Chapter 26

High Power RF Sources for S-Band Electron Linac

– Shiv Chandan

For Industrial and Cargo scanning applications, high power RF sources based on Klystron & Magnetron are widely used [133]. Electrons are accelerated in presence of electromagnetic fields in Linac cavity. RF waveguide components are cold tested at low power on Vector network analyzer (VNA) and then leak tested using SF_6 or nitrogen. The RF sources are tested on matched water load & then connected to Linac beam line. Cavity is RF conditioned without any beam up to peak power level of 1.5 MW and then loading it with beam above 1.5 MW. This chapter presents the operation of RF sources and their testing details for 10 MeV & 6 MeV Linac. Selection criterion for RF power source is also discussed along with the details of waveguide components.

26.1 10 MeV Linac for Industrial Application

A 10 MeV LINAC is in operation at EBC, Kharghar [134]. This LINAC uses a Toriymake Klystron at 6 MW peak power with duty cycle of 0.4% (i.e. 10μsec, 400 Hz) operating at 2856 $\pm$5 MHz. Klystron is powered by line type pulse modulator operating at 55 kV, 240 A. RF Power generated from the Klystron is coupled to the Linac through the waveguide plumb-line, which includes flexible waveguide sections, E & H-bends, 4-port circulator, water load, directional coupler & RF window. Circulator protects the Klystron from reflected power due to mismatch between Linac and RF source. The directional couplers are used to measure the forward and reflected power. RF bends changes the physical orientation of waveguide line in the desired direction. RF driver amplifier of 150 W gives low RF power to Klystron input cavity for amplification. Klystron amplifies this RF Signal to the power level as required by the Linac. Specifications of Klystron-based RF source are given in Table 26.1. Klystron is

Table 26.1: Specifications of Klystron based RF source.

Parameters	**Value**
Operating Frequency range (MHz)	2856 $\pm$5
Peak RF power (MW)	6
Average RF Power (kW)	25
RF Pulse Width (μsec)	10
Pulse Repetition rate (Hz)	415
Anode Voltage (kV)	55
Anode Current (A)	240
Efficiency (%)	45
Heater Voltage (V)	22
Heater current (A)	26
Load VSWR	1.3

tested on matched water load first. For this, water load is connected at port 2 of circulator. Power is measured using a directional coupler with coupling factor of 55 dB and directivity of 25 dB. A VI characteristic of Klystron is measured in diode mode with 21 μPerveance of beam. Klystron is then tested with RF up to power of 5.5 MW, 200 Hz. The Klystron is tested on LINAC as per schematic shown in Fig. 26.1. RF window is connected between the waveguide line and Linac to isolate the Linac vacuum from the SF_6 pressure in waveguide line. Waveguide line is pressurized with 22 psi SF_6. The schematic for testing the Klystron on LINAC is shown in Fig. 26.1.

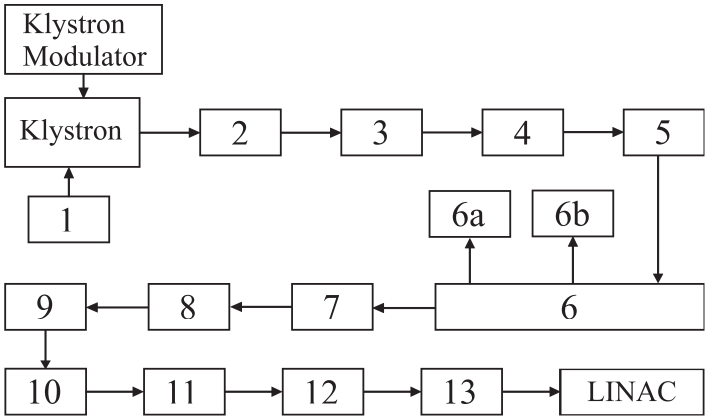

Figure 26.1: Schematic for Klystron testing on LINAC : (1) Driver Amplifier, (2) Flexible waveguide-1, (3) DDC-1, (4) E bend-1 with arc detector, (5) H-bend-1, (6) 4-port Circulator with (6a & 6b) water loads, (7) H-bend-2, (8) E-bend-2 with arc detector, (9) Flexible waveguide-2, (10) DDC-2, (11) Straight waveguide section, (12) Flexible waveguide-3, and (13) RF Window.

