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A HIGH POWER PENNING SOURCE FOR MULTIPLY CHARGED HEAVY IONS

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The performance of a continuously operated PIG source for multiply charged heavy ions is described. The source was initially designed with large cathodes to operate in a nonuniform magnetic field to increase the power dissipation but the output of highly charged ions was disappointing. Operation of the source in a uniform field produced large fractions of the ion current in the high charge states. Changes to the anode resulted in further improvement. Nitrogen and argon gases were used in the experiments and the best percentages of ion currents in the higher charge states were 1.5 per cent of A^{8+}, 0.3 per cent of A^{9+} and 0.8 per cent of N^{5+}. Xenon was also tried, but confusion of the charge states higher than Xe^{9+} with argon contamination prevented analysis of the spectrum. Finally water-cooled cathodes were used, but the gas flow had to be relatively high to maintain the discharge and the yield of the high charge state ions was poor.

1. INTRODUCTION

The Penning Ionization Gauge (PIG) discharge is frequently used as a powerful source of highly charged ions.[1] For continuously operated sources the output of the high charge states increases as the arc current and voltage are increased and the operating gas pressure in the source is reduced. Most of the electrical power is dissipated in the cathodes and this results in an upper limit of the applied arc power when the cathodes begin to melt. The cathodes in most sources lose their heat by radiation. Although greater dissipation can be achieved by water cooling this has some difficulties in practice. The front surface of the cathodes must be allowed to reach a high temperature where electrons can be emitted thermionically. Unfortunately this surface wears quite rapidly due to sputtering by ions from the discharge. Hence the water passages cannot be placed close to the front surfaces of the cathodes.

To increase the power dissipation a source was constructed with cathodes of much larger diameter than previously had been used. The anode bore was made considerably smaller than the cathodes. The cathode diameter was 1 in. and the anode diameter $\frac{3}{8}$ in. By placing the discharge in a nonuniform magnetic field which decreased strongly near the cathodes, electrons from the whole of the front emitting surface of the cathodes were able to follow the magnetic field lines through the anode and thereby entered into the discharge. These features were expected to give several advantages. The larger total cathode area allows greater powers of up to 20 to 30 kW to be dissipated. The increased cooling should also result in a higher arc impedance at a given arc current. Hence large currents should be attainable whilst maintaining a high arc voltage. The small anode diameter increases the current density in the anode, and hence the ionization rate.

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2. DESIGN OF THE ION SOURCE

Figure 1 shows a section through the ion source. The end caps of iron shape the magnetic field so that the lines of force diverge near the cathode. Dotted lines in the figure indicate the field shape. The source assembly was placed between the poles of an electromagnet. Slots were cut in the pole pieces to allow the source to be inserted into the magnet so that the inner surface of the end caps was flush with the pole faces. This gave a uniform field in the magnet except at the ion source where the end caps caused a local reduction. The shape

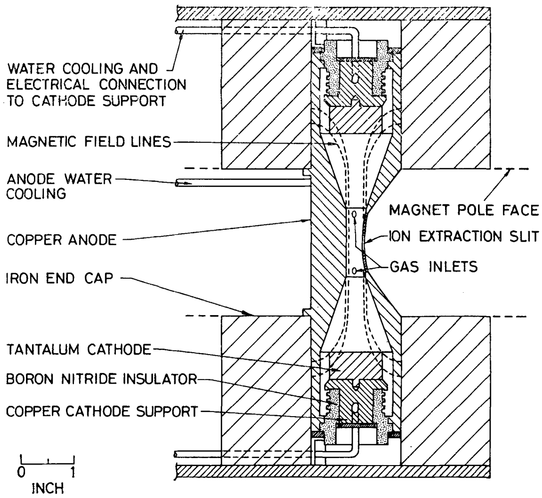

FIG. 1. A section through the PIG ion source. The shape of the magnetic field lines in the region of the discharge are shown dotted.

of the end caps was deduced from a computer calculation. The field in the resultant design was not measured, but the erosion of the cathodes over nearly the whole of their diameter by the discharge was obvious proof of the correct field shape.

