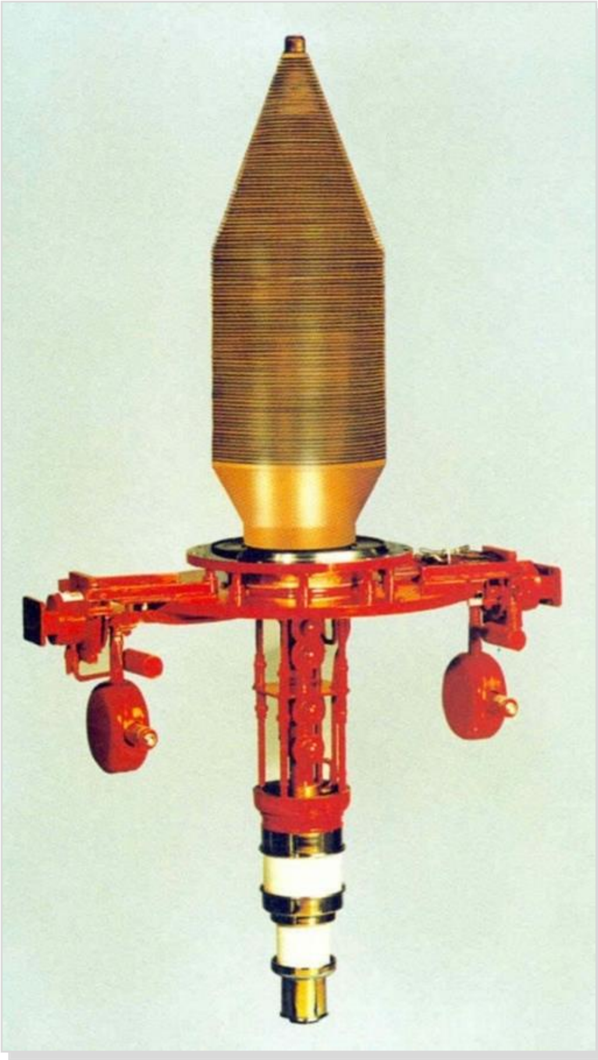
Section 3.1

KLYSTRON



Interaction Principle of Klystron

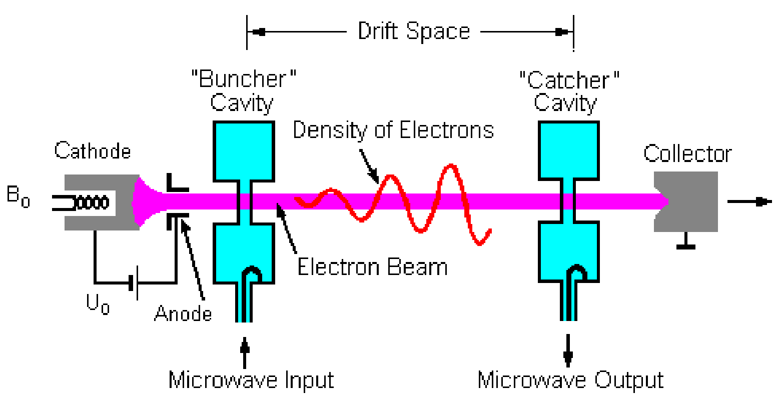
Greek:

Klystron

Klyzein = Braking of Waves — **Place of Action**

1935 **O. Heil,**
A. Arsenjeva-Heil: **Theory of Linear Beam Device**

1937 **R.H. Varian,**
S.F. Varian: **First Experiments at 2.3 GHz „Rumbatron"**



(1) Two-Cavity Klystron:

(a) Input Cavity : Velocity Modulation (powerless)

⬇

(b) Drift Tube : Density Modulation Electron Bunching

⬇

(c) Output Cavity : Generation of Strong Microwaves by Current Induction

(2) Multi-Cavity Klystron (for high output power)

High Current ⇒ Space-Charge Effects ⇒ Weaker Modulation

(d) Intermediate Cavities (Idler Cavities)

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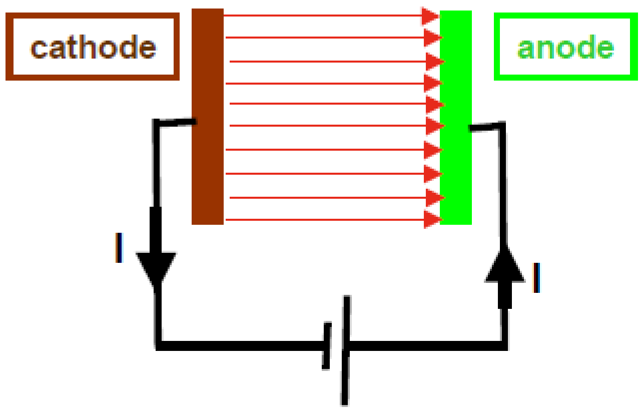
General Principle of Electron Beam Tubes (I)

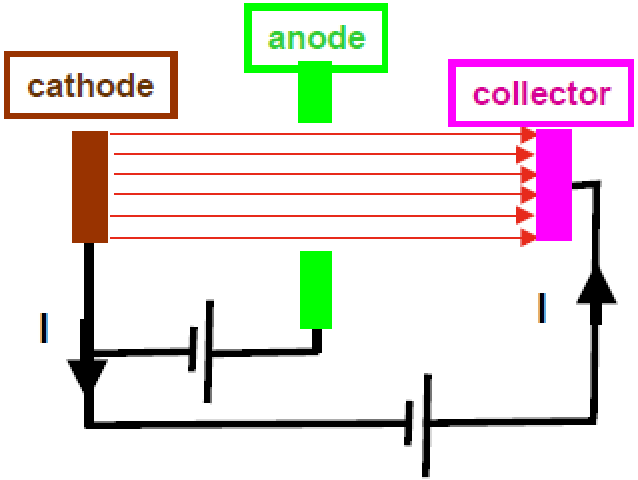
Voltage („anode voltage") between cathode (negative) and anode (positive)

Elektrons are emitted from cathode and then accelerated between cathode and anode

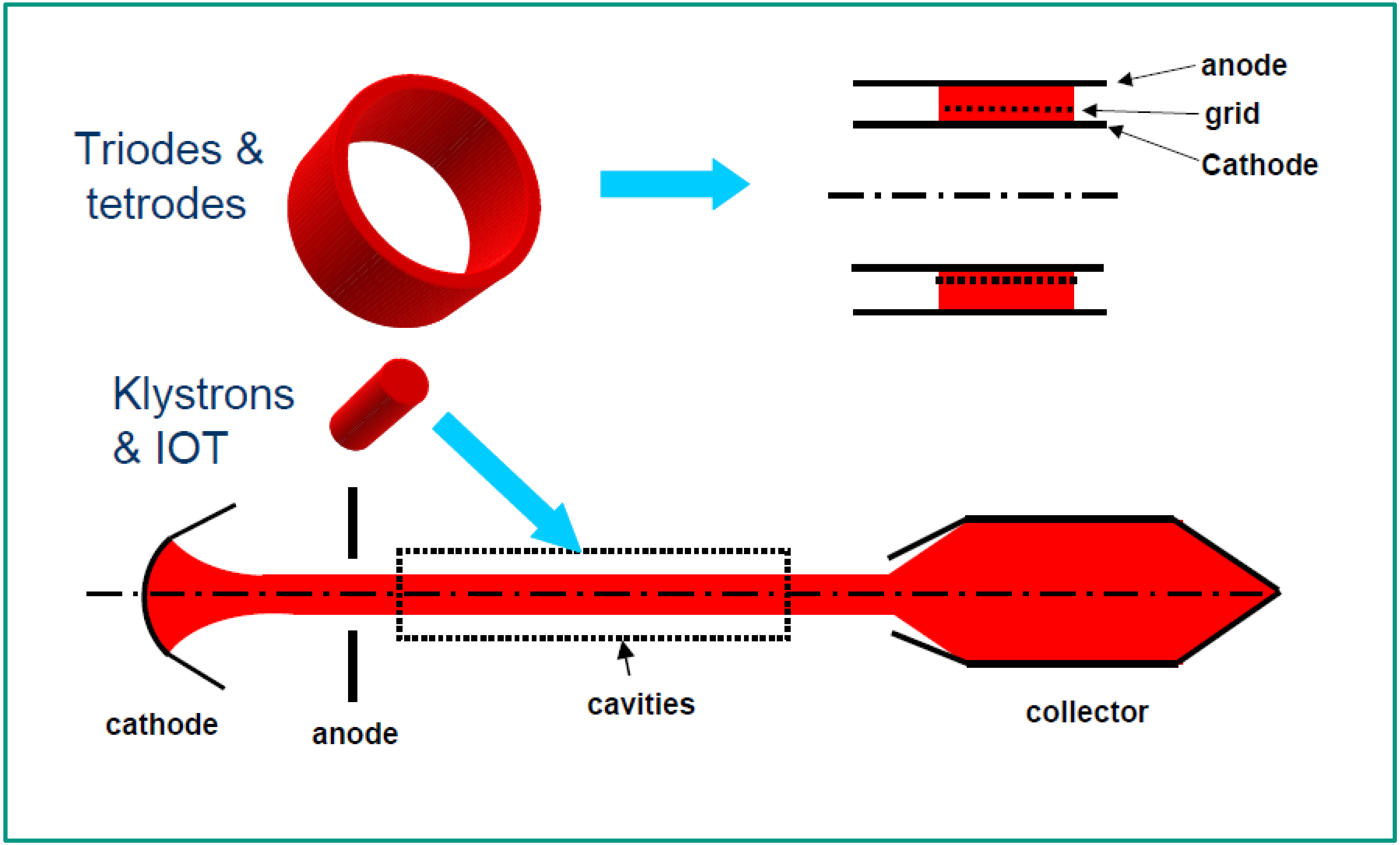
In contrast to grid-controlled tubes, the electrons are catched by the collector and not by the anode

A simple collector without energy recovery (not depressed) is at the same potential as the anode (usually: ground).





General Principle of Electron Beam Tubes (II)



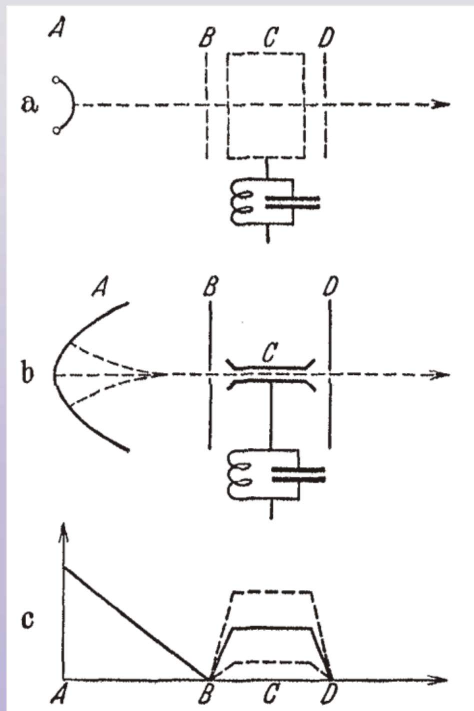
Oskar Ernst Heil (20.03.1908 - 15.05.1994)

Karlsruher Institut für Technologie

Eine neue Methode zur Erzeugung kurzer, ungedämpfter, elektromagnetischer Wellen großer Intensität.

Von **A. Arsenjewa-Heil** und **O. Heil** in Bormio.

Mit 10 Abbildungen. (Eingegangen am 20. April 1935)



A : cathode

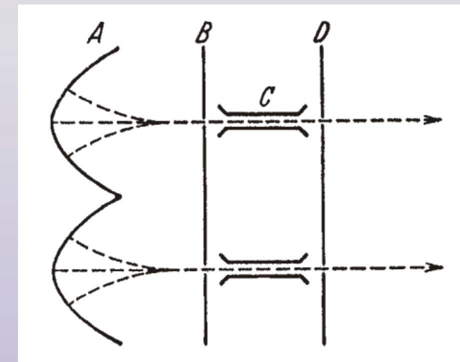
B,D : anode

C : resonance circuit (influence)

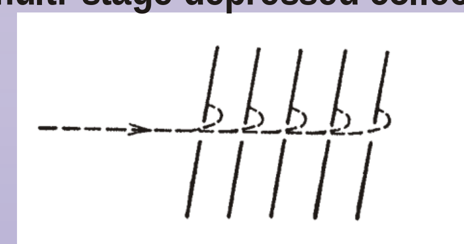
velocity modulation

density modulation

two-beam electron gun

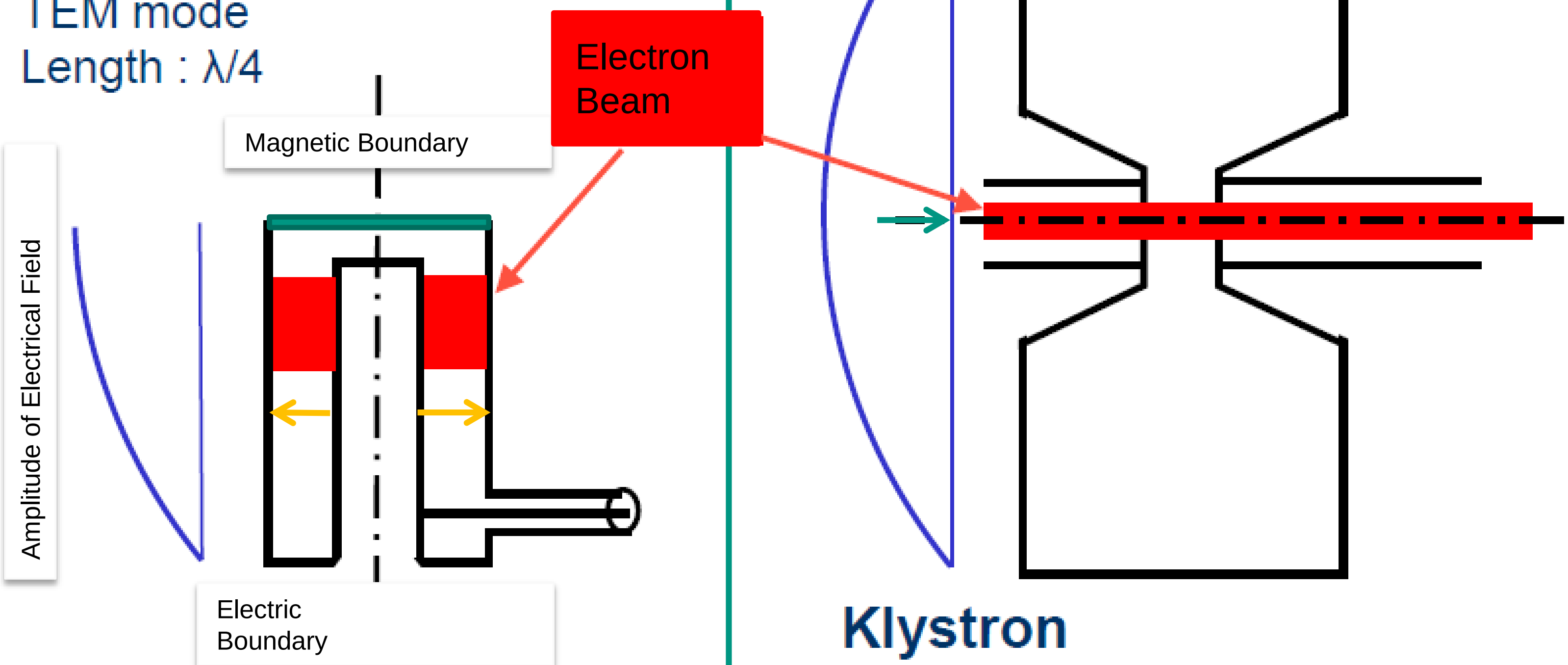


multi-stage depressed collector



Interaction Circuit („Resonator“, „Cavity“)

triode
coaxial cavity
TEM mode
Length : λ/4



Klystron
Pill box cavity with noses
TM01 mode
Diameter : λ/2

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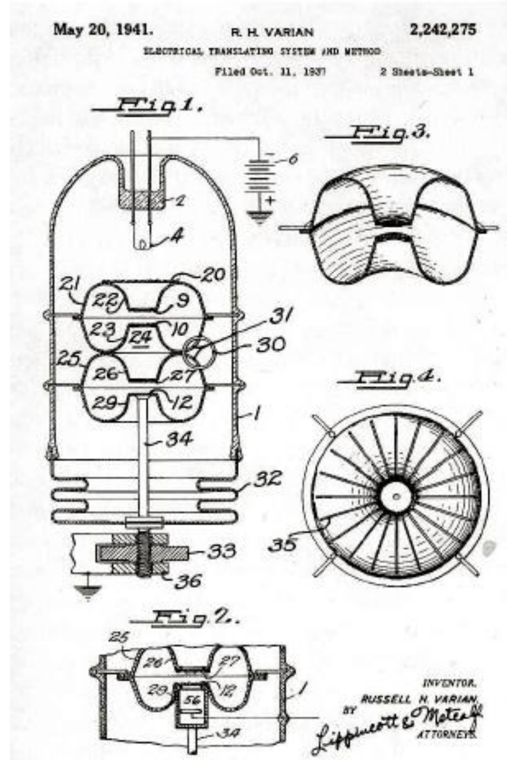
The First Klystron



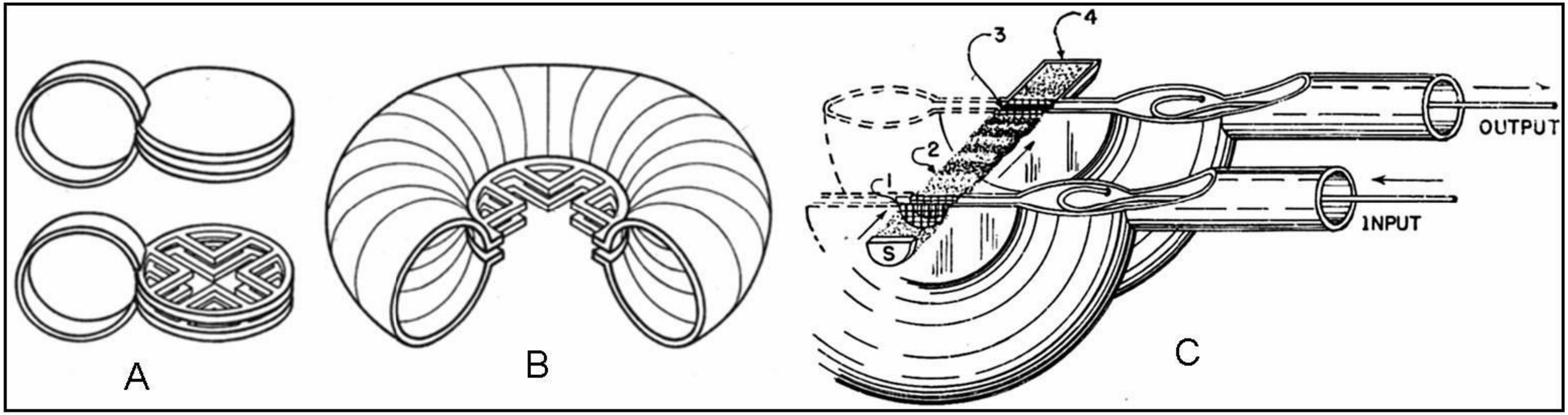
A High Frequency Oscillator and Amplifier

Russell H. Varian and Sigurd F. Varian
Stanford University, California

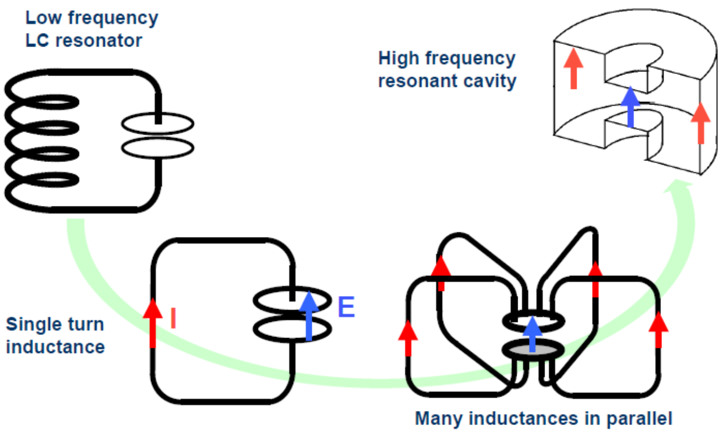
(Received January 6, 1939)

A d.c. stream of cathode rays of constant current and speed is sent trough a pair of grids between which is an oscillating electric field, parallel to the stream and of such strenght as to change the speeds of the cathode rays by appreciable but not too large fractions of their initial speed. After passing these grids the electrons with increased speeds begin to overtake those with decreased speeds ahead of them. This motion groups the electrons into bunches separated by relatively empty spaces. At any point between the grids, therefore, the cathode-ray current can be resolved into the original d.c. plus a nonsinusoidal a.c. A considerable fraction of its power can then be converted into power of high frequency oscillations by running the stream trough a second pair of grids between which is an a.c. electric field such as to take energy away from the electrons in the bunches. These two a.c. fields are best obtained by making the grids form part of the surfaces of resonators of the type described in this Journal by Hansen.

