RF Generation

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Overview

- High power RF sources required for all accelerators > 20 MeV
- Amplifiers are needed for control of amplitude and phase
- RF power output
  - 10 kW to 2 MW cw
  - 100 kW to 150 MW pulsed
- Capital and operating cost is affected by
  - Lifetime cost of the amplifier
  - Efficiency (electricity consumption)
  - Gain (number of stages in the RF amplifier chain)
  - Size and weight (space required)

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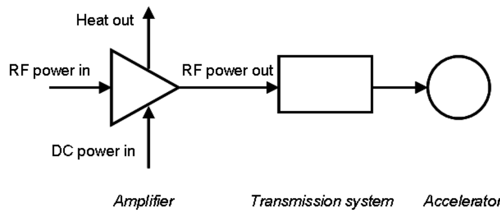
General principles

- RF systems
  - RF sources extract RF power from high charge, low energy electron bunches
  - RF transmission components (couplers, windows, circulators etc.) convey the RF power from the sourc to the accelerator
  - RF accelerating structures use the RF power to accelerate low charge bunches to high energies
- RF sources
  - Size must be small compared with the distance an electron moves in one RF cycle
  - Energy not extracted as RF must be disposed of as heat



$$P_{RF\ in} + P_{DC\ in} = P_{RF\ out} + Heat$$

$$Efficiency = \frac{P_{RF\ out}}{P_{DC\ in} + P_{RF\ in}} \approx \frac{P_{RF\ out}}{P_{DC\ in}}$$

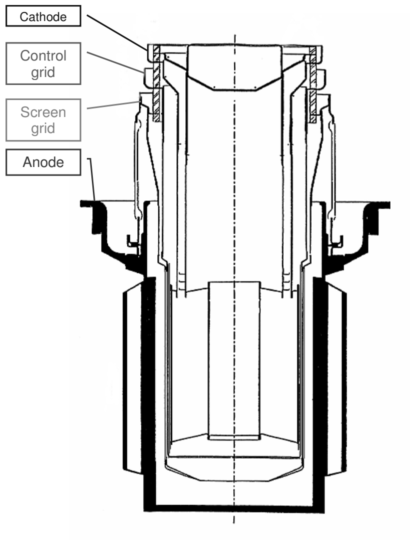
$$Gain(dB) = 10\log_{10}\left(\frac{P_{RF\ out}}{P_{RF\ in}}\right)$$

RF Sources for Hadron Accelerators

Continuous Wave Machines					
Lab	Accelerator	Type	RF Source	Freq. (MHz)	Power (kW)
RIKEN	RIBF SRC	Cyclotron	Tetrode	18 to 42	150
TRIUMF	TRIUMF	Cyclotron	Tetrode	23.06	125
PSI	PSI	Cyclotron	Tetrode	50	850
IFMIF	IFMIF	Linac	Diacrode	175	1000
CERN	SPS (Philips)	Synchrotron	Tetrode	200	35
CERN	SPS (Siemens)	Synchrotron	Tetrode	200	125
CERN	LHC	Synchrotron	Klystron	400	300

Pulsed Machines						
Lab	Accelerator	Type	RF Source	Freq. (MHz)	Peak (MW)	Duty
RAL	ISIS Synchrotron	Synchrotron	Tetrode	1.3 to 3.1	1	50%
GSI	FAIR UNILAC	Linac	Tetrode	36	2	50%
GIST	FAIR UNILAC	Linac	Tetrode	108	1.6	50%
RAL	ISIS Linac	Linac	Triode	202.5	5	2%
GSI	FAIR Linac	Linac	Klystron	325	2.5	0.08%
ESS	ESS DTL	Linac	Klystron	352.2	1.3 and 2.5	5%
ORNL	SNS RFQ & DTL	Linac	Klystron	402.5	2.5	8%
ESS	ESS Ellipt	Linac	Klystron	704.4	2	4%
ORNL	SNS CCL	Linac	Klystron	805	5	9%

