Understanding extraction and beam transport in the ISIS H^- Penning surface plasma ion source[a)]

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The ISIS H^- Penning surface plasma source has been developed to produce beam currents up to 70 mA and pulse lengths up to 1.5 ms at 50 Hz. This paper details the investigation into beam extraction and beam transport in an attempt to understand the beam emittance and to try to improve the emittance. A scintillator profile measurement technique has been developed to assess the performance of different plasma electrode apertures, extraction electrode geometries, and postextraction acceleration configurations. This work shows that the present extraction, beam transport, and postacceleration system are suboptimal and further work is required to improve it.
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I. INTRODUCTION

An understanding of beam extraction and transport is essential when generating low emittance beams. The ISIS ion source is a world class H^- Penning surface plasma ion source with over 20 years of operational experience. It routinely delivers 50 mA of H^- ions with a 300 μs, 50 Hz duty cycle for periods of up to 30 days. Developmental ion sources have produced beam currents up to 70 mA and duty cycles up to 1.5 ms at 50 Hz. When run in "standard conditions" both the developmental ion source and the operational ion source suffer from very large emittances of about 0.9 πmm mrad rms normalized.

The beam from the operational ion source enters a magnetic low energy beam transport (LEBT) and is collimated and focused by solenoids down to a 30 mA, 0.5 πmm mrad rms normalized beam for entry into an radio frequency quadrupole. There is still enough beam current for operational purposes so this large loss of beam in the LEBT is not a problem.

For future high intensity machines[1] this large loss of beam is not acceptable; this has motivated a study of beam extraction and transport.

II. ION SOURCE

The design of the ISIS H^- source has previously been described in detail.[2] The source is of the Penning type, comprising a molybdenum anode and cathode between which a low pressure hydrogen discharge is produced. A transverse magnetic Penning field is applied across the discharge. Hydrogen and cesium are fed into the discharge via holes in the anode. The anode and cathode are housed in a stainless steel source body.

The beam is extracted through an aperture plate (plasma electrode) using an extraction electrode. On the ISIS operational source the aperture is a 0.6×10 mm^2 slit and the extraction electrode is of an open ended jaw design, with a jaw length of spacing of 2.1 mm and a separation from the aperture plate of 2.3 mm. A +17 kV extraction voltage is used operationally.

After extraction the beam is bent through a 90° sector magnet (with an $n=1$ field gradient) mounted in a refrigerated coldbox. The sector magnet has two main purposes: to analyze out the electrons extracted with the H^- ions, and to trap cesium vapor escaping from the source.

The H^- beam emerges through a hole in the coldbox and is further accelerated by a 55 mm postacceleration gap. On the ISIS operational source this is an 18 kV postacceleration voltage giving a total beam energy of 35 keV. There are no other focusing elements in the ion source.

III. DIAGNOSTICS

The key to understanding beam behavior is a comprehensive set of diagnostics. The Ion Source Development Rig[3] (ISDR) is equipped with a diagnostic vessel onto which various measurement devices can be mounted.

- A pair of X and Y slit-slit emittance scanners is permanently mounted on the sides of the diagnostic vessel and can be retracted without stopping the source.
- A pepperpot emittance device[4] can be mounted on the rear of the vessel. The pepperpot can be moved along the axis of the beam and can be moved onto the same measurement plane as the slit-slit scanners while the beam is running.
- The head of the pepperpot can be replaced by a scintillator profile measurement head, allowing profile measurements along the axis of the beam.
- A retarding potential energy analyzer can be mounted on

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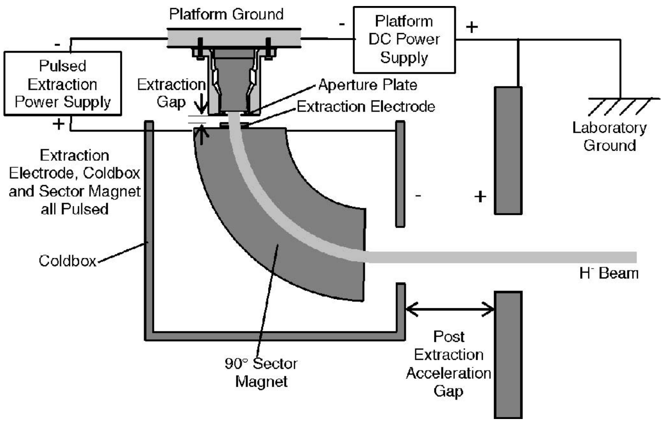