The Rumbatron: First Klystron

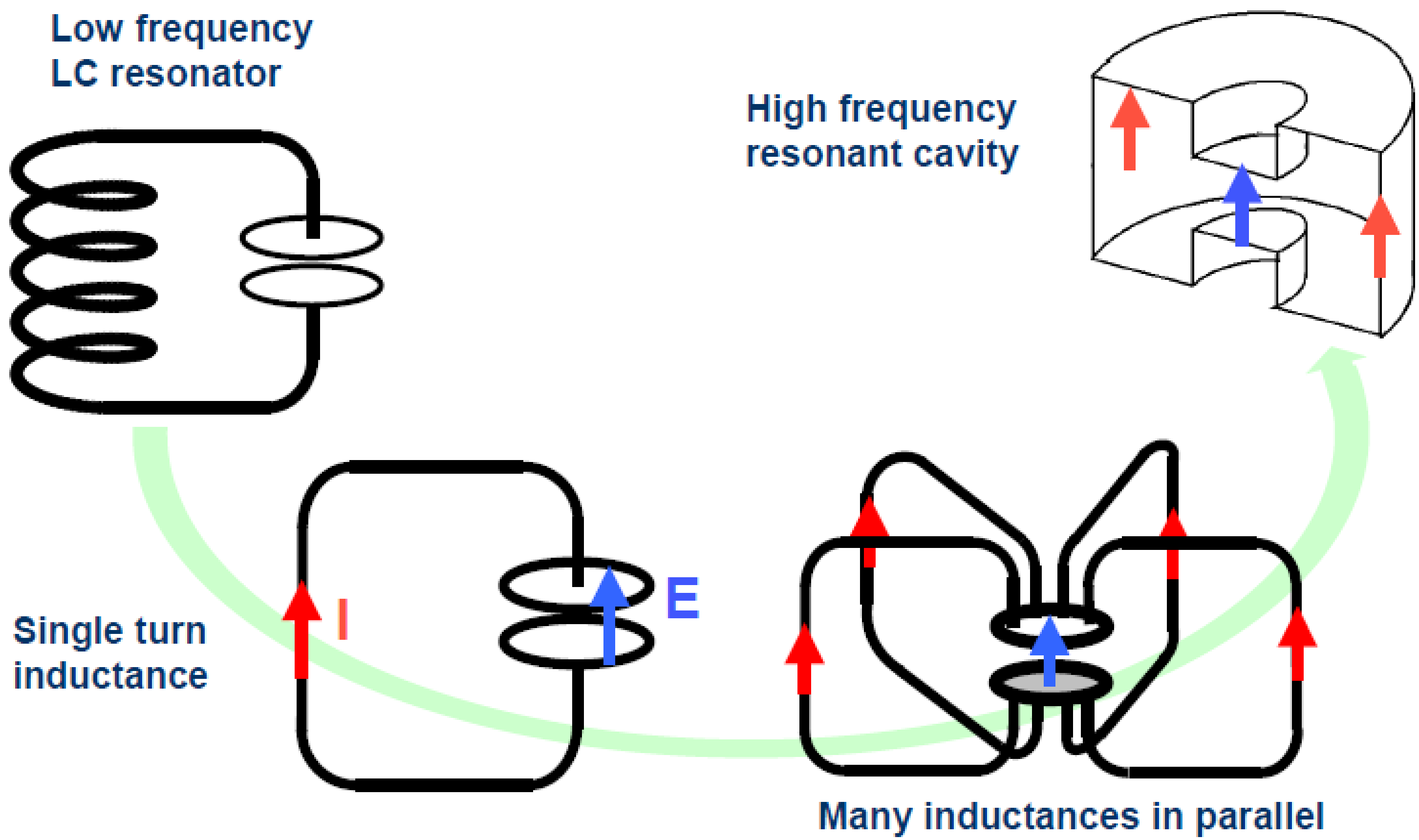


S: Electron source
(1): Slit of Bunching Resonator
(2): Drift Tube - for Generation of Electron Bunches
(3): Slit of Output Resonator
(4) Catcher



Equivalent LC Circuit

Klystron Cavity: Equivalent Circuit



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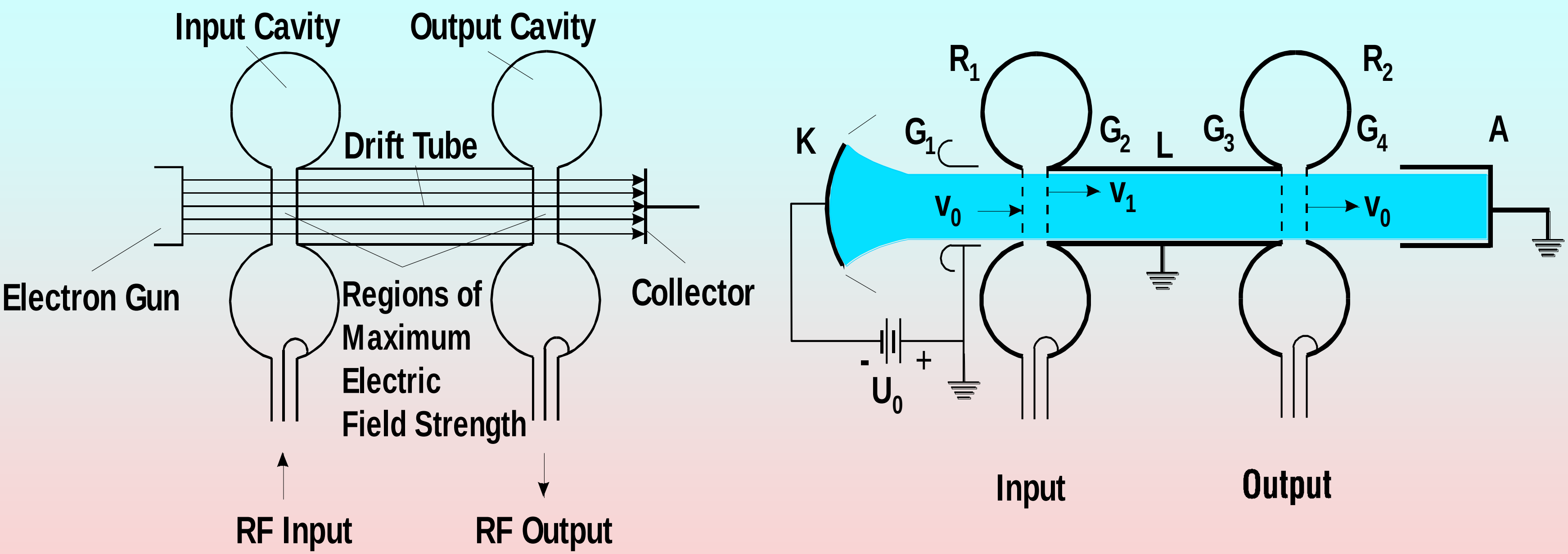
Scheme of Two-Resonator Klystron Amplifier



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Interaction in a Klystron: Modulations and Energy Extraction

Pierce type of electron gun generates an electron beam:

$$I_0 = P\,V_0^{3/2}$$

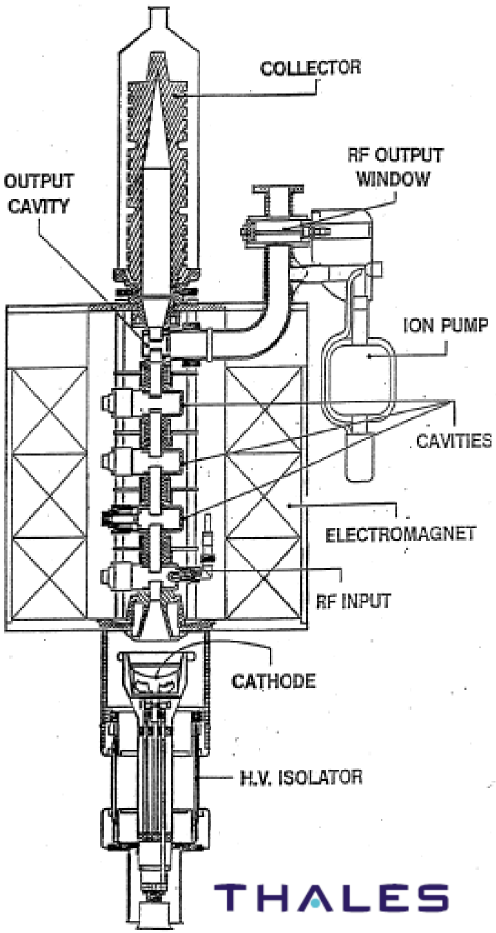
with P = perveanvce

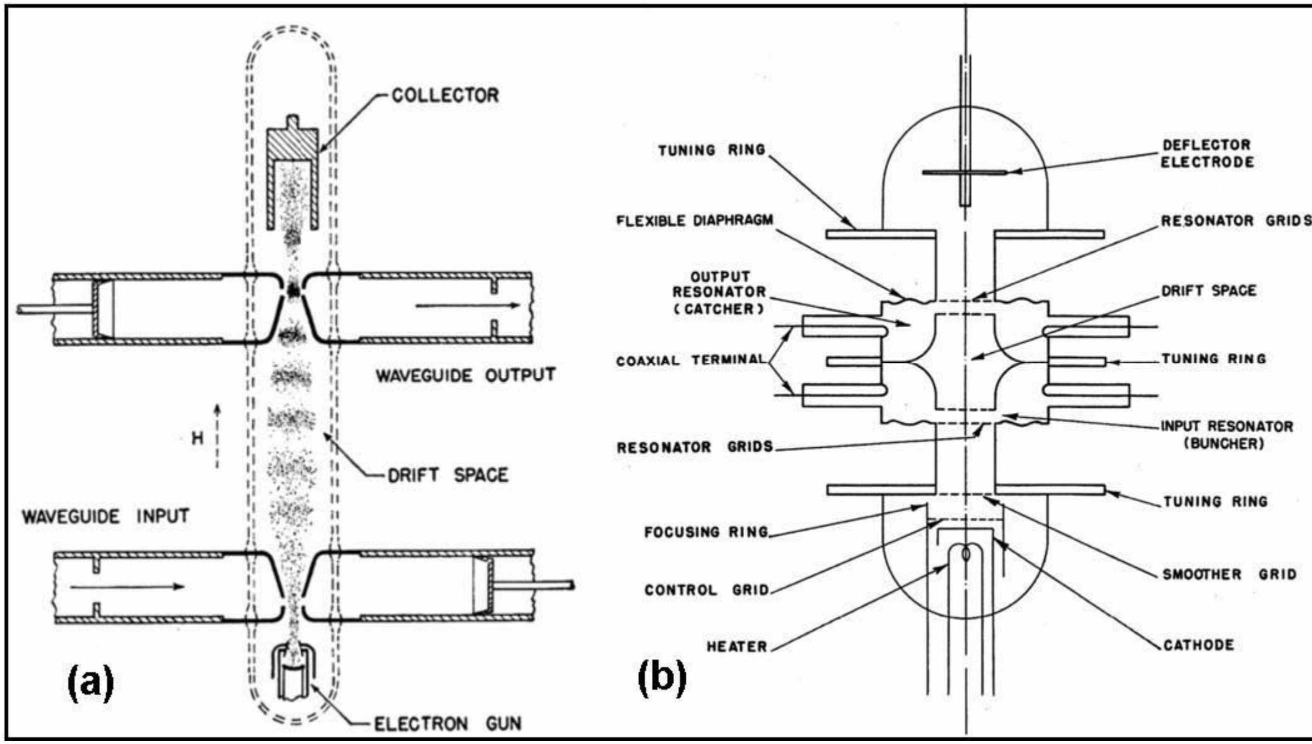
Input Cavity: TM_{110} (rectangular) or TM_{010} (circular)

Drift Tube: Cut-off for EM-waves
Velocity modulation → Density modulation

Output Cavity: Extraction of energy

Real Construction of a Two-Cavity Klystron





The „Pillbox“ TM_{010}-Mode Cavity

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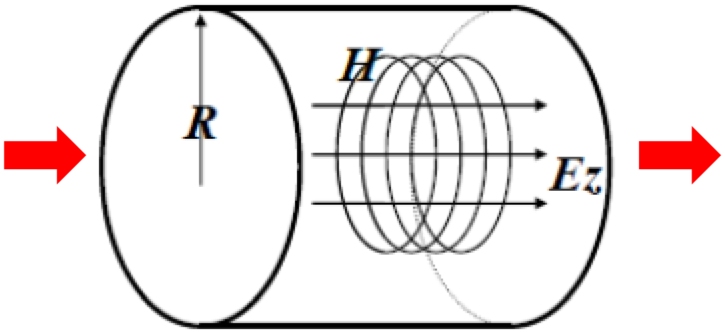
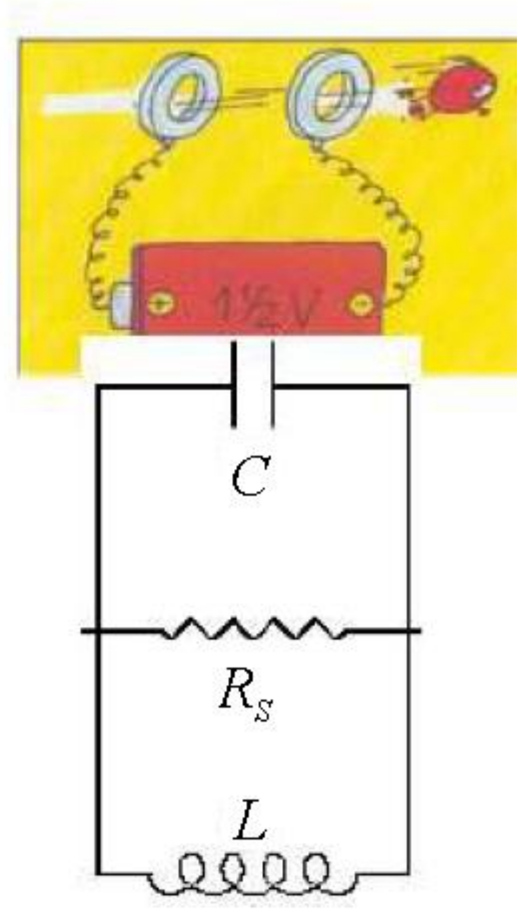
TM_{010} mode



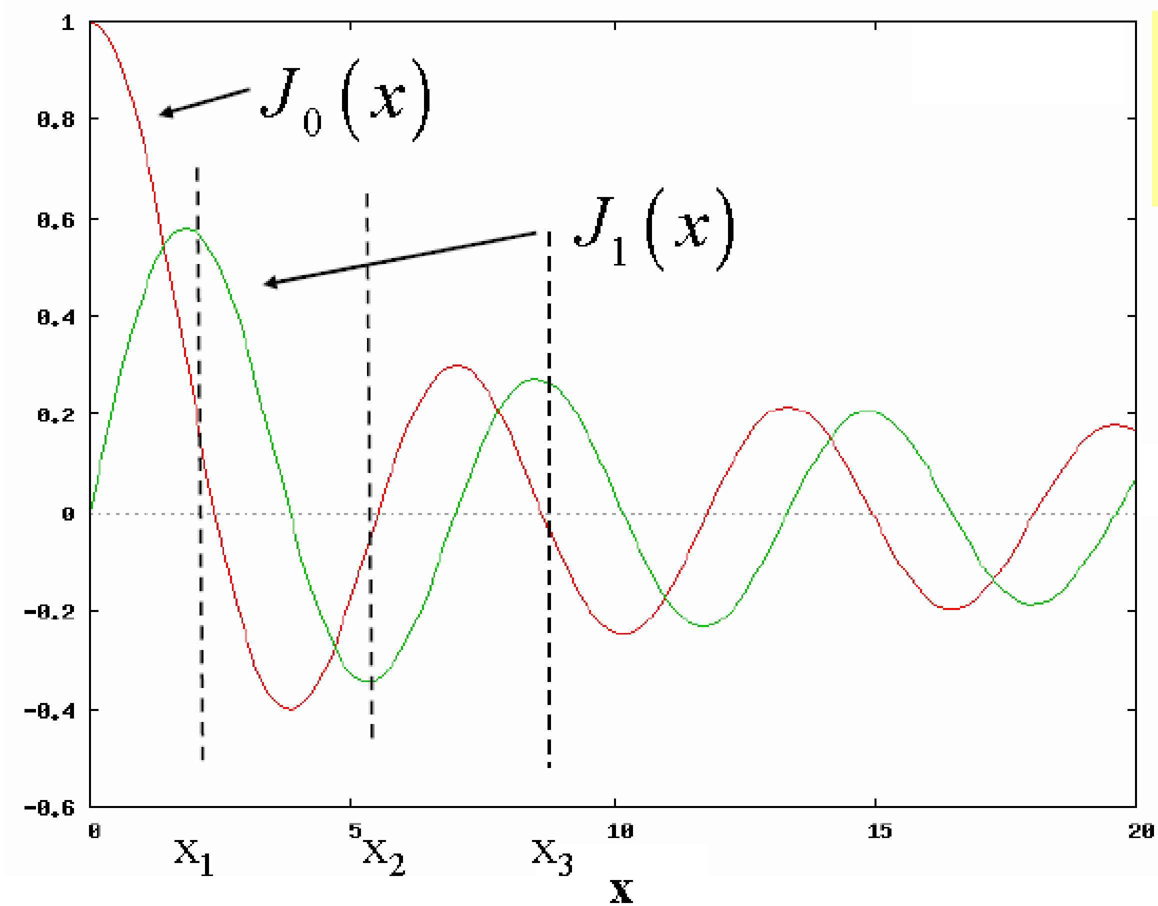
$$E_z = E_0 J_0\left(\frac{2.405r}{R}\right)e^{-i\omega t}$$

$$H_\varphi = -iH_0 J_1\left(\frac{2.405r}{R}\right)e^{-i\omega t}$$

$$\omega_{010} = \frac{2,405c}{R}$$



Bessel Functions



$$f_{010} = \frac{c}{2\pi}\frac{2.405}{R}$$

Example:

