

## HEAVY ION ACCELERATION AT THE BERKELEY 88-INCH CYCLOTRON\*

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## ABSTRACT

A new internal heavy ion source of the Penning type has been in operation at the Berkeley 88-Inch Cyclotron for 10 months. Beams of lithium, carbon, nitrogen, oxygen, neon, and iron have been accelerated and used in experiments in the energy range 4-18 MeV/nucleon. External beam intensities are 1-10  $\mu$ A of most carbon, nitrogen, and oxygen beams. Many experiments have used the new high-resolution reaction product magnetic spectrometer and resistive wire focal plane detector.

## INTRODUCTION

The use of heavy ion beams has grown in importance during the past several years at the Berkeley 88-Inch Cyclotron. About half the scheduled time is now used for ions heavier than  $\alpha$ -particles. The principal requirement has been for beams of lithium, carbon, nitrogen, oxygen, and neon at energies of 5-10 MeV/nucleon, and external beam intensities of 1-10  $\mu$ A for nuclear reaction studies. Another requirement is for the highest possible energy of nitrogen at intensities of a few nanoamps for biomedical studies. A third type of experiment is an occasional request for the highest possible energy of ions in the mass range 50-100 at very low intensities of only a few particles/sec for calibration of cosmic ray tracks in plastics or minerals.

The intensity of heavy ions from the ion source is strongly dependent on the arc power. The original ion source for the cyclotron<sup>1</sup> used a hot filament and a 1/8 inch diameter arc defining hole. The maximum arc power was 500-800 watts. The heavy ion output was about a microamp external beam of nitrogen and oxygen at 5-10 MeV/nucleon. External beams of  $N^{5+}$  were a few nanoamps. Short filament life of only a few hours resulted from heavy ion sputtering. Since the PIG (Penning Ion Gauge) type source with arc-heated cathode buttons is known to give much higher heavy ion currents,<sup>2</sup> we built a PIG source which started operation in Sept. 1971.<sup>3</sup> The following sections describe the PIG source, heavy ion cyclotron acceleration, and use of the beams in experiments. The external PIG source<sup>3</sup> has been tested on lithium beam injection. It has given external

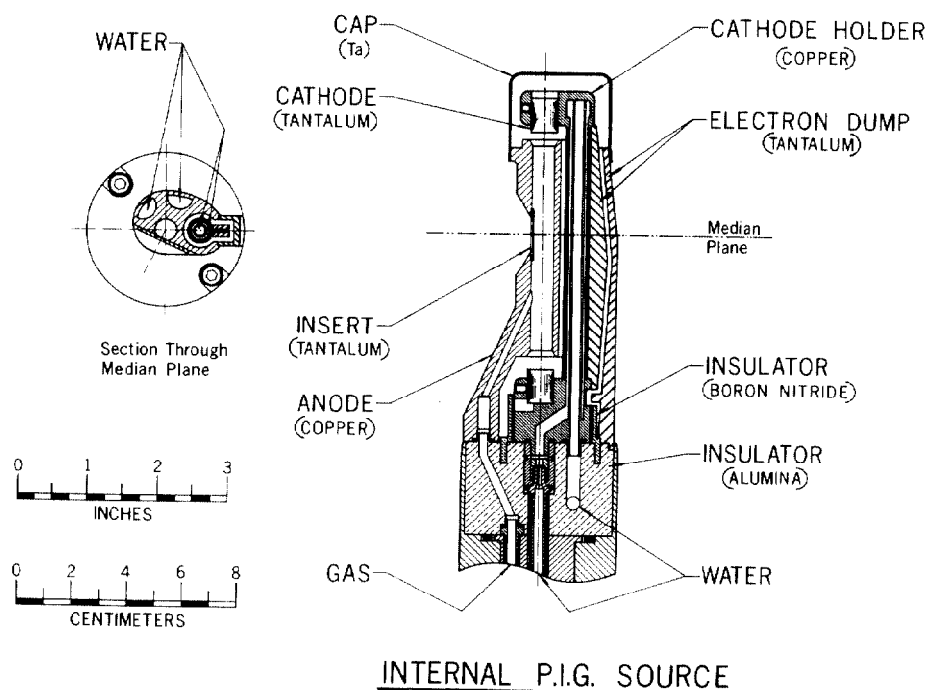
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cyclotron beams of 50-80 MeV  $\text{Li}^{2+}$  at intensities up to 50 nanoamps, without bunching. But the lithium feed system needs improvement. Since the internal PIG source is giving good beams of all required ions, including lithium, very little effort has been put on the external source recently.