The anode bore was $\frac{3}{8}$ in. diameter in the centre region but soon enlarged gradually towards the cathodes to $1\frac{3}{8}$ in. diameter. This allowed the electrons and ions to follow an unobstructed path along the curved field lines through the anode. The ion extraction slit was curved inwards to the discharge to ensure that the slit was close to the plasma. The slit protruded about 0.02 in. into the bore, and was clearly close to the plasma since the slit became very hot, sometimes melting locally.

The design of the remainder of the source followed that of earlier designs[2] that have proved successful. The cathodes are not heated internally, but solely from the discharge itself. At first the cathodes are cold and several thousand volts must be applied between anode and cathodes to start the discharge at a low current. As the cathodes heat up thermionic emission of electrons begins to occur and the arc current increases and the arc voltage drops. The mode of the discharge then begins to change rapidly from that with cold cathodes to that with hot cathodes. The arc runs at several amperes and several hundred volts.

The slit plate was made from 0.02 in. thick tantalum plate and the ion extraction slit was $\frac{1}{4}$ in. long and $\frac{1}{32}$ in. wide. The slit was secured by small stainless steel screws to the water-cooled copper anode. Gas entered the anode chamber through two small holes spaced about $\frac{1}{2}$ in. either side of the centre of the anode. The drillings for these holes sloped so that the gas was directed at about 45° towards the nearest cathode. The cathodes were machined from 1 in. diameter tantalum bar and screwed into water-cooled copper supports which are located in insulators of boron nitride.

3. THE TEST ARRANGEMENT

The analysis of the beam from the ion source into the various charge states was by a conventional 180° mass spectrometer arrangement. The ion source, at ground potential was placed in a 20 in. diameter magnet. A high voltage 'dee' electrode accelerated the ions from the source slit and a moveable Faraday cup in the dee collected the current after the beam had rotated through 180°. An X–Y recorder monitored the current entering the cup as a function of its position.

The arc supply could deliver 25 A and 10 kV. A large series resistor of 500 Ω was used to stabilize the arc. The dee voltage was stabilized and could be varied up to 20 kV. The current available was 25 mA. The magnetic field was stabilized and variable up to about 12 kG. A simple needle valve was used to control the gas flow into the source and the flow monitored by a commercial instrument. The input flow rates given in the tables of results are probably misleading. The important parameter is the gas density in the arc chamber, which can be largely determined, depending on conditions, by the amount of material sputtered from the cathodes, the outgassing in the source and any local vaporization of flakes of cathode material in the anode chamber. With the slit sizes used in the source the measured gas flows were usually between 1 and 0.01 STP cc/min. In taking the measurements the arc current and gas flow were varied until the optimum was found which gave the greatest percentage yield of high charge state ions.

4. RESULTS

The source operated reliably and large powers were dissipated. However the analysis of the

TABLE I
Performance of the source in the nonuniform field. Nitrogen gas. The percentage of current in different charge states is shown for a few of the best operating conditions of the ion source. The best values are shown on the next to last line and the last line in italics gives the performance of another PIG source for comparison purposes

Arc conditions				Percentage of ion current in charge states					
Potential A	Current V	Power kW	Gas Flow STP cc/min.	N_2^+	N^+	N^{2+}	N^{3+}	N^{4+}	N^{5+}
1,300	6.1	7.9	1.65	2.9	45.8	42.7	8.2	0.2	
600	6.9	4.1	0.22	2.5	47.4	42.3	7.5	0.35	
550	7.0	3.9	0.22	3.1	48.7	40.4	7.3	0.5	
450	9.8	4.4	0.12	0.8	39.1	45.2	14.2	0.7	0.004
730	*8.0*	*5.8*	—	*~0*	*15.8*	*37.0*	*37.0*	*9.6*	*0.6*

spectrum of the charge states of nitrogen was considerably worse than other conventional sources operated in uniform magnetic fields. Table I shows the best performance and that of another PIG source[2] for comparison. The appreciable percentages of molecular nitrogen ions are a good indication of the poor performance. Figures for other operating conditions are also shown. Even when operating at 6.1 A, 1300 V (7.9 kW) the output of multiply charged ions is low. Better results might have been found at significantly different magnetic fields from the 5 kG in which the source was usually operated, but this was not examined.

