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OPERATING EXPERIENCE WITH AN ION SOURCE IN A SUPERCONDUCTING CYCLOTRON

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Summary

We have developed a PIG ion source for axial insertion in the K500 cyclotron. The operation of the ion source has been limited to the requirements demanded by the operation of the cyclotron. These requirements have been for moderate charge state light heavy ions, of principally carbon, nitrogen and neon. The source design is more than adequate for moderate charge states with lifetimes of 8-12 hours for carbon and in excess of 15 hours for nitrogen and neon. We are now just starting to push the source to produce high charge states, and we have not yet established whether this source design will be adequate.

Introduction

The development of heavy ion sources for the K500 cyclotron has occured in many stages. The basic design was carried-over from the cold cathode PIG source operated in the K50 cyclotron in the mid-1970's. Dc testing of the same source in the K500 cyclotron magnet occurred in 1976 and 1977. The dc testing established that a PIG source could indeed operate in a high magnetic field and give performance equal to operation at lower fields. There followed a period of inactivity in which the laboratory effort centered on completing the K500 cyclotron. During that time modifications were made to the source design to accomodate it within the K500 central region. Fabrication of the first ion source specifically for the K500 cyclotron was completed in October of 1981, and we went back to the then de-commissioned K50 to test this source, in parallel with the first operation of the cyclotron rf system. In late 1981 these tasks came together and internal beams were obtained. In 1982 this first ion source was operated exclusively, while a mirror image for the other center plug was being fabricated. That second ion source was commissioned in January 1983, and we have since employed both sources for the production of cyclotron beams. Shortly we will add automatic source insertion and extraction equipment. This will allow us to remotely retract a spent source and insert a fresh source, already sitting in the other air lock ready to run.

K500 Ion Source Design

For heavy ions we have developed a discharge-heated PIG-type ion source, shown in Fig. 1. This source is inserted axially thru an air lock in the 7-inch diameter center plug. The overall length is about 6 feet and the body diameter 1.375 inches. Of course the axial magnetic field of the K500 is quite large, so we have built the source without iron to allow insertion and removal during operation of the magnet. The N=1 central region fixes precisely the location of the ion source extraction slit and the shape of the source anode.[1] The ion source extraction slit resides 0.32 inches off center with a 1 cm gap between the chimmey face and the puller electrode, as shown in Fig. 2. The anode terminates the rf electric field in the center, and has a precise shape to boost the energy gain on the first turn to clear the ion source and dee tip electrodes. Provision has been included for a $\pm 5^{\circ}$ rotation of the source to optimize the extraction angle and an external rotation drive accomplishes this.

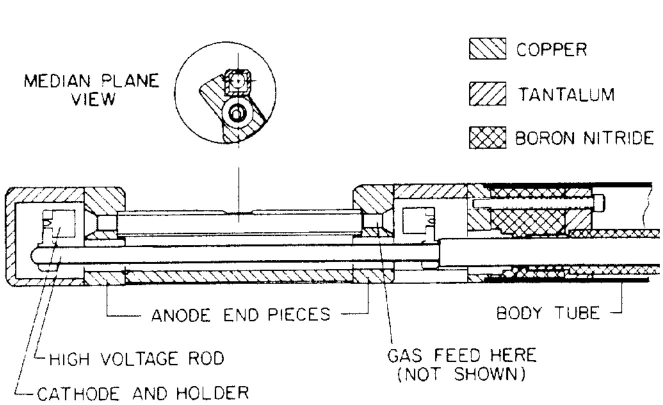

FIG. 1. Sectional view thru the anode of the axial PIG source for the K500 cyclotron.

FIG. 2. The central region of the K500 cyclotron, showing the ion source and all three dees. The dee with the puller is on the right.

The source design emphasizes rapid recycling. Surfaces exposed to the arc and hence eventually will wear out can be removed for replacement. The core of the anode is a water-cooled copper part that is not intended to be replaced during source recycling. Replaceable copper end pieces define a .250 inch diameter anode aperature and seat the chimney. The tantalum chimney has a .25 inch square bore with a machined exit slit. We fold the chimneys out of .050 inch sheet stock and TIG-fuse the resulting seam located along one edge. When the exit slit has eroded away the chimney is replaced, typically after about 30 hours. The 3/8 inch diameter cathodes are swedged into tantalum holders that slide over a water cooled copper high voltage rod. Normal recycling takes about fifteen minutes.