#### THE INTERNAL PIG SOURCE

The internal PIG source was designed to fit on the standard 2 1/4 inch diameter shaft which is inserted through the lower pole of the cyclotron. It is shown in cross-section in Fig. 1. The anode and



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Fig. 1. Internal PIG ion source.

cathode holder are made of water-cooled copper. The cathode holder makes the electrical connection between cathodes, eliminating the need for an external connection to the top cathode. The cathodes are now usually made with a shoulder and dropped in to the holders, so set screws are not required. A loose fit gives lower operating voltage, resulting in longer cathode life. The alumina base insulator forms a vacuum seal and makes insulated water connections to the anode and cathode circuits from two water lines coming through the source shaft. A drop-in boron nitride cover insulator protects the alumina, and is easily removable for cleaning. The electron dump provides a component of electric field,  $E$ , parallel to the magnetic field,  $B$ , causing

electrons circulating around the cathode holder in an ExB mode to be dumped on the outer tantalum cover. Photos of the assembled and partly disassembled source are shown in Figs. 2 and 3. The top and

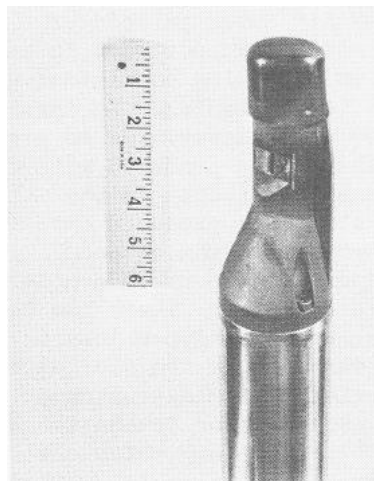


Fig. 2. Internal PIG source assembled on shaft. Scale is in inches.

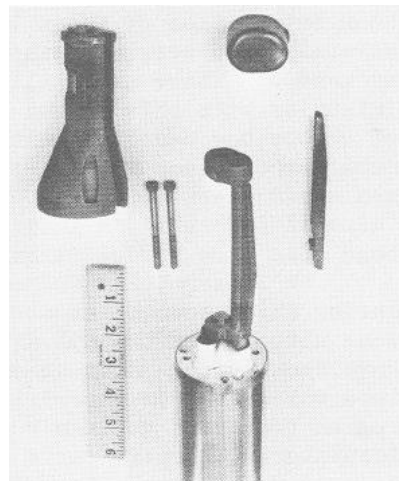


Fig. 3. Internal PIG source disassembled for cathode change.

side covers slide off, and the anode is removed by loosening 2 screws.

To start the arc, the voltage is raised to 3 kV and the gas flow increased. When the arc strikes, the current increases to 2-4 A and the voltage drops to 400-800 V. The gas is then reduced for maximum stable beam. The arc power is thus 2-3 kilowatts, compared to 500-800 watts of the old filament source. Since the high charge state heavy ion output increases exponentially as the second or third power of the arc power, the output of heavy ions is greatly increased over that of the filament source. For example, the  $N^{4+}$  and  $O^{4+}$  beams are 3-10 times more intense, and the  $N^{5+}$  output is 200 times larger than that of the filament source.

The first anode had an arc chamber of 5/16 inch diameter. A second anode was built with a 3/8 inch arc hole to investigate the effect on performance. The heavy ion beam currents went down about a factor of 2. When a tantalum sleeve was inserted to reduce the arc hole diameter to 5/16" again, the beam came back up again to approximately the original value. This sleeve proved to be quite useful for accelerating solid materials.

