4.1 Microwave frequencies, Applications, Traveling wave tube amplifier

Module:4 Microwave Sources

Course: BECE305L – Antenna and Microwave Engineering

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Module:4 Microwave Sources 5 hours

- Microwave frequencies and applications, Microwave Tubes: TWT, Klystron amplifier, Reflex, Klystron & Magnetron. Semiconductor Devices: Gunn diode, Tunnel diode, IMPATT – TRAPATT - BARITT diodes, PIN Diode.

1. Introduction

- IEEE Frequency bands
- Standard Radar-Frequency Letter Band Nomenclature

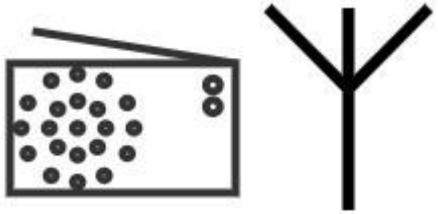
Band Designation	Nominal Frequency Range	Specific Frequency Ranges for Radar Based on ITU Assignments for Region 2, see Note (1)
HF	3 MHz–30 MHz	Note (2)
VHF	30 MHz–300 MHz	138 MHz–300 MHz 216 MHz–225 MHz
UHF	300 MHz–1000 MHz (Note 3)	420 MHz–450 MHz (Note 4) 890 MHz–942 MHz (Note 5)
L	1000 MHz–2000 MHz	1215 MHz–1400 MHz
S	2000 MHz–4000 MHz	2300 MHz–2500 MHz 2700 MHz–3700 MHz
C	4000 MHz–8000 MHz	5250 MHz–5925 MHz
X	8000 MHz–12,000 MHz	8500 MHz–10,680 MHz
K_u	12.0 GHz–18 GHz	13.4 GHz–14.0 GHz 15.7 GHz–17.7 GHz
K	18 GHz–27 GHz	24.05 GHz–24.25 GHz
K_a	27 GHz–40 GHz	33.4 GHz–36.0 GHz
V	40 GHz–75 GHz	59 GHz–64 GHz
W	75 GHz–110 GHz	76 GHz–81 GHz 92 GHz–100 GHz
mm (Note 6)	110 GHz–300 GHz	126 GHz–142 GHz 144 GHz–149 GHz 231 GHz–235 GHz 238 GHz–248 GHz (Note 7)

Table 2—Comparison of Radar-Frequency Letter Band Nomenclature with ITU Nomenclature

Radar Nomenclature		International Telecommunications Union Nomenclature			
Radar Letter Designation	**Frequency Range**	**Frequency Range**	**Band No**	**Adjectival Band Designation**	**Corresponding Metric Designation**
HF	3 MHz–30 MHz	3 MHz–30 MHz	7	High frequency (HF)	Dekametric waves
VHF	30 MHz–300 MHz	30 MHz–300 MHz	8	Very high frequency (VHF)	Metric waves
UHF	300 MHz–1000 MHz				
L	1 GHz–2 GHz	0.3 GHz–3 GHz	9	Ultra high frequency (UHF)	Decimetric waves
S	2 GHz–4 GHz				
C	4 GHz–8 GHz				
X	8 GHz–12 GHz	3 GHz–30 GHz	10	Super high frequency (SHF)	Centimetric waves
K_u	12 GHz–18 GHz				
K	18 GHz–27 GHz				
K_a	27 GHz–40 GHz				
V	40 GHz–75 GHz	30 GHz–300 GHz	11	Extremely high frequency (EHF)	Millimetric Waves
W	75 GHz–110 GHz				
mm	110 GHz–300 GHz				

1.2. Few applications

Motor, Generator



Radio, Antenna

Mobile, Communication

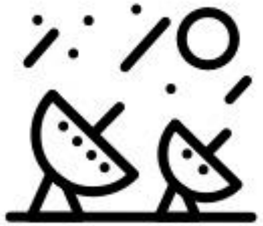
Text

Transmission line, computer

Cars

RADARs

Satellite communication



Deep space research

1.3. Recent topics of interest

- Bio-electromagnetics
- Electromagnetic interference and compatibility
- Nuclear research
- Plasmas
- Fiber optics
- Millimetre wave and terahertz applications

2. Classification of microwave devices

1) **Electron beam interaction**:

Forward wave tubes: fundamental harmonic of forward propagating wave interacts with the electron beam as in TWTs. [21]

