RECENT DEVELOPMENTS IN HIGH CHARGE STATE HEAVY ION BEAMS AT THE LBL 88-INCH CYCLOTRON

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Abstract

Recent advances in design and operation of the internal PIG sources at the LBL 88-Inch Cyclotron have led to the development of high charge state ($0.4 \lesssim Q/A \leqslant 0.5$) heavy ion beams between lithium and neon with energies $20 \lesssim E/A \lesssim 32$ MeV per nucleon, including fully stripped ions up to $^{16}O^{8+}$. Total external intensities of these beams range from 10^{12} particles/s for $^{6}Li^{3+}$ to 0.1 particles/s for $^{16}O^{8+}$. Techniques have been developed for routine tune-out of the low intensity beams. These include use of model beams and reliance on the large systematic data base of cyclotron parameters which has been developed over many years of operation. Techniques for delivery of these weak beams to the experimental target areas are presented. Source design and operation, including special problems associated with Li, Be and B beams, are discussed.

Introduction

The emphasis in heavy ion nuclear physics has, in recent years, shifted markedly to experiments requiring higher and higher beam energies. These demands are being met in part by construction of new accelerators such as the MSU superconducting cyclotron and the use of sophisticated injection systems such as at the Bevalac and Holifield machines. There is, in addition, a very strong demand on existing smaller cyclotrons to increase their heavy ion energy capabilities by accelerating higher charge state ions. In order to meet present experimental needs, several new beams have been developed using the internal PIG source at the Berkeley 88-Inch Cyclotron. Most heavy ion beams that have been developed over the past eight years have been magnetic field limited at K = 140 MeV. (Efforts to increase the current output of the main magnet power supply are in progress and one beam has been accelerated at K = 145 MeV.) Fully stripped heavy ions at K = 140 MeV, can be accelerated to 35 MeV/nucleon. The reliability of the three-channel electrostatic deflection system becomes marginal for beams with energy/charge ratio $E/Q > 60$, but with adequate voltage conditioning it has been possible to obtain external beam intensities ~0.5 eμA of 140 MeV alpha particles ($E/Q = 70$). This beam will serve as an analogue in pretuning the cyclotron and beam transport systems for lower intensity 35 MeV/nucleon heavy ions. This technique has already been used successfully for several experiments requiring heavy ion beams at 32 MeV/nucleon.

Ion Source

The internal PIG source for the 88-Inch Cyclotron was first developed in the early 1970's and is described at an earlier conference[1]. The source design used in the present work is shown in Fig. 1. Though similar to the source described in Ref. 1, it has undergone slight modification to improve reliability and high charge state performance. The source shown in Fig. 1 has a bore diameter of 9.4 mm and was used for the $^{6}Li^{3+}$ and $^{9}Be^{4+}$ beams discussed below. For good production of the heavier beams reported in this paper, anodes having a 4.7 mm bore diameter were used. The narrower bore anodes have a shorter lifetime, but produce >10 times the intensity of the higher charge state beams. Typical lifetimes for sources producing fully stripped heavy ions at maximum intensity is 2-3 hours. An RF extractor electrode at dee potential is used with the internal source.