$f_c = 50MHz$ R = 230 cm

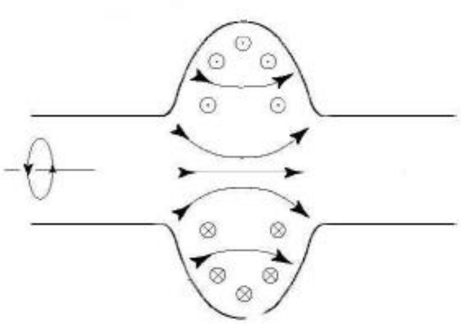
$f_c = 500MHz$ R = 23 cm

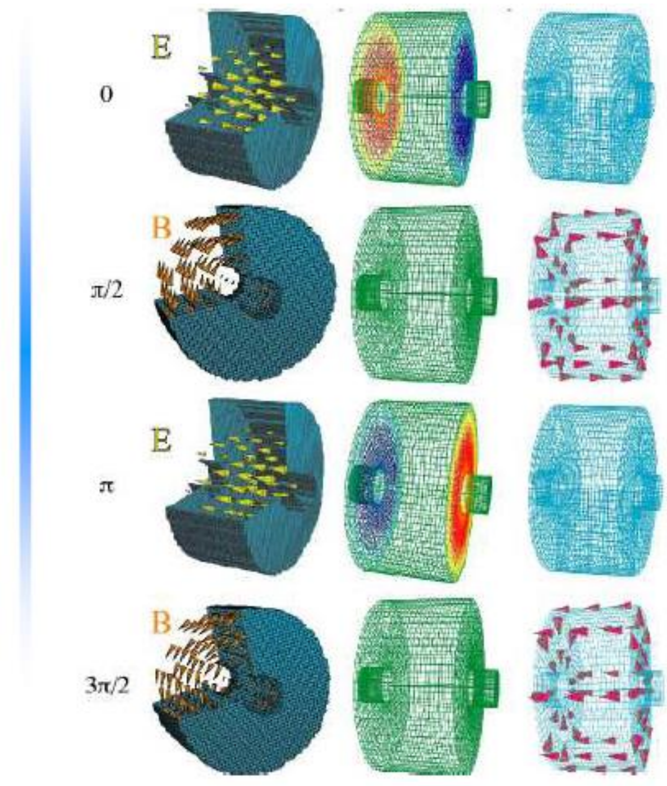
$f_c = 1300MHz$ R = 8,85 cm

$f_c = 3GHz$ R = 3,8 cm

Fields and Currents in Pill-Box Cavity

FE or FDTD
Calculations





Phase Fields Surface Charges Currents

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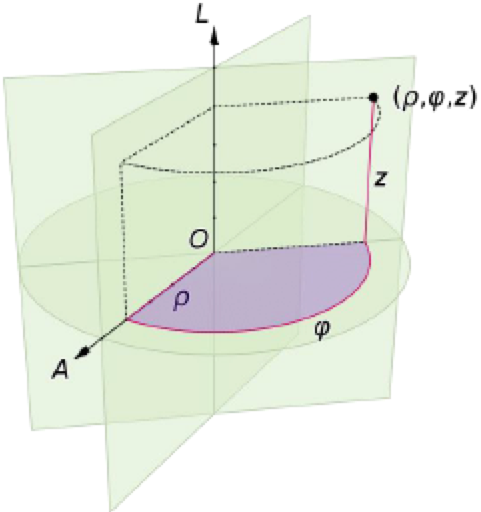
Possible Modes in Pill-Box Cavity

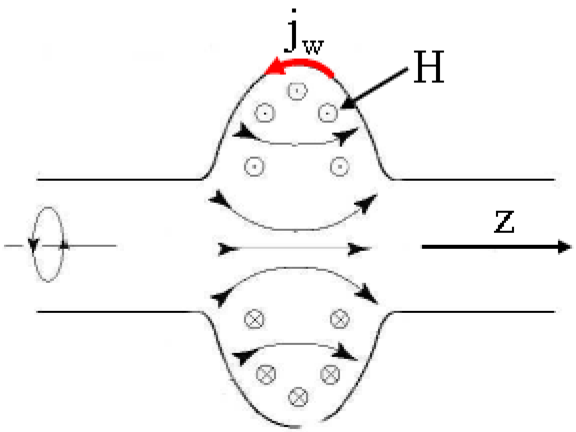
- TM_{010}
  - Electric field is purely longitudinal
  - Electric and magnetic fields have no angular dependence
  - Frequency depends only on radius, independent on length
- TM_{0np}
  - Monopoles modes that can couple to the beam and exchange energy
- TM_{1np}
  - Dipole modes that can deflect the beam
- TE modes
  - No longitudinal E field
  - Cannot couple to the beam

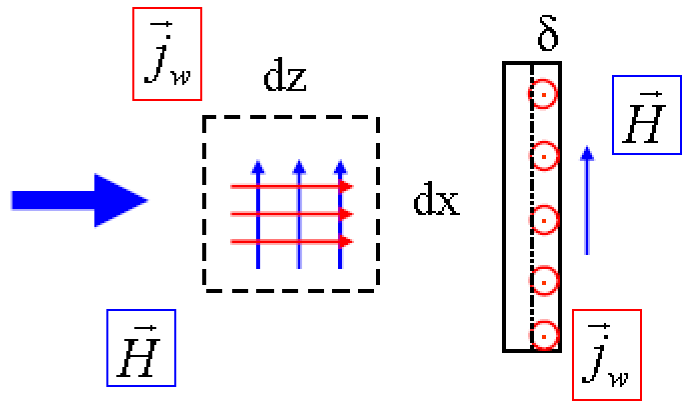


$$TM_{mnp}$$

The integer indices m, n, and p are measures of the number of sign changes E_z undergoes in the ϕ, ρ, and z directions, respectively.

Wall Currents, Skin Effect, Wall Losses

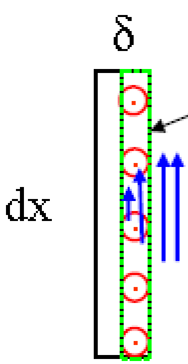




$$rot\vec{H} = \vec{j}_w + \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \quad \left(\varepsilon_0 \frac{\partial \vec{E}}{\partial t} = 0\right)$$

δ= Skin Depth

Exponential Decay of *H* and *j* in Wall
Sceening by Eddy Currents



$$\oint_S \vec{H}\, d\vec{s} = \iint_{F(S)} \vec{j}_w\, d\vec{F}$$

$$H_w dx = j_w \delta dx$$

$$H_w = j_w \delta$$

$$\delta = \sqrt{\frac{2\rho}{\omega_0 \mu_0}}$$

$\rho = 1/\sigma =$ Specific Resistance

Cavity Characteristics

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- **Resonance Frequency**: Frequency $f_{r,}$ for which the stored energy is maximum

- **Stored Energy:** W_s:

$$W_s\left(f_r\right)=\iiint_V \frac{1}{2}\varepsilon\left|\vec{E}\left(f_r\right)\right|^2 \mathrm{dxdydz}$$

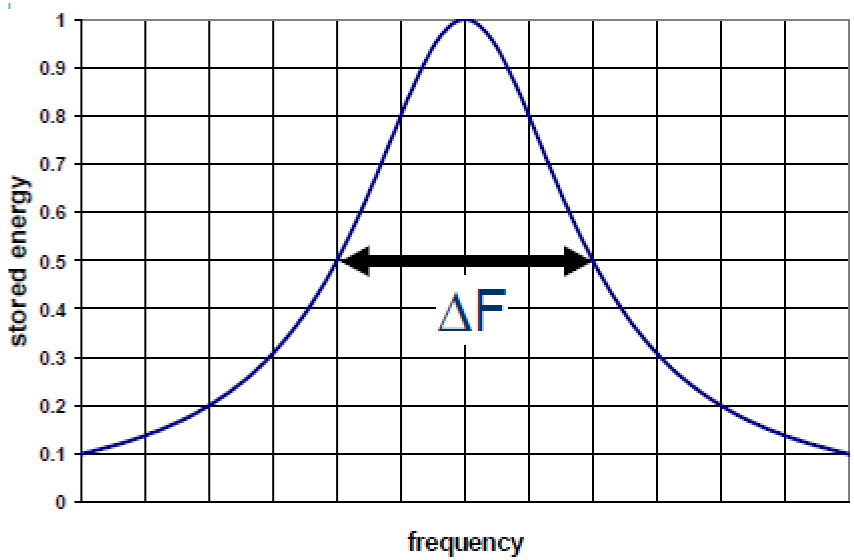
- **Filling Time:** Time needed to store the maximum energy at the resonance frequency.

Definition of Cavity Bandwidth

Bandwidth of resonator ΔF is defined as frequency range in which the stored energy is larger than half of the maximum stored energy at the resonance frequency.

The „Quality Factor" Q_L is defined as

$$Q_L = \frac{f_r}{\Delta F}$$



Quality Factor of a Cavity

The quality factor of a resonator depends on its losses.

There are the following three parts of the total quality factor:

- **unloaded quality factor Q_0** related to the wall losses (skin effect)

$$Q_0 = \omega \frac{stored\ energy}{cavity\ power\ losses} = 2\pi \frac{stored\ energy}{energy\ loss\ during\ one\ period}$$

- **external quality factor Q_X** related to the coupling losses (hole , electric antenna , magnetic loop)

$$Q_{ext} = \omega \frac{stored\ energy}{coupling\ losses}$$

- **Loaded quality factor Q_L** , taking into account all losses :

$$Q_L = \omega \frac{stored\ energy}{total\ losses} \qquad \frac{1}{Q_L} = \frac{1}{Q_o} + \frac{1}{Q_{ext}}$$

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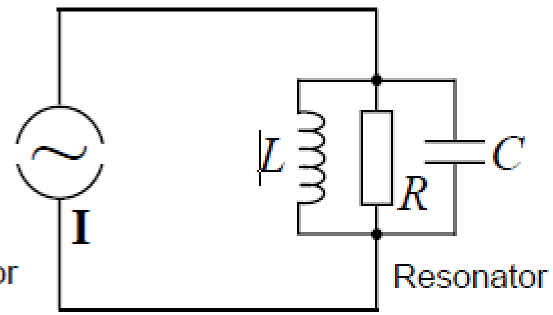
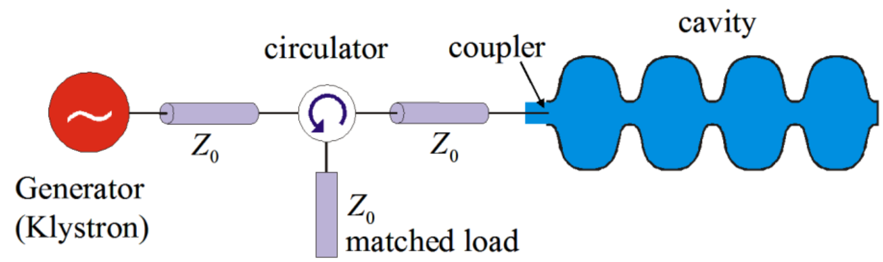
The Complete Equivalent Circuit of Cavity

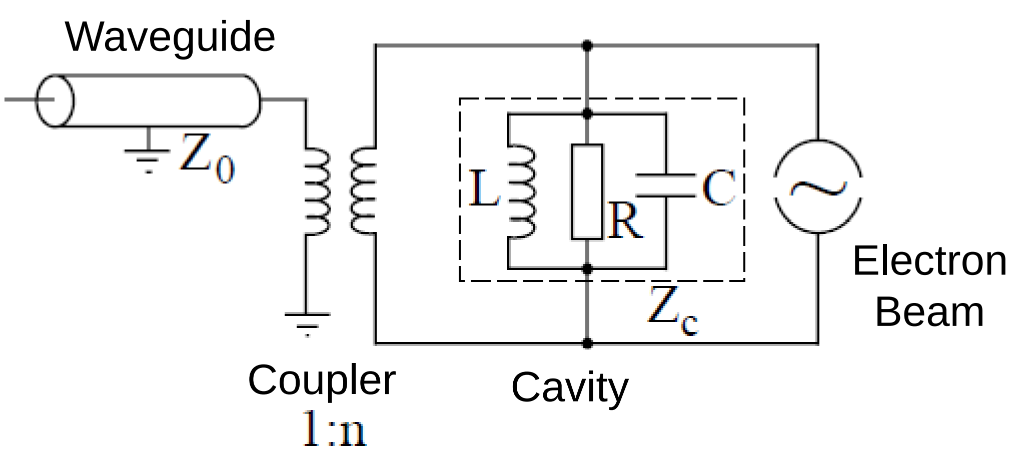
Electron beam is the current source

$$\mathbf{Z}_c = \frac{R}{1 - iR\left(\frac{1}{\omega L} - \omega C\right)}.$$





Coupling to the input or output waveguide

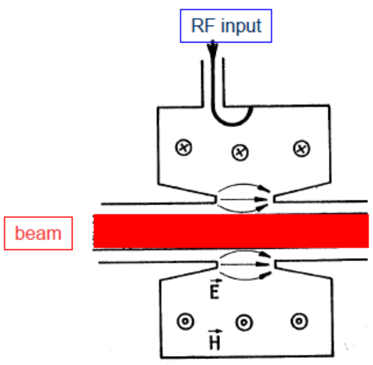


Interaction Principle:
Electric Field in Slit of Cavity

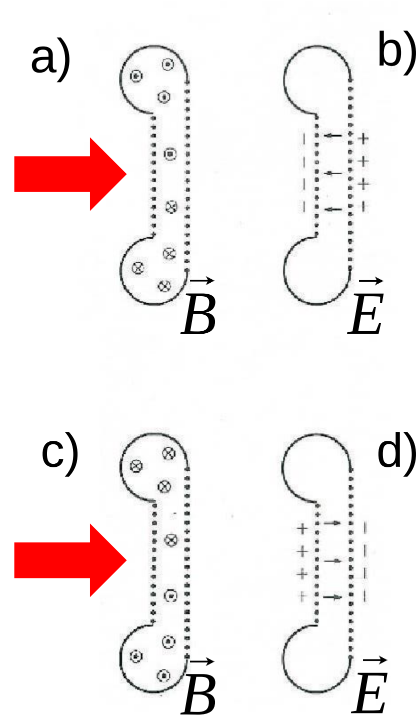
Impedance of resonator is different from that of input waveguide

$$P_{Reflected} = P_{Input} \cdot \Gamma^2$$

Γ : Reflection Factor



Goal: Form of resonator and coupler has to be optimized to get maximum longitudinal electric field on the axis of the electron beam.

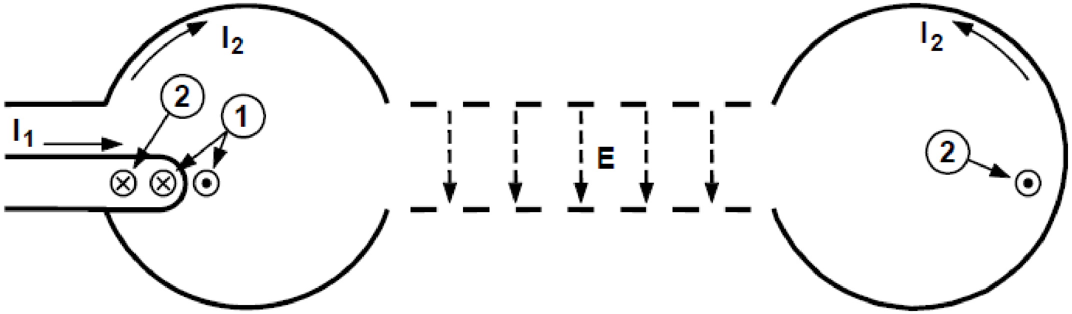


Fields in velocity bunching resonator at times a) t = 0, b) t = 1/4T, c) t = 1/2T d) t = 3/4T

Then follows the next cicle.

Functional Principle

- RF Current I_1 is injected into the coupling loop
- As a result, a magnetic field is established → induce a current flow I_2 in the cavity wall
- The resulting flow of charge produces an electric field, E, across the capacitive portion of the cavity.
- As the RF input current I_1 oscillates, the magnetic field, the current I_2 and the electric field E are all caused to oscillate.
- The oscillating electric field bunches the electrons in the first cavity.
- When energy **is extracted** from a cavity by a coupling loop, the situation **is reversed.**



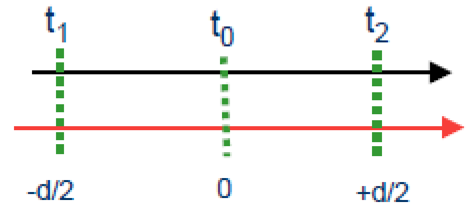
Velocity Modulation in Slit of First Cavity

Ansatz:

The electric field is periodical in time: $\vec{E} = E \sin \omega t$

Force on electron in the cavity slit: $\vec{F} = e \cdot E \sin \omega t$

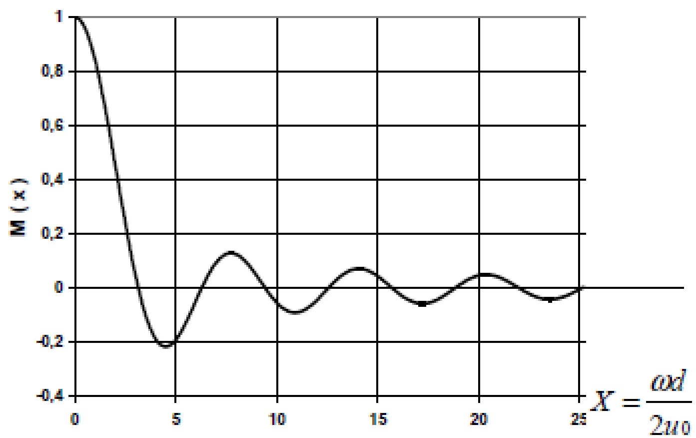
$$m \frac{du}{dt} = m \frac{d^2 z}{dt^2} = e\, E \sin \omega t \qquad \frac{1}{2} m u_0^2 = e V_0$$



$$\frac{dz}{dt} - u_0 = -\frac{eE}{m\omega}\left(\cos \omega t_2 - \cos \omega t_1\right) = \frac{2eE}{m\omega} \sin \omega t_0 \, \sin \frac{\omega d}{2 v_0}$$

$$u(t_2) = u_0 \left[1 + \frac{E\,d}{2 V_0} \left(\frac{\sin \frac{\omega d}{2 u_0}}{\frac{\omega d}{2 u_0}} \right) \sin \omega t_0 \right]$$

$$M\left(\frac{\omega d}{2 u_0}\right)$$



V_0: Voltage in slit

u: Electron velocity

d: Length of cavity slit

M: Coupling coefficient

From the First to the Drift Tube (I)

Assuming several simplifications, the square of the Voltage in the first cavity V_1^2 is proportional to:

$$P_d\left[1+Q^2\left(\frac{f}{f_0}-\frac{f_0}{f}\right)^2\right]^{-1}$$

with f_0 the cavity resonance frequency and f the operating frequency.