FIG. 1. The ISIS ion source, aperture plate, extraction electrode, sector magnet, and postacceleration gap.

the rear of the vessel in the place of the movable pepperpot/profile device.

- Beam current is measured via a torriod permanently mounted on the entrance to the diagnostics vessel.
- A buffer gas delivery system mounted directly after the beam current torriod allows for the controlled and measured introduction of various gases to study the effect of space charge.
- A dipole magnet can be installed in the vessel to study the degree of stripping in the beam.

In addition there is diagnostic vessel pressure monitoring and a full set of ion source parameter monitoring; source temperatures, power supply voltage, and current monitoring.

In this paper beam profile and pepperpot measurements have been taken at two positions: 615 and 355 mm downstream from the ground plane of postacceleration gap. The first position (615 mm) is on the same plane as the slit-slit emittance scanners. The second position (355 mm) is with the measurement head as close to the ion source as the apparatus will allow.

IV. VARIATION OF OPERATING VOLTAGE CONDITIONS

Modifications to ISDR (Ref. 5) allow the sector magnet field to be varied independently of the Penning field. The sector magnet current must be matched to the extracted beam energy, so this facility allows different extraction voltages to be studied while maintaining the Penning field.

Reducing the extraction voltage while keeping postacceleration voltage constant reduced the beam current, emittance, and profile size as shown in Fig. 1. A study comparing integrated quartz scintillator light output to beam current has confirmed scintillator linearity to allow an approximate current density scale to be indicated. A beam shutter is used to minimize scintillator exposure.

Figure 2 shows that when running at the operational voltage of 17 kV the beam is collimated by the holes in the postacceleration electrodes. At 8 kV extraction voltage the profile of the beam takes on the shape of a cobra head. Remembering that the initial profile must be the same shape as the aperture slit, it is clear that there is either a problem with the extraction, transport, postacceleration optics, or all three.

Either the beam is emitted from the aperture slit with nonuniform divergence along its length or the beam has undergone nonlinear focusing in the horizontal plane.

Varying the postacceleration voltage while keeping the extraction voltage constant altered the size of the beam, with higher postacceleration voltages producing smaller beams; this implies the postacceleration electrodes focus the beam.

V. GEOMETERY MODIFICATIONS

Modeling work showed that reducing the postacceleration gap would reduce the beam size. An electrode extension to the ground electrode in the postacceleration gap was manufactured and installed; this allowed the gap length to be altered.

Figure 3 shows beam measurements at 8 kV extraction voltage with the shorter postacceleration gap; these can be compared with the measurements shown in Fig. 2(b) for the original 55 mm postacceleration gap. The orientation of the *X*-axis is across the narrow side of the aperture plate slit width; the *Y*-axis is along the 10 mm length of the slit. The *Y*-axis is in the bending plane of the sector magnet. Processed pepperpot measurements are also shown in Fig. 3. Using the pepperpot data it is possible to calculate beam profile and overlay a quiver plot showing beam divergence. Emittances can also be calculated; these compare reasonably well with the slit-slit measurements. The small discrepancies are caused by different cut levels applied to the data. The pepperpot data can be used to generate particle distributions for particle tracking codes.

