Chapter 1.5

BASIC PRINCIPLES OF THE ELECTRON VACUUM TUBES

Institut für Hochleistungsimpuls- und Mikrowellentechnik (IHM)

Literatur Chapter 1.5

Shulim E. Tsimring, **Electron Beam and Microwave Vacuum Electronics**,
John Wiley & Sons, New Jersey 2007

M. Hein, **Schaltungen und Bausteine der HMT,**
TU Ilmenau

Gilmour, A. S., Jr., **Microwave Tubes**,
Artech House, Norwood, MA, 1986

Whitaker, Jerry C. **Power Vacuum Tubes Handbook**
Boca Raton, Morgan Hill, California, 2000

History

1864	Prediction of Radio Waves	J. C. Maxwell
1888	Experimental Evidence of Radio Waves	H. Hertz
1895	Signal Transmission over 10m	M. G. Marconi
1899	Idea of Power Transmission	N. Tesla
1901	Signal Transmission over the Atlantic Ocean	M. G. Marconi
1921	Magnetron	A. W. Wells
1926	Study of Power Transmission	H. Yagi, S. Uda
1928	Divided Anode-type Magnetron	K. Okabe
1935	Theory of the Klystron	Heil Family
1937	Klystron	Brothers Varian

ANNALEN
DER
PHYSIK UND CHEMIE.

BEGRÜNDET UND FORTGEFÜHRT DURCH
F. A. C. GREN, L. W. GILBERT, J. C. POGGENDORFF.

NEUE FOLGE.
BAND XXXI.
DER GANZEN FOLGE ZWEIHUNDERT SIEBENUNDSECHZIGSTER.

UNTER MITWIRKUNG
DER PHYSIKALISCHEN GESELLSCHAFT IN BERLIN
UND INSBESONDERE DES HERRN
H. VON HELMHOLTZ

HERAUSGEGEBEN VON
G. WIEDEMANN.

NEBST SIEBEN FIGURENTAFELN.

VI. *Ueber sehr schnelle electrische Schwingungen;*
von H. Hertz.
(Hierzu Taf. III Fig. 23—29.)

Die electrischen Oscillationen geöffneter Inductionsapparate haben eine Schwingungsdauer, welche nach Zehntausendtheilen der Secunde gemessen werden kann.[1]) Etwa hundertmal schneller erfolgen die Schwingungen oscillirender Flaschenentladungen, wie sie Feddersen beobachtete.

1) Für die Litteratur siehe Colley, Wied. Ann. **26.** p. 432. 1885.

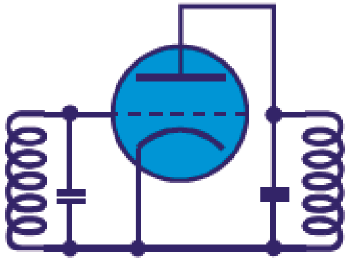
422 *H. Hertz.*

Schnellere Schwingungen noch als diese lässt die Theorie als möglich voraussehen in gutleitenden ungeschlossenen Drähten, deren Enden nicht durch grosse Capacitäten belastet sind, ohne dass freilich die Theorie zu entscheiden vermöchte, ob solche Schwingungen je in bemerkbarer Stärke thatsächlich erregt werden können. Gewisse Erscheinungen legten mir die Vermuthung nahe, dass Schwingungen der letztgenannten Art unter bestimmten Verhältnissen wirklich auftreten. und zwar in solcher Stärke, dass ihre Fernwirkungen der Beobachtung zugänglich werden. Weitere Versuche bestätigten meine Vermuthung, und es soll deshalb über die beobachteten Erscheinungen und die angestellten Versuche hier berichtet werden.

Appointment into operating principle

Evacuated glass, metal or ceramic vessel in which at least 2 electrodes are appropriated:
Cathode: Electron emitter, Anode: electron collector

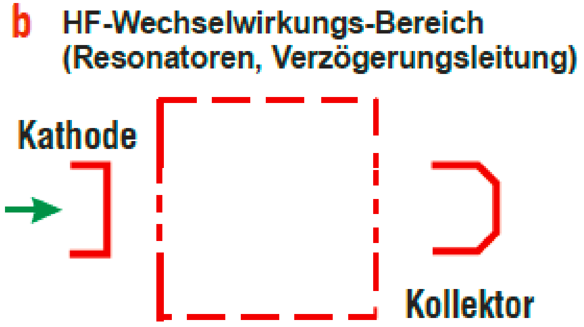
a



Grid controlled Tube
(< 200 MHz)

