High current microwave proton ion source

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A high current, high-density microwave proton ion source having 40 keV beam energy and 30 mA proton beam current has been designed and under development at CAT, Indore. The source will be used as an injector to Radio Frequency Quadrupole (RFQ). The major components of the Microwave Ion Source (MIS) are: plasma chamber and vacuum system, microwave system, electromagnet and its power supply, high voltage insulator dome and platform, beam extraction system and supervisory control system. This paper describes the design in detail of high current microwave proton ion source and its various subassemblies.

1 Introduction

Microwave based ion sources are classified into two types according to their operating conditions. The first type is Electron Cyclotron Resonance (ECR) is used to obtain highly multiply charged ions. An ECR plasma is produced by matching the cyclotron frequency of an electron, in a dc applied magnetic field, to microwave frequency. The second type is operated at off-resonance/higher magnetic field than that of ECR to obtain high current singly charged ions. This type of source is called as Microwave Ion Source (MIS) which is used as injectors to RFQ and in ion implanter machines. This non-filamentary ion source has distinct advantages over the conventional ion sources like higher beam current, longer life time, low beam emittance, less energy spread/dispersion, higher power efficiency, higher reliability, stable ion beam and high ionization efficiency. Invariably, all the microwave ion sources are built at ISM band (at 2450 MHz) using magnetron source. Hence the cost of the source is less and the size of the source is compact. For a high current ion source, a high temperature, high-density plasma is required. In ECR ion source, the plasma density is limited by microwave frequency. For example, the cut-off plasma density \( n_c \) corresponding to the microwave frequency of 2450 MHz is \( 7.46 \times 10^{10} \) cm\(^{-3} \). Also, it is found experimentally that the plasma density saturates nearly at \( n_c \) and coupling of higher power into plasma does not help for density enhancement. However, high-density plasma can be obtained at off-resonance \( (\omega_{ec} > \omega_e) \), where \( \omega_e \) and \( \omega_{ec} \) are electron cyclotron and microwave frequencies respectively, with low gas pressure \( (10^{-1}-10^{-3} \) mbar) using the off-resonance technique/higher magnetic field. The plasma density can be obtained nearly 100 times higher than the cut-off plasma density. The microwave ion source is operated in off-resonance mode. From the microwave ion source current density obtained is of the order of \(-200 \) mA/sq. cm, hence maximum beam current can be obtained. The design details of the high current microwave proton ion source are presented in this paper.

2 Source geometry and Microwave System

The schematic diagram of the integrated assembly of the microwave proton ion source is shown in Fig. 1.

The plasma chamber is made water-cooled. The plasma chamber and water-cooling jacket are fabricated in seamless SS-304 L. The dimension of the plasma chamber is \( \phi 114.3 \) mm, length 500 mm. The plasma chamber requires a base pressure of \( 10^{-5} \) mbar and the operating pressure is \( 10^{-3} \) mbar. Turbo molecular pump of 400 litre/sec. is used. High purity hydrogen gas is fed to the plasma chamber through an SS tube of 5 mm and flow is monitored through a micro precision valve.

The microwave system consists of a microwave source, wave-guide system for transferring...
microwave power from the source to plasma chamber and microwave coupling device. The microwave system is sourced by a 1.9 kW (CW) magnetron (variable power source), at a frequency 2450 MHz. A high power isolator (isolation 25 dB) is used to protect the magnetron from load imperfections by directing the reflected power to the load. Forward and reflected power is monitored using a 50 dB loop directional coupler and a power meter. The power supply for the magnetron was fabricated at CAT, Indore. The microwave transfer line has been designed and developed using WR-284 waveguide section. The output of the magnetron is co-axial type; hence we require a waveguide to co-axial adapter. The magnetron mount was procured from M/s Richardson Electronics Ltd., USA. The co-axial port is located at the distance of $(\lambda_v/4)$ from the end plate of the wave-guide. A WR-340 to WR-284 waveguide transition has been designed and developed. The length of the transition is approximate equal to one wavelength. The measured VSWR is 1.06. A loop type directional coupler has been designed and developed at 2450 MHz for 50 dB coupling factor using WR-284 wave-guide. The coupling was calculated using the relation:

$$C = 20 \ln \left[ b \sqrt{\lambda_v/\lambda_s} \right] \text{ dB}$$

where,

- $b$ = Narrow dimensions of waveguide, cm;
- $\lambda_v$ = Guide wavelength, cm;
- $\lambda_s$ = Free space wavelength, cm and $A = \text{loop area, cm}^2$.

