Chapter 29

Electron Linear Accelerator for Radiotherapy

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29.1 Introduction

Electron Linear accelerators (linac) are used worldwide for medical treatment. Ever since the medical linear accelerators were introduced for radiation therapy in 1950s, this technology has successfully replaced the radionuclide based (Co-60) radiation sources [136]. The common applications that use medical linac system are the "External Beam Radiotherapy" and the "Intra-Operative Radiation Therapy" (IORT), where the radiation is directly delivered at the treatment site during surgery. This chapter gives a brief overview of the design philosophy of compact linac based X- ray source machine for cancer treatment.

29.2 Overview of the Medical Linac System

Medical linac based systems are prevalent in S-band (3 GHz) frequency. But for more advanced treatment techniques like tomotherapy and stereotactic radiotherapy (Fig. 29.1), where the real time imaging is required along with radiation therapy, more compact and light weight linacs are required. Electron linacs at X-band frequency are good candidate for such application. The X-band medical linacs which usually operates at 9.3 GHz frequency offers several advantages for medical application such as small size of the X-ray source, light weight, higher shunt impedance value as compared to S-band linac, short fill time for RF, and higher accelerating gradient and higher breakdown level which scales with operating frequency of the linac.

Figure 29.1: CyberKnife: A linac based radiation delivery system [145].

29.2.1 Operation Principle of a Medical Linac

A linear accelerator is a device that accelerates electron to a desired energy level in a linear beam line. Electron linac consists of electron beam source which is known as electron gun. Electron beam from the gun exit is injected into RF cavities for further acceleration of beam to higher energy level (typically around 4-8 MeV). RF power sources like klystron or magnetron are required to energize the RF cavities for electron accelerations. For a medical electron linac, the accelerated electron then hit a suitable target of high Z material to produces high energy X-ray. The high energy X-ray will be directed to deliver radiation to patient's tumor.

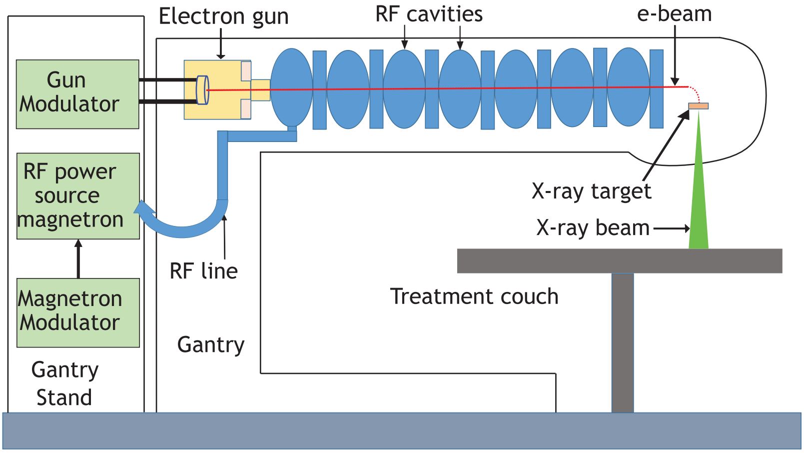

Figure 29.2: Schematic of medical linac.

29.2.2 Key Components of a Medical Linac

The medical linac components can be broadly divided into two parts namely internal and external components. Figure 29.2 depicts some of the key components of a linac based radiotherapy machine.

Internal Components

a. Electron gun and gun modulator: Electron gun or electron beam source is an integral part of the linac system. It is the first building block of the linac assembly. The function of the gun is to deliver electron beam of desired voltage and current for further acceleration in the RF cavity section. The gun modulator power supply system generate the gun voltage micro pulse with pulse width typically 2-10 μs and PRF (typically 100-200 Hz).

b. Linac RF cavities: A series of RF cavities are sued to accelerate beam up to desired energy level. The linac RF cavities are made of OFHC copper and they are powered by the RF power source. As the electron beam is injected into the RF cavities they are bunched inside and gain energy as they travel along.

c. RF power sources: For RF power sources Klystron or magnetron are used at the linac design frequency to generate MW level peak power.

d. RF Line components: For transferring power to RF cavities from RF sources, RF plumb line is required which consist of several combinations of waveguides, waveguide bends, RF circulator with RF load, RF transmission window, pressurized section of RF waveguide, directional coupler for power measurement etc.

e. X-ray target and treatment head: Accelerated electron beam from RF cavities are focused into an X-ray target for high energy X-ray production. The target is housed inside treatment head which also house scattering foils, beam shaping collimators and the optical distance indicator etc.

f. Auxiliary systems: The whole linac from electron gun to X-ray target should be kept at ultra-high vacuum level for its operation. Vacuum line components like TMP, SIP, pressure gauges, and gate valves are required. Water or air cooling system is required for efficient heat removal due to microwave power losses inside linac cavities to maintain a stable operation of linac.