- Cathode and anode operate with DC and RF power, dimensions are limited

b

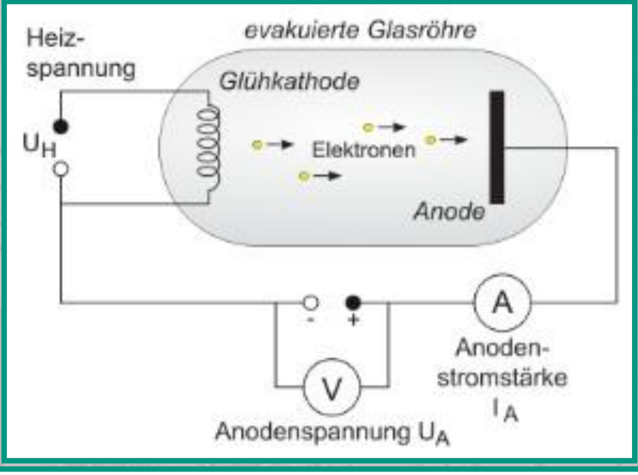


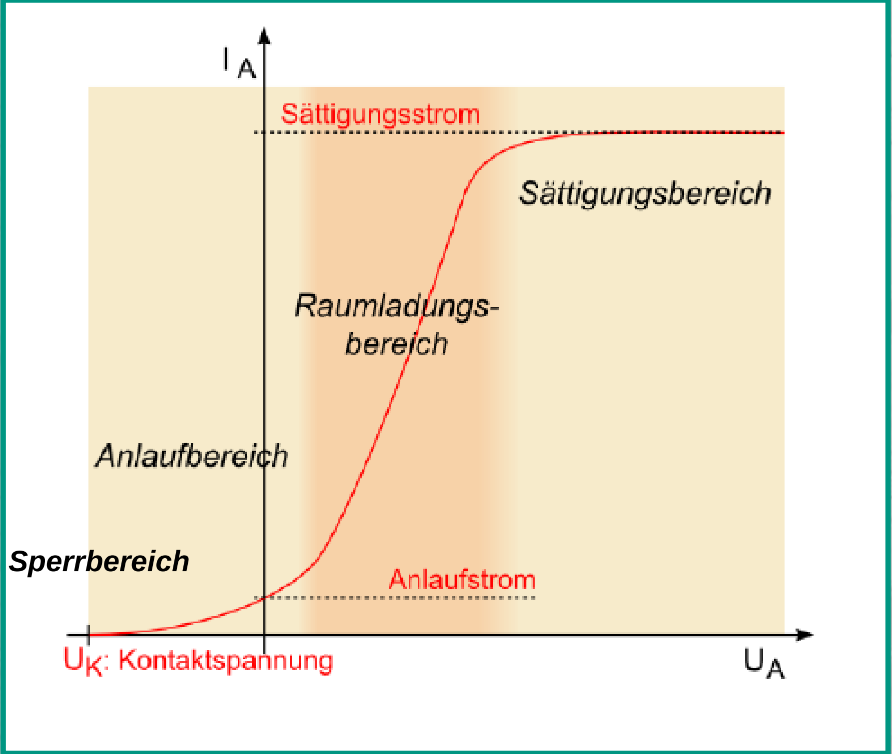
Elektronenstrahlanordnungen

- Cathode and anode (collector) are at the outside of the RF interaction region
- Opposite potential for efficiency increasing possible
- Electron transit time influences are usable:
  Velocity control
  Lengthwise: Klystron
  Crosswise: Gyrotron

Grid Controlled Tubes | **Elektron ray tube**

The classical vacuum diode





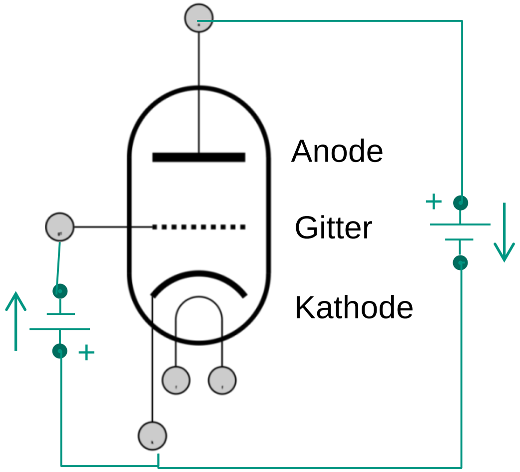
Starting range: Even if no voltage is applied, electrons will leave the cathode due to heating power of the filament. A few electrons travel towards the anode. At a constant contact voltage U_k, the current comes to a complete standstill. The current depends exponentially on the voltage.