In our case, for a coupling factor of 50 dB the hole diameter comes to be 4.0 mm. The impedance of the plasma is not fixed but has a variable impedance nature due to its chaotic behaviour. A water-cooled triple stub tuner (TST) has been designed and developed. So that maximum power can transfer between the generator and load i.e. plasma. The TST consists of a variable depth screw which presents a shunt capacitive susceptance and separated by a distance of $3 \lambda_v/8$. A Teflon sheet of thickness 3 mm is used as a waveguide window. The window provides the vacuum isolation to the plasma chamber from the microwave source side and also prevents the flow of plasma into the microwave line. The teflon sheet (as a window) is sandwiched between a choke type flange and an ordinary flange. A dielectric window made of aluminium nitride or alumina will be used when the system will be energized for high power. The solenoid coils are electrically isolated from the plasma chamber using high voltage glass epoxy insulator dome.
2.1 Microwave launcher (as a microwave-coupling device)

To match the impedance of the line to the equivalent impedance of the plasma a homogeneous quarter wave transformer has been designed and fabricated. A rectangular four section homogeneous transformations to achieve electric field breakdown easily i.e. microwave launcher was designed with a field enhancement factor of 1.913. The dimensions of the larger side, and hence, the guide wavelength is the same for all four sections:

\[ a = 72.14 \text{ mm} \]
\[ \lambda_r = 23.09 \text{ cm} \]

The length of each section is \( (\lambda_r/4) \) i.e. 57.45 mm and the total length of the transition is equal to one guide wavelength.

For plasma impedance of 131.7\( \Omega \) and waveguide impedance of 527\( \Omega \) the computed values are:

<table>
<thead>
<tr>
<th>Section</th>
<th>Impedance</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Z ( \Omega )</td>
<td>( b \text{ mm} )</td>
</tr>
<tr>
<td>1</td>
<td>482.700</td>
<td>31.20</td>
</tr>
<tr>
<td>2</td>
<td>341.322</td>
<td>22.00</td>
</tr>
<tr>
<td>3</td>
<td>203.460</td>
<td>13.00</td>
</tr>
<tr>
<td>4</td>
<td>143.870</td>
<td>09.30</td>
</tr>
</tbody>
</table>

The microwave launcher is used to inject the microwave power to the plasma chamber.

2.2 Electromagnet and power supply

The magnetic field required for ECR action is given by:

\[ f_\omega = 2.8B \quad (\text{from } \omega_\omega = eB/m) \]

where,

\[ f = \text{microwave frequency in GHz; } B = \text{critical magnetic field in kG and } m = \text{mass of an electron, kG.} \]

The axial magnetic field profile of the electromagnet coil as a function of the coil current is shown in Fig. 2.

The resonant magnetic field corresponding to the microwave frequency 2.45 GHz is 875 Gauss. In our case, solenoid coils are required to produce greater than 875 Gauss magnetic field of 1400 Gauss is chosen, because microwave ion source is operated at off-resonance principle. To obtain uniform magnetic field axially in the center of the plasma chamber large number of iteration was done using the POISSON software. Three water-cooled solenoid coils were designed and developed. The field patterns for the coil 1 and 3 are similar. The magnetic field in the plasma chamber was produced using the three electromagnet coils was placed in core. This core was fabricated using soft MS. The core of the electromagnet was fabricated in five parts consisting of two side plates and three cylindrical shapes bore equal to electromagnet. The solenoid coils was placed in it and was covered by two side plates fixed with Allen bolts. The core and electromagnet was having bore of 150 mm, so that plasma chamber/water-cooling jacket can be fitted in this. One side flange of the plasma chamber was fabricated in splitting type, so that electromagnet with core can be fitted to plasma chamber. All three electromagnet coils were energized by three constant current power supplies of 0-32V, 100 mA ratings. The electromagnet coils, produces the uniform field of 100 mm axial direction in the center region of the plasma chamber. The coils were water-cooled and they were fabricated using OFHC rectangular copper tubes of 5mm \( \times \) 5mm with bore diameter of 3mm. The salient features of the system and solenoid coil design parameters are presented in Table 1.

![Graph between magnetic field versus distance](image)

Fig. 2 — Graph between magnetic field versus distance

2.3 High voltage insulator dome and platform

The high voltage insulator dome for 60 kV insulation designed and fabricated at M/s DS Electricals, Indore. The dome was fabricated using high voltage glass epoxy with proper composition. The overall thickness of the insulation dome was kept around 15 mm. The dome was tested at high
voltage platform of 100 kV at Power Supply Group, CAT, Indore. The dome was fitted over the plasma chamber and electromagnet coils were fitted on it, to keep it at ground potential. The dome was fabricated in two parts having one side-corrugated flange, which also provides the sides of the magnet at ground potential. After assembly the complete setup was tested up to 40 kV.