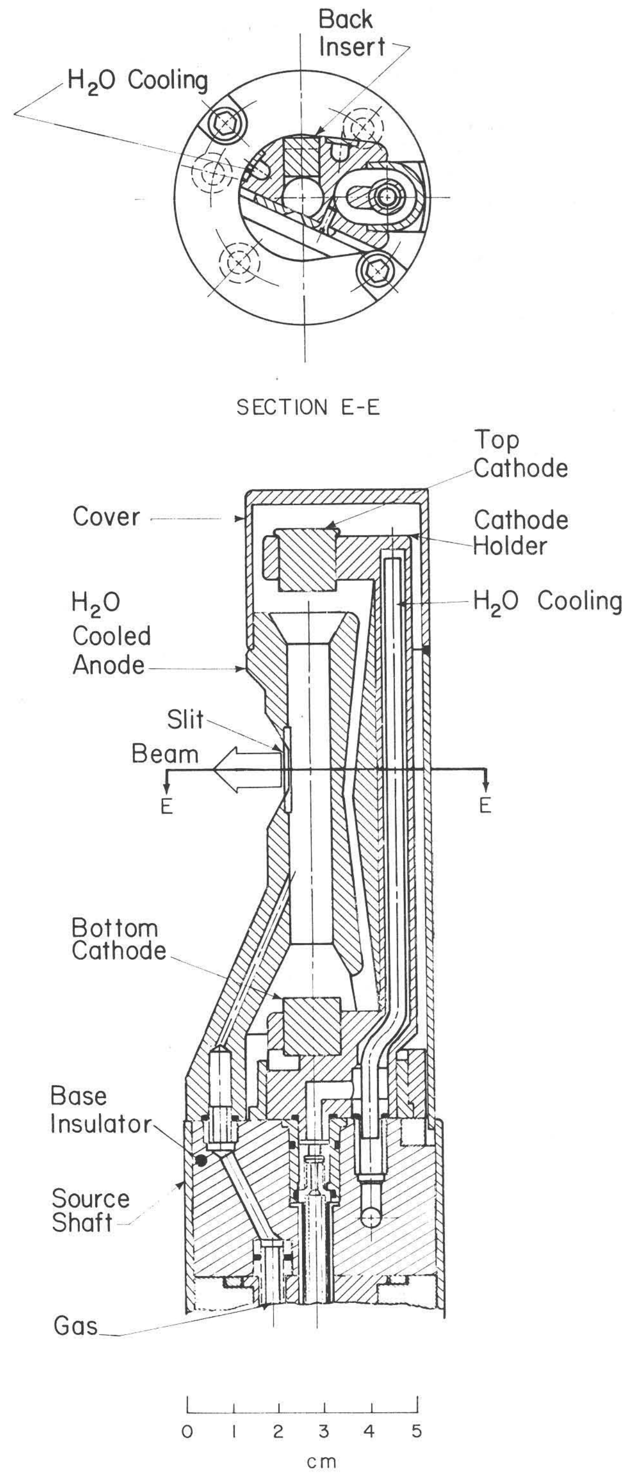

Fig. 1. Schematic cross section of the internal PIG source of the 88-Inch Cyclotron. The anode shown has a 9.4 mm diameter bore and was used for the Li and Be beams reported in this paper.

For all of the beams discussed in this paper, proper arc conditions were found to be very important. In particular, a high arc voltage (0.8-2.0 kV) is a necessary condition for good production. The higher the ionization potentials of the ion, the more important the arc voltage requirement. Arc currents as low as ~1 A for Li^{3+} and Be^{4+} and ~2 A for heavier ions are adequate provided the arc voltage is sufficiently high. Various methods of inducing a high arc voltage mode of operation are utilized. These include use of a narrow bore PIG anode, improving the cooling of the cathode, pulsing the arc, and simultaneous reducing of the arc current and source gas. It should be noted that the arc impedance characteristics change somewhat as the sources grow older and do not repeat exactly from source change to source change. Consequently the experience and skill of the operator has been an important factor in obtaining consistently good source performance.

The beam intensities quoted in this paper can normally be obtained under dc arc conditions. At present there is only limited experience with these beams, but pulsing the arc (20-20,000 Hz, 20-50% duty factor) usually increases the intensity. Occasionally the arc will operate in a self-pulsed mode (~100 Hz). That is, even when operating with a highly regulated dc series tube power supply, the arc will oscillate on and off with high peak arc voltages. While this usually produces a high average beam current, it is often disadvantageous for users doing coincidence work. This self-pulsing mechanism is not well understood and further study might improve our overall understanding of ion source behaviour.

Special source and handling problems for Li, Be and B beams are worthy of mention. Lithium is introduced into the source as LiF in a manner described in Ref. 1. A thin semi-cylindrical sleeve made of tantalum is inserted coaxially into the anode bore. It is loaded uniformly with LiF by heating the sleeve with an acetylene torch to a red hot condition, permitting the LiF to flow evenly over the entire surface. Excess LiF is filed off. Cathode "buttons" consisting of ~40% LiF and ~60% Ta (by volume) hydraulically pressed at 80,000 lbs/in^2 are also used. It is important to start operation of each source at low arc power (~0.5 kW). This power can be increased through the life of the source to $\gtrsim$ 2.5 kW. Too much arc power at the beginning of a new source shortens its productive lifetime. External beam intensities of 300-500 enA can be maintained throughout a 4-5 hour average source life. Use of a larger source exit slit enhances the RF back bombardment mechanism and generally improves intensities.

$^{9}Be^{4+}$ beams at 200 and 246 MeV were recently developed at the 88-Inch Cyclotron. The source feed consisted of a 6.25 mm × 6.25 mm × 10 mm Be metal block held in place behind the source slit by the Ta back insert shown in Fig. 1. (The shape of the Be block was kept simple to minimize the machining of this hazardous material.) The back insert was hollowed out and the Be block could be held in place using a press fit. Best results were obtained with a 1.5-2 mm protrusion of the Be into the arc bore. Significantly more beam was obtained when the source slit was increased in width from 3 mm to 3.75 mm. The slit height was held constant at 6.25 mm. It was possible to maintain external beam intensities of ~100 enA over a 4 to 5 hour source life.

