The 46th European Microwave Conference

The Basics of Travelling Wave Tube Amplifiers

SCM01

Roberto Dionisio, Claudio Paoloni

European Space Agency
Lancaster University

roberto.dionisio@esa.int

c.paoloni@lancaster.ac.uk

Programme

14:20 – 14:30	**Welcome**
14:30 – 15:00	**Microwave tube, a key element in the modern world of communication** Ernst Bosch, Thales Electronic System GmbH , Ulm , Germany
15:00 – 15:30	**TWT basic operation principles and building blocks** Rosario Martorana, Leonardo Finmeccanica, Palermo, Italy
15:30 – 16:00	**Slow wave structures for micro- and millimeter- waves** Claudio Paoloni, Lancaster University, UK
16:00 - 16:40	Coffee Break
16:40 – 17:25	**Materials and techniques in TWT manufacturing** Roberto Dionisio, ESA ESTEC, Noordwijk, The Netherlands
17:25 – 18:10	**Traveling Wave Tube Design with Simulation** Monika Balk, CST AG, Darmstadt, Germany
18:10 - 18:20	**Open discussion and concluding remarks**

Microwave tube, a key element in the modern world of communication

Ernst Bosch

Thales Electronic System GmbH , Ulm , Germany

Ernst.BOSCH@thalesgroup.com

AGENDA

- **Introductions**
- Principle of Micro Wave Tubes
- Microwave tubes & Applications
- Future

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About 100 Years of using electromagnetic

starting with Diodes and Triodes in 1902

as amplifiers for radio

Nearly 70 Years of Micro wave tubes

as powerful amplifiers of electromagnetic waves

at frequencies from about 300 MHz to several hundreds of GHz and THz

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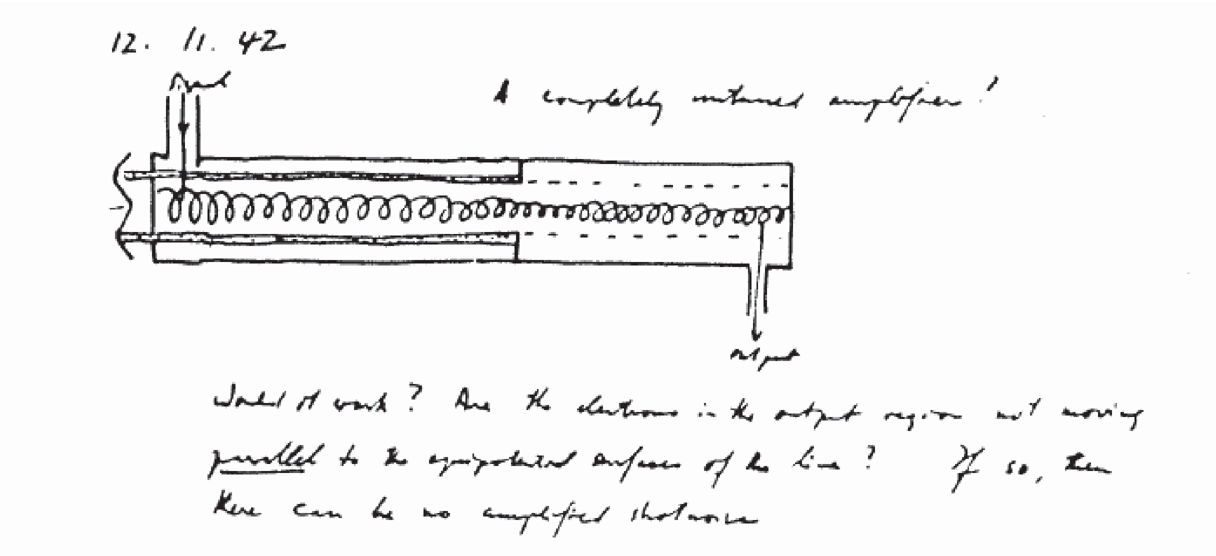
Invention from Rudolf Kompfner through Nils in1942-43 for Traveling Wave tu



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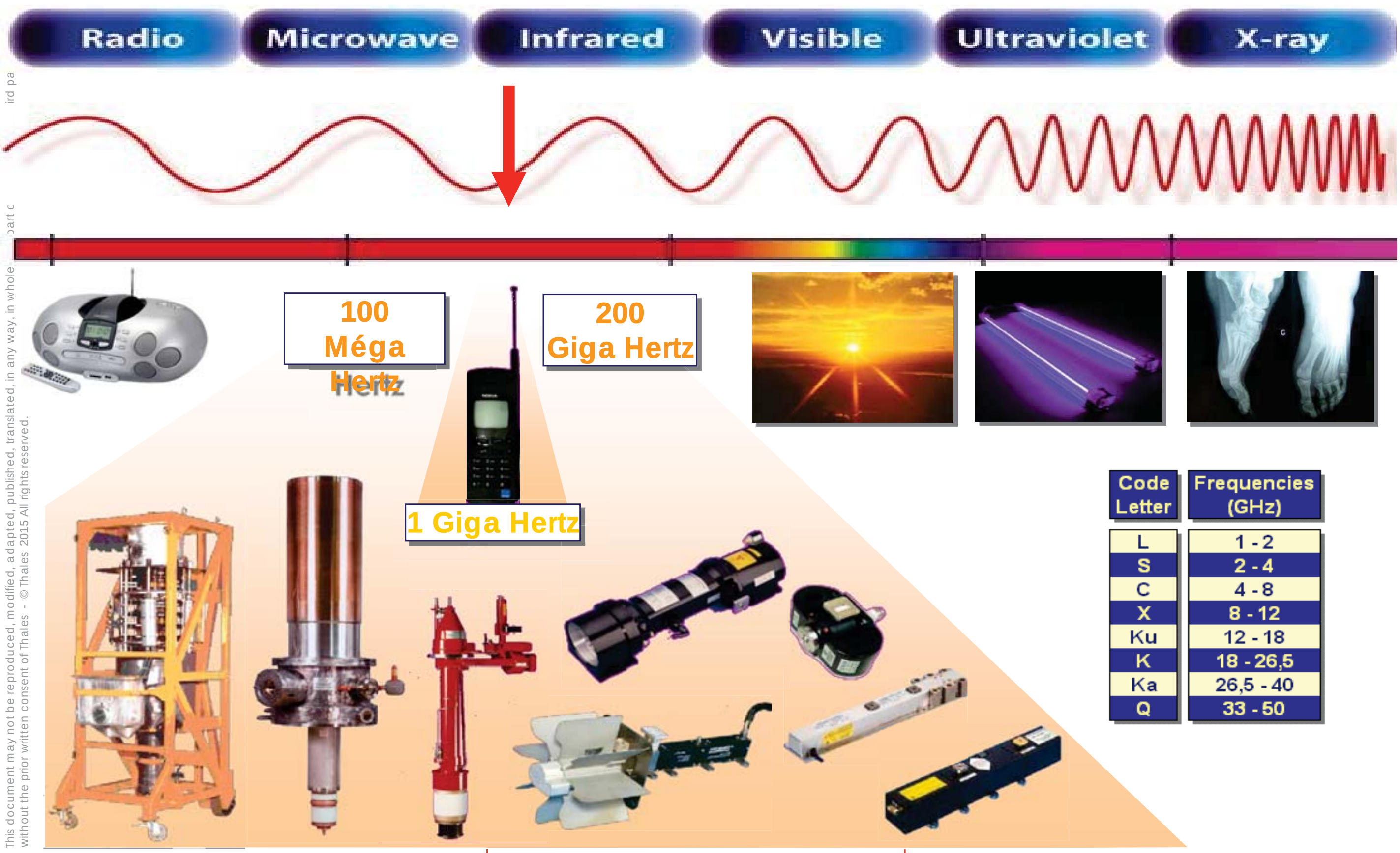
Frequency overview



Code Letter	Frequencies (GHz)
L	1 - 2
S	2 - 4
C	4 - 8
X	8 - 12
Ku	12 - 18
K	18 - 26,5
Ka	26,5 - 40
Q	33 - 50

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Micro wave amplifiers in our daily life

- Radio, TV , Telecommunication
- Radars, military systems
- Industrial applications
- Scientific
- Medical
- acceleration for fusion
- source for rf- heating
- microwave oven

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Applications

Application	Communications			TV transmitters	Radar and ECM				Industrial Scientific and Medical		
Sub-application	*Space*	*Ground Station*	*Tropo Scatter*		*Ground based radars*	*Airborne radars*	*Missile Seekers*	*ECM*	*I*	*S*	*M*
Helix TWTs	●	●			●	●	●	●			
Coupled-Cavity TWTs		●			●	●					
Gridded tubes Triodes and Tetrodes				●	●						
Klystrons		●	●	●	●	●	●		●	●	●
IOTs				●							
Diacrodes				●							
Magnetrons					●	●	●				
Crossed-field amplifiers					●						
Gyrotrons										●	

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Main events in the last decades

- 1902 start with diodes 1912 with triodes
- 1921 with magnetrons
- 1939 Kylstron
- coaxial magnetron, frequency agility magnetron, mass production of magnetrons n 1960 (mainly oven)
- 1980: brazed and pressed helix TWTs (radar, transmissions ground radio links,..)
- 1962 space TWTs
- tunable Klystron for TV (Inductive output tubes –IOT)
- 1995: Multi beam klystrons, EIKs
- Gyrothrons > 100GHz and for MW

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Micro Wave Tube Overview

- **Mirco Wave tubes**
  - **Drift Tubes**
    - **More section tubes**: Klystron, MBK
    - **Single section tubes**: Reflex Klystron
  - **Travelling field tubes**
    - **Without magnetic cross field**: TWT, Back wave Tube
    - **With magnetic cross field**: Magnetron, Cross field amplifie[r], Backwave magnet[ron], Gyrothron

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Micro Wave tubes

Transmitting Tubes

Continuous Wave Magnetron

Plused Magnetron

High-Power Klystrons

Gyrotrons

Couplers

Traveling Wave Tube

Proportional Counter

Neutron Proportional Counter (NPC)

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- Introductions
- **Principle of Micro Wave Tubes**
- Microwave tubes & Applications
- Future

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Technologies for Microwaves Tubes

- **high frequency technology**
- **high vacuum technology**
- **high voltage technology**
- **vacuum electronics**
- **precision mechanics**

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Basic Operation Principles:

- Formation and acceleration of an electron beam (example gun, cold cathodes,..)
- Periodic bunching of electrons at defined frequency
- Bunching start at rf input, or drive power or electromagnetic noise
- Deceleration of the bunch (or reduction of relativistic mass) to push kinetic energy or potential energy into electromagnetic energy
- Out coupling of the microwave energy through a rf window as output power

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Equation of motion of a single Electron

The electromagnetic **Lorentz Force** $\boldsymbol{F} = q\,(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$ leads with

Newton´s Force Law: $\boldsymbol{F} = m_e \cdot d\boldsymbol{v}/dt$

or with relativistic mass: $\boldsymbol{F} = d(m_e \cdot \boldsymbol{v})/dt$ to the

equation of motion of a single electron: $d\boldsymbol{v}/dt = -\eta \cdot (\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$ with $\eta = e/m_e$

$\eta = 1.76 \cdot 10^{11}$ C/kg

or

$1.76 \cdot 10^{11}$ m²/Vs²

There is an important consequence of the Lorentz force equation:

Since the magnetic Lorentz force vector $F_L = q(v \times B)$ is perpendicular on both, the velocity v and B, the magnetic field can not increase the kinetic energy of the electron

$$dE_{kin} = \boldsymbol{F} \cdot \boldsymbol{ds} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \cdot \boldsymbol{v}\, dt \;; \qquad = 0 \text{ for } \boldsymbol{E} = 0$$

(***ds*** is the line path element along the trajectory)

because the scalar product of two orthogonal vectors is zero.

A magnet field can only change the direction, but not the amount of the velocity!

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Basic Properties of Electrons

Mass	$m_0 = 9.11 \cdot 10^{-31}$ kg
Charge	$q = -e = -1.60 \cdot 10^{-19}$ C
Spin	$\underline{s} = (+1/2 \text{ or } -1/2) \cdot h/2\pi$
/magnetic Moment	$\mu_B = 9.28 \cdot 10^{-24}$ J/T
Momentum [5]	$p = m_0 \cdot v_e = h/\lambda = \sqrt{2 \cdot e \cdot m_0 \cdot U}$

Related Force / Magnitude

Related Force		Magnitude
Gravitation	$F_g = m_0 \cdot g$	$\approx 8.9 \cdot 10^{-30}$ N [1]
Electrostatic	$F_E = q \cdot E$	$\approx 2.4 \cdot 10^{-13}$ N [2]
Spin /Dipole in field gradient	$F_m = grad \cdot (\mu_B \cdot B)$	$\approx 7.4 \cdot 10^{-24}$ N [3]
Lorenz Force	$F_L = q \cdot \mathbf{v} \otimes \mathbf{B}$	$\approx 1.2 \cdot 10^{-13}$ N [4]

Conditions for Magnitude Calculations

Gravitation [1]	Weight of electron at earth surface
Electrostatic [2]	Typical E-Field of 150 V/0.1 mm or 1.5kV/mm
Spin / Dipole in field gradient [3]	Field Gradient of 0.1 T/ 10 mm
Lorenz Force [4]	150 eV electron in a 0.1 T transverse magnetic field

De Broglie Wavelength at 150 eV [5] $\lambda = 1/k = 1e\text{-}10$ m, (Planck's constant h =6.63e-34 J*sec)

$v_e = \sqrt{2 \cdot |q| / m_0 \cdot U} = 5.93 \cdot 10^5 \sqrt{U}$ (U in V) $\Rightarrow$ $v_e/c > 0.1$ for U >3kV $\Rightarrow$

relativistic correction

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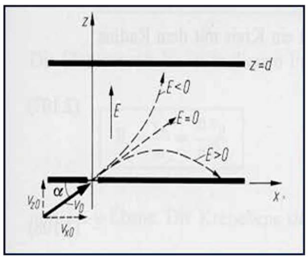
Examples of electron trajectories:

Here cyclotron frequency $\omega = \eta \cdot B$

Figures from J. Eichmeier, Moderne Vakuumelektronik, Springer Verlag, 1981



A) homogeneous electric field with starting angles α different E-fields :

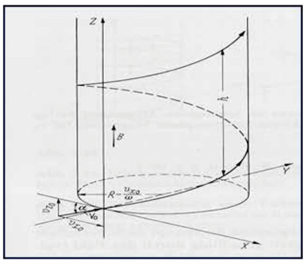
Parabolic Trajectory

E=Ez ; ***B***=0

v0 : v_x0, v_z0

x= vx0 · t

z = vz0 · t -1/2 · η · t²



B) homogeneous magnetic field: Helical Trajectory

E= 0 ; ***B***=Bz

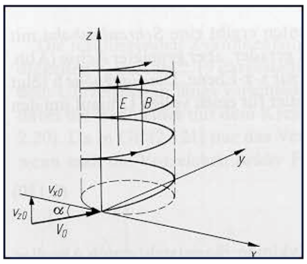
v0 : v_x0, v_z0

with: R=v0/ω · cosα

x= R · sinωt

y= R · (1- cosωt)

z = v0 · t · sinα



C) superposition of parallel electric & magnetic field:

E=Ez; ***B***=Bz;

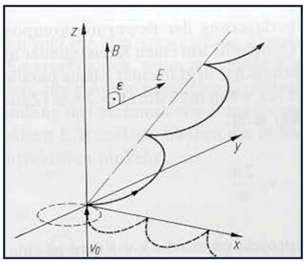
v0 : v_x0, v_z0

with: R=v0/ω · cosα

x= R · sinωt

y= R · (1- cosωt)

z = v0 · t sinα - 1/2ηEt²



D) superposition of crossed electric & magnetic field

E=Ey; ***B***=Bz;

v0 : v_{z0}

x= -E/ωB · sinωt + E/B ·t

y= -E/ωB · (1- cosωt)

z= v_{z0} · t

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1) In all typical vacuum-electronic applications the effect of gravitation and electron spin can be neglected, since the respective forces are many orders of magnitude below the electrostatic and the Lorentz force.

2) The quantum mechanical nature of the electrons (de Broglie: Nobel Prize 1929) in vacuum can be neglected, since even for slow 150 eV electrons the de Broglie wavelength $\lambda = 1*10^{-10}$ m is many orders of magnitude below the typical dimensions of the vacuum envelope, But the quantum-mechanical effects appear for very low voltages and localised interactions of electrons with other "particles" as phonons, photons, electrons and neutrals especially in electron emission processes.

3) The relativistic mass correction $m_e = \frac{m_0}{\sqrt{1-(v_e/c)^2}} = m_0(1+V/V_n)$ should be applied for voltages V > 5kV (already 1%-mass increase at 5kV).

4) The equation of motion and the Maxwell equations apply to describe electron beam motion in vacuum.

5) The magnetic self field of the beam current can be neglected in most cases compared to external fields, which allows to introduce a scalar magnetic potential.

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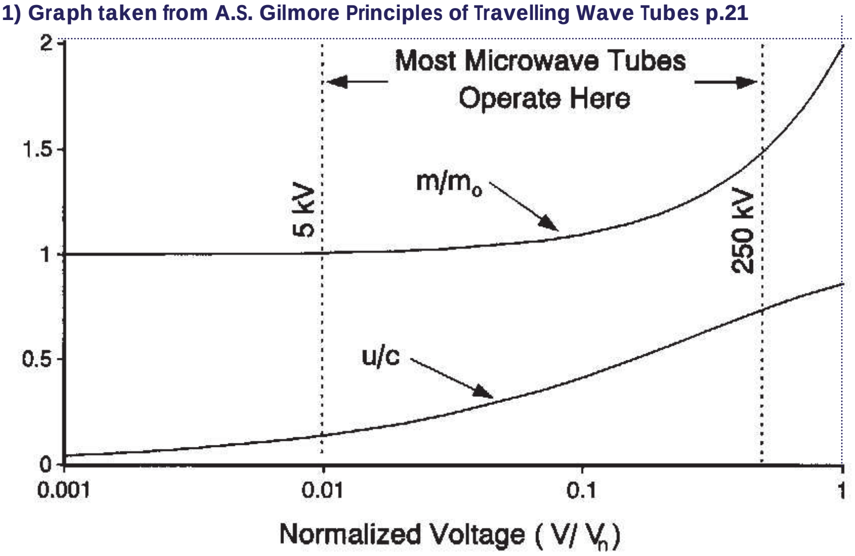
Relativistic Effects - important for Gyrotron

Normalised Mass and Velocity as function of normalised Voltage 1)

1) Graph taken from A.S. Gilmore Principles of Travelling Wave Tubes p.21



With **Vn= m_0c^2/e**

Vn= 511 kV

Energy corresponding to electron rest mass m_0 511 keV.

The relativistic mass as function of the normalised acceleration voltage:

$m_e = m_0 (1 + V/V_n)$

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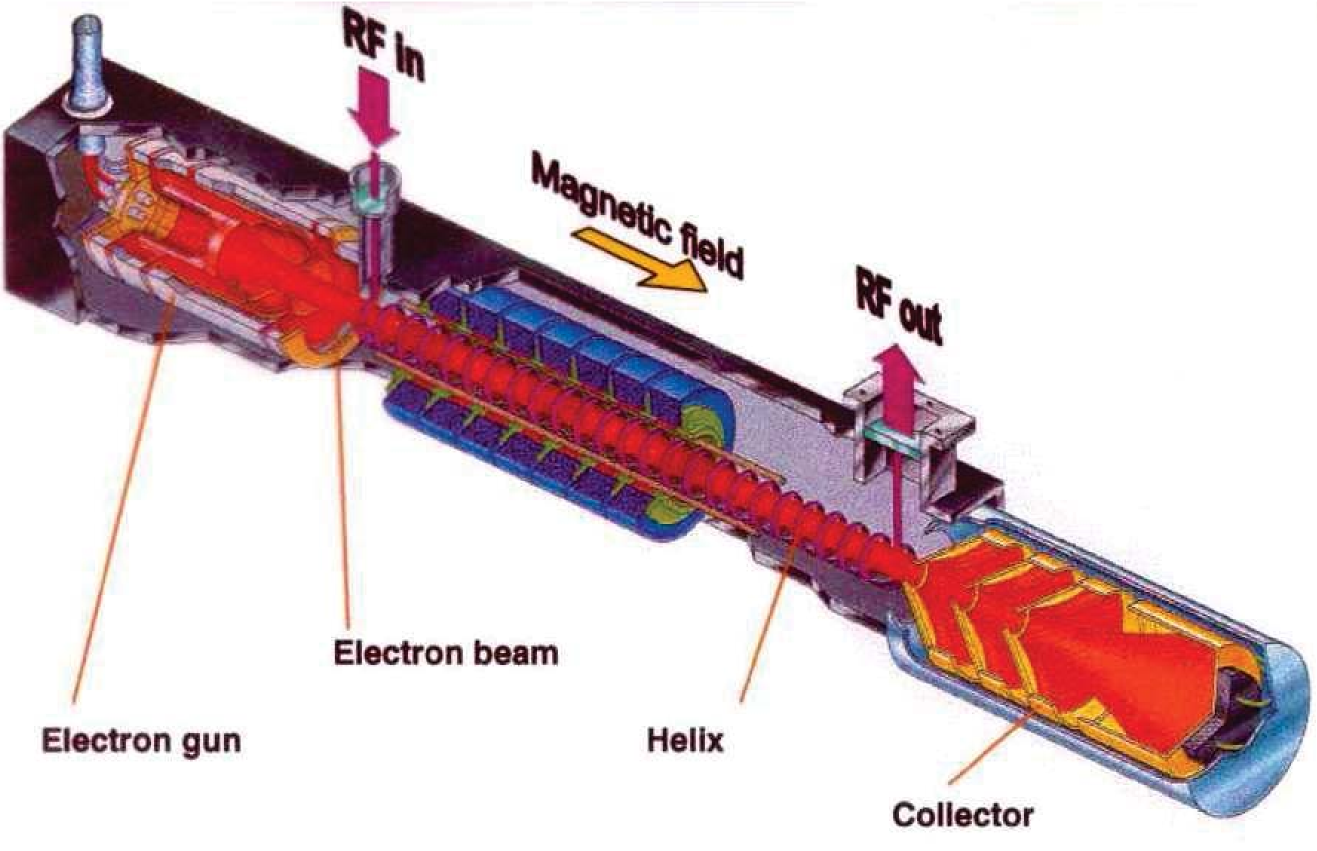

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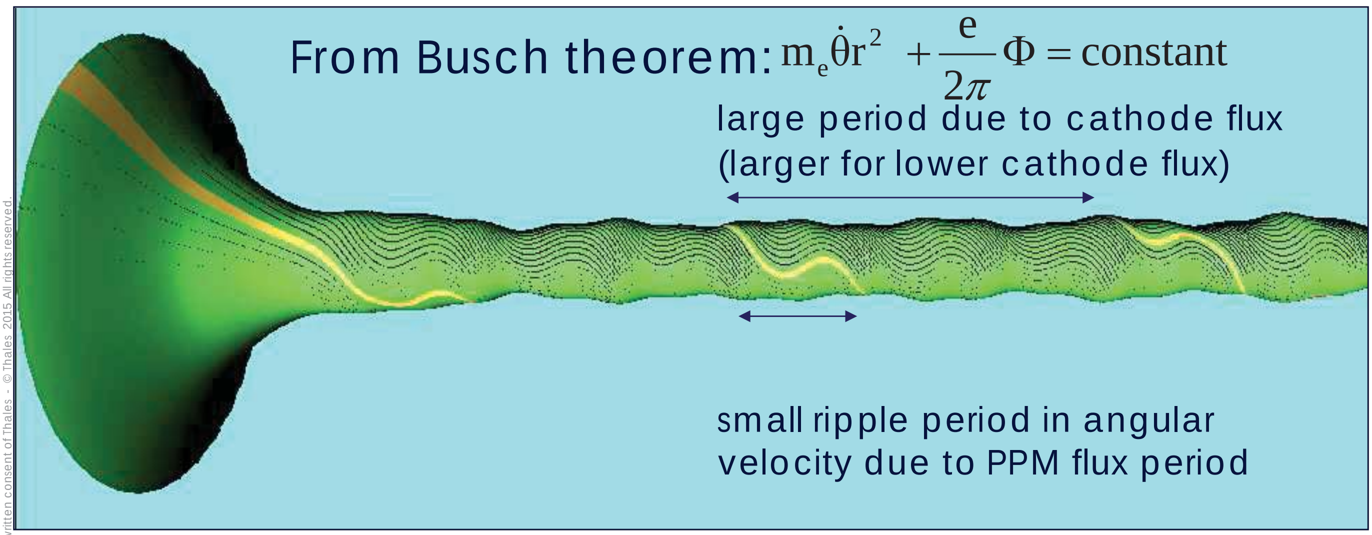
5.5) "Golden" trajectory and beam envelope from a 150 mA, 7.5kV modified Pierce gun into a 1mmϕ grounded tunnel, B_{peak} = 0.325 T

simulated with 2D-gun program and visualised with virtual reality shareware code by W. Schwertfeger TED, Ulm



Different scaling in r and z direction! r = 10x

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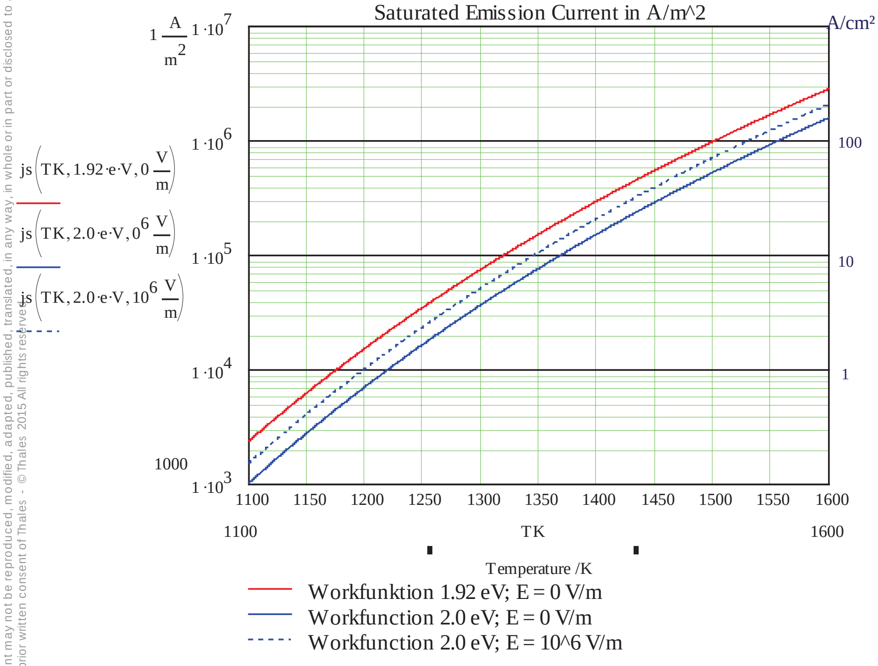
Thermal emission, effect of work-function and applied field



$$js(T,\phi,E) := A\cdot T^2\cdot \exp\left(\frac{-\phi}{k\cdot T}\right)\cdot \exp\left(Ka(T)\cdot E^{\frac{1}{2}}\right)$$

$$Ka(T) := \frac{\left(\dfrac{e^3}{4\cdot\pi\cdot\varepsilon_0}\right)^{\frac{1}{2}}}{k\cdot T}$$

Conclusion:

1) A decrease of the workfunction by 0.08 eV increases emission by a factor 2 or
2) reduces the required temperature for the same emission by 50 K.
3) the electric field E can be changed by 6 orders of magnitude without increasing dramatically the saturated emission.

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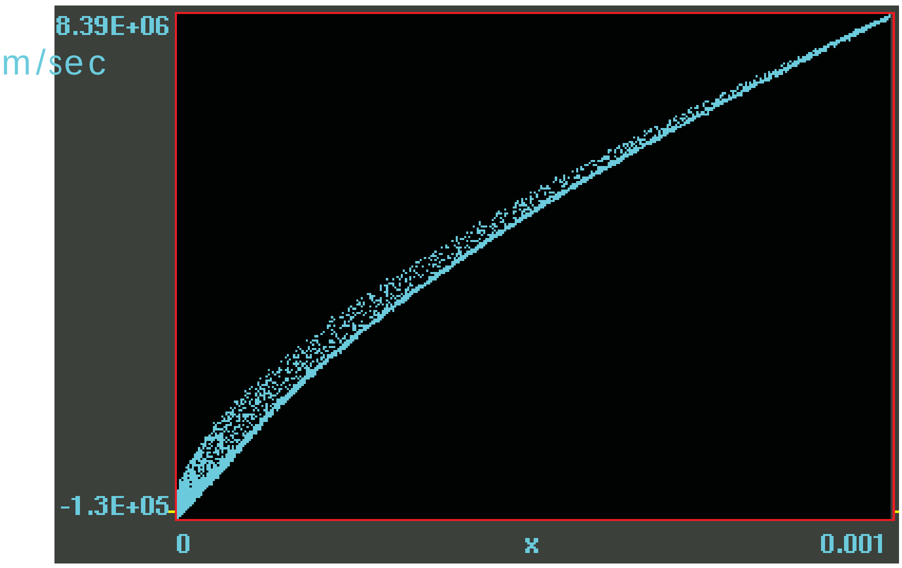
Velocity spread ux(x) of thermally emitted electrons in a space charge limited diode



Close to the cathode surface some electrons have a negative voltage because their thermal velocity is not sufficient to overcome the negative potential barrier in front of the cathode (-0.5V).
If the temperature is increased, the depth and width of the negative barrier increases such, that the space charge current is maintained

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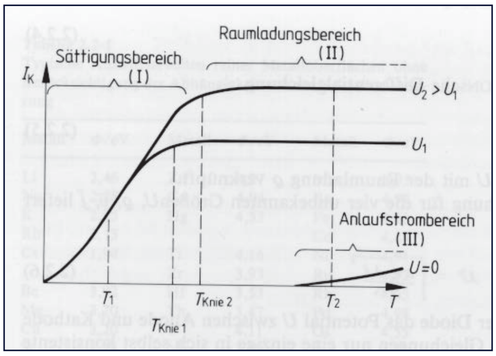
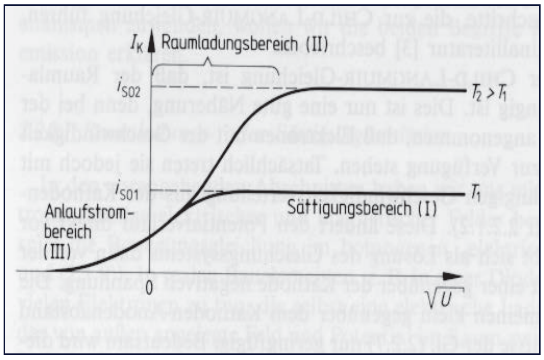
Thermal emission in a diode as function of temperature T and voltage U [1)]



Temperature dependence



Voltage dependence

Range I : Temperature limited emission according to Richardson-Dushmann-Schottky equation

Range II : Space charge limited emission according to Child-Langmuir law

Range III: Reversed field current

1) Figures from J. Bretting, Technische Röhren, Hüthig Verlag, 1991

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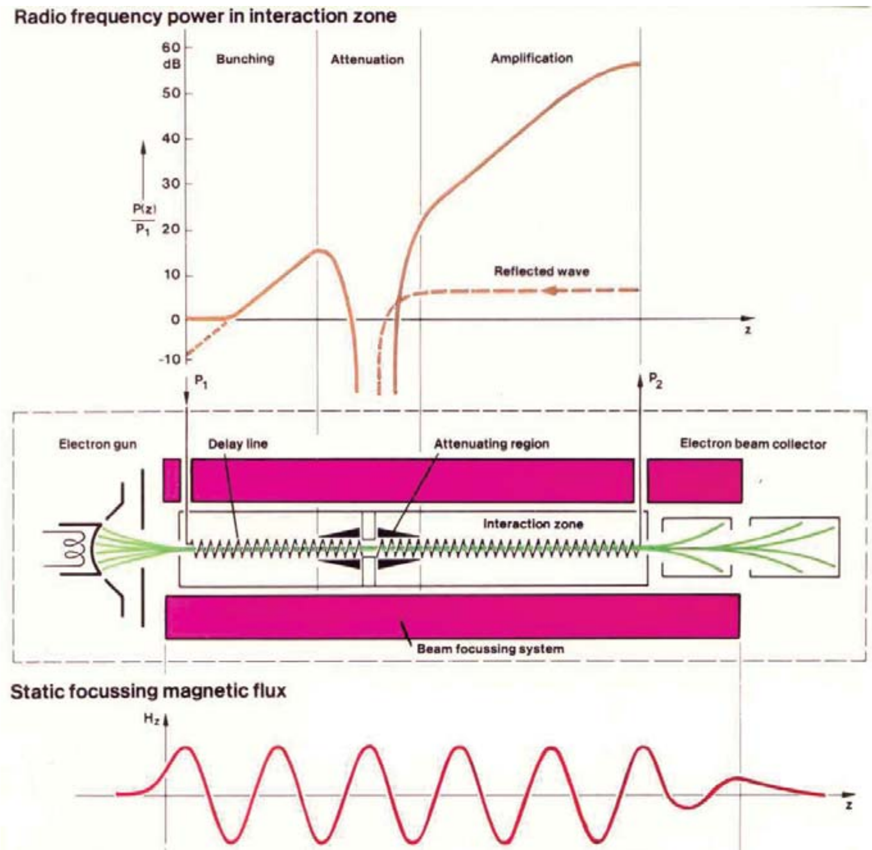

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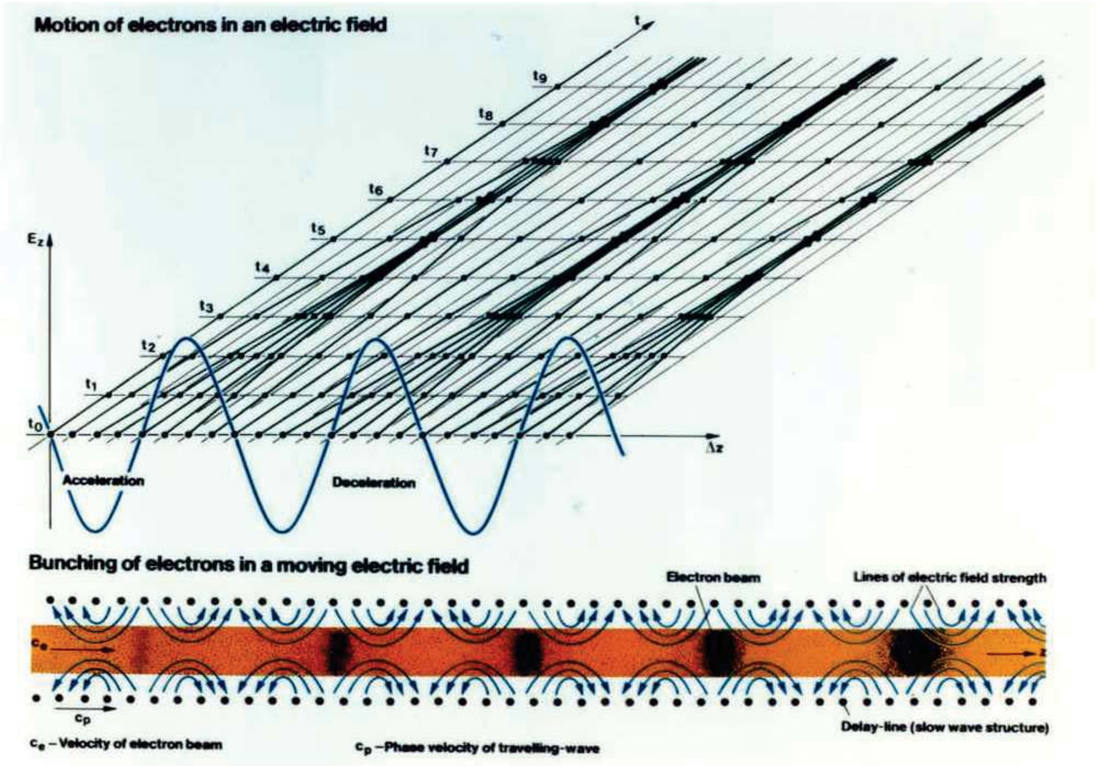

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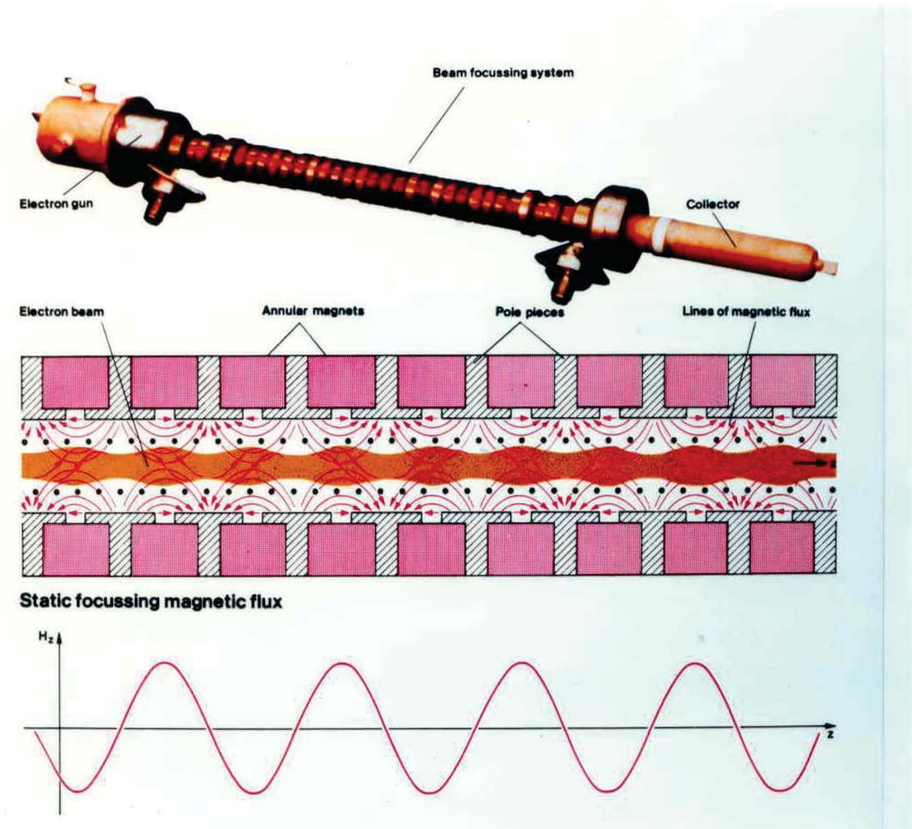

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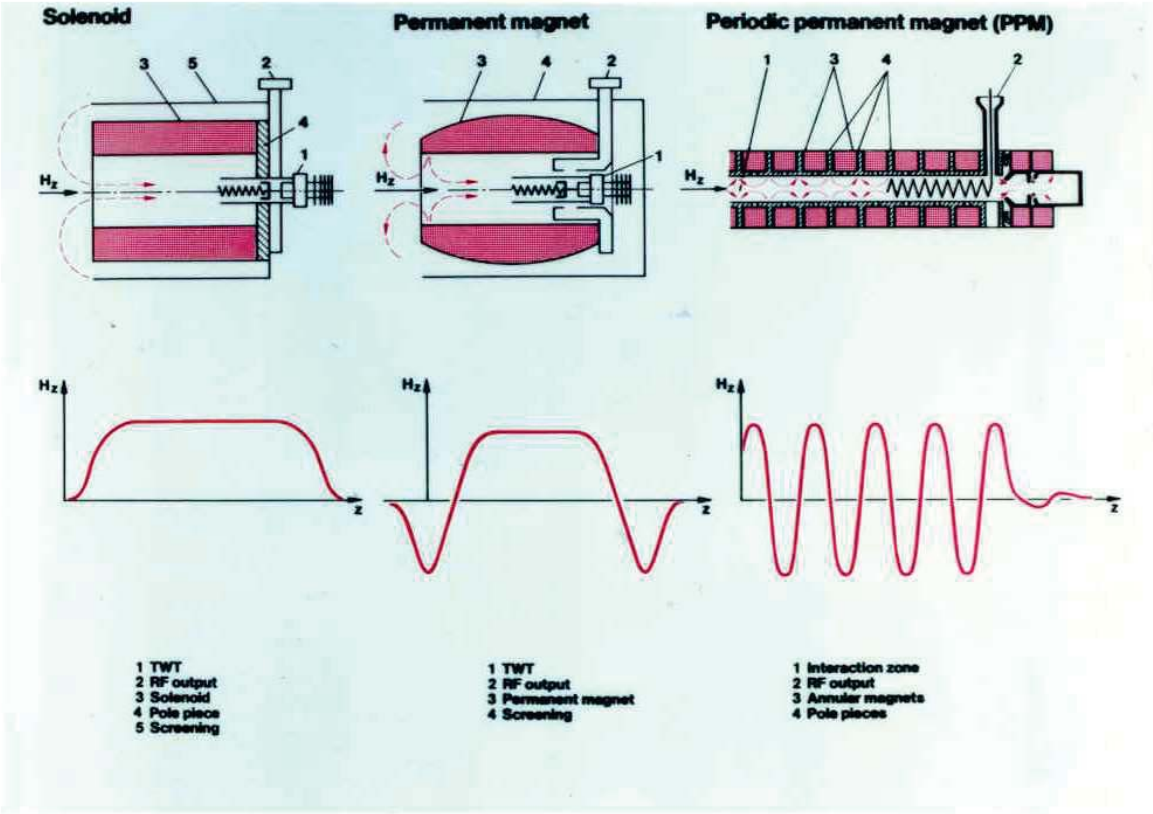

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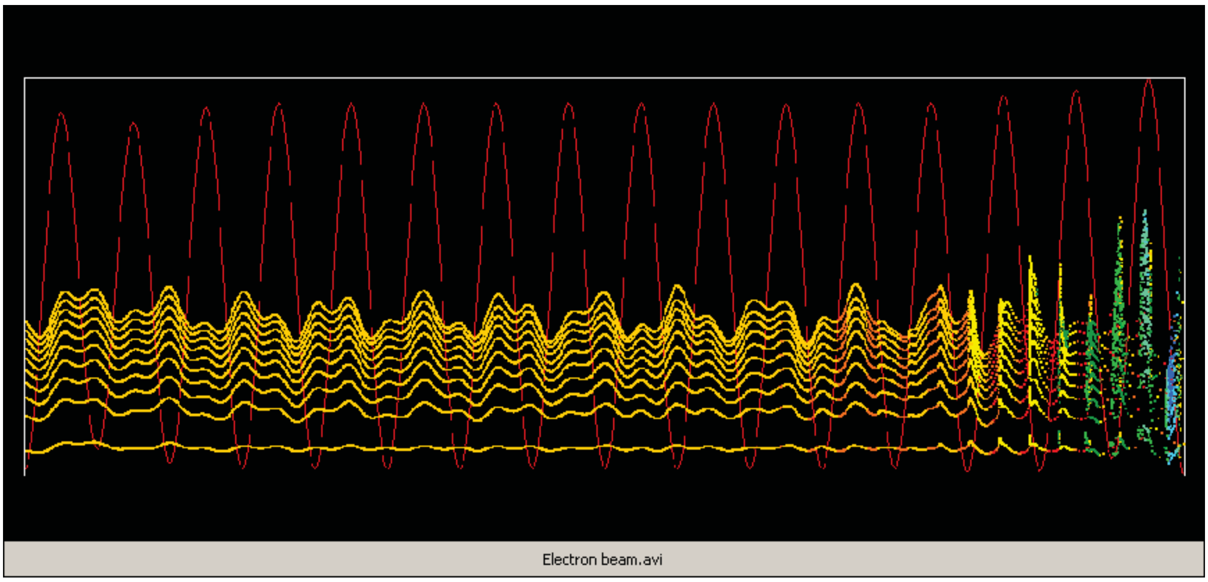
Micro Wave Tube Principles - TWT



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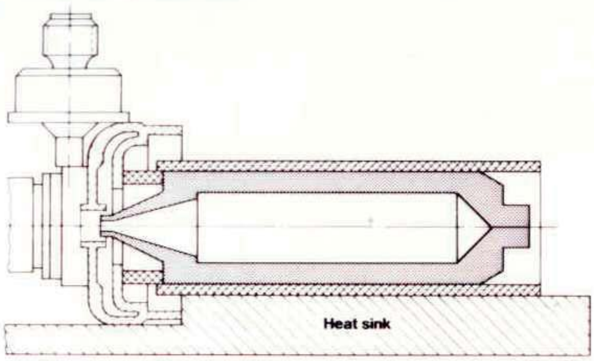
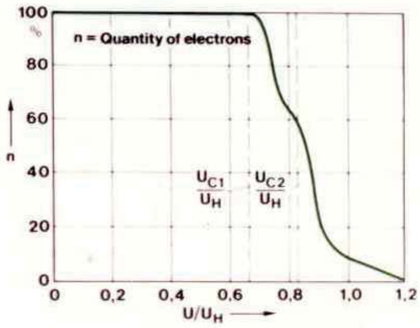
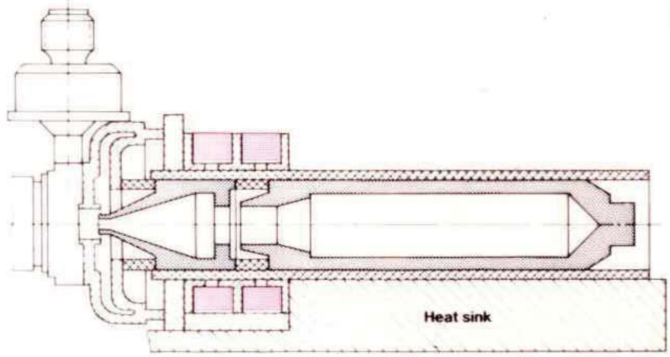
Single-stage collector



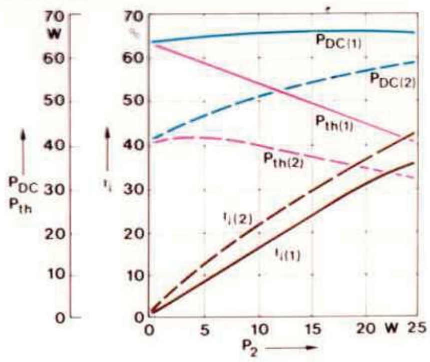
Electron velocity distribution



Double-stage collector



Efficiency, d.c. power and dissipated power for single and double-stage collectors



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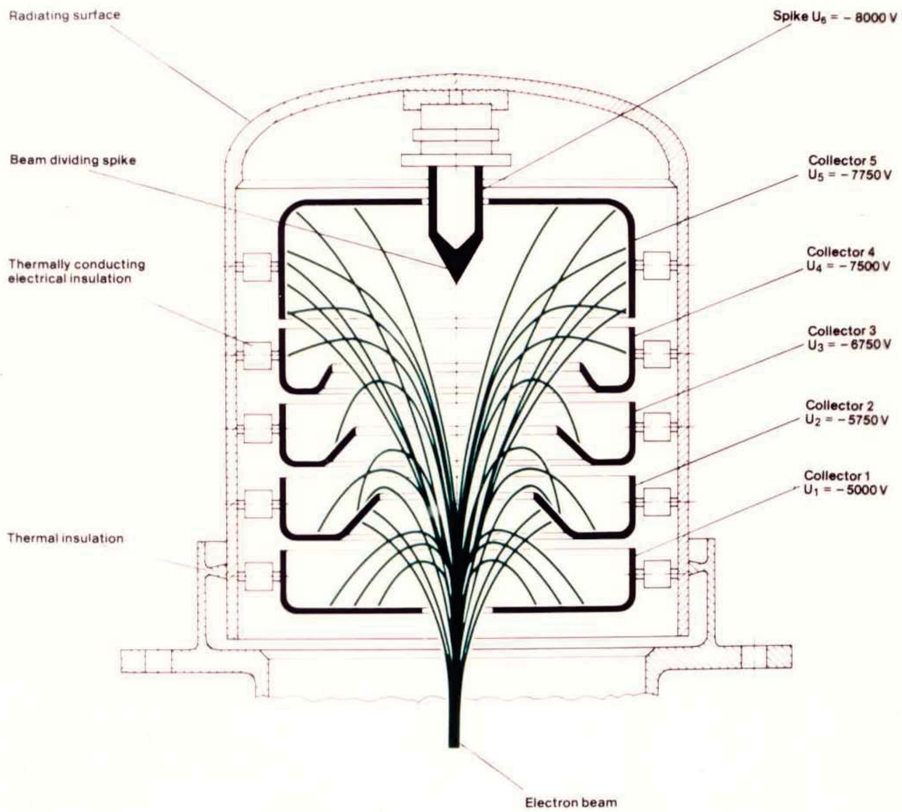
Micro Wave Tube Principles - TWT



Voltages referred to ground

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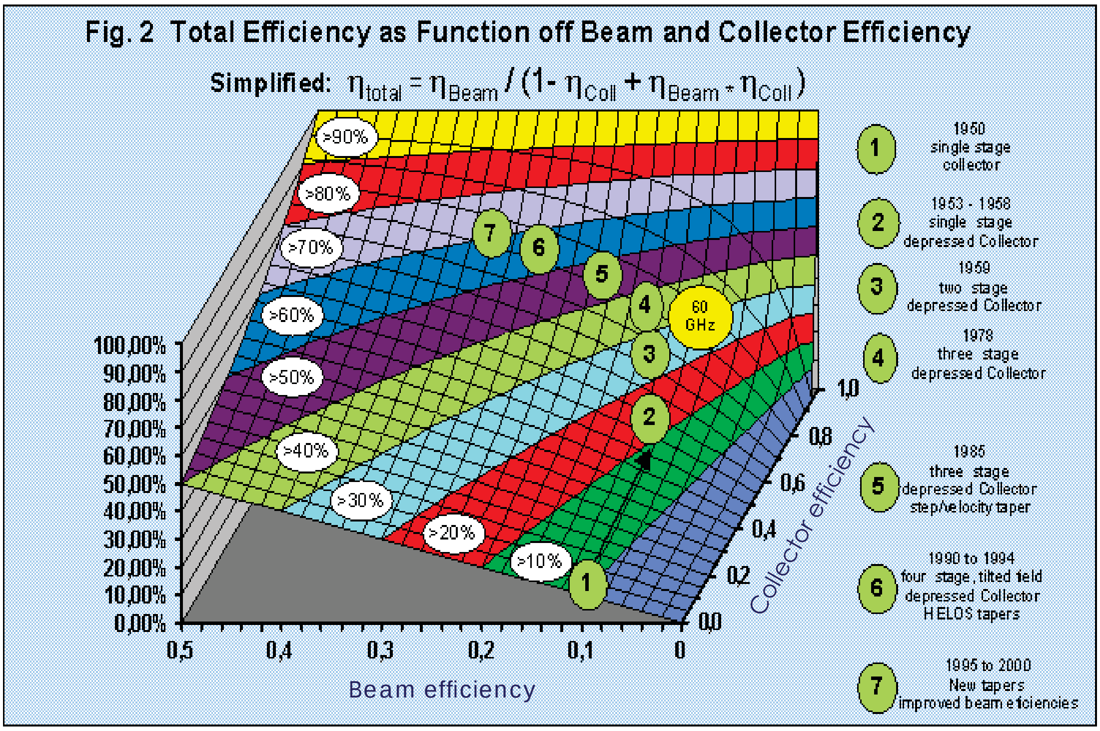

Fig. 2 Total Efficiency as Function off Beam and Collector Efficiency

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Transmitting Tubes

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TH 628 - High power diacrode.

