# HIGH CURRENT DC ION BEAMS

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## Summary

Development of high-current cw accelerators such as ZEBRA and FMIT, use of high current dc ion beams in industry for sputtering and material treatment, and scientific applications such as heavy-ion fusion and plasma physics diagnostics have provided the impetus for ion source development programs at many laboratories. At Chalk River, development of efficient plasma generators and reliable extraction columns to provide high quality beams of hydrogen, nitrogen, argon and xenon is underway. DC beams of up to 850 mA (limited by available power supplies) of hydrogen, 200 mA of nitrogen, 155 mA of argon and 100 mA of xenon have been produced with good reliability. DuoPIGatrons, with and without magnetic cusps, are used to generate a high density, reasonably quiescent plasma. Multi-aperture accel-decel columns are used for extraction with shaped apertures and beamlet steering to improve beam quality. This paper describes the performance of these sources and identifies some of the remaining problems. Guidelines for extraction column design, and experience with transporting high current beams are also presented.

## Introduction

Increased applications for high current dc ion sources has led to renewed interest and development effort. High current cw accelerators such as the Fusion Material Irradiation Test Facility at Los Alamos, and the Zero Energy Breeder Accelerator at Chalk River[1] exemplify one application. High current ion beams are finding increasing use in industry for sputtering and for material treatment (e.g., hardening of steel tools with nitrogen beams). Research applications include xenon and bismuth beams for heavy ion fusion and hydrogen and heavy ion beams for plasma diagnostics in fusion research. For these applications, the current ranges from about 50 mA of xenon for heavy ion fusion, through 200 mA of nitrogen for steel case-hardening and up to a few amperes of neutral hydrogen for plasma diagnostics. In addition, these applications all have specific requirements in regard to beam quality (emittance, divergence, ion species), reliability and component lifetime.

The ion source and injector development program at Chalk River has, as its primary goal, the development of ion sources and injector systems to provide dc proton beams with currents of up to 400 mA at energies up to 75 keV. These beams are to be injected into radiofrequency accelerators that will be operated near their current limit, therefore beam emittance, size and divergence must meet stringent requirements, not only from the ion source but also through the beam transport system. In parallel with this, we have developed high current dc heavy ion sources suitable for sputtering, material treatment and heavy ion fusion; some work on dc neutral beam injection has also been carried out.

Two ion source development facilities are currently in operation. The Ion Source Test Stand (ISTS) is being upgraded to provide 900 mA dc at 85 kV. In addition, a 50 kV, 100 mA supply is available for development of tetrode columns. The ISTS features an emittance measuring unit with a dynamic range of $10^5$, permitting measurements far into any halo. Power dissipation levels in the beam stop on the unit restrict measurements to beams of less than 150 mA at 40 keV. This is adequate for studies of up to three beamlets, permitting studies of beamlet-beamlet interaction. This facility is used mainly for plasma generator and extraction column development. The power supply on the Injector Test Experiment (ITE) can provide over 850 mA at 50 kV. The ITE beam line has a 60° bending magnet $\sim$1 m from the source, the proton beam stop is $\sim$1.5 m farther downstream and a solenoid is being installed between ion source and bending magnet. A simple pepper-pot plate emittance device can be installed in place of the proton beam stop for measurements on low power ($\sim$ 2.5 kW) beams. This facility is used for beam transport studies and development of non-intercepting beam diagnostics. The ITE will also be used to commission injector packages. Two other useful devices are a cathode test facility used to develop long-lifetime cathodes for the plasma generators and plasma bridge neutralizers for space charge neutralization of high current ion beams, and a Langmuir probe carriage and drive circuit that is used to measure plasma density and electron temperature in the plasma generator.

## Plasma Generators

A desirable plasma generator should provide a high current density ($\sim$ 400 mA/cm$^2$ for hydrogen, 65 mA/cm$^2$ for argon) low noise (< 1%) plasma with good uniformity ($\pm$ 2.5%) over the extraction area (from 3 cm$^2$ to 75 cm$^2$ for the applications listed above). It should provide a high fraction of the desired ion species and have good gas and arc efficiency. For most industrial and research applications, component lifetime should give over 500 hours of full current operation without significant degradation.

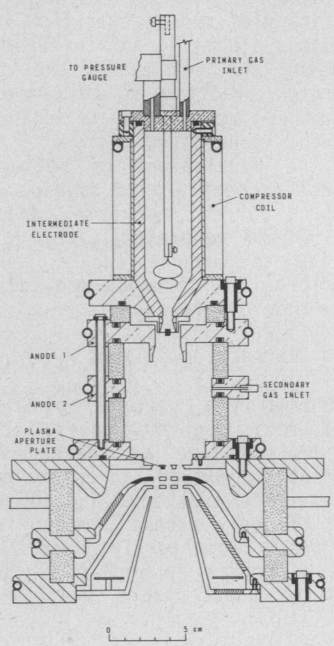


Figure 1 Simple duoPIGatron plasma generator on accel-decel extraction column.

