# CHAPTER 6

# DEVELOPMENT AND CHARACTERIZATION OF THE GYROTRON GUN-COLLECTOR MODULE*

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## 6.1 Introduction

Gyrotron oscillators are mainly used as the high power millimeter wave sources for electron cyclotron resonance heating (ECRH), electron cyclotron current drive (ECCD) and diagnostics of magnetically confined plasmas for generation of energy by controlled thermonuclear fusion [Edgecombe (1993), Nusinovich *et al*. (1999), Kumar *et al*. (2011)]. The fabrication of the gyrotron gun-collector module is an important step towards the development of the gyrotron gun, that is, magnetron injection gun (MIG) and a test collector. The assembly is purposely integrated with aim to test the performance of MIG in a best possible manner as the vacuum can be easily created inside a closed system having MIG. The MIG is basically an electron beam source used in a gyrotron and consist of two major sub-assemblies: (i) cathode-heater assembly for the electron beam emission and (ii) anode-cathode assembly for acceleration of the emitted electron beam. The designs of the piece-parts of MIG are completed with the help of synthesis and electron beam trajectory analysis (Chapter 2). The cathode-heater assembly has also been elaborated previous in Chapter 3 of this thesis. The design and development of test collector for use in gun-collector module has already been discussed in the preceding chapter of this thesis, Chapter 5.

The MIG consists of several piece parts including the cathode-heater assembly. The development of magnetron injection gun (MIG) was completed with the help of BEL, Bangalore, India. The materials used to fabricate MIG are molybdenum, monel and high voltage ceramics. The development of gun-collector module is discussed in Section 6.2. The characterization of the MIG is also carried out and described in Section 6.3.

## 6.2 Development of Magnetron Injection Gun (MIG)

The engineering drawings of all the piece-parts of magnetron injection gun (MIG) are made using the commercial mechanical design software, AUTOCAD. Fig. 6.1 shows the MIG with all the piece-parts, which clearly shows that there are 46 piece-parts consisting of cathode, high voltage ceramics, metal parts, etc. Table 6.1 presents the list of all the piece-parts with the materials. MIG consists of 32 separate piece-parts having one piece of cathode, five different type of ceramic parts (total nine ceramic parts) and the rest are metal parts. The quantity and material of each piece-part are also given in Table 6.1.