26.1.1 RF Conditioning of LINAC Cavity

RF conditioning is started from 0.1 MW. Frequent arcing and out-gassing is observed in the cavity initially. On continuous arcing, Modulator is tripped on detecting the arc through the ARC detector. Also the Linac vacuum level deteriorates to 10-5 mbar range and vacuum fault occurs. Cavity is RF conditioned by varying the Pulse repetition frequency from 10 Hz to 200Hz at each power level of 0.5 MW to 1.5 MW in steps of 0.1 MW. Vacuum level 10^{-7} mbar was maintained during RF conditioning of cavity. Cavity vacuum and reflected power signals are monitored during RF conditioning. Driver amplifier frequency is tuned tominimize the reflected power in 2856 $\pm$0.5 MHz. The reflected power is $<$ 10% of the forward power. Forward power, reflected power and klystron current pulse is shown in Fig. 26.2. Figure 26.3 gives the schematic diagram of RF source used for RF conditioning of Linac. Beam energy dependence on RF power and beam current (Theoretical analysis) is shown in Fig. 26.4. Table 26.2 below shows the RF power requirement for different beam currents for 10 MeV Beam Energy (Experimental values).

Table 26.2: RF power requirement for different beam currents for 10 MeV Beam Energy (Experimental values).

Beam Current (mA)	**RF power (MW)**
50	2.50
100	3.25
150	3.75
200	4.50
250	5.00

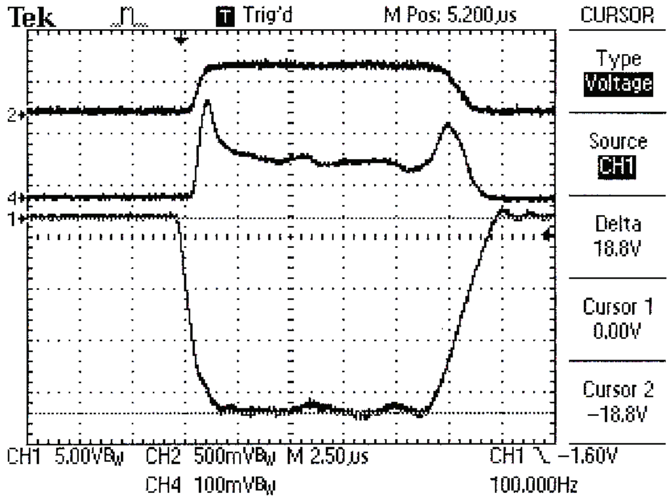

Figure 26.2: Forward power, reflected power and klystron current pulse during testing of klystron on LINAC at 4 MW peak, 4 kW avg. power: Ch1 - Klystron current; Ch2 - Forward power envelope; Ch4 - Reflected power envelope.

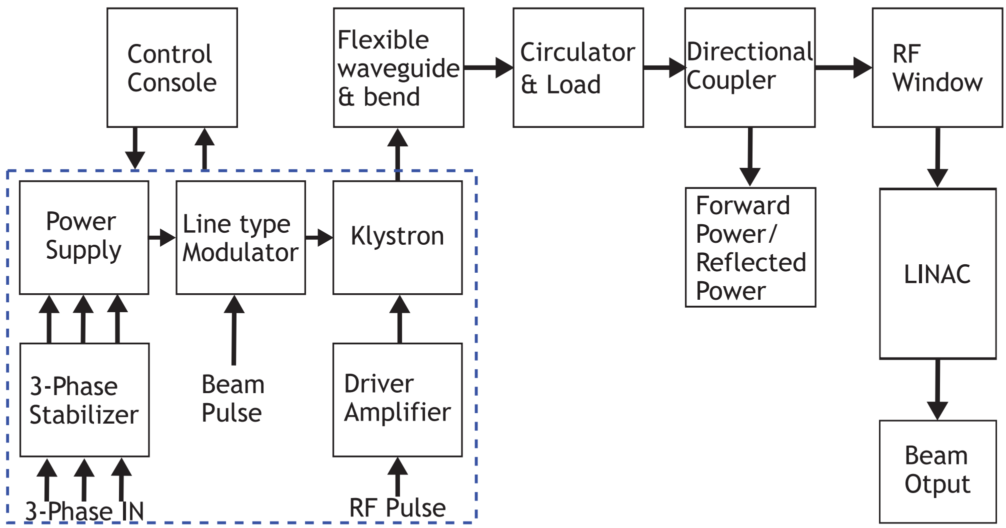

Figure 26.3: Block Diagram of the Klystron based RF Source.

