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HEAVY-ION SOURCE FOR THE TEXAS A&M 88-INCH CYCLOTRON

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Abstract

An internal cold-cathode PIG source has been developed at the Texas A&M cyclotron to accelerate high-charge state beams. It produces a variety of beams ranging from lithium to xenon, e.g., Li^{3+}, Be^{3+}, B^{4+}, C^{5+}, N^{6+}, O^{6+}, F^{7+}, Ne^{7+}, S^{8+}, Cl^{8+}, Ar^{9+}, Fe^{8+}, Zn^{8+}, Kr^{7+} and Xe^{8+}, with intensities of practical use (for instance 5.2 eμA for $^{14}N^{5+}$). This source can be operated in dc or pulsed mode. The pulsed mode operation yields output currents for higher charge state beams greater by an order of magnitude or more compared to dc mode, although limits exist. A new gas system, consisting of a piezoelectric valve, has been utilized effectively for operation of the cold-cathode heavy-ion source. A simple ionization chamber was installed in the beam line to enable easy detection of low intensity beams.

Introduction

The Texas A&M 88-inch variable energy cyclotron has the capability to accelerate heavy-ion beams up to an energy of $E = 147\ Q^2/A$ MeV, where Q and A are ion charge and mass in proton units. The development of a heavy-ion source began at the Texas A&M cyclotron in 1970. As a first approach, the regular source for light ions of the type developed by Ehlers[1] was modified to the high-powered filament type source, and a cold-cathode PIG source[2] (installed horizontally) was constructed to obtain higher charge state beams. Using the modified Ehler source, $^{14}N^{3+}$, $^{14}N^{4+}$ and $^{12}C^{4+}$ beams were extracted. With the heavy-ion PIG source an internal beam of $^{14}N^{3+}$ was obtained. In 1971, another cold-cathode PIG source[3] (installed axially) was designed and constructed as a prototype from which low charge state carbon, nitrogen, oxygen, neon and argon beams were extracted. It was later developed to produce $^{16}O^{6+}$, $^{40}Ar^{8+}$ and other beams; however, it was difficult to use in experiments because of cathode-anode shorting due to "stalactites" of evaporated anode material. The high-powered filament type source, on the other hand, provided many heavy-ion beams, but charge states and beam currents of these ions were generally low.

In October, 1977, a new internal cold-cathode PIG source was developed which was a significant improvement of the previous source. At the same time, the power supply for the source was improved to provide high arc power and the capability of pulse mode operation. The combination of the ion source and power supply has successfully produced high-charge state beams. The number of ions and beam intensities increased enormously (see Table I). These beams have increasingly been utilized for experiments, and about 35% of the total machine experiment time at Texas A&M is now devoted to heavy-ion work.

Source Design

A schematic drawing of the source is shown in Figure 1. The anode is water-cooled copper. The plasma chimney has a 6.5 mm inside diameter, with a 0.8 mm tantalum extraction slit of 11 x 2.5 mm. A tantalum cover is installed to form a gas seal. The upper and lower cathodes are made of tantalum with an outside diameter of 7.5 mm and 13 mm, respectively. The cathodes are connected electrically to a water-cooled copper rod which is covered by a tantalum sleeve. Behind the sleeve a small tantalum bar is attached with a spot welder. The projection formed by the bar serves as an electron dump.[4] The use of a perfectly circular sleeve would cause the bottom of the cover to be destroyed by discharge. The bar is effective with hard-to-strike gases and in restriking with eroded cathodes; but for easy-to-strike gases such as nitrogen or argon, the electron dump is not required. The cathode assembly is kept in place and insulated by simple ceramic and boron nitride insulators. These elements are easily assembled in the source shaft; time required to change them is approximately one hour.

Operation causes erosion of the plasma chimney. This gradual enlargement of the chimney results in a simultaneous decrease in high-charge state beam current. Figure 2 shows a PIG source with a replaceable chimney. A changeable plasma chimney means less waste, as only a small part must be changed; it also permits study of performance using various chimney diameters (5 mm through 9 mm with 1 mm increments).

