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A 100-mA Low-Emittance Ion Source for Ion-Beam Fusion*

R. P. Vahrenkamp and R. L. Seliger
Hughes Research Laboratories

A Penning-type ion source is described that meets the following requirements for ion-beam fusion: Pulsed capability, high currents of heavy ions, and low emittance. The source is a scaled version of a lower-current ion source that produces 2 mA of singly charged xenon ions with a normalized emittance of 0.0015 mrad-cm. The scaled source, which utilizes permanent magnets and a filament cathode, was tested with both multiple- and single-aperture extraction. In the former case, pulsed xenon-ion currents of 100 mA at 2.5 keV were achieved at a current density of 15 mA/cm^2; in the latter case, 30 mA at 4.5 mA/cm^2 was extracted at 100 keV. The 30-mA case represents the first-gap conditions of a high gradient 1.5 MeV dc pre-accelerator. In all tests, the pulse length was ~1 msec with a repetition rate of 0.2 to 1.0 Hz. The experimental perveance data are in good agreement with the theoretical calculations.

The selection of the best ion source for ion-beam fusion is based on the ability of the source to provide the desired beam current, emittance, and long-life operation with heavy ions. In addition, the source must be compatible with state-of-the-art dc preaccelerator designs (the Argonne preaccelerator is described in an accompanying paper). A low-voltage Penning discharge source coupled with a Pierce extraction system has the capability of meeting these requirements. The low-voltage discharge is essential because of its inherently low energy spread; the Pierce-type extraction system is essential because of its low aberrations.

The high-current source discussed here is a scaled version of a Penning source designed for ion-implantation systems at Hughes Research Laboratories (HRL). A copy of this low-current source was delivered to Argonne National Laboratories (ANL) for testing, where measurements indicated a normalized emittance of ~0.0015 mrad-cm. The source operated on xenon with a beam current in the range of ~2.0 mA at a beam voltage of 100 kV. The encouraging results of these tests suggested that a scaled version of this source would be appropriate for the ion-beam fusion experiments underway at ANL.

Figure 1 shows the high-current xenon source with the optics system detached. Figure 2 is a schematic of the source as it will be mounted in the ANL preaccelerator column. The source has 16 permanent magnets located around the periphery of the discharge chamber. These, when combined with the anode and cathode pole pieces, produce a divergent magnetic field on the order of tens of gauss. The cathode is a 0.025-cm-diameter tungsten filament located immediately downstream from the cathode pole piece. The gas pulsing is achieved with a commercially available precision leak valve. The response time of the valve is 2 msec with a throughput of ~3 Torr-liters/sec.

The xenon source was tested in two phases. In the first, a high-perveance, multi-aperture optics set was used; in the second, a single-aperture optics system was used that simulated the first gap of the preaccelerator. The use of multiple-apertures

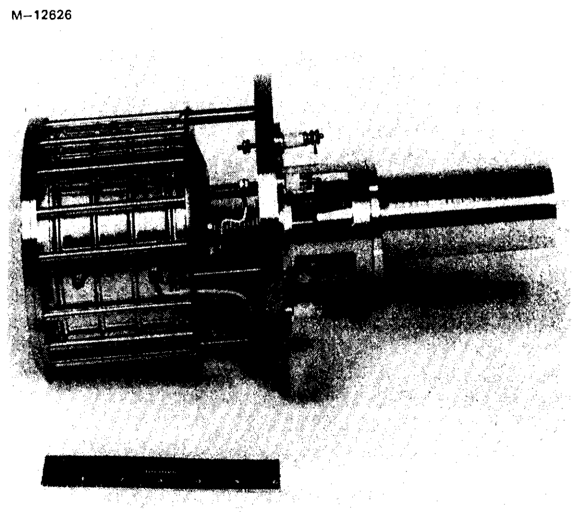

Figure 1. Xenon ion source.

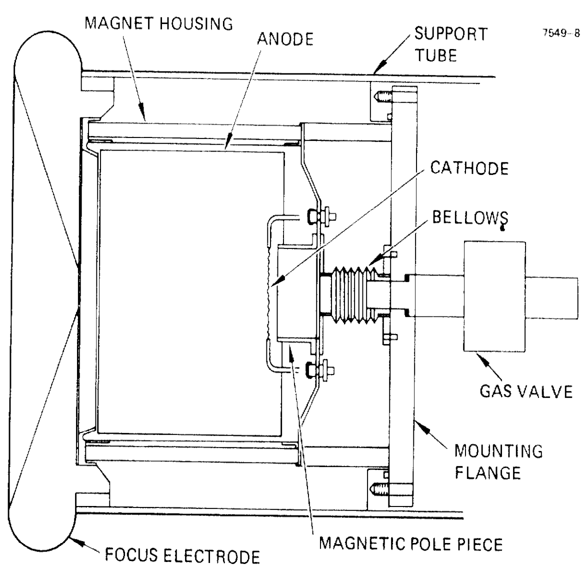

Figure 2. Schematic of the ion source and mounting structures.

allowed a convenient first-order assessment of source operating conditions to be made without having to worry about high-voltage isolation, X rays, etc. Once the operating characteristics of the source were known, a single-aperture Pierce optics set was substituted and the source operated without incident.