External Components

a. Treatment couch: The treatment couch mainly supports and positions the patient during treatment. The couch is given 3D movement for accurate patient positioning.

b. Electronic portal imaging device (EPID): The electronic portal imaging device forms an image using the MV treatment beam for real time monitoring during treatment.

c. Gantry: The linac is housed inside rotating gantry which can deliver treatment to the patient from multiple angles.

d. Gantry Stand: The stand contains electronics and other auxiliary systems required for linac operation. It also connects the gantry to the treatment room floor.

29.3 Accelerator Design for a Medical Linac

The design of the medical linac [146] is crucial for its reliable operation. In this chapter we discuss the design criterion of different linac components in detail.

29.3.1 Electron gun

Electron Gun Design

Electron gun is an essential component of any electron accelerator system. The electron beam produced by an electron has particular voltage and current rating. Beam size and emittance of the beam are also crucial parameter for injection of the beam in to accelerating RF fields. There are two important aspects for a gun design.

Selection of Cathode Material for Electron Generation

There are different emission process namely, thermionic emission, field emission, photo emission. The most widely used method to generate electron current in a linac system is thermionic emission where a cathode is heated at high temperature to produce electron beam. The Current density produced by a cathode material is governed by Richardson Dushmann equation where current density J is given as a function of cathode temperature in Eq (29.1)

$$J = AT^2 exp(-\frac{e\varphi}{kT}) \tag{29.1}$$

Where φ is the work function of the material, k is the Boltzmann constant and T is the operating temperature of the cathode. The value of $A = 1.2 \times 10^6$ A/m^{2}K^2 is Richardson's constant. The ideal candidate for cathode material is a material having high melting temperature and low work function. Typical cathode materials are Tungsten, Thoriated Tungsten, Lanthanum hexaboride (LaB_6), and dispenser cathode. Figure 29.3b depicts a single crystal LaB_6 cathode assembly with molybdenum heat shield and heater assembly to be employed in an X-band linac system. The cathode size is decided on the basis of current rating of the beam and beam size required at the gun exit. For instance, for an X-band linac, the beam size at the linac RF section input should be less than 2 mm with beam current at 250 mA. A cathode with ∼3 mm diameter can generate required amount of current in such an electron gun system and can be also focused to produce desired beam diamater.

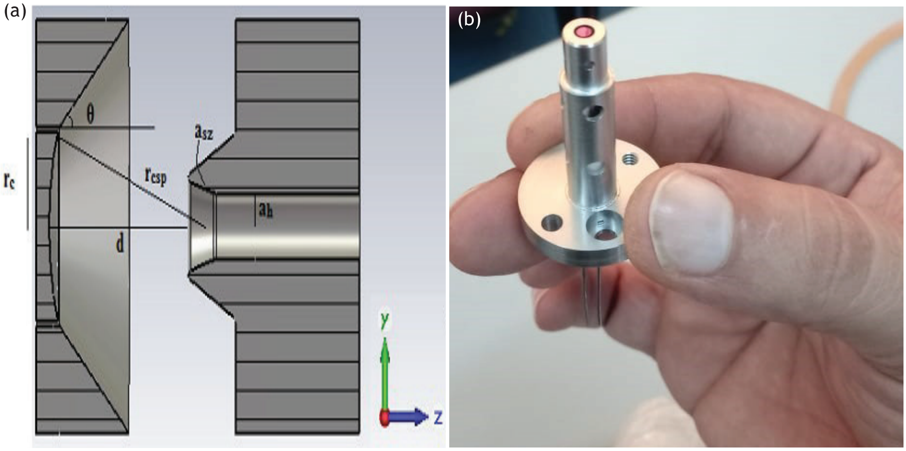

Figure 29.3: (a) Electron gun diode architecture, and (b) single crystal LaB$_6$ cathode assembly.