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At Chalk River, we are developing a series of plasma generators to satisfy these requirements. All of the generators presently under development use the duoPIGatron configuration - a hot-cathode reflex (PIG) arc that uses both electric and magnetic fields to confine the ionizing electrons and thus provide high efficiency. This design provides a well protected environment for the cathode - either oxide-coated or refractory material (e.g., lanthanum-hexaboride). For the smaller hydrogen sources, and for the heavy ions sources a plain PIG region is used (Fig. 1). This source does not provide a sufficiently uniform plasma in sources larger than 5 $cm^2$. Plasma uniformity can be improved by providing better confinement of electrons and ions by adding a magnetic multipole-cusp field in the reflex region of the generator. We have studied two types of cusp. The axial cusp generator uses a set of linear magnets of alternating polarity arranged parallel to the long axis of the generator - rather like a stockade. This configuration provides poor efficiency for extraction areas of less than 15 $cm^2$ because of losses between the cusps, but is presently the best choice for larger sources. The ring cusp generator uses doughnut-shaped magnets with radial magnetization. These magnets are stacked with alternating polarity with their axes parallel to the long axis of the generator. The ring cusp duoPIGatron has an efficiency only slightly less than that of the simple duoPIGatron, but its $H_1^+$ fraction is significantly better. The ring cusp also has a higher arc efficiency than the axial cusp. Optimization of the magnetic circuit for the ring-cusp generator is continuing.

One characteristic of the duoPIGatron sources that has limited their application is that relatively small changes to the geometry can make rather large changes not only in the output, but also in ease of operation. For example, a change in the geometry of the intermediate electrode nose piece on a heavy-ion source led to stable operation at a current 50% higher than was previously possible[2]. Heavy ion operation with the cusp sources has not been attempted.

Two main improvements remain to be made to these sources. First, the proton fraction should be increased - operation at reduced gas flow improves the fraction but reduces stability and increases the noise level. Increasing the volume of the cusp source improves the proton fraction at the expense of arc efficiency. Further improvement is expected by the refinement of the generator design. The second improvement is the development of better cathodes. The oxide cathodes presently used degrade after about 250 hours of full current operation and even more rapidly if the plasma generator is operated at the edge of stability to enhance the proton fraction. Refractory ceramic hollow cathodes provide a possible solution, but further development is required.

## Extraction Columns

Besides providing a suitable plasma, the ion source should form a high-brightness, low-halo ion beam with the desired size and divergence. As a further requirement the extraction column must operate reliably. Catastrophic breakdown and subsequent loss of beam are not the only problem, microdischarges in the column will cause, momentarily, poor quality beam. This may not be a problem in industrial applications but could lead to unacceptable beam spill in an accelerator.

For good quality beams, the electrode geometry, especially in the region of the plasma surface, is critical. Small aberrations that would not be noticed in most accelerators are intolerable in high current beams. Shaping of the downstream side of the plasma grid is used to reduce aberrations by controlling the shape of the plasma surface. This shaping gives good beam brightness without the complication of an additional electrode (as used in tetrode columns).

For most of our designs, we use a perveance of $\sim$ 0.4 $P_o$, where $P_o$ is the Child-Langmuir perveance, to counteract the defocusing effect of the aperture in the extraction electrode. The maximum current density is set by the maximum voltage that can be held across the gap without frequent sparkdown. For typical extraction geometries, the maximum voltage is given by

$$V_b \approx 5 \times 10^4 \, d^{1/2}$$

where d is the gap spacing in centimeters. A "first guess" at the electrodes allows use of an optics simulation code like BEAM[3] to calculate the beamlet shape, divergence and emittance (Fig. 2). The electrode shapes are then modified and the optics recalculated iteratively to arrive at a suitable design. The final step is to measure the beamlet emittance size and divergence on the Ion Source Test Stand to verify the calculation. In our experience, the agreement between calculation and measurement has been very good. For example, the experimentally determined optimum extraction voltage is within 5% of the calculated value.

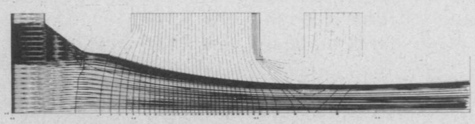

Figure 2 Computer simulation of extraction geometry and calculated beam trajectories.