Power Supply and Gas Feed System

The arc power supply for the cold-cathode PIG source is operated by a series regulator composed of two tetrode tubes (4CW 25,000), similar to the type used at the ORIC cyclotron.[5] The output current of the supply is adjusted by varying the control grid voltage of the tetrodes between -5 and -320 volts. The supply can deliver up to 14 A of dc current at 3.5 kV. It can also operate in pulse mode without switching dc to pulse, making it possible to superpose these voltages and currents. The pulse width (on-time) is adjustable from 0.1 to 3 ms. The time between pulses (off-time) is adjustable from 0.2 to 4 ms. The maximum output current of pulse mode condition is limited to 18 A under 75% duty factor.

Gas flow rate is a very important parameter for a cold-cathode PIG source. It is normally less than 2 cc/min but about 5 cc/min is required to strike an arc at 3.5 kV. For acceleration of high-charge state beams, it is necessary to retain a critical flow rate just above the point at which the arc breaks down. A block diagram of the gas feed system is shown in Figure 3. Non-corrosive gases are supplied through the A-system. Corrosive and poisonous gases are supplied through the B-system, which is kept within a vented box for safety. The C-system is used for oxygen and also for mixing a gas with another gas supplied through the A-system. The A-system was improved by adding a low pressure regulator and a piezoelectric valve which replaced a needle valve. The spring-operated regulator keeps gas pressure at 1.03 kg/cm^2. The peizoelectric valve is opened by a pulse signal with a pulse amplitude of 60 V and width of 2.2 ms. Thus, the gas flow rate is determined by the number of pulses per second, as shown in Figure 4. For instance, in the case of argon gas, the potentiometer of the controller is set at 500 to strike an arc; then it is turned down to 22. The new system provides a much more sensitive response for flow control than the needle valve system. Also the

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flow can be completely closed by turning off the switch of the driver circuit. This is useful in a gas mixing test, where it is sometimes important to eliminate a mixed gas.

Source Operation

A typical arc condition is 4 A at 500 V in dc mode. This arc current is limited by rf-ion load. Using pulse mode, the arc is 12 A at 500 V with 1 ms on-time and 2 ms off-time, because beam current output saturates between 12 and 15 A of arc current. A survey of PIG sources by Bennett[6] and a result of the test facility at the Berkeley cyclotron[7] show that high charge-state ions have been obtained under pulsed conditions. The PIG source at Texas A&M has shown similar results (see Figure 5). However, for elements heavier than chlorine, the beam current is comparable with either dc or pulse mode arc conditions. The yields of lower charge state ions are sometimes greater with dc rather than pulsed conditions.

Figure 6 shows the intensity of the $^{16}O^{6+}$ beam as functions of pulse on-time and off-time in which the optimum conditions can be seen. The intensity for this beam appears to be independent of the total arc power. Similar characteristics were also obtained for other beams of the highest charge states, e.g., $^{12}C^{5+}$, $^{14}N^{5+}$, $^{20}Ne^{7+}$, etc. The optimum on-time varies for each of these ions. It was found that ionization potential affects the optimum on-time condition; higher potentials require less time (e.g., about 0.5 ms for $^{12}C^{5+}$ beam). Other charge-state beams do not show such peaking; also the beam current increases proportionately with the total arc power.

In some of the trials, certain combinations of the upper and lower cathode diameters were found to increase cathode lifetime. Long cathode lifetime is achieved when the upper cathode diameter is equal to or no more than 1 mm larger than the size of the plasma chimney. Such a small upper cathode insures erosion to be rather shallow, which in turn makes the arc stable until the depth of the eroded crater of the bottom cathode is equal to or more than the chimney size. The erosion may reach as deep as 9.5 mm with a 6.5 mm chimney. With this technique cathode lifetimes have been as long as 21 hours for a $^{14}N^{4+}$ beam, 14 hours for a $^{20}Ne^{6+}$ beam and 8 hours for an $^{40}Ar^{8+}$ beam.

An attempt to enhance the beam by means of gas mixing[8] has also been made. $^{20}Ne^{6+}$ ions have been accelerated using a neon and nitrogen gas mixture. The mixed-gas beam current increases by a factor of 4 compared with neon gas only. However, the use of a nitrogen gas mixture for a $^{20}Ne^{3+}$ beam results in a decrease of beam current. A $^{16}O^{6+}$ beam increases with the admixture of krypton gas by a factor of 2 with a 7 mm plasma chimney. Using other chimney diameters (6 mm, 8 mm), the optimum condition was achieved without the supporting gas. The low-charge state beam $^{15}N^{+}$ is increased by a factor of 3 with the addition of chorine gas as a mixing gas.