To obtain a beam of lithium, a solid material containing lithium must be used in the source, since no gas containing lithium was available. Other laboratories have used solid material in the cathodes or in the anode.<sup>2</sup> Trials were made using 10-20% lithium fluoride or

oxide mixed with tungsten powder and pressed into a cylinder for use as a cathode. Some  ${}^7\text{Li}^{2+}$  beam was obtained. Later LiF was melted into the tantalum insert placed in the 3/8 inch diameter arc hole of the second anode. This produced more lithium vapor near the beam exit slit and gave more beam. In the latest version, holes are drilled in the tantalum insert and LiF melted into them. This gives external beam intensities of about 1  $\mu\text{A}$  of 60-80 MeV  $\text{Li}^{2+}$  over periods of several hours between cathode charges.  $\text{N}_2$  or  $\text{CO}_2$  support gas is used as needed. There are still some problems in obtaining consistent good intensity with this system and development is continuing. An insert of carbon has been used with some  $\text{O}_2$  or  $\text{CO}_2$  as a support gas to produce carbon beams which are more intense than those produced with  $\text{CO}_2$  gas and no carbon insert. This is sometimes referred to as the "hibachi effect". An insert of stainless steel has produced more iron beam than iron powder mixed with tungsten powder in the cathode.

The internal PIG source has been in operation about 10 months during which some maintenance problems have appeared. There has been some chipping of the 85% alumina base insulator, so copper inserts have been added. When excess pressure appears inside the source, due to a water leak or vaporizing of some material, the electron dump region overheats and can bend the cathode structure or damage the base insulator. So spare parts are available to replace any which are damaged during operation. Operation is now fairly reliable, with source maintenance problems occupying about 10% of the time when running gases, and 20-30% of the time running solid material. In addition, cathode changes take about 30 minutes and occur every 3-5 hours when running oxygen gas. When nitrogen gas is run, the cathode life is 5-10 hours. The old filament source is still normally used for light ions because it is more controllable at low arc power, and has a filament life of a week or more.

#### ACCELERATION

The range of particles and energies which can be accelerated in the cyclotron is shown in the resonance chart, Fig. 4. The higher energy heavy ions use first harmonic acceleration and the lower energies use third or occasionally fifth harmonic. The maximum energy for ions heavier than  $\alpha$ -particles is  $E = 140 Q^2/A$  MeV where  $Q$  and  $A$  are ion charge and mass in proton units. This is set by the maximum magnetic field of 17 kilogauss.

The narrow gap of the center region inserts<sup>4</sup> reduces the gap transit time. This is especially useful for the higher energy third harmonic beams. Operation with the inserts gives a beam intensity twice that produced without the inserts for 60 MeV  $\text{O}^{3+}$ , for example. The sliding edge on the dummy dee insert installed in 1969<sup>4</sup> caused numerous operational problems and was replaced by a fixed edge with an open area for ion source motion. The center region settings used for heavy ions are similar to those of light ions with the same number of turns. Because of the charge exchange beam loss during acceleration of a factor of 2-3, high dee voltages of 60-70 kV are used to minimize the number of turns. Trim coil solutions are calculated with the computer code CYDE.<sup>5</sup> Tuning has to be done more