The plasma current density is less than the space charge current density the extracted current is controlled by the value of $J_p$. High extraction voltage is required for high ion currents. A three-electrode system has been designed and fabricated to extract the proton ion beam current of 30 mA and 40 keV beam energy. The schematic diagram of the three-electrode system is shown in Fig. 3.

**Table 1 — The salient features of the system and solenoid design parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (keV)</td>
<td>40</td>
</tr>
<tr>
<td>Beam current (mA)</td>
<td>30</td>
</tr>
<tr>
<td>Beam diameter (mm)</td>
<td>08</td>
</tr>
<tr>
<td>Emittance ($\pi$ mm·mrad)</td>
<td>0.8</td>
</tr>
<tr>
<td>Microwave frequency (MHz)</td>
<td>2450</td>
</tr>
<tr>
<td>Microwave power (kW)</td>
<td>2.0</td>
</tr>
<tr>
<td>Magnetic field (gauss)</td>
<td>1350</td>
</tr>
<tr>
<td>Coil NI (for each coil 1 and 3)</td>
<td>16.380</td>
</tr>
<tr>
<td>Coil NI (for coil 2)</td>
<td>9200</td>
</tr>
<tr>
<td>Power supply (for each coil)</td>
<td>0-32 V, 100 A</td>
</tr>
</tbody>
</table>

**2.4 Beam extraction system**

The plasma current density ($J_p$) is given by:

$$J_p = q n_i + \sqrt{k T_i m_i}$$

where,

- $k$ = Boltzmann constant; $T_i$ = electron temperature, eV; $m_i$ = mass of the ion, $k G$ and $n_i^*$ = ion density, cm$^{-3}$

The space charge current density ($J_{sc}$) is computed using the expression:

$$J_{sc} = 4/9 \varepsilon \omega [\sqrt{2e/m}] V_o^{3/2} \delta^2$$

where,

- $\varepsilon$ = permittivity; $\delta$ = extraction gap width and $V_o$ = extraction potential, kV.

For practical cases, Keller proposes a handy formula, where gap width = radius of extraction aperture, Now,

$$I^* (mA) = 0.7 [q/A]^{1/2} V_o^{3/2} (kV)$$

where,

- $A$ = atomic weight of the ion, amu
- $q$ = charge state of the ion.

Therefore, for a proton beam current of 100 mA an extraction voltage of 27 kV is required. For a 50 kV extraction potential the current that can be extracted is greater than 250 mA but in this case as

- The plasma current density is less than the space charge current density the extracted current is controlled by the value of $J_p$. High extraction voltage is required for high ion currents. A three-electrode system has been designed and fabricated to extract the proton ion beam current of 30 mA and 40 keV beam energy. The schematic diagram of the three-electrode system is shown in Fig. 3.

The plasma electrode (PE) will be kept at a potential of 30 kV and accelerating electrode (AE) will be negative with respect to ground and varies to few kV. The third electrode is at ground potential. The PE made water-cooled to prevent the emission of secondary electrons. The electrodes are separated by corrugated type Teflon flange that provides the dc isolation of 65 kV. The spacing between the plasma electrode (PE) and the acceleration electrode (AE) is very critical and governs the beam current. To obtain maximum beam current the spacing has to be optimized. The beam current will be measured by using Faraday cup.

The emittance of the ion beam $\varepsilon_a$ is calculated being the expressions given by Taylor:

$$\varepsilon_a = 1.6 \times 10^{-3} (q/A) B r^2 \pi \text{ mm-mrad}$$

where,

- $B$ = magnetic field in Gauss; $r$ = radius of the extraction aperture in mm; $A$ = atomic weight of the ion, amu; and $q$ = charge state of the ion.

The computed emittance comes out to be between 0.22 < $\varepsilon_a$ < 0.36 $\pi$ mm-mrad for 875 gauss < $B$ < 1400 Gauss.
Supervisory Control system — Supervisory control system for MIS is designed with Computer eXtended Instrument (CXI) unit. Raw digital and analog data received from various sub-systems of MIS are conditioned using Signal-conditioning units. These conditioned data is fed to data acquisition cards inside a PC. GUI based software has been prepared to monitor and control various parameters of the system. This software presents whole of the system in block diagram format. Each of the blocks can be monitored in detail by activating that block. This helps monitoring and supervising of the system.

References