DESIGN & DEVELOPMENT OF RF STRUCTURE FOR 10 MeV, 10 KW INDUSTRIAL RF ELECTRON LINAC

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Abstract

A prototype RF Electron Linear Accelerator (eLINAC) capable of delivering a beam of energy 10 MeV, and Beam power of ~ 10 kW (av.) has been designed, manufactured and commissioned. The linac is being regularly operated at a beam energy of ~ 10 MeV and beam power of ~ 3 kW (av.) at Electron Beam Centre (EBC), Kharghar, Navi Mumbai and is being used for industrial applications as well as applied research. In this paper, design details of the linac RF structure, RF measurement studies and brazing experience on copper cavities of the electron accelerators have been discussed.

Introduction

Electron beams have played a key role in the field of basic sciences, applied sciences, medicine and agriculture. Over the last decade or so, the focus has shifted more towards industry. Depending upon the beam power and its energy, the electron beams have made tremendous impact in the area of food preservation, medicine, agriculture, biology, etc. Keeping in tune with the present and future scenario, the Accelerator and Pulse Power Division (APPD) of BARC has initiated the design and development of various types of electron accelerators and the 10 MeV electron RF linac is one of them. This will mainly be used for food preservation, medical sterilisation, semiconductor irradiation, radiography, radiation therapy, etc. In addition, bremsstrahlung radiation generated from the electron beam are being used for applied sciences studies.

The 10 MeV Linac assembly installed at EBC, Kharghar is shown in Fig. 1. It is being regularly operated at a beam power level of ~ 3 kW (av.) at a frequency of 2856 MHz, having pulse width of 10 μsec and repetition rate...
The electron gun (EG) is directly mounted on the linac, injects a beam of ~ 50 -70 keV into the linac. The beam is accelerated to the required energy from 50 keV to 10 MeV in the RF structure of linac before being passed to the magnetic sweep scanner (MSS) which sweeps the beam over a target and finally extracted through a titanium window of ~ 50-75 μm thick sheet for the target irradiation. The beam current is monitored with the help of beam current transformer (FCT) in Diagnostic Box Chamber. A vacuum of the order of 10⁻⁷ -10⁻⁸ torr is maintained with the help of a turbo & sputter ion pumps (TP/SIP) combination system. The RF power to the linac is fed via a waveguide (WR284) operated in the TE₁₀ mode. The linac has a vertical configuration so that the products to be irradiated can be moved horizontally on the conveyor belt. Both x-rays and electron beams are available for the purpose of irradiation.

### Design of RF Structure

For the sake of simplicity of fabrication, constant impedance, on-axis coupled cavity linac configuration has been selected, as shown in Fig. 2. It consists of 3 buncher cavities followed by 14 acceleration cavities, and 16 coupling cavities comprising a total length of 871 mm. The length of the acceleration cavity is 52 mm, whereas the buncher cavities are 45, 48 and 50 mm respectively. Some of the salient features of the accelerating cavity and coupling cavity, are shown in Fig. 3. The outer and inner nose radii have been optimized to be 3 mm and 1 mm resp. An acceleration field gradient of 15 MV/m to 18 MV/m has been used for design considerations, leading to a Kilpatrick value of ~ 1.4, with a maximum field on the boundary as 62.712 MV/m. The effective shunt impedance for the buncher cavities is ~ 80MΩ/m, while for the accelerating cavities, it is ~ 90MΩ/m. The electric field distribution and profile are shown in Fig. 4. The electric field in the center of the gap has been found to be uniform within ± 3.5%. The total RF power dissipated into the structure at the operating frequency of 2856 MHz is estimated to be 1.083 MW (peak). Most of the design features of the linac have been worked out using SUPERFISH®.
For the RF power feed at the center of the 33-cavities (17 accelerating cavities, 16 coupling cavities), the droop at the last cavity works out to be 0.15%. This would otherwise have been 0.66% if the feed is chosen as the beginning or the end of the accelerator. The phase shifts between the adjacent acc. cavities for a random frequency deviation of ± 150 kHz, due to fabrication errors, have been estimated and found to be about 180 ± 0.25 Deg.