Solving the equation for the movement of an electron entering the gap of the cavity at a velocity v_0 , yields the velocity $v(d_1)$ at the output of the gap:

$$v(d_1)=v_0(1+\frac{M_1V_1}{2V_0}e^{j\omega t})$$

Where t is the time when the electron passes the center of the gap, and

$$M_1=sin(\frac{\omega d_1}{2v_0})/(\frac{\omega d_1}{2v_0})$$

M_1 is called the „coupling coefficient“. The electrons leave the cavity and travel in the following drift tube at the velocity *$v(d_1)$.*

Density Modulation in Drift Tube

Velocity modulation from 1st cavity:

$$u(z) = u_0 \left[1 + \frac{E\,d}{2V_0} M \sin\omega t_0 \right]$$

$$z = u_0 \left[1 + \frac{E\,d}{2V_0} M \sin\omega t_0 \right] (t - t_0)$$

Charge conservation: $Q = I \cdot \mathrm{d}t = I_0 \cdot \mathrm{d}t_0$

$$t = t_0 + \frac{\frac{z}{u_0}}{1 + \frac{E\,d}{2V_0} M \sin\omega t_0} = t_0 + \frac{z}{u_0} \left(1 - \frac{E\,d}{2V_0} M \sin\omega t_0 \right)$$

$$dt = dt_0 \left(1 - \frac{\omega z}{u_0} \frac{E\,d}{2V_0} M \cos\omega t_0 \right)$$

$$I(z) = I_0 \frac{dt_0}{dt} \approx I_0 \frac{1}{1 - \frac{\omega z}{u_0} \frac{E\,d}{2V_0} M \cos\omega t_0} \approx I_0 \left(1 + \frac{\omega z}{u_0} \frac{E\,d}{2V_0} M \cos\omega t_0 \right)$$

[Kein Titel]

Phase between *u(z)* and *i(z)* is ~90°

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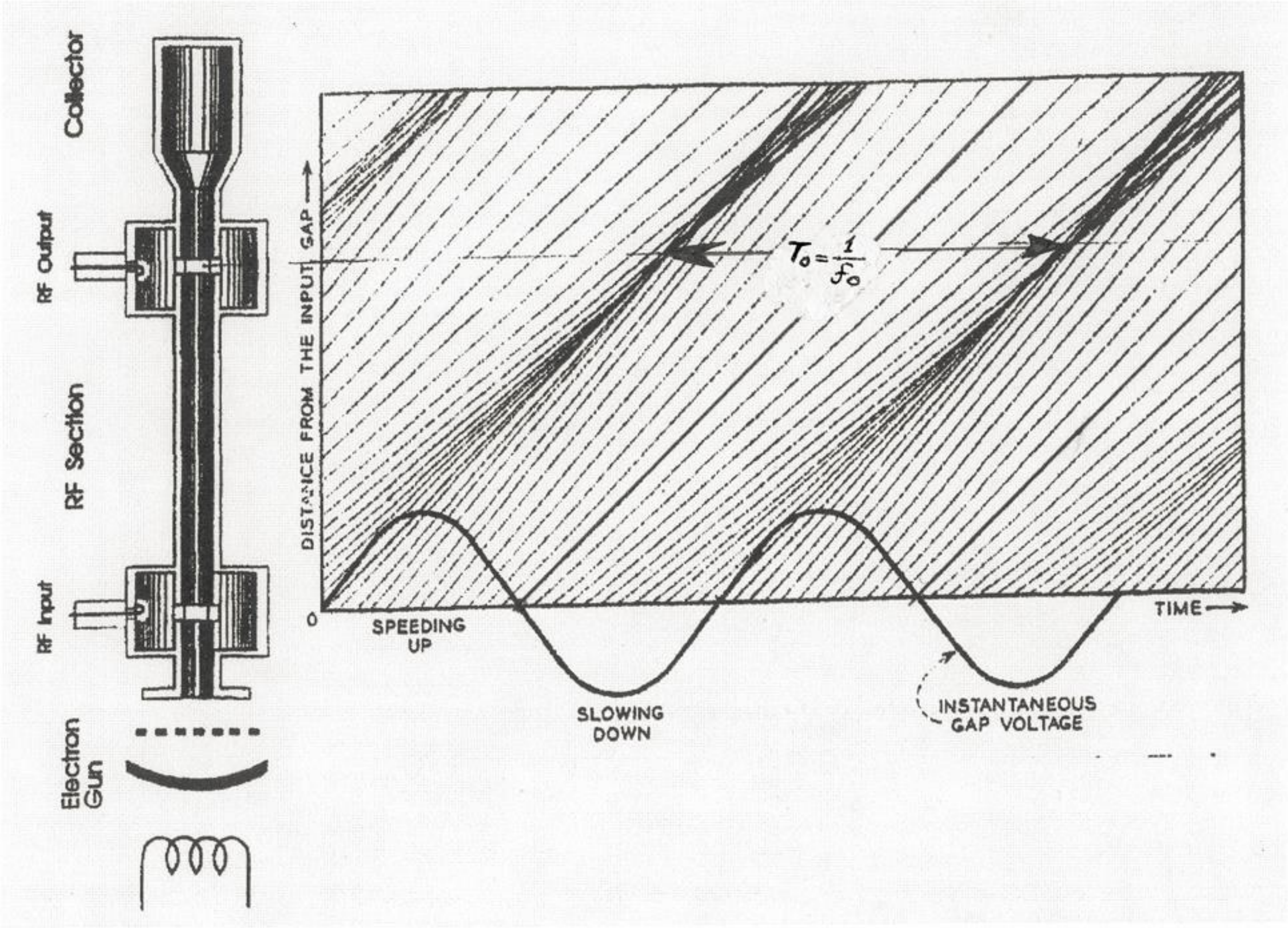
The „Applegate“ Diagram



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Distance-Time Curves for Electrons in Two-Cavity Klystron

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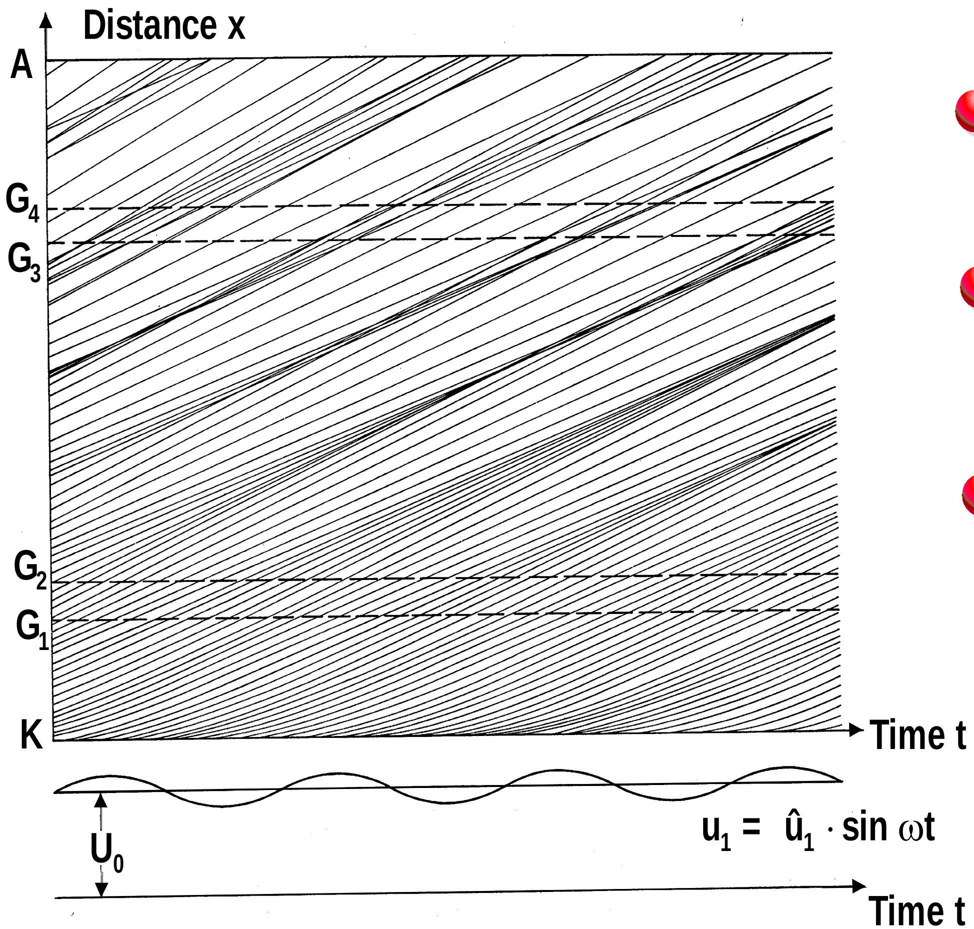


- Space-charge forces between electrons are ignored
- Short gap between G_1 and G_2 (modulation gap)
- G_3 and G_4 not at location of maximum electron bunching, due to higher fundamental frequency content of density modulated electron stream

$u_1 > 0$: Deceleration

$u_1 < 0$: Acceleration

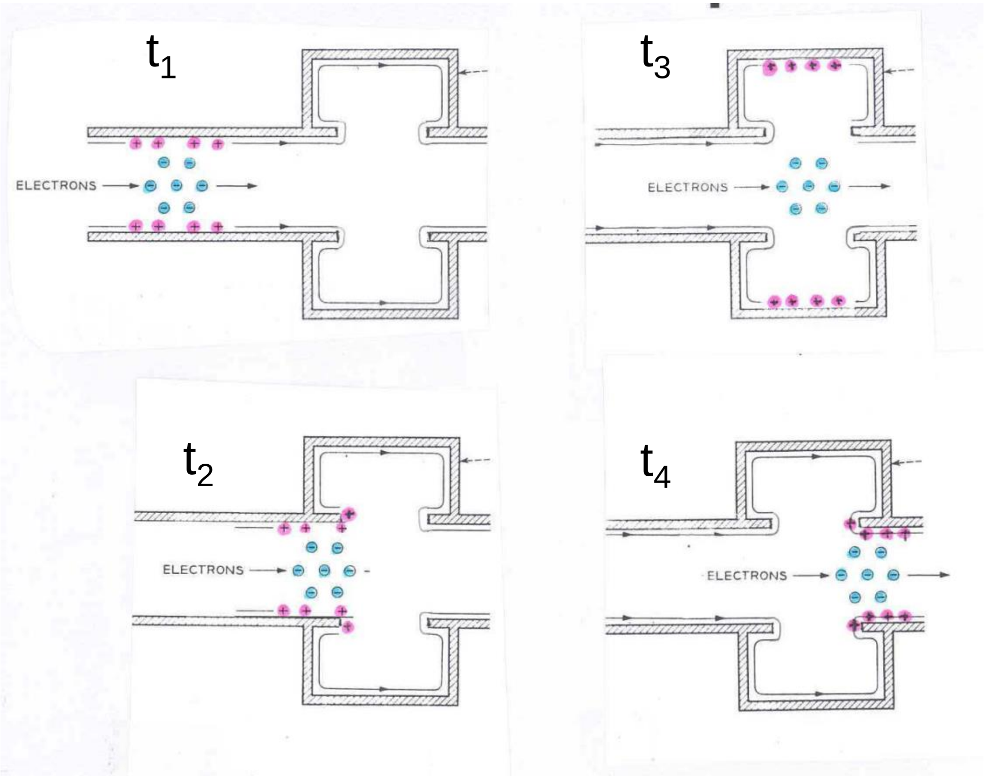
Interaction Principle: Output Cavity (Transition Radiation)

Each electron induces an image charge

The image charges follow the electron bunches.

They are equivalent with a current I_{cav} in the cavity.

The current I_{cav} induced in the cavity is proportional to the electron current I_1 multiplied by a coupling coefficient M



$$I_{cav} = M \cdot I_1$$

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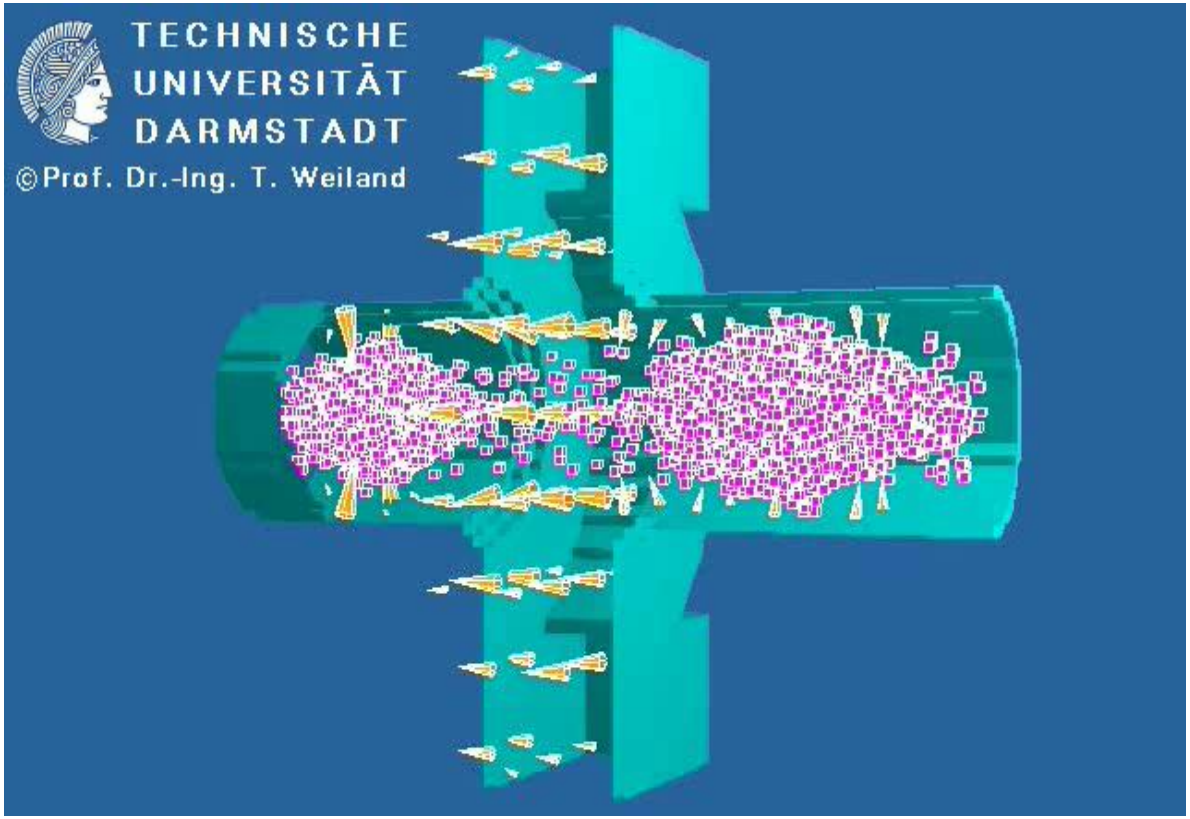
Energy Extraction in the Output Cavity



Current Induced in Output Cavity

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In buncher cavity and drift tube periodically modulated electron beam:

Fourier expansion:

$$I_{\text{mod}} = I_0 + I_1 e^{j\omega t} + I_2 e^{j2wt} + \dots$$

The fundamental component induces in the output cavity the current I_{cav2} and the Voltage V_{cav2}

$$I_{cav2} = M_2 \cdot I_1$$

The voltage V_{cav2} also modulates the velocity of the electrons and therefore is higher than the voltage V_1.

The voltage V_{cav2} induces in the gap of the output cavity the curren I_{cav2}. This additional component has to be added to the beam current:

$$I_{cav2} = M_2 I_1 + (G + jB) V_2$$

$Y_B = G_B + jB_B$: „Beam Loading: Generator Admittance

G_B : Conductance: current and voltage in phase at slit

B_B : Susceptance

Electron Velocity and Electron Beam Modulation in 5-Cavity Klystron

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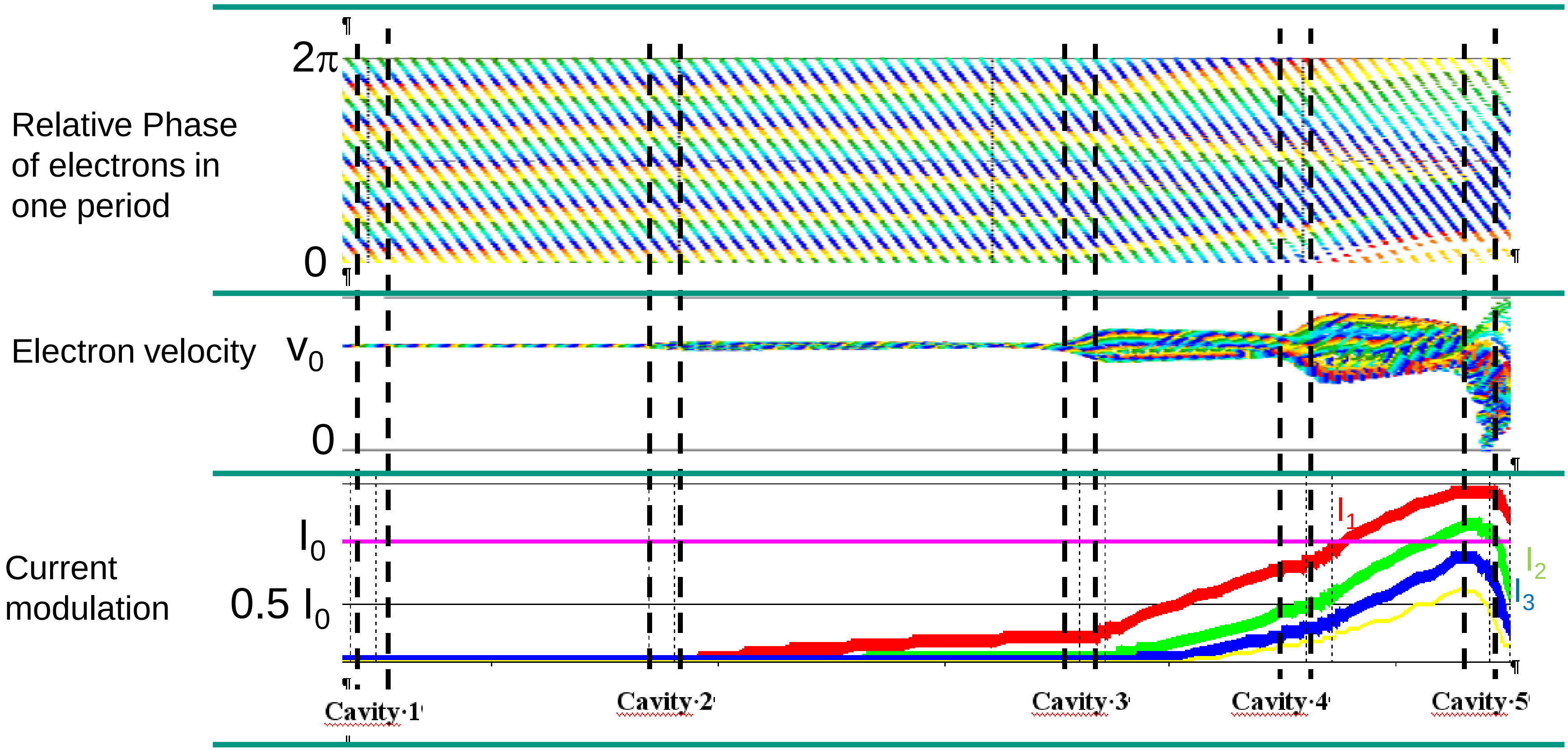


Quality Factor of Output Cavity

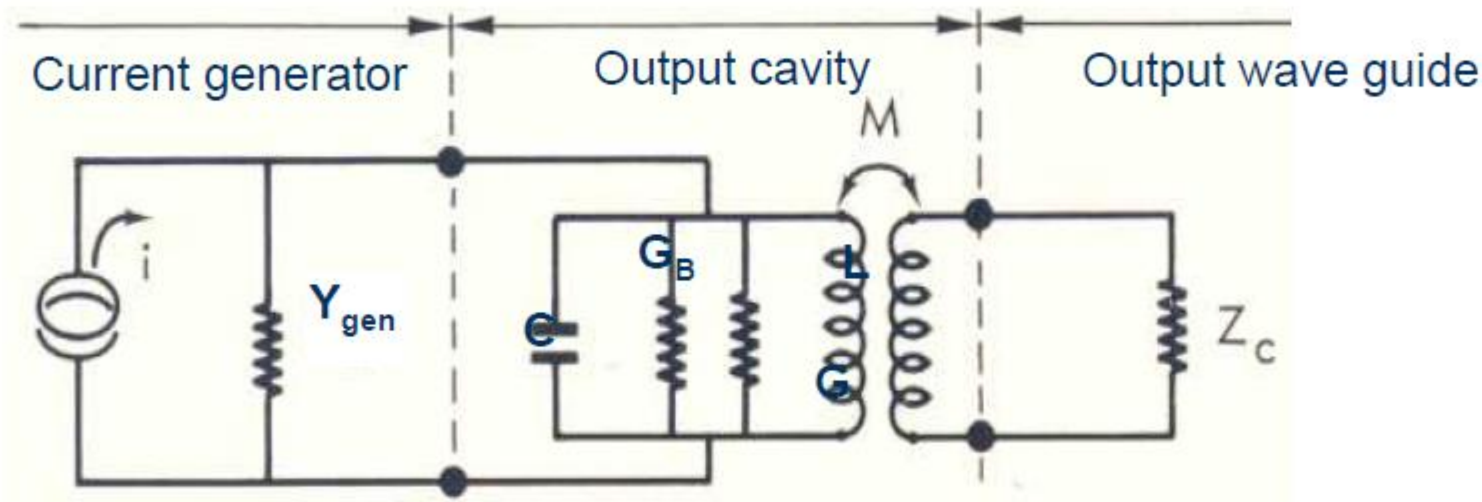
Admittance of load has 3 components:

- beam loading admittance : $Y_B = G_B + B_B$
- Output cavity admittance : $Y = G + j\,(C\omega - 1/L\omega)$
- Output wave guide admittance (characteristic impedance Zc)

The reactances of the 3 terms result in the attenuation (damping) of the cavity:

Therefore the quality factor of the output cavity is:

$$1/Q_L = 1/Q_B + 1/Q_0 + 1/Q_{ext}$$



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Coupling to Electron Beam

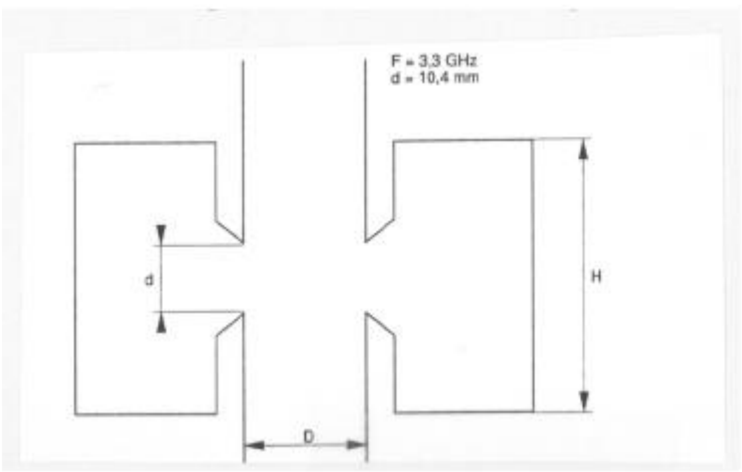
We define an effective voltage and the „shunt impedance“ R/Q.