Following are the steps for RF Testing of RF Components before connecting to Linac:

1. Low Power VNA tests of waveguide components: All waveguide components are tested for VSWR (or Return loss) & Insertion loss.
2. Additional test for directional coupler is Coupling factor, Isolation & Directivity. Additional test for Circulator is Isolation.
3. RF Waveguides components are then connected to Klystron output.

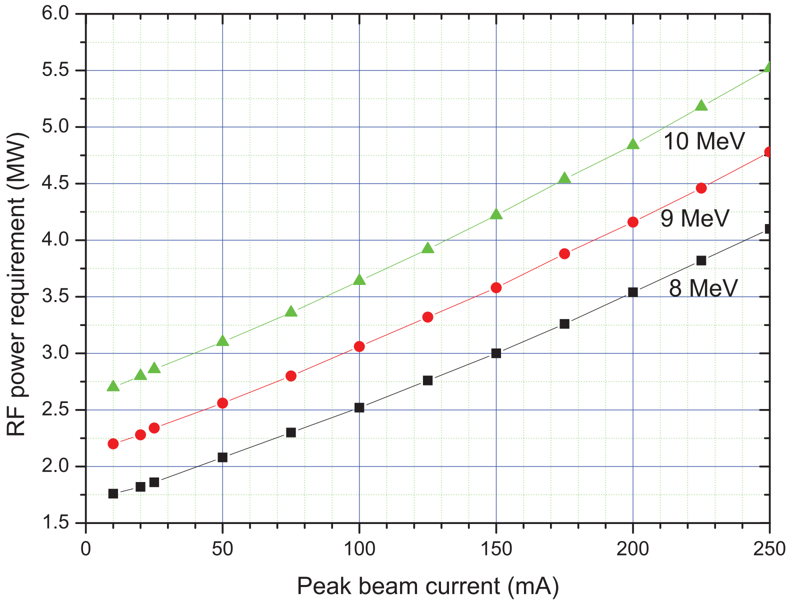

Figure 26.4: Beam Energy Relation with Beam Current & RF Power.

4. SF_6 is filled at 22 psi and checked for any leaks.
5. Driver amplifier is tested separately on matched load. It is then connected to Klystron input
6. Klystron is tested in diode mode (VI characteristics) using Line type Klystron Modulator.
7. Klystron is tested on matched water load. Forward power and frequency spectrum measurement is done.
8. Klystron is then tested on Linac load for RF conditioning up to 1.5 MW without beam and up to 3 MW with beam loading. Forward and reflected power measurement is done.

Following are the Check List for RF Conditioning:

1. LCW Cooling: Check Flow of Individual components
2. Vacuum: All 5 SIP's ON and GV open
3. SF_6 pressure in waveguide line (10 to 22 psi)
4. Klystron SIP ON: Current in μA
5. Check Fan cooling
6. Ozone blower ON, Plug IN door Closed, Radiation meter ON
7. Search & Secure should be OK.

Following are the RF Conditioning Steps:

1. Start Klystron Filament heating at 22 V, 26 A (~57 0W) for 20 min.
2. Give the trigger pulse to Klystron Modulator and RF Driver Amplifier.
3. Switch ON the Klystron driver. Increase the RF setting to 85 for saturated output.
4. Switch ON the Klystron Modulator.
5. Increase HV to increase the RF power in steps of 0.1 MW and PRF in steps of 10Hz
6. Measure Forward and reflected power.
7. As the PRF is being changed and the other parameters are changed, vary the driver amplifier frequency, so as to get a minimum reflected Power signal on CRO.
8. Increase RF power by changing the Modulator HV and observing the vacuum in the Linac SIP
9. Trigger generator/ High Voltage is switched OFF in case of Fault (Vacuum or Arc)
10. In case of no vacuum deterioration & arc fault, reduce the PRF to 5 Hz, increase the peak RF power by ~0.1 MW & do conditioning up to 200 Hz as mentioned in points 5 to 8.
11. Do the RF conditioning up to 1.5 MW by repeating points 5 to 10.