Tetrode construction



Images courtesy of e2v technologies

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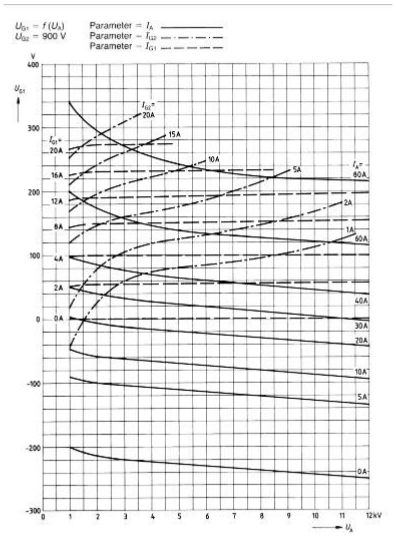
Tetrode characteristics



$$I_a \approx C\left(V_{g1} + \frac{V_{g2}}{\mu_2} + \frac{V_a}{\mu_a}\right)^n$$

- n = 1.5 to 2.5
- DC bias conditions relative to cathode
  - Anode voltage positive
  - Screen grid positive (~ 10% V_a)
  - Control grid negative
- Anode current depends
  - Strongly on control grid voltage
  - Weakly on anode voltage
- In practice Anode is at earth potential

Graph courtesy of Siemens AG

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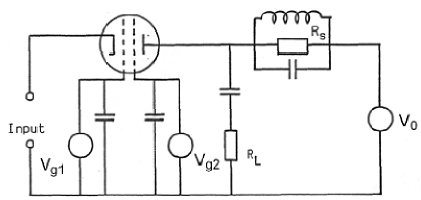
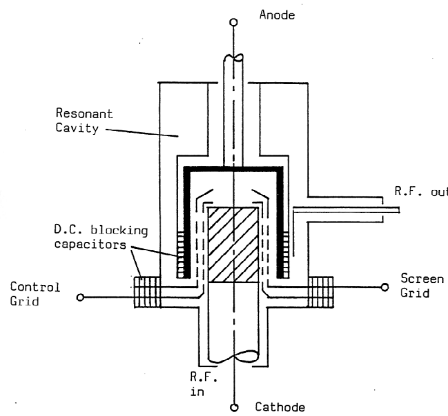
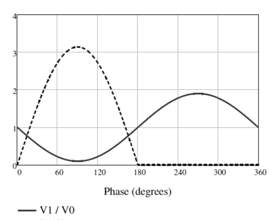
Tetrode common grid connection

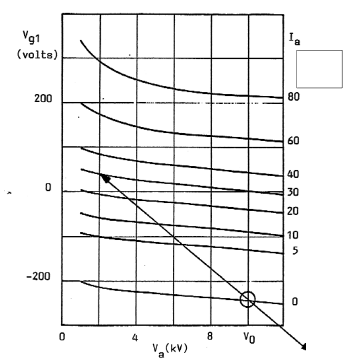




- Grids held at RF ground isolate input from output
- Input is coaxial
- Anode resonant circuit is a coaxial cavity
- Output is capacitively or inductively coupled

Class B operation





- Control grid bias set so that anode current is zero when no RF input
- Conduction angle = 180°
- Resonant circuit makes anode voltage variation sinusoidal
- $V_a > V_{g2}$ always
- Theoretical efficiency ~70%

$$V_2 \le 0.9V_0 \qquad I_2 \simeq \frac{\pi}{2} I_0$$

$$P_2 = \frac{1}{2} I_2 V_2 \le \frac{0.9\pi}{4} I_0 V_0$$

Classes of amplification

Class	Conduction angle	Maximum theoretical efficiency	Gain increasing	Harmonics increasing
A	360°	50%		
AB	180° – 360°	50% - 78%		
B	180°	78%		
C	< 180°	78% - 100%		

- All classes apart from A must have a resonant load and are therefore narrow band amplifiers
- Class AB or B usually used for accelerators

CERN 62 kW 200 MHz amplifier

- RS 2058 CJ tetrode
  - Siemens (now Thales)
- Class AB operation
- Efficiency - 64%