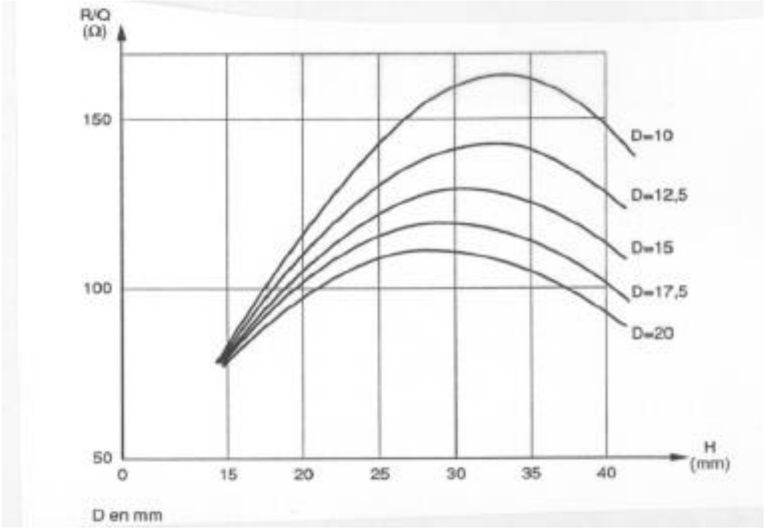
$$V = \int E .\, dz \qquad R/Q = \frac{V^2}{2\,\omega\,W_s}$$

W_s: stored Energy

Shunt impedance depends on cavity geometry.

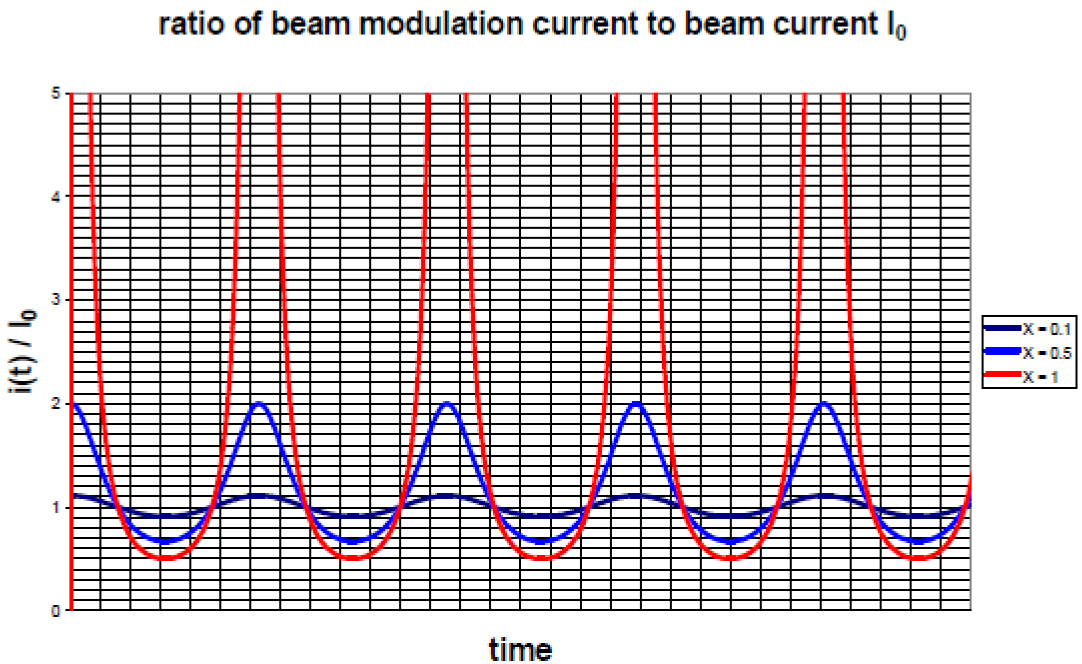
Example of a 3.3 GHz cavity:





Ballistic Theory of Klystron (I)

See above: $$I(z) = \frac{I_0}{(1 - \frac{\omega z}{u_0} \frac{E d}{2 V_0} M \cos \omega t_0)}$$ $$X = \frac{\omega z}{u_0} \frac{E d}{2 V_0} M$$



The current *I(z)* is periodical in time.

The ratio das I/I_0 increases with the „bunching“ parameter *X*.

Ballistic Theory of Klystron (II)

The time periodic current is represented by a Fourier series

$$I(z) = I_0 + \sum_1^{\infty} a_n \cos n(\omega t - \theta) + b_n \sin n(\omega t - \theta)$$

with the coefficients

1

$$a_n = \frac{1}{\pi} \int_0^{2\pi} I(z) \cos n(\omega t - \theta) \; d(\omega t) \qquad \theta = \frac{\omega z}{u_0}$$

$$\omega\left(t - \frac{z}{u_0}\right) = \omega t - \theta = \omega\left(t_0 - \frac{\omega z}{u_0} \frac{E d}{2 V_0} M \sin \omega t_0\right) = \omega(t_0 - X \sin \omega t_0)$$

As a consequence of charge conservation follows

$$a_n = \frac{1}{\pi} \int_0^{2\pi} I_0 \cos n(\omega t - \theta) \; d(\omega t)$$

$$= \frac{I_0}{\pi} \int_0^{2\pi} \cos n(\omega t_0 - X \sin \omega t_0) \; d(\omega t_0) \quad = 2 I_0 J_n(n X)$$

$$I(z) = I_0 \left[1 + 2 \sum_1^{\infty} J_n(n X) \cos n(\omega t - \theta) \right]$$

Ballistic Theory of Klystron (III)

- The amplitude of the fundamental component (n=1) is I_1=2$J_0(X)$
- Its maximum value is $J_1(X)$=0.58 for X=1.84

  and the maximum current $I_1 = 1.16\ I_0$
- To avoid reflected electrons, the peak value of the RF voltage must be smaller than V_0 . Therefore the maximum allowed output power is $0.5\ V_1\ I_1 = 0.58\ V_0\ I_0$
- It has to be emphasized, that according to the ballistic theory the amplitudes of the higher harmonics are also large
- The amplitude of the 2nd harmonic (n=2) is $I_1 = 2*0.48 = 0.96\ I_0$.
- However, due to the space charge and the low-pass feature of the output cavity, the real amplitudes of harmonics are lower.

Influence of RF Field on Beam Modulation (I)

Approach:

- The position of the cavity opening in z-direction is given by $z=z_1$ und $z=z_1+d$

  where *d* is the gap width
- The RF electric field and voltage are given by

$$E_1 = \frac{U_1}{d} e^{j\omega t}; \quad U_1 << V_0$$

  here the space charge of the electrons is neglected.
- The density modulation of the beam is represented by the current density *J(z,t)* and the velocity modulation by *u(z,t)*

The electron velocity has the DC component u_0 and the AC component u_1

$$\frac{dz}{dt} = u(t) = u_0 + u_1 \qquad \text{and} \qquad \frac{\partial u_1}{\partial t} = j\,\omega\, u_1$$

The same is valid for the current density and the space charge density

$$J(t) = J_0 + J_1 \qquad \rho(t) = \rho_0 + \rho_1$$

Influence of RF Field on Beam Modulation (II)

The equations for the movement of the electrons are given by

$$\frac{du_1}{dt} = \frac{\partial u_1}{\partial z}\frac{\partial z}{\partial t} + \frac{\partial u_1}{\partial t} = \frac{\partial u_1}{\partial z} u_0 + j\omega u_1 = -\frac{e}{m} E_1 \quad \Longrightarrow \quad \frac{\partial u_1}{\partial z} + j\frac{\omega}{u_0} u_1 = -\frac{\eta}{u_0} E_1$$

The current density is deascribed by (under the assumption that u_1 is small)

$$J_0 + J_1 = (\rho_0 + \rho_1)(u_0 + u_1) = \rho_0 u_0 + \rho_1 u_0 + \rho_0 u_1 \qquad J_1 = \rho_1 u_0 + \rho_0 u_1$$

Charge conservation leads to

$$div\ J_1 + \frac{\partial \rho_1}{\partial t} = \frac{\partial J_1}{\partial z} + j\omega\rho_1 = 0 \quad \Longrightarrow \quad \frac{\partial J_1}{\partial z} + j\frac{\omega}{u_0}(J_1 - \rho_0 u_1) = 0$$

We get two coupled differential equations

$$\frac{\partial u_1}{\partial z} + j\frac{\omega}{u_0} u_1 = -\frac{\eta}{u_0} E_1 \qquad \frac{\partial J_1}{\partial z} + j\frac{\omega}{u_0} J_1 = j\frac{\omega \rho_0}{u_0} u_1 \qquad \beta_e = \frac{\omega}{u_0}$$

With the following new definitions of the unknown observables

$$W_1 = e^{j\beta_e z} u_1 \qquad K_1 = e^{j\beta_e z} J_1$$

we get

$$\frac{\partial W_1}{\partial z} = -\frac{\eta}{u_0} e^{j\beta_e z} E_1 \qquad \frac{\partial K_1}{\partial z} = j\frac{\omega \rho_0}{u_0} e^{j\beta_e z} u_1$$

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Influence of RF Field on Beam Modulation (III)

The solution of the two coupled differential equations is

$$u_1 = -e^{-j\beta_e z}\frac{\eta}{u_0}\int_0^z e^{j\beta_e x} E_1\, dx = \frac{j\eta}{\omega} E_1 \left(1 - e^{-j\beta_e z}\right)$$

$$J_1 = -e^{-j\beta_e z}\frac{\eta\,\rho_0}{u_0}\int_0^z \left(1 - e^{j\beta_e x}\right) E_1\, dx = -\frac{j\eta\,\rho_0}{\omega} E_1 \left(1 - e^{-j\beta_e z} - j\beta_e z\, e^{-j\beta_e z}\right)$$

The energy loss of the electron beam is given by

$$W = \frac{1}{2}\Sigma\int_0^d J_1 E_1^* \, dz = \frac{1}{2}\frac{j\eta\,\rho_0}{\omega}\Sigma\left|E_1\right|^2\int_0^d \left(1 - e^{-j\beta_e z} - j\beta_e z\; e^{-j\beta_e z}\right) dz$$

$$W = \frac{\eta\,\rho_0\,\Sigma}{2\,u_0\,(\beta_e d)^2}\left|E_1 d\right|^2 \left(2 - j\beta_e d - e^{j\beta_e d}\left(2 + j\beta_e d\right)\right)$$

$$W = \frac{1}{2} Y \left|E_1 d\right|^2 = \frac{1}{2} Y V_1^2 = \frac{1}{2}\left(G + jB\right) V_1^2$$

Σ is the cross section of the beam

$V_1 = E_1 d$ is the gap voltage

$Y = G + jB$ is the beam loading admittance

Influence of RF Field on Beam Modulation (IV)

with $$\frac{\eta\,\rho_0\,\Sigma}{u_0} = \frac{\eta\,\rho_0\,u_0\,\Sigma}{u_0^2} = \frac{\eta\,J_0\,\Sigma}{\eta\,V_0} = -\frac{I_0}{V_0} = -g_0$$

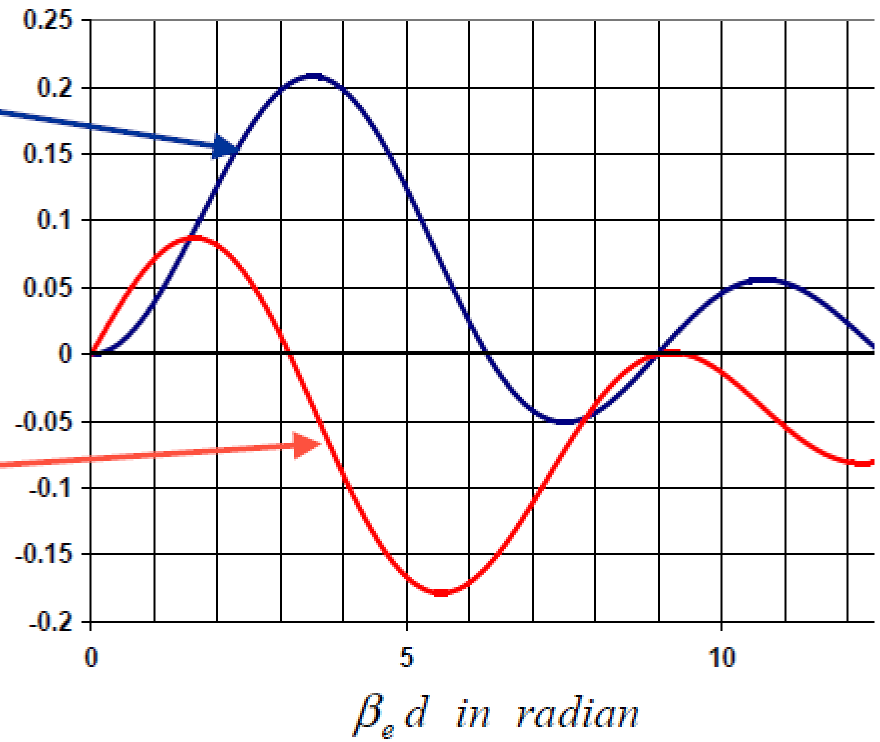
Follows for the real part (conductance G_b) and the imaginary part (susceptance B_b) of the beam loading admittance:

Power loss of cavity

$$G_b = g_0\,\frac{2\,(1-\cos\beta_e d\,) - \beta_e d\,\sin\beta_e d}{2\,(\beta_e d)^2}$$

Shifting of resonance frequency

$$B_b = g_0\,\frac{2\sin\beta_e d - \beta_e d\,(1+\cos\beta_e d\,)}{2\,(\beta_e d)^2}$$



Influence of RF Field on Beam Modulation (V)

In the case $G_b > 0$ energy is transfered from the resonator to the electron beam.
The losses of the cavity are increasing. Therefore the quality factor decresases:

$$1/Q_L = 1/Q_B + 1/Q_0 + 1/Q_{ext}$$

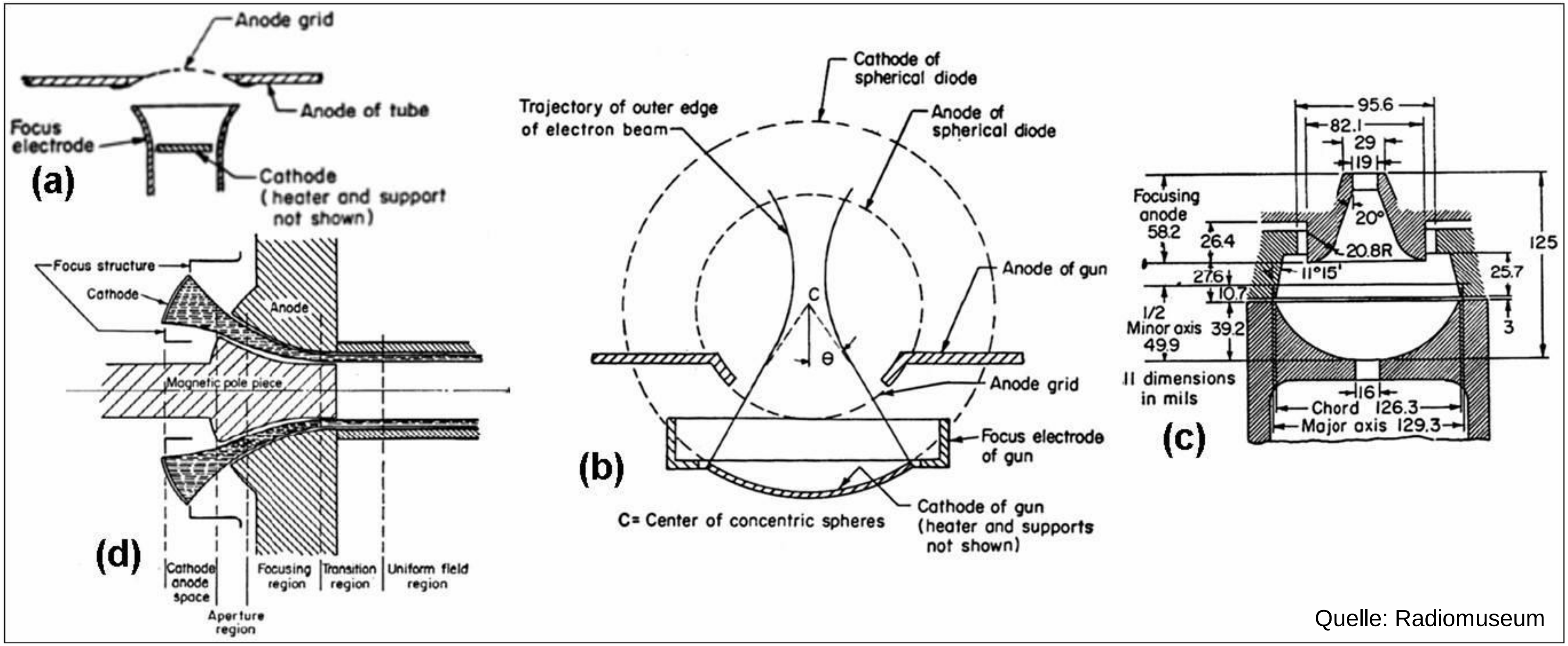
In the case when the electric field in the cavity is not constant, the calculation of current density and velocity modulation is more complicated:

$$u_1(z,r) = -e^{-j\beta_e z} \frac{\eta}{u_0} \int_0^z e^{j\beta_e x} E_1(x,r)\, dx$$

$$J_1(z,r) = -e^{-j\beta_e z} \beta_e \rho_0 \int_0^z e^{j\beta_e x} u_1(x,r)\, dx$$

$$W = \frac{1}{2} \int_0^{r\max} 2\pi \int_0^d J_1 E_1^* \, dz \; r\, dr$$

Electron Guns for Klystrons

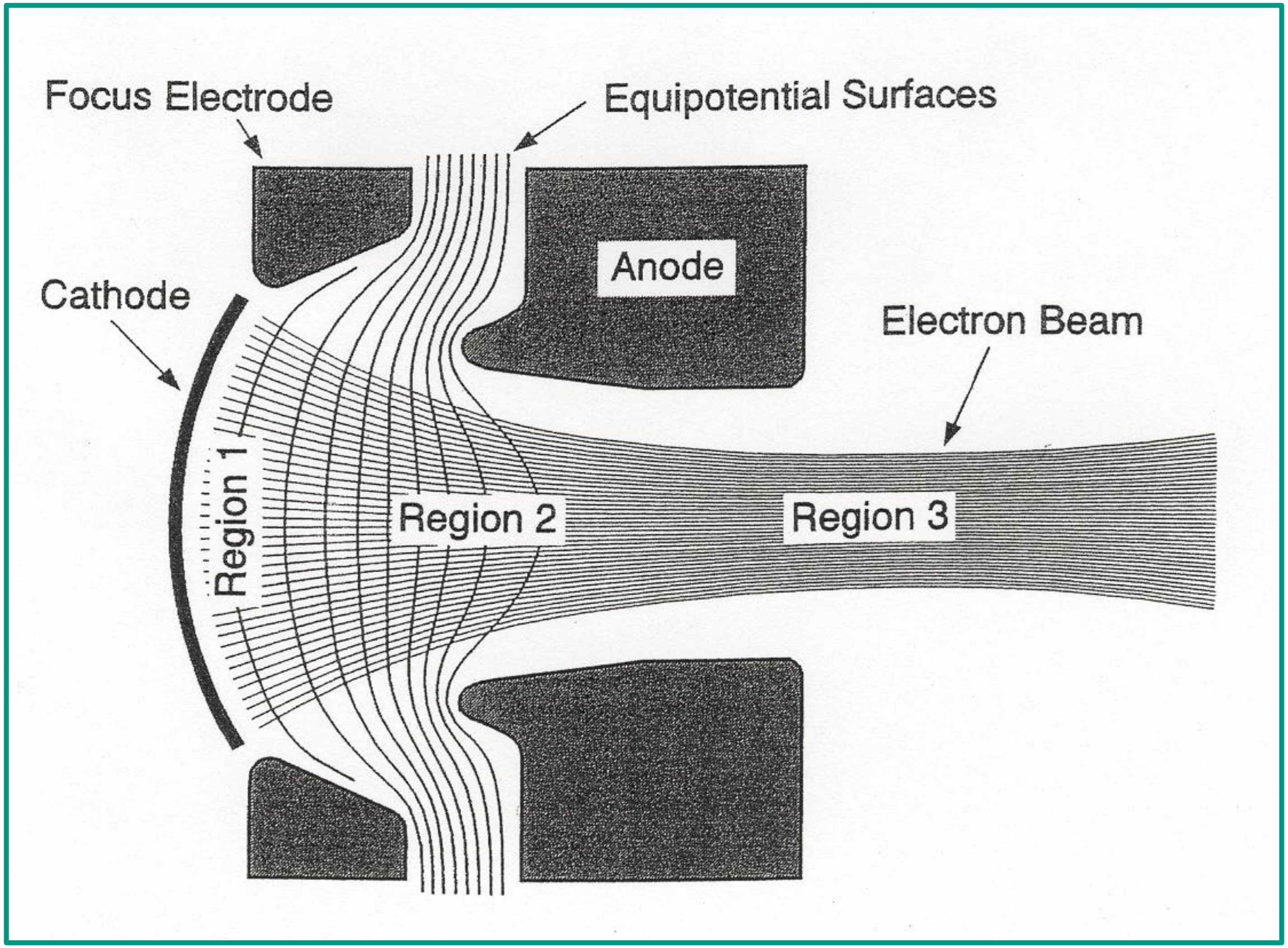


(a) Gun with empirically designed cathode (Klystron 2K25)

(b) Pierce gun as part of a spherical diode with focussing electrode

(c) Cathode developed at Bell System by O. Heil.