TH 781 - High power tetrode.

- ✓Air Cooling, Water Cooling
- ✓Triodes Tetrodes
- ✓Applications: Induction Heating for Industry

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Klystron - Function

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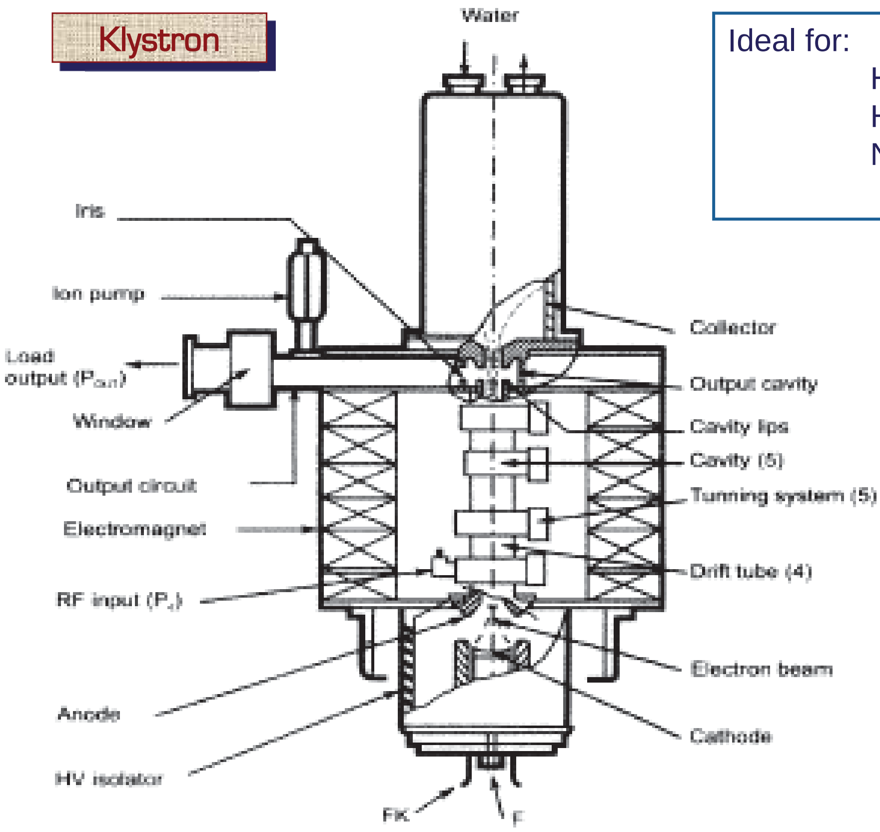
Klystron

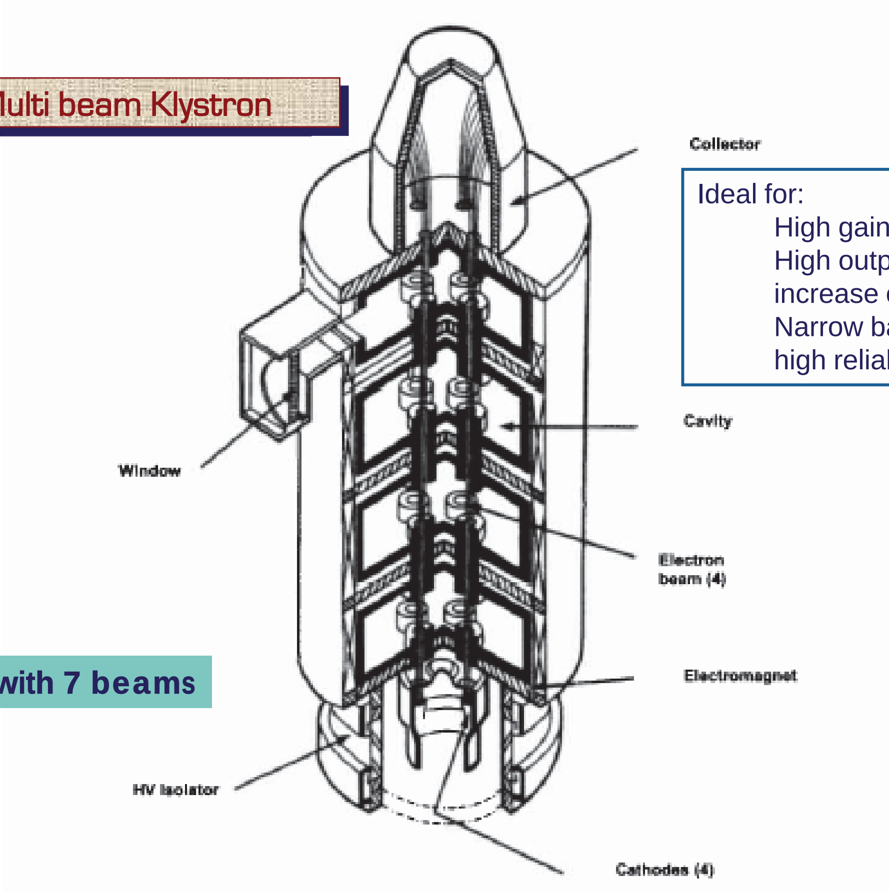


HV connections
(F: filament, FK: filament and cathode)

Ideal for:
- High gain
- High output power
- Narrow bandwidth (2%)

Multi Beam Klystron (MBK) - Function

Multi beam Klystron



Ideal for:
- High gain
- High output power without increase of voltage (less x-ray)
- Narrow bandwidth (1%)
- high reliability

MBK with 7 beams

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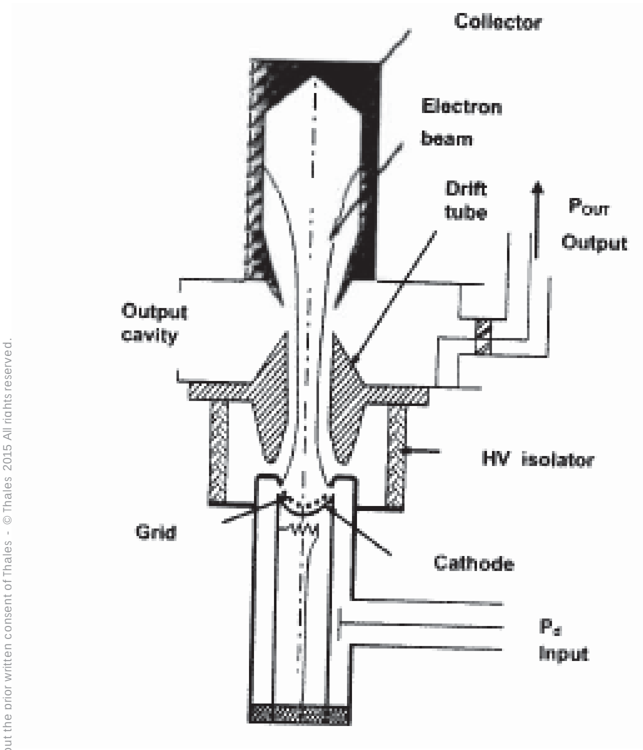
IOT

IOT



Ideal for:
- High gain compared to tetrode (22 dB instead of 15 dB)
- High output power at low frequency

1,3 GHz,
16 kW CW 34 kW peak
efficiency59 %

470 MHz,
80 kW CW
Efficiency 70 %

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Features :

- High efficiency and high gain.
- High power performance, with a multipactor discharge-suppressing coating of titanium nitride on the output window.
- long life and high -current-density cathodes.
- High reliability, based on advanced high-vacuum, and high-voltage technologies created in the development of various type of electron tubes.

Applications:

- High energy accelerators/Medical accelerators
- Experimental nuclear fusion research facilities
- Medical accelerators
- Air traffic control radars
- Airport ground control radars
- Industrial microwave heating

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Klystrons

Microwave tubes: High-power klystrons

Frequency	Reference	Peak output Power	Average output Power	Efficiency	Gain	Pulse duration	Beam voltage	Beam current	Magnet	Windows number	Windows accessory
GHz	klystron	typ. MW	typ. KW	typ. %	typ. dB	max. µsec	typ. KV	typ. A			
1.300	TV 2022B	20	60	42	51	10	229	208	TH 20100	1	TH 20141
	TH 2104D	5	250	45	46	500	125	88	TH 20277 A	1	TH 20141 (<165 KW) TH 20617 (250 KW)
2.856	TH 2163	5.5	10	48	45	8	135	84	TH 20678	1	TH 20670
		7.5	8	48	48	6	148	106			
	TH 2163A	10	10	48	50	3.5	175	125	TH 20678	1	TH 20670
	TH 2158	5	45	48	48	27	122	85	TH 20649	1	TH 20669
	TH 2173F	5	36	50	48	17	122	84	TH 20444	1	TH 20669
2.9985	TH 2157	5.5	10	48	45	8	135	84	TH 20678	1	TH 20673
		7.5	8	48	48	6	148	106			
	TH 2157A	10	10	48	50	3.5	175	125	TH 20678	1	TH 20673
	TH 2173K	5	36	50	48	17	122	84	TH 20444	1	TH 20674

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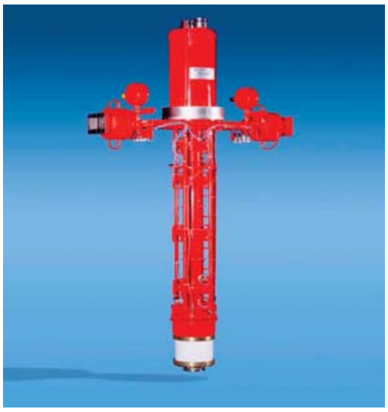
Klystrons

Klystron

Multi Beams Klystron (MBK)



TH 2103 -
Five-cavity high
power klystron.

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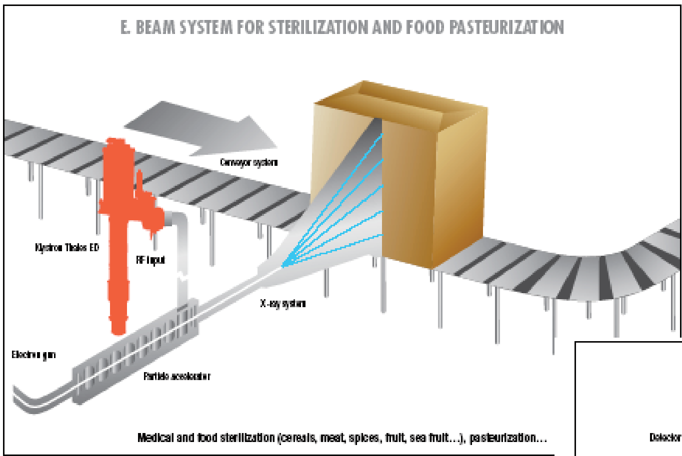
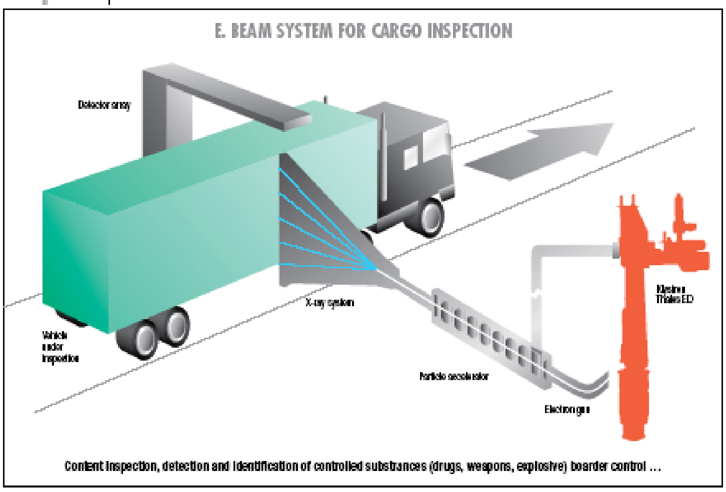
Applications Klystrons



Industrial Applications



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Medical Applications

Linac: Conventional X-ray therapy

Linac systems use our klystrons, which offer a wide range of photon and electron energies compatible with the latest beam conformation and modulation techniques.

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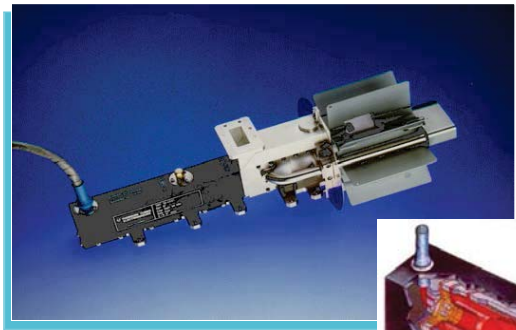
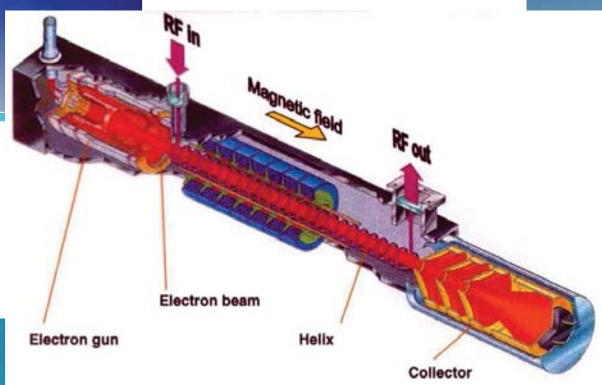
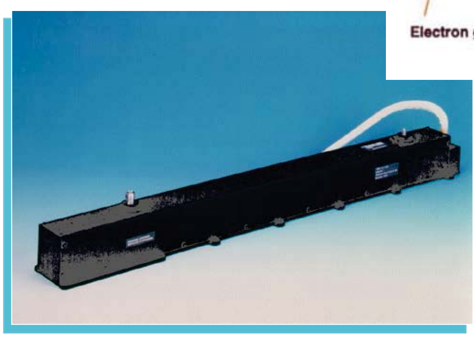
Travelling Wave Tubes







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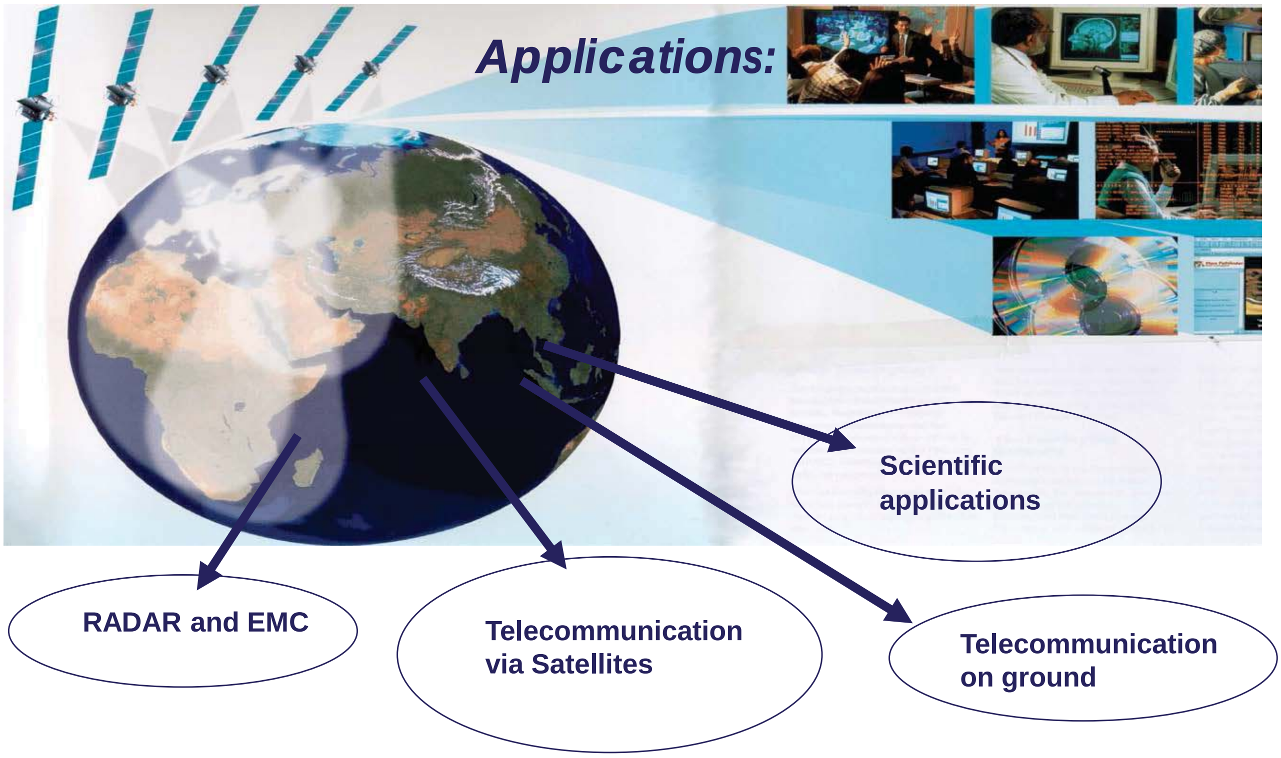

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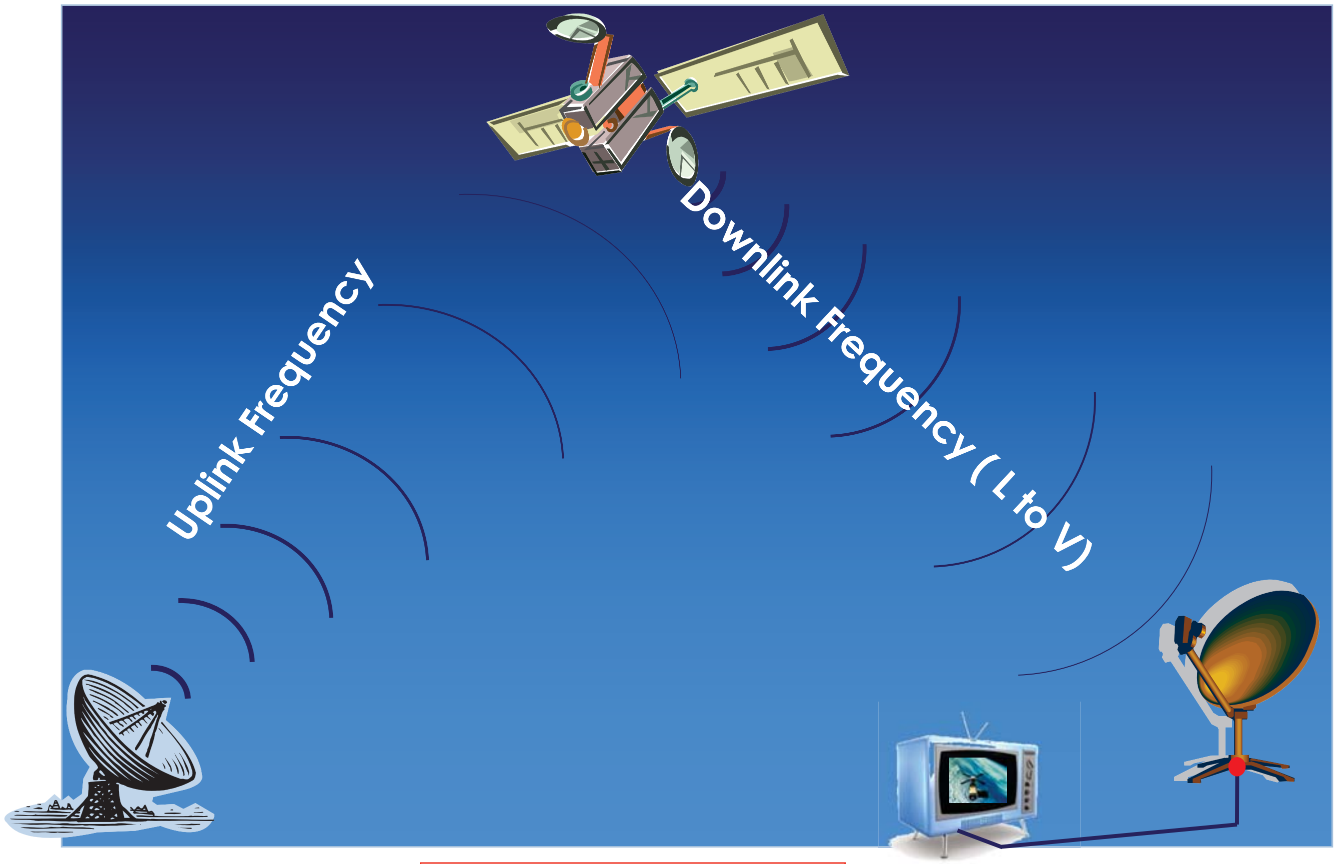

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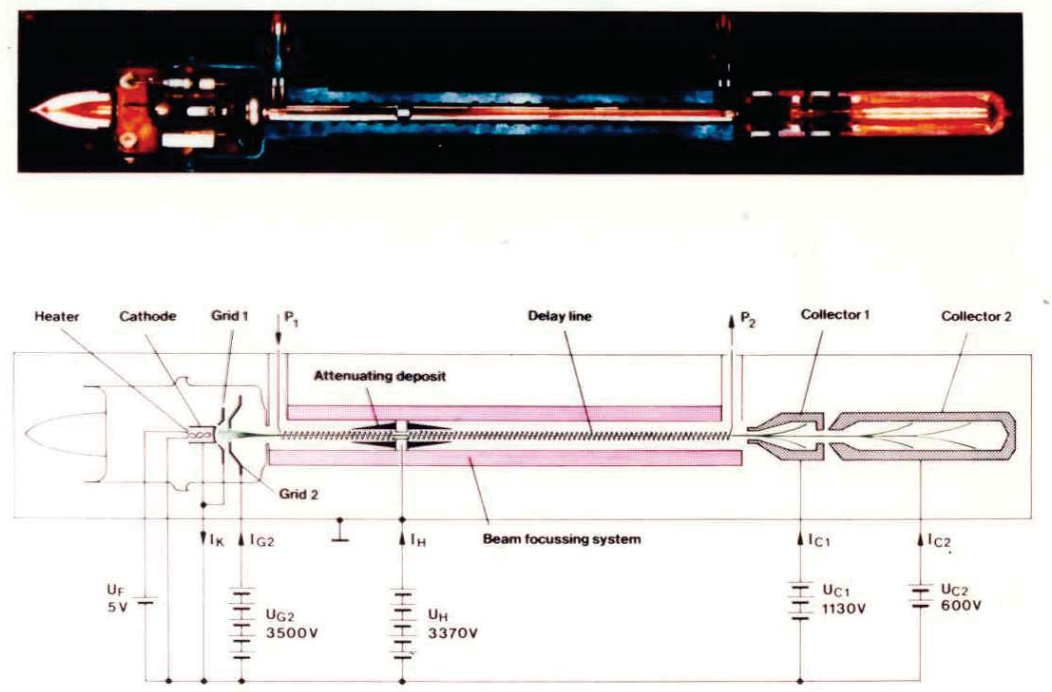
Cross-section of a travelling-wave tube with double-stage collector



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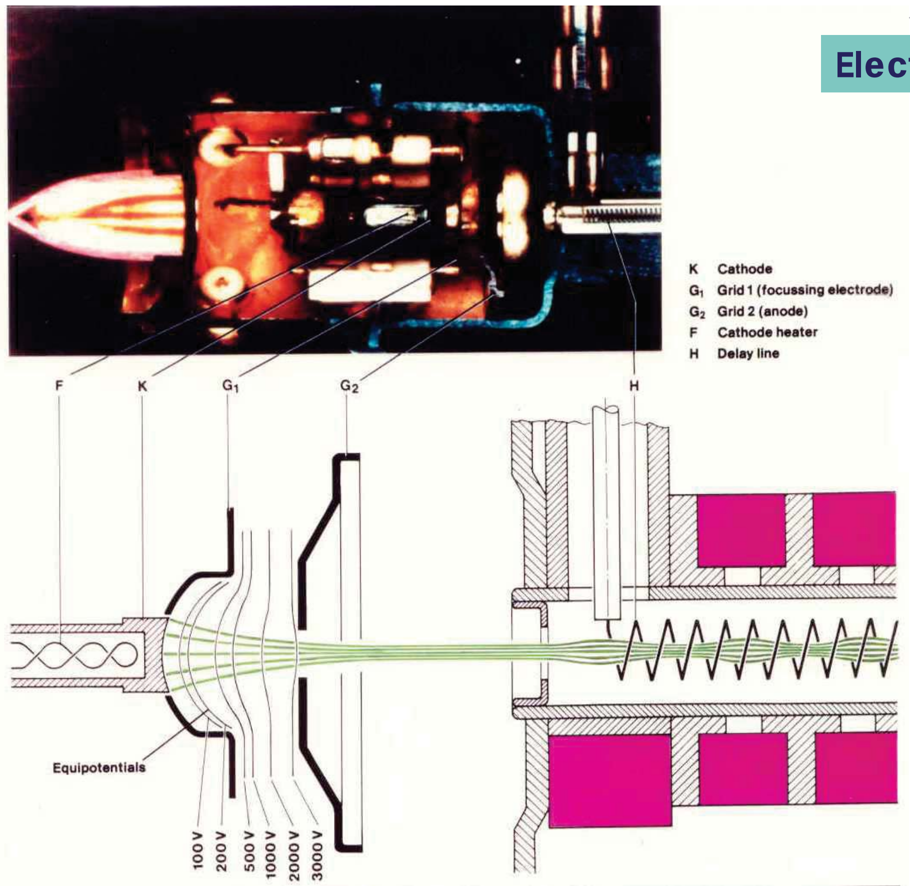
Electron Gun



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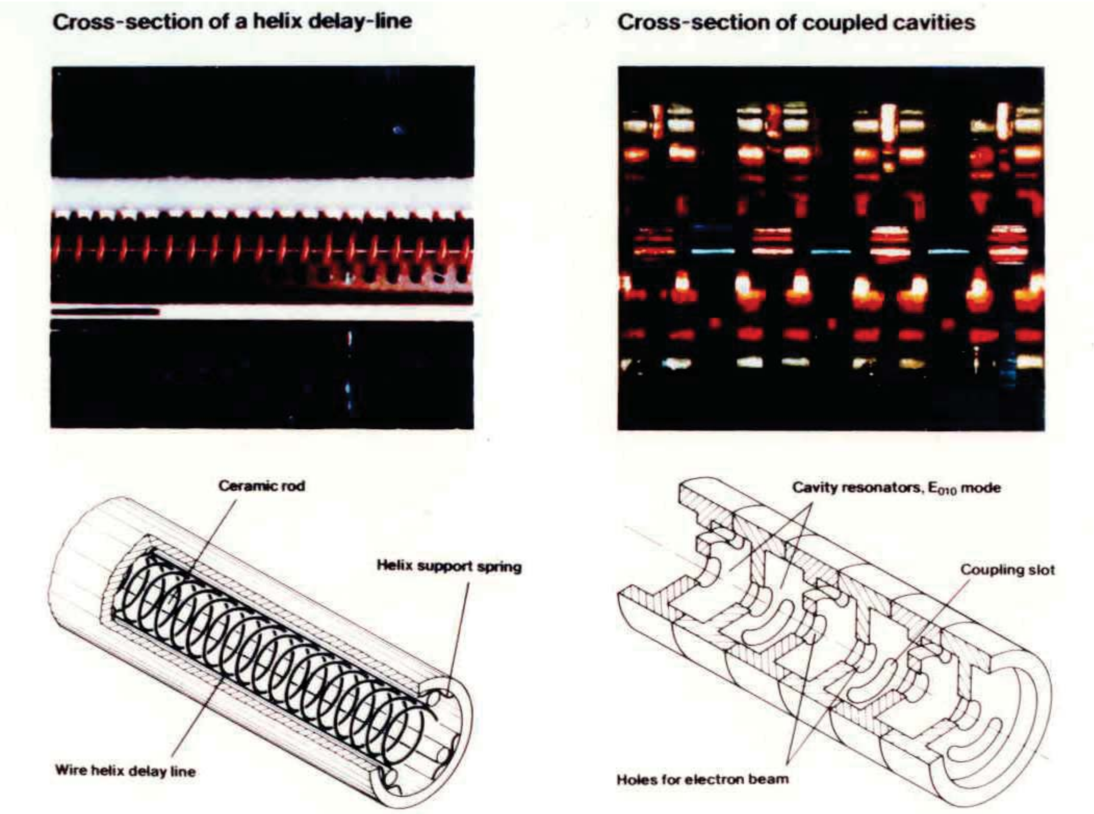
Travelling Wave Tubes

Delay Line structure



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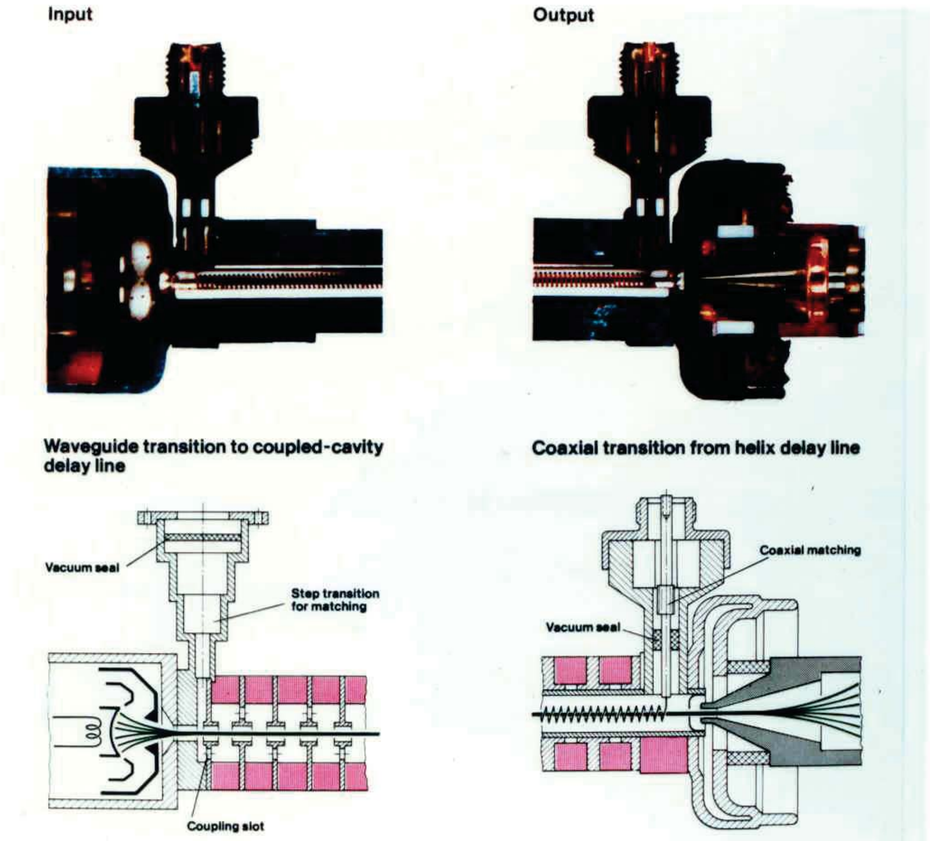
Travelling Wave Tubes



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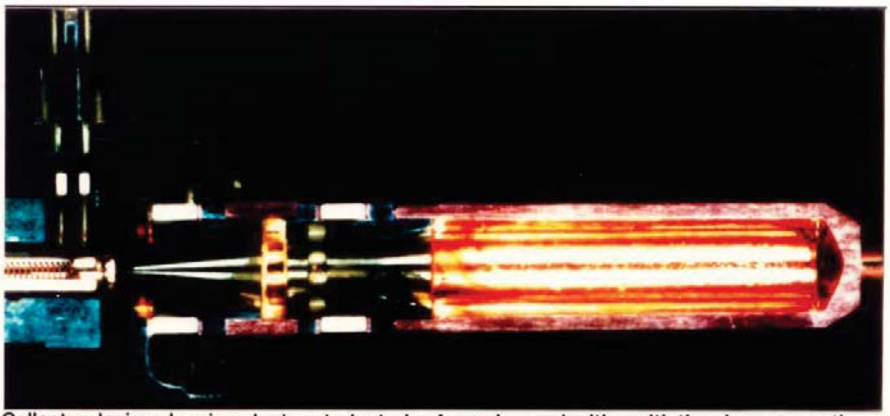
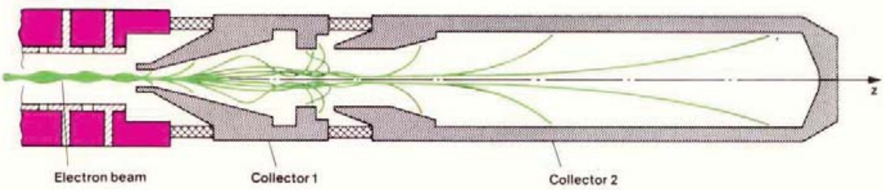


Collector design showing electron trajectories for various velocities with the given magnetic field distribution



Static focussing magnetic field

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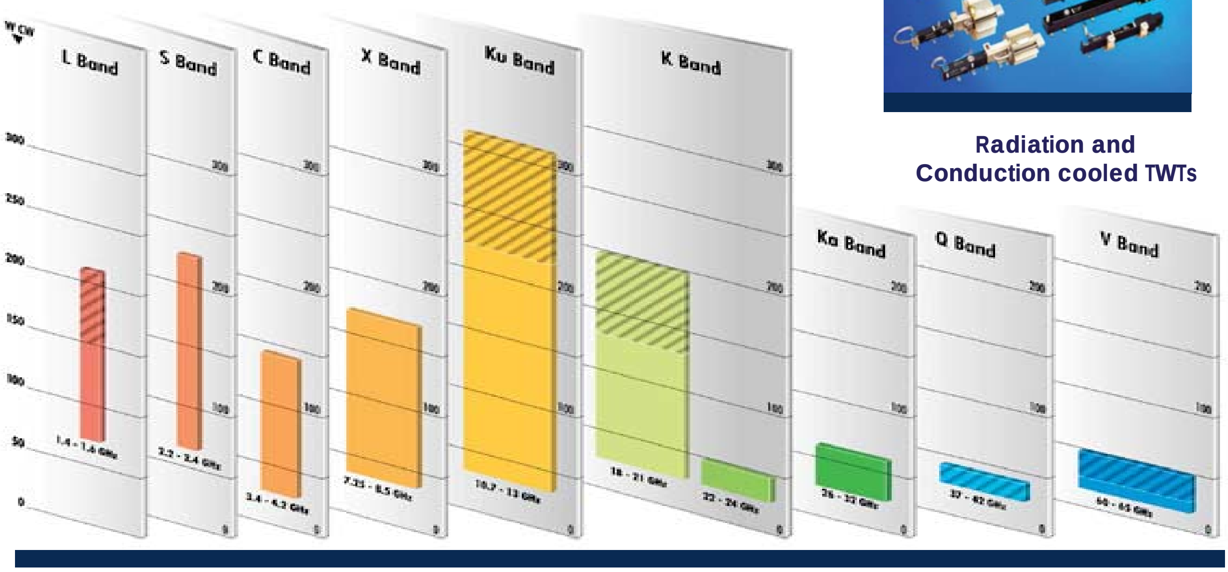
Travelling Wave Tubes

The complete production spectrum L- to V- Band
With RF output power up to 300 W.

TWT- Amplifiers

Radiation and Conduction cooled TWTs



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Comparison of the first 4 GHZ TWT and the state of the art

Program	FirstTWT TV Ground Link	First Space TWT Telestar 1	First European TWT Symphonie	Imorproved C-band	New C-Band
Manufacturer	STC	Bell Lab	AEG	Thales	Thales
Year	1952	1962	1973	2002	2015
Frequency	3.6 – 4.4 Ghz	3.7 – 4.2 Ghz	3.7 – 4.2 Ghz	3.6 – 4.2 GHz	3,6 – 4,2
Output Power	2 Watt	2 Watt	13 Watt	115 Watt	➢ 125 W
Gain	25 dB	40 dB	46 dB	50 dB	50 dB
Efficiency	1 %	< 10 %	34 %	70 %	➢ 72 %
Nonlinear Phase	?	50 °	50 °	50°	50 °
Mass	> 5000 g	> 1000 g	640 g	790 g	900 g
Collector	1 stage	1 stage	1 stage depressed	4 stage depressed	5 stage depressed
Focusing System	Solenoid	PPM PtCo	PPM PtCo	PPM CoSm	PPM CoSm
Cathode	Oxide	Oxide	Oxide	Mixmetall	Mixmetall

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Travelling Wave Tubes

Survey on surface Radars

Freq Band GHZ	L 1,26 – 1,36	S 2,7- 3,5	C 5,4 – 5,9	X 8,5 – 10.5	Ku 15 - 18	Ka 33- 38
Rel Bandwidth	3%	3- 15 %	5 – 10 %	10 %	10 .-20 %	3 – 10 %
Peak Power	4 MW	20 MW	1 MW	120 kW	2,5 kW	1 kW
Average power	12 kW	20 kW	20 kW	5 kW	200 W	200 W

Survey on missile Radars

Freq Band GHZ Type	X Helix TWT	X CC TWT	X Magnetron	Ku TWT	Ka TWT	W TWT
Rel Bandwidth	2%	3 %	600 MHz	20 %	3 %	1 %
Peak Power	20 kW	120 kW	220 kW	2 kW	1 kW	0,15 kW
Average power	800 W	1500 W	200 W	400 W	200 W	15 W

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Travelling Wave Tubes

Airborne Radar

Microwave tubes (magnetrons and TWTs) are used in airborne radar transmitters in 2 categories:

- Multimode and multifunction radars
  TWTs are widely used in coupled cavity or slow wave structure or helix design
- Terrain following radars, Generally with TWTS

Missles Seeker

Requirements for microwave tubes (magnetrons, Klystrons, TWTs) used active RF missile seeker in small size, mass and high efficiency, short start up operation and strong environmental conditions

EMC Application

Need for very wide instantaneous frequency) several octaves) in small size, mass and high efficiency, Mainly TWTs used

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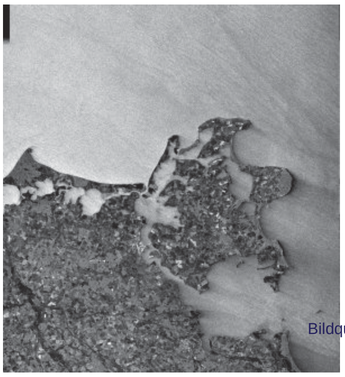
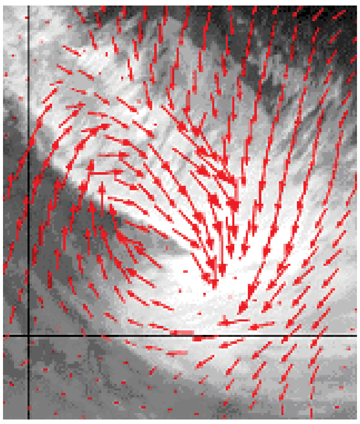
Radar applications

Synthetic Aperture Radar (SAR):



Bildquelle: ESA

Scatter meter:



Altimeter (attitude measurement):

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Extended Interaction Klystron(EIK)

TWT
Large bandwidth
High efficiency

Klystron
High power
Very robust

EIK
Combin the benefit of both
Large bandwidth
High efficiency
robust

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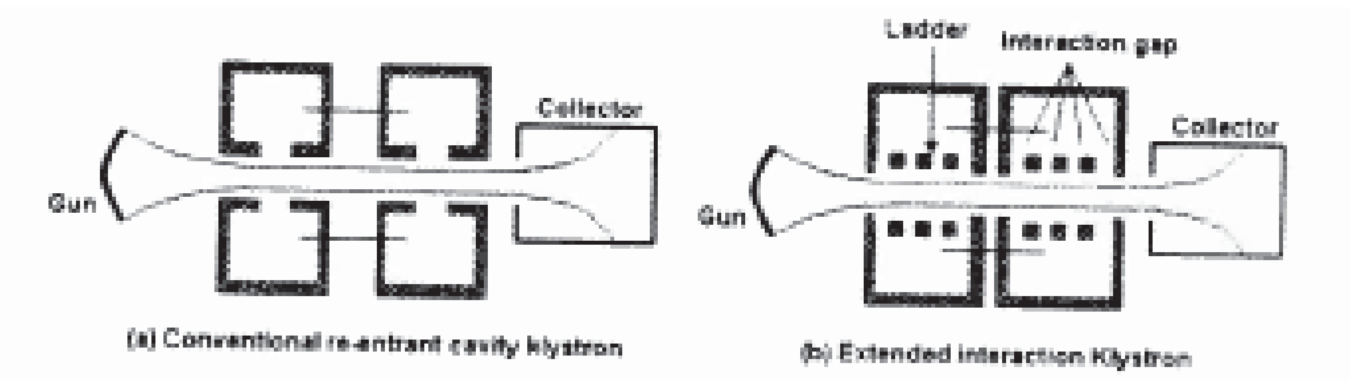
Extended Interaction Klystron(EIK) - Function



Pulse EIK		CW EIK	
3000 W	30to 95 GHZ	1500 W	At 30 GHz
400 W	At 140 GHz	100 W	At 95 GHz
50 W	At 220 GHz	30 W	At 140 GHZ
5 W	At 280 GHz	1 W	At 220 GHZ

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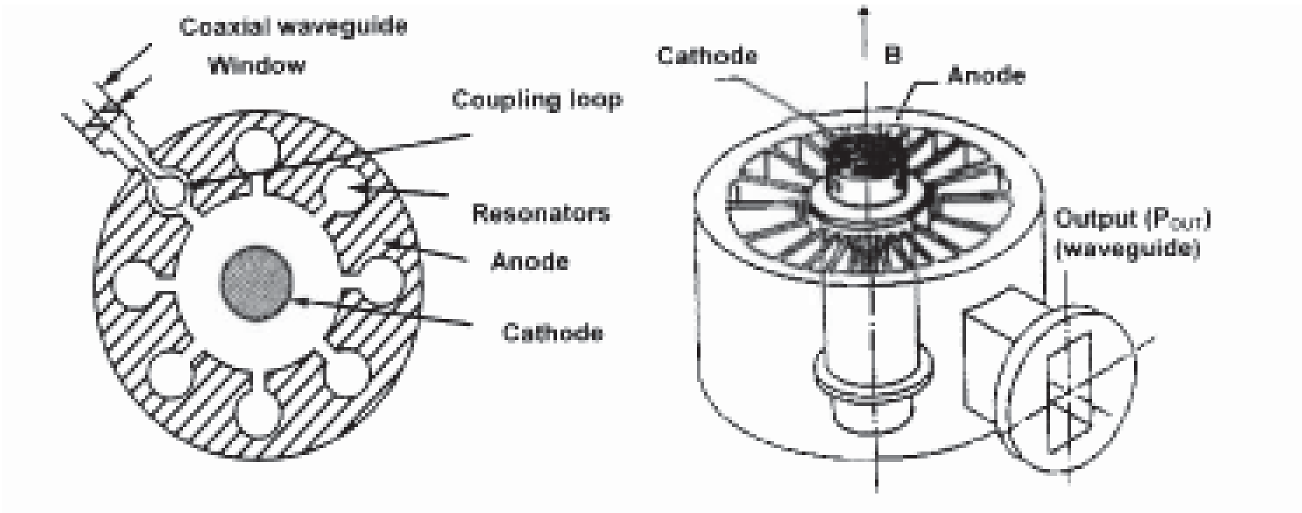
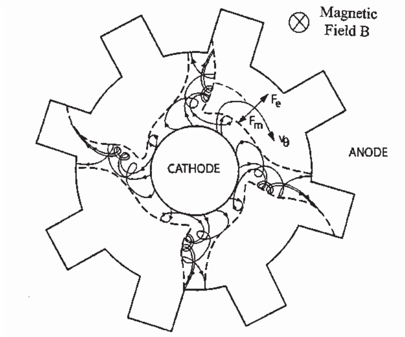
Magnetron

Magnetron and Cross Field Amplifiers





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Magnetrons

Features

- Low spurious and low noise.
- Small magnetic field leakage.
- Low anode voltages.
- Compact and lightweight.
- High frequency stabilily (especially in our coaxial magnetrons).

Continuous Wave Magnetron

Continuous wave magnetrons are used for plasma processing and in industrial microwave heating applications.

Pulsed Magnetron

Plused magnetrons are used for various radars such as weather radars and airplane monitoring applications.