Space Charge Area: The emitted electrons from the filament are captured in the space charge area in front of the hot cathode. The space charge insulate the effect of the anode. With increasing anode potential the amount of electrons travelling to the anode increase significantly. It appears an exponential characteristic increase in a huge voltage area. The dependency is described by the **Schottky-Langmuire Space Charge Law.**

$$J = \frac{4}{9}\varepsilon_0 \sqrt{\frac{2e}{m_e}} \cdot \frac{(U_A - U_K)^{\frac{3}{2}}}{l^2}$$

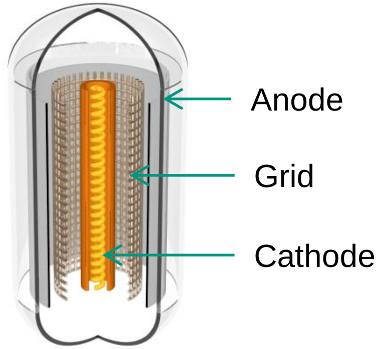
Saturation region: The space charge is dissipated. The current increases weaker. The electron reservoir is exhausted. The current achieves his maximum as soon as the space charge is completely disappeared. All electrons which leave the filament are directly attracted to the anode.

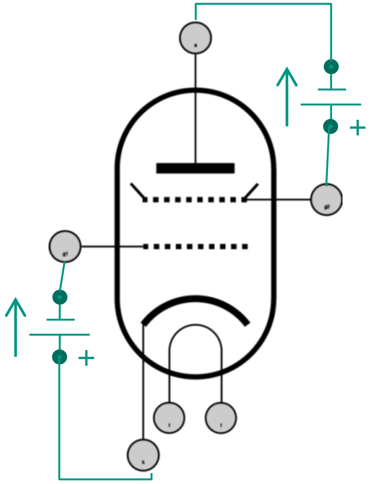
Improvement – grid controlled tubes



The **Triode** dispose of a scatter grid.

The current can be controlled by the grid voltage which is negative opposite to the cathode.

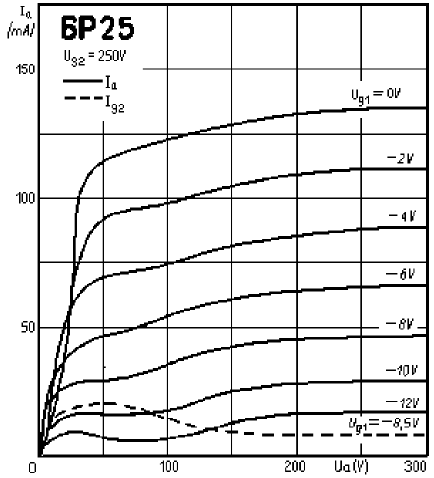


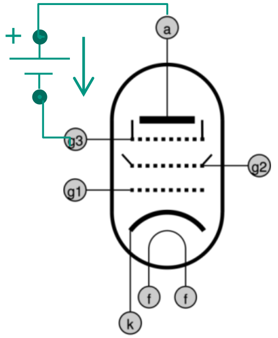


The **Tetrode** offers an additional shield (protection-) grid.

The shield grid is against the cathode with a constant voltage supplied. The control grid is shielded by the anode:

- This reduces the parasitic capacitance between the grid and the anode and therefore the „Miller“- effect (the reaction of the output to the input and therefore the tendency to oscillate)
- This reduces the appeared space charge effect between the cathode and grid.





At the **Pentode** the wide meshed suppressor grid (g3) prevents, that the secondary electrons, emitted from the anode, reach the shielding grid.