**Beam Dynamics in Linac**

The beam behaviour in the linac has been studied using the computer code PARMELA. 6-dimensional phase space with random distribution have been taken for evaluation of the beam properties. The beam injection is done at 50 keV with an energy spread of 0.5 keV and a normalised emittance of 25 mm.mrad.MeV/c. A phase width of 180° has been considered for the beam pulse. About 10,000 particles are scanned. Optimum transmission of the beam is obtained at an injection phase of -50°. Since the linac does not use any solenoid or focussing element, the beam loss in the first four cavities is found to be 16%, 13%, 9% and 5% respectively. In the remaining cavities, the beam loss is found to be negligible. The total transmission through the linac is 48% with an average energy of 11.676 MeV and a beam power of 11.248 kW. The maximum energy of the beam is 12.547 MeV, energy spread as ± 1 MeV and a phase spread of ± 90°. The output beam has a gaussian distribution with FWHM as ± 2.5 mm and maximum divergence as ± 2.5 mrad. The energy of the beam can be varied between 7 to 11 MeV.

**Fabrication and RF Testing**

The 33 cavities of on-axis coupled cavity linac were manufactured at CDM, BARC within the dimensional tolerances of ± 20 mm. Pre-brazing RF measurements were carried out. The RF coupling coefficients $k_1$, $k_2$, $k_3$ evaluated as −4.62%, 0.26 %, -0.21 % respectively from the dispersion curve of the measured 31 peaks. (normal mode frequencies) $Q_0$ value was measured − 13500. The shunt impedance evaluated comes out to be − 85 MW/m. Along the accelerator length 17 peaks corresponding to electric field in the accelerating cavities while 16 coupling cavities are devoid of the electric field were measured, within − ± 1.25 % of uniformity of the electric field, identified as π/2 mode.

For brazing, whole assembly of 33 cavities was divided into three parts i.e., 2 parts of 14 cavities (top and bottom) and one part of 5 cavities (central) (Fig. 2). The top and bottom assemblies were brazed in vacuum furnace at 820 °C with a soaking period of − 20 min. at CEEM, BARC. The vacuum leak tightness measured to be −5x10^9 mbar-lit/sec after brazing.

The resonant frequency and Q0 values measured to be −2.8555 GHz and 12000 resp. More crucial is the electric field measured along the beam axis found to be same as before and after the brazing. The central portion (5 cavities) along with waveguide and shorting plate with coupling aperture was brazed at CDM. The vacuum leak rate −10^9 mbar-lit/sec was measured after brazing. Copper-nickel end flanges as well as water cooling tubes were brazed to all the three portions with Incusil wire − 760 °C and achieved vacuum leak upto − 4 x 10^9 mbar-lit/sec. Later, the flanges were machined as per CF100 and CF150 specifications and alignment of − 20 mm to the beam axis. Soldering was done at CDM, on the brazed water cooling tubes outside the cavities, to have − 100 % thermal contact with the cavities. RF measurements were performed for integrated 3 parts after putting silver o-rings between the joints and tested for vacuum leak tightness upto − 3.0 x 10^9 mbar-lit/sec.. The operational frequency has been found to be within 2856 ± 0.5 MHz.

**Fig. 5 : Cut view of Brazed Joints of the RF Structure**
which is acceptable. The field amplitude along the length has been measured within ± 3.5 % (Fig. 6).

The RF structure then integrated into 10 MeV assembly as shown in Fig. 1 and whole system vacuum leak tested upto — 2.0 x 10⁻⁹ mbar-lit/sec and achieved ultimate vacuum — 4.0 x 10⁻⁷ mbar. RF conditioning of cavity was done at different power level such as, a forward peak power of 3.3 MW, 3.5 MW, 4.0 MW at a PRF of 100 Hz, 70 Hz, 15 Hz respectively. During the RF conditioning, a vacuum of — 3.0 x 10⁻⁷ mbar was maintained throughout the complete linac system. The first electron beam of — 200 mA was extracted in May’06 . The Gun Filament power was 140 W and the Gun Modulator was operated at 50 kV with pulse width of 10 msec and PRF of 15 Hz. A forward RF power of — 3.5 MW peak was fed to the linac and the reflected power was — 940 kW.

Energy analysis of the electron beam was done by measuring penetration depth in aluminium plates. With this arrangement no beam signal was observed in the collector plate when the stack had 7 aluminium plates (total 22 mm thick). Beam current was measured upto after six plates (19 mm), corresponds to beam energy of 10 MeV².

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References
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