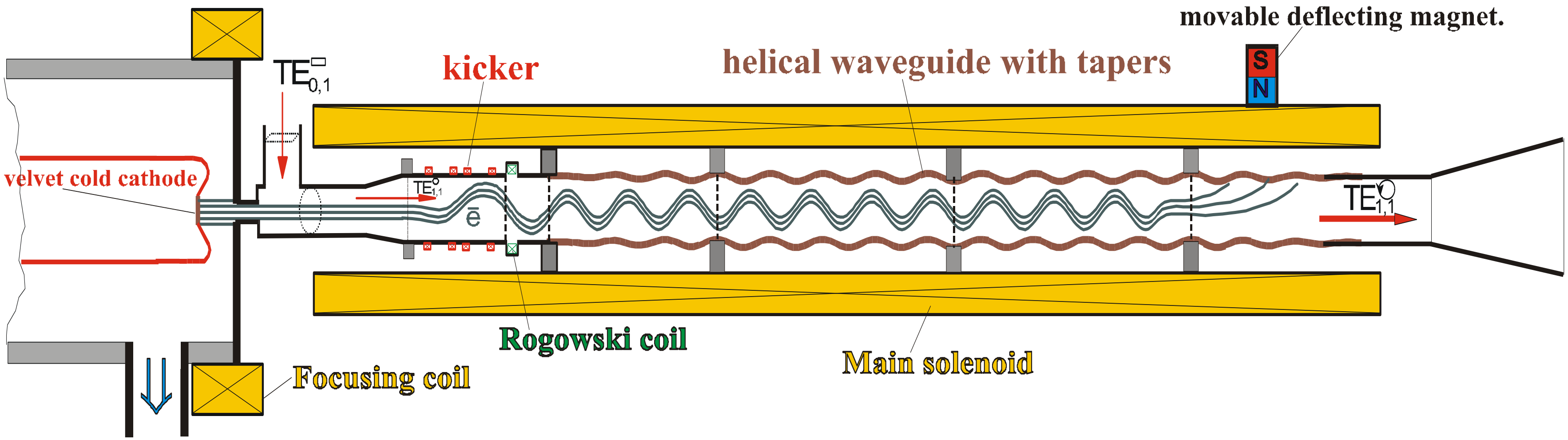
$$s = 1, 2, 3\ldots$$

TH1506 Gyrotron Oscillator

Frequency	118 GHz
V_0	85 kV
I_0	22 A
Power	500 kW peak
Efficiency	30 %
Pulse	210 sec

Photo courtesy of Thales Electron Devices

Gyro-TWT Amplifier



Output power (TE_{11})	1.1MW
Efficiency	29%
3 dB bandwidth at 9.4GHz	21%
Saturated gain	37dB
Small-signal gain	48dB

State of the art