HEAVY ION BEAMS AT THE TEXAS A&M CYCLOTRON USING A COLD-CATHODE SOURCE*

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ABSTRACT

An internal cold-cathode Penning source which is highly compatible with the instrumentation for the conventional filament source has been used to accelerate heavy ions. Initial unoptimized operation has produced external beam currents ≥5 eua of C^{3+}, C^{4+}, N^{3+}, N^{4+} and O^{4+}. External currents <1 eua of Ne^{5+} and Ar^{5+} have also been obtained. Extraction efficiency for these beams ranges from 30% to 60%. Acceleration and extraction of ions has so far been limited to first and third harmonic operation and beam velocities range from 2.1 MeV/nucleon (Ar^{5+}) to 16.5 MeV/nucleon (C^{4+}). Typical arc power is 1.5 to 3 kW although it has been operated at 5 kW for extended periods. Source lifetime has been limited to 4-6 hours by cathode-anode shorting due to "stalactites" of evaporated anode material. Some of the techniques used for tuning new heavy ion beams to extraction are described.

INTRODUCTION

The upper limit of energy for heavy-ion beams at the Texas A&M cyclotron is $E_{max} = 147\ Q^2/A$ MeV for an extraction radius of 1 meter and a main coil current of 2800 amperes ($\overline{B} = 17.5\ W/m^2$). The heavy-ion beams produced thus far have been used for radioactivity studies (both in and out of beam), atomic ionization phenomena, total fusion cross-section measurements and spallation studies. Many of these experiments have not required the utmost beam current and have utilized the standard light-ion Livingston source. The best extracted beam intensities obtained with this source are shown in Table I. Experimenters have generally preferred to use this source for experiments with carbon or nitrogen ions because of the greater flexibility of intensity control, longer life (at moderate currents), and greater experience of the operators.

*This work was partially supported by the Atomic Energy Commission (Contract No. AT-(40-1)-3398) and grants from the National Science Foundation and the Robert A. Welch Foundation.

Table I. Performance for heavy ions with the Livingston source.

Ion	$^{12}C^{3+}$	$^{12}C^{4+}$	$^{14}N^{3+}$	$^{14}N^{4+}$
$I_{extracted}$(eua)	1	0.08	10	3
E(MeV)	100	180	90	159

MODIFIED SOURCE

Since higher charge states and higher currents were desired we began designing a different source in September, 1971, and first operated it successfully in January, 1972. The success of the Oak Ridge cyclotron heavy ion source[1] fixed for us the essential features of cathode-anode geometry, which we then adapted to the standard 5.6cm. diameter ion source shaft which inserts axially on our machine. This allowed use of the accurate positioning mechanisms already in use for the standard source, which was in fact the primary reason for choosing an axial rather than median-plane configuration. Figure 1 is a photograph of the modified source and a section view of this source is shown in Fig. 2. The gas feed line does not appear in this section view; gas enters near the lower end of the plasma chamber. Our cathode water cooling flow rate is 2.2 g.p.m.

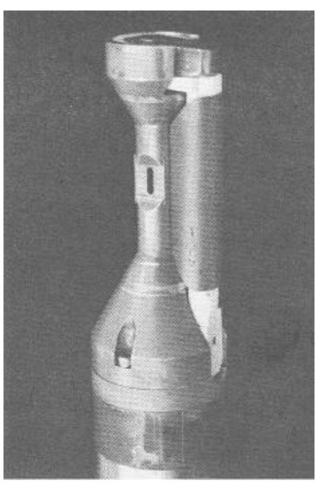

Fig. 1. A view of the modified source.

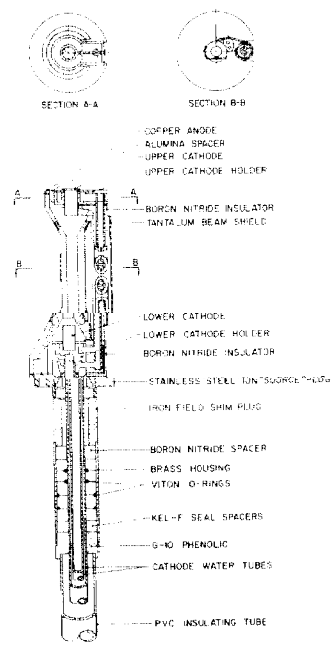

Fig. 2. Section view of the modified source.