The characteristics of the source were generally similar to that of other PIG sources. At low arc powers the source showed cold cathode characteristics; a high arc voltage and low current and a positive impedance. At higher powers of about 1 kW the cathodes emitted electrons thermionically giving rise to a negative arc impedance. The output of highly charged ions increased as the gas flow was reduced. The highest power that it was possible to put into the source was 12 kW (3 kV and 4 A). Attempts to dissipate more power would result in the arc changing to a low voltage high current mode at lower power. If the gas flow was reduced too much in an attempt to increase the arc impedance and hence arc power the discharge would extinguish.

5. OPERATION IN A UNIFORM FIELD

Following the disappointing results described in the previous section it was decided to check the source to determine whether it would perform as well as other PIG sources in a uniform magnetic field. This would show whether there was some design fault in the source not necessarily connected with the uniform field.

The iron caps on the source were removed and the magnet gap increased to 10 inches to give a uniform field with a maximum attainable value of 6 kG.

Operation of the source showed an *immediate* marked improvement. The molecular nitrogen peak was no longer present and N^{4+} and N^{5+} peaks were very strong. It was possible to dissipate up to 20 kW in the arc. Table II shows the results

TABLE II
Best performance of the source in a uniform field on nitrogen and argon gases

Gas	Arc conditions				Percentage of ion current in charge state								
	Potential A	Current V	Power kW	Gas Flow STP cc/min.	1	2	3	4	5	6	7	8	9
Nitrogen	1,980	10.2	20.2	0.23	26.0	42.7	26.0	4.9	0.5				
	600	6	3.6	1.5	32.8	43.0	20.7	3.3	0.4				
Argon	600	12	7.2	0.185	4.0	15.2	34.3	31.0	12.2	3.0	0.3	0.04	0.003

at high and medium arc powers. Even at the 3.6 kW level the fraction of N^{5+} ion currents is very good. Little improvement is found when the power is increased to 20 kW.

Argon gas was tried in the source and worked successfully, powers up to 15 kW being dissipated. At this point a crack opened up in the source slit plate due to overheating by the arc. The slit plate was remade with less curvature so that it did not protrude so far into the discharge. Then the slit did not become hot and it was not found possible to dissipate large powers in the arc. The maximum power was 8.4 kW. However this is considerably in excess of that previously reported[1] for continuously operated PIG sources with argon gas. A small peak of A^{9+} was clearly seen.

Lowering the gas pressure forces the arc to run at a higher arc voltage for the same arc current. Of course this is very desirable in order to obtain the best output of highly charged ions. However, there is a practical limit to the reduction of gas flow when the arc extinguishes. It was found that below a certain gas flow the arc would begin to pulse slowly at about 1 Hz, the arc voltage going up and the current down. Increasing the applied voltage would not stabilize the arc and eventually it would extinguish. A similar pulsing instability could occur at a fixed gas flow if the arc current was increased too much. The pulsing could be eliminated at the higher arc current by increasing the gas pressure.

The PIG discharge creates a strong pumping action, taking ions and gas to the cathodes. At low gas flows or high arc currents the central region of the anode is probably starved of gas, causing the arc to extinguish. However, as the arc current drops, the pressure in the centre of the anode chamber can rise since the pumping action is reduced. The arc current can then increase towards its original value. This is the likely cause of the oscillations observed in the arc at low gas flow and high arc currents. After some seconds of pulsing the arc extinguishes either because the gas pressure has dropped too low or the cathodes have cooled a little due to a lower mean power dissipated when the arc is pulsing.

In an attempt to increase the power input and allow the source to run at lower gas flows the ends of the anode chamber were filled-in, making the bore $\frac{3}{8}$ in. diameter over the whole length to within $\frac{5}{16}$ in. of the cathodes. In this way it was hoped to decrease the pumping speed from the centre of the anode to the cathodes. At the same time the gas feed was altered so that there was only one admittance hole at the centre of the anode. Again this helps to keep the pressure up in the central region. Figure 2 shows the modified source design.