For $^{16}O^{4+}$ and $^{14}N^{5+}$ beams, the beam current output was measured while varying chimney size with the changeable plasma chimney source. The $^{16}O^{4+}$ beam increases almost linearly with chimney sizes. On the other hand, a $^{14}N^{5+}$ beam gradually decreases with increasing chimney size. The ratio of output intensity between 5 mm and 8 mm is about a factor of 10.

After arc breakdown due to cathode erosion, the beam can be recovered on target within 30 to 45 minutes with these sources.

Heavy Ion Acceleration

With the cold-cathode PIG source, beams of elements, $^{6}Li^{2+}$ to $^{136}Xe^{8+}$, have been accelerated in the cyclotron; their energies and extracted currents are shown in Table I. Because a computer code was not available to set the 17 trim coil currents to produce an isochronous field, acceleration of these beams has been achieved by means of the analogue beam method.[4,9] Using this method, the $^{11}B^{4+}$ beam was found from the parameters for the $^{14}N^{5+}$ beam. Accelerations of $^{10}B^{4+}$ and $^{12}C^{5+}$ beams were then achieved. However, the initial beam current at each step was very low, necessitating renewed adjustments of the trim coil currents for each different beam. A highly sensitive current detector was then required for these new high charge-state beams.

A small ionization chamber, originally designed for emittance measurement, is located at about 2 m from the exit port of the machine in the beam line. The chamber has a tantalum slit, 0.5 x 77 mm, with a nickel foil of about 10 mg/cm^2. The inside chamber is filled with air and an electrode is connected to a current integrater circuit through a 100 K ohm resistor and an electric cell with 225 V. Such simple and inexpensive equipment enables detection of a $^{14}N^{6+}$ beam with 2 x 10^4 particles per second; moreover, it is not sensative to ghost beams coming from the cyclotron. This detector is simple to operate compared to other types of detectors commonly used, and it is essential for detection of such heavy-ion beams.

Metal and non-metal ions from solids are produced by a technique developed at the ORIC cyclotron group,[10] that of introducing solid materials into the arc. With this technique, Li, Be, Mg, Ca, Cr, Fe, Cu and Zn beams are accelerated with the use of argon or krypton as a support gas. The attempt to increase the $^{10}B^{4+}$ beam current was made in response to requests for experiments. Beam currents up to 25 enA for $^{10}B^{4+}$ and 200 enA for $^{11}B^{4+}$ had been achieved with BF_3 gas, but are not of sufficient intensity. When pressed boron powder was introduced into the arc only 40 enA of $^{11}B^{4+}$ beam was obtained with argon support gas. However, the $^{11}B^{4+}$ beam current increased by a factor of 2 when BF_3 gas and pressed boron powder are used together. Thus $^{11}B^{4+}$ beam current is increased to 400 enA and $^{10}B^{4+}$ beam current is increased to 55 enA.

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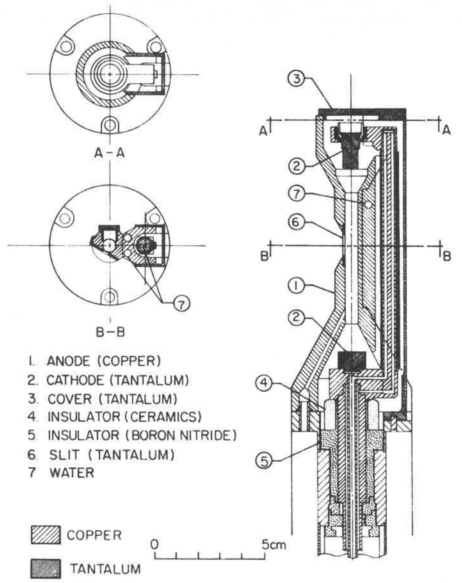

Fig. 1 Cross section views of the internal cold-cathode PIG source for heavy ions.