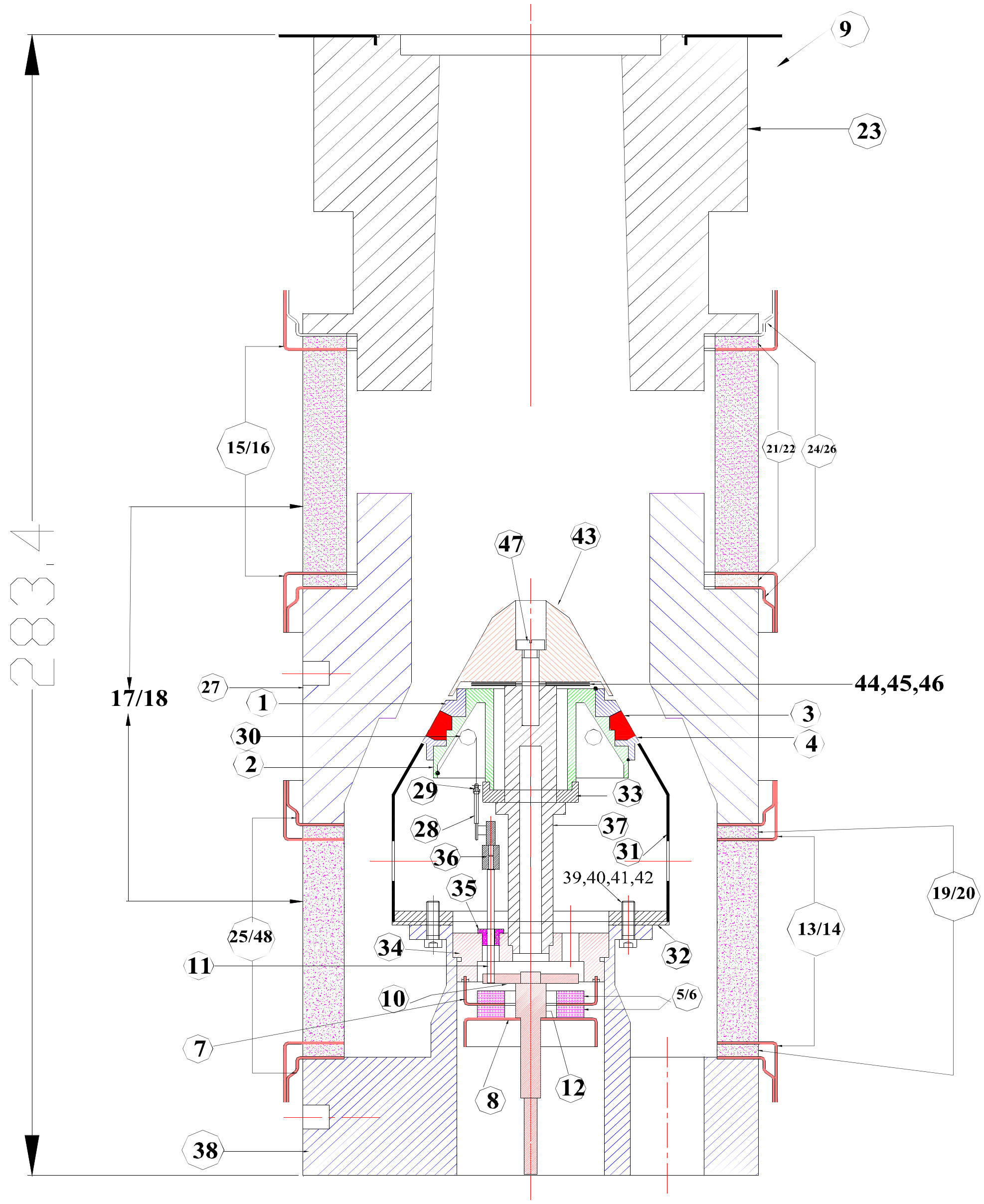



**Fig. 6.1:** 42 GHz gyrotron magnetron injection gun (MIG).

For example, ceramic ring numbered as Sr. No. 14 are required in four numbers as piece-part numbers P19, P20, P21 and P22, respectively, shown in Fig. 6.1 and each piece-part is made of alumina (94-96%). Similarly, cup numbered as Sr. No. 16 are required in four numbers as piece-part numbers P24, P25, P26 and P48, in Fig. 6.1 and each piece-part is made of monel 404. Cathode is made of porous tungsten while heater is also of tungsten. Further, all the anode materials are made of molybdenum due to its property of having high melting point, mechanical strength, vacuum compatibility, etc. The selection of materials is a critical issue and depends upon its role and function in the device and thus needs various factors to be addressed.

**Table 6.1: Detailed List of MIG Piece-parts.**

| SN | Part No. | Part Name | Quantity | Material |
|---|---|---|---|---|
| 1 | P1 | Cathode support lower | One | Molybdenum |
| 2 | P2 | Cathode base | One | Molybdenum |
| 3 | P3 | Cathode | One | Tungsten |
| 4 | P4 | Cathode support upper | One | Molybdenum |
| 5 | P5/P6 | Insulator | Two | Alumina (94-96%) |
| 6 | P7 | Cup-1 | One | Monel 404/Cu-Ni |
| 7 | P8 | Cup-2 | One | Monel 404/Cu-Ni |
| 8 | P9 | Control anode sheet | One | Monel 404/Cu-Ni |
| 9 | P10 | Connecting plate | One | Monel 404/Cu-Ni |
| 10 | P11 | Connecting rod-1 | One | Monel 404/Cu-Ni |
| 11 | P12 | Connection bush-1 | One | Monel 404/Cu-Ni |
| 12 | P13/P14/P15/P16 | Connecting Cup-1 | Four | Monel 404 |
| 13 | P17/P18 | Ceramic | Two | Alumina (94-96%) |
| 14 | P19/P20/P21/P22 | Ceramic ring | Four | Alumina (94-96%) |
| 15 | P23 | Control Anode | one | Molybdenum |
| 16 | P24/P25/P26/P48 | Connecting cup-2 | Four | Monel 404/Cu-Ni |
| 17 | P27 | Modulating anode | One | Molybdenum |
| 18 | P28 | Connecting rod-2 | One | Molybdenum |
| 19 | P29 | Connecting hook | one | Molybdenum |
| 20 | P30 | Heater | One | Tungsten |
| 21 | P31 | Cathode cover | One | Molybdenum |
| 22 | P32 | Cathode cover Base | One | Molybdenum |
| 23 | P33 | Connection bush-2 | One | Molybdenum |
| 24 | P34 | Guide Base | One | Monel 404/Cu-Ni |
| 25 | P35 | Insulator | One | Alumina (94-96%) |
| 26 | P36 | Connection joint | One | Molybdenum |
| 27 | P37 | Connection Bush 3 | One | Molybdenum |
| 28 | P38 | Gun Base | One | Molybdenum |
| 29 | P39/P40/P41/P42 | Screw-1 | One | Molybdenum |
| 30 | P43 | Nose cap | One | Molybdenum |
| 31 | P44/P45/P46 | Cooling fin | Three | Molybdenum |
| 32 | P47 | Screw-2 | One | Molybdenum |

The criteria for selection of materials for the different MIG piece-parts are of variant nature, such as, anode must have (i) high melting point, due to handling of high energy electron beam, (ii) high mechanical strength due to high ruggedness, (iii) high vacuum compatibility due to function of MIG in high ultra vacuum, such as, $10^{-9}$–$10^{-10}$torr, (iv) brazing joining compatibility with ceramic due to high insulation use to get the optimum metal-ceramic joints, (iv) machine finish compatibility due to high voltage handling, (v) low outgassing rate due to maintenance of high vacuum, etc. Similarly, for insulating ceramic, the criteria are confined to its vacuum compatibility, brazing tendency, high breaking strength, etc.

### 6.2.1 Development and vacuum processing

Magnetron injection gun is assembled following the developed assembly sequence. The assembly algorithm is established for joining the various piece-parts before integration of a complete assembly. This is accomplished after lot of exercises and finally a assembly sequence is formulated and successfully implemented.

At first, the cathode-heater assembly and all the ceramic piece-parts as per our engineering designs are procured from the vendors. The rest metal piece-parts are procured from CEERI workshop and other fabricators situated at Pilani. All the piece-parts are thoroughly examined for dimensions, surface finish, etc. The cathode-heater assembly is characterized in bell-jar system as discussed in Section 3.3 (Chapter 3). Major sub-assemblies are fabricated at CEERI, Pilani and the final integration of gun-collector module is carried out at BEL, Bangalore. The test collector is used after its development as per design discussed in Section 5.5. Leak tastings are carried-out at each stage of the development of sub-assemblies in the range of $10^{-10}$ torr-lit/sec with the help of a leak detector system. It is worth to mention that all the piece-parts are thoroughly degreased and chemically cleaned as per requirement before use in the development. Afterwards, the vacuum processing of gun-collector module is carried out at BEL, Bangalore. Fig. 3.11 shows the mounting of gun-collector module at BEL, Bangalore during vacuum processing. The vacuum processing is carried upto 400°C with a holding time of ~ 40 hours. Around $10^{-8}$torr vacuum is achieved inside the gun-collector module. The cathode characterization is also carried out during vacuum processing and discussed in Sub-section 3.4.1 (Chapter 3). Finally, the vacuum processed gun-collector module at BEL, Bangalore is successfully transported to CEERI for further testing through proper packaging.