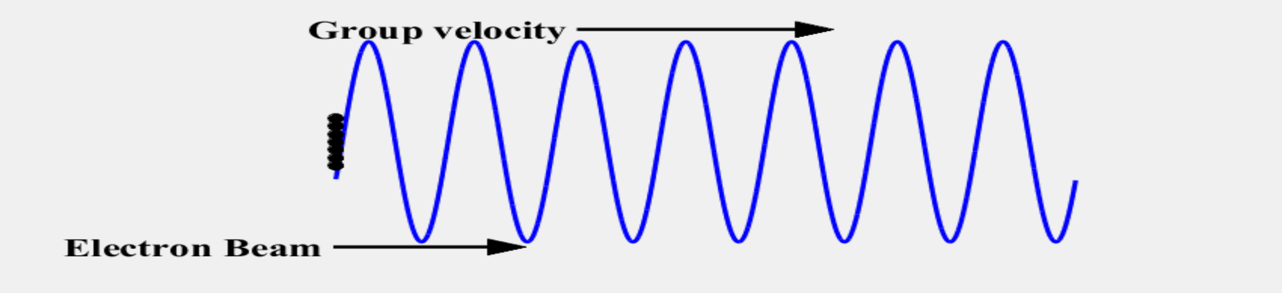


Fig. 2a. BWI in forward wave tubes

Backward wave tubes: Negative spatial harmonics interact with the electron beam

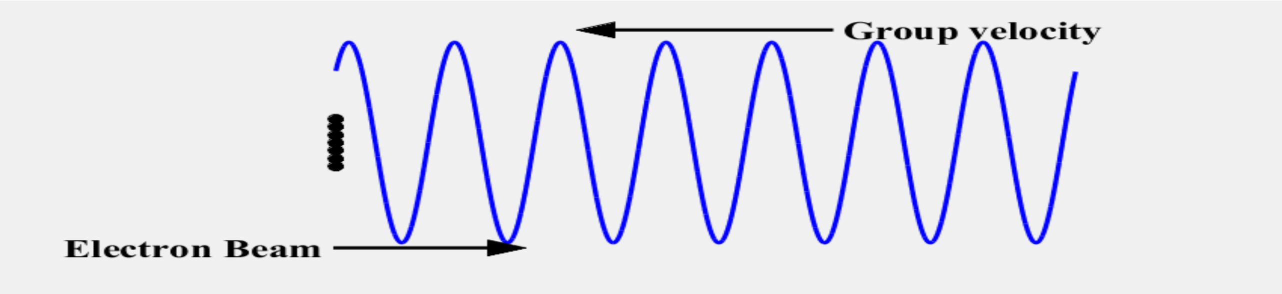


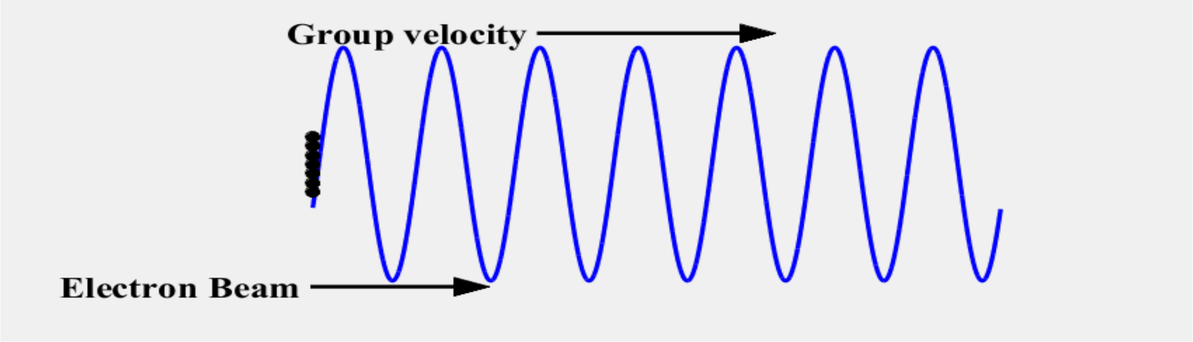
Fig. 2b. BWI in backward wave tubes

2. Classification of microwave devices

2) Static magnetic field direction

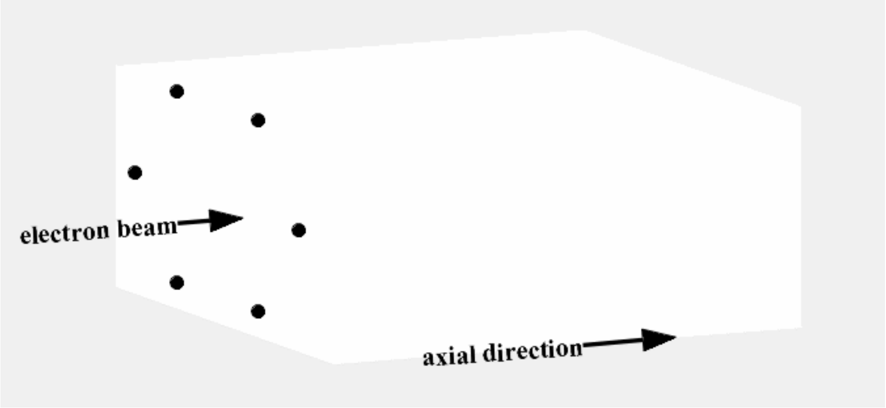
O-type devices: Longitudinal component – for rectilinear electron beam focusing [21]

Fig. 3a. Electron motion in O-type devices



M-type devices: Transverse static magnetic field for controlling beam wave interaction (BWI)

Fig. 3b. Electron motion in M-type devices



3.0 Features of Traveling Wave tube amplifiers

- High gain (>40dB) For input power of 0.01watt,
  output power will be over 100watts (few kW)
- Low noise (Noise floor <10dB)
- Wide band (>octave) example: Ku-K band (12-27GHz)
- Helix traveling wave tube amplifiers: 0.3-50GHz)

