RF Power Generation I

Gridded Tubes and Solid-state Amplifiers

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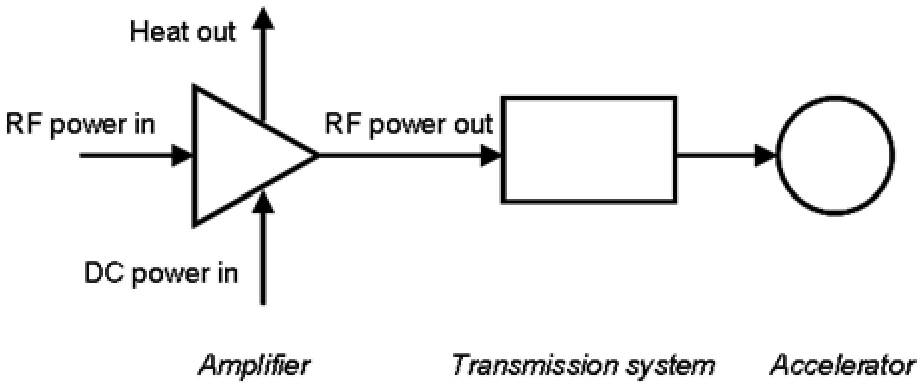
Overview

- 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
- Frequency range
  - 50 MHz to 50 GHz
- 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)

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 source 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



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

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

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

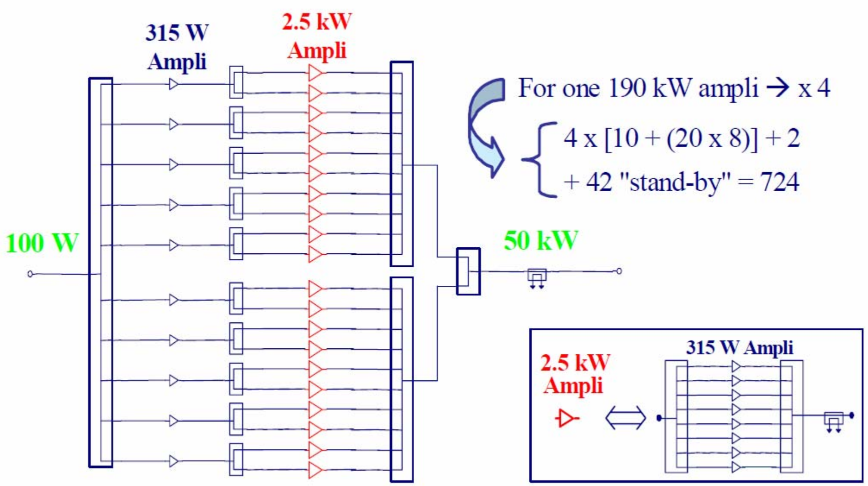
RF Source Technologies

- Vacuum tubes
  - High electron mobility
  - Large size
  - High voltage
- Tube types
  - Gridded Tubes (Tetrodes)
  - Inductive output tubes (IOTs)
  - Klystrons
  - Gyrotrons
  - Magnetrons (locked oscillators)

- Solid state
  - Wide band-gap materials (Si, GaAs, GaN, SiC, diamond)
  - Low carrier mobility
  - Small size
  - High current
  - Low voltage
- Single Transistors
  - Si LDMOS: 450 W at 860 MHz
  - GaN: 180W at 3.5 GHz; 80 W at 9.6 GHz
  - GaAs: 65 W at 14 GHz

SOLEIL 352 MHz amplifier

- Output power 180 kW
- 726 × 315 modules in 4 towers
- 2 × Si LDMOS transistors per module in push-pull
- 53dB Gain
- Overall efficiency ~ 50%



