LA-UR-95-3166

Title:

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Submitted to:

ICIS '95 6th International Conference on Ion Sources
 September 10-16, 1995
 Whistler, B.C., Canada

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Development of a Toroidal-Filter H^- Ion Source*

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High brightness H^- ion beams will be required for the next generation of accelerator-driven, neutron spallation sources. Volume H^- ion sources have the potential for providing these beams at high duty factor with moderate beam currents and with the long-term operational stability and reliability needed. We report on the results of a continuing study of the LANL version of a toroidal-filter, volume H^- ion source which was designed to provide such beams. The H^- beam current, emittance, and electron loading have been measured with the source equipped with a 3-mm and a 10-mm dia. emission aperture and with several configurations of the plasma filter. The results are compared to beam simulations.

I. Introduction

High-intensity proton compression rings, such as that now in operation at the Los Alamos Meson Physics Facility (LAMPF), are being considered as drivers for the next generation of pulsed spallation neutron sources. Substantial increases in beam intensity over what is now achievable in these rings will require the further development of high-brightness H^- ion sources. The requirements for the proposed upgrade to the LAMPF proton storage ring, for

*Work performed under the auspices of the U. S. Department of Energy

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example, entail operation with moderate (30 mA) H^- peak currents up to 12% duty factor to obtain the desired average currents. Although there are several candidate ion sources that meet many of the requirements imposed by this choice, none has yet demonstrated the simultaneous combination of intensity, emittance, duty factor, reliability, and availability that are needed in this application.

A development program was therefore started at the Los Alamos National Laboratory (LANL) to provide such a source. After a preliminary evaluation of available ion sources was made, work was initiated to develop the Brookhaven National Laboratory (BNL) toroidal-filter volume source. A high duty factor version of this source was built and the initial tests were carried out on the LAMPF H^- injector [1]. The work reported here is a continuation of this initial study.

II. Experimental Apparatus

The high duty factor version of the toroidal-filter ion source was mounted on an ion source test stand which is capable of operating at up to 80 kV with 12% duty factor beams. This test stand has all the necessary beam diagnostics installed on a mass-analyzed beam line (Fig. 1). A single solenoid lens provides the required focusing and a 45° analyzing magnet is used for the mass analysis. Electron currents were inferred by subtracting the measured, mass-analyzed, H^- beam currents from the total drain current of the high voltage power supply. There was less than 2% contamination of heavy ions (O^- and OH^-) observed in the extracted beams. Beam currents were measured both with toroids (CM1 and CM2) and with an electron

suppressed Faraday cup. Emittance measurements were carried out on the mass-analyzed beam line using a conventional slit and collector emittance scanner [2]. The operating vacuum on the beam line was maintained in the 10^{-6} torr to the low 10^{-5} torr range, depending on the gas flow from the ion source. For the higher gas pressures, some stripping loss (10%) was observed and correspondingly higher beam currents could have been obtained if more beam line pumping were used. Our reported H^- results have not been corrected for this stripping loss. Most of the experiments were carried out with beams at 30 Hz and 500 μs pulse length in order to limit power loading on the emittance scanners, but some data were taken at higher duty factors up to 12% (120 Hz and 1000 μs). There was no dependence of either beam current or emittance on duty factor up to 12%.

The original BNL ion source employed a filter magnet configuration [3] in which a conical, transverse magnetic field was set up between the filter magnet and the inner ring of cusp-field magnets in the front of the source. The beam currents observed in Ref. 3 could not be obtained in our source with this configuration. However, significantly better performance, similar to that in Ref. 3, was obtained when the magnet polarity on the filter was reversed, thus producing a cusp-mirror filter. All results presented here are for this cusp-mirror configuration. The details of the construction of the LAMPF ion source and of this filter are described in reference [1].

The previous work on this ion source was performed using a low-gradient accelerating column. This column was not able to accelerate the higher peak currents without beam impingement on

the extractor electrode. A higher gradient column was therefore designed and built for the test stand. A four-electrode design was chosen to permit independent variation of the voltage on the first extraction gap and the total accelerating voltage. The plasma electrode on the ion source was fitted with an insert so that the extractor gap spacing and emission radius could be varied. Beam simulations were carried out using the ion beam code PBGUNS [4] for a range of extraction voltages and current densities in order to determine the optimum extractor gap spacing. The beam parameters predicted by this code at the exit of the accelerating column were in agreement with tracebacks from the emittance measurements on the mass-analyzed beam line. The minimum divergence beams occurred when there was a perveance match in the extraction gap.

III. Experimental Results

A series of measurements of H^+ beam current, beam emittance, and the associated electron loading current were taken for two emission apertures (3-mm dia. and 10-mm dia.) and for a range of ion source operating conditions and extraction voltages. For each emission aperture, the hydrogen gas flow was adjusted to give maximum extracted beam current. Using the observed gas flow rates, an operating pressure in the ion source of 20 mtorr was inferred. The source plasma was cesiated as described previously [1]. The arc voltage was usually run at 150 volts. There was only a weak dependence of beam parameters on arc voltage above this level.