Pierce E-gun



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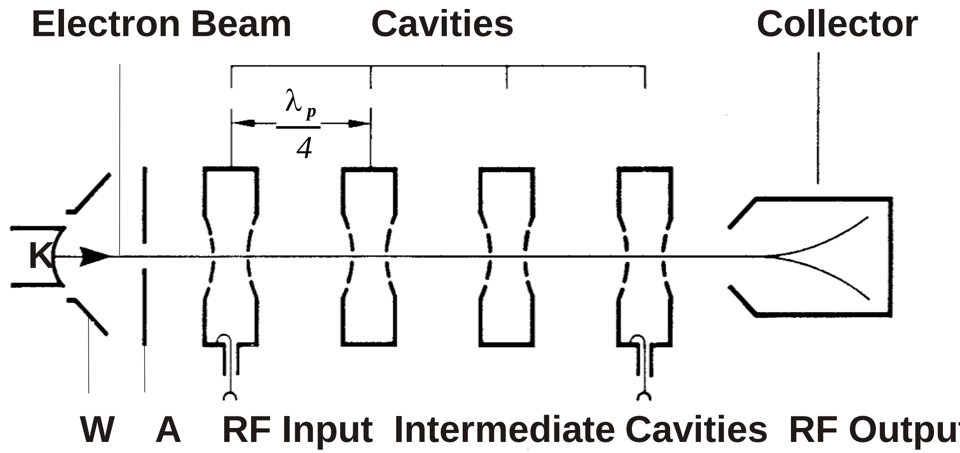
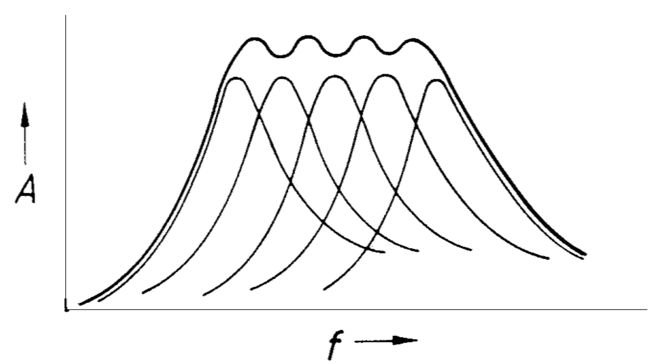
Multi - Cavity Klystron

Elements of a

Multi- Cavity Klystron

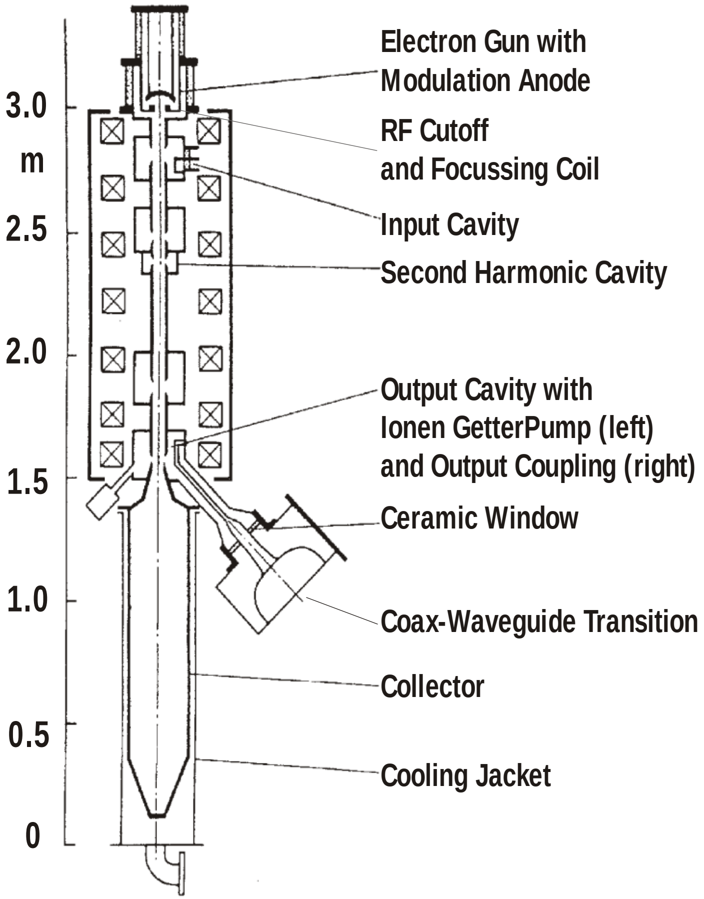


Typical Cavity Resonant Frequencies for a Broadband Tuned Multi- Cavity Klystron (staggered resonance frequencies)



The axial magnetic guiding field is not shown

Valvo High-Power Klystron Amplifier YK 1353



High-Power
Klystron Amplifier
YK 1353

Frequency
352 MHz

RF Power
1.3 MW

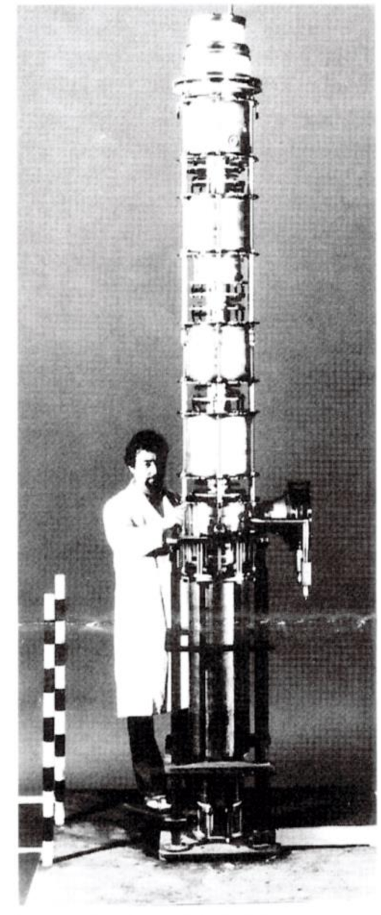
Efficiency
67%

Collector Voltage
100 kV

Cathode Current
19.4 A

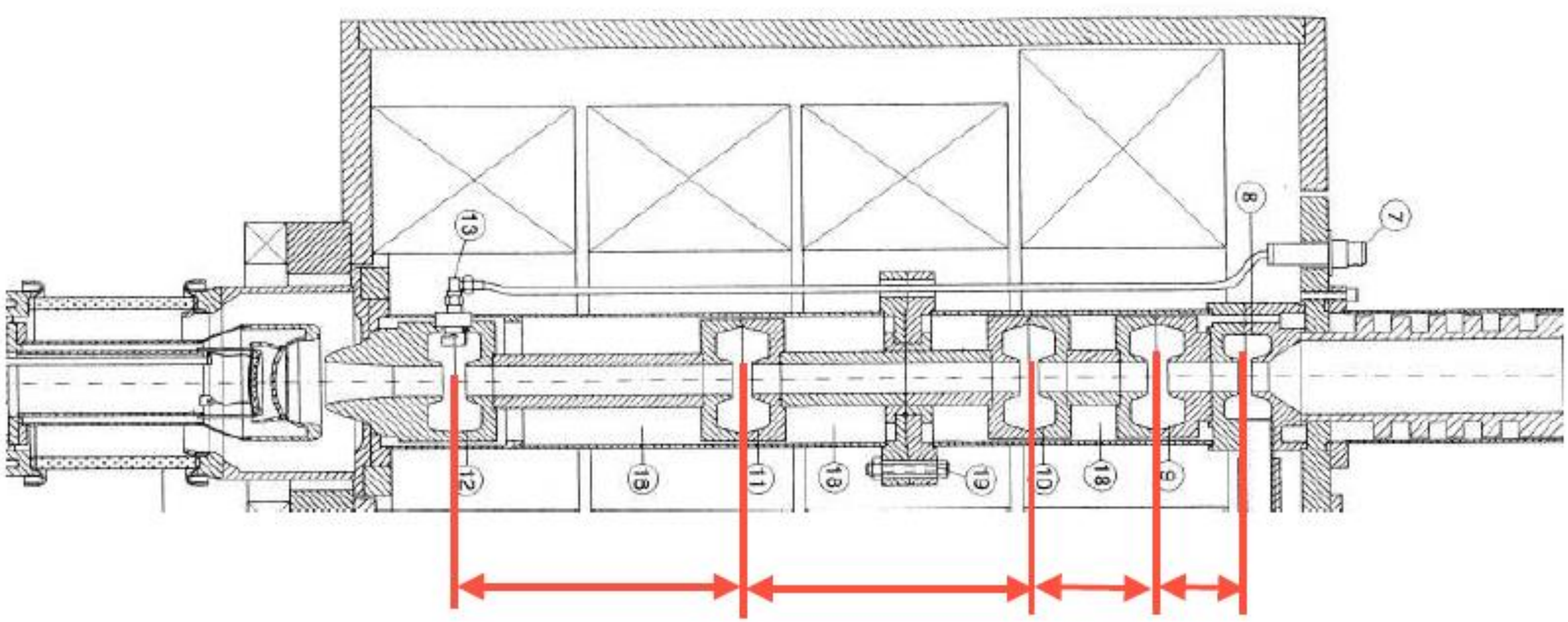
Weight
ca. 2000 kg

Length
ca. 4 m



Influence of the Increasing RF Field along the Klystrons on the Tube Design

Since the RF electric field is increasing from the input cavity to the output cavity, the length of the dift tubes is decreasing:



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Influence of the Wavelength on the Design

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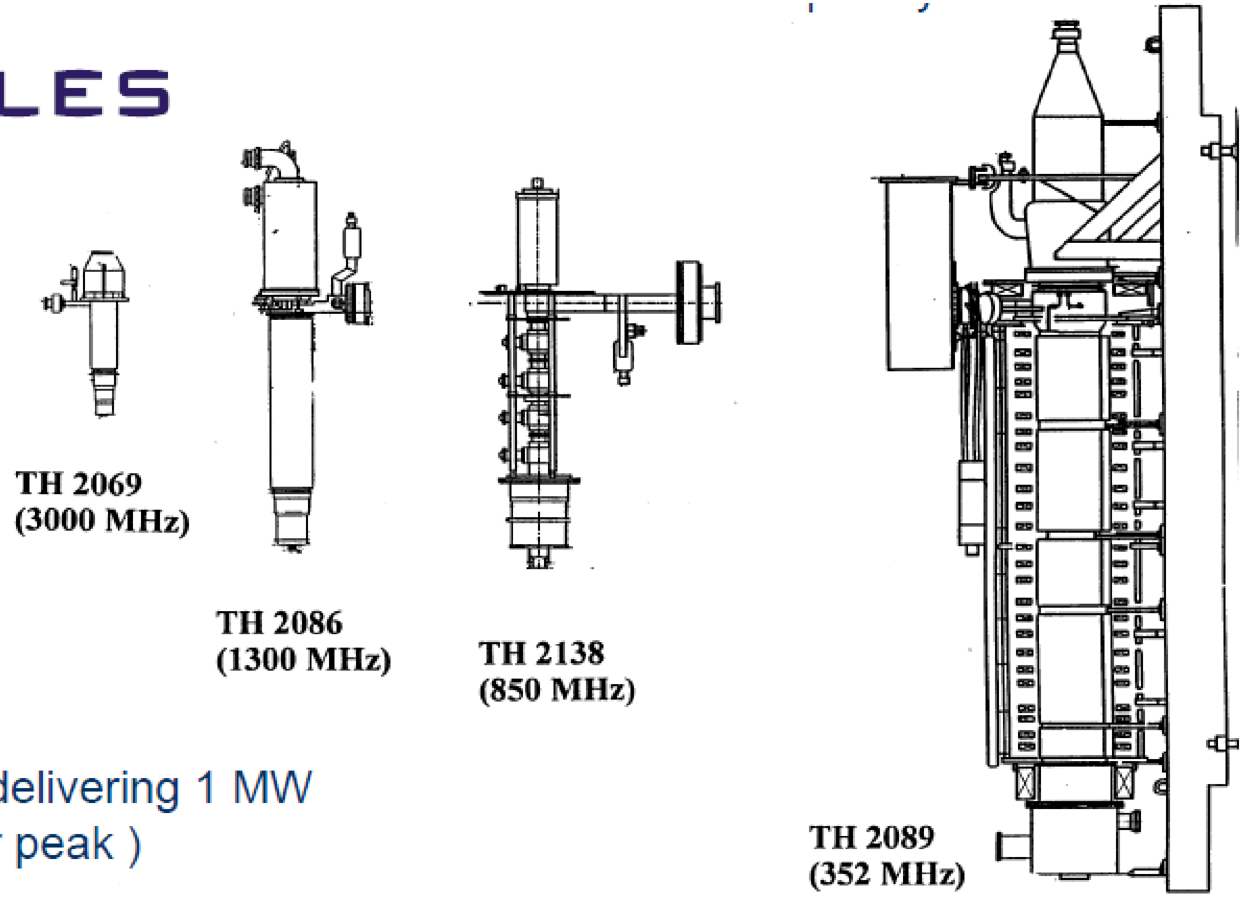
Size of cavity and length of drift tubes are proportional to the wave length

THALES



Tubes delivering 1 MW
(CW or peak)

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TED High Power 1.3 MW, 352 MHz, CW Klystron

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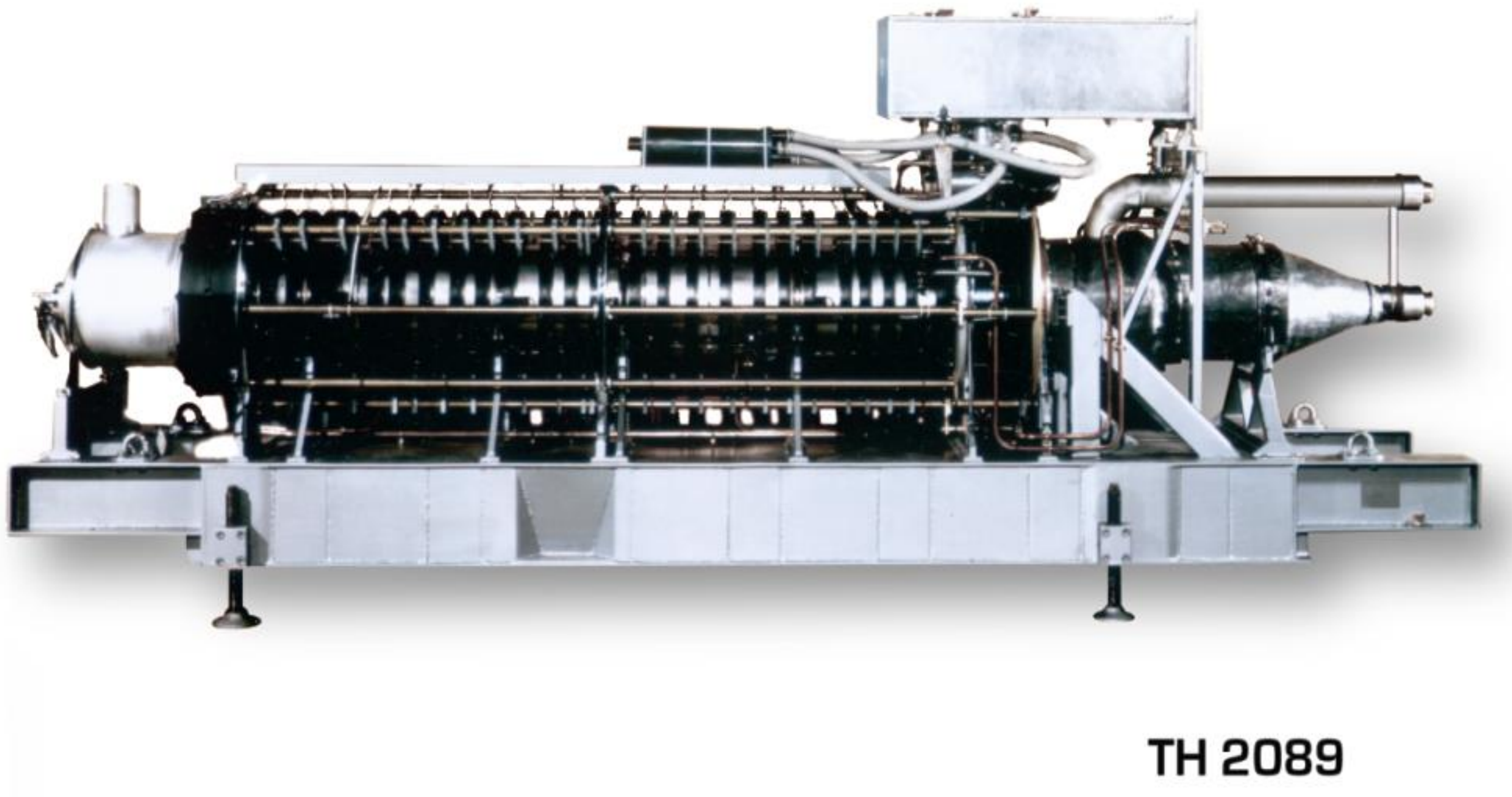


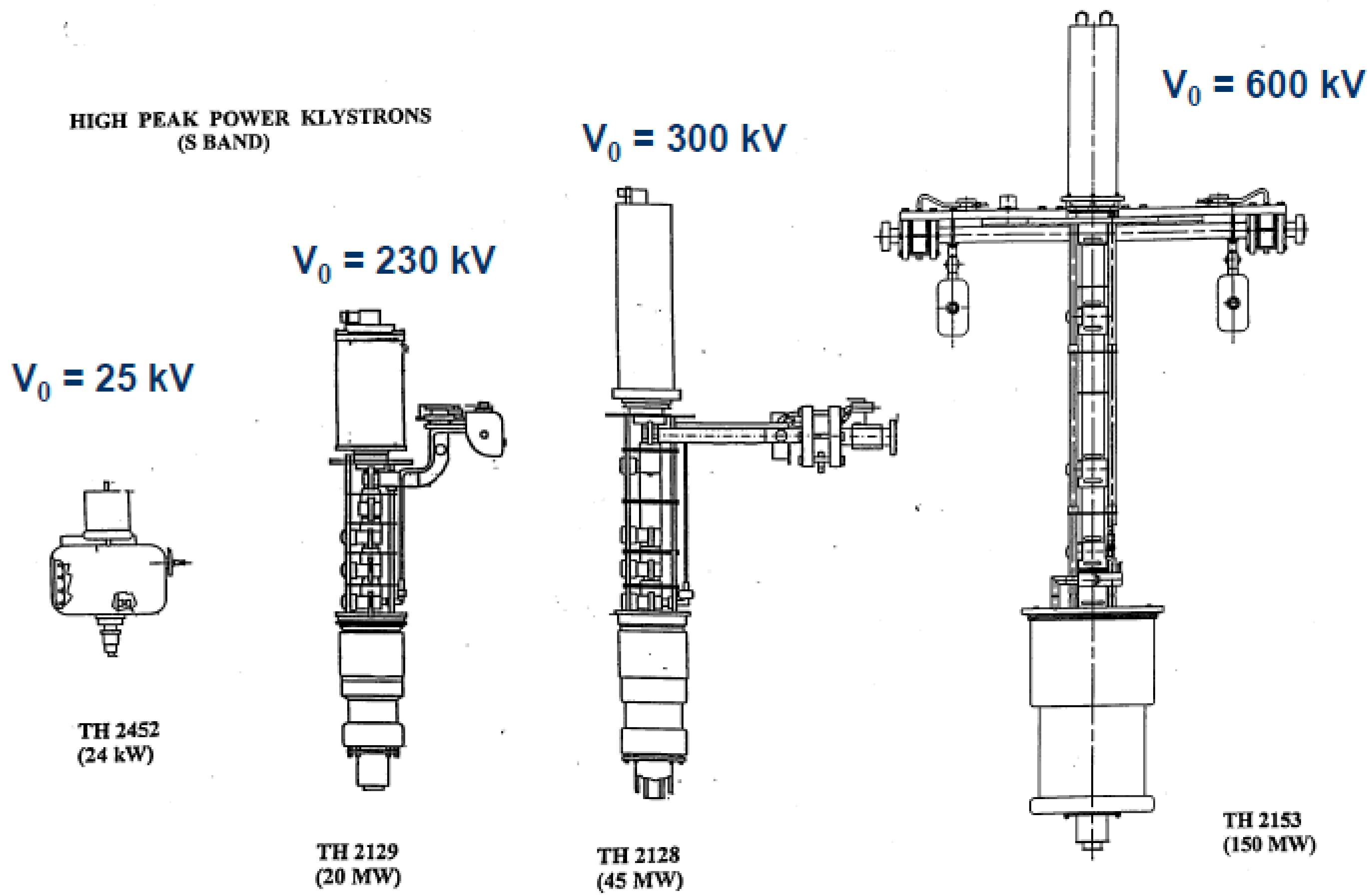
CPI High Power CW Klystron for HERA (DESY)

VKP – 7958 A

Frequency:	499.67 MHz
Power:	0.8 MW / CW
Efficiency:	64 %
Beam Voltage:	74 kV
Beam Current:	18 A
Gain:	40 dB

Influence of the Beam Voltage on the Size of Klystrons

The length of the drift tubes depends on the electron velocity.
The length of the interaction circuits increases with increasing beam voltage.