Ion Source Operation

DC Ion Source Testing in the K500 Magnet

Before the K500 was proposed, cold-cathode PIG sources never had to operate 30-50 kG levels, and the extrapolation to high field operation was not clear. PIG sources typically use an existing accelerator magnetic field, so performance is strongly dependent upon the prevalent geometry, and hence the exact dependence on magnetic field is difficult to ascertain. There is also the issue of the field shape and its effect on the plasma location to consider. For these reasons a program of dc source measurements in the K500 at high fields was developed.

The K50 cyclotron PIG source was operated in the K500 with a dc extraction electrode and a grid of current sensing wires to analyze q/m. This established several important points. The source could be struck at fields as high as 50 kG without difficulty. When struck at 30 kG, ramping the field to 50 kG did not affect the arc parameters. One interesting observation concerned the appearance of a bright glow discharge in the chimney slit with a mode 1 discharge ($V \simeq 4.5$ kV, $I \simeq .5$A). At low field a glow discharge is not normally visible for the same arc conditions, instead being observed only in mode 2. With a dc extraction electrode installed in one of the K500 valleys, currents were measured for N, O, Ne, Ar and Kr ions. This data compares well with the performance of similar sources, as shown for nitrogen in Fig. 3. However it was expected that there would be an enhancement in high charge states at high field because of an increase in the radial magnetic pressure, which goes with B^2, and is about 10 times larger in a superconducting cyclotron. Since performance is no better, lends further support to the argument that the ion confinement time is dominated by the axial drift time to the cathodes; this being unaffected by the increase in radial confinement.

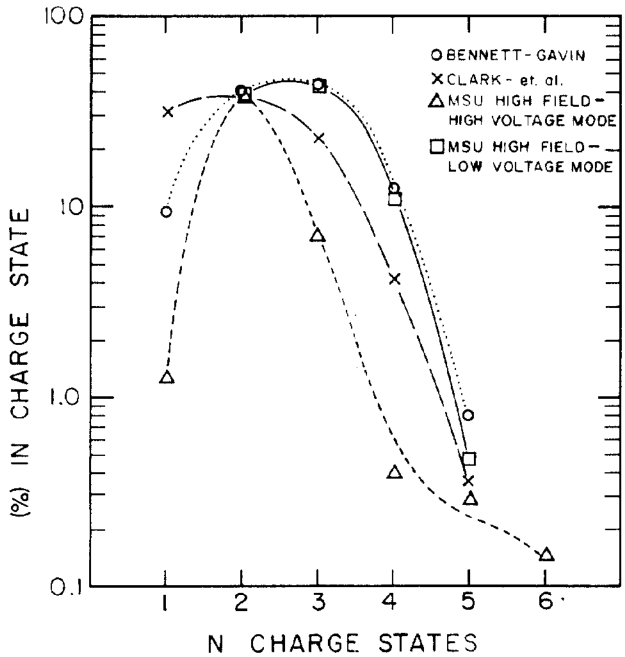

FIG. 3. Comparison of the relative production of nitrogen charge states for three PIG sources: a PIG operated with DC extraction in the K500 and two from the literature. For the MSU source, both the cold cathode and discharge-heated cathode modes are shown.

K500 Ion Source Commissioning Experience

The ion source design for the K500 was first tested in the de-commissioned K50 cyclotron. The major difficulty encountered there was the failure of the vacuum voltage feedthru, an alumina insulator at the external end of the ion source. We found that the pressure inside the ion source body was high enough during operation to initiate a glow discharge and crack the insulator. The problem was eliminated by drilling holes in the side of the source body to vent it to the center plug interior, and then to pump on that space to improve the vacuum.