With the gap reduced from 55 to 10 mm the beam profile size was reduced and emittance was decreased by up to

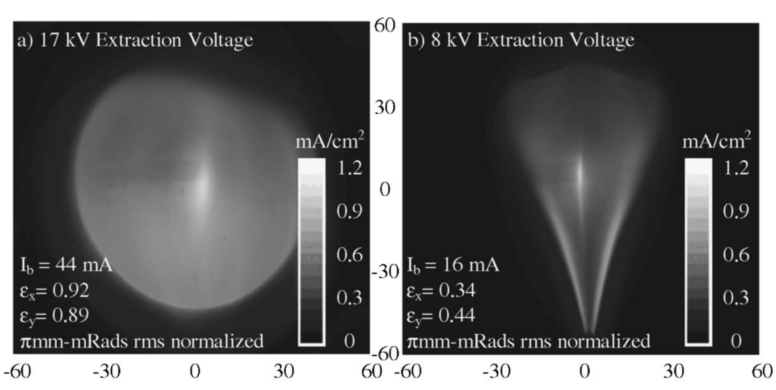

FIG. 2. Beam measurements 615 mm downstream from the ground plane of postacceleration gap with constant postacceleration voltage of 18 kV.

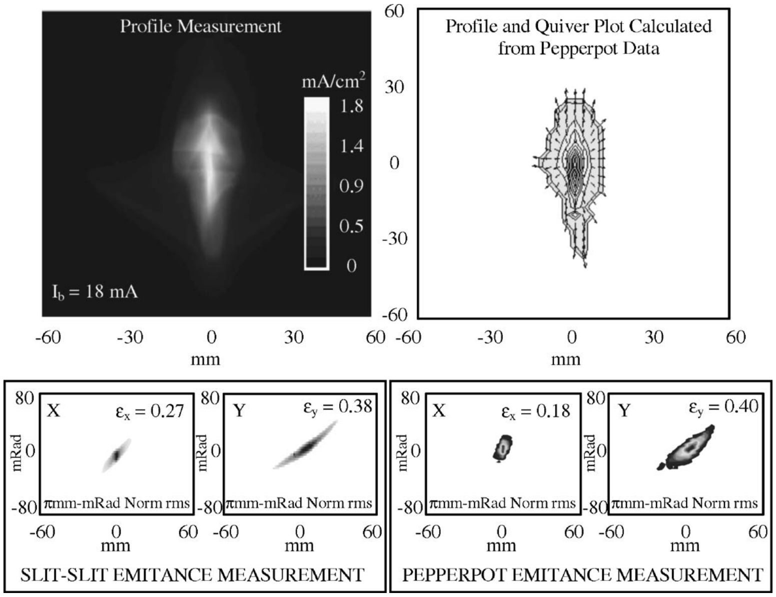

FIG. 3. Beam measurements taken 615 mm downstream from the ground plane of postacceleration gap with extraction voltage=8 kV and postacceleration voltage=18 kV with extraction gap reduced from 55 to 10 mm.

20% at lower extraction voltages. This implies that a higher field in the postacceleration gap increases beam focusing. The reduction in beam profile and emittance was smaller at higher extraction voltages because the beam was collimated on the electrodes.

Figure 4 shows how beam current was also slightly increased, presumably because a smaller beam meant less collimation on the electrodes.

The extraction electrode jaw gap was reduced from 2.1 to 1.1 mm; this had the effect of increasing the beam current as shown in Fig. 4. The smaller jaw gap slightly reduced emittance and profile width at lower extraction voltages but increased them slightly at higher extraction voltages.

Figure 4 shows that the data follow the $V^{3/2}$ law very well for low extraction voltages. For higher extraction voltages the beam current is slightly below trend, as the beam gets larger more beam is collimated on the postacceleration electrodes. This is confirmed by the fact that the 55 mm postacceleration case deviates from the $V^{3/2}$ line above a 12 kV extraction voltage, whereas the smaller beam for the 10 mm postacceleration case does not do so until extraction voltages exceed 15 kV.

To simplify things further an axisymmetric extraction system was tested. An aperture plate with a 2.7 mm diameter hole having the same area as the 10×0.6 mm^2 slit and a matching 4 mm diameter circular extraction electrode were tested. Figure 5 shows a profile measurement obtained for a 10 kV extraction voltage. The initially circular beam has been distorted into the same cobra-head shape seen for the slit extraction in Figs. 2(b) and 3. This suggests that the distortion is not caused by nonuniform emission along the length of the slit and must be caused by the extraction and transport system. The extent of the defocusing in the vertical plane is now evident; this was not clear for the slit extraction because the bottom of the beam was collimated on the postacceleration electrodes.