The maximum current per beamlet is limited by two factors in addition to the current density limit above. First, for good optics, the extraction gap should not be less than the aperture diameter. Second, for good suppression of backstreaming electrons, the maximum current per beamlet should not exceed 100 $\sqrt{A/Z}$ mA where A/Z is the (average) mass-to-charge ratio of the particle. Thus, for high currents, a number of apertures are required. One advantage of a multi-aperture source is that the beamlets can be steered by displacing the apertures in the plasma grid. One could provide at a target a concentrated beam by superimposing individual beamlets, or a broad beam by slightly overlapping them. For accelerator applications, initial results show that it is possible to use beamlet steering to improve the beamlet distribution in phase space to better match the accelerator acceptance.

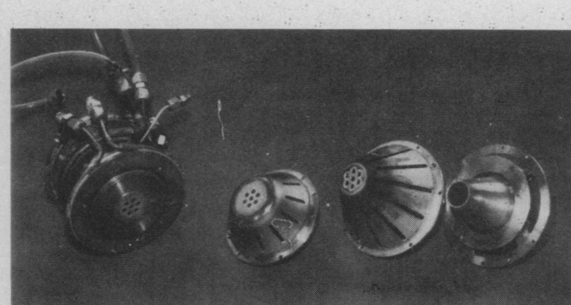

Figure 3 Electrodes from Mark I extraction column.

Extraction column reliability (freedom from sparking) is of special concern for dc operation. The major factor affecting reliability[4] is the generation of x-rays by backstreaming electrons. These x-rays generate photo-electrons on ceramic insulators, leading to sparkdowns. They also lead to increased sparking from some electrode materials. To improve reliability, backstreaming must be minimized, materials must be chosen to reduce sparking, and ceramic insulation must be shielded from the x-rays. Backstreaming can be reduced by (a) reducing beam spill on electrodes, (b) reducing the neutral gas pressure in the extraction column and (c) providing effective suppression of electrons from the beam plasma. Our extraction column uses molybdenum-faced accel electrodes (Fig. 3), which have more than doubled the operation current limits, and extensive water-cooling of the electrodes.

## Ion Source Performance

Table 1 shows the performance achieved to date with these ion sources. The 850 mA hydrogen beam was limited by the capability of the high voltage power supply. A seven-aperture ion source was operated at 45 keV, 490 mA for over three hours spark free. Operation time for the heavy ion sources was terminated to limit erosion of the beam stop by sputtering. In general, operation of the extraction column is satisfactory, but the plasma generator still requires further development.

Table 1

Ion Source Performance

Hydrogen

| Current (mA) | Energy (keV) | Emittance ($\pi$ mm-mrad) | Arc Current (A) | Remarks |
|---|---|---|---|---|
| 850 | 42 | NA | 30 | 13 apertures, axial-cusp source, 320 mA protons to dump 2.5 m downstream |
| 650 | 46 | 7.9$^{\dagger}$ | 14 | 7 apertures, 3-1/2 hour run |
| 560 | 42 | 3.9$^{\dagger}$ | 13 | 7 apertures, displaced to reduce emittance |

$^{\dagger}$ derived from 3 beamlet measurements.

Heavy Ions

| Ion | Current (mA) | Emittance ($\pi$ mm-mrad) | Arc Current (A) | Remarks |
|---|---|---|---|---|
| $N_2$ | 190 | NA | 12 | 7 apertures |
| Ar | 155 | 0.055* | 13 | 7 apertures |
| Xe | 99 | 0.037* | 10 | 7 apertures |

* single beamlet value.

## Beam Transport

For most industrial applications, the beam can be used "as is" with a reasonably high background gas pressure to reduce space charge blowup. For accelerator applications, the beam must generally be transported a few meters, with possibly some species selection along the way, and matched to the acceptance of the rf accelerator. Our experience ranges from a simple system designed[5] for a heavy-ion fusion accelerator using only an Einsel lens, to an RFQ injector presently being developed which has two solenoids, a shaped-pole 60° bending magnet and about 2 meters of beamline crammed with diagnostics, vacuum pumps and beam dumps. A major concern in the transport system is emittance growth from non-uniform space charge neutralization. These high current beams generally require a gas pressure of 2-7 x $10^{-3}$ Pa for good space charge neutralization - the higher the pressure the better the neutralization. This is unfortunately accompanied by significant production of fast neutrals - 15-20% for a system like ITE.

Perturbation of the potential in the beam can lead to some rather strange effects. On ITE, a protection cone that contacted the beam asymmetrically produced a 20%, 100 kHz modulation on the beam. By careful alignment, we have been able to transport 320 mA of protons to the ITE proton dump, a distance of 2.5 m from the source, with low noise on the beam and with no gross blowup. Solenoids will be required in future injectors and we will be studying their effect on space charge neutralization and emittance growth.

## Acknowledgements

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