Impact of Ion Beams

Like electrons, ion beams are also playing crucial roles in our lives. These beams with energies ranging from a few hundred keV to a few TeV and currents ranging from a few pico-ampere to a few hundred milli-ampere, are being employed in almost all the areas. Ion beam accelerators like TEVATRON, HERA, SIN, SIS, RHIC, etc., have contributed vastly towards the advancement of our knowledge. Apart from the valuable contributions made towards the basic sciences, ion beams have percolated into the applied fields as well. The industrial, medical, metallurgy and power sectors as well as strategic areas, like defence, are the fields that have been immensely benefited by these beams.

Semiconductor industry is among the first ones which has used ion beams extensively. In this case, low energy, high current, heavy ion beams of boron, phosphorous, etc., are implanted in Si, As and Ga to change their physical and electrical properties. The devices thus produced have totally transformed the vacuum tube based electronics industry into a solid state one. This, in turn, has brought in the much needed ruggedness and reliability in this industry. Focused Ion Beams (FIB) are used for tailoring the ICs & Memories. Ion cluster deposition, ion milling, buried conductors, deep amorphous layers and ROM program are some of the other areas where ion beams have made a big mark. Now, MeV beams are...
even being used for ion implantation. Bombardment of a few MeV proton beam on Si, produces GTO Thyristors having much more improved characteristics [1].

Xenon beams with energy as high as 10 MeV / nucleon are being used for making micro porous membranes [1]. These membranes have wide applications in the filter industry.

Medical field is another area where ion beams have made a big impact. Accelerated ions are used for producing radio-isotopes like C\textsuperscript{11}, N\textsuperscript{13}, O\textsuperscript{15}, F\textsuperscript{18}, Ga\textsuperscript{67}, In\textsuperscript{111}, I\textsuperscript{123}, Co\textsuperscript{55}, etc. These isotopes are employed for investigating the functioning of human organs like lungs, heart, brain, throat, bones etc. Ion beams are also being used for the treatment of cancers and tumours. For this purpose, proton beams of about 200 MeV and heavy ion beams of 500 MeV/nucleon are being commonly employed [2].

Ion beams are also used for producing secondary beams like neutrons and \(\gamma\) rays. Neutrons, in addition to being used for radiography, are also being employed for therapy [2] and detection of explosives [1], buried in mines.

Accelerator Driven Subcritical Systems (ADS) are being conceived worldwide as viable sources for producing electrical power, breeding of fuel and transmutation of nuclear waste. These systems [3-6] need proton or deuteron beams of about one GeV with beam current of 50 mA to 100 mA. For ADS to be a commercially viable venture, the accelerator efficiency should be close to 50 \%. If achieved, not only a clean source of power, but also a good breeder of fissile material will become available.

Accelerator based Heavy Ion Inertial Fusion is another mechanism through which the production of power is being contemplated [7]. For this process, heavy ion beams of Bismuth / Lead, with energy as large as 10 GeV and current as high as 25 kA, are being conceived.

The sphere of utilization of ion beams is expanding at a fast pace with more and more avenues opening up daily.

**Ion Beam Technology**

Since 1930, along with the inception and growth of accelerators, Ion Beam Technology has also gone through a drastic change and transformation. In the beginning, ion sources of protons & deuterons were developed. The demand for higher energy and higher beam current, pushed the development to new and different types of ion sources. The arrival of heavy ion beams with multiple charge states boosted the energy of the accelerators. The entry of Tandems ushered in a new era of negative ion beam technology. As per the present scenario, ion sources for light and heavy ions with positive, negative and multiple charge have been developed with currents varying anywhere from a few pico - ampere to a few 100 mA. Duoplasmatron, PIG, Duopigatron, Cusp field, EBIS (Electron Beam Ion Source) and ECR (Electron Cyclotron Resonance), SNICS, are some of the ion sources which have been developed to meet the diverse needs.

In India too, extensive efforts are being put to establish this technology. Among all the organisations, DAE has taken a major lead. Different types of ion sources are being developed at BARC-Mumbai, TIFR-Mumbai, VECC-Kolkata and CAT-Indore. NSC-Delhi (under UGC) has also initiated steps in this direction.