Several improvements in the way we prepare and operate these sources in the K500 cyclotron has resulted in a improvement in the source lifetime. The histogram in Fig. 4 shows a steady improvement in the lifetime with the total number of source runs. This data includes both source terminated and cyclotron terminated runs, with the intrinsic source lifetime higher than the values in this histogram by about 25%. The first runs in the K500 can be characterized as being dominated by failure of the source center conductor, its support insulators, and parts of the anode that draw arc power. Generally these problems were the result of the conflict between the requirement that the source have a small cross-section for clearance of ions on the tight first turn, and the need to pass source voltage, current and water-cooling, thru the median plane to the other cathode. This is of course a problem characteristic of both the highly optimized central region design and the large magnetic field, which makes the first turns small. Many small modifications to the high voltage rod and support insulators pushed the lifetime to about 4 hours after 30 sources. In the next phase we were running mainly carbon beams, and the source lifetime was a very poor 2.5-3 hours. Source operation with CO or CO_2 degrades the resistance of the boron nitride stand-off insulators, thru the build-up of a conducting layer on the surface, and eventually the source would short out. After about 55 sources we started tracking the center conductor resistance to ground during cathode changes and replacing insulators when the voltage holding threshold went below 1000 volts.

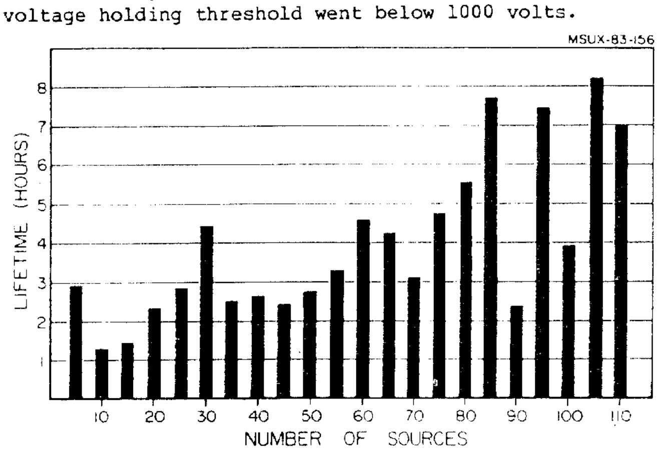

FIG. 4. The increase in the average lifetime of the K500 PIG source with operating time.

The source lifetime improved and the operating limit shifted to either the build-up of ash between the anode and cathodes, or a reduction in the beam current due to a slow strangling of the anode aperatures (which shifted the plasma boundary away from the extraction slit). At about 80 sources we started supporting the arc in a carbon run with N_2, and bleeding in only enough CO to produce adequate beam intensity. This produced another jump in the lifetime. The combination of voltage testing and N_2 + CO operation raised the source lifetime more than a factor of two. Since that time the average lifetime has been 7-8 hours, with the dip at 90 sources being due to start-up work after a 1.5 month shut-down, and that at 100 sources being the commissioning of the second source. With this steady improvement in source lifetime with time we soon expect to be routinely operating with source lifetimes in excess of 10 hours for all gases.

Present Status

We have 500 hours of operating time on our two PIG sources. Because the accelerator has been under development during this period, source performance data is sparse. Currents required so far have been modest, so we have worked most on obtaining stable operation and long source life. Thus the present design is free from weak operating characteristics, strikes easily, and now has lifetimes greater than 8 hours for most species. The dependence of extracted current on arc current is shown in Fig. 5 for 53 MeV/n deuterium. (It is similar for other species.) The arc was supported on CO_2, with deterium fed in as required for beam intensity. CO_2 was choosen because it is easily cryopumped. With the main chamber vacuum coming principally from cryopanels located in the lower dee shells, we often choose arc support gases on the basis for how well they are pumped.

The source strikes at 1.5-3.5 kV and a gas flow rate of 5 sccm. We then reduce gas flow to 1-3 sccm for normal operation and raise the arc current to 1.8-2.5 amps. A breakdown of extracted currents obtained so far on the basis of charge state is shown in Table 1. The extracted beam is typically 40% of the internal beam. With the exception of neon, all currents have been limited to reduce activation or to keep the lifetime up.