Images courtesy of Synchrotron SOLEIL

Solid State

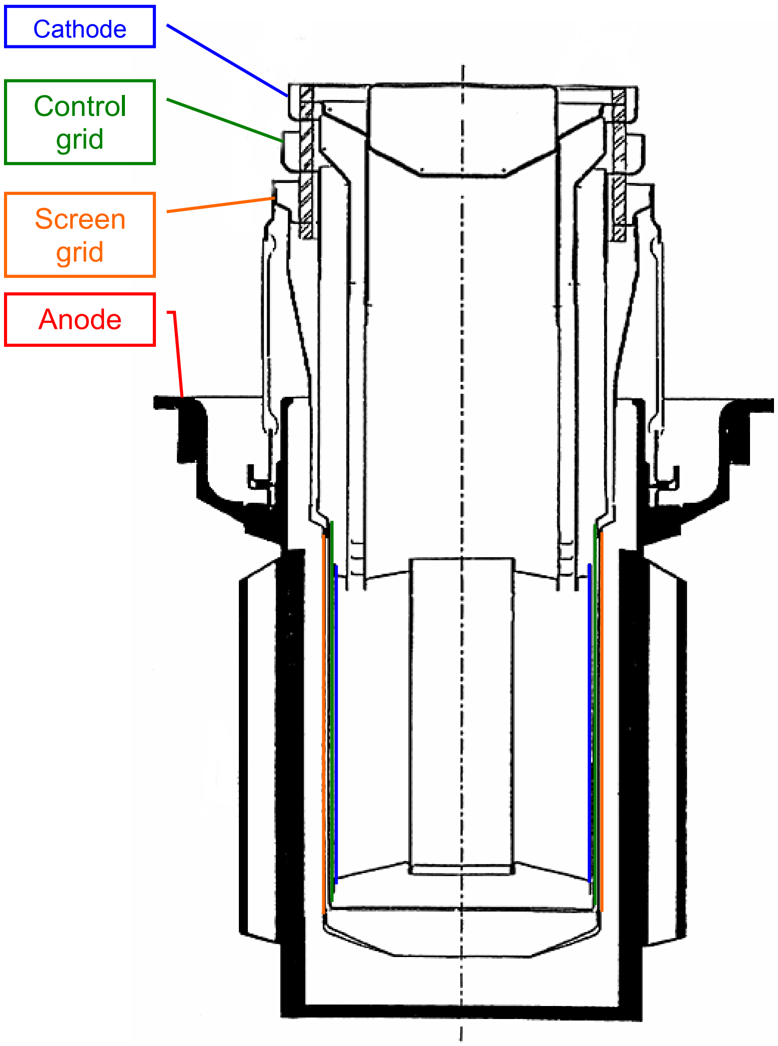
Advantages

- No warm-up time
- High reliability
- Low voltage (<100 V)
- Air cooling
- Low maintenance
- High stability
- Graceful degradation

Disadvantages

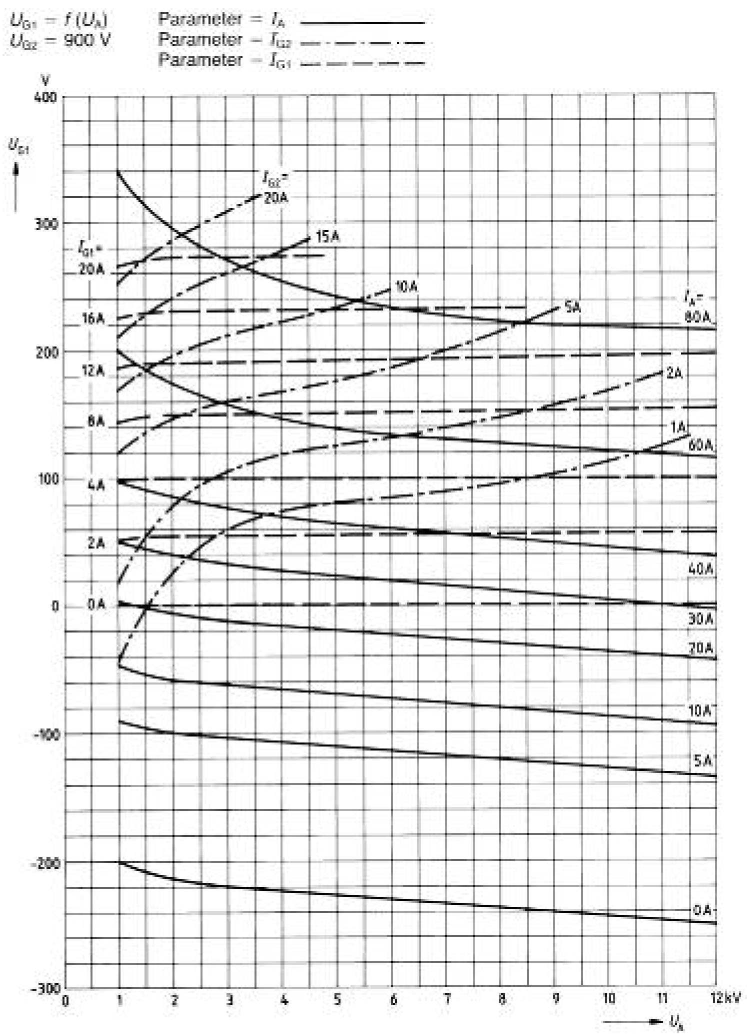
- Complexity
- Losses in combiners
- Failed transistors must be isolated
- Electrically fragile
- High I^2R losses
- Low efficiency