Design of the Electron Gun Geometry

The electron gun geometry can be of two types namely diode geometry and triode geometry. Triode geometry has an additional electrode called grid which is used for current modulation. Usually for designing an electron gun for linac system we use Pierce diode geometry which uses a focussing electrode to focus beam into desired beam size at the injection point. For a diode geometry gun, the focusing electrode and cathode is floated at the negative potential and the anode is grounded. Figure 29.3a shows the schematic of a typical gun geometry. The electron gun to be designed should operates at space charge limited emission regime. In a space charge limited region (SCL) of operation, the current density is as a function of applied voltage (V) and given by

$$J = PV^{\frac{3}{2}} \tag{29.2}$$

Where P is the perveance of the gun which is purely depends on the gun geometry. Design of an efficient electron gun depends on the design of the electron optics system which provides the electron beam with exact perveance and the beam focusing system which confines the beam for transport in the accelerating tube. The gun parameters such as the gun convergence half angle (θ), the cathode disc radius (r$_c$), spherical radius (R$_c$), the anode-cathode spacing (z), the radius of the anode aperture (r$_a$) and the beam cross-over point (z) are to be optimized for design simulation of the gun. One can use a numerical code or a commercial software for trajectory calculation for iteratively solving the optimized gun parameter. Figure 29.4 depicts one such simulation result of an electron gun for X-band medical linac. The preliminary gun geometry was obtained from MATLAB simulations [26] and had been verified and altered by performing simulations with a 3D particle tracking code "CST particle Studio" [147]. The solver tracks electron particles in pre-calculated electromagnetic fields by using Lorenz force equations. Gun iterations option has been used which take care of space charge effects on electromagnetic fields while tracking. From simulation result it is evident that beam diameter $\sim$400 μm at the anode exit has been achieved at the design perveance value (0.08 μPerv) of the gun.

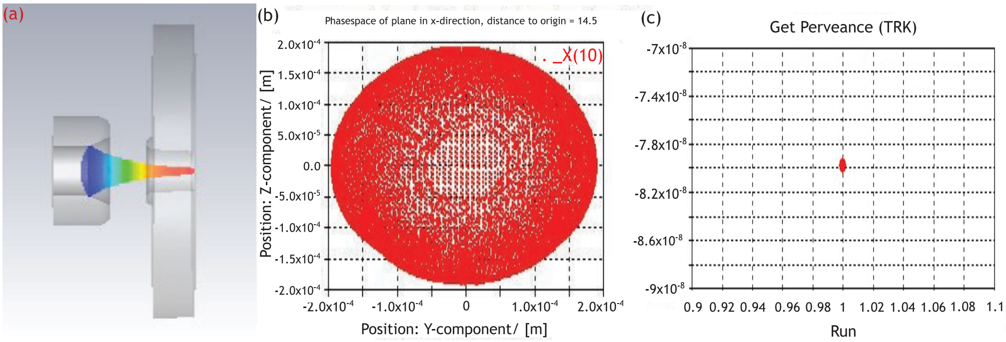

Figure 29.4: CST-PS simulation results: (a) Electron trajectory, (b) Beam size at the electron gun exit, (c) Simulated Perveance.

Electron Gun Development and Testing

After the design simulation, different components of electron gun (as can be seen in Fig. 29.5) are fabricated, assembled and tested at gun test bench before deploying it in a linac system. Figure 29.5 depicts the components and assembly of one such gun for X-band medical linac. The electron gun was tested in an in-house developed test facility. The base vacuum of the experimental setup was maintained at 10^{-7} mbar vacuum level or better. After establishing the vacuum in the gun chamber, filament conditioning of the gun is carried out. Depending on the cathode material and operating temperature of the cathode power requirement for filament varies. For a single crystal directly heated type LaB_6 cathode power requirement is roughly 16 W for cathode temperature ∼1600 K. The power requirement increases for an indirectly heated cathode assembly. For a medical electron gun, compactness and overall weight reduction of the gun are important. Hence, thermal management becomes important for one such gun assembly. Refractory material like Molybdenum or Rhenium is used as heat shield for cathode assembly. Once the filament conditioning is done we apply DC pulsed negative HV from gun modulator system to cathode and focusing electrode terminal. The typical pulse duration from the gun modulator output is 2-10 μs. The beam current was measured using fast current transformer (FCT) which is in line with the beam. Experiments are then performed to record I-V characteristics of the electron gun. Figure 29.6 depicts the experimental results of an X-band gun. The Fig. 29.6a and b shows FCT signal at -20 kV and -40 kV respectively. From the figure it is evident that gun operates in space charge limited domain where the beam current varies as a function of applied voltage which is desirable since the beam current is independent of the cathode temperature fluctuation. Table 30.1 compares the result of simulation and experimental values with design goals. As evident from the result, experimental results are in good agreement with the simulation results.