## 6.3 Characterization of MIG

Magnetron injection gun (MIG) of the 42GHz, 200kW gyrotron is successfully fabricated and then integrated with the test collector to make sealed gyrotron gun-collector. This module is used to test the MIG performance. For this purpose, at first, the protocol and test parameters are prepared, as given in Table 6.2. All the tests mentioned in Table 6.2, such as, continuity test, vacuum test, breakdown test and beam emission test are successfully performed. Table 6.2 also shows the list of estimated results to be expected for all these tests. Such as, for vacuum test, the tube must hold HV ≥ 15kV and leakage current ≤ 15 μA for breakdown testing between high voltage (HV) connector and ground pin of ion pump in the case switched off condition of ion pump. Further, in the case of switched on condition of ion pump, ion pump pressure ≤ $10^{-8}$ torr and pump current ≤0.2μA at pump voltage 3 kV are maintained. It is worth to mention that 2.0lit/sec Agilent Ion pump is connected with the MIG for the checking of the pressure, that is, vacuum inside sealed MIG. Fig. 6.2 shows the relation between ion pump current and pressure of Agilent ion pump. The plot shown in Fig. 6.2 directly helps in the estimation of pressure, that is, vacuum, inside the sealed MIG. All the tests are carried-out in air ambient and at room temperature. Obviously, the related experimental set-up for each test is properly designed, developed and executed.

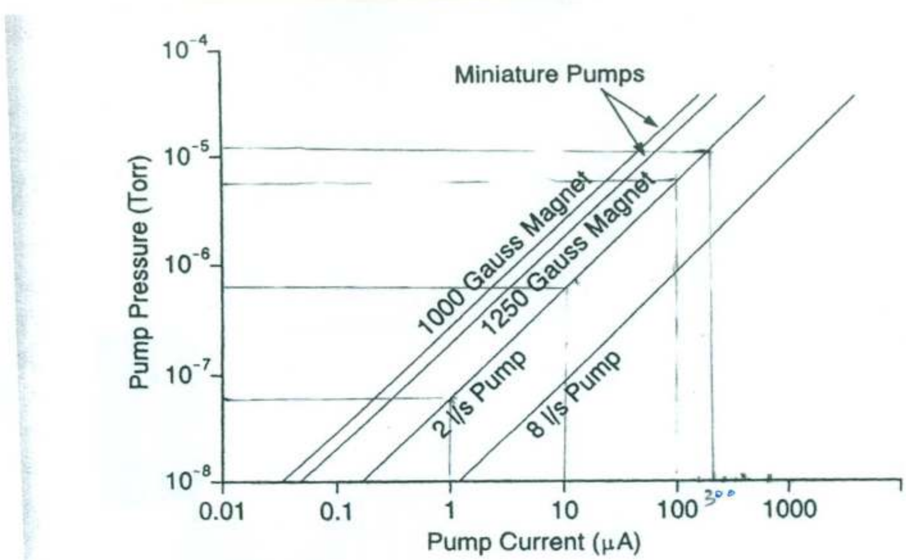



**Fig. 6.2:** Pump pressure versus pump current of miniature ion pump.

**Table 6.2:** Protocol and Parameters for MIG Tests

| S.N. | Type of test | Test Procedure | Test condition | Estimated result |
|---|---|---|---|---|
| 1 | Continuity test | a)Between heater filament connector and cathode base | Ion pump can be switched on or off. | Must hold continuity |
| 2 | Vacuum test | a)Breakdown test between high voltage (HV) connector and ground pin of ion pump<br><br>b) Connect the ion pump controller | Ion pump should be switched off.<br><br>No other electrical connection | Must hold HV ≥ 15kV and leakage current ≤ 15 µA<br><br>Pump pressure ≤ $10^{-8}$ mbar and pump current ≤0.2 µA at pump voltage 3 kV |
| 3 | Breakdown test | a) Apply HV voltage between cathode and 1st Anode (also called as modulating anode).<br><br>b) Apply HV voltage between 1st Anode and 2nd Anode (also called as control anode).<br><br>c) Apply HV voltage between cathode and 2nd Anode. | Ion pump can be switched on or off. 2nd Anode, collector may be floating.<br><br>Ion pump can be switched on or off. Cathode, collector may be floating.<br><br>Ion pump can be switched on or off. 1st Anode must be floating. | Must hold HV ≥30 kV voltage<br><br>Must hold HV ≥35 kV voltage<br><br>Must withstand >65 kV voltage |
| 4 | Beam emission test | a) Apply AC voltage between heater filament and cathode base to the desired rating.<br>b) Apply AC voltage between heater filament and cathode base to the desired rating (<300W). Apply HV voltage between cathode base and 1st Anode and slowly increase the voltage upto 25 kV and read the current flowing through the cathode base. | Ion pump should be switched on | Pump pressure ≤ $10^{-7}$ -$10^{-6}$ torr at pump voltage 3 kV.<br><br>Pump pressure ≤ $10^{-7}$ -$10^{-6}$ mbar at pump voltage 3 kV. Emission current ≥8A and ≤12A |

### 6.3.1 Continuity test

The continuity test is carried out between the heater filament connector and the cathode base as per criteria mentioned in Table 6.2. Fig. 6.3 shows the developed and assembled MIG with ion pump. For the continuity test, at first, the ion pump is switched off. Using Fluke digital multimeter, continuity is checked and found satisfactory. The measured cold resistance of the heater filament is found 50mΩ.