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Magnetrons

Magnetron

Used for terrestrial communication

Or in the extreme low cost range for oven

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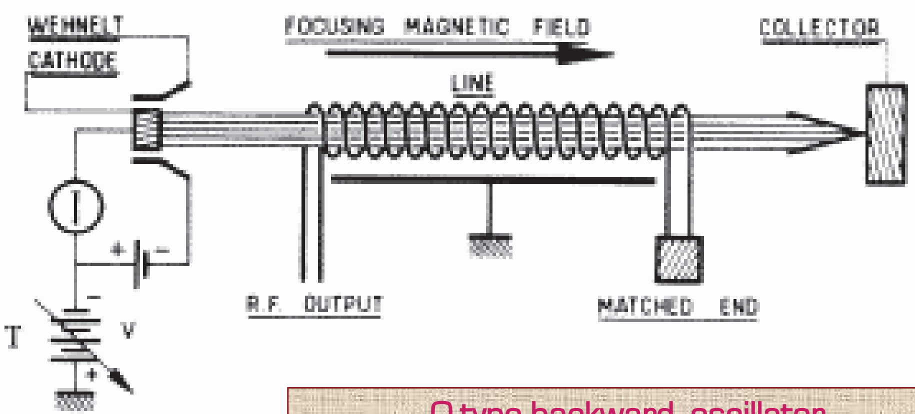
Backward Wave Oscillator (BWO)



O-type backward-oscillator

Main Application is THz:
range at 0,1 to 1,5 THz
with about 10 mW CW

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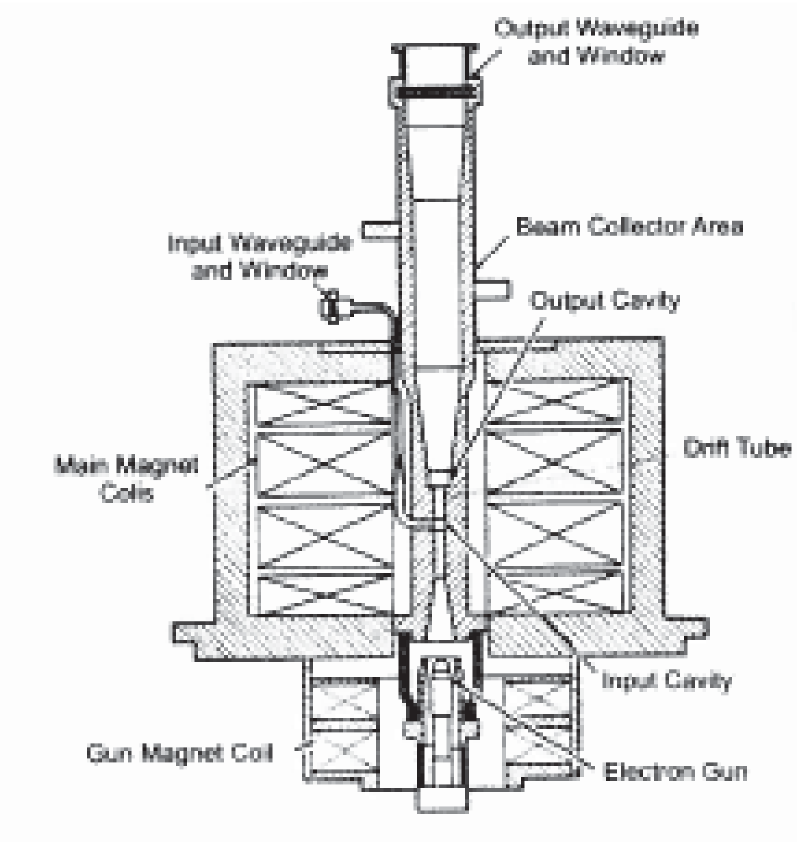
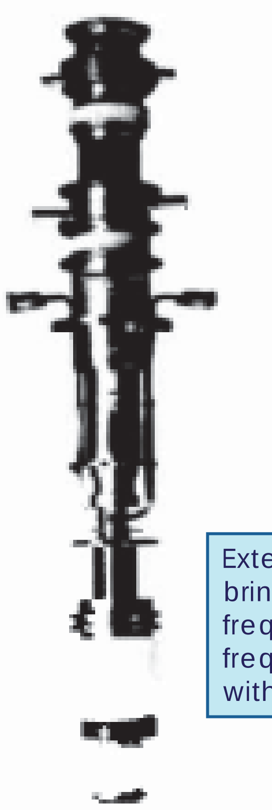
Gyrotron -Function

Gyrotron





External magnetic filed to bring the cyclotron frequency or harmonic frequency in interaction with the rf filed

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Gyrotron for Fusion

Development status of long pulse Gyrotron

Institution	Frequency (GHz)	Cavity mode	Output mode	Power (MW)	Efficiency (%)	Pulse length(s)	Fusion device
CPI, Palo Alto	110	$TE_{22,6}$	TEM_{00}	1.05	31	5.0	D III-D
				0.6	31	10.0	D III-D
	140	$TE_{28,7}$	TEM_{00}	0.9	33 (SDC)	1800	W7-X
GYCOM-M (TORIY, IAP), Moscow, Nizhny Novgorod	110	$TE_{19,5}$	TEM_{00}	0.93	36	2.0	D III-D
				0.5	35	5.0	D III-D
				0.35	33	10.0	D III-D
	140	$TE_{22,6}$	TEM_{00}	0.96	36	1.2	ASDEX-U
				0.54	36	3.0	W7-AS
	170	$TE_{25,10}$	TEM_{00}	0.9	44 (SDC)	21	ITER
				0.5	40 (SDC)	300	ITER
GYCOM-N (SALUT, IAP), N. Novgorod	140	$TE_{22,6}$	TEM_{00}	0.8	32	0.8	W7-AS
				0.88	50.5 (SDC)	1.0	W7-AS
	158.5	$TE_{24,7}$	TEM_{00}	0.5	30	0.7	T 10
JAEA, TOSHIBA, Naka, Otawara	110	$TE_{22,6}$	TEM_{00}	1.2	38 (SDC)	4.1	JT 60-U
				1.0	36 (SDC)	5.0	JT 60-U
				0.5	34 (SDC)	16.0	JT 60-U
	170	$TE_{31,8}$	TEM_{00}	1.0	43.4 (SDC)	800	ITER
				0.6	45.5 (SDC)	3600	ITER
THALES, CEA, CRPP,	118	$TE_{22,6}$	TEM_{00}	0.53	32	5.0	TORE SUPRA
				0.35	23	111	TORE SUPRA
FZK, EUROPE	140	$TE_{28,8}$	TEM_{00}	1.0	49 (SDC)	12	W7-X
				0.92	44 (SDC)	1800	W7-X

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Gyrotrons

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Features

small collector thanks to the high efficiency of the Gyrotron.
Creates a compact, low cost, and energy saving power supply unit and cooling unit, thanks to the high efficiency performance of the Gyrotron.
Decreases undesirable X rays.
Improved high-power performance, thanks to a uniform output distribution.
unique long life and high-current-density cathodes.
High reliability, based on advanced high-vacuum, and high-voltage technologies created in the development of various type of electron tubes.

Applications

Plasma heating in experimental nuclear fusion facilities
Plasma measurement in experimental nuclear fusion facilities
Sintering ceramics

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Gyrotrons

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Gyrotron

Acceleration for fusion

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Micro Wave Tube Principles

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- Introductions
- Principle of Micro Wave Tubes
- Microwave tubes & Applications
- **Future**

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Development for Micro Wave tubes

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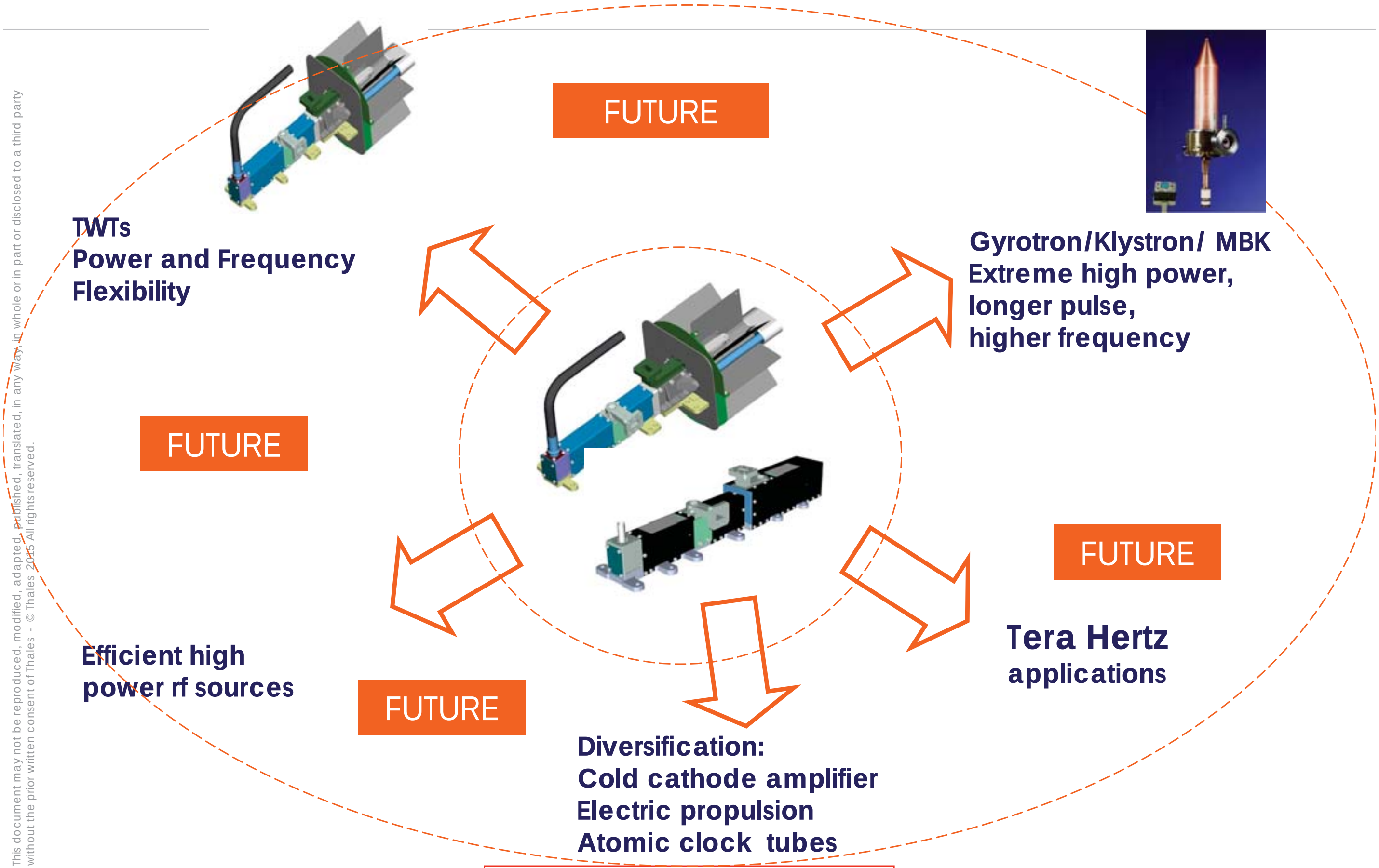

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References for literature sources:

- Vacuum Electronics/ Springer/ Eichmeier/Thumm
- Moderne Vakuumtechnik / Springer / Eichmeier
- Thales internal prospects
- Data of internet
- Several article for TWTs
- From History to Future TWT Amplifiers (Bosch/Kornfeld)
- TWT presentations (E.Bosch)

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Thanks for your attention !!!!

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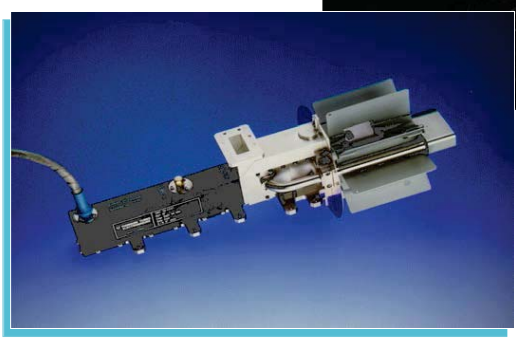

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TWT basic operation principles and building blocks

Rosario Martorana

LEONARDO
AIRBORNE & SPACE SYSTEMS

rosario.martorana@leonardocompany.com

Introduction

Scope of this presentation is to give the basic concepts of Linear O-type microwave tubes, with focus on the Traveling Wave Tube. Obviously it is not exhaustive, it gives some hints for future readings and deeper study to whom may be interested and, may be, wants to begin the job of Microwave Tube Engineer.

We are not so many !

Contents

- Basic Interaction
- Linear Beam Tube Configuration
- Gap Interaction
- Velocity Modulation
- Velocity Modulation to Density Modulation: Applegate diagram, basic and multi-cavities Klystron
- Space Charge Wave Theory I

Contents

- TWT Slow Wave Structures
- Space Charge Wave Theory II
- TWT Pierce Model
- TWT Equations: electronic, circuit and determinantal equations, Pierce's parameters
- TWT at synchronism
- Periodic Structures: SWS characteristics & interaction SWS-Electron beam.
- The Helix SWS

The Microwave Tube

The Microwave Tube is a form of thermionic valve or tube that converts the continuous DC Kinetic energy of an electron beam, into radiofrequency energy that is used for high power microwave amplifier or oscillator.

Basic Interaction

Electron interaction with electric and magnetic field is governed by Lorentz force:

$$\mathbf{F} = -e\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

e: electron charge
v: electron velocity vector
E: electric field vector
B: magnetic field flux density vector

Basic Interaction

Only the Electric field can change the particle energy because the vector product **v** x **B** is perpendicular to **v** and modifies only the direction of motion.

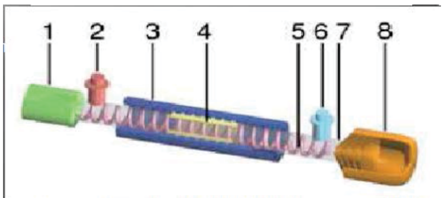
Therefore in order to convert kinetic energy of an electron beam into RF an electric field has to be considered: for example Ez(x,y,z,t) field for reducing the velocity of an electron beam flowing along z axis.

The B field is useful for electron beam focusing.

Linear Beam Tubes Configuration

A Linear O type tube, Travelling wave tube (TWT) or Klystron, is made of a number of separate major elements:

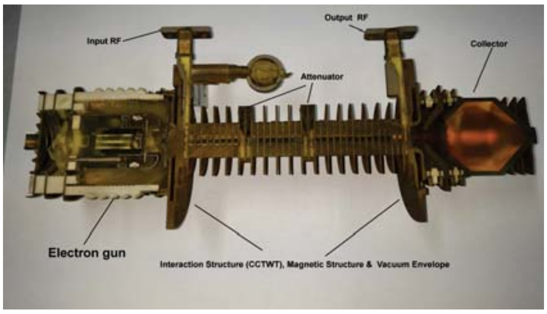
- Vacuum Envelope: contains the interaction structure or is part of it, it may be part of the magnetic structure.
- Electron gun: generates the electron beam suitable for the interaction
- Magnet and focusing structure: produces the magnetic field necessary for electron beam focusing
- RF input: injects the low level RF signal to be amplified
- Interaction structure: metallic line sustaining the RF electromagnetic field interacting with the electron beam
- Attenuator: limits the gain, avoids internal reflections
- RF output: extracts the high level RF signal
- Collector: collects the electron beam after the interaction



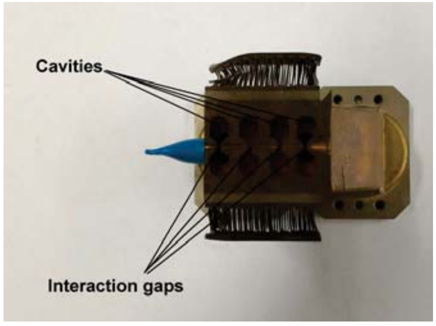
Cutaway view of a TWT. (1) Electron gun; (2) RF input; (3) Magnets; (4) Attenuator; (5) Helix coil; (6) RF output; (7) Vacuum tube; (8) Collector.

Linear Beam Tubes Configuration

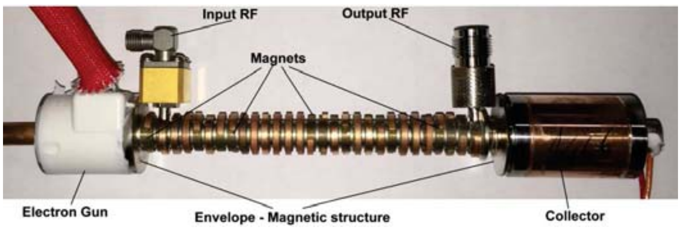
Coupled Cavities TWT (CCTWT)

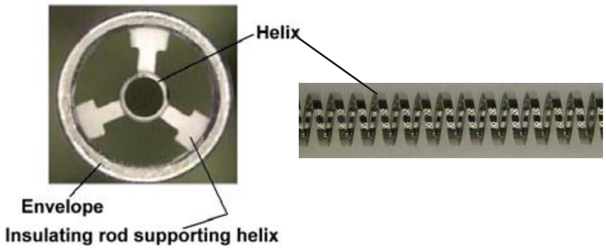


Klystron

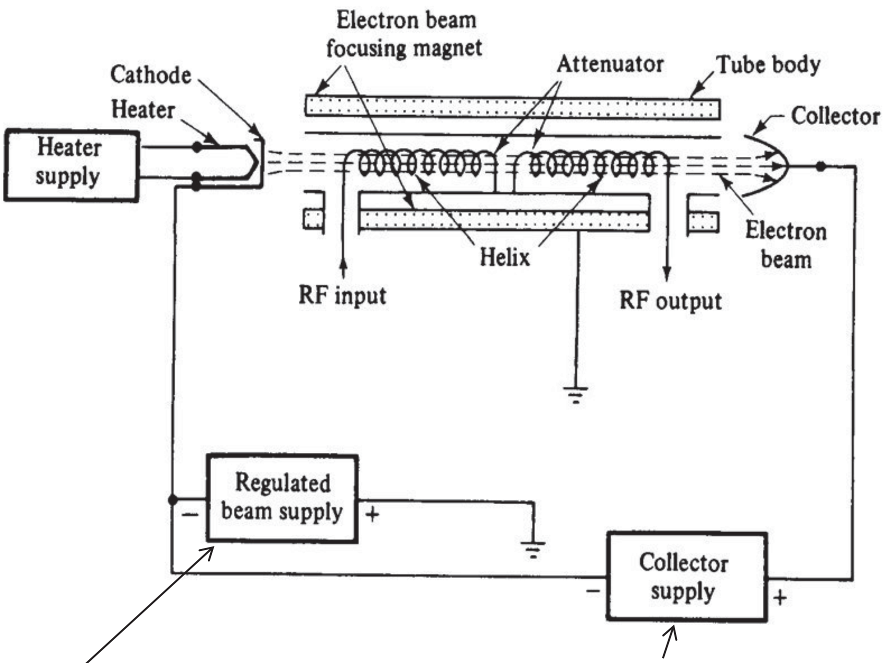


Helix TWT





Linear Beam Tubes Configuration



Produces the Electron beam Voltage

Produces the Collector Voltage for depressed operation

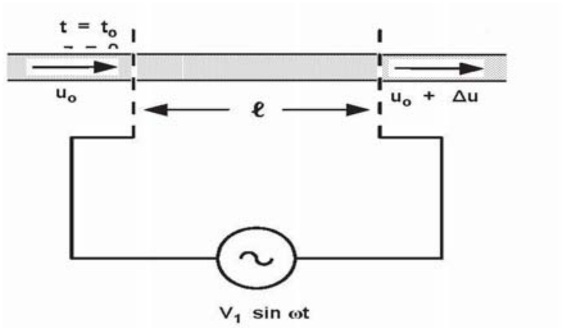
Linear Beam Tubes Configuration

The Electron Beam Supply, connected between cathode and ground, produces the potential difference to accelerate the electron beam toward the interaction structure. Here the electron beam flows at constant axial velocity (in absence of RF field); it is focused by the magnetic field, produced by the surrounding magnets and magnetic structure.
The Collector Supply produces the potential difference to decelerate the electron beam after the interaction region for efficiency increase.

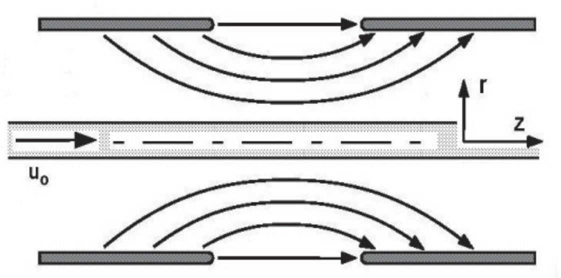
Gap Interaction

In linear type tubes, like the Klystron and the Traveling Wave Tube, the interaction between the electron beam moving along the axial tube direction, z, and the RF filed takes place within a gap that enhances the electric field in the axial direction.

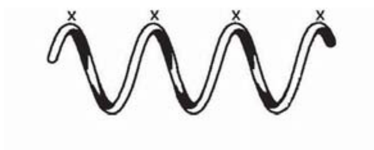
Gap Interaction



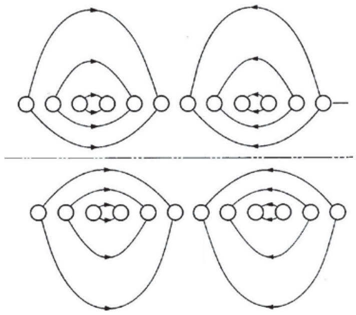
Gridded Gap



Griddles Gap



Electric field lines between helix turns



Velocity Modulation

The electric field developed across the gap, interacting with the electrons, produces velocity modulation of the electron beam itself that in turn produces an induced current on the conductors of the gap at the frequency of the electromagnetic field.

If the gap is part of a cavity, resonant at the frequency of the modulating signal, electromagnetic energy is stored in the cavity which in turn interacts with the electron beam.

If the gap is the space between two turns of a helix the induced current travels on the helix; particular conditions must be satisfied in order to obtain cumulative interaction and amplification.

Velocity Modulation to Density Modulation

Velocity modulation causes some electrons go faster some slower than the DC unmodulated beam, and some with unchanged velocity. The faster electrons overtaking the slower ones participate to the formation of bunches along the beam; the electron beam becomes density modulated. If a second cavity is located where the electron bunches has grown, greater current on the cavity gap is induced and greater energy is stored in the cavity.

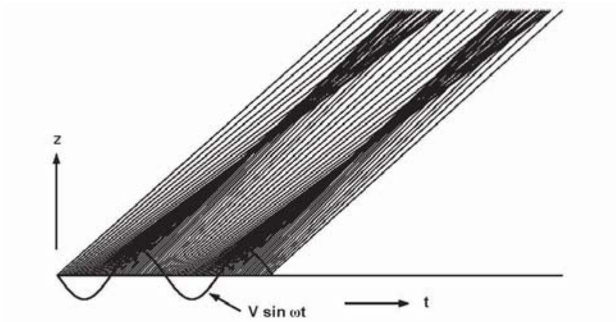
Radiofrequency energy is produced from Kinetic energy of the unmodulated electron beam.

Velocity Modulation to Density Modulation: The Applegate diagram

The Applegate diagram shows the bunching formation: on the x axis it is reported the time elapsed since an electron has left the modulating gap, on y axis the distance the electron has travelled; so each line represent an electron trajectory, the slope is proportional to electron velocity. Crossing lines points give time and position of bunches formation.

Velocity of an electron passing the modulating gap

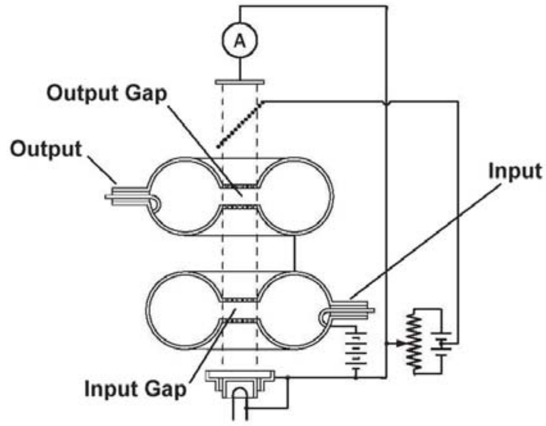
$$u = u_o \left(1 + \frac{\alpha M}{2} \sin \omega t\right)$$



Distance-time curves for the electrons in a velocity-modulated beam in a field free drift space (Applegate diagram).

Basic Klystron

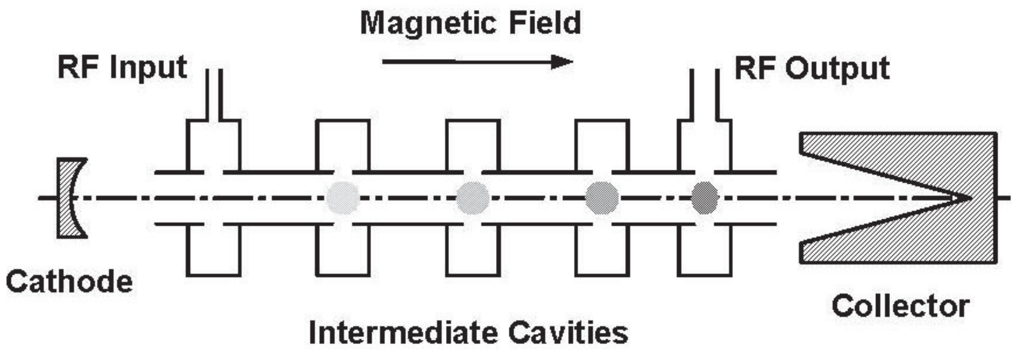
Radiofrequency energy is produced from Kinetic energy of unmodulated electron beam.
The basic two cavity Klystron is obtained.



Basic klystron configuration shown by the Varian brothers.
(From: R. H. Varian and S. F. Varian, *Jour. App. Phys.*, May 1939.)

Multi-Cavities Klystron

Two cavity klystron is inherently a narrow band amplifier. The addition of cavities to the basic configuration allows wider bandwidth and higher efficiency to be obtained.



Basic elements of a five-cavity klystron.

Klystron vs TWT interaction

An important characteristics of the Klystron is that the interaction between the electromagnetic field and the electron beam takes place at discrete position along the beam: the cavity gaps; and there is no RF propagation along the drift tunnel

This characteristics makes the difference with the Traveling Wave Tube where the propagation along the structure takes place and interaction may take place also.

Space Charge Wave Theory I-1

Nevertheless the differences between the Klystron and the Traveling Wave Tube a common theory is useful for explanation of operation.

The space charge wave theory

The bunches can be thought due to plasma oscillations of the electron cloud.

Space Charge Wave Theory I-2

To understand plasma oscillation it is useful to consider first an unbounded electron cloud not moving, uniformly distributed in the space.

This cloud is similar to an elastic medium where the restoring force is due to repulsion force due to the electron charge. If the cloud is perturbed from its equilibrium state, the restoring force trays to restore the equilibrium, the charges overcome the equilibrium position due to inertial forces and so on causing the build up of a wave like behaviour.

Space Charge Wave Theory I-3

The unbounded electron cloud behaves like a elastic medium, like the propagation of acoustic wave in an elastic medium (air).

The natural oscillation frequency of the electron cloud is :

$$\omega_p = 2\pi f_p = \left(\eta \frac{\rho_o}{\varepsilon_o}\right)^{1/2}$$

where: η = electron charge /electron mass

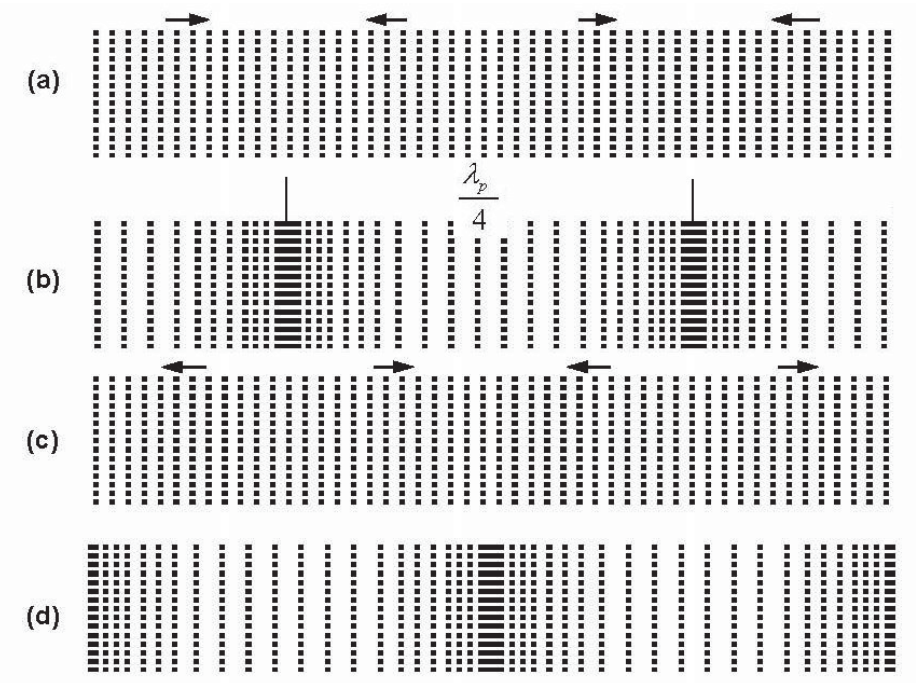
ρ_o = electron charge density

ε_o = free space permittivity

Space Charge Wave Theory I-4

If the perturbation is produced on a moving electron beam, superimposed on its own drift velocity, u_o, a wave like propagation of the perturbation itself is obtained, giving the possibility to convert the kinetic energy into radiofrequency energy, like it occurs in Klystron and Traveling Wave Tube.
The perturbation travels at the velocity of the electron beam, u_o, and a plasma wavelength can be associated.

Space Charge Wave Theory I-5



Electron distributions during plasma oscillations.

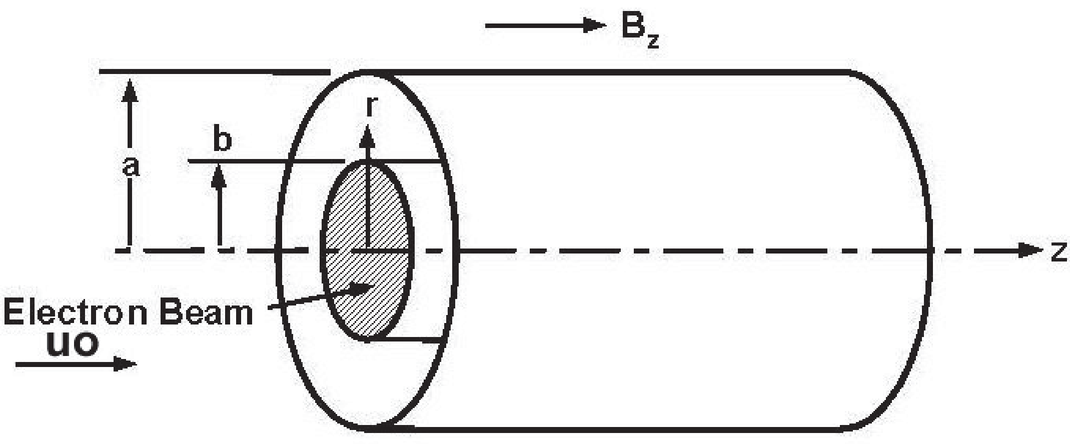
Space Charge Wave Theory I-6

The electron beam moving inside the conductor drift tunnel has its own natural plasma frequency that can be calculated as modification of the unbounded electron cloud configuration. This is called reduced plasma frequency because it is lower than the previous one:

$$\omega_q = \omega_p R_q \qquad R_q < 1; \qquad \lambda_q = 2\,\pi u_o / \omega_q = 2\,\pi u_o / \omega_p R_q$$

In any case the plasma frequency depends only the electron density, ρ_o , and on the configuration through R_q .

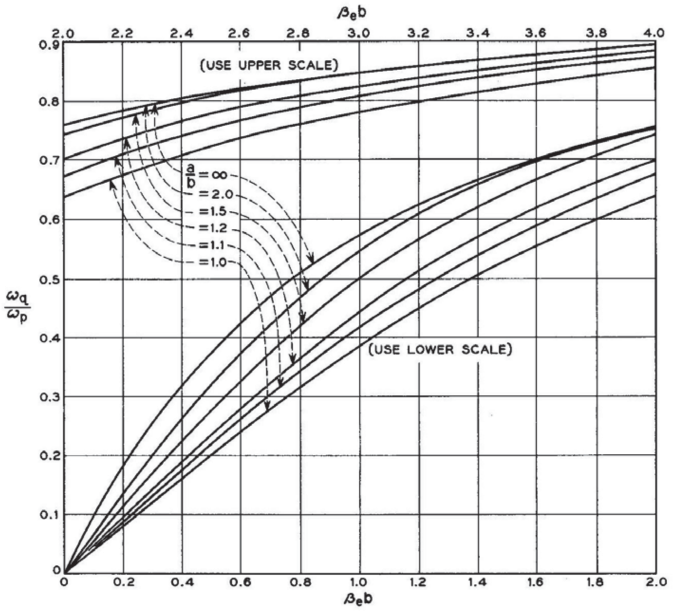
Space Charge Wave Theory I-7



Cylindrical beam in a cylindrical tunnel.

$$\omega_q = \omega_p R_q \qquad R_q < 1 \qquad \lambda_q = 2\,\pi u_o / \omega_p R_q$$

Space Charge Wave Theory I-8



Plasma frequency reduction factor vs. beam diameter for a solid, cylindrical beam of radius *b* in a concentric, perfectly conducting cylinder of radius *a*

G. M. Branch and T. G. Mihran, "Plasma Frequency Reduction Factors in Electron Beams," *Trans. IRE* **ED-2**, 3–11, April, 1955.

Linear Beam / O-Types Tubes

The Klystron and the Traveling Wave Tube (TWT) are the two major categories of microwave devices known as linear beam or O-type tubes.

The main differences between Klystron and TWT are:

•The microwave circuit is non-resonant in TWT, while resonant circuits are used in klystrons.

•The wave in the TWT is a propagating wave , the wave in the klystron is not.

•The interaction between the electron beam and the RF field in the TWT can be continuous over the entire length of the circuit, or concentrated in gaps like it happens in the klystron.

TWT Slow Wave Structures

In order for the interaction between the space charge wave can take place a slow wave circuit is necessary so that the electromagnetic field phase velocity, v_{ph}, is close to electron beam velocity, u_o.

Slow wave circuits examples:

- Helix
- Ring and bar
- Coupled Cavities
- Folded waveguide
- Ladder

SWS are periodic along their axis: combination of translation and rotation makes the structure coinciding with itself. This characteristic makes the electromagnetic field periodic and the structure can be studied on basis of the elementary cell.

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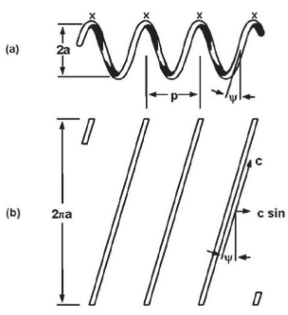
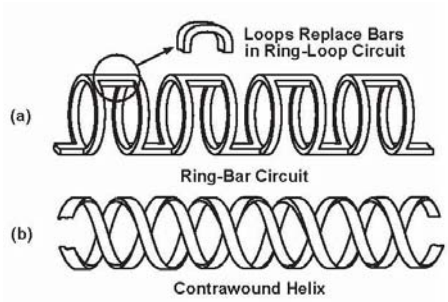
Slow Wave Structures

Continuous Interaction SWS

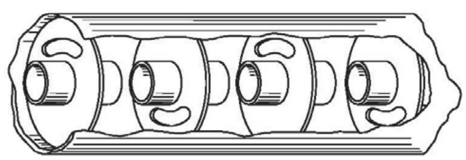


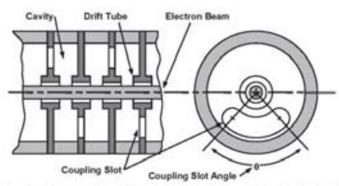
(a) Helix and (b) view of helix cut at each x and unrolled.



(a) Ring-bar and (b) two-tape contrawound helix circuits.

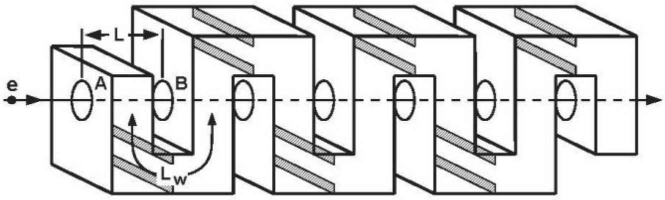
Discrete interaction (gaps) SWS


A staggered-slot fundamental backward wave circuit. (Adapted from: *Power Travelling Wave Tubes* by J. F. Gittins, published 1965 by American Elsevier, Inc.)

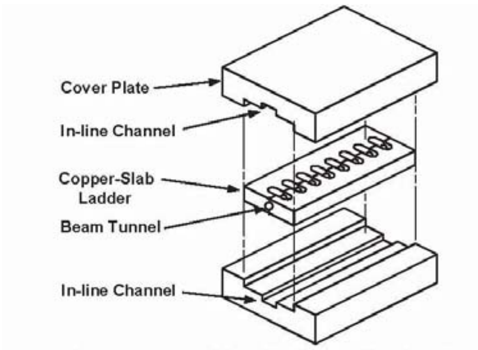


A coupling slot between cavities. (From: Hughes Aircraft Co., *TWT and TWTA Handbook*.)

Slow Wave Structures



Folded waveguide that permits electron interaction below the velocity of light.



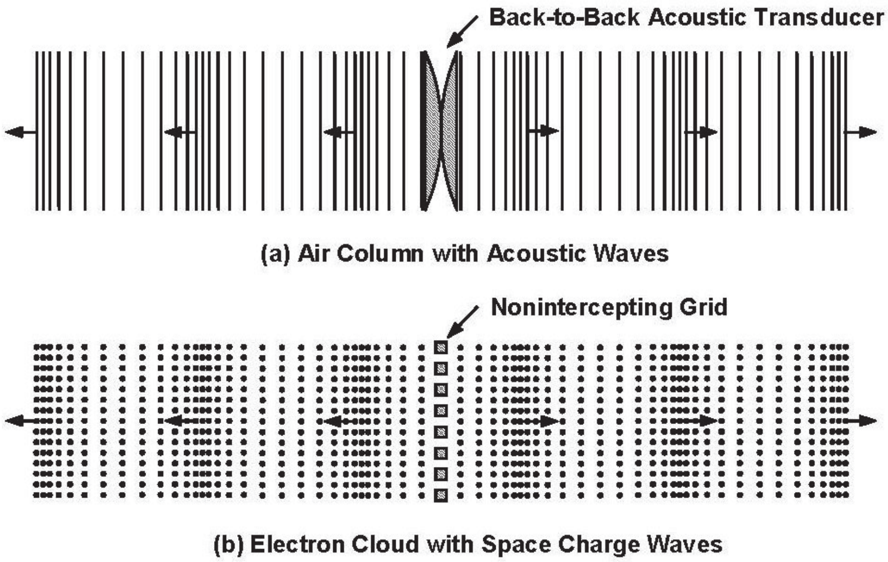
Ladder-core structure with dual in-line coupling channels.
(Adapted from: Bill G. James, *MSN & CT*, September 1986.)

Space Charge Wave Theory II-1

The fundamental aspects of the propagation of the bunches can be understood by considering an analogy with acoustic wave propagation. In the next figure a back-to-back acoustic transducers launch acoustic pressure (and density) waves in the air. The waves result from motion of the diaphragms in the transducers, which periodically compress the air. The waves propagate to the right and to the left at a velocity that is dependent on air pressure. With increased pressure, wave velocity increases.

Space Charge Wave Theory II-2

Comparison between acoustic waves and Space Charge Waves

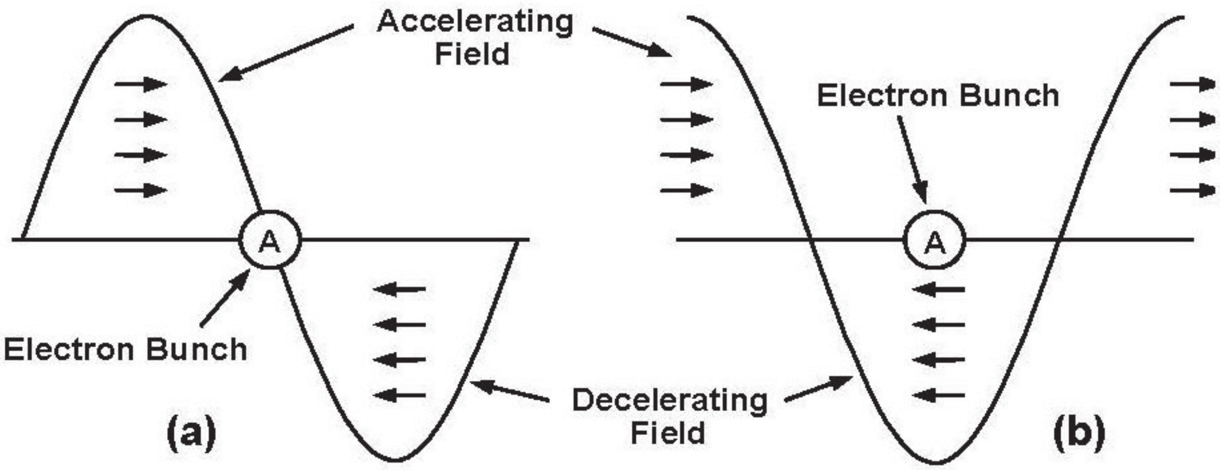


Arrangements for launching (a) acoustic waves and (b) electron density (space charge) waves.

Space Charge Wave Theory II-3

A grid is shown inserted in an electron cloud that is not moving. Let’s assume that the grid does not collect electrons. As the voltage on the grid oscillates from positive to negative and back to positive again, electrons are attracted, then repelled and then attracted again. As a result, the electron density near the grid is alternately reduced and increased and electron density waves are launched to the right and to the left. The velocities of these waves are dependent on the electron density. With increased density, wave velocities increase. These ***electron density waves*** are called ***space charge waves***.

Space Charge Wave Theory II-4



Axial field that bunches and extracts energy from beam (a) as beam enters circuit and (b) after interaction has occurred.

Space Charge Wave Theory II-5

Next, let the electron column move to the right at a velocity that is much higher than the velocities of the space charge waves. The moving electron column is, of course, an electron beam. Both space charge waves are moving to the right with the beam. One is moving faster than the beam and is called a fast space charge wave. The other is moving slower than the beam and is called a slow space charge wave. The bunches produced by the decelerating field constitute a slow space charge wave.

The energy extracted from the electron beam in slowing electrons to the bunch velocity is transferred to the circuit field, thereby producing amplification of that field. The mutual interaction of the beam and circuit results in an exponential growth of the circuit voltage.

Space Charge Wave Theory II-6

As the interaction process continues, more electrons are slowed to the bunch velocity and space charge forces within the bunches continue to increase. Eventually, these forces become large so that a portion of each bunch is retarded in phase enough so that it leaves the decelerating field region and enters an accelerating field.
Electrons in the acceleration portion of each bunch extract energy from the circuit field. Eventually, as the bunches continue to fall back in phase, energy extracted from the circuit wave becomes equal to the energy supplied and the wave on the circuit stops growing. At this point, "saturation" is said to occur and the signalamplitude is maximum.

Space Charge Wave Theory II-7

Two Space charge waves travel on the electron beam:

Slow space charge: $\beta = \beta_e + \beta_q$, phase velocity $< u_o$

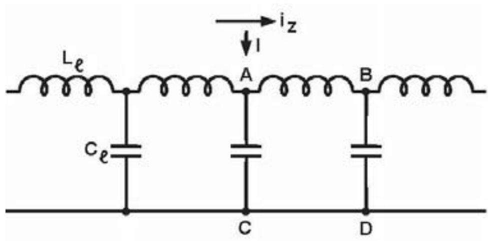
Fast space charge: $\beta = \beta_e - \beta_q$, phase velocity $> u_o$

$$\beta_e = \omega / u_o \qquad \beta_q = \beta_p R_q \qquad \beta_p = \omega_p / u_o$$

Pierce Model

J. R. Pierce developed the theory of TWT, based on a transmission line as model of the SWS circuit with impressed current flowing very close to the circuit modelling the electron beam. The model brings to a 4th degree determinantal equation giving the eigenvalues of the coupled electron beam – circuit system.

The analysis is generalized so that it can be applied to any of the SWS considered before. The line has distributed inductance and capacitance per unit length of $L\ell$ and $C\ell$. The beam with current i_z is assumed to pass very close to the circuit and the current induced in the circuit is $I = i_z$ (Ramo's theorem).



Transmission line model for a slow wave circuit.

Electronic Equation

Another approach starting from the definition of, total velocity u_{tot}, current, i_{tot}, charge density ρ_{tot}, and convection current $i_{tot} = \rho_{tot} * u_{tot}$, applying the continuity equation arrives, after linearizatiation and approximations, to the so called electronic equation.

All RF quantities are supposed sinusoidal in time and with exponential dependence along the propagation direction z:

$e^{(j\omega t - \Gamma z)}$

The propagation constant Γ is a complex number

Total quantities

$$u_{tot} = u_o + u$$
$$i_{tot} = -I_o + i$$
$$\rho_{tot} = -\rho_o + \rho$$

Continuity Equation

div i = - $(\partial \rho / \partial t)$

$$i = \frac{j\beta_e I_o E_{zn}}{2V_o\left[(\Gamma - j\beta_e)^2 + \frac{\omega_q^2}{u_o^2}\right]}$$

Electronic Equation

Relating the convection current to the field on the circuit

Circuit Equation

The action of the circuit on the electron beam is obtained by defining the concept of interaction impedance that is a measure of the capacity of the circuit to interact with the electron beam.
The result is the circuit equation:

$$E_{zn} = \frac{\Gamma_o \beta_n^2 K_n i}{\Gamma^2 - \Gamma_o^2}$$ ***Circuit Equation***

Where $K_n = \frac{\int |E_{zn}|^2 dS}{2\beta_n^2 P S}$ is the interaction impedance of the nth circuit harmonic

$\Gamma_o = \alpha + j\beta_n$ is the circuit propagation constant of the nth harmonic (losses + Jphase constant)

Determinantal Equation

The propagation constant, Γ, is the unknown in the electronic and in the circuit equations. In order the two equations to be satisfied simultaneously one is substituted in the other and the elimination of Ez/I results in the following 4th degree determinantal equation:
The solution of which gives four values of Γ.

$$(\Gamma^2 - \Gamma_o^2)\left[(\Gamma - j\beta_e)^2 + \frac{\omega_q^2}{u_o^2}\right] = \frac{j\beta_e \beta_n^2 \Gamma_o K_n I_o}{2V_o}$$ **Determinantal Equation**

Determinantal Equation

In order to maintain a physical meaning between the model and TWT operation Pierce defined the following 4 parameters:

$$C^3 = \frac{K_n I_o}{4V_o}$$ Small Signal Gain parameter

$$QC = \frac{\omega_q^2}{4C^2\omega^2}$$ Space charge parameter

$$b = \frac{\beta_n - \beta_e}{\beta_e C} = \frac{u_o - v_{pn}}{v_{pn} C}$$ Velocity or synchronism parameter

$$d = \frac{\alpha}{\beta_e C}$$ Loss parameter

V_o Beam Voltage, I_o Beam Current, u_o Beam velocity, ω_q Reduced plasma frequency
$\omega = 2\pi f$, $\beta_e = \omega/u_o$, v_{phn} phase velocity of nth circuit harmonic, $\beta_n = \omega/ v_{phn}$

Determinantal Equation

With the definition of the 4 parameters the circuit propagation constant Γo and the propagation constant Γ can be written as:

$$\Gamma_o = j\beta_e(1 + Cb - jCd)$$

$$\Gamma = j\beta_e(1 + jC\delta)$$

where δ=X+jY is a complex number related to the propagation constant Γ whose real part gives the growing or decaying factor and the imaginary part gives the phase factor
Consequently the determinantal equation can be written in terms of δ.

Determinantal Equation: synchronous case

A very useful condition is that for which:

b=0, QC=0, d=0

called **synchronous case without losses and space charge forces.**

The determinantal equation is simplified a lot, this case is very instructive for physical understanding also for the general situation where the three parameters are different from zero.