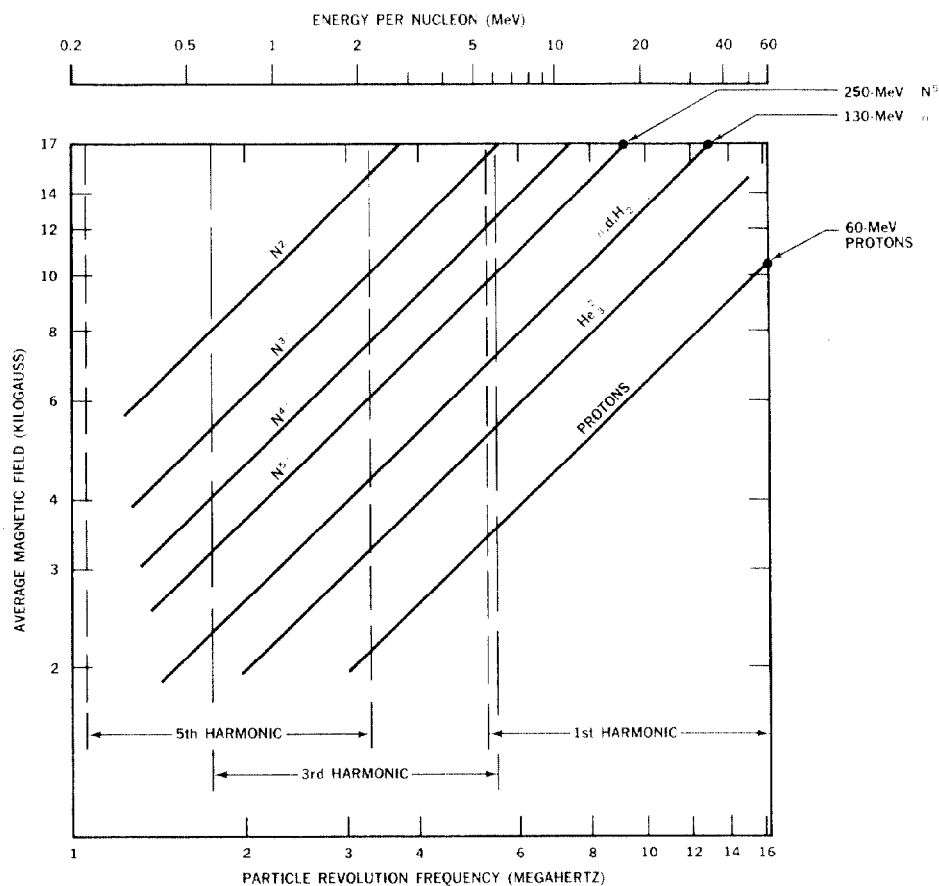


Fig. 4. Resonance chart for 88-Inch Cyclotron.

carefully with heavy ions since beams of lower charge states on higher harmonics can be accelerated simultaneously with the required beam through a number of turns, and can spiral out along a hill-valley boundary and appear on an external beam probe without going through the deflector. Tuning is sometimes done after the first external switching magnet to eliminate these spurious beams. A useful technique for the very high charge, low intensity beams is to start the tuning with a lower mass ion with the same charge/mass ratio, and then change frequency slightly to get the required ion. If the charge to mass ratio is different by more than about 1%, the scaling method of Ref. 3 can be used.

The acceleration of heavy ions presents some operating problems not present for light ion work. The high arc powers used in the source sometimes loaded the self-excited rf system oscillator, so that the arc had to be turned down or off to get the dee voltage back on after spark-off. The new master-oscillator power-amplifier rf system installed this year eliminates this problem. The large intensity of lower charge states accelerating for half a turn from the source cause heating and sputtering erosion of any structure in the median plane in the center region. The post supporting the center region insert<sup>4</sup> in the dee has recently been removed because of erosion. The top and bottom halves of the insert are now supported separately.

Most of the heavy ion beams which have been accelerated and extracted from the cyclotron with the internal source are listed in Table I. The PIG ion source is now always used for heavy ions. But

Table I. Heavy Ion Beams

Ion	Energy (MeV)	Harmonic	Source	External Beam
${}^7\text{Li}^{2+}$	60-80	1	PIG	1-3 $\mu\text{A}$
${}^{12}\text{C}^{3+}$	65-105	3,1	PIG	5-14 $\mu\text{A}$
${}^{14}\text{N}^{4+}$	100-160	1	PIG	5-10 $\mu\text{A}$
${}^{14}\text{N}^{5+}$	250	1	PIG	1-7 $\mu\text{A}$
${}^{14}\text{N}^{6+}$	360	1	PIG	$10^3$ part./sec
${}^{16}\text{O}^{3+}$	50-75	3	PIG	5-18 $\mu\text{A}$
${}^{16}\text{O}^{4+}$	105-140	1	PIG	5-44 $\mu\text{A}$
${}^{20}\text{Ne}^{5+}$	130-150	1	PIG	.5
${}^{56}\text{Fe}^{9+}$	175	3	PIG	10 part./sec
${}^{56}\text{Fe}^{10+}$	220	3	PIG	1 part./sec
${}^{84}\text{Kr}^{11+}$	174	3	Filament	1 part./sec
${}^{84}\text{Kr}^{12+}$	207	3	Filament	1 part./sec