Photo courtesy of e2v technologies

Photo courtesy of CERN

Cooling and protection

Anode Cooling

- Air
- Water
- Vapour phase

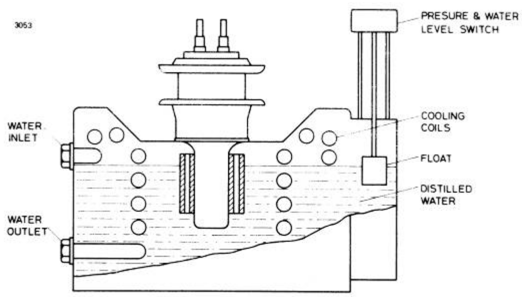


Image courtesy of e2v technologies

Protection

- Coolant flow
- Coolant temperature
- Tube temperature
- Anode, screen and grid overcurrent
- Anode voltage (fast)

Switch-on sequence

- Heater voltage
- Grid bias

  (pause)
- Anode voltage
- Screen grid voltage
- RF drive

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Combining tetrode amplifiers

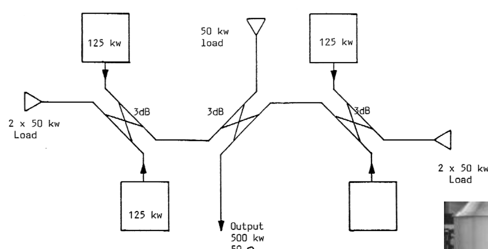

Photo courtesy of CERN

CERN SPS 200 MHz, 500 kW, amplifiers

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Tetrode limitations

- Cathode current density
- Anode dissipation
- Transit time
  - V_a least when I_a greatest
- Voltage breakdown
- Anode length << λ_0
- Anode diameter
- RF screen grid dissipation

Thales Diacrode® reduces this

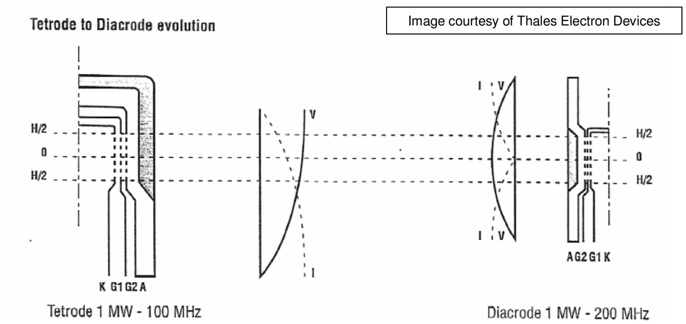
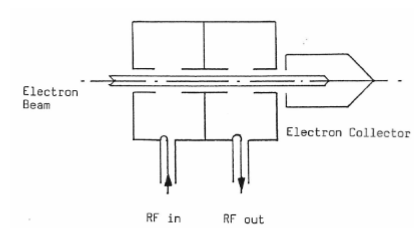
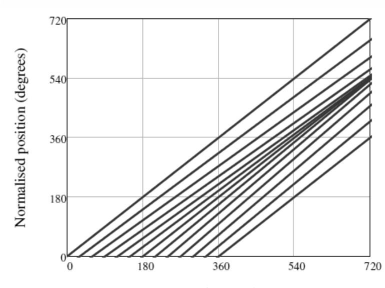


Image courtesy of Thales Electron Devices

Velocity modulation

- The output of a tetrode is limited to around 1 MW at 200 MHz by transit time effects
- At higher frequencies and higher powers
  - the electrons must be bunched in another way
  - The RF output must be separated from the collecting electrode
- 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
- This is a simple 2-cavity klystron