3.1 Traveling wave tube – Cross sections

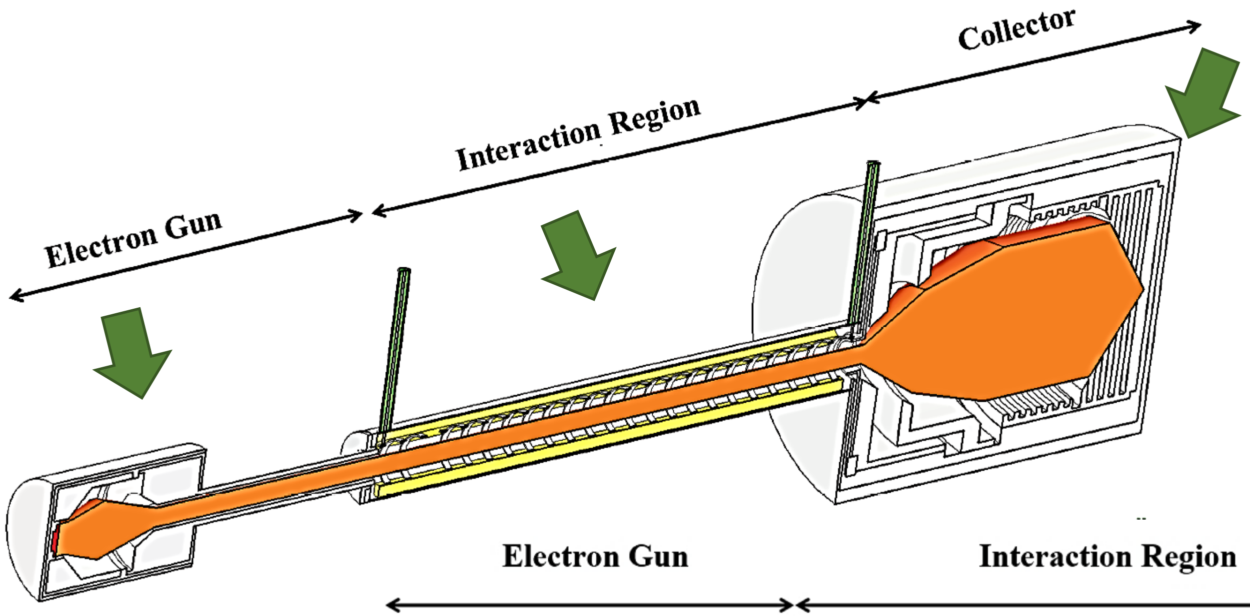


Fig. 4a. Cross sectional view of Travelling wave tube amplifier without the periodic permanent magnets

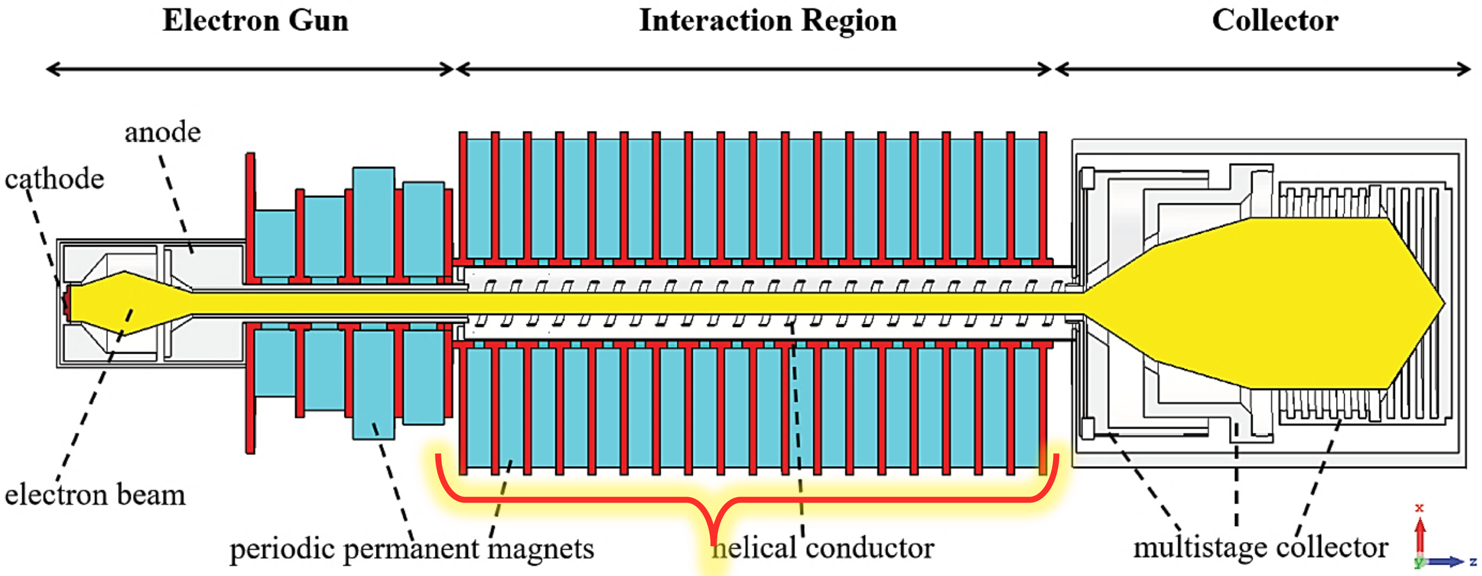


Fig. 4b. Cross sectional view of 3 major parts of the TWTA:
1. **Electron gun**, 2. **Interaction region** and 3. **Collector**