Tetrode construction



Images courtesy of e2v technologies

Tetrode characteristics

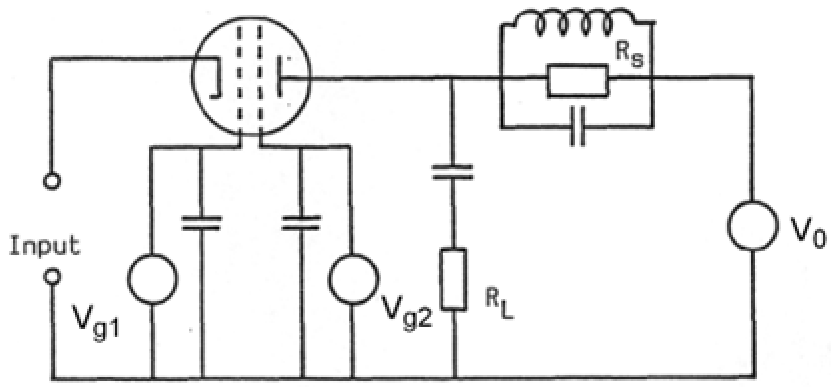


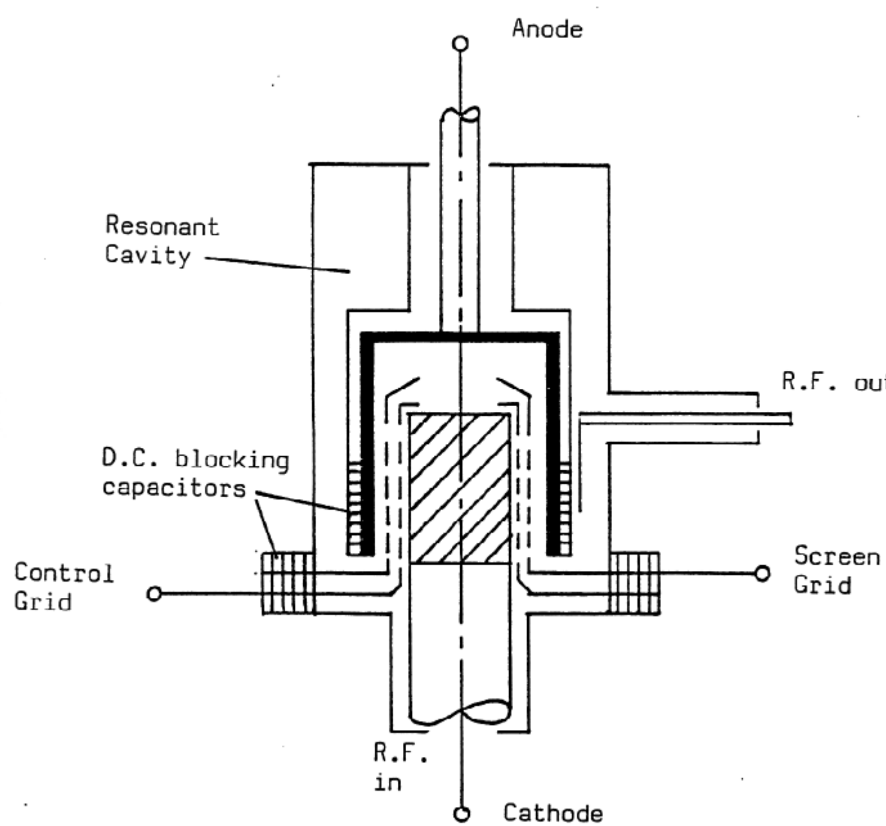
$$I_a \approx C\left(V_{g1} + \frac{V_{g2}}{\mu_2} + \frac{V_a}{\mu_a}\right)^n$$