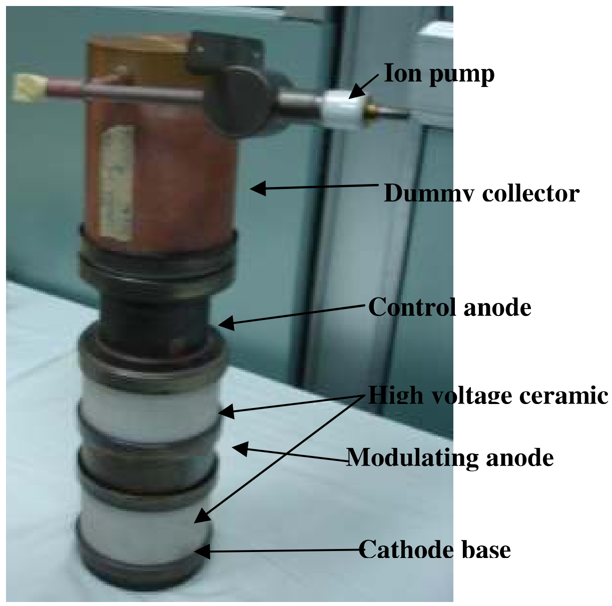


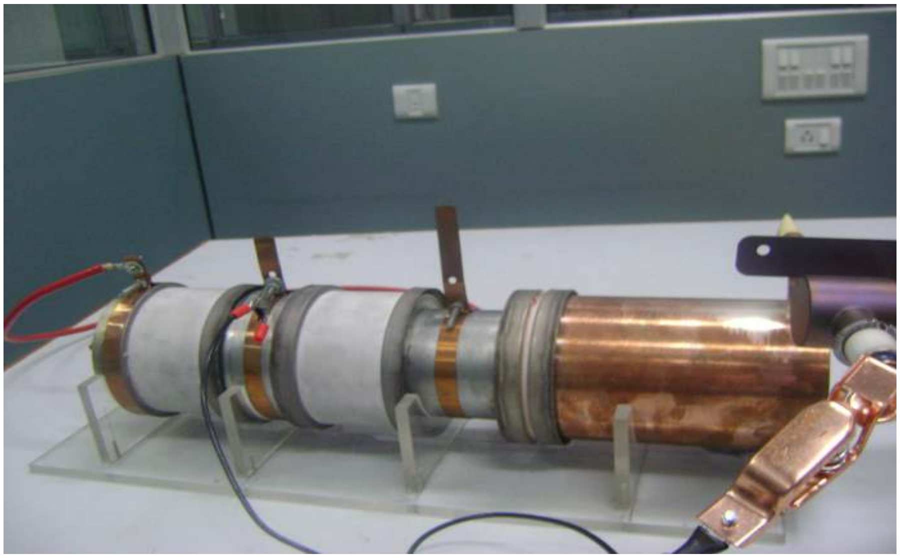

**Fig. 6.3:** Developed MIG collector module for the 42GHz 200kW gyrotron.

### 6.3.2 Vacuum test

For the vacuum test, the ion pump is switched off again as mentioned in Table 6.2. Then, the high voltage DC is applied between HV (HV) connector and ground pin of the ion pump. Fig. 6.4(a) shows the high voltage connection and Fig. 6.4(b) shows the typical measured high voltage reading. The equipment used is 120kV/5mA breakdown tester (M/s Megger, USA). At 22kV, the breakdown is observed and the leakage current is found as 0.1µA. After connecting the pump controller unit to 2lit/s, the pump voltage is found equal to 3kV, the pump current was 0.1µA and thus pump pressure was $\leq 10^{-8}$ mbar. The results clearly satisfy the requirement of vacuum test (Table 6.2).

### 6.3.3 High voltage breakdown test

The high voltage (HV) breakdown tests between the two electrodes in MIG are carried out to estimate the safe operation limit of high voltage. The tests are carried out for three different cases, as shown in Fig. 6.5 and discussed as follow. The connections are made in direct way, that is, the lower operating voltage connection at lower or negative voltage electrode and also in reverse condition, that is, the lower operating voltage connection at higher or positive voltage electrode.



**(a)**


**(b)**

**Fig. 6.4:** **(a)** High voltage connection and **(b)** Measured reading during vacuum test of gun-collector module.

**(a) Case 1:** The ion pump is switched on and the test is carried out in air ambient, that is, MIG is kept in air atmosphere. The electrical connection is made according to case 1 in Fig. 6.5. The 2$^{nd}$ anode (Control anode) and collector are kept floating. The negative HV voltage is applied to cathode base and 1$^{st}$ anode (also called as modulating anode) is grounded. The leakage current is measured by analog multimeter and Megger digital display. Fig. 6.6 and Table 6.3 show the applied voltage with respect to the leakage current. At 40 kV, voltage breakdown is observed. The equipment used are 120kV/5mA Breakdown Tester, Analog multimeter (M/s Motwani).

**Testing with reverse connection:** A reverse connection is made for this case 1, that is, negative voltage applied to the 1st anode and cathode base is grounded. At 20kV, observed fluctuation in leakage current is found from 5μA to 20μA.