Table 29.1: Comparison of Results.

Parameter	**Design Value**	**Simulation result**	**Experimental result**
Beam Voltage (kV)	20	20	20
Beam Current (mA)	230	227	224
Pulse Duration (μs)	4	4	10
Pulse Repetition (Hz)	250	250	Up to 20
Gun Perveance (μPer)	0.081	0.08	0.079

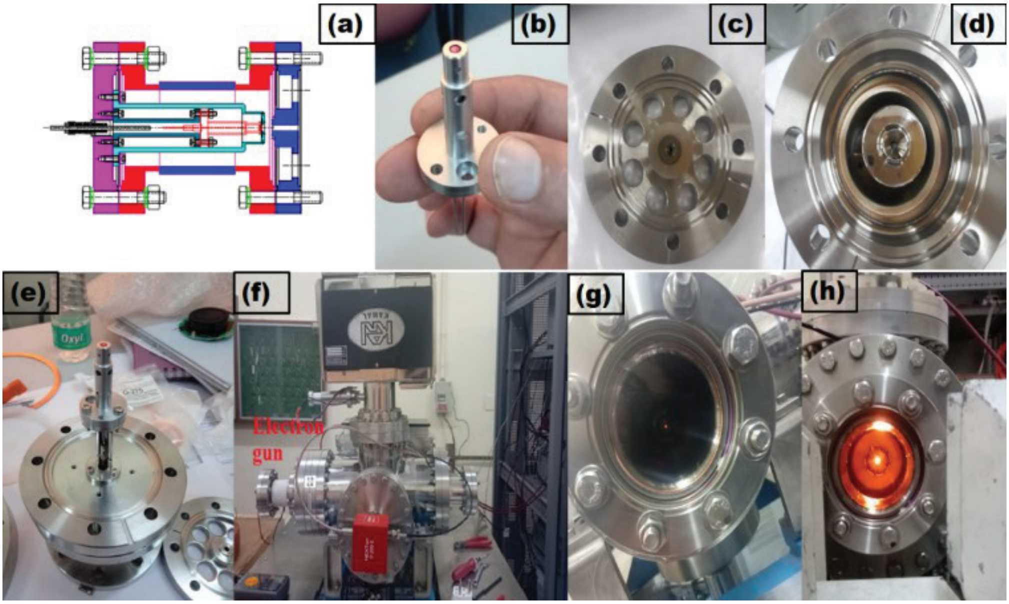

Figure 29.5: (a) Fabrication drawing of electron gun components, (b) single crystal LaB_6 cathode with heater assembly, (c) Anode flange, (d) Focusing electrode assembly, (e) Cathode assembly (f) Integration of X-band electron gun with test set up, (g) faint glow of cathode at 1200 K, and (h) Bright glow of cathode at 1600 K.

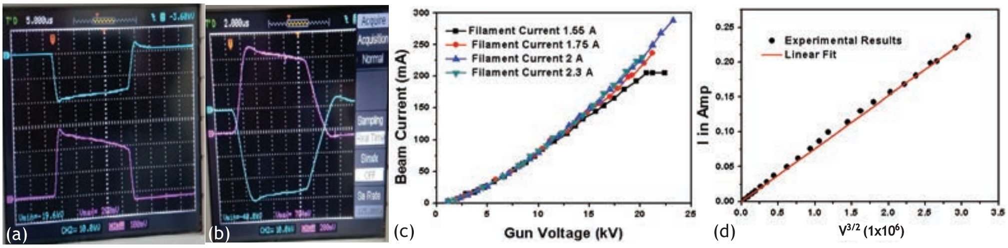

Figure 29.6: Experimental results: (a) & (b) FCT signal at -20 kV & -40 kV respectively; (c) I-V characteristics of gun, and (d) Experimentally calculated perveance.