3.2 Electron Gun

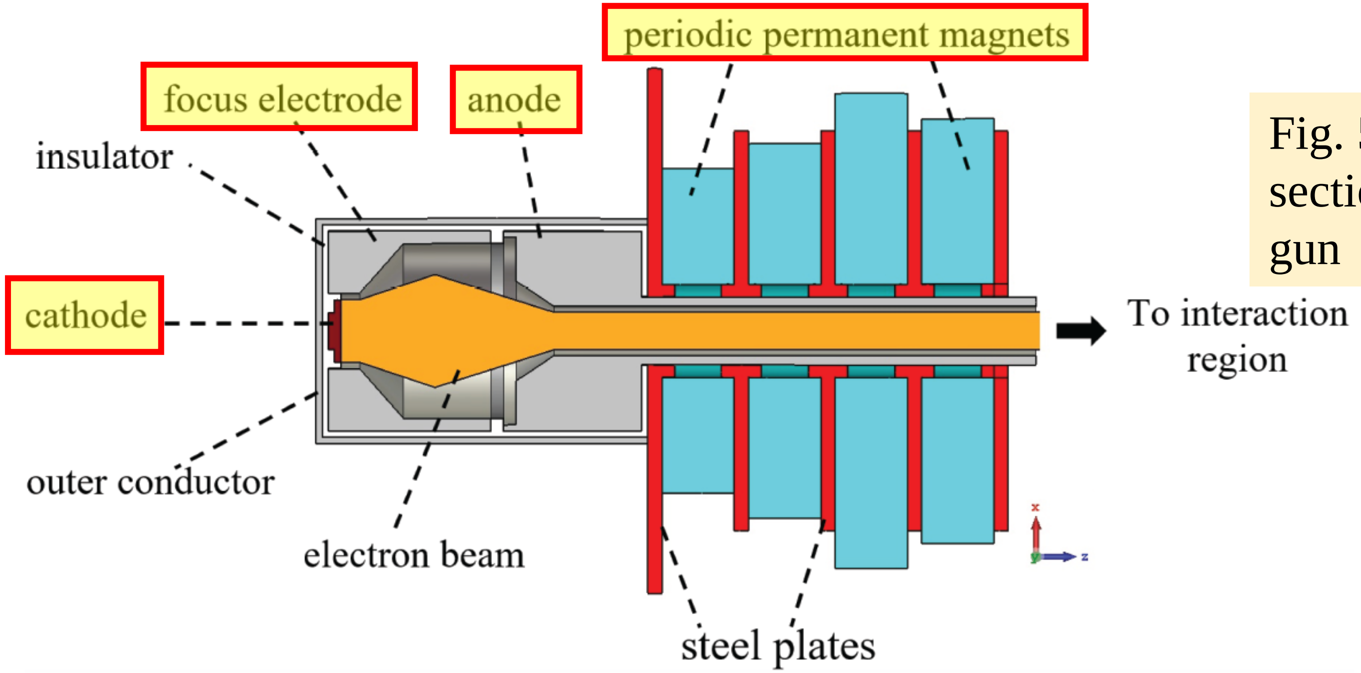
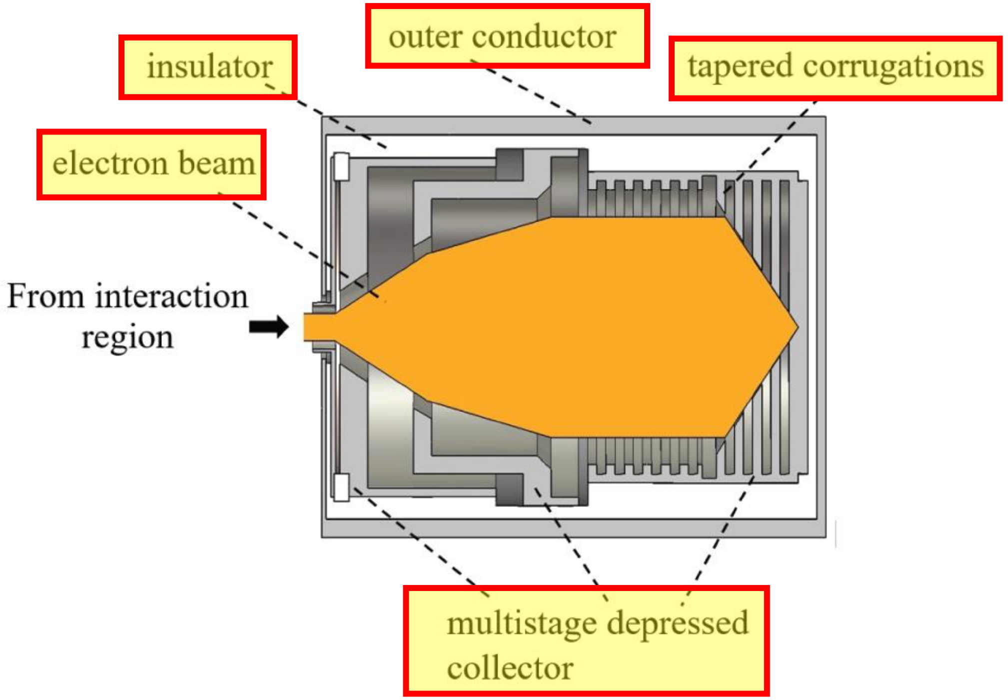


Fig. 5. Cross section of electron gun

- **Cathode** – electrons tend to diverge
- **Focus electrode** – for convergent electron flow
- **Anode** – defocussing of electron beam
- **Periodic permanent magnets** – prevent electron divergence

3.3 Collector

Fig. 6. Cross sectional view of collector



Collector – held at negative potential below RF Circuit to slow down the fast moving electrons

- **Electron beam** – Spent electron bunches
- **Multistage depressed collector** – progressively decreasing negative potentials
- **Tapered corrugations** – Secondary electron emissions are prevented
- **Outer conductor**