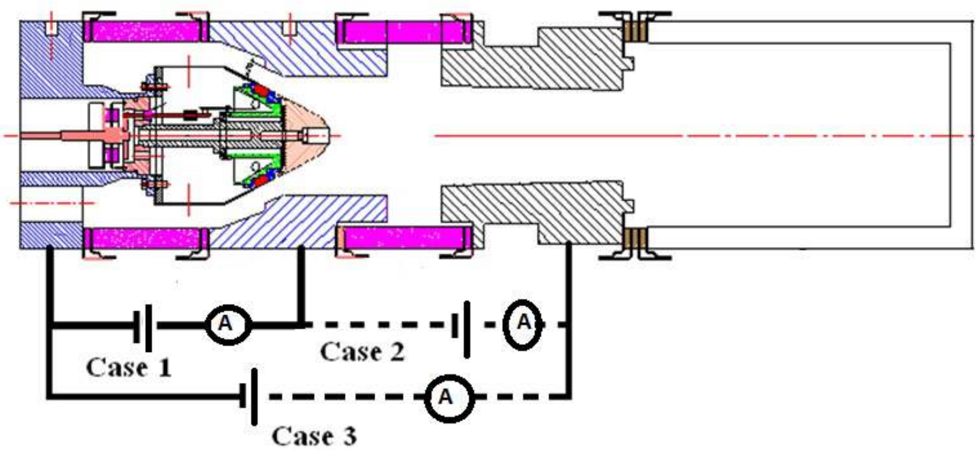



**Fig. 6.5:** Schematic circuit diagram for High Voltage breakdown test.

**(b) Case 2:** The ion pump is switched on. The cathode and collector are kept floating. The HV voltage is applied between 1st Anode (modulating anode) and 2nd Anode (also called as control anode). The electrical connection is made according to case 2 in Fig. 6.5. Fig. 6.6 and Table 6.3 again show the applied voltage with respect to leakage current in case 2. At 40kV again the same high voltage breakdown is observed. Here, a reverse connection is also made, that is, the negative voltage applied to the 2nd anode and 1st anode is grounded. No fluctuation is observed upto 40kV.

**(c) Case 3:** The ion pump is switched on. The 1st anode and collector were floating. The HV voltage was applied between cathode and 2nd Anode, according to the case 3 in Fig. 6.5. Fig. 6.6 and Table 6.3 show the applied voltage with respect to leakage current. Upto 70kV, no voltage breakdown is observed. The reverse connection is made between second anode and cathode base, that is, the negative voltage applied to the 2nd anode and cathode base is grounded. Initially, observed sparking near the collector ceramic at 6kV. Then the collector and 2nd anode are kept at the same potential. Again observed sparking towards the collector side. Then the ion pump is switched off. At 55kV, observed fluctuation in leakage current found between 40 µA to 50µA.

Fig. 6.7 shows the breakdown test on MIG in operation. From all the above-mentioned results, the following observations are found and it is concluded that (a) "hold off" voltage between cathode base and 1st anode is 40kV and the leakage current is 28µA, (b) "hold off" voltage between 1st anode and 2nd anode is 40kV and the leakage current is 12µA. In reverse HV connection, the hold off voltage remain the same whereas the leakage current is 35µA and (c) "hold off" voltage between cathode base and 1st anode is 70kV and the leakage current is 109µA. At reverse HV 55kV, the fluctuations are observed. These hold off conditions for three different situations are well under the safe operation limit of MIG.

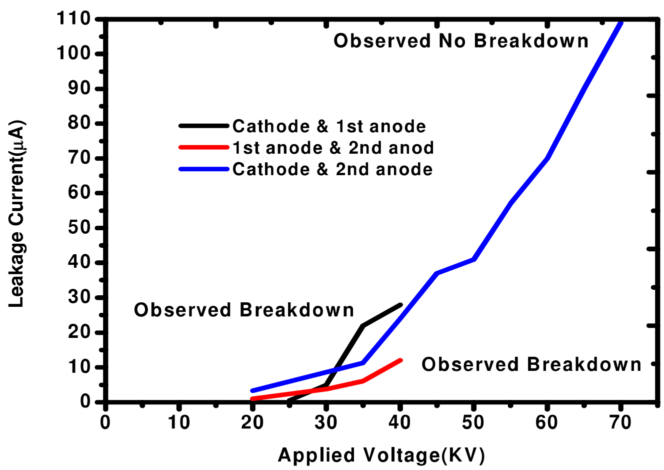



**Fig. 6.6:** Leakage current versus applied voltage for three different case.

**Table 6.3:** Data of applied voltage and leakage current for three different cases.

| **Between Cathode & Modulating Anode** | | **Between Modulating Anode & Control Anode** | | **Between Cathode & Control Anode** | |
|---|---|---|---|---|---|
| Voltage (KV) | Current (µA) | Voltage (KV) | Current (µA) | Voltage (KV) | Current (µA) |
| 25 | 0.5 | 25 | 1 | 20 | 3.3 |
| 30 | 5 | 30 | 3.7 | 35 | 11.3 |
| 35 | 22 | 35 | 6 | 40 | 24 |
| 40 | 28 | 40 | 12 | 45 | 37 |
| | | | | 50 | 41 |
| | | | | 55 | 57 |
| | | | | 60 | 90 |
| | | | | 70 | 109 |


**(a)**

**(b)**

**Fig. 6.7:** Voltage breakdown test on MIG in operation: **(a)** measuring equipment and MIG, **(b)** voltage and leakage current readings.

### 6.3.4 Electron beam emission test

The beam emission test is carried out with the ion pump in switched on condition. For this purpose, at first, the heater is made ready for operation by giving the required heater wattage and then high voltage is applied between cathode and anode. The electrical connection for heater filament and HV are made as shown in Fig. 6.8. The AC voltage between heater filament and cathode base is applied and initially increased slowly in step of 0.5V with hold time 5 minutes to maintain the sudden drastic increase in heater current as well as to maintain the ion pump pressure, $10^{-7}$-$10^{-6}$torr. Within 30minutes, the heater voltage reached 7.7V and the heater current is 33.7A. Then afterwards, the HV voltage is applied between cathode base and 1$^{st}$ Anode, that is, the modulating anode and the voltage is increased slowly in step upto 25kV. The pulse width set at 20μs and PRF is 100Hz. The typical beam voltage and beam current characteristic for the connection between cathode and modulating anode is shown in Fig. 6.9.