29.3.2 RF Cavity

RF cavity of the linac is the most important part in linac design. In the following section, the design philosophy and development aspects of the RF cavity has been touched upon.

RF Cavity Design

Selection of Frequency and RF Structure

The design of accelerating cells starts with the frequency selection. The diameter of the cavity is inversely proportional to the frequency of the cavity structure. For medical linac application, higher frequency is preferred because of the compactness of the structure. A bench top linac at X-band (9.3 GHz) frequency is ideal. Another criterion for frequency selection is the availability of RF power source and RF line components at the operating frequency of the linac. Unavailability of high power RF sources at higher frequency and also the thermal management of normal conducting linac cavities due to RF power loss are the two reasons that impede development of linac at even higher frequency. For the RF linac there are two different RF structure for acceleration namely standing wave (SW) structure and travelling wave (TW) structure. In a SW linac system microwave power is fed into coupled cavity oscillator where both ends are effectively shorted. As the wave propagates and get reflected back and forth they build up a standing wave pattern inside linac structure. If the electron beam is injected in the proper phase, the beam should see proper electric field and will be accelerated in the cavity. In TW linac on the other hand, RF power enters at the cavity structure and travels through the coupled cell structure and gets absorbed in the RF load at the end of the cavity section. The electron beam also propagate along with RF power in synchronous phase and accelerates as it travel through the linac structure. There are two different types of TW linac structure constant impedance and constant gradient structure.

Design simulation of RF structure

In APPD, for the linac design, on-axis coupled SW cavity structure has been considered which operates at "$\pi/2$" mode. The cavity section has both accelerating as well as coupling cells where the cells are magnetically coupled to each other. The advantage of using "$\pi/2$" mode is the stable operation against frequency perturbation. There are three different aspects for design simulation of RF cavities. The first being RF design of the cavity. For RF design simulation of the cavity 2D cavity tuning program like "SUPERFISH" or 3D eigen mode solver like "CST Microwave studio" are used. The cavity structures are optimized through simulation to achieve required RF parameters of the cavity like frequency, Q value, Shunt impedance, effective shunt impedance etc. For the full RF cavity structure design beam dynamics simulation is essential. For the linac structure, beam dynamics simulation using computer codes like "ASTRA" is usually carried out from gun exit to the end of the accelerator. For instance, the X-band linac has total 49 cells with 24 accelerating cells and rest coupling cells. The overall structure of the cells have been decided on the basis of RF and beam dynamics simulation. Figure 29.7 shows the ASTRA simulation result for the X-band linac [148]. The thermal and mechanical simulation of the RF cavity is also important. The structural changes in the cavity due to heating has the capability to detune the cavity structure. An efficient heat removal system from the cavity surface needs to be employed.

RF Cavity Fabrication and Testing

After finalization of the design, the linac cavity structure are made from OFHC copper. Precision fabrication of the cavities is needed in order to maintain the dimensional tolerances within ±10 microns and surface finish of ±0.4 micron. Each cell is fabricated separately and then all of them are brazed together. Cooling jackets are welded over the linac structure and its end flanges. Figure 29.8 shows the schematic of RF linac structure assembly with actual photograph of the brazed 6 MeV X-Band Linac structure. The low power testing of RF cavities are done using Vector network analyzer (VNA) to measure cavity RF parameters before and after brazing.

29.3.3 RF Line of the Linac

Microwave power sources are required to provide RF power in the linac cavity structure. The RF power is coupled to cavity structure through RF coupler to develop electromagnetic fields in the cavity to accelerate the electron beam. Depending on the final energy and power requirement of the beam, RF sources chosen at the cavity operating frequency. High power magnetron and klystron are the two RF sources which are typically used to power

