Fabrication of an Ultra High Vacuum Compatible Faraday Cup for Qualification of Electron Gun for 10 kW Industrial LINAC

Ajay Kak, A. Kher, S. C. Vishwakarma, Abhay Kumar, Manoj Gandhi, Pramod Radheshyam, Ajay Kumar and Lala Abhinandan

Raja Ramanna Centre for Advanced Technology, Indore 452013, India
Email: lala@rrcat.gov.in

Abstract. In this paper, we report fabrication and testing of a unique Faraday Cup designed for qualification of Electron Gun for a 10 kW industrial LINAC. This is a compact device consisting of a tapered copper cavity electrically isolated by a ceramic cylinder metalized at both ends. Kovar tubes matching with the diameter of ceramic isolator were used at both ends to facilitate high quality UHV compatible joints with copper cavity at one end and standard knife edge stainless steel flange at the other end. The Kovar tube was flared at both ends to form a collar matching with the outer diameter of the ceramic isolator. The joint between Kovar collar and ceramic isolator was done by hydrogen brazing using copper silver eutectic alloy. All the joints were tested with helium leak detector and leak rates were found to be below $1 \times 10^{-10}$ mbar.litre/second.

1. Introduction
A Faraday cup is a device used for measuring current in a beam of charged particles. The device intercepts the electron beam and conducts the current to a measuring instrument through an electrical lead. Secondary emission and back scattering of the striking electron beam are the main reasons of measurement inaccuracies. The accuracy of measurement can be improved by giving proper geometrical shape to the cup and by applying bias voltage to the cup.

A Faraday cup has been developed for qualifying the electron gun being developed for a 10 kW industrial RF linear accelerator. The electron gun has been designed to give mono-energetic electrons of 70 keV energy and 1 ampere pulsed beam current with 15 microsecond pulse width at 1 Hz - 300 Hz pulse repetition rate. This configuration demands the Faraday cup to dissipate average power of 315 W.

The Faraday cup measures the collected current by measuring the voltage drop across a resistor as the current passes to the ground under the potential developed by the same collected electrons. The collector of the device has to be isolated from the electron gun’s anode which is also at the ground potential. This isolation has been achieved through the use of a ceramic isolator(99.5% Alumina) between the collector and the knife edge flange of the device attached to the gun’s anode. Kovar transition tubes must be used between the knife edge flange on the side of the electron gun’s anode and the ceramic isolator and also between the ceramic isolator and the collector cup. The joint between the Kovar tube and collector cup is a brazed joint and experiences the shear stresses due to thermal expansion of the collector cup. The physical dimensions of the faraday cup have been selected to keep the ceramic and Kovar tubes away from beam path. This does not allow a temperature difference between Kovar and ceramic. However, the brazed joints between Kovar and ceramic and Kovar and
collector cup do see the effect of thermal expansion of collector cup. Hence, in order to limit these thermal stresses for retaining the vacuum leak tightness of the brazed joints, it is important to limit the temperature rise of the collector cup.

As the energetic electrons strike the walls of the collector cup, they undergo secondary emission, elastic scattering and inelastic scattering. Elastic scattering is a relatively low energy phenomenon and the secondary emission coefficients are also very small at higher energies (>20 keV). At higher energies, re-diffusion or inelastic scattering of primaries dominates. These phenomena can lead to some electrons leaving the collector and escaping to the knife edge flange side beyond the ceramic isolator. Extra electrons would flow from earth to make up for these electrons and thus would produce inaccuracy in the measurement. These phenomena can be controlled by having geometry of the collector that invites multiple surface interactions of secondary and backscattered electrons, thus increasing the probability of retaining them inside the cup. Another method to do the same thing is by using a positive bias voltage between the collector cup and the ground so that these secondary and backscattered electrons are forced to go to the ground. Looking at all the requirements of the design, OFE copper appears to be appropriate material for the collector cup due to its high thermal conductivity and brazability. Although, all good thermal conductors have large secondary emission coefficients (SEC), its value decreases sharply with increasing impact energy of primary electrons and at impact energies larger than 20 keV, the value approaches 1% and goes down even further beyond this impact energy. A conical taper has been provided in the cup to distribute the heat and decrease the heat flux. This also helps to increase the probability of the surface interactions of the secondary and backscattered electrons with the collector cup surface. It has four circumferential fins on the external surface for dissipation of heat load of 315 W. A small fan with a 12V DC motor is mounted near the fin surfaces to allow a forced air flow convection conditions. The gap between the fins has been kept more than twice the thickness of boundary layer to allow optimum flow conditions. Figure-1 explains the engineering design features of the gun.

![Fig.1](image)

2. **Design for Manufacturing (DFM)**
Vacuum leak tightness of the order of $1 \times 10^{-9}$ mbar.litre/sec was required from the brazed and the welded joints. The brazed joints shall also have enough strength to take the thermal stresses due to differential thermal expansions of the material at both sides of the joint. The forces of handling during the cleaning and assembly have to be taken by these joints.
The brazed joint between Kovar pipe and ceramic pipe uses a flared construction of Kovar described below. Copper has a coefficient of expansion that is approximately three times that of Kovar. This allowed a large clearance at room temperature for putting the brazing filler foils between them. Due to small clearance at brazing temperature, the joint strength is expected to be on its theoretical maximum (Figure-2). Although, the joint between Kovar and copper sees a residual tensile stress but since copper is completely annealed at brazing temperature, the yield strength of the material becomes very small and thus it yields under the residual stresses at brazed joint. This provides a high strength brazed joint with negligible residual stresses.