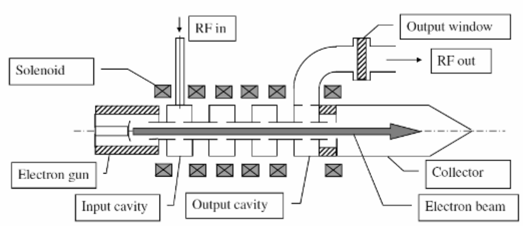


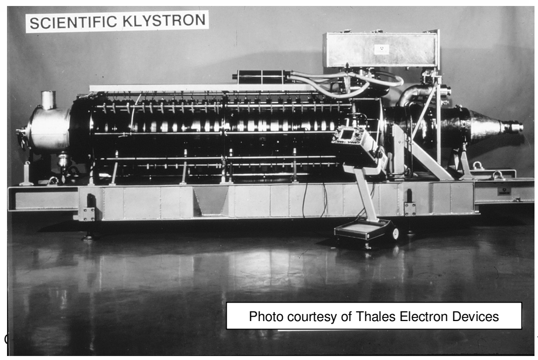
Multi-cavity klystron

- 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





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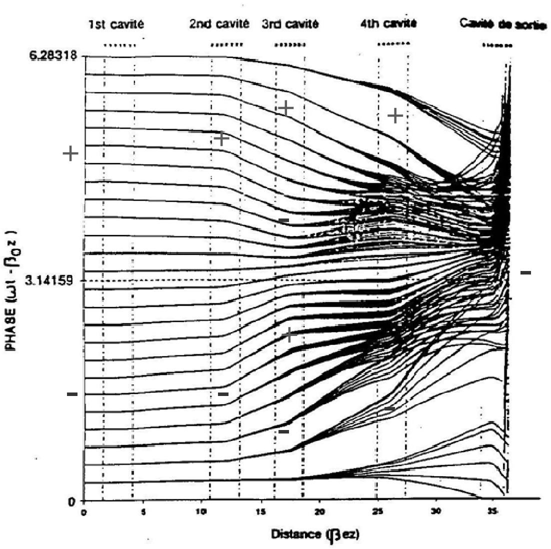
Typical Applegate diagram



- 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 ~ eV_0

Image courtesy of Thales Electron Devices

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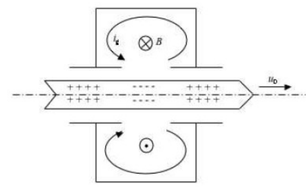
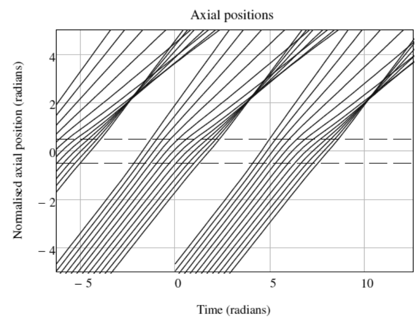
Klystron output gap interaction

- Beam current class AB or B like a tetrode
- At resonance electric field in the gap is maximum retarding when bunch is in the centre of the gap
- Effective gap voltage reduced by transit time effects
- Effective gap voltage less than ~0.9V_0 to allow electrons to pass to the collector
- Theoretical efficiency ~ 70%