26.2 6 MeV Compact Cargo Linac

For scanning the cargo using x-rays at maximum beam energy of 6 MeV [135] and maximum average beam power of 1.0 kW, the RF source required should have peak power capability in the range of 2.0 MW to 2.5 MW and average power of 1.25 kW to 2.5 kW [135]. Magnetron based RF source is best suited for this application because of its compactness, non-requirement of external drive input power and lower cost. Specifications of magnetron-based RF source are given in Table 26.3.

Table 26.3: Specifications of the RF source.

Parameter	**Value**
Magnetron model	EEV Model No. M5028
Operating Frequency range (MHz)	2856 ± 1
Peak RF power (MW)	5.5 (Nominal 2.35 MW)
Average RF Power (kW)	3.2
RF Pulse Width (μsec)	4
Pulse Repetition rate (Hz)	10-600 (Nominal 250 Hz)
Duty Cycle (%)	0.12
Anode Voltage (kV)	Max. 55 kV (Nominal 40 kV)
Anode Current (A)	Max. 240 A (Nominal 170 A)
Efficiency (%)	41
Heater Voltage (V)	12-13.2
Heater current (A)	16-18
Load VSWR	1.3

The layout of the RF source, with all the components, is shown in Fig. 26.5. The magnetron is fed with pulsed power from the magnetron modulator. RF Power generated from the magnetron is coupled to the linac through the waveguide plumb-line, which includes flexible waveguide sections, E & H-bends, waveguide twist, 3-port circulator, water load, directional coupler, RF window adapter & RF window. Circulator protects the magnetron from reflected power due to mismatch between linac and RF source. The directional couplers are used to measure the forward and reflected power in the line. Optical arc detectors located in the bends detect arcing in the waveguide line and this signal is used as an interlock for safe operation.

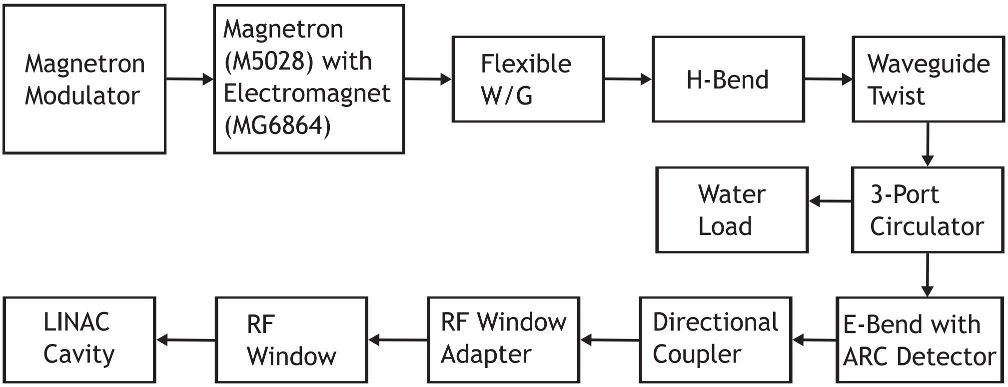

Figure 26.5: Components of RF source.

26.2.1 RF Conditioning of Linac

Cavity is RF Conditioned up to 1.50 MW, 4 μs, 100 Hz without beam and up to 3 MW with beam loading. Using the stepper motor tuning, Magnetron frequency was matched cavity resonance frequency for minimum reflected power. Vacuum in the cavity was maintained in the range of 10^{-6} mbar. RF frequency spectrum at 2.5 MW, 100 Hz is shown in Fig. 26.6.