3.4 Slow wave structure

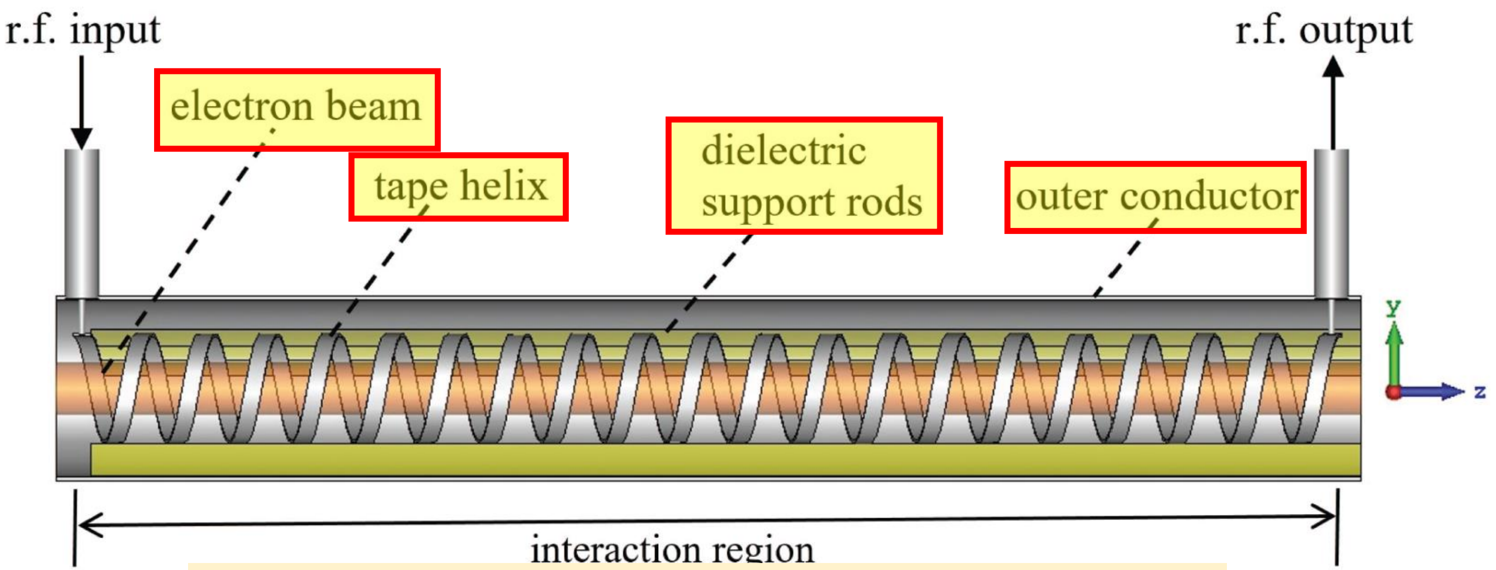


Fig. 7. Cross sectional view of interaction region

- **Electron beam** – For beam wave interaction
- **Slow wave structure (SWS)** – Tape helix conductor slows down the RF signal
- **Dielectric support rods** – support the SWS
- **Outer conductor** – encapsulating the vacuum tube
- **Periodic permanent magnets** – Prevent electron divergence

Low impedance transmission line

4.1 Beam wave interaction in SWS

- The helical slow wave structure (**SWS**) helps in the interaction of the electric fields and the electron beam in the interaction region, by **slowing down** the velocity of the RF fields.
- DC **beam velocity** of the beam is maintained slightly **greater** than that of the axial field.

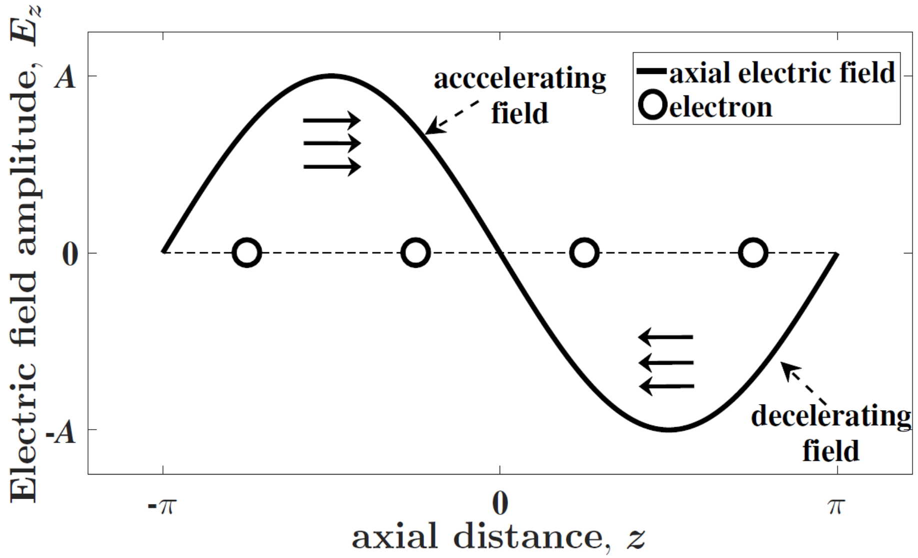
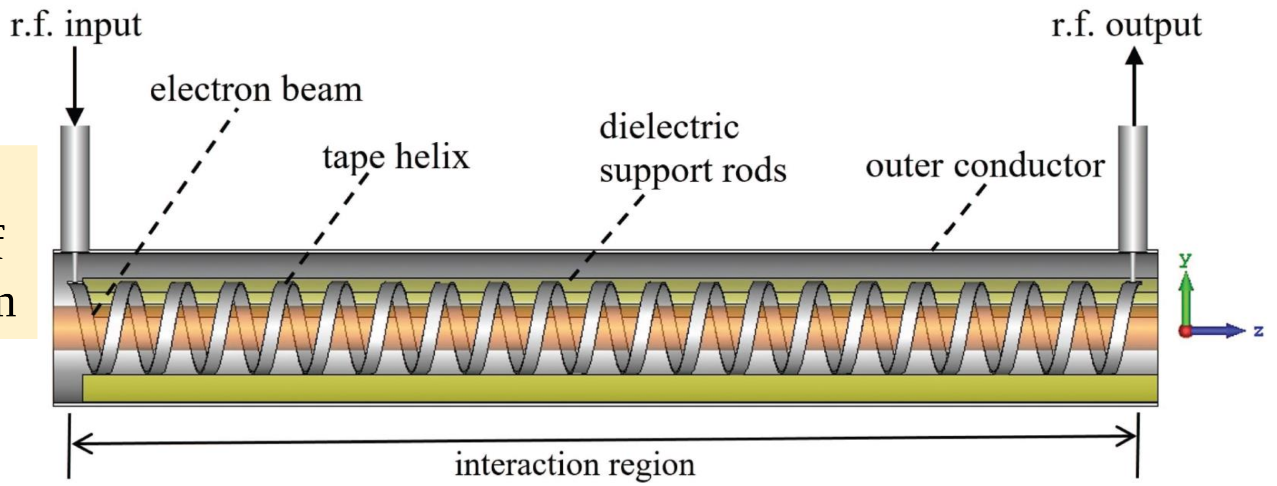


Fig. 8. Forces acting on electrons due to one RF cycle of the axial electric field. [21]
The direction of periodic forces on the electrons is indicated by the horizontal arrows.