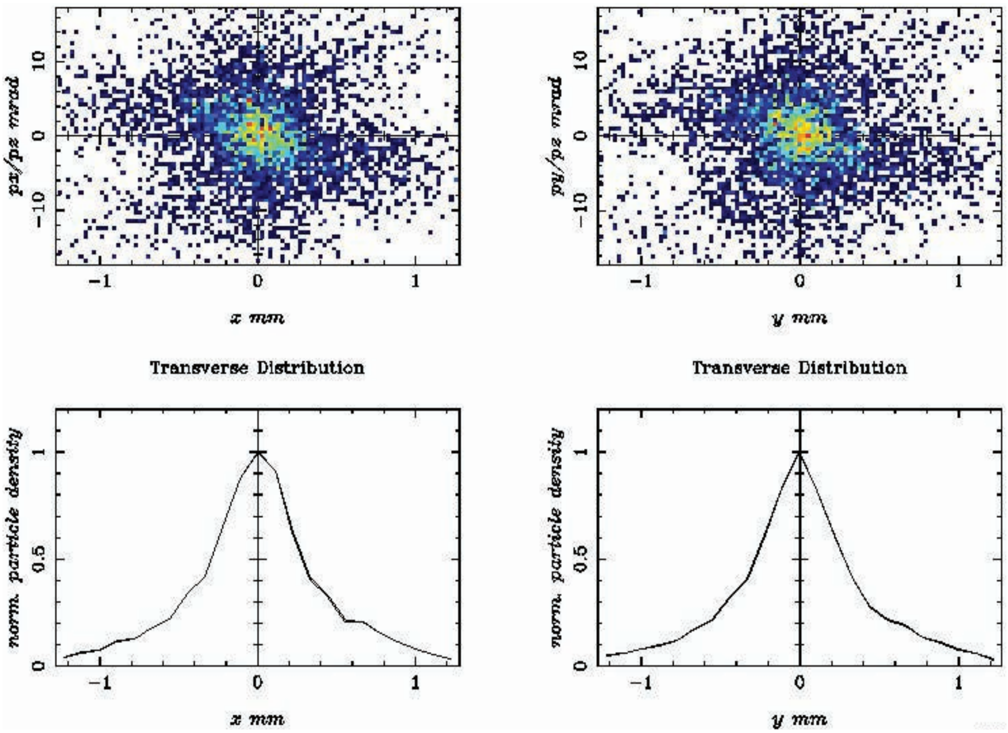

Figure 29.7: ASTRA simulation of Transverse phase space of electron beam at the linac output.

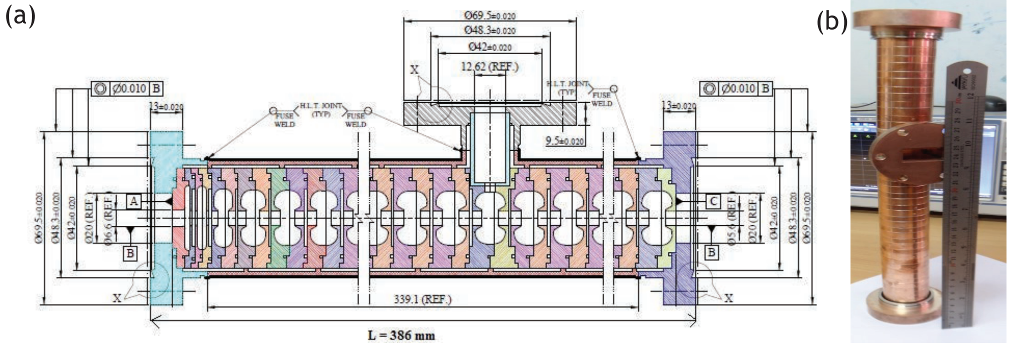

Figure 29.8: (a) X-band cavity mechanical assembly drawing, and (b) Brazed RF cavity structure.

linac. For instance, in a medical linac using X-rays at maximum beam energy of 6 MeV and maximum average beam power of 1.0 kW, the RF source required should have peak power capability in the range of 2-2.5 MW. Magnetron based RF sources are best suited for medical application due to its compactness, non-requirement of external drive input power and lower cost. Figure 29.9 depicts the layout of the RF line with RF sources and other components. The magnetron also requires a pulse modulator known as magnetron modulator to be fed with pulsed power. RF Power generated from the source is coupled to the linac through the waveguide line and RF window which all operates at the same frequency as that of linac. The RF line includes 3-port circulator with RF load for protection of the RF power source, a pressurized waveguide section to transmit power without breakdown, directional coupler for power measurement.