Barkhausen‘sche Tube Equation

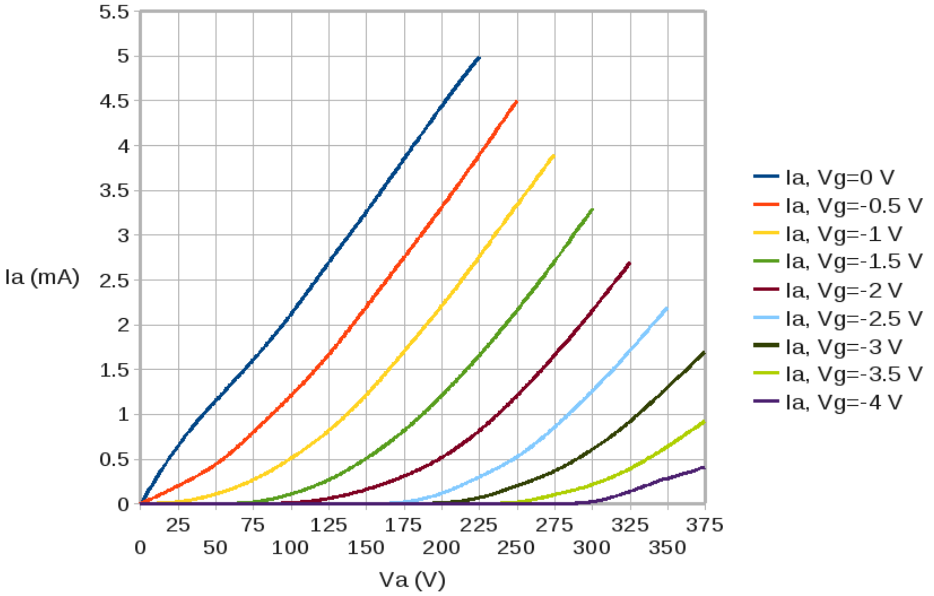
Control Factors

Transadmittance $S = \left.\frac{\partial I_a}{\partial U_g}\right|_{U_a=\text{const.}}$

Penetration factor $D = -\left.\frac{\partial U_g}{\partial U_a}\right|_{I_a=\text{const.}}$

$u_{st} = u_g + D \cdot u_a$

Internal resistance $R_i = \left.\frac{\partial U_a}{\partial I_a}\right|_{U_g=\text{const.}}$

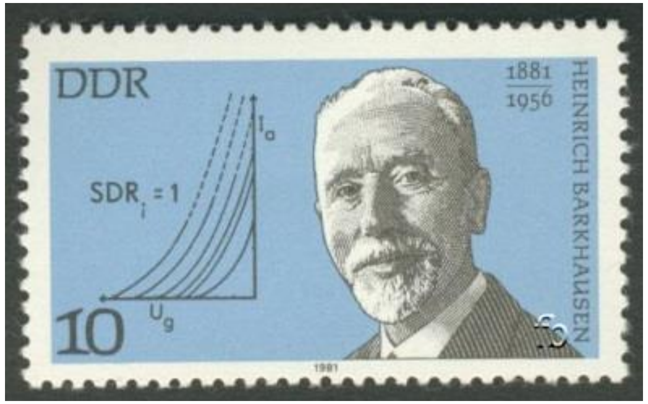


Barkhausen‘sche Tube Equation

$$dI_a = S \cdot dU_g + 1/R_i \cdot dU_a$$

$$dI_a = 0 \Rightarrow S \cdot D \cdot R_i = 1$$

The Barkhausensche tube equation is an application of the Euler‘sche chain rule for partial derivatives. Thereby I_a is assumed as a constant (so $dI_a = 0$).



Properties of a grid controlled tube amplifier

Grid controlled microwave Tubes

Properties at high frequencies

Transadmittance is getting complex Re{S} decrease with $\Theta = \omega\tau$

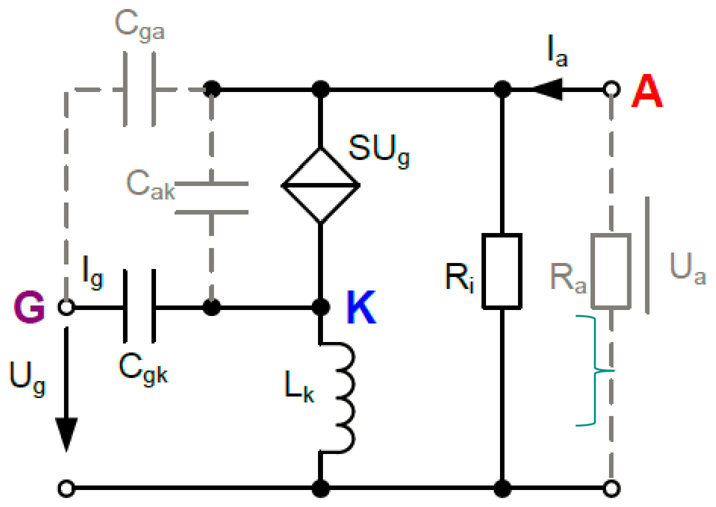
$$S(\omega) = S_0 e^{j\omega\tau}$$

Control uses power

(Input admittance: Re{Y} ~ $\Theta^2 \sim \omega^2$)