4.1 Beam wave interaction in SWS

Fig. 9. Cross sectional view of interaction region



RF input given in Helix ⇘ ⇙ Generation of Electron beam

Interaction of RF Signal(Axial E field) with electron beam

⇩

Velocity modulation: Electron Bunches <=>Amplification of RF Signal

⇩

Amplified RF Signal received at output terminal

4.1Beam wave interaction in SWS

Fig. 10a. Cross sectional view of interaction region

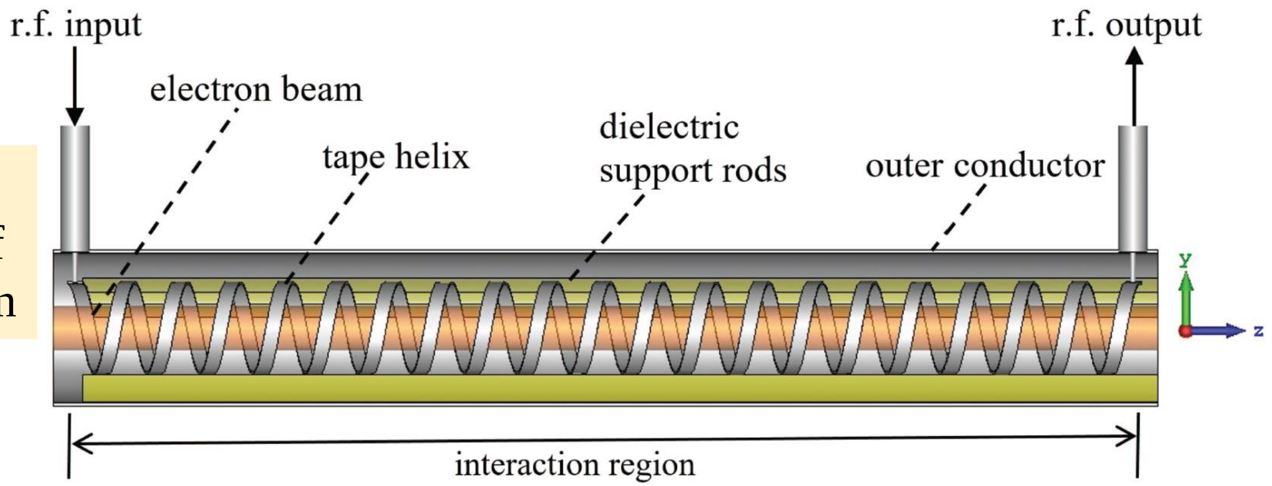
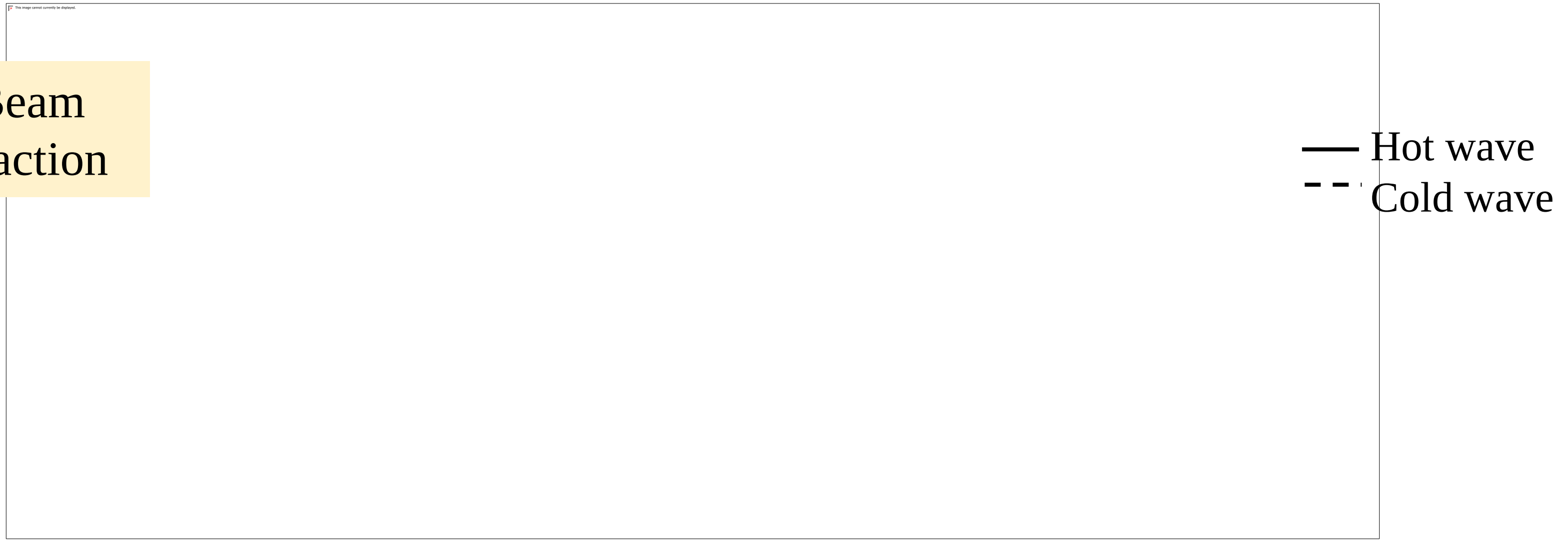