**BARC Scenario**

At BARC, the first attempt towards this direction was made by designing and developing a high current duoplasmatron ion source followed by a compact, microwave cathode plasma source. The experience, thus gained, is being utilised to develop an ECR source which will deliver 50 mA of proton beams at a voltage of 50 kV. The present article is a brief account of the efforts being made by BARC in establishing the high current ion beam technology.
**Building a base**

Realising its importance, Accelerator & Pulse Power Division, BARC initiated an elaborate programme in this direction about a decade back. Development of high current Duoplasmatron Ion Source was the first step.

**Duoplasmatron Ion Source:** The source was designed to deliver proton/deuteron beams with a current of 20 mA [8, 9] at an energy of 20 keV. Figures 1 & 2 give the glimpses of this source.
The source was used as an injector to the Low Power RFQ (LPRFQ) [10]. It is a filament-based source consisting of two plasma chambers. For damping the oscillations, the beam was allowed to expand and cool in an expansion cup. The beam properties and the transmission was controlled through a set of five electrodes. To focus the beam downstream, a pair of einzel lens was employed. The emittance characterisation was done by using a slit and wire detector. This source was tested up to a voltage of 15 kV and yielded about 12 mA of proton beam at an arc current of 2.5 A and magnetic field of 1.7 kG. The beam was found to be highly space charge limited. This is the only indigenously developed ion source in the country which can yield proton beams as high as 12 mA.

**Microwave Cathode Plasma Ion Source (MCPIS):** The filament based sources have short life. Duoplasmatron ion sources fall in this category. For a long operation time of a few days, weeks or even months, one has to look for filamentless ion sources.

The first indigenous attempt in this direction was made by developing a compact permanent magnet based, microwave cathode plasma ion source [11]. A close up view of this source is shown in Figure 3. Figure 4 shows the characterisation set up for the same. A 2.45 GHz, 100 Watts, microwave generator in conjunction with Sm-Co permanent magnets was used for initiating the plasma. At a meagre 4 kV extraction voltage, the deuteron current of

![Fig. 3 A view of the MCPIS](image1)

![Fig. 4 Commissioning of the MCPIS](image2)
about 0.6 mA was obtained. For this, a microwave power of 60 Watts was consumed. The proton and helium beams of about 0.5 mA, and 0.2 mA respectively, were also obtained.

The experience thus gained in commissioning these two sources was extremely useful. It gave us the confidence to take up the task of designing and developing a 50 kV, 50 mA, DC, ECR proton ion source. Again, this will be the only indigenously developed source in the country, capable of delivering as high as 50 mA of proton beams.

**Design & development of a 50 mA proton ECR source**

The detailed design features of this source are described in references [12] & [13]. The major design parameters are given in Table I & its schematic is shown in Figure 5. The source consists of: 1) Microwave generator, 2) Microwave transmission components, 3) Plasma chamber, 4) Solenoids, 5) Ion extraction assembly, 6) Vacuum systems, 7) Gas injection assembly, 8) Beam diagnostics, 9) Einzel lenses, and 10) Power supplies. The plasma is initiated by a microwave discharge in the presence of a magnetic field created through a pair of solenoids. The microwave power is generated by a 2.45 GHz, 2 kW, cw Magnetron and is fed to the source via a plumbing line. To prevent the electrodes from getting overheated, the portion of the aperture close to the beam is made from molybdenum. A 30 cm long HV column, having three successive insulating rings of Alumina, brazed at the ends with the metallic flanges, are used to hold the high voltages.

<table>
<thead>
<tr>
<th>Table 1: Design parameters of the ECR source</th>
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<tbody>
<tr>
<td>Beam Energy (keV)</td>
</tr>
<tr>
<td>Proton Current (mA)</td>
</tr>
<tr>
<td>Discharge Power (W)</td>
</tr>
<tr>
<td>Frequency (GHz)</td>
</tr>
<tr>
<td>Axial Magnetic Field (G)</td>
</tr>
<tr>
<td>Duty Factor (%)</td>
</tr>
<tr>
<td>Proton Fraction (%)</td>
</tr>
<tr>
<td>Beam Emittance (π mm·mrad)</td>
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</table>

![Fig. 5 Schematic of the 50 keV, 50 mA ECR Proton Ion Source](image.png)
The design of the electrodes has been optimised with the help of a multi-particle code “PBGUNS” [14]. In order to generate low emittance proton beam, five-electrode extractor geometry, as used in the duoplasmatron source, has been adopted. The puller electrode is found to be highly effective in controlling the transmission of the downstream beam as is evident from Figure 6. The beam trajectory for 50 mA current simulated through PBGUN is depicted in Figure 7.