Due to the toxic nature of Be, great care had to be excercised in preparing and cleaning the sources. All source handling was done in a vented glove box maintained at a slight negative pressure. Ion source parts were substantially Be-contaminated at the end of a Be run and had to be subjected to a specially developed ultrasonic cleaning procedure before the parts could be released for unrestricted service. Swipes of the center region components of the cyclotron after a long Be run revealed only below-tolerance levels of Be contamination.

For B^{4+} and B^{5+} beams, unlike the lower charge states of B, we have not yet been able to develop a solid source feed which is competitive in production with BF_3 gas or BCl_3 vapor. Because of the hazardous nature of these gases, a well-ventilated, shielded area has been constructed for the source bottle (usually a Matheson-type lecture bottle). The gas is transferred via an 8 m long stainless steel line to special stainless steel needle valves for metering gas into the source. This transfer line is equipped with a dedicated mechanical pump and a N_2 purging system. Careful maintenance of this line is crucial to trouble-free operation of the needle valves. Both $^{10}B^{4+}$ and $^{11}B^{4+}$ have been produced with intensities ~300 enA. The $^{10}B^{5+}$ beam was only recently obtained (at 250 MeV) and an external beam intensity of 1-2 eμA was observed. The boron results were achieved using the narrow 4.7 mm anode bore.

Cyclotron and Transport Line Tuning

Over many years of operation of the 88-Inch Cyclotron, a large and systematic data base of machine parameters has evolved[2]. This has proven to be a great asset in tuning out new beams, especially those whose intensities are below the sensitivity of our conventional beam monitoring gear. In many cases a high intensity analogue beam is available (such as alphas for $^{12}C^{6+}$, $^{14}N^{7+}$ etc.). Another (less obvious) example of analogue beams is found in the machine settings for 426 MeV $^{16}O^{7+}$. Both $^{14}N^{6+}$ and $^{9}Be^{4+}$ beams have been run using essentially the same cyclotron settings. The calculated phase histories of 426 MeV $^{16}O^{7+}$ and several $^{9}Be^{4+}$ beams are shown in Fig. 2 using a trim coil solution optimized by the computer code CYDE[2] for 426 MeV $^{16}O^{7+}$. It is seen from Fig. 2 that the differing isochronous requirements for acceleration of these two ions can be minimized by choosing an appropriate $^{9}Be^{4+}$ beam energy. In this case a Be energy of 245.5 MeV is best matched to the $^{16}O^{7+}$ trim coil solution. This approximate phase history matching is believed to result from first order compensation of the radial magnetic field profile due

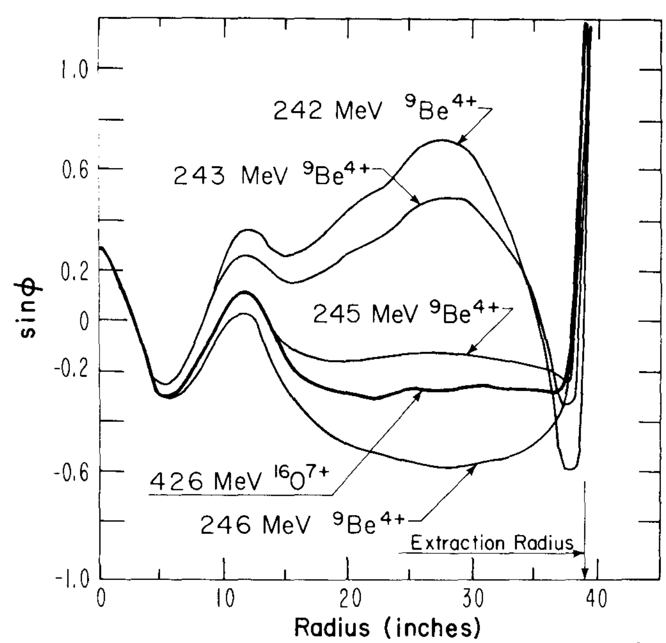

Fig. 2. Phase histories for several beams calculated with the computer code CYDE[2] using a trim coil solution optimized for 426 MeV $^{16}O^{7+}$.

to saturation effects in the main magnet. A simple method for estimating this matching has been developed and appears to be in good agreement with computer calculated phase histories. This has saved much computer and beam development time.