Synchronous case: the four roots

The four roots are complex or pure imaginary; the resultant wave is a linear combination of the 4 exponentials:

$$A(z) = A_1 * e^{-\Gamma 1z} + A_2 * e^{-\Gamma 2z} + A_3 * e^{-\Gamma 3z} + A_4 * e^{-\Gamma 4z}$$

$$-\Gamma(1) = -j\beta_e - j\frac{\beta_e C}{2} + \beta_e C\frac{\sqrt{3}}{2}$$

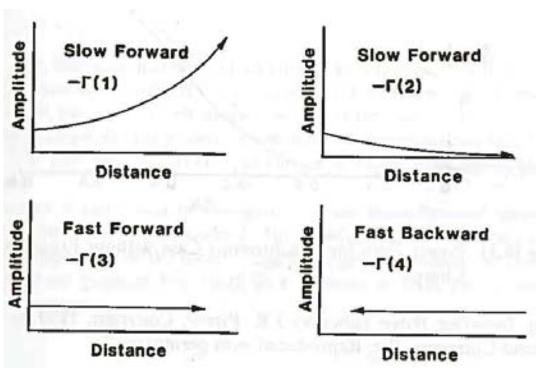
$$-\Gamma(2) = -j\beta_e - j\frac{\beta_e C}{2} - \beta_e C\frac{\sqrt{3}}{2}$$

$$-\Gamma(3) = -j\beta_e + j\beta_e C$$

$$-\Gamma(4) = +j\beta_e - j\beta_e\frac{C^3}{4}$$

$$V_{phi} = \omega / \mathrm{Im}[\Gamma_i] \begin{cases} < u_o & i = 1,2 \\ > u_o & i = 3,4 \end{cases}$$

Γ1 & **Γ2** complex



Γ3 & **Γ4** pure imaginary

Synchronous case: the growing wave

The wave corresponding to Γ_1 is called "***growing wave***"; it is the wave producing the gain in the TWT. Independently on the values of b, QC and d, there are always four waves because the determinantal equation is of 4th degree.

The growing wave will predominate as long as the electron beam flows down the tube axis.

The synchronous case is also important because it shows that even if

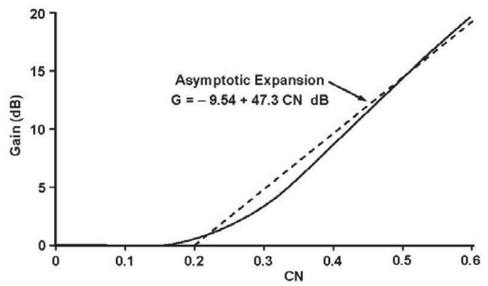
$$b = \frac{\beta_n - \beta_e}{\beta_e C} = \frac{u_o - v_{pn}}{v_{pn} C} = 0 \quad \text{implying that } v_{pn} = u_o$$

the phase velocity of the space charge growing wave is lower than electron beam velocity for obtaining energy transfer from the electrons to the RF wave.

This results must be true regardless of the values of b, QC and d.

Small Signal Gain

$$G = -9.54 + 47.3CN \quad \text{dB}$$



Power gain in a TWT for the synchronous case with zero loss and no space charge. (Adapted from: *Traveling Wave Tubes*, by J. R. Pierce, copyright 1950 by D. Van Nostrand Inc.)

b=0, QC=0, d=0

Where: C is the gain parameter, N the number of wavelength,

-9.54 dB is called "***initial launch loss***" because it is due to the fact the electron beam takes some length for starting the interaction (beginning of velocity modulation).

Wave velocity and Dispersion

For amplification to occur in a traveling wave tube, the axial component of the velocity of the wave on the RF circuit must be close to the velocity of the bunches of electrons in the beam. If, as frequency is varied, the velocity of the wave on the circuit moves away from the electron bunch velocity, gain will decrease. As a result, the variation of circuit wave velocity with frequency is an important consideration in the design of a TWT. A circuit in which the wave velocity varies with frequency is said to have dispersion or to be dispersive.
A waveguide is a dispersive circuit, the TEM mode in the coaxial cable is not dispersive because the phase velocity equals the velocity of the light in the medium independently of the frequency.
SWS are periodic along their axis: combination of translation and rotation makes the structure coinciding with itself. This characteristic makes the electromagnetic field periodic and the structure can be studied on basis of the elementary cell.

Periodic Structures: Floquet's theorem

SWS, like the coupled cavity structure or the helix are periodic along the axis. This characteristic makes the electromagnetic field periodic, it can be expanded in space harmonics and according to Floquet's theorem the structure can be studied on basis of the elementary cell.

If the field in the unit cell is given by **E**(x,y,z) , **H**(x,y,z), in a cell located at a distance equal to the pitch, p, it is given by:

$e^{-\Gamma p}\,\mathbf{E}(x,y,z-p)$, $e^{-\Gamma p}\,\mathbf{H}(x,y,z-p)$ ***Floquet's theorem***

Since the structure is periodic the field has the form:

$$\mathbf{E}(x,y,z) = e^{-\Gamma z}\,\mathbf{E}_p(x,y,z) \qquad \mathbf{H}(x,y,z) = e^{-\Gamma z}\,\mathbf{H}_p(x,y,z)$$

where $\mathbf{E}_p(x,y,z)$ $\mathbf{H}_p(x,y,z)$ are periodic functions of z, with period p.

Periodic Structures: space harmonics

A periodic function may be expanded into an infinite Fourier's series, therefore the field can be expressed as:

$$\mathbf{A}_p(x,y,z) = \sum_{n=-\infty}^{\infty} \mathbf{A}_{pn}(x,y) e^{-j2n\pi z/p}$$

being $\mathbf{A}_p(x,y,z)$ the electric field $\mathbf{E}_p(x,y,z)$ or the magnetic field $\mathbf{H}_p(x,y,z)$. The harmonics amplitudes $\mathbf{A}_{pn}(x,y)$ can be found applying the usual methods for solving this type of problems, the result is:

$$\mathbf{A}(x,y,z) = e^{-\Gamma z}\,\mathbf{A}_p(x,y,z) = \sum_{n=-\infty}^{\infty} \mathbf{A}_{pn}(x,y) e^{-j\left(\beta z + \frac{2n\pi z}{p}\right)} = \sum_{n=-\infty}^{\infty} \mathbf{A}_{pn}(x,y) e^{-j\beta_n z}$$

where: $\Gamma = j\beta$ for lossless SWS

$\beta_n = \beta + 2n\pi/p$

Periodic Structures: phase velocity & group velocity

The $\mathbf{A}_{pn}(x,y)$ are called ***space harmonics;*** $\boldsymbol{\beta_n = \beta + 2n\pi/p}$ is the **phase constant of the** $\mathbf{n_{th}}$ **harmonic**; since n can take positive and negative values β_n can be negative.

The corresponding phase velocity is:

$v_{pn} = \omega / \beta_n$ that will be negative with β_n

The ***group velocity***, representing the "velocity of energy transfer", ***is the same for all of the harmonics***:

$V_{gn} = d\,\omega / d\beta_n = (d\beta_n / d\,\omega)^{-1} = (d\beta / d\,\omega)^{-1} = Vg$

Harmonics having phase velocity and group velocity in the same direction (same sign), are called forward, otherwise are called backward wave and my be used for traveling wave tube oscillator.

Periodic Structures:
field configuration & the group velocity

For a given field configuration

$$\mathbf{E}(x,y,z) = e^{-\Gamma z}\, \mathbf{E}_p(x,y,z) \qquad \mathbf{H}(x,y,z) = e^{-\Gamma z}\, \mathbf{H}_p(x,y,z)$$

an infinite number of space harmonics $\mathbf{A}_{pn}(x,y)$ is necessary for reproducing that configuration; each space harmonics travels with its own phase velocity, but the group velocity is the same for all of the harmonics because it is related to the total field as a whole.

The field configuration depends on the structure type:
Helix, Ring and Bar, CCTWT and so on

Periodic Structures:
interaction with the electron beam

For amplification to occur in a TWT, the ***axial component of the velocity of the wave on the RF circuit must be close to the velocity of the bunches of electrons.***
The interaction with the RF circuit takes place with the ***space harmonic having the phase velocity close the electron beam velocity*****.**

Another important characteristic of the SWS, introduced in the small signal model of the TWT, is the ***interaction impedance*** that is a measure of the force of the interaction between the SWS and the electron beam.

$\beta_n = (\beta + 2n\pi/p)$ phase constant of n_{th} space harmonic

$V_{pn} = \omega / \beta_n$ phase velocity of n_{th} space harmonic

$K_n = \dfrac{\int |E_{zn}|^2 dS}{2\beta_n^2 PS}$ interaction impedance of n_{th} space harmonic

Helix SWS: The E.M. Field & the Space Harmonics

The E. M. field in the helix SWS can be expressed in cylindrical coordinates (r,θ,z) as:

$$E_z = \sum_{n=-\infty}^{+\infty} e^{-j\beta_n z}(A_{n,p} I_{n,r} + B_{n,p} K_{m,r}) e^{jn\theta}$$

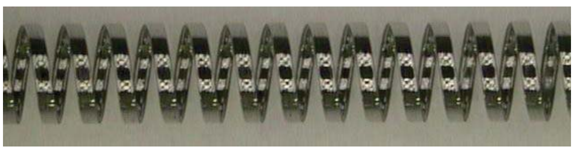
$$H_z = \sum_{n=-\infty}^{+\infty} e^{-j\beta_n z}(C_n \; I_{n,r} + D_n \; K_{n,r}) e^{jn\theta}$$

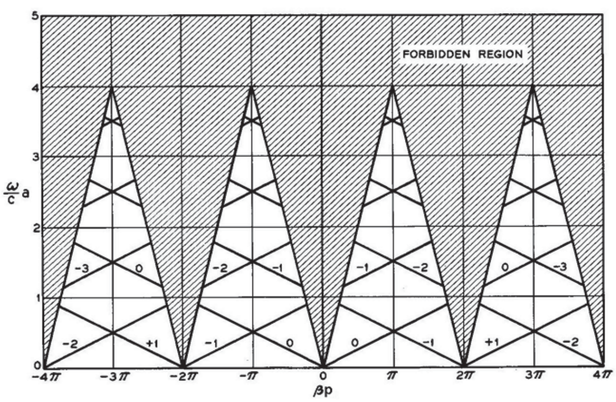
E_z and H_z are the component along the axis expressed in term of the space harmonics; on the right it is given the expression of space harmonics of r and θ components E_r, E_θ H_r, H_θ.
A_n, B_n, C_n, D_n are coefficients determined by boundary conditions
$I(\gamma_n r)$ (I'), $K(\gamma_n r)$ (K') are modified Bessel functions of 1_{st} and 2_{nd} type (derivatives) being $\gamma_n = \sqrt{(\beta_n^2 - K_o^2)}$.

$\beta_n = (\beta + 2n\pi/p)$

$$\begin{aligned}
E_{rn} &= \frac{j\beta_n}{\gamma_n}[e^{-j\beta_n z}(A_n \; I'_{n,r} + B_n \; K'_{n,r})e^{jn\theta}] \\
&\quad - \frac{\omega\mu_0 n}{\gamma_n^2 \; r}[e^{-j\beta_n z}(C_n \; I_{n,r} + D_n \; K_{n,r})e^{jn\theta}] \\
E_{\theta n} &= \frac{-\beta_n}{\gamma_n^2}\frac{n}{r}[e^{-j\beta_n z}(A_n \; I_{n,r} + B_n \; K_{n,r})e^{jn\theta}] \\
&\quad - \frac{j\omega\mu_0}{\gamma_n}[e^{-j\beta_n z}(C_n \; I'_{n,r} + D_n \; K'_{n,r})e^{jn\theta}] \\
H_{rn} &= \frac{j\beta_n}{\gamma_n}[e^{-j\beta_n z}(C_n \; I'_{n,r} + D_n \; K'_{n,r}) \\
&\quad \cdot e^{jn\theta}] \\
&\quad + \frac{\omega\varepsilon_0\varepsilon_r \, n}{\gamma_n^2 \; r}[e^{-j\beta_n z}(A_n \; I_{n,r} + B_n \; K_{n,r}) \\
&\quad \cdot e^{jn\theta}] \\
H_{\theta n} &= \frac{-\beta_n}{\gamma_n^2}\frac{n}{r}[e^{-j\beta_n z}(C_n \; I_{n,r} + D_n \; K_{n,r}) \\
&\quad \cdot e^{jn\theta}] \\
&\quad + \frac{j\omega\varepsilon_0\varepsilon_r}{\gamma_n}[e^{-j\beta_n z}(A_n \; I'_{n,r} + B_n \; K'_{n,r}) \\
&\quad \cdot e^{jn\theta}]
\end{aligned}$$

Helix SWS: Dispersion Diagram





Approximate Brillouin diagram for the tape helix, with tan ψ = 0.125. In this approximation, changing the pitch angle changes only the lower extent of the forbidden regions. The branches are numbered as to the order of the space harmonic.

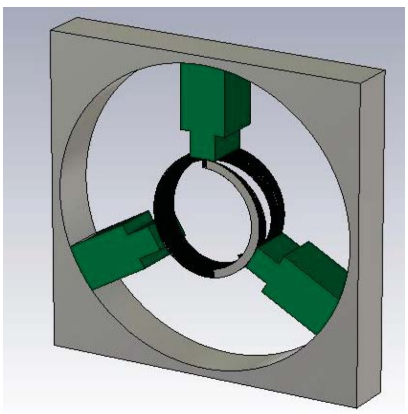
Helix SWS:
calculations with CST MWS Suite

On the axis (r=0) of the helix only the space harmonic n=0 exists and only E_z and H_z exist.
It is responsible for the amplification process, for this reason it is important to calculate: the phase velocity, v_{ph}, and the interaction impedance, K:

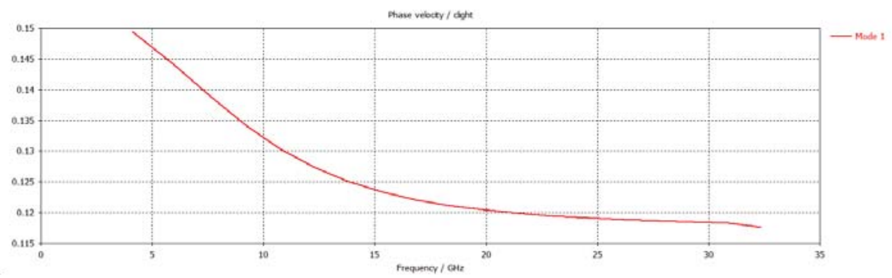
$v_{ph}/c = 0.11 \div 0.22$ (c is light velocity in vacuum)
depending on TWT electron beam voltage,
operating frequency.

$K = 100 \div 40\ \Omega$ depending on the frequency, i.e. $6 \div 18$ GHz.

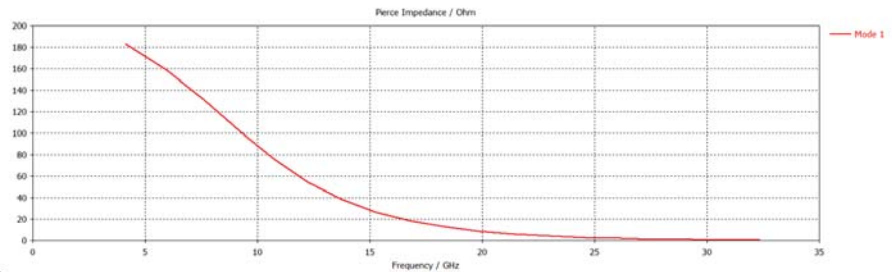
Helix SWS:
calculations with CST MWS Suite



Fundamental Harmonic (n=0) Phase Velocity vs Frequency

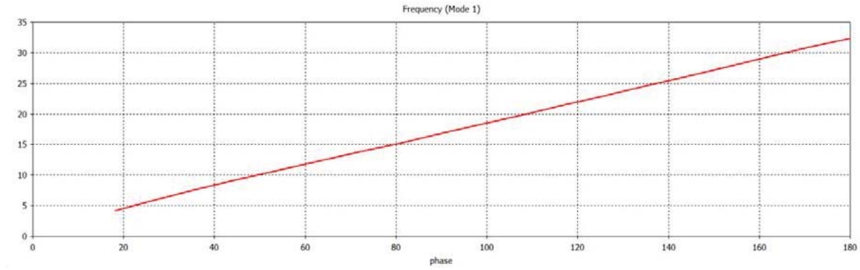


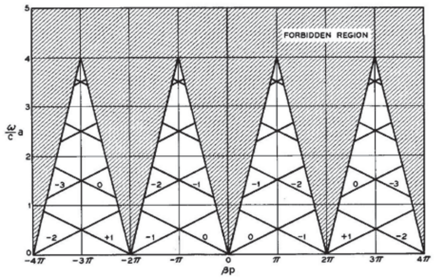
Fundamental Harmonic (n=0) Interaction impedance vs Frequency



Helix SWS: calculations with CST MWS Suite

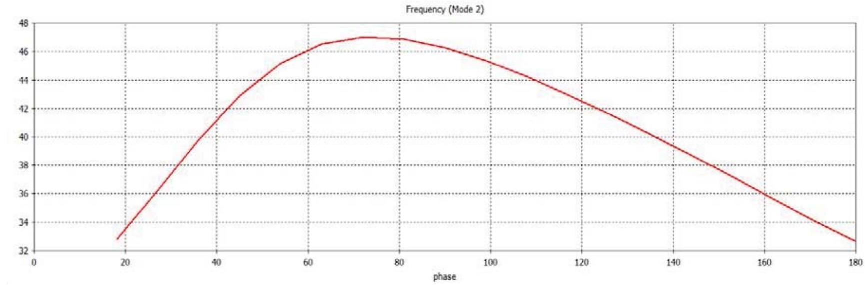
Fundamental Harmonic (n=0) Dispersion Diagram





Approximate Brillouin diagram for the tape helix, with $\tan \psi = 0.125$. In this approximation, changing the pitch angle changes only the lower extent of the forbidden regions. The branches are numbered as to the order of the space harmonic.

Backward Harmonic (n=-1) Dispersion Diagram



LEONARDO AIRBORNE & SPACE SYSTEMS

EuMW 2016 Microwaves Everywhere

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Slow wave structures for micro- and millimeter- waves

Claudio Paoloni

Lancaster University

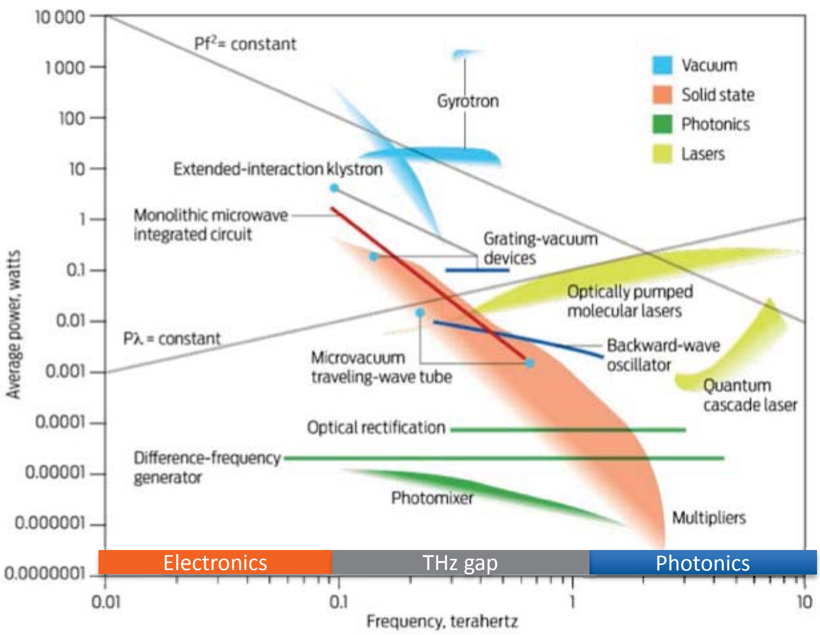
c.paoloni@lancaster.ac.uk

Summary

- Vacuum electron devices toward THz frequencies
- State of the art
- Slow Wave Structures for millimeter waves
  - Folded Waveguide
  - Double Staggered Grating
  - Double corrugated waveguide
  - Photonic Cristal assisted SWS
- Fabrication techniques
- Future perspectives

THz gap

- **Sub-THz 100 -1000 GHz**
- **Gap refers to compact and portable devices**



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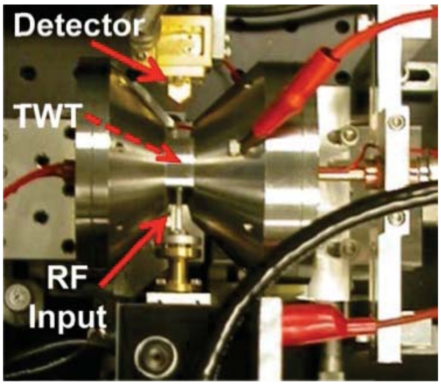
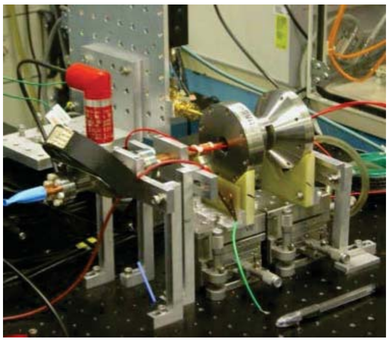
The challenges

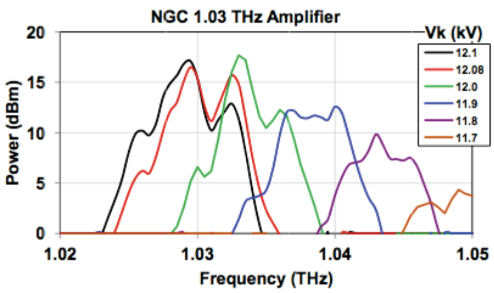
- Wavelength shorter than 3 mm (100 GHz)
- Fabrication processes with high accuracy and precision at micrometric level
- High quality cathode to generate cylindrical electron beam or sheet electron beam with high beam current and narrow diameter
- Reliable and repeatable assembly
- Low beam voltage e-gun (10-15 kV) for portability
- Control of the surface roughness of the metal walls to reduce the losses
  (100 nm skin depth at 0.6 THz, not more than 50 nm surface roughness)
- High vacuum level (10^{-7} Torr)

VEDs - state of the art

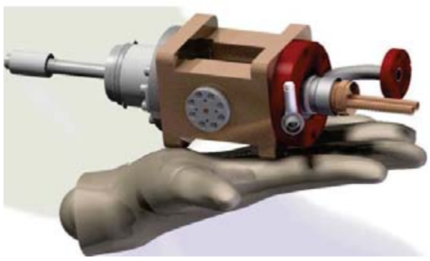




1 mW 1 THz BWO (THALES)



141 mW 0.85 THz
(Northrop Grumman)



50 W 220 GHz (UC Davis)

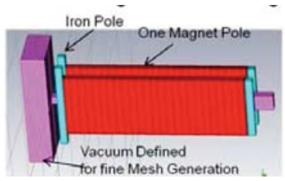
29 mW 1 THz (Northrop Grumman IVEC2016)

VEDs

Traveling wave tubes

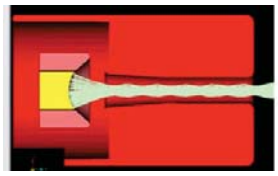
Backward wave oscillators

Sheet beams
- High current
- Low current density
- Low cathode loading
- Demanding magnetic focussing



Baig, Ivec 2011

Cylindrical beams
- High current
- High current density
- High cathode loading
- Easy magnetic focussing

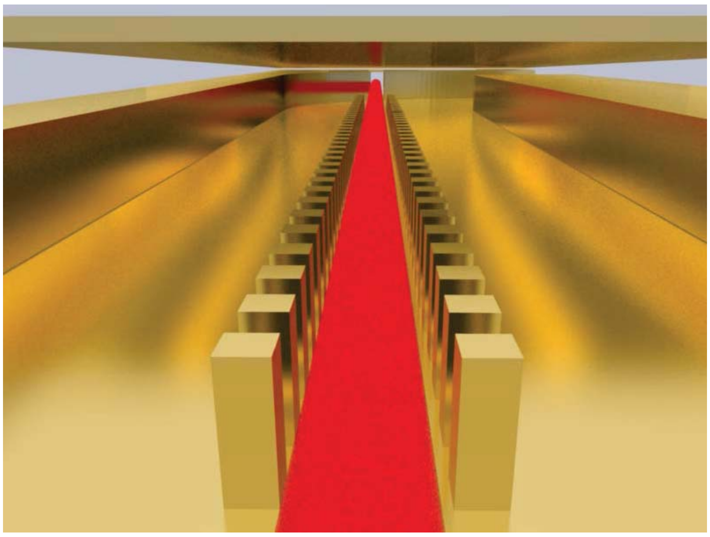


Reed, IVEC 2010

Slow wave structures

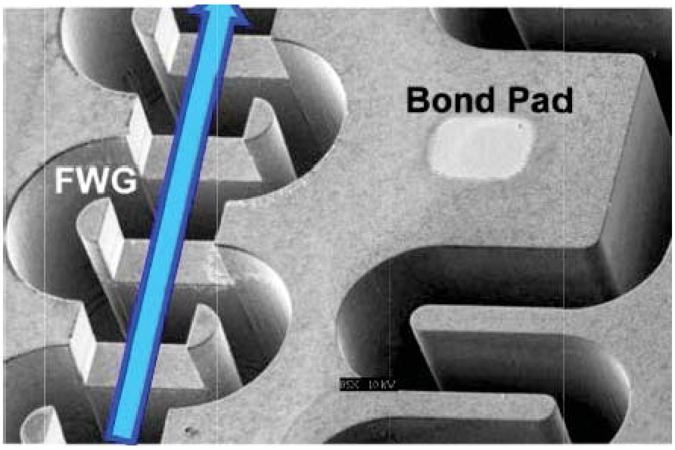
- Folded Waveguide
- Double Staggered Grating
- Double corrugated waveguide
- Planar Helix
- Photonics Cristal assisted SWS

Double Corrugated Waveguide



- Supports a cylindrical electron beam
- Good interaction impedance in forward and backward wave regime
- Easy to realize by micromachining or photolithographic processes (UV-LIGA, DRIE,)
- Easy assembly
- Fabricated up to 1 THz

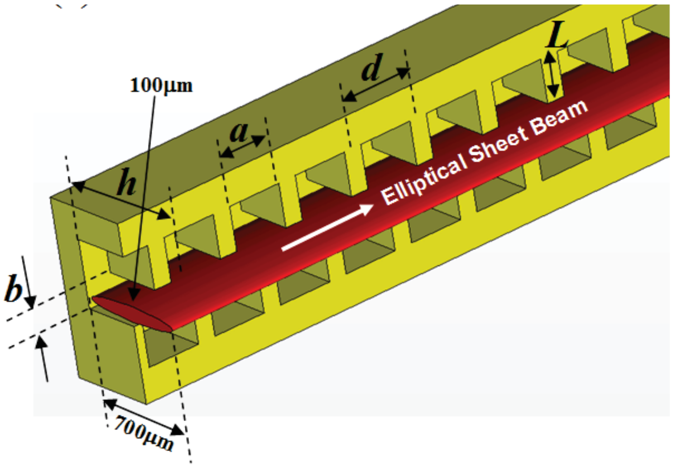
Folded waveguide



Northrop Grumman IVEC 2016

- TE_{01} mode
- Easy coupling
- Good interaction impedance
- Wide frequency band
- Cylindrical electron beam
- CNC milling or UV LIGA
- Fabricated up to 1 THz

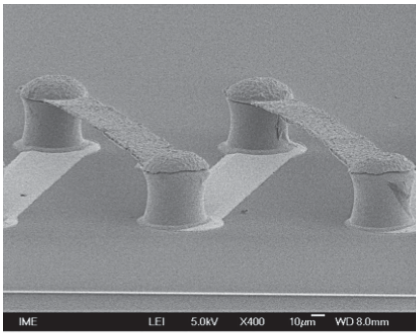
Double Staggered Grating



- Supports a sheet beam
- Suitable for high power
- CNC milling or UV LIGA
- Fabricated up to 0.346 THz
- High interaction impedance

UC Davis

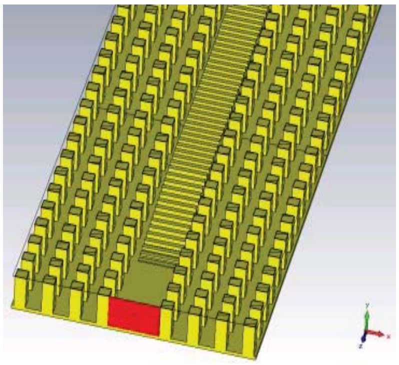
Planar Helix



- Very wide band
- Helix type
- MEMS technology
- High interaction impedance

NTU – Singapore
IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 58, NO. 11, NOVEMBER 2011

PhC assisted corrugated WG



- Open structure
- Same electrical behaviour of corrugated waveguide
- Easy assembly
- Sheet electron beam
- CNC milling and UV-LIGA

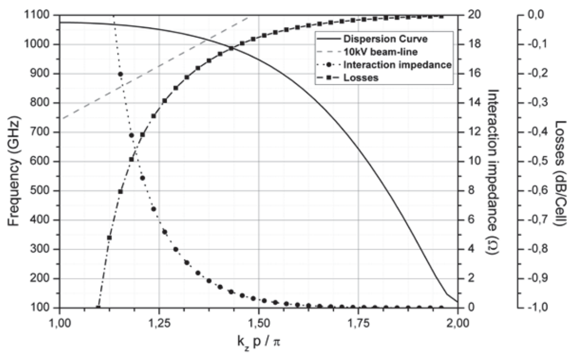
R. Letizia, IEEE Trans. On Electron Devices

Design Corrugated waveguides

- The operating frequency is mainly related to the period
- The period of a corrugated waveguide is a function of the beam voltage, the frequency and the phase shift

$$p = \frac{\phi 5.93 * 10^5 \sqrt{V_0}}{2f}$$

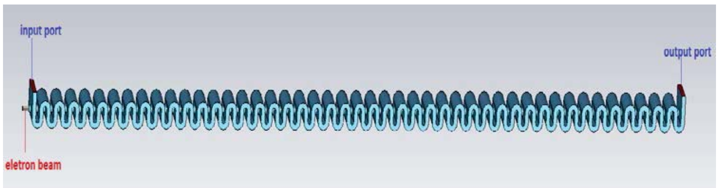
Where V_0 is the beam voltage
f is the frequency
$\Phi = k\,p/\pi$ is the phase shift

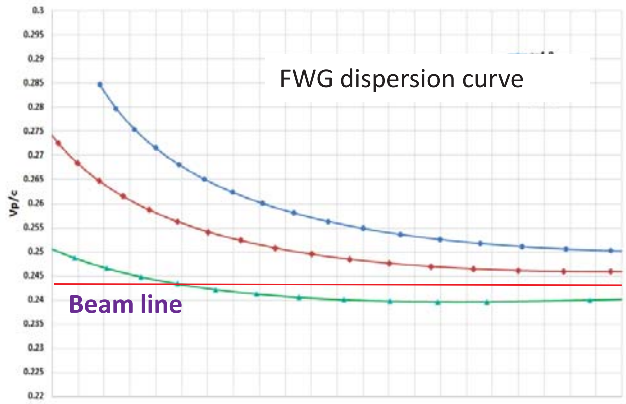


If V_0=10 kV , f= 1 THz, $\Phi = 0.5\,\pi$ τ the period is $p = 15\ \mu m$

To operate at low beam voltage for portability is necessary to have an adequate fabrication technology.
This equation apply to all the SWS derived from corrugated waveguide

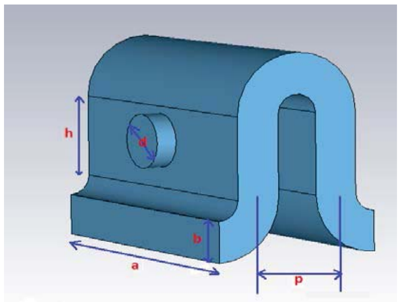
Design - FWG

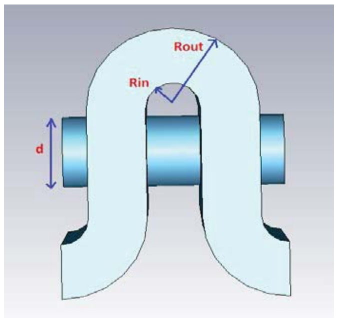




$$\phi_z = k_s L + \pi.$$

$$L = h + \pi p/2$$





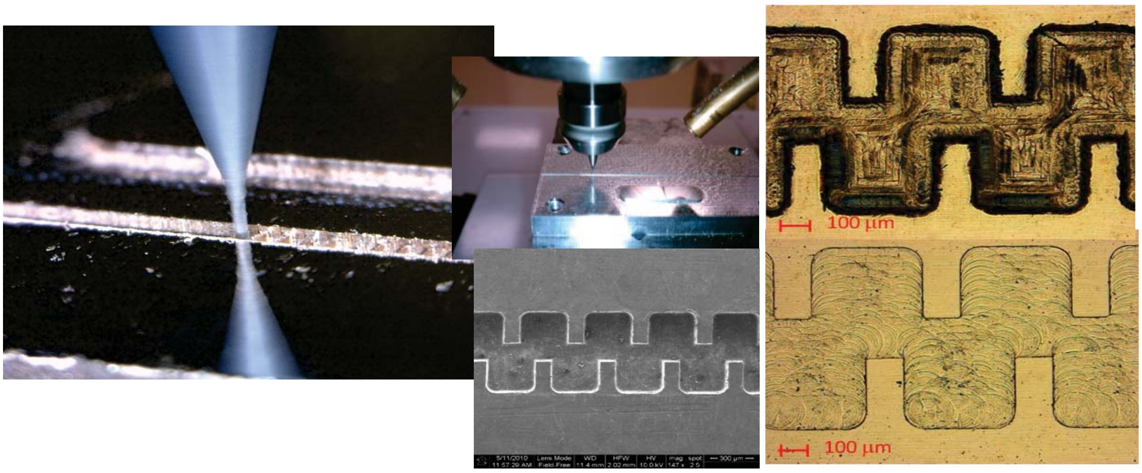
Microfabrication

Technique	Accuracy	Surface roughness
UV LIGA	3-5 μm	> 30 nm
Deep X-ray LIGA	3-5 μm	> 30 nm
DRIE	1 μm	> 30 nm
Nano CNC	0.5 μm	> 10 nm

DRIE Deep Reactive Ion Etching
CNC Computer Numerical Control
LIGA Lithography, Electroplating, and Molding

Source UC Davis

UC Davis Precision Nano-CNC



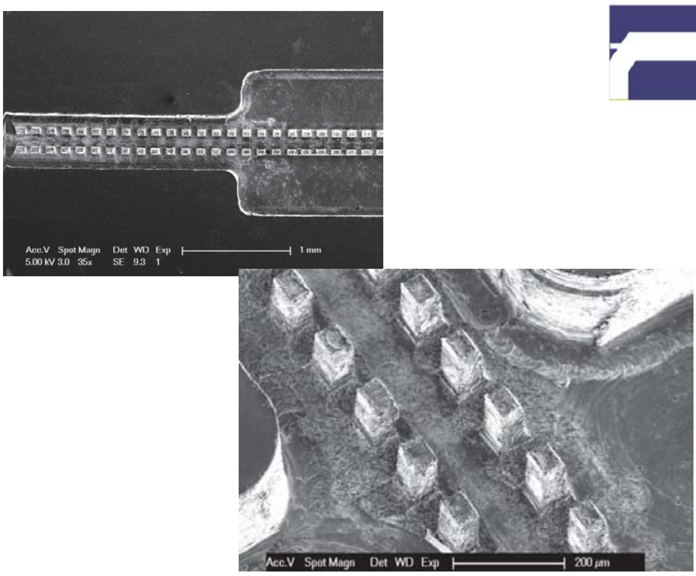
Tungsten Carbide
□70 nm R_a

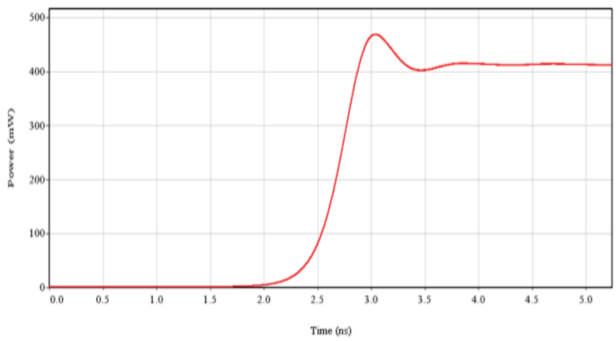
Diamond Tooling
□40 nm R_a

developed by DTL, a subsidiary of DMG-Mori-Seki

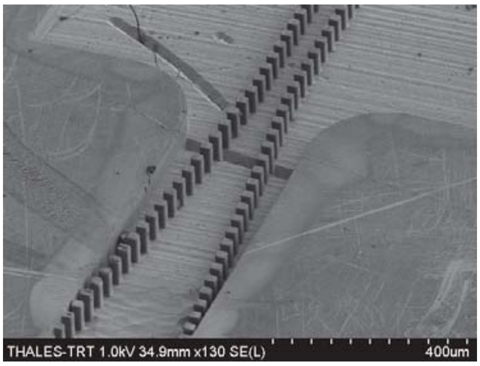
CNC milling 0.346 THz DCW

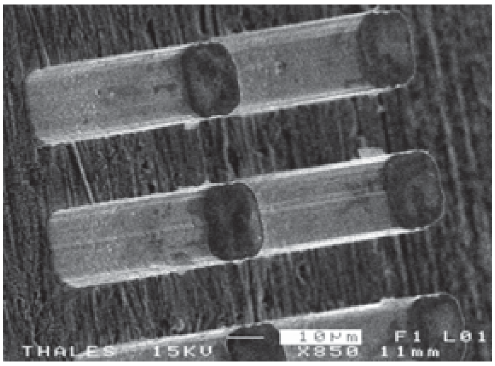
Double Corrugated Waveguide for 0.346 THz BWO for plasma diagnostic in collaboration with UC Davis, US, and Beijing Vacuum Electronic Research Institute, China



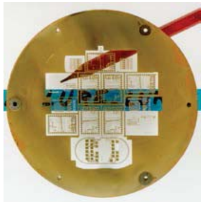


Deep X-Ray LIGA for 1 THz TWT



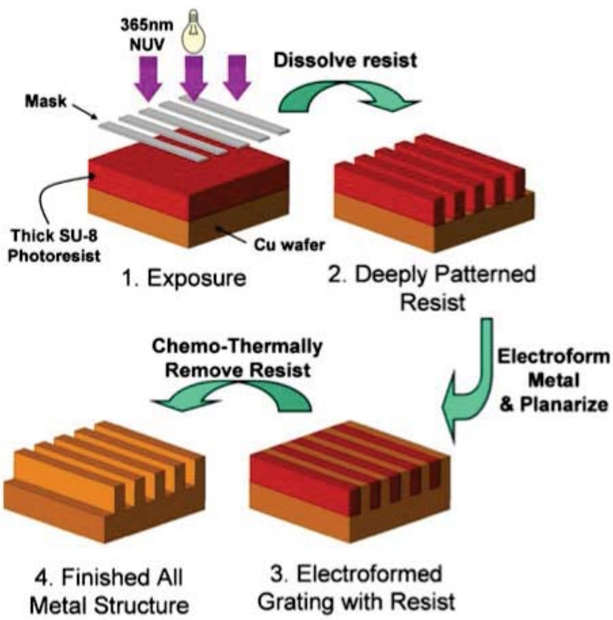


Opther Project

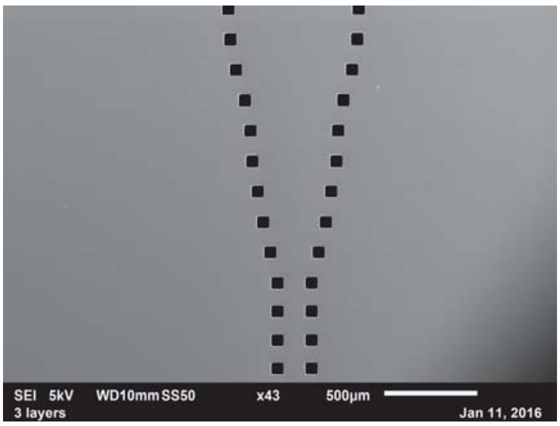


Soleil Synchrotron

UV - LIGA



J. Micromech. Microeng. **20** (2010) 125016



SU-8 Mold

Future development

- Low cost fabrication
- Compact power supply
- High interaction structures
- High efficiency
- Multiple beams

Thank you!

For the most recent advancements in Vacuum Electronics follow:

www.vacuumelectronics.org

www.tweether.eu
Traveling wave tube based W-band wireless networks with high data rate distribution, spectrum and energy efficiency"

@h2020tweether

@ClPaoloni

Materials and techniques in TWT manufacturing

Roberto Dionisio

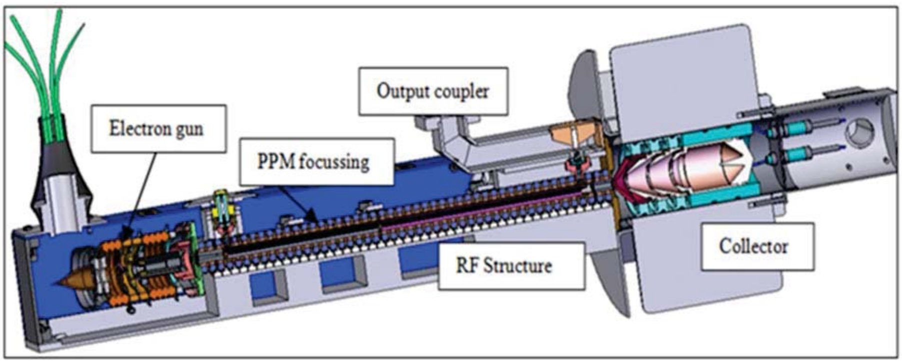
European Space Agency, Noordwijk, The Netherlands

roberto.dionisio@esa.int

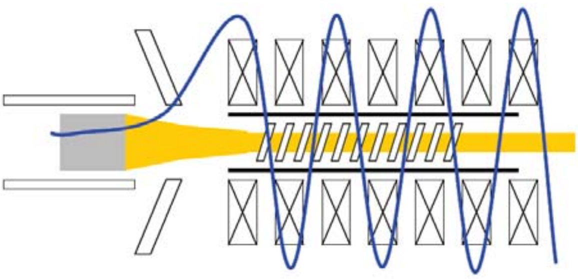
Materials and techniques in TWT manufacturing

Summary

- Electron guns and linear beam magnetic focusing
  - Cathode Technology
- Helix interaction structure
- Collector
- Vacuum Technology
- Breakdown

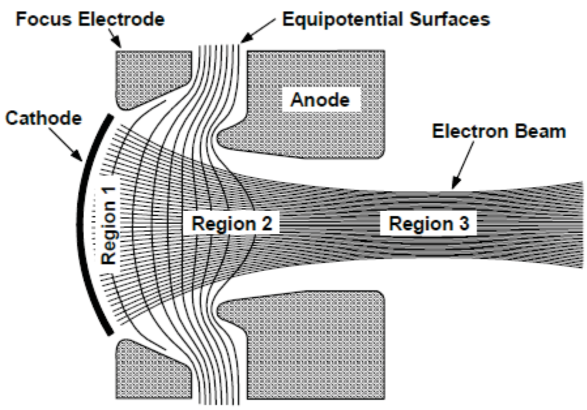


Electron guns
&
Linear beams magnetic focusing



Electron guns

The electron gun in a microwave tube is used to form the electrons from the cathode into a beam suitable for interaction with a microwave circuit.



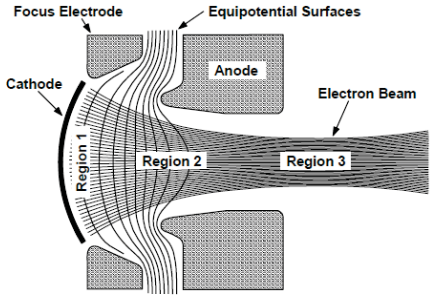
Most of these guns are designed using guidelines set forth by J. R. Pierce and are known as "Pierce guns" handling the following two basic problems:

1. Electrostatic repulsion forces between electrons tend to cause the beam to diverge.
2. The current density required in the electron beam (Region 3) is normally far greater than the emission density that the cathode can supply with an acceptable life expectancy.

Electron guns - Linear circular section beams

The gun is divided into three regions.

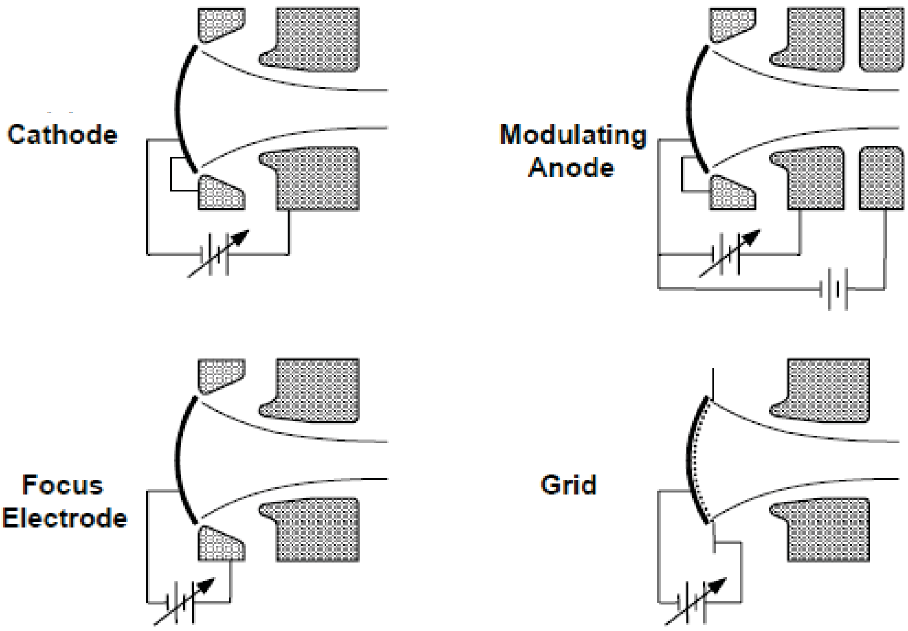
Region 1: Spherical cathode disk, focus electrode designed to produce equipotential surfaces that are nearly spherical, with the same center of curvature as the cathode. Electrons flow toward the center of curvature of the cathode.



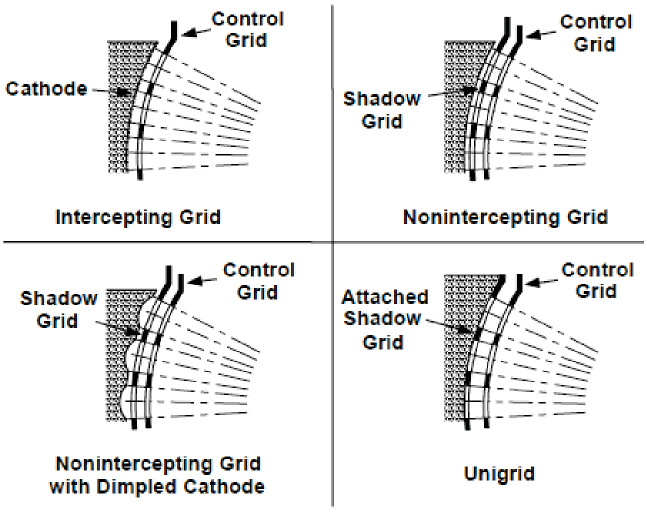
Region 2: Because the anode must contain a hole to let the electron beam pass through, equipotential surfaces bow into the anode aperture. A divergent electrostatic lens exists that produces a defocusing action on the electron beam.

Region 3: The electrons have escaped from the accelerating field of the cathode-to-anode regions and are drifting under the influence of space charge forces. Thus, the electrons in the beam follow universal beam-spread trajectories.