A photograph of the multi-aperture-optics set (as mounted on the ion source) is shown in Figure 3. Approximately 165 apertures, each 0.19 cm in diameter, are arranged in a closely packed hexagonal array over the central 3 cm of the optics. The focus and extraction electrodes are identical and are spaced

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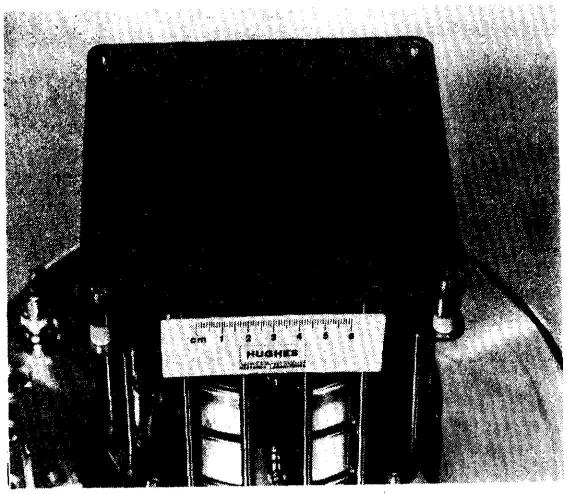

Figure 3. Multiaperture ion-extraction assembly.

~0.08 cm apart. The typical operating potential for the source at 100 mA of beam current is 2 kV with an extraction potential of -0.5 kV to prevent electron backstreaming.

Because the response time of the ANL Dynamitron is typically 5 to 10 msec, the extraction voltage can be considered steady state with respect to the discharge pulse. Thus, in addition to the continuous filament-heating current, the high-voltage power supply was operated steady state for all the tests. The pulsing sequence began with the gas valve opening. At t = 0, the valve was opened for 5 msec; then, after a delay of 10 to 50 msec, the discharge voltage pulse was initiated. The discharge rise time can be minimized by using a short initial pulse of several hundred volts, after which the discharge voltage stabilizes to the value set by the power supply. The discharge current and, in turn, the beam current are determined by the filament emission. In all tests, the discharge pulse length was maintained at the desired value of 1 msec.

The waveforms for the beam, discharge, and extractor currents are shown in Figure 4. The ignition voltage is 200 V. Expanded views of the pulse show a rise time of 10 μsec for the discharge current and 20 μsec for the beam current. The fall time for the discharge is 5 μsec, while the beam current continues to trail for about 160 μsec. It takes ~160 μsec for an ion to traverse a 10-cm-long discharge chamber having a plasma electron temperature of 1 to 2 eV. Thus, it appears that the current-pulse decay corresponds to the time it takes for the existing ions to drift to the optics system and be accelerated.

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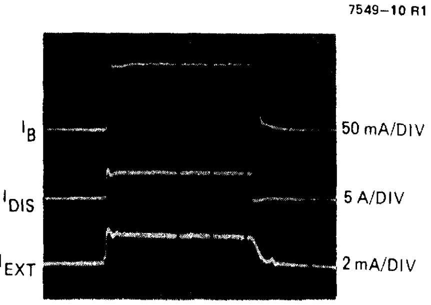

200 μsec/div

Figure 4. Source pulse characteristics.

Preliminary measurements using an ExB velocity filter have indicated a 5 to 10% doubly charged ion contribution in the beam. However, more exact measurements will be made once the source is running at ANL.

A photograph is shown in Figure 5 of the ion-source configuration for single-aperture extraction including the ground screen and focus electrode. This source and the first intermediate electrode structure were mounted in the vacuum facility in a manner similar to the way it will be done in the Argonne preaccelerator. All power supplies (except the beam supply) and the pulsing network remained unchanged for these tests. The performance data for the source is shown in Table 1; Figure 6 compares the theoretical and experimental perveance curves for beam currents up to 30 mA. As the data indicate, the source

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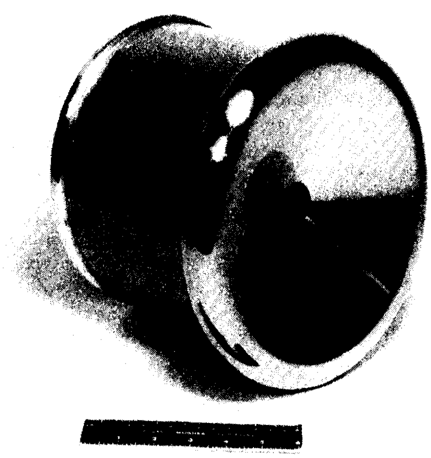

Figure 5. Ion source with single-aperture focus electrode.