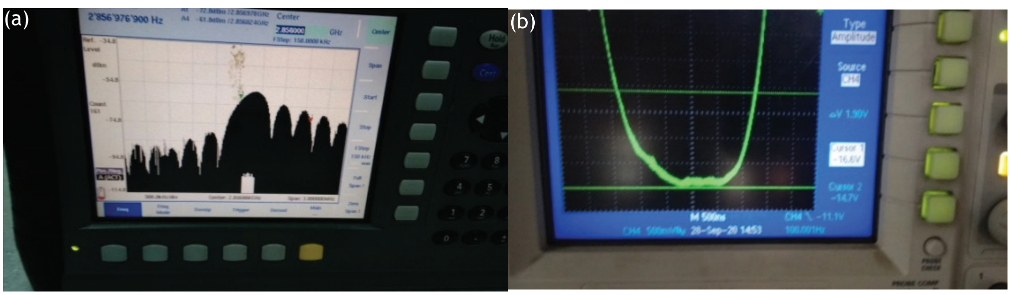

Figure 26.6: (a) RF frequency spectrum, and (b) Magnetron current (164 A) at 2.5 MW.

26.3 RF Devices and Component Selection

26.3.1 Criterion for Selection of RF Source (Magnetron or Klystron)

1. **Based on Linac field value to get the desired output Energy:**

(a) For 10MeV output energy, ∼18 MV/m needs ∼5 MW of peak RF power. As Magnetrons of this peak power are not available, Toriy make Klystron with 6 MW peak and 25 kW average power was selected. Linac RF efficiency is ∼40%. So, 25 kW klystron output will give 10 kW output beam power. Magnetrons with such high average power (25 kW) are not available because of the thermal constraint. Klystrons are the most efficient of linear beam tubes [136] and are capable of the highest peak and average powers The process of electron generation, RF-beam interaction and spent electron beam power dissipation are separate and distributed in the Klystron but are all wound up in a small volume in a Magnetron. Klystron is an amplifier and its frequency is determined by the external RF driver.

(b) For 6 MeV output energy, based on field profile inside the cavity and accelerating gradients, RF power is chosen. As the RF power requirement for our Linac is 2.5 MW to 3 MW, Magnetron is chosen. Magnetron (which is a crossed type, self oscillating tube) based RF source is best suited for application up to 6 MeV because of its high operating efficiency (50-60%), ruggedness, compactness, non-requirement of external drive input power (which saves extra cost and hardware) and lower cost (Klystrons ∼3-4 times more costly).

26.3.2 High Power RF Waveguide Components Selection

1. Waveguide Selection

For S-band (2-4 GHz) Linac, Rectangular waveguide WR 284 is selected having following details:

1. Frequency Range: 2.6 to 3.95 GHz
2. Cut off Frequency (f_c) = 2.079 GHz
3. Dimensions: a= (2.84 ± 0.005)", b= (1.34 ± 0.005)"
4. Impedance $= 377(\frac{b}{a})(\frac{\lambda_g}{\lambda})$, $\lambda_g = \frac{\lambda}{[1-(f_c/f)^2]}$
5. Power Handling Capacity: $6.63 \times 10^{-4} ab(Emax)^2(\frac{\lambda}{\lambda_g})$

Following parameters are measured on VNA

1. Reflection Coefficient $(\tau) = \frac{V_{reflected}}{V_{incident}}$
2. Return Loss (RL) = -20 $\log_{10} \rho$
3. VSWR $= \frac{V_{max}}{V_{min}} = \frac{1+\rho}{1-\rho}$

2. Dual Directional Coupler

Directional coupler (Fig. 26.7) is a reciprocal device which measures the forward and reflected RF power.
Following are its specification:

1. Frequency: 2856 ±20 MHz
2. VSWR: $<$ 1.10
3. Insertion Loss: $<$ 0.05 dB
4. Coupling : 60 ± 1 dB
5. Directivity: $>$ 25 dB

Characteristics of 4-port Directional coupler:

1. Coupling, C $= 10\log_{10}(\frac{P_1}{P_4})$ dB
2. Insertion Loss, L $= 10\log_{10}(\frac{P_1}{P_2})$ dB

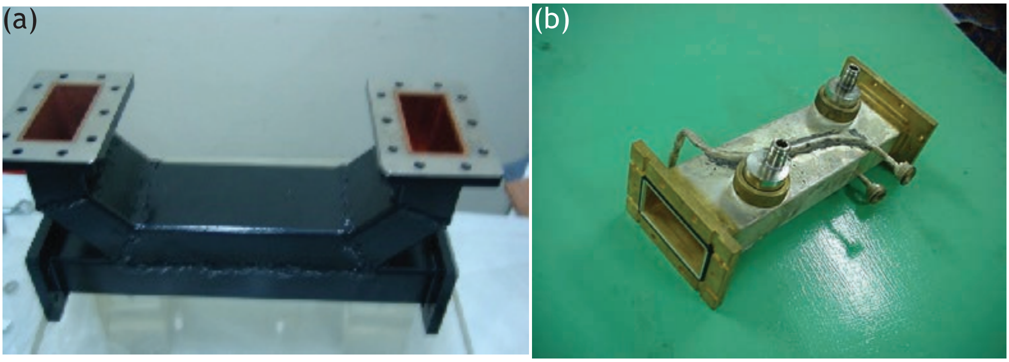

Figure 26.7: (a) Cross type directional coupler, and (b) Loop type coupler.

3. Isolation, I = $10\log_{10}(\frac{P_1}{P_3})$ dB
4. Directivity, D = I – C – L,

Design equation of Dual Directional Coupler is given by:

1. AI = $(\frac{\pi d^3}{24a^2b})(\frac{2a}{\lambda_g}+\frac{\lambda_g}{2a})$
   AI is Forward Coupled wave, λ_g is guide wavelength
2. Coupling Factor (CF) = $20\log_{10}(|2\ \text{AI}|)$
3. Hole diameter for 60 dB coupling is 11 mm
4. Hole separation is $\lambda_g/4 = 5.79$ cm

3. E & H plane bend

E & H-bends (Fig. 26.8) changes the physical orientation of waveguide line in the desired direction. Following are its specification:

1. Frequency: 2856 $\pm$ 20 MHz
2. VSWR: $<$ 1.10
3. Insertion Loss: $<$ 0.05 dB

For Design of E & H plane bend, Length of Waveguide bend is $\lambda_g/4 = 5.79$ cm With precision machining or casting technique, it is possible to make low VSWR bends with radius of curvature R $\geq$ 1.5b for E plane bends and R $\geq$ 1.5a for H plane bends, where a and b are the width and height of the waveguide, respectively.

4. Circulator

The RF source (Klystron/ Magnetron) is isolated from the linac by a ferrite-loaded circulator that divert the reflected power from the linac into a matched water load. Circulators (Fig. 26.9) are either three or four port devices using ferrites, a magnetic material which rotates electromagnetic fields. A three port circulator has the property that a wave incident in port 1 is coupled into port 2 only; a wave in port 2 is coupled into port 3 only, and so on.
Material selection - following material selection are available:

(a) Ni-ferrite: Ni-ferrites are cheaper and were the earlier days choice, based on their better power handling due to high spin line width (ΔH_k) and curie temperature.

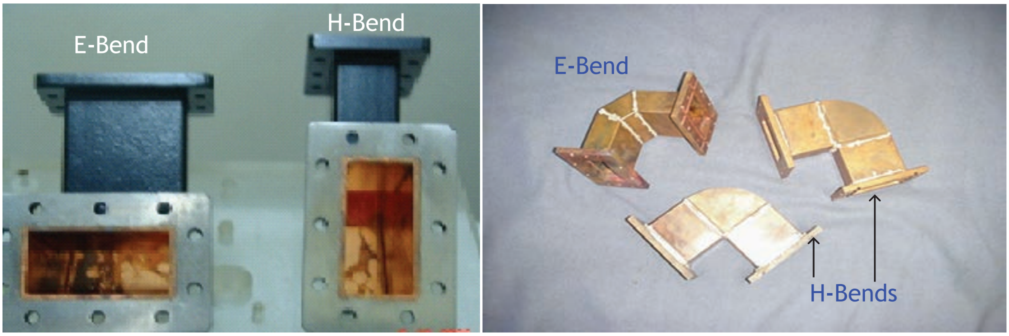

Figure 26.8: E & H bends to change the physical orientation the waveguide line.

(b) Yttrium Iron Garnets (YIG): Latest used is YIG doped with rare earth metals either Gd, Dy, Ho or combination of any. These materials are more expensive compared to Ni-ferrites but are capable of high power due to their low insertion loss properties, with moderate ΔH_k and high curie temperature.