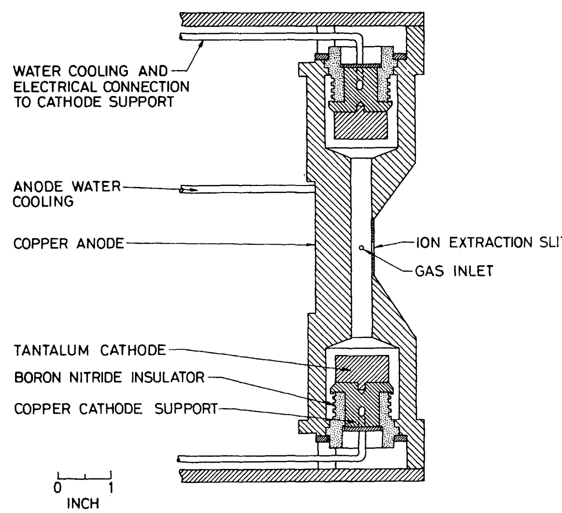

FIG. 2. A section through the ion source used in a uniform field after modifications to the anode geometry.

These changes resulted in some very large proportions of highly charged nitrogen and argon ions. The best results gave 0.8 per cent of the total nitrogen current in the 5th charge state and 12.6 per cent in the 4th. With argon the figures were 1.5 per cent of A^{8+} and 0.3 per cent for A^{9+}. A very small peak of A^{10+} was observed, about 25 times smaller than A^{9+}. However, confusion of the peak with the third and fourth charge states of the common impurities carbon and oxygen, respectively, precludes its positive identification as A^{10+}. Table III shows the best results and also the best results previously quoted for a continuously operated PIG source.[2] The results for argon are particularly encouraging, the performance exceeding that of pulsed PIG sources (see Ref. 1 for a comparison of source performance). A short run with xenon gas was unfortunately contaminated with argon from the previous runs and although Xe^{9+} and Xe^{12+} were strongly in evidence, Xe^{10+} and other

TABLE III
Best performance of the source in a uniform field after modification to the anode. The figures in italics are the previously reported best performance data for a continuously operated PIG source

Gas	Arc conditions				Percentage of ion current in charge state										Mean charge state
	Potential V	Current A	Power kW	Gas Flow STP cc/min.	1	2	3	4	5	6	7	8	9	10	
Nitrogen	450	6.2	2.8	0.35	9.1	33.1	44.3	12.6	0.8						2.3
	730	*8.0*	*5.8*	—	*15.8*	*37.0*	*37.0*	*9.6*	*0.6*	*0.006*					*2.0*
Argon	600	5.0	3.0	0.052	1.9	5.8	15.5	20.8	27.1	18.8	8.2	1.5	0.3	0.01(?)	4.0
	800	*2.0*	*1.6*	—	*6.4*	*16.5*	*33.0*	*33.0*	*7.9*	*2.4*	*0.6*	*0.1*			*2.7*

higher charge states could not be clearly distinguished from the argon peaks. The operating conditions of the arc were around 500 V at 6 A.

Although the performance of the source was improved with the changes to the anode, the power levels were only up to 3 kW. In one respect that is an advantage since the cathodes wear more slowly. It was not possible to decrease the gas flow to raise the arc voltage at a given current at the power level of about 3 kW because the arc would extinguish. There was a very marked optimum in the arc conditions for producing the high charge state ions. For example, at 10 A and 300 V the output of A^{7+}, A^{8+} and A^{9+} was greatly reduced from the best values obtained at 5 A and 600 V. It is quite possible that even better results could have been obtained if it had been possible to increase or even maintain the arc voltage at higher arc currents.

