ION SOURCE AND TRANSPORT SYSTEM FOR BNL-HIF PRE-ACCELERATOR*

G.M. Gammel, E.F. Meier and R.M. Mobley
Brookhaven National Laboratory
Upton, N.Y.

SUMMARY

The operating characteristics of the ion source and an initial model of a transport system developed by the Heavy Ion Fusion group at BNL will be presented. The purpose of the assembly, was to transport a 30 mA beam of heavy ions a few feet inside a small, inexpensive Cockcroft-Walton, at the source voltage ($\leq$ 50 kV) to a single 3" diameter high voltage gap ($\leq$ 500 kV).[1] This isolation of the gap from the source prevented high voltage breakdown due to gas loading from the source. After the gap, the beam was to be matched into a 2 MHz electrostatic quadrupole linac, which would in turn, be the first stage of a heavy ion fusion accelerator.[2]

ION SOURCE

The ion source shown in Fig. 1 is a modified version of the original prototype of the LBL CTR sources developed by K. Ehlers and others.[3] At least three other small versions are described in the literature,[4,5,6] The arc chamber is fabricated using a copper-plumbing end cap for the barrel. The end is slotted radially to allow the filaments to protrude into the chamber. The filament plate is of stainless steel, with silver-brazed filament feedthroughs and gas inlet pipe. The anode consists of 3/4 inch copper-plumbing end caps. Four of these are connected together outside the vacuum region.

The arc is struck between the filament and the anode by pulsing the center-tap of the filament secondary ac-winding with ∿50 V. The whole arc chamber (including the vacuum flanges, filament plate, and beam hole cover) floats to a potential slightly below the arc potential, forming a sheath, to maintain plasma neutrality in the usual way.

The extraction electrode can be grounded in several ways. The source and power supplies are isolated at high voltage.

Favorable features of this source may be separated into two categories: 1) features in the original concept and 2) features in this modified version.

1) • The plasma density can be uniform to 5% over 90% of the beam cover plate.

- The filaments are inexpensive, run-of-the-mill, tungsten wire.
- The plasma is very quiet, due to the low magnetic fields, and to space charge shielding of the filaments from the anode potential. That is, the electrons are freely generated by thermionic emission and arc "spotting" can be avoided.

2) • Few vacuum seals (three as shown).

- The anodes are separate from any other parts, and the area of the anode surface can be easily varied.
- The gas inlet pipe, as well as the entire inner surface of the arc chamber, can run at elevated temperatures for Hg operation.
- The filament plate can be removed easily to replace the tungsten wires. Since modest arc densities exist, compared to CTR applications, no filament has yet worn out.
- The high voltage insulator is an inexpensive item. The 4" ID size shown here costs $60, including the end clamps (not shown).

The requirements for pellet ignition favor the heaviest possible ions for overall system economics. This means the use of heavy metal ions. This source can readily be run with Hg^+, and uranium sources are being investigated.

ION SOURCE OPERATION

For the Gabor lens transport system presented here, a Veeco piezoelectric gas valve was used to admit Xe into the arc chamber. The filaments were run cw with 6-9 Vac and 10-20 amps/filament. The source is at a dc potential of up to 50 kV, and the beam pulse is generated by the arc pulser. The arc pulser is a BNL duoplasmatron unit with the following features:

1) Arc voltage up to 300 V, arc current up to 40 Amperes.

2) Variable repetition rate from 1 pulse/10 sec to 10 pulses/sec. The arc-on time is synchronized with the ac line.

3) Light pipe controls for variable beam width to 1 msec, and variable beam delay.

4) HV spark overload protection as developed for the AGS Cockcroft-Waltons.

The source can be run in an ion gauge mode (Ehlers gauge) to allow tuning of the timing between gas-on and start of arc. This feature led to the observation that the main gas load was coming in a large burst some 40 msec after the chamber pressure was ideal for arc pulsing. This has not yet been corrected and is largely responsible for the low repetition rates attained

---

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

with the Gabor lens transport system. It would also cause unnecessary gas loading the Cockcroft-Walton accelerating gap.

ION SOURCE PERFORMANCE

Emittance measurements for this type of source made at BNL and elsewhere are shown in Table I. For acceleration of beams of high 6-D phase-space density, the major problem is to preserve this high brightness. Gabor lenses, as well as magnetic quadrupoles, allow neutral beam transport to the high gradient gap.