Some sensitive beam monitoring equipment has been installed in various beam lines to facilitate both cyclotron tuning and beam transport. A position-able Si(Li) detector/scatter foil arrangement located in the exit beam line provides a readout for primary beam intensities of 10^{-1} - 10^{10} particles/s. The signals from this detector drive a count rate meter which is used to optimize cyclotron settings. Very sensitive phosphors and standard television monitoring equipment are used to visually observe beam focusing with heavy ion intensities as low as 1 electrical picoamp. Plastic scintillators coupled to photomultiplier tubes are also used in certain beam lines. These can monitor intensities from 10^{-1} to 10^{10} particles/s and provide some beam energy resolution. In a recent experiment[3] at the 88-Inch Cyclotron, a Ta energy degrader was placed over one-half of the scintillator so that the resulting two-component energy spectrum could be used to provide left-right beam alignment signals.

Heavy ions which are presently accelerated by the 88-Inch Cyclotron to energies from 20 to 32 MeV/nucleon are shown in Table 1. The observed external intensities of these beams are plotted in Fig. 3 as a function of total ionization potential. Since we have only limited experience with some of these beams, further improvements in intensity are expected (for example with $^{12}C^{6+}$). Figure 3 does, however, provide a rough guide to intensities which can be expected for other high charge state beams.

Future Plans

Use of the beams discussed in this paper is expected to increase over the next few years. Development of an external state-of-the art PIG source is in progress. A project to increase the K of the cyclotron to perhaps as high as 160 MeV is underway. Further study of the vertical focusing limit of the 88-Inch Cyclotron may be required to ensure full utilization of an increased K value. Improvements to the present deflector system to increase its reliability for these rigid beams are planned.

Table I. Heavy ion beams between 20-32 MeV/nucleon.

Ion	Energy (MeV)	Observed Intensities (particles/s)
$^{6}Li^{3+}$	153	10^{12}
$^{9}Be^{4+}$	200,246	10^{11}
$^{10}B^{4+}$	224	4.5×10^{11}
$^{10}B^{5+}$	250	10^{9}
$^{12}C^{5+}$	292	6×10^{10}
$^{12}C^{6+}$	384	$\sim 10^{5}$
$^{14}N^{6+}$	360	10^{6}
$^{14}N^{7+}$	448	$\sim 10^{2}$
$^{16}O^{7+}$	426	$\sim 10^{7}$
$^{16}O^{8+}$	512	$\sim 10^{-1}$
$^{20}Ne^{8+}$	448	10^{6}

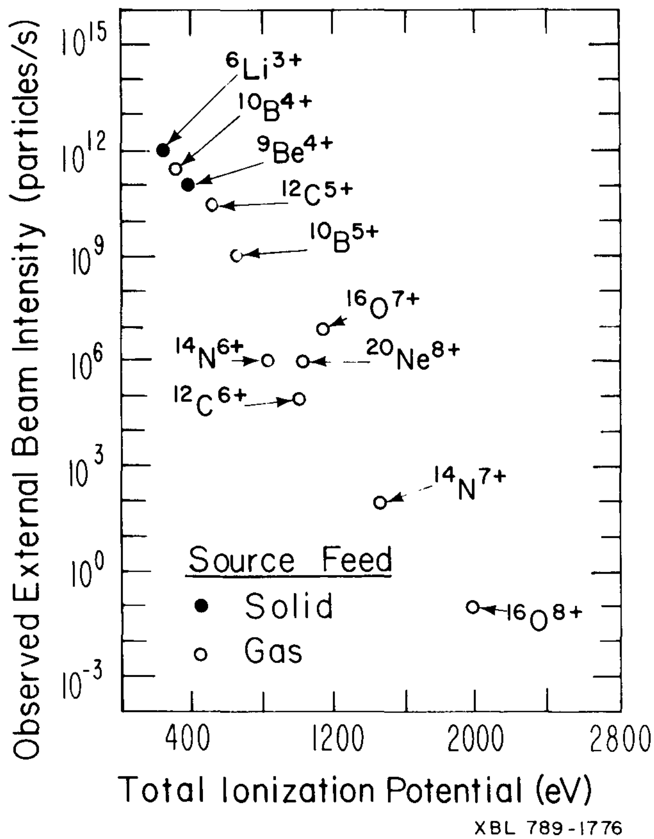

Fig. 3. Observed external beam intensities for 20-32 MeV/nucleon heavy ion beams are plotted as a function of total ionization potential.

Acknowledgements

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