Beam control techniques

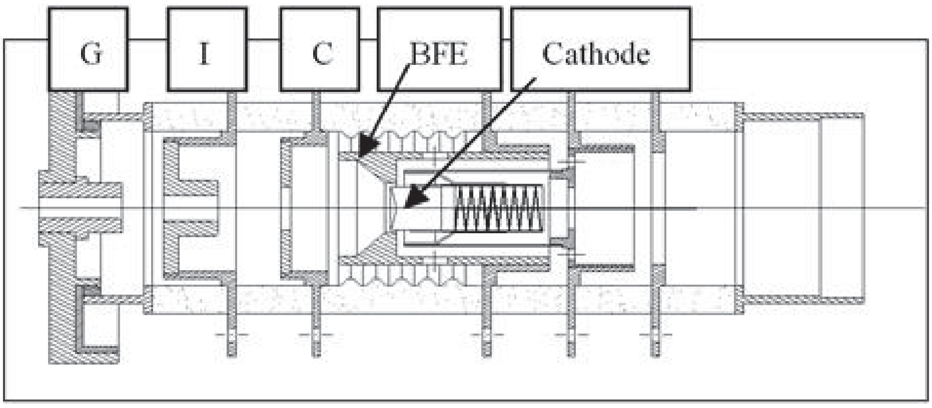


Grids

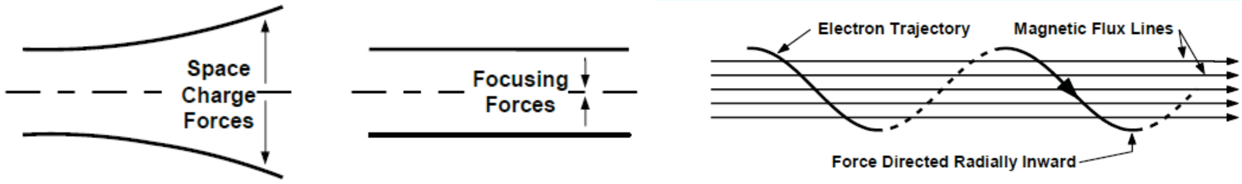


- Grid potential is positive with respect the cathode (negative to switch off the beam) leading to current interception with excessive heating of the grid at high duty cycles.
- Shadow grid configuration minimizes current interception

Electron gun assembly structure



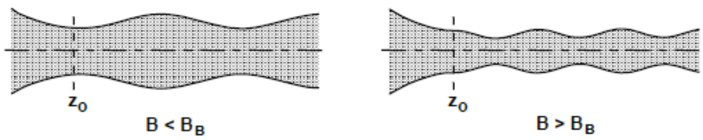
Linear beams magnetic focusing



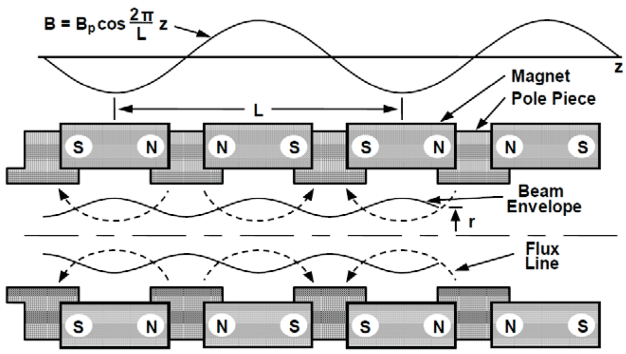
- In linear-beam tubes, the focusing forces are provided by a magnetic field aligned with the axis of the electron beam.
- The magnetic force on the electrons is in the reverse direction from the *u* x *B*
- The magnetic flux level that produces a magnetic force that exactly balances the space charge and centrifugal forces is called the *"Brillouin flux"* level, commonly denoted by B_B.

$$B_B = 0.83 \times 10^{-3} \frac{I^{1/2}}{aV^{1/4}} \text{ [T] } (a = \text{equilibrium beam radius})$$

- When the actual magnetic flux level differs from B_B the electron beam starts to expand and compress (*scalloping*)



Focusing with Periodic Permanent Magnets



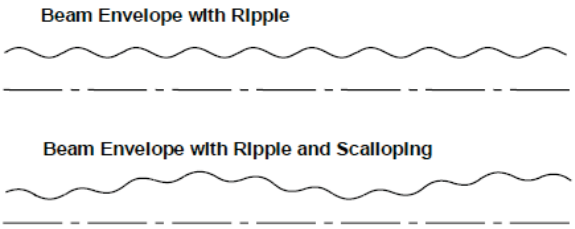
As a beam enters the field of a magnet section, the forces on the electrons let the beam start to rotate and the interaction of the rotational motion with the axial field produces a radial force that compresses the beam.

As the beam leaves the magnet section, rotation stops, focusing forces vanish, and the beam expands under the influence of space charge forces. The beam then enters another magnet section with the field in the opposite direction from the previous one. Then the beam rotates in the opposite direction, but is focused just as it was in the previous section.

Focusing with Periodic Permanent Magnets

The overall result, as the beam traverses the alternating field of the PPM structure, is that its rotation oscillates back and forth, producing alternating periods of magnetic focusing and beam expansion (beam ripple).

Below the difference between beam ripple, which results from the periodicity of focusing, and beam scalloping, which is the oscillation of a beam that is not in equilibrium.



The weight reduction of a PPM focusing system, when compared with a solenoid or a unidirectional magnet, can be one to two orders of magnitude

Cathode Technology

The cathode is the source of electrons for the electron beam in every microwave tube.

The current density of electron emission from the cathode ranges from milliamperes to tens of amperes per square centimeter of cathode area.

An ideal cathode should:

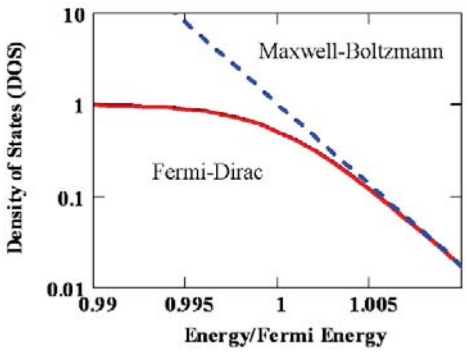
- emit electrons freely, without any form of persuasion such as heating or bombardment (electrons would leak off from it into vacuum as easily as they pass from one metal to another);
- emit copiously, supplying an unlimited current density;
- last forever, its electron emission continuing unimpaired as long as it is needed;
- emit electrons uniformly, traveling at practically zero velocity.

Electron Statistics and Emission Processes

Elementary particles in general can be classified as either bosons or fermions depending upon whether they have integer or half integer spin, respectively.

- Bosons obey classical Maxwell-Boltzmann (M-B) statistics: $f_{MB} = e^{-E/k_BT}$
- Fermions follow Dirac-Fermi(F-D) statistics: $f_{FD} = \frac{1}{1+e^{\frac{(E-E_F)}{k_BT}}}$

These statistics define the probability a particle occupies an given energy state



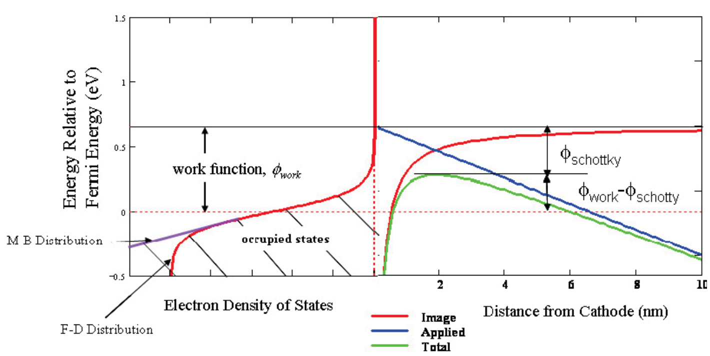
- Distributions have very nearly the same high energy tails.
- During thermionic emission the cathode is heated to high temperature to increase the high energy tail of the distribution and promote emission.
- M-B statistics is completely valid and the classical concept of temperature applies.

Fields Near the Cathode Surface

The total external potential, Φ, is the sum of applied and image fields for a single electron, and peaks approximately 2 nm from the surface.

Electrons can escape with energies greater than the work function or those with lower energy can tunnel through the barrier.

- For thermionic emission, the escaping electrons must have energies greater than the barrier.
- For field emission, electrons tunnel through the barrier.



- The temperature of the electron gas in the bulk material affects the probability of emission and the emitted electron energy distributions .
- The reduction of the barrier by the applied field is called the Schottky effect and plays a central role in all emission processes, especially field emission.

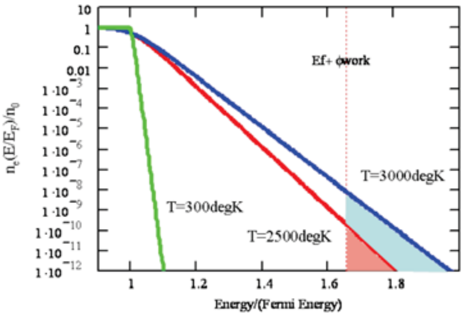
Thermionic Emission

An electron can escape a metal if it has sufficient kinetic in the direction of the barrier

to overcome the work function $\frac{mv_x^2}{2} > e\emptyset_{work} \Rightarrow v_x > \sqrt{\frac{2e\emptyset_{work}}{m}}$

Then the thermionic current density for a cathode at temperature T is given by

$$j_{thermionic} = n_0 e \langle v_x \rangle = n_0 e \int_{v_x > \sqrt{\frac{2e\emptyset_{work}}{m}}} v_x f_{FD} d\vec{v} \quad \Rightarrow \quad j = A(1-r)T^2 e^{-\emptyset_{work}/k_B T}$$



Richardson-Dushman (R-D) equation for thermionic emission where

- A is the universal constant $A = -\frac{em}{2\pi^2 h^3}$
- $A = 120 \frac{amp}{cm^2 degK^2}$
- (1-r) accounts for the refection of electrons at the metal surface.

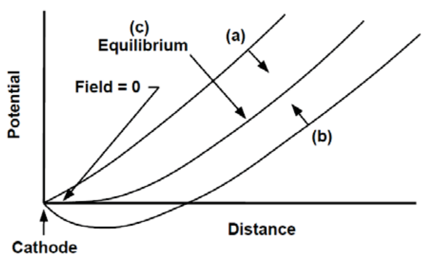
The exponential dependence upon temperature of the R-D equation illustrates how thermionic current rises rapidly with temperature, and with decreasing work function

Space Charge

The effect of the negative charge of an electron is to reduce the potential that is present in the absence of the electron. As the electron emission rate is increased (by increasing temperature, for example), the potential is further decreased.

The electron emission rate is limited by the density of electrons adjacent to the cathode surface.

When the electric field at the cathode surface is forced to zero by the electron cloud near the cathode surface, the emission is said to be **space charge limited**.



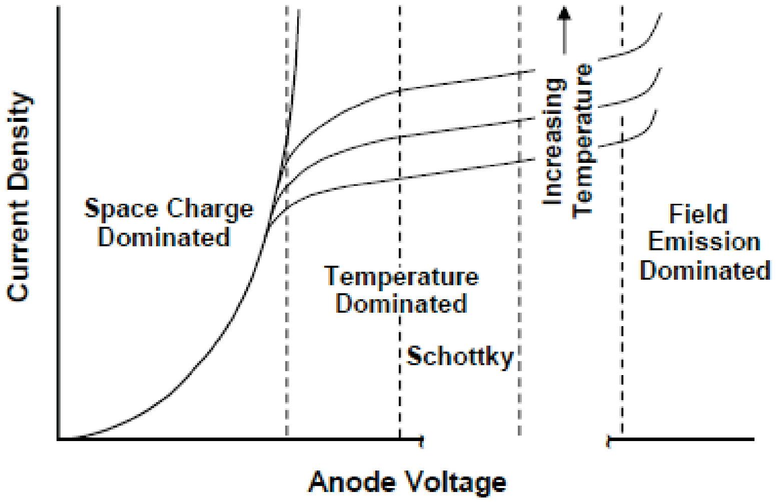
Relation between voltage and current in a space charge limited diode is governed by the **Child-Langmuir law**

$$I = kV^{3/2}$$

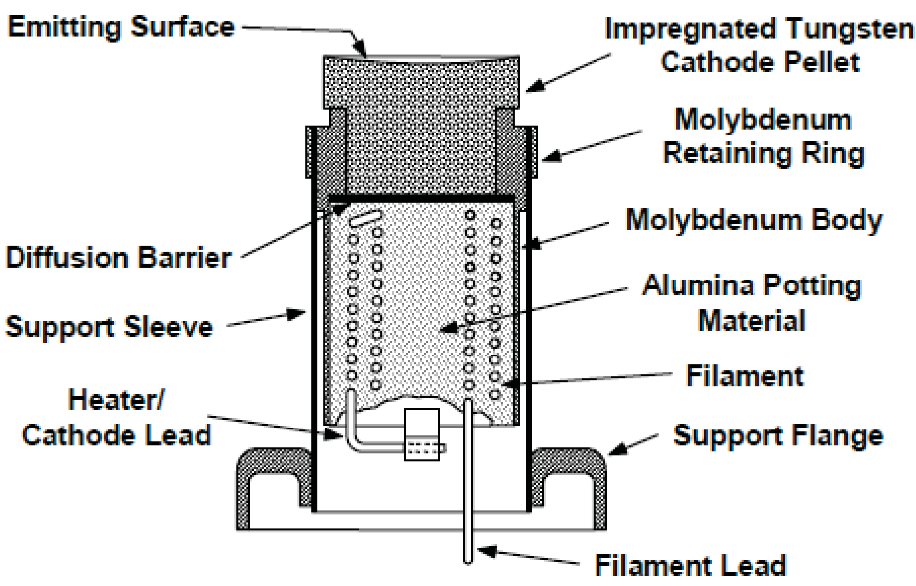
where *k* is a constant depending on diode geometrical characteristics only.

Thermionic diode

Mechanisms dominating current flow in a thermionic diode



Impregnated dispenser cathode



Impregnated dispenser cathode types

B-type: the pores of a porous tungsten pellet are impregnated with a compound of BaO, CaO, and Al_2O_3. Barium is released when the impregnant reacts with the tungsten. The freed barium migrates to the surface of the porous tungsten to form the emitting surface. It provide emission densities of several A/cm^2, operating at a temperature of 1,100°C or higher.

M-type: B-type with a film several thousand Angstroms thick of osmium, iridium, or ruthenium applied to the surface. Compared to a B cathode, the effect of the film is to reduce the work function ~0.2eV and the cathode operating temperature ~90°C (dependent on film metal)

MM-type: B-type with tungsten pellet containing particles of the enhancing metal (i.e. Scandium Oxide).

Impregnated dispenser cathode M-Type fabrication

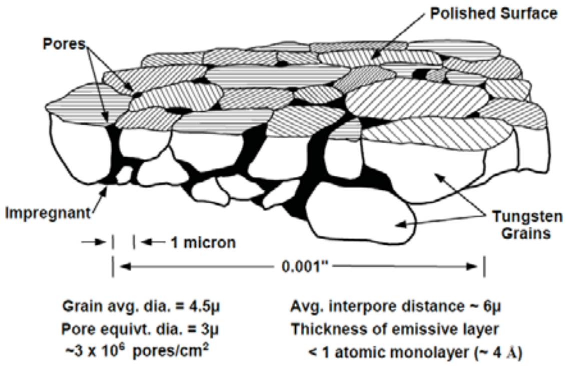
Porous billet: Small grains of tungsten are pressed together under high pressure and sintered at a temperature of over 2,000°C in hydrogen atmosphere for 1 to 2 hours to form porous billets.

Cathode pellet: Machining to the desired shape of porous billets with pores filled with a plastic material to facilitate. After machining, the plastic is removed.

Impregnation: The porous matrix is filled by melting a compound containing BaO, CaO, and Al_2O_3. Cathode surface is cleaned by removing the excess impregnant.

Coating: Sputtering 2,000 to 10,000 Å thickness layer of osmium-ruthenium

Coat sintering: Firing in hydrogen atmosphere for several minutes



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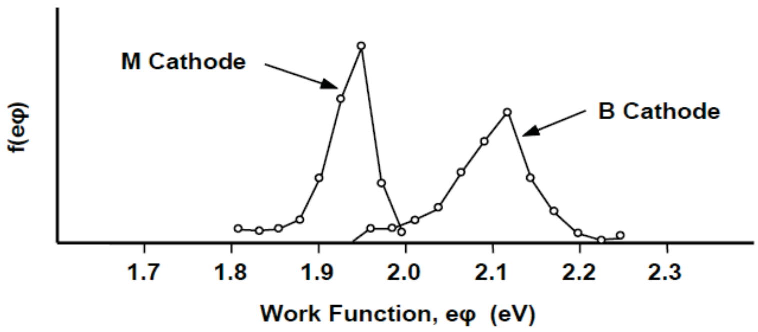
Work Function Distribution

esa

The rate of diffusion of barium to the surface, along with the energy of desorption of barium atoms from the surface (which controls the evaporation rate), determines the surface coverage.

The work function of the cathode depends on the fraction of the cathode surface that is covered by barium along with the work function of the metal substrate.

The work function of a cathode is not a single valued quantity but instead has a distribution of values because the energy of desorption and the work function vary from grain to grain.



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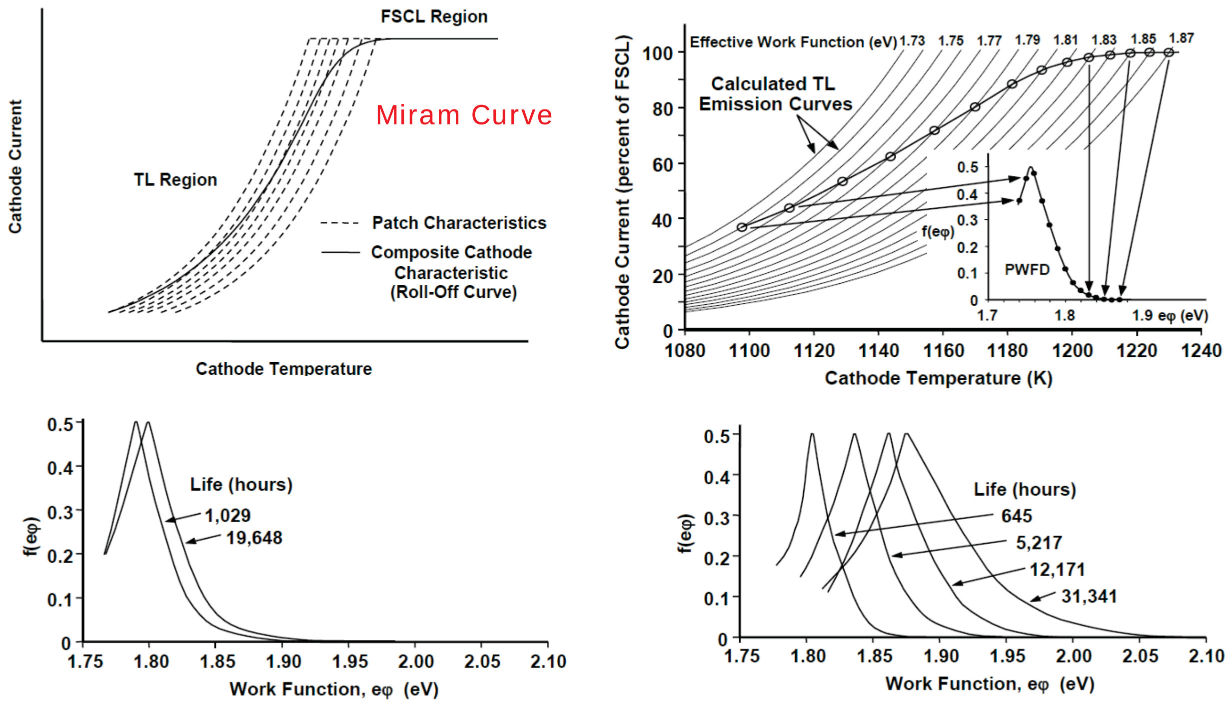
Work Function Distribution

esa



Best-of-class

Types of emission degradation mechanisms

1. Gradual decrease in perveance, that is, space charge limited emission decreases with time

   Usually due to the gradual depletion of the barium supply in the impregnated tungsten pellet. The rate at which barium diffuses to the cathode surface decreases, so the barium coverage of the surface decreases and work function increases

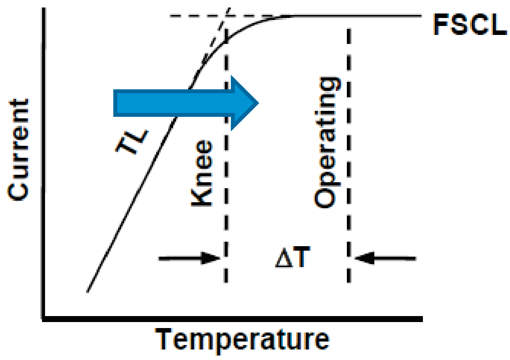
2. Change in work function distribution with time and without dependence on changes in cathode temperature

   It results from a change in the base metal work function with time. This mechanism applies to coated cathodes and is attributed to the diffusion of tungsten through the coating

3. Change in work function distribution with temperature as well as with time

   It is attributed to an insufficient supply of barium, a change in sticking coefficient of the barium to the cathode surface or to external poisoning.

Operating temperature



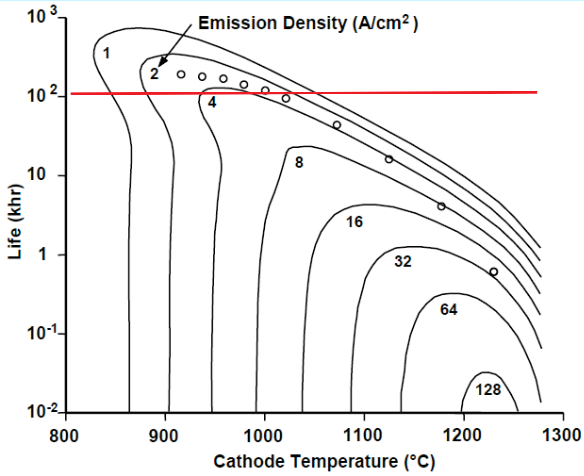
The result from barium depletion is the movement with time of the roll-off curves toward higher temperatures

Ideally, the operating temperature should be chosen so that end of life is determined when the cathode current in a tube has decreased by an amount that causes one of the operating parameters of the tube to fail to meet specification. In this case the "knee" temperature is the temperature that produces that cathode current.

Cathodes for space

- Life > 10 years (90,000 hours)
- Switch ON/OFF cycles > 250,000
- Minimal evaporation rate
- Resistance to shock and vibration
- Low heater power
- High reliability and predictability

M-type cathodes are limited to 4 A/cm2 emission density.

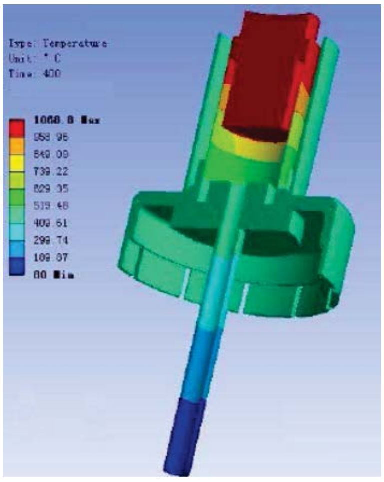


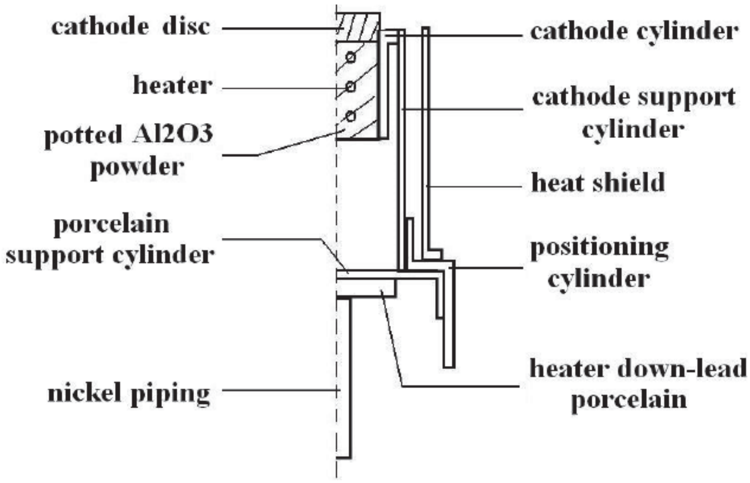
Life of an M-type cathode

New materials are requested to reduce the work function and thereby increase the emission density, which would vastly simplify the focusing of the fine electron beams needed in higher-frequency millimeter- and submillimeter-wave tubes.

Cathodes made from nanocrystalline powders of scandium oxide and tungsten resulted in a robust emitter with a work function of **1.43 eV**

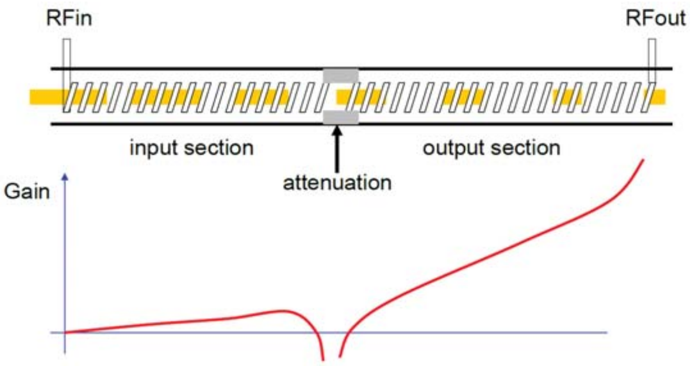
Cathode-Heather assembly structure



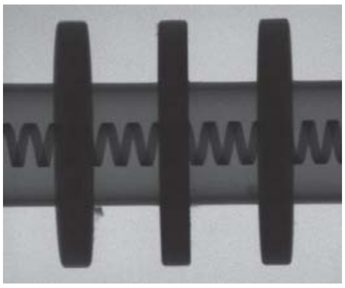


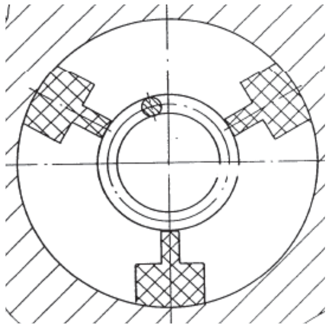
- Support element operating at 1000°C
- Minimize Power losses
- Minimize cathode surface mechanical displacement
- Withstand thermomechanical stress due to switch ON/OFF

Helix interaction structure



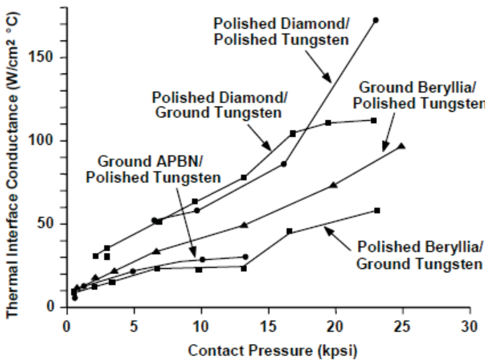
Helix slow wave structure

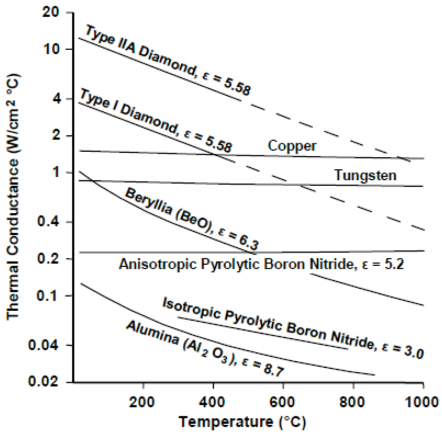


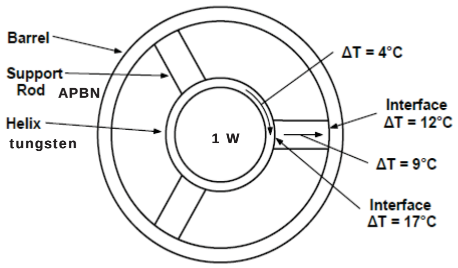


- The helix of a TWT is a relatively delicate structure. As an example the helix of a 200 W Ku-Band TWT has 1.5 mm outer diameter and it is made of 0.2 mm by 0.35 mm tungsten tape.
- Two dielectric materials are widely used for supporting the helices of TWTs: beryllium oxide (BeO) and anisotropic pyrolytic boron nitride (APBN). Unfortunately, their dielectric constants is high.
- To minimize the loading effect of a ceramic support structure, it is necessary to minimize the amount of ceramic material used. As a result, thin rectangular or T-shaped support rods are often used

Helix slow wave structure



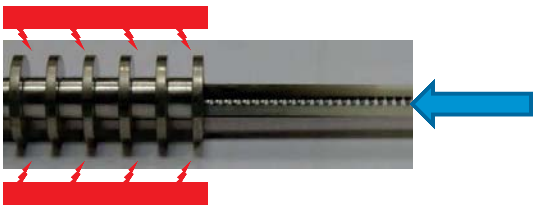




- Thermal resistances of the interfaces between the helix and the support rods and between the support rods and the barrel are the predominant.
- The temperature drops across the interfaces are extremely dependent on the pressure applied to the interface.
- Also, the surface finishes of the materials in contact are important.
- Diamond has an outstanding thermal conductivity and there is a strong interest in using it for Q/V band TWTs.

Helix slow wave structure

- Because of the large thermal drops at the support rod interfaces, the helix and support rod structures in high-power helix TWTs must be assembled using techniques that minimize the thermal interface resistances by increasing contact pressure and reducing surface roughness. A limit is reached, however, when the forces are high enough to distort the helix excessively. For helix strength, the material normally used is tungsten or molybdenum.
- One technique used is the hot insertion:
  - The helix and rod assembly are machined with tolerances for an interference fit with barrel at ambient temperature
  - During assembling the barrel is heated up to allow the insertion with low friction.



Collectors

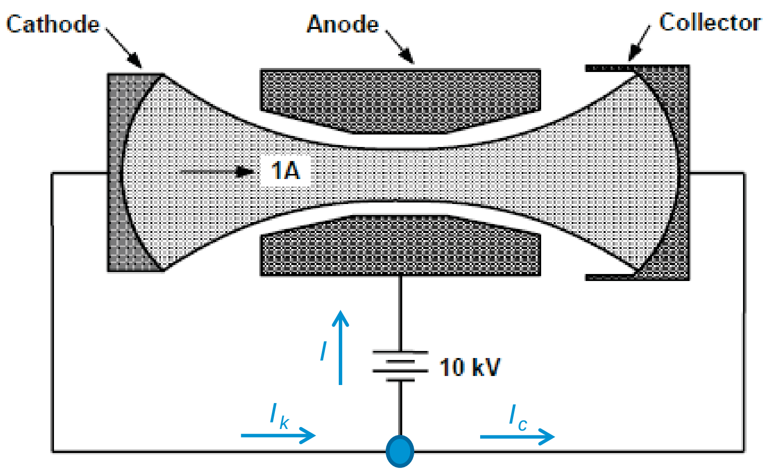
Electrons must be collected after the interaction process.

Electrons kinetic energy at the time of the impact is converted to heat.

Role of the collectors is:

- reduce impact electrons kinetic energy (power recovery)
- dissipate heat generated

Understanding power recovery



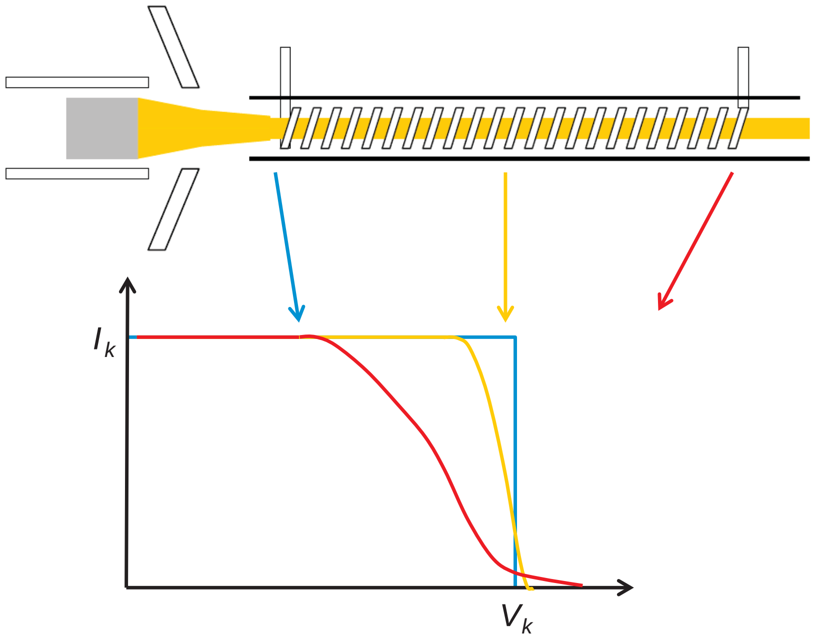
$I_k = I_c$

$I = 0$

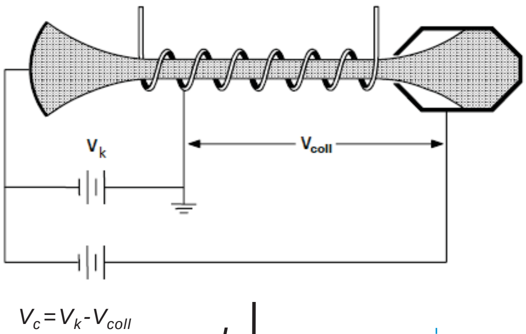
No power is provided by the 10 kV supply because there is no current flowing to it

- With 10 kV applied to the anode, a 10 kW electron beam is generated
- As the beam enters the collector, it is slowed down and the electron velocity drops to zero as the electrons land on the collector
- No heat is generated in the collector and there are no other losses and so no power is dissipated

Electron energy distribution

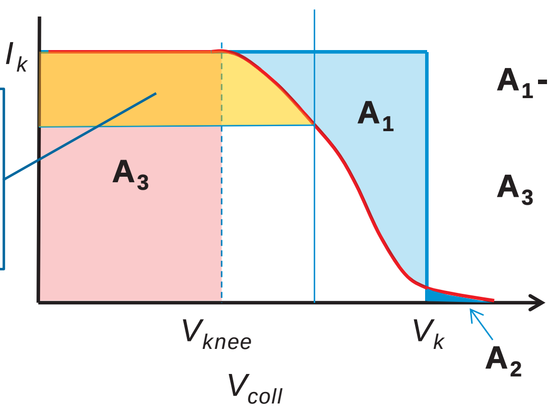


Electron energy distribution



Question: what if we apply $V_{coll} > V_{knee}$?

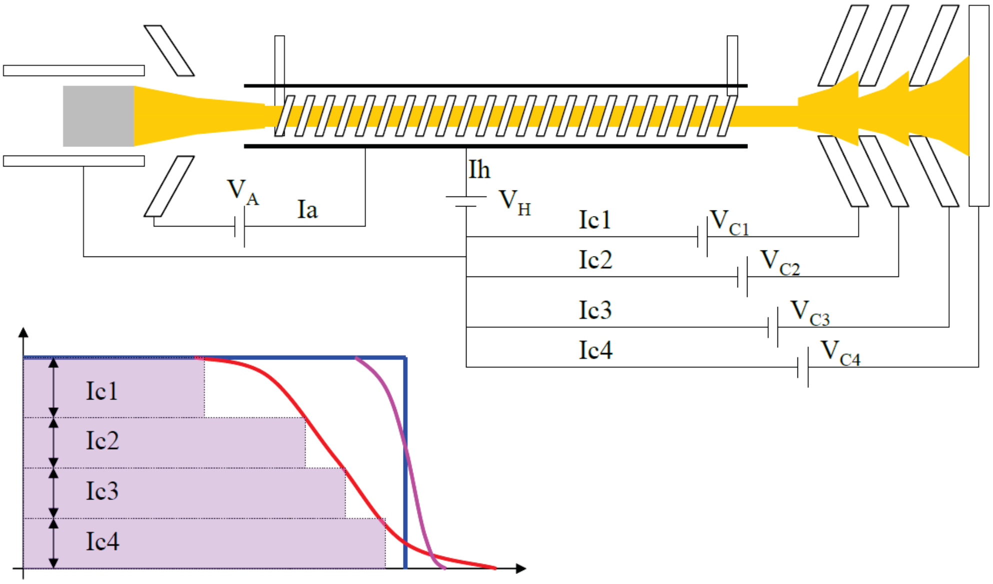
These electrons are reflected back into the RF circuit (backstreaming)



A_1-A_2 = Power converted into RF + losses

A_3 = Max power recoverable by a single stage collector

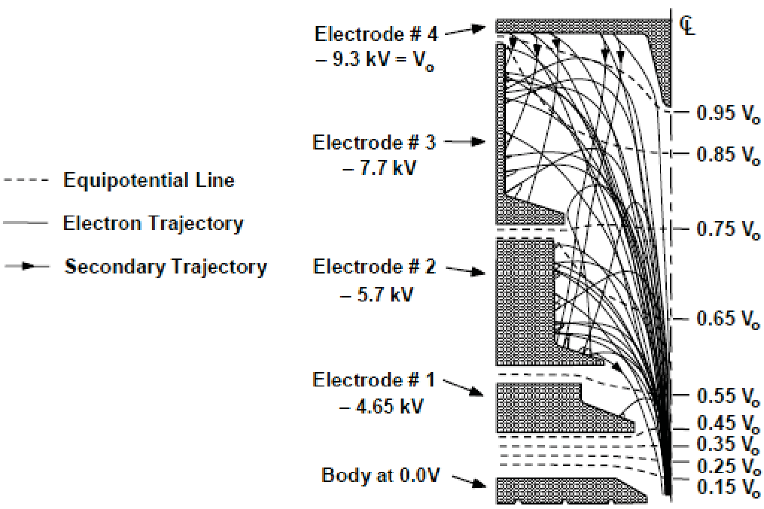
Multistage collector

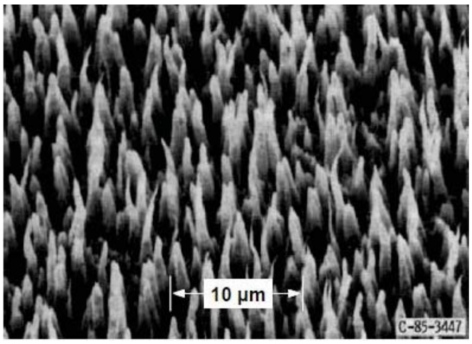


Multistage collector

Secondary emission can cause:

- Escape of secondaries from the collector, which may result in excessive noise, signal distortions, and heating of the RF circuit
- Current flow between collector electrodes and resulting in the reduction of collector efficiency





Surface ion texturing to reduce the “apparent” secondary emission yield

Vacuum Technology

A microwave tube to operate properly, requires that a high or ultrahigh vacuum must be maintained throughout its life.

As a result, special techniques, processes, and materials must be used.

Vacuum Technology

Units of Measurement

1 torr ≈ 1 mmHg ≈ 1.33×10^2 pascal (atmospheric pressure is 760 mmHg)

1.33 mbar = 1 torr

In microwave tube work, it is rarely and perhaps never necessary to know pressure to an accuracy better than a factor of two or so.

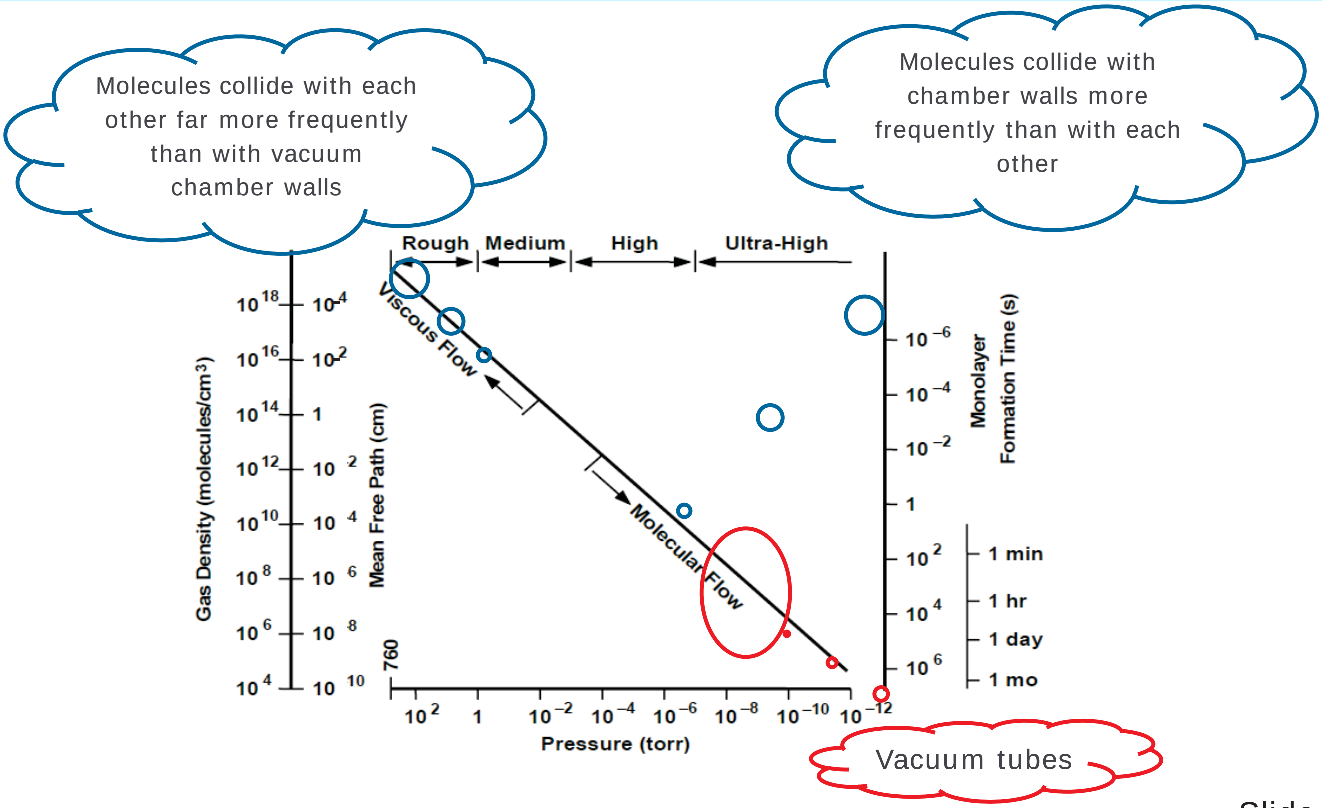
It is safe to remember that

1 torr ≈ 1 mmHg ≈ 1 mbar

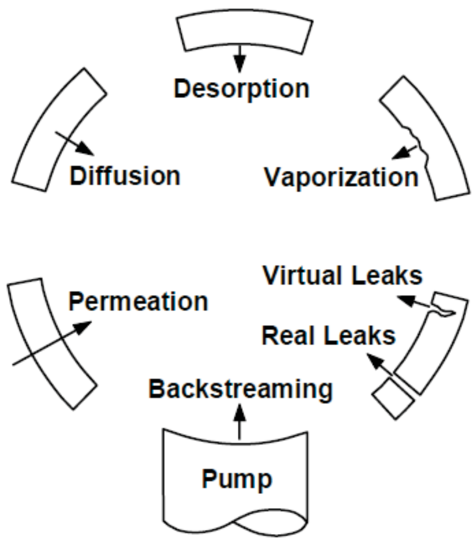
Ranges of Operation

760 torr to ~1 torr	Rough vacuum
1 torr to ~10^{-3} torr	Medium vacuum
10^{-3} torr to ~10^{-7} torr	High vacuum
< 10^{-7} torr	Ultrahigh vacuum

Degree of Vacuum



Sources of Gas



Permeation

Results from an electronic interaction between a gas and a solid. The only appreciable permeation rate of interest for vacuum-tube design is H_2 through iron and iron alloys

Diffusion

Movement of one material through another.

Desorption

Release of gas molecules from a surface

Vaporization (sublimation)

Phase transition from the liquid phase to vapor (phase transition from the solid phase to the gas phase)

Virtual Leaks

Release of gases chemically or mechanically trapped inside the vacuum envelope

Real Leaks

A pore in the wall of the vacuum envelope

Diffusion

In vacuum tubes, we are concerned mostly about the diffusion of gases through the metallic parts of the vacuum envelope to its interior surfaces. There, the gas is desorbed and contributes to increase the pressure inside the tube.

The rate at which gas diffuses through metals is an exponential function of temperature so the use of heat (baking) to accelerate the diffusion process is often used as well as outgassing the parts or sub assemblies during the fabrication process.

Desorption

Gas molecules adhere to surfaces within a vacuum envelope are said to be adsorbed on the surfaces. The source of this gas can be the atmosphere within the envelope or diffusion or permeation from the walls of the envelope. Gas-free surfaces in vacuum can become covered with gas molecules very quickly. For example, at a pressure of 10^{-6} torr, the time required to form a monolayer of gas on a gas free surface is only one second.

The rate of desorption is an exponential function of temperature so baking is very effective in removing desorbed gas.

Many adsorbed gasses are too tightly bonded to surfaces to be set free by baking. These can be desorbed by electron impact. As a result, many microwave tubes are operated with a pump attached for several hundred hours with the electron beam being used to assist in the outgassing process.

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Virtual Leaks

Some examples of sources of virtual leaks are:

- A weld joint that is made on the outside (atmospheric side) of the vacuum envelope. Dirt or other contaminants, which are trapped between the welded parts on the inside (vacuum side) of the joint, release gas that slowly leaks into the vacuum tube.
- A screw that is used to fasten a part in an electron gun. The threads of the screw have not been properly vented and so gas that is trapped and not completely driven out during bake-out is slowly released.
- An inadequately outgassed part inside the vacuum envelope. Gas from the part slowly diffuses into the vacuum envelope.
- During thermal cycling, a microscopic crack that develops on the inner (vacuum side) of a ceramic insulator. This crack exposes a tiny gas-filled void and the gas slowly leaks into the vacuum envelope.

Virtual leaks are avoided by following good design practice, eliminating gas traps, and properly processing parts.

There is no external test that can detect a virtual leak.

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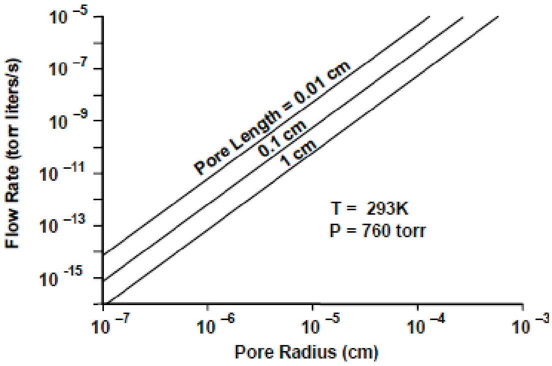
Real Leaks

Examples of pores are voids caused by impurities or inclusions in the wall material or cracks caused by thermal or mechanical stress.

A hole size on the order of at least 3 molecular diameters (~10Å or 10^{-7} cm) is required for pore leakage. Smaller holes are likely to be plugged by large molecules.

Thus, pore leakage is unlikely to occur below a leak rate of about 10^{-15} torr-liters/sec for a 1-mm-long pore. (1 torr-liter/sec ≈ 1 cm^3/sec at standard temperature and pressure). At this leak rate, the pressure in a dormant TWT with an internal volume of 0.025 liter would increase to about 10^{-6} torr in one year. At this pressure, there is high likelihood that proper tube operation would not be possible.



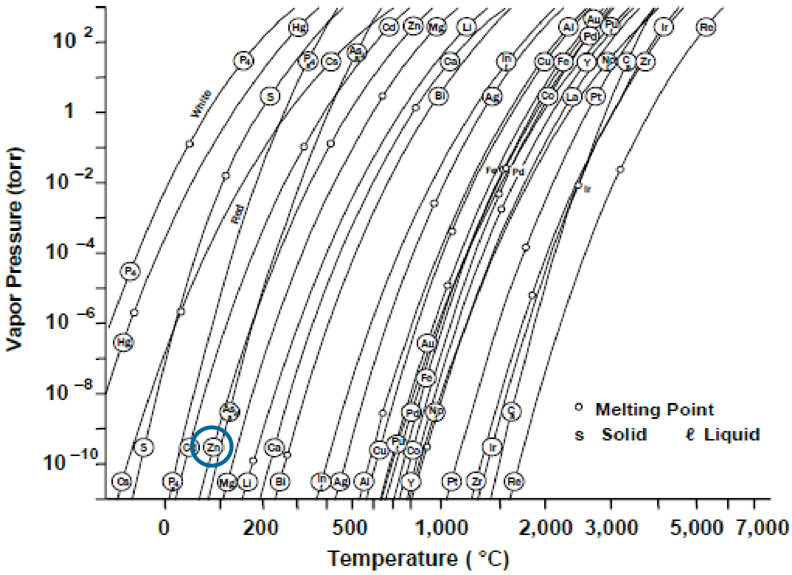
Thus, even the smallest pore leak is unacceptable for most applications.