- 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

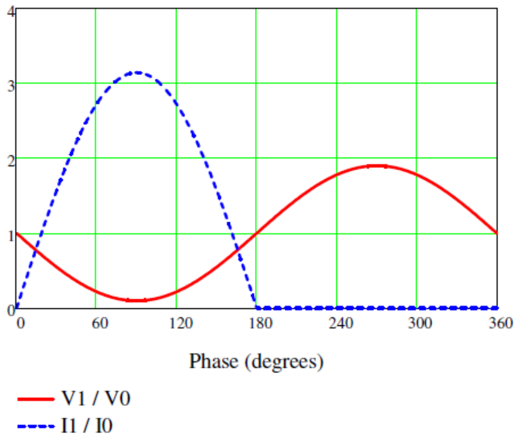
Tetrode common grid connection

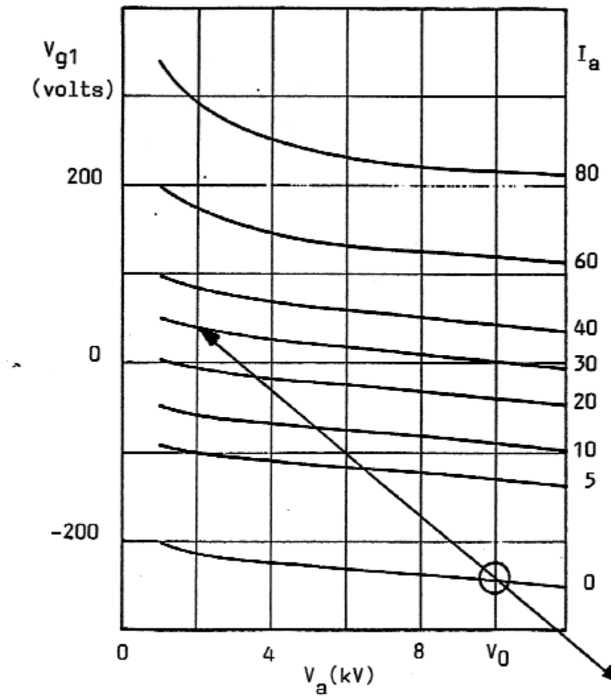




- Grids held at RF ground isolate input from output
- Input is coaxial
- Anode resonant circuit is a re-entrant coaxial cavity
- Output is capacitively or inductively coupled

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%

$$V_2 = 0.9V_0$$

$$I_2 \simeq \frac{\pi}{2} I_0$$

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

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
  - Assume Class B for illustration
- Efficiency - 64%

Photo courtesy of e2v technologies

Photo courtesy of CERN

Tetrode amplifier design

- Choose V_a = 10 kV, V_{g2} = 900 V
- Choose V_a = 1.5 kV when I_a = I_{pk}
- Theoretical Class B efficiency

$$\eta_{th} = \frac{0.85\pi}{4} = 67\ \%$$

$$P_0 = \frac{62}{0.67} = 92.5\ \text{kW}$$

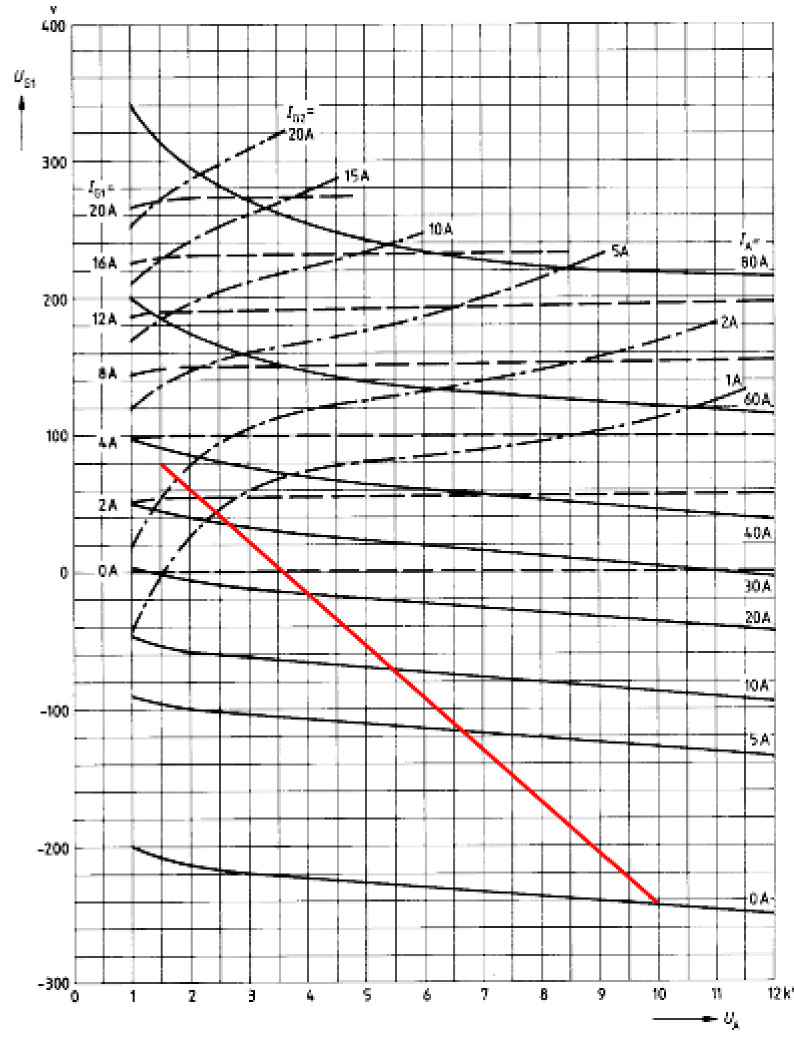
$$I_0 = \frac{88.6}{10} = 9.25\ \text{A}$$