Extractor design is largely dictated by the Langmuir-Child formula:

$$K = \frac{4}{9}\, \epsilon_o \sqrt{\frac{2e}{m}}\, A\, V^{3/2}/d^2 \quad , \qquad (1)$$

in which

A = area

m = ion mass

d = extraction gap

ϵ_o = permittivity of free space

e = ion charge .

On inserting values for Xe^{+1}:

$$I = 4.76 \times 10^{-9}\, A\, V^{3/2}/d^2 \text{ Amperes.} \qquad (2)$$

The flux of ions J, within the arc and arriving at the extraction hole, must match the space-charge limit to maintain nearly planar geometry at the plasma meniscus.

Moreover, to keep the beam divergence reasonably low, the gap d, should be about twice the radius of the extraction hole. For a circular aperture and an extraction voltage of 50 kV, Eq. (2) then yields 45 mA, independent of the hole size. Considering extractor geometry only, one can substantially defeat this limit two ways: 1) use a slit extractor, in which case it has been measured that an aspect ratio of 3:1 yields $\epsilon_x = \epsilon_y$. 2) use a multiple aperture array, in which case the current increases linearly with the number of holes. The best solution is a combination of both ideas, that is, a multiple slit array.

The best result was obtained using an extractor shaped in a cross, with the slits measuring 1-1/8" x 3/16" for an extraction area of 7 cm^2. The gap d was .7".

Extraction voltage	44 kV
Filament voltage	7 volts
Filament current	145 Amps
Anode voltage	70 volts
Arc current	15 Amps
Plasma current density $\vec{J}$	15 mA/cm^2 (inferred)

Applying Eq. (2) yields 97 mA, and the 7 cm^2 extraction area provided 105 mA total current, in good agreement. Thus, about 85% of beam loss was in the transport system.

The beam purity was measured and the results obtained are shown in Fig. 2.

TABLE I

$$Xe^{+1} \text{ Emittance} = \frac{A(x,x')}{\pi}\, \beta\gamma$$

I(mA)	V(kV)	Emit. cm-mrad.	Extractor	Ref.
22.5	20	27×10^{-3}	13 holes	2
35	500	84×10^{-3}	13 holes	2
25	30	3.5×10^{-3}	0.2" x 1.25" slit	BNL (un-pub)
10	44	11×10^{-3}	Crossed slits	This report
180	35	10×10^{-3}	(0.2 cm x 7 cm slits)	7

TRANSPORT SYSTEM

A pair of large aperture Gabor lenses[8] (see Fig. 3) was chosen for the transport system. These are electrostatic elements, which are superior to magnetic focusing for low velocity particles, such as heavy ions. The large aperture was needed because the beam was emerging from the source at a 15 to 20 degree half-angle, and the first lens could not be much closer to the source than 10 inches, otherwise gas from the source tended to initiate glow discharge breakdown in the lens. The first lens rendered the diverging beam from the source approximately parallel, and the second lens, which had to have about the same aperture, brought the beam to a waist of less than 3" diameter.

The magnetic fields in the two lenses were not measured precisely, but were around 200 Gauss, and were independently adjusted for best strength. Some interesting features about the lens operation are brought out in Fig. 4. First, it was observed that 25 ms were required after the magnetic field pulse started for the electron population in the lens to build up. At that time, high frequency pick-up was observed on the Faraday cup signal, indicating that the lens was "active". Second, if the magnetic field was left on too long, the noise would worsen and the lens would eventually break down into a glow discharge. This also happened if the repetition rate of the beam was too high. In this case, if a spark occurred, gas was released in the neighborhood of the lens and the lens broke down with no chance to recover before the next pulse. The maximum safe rate was one pulse every five seconds, in which case the pressure always recovered to below a few times 10^{-6} Torr before the next pulse.

Best results for 3 and 5 foot transport are given in Table II. It should be noted that this transport system has the same focusing strength for any heavier ion at the same energy as for the test case of Xenon.