Then, HV voltage is applied between cathode base and 2nd anode whereas the 1st anode is kept floating. The V-I characteristics for the connection between cathode and control anode shown in Fig. 6.10 confirmed that the beam is not collecting at the 2nd anode, that is, control anode. At one stage, high voltage, beam emission tests, etc. are demonstrated before the colleagues of Institute of Plasma Research (IPR), Gandhinagar too (Fig. 6.11). The equipment used in the beam emission test are DC Pulsed power supply (40kV/ 50A/ PRF: 50Hz-1kHz/ PW:1μs-100μs), AC Filament power supply with 40kV isolation (20V/40A), HV probe (1000:1; M/s North Star), CT(1V/A; M/s Pearson), 4 channel oscilloscope (500MHz), analog multimeter. It is worth mentioning that the DC pulsed power supply and filament power supply are fabricated in-house at the Institute CEERI.

From the results obtained during the beam emission tests, it is concluded that the beam emission characteristics follow the temperature limited operation characteristics of the cathode. The comparative study of experimental (shown by solid line) and theoretical (shown by dotted line) results is given in Fig. 6.12, which clearly shows a satisfacory agreement. Further, the vacuum results during beam emission tests are achieved as per objective mentioned in Table 6.2 durning beam emission test, that is, (a) pump pressure is in the range of $\leq 10^{-7}$ -$10^{-6}$ torr at the pump voltage 3kV and the beam emission is in the range of ≥8A and ≤12A.

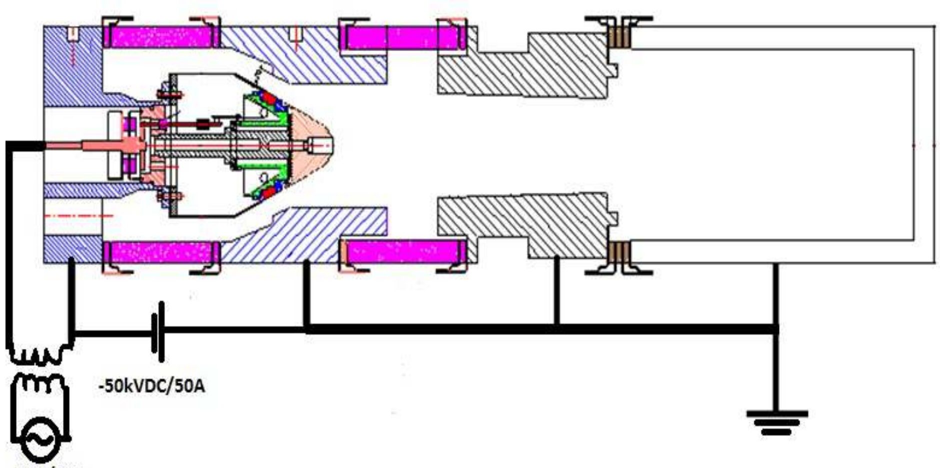



**Fig. 6.8:** Schematic circuit diagram of beam emission test.

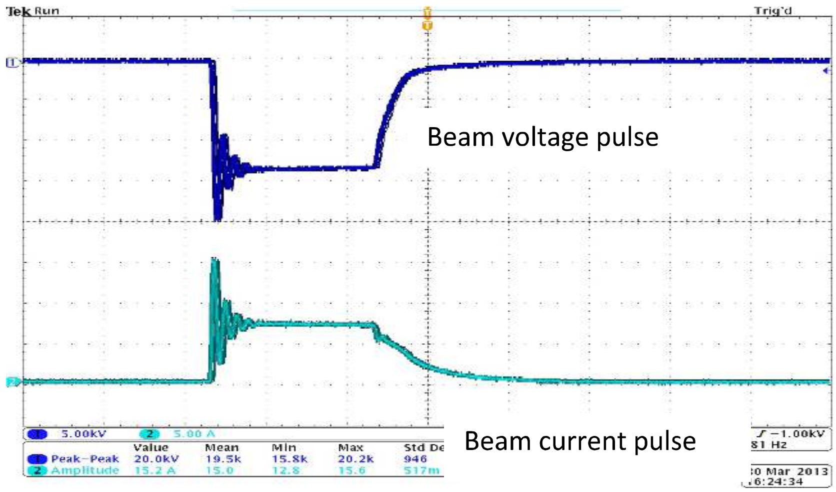



**Fig. 6.9:** Typical pulsed current-voltage waveforms at fixed heater wattage for the connection between cathode and modulating anode.

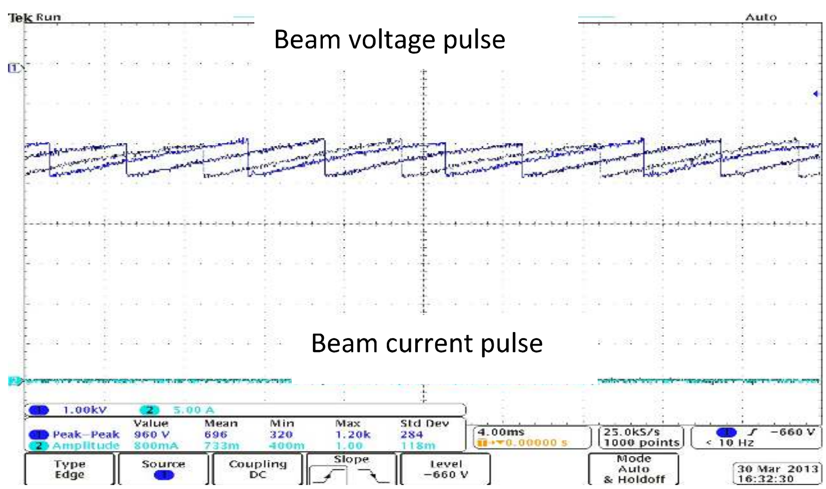



**Fig. 6.10:** Typical pulsed current-voltage waveforms at fixed heater wattage for the connection between cathode and control anode.