![Variation of brazed joint strength with the gap](image)

**Fig. 2.** Variation of brazed joint strength with the gap

The TIG (GTAW) welding between stainless steel and Kovar leads to excessive thermal stresses on the brazed joint between Kovar and ceramic due to high heat input of the process. The design has been done to mitigate the problem in two ways. The length of the Kovar pipe between the knife edge flange and the alumina ceramic pipe was kept on the higher side to allow flexibility resulting in lower thermal stresses on the brazed joint during the welding operation. Higher length of Kovar pipe also increased the thermal conduction length and thus decreased the temperature of the brazed joint. The usual TIG welding process was replaced with indigenously developed Nd-YAG laser welding to have high heat intensity and low total heat input.

The orifice plate has been kept removable to retain the possibility of changing the same with the ones with higher or lower orifice diameters.

3. Fabrication

As explained above the design features were realized by careful fabrication of the device. The main problem in fabrication of this assembly was to prepare Kovar tube with collar to suit outer diameter of metalized ceramic isolator. One alternative was to fabricate the collar by welding a Kovar flange on the tube followed by brazing with ceramic isolator. However, it would involve more number of components and also increase the number of joints. Further, Kovar is difficult to machine as it is soft and gummy. The tools tend to plough the alloy instead of cutting into it, and do not easily form chips. Surface scale oxide tightly adheres to and penetrates the surface of the tool \[^1\]. Cold working requires a temperature of 450\(^\circ\) - 500\(^\circ\)C. Finally, it was decided to go for flaring of the Kovar tube by making an outer and inner guide to hold Kovar tube and then applying pressure manually on the tube through tailstock of lathe machine at room temperature. After a few trials, a proper flared tube was made. The flatness of the flared end was achieved by careful machining of the face.

The joint between Kovar flared tube and ceramic isolator was done by hydrogen brazing using copper silver eutectic having melting point of 779\(^\circ\)C \[^2\]. Hydrogen brazing ensures removal of oxides of copper by reduction with hydrogen at brazing temperatures. The Kovar interface is initially plated with a thin layer of electrolless copper to prevent intergranular penetration of silver bearing brazing alloy which may lead to stress corrosion cracking. Proper heating and cooling cycle lasting for more
than 12 hours in a Linn (model HT 1600 G) hydrogen atmosphere furnace was employed to minimize the stress on the interface of ceramic isolator and Kovar tube. The moly-manganese metallized layer consisting of a glassy phase and modified refractory metal on the face of the ceramic isolator helps its proper bonding with Kovar flared tube. Finally, the joint between Kovar tube and knife edge flange was done by laser welding method using a 250 watt average power fiber coupled pulsed Nd:YAG laser having pulse duration in the range of 2-20 ms and repetition rate from 1-100 Hz.

4. Measurement Circuit

After the assembly of the Faraday cup with the electron gun, high voltage pulses of negative polarity of 2 µs pulse-width duration, repeating at 1Hz and having rise and fall time of 350 ns were applied to the electron gun’s cathode with respect to its anode. The pulse amplitude was gradually raised from 15 kV to 40 kV while keeping filament heater current at estimated RMS value of about 35 A. The application of high voltage pulse was synchronized at the zero crossing of the line voltage.

As explained earlier, the collector cup is isolated from the gun’s anode. With this arrangement, we could separate out the displacement current flowing between the cathode and anode from the beam current. A pulse beam current measurement circuit was developed earlier during a dedicated experiment using a pulsed 40 kV electron gun. The same measurement circuit was employed with this Faraday cup. Several improvements were made in the circuit to reduce the noise during the qualification of the Faraday cup. The connection between the Faraday Cup and the ground was established through a 50 Ω resistor and a 50 Ω coaxial cable. The inner conductor of the coaxial cable was connected to the copper collector cup. The outer conductor was connected to the nearest point of the grounded anode flange, for keeping the unshielded wire length to a minimum. The 50 Ω resistor was placed between the inner conductor and the outer conductor. A common-mode and differential filter was used in the beam current measurement circuit to remove noise from the measurement signal. The voltage drop across the 50 Ω resistor was measured. The beam current was also monitored with the help of Tektronix made current probe, TCP-303, and amplifier, TCPA- 300, on digital storage oscilloscope, TPS-2024, to cross-check the measurements made with the 50 Ω resistor. Figure-3 explains the measurement circuit. The effect of a positive bias was also studied but no change in the collected beam current was observed when the bias voltage was varied from 0 to 50 V. This indicates that secondary and backscattered electrons are being retained in the collector cup effectively only by the geometry of the cup.

![Diagram of Measurement Circuit](image)

Fig. 3. Set up for measuring pulsed beam current with the Faraday Cup

5. Measurement Results and conclusion:

The Faraday cup measurement has been used in the low power tests on a vertical test bench for initial qualifications of the electron gun being developed. The Faraday cup and the vertical test bench is shown in Figure 4 and Figure 5 respectively. Figure-6 gives a picture of current and voltage pulse on digital storage oscilloscope. The Faraday cup has measured up to 400 mA current at 40 kV pulse voltage. This finding is extremely useful and confidence building as it confirms that the gun will...
deliver 1 ampere beam current at 70 kV pulse voltage. Development of a horizontal test bench is in progress for measurement of other important beam parameters like transverse beam emittance and beam size. 70 kV pulse power supply matching with gun’s requirements is also under development.

The fabrication technique used in the development of Faraday cup has shown that faithful devices can be made with joints made by furnace brazing and laser welding and they are superior to the conventional joining techniques due to their unique ability to join dissimilar materials. The experience gained in the design and manufacturing of Faraday cup would pave way for development of beam diagnostics devices where such fabrication techniques can be employed with success.

References
[1] www.kovaralloy.com
[2] Kak A. et al 2009 InPAC Section 19 - Abstract 233
[3] Kumar R et al 2009 InPAC section 19 Abstract 233