- Assume $I_{pk} = 4I_0$ (theoretically πI_0)

$$I_{pk} = 37\ \text{A}$$

- and draw the load line

Graph courtesy of Siemens AG



Calculation of performance (1)

Angle	V_a		I_a		
(deg)	(kV)		(A)		
0	1.5		37		
15	1.8		35		
30	2.6		30		
45	4.0		20		
60	5.7		8.5		
75	7.8		3		
90	10.0		0		
V_0 =	10.0	kV	I_0 =	9.6	A
V_2 =	8.5	kV	I_2 =	16.2	A
P_0 =	96	kW	P_2 =	69	kW
η	72	%	R_2 =	524	Ω

- Find V_a and I_a in 15° steps

$$V_a = V_0 - V_2 \cos\theta$$

- Find I_0 and I_1 by numerical Fourier analysis

$$P_0 = I_0 V_0 \qquad P_2 = \frac{1}{2} V_2 I_2$$

$$\eta = \frac{P_2}{P_0} \qquad R_2 = \frac{V_2}{I_2}$$

- Initial estimate of I_{pk}/I_0 was too high
- Iterate for self-consistent solution

$$I_0 = \frac{1}{12}(0.5 I_{a0} + I_{a15} + I_{a30} + I_{a45} + I_{a60} + I_{a75})$$

$$I_2 = \frac{1}{12}(I_{a0} + 1.93 I_{a15} + 1.73 I_{a30} + 1.41 I_{a45} + I_{a60} + 0.52 I_{a75})$$

Calculation of performance (2)

- Grounded grid operation

$$V_1 = 80 + 240 = 320 \text{ V}$$

$$I_1 = I_2 + I_{g1\,RF} \approx I_2$$

$$R_1 = \frac{V_1}{I_1} = 20\ \Omega$$

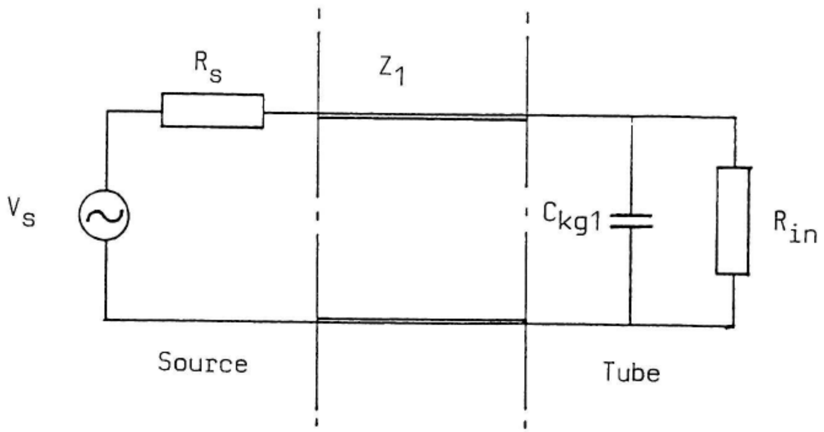
$$P_1 = \frac{1}{2} V_1 I_1 = 2.59 \text{ kW}$$

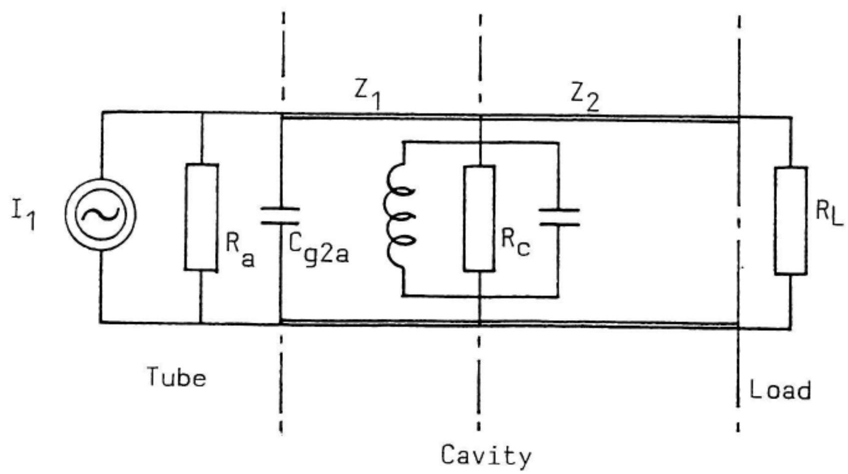
$$\text{Gain} = 10 \log_{10}\left(\frac{P_2}{P_1}\right) = 14.3 \text{ dB}$$