TABLE II

	3' Transport	5' Transport
Extractor voltage	26 kV	47 kV
Upstream lens		
voltage	4.3 kV	9 kV
radius	2.2"	2.5"
length	4"	3"
Downstream lens		
voltage	8.2 kV	9 kV
radius	2.65"	2.65"
length	2"	2"
From source to center of up-stream lens	10.5"	14.5"
Lens separation	14.5"	33.5"
Xe current into 3" diameter (1' downstream of 2nd lens)	14 mA	11 mA

CONCLUSIONS

The lenses worked well, although the repetition rate had to be kept to less than one pulse per five seconds, in order to obtain smooth operation. The best current, of 14 mA, did not reach the desired 30 mA, but we feel that with further development--just putting more power into the source or adding yet another lens, more current could have been obtained. However, about a month before this conference, the Gabor lens transport system was abandoned in favor of a better idea.

A multiple beamlet transport and acceleration system (1 or 2 mA per beam) with electrostatic quadrupole focusing is now being investigated. In this scheme, rf acceleration begins directly from the source, and the bulky Cockcroft-Walton pre-accelerator is no longer needed. Single channel models for transport only have already been built and tested, and a current density 7.5 times greater than that obtained with the Gabor lens system has already been obtained at lower beam energy (15 keV). The transport system is not pulsed, and the beam repetition rate has been increased to 10 pulses per second. The progress of this work will appear in future reports.

1. J. Brodowski, et. al., IEEE Trans. Nucl. Sci., NS-26, #3, 3039 (June 1979).
2. BNL 50817, A.W. Maschke.
3. K.W. Ehlers et. al., Proc. 2nd Symposium on Ion Sources and the Formation of Ion Beams, Berkeley, 1974, pp. 1-5, UCRL Report.
4. W. Chupp et. al., IEEE Trans. Nuc. Sci. Vol. NS-26, No. 3, June 1979.
5. R.W. Bickes, Jr. et. al., Rev. Sci. Instrum., 49 1513, Nov. 1978.
6. G. Fisher et. al., J. Phys. E Sci. Instrum., 12, p 522, 1979.
7. R. Mobley, Proceedings of the Heavy Ion Fusion Workshop ANL-79-41, Sept. 1978 p. 265.
8. R. Mobley, et. al., IEEE Trans. Nucl. Sci., NS-26, #3, 3112 (June 1979); see also R. Booth and H. Lefevre, Nucl. Instr. and Meth., 151, 143 (1978).

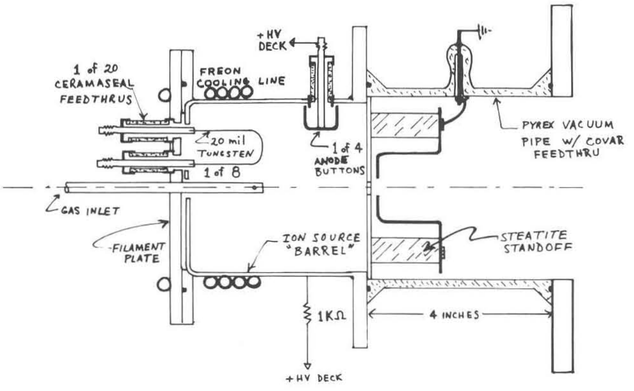

Fig. 1 Schematic of ion source.