$$P_2 = \frac{1}{2} I_2 V_{g,eff} \approx \frac{\pi}{4} 0.9 I_0 V_0$$



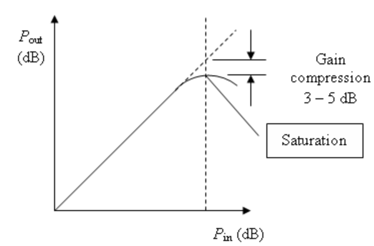


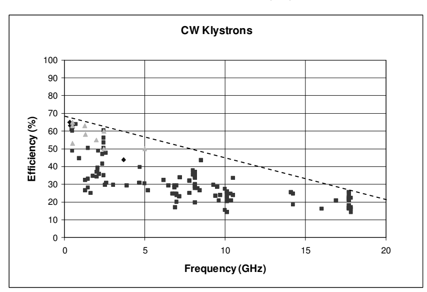
Output saturation

- 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

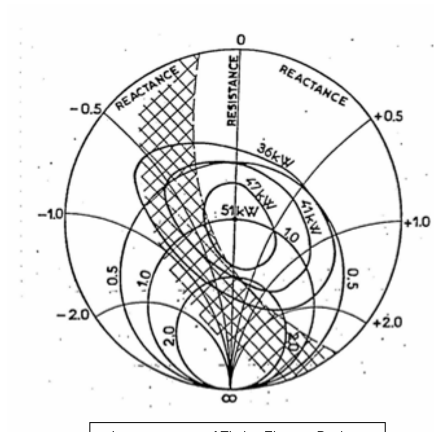


Image courtesy of Thales Electron Devices

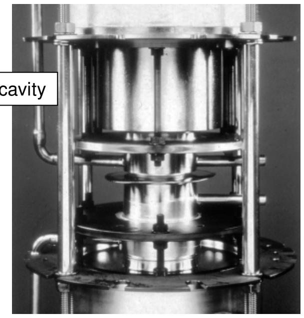
Accelerator klystron

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

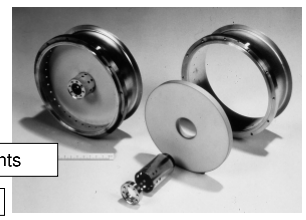
Photos courtesy of Phillips

Accelerator klystron

Second harmonic cavity



Output cavity and coupler



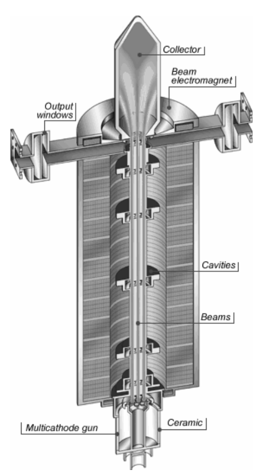
Window components

Photos courtesy of Phillips

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**

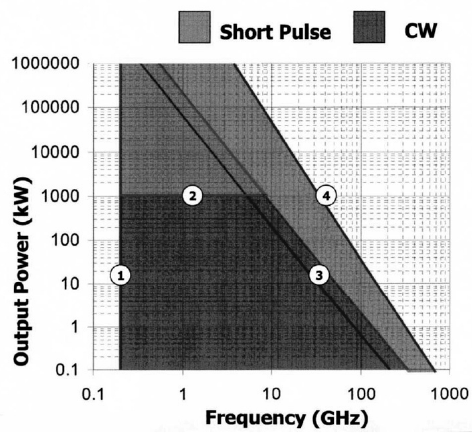


Images courtesy of Thales Electron Devices

Klystron technology limitations

- Plot showing the PF spectrum for klystrons, both short pulse and CW
- Approximate limitations

(1) Size (CW & Pulsed)
(2) Window (CW)
(3) O/P Cavity Power Density / Cyclical Fatigue (CW)
(4) RF Breakdown (Pulsed)

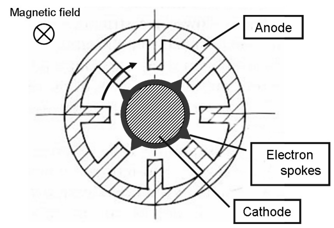


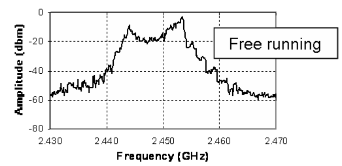
HP Bohlen, "Vacuum electronic device limitations for high-power RF sources", CWRF 2008, CERN, Geneva, March 2008

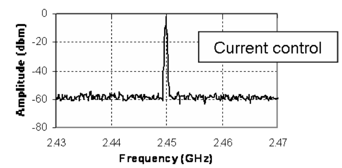
Klystron performance limited by:

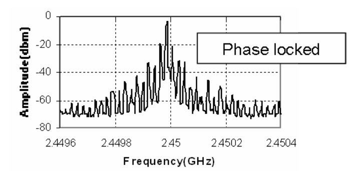
- Voltage breakdown
  - Electron gun
  - Output gap
- Cathode current density
- Output window failure caused by
  - Reflected power
  - Vacuum arcs
  - Multipactor discharge sustained by secondary electron emission
  - X-ray damage
- Heat dissipation

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

State of the art