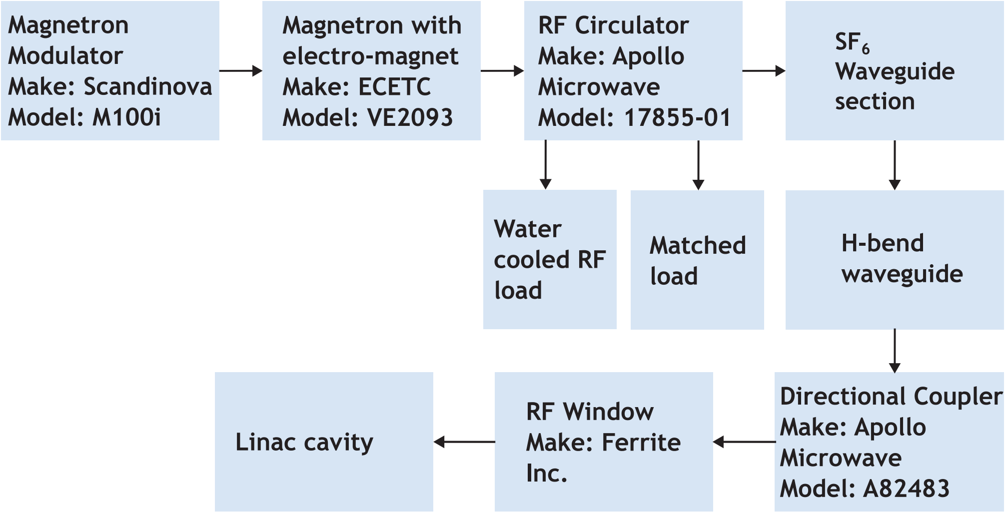

Figure 29.9: Schematic of RF line with RF source and other components.

29.3.4 X-ray Target

The medical linac based system requires high energy sources for radiosurgery application. High energy electron beam from linac output hits a suitable X-ray target and produces required doses of X-ray. High Z materials like Tungsten and Pb are selected to improve X-ray conversion efficiency. Simulation using Monte Carlo method based code (e.g. FLUKA) is required to decide the thickness of the target material and also thickness of leakage electron attenuator plate. The X-ray target is also subjected to heat load from electron beam which is required to be removed for reliable operation of linac. The thermal and structural simulation using finite element based software (e.g. ANSYS, COMSOL) is also required for target design. Figure 29.10 shows the actual image of an X-ray target for X-band medical linac. The X-ray target material is W. Copper channels for water cooling is also provided for efficient heat removal from the target.

29.3.5 Auxiliary Components of Linac

The other auxiliary components of the linac system includes, vacuum system for maintaining UHV vacuum level $\sim 1 \times 10^{-7}$ mbar or better inside RF cavities, split type of water chiller system for cooling, linac control and monitoring system and shielding of the linac for its safe operation.

29.4 Conclusion

One of the most important application of RF linac systems for societal application are medical linacs for cancer treatment. This chapter gives a brief overview of the working principal of

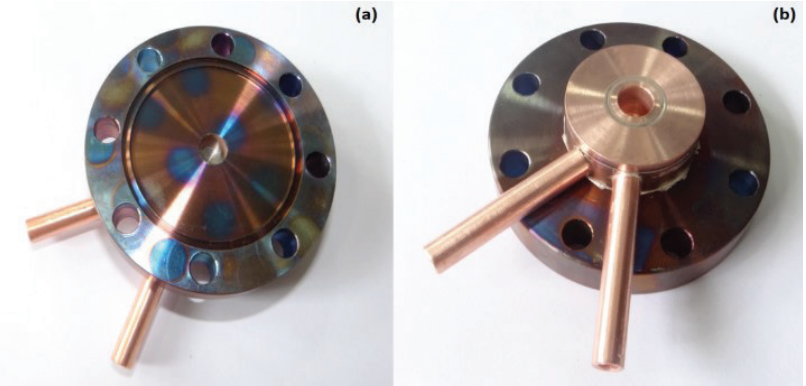

Figure 29.10: X-band target: (a) vacuum side of the target, and (b) Outer part of the target.

RF linac based medical devices. The chapter also discusses the design criterion of different sub systems of a medical linac assembly.