

## CHAPTER – 2

### TRAVELLING WAVE TUBE OPERATION

In order to design a helix-type traveling wave tube amplifier (TWTA), it is necessary to understand the operating physics of a travelling wave tube (TWT). This chapter provides the basic description of the TWT structure and its various components. The functionalities of these components are briefly explained in order to have a basic knowledge about the different practical constraints in modelling a TWTA. As the focus of the research is on helix-type slow wave structures, the associated electromagnetic theory and mathematical techniques are dealt in detail towards the end of the chapter. We will assume the Pierce theory of small-signal TWT interaction and discuss its use and the basic TWT metrics needed for the design of an interaction structure.

#### 2.1 TWT Operation – An Overview:

The basic structure of the TWT is as shown in Figure 2.1. TWT consists of four major components generally assembled in the configuration shown in Figure 2.1. The electron gun generates the electron beam, which is confined by a distributed magnet system into the helix slow wave structure's beam tunnel. A helix-like slow wave structure is used for the electron wave beam interaction and a collector at the end of the tube stops the electron beam after it has travelled through the tube.

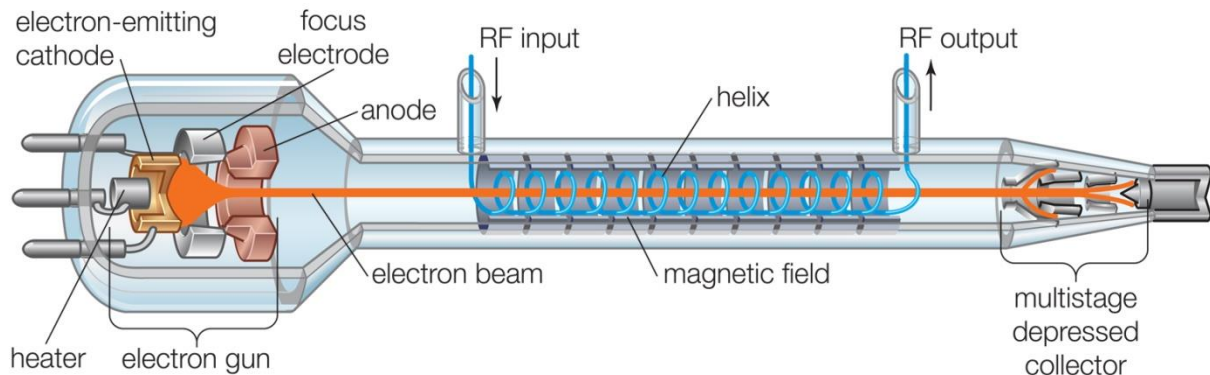


Figure 2.1 Basic TWT Structure. Source: [www.brittanica.com](http://www.brittanica.com)

### 2.1.1 Electron Gun

Electron guns, for TWTs, are designed to output an electron beam with circular cross section with current  $I_0$  at a voltage  $V_0$ . Such electron beams are often called pencil beams or O-beams for their round long shape. Electron beams are generally generated either by thermionic emission or field emission. In thermionic emission, electrons are generated by heating the cathode of the electron gun to a temperature typically between  $750^\circ\text{C} - 1200^\circ\text{C}$  so that the electrons will have enough thermal energy to be regularly emitted from the surface. The typical voltage applied to this cathode generally varies from several thousands of volts to several hundreds of thousands of volts. These cathodes are generally *oxide coated cathodes* also known as *hot cathodes*. They are a mix of carbonates, sprayed onto a nickel surface, and once heated break down into oxides and provide the source of electrons for the vacuum device. The generated electrons are accelerated by the application of an electric field through the anode surfaces imparting an axial velocity, and travel through the slow wave structure. For a high frequency TWT, where the interaction structure is small and requires a high-density electron beam, the size of the cathode is larger than the size of the electron beam, and with the help of the anode focusing arrangements electron beam of high density are focussed into the SWS structure.

### 2.1.2 Focusing Magnets

The accelerated electron beam tends to diverge while moving through the slow wave structure (SWS) due to space charge forces. When there is large divergence of the electron beam leading to interception by the slow wave structure, it results in the heating of the SWS. Such heating can lead to the destruction of the structure. To combat divergence, an axial magnetic field is applied, forcing the electrons to travel the length of the tube without interception. TWT designs utilize two types of magnet systems: periodic permanent magnets (PPM) and electromagnetic solenoids. A PPM system utilizes permanent magnets to confine electrons. These magnets create magnetic field that confine the electron beam, but the field is not uniform within the length of the SWS. Such a system can be more compact, and weigh less than an electromagnet and does not require a power supply making it potentially more energy efficient. However, PPMs require a complex design to prevent additional beam instabilities. The electromagnetic solenoid easily provides near uniform axial field and has the potential for much higher field strengths. The design of an electromagnetic solenoid is much simpler, compared to a PPM magnet. The general drawbacks

are the requirement of a power supply and the size of the magnet. The minimum field required to stop the beam from diverging is known as the Brillouin field. In practice this field is too small. Beam bunching will cause local density to increase in certain regions; such increases in current density will increase the beam diameter, creating a scalloped beam. For significant bunching, which will occur in high gain TWTs, the beam diameter may increase to such an extent that it will hit the SWS. To prevent the beam from destroying the circuit, the magnetic field is operated at two to three times the Brillouin field level to minimize scalloping.