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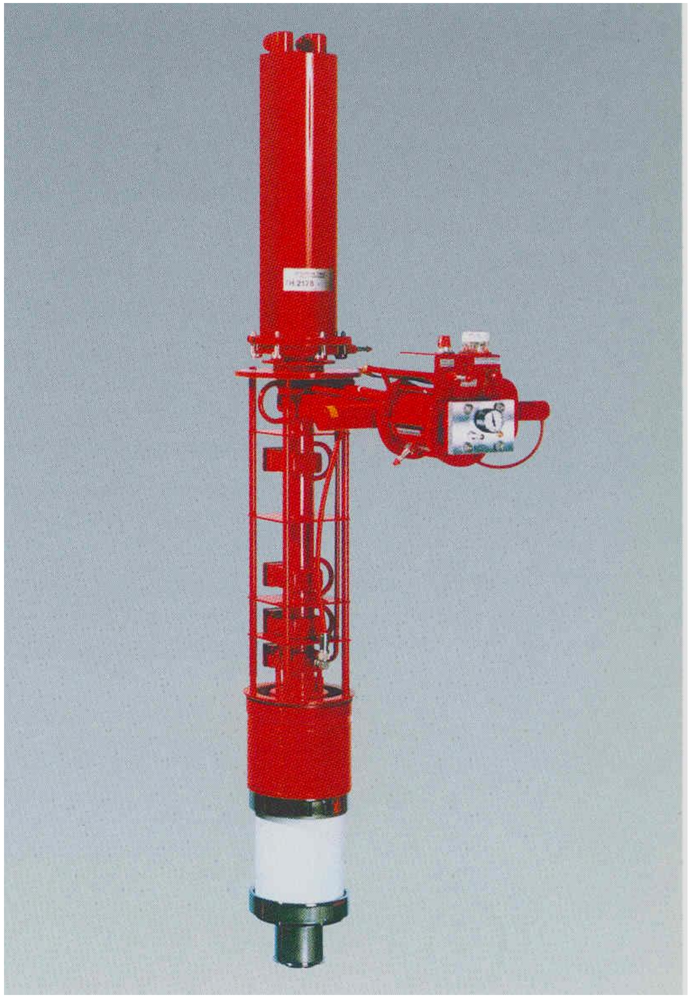
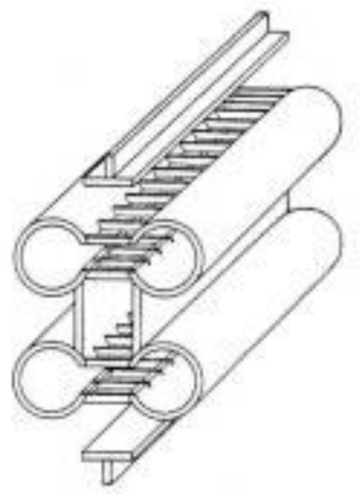
TED Standard Production
High Power ms-Pulse S-Band Klystron

TH 2128

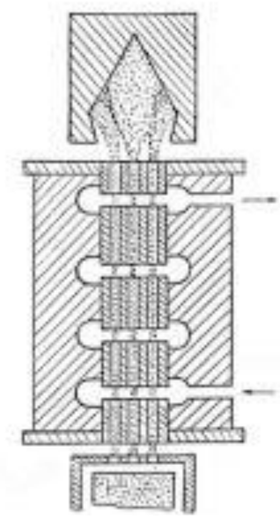
Frequency:	2856 MHz
Power:	45 MW (4.5 μs) 10 kW (50 Hz)
Efficiency:	44 %
Beam Voltage:	314 kV
Beam Current:	350 A
Gain:	54 dB



Klystron Variants



Sheet-Beam Klystron



Multi-beam Klystron

Large current, but less space charge forces compared to solid circular beam

Source: George Caryotakis , „The Klystron: A Microwave Source of Surprising Range and Endurance” SLAC–PUB–7731, 1998

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Multibeam Klystron (MBK)

The space charge forces are opposed to a perfect electron bunching. These repulsion forces appear in the form of the plasma frequencies ω_q or ω_p, which is proportional to the square root of the perveance *P*.

In a conventional klystron, the perveance of the beam is in the range of 0.5 to $2.5 \cdot 10^{-6}\ AV^{-3/2}$.

A perveance $P = 2.5 \cdot 10^{-6}\ AV^{-3/2}$ is the practical limit, beyond which the electron beams are difficult to be maintained fairly cylindrical and to be focused without notable body interception. When the perveance is high, the efficiency is low. At the same time the instantaneous bandwidth is enlarged to ≈ 5% or more, instead of the usual 1 to 2%. This last point is explained by the high value of the beam loading conductance G_{bl} proportional to $PV_0^{1/2}$, which damps all the cavities.

On the contrary, a perveance $P = 0.5 \cdot 10^{-6}\ AV^{-3/2}$ is the practical lower limit under which the smallness of the current I_0 dictates unacceptable high beam voltages V_0 and involves many electrical insulation difficulties on the tube itself as well as on the whole transmitter or equipment. But the low perveances are favourable for high interaction efficiencies because a strong bunching can be achieved.

For example the number of beams is 6 or 7. The perveance of a single beam is about 0.5 to $0.6 \cdot 10^{-6}\ AV^{-3/2}$. The interaction efficiency is approximately 65%.

TED High Power 1.3 GHz, 10 MW, 1.7 ms-Pulse MBK

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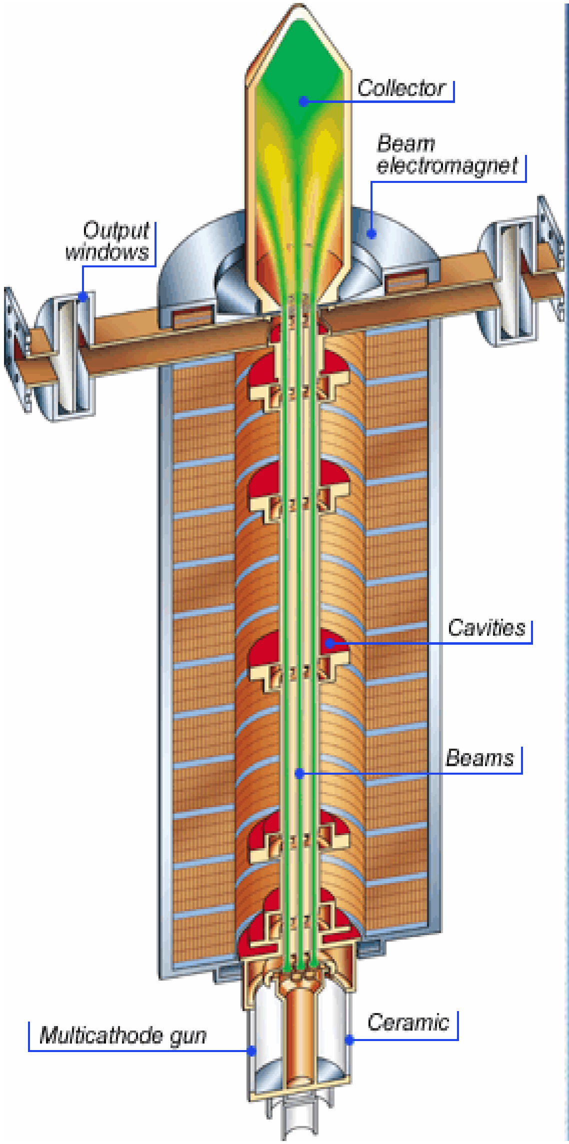

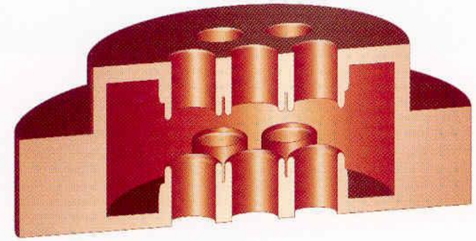

Multigap cavity

Multicathodes electron gun

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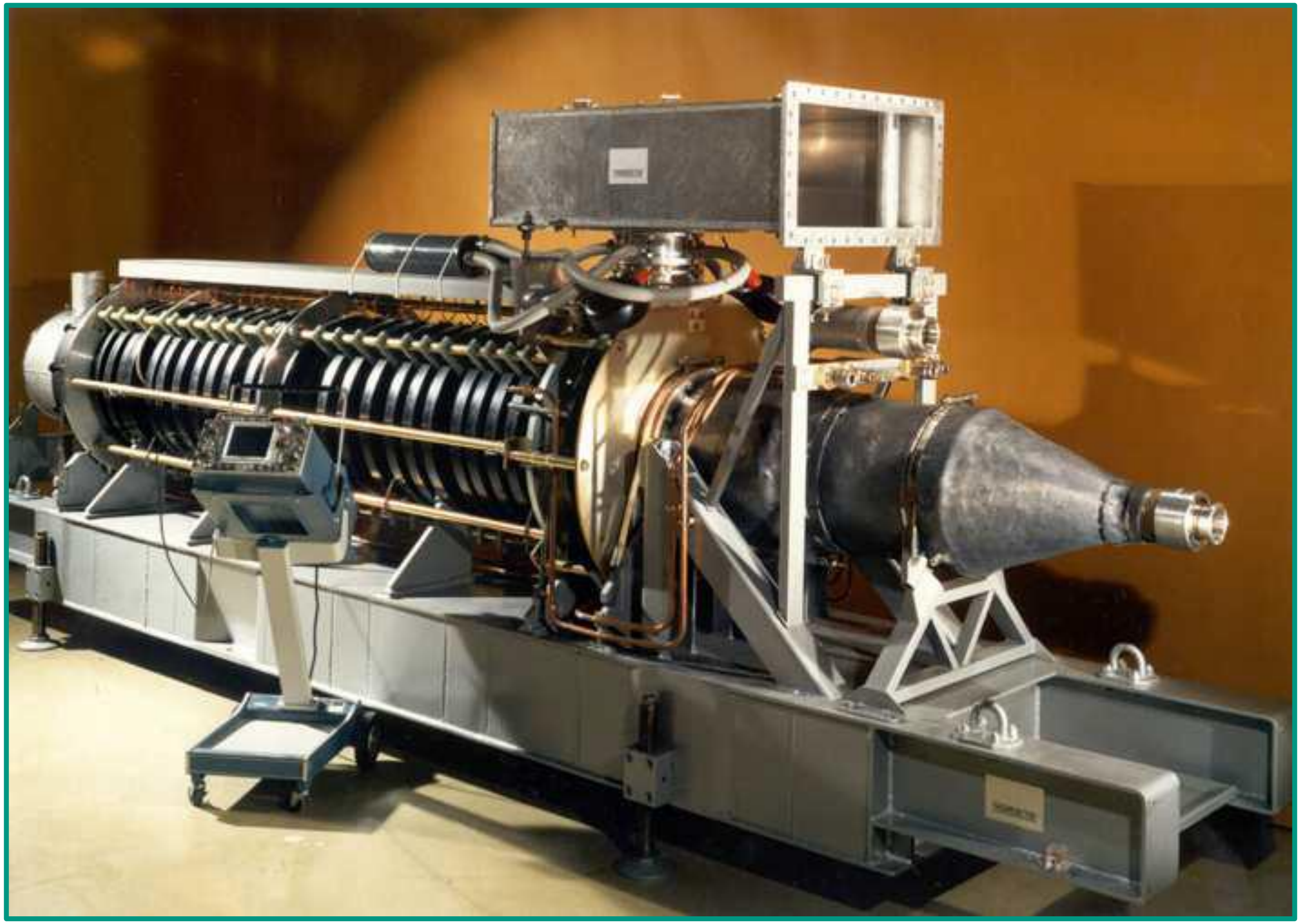
Power Capabilities of Klystrons of Thales Electron Devices (I)

Band	P	P	P	P	P	L	L	S	S	C	C
Frequency (MHz)	352	400-402	500	704	805	1300	1500	2450	2856-2998	3700	4900
Short Pulse < 10 µs						30 MWp	20 MWp		45 MWp		
						60 kWa	10 kWa		50 kWa		
Long Pulse ~ 1.5 ms	2,8 MWp	2,5 MWp			5 MWp	10 MWp					
	210 kWa	200 kWa			450 kWa	150 kWa					
CW	1300 kW	300 kW	800 kW					50 kW		700 kW	50 kW

TH2089: 1300 kW CW 352 MHz



TED Multi-Beam Klystron: TH1802 : 10 MWp 150kWa 1300MHz

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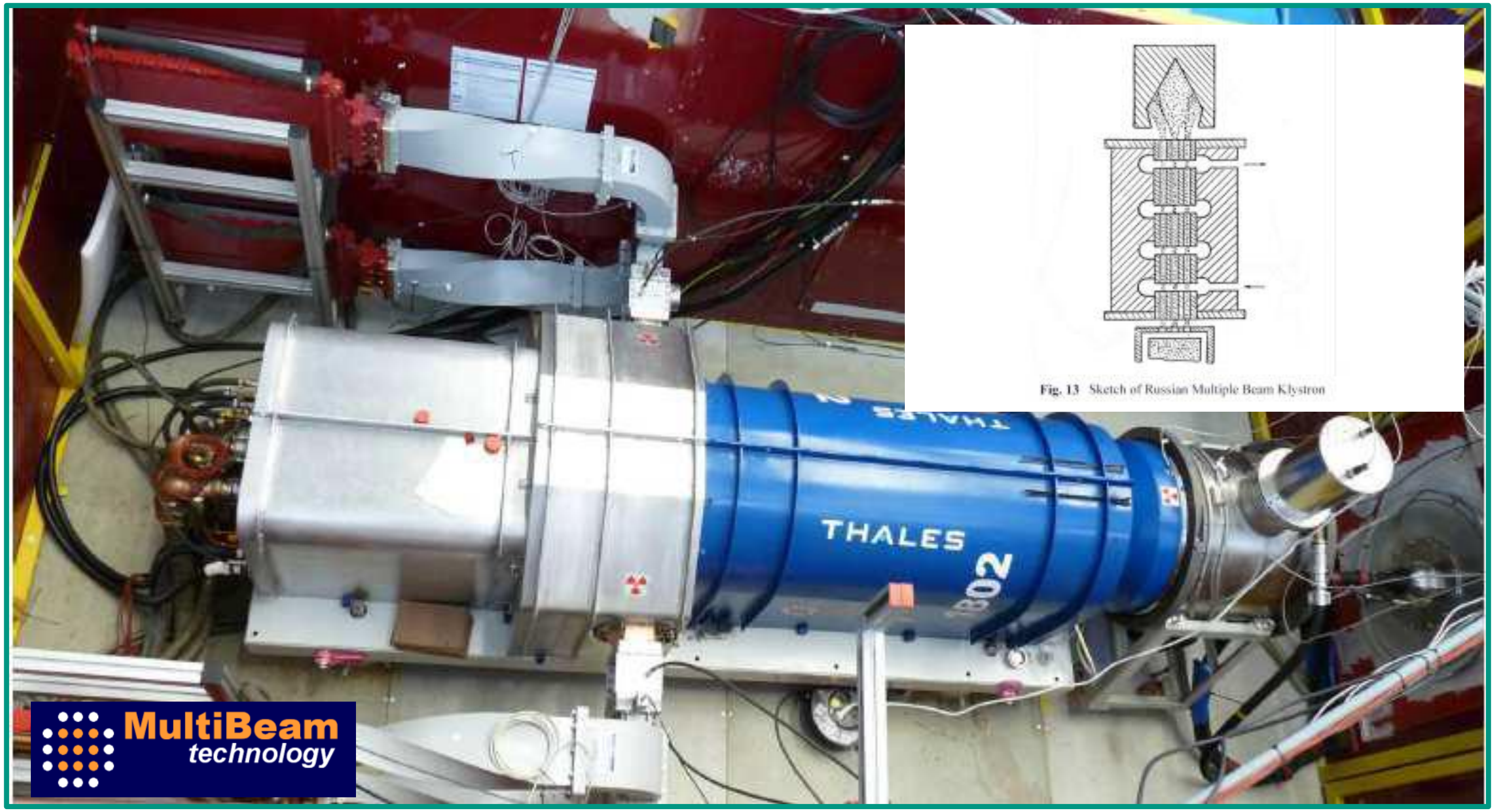


State-of-the-art of Short-Pulse Accelerator Klystrons (5 µs)

H.P. Bohlen, CPI (1999)

Standard Production (LEP/CERN, KEK)

Type	Frequency	Power/ Pulse width	Average Power	Company
YK 1600	2998 MHz	35 MW 4.5 µs	16 kW	Valvo (now: EEV)
TH 2094 TH 2100	2998 MHz	35 MW 4.5 µs	16 kW	TED
5045	2998 MHz	60 MW 3.5 µs	60 kW	SLAC

Prototype and Development (SLAC, DESY)

Type	Frequency/ Focusing	Power/ Pulse width	Average Power	Company
	2998 MHz EM*	150 MW 3 µs	27 kW	SLAC
VKS-8333	2998 MHz EM*	150 MW 3 µs	27 kW	CPI
TH 2153	2998 MHz EM*	150 MW 1.2 µs	-	SLAC
XL 4	11.4 GHz EM*	75 MW 1.2 µs	-	SLAC
	11.4 GHz PPM*	50 MW 1.5 µs	-	SLAC
E 3717	11.4 GHz EM*	100 MW 0.5 µs	-	Toshiba

*** PPM: periodic permanent magnet**

EM: electro-magnet

State-of-the-art of Short-Pulse Accelerator Klystrons (1-10 ms)

H.P. Bohlen, CPI (1999)

Type	Frequency	Power Pulse width	Accelerator	Company
YKP 8290	805 MHz	2.5 MW 1.7 ms	SNS/LANL	CPI
	805 MHz	2.5 MW 1.7 ms	SNS/LANL	Litton
MBK (7beams)	1.3 GHz	10 MW 1.5 ms	TESLA/DESY	TED

State-of-the-art of CW Accelerator Klystrons

H.P. Bohlen, CPI (1999)