Table 1. Extracted Beams
Charge State (eμA)

SPECIES	1	2	3	4	5	6	gas feed
Helium	.4	.25					1% He in N_2
Carbon			.38	.3			CO + N_2
Nitrogen				.075			N_2
Oxygen				.025			CO (during carbon run)
Neon				.025	.075	1.2nA	Ne

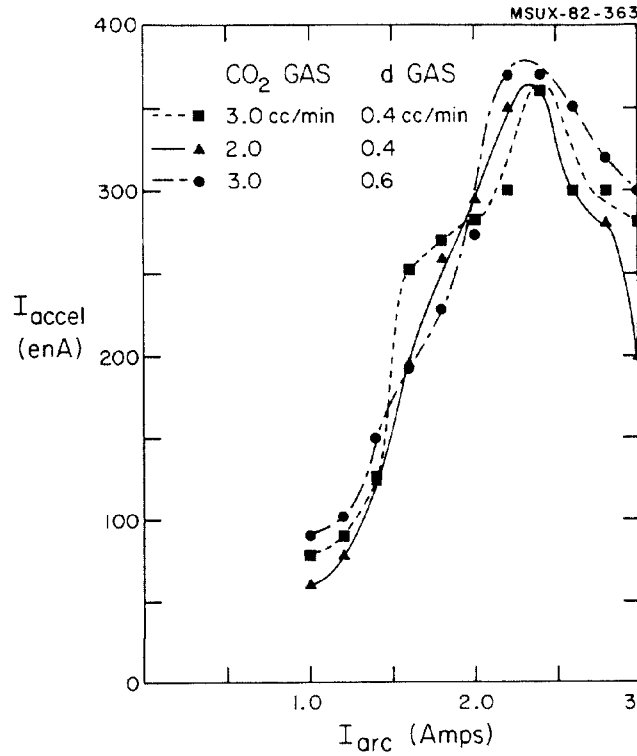

FIG. 5. Dependence of an accelerated beam on the arc current, for a 53 MeV/n deuteron beam in a PIG supported by CO_2 gas.

Hafnium Cathodes for Carbon and Oxygen Beams

Our experience with supporting the arc with CO to produce carbon beams is that the lifetime is about 1/3 to 1/4 of the lifetime for N_2 or Ne. Carbon deposits on insulators, a reduction in the anode aperature causing a decrease in beam, or a faster rate of ash build-up across the arc gap all contribute to the lower lifetime. Using hafnium cathodes in place of tantalum increases the source lifetime. Hafnium cathodes were first tried during K50 cyclotron operation[4]. The lifetime increased from about 3.5 to 24 hours using Hf cathodes for carbon beams. Since the Hf cathodes were operated at reduced arc power, the extracted currents were 3 to 10 times lower than higher power operation with Ta cathodes. It was noted that just reducing the arc power when using Ta cathodes did not produce the same increase in source lifetime. Lifetime with Hf cathodes decreased with N_2 or Ne feed.

We have recently repeated that work in the K500 cyclotron. We have tried Hf cathodes for both 15 MeV/n C^{3+} and 30 MeV/n C^{4+} beams. In the case of the C^{4+} beam, we tried both Ta and Hf cathodes in succession. The results are summarized in Table 2 below. The best carbon run with N_2 mixing is included for comparison. With Hf cathodes the lifetime decreases as the percentage of nitrogen in the arc increases. At low power levels hafnium cathodes appear to improve the lifetime for carbon beams. Since the likely cause of poor lifetime for CO feed is the formation of tantalum oxide, then the use of hafnium should improve the source lifetime with oxygen beams as well. Longer lifetime for moderate charge states would certainly be desirable for injector mode operation of the K500, where maximum facility energy would be obtained without accelerating fully stripped ions in the K500.

References

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Table 2. Hafnium Versus Tantalum Cathodes

Beam	Int. Current (μA)	Cathodes	CO Flow (sccm)	N_2 Flow (sccm)	Arc Power (watts)	Lifetime (hr:min.)
30 MeV/n C^{4+}	0.42	Ta	1.05	1.05	760	6:10
30 MeV/n C^{4+}	0.5	Hf	1.5	0.5	700	16:34
15 MeV/n C^{3+}	0.8	Hf	0.7	1.7	500	11:59
25 MeV/n C^{3+}	0.4	Ta	0.5	1.7	660	11:57