Effect of the tube reactance increase with the frequency f

Inductivity L_k, grid-cathode-capacity C_{gk}



Θ small → distances small
C small → area small
→ Current density high

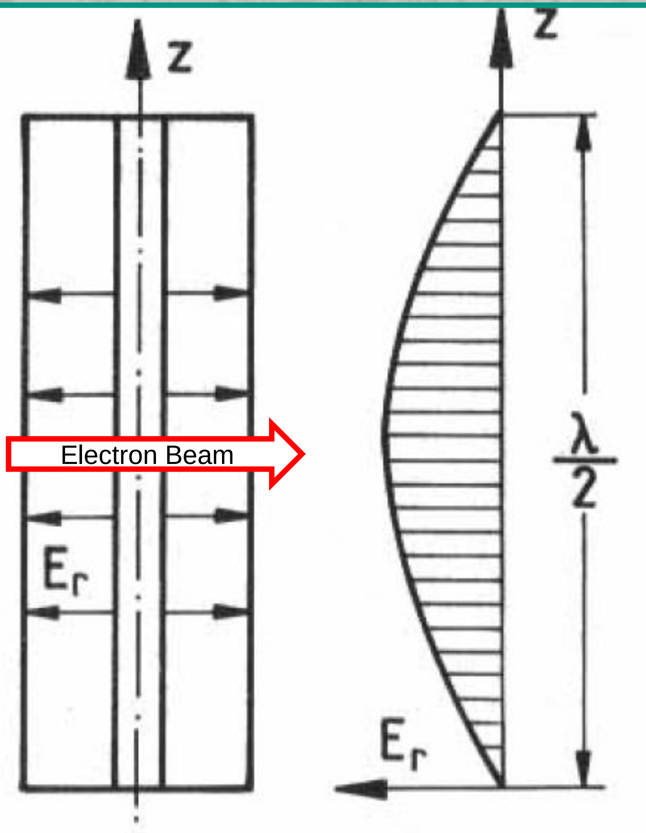
Opimal geometry enforce high current density

Example: Power Tetrode (6448)

www.röhrenmuseum.de

- **Application:** Coaxial Tetrode for RF- power levels till 1 GHz. All feedings are water cooled.
- **Heating:** direct;
  U_f = **1.35V**; I_f = 1000 A; t_h = 10 s
- **Maximum Ratings**
- U_a = 8 kV;
  P_a = 26kW; U_{g2} = 1000V;
  P_{g2} = 600W
- **Operating Data:**
  RF C-Amplifier (f = 450 MHz)
  U_a = 6.5 kV; I_a = 6 A
  U_{g2} = 800 V; I_{g2} = 0.5 A
  U_{g1} = -140 V; I_{g1} = 0.5 A

The pre-stage for the electron ray tube: The Heil‘sche generator

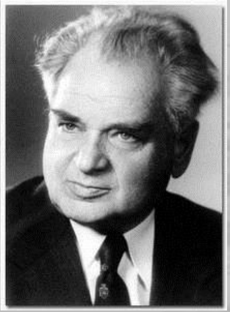


Oskar Ernst Heil (1908 - 1994) und
Agnesa N. Arsenjeva-Heil (1901 - 1991)

- **The three essentially elements of the Heil‘sche generator are:**
  - The velocity control (modulation) of a electron beam in a control field.
  - The bunching of the electrons in a drift space
  - The energy- (RF) extraction

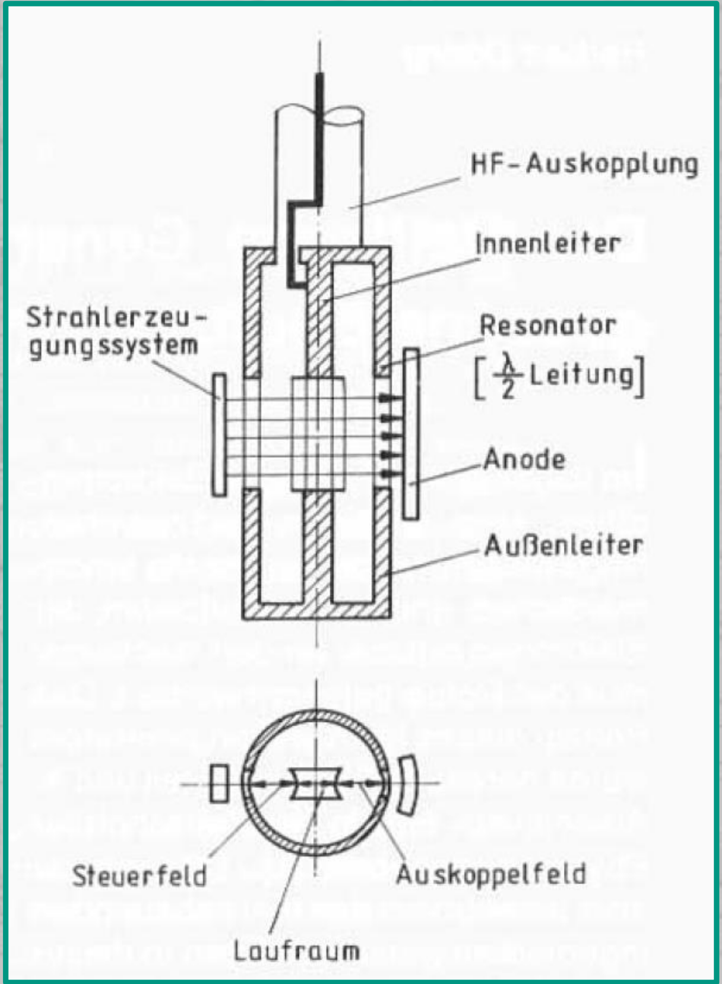
- **The functional basics:**
  - The TEM fundamental wave of a coaxial line resonator is excited.
  - An electron beam is feeded through the middle of the perforated resonator.
  - In the control field the electrons suffer a velocity modulation.
  - In the drift space (the perforated inner layer)the electrons are focused
  - The occurred charged packages influence current at the inner and outer layer when they passing through the bore hole.