which allows, in principle, a cathode dissipation of 8 kW for a 40°C temperature rise. The OFHC copper anode wall contains a wrap-around water channel extending the full length of the anode with a flow rate of 1.8 g.p.m. Cathodes are of 0.95 cm. diameter Ta rod and are separated by an 8 cm. gap. The anode bore is 0.48 cm. in diameter with an extraction slit 2.5 x 11 mm. and wall thickness ~0.9 mm. at extraction. D. C. voltages in excess of 7 kV can be sustained without breakdown by this structure whereas the arc will strike at ≲6 kV for a gas flow ≳3 atmospheric cc./min. Operating in the negative resistance mode with a current-regulated power supply, the gas flow determines the operating voltage; typical optimum conditions are found from 2 to 6 amperes and from 2500 to 350 volts. We find that the arc is unstable for gas flow less than ~1.5 cc./min. Our best extracted beam currents so far with this source for various heavy ions are listed in Table II.

Table II. Present performance of the heavy-ion source.

Ion	C^{3+}	C^{4+}	N^{3+}	N^{4+}	O^{2+}	O^{4+}	Ne^{4+}	Ne^{5+}	Ar^{5+}
$I_{ext.}$ (eμa)	10	5	15	10	1	6	0.4*	0.5*	0.4*
E(MeV)	100	180	90	159	33.6	133	128	166	84

*These intensities were limited by a recently acquired vacuum leak that produced a tank pressure of 1.1 to 1.5 x 10^{-5} torr during these ion source tests.

Sometimes the source lifetime is limited by cathode erosion (i.e. the cratering becomes deep enough to inhibit striking the arc) but more often the source is shorted by a buildup of anode material around the lower entrance to the arc chamber. Lifetimes are limited to from 2 to 6 hours, depending on the source gas. Often the short can be burned off with a current surge of up to 20 amperes from the power supply.

HEAVY ION TUNING

Tuning of the heavy ion beams can be relatively difficult compared to light ion beams because of the presence of high intensities of different species either accelerated on various harmonics or as spill beams and because the large current from the source results in a strong coupling to the R. F. system. The latter can quench the arc if it is operating close to instability when the R. F. is turned on or, alternatively, the source can load the R. F. so heavily that it will not start at high arc power. Although computer-generated tunes for the trim coils have been useful to some extent as a starting point for a new beam, it is found that the valley coils and center geometry are extremely critical for successful acceleration and extraction. Therefore, to obtain a range of energies for each beam we move adiabatically along its resonance line adjusting many of the cyclotron tuning parameters until we obtain the best extracted beam. In this way we have followed the N^{3+} resonance from 90 to 99 MeV, C^{3+} resonance from 75 to 115 MeV (1st harmonic) and from 20 to 45 MeV (3rd harmonic), and the C^{4+} resonance from 145 to 197 MeV. We have not spent any time developing acceleration on harmonics greater than 3rd because of a general lack of interest by the experimentalists in ultra-low velocity beams.

We have made extensive use of the "analog beam" (i.e. nearly identical q/m) technique for tuning (using the $^3He^+$ and $^4He^+$ resonances especially) with a solid state detector to verify identification. Fig. 3 shows some spectra scattered from a gold target at