**(a)**

**(b)**

**Fig. 6.11:** Beam emission test in operation (a) test set up, (b) measurement process.

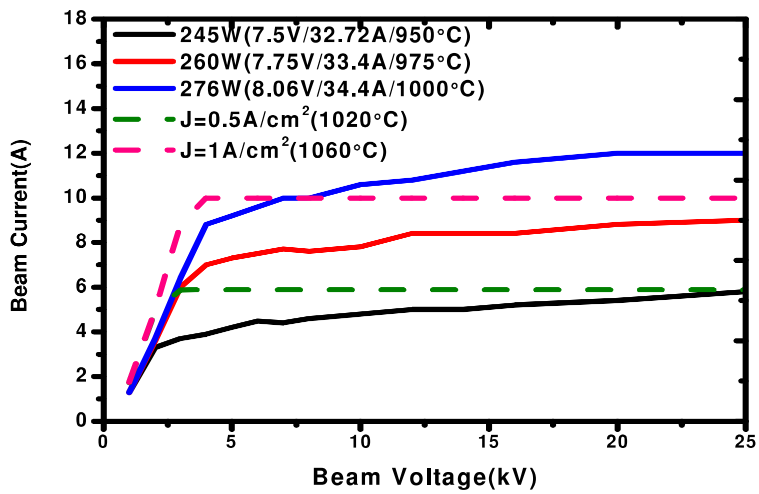



**Fig. 6.12:** Comparison of experimental and theoretical results of V-I characteristics of cathode (dotted lines: theoretical values and solid line: experimental values).

### 6.3.5 Electron beam transmission test

The magnetic field plays an important role in the transmission of the electron beam emitted from the magnetron injection gun. Thus, a beam transmission test is also planned to perform at CEERI in limited condition, that is, in air ambient. For this a typical solenoid coil type of magnet of strength 1000 Gauss is designed and fabricated and then an experimental set-up is created with the ambient air atmosphere. Fig. 6.13 shows the high voltage connection plan and Fig. 6.14 shows the experimental set-up during beam transmission set-up. Without magnetic field, it is clearly found that there is no beam current on the control anode and the whole current is found at the modulating anode only. When the magnetic field is applied, the beam current is found on the control anode situated away from the cathode on different value of applied voltage.

Some almost negligible current equal to around 100 mA is also found on the modulating anode situated opposite to the cathode due to some resistance in the external connection. Table 6.4 presents some typical results during beam transmission test, which clearly confirm the beam transmission from cathode to control anode under the influence of magnetic field at the cathode. The results presented in Table 6.4 are obtained with tube pressure: $10^{-7}$-$10^{-6}$torr at pump voltage = 3kV, heater wattage = 267W, duty cycle = 0.2%, that is, voltage signal pulse width = 20μs and pulse repetition frequency (PRF) = 100Hz. The experimental results presented in Table 6.4 and the simulated results presented in Fig. 6.15, we found in close agreement with related to beam emission under the influence of magnetic field and transmission on the control anode. A typical simulated results of beam emission with modulating anode voltage =5.6kV, control anode voltage =10kV, magnetic field at cathode centre = 1007Gauss is presented in Fig. 6.13 shows very clearly that the beam is collected on the control anode in the presence of the magnetic field.

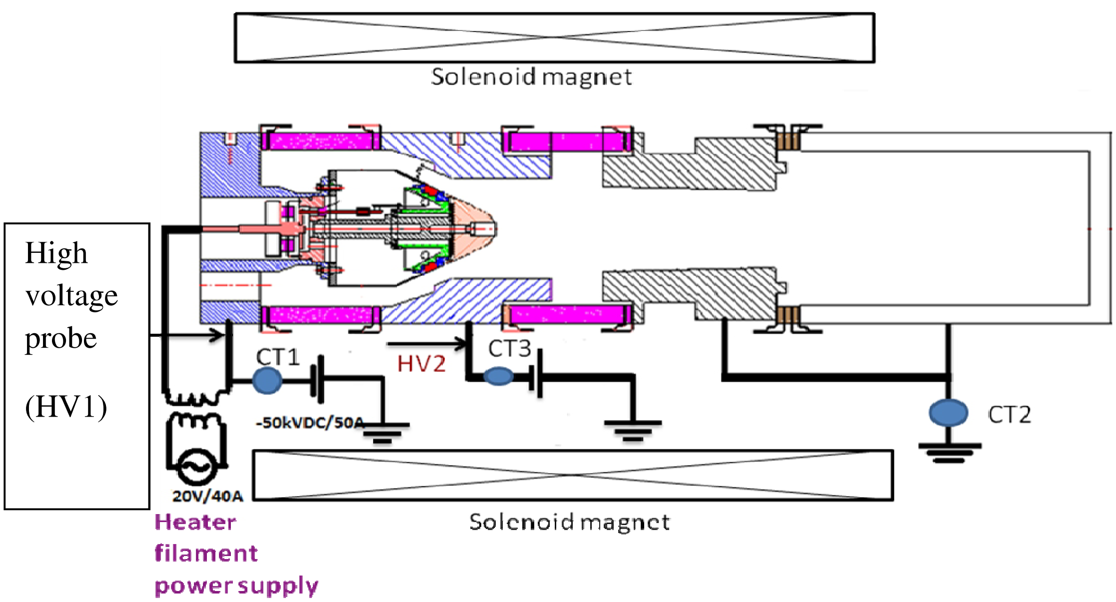



**Fig.6.13:** Schematic of high voltage connection during beam transmission test (CT1, CT2 and CT3: Current transformer positions)