The Heil‘sche generator (RD12 L)



Herbert Döring, 1911 - 2001

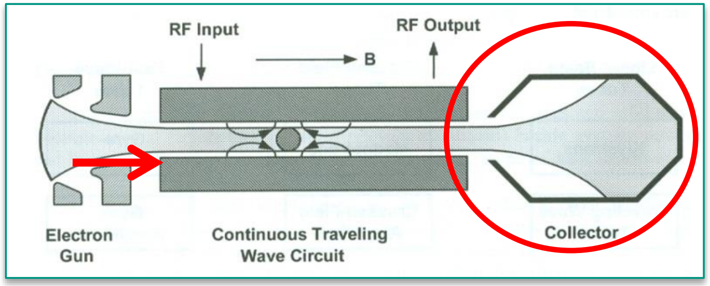
DC Power: ~100 W
RF-Power: 10 W – 20 W
U_a: 2 kV



One reason for the high capability: Disposal of the electron energy at the collector

The electron beam lose after the energy exchange with the electro magnetic field a huge amount of its kinetic energy. This energy was transferred into RF power. The residual energy is exhausted due to the creation of

- **Bremsstrahlung** (from roughly 1 kV as X-radiation) or rather as animation of a characteristic radiation by animation of metal atoms.
- **Heat** (production of lattice vibration)
- **Secondary electrons**



Additionally, the excessive kinetic energy can be re-converted by a retarding field into electric energy.

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Methods for heat dissipation

Cooling types	Cooling form	Characteristic
radiation	Graphit, Molybdän	The system is isolated without a contact outward. At power tubes the anode and grids are occupied with cooling fins.
air	Cooling fins	Disadvantage: heat transfer coefficient between air and a solid body is by the factor 50 to 100 lower than the heat transfer coefficient between water and the solid body.
Water and oil	From coolant flowed	Water (effective heat capacity C ~ 4,18 kJ/(kg·K))
Boil cooling	Water is vaporized	Temperatures above über 100 °C, Saturation of the evaporation heat (~ 2257 kJ/kg @100°C/1013 mbar)

→ 540x evaporation heat of water!

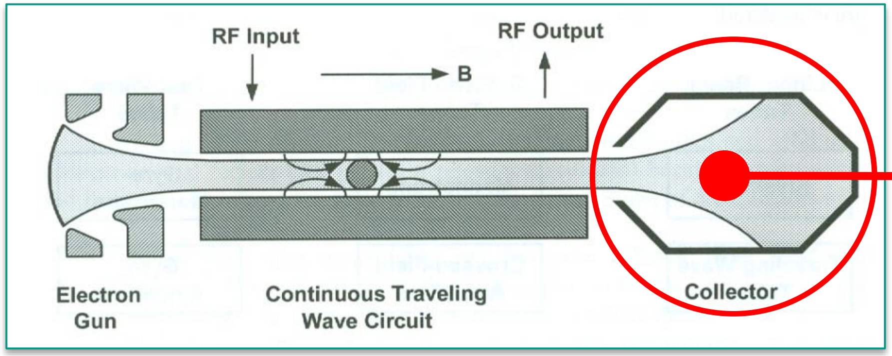
Example:

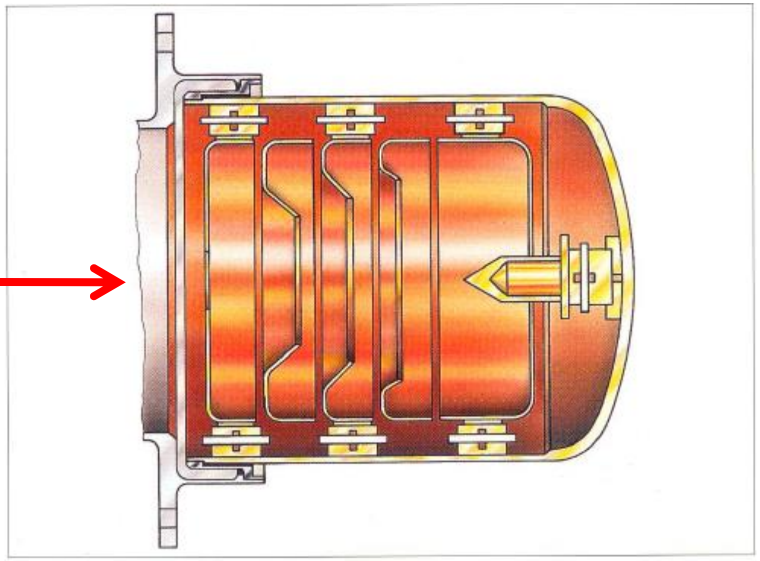
Radiation cooling

Air cooling

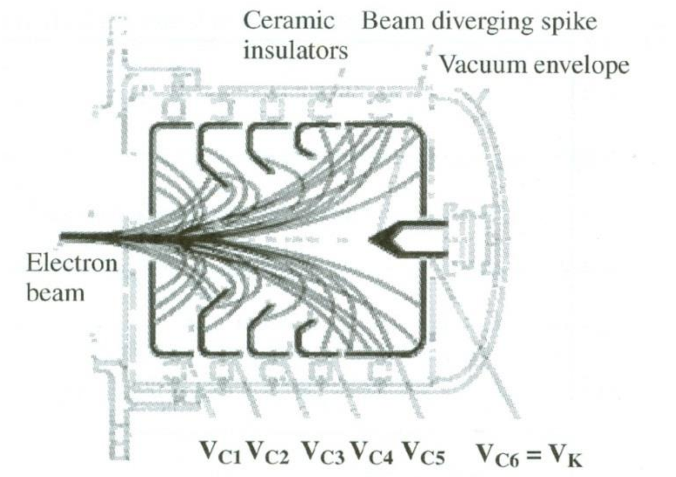
Evaporation cooling

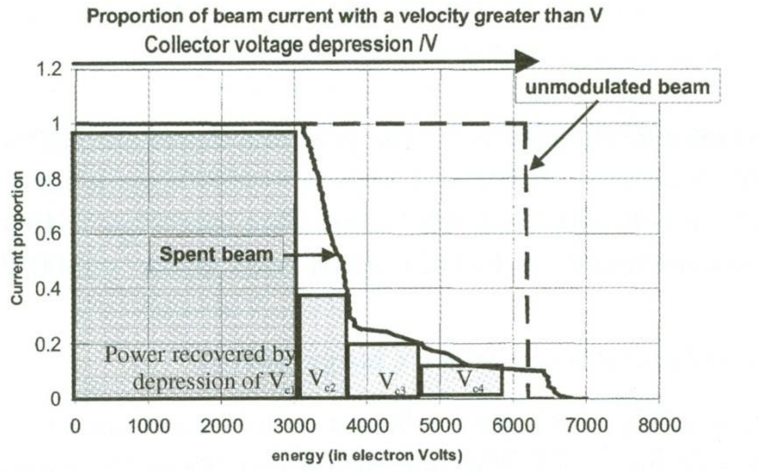
The principle of the energy recovery

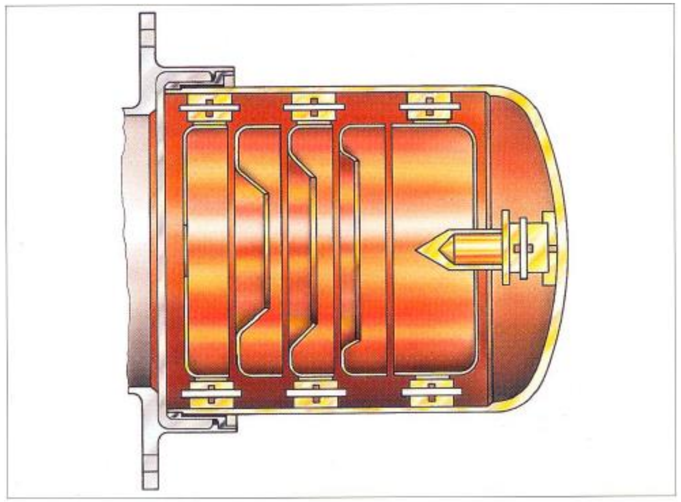




- The electrons are emitted with a almost similar kinetic energy.
- After the electron field interaction the electrons have a specified residual energy. Furthermore, a velocity modulation exist (typically 60 % - 105 %).
- In order to increase the efficiency, the **collector** is divided into one or more levels.
- The levels are isolated from each other and have a positive potential against the acceleration voltage.
- The electrons deliver their kinetic energy to the incidental **retarding field**.