Choice of Magnet - following Magnets are available:

Alnico (Aluminium-Nickel-Cobalt), Sm-Co (Samarium-Cobalt) and Nd-Fe-B (Neodymium, Iron, Boron) Magnets. Me-Fe-B magnets have a higher Maximum energy product (B_H max) than Sm-Co magnets. As the operating temperature of circulator is < 80 ℃, Nd-FE-B is selected.

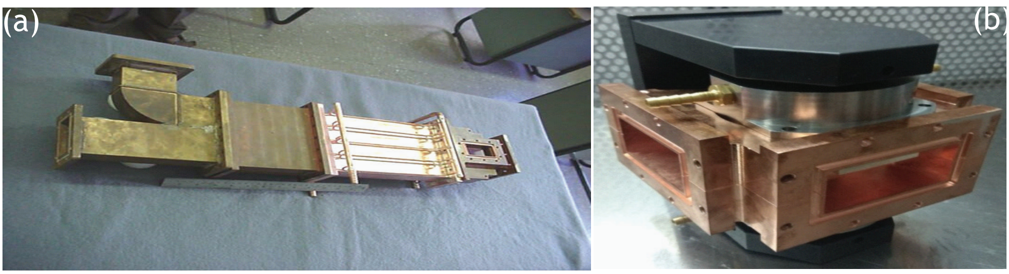

Figure 26.9: (a) Four-port Circulator, and (b)Three-port Circulator.

5. RF Window

RF window (Fig. 26.10) is used to isolate the vacuum in the cavity from the SF_6 in the waveguide transmission line. RF ceramic window is transparent to microwave power but acts as a pressure barrier between the pressurized waveguide line and the vacuum in linac. It was designed and developed at 2856 ± 5 MHz with DN100 Flange at Vacuum side and rectangular WR284F flange at pressure side. Length of pillbox is $\lambda_g/4$, 90 mm ceramic diameter and ceramic thickness is optimized to be 3 mm. The window ceramic material should have high dielectric strength, low loss tangent and high thermal conductivity. For this 99.7% Alumina ceramic disc is selected. RF window was tested for VSWR < 1.10 and insertion loss of 0.05 dB (1.1% loss). Vacuum leak rate of 10^{-10} mbar/lit-s was measured.

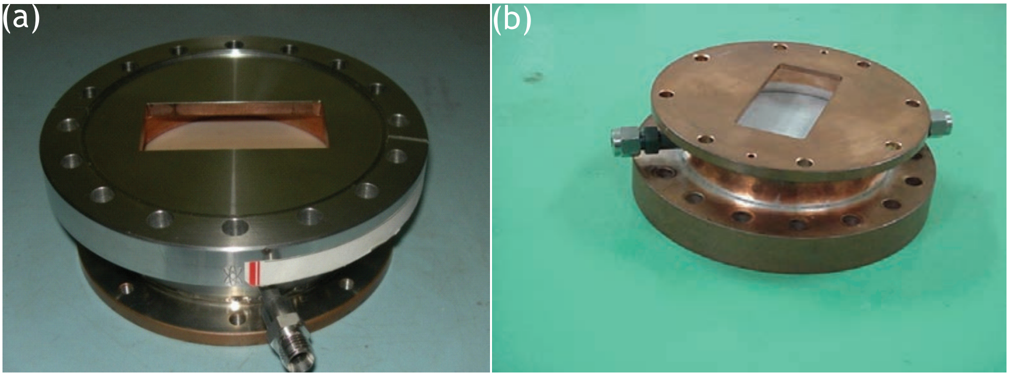

Figure 26.10: Two types of RF windows.

6. Water Load

Matched water loads (Fig. 26.11) are designed to absorb the incident RF power without any reflection. Waveguide type water loads used in accelerators are of two types namely, water

Figure 26.11: Two different Matched Water Loads.

filled load and water cooled dry load. The water filled load is designed such that the incident microwave power entering via the ceramic window in absorbed directly by the cooling water. Ceramic window acts as quarter wave matching section between SF_6 and water filled section. Alumina ceramic having low loss dielectric of dielectric constant 9 is chosen for impedance matching. Optimum thickness of water load window is computed by: $t = \frac{\lambda_g}{[4(\varepsilon_w)^{1/2}]}$, where λ_g is guide wavelength and ε_w is dielectric constant of ceramic. Water Load VSWR is < 1.10.

Suggestions for Further Reading

a) [137, 138]