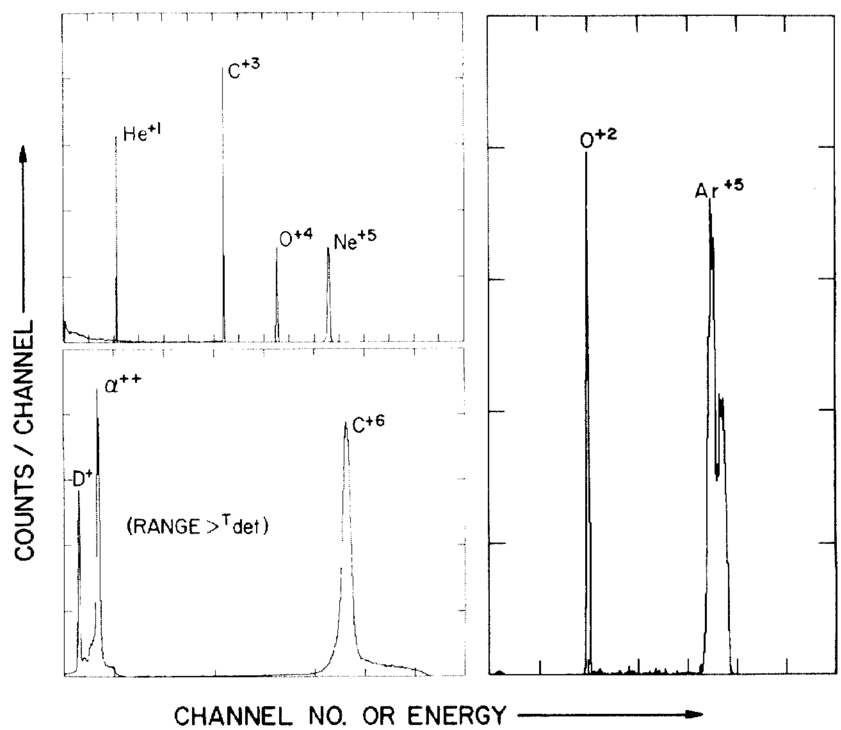

Fig. 3. Heavy ion scattering spectra from gold at 20° (except for C^{6+}, which is <5°)

20° using this technique. The resonances are usually well-resolved in practice, so that contamination of the desired beam by the "analog" beam is avoided. When interfering internal beams on high harmonic (or spill beams) are present, we have found it useful to monitor the neutron flux. Since the beam on n^{th} harmonic has $1/n^2$ of the fundamental energy, neutrons generated by the copper-tipped internal probe are greatly enhanced for the beam of interest and it can be selectively tuned to extraction from 0.5m to 1m. radius even in the presence of a high background of other beams.

VACUUM CONSIDERATIONS

Improvement of vacuum conditions in the accelerator and in the transport system are in order for more efficient operation with the heavy-ion beams. Previously, very relaxed vacuum requirements were the rule because no heavy ion experiments were performed (up to 13 months ago); all experiments were performed with fully stripped H and He beams. Typical beam line vacuum at present is from 1×10^{-5} to 1×10^{-4} Torr. Fig. 4 shows a measurement we made of the relative population (non-equilibrium) of charge states for

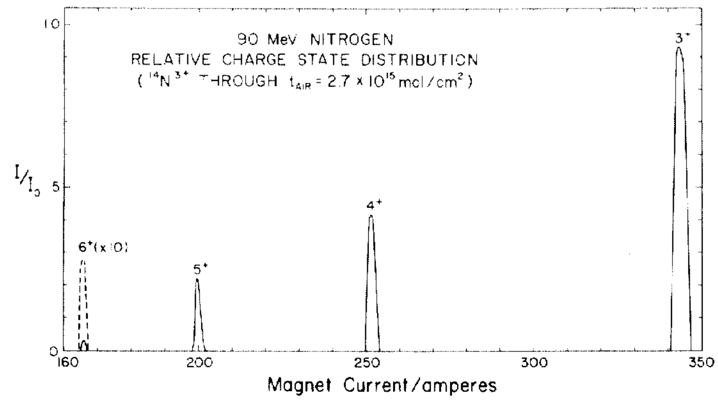

Fig. 4. A test of beam attenuation due to residual gas through the n=1/2 analyzing magnet.

a 90 MeV $^{14}N^{3+}$ beam after passage through 8.4m. at ~1×10^{-4} Torr. Since the path length to the magnetic spectrograph is several times greater than this, we have not yet attempted high resolution spectroscopy with the heavy ion beams. Fig. 5 shows current versus radius for 100 MeV C^{3+} at a "good" vacuum of ~3×10^{-6} Torr and a "poor" vacuum of 1.3×10^{-5} Torr. Fig. 6 shows a measurement of beam attenuation for 90 MeV N^{3+} at a pressure of 2.3×10^{-5} Torr. The dashed curve is calculated for nitrogen ions in N_2 using a fit to the charge change cross section data of Nikolaev, et. al[2] and of Dimitriev, et. al[3] and using an extrapolation to higher velocities following Schmeltzer[4]. We are presently plagued by a leak in the main tank (up to 1.5×10^{-5} Torr at high magnetic field). During the annual shutdown in August we will make every effort to achieve conditions for operation below 1×10^{-6} Torr, through careful reassembly, refitting and leak-testing of the main tank. A base pressure near 1×10^{-6} will also be aimed for in the transport system by more stringent operational and experimental practice and by replacement of some materials.