The ion source rms normalised emittance has been theoretically estimated to be \( \sim 0.1 \pi \text{ mm-mrad} \). This corresponds to an ion temperature of \( kT_i = 1.5 \text{ eV} \). Lower the plasma ion temperature, lower is the emittance and better the beam quality. Variation of ion source emittance with plasma ion temperature is shown in Figure 8. This value becomes minimum at a puller voltage of 40 kV as is depicted in Figure 9.
The beam charge neutralisation is an important aspect of space charge dominated beams. It can reduce the emittance and hence improve beam quality considerably. This feat can be accomplished by providing extra electrons through the deterioration of vacuum in the beam line of the source. The beam characteristics at a distance of 40 cm downstream is shown in Figure 10. The reduction in the beam radius and normalised emittance, $\varepsilon$, with increase in neutralisation, clearly indicates that the beam is highly space charge dominated. With more and more neutralisation, both the beam radius and the emittance values can be brought down to a minimum. In our case, this minima is attained when the beam is more or less fully neutralised which happens at a level of about 98%.

The 2.45 GHz Microwave generator used for this purpose is magnetron based. It can deliver cw power up to 2.0 kW. The power can be continuously varied from 300 Watts to 2.0 kW. An RF plumbing line consisting of a circulator, dual directional coupler and a four-stub auto-
tuner is used to feed the source. The circulator is used to protect the magnetron from the reflected power, the directional coupler to measure the power and the auto tuner for matching the impedance to that of the load. The generator has been tested up to a power level of 1.8 kW. In Figure 11 is shown the complete set up of this microwave generator. Its performance characteristic is shown in Figure 12. The operation of the microwave generator is controlled through a micro-controller [15]. The system shown in Figure 13 is presently going through a phase of debugging.

![Fig. 11: Microwave Generator and the Plumbing Line](image1)

![Fig. 12: Performance of the Magnetron](image2)

![Fig. 13: Computer control of Microwave Power Generator](image3)
Table 2: Design parameters of solenoid magnets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID of the solenoid</td>
<td>20 cm</td>
</tr>
<tr>
<td>OD of the solenoid</td>
<td>36 cm</td>
</tr>
<tr>
<td>Length of the solenoid</td>
<td>5 cm</td>
</tr>
<tr>
<td>Field on axis</td>
<td>1 kG</td>
</tr>
<tr>
<td>Copper conductor (hollow)</td>
<td>10mm x 10 mm</td>
</tr>
<tr>
<td>Voltage drop</td>
<td>4.83 volts</td>
</tr>
<tr>
<td>Total power dissipation</td>
<td>3.3 kW</td>
</tr>
<tr>
<td>Water flow per circuit</td>
<td>5 litres / min</td>
</tr>
</tbody>
</table>

Fig. 14: Double Pancake Solenoid

Fig. 15: Magnetic field profile for the ECR discharge

Fig. 16: A view of the Plasma Chamber
The axial magnetic field of 875 G, needed for generating the ECR discharge, is provided by water cooled solenoids. The discharge will be generated at two places. One will be near the microwave window and the other close to the extraction hole.

The design parameters of the solenoid are shown in Table II. These solenoids have been fabricated from a hollow square copper conductor and are in the form of a double pancake. Both the solenoids are independently powered. A view of one of the solenoid is shown in Figure 14. The profile of the magnetic field is given in Figure 15.

The plasma chamber for the source has a quartz window on the front side. A 1600 litre/sec turbo pump will be used to evacuate the source. The flow of hydrogen gas will be monitored through a mass flow controller. The plasma chamber has been made and tested up to a vacuum of $10^{-6}$ Torr. A view of the chamber is depicted in Figure 16.

The ion beam current will be monitored by a DCCT and a Faraday cup. Video diagnostics will be used for knowing the beam profile, the slit & wire scanner for getting the emittance, the four grid energy analyser for neutralisation and Wien filter for the mass analysis. The source is expected to be operational by 2007.

Conclusions

High current ion beam source technology is foreseen to be playing a crucial role in almost all the sectors. They form the backbone of Accelerator Driven subcritical Systems (ADS), Spallation Neutron Sources, Accelerator based Fusion programmes as well as many other applications, requiring high current ion beams. Internationally, proton beams of about 100 mA have been already realised. Although APPD, BARC, has established a good base in this technology, but it has still a long way to go.

References