previously, the old filament source gave the surprisingly high charge states of  $\text{Kr}^{11+}$  and  $\text{Kr}^{12+}$  at very low intensities. The beam currents are listed as electrical  $\mu\text{A}$  or nA or particles/sec. The lower number is a typical good beam and the higher number is the highest value recorded.

#### EXPERIMENTS

The experimental area is shown in Fig. 5. The principal use of heavy ion beams at present is in the study of nuclear reactions with bombarding energies of 5-10 MeV/nucleon in Caves 1, 2 and 4C. The ions used are Li, C, N, O, and Ne. The high resolution work is done by B. G. Harvey's group in Cave 4C using the analyzing magnets in

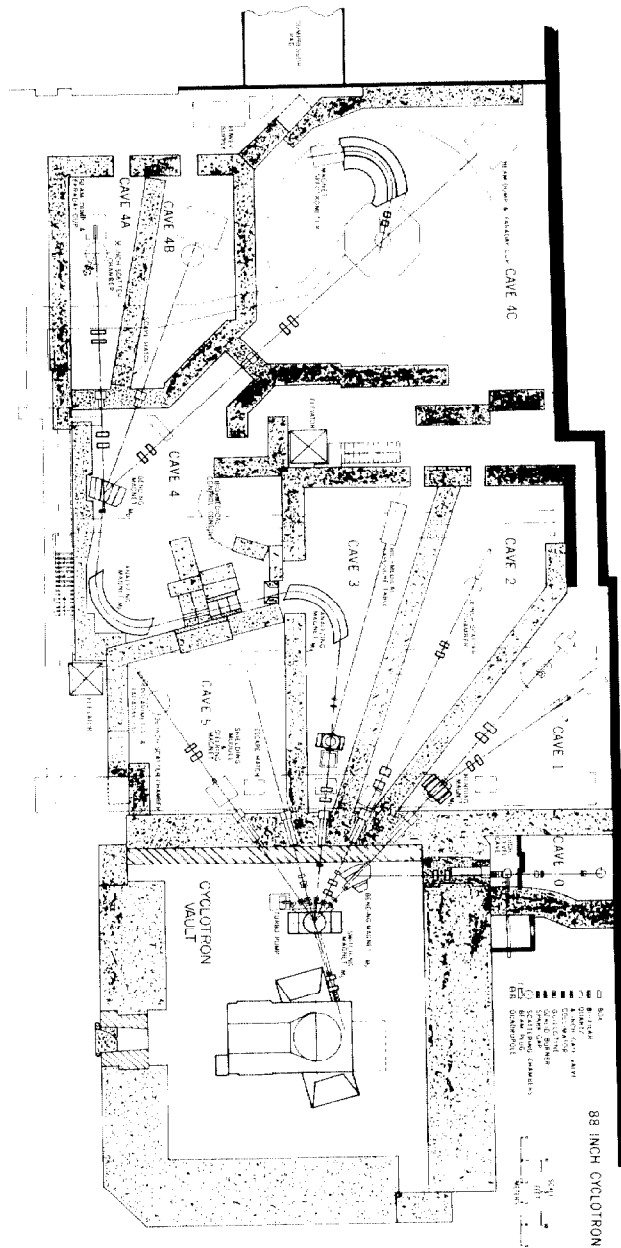
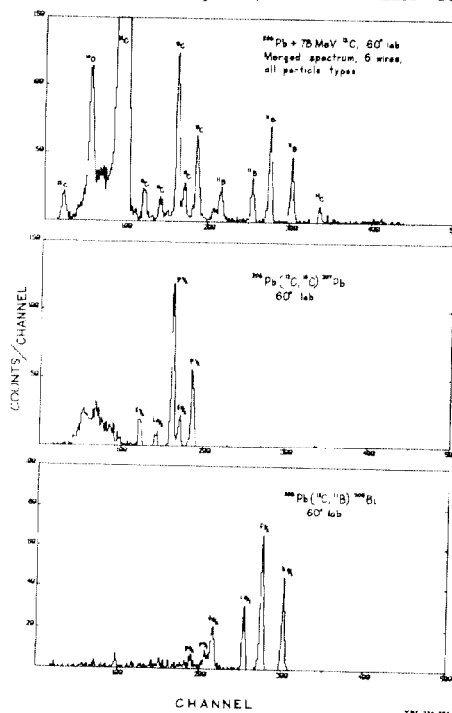