For each of the emission apertures, the parametric dependence

of the H^- beam current and emittance on the arc current and on the extraction voltage was measured. In general, the extracted current density varied linearly with arc current but was relatively insensitive to extraction voltage. Data are presented in Fig. 2 showing the dependence of the extracted current density on arc current for the two apertures studied both for a weak and a strong plasma filter. One data point from the previous work for a 7-mm dia. aperture with a weak filter is also included. As the strength of the plasma filter was increased, the extracted current density decreased approximately 25% while the associated electron loading decreased by a factor of three to four depending on the aperture size and arc current. It was found that a reasonable compromise between loss of H^- current and reduction in electron loading could be obtained in which an electron to H^- ratio of 2:1 could be achieved with only a small (20%) decrease in the maximum H^- current. This choice of filter strength is an adequate compromise for a practical ion source.

We note that there is an explicit dependence of the extracted current density j on aperture radius R consistent with $jR = \text{constant}$ scaling law (Table I).

Table I. jR Scaling for 150 Amps Arc Current

$j(\text{mA/cm}^2)$	$R(\text{cm})$	$jR(\text{mA/cm})$
92	0.15	13.5
40	0.35	14
25	0.50	12.5

Similar behavior has been observed in other volume H^- ion sources [5]. This behavior is believed to be due to the gas stripping that occurs as the beam is extracted from the ion source and the fact that the gas flow was optimized for each aperture radius.

Beam emittance measurements were also taken as the ion source parameters and extraction voltage were varied. The dependence of beam emittance on arc current is shown in Fig. 3 for a 3-mm dia. emission aperture. The normalized emittance at a given beam fraction F is plotted as a function of $-\ln(1-F)$ for a range of arc currents from 40 to 140 Amps. For a Gaussian distribution in phase space, this plot will give a linear graph with a slope of $2\epsilon_{rms}$. At low values of beam fraction F , this slope gives an rms emittance of $0.0025 \pi\text{cm-mrad}$. This rms emittance is independent of arc current for low values of arc current, but increases slightly at higher values. At high values of beam fraction, there is substantial departure from linearity in this plot due to the third order aberrations in the beam emittance distributions. Tests performed by varying the excitation of the solenoid focusing lens with a constant input beam showed these third order aberrations increased rapidly as the lens strength was increased. Only a small change was observed as the extraction voltage or other ion source parameters were varied. Thus, we conclude that the major source of emittance growth at large beam fractions is due to ion-optical effects in the small bore solenoid lens.

The dependence of beam emittance on extraction voltage is

shown in Fig. 4 where similar graphs of beam emittance vs $-\ln(1-F)$ are plotted for a series of extraction voltages. In these cases, the rms emittances inferred at low beam fractions increase with increasing extraction voltage. The extractor is perveance matched at 8kV so there is an increasing departure from the matched condition as the extraction voltage is increased, resulting in larger, more divergent extracted beams which then experience greater emittance growth in the beam line. At large beam fractions, these curves again depart from linearity due to solenoid lens aberrations.

The dependence of normalized rms emittance with emission aperture size is shown in Fig. 5. These data were taken for optimal beams at 100 A of arc current and at an optimized extraction voltage (perveance match in the extraction gap). The 3-mm and 7-mm dia. emittance values scale linearly with emission aperture radius while the value for the 10-mm dia. case is higher than a linear extrapolation. Again, similar behavior has been observed in other volume H^- ion sources [5].

For the proposed upgrade to the LAMPF storage ring, rms emittances of less than $0.01 \pi\text{cm-mrad}$ are required, so the emission aperture size must not exceed 7-mm dia. if this ion source is used.

IV. Conclusions

The LAMPF version of the BNL toroidal-filter H^- ion source was operated with a 3-mm and a 10-mm dia. emission

aperture. Detailed beam measurements were taken and compared to previous data taken with a 7-mm dia. aperture. Optimum performance of the ion source was obtained for the cusp-mirror configuration of the plasma filter. The peak currents and rms emittances were independent of duty factor up to 12%. The measured current density decreased with increasing aperture size, consistent with a $jR = \text{constant}$ scaling law. The rms, normalized emittances (inferred at low beam fractions) increased linearly with emission aperture size up to the 7-mm dia. case, but the value for the 10-mm dia. case was higher than a linear extrapolation. Significant emittance growth, which was primarily due to solenoid lens aberrations, was observed with both apertures in the large beam fraction data. For the LAMPF application, an emission aperture no greater than 7-mm dia. must be used in order to obtain beam emittances less than $0.01 \pi \text{cm-mrad}$. Further development of the cusp-mirror filter and optimization of the arc efficiency in the ion source are now required to obtain higher beam currents with the desired brightness.

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Fig. 1. Layout of the LAMPF high-duty-factor test stand.

Fig. 2. Dependence of extracted current density on arc current for both a weak and a strong filter.

Fig. 3. Marginal normalized emittance as a function of $-\ln(1-F)$ for a range of arc currents from 40A to 140A. The source was configured with a 3-mm dia. emission aperture and a weak cusp-field filter.

Fig. 4. Marginal normalized emittance as a function of $-\ln(1-F)$ for a range of extraction voltages from 6 kV to 16 kV. The source was configured with a 3-mm dia. emission aperture and a weak cusp-mirror filter and was operated with an extracted current density of 28 mA/cm².

Fig. 5. Dependence of beam emittance on emission aperture size.
Source operation was optimized in each case at 100A of arc current.