### 2.1.3 Helix Slow Wave Structures

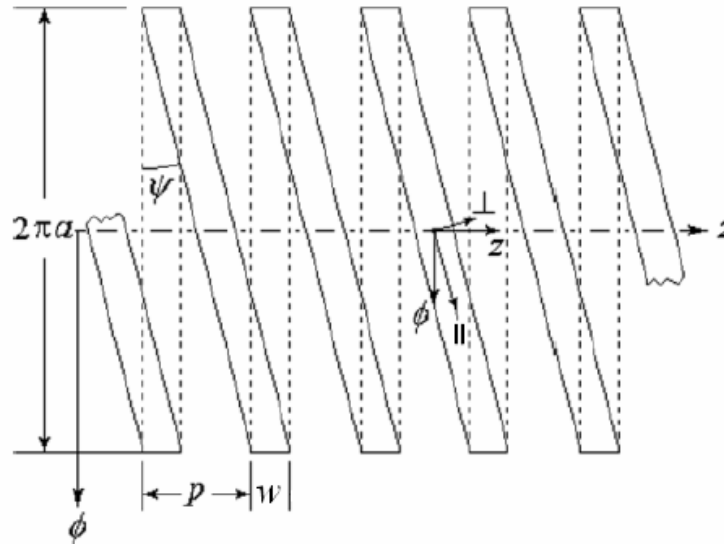
In travelling wave amplifiers and particle accelerators, an electron or ion beam interacts with a travelling electromagnetic wave. For effective interaction, the charged particles (electrons or ions) need to be kept in phase with a retarding field in the case of a TWTA and an accelerating field in the case of a particle accelerator over a distance of several wavelengths. This means that the speeds of the charged particles need to be approximately equal to the phase speed of the wave. The phase speed is the speed with which an observer has to move so as to remain in the same phase of the wave. In general, the phase speed of the EM wave,  $v_p$  is defined as the ratio of angular frequency  $\omega$  to the axial propagation constant  $\beta$ :

$$v_p = \omega/\beta \tag{2.1}$$

Since electrons and ions can only be accelerated to speeds strictly less than the speed of light, we need to look for electromagnetic structures capable of supporting waves propagating with phase speed less than that of a plane wave in free space, i.e., the speed of the light. Such waves are called **slow waves** and the wave guiding structures capable of supporting such waves are called **slow-wave structures**. The earliest slow wave structure used in TWTA is the helix. It is employed in all low and medium-power TWTAs and backward oscillators. The helix is made of a metallic ribbon invariably of rectangular cross section with rounded corners wound into a helical structure. The parameters describing a helix are the pitch  $p$  or turn-to turn spacing in the axial direction, the mean radius  $a$  and the pitch angle  $\psi$ . The ratio of the pitch  $p$  to the circumference  $2\pi a$  is the tangent of the pitch angle  $\psi$

$$\tan \psi = \frac{p}{2\pi a}$$

The above geometrical relation among the parameters may be easily seen from a developed view of the helix in Fig 2.2. The ribbon width of the axial direction is  $w$ . The helix is geometrically simple and easy to fabricate. The helix is usually made of tungsten measuring 0.010-inch by 0.075-inch [24].



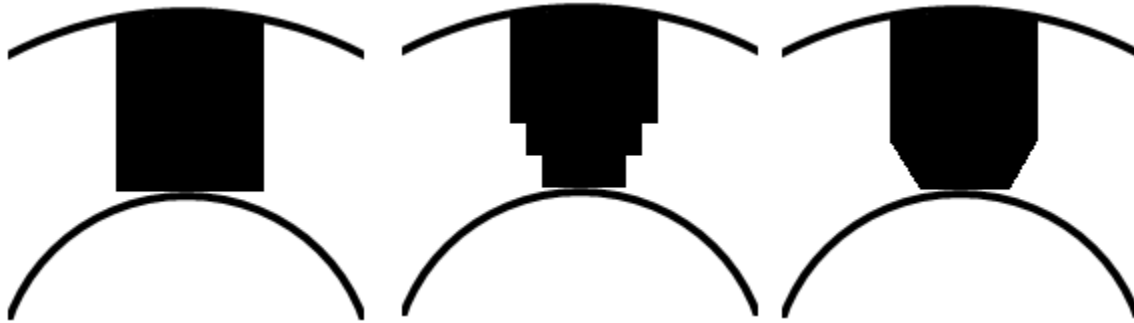
**Figure 2.2** Expanded View of tape Helix [13]

The helix is usually supported by an insulating structure that often takes the form of three equally spaced dielectric support rods as indicated in Fig 2.3a. These support rods are symmetrically disposed along the helix and are usually made of Anisotropic Pyrolytic Boron Nitride (APBN) commonly known as CVD, Boron Nitride or Beryllium Oxide (BeO). The dielectric support rods have permittivity varying between  $\epsilon_r = 3$  to 8.3 as shown in Table 2.1. It should be noted that diamond has a very large value of thermal conductivity and this is why there has been strong interest in using diamond for many years. The helical slow wave structure along with the dielectric support rods are shielded by a coaxial metallic cylindrical envelope (running along the entire length of the helix).

