EMITTANCE MEASUREMENTS OF HIGH CHARGE STATE ARGON BEAMS FROM A PIG SOURCE*

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Summary

The emittances of beams of Ar^{+} to Ar^{22+} have been measured in the axial and radial planes. The extraction voltage was 10 kV and the magnetic field was varied from about .5 to .6 Tesla. The anode slit was varied in its distance from the arc which was run both dc and pulsed. The emittance was found to be nearly independent of charge state but to increase with total beam current. A small bowing of the arc column was discovered, which made evaluation of mirror field effects difficult.

Introduction

The test facility used for these measurements was installed in the summer of 1974 by the 88-Inch Cyclotron group. Its purpose is to develop Penning Ion Gauge (PIG) sources of highly charged positive heavy ions for use both inside the cyclotron and in external injectors for all ABL accelerators. The source in the test facility is an external version of the hot cathode source used internally in the 88-Inch Cyclotron.¹ The test facility source is biased to +10 kV to allow beam measurements to be made at ground potential, compared to the cyclotron source which is operated at ground potential with extraction by the dee voltage. Details of the test facility and early results have been published elsewhere.² It is important to measure the emittance area of the source in order to match it to the associated accelerator, and to find methods of reducing the area by improvements in the source and extraction system.

Fig. 1. Sectional view of source and emittance measuring system.

Description of the Source and Emittance Measuring System

The ion source and emittance measuring probes are shown schematically in Fig. 1. The source anode is made of water-cooled copper and has an arc bore of 9.5 mm. It is biased to about plus 10 kV. The anode slit through which the ions are extracted is made of tantalum or tungsten and protrudes 0.7 mm or 1.7 mm into the arc bore. The puller electrode, at ground potential, is comprised of two replaceable tungsten blades located 1.2 mm from the anode slit.

*Work performed under the auspices of the U.S. Energy Research and Development Administration.

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The beam is bent through an angle of 120° in the source magnet (see Fig. 1) and the currents for the various charge states are collected by a Faraday cup with an entrance collimator $21 \times 13 \text{ mm}^2$, axial by radial. For high intensity beam measurements and when the charge states are well separated we use a Faraday cup with a bigger entrance collimator $50 \times 25 \text{ mm}^2$. A cylindrical electrode biased at -300 V is used inside the cup to suppress secondary electrons. Beam currents are measured in electrical μA .

We hoped to report at this conference on the effect of a mirror magnetic field on the charge state distribution. However we recently discovered that the arc is curved or "bowed" by several mm between the cathodes and the anode slit. This bowing is caused by the curved magnetic field lines, because the source is near the edge of the magnet. The main effects on the arc are that of moving the arc away from the anode slit and moving it off center on the cathodes. The first effect was compensated by moving the anode slit toward the arc (next section). But since the bowing of the arc changes slightly with mirror field, it is difficult to separate the two effects of bowing and mirror field. Some tests were also done with the arc centered on the cathodes.

For the axial emittance measurements a plate with .25 mm slits spaced 7.6 mm apart or a plate with 1 mm diameter holes also spaced 7.6 mm apart was used. For the radial emittance measurements a plate with .25 mm slits spaced 3.8 mm or 7.6 mm apart or a plate with .5 mm diameter holes also spaced 3.8 mm apart was used. The beam patterns produced by the emittance plates were scanned by a pair of perpendicular 1 mm diameter wires, the positions of which varied sinusoidally as a function of time. For the present experiment the period was 400 ms; 80 ms were required to scan completely across the beam. The scan wire currents were recorded by a storage oscilloscope and photographed for subsequent analysis.

The emittances were obtained directly from the oscillograms by measuring the peak widths at a level of 5% of the central peak amplitude. We estimate the fraction of the total beam represented by our emittance curves to be at least 90%. Knowing the approximate beam diameter at each emittance probe provided an extrapolated closure of the emittance curves at each extremity. The extrapolated part is shown by a dashed line. The values of the emittances are calculated to a precision of $\pm 15\%$. Each emittance is plotted at the plate position used for its measurement. The plate positions are drawn to scale in Fig. 1.

Source Operating Parameters

The gas used in the source was argon. Charge states 4+ through 8+ were investigated. The 9th electron lies in the next inner shell. No production of Ar^{22+} was observed during these measurements because the ionization potential of the 9th electron (396 eV) is much higher than that of the 8th (152 eV).

Figure 2 shows the shape of the magnetic field on the axis of the arc bore for two values of current in the main magnet and a current of 500 A in the "mirror coils". Most of the magnetic fields used in the present measurements fall within this range. This value of mirror coil current was selected to produce an approximately uniform field.