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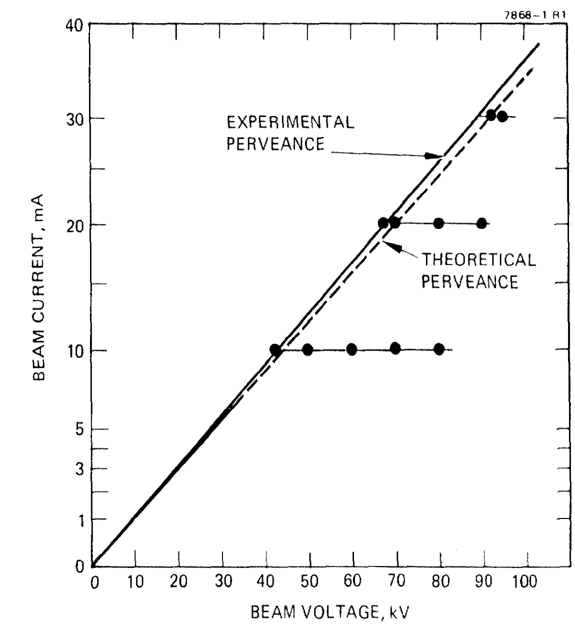

Figure 6. Ion source performance data for first gap of accelerating column.

Table 1. Performance Characteristics for Single-Aperture Extraction; V_{dis} = 45 V

I_{beam}, mA	V_{beam}, kV	I_{dis}, A	I_{ext}, mA
10	42	0.3	1.5
10	50	0.3	1.5
10	60	0.3	1.5
10	60	0.3	1.5
10	70	0.3	1.5
10	80	0.3	1.5
20	67	0.6	3.0
20	70	0.6	3.0
20	80	0.6	3.0
20	90	0.6	3.0
30	93	1.0	5.0
30	95	1.0	5.0

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operated as expected with very little change from the operation with multiple-apertures. The pulse characteristics shown in Figure 7 are also similar to those from the multi-aperture extraction, the only significant difference being the magnitude of the extractor (first intermediate electrode) current. This current, most of which is probably caused by charge-exchange ions, is higher for single-aperture extraction because: (1) the effective open area for neutral particle loss is about 30% higher, (2) the effective path length for charge exchange is about 60 times greater, and (3) the aspect ratio (aperture diameter to electrode spacing) is ~2:1 for the multi-aperture case versus ~1:2 for the single-aperture configuration. In addition, the secondary-electron yield from the extracion electrode could conceivably be a factor-of-two greater because of the higher energy of the charge-exchange ions. Thus, a portion of the current could be due to electron rather than ion current. No serious arcing occurred during the tests, and the loss of a few milliamperes of beam current to charge exchange implies that the experimental perveance curve given in Figure 6 would be somewhat higher under ideal conditions.

Plasma sheath stability was not a problem, although it had been a major question before these tests. The good agreement between the experimental and theoretical perveance curves implies that the sheath was nearly planar, as predicted, and that no instability or plasma nonuniformity resulted from the use of a 3-cm-diameter aperture.

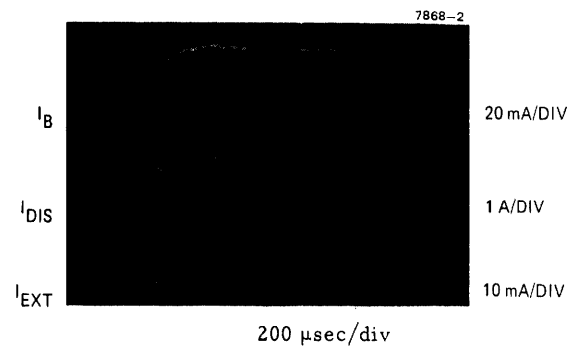

Figure 7. Source pulse characteristics when operated with a single aperture.

In summary, the xenon ion source was operated successfully with both multiple and single-aperture extraction. Beam-current pulses of 100 mA were easily achieved with the high-perveance (2 kV) multi-aperture system. Beam pulses of 30 mA were obtained with single-aperture extraction at 100 kV. The pulse shapes and operating characteristics were very similar for both testing phases and were in excellent agreement with design calculations. The emittance of the high-current source is expected to be low since the design of the high-current source was based on the same design criteria as was the low-current source. In view of the demonstrated source operation (with a minimum of difficulty) during the testing phases at HRL, this particular source should operate reliably in the forthcoming ion-beam-fusion experiments at ANL.