P_0: Beam power

P_{rec}: am Kollektor zurückgewonnene Leistung

P_{out}: Recovered power at the collector

$$\eta_{tot} = \frac{P_{out}}{P_0 - P_{rec}}$$ Total efficiency

$$\eta_{el} = \frac{P_{out}}{P_0}$$ electrical efficiency

$$\eta_{col} = \frac{P_{rec}}{P_0(1-\eta_{el})}$$ collector efficiency

$$\rightarrow \boxed{\eta_{tot} = \frac{\eta_{el}}{1-\eta_{col}(1-\eta_{el})}}$$

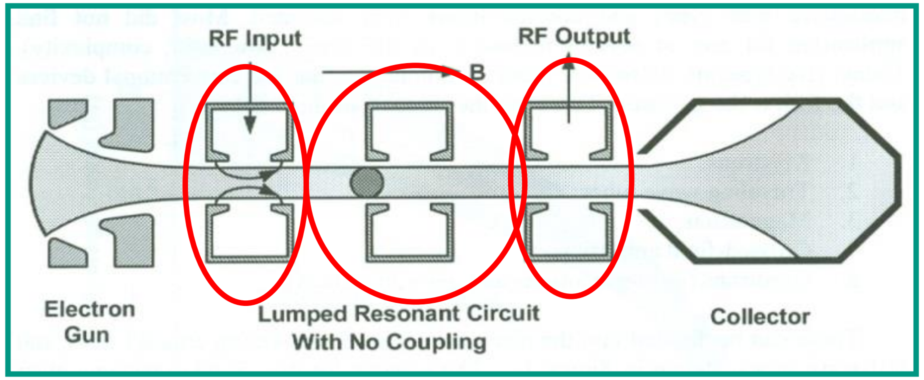
Appointment of the electron ray tubes towards the type of the interaction with the EM field

Karlsruher Institut für Technologie

- **Vakuum-tubes**
  - Grid controlled tubes
  - **Classical electron ray tubes**
    Phase velocity
    $V_{ph} \sim v_{el}$
    - **Drived tube**
      - **One cycle**
        Reflexklystron
      - **Multi cycle**
        Zweikammerklystron
    - **Travelling field tube**
      - **Linear beam tubes**
        Without magnetic Cross field
        („O-type“)
        Travelling Wave Tube
      - **Cross field tubes**
        mit magnetischem Querfeld
        („M-type“)
        Magnetron
  - **Gyrotron**
    Phase velocity
    $v_{ph} >= c$

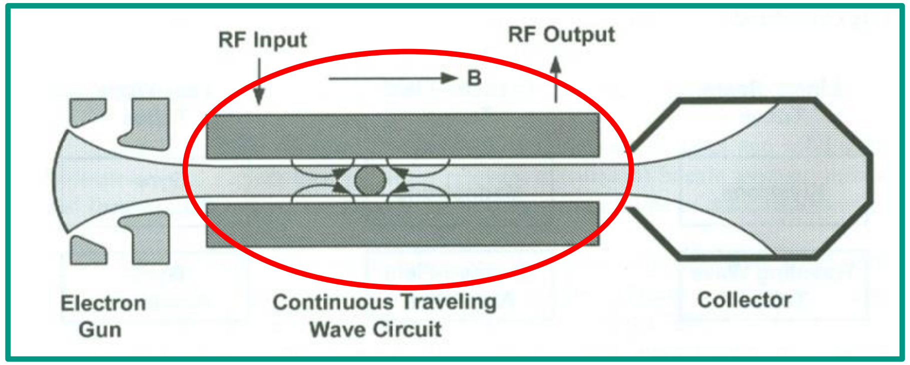
Example:

Drift tube: The Klystron (see Heil'scher generator)



1. **Velocity modulation at the entrance cavity**
2. **Phase focusing in the drift room**
3. **Energy extraction**

Travelling field tube: TWT



1. **Velocity modulation and phase focusing in the drift room.**
2. **Interaction with an electro magnetic wave, for this applies**

$$V_{ph} \sim V_{el}$$

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Cross field tube: The Magnetron