Fig. 5. 88-Inch Cyclotron building layout showing cyclotron and beam lines.

Caves 3 and 4 to prepare the beam, and the spectrometer magnet in Cave 4C to analyze reaction products. The last element in this system, the focal plane detector, was recently completed.<sup>6</sup> It is a resistive wire proportional counter giving mass identification up to  $A = 20$  by measuring position,  $dE/dx$  and time-of-flight. A focal plane position



spectrum is shown at the top of Fig. 6. The lower parts of the figure show the separation of  $^{13}\text{C}$  and  $^{11}\text{B}$ . The energy resolution is typically .15% at 100 MeV for heavy ions, with a 1 msr solid angle. This is a real improvement over counter telescopes, which give about .4% for heavy ions, with a .1 msr solid angle. The beam through the target is typically 400 nA, fully stripped.

The higher energy heavy ions are used in other types of experiments. Biomedical studies use the 250 MeV  $\text{N}^{5+}$  beam. The high energy iron beam was used to make tracks in plastics and minerals to calibrate them for cosmic ray research.

Fig. 6. Heavy ion reaction product spectrum for 78 MeV carbon beam on lead target.

#### ACKNOWLEDGEMENTS

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## DISCUSSION

WEGNER: What source lifetime do you expect for full current performance of the 88-inch cyclotron and what operational duty cycle do you experience on a long, high-resolution spectrometer run?

CLARK: Our source life is 3 to 5 hours on oxygen, and 4 to 8 hours on nitrogen. The cathode change time is 30-45 min, and there are sometimes other problems which come up during runs, so I think overall the beam is on about 75% of scheduled time.

RICKEY: I wonder why you feel that the internal source is preferable to the same source outside. It would seem that you could cut down on the replacement time. It would be much easier to change it more quickly if it were outside and also it gets away a great deal of the gas-stripping problem. The vacuum burden would be much less if the source were outside. Would you say something about that?

CLARK: I was speaking mainly of the transmission when I said the internal source was better. You are certainly right. In fact that was one of the things we had in mind in developing the external source. One could certainly have dual sources and switch them back and forth. So the change time would be very much reduced, but in our case we need quite a bit of development to get the transmission anywhere near what the internal source gives. It is partly a problem of space-charge neutralization while transmitting high-intensity beams at only 10 kV injection energy, whereas with the internal source you go directly into 50 kV internal beams, so you are accelerating fast. With the external source we are about a factor of ten down in intensity from the external source. Eventually we would hope that one could build better external sources giving high intensity and also the interchangeability features. The internal PIG source acts as an ion pump to remove 70-90% of the gas, reducing the stripping problem.

FINLAN: Can you tell me if you suffer significant sputter erosion behind your tantalum slit, inside the source?

CLARK: We do have some back-bombardment from the decelerated ions. It doesn't seem to be serious. We do have a lot of erosion of anything that is in the median plane. Any posts across the median plane get eroded pretty rapidly, so we have to cover them with tantalum or tungsten and then replace that periodically.

CHAMBERLIN: Have you encountered any contamination in your central region using lithium in your source?

CLARK: Not yet. We were worried about that. We have had several long runs and we haven't observed any problem of holding dee voltage, but we haven't run a lot yet. There may be a problem later.