	Calculated	Measured	
V_0	10	10	kV
I_0	9.6	9.4	A
P_2	69	62	kW
P_1	2.6	1.8	kW
Gain	14.3	15.4	dB
η	72	64	%

W.Herdrich and H.P. Kindermann,
“RF power amplifier for the CERN SPS operating as LEP injector”,
CERN SPS/85-32, PAC 1985

Tetrode input and output circuits





(b)

- Input and output circuits are coaxial

$$Z_0 = 60 \ln\left(\frac{b}{a}\right) \quad \Omega$$

- *a* = inner diameter, *b* = outer diameter
- Characteristic impedance is very low (~ few ohms)
- Careful design of matching is essential

$$R_{in} = 20\ \Omega \quad X_{kg1} = 5.7\ \Omega$$
$$R_{out} = 524\ \Omega \quad X_{g2a} = 20\ \Omega$$

Cooling and protection

Anode Cooling

- Air
- Water
- Vapour phase

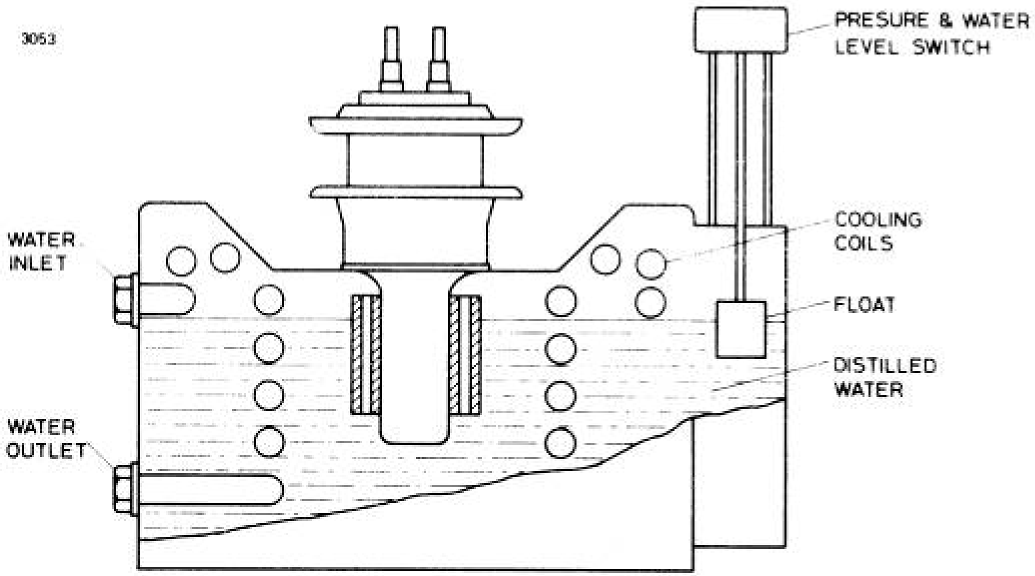


Image courtesy of e2v technologies

Protection

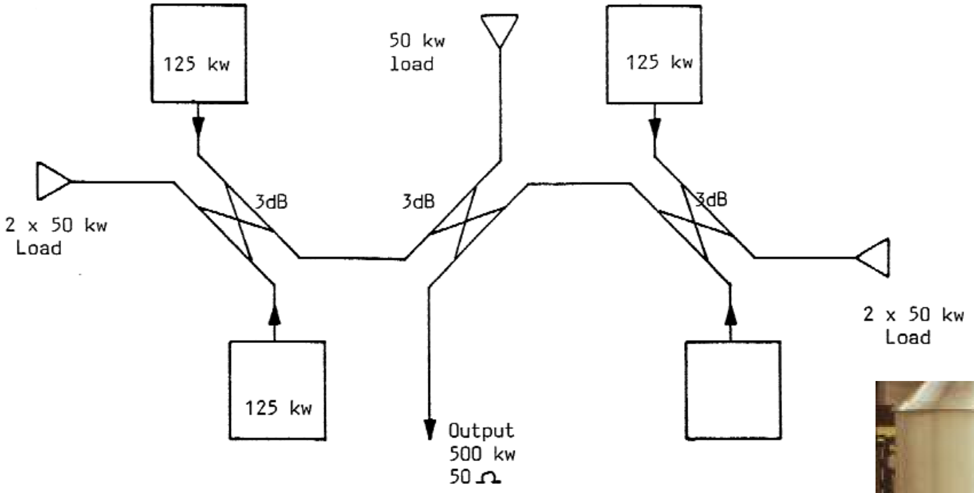
- Coolant flow
- Coolant temperature
- Tube temperature
- Anode, screen and grid overcurrent
- Anode voltage (fast)