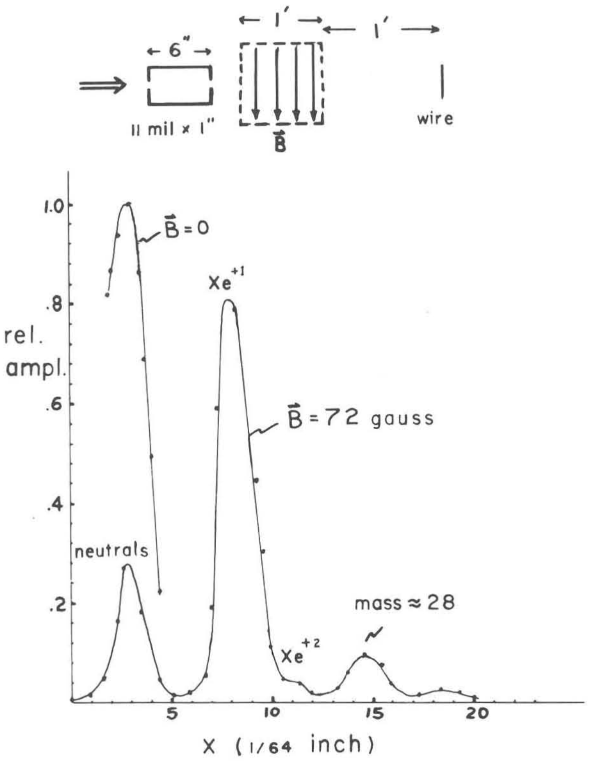

Fig. 2 Spectra of ions obtained with and without deflecting B field, showing ∿80% Xe^{+1} purity. Note that dip between neutral peak and deflected Xe^{+1} peak indicates that charge exchange losses occur near the source only.

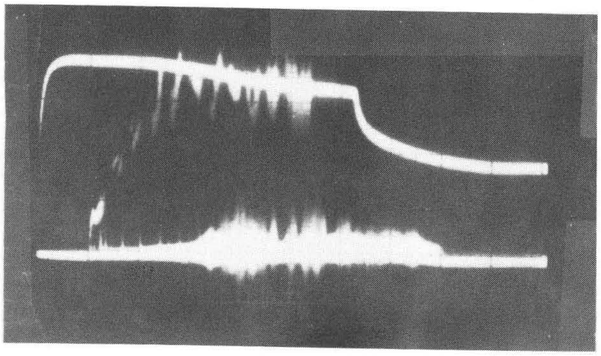

Fig. 4 Upper trace measures the magnetic field in the lens; (∿60 ms duration) lower trace is a multiple exposure of Faraday cup beam measurements at different times (beam is ∿ 1 ms wide).

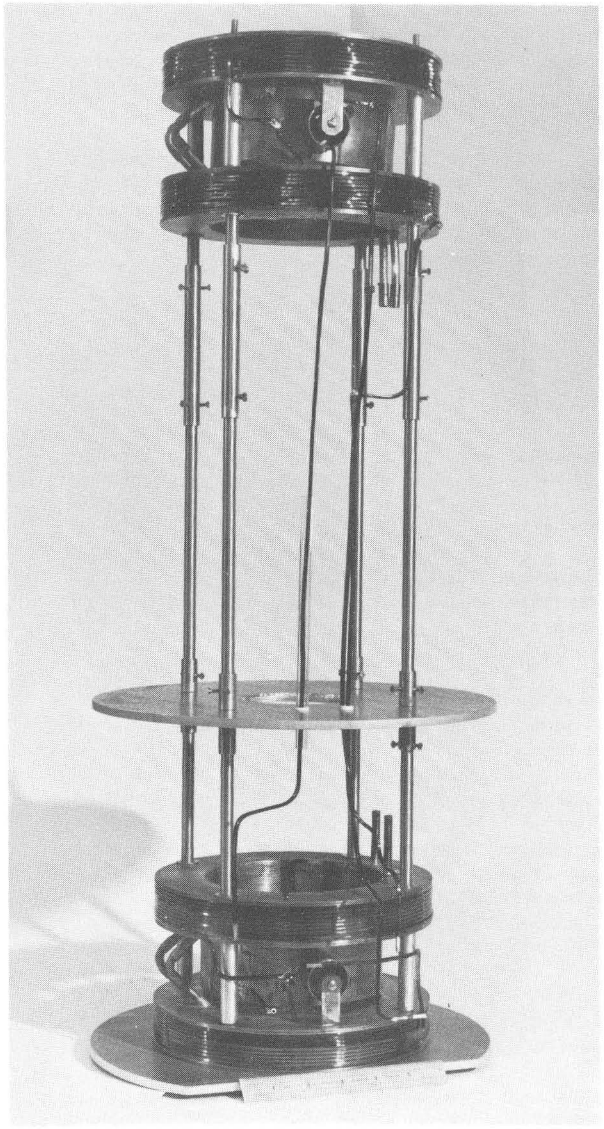

Fig. 3 Pair of Gabor lenses used for beam transport from source. Ruler is 6" long. Each lens consists of an electrode sandwiched between grounded electrodes around which coils are wrapped in a Helmholtz configuration. For typical voltages, such as indicated in Table I, typical magnetic field strengths were ∿200 Gauss. Freon cooling tubes for dc operation of the coils are visible. The plate between these lenses was not used in the experiments described in this paper.