Microwave Tube Materials

The most important factor in achieving and maintaining an acceptable vacuum level is the use of the correct materials for fabricating a tube. The primary factor considered in selecting a metal for use inside the vacuum envelope is vapor pressure

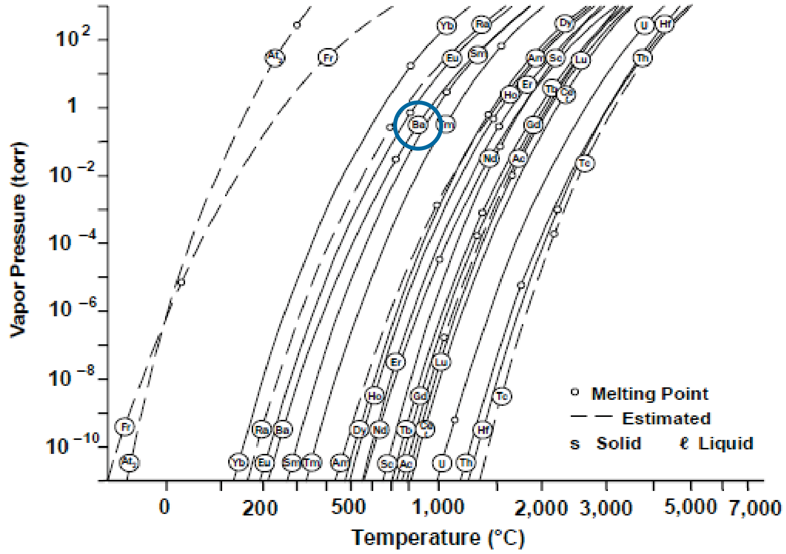
	Aluminum (O_2)	Barium	Beryllium (O_2)	Boron (Nitride)	Calcium	Carbon	Chromium	Copper	Gold	Iridium	Iron	Manganese	Molybdenum	Nickel	Osmium	Palladium	Platinum	Rhenium	Rhodium	Scandium	Silver	Strontium	Thorium	Titanium	Tungsten	Vanadium	Zirconium
Heater	■																	■							■		
Cathode	■	■	■		■					■				■	■		■			■		■	■		■		
Grids						■		■	■				■												■		
Anode								■																			
Cavities								■																			
Helix								■	■				■					■							■		
Support	■		■	■		■																					
Attenuator						■																					
Collector						■		■																			
Envelope							■	■			■			■													
Brazes								■	■			■	■			■	■		■		■						■
Polepieces											■															■	
Window	■		■			■																					
Getter		■																						■		■	■

Vapor pressure of elements



Example: Zinc (Zn). At low temperatures, the vapor pressure is reasonable (10^{-9} torr at 100°C). At a somewhat elevated temperature (400°C), the vapor pressure is only 10^{-1} torr. This shows why brass (which contains zinc) must not be used in a vacuum system that may be heated. If brass was used and baked at 400°C or higher, zinc vapor would permeate the entire system

Vapor pressure of elements



Example: Barium (Ba). At a cathode operating temperature of 1,000°C, the vapor pressure of barium is over 1 torr. Thus, excess barium (over ~ monolayer) on the cathode surface evaporates very rapidly. This evaporated barium may eventually deposit on insulating surfaces and cause electrical leakage or breakdown. To remove excess barium, a new cathode is often placed in vacuum and operated at a high temperature before it is placed in a tube.

Joining Techniques

Microwave tubes fabrication requires dissimilar materials to be joined together with stated mechanical and thermal properties. In addition, joint of parts belonging to the vacuum envelope must be “vacuum tight”

- Materials must be properly selected and cleaned.
- Metals may be joined by brazing or welding
- Ceramics may be joined to metals by brazing

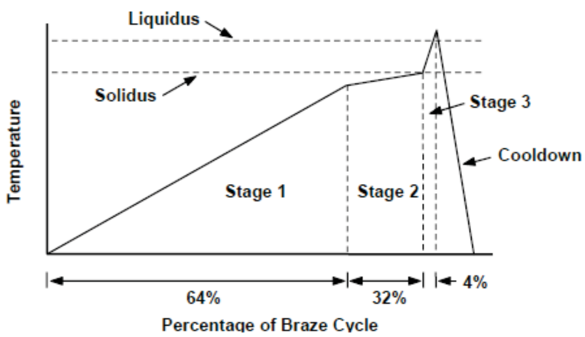
Solid fluxes cannot be used because they may become trapped in joints and then produce virtual leaks, that is, they very slowly leak out of joints and produce contamination.

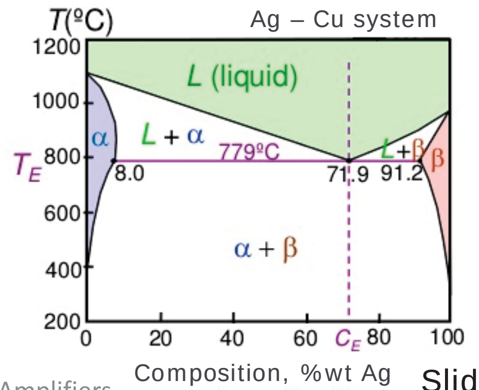
Brazing

“The joining process of two metal parts with a third one having a lower melting point is generally known as *soldering*”

Brazing is defined as the metal joining process in which melted filler metal is drawn by capillary attraction into the space between the closely adjacent surfaces of the parts to be joined.

- The temperatures required for brazing are very high and it is important to properly control the variation of temperature with time.
- Brazes must be performed in vacuum or in a reducing atmosphere of hydrogen because fluxes cannot be used





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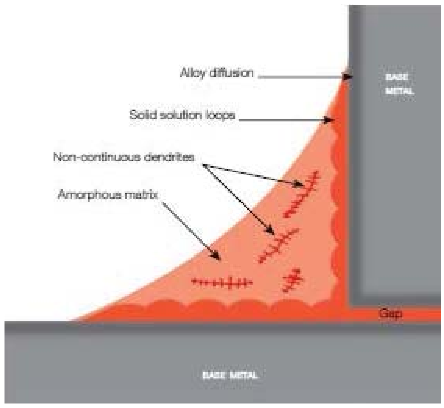
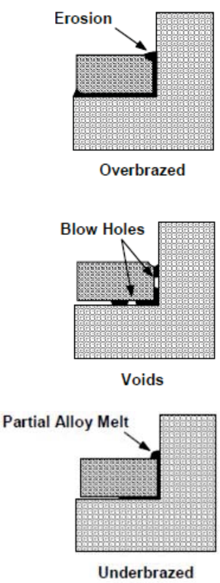
Brazing

- **The ideal braze joint**

The full fillet



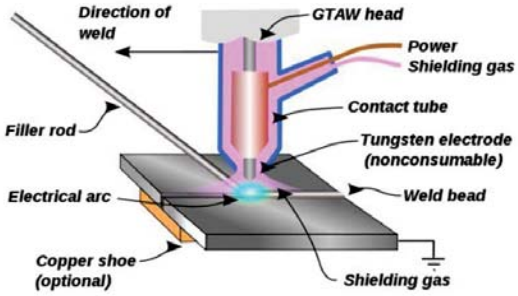


- **Too high temperature or too long time that the parts are held**
  The filler may alloy with the parts being brazed and cause erosion
- **Parts not properly cleaned or incorrect joint tolerance**
  Voids may occur which can result in leaks or virtual leaks
- **Inadequate either temperature or time**
  Filler material may not be completely melted and so the underbrazed condition results.

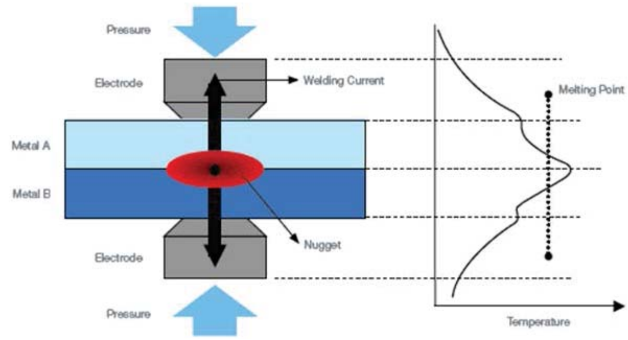
Welding

Several types of welding are used in the manufacture of microwave tubes:

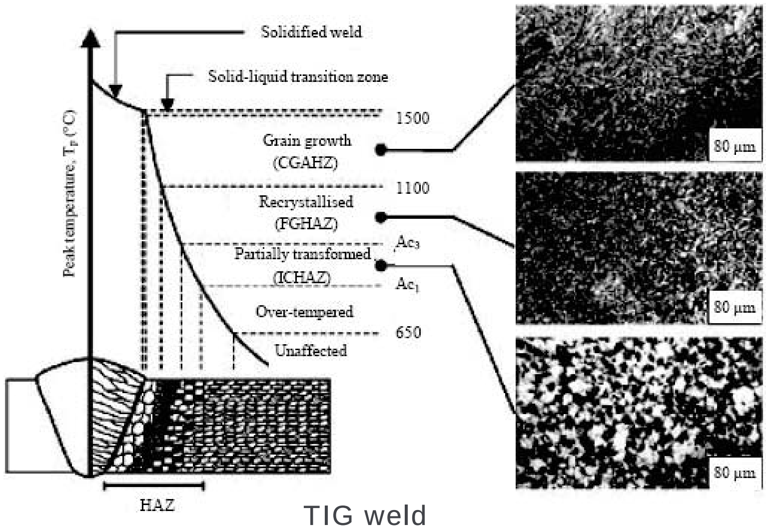
- **Tungsten inert gas (TIG)**
- **Laser**



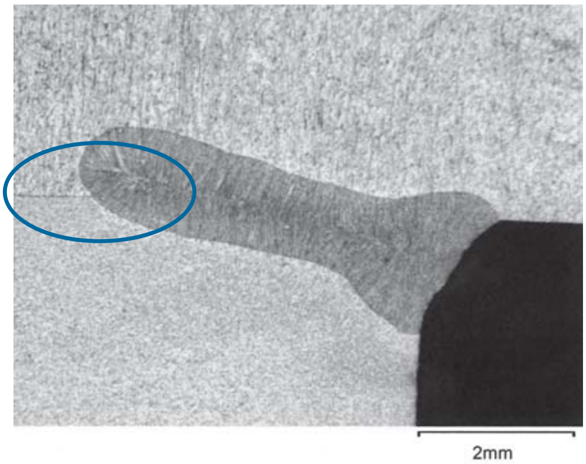
- **Resistance**
  (spot welding)



Welding



TIG weld



Laser weld

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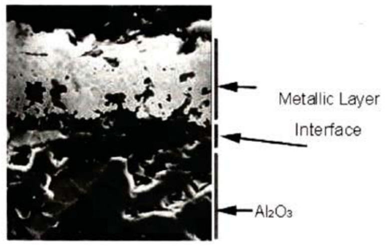
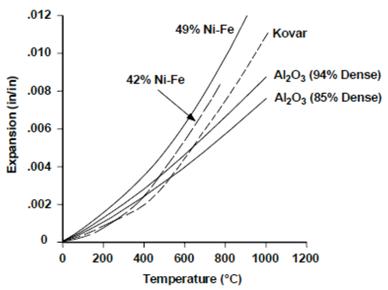
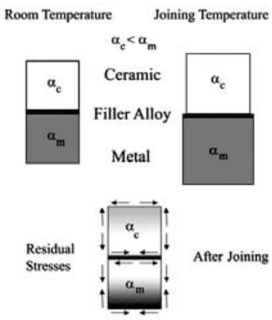
Ceramic-to-Metal seals

esa

Ceramic-to-metal seals are made by first metallizing the ceramic and then brazing the metallic part to the metallized surface or using active filler alloys.

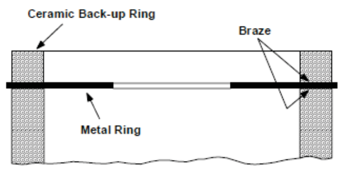






One of the most important factors to be considered is the thermal expansion of the parts. In some cases the metal element is designed to be flexible in the region of the braze.

In a butt ceramic-to-metal seal the metal is sandwiched between ceramic pieces that are massive enough to force the metal to expand and contract with the ceramic



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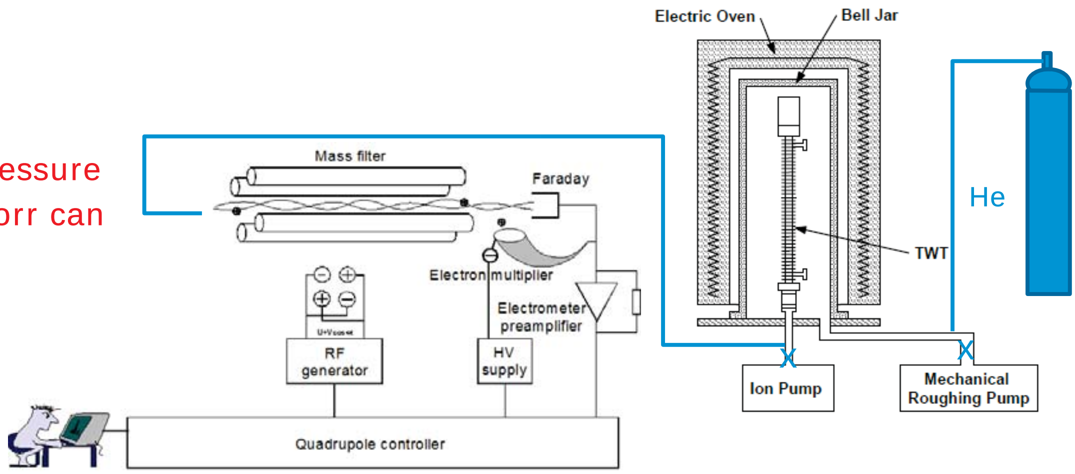
Bake-out
Leak check

esa

Bake-out is the process of heating a tube to facilitate evacuation. As pointed out previously in this appendix, the rates of diffusion and the desorption of gases vary exponentially with temperature, so heat is used to aid in the evacuation process. The bake-out temperature commonly used in the microwave tube industry is ~500–525°C. The tube to be evacuated is connected to a vacuum pump and heated until the desired vacuum level is obtained.

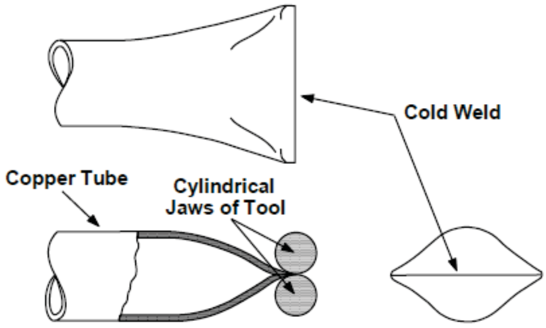
He partial pressure up to 10^{-12} torr can be detected



Pinch-off

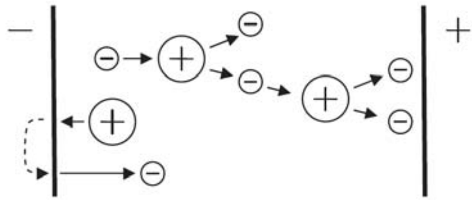
By squeezing the tubulation with a special tool, the internal mating surfaces of the copper can be forced to flow together to form a cold weld. In its crudest form, the tool is similar to a manually operated bolt cutter with the cutting edges replaced by cylindrical tungsten carbide bars.

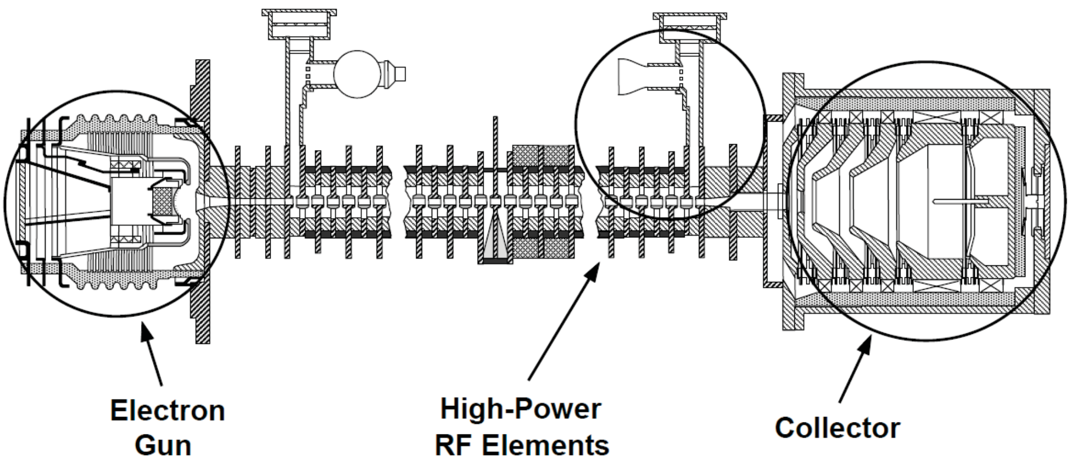
Because the manual squeeze-off (pinch-off) operation with the tool that is much like a bolt cutter is highly operator dependent, an automated system is normally employed.



Electrical Breakdown

The basic breakdown mechanism (discharge) is caused by collision of charge carriers in the gas volume and interactions with the electrode surfaces (Townsend mechanism).





Breakdown

Whether or not breakdown will occur depends on two factors:

1. The applied field level and local field enhancement effects;
2. The breakdown field of the medium (gas, vacuum, liquid, or solid)

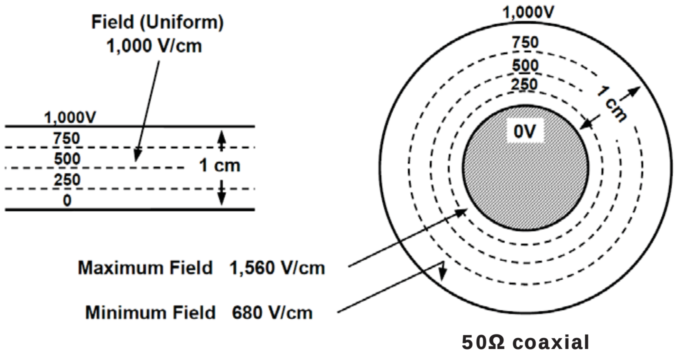
Breakdown fields for various media

- Gas ~ tens of V/cm to 10^5 V/cm depending on pressure and type;
- Vacuum ~ 0.5–3×10^5 V/cm;
- Liquid ~ 0.5–1.0×10^6 V/cm;
- Solid ~ 0.5–1.0×10^6 V/cm.

Field enhancement

- Parallel plate:1000 V/cm
- At inner conductor of 50Ω coax line: 1560 V/cm

$\beta = 1.56$

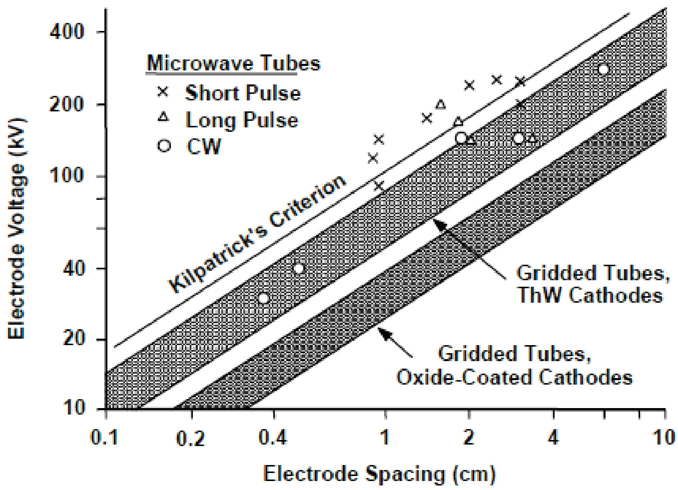


DC Breakdown in vacuum

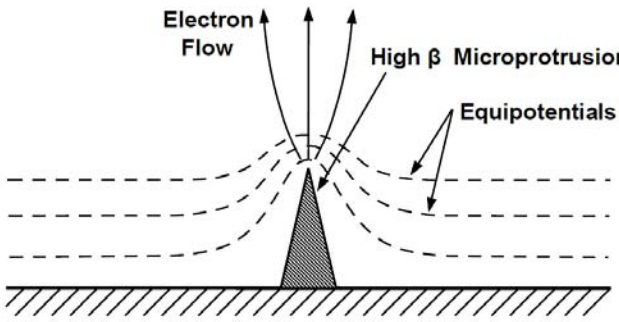
Under ideal conditions, the breakdown field for vacuum exceeds that of all media including liquids and solids, and may be 10 MV/cm or higher. The upper limit results from field emission from the negative electrode.

In practice, the field at which breakdown occurs is two to three orders of magnitude below the upper limit.

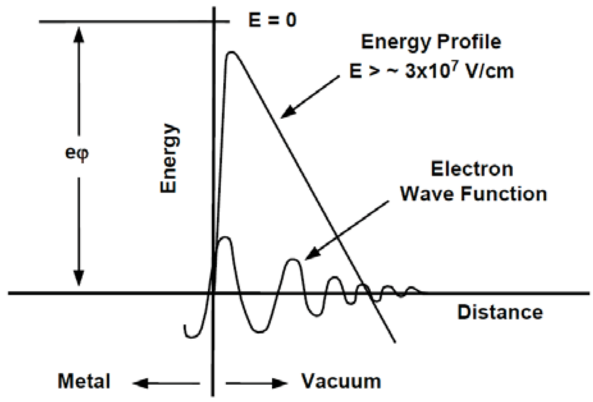
For many vacuum tube applications, "Kilpatrick's criterion" is used as the guideline to the maximum electric field that can be used in vacuum.



DC Breakdown by microprotrusions



β ~ 100



Tunnel effect

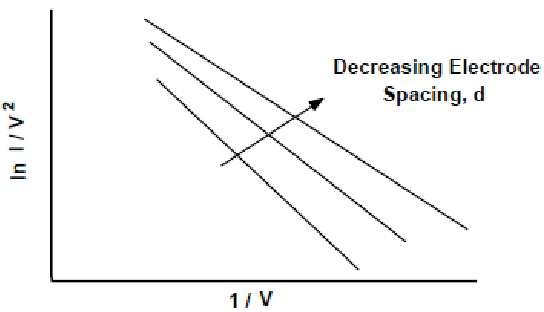
Field emission can occur in at average field level of ~10^5 V/cm

DC Breakdown by microprotrusions

Field emission is modelled by Fowler-Nordheim equation

$$J_0 = C_1 E^2 e^{-C_2/E}$$

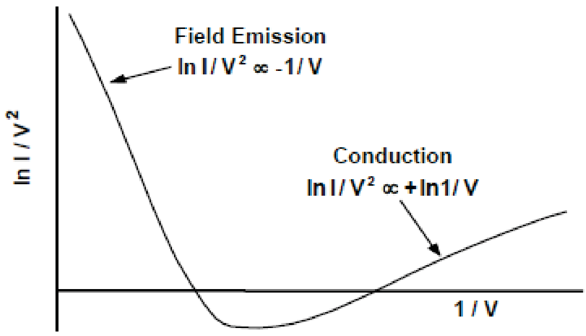
$J_0 = I/A$, $E = V/d$ $$I = A \cdot C_1 \cdot \left(\frac{\beta \cdot V}{d}\right)^2 e^{-\frac{C_2 d}{\beta V}} \Rightarrow ln\left(\frac{I}{V^2}\right) = lnAC_1\left(\frac{\beta}{d}\right)^2 - \frac{dC_2}{\beta}\left(\frac{1}{V}\right)$$

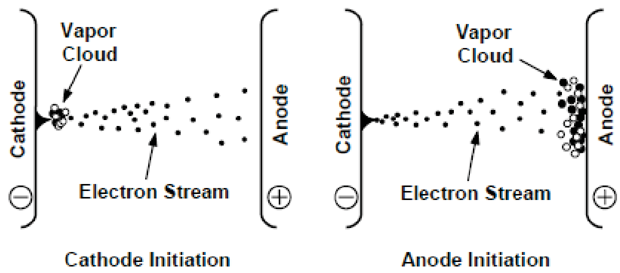


DC Breakdown by microprotrusions

How to distinguish field emission current from leakage current (ohmic losses)?

$$I = C \cdot V \rightarrow \frac{I}{V^2} = \frac{C}{V} \rightarrow ln\left(\frac{I}{V^2}\right) = \ln(C) + ln\left(\frac{1}{V}\right)$$

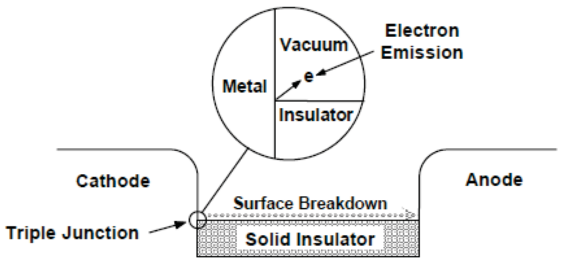


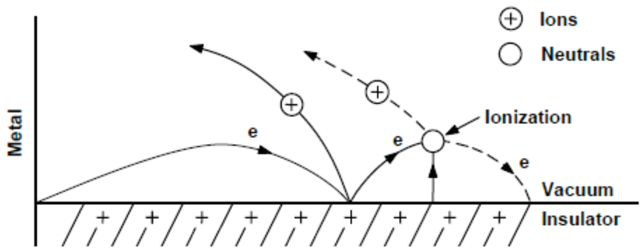


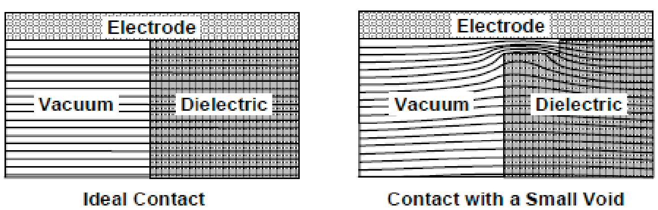
DC Breakdown on insulator surfaces

The interface between a metal, an insulator, and a vacuum is one of the weakest points in a vacuum device, for electrical breakdown.

This interface is called the **"triple junction"**.

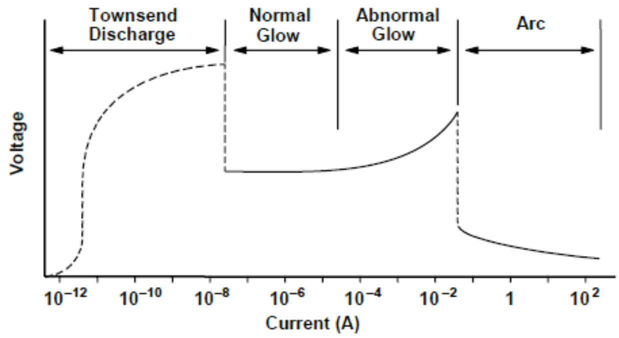


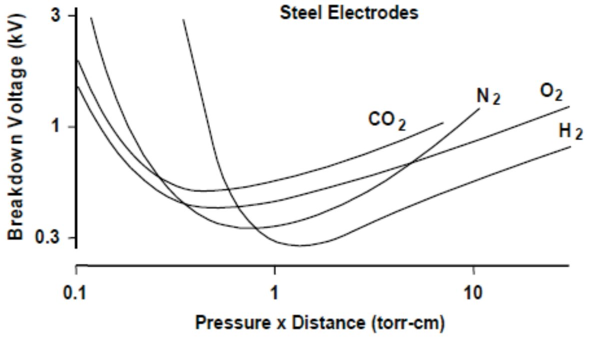




DC Breakdown in gas

Electrical discharges in gases are extremely complex





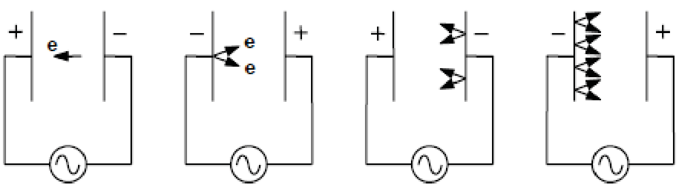
Paschen curves

Q: How to check tube vacuum integrity after prolonged storage?

A: Make a Hi-Pot test measuring leakage current

RF Breakdown (Multipaction)

In its simplest form, this discharge occurs when electrons move back and forth between two electrodes in synchronism with an RF field. If the secondary emission coefficient of the electrodes is greater than unity, then the number of electrons involved in the process builds up with time.



The theory of two-surface electric-field multipactor has been presented by Vaughan.

Multipactor depends primarily on the peak RF voltage, the frequency of the RF and the gap width.

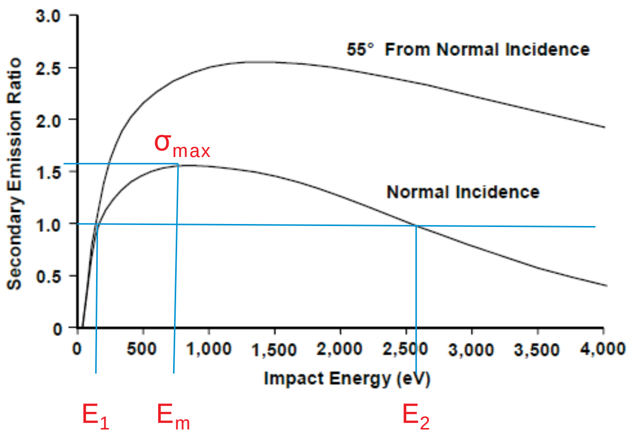
There are several combinations (zones) of voltage, frequency and gap width that can produce a multipactor discharge.

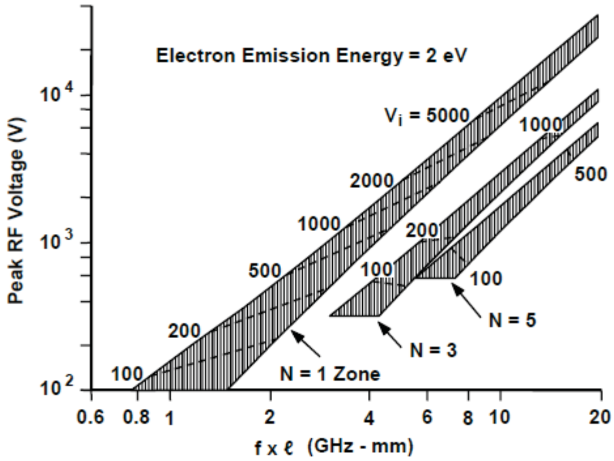
RF Breakdown (Multipaction)

In the N = 1 zone, electrons move back and forth between the surfaces in synchronism with each half cycle of the alternating RF.

In the N = 3 zone, the electron transit time across the gap corresponds to 3/2 cycle of the applied RF voltage.

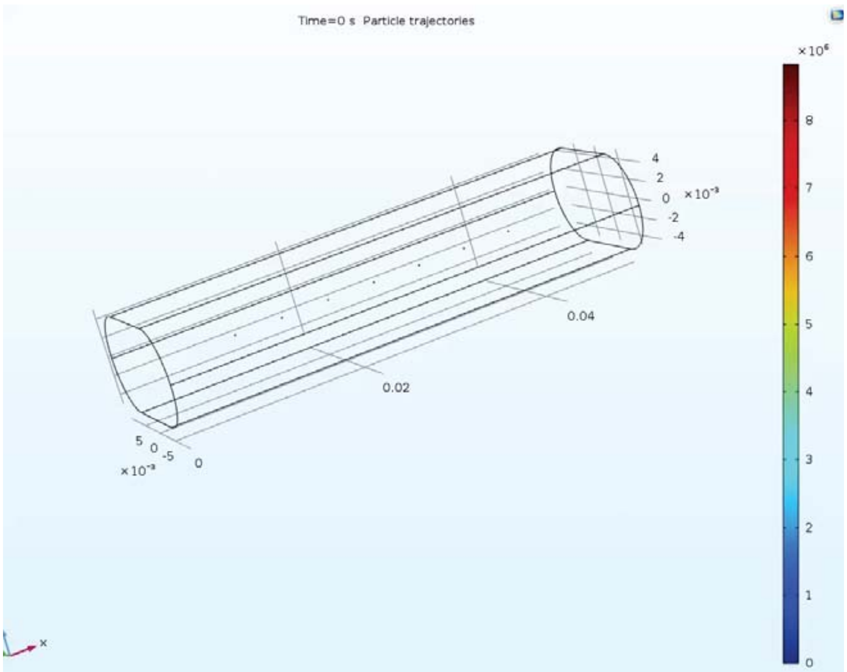
In the N = 5 zone, the electron transit time across the gap corresponds to 5/2 cycle of the applied RF voltage.





RF Breakdown (Multipaction)

In



Avoiding Breakdown

By design:

- Don't exceed maximum electrical field strength E_{max}

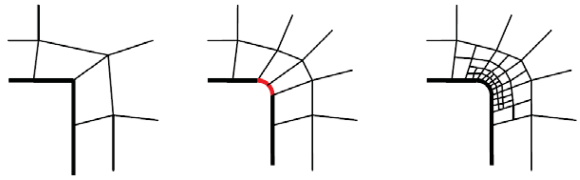
E_{max} [kV/mm]	Typical safe operating range
1 - 2	Air (ambient)
5 - 8	High insulating and pressurized gaseous insulation (SF_6)
0.5 - 2	Solid insulating material (AC voltage)
1 - 10	Solid insulating material (DC voltage)
0.3 - 0.6	Solid insulation creepage path
1 - 10	Vacuum insulation

- Use appropriate electrode materials

Avoiding Breakdown

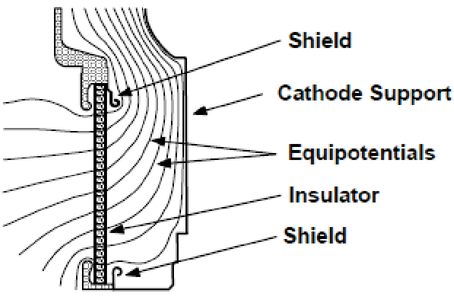
By design:

- Use appropriate geometries to minimize field enhancement (β) (i.e. radii should be as large as possible)
- Numerical FEM: verify that sharp edged shapes and curvatures of the analysed model are sufficiently meshed.



Edge of HV Structure insufficiently modelled and meshed! | Approximation edge of with "realistic radius insufficiently meshed | Adequate meshing of radius correctly modelled and meshed.

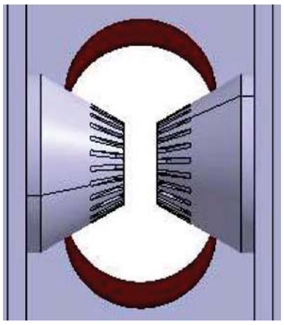
- Shield triple junctions

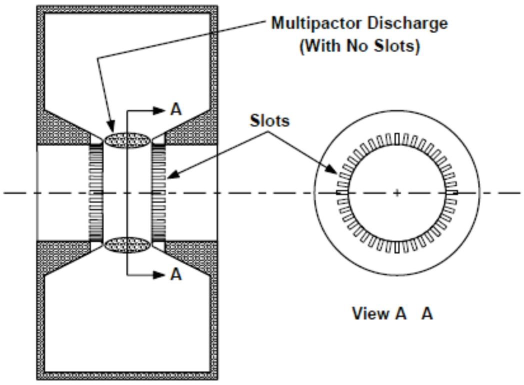


Avoiding Breakdown

By design:

- Use appropriate geometries to reduce below unity the apparent secondary emission





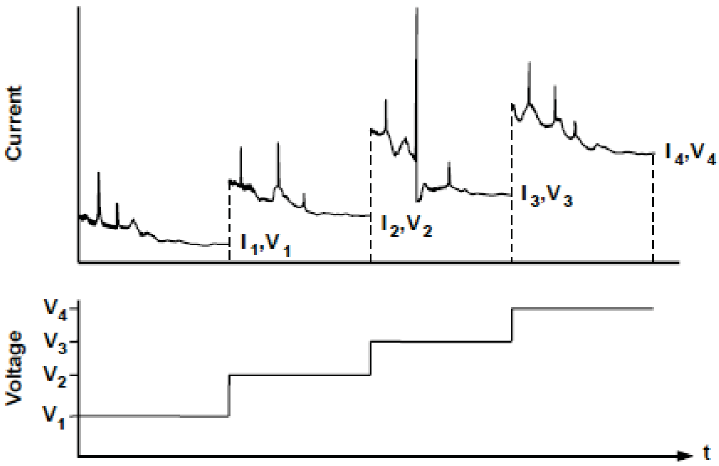
Klystron output cavity

Avoiding Breakdown

By electrode surface preparation:

- Microscopic polishing
- Final cleaning

By electrode surface conditioning:



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  ESA
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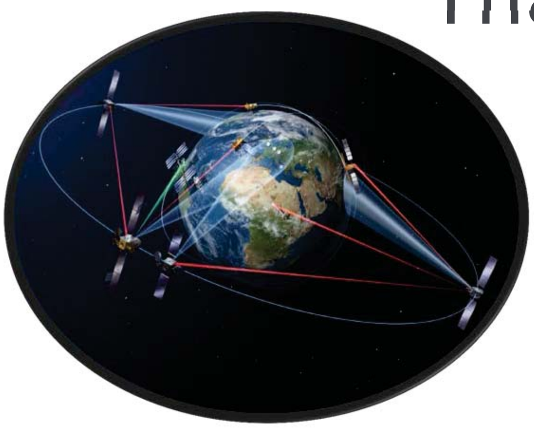
Thank you!



Traveling Wave Tube Design with Simulation

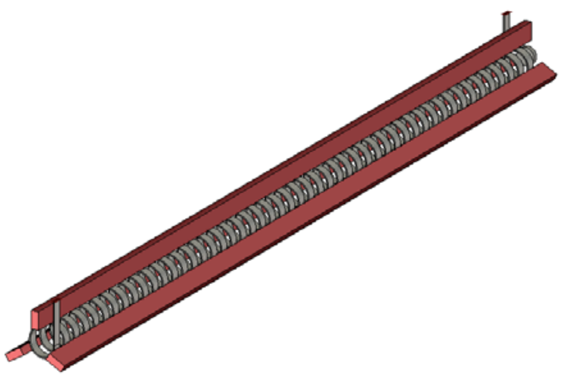
Monika Balk

CST AG, Darmstadt, Germany

Monika.Balk@CST.com

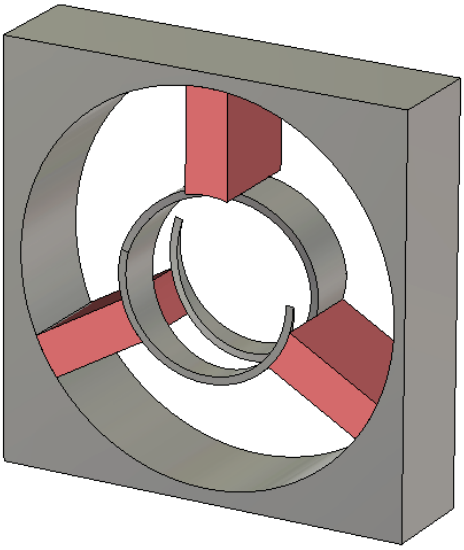
Traveling Wave Tube Simulation

Obtaining the Dispersion Diagram



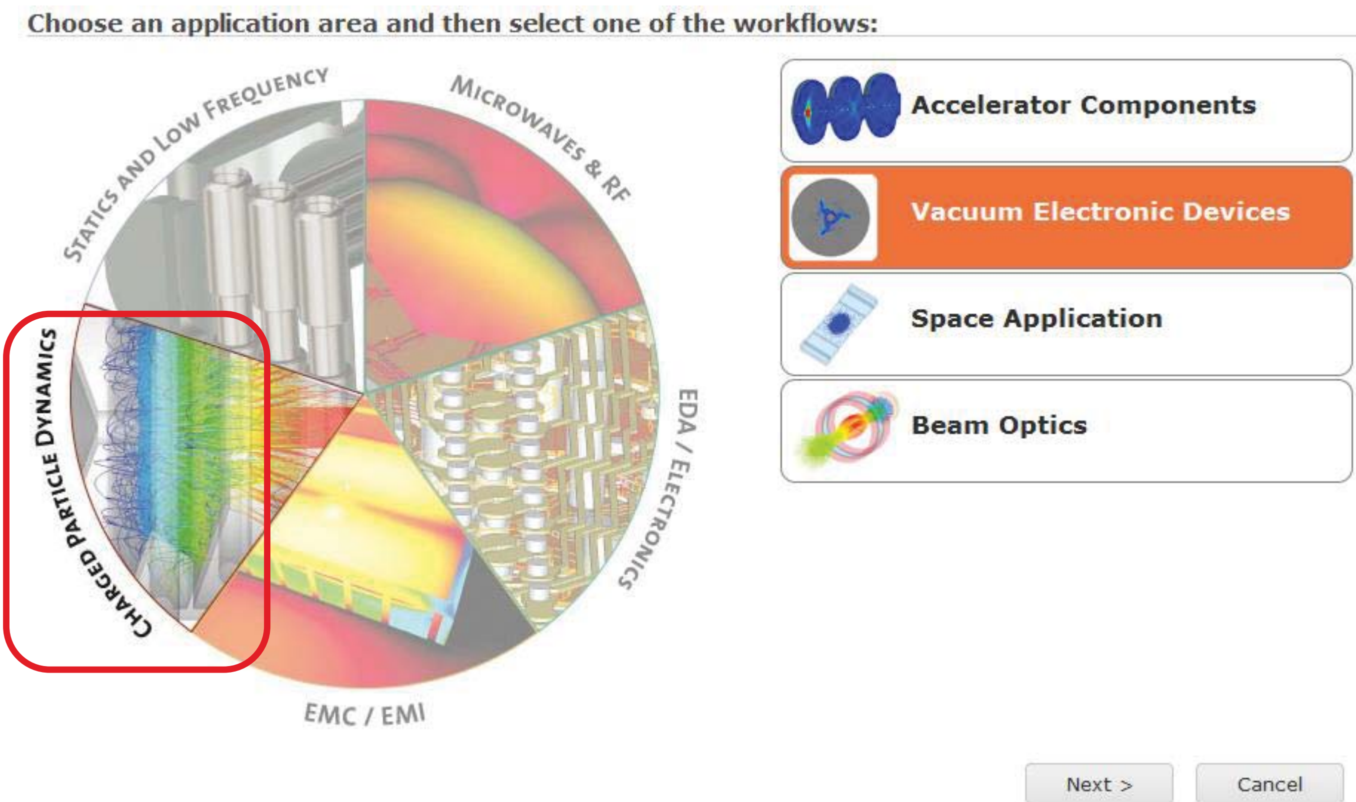
Start with one Pitch

The phase velocity of the wave along the circuit is a necessary input for the hot test. It can be evaluated by analyzing a single pitch using the eigenmode solver.



Also see:
Online Help\Contents\Examples and Tutorials\...
...CST MWS Examples\Eigenmode Analysis Examples\Slow Wave.

Open CST MWS



Select Solver

Particle Gun | **TWT, BWO** | Magnetron | Klystron

Vircator

↓

Slow Wave Structure | Coupler | Hot Test

↓

Eigenmode

Set Units

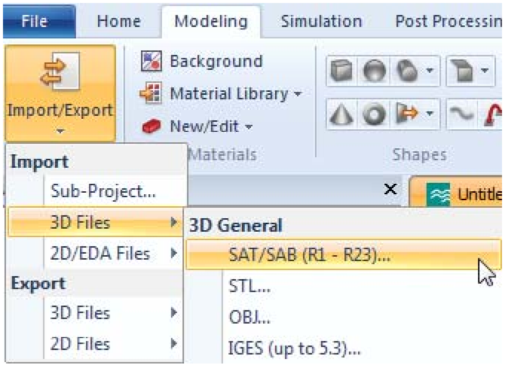
Create a new template

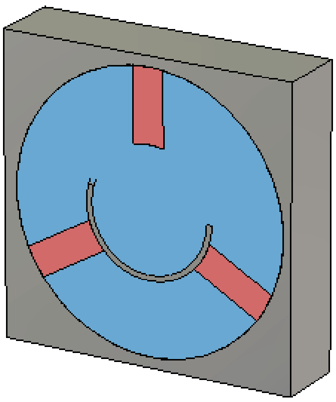
CHARGED PARTICLE DYNAMICS | Vacuum Electronic Devices

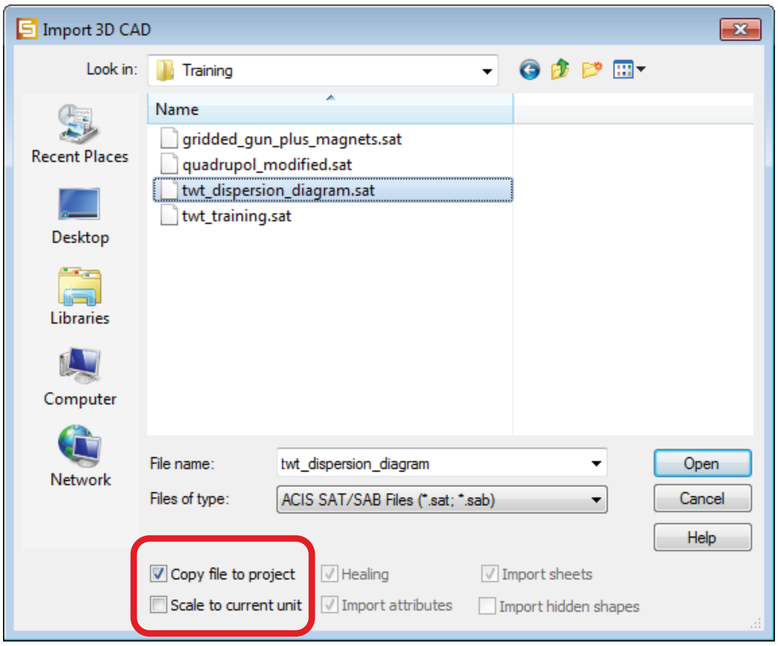
Please select the units:

Dimensions:	mm
Frequency:	GHz
Time:	ns
Temperature:	Kelvin

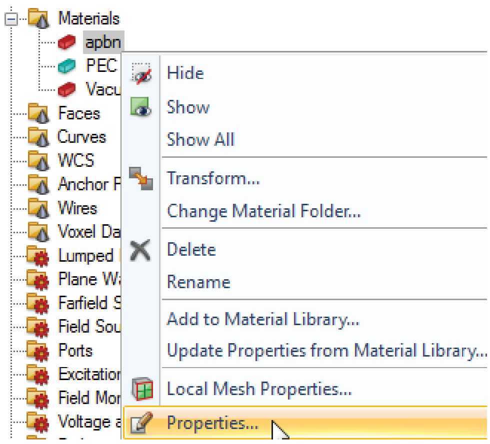
Import Structure



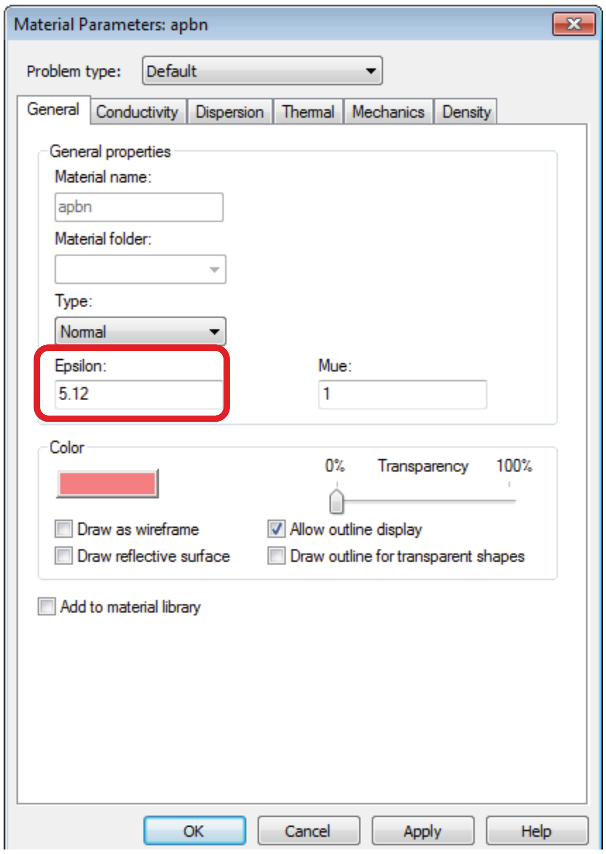




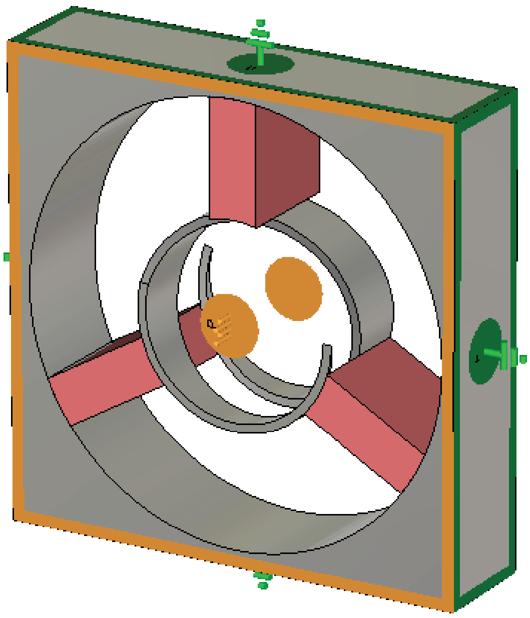
Define Materials

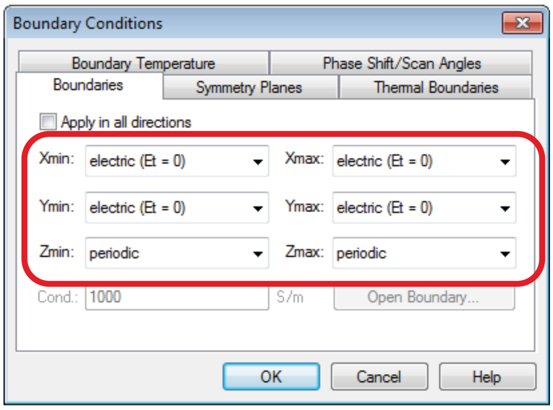


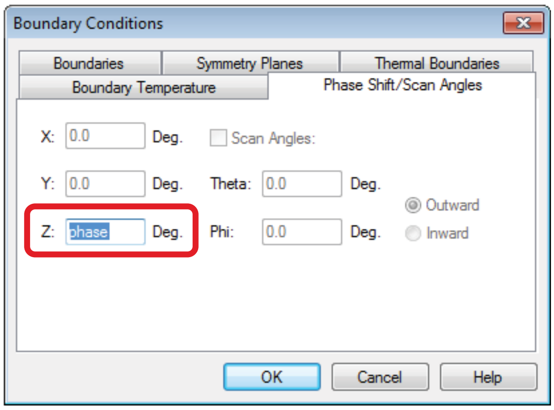
Vacuum and PEC are already predefined



Boundary Settings

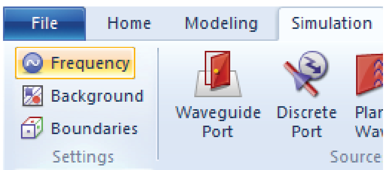


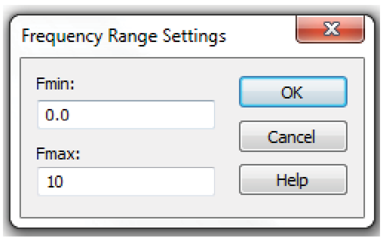




Set up periodic boundaries in z direction and parameterize the phase shift.