Switch-on sequence

- Heater voltage
- Grid bias

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

Combining tetrode amplifiers



CERN SPS 200 MHz, 500 kW, amplifiers

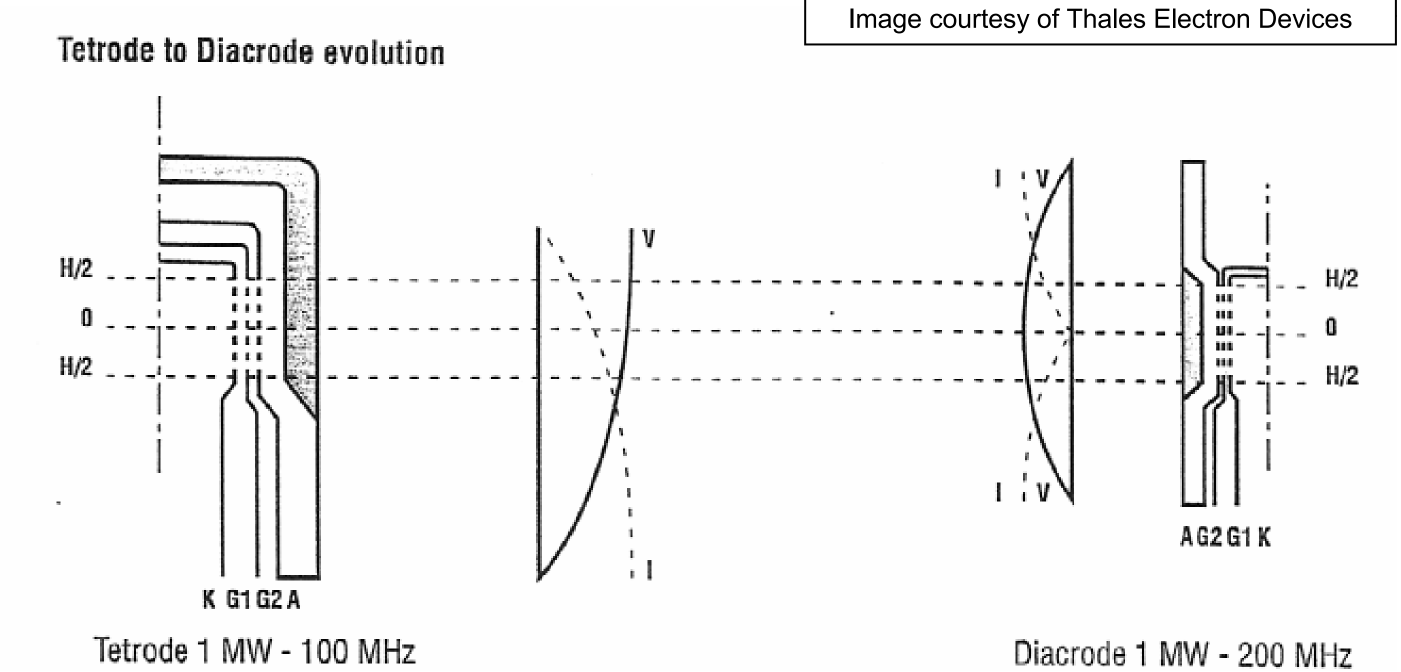
Photo courtesy of CERN

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

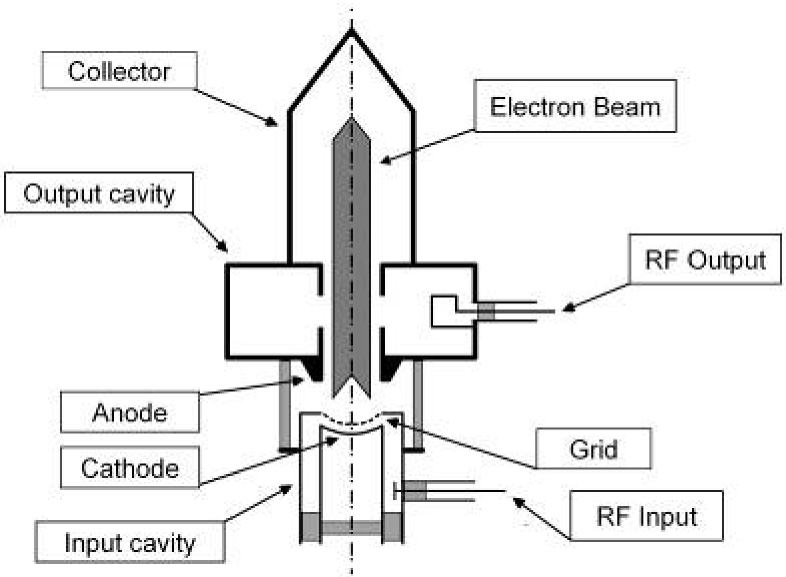
Image courtesy of Thales Electron Devices



Inductive output tube (IOT)

Differences from tetrode

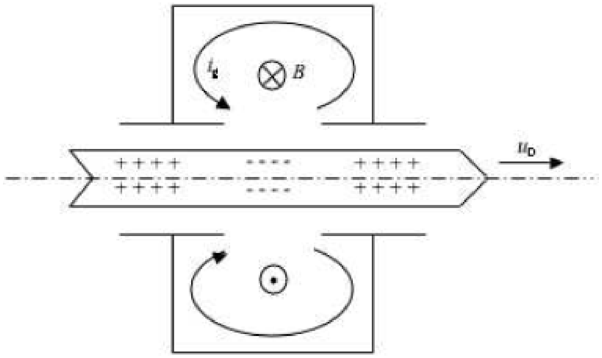
- Electron flow axial
  - Requires axial magnetic field to prevent beam spreading
- Anode voltage is constant
  - Electron velocity is high
- Bunched beam induces current in output cavity