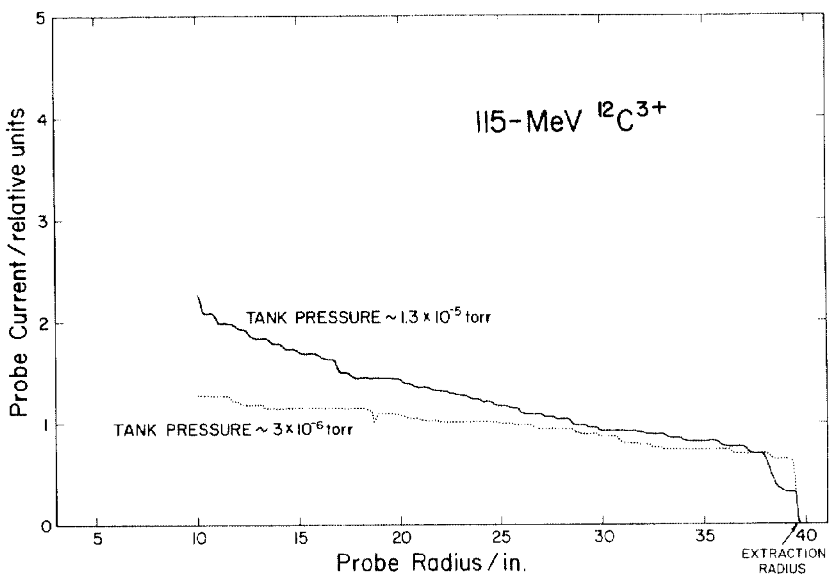

Fig. 5. I vs. R for carbon ions on two different occasions.

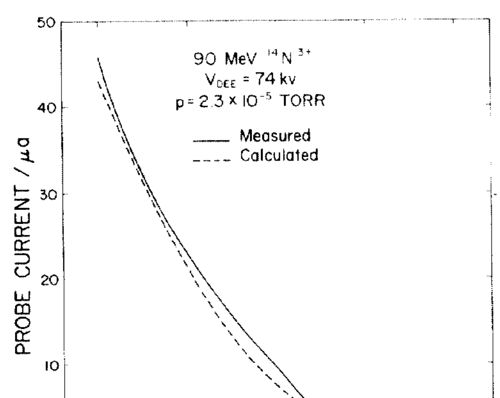

Fig. 6. Observed and calculated attenuation of nitrogen ions in the case of a deliberately introduced high tank pressure.

ACKNOWLEDGEMENTS

The authors wish to express appreciation to L. Sivley, M. Nowak, R. Hamm, and the accelerator operators for their contributions to the work described here. One of the authors (R. A. K.) wishes to acknowledge a useful discussion with M. L. Mallory and one with J. Steyaert.

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DISCUSSION

MALLORY: We have just recently found a very useful technique for controlling the beam intensity with the cold cathode ion source. As you know, controlling the intensity by controlling the arc voltage and current is not very reliable. We have inserted a controlled air leak in the centre of our cyclotron. We operate the ion source at its most favourable parameters. The beam intensity is decreased by degrading our vacuum by the controlled leak. This is because the charge exchange probability increases with higher pressure. We find the air leak works quite smoothly and, more importantly, we find the experimenters are quite happy with this intensity control. That is because this type of loss does not degrade the beam emittance as, for example, detuning the trim coils does. Also, running the source at its optimum operating point seems to allow extended source lifetime.

WEGNER: In terms of a two-to-four-hour lifetime for the source, working, say, a 36-hour experimental run, what kind of duty cycle do you find on the machine? In other words, is the repair time on the ion source comparable to that time, or does it only take a few minutes or what?

KENEFIK: Getting the source out and replacing the cathodes takes about 45 min. We have two identical shafts - complete ion source shafts - which can be ping-ponged. This means that we can therefore just pull the source out and replace it, in principle, in under half an hour. So this gives you a duty cycle or efficiency of 75%. I might add we are working very hard to improve the lifetime.