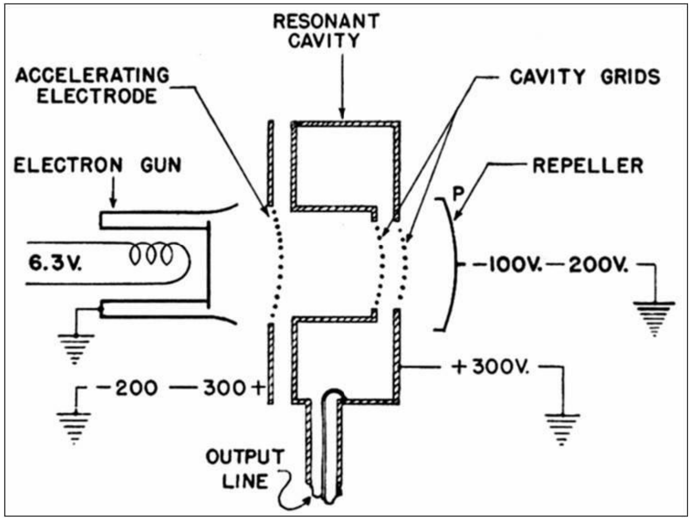
Type	Frequency	Power	Source	Accelerator
TH 2089B	352 MHz	1.3 MW	TED	
K3513G	352 MHz	1.3 MW	EEV	
B-Factory Klystron	476 MHz	1.2 MW	SLAC/CPI	
VKP-7958	500 MHz	800 kW	CPI	
YK 1300	500 MHz	600 kW	Valvo	
E3732	509 MHz	1.2 MW	Toshiba	
K3510L	700 MHz	1 MW	EEV	
VKP-7952	700 MHz	1 MW	CPI	

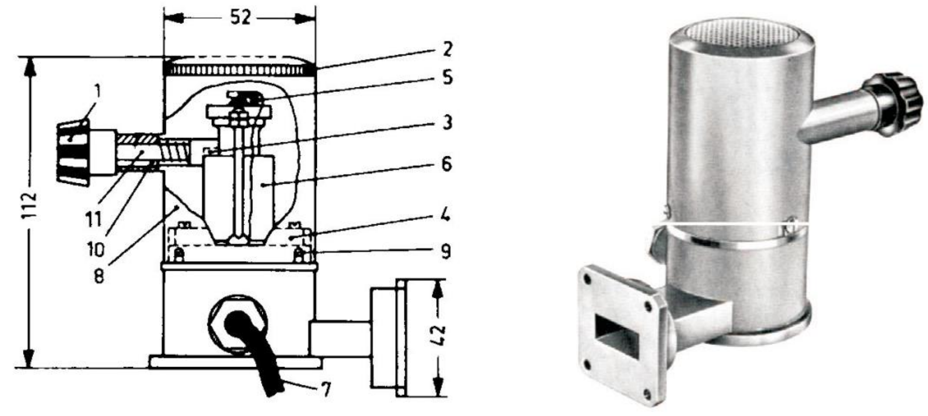
High-Power CW Multi-Cavity-Klystron Amplifiers

Company	Frequency [GHz]	Power [kW]	Efficiency [%]	Beam Voltage [kV]	Gain [dB]
CPI, *Palo Alto*	0.915	100	45	34.0	40
	2.45	60	62	32.0	50
	2.45	120	62	32.0	38
	5.80	14	36	16.5	52
Istok, *Fryazino*	0.915	100	75	20.0	50
	2.45	100	50	34.0	50
Kontakt, *Saratov*	2.45	50	50	15.0	45
	5.80	22	50	20.0	45
	5.80	40	60	24.0	45
Thales, *Velizy*	2.45	50	62	25.0	50
Torij, *Moscow*	0.915	5	55	10.0	50
	2.45	20	60	10.0	45

CPI: Communications and Power Industries

Oscillator –Configuration: „Reflex Klystron“





Reflex klystron *2K25* (left). Schematics (right): 1 mechanical tuner 2 perforated closure plate, 3 tuning srew, 4 fixture, 5 reflector, 6 *2k25* klystron, 7 connection cable, 8 housing, 9 fixture srew for housing, 10 splint, 11 tuning

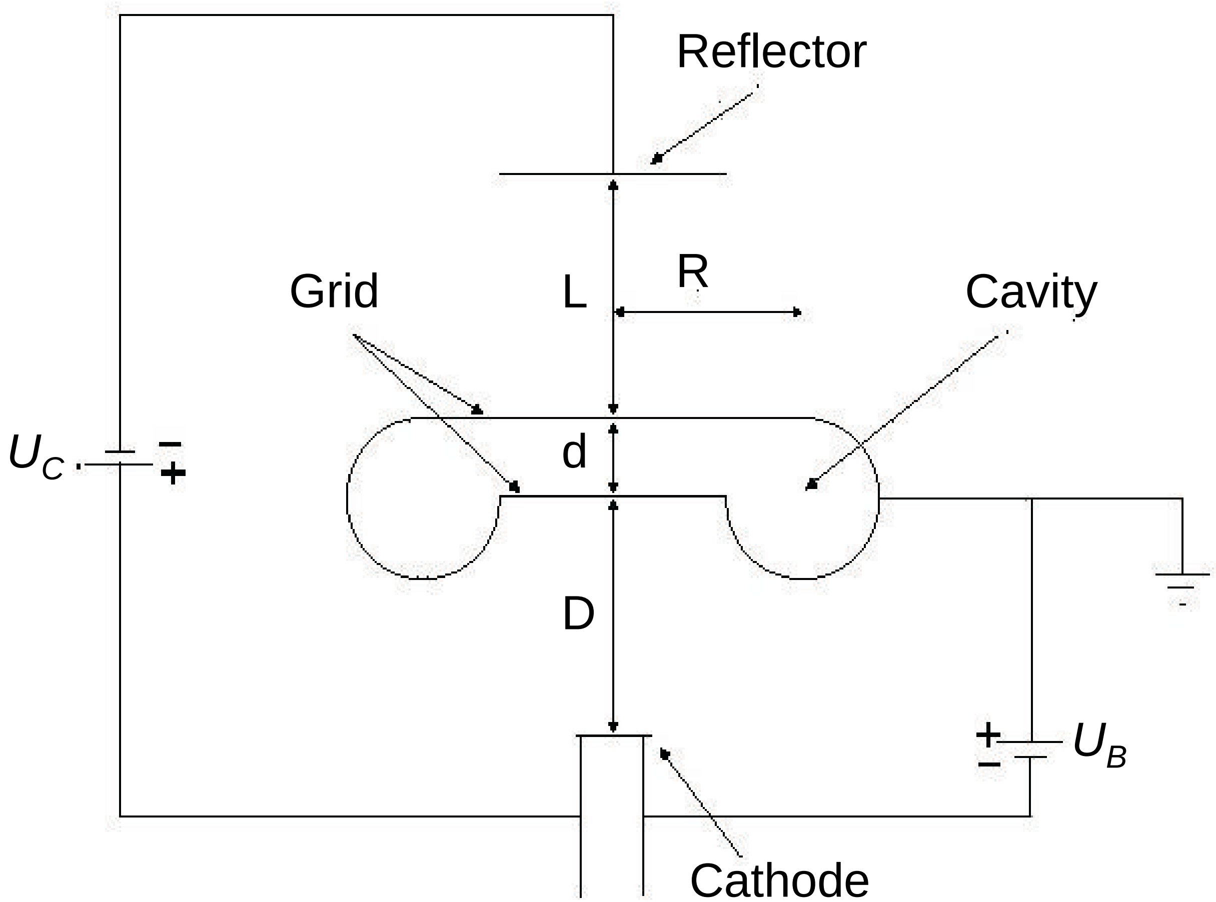
In principle each klystron can be operated as oscillator:

Positive feedback from output to input cavity is necessary.

However for an oscillator the structure can be strongly simplified.
Only one cavity and socalled “repeller” (reflector) are needed.

The repeller has negative voltage, so that the electrons are reflected back to the cavity.
The buncher cavity also is the output cavity

Schematic Setup of Reflex Klystron



Institut für Hochleistungsimpuls- und Mikrowellentechnik (IHM)

Calculation of Resonanz Condition (I)

Kinetic energy and velocity of electrons at cavity input

$$
\begin{aligned}
eU_B &= \tfrac{1}{2}mv_0^2 \\
\Rightarrow \quad v_0 &= \sqrt{\tfrac{2eU_B}{m}}
\end{aligned}
$$

Kinetic energy and velocity of electrons at cavity output

$$
\begin{aligned}
v_g &= v_0 \cdot \sqrt{1 + \tfrac{\hat{U}}{U_B}\sin\omega t} \\
&\approx v_0 \cdot \left(1 + \tfrac{\hat{U}}{U_B}\sin\omega t\right) \\
&= v_0 + \Delta v
\end{aligned}
$$

Traveling Times of Electrons

Acceleration of electrons in the space after grid 2

$$a = \frac{eE}{m} = \frac{e}{m} \cdot \frac{U_B + U_C}{L}$$

We set s(t)=0 to detemine the time when the electrons are back at grid 2

$$\begin{aligned} 0 &= s(t) = t((v_0 + \Delta v) - \tfrac{1}{2}at) \\ \Rightarrow \quad t &= 0 \; \ldots \text{ triviale Lösung} \\ t &= 2 \cdot \frac{v_0 + \delta v}{a} \\ &= 2 \cdot \frac{v_g}{a} \end{aligned}$$

Different traveling times for different v_g

Oscillation Modes of Reflex Klystron

Average traveling of electrons in reflector section for different oscillation modes:

$$\tau = \left(n + \frac{3}{4}\right) \cdot T$$

Change of reflector voltage leads to different oscillation modes *n*.

No oscillations for intermediate voltagesangeregt werden können.

For the special case that the electrons are neather accelerated nor decelerated ($U_w = 0$, $v = v_0$), follws:

$$\begin{aligned}\left(n + \tfrac{3}{4}\right) \cdot T &= t \\ &= \frac{2v_0}{a} \\ &= \frac{2mv_0}{e} \cdot \frac{L}{U_B + U_C}\end{aligned}$$

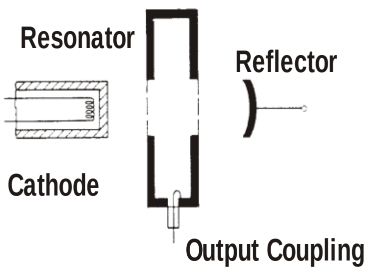
and with

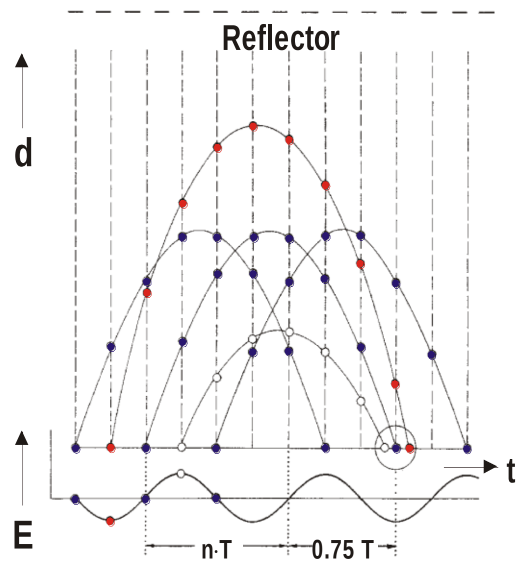
$\nu = 1/T$

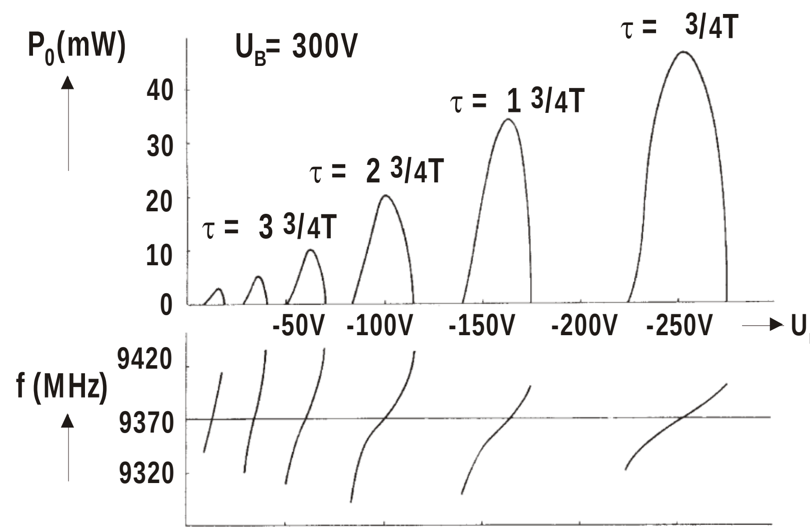
$$n + \frac{3}{4} = L\nu \cdot \frac{\sqrt{8U_B m/e}}{U_B + U_C}$$

For a given U_B for each mode *n* there is a specific U_C.

Reflex Klystron (Oscillator)







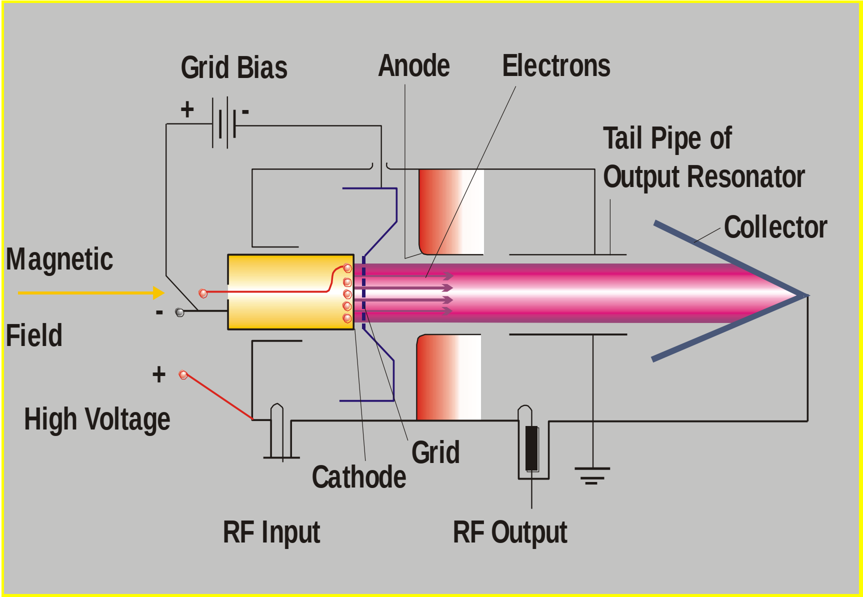
"Electron Bunching„

Flight Time (no RF field)

Resonator – Reflector - Resonator
$\tau = (n + 0.75)T$
with n = 0, 1, 2, 3

Power Output and Frequency Behavior

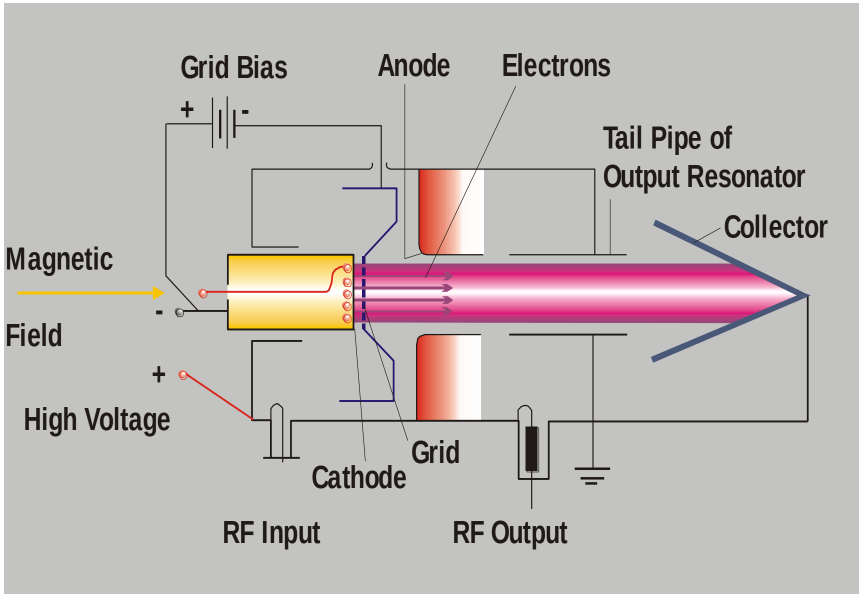
NF = 6.5 dB @ 35 GHz



INDUCTIVE OUTPUT TUBE (IOT)

Inductive Output Tube (IOT) or „Klystrode“

1939 *A.V. Haeff* : Inductive Output Tube (IOT)
1940 *A.V. Haeff* : 100W, CW at 450 MHz and η = 35%
L. Nergaard
(RCA)
1982 *D.H. Preist* : Klystrode
M.B. Shrader
(VARIAN EIMAC)

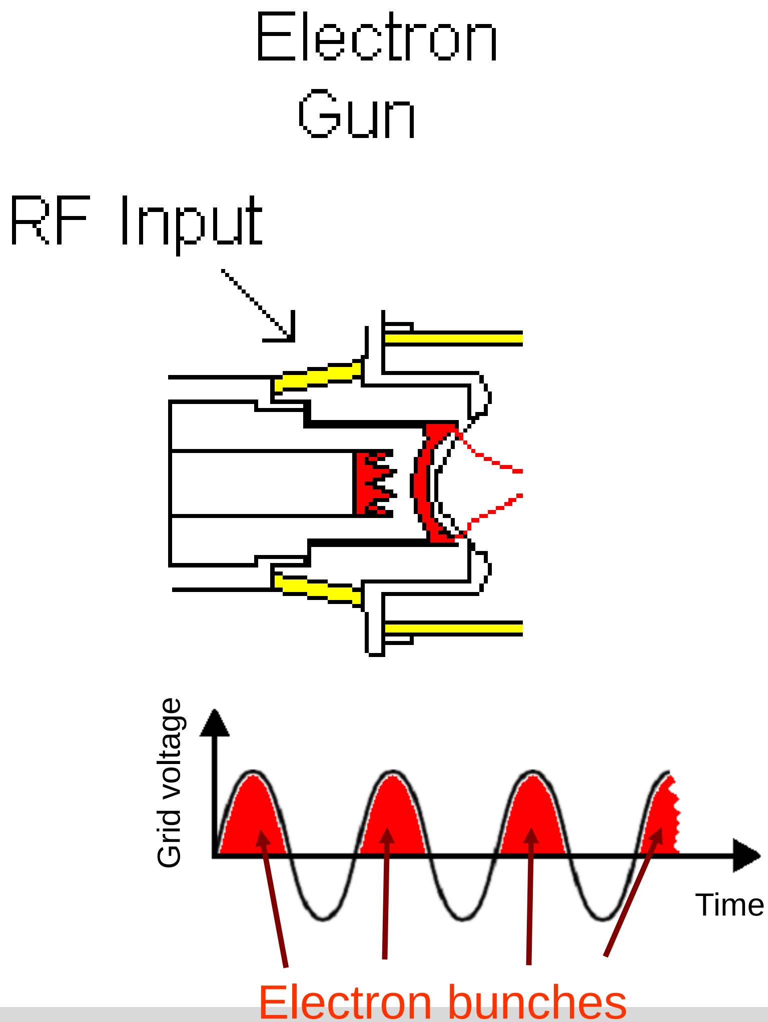


To avoid time-of-flight effects, limitation to UHF - Band, e. g. :

- Frequency Band of Single Device — 600 MHz - 800 MHz,
- Bandwidth — ca. 8 MHz - 10 MHz,
- Output Power — 65 kW CW,
- Efficiency — 50% - 70%,
- Gain — 20 - 23 dB.

Klystrode very important for powerful TV- and Radio Transmitters (470 – 830 MHz).

IOT Schematics



Density Modulation

State-of-the-art of CW HOM - IOT

High-Order Mode Inductive-Output Tube 1 MW, CW / 700 MHz CPI

H.P. Bohlen, CPI (1999)

Device	HOM - IOT expected results	Klystron
Effective efficiency *	73 %	60%
Relative consumption	82 %	100 %
Assembly volume (approx.)	30 cbf	200 cbf
Assembly weight (approx.)	1,000 lbs	5,000 lbs
DC beam voltage	45 kV	90 kV
Gain	25 dB	46 dB

* For the purpose of amplitude regulation, the klystron has to be operated about 10 % below its power saturation point, while the HOM-IOT (like any IOT) does not saturate at the point of its highest efficiency.