- Separate electron collector
  - Large collection area
- Increased isolation between input and output

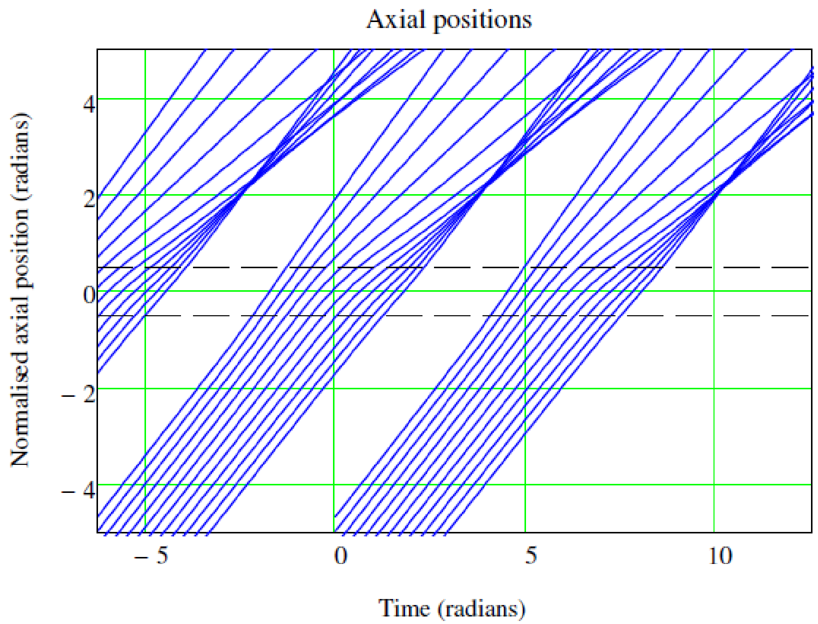


IOT output gap interaction

- 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%

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





UHF IOT for TV broadcasting

Frequency	470 - 810 MHz
Power	64 kW
Beam voltage	32 kV
Beam current	3.35 A
Gain	23 dB
Efficiency	60%

Photos courtesy of e2v technologies

Examples of IOTs for accelerators

Frequency	267	500	1300	MHz
Beam voltage	67	40	25	kV
Beam current	6.0	3.5	1.0	A
RF output power	280	90	16	kW
Efficiency	70	>65	62	%
Gain	22	>22	21	dB