In a final attempt to increase the arc voltage at high current the source was operated with water-cooled cathodes. The tantalum cathode discs were vacuum brazed to the water-cooled copper supports. Voltages as high as 8 kV were required before the arc went into the high current negative resistance mode and the arc would only operate at significantly higher gas flows than previously. Operating conditions were varied from 6.1 kV at 1 A to 650 V at 9.2 A. The characteristic curves of the arc are shown in Fig. 3. Only argon gas was used. The output of highly charged ions was poor, only small currents of A^{8+} were observed and A^{9+} was not detected. Table IV shows the best results. It is probable that the output would have been improved if it had been possible to operate the arc at lower pressures. Unfortunately a fault in the power supply prevented operation of the arc at high currents in the 10–20 A range where it might have

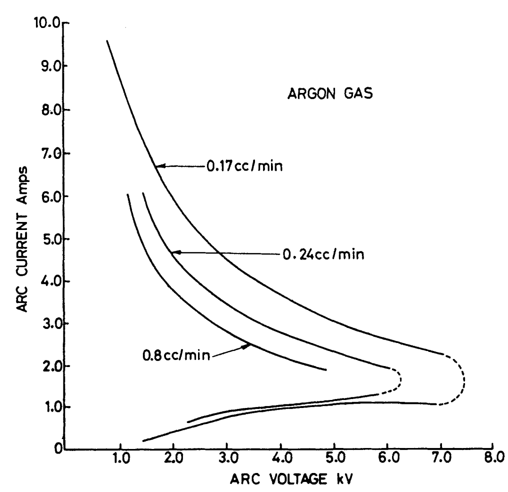

FIG. 3. The arc characteristics of the ion source with water-cooled tantalum cathodes.

TABLE IV
Best performance of the source with water-cooled cathodes. Argon gas

Arc conditions				Percentage of ion current in charge state								Mean charge state
Potential V	Current A	Power kW	Gas Flow STP cc/min.	1	2	3	4	5	6	7	8	
650	9.2	6.0	0.17	4.6	15.5	26.3	27.7	17.3	6.5	1.8	0.2	3.0

been possible to reduce the gas flow. The cathodes eroded very quickly at the high arc voltages and had lives of only about 4 hours.

No attempt was made to examine the effects of field strength on the ion source performance. Most of the measurements were taken at fields of 4 to 6 kG. Within this range no change in performance was seen. Since 6 kG was the maximum attainable field it was not possible to explore higher fields. Heavy ion PIG sources have not previously shown any marked change in output with magnetic field levels of up to about 15 kG.

6. DISCUSSION

The nonuniform field configuration used here was not beneficial in the production of highly charged heavy ions. The application of a uniform field to an otherwise unchanged source produced an immediate improvement and showed fairly conclusively that the nonuniform field was undesirable. The reason for this may be that the multiply charged ions which are formed mainly by a stepwise ionization process do not stay in the discharge long enough if the field is of the shape used in these experiments. There could be a definite advantage in shaping the field in the opposite way so that it is stronger near the cathodes, giving a mirror field shape which can help to trap ions axially. This configuration has already been studied briefly at Oak Ridge on a device known as Burnout[3] and the spectrum of highly charged argon and xenon ions was encouraging at the quite low arc currents which were used. Unfortunately the series of experiments described in this article was too short to allow the mirror field geometry to be tried, but it should be well worth pursuing.

Although high arc currents and voltages are advantageous for the production of multiply charged heavy ions one of the most important criteria is the correct conditions in the discharge for a long ion containment time. There were indications that the highest powers did not give very much improvement perhaps because the containment time was adversely affected under these arc conditions. It was only possible to dissipate the very large powers (up to 20 kW) in the source when the slit plate protruded well into the discharge and became very hot. It is possible that the slit plate contributed electrons to the discharge enabling it to run stably at lower gas flows and higher arc voltages than was otherwise possible. It would be interesting to test the source (with the improved anode geometry) with a 'hot' slit in the uniform magnetic field.

It is not clear why the final form of the source operated so well and at relatively low power. The containment time for the ions in the discharge was presumably quite long. The geometry of the source is similar to that of many others, although the cathodes are much larger. It is clear that a great deal has yet to be learnt about these sources and that they have not reached the limit of their development.

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