Fig. 10b. Beam wave interaction



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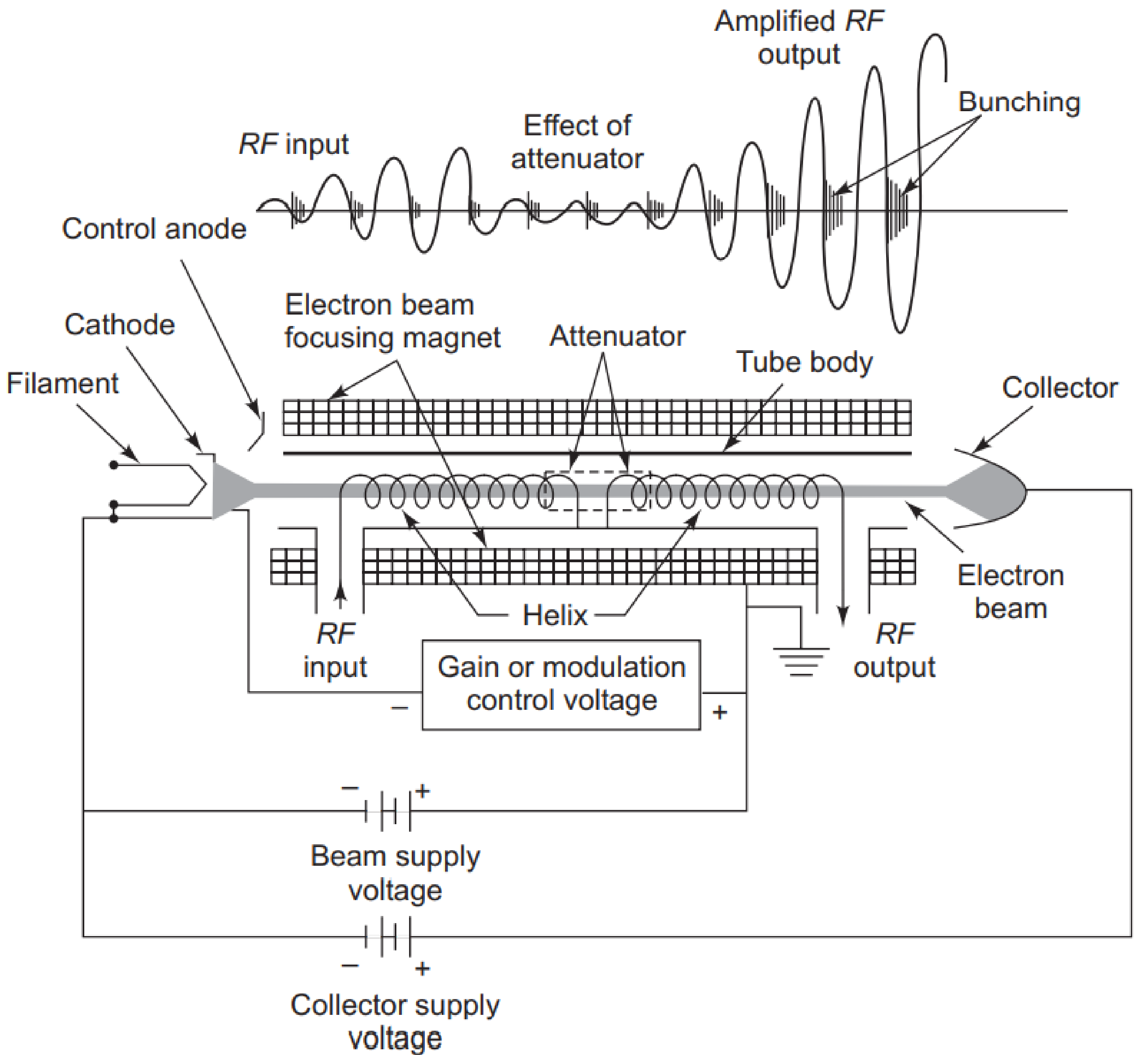
- Density modulation with respect to input signal
- Dc beam velocity slightly greater than v_p (phase velocity of traveling wave)
- More electrons face retarding field than accelerating field:
- More energy is transferred from kinetic energy of electrons to the electromagnetic field.



Source: Microwave engineering by Annapurna Das

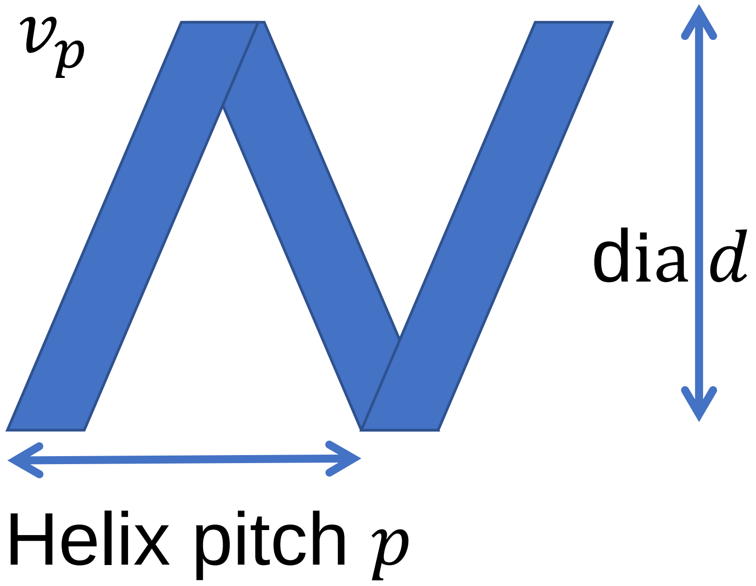
4.2 Role of attenuator, Cooling systems

- Attenuator: Placed over part of Helix on midway
- Attenuates reflected wave due to impedance mismatch
- Reduces the gain

- Cooling: Through air-conditioning or liquid-cooling systems

5.1 Analysis of TWTA: Wave propagation in Helix

- Signal travels at close to velocity of light c along the helix conductor profile
- Helix reduces the phase velocity of RF signal to v_p
- Electron beam velocity $v_e > v_p$ (slightly)
- d: diameter of helix, p: helix pitch



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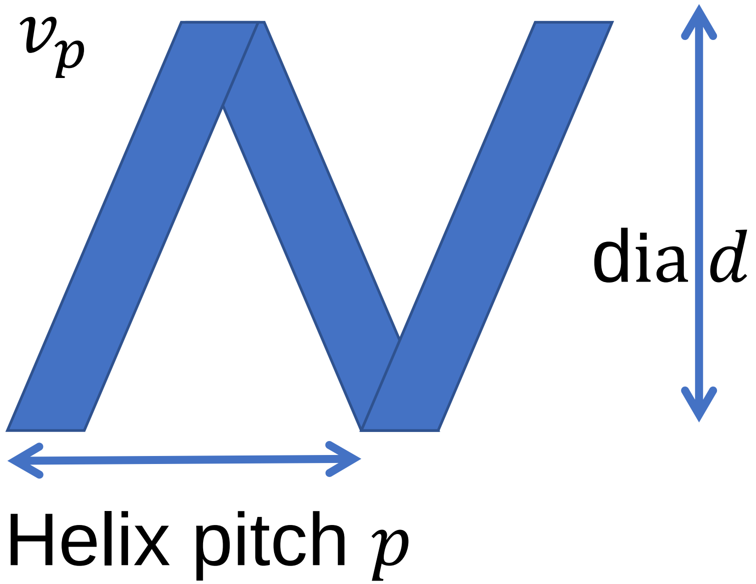
time taken by axial component of E(E_z)