Frequency Settings





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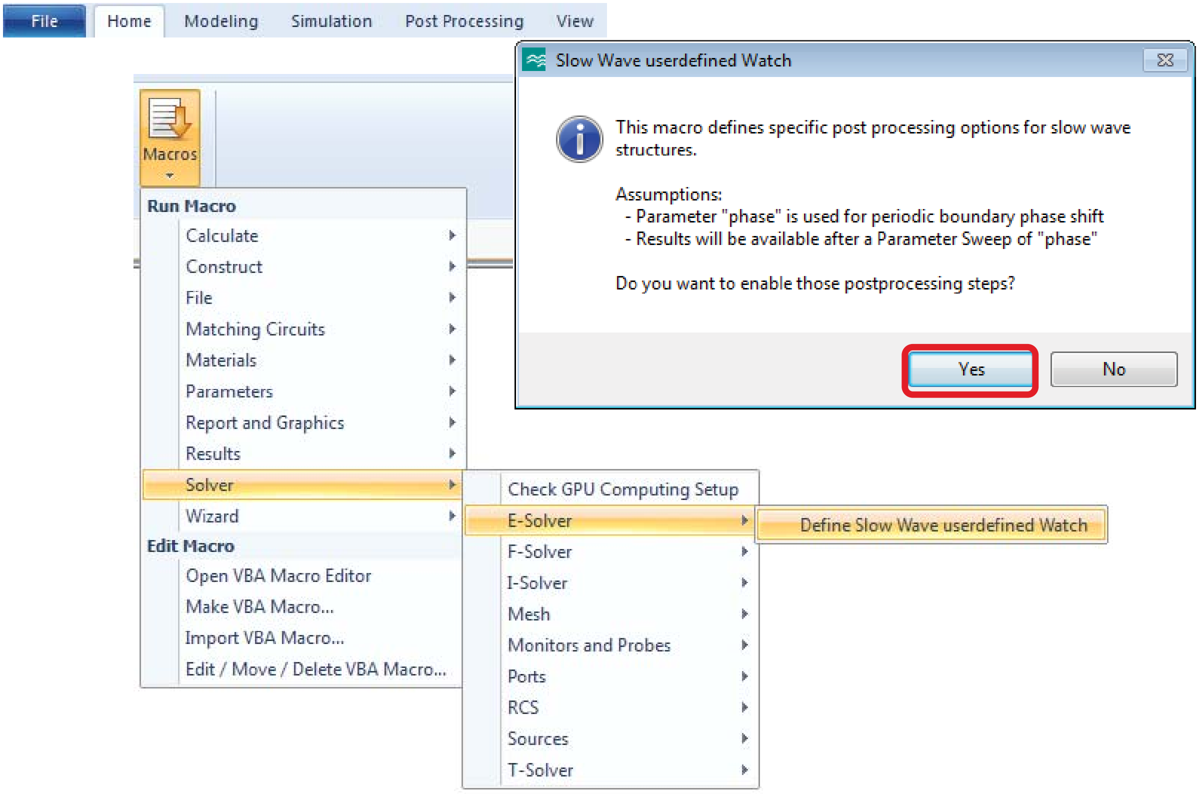
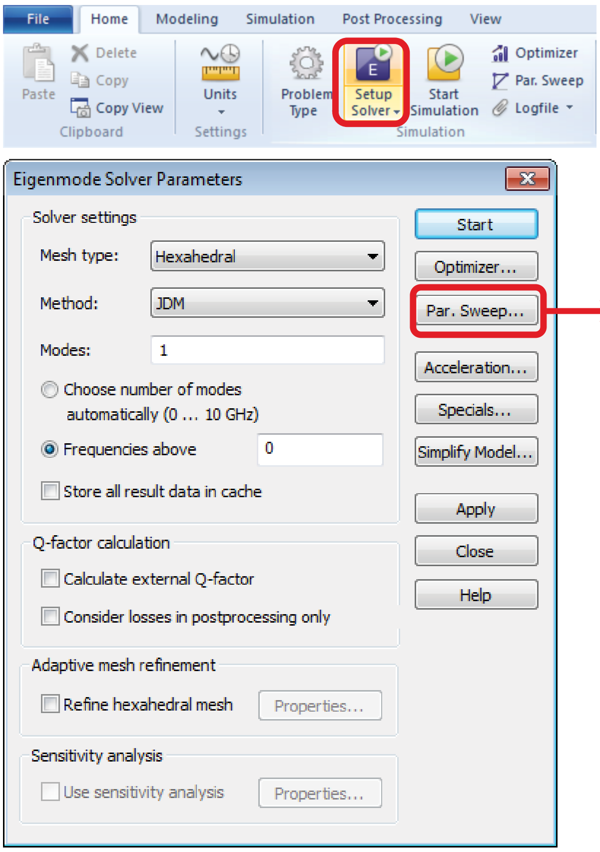
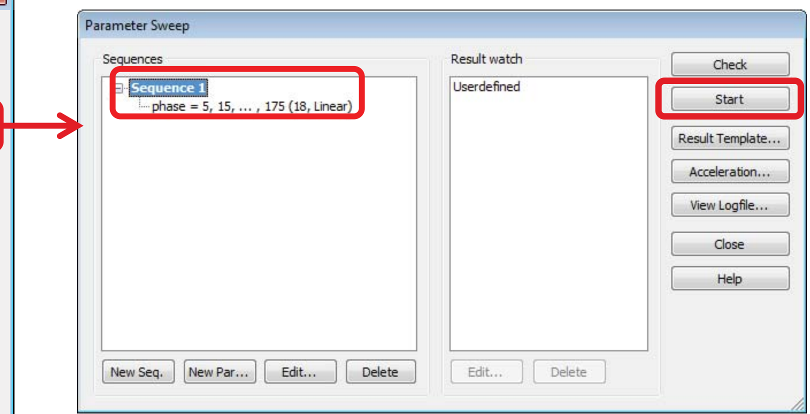
Set Up Eigenmode Solver



Run Parameter Sweep

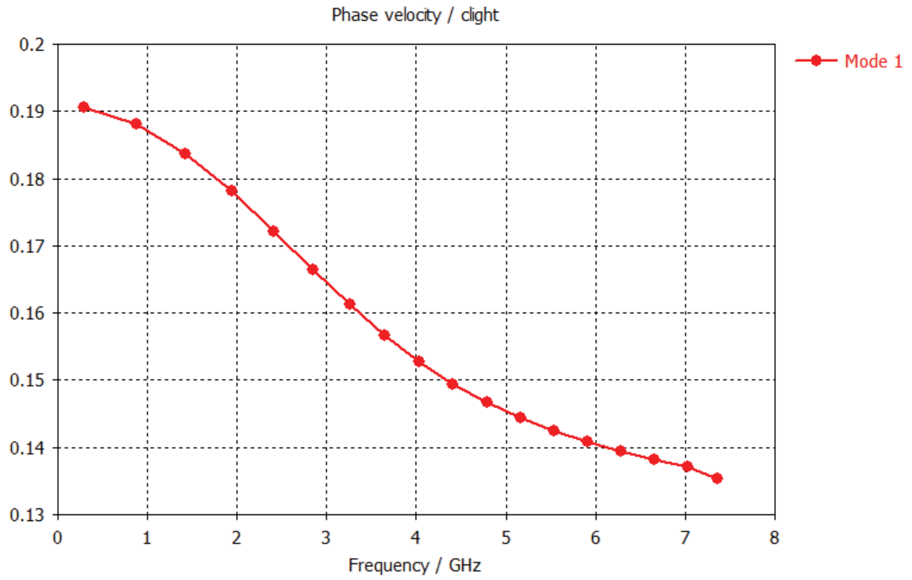




Defines the phase shift of the field between the periodic boundaries and therefore the order of the mode.

Results

- 1D Results
  - Convergence
  - Power Flow
  - Dispersion Diagram
  - Eaxis Amplitude
  - Group Velocity
  - Phase Velocity
  - Pierce Impedance



Results

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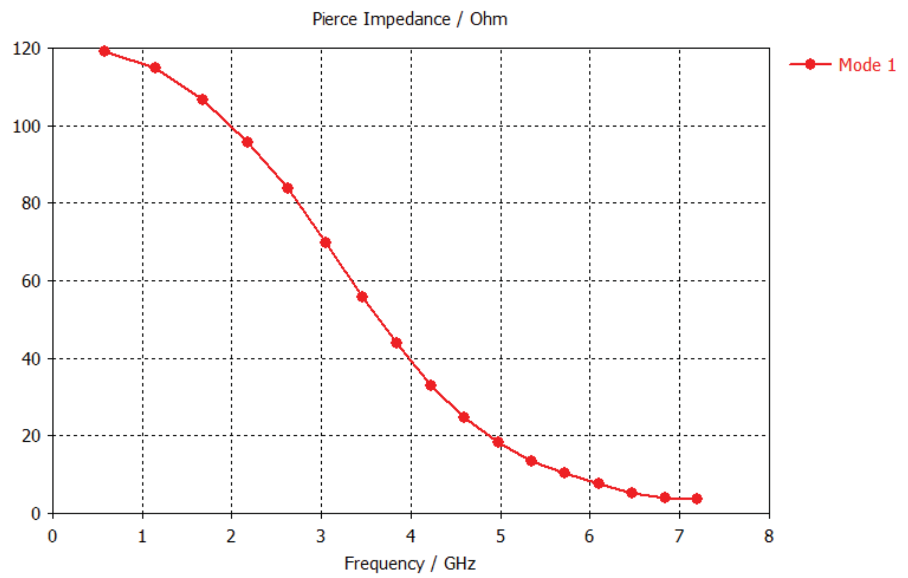
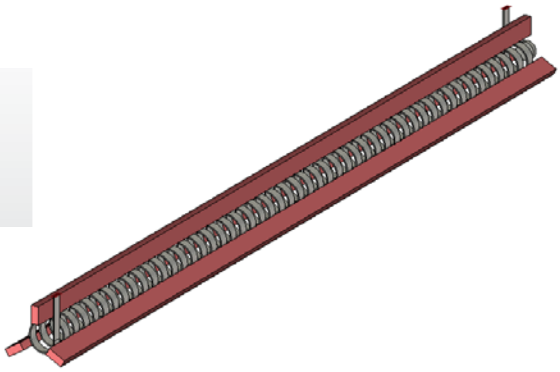


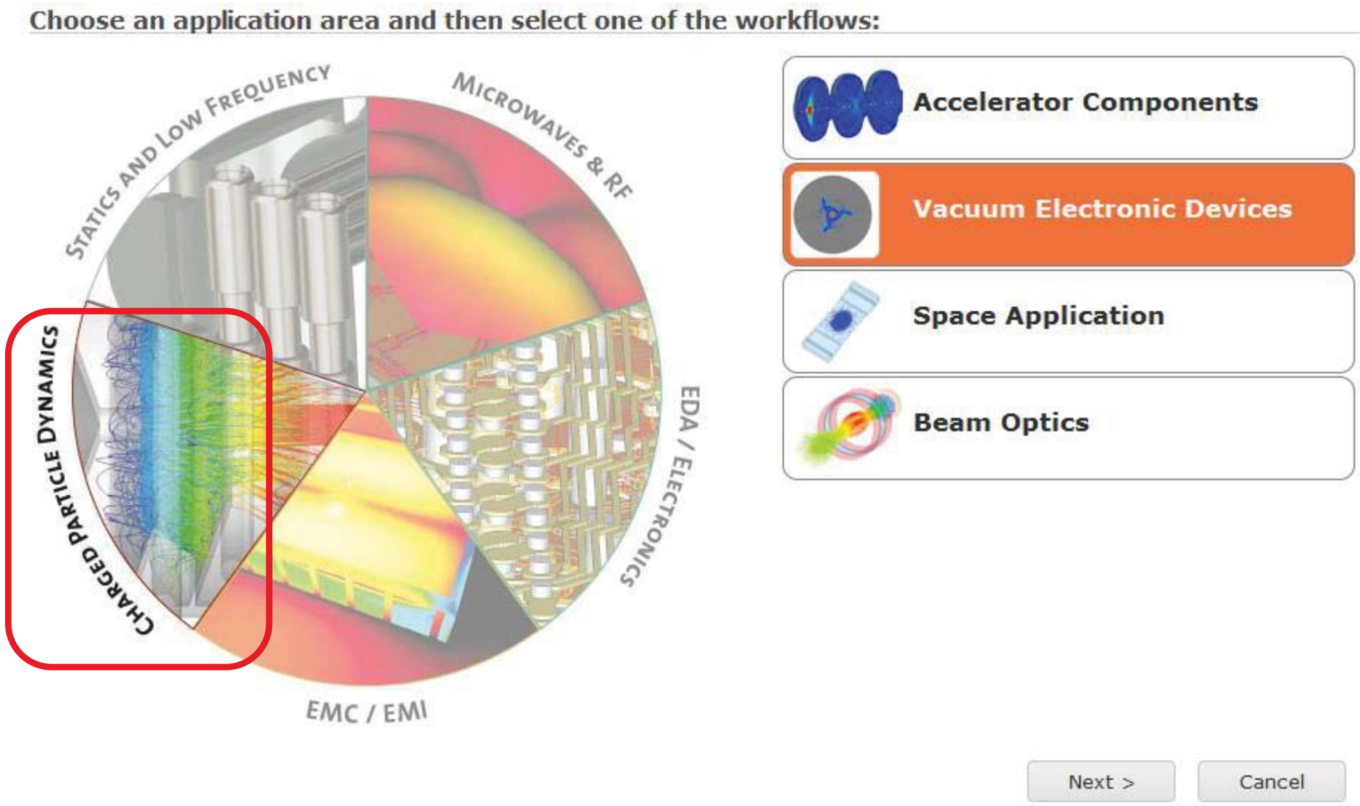
Traveling Wave Tube Simulation

Cold Test

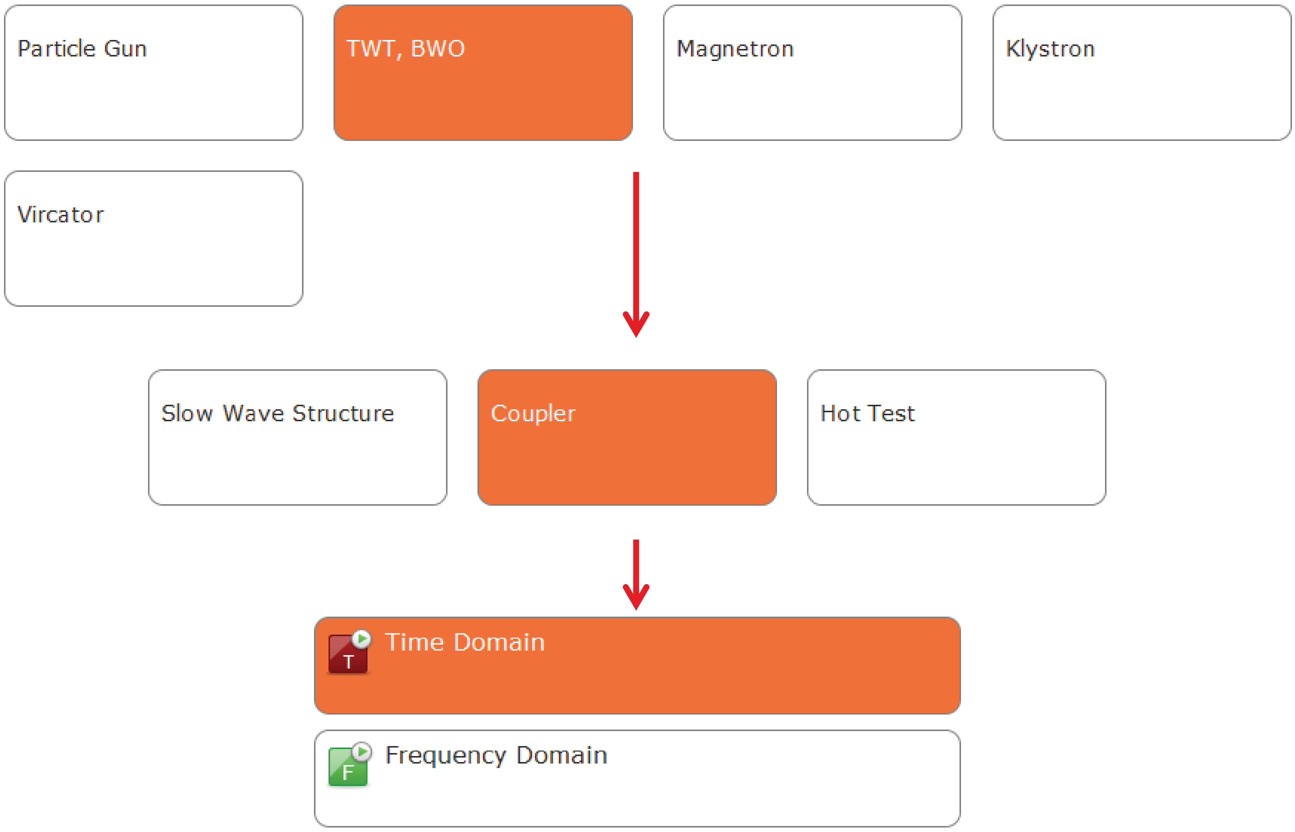
Purpose:
Obtain cold test coupler properties



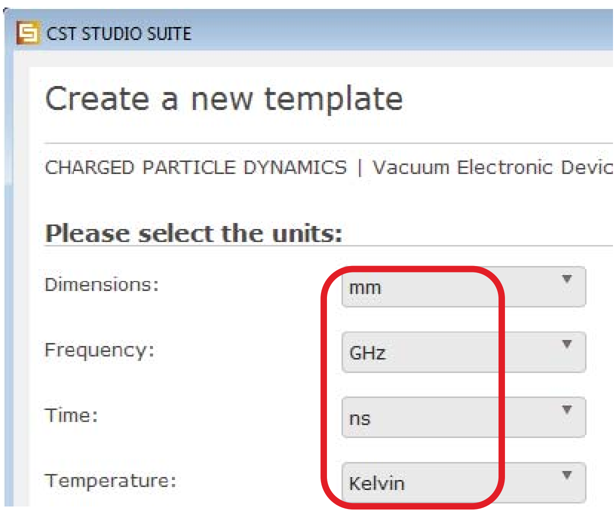
Open CST MWS

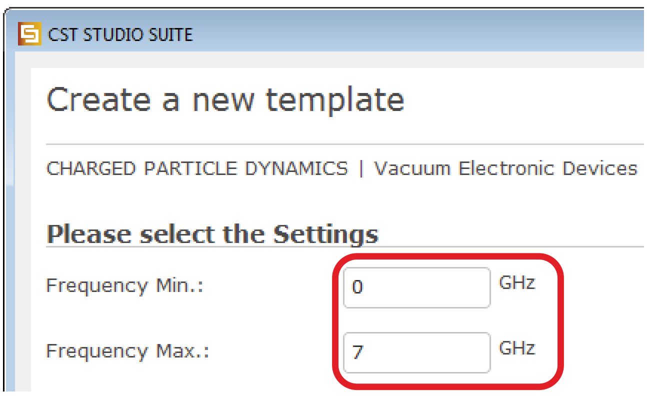


Select Solver

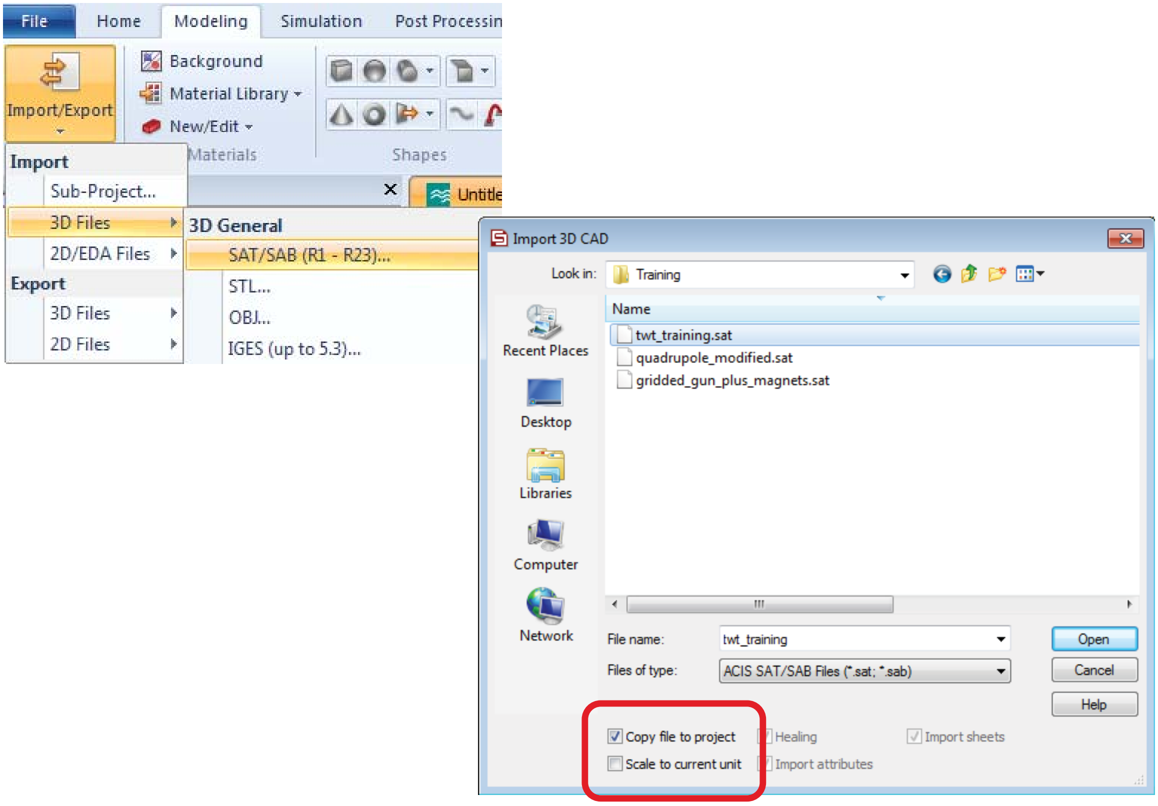


Specify Units and Other Settings

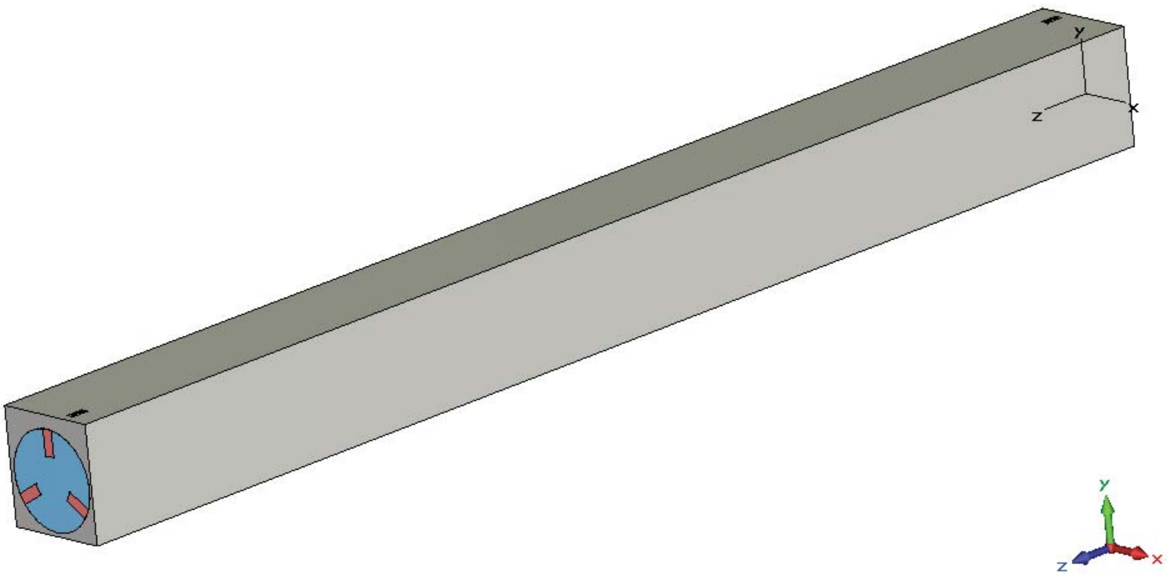




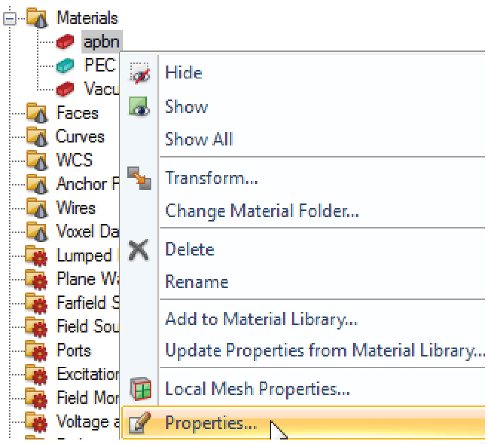
Import Structure



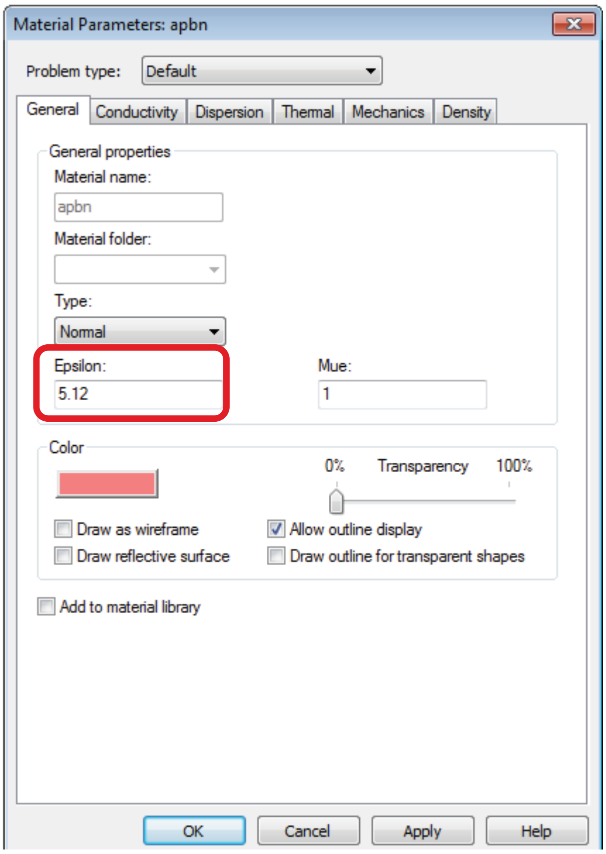
Structure



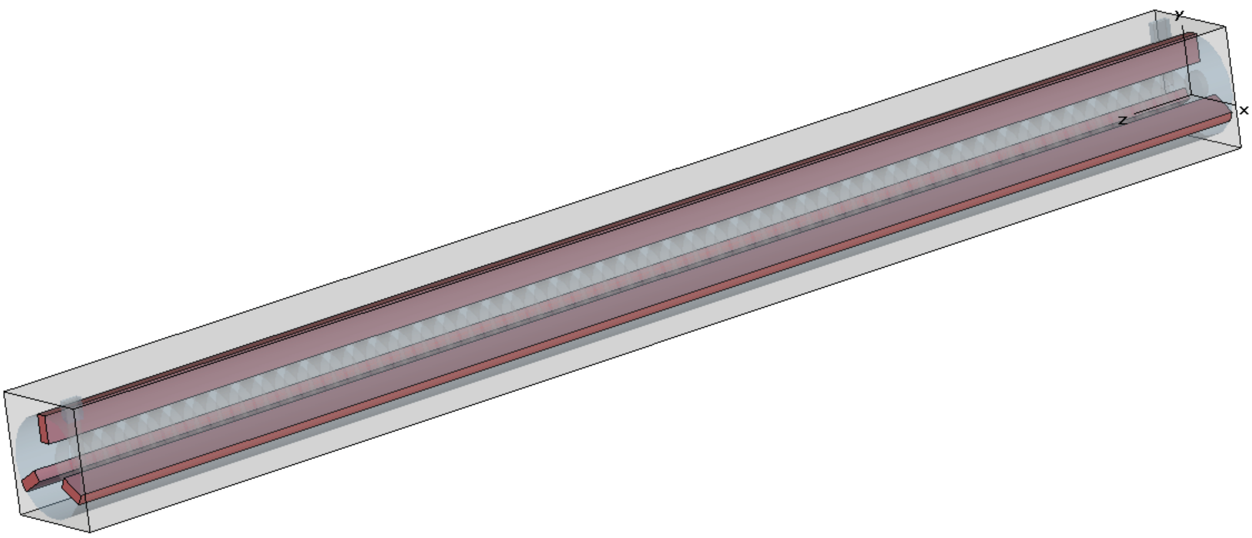
Define Materials



Vacuum and PEC are already predefined

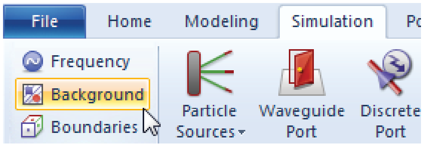


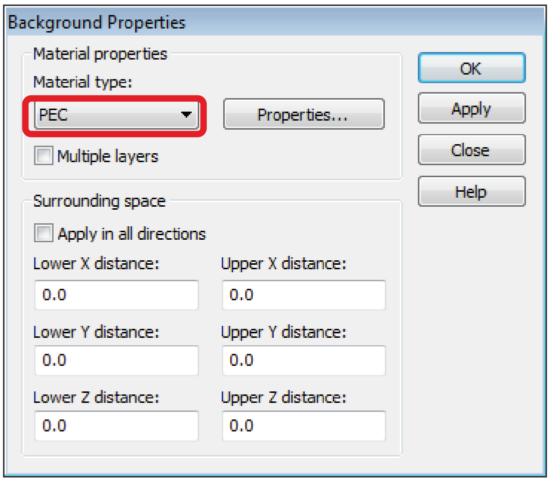
Materials



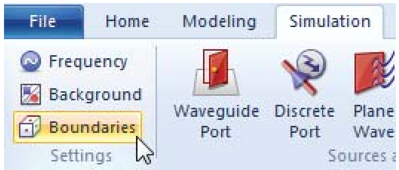
Material	apbn
Type	Normal
Epsilon	5.12
Mue	1

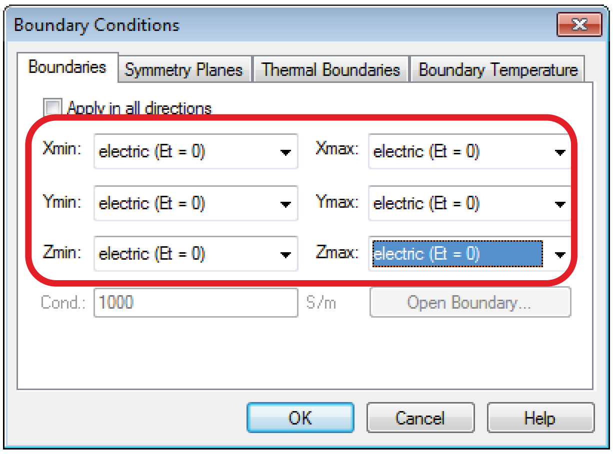
Define Background and Boundaries





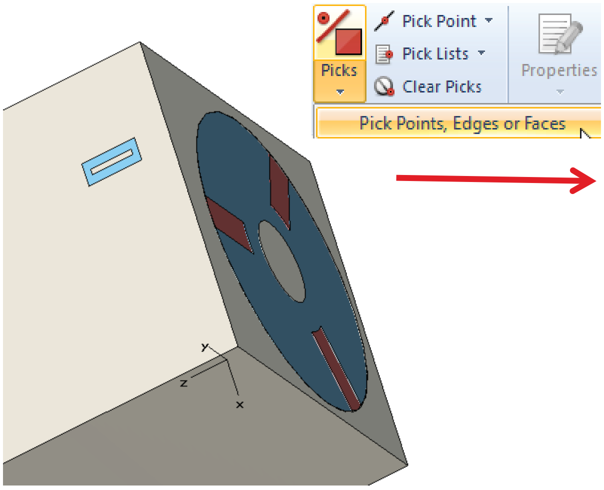
Default is PEC, then you need to model the vacuum. Otherwise change the background and model metallic parts

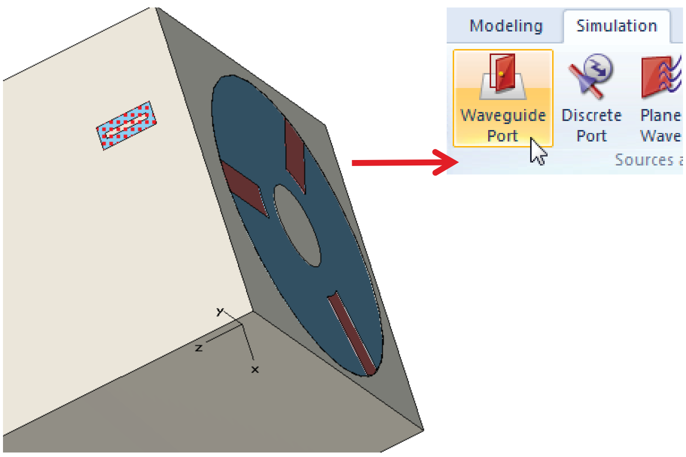




In most of the PIC cases electric boundaries are quite fine. Especially since they later on can serve as return path for crashing and emitting particles in order to avoid static charging.

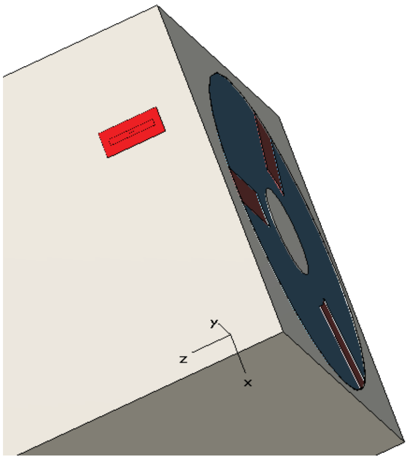
Define Excitation

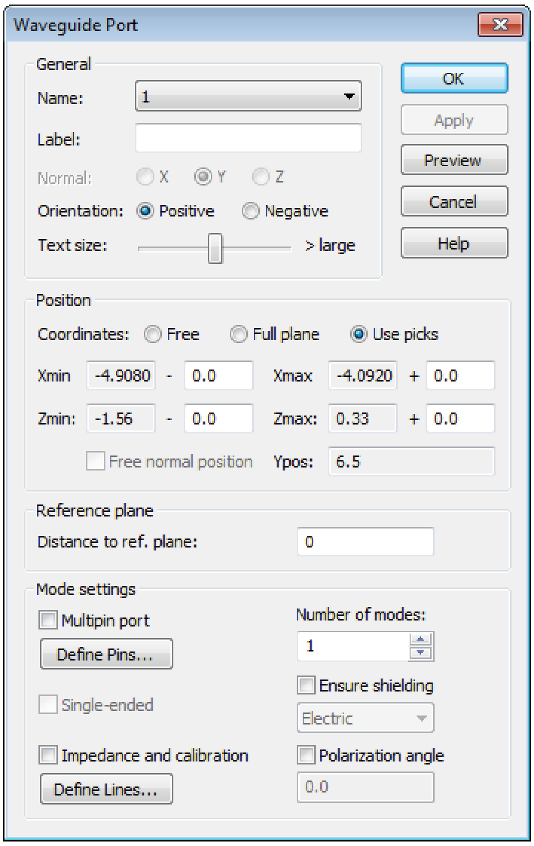




In most of the PIC cases waveguideports will serve nicely for excitation and absorption. Depending on the structure also discrete ports can be useful. But they only serve for TEM type modes.

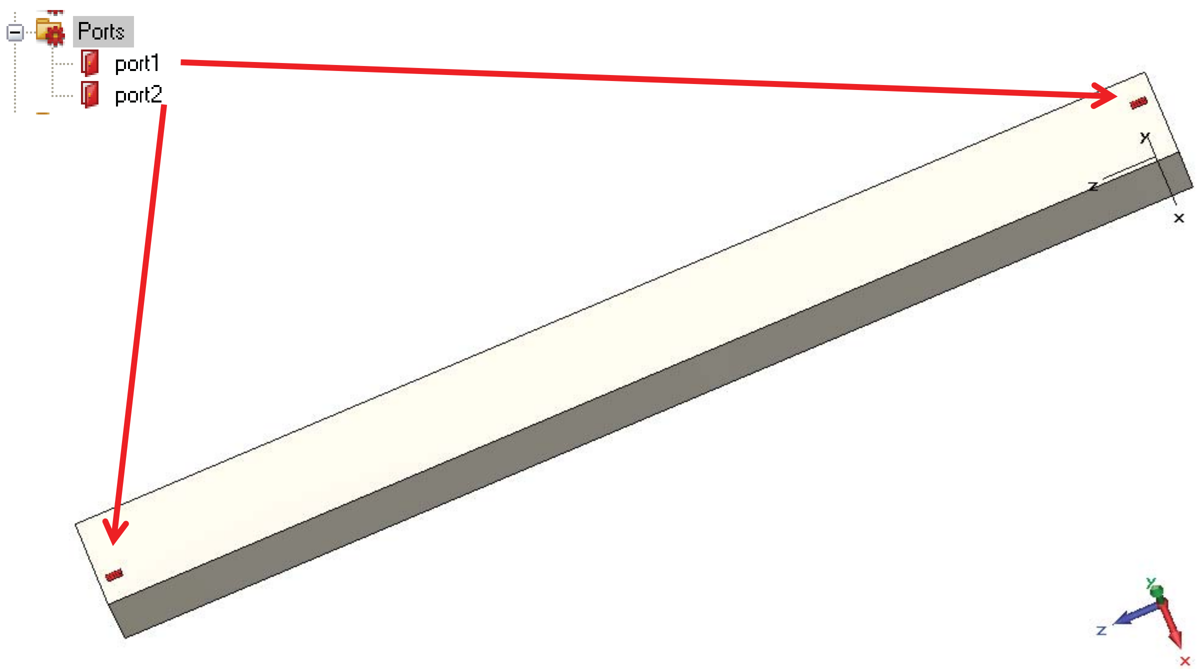
Define Excitation



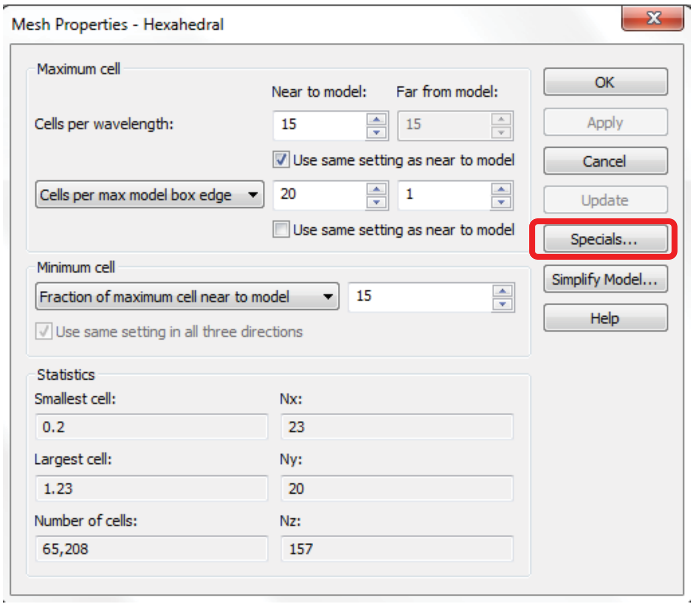


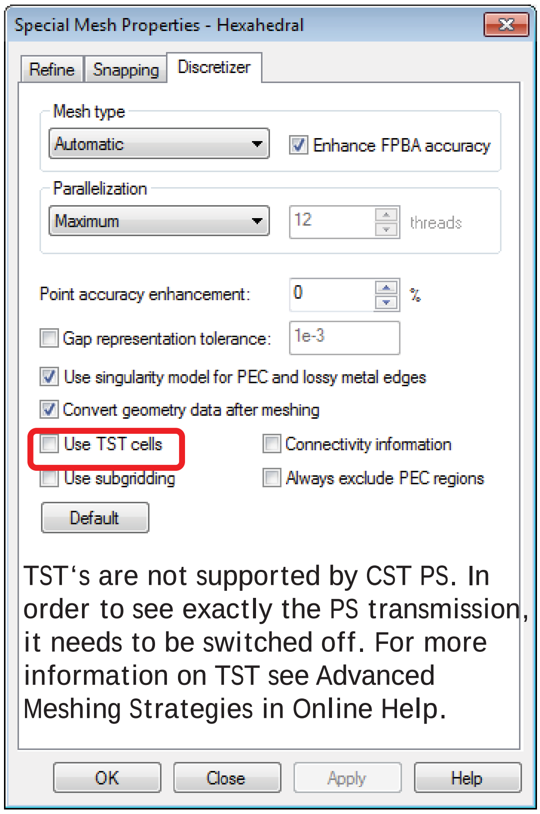
Define Excitation

Repeat the procedure for second coupler to obtain:



Modify Mesh Creation

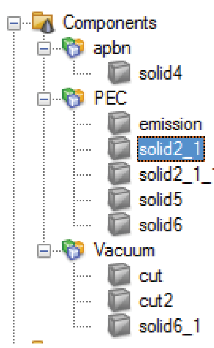




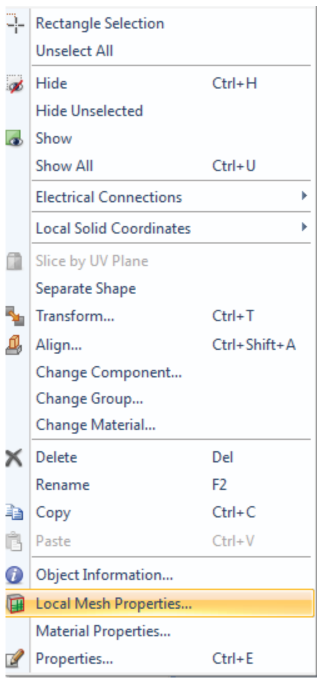
TST's are not supported by CST PS. In order to see exactly the PS transmission, it needs to be switched off. For more information on TST see Advanced Meshing Strategies in Online Help.

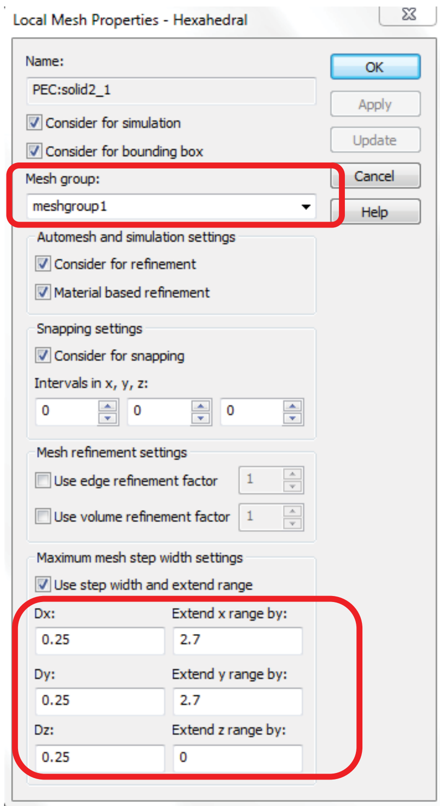
Local Mesh Properties

Just refine inner part of helix.



Select Object->
Right Mouse button

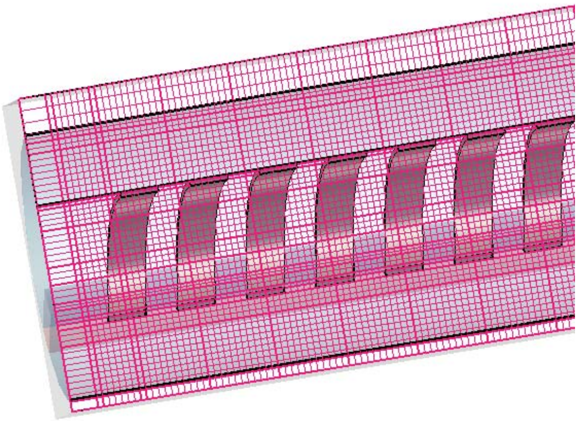




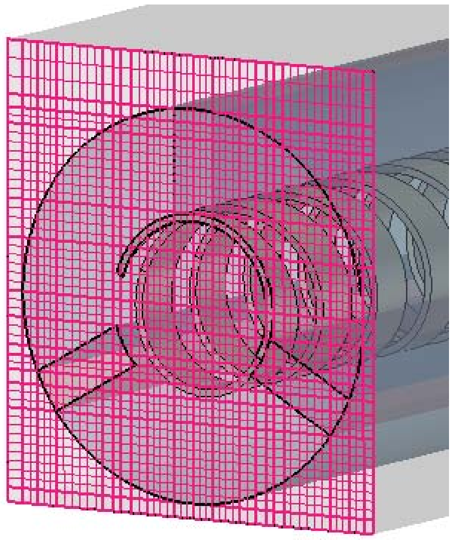
Final Mesh

The structure should now have approximately 1 Million mesh cells.