**Table 2.1** Permittivity values of various dielectric support rods

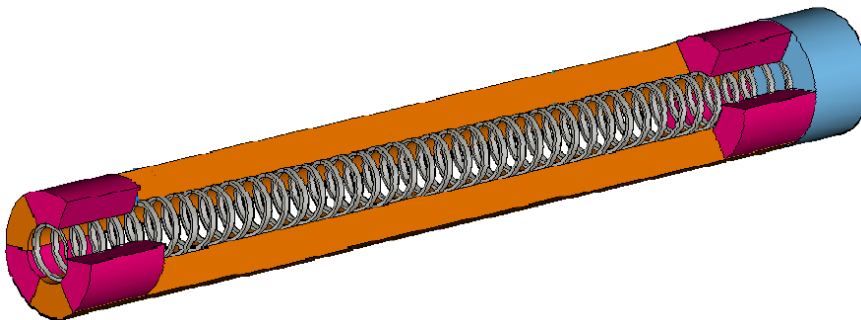
<i>Dielectric Materials used as support rods in TWTA</i>	<i>Relative Permittivity (<math>\epsilon_r</math>)</i>
Isotropic Pyrolytic Boron Nitride	3.0
Anisotropic Pyrolytic Boron Nitride	5.2
Diamond	5.58
Beryllia Oxide ( <i>BeO</i> )	6.3
Alumina ( <i>Al<sub>2</sub>O<sub>3</sub></i> )	8.7

Dielectric support rods are typically rectangular in shape. Sometimes they are shaped as shown in Fig 2.3.



**Figure 2.3** Typical cross sections of dielectric support rods

In this thesis, dielectric support rods of wedge type is assumed with Beryllia as the dielectric material as shown in Fig 2.4. From table 2.1, it is seen that Beryllia has a permittivity,  $\epsilon_r = 6.3$ .



**Figure 2.4** Actual helix with wedge shaped dielectric support structure

### 2.1.4 Collector

After the amplified RF output is ported out from the TWT, the spent electron beam passes through the end of the beam focusing section and space charge forces cause the beam to expand as it enters the collector. Upon entering the collector, the beam is highly disordered with a broad spectrum of energies and spreads out as shown in Fig 2.5. The electron beam at this point still possesses a large amount of kinetic energy as only about 5 to 30 percent is extracted during interaction with the RF wave. If the collector were at the same potential as the body of the tube, this kinetic energy would be dissipated as heat on the collector surface. By operating the collector electrode at a potential below that of the RF circuit, the beam is decelerated before it hits the collector surface. Thus, some of the remaining kinetic energy from the electron beam is converted to electric potential energy. This negative potential operation is known as depressing the collector. The greater the amount of recovered power, the higher is the total efficiency of the tube. The impact of an efficient collector is made clear by considering the efficiency formula. Overall efficiency can be expressed as the ratio of the output power to input power or

$$\eta_{ov} = \frac{P_{out}}{P_{in}}$$

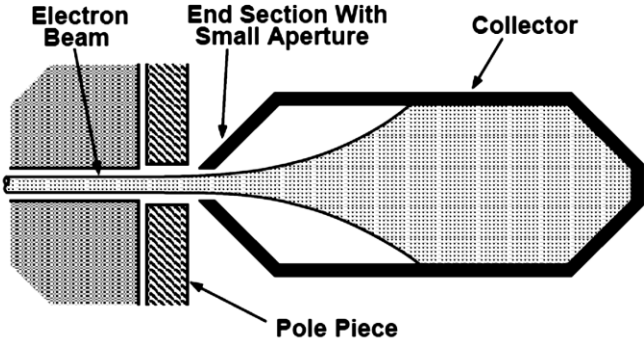
where  $P_{out}$  is the RF power output and  $P_{in}$  is the input power expressed as

$$P_{in} = P_h + P_o + P_m + P_{RFin} - P_{rec}$$

where  $P_h$  is the heater power,  $P_o$  is the beam power from the gun,  $P_{RFin}$  is the RF input power,  $P_m$  is the power to the magnetic focusing system and  $P_{rec}$  is the power recovered by the collector.

Several phenomena complicate the collector operation including space-charge effects of the electrons already in the collector repelling those electrons entering, secondary electron emission from the surface caused by incident electrons, and electrons having different amounts of kinetic energy, thus traveling with different velocities. Multistage depressed collectors (MDC), where several electrodes are used at different depressed potentials, incorporate multiple velocity sorting stages. This directs high velocity electrons to the stages having the greatest depression and the slow electrons to the stages with the least depression. This design has proven

to greatly increase the overall efficiency of TWTs. In practice, typical MDC designs incorporate no more than five collector stages.



**Figure 2.5** Collector for a linear beam tube