- $T = \frac{p}{v_p} = \frac{\sqrt{p^2+(\pi d)^2}}{c}$ $2\pi r = \pi d$ (Circumference)



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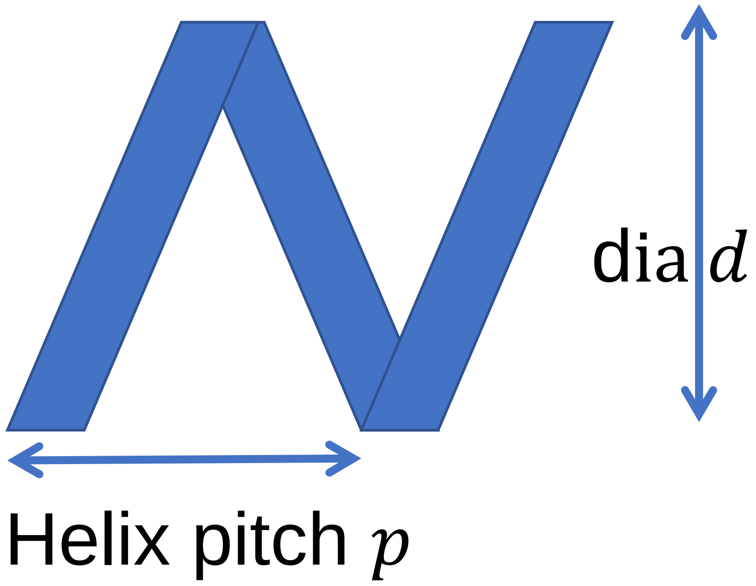
- $v_p = \frac{cp}{\sqrt{p^2+(\pi d)^2}} \approx \frac{cp}{\pi d} \approx \frac{\omega}{\beta}$



5.2 Gain characteristics

- Detailed theory and design developed by Pierce:

$\cancel{-9.54 + 476.3NC \text{ dB}}$

Output power gain: $A_p = 10\log_{10}\left|\frac{Output\ voltage}{Input\ voltage}\right|^2 = -9.54 + 47.3NC \text{ dB}$

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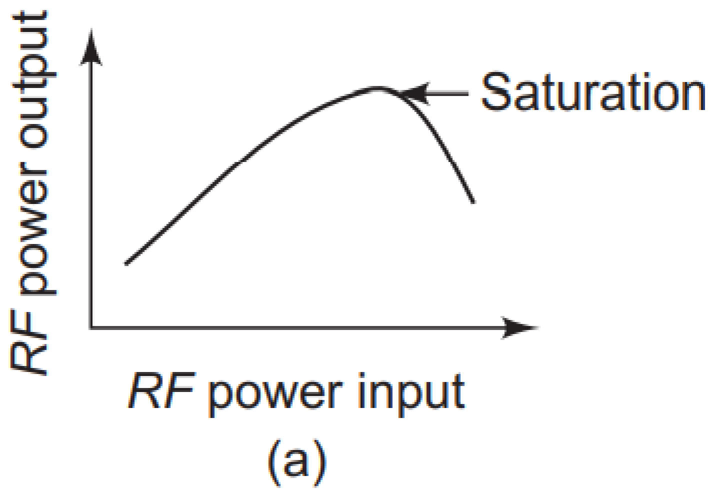
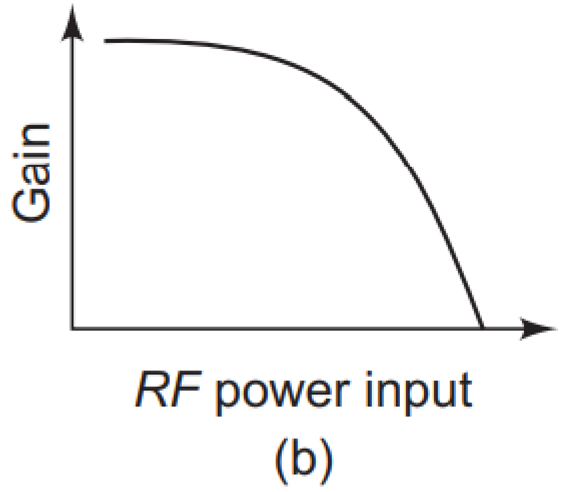
- I_0:Beam current, V_0: Beam voltage, Z_0: characteristic impedance of helix

5.3 RF Characteristics

- Output power saturates after increase in input power beyond a certain value : Saturation point
- Gain drops beyond saturation RF output





Problem:A helix travelling-wave tube operates at 4 GHz under a beam voltage of 10 kV and beam current of 500 mA. If the helix impedance is 25 ohms and the interaction length is 20 cm, fi nd the output power gain in dB.

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- $u_0 = 0.593 \times 10^6 \sqrt{V_0}$
- $N = \frac{l}{\lambda_e} = l \frac{\omega}{2\pi\mu_0} =$
- $C = \left(\frac{I_0 Z_0}{4V_0}\right)^{1/3}$
- (Wrong: $\cancel{A_p = -9.54 + 476.3NC \text{ dB}}$)
- Correct gain: $A_p = -9.54 + 47.3NC$ dB

- https://www.youtube.com/watch?v=LKX5VCnntX0&pp=ygUedHJhdmVsaW5nIHdhdmUgdHViZSBhbXBsaWZpZXIg
- https://www.youtube.com/watch?v=ndxbBIMLXEs&pp=ygUedHJhdmVsaW5nIHdhdmUgdHViZSBhbXBsaWZpZXIg