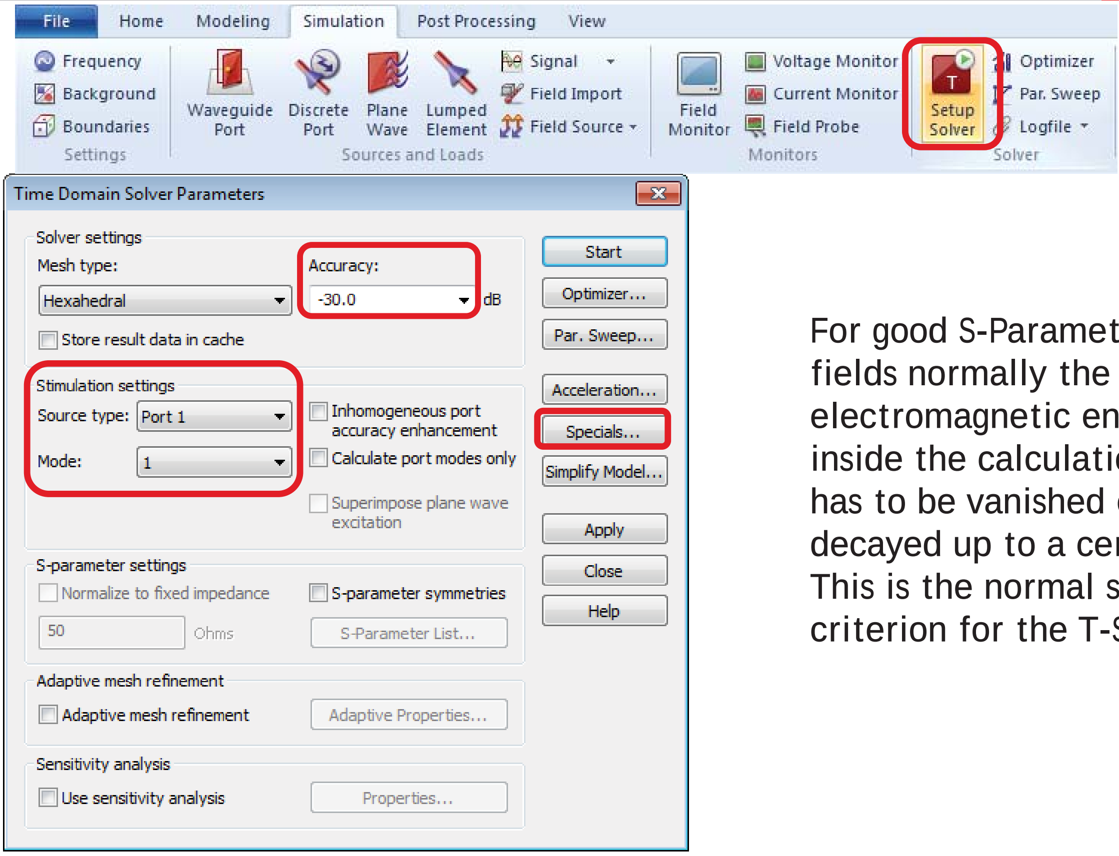
x plane



z plane

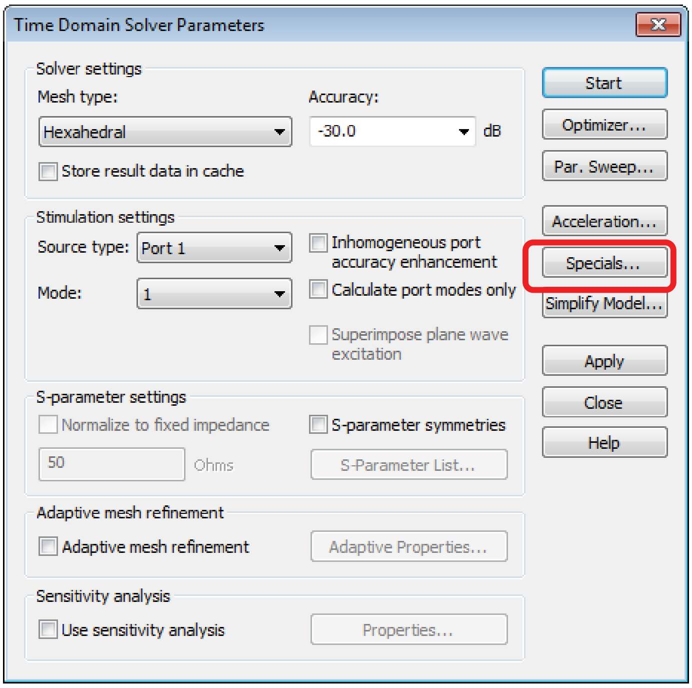


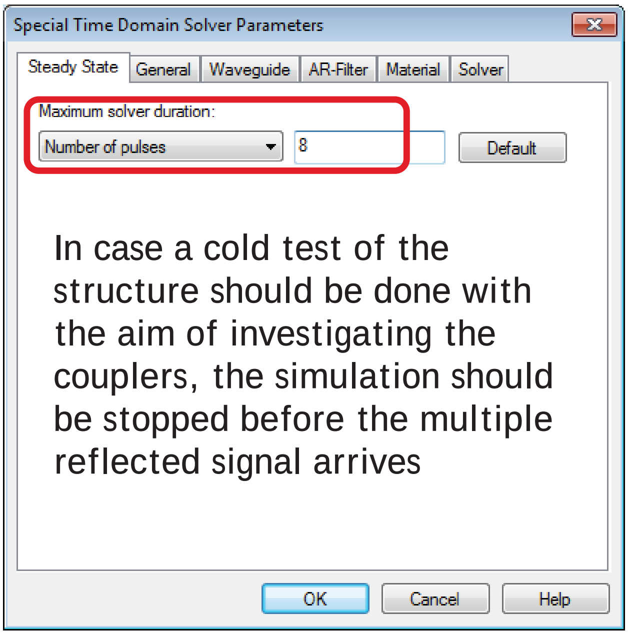
Start Solver



For good S-Parameters and fields normally the electromagnetic energy inside the calculation domain has to be vanished or at least decayed up to a certain limit. This is the normal stopping criterion for the T-Solver.

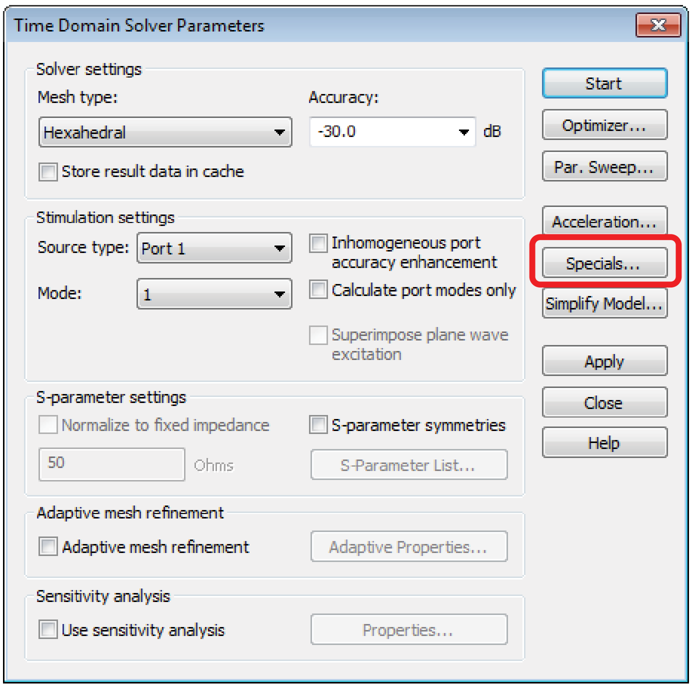
Start Solver

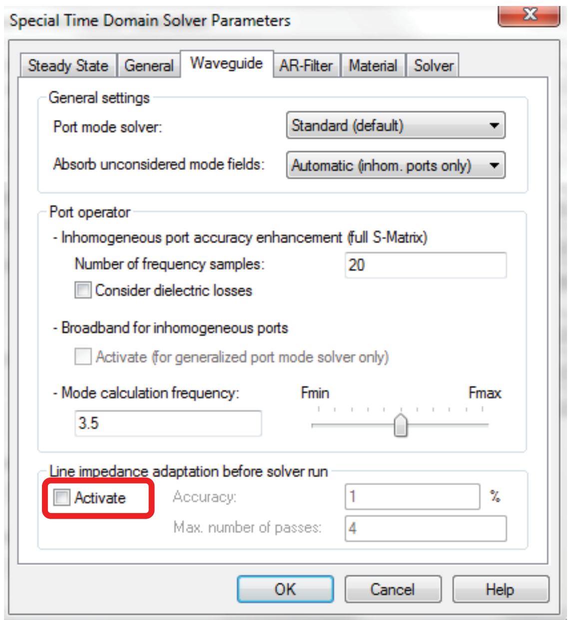




In case a cold test of the structure should be done with the aim of investigating the couplers, the simulation should be stopped before the multiple reflected signal arrives

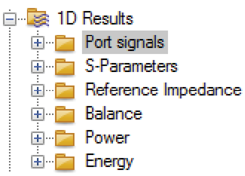
Start Solver

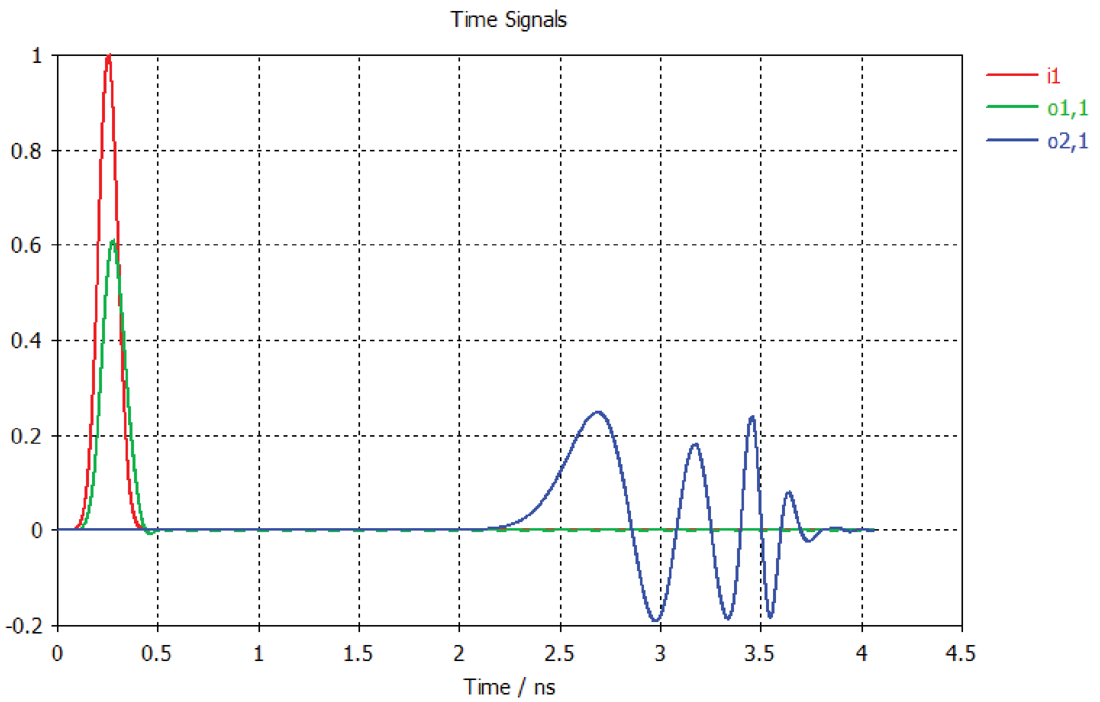




Saves some time and gives the actual matching to the circuit.

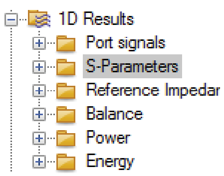
1D Results > Port Signals

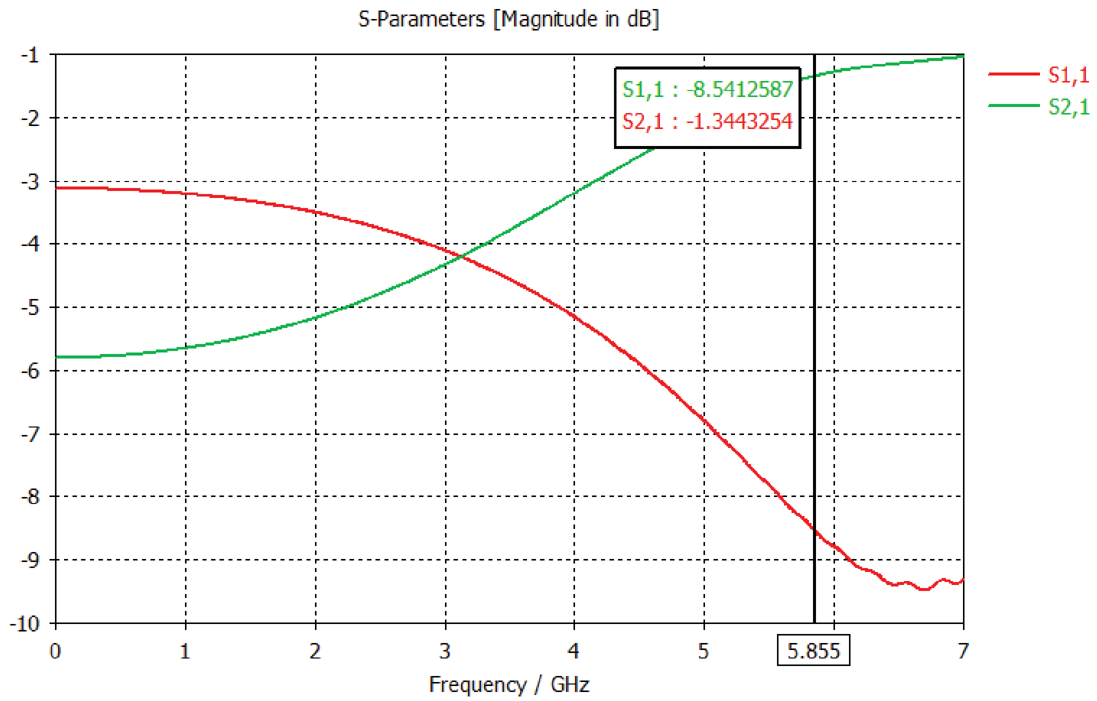




Simulation has been stopped before next reflection reaches port 1
=> Only coupler influence is investigated

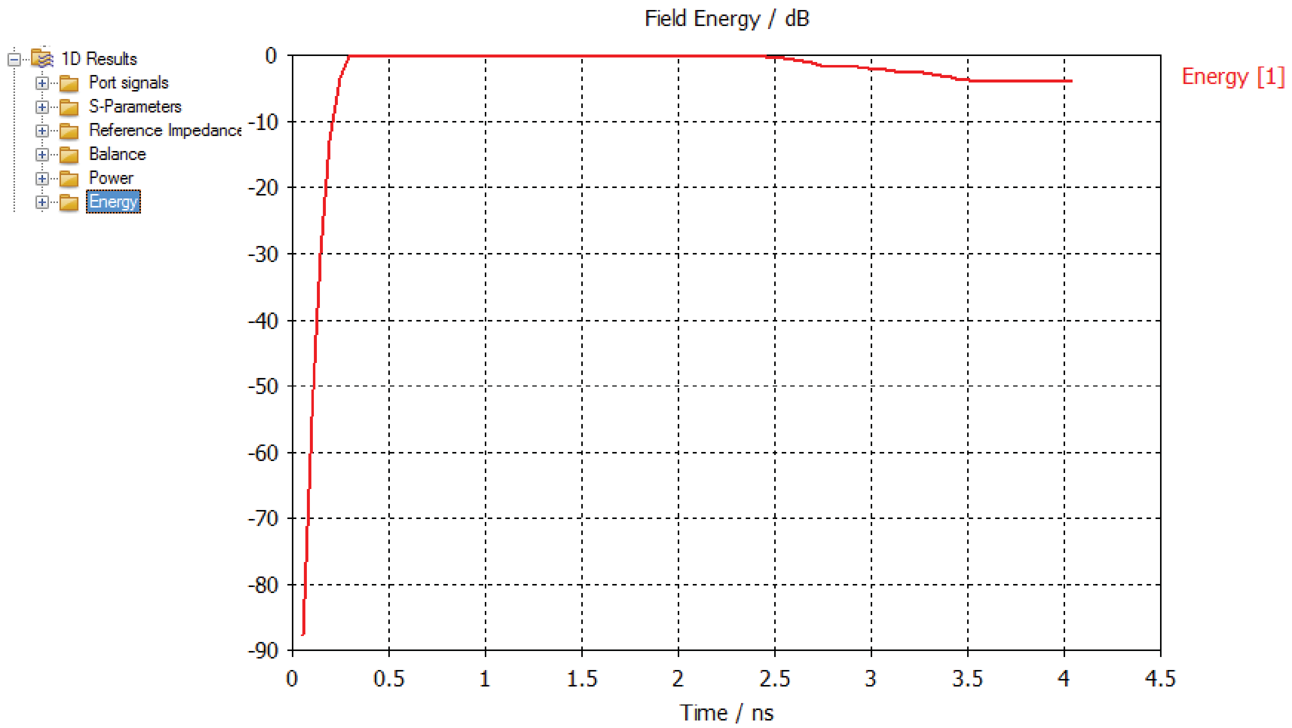
1D Results > S-Parameters





At the frequency of interest, the coupler works alright.

1D Results > Energy



As given also as message, the energy criterion has not been reached.

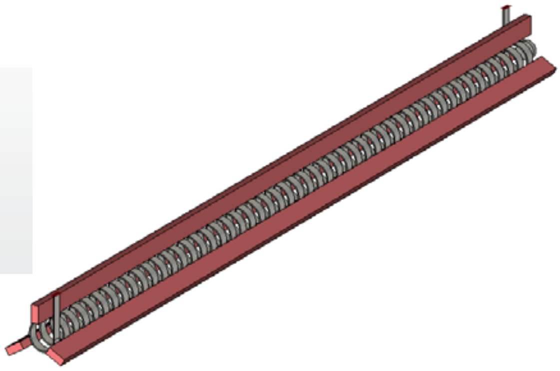
Workflow

- Choose an Application Area.
- Create your model.
  - parameters + geometry + materials
- Define ports.
- Set the frequency range.
- Specify boundary and symmetry conditions.
- Define monitors.
- Check the mesh.
- Run the simulation.
- Stop simulation before reflection arrives.

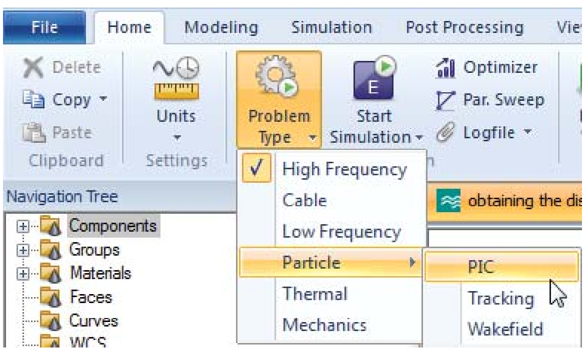
Traveling Wave Tube Simulation

Hot Test

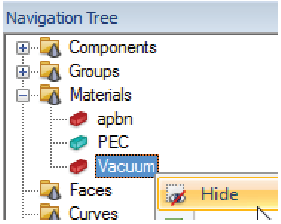
Purpose:
Obtain Gain, Investigate eventual interceptions of particle and circuit

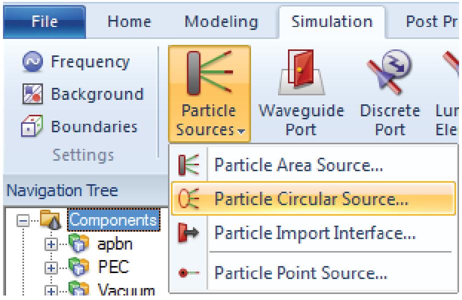


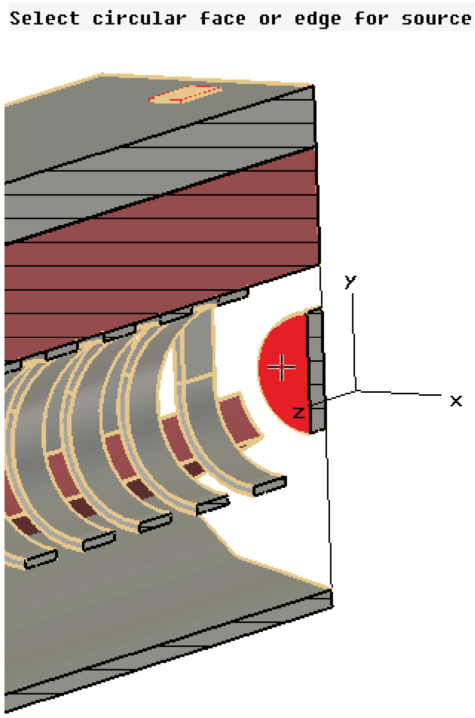
Change Problem Type



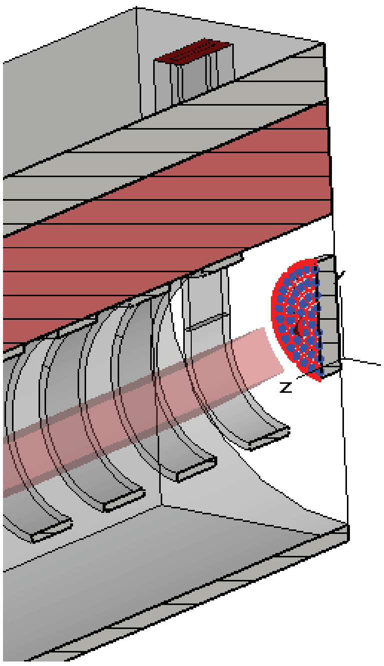
Define Particle Source

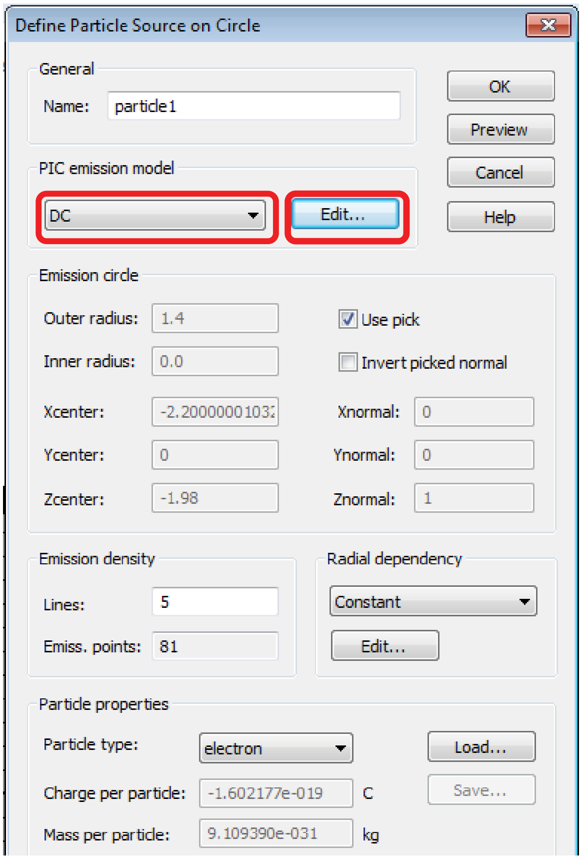






Define Particle Source





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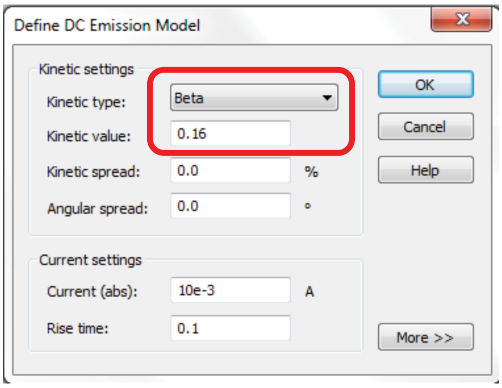
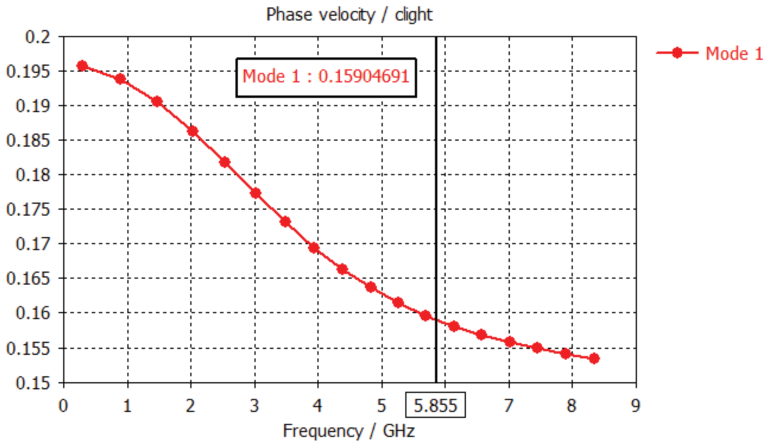
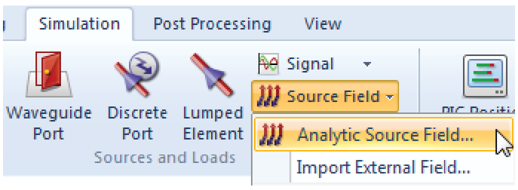
Define Particle Source

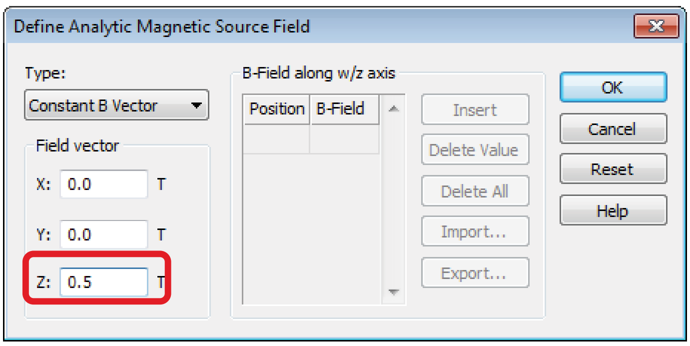




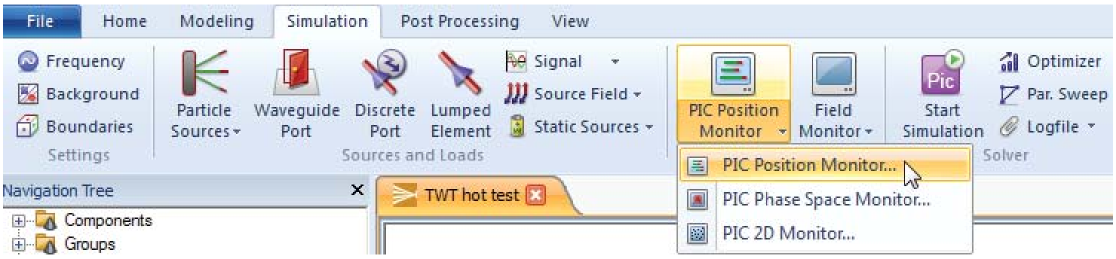
Particles are in synchronism with the wave (velocity is slightly higher in order to provide energy transfer from beam to wave).

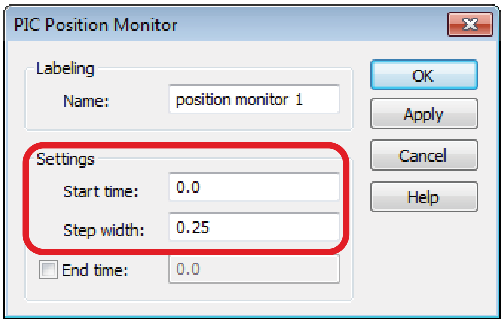
Define Focusing Magnetic Field



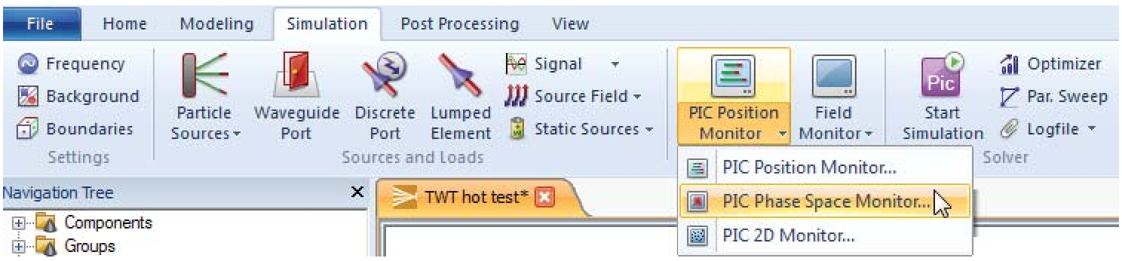


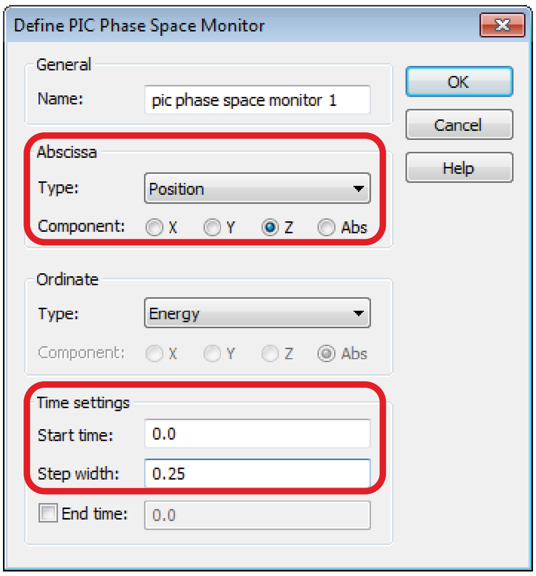
Define Particle Monitor





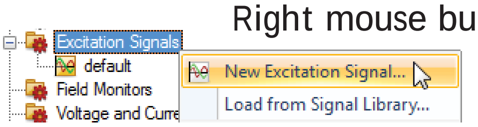
Define Phase Space Monitor

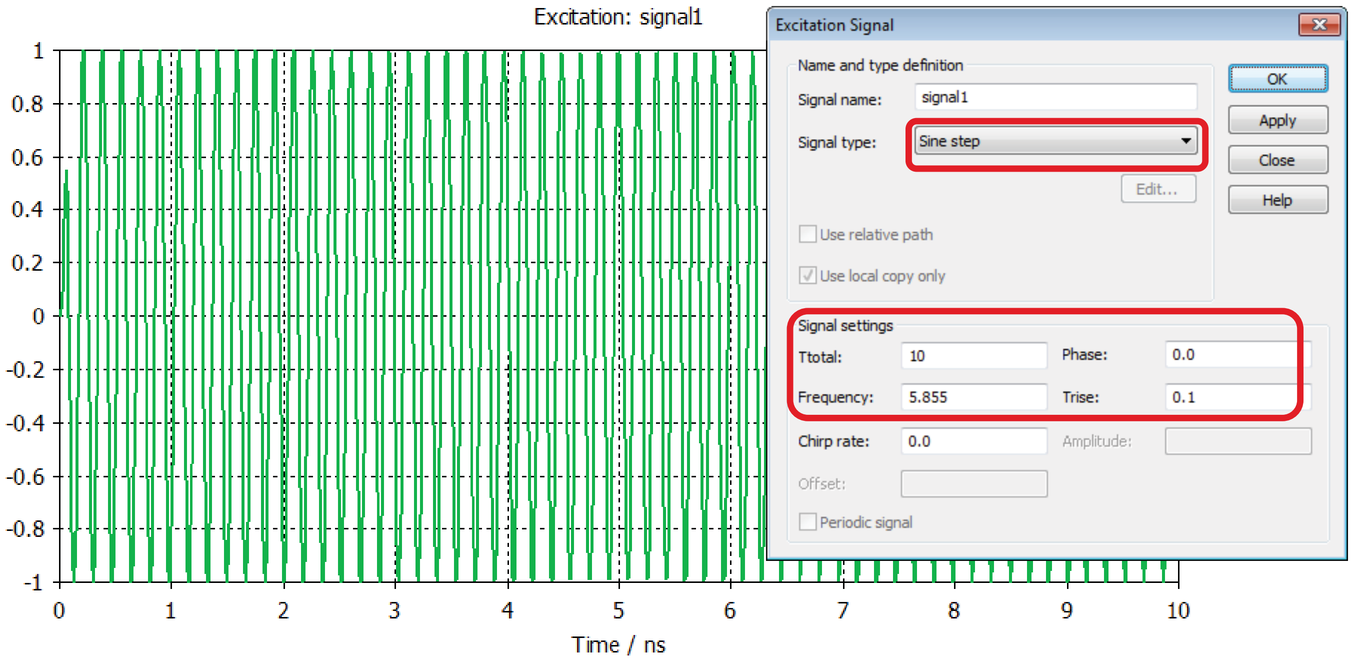




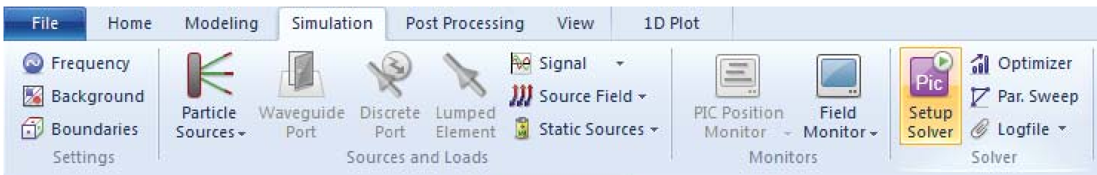
Define Excitation Signal

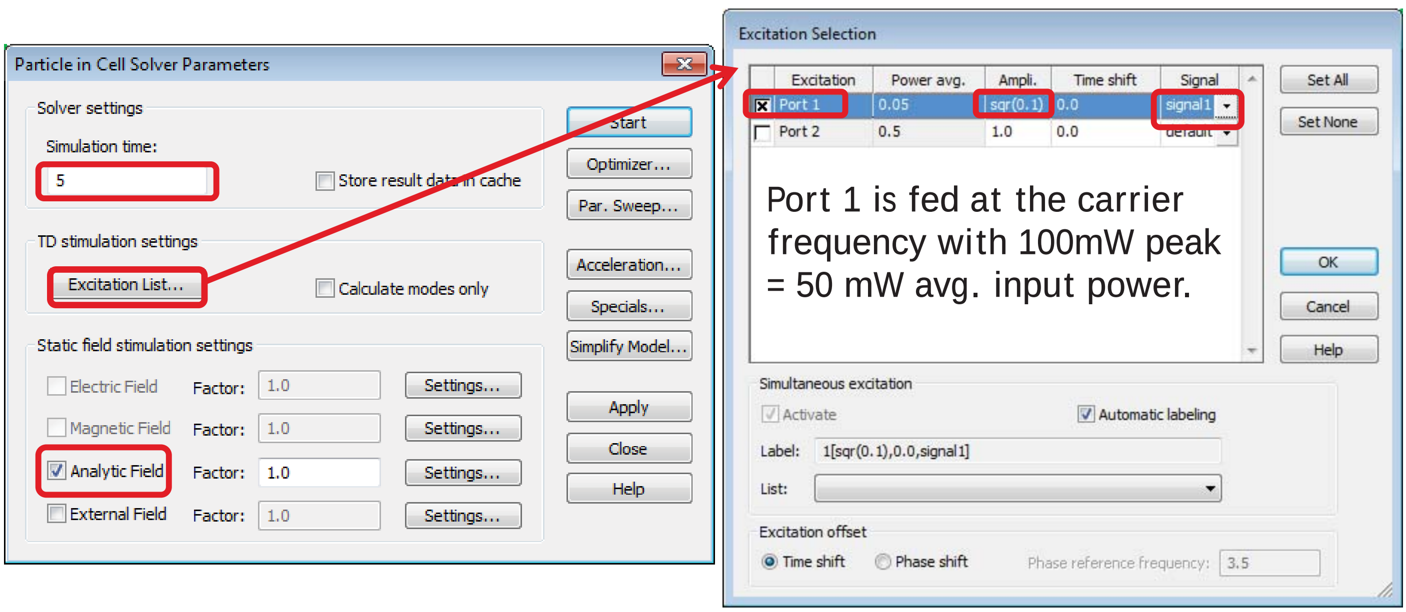
Right mouse button



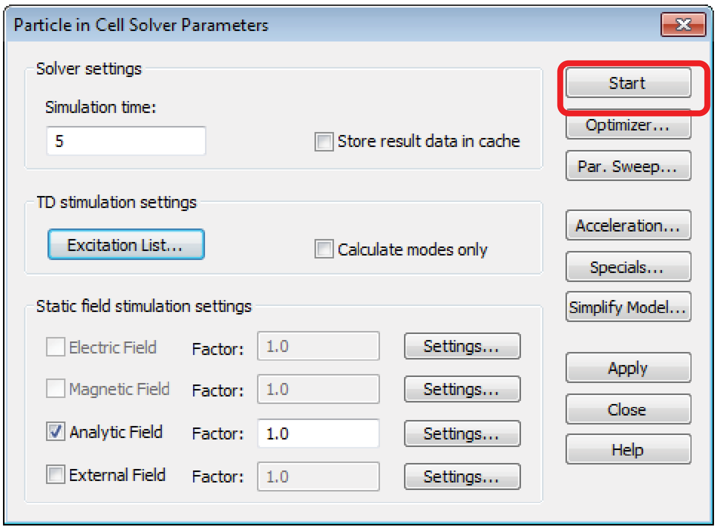


Define Excitation and Input Power

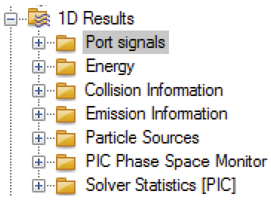


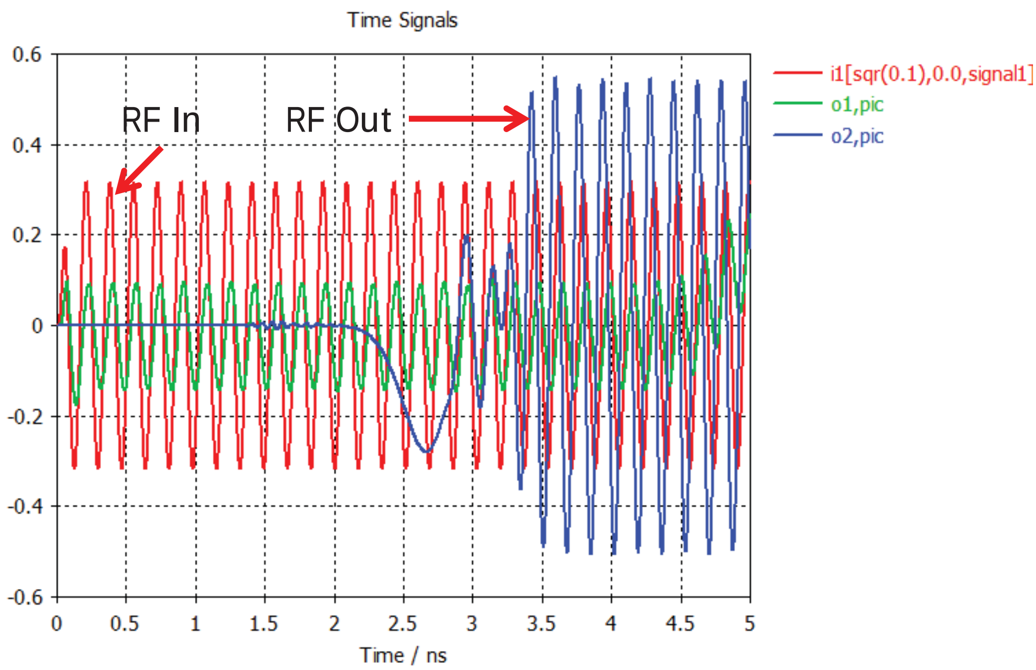


Start Solver

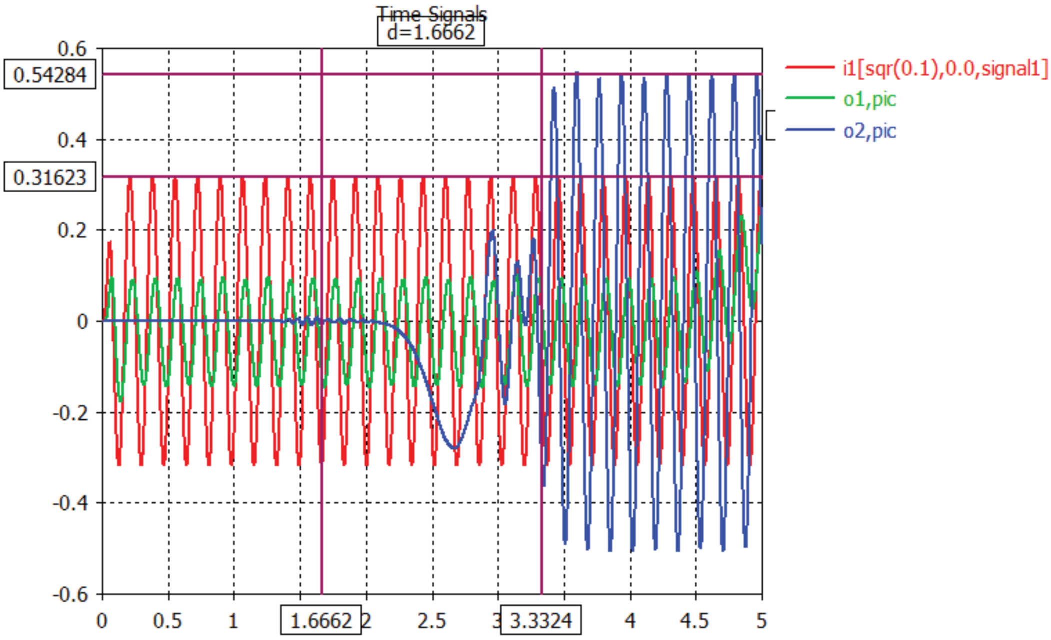


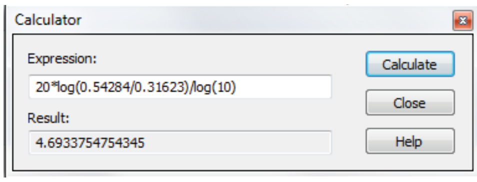
Analyze Results





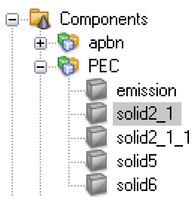
Evaluate Gain

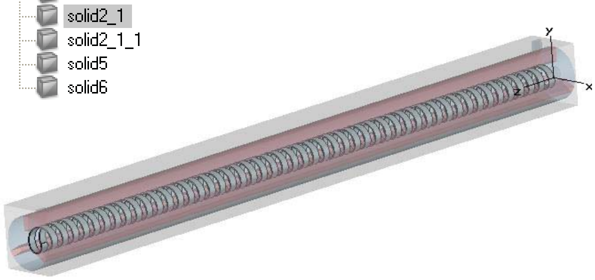


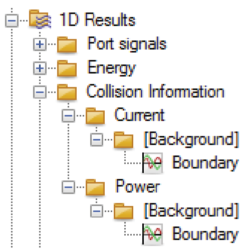


Tube shows 4.6 dB gain.

Interception of particles and circuit?





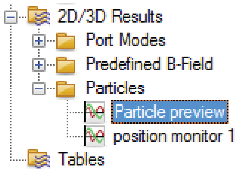


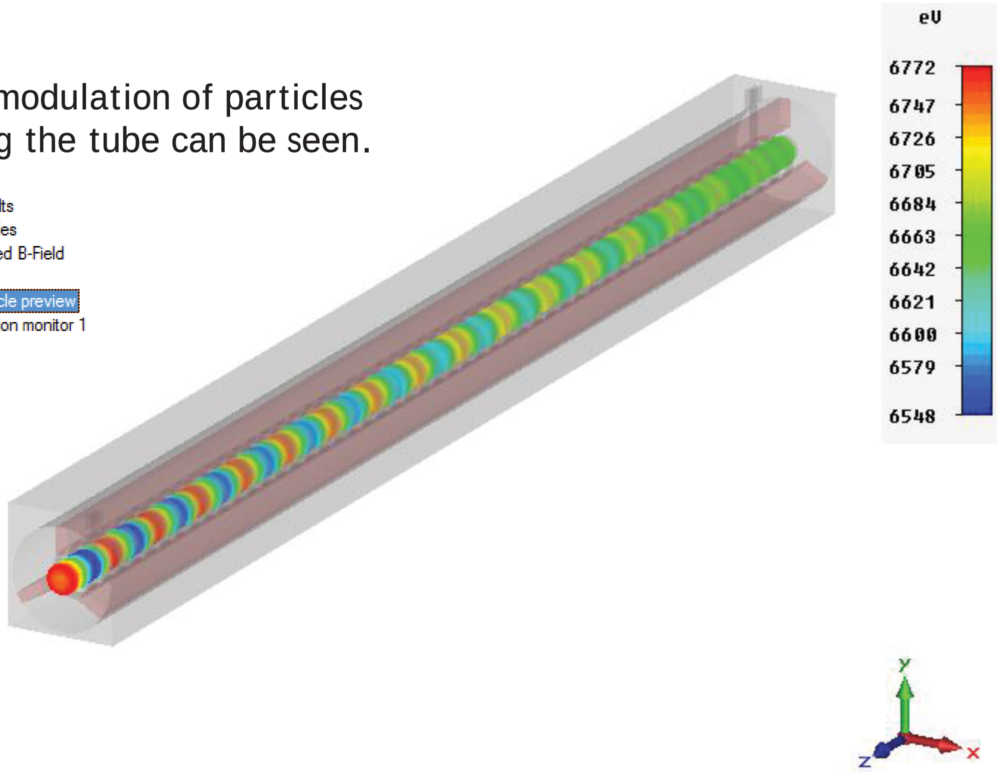
If any particles would be intercepting, solid2_1 would also have an entry in the collision information.

=> No Interception

Trajectory

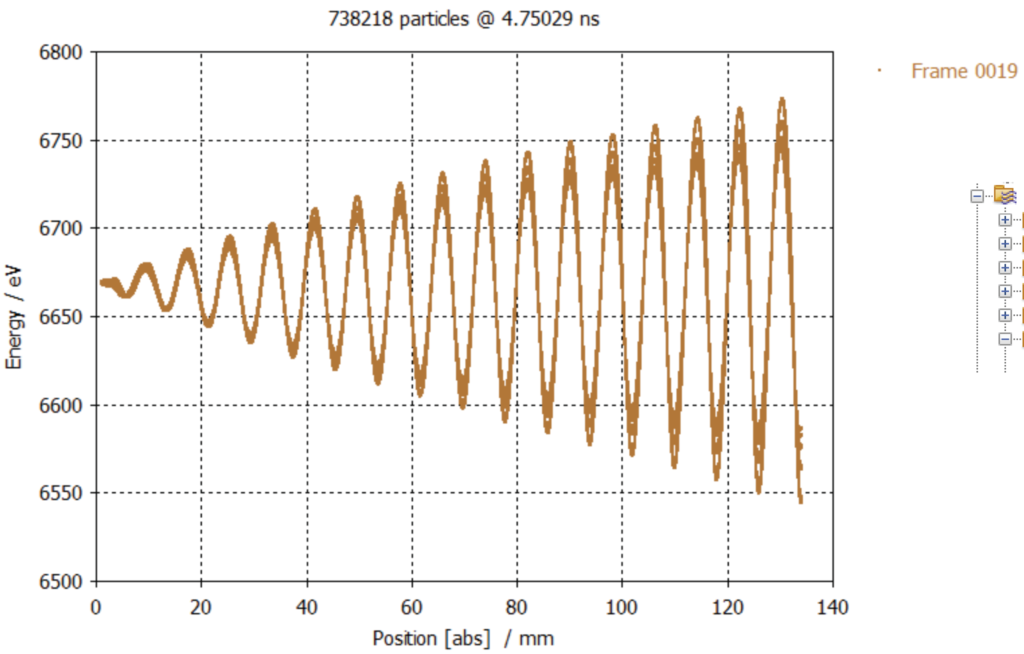
Velocity modulation of particles traversing the tube can be seen.

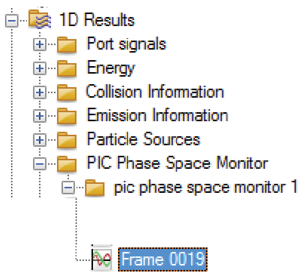




Phase Space Monitor

Velocity modulation, entry energy and loss of mean energy can be seen in the phase space plot.





Workflow

- Choose Application Area.
- Create your model.
  - parameters + geometry + materials
- Define ports.
- Set the frequency range.
- Specify boundary and symmetry conditions.
- Define field and particle monitors.
- Define particle source and emission properties.
- Define focusing field.
- Check the mesh.
- Define excitation signal and input power.
- Run the simulation.

Open discussion

concluding remarks