The arc is struck by initially increasing the gas pressure and bringing the arc voltage to 3 kV. The gas flow is subsequently reduced to the minimum value (typically 0.1 cc/min) required to maintain a stable arc. This maximizes the high charge states. The gas could be injected at different locations along the anode bore. Injecting the gas near the cathodes gave good results both in terms of arc stability and cathode lifetime (5 to 8 hours). In our operation the arc current was 3.5-5 A and the arc voltage 500-800 V. In

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pulsed operation (pulse length = 2 ms; period = 6 ms) the arc was run at 15 A peak current and 900 V peak voltage. The cathodes were heated by ion bombardment and the source operated in the hot cathode mode. The magnetic field at the anode slit varied from 0.47 Tesla for Ar^{4+} to .61 Tesla for Ar^{6+} . The extraction voltage for the ions was 10 kV and the average drain current drawn by the extraction supply was 20 to 40 mA.

Fig. 2. Schematic section of source. Magnetic field along arc.

The radial emittance is increased by ripple or drift in the extraction voltage. The measured emittance in the radial plane must be the envelope of the true emittance as it is shifted in the emittance diagram plane by virtue of the changing extractor voltage. In order to estimate the importance of this shift, the radial emittance was calculated at extractor voltages of 10 kV and 10.1 kV (a 1% change). To accomplish this, a computer program called BLUSER⁴ was used to trace the paths of charged particles in the radial plane from the puller slit to the edge of the magnetic field. The slit width was taken to be 1.50 mm. From each point along the slit width, it was assumed that the rays emerge at $\pm 9^\circ$ with respect to the central ray. This gives an emittance of $150\pi \times 10^{-6}$ m² rad. Figure 3 shows the calculated emittance at 10 kV and 10.1 kV. It is seen that the emittance diagram is shifted. The envelope is greater than the true emittance by about 25% or $38\pi \times 10^{-6}$ m² rad. A ripple of less than 15 volts peak-peak was measured during the dc measurements. This will then contribute $< 6\pi \times 10^{-6}$ m² rad, $\leq 10\%$ of the smallest value shown in Table 1. During pulsing the droop and dc drift were held to 10 volts by using a capacitor, so the increase in emittance area is $\leq 10\%$. No ripple correction was made to the radial emittance areas. Figure 3 also shows some aberrations in the radial emittance due to magnetic field non-linearities.

Results

Figure 4 shows the dc current of Ar^{4+} to Ar^{6+} beams. The data B and C show an increase in high charge state production relative to results A, the dc data reported in Ref. (2). The improvement from A to B appears to be due mainly to a change from loose set screw to screw-in type cathode mountings. The arc current then optimized at

RADIAL EMITTANCE CALCULATED FOR AN Ar^{7+} BEAM AT 41 cm FROM MAGNET EDGE

Fig. 3. Calculated emittance of source illustrating the effect of extractor voltage drift and aberrations.

5A instead of 3.5A. A larger Faraday cup also increased the beam by a factor of about two for the lower charge states. The results of curve C are taken with the anode beam exit slit 1.0 mm farther into the anode bore than for A and B. The slit dimensions were decreased slightly to stabilize this higher output mode and eliminate arc instability caused by extraction voltage. Pulsed operation with the source geometry of curve C required more gas flow than dc and gave less peak beam than the dc data in curve C. The bowing effect of the arc, described earlier, causes the arc to be about 2 mm off center on the cathodes, but preliminary tests indicate that this does not significantly reduce the beam.

The emittance measurements with scan wires and the fluorescence of an alumina target give the dimensions of the cross section of the beam. The beam cross section at the first emittance plate is approximately an ellipse whose major axis (axial) is 20 to 30 mm and whose minor axis (radial) is 10 to 30 mm. We estimate the effect of finite scan wire diameter on the emittance area to be 5-15%. The emittance areas quoted on Figs. 5, 6 and 7 have not been corrected for this effect. All of the LBL emittance areas in Table 1 (below) were reduced by 10% to correct for the finite wire diameter.

Figure 5 shows a comparison of emittance measurements using a slit plate and a hole plate in each plane. The agreement between slit and hole plates is good, and becomes even better when the small drift length between each pair of slit and hole plates is taken into account. The slit plates were used for the remaining data of this paper, since they give higher intensity than the hole plates. The two oscillograms shown at the bottom of Fig. 5 were used for the slit plate emittance plots. Very similar oscillograms were used for the hole plate plots.

Figure 6 shows several axial emittance measurements for an Ar^{7+} beam from the same source configuration to illustrate the fluctuations in shape which can occur during the lifetime of the source. The only variations in operation were small adjustments of puller position. Plots a and b show shape fluctuations which change the virtual source position, maximum divergence and area. Beam current dropped for case b. The oscillogram shows the large divergence character of the abnormal case b. This can be compared with an oscillogram of a normal case such as the oscillogram shown in Fig. 5 (axial). Case c plot and oscillogram show an emittance with aberrations. The emittance areas and beam currents for all cases are shown at the bottom of the figure.