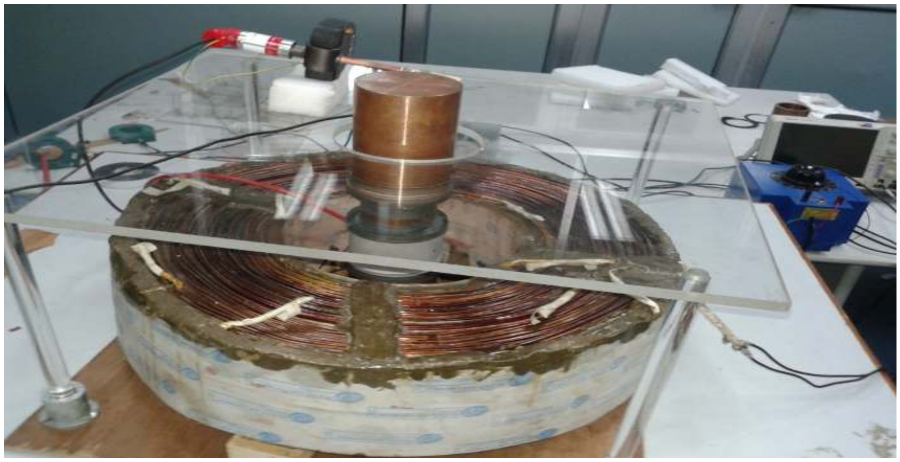


**Fig. 6.14:** Beam transmission experimental set-up.

**Table 6.4:** Beam paramterers at the various electrodes of MIG during beam transmission test.

| **Magnetic field at cathode** | **Beam parameters at Cathode Base** | | **Beam parameters at modulating anode** | | **Beam parameters at Second anode (at ground potential)** | |
|---|---|---|---|---|---|---|
| 1000 Gauss | Voltag (kV) | Current (A) | Votge (KV) | Current (mA) | Voltage (V) | Current (A) |
| | 5 | 4 | 2.8 | 100 | 0 | 2.8 |
| | 10 | 7 | 5.6 | 100 | 0 | 5.0 |
| | 15 | 8.8 | 8.5 | 100 | 0 | 6.2 |
| | 20 | 11 | 11 | 200 | 0 | 8.0 |
| | 25 | 13 | 14 | 300 | 0 | 8.8 |
| | 30 | 14 | 16 | 300 | 0 | 9.6 |

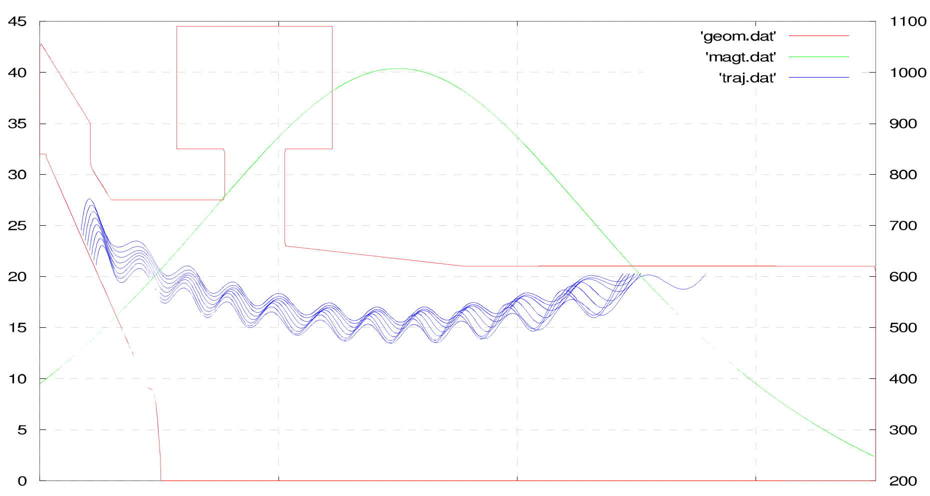



**Fig. 6.15:** Simulated results of beam emission with modulating anode voltage =5.6kV, control anode voltage =10kV, magnetic field at cathode centre = 1007Gauss.

## 6.4 Conclusion

Development and characterization of gyrotron gun-collector module have been discussed in this Chapter 6. The gyrotron gun-collector module is basically an assembly of actual magnetron injection gun (MIG) and a test collector with insulating ceramic in between. The MIG is the gyrotron electron beam source designed for 42GHz gyrotron. The test collector is attached with the fabricated MIG and then the complete module becomes assembly and thus used for the characterization of MIG parameters. For this purpose, at first, all the piece-parts necessary for MIG have been fabricated as per design and discussed in Section 6.2. The development of gun-collector module has also been discussed in Section 6.2. Finally, the MIG has been characterized for various tests such as continuity, vacuum, high voltage breakdown, beam emission, etc and presented in Section 6.3. It is worthy to mention that the voltage breakdown between the two electrodes have passed the design values such as the high voltage breakdown between cathode and control anode has been found more than 65kV. Further, the designed beam current of 10A has also been achieved during beam emission test. Further, the beam transmission test carried out with the satisfactory results.