To study how the beam transport varies at different radii within the sector magnet an aperture plate with five 1 mm diameter holes in the direction of the original slit was tested with an extraction electrode with 2.1 mm wide jaws. Each of the five holes should produce a separate beamlet. A profile measurement for an 8 kV extraction voltage is shown in Fig. 6. The five separate beamlets can be seen, each beamlet is distorted into the same cobra-head shape seen previously;

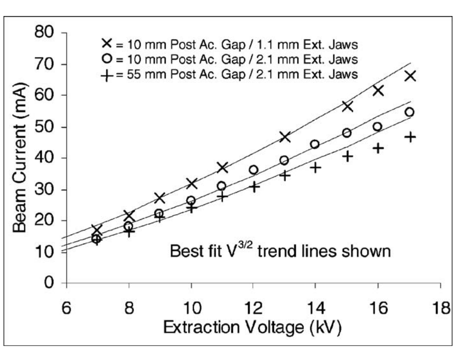

FIG. 4. Beam current vs extraction voltage for different postacceleration gaps and extraction electrode jaw gaps.

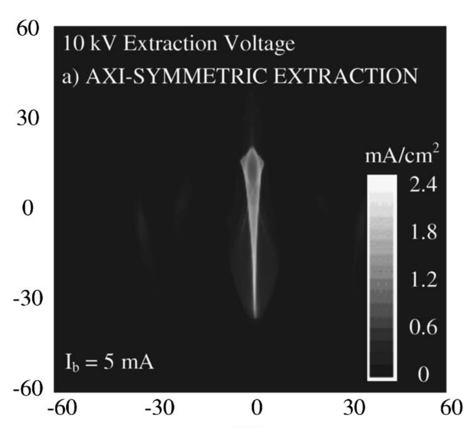

FIG. 5. Beam profile measurement 355 mm downstream from the ground plane of postacceleration gap for axisymmetric extraction.

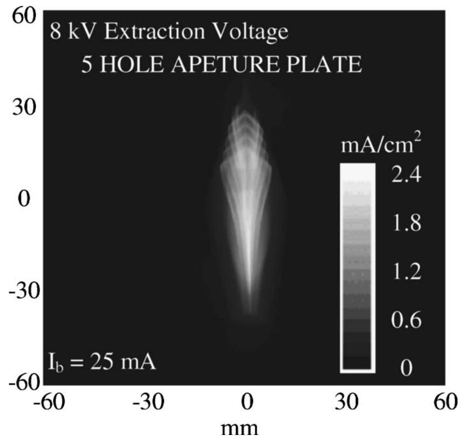

FIG. 6. Beam profile measurement 355 mm downstream from the ground plane of postacceleration gap for a five hole aperture plate.

however, the beamlets at the top of the scintillator profile are wider. Beam at the top of the image has gone through the smallest radius of the sector magnet, and beam at the bottom though the largest radius. Therefore the amount of horizontal divergence varies with radius or path length.

The source is pumped through the hole in coldbox, so there will be a pressure differential across the sector magnet, so this could be space charge effect; however, studies varying the pressure in the source do not show very large changes in beam profile so this is an unlikely cause.

VI. DISCUSSION

This work is still in progress and aperture plates with slits of different dimensions await testing, including aperture plates with one hole in the position of each of the five holes in the five beamlet aperture plate; this will show how the beam interacts with itself. A detailed modeling investigation of beam transport is underway. The effects of beam entering the fringe field of the sector magnet will be studied. A previous simulation study using MAFIA (Ref. 6) showed that for a beam emitted perpendicular to the slit with no space charge the beam was transported with no aberration. This work shows that these assumptions are not valid and further investigation is required.

It is clear that the present extraction and transport arrangement on ISIS are suboptimal and improvements will yield higher output currents and lower emittances.

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