Fig. 4. Charge state distributions from several source configurations:

- A Anode slit $1 \times 13 \text{ mm}^2$. Cathode diameter: 12.7 mm dc arc current: 3.5 A
 - B Anode slit $1 \times 13 \text{ mm}^2$. Cathode diameter: 19.1 mm dc arc current: 5 A
 - C Anode slit $0.89 \times 11.4 \text{ mm}^2$. Cathode diameter: 19.1 mm, dc arc current: 5 A
- The anode slit was 1 mm further into the arc than in A and B.

Figure 7 shows the radial emittance plot of an Ar^{3+} beam obtained for pulsed operation of the source. The oscillogram represents the superposition of about 10 slightly displaced images (from ~ 10 consecutive scans). This superposition was used to smooth the pulsed data. The emittance is larger than the corresponding dc results. The peak arc current is 15 amps, 3 times the value run for dc measurements, although the peak beam current is less than for the dc cases.

Summary of Results

In Table 1 we summarize the emittance measurements of this report and show measurements of some other groups for reference. The present data, all at 5 A average arc current, show an increase in emittance area from case (B) to (C) (Fig. 4) where the anode slit was moved 1 mm farther into the arc, and the beam intensities increased a factor of 2 or more. The area also increases with peak arc current, which increased from 5 to 15 amps between dc case (C) and the pulsed case (P). The results of Alice show an increase in area with beam (and arc) current. The Grenoble data show a significant increase of radial area with decreasing charge states, not observed in the present data. The comparisons illustrate the need for more experimental data to understand and optimize the emittance from Penning sources.

EMITTANCE MEASUREMENTS FOR $60 \mu\text{A}$ D.C. BEAM CURRENT OF Ar^{3+} AT 10 kV EXTRACTION VOLTAGE

Fig. 5. Measured axial and radial emittances showing agreement of slit plate and hole plate methods.

AXIAL EMITTANCES OF Ar^{3+} BEAMS SHOWING SHAPE FLUCTUATIONS AND ABERRATIONS

Fig. 6. Measured axial emittance showing fluctuations during operation.

Acknowledgments

The authors wish to thank the following 88-Inch Cyclotron support people who made this work possible: the electronic engineering group of P. Frazier, M. Renkas and R. Lam; the mechanical group of D. Morris, D. Flo, F. Hart and D. Striver.

RADIAL EMITTANCE OF A PULSED Ar^{16+} BEAM

Fig. 7. Measured radial emittance for pulsed beam. Area is large for this case.

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Table 1. Comparison of Present Penning Source Emittance Measurements with Some Previous Work

Lab	Ion	Acceleration voltage kV	Beam Current		Energy per nucleon keV/A	$\beta \times 10^{-3}$	Anode Slit dimensions mm X mm	Emittance $\mu \times 10^{-6} \text{ m}^2 \text{ rad}$		Normalized emittance* $\pi \times 10^{-6} \text{ m}^2 \text{ rad}$		Percentage of beam %
			Peak Current μA	Duty Factor				Axial	Radial	Axial	Radial	
80 Inch Cyclotron (LBL) (B)	Ar^{16+}	10	200 - 7.5	1	100 - 2.00	1.46 - 2.06	11 X 1 0.7 mm inside the arc bore	74-117	50-78	0.14 - .22	0.08 - 0.15	> 90
	Ar^{16+}	10	1100	1	1.00	1.46	11.4 X 0.9 1.7 mm inside the arc bore	~ 135	180-270	0.20-0.24	0.26-0.49	> 90
	Ar^{16+}	10	400	1	1.25	1.63						
	Ar^{16+}	10	200	1	1.50	1.79						
	Ar^{16+}	10	240	.33	1.25	1.63	Same as (C)	131-158	~ 350	0.21-0.26	~ 0.59	> 90
Alce (S) (IPN, Orsay)	Kr^{36+}	135	205	.29	12.66	5.23	20 X 1	89		0.47		100
	Kr^{36+}	135	275	.29	12.66	5.23	20 X 1	127	233	0.67	1.16	100 (Axial) 100 (Radial)
	Kr^{36+}	135	340	.29	12.66	5.23	20 X 1	183		0.97		100
Super (6) (ILL, (7) (LBL)	Ne^{20+}	750	300	.15	113.	15.3	19 X 1.3		25.8	0.40		90
	Ar^{16+}	14.3	300	.31	1.07	1.31	4.1 X 1.3	200	310	0.302	0.47	90
Grenoble Cyclotron (R)	Ne^{20+}	10	510	.37	2.86	2.47	5 X 1		484		1.19	
	Ne^{20+}	10	46	.37	1.57	2.76	5 X 1		134		0.37	
	Ne^{20+}	10	160	.37	2.00	2.06	5 X 1		660		1.38	
	Ne^{20+}	10	54	.37	2.50	2.31	5 X 1		127		0.29	

*Normalized emittance = $\beta \times$ measured emittance.