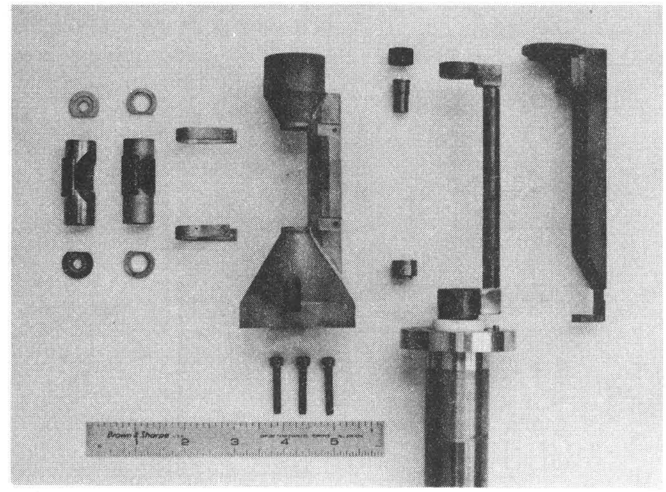

Fig. 2 Disassembled components of the cold-cathode PIG source with the replaceable chimney, plasma chimney, anode, cathode holder and Ta cover.

Table I. Texas A&M Cyclotron Extracted Beams

Ion	Energy (MeV)	External Beam Current (eμA)[a]
$^{6}Li^{2+}$	90	0.04
$^{6}Li^{3+}$	153	1.3 enA
$^{7}Li^{2+}$	82	5
$^{7}Li^{3+}$	182	3 enA
$^{9}Be^{2+}$	63	2
$^{9}Be^{3+}$	148	0.01
$^{10}B^{2+}$	60	5
$^{10}B^{3+}$	131	5
$^{10}B^{4+}$	220	0.055
$^{11}B^{2+}$	35	10
$^{11}B^{3+}$	120	12
$^{11}B^{4+}$	200	0.4
$^{12}C^{+}$	12.5	3
$^{12}C^{2+}$	34	0.8
$^{12}C^{3+}$	110	3
$^{12}C^{4+}$	197	3.5
$^{12}C^{5+}$	295	0.025
$^{13}C^{+}$	11.5	0.035
$^{13}C^{2+}$	40	0.016
$^{13}C^{3+}$	102	0.05
$^{13}C^{4+}$	180	2 [b]
$^{14}N^{+}$	10.5	3
$^{14}N^{2+}$	37	10
$^{14}N^{3+}$	100	15
$^{14}N^{4+}$	165	20
$^{14}N^{5+}$	275	5.2
$^{14}N^{6+}$	364	150 epA
$^{15}N^{+}$	8.7	0.02
$^{15}N^{2+}$	35	0.2
$^{15}N^{3+}$	90	0.12
$^{15}N^{4+}$	107	0.012

Ion	Energy (MeV)	External Beam Current (eμA)[a]
$^{16}O^{+}$	8	0.15
$^{16}O^{2+}$	32	10
$^{16}O^{3+}$	55	7
$^{16}O^{4+}$	144	15
$^{16}O^{5+}$	230	2.1
$^{16}O^{6+}$	310	0.3
$^{17}O^{2+}$	30	0.015
$^{18}O^{2+}$	28	0.05
$^{18}O^{4+}$	125	0.11
$^{18}O^{5+}$	191	3 enA
$^{19}F^{4+}$	129	2.5
$^{19}F^{5+}$	189	5
$^{19}F^{6+}$	223	0.1
$^{19}F^{7+}$	354	4 enA
$^{20}Ne^{2+}$	29	2
$^{20}Ne^{3+}$	60	4
$^{20}Ne^{4+}$	120	2.8
$^{20}Ne^{6+}$	264	0.5
$^{20}Ne^{7+}$	337	3 enA
$^{22}Ne^{2+}$	27	0.6
$^{22}Ne^{3+}$	54	0.7
$^{22}Ne^{4+}$	70	2
$^{22}Ne^{5+}$	140	0.3
$^{24}Mg^{4+}$	67	0.01
$^{24}Mg^{5+}$	148	0.1
$^{24}Mg^{6+}$	216	0.3 enA
$^{28}Si^{5+}$	86	0.03
$^{28}Si^{6+}$	180	0.015
$^{29}Si^{6+}$	174	2 enA

Ion	Energy (MeV)	External Beam Current (eμA)[a]
$^{32}S^{5+}$	105	3
$^{32}S^{6+}$	110	0.7
$^{32}S^{7+}$	214	0.15
$^{32}S^{8+}$	288	0.015
$^{35}Cl^{5+}$	94	3
$^{35}Cl^{6+}$	100	2.5
$^{35}Cl^{7+}$	210	1.7
$^{35}Cl^{8+}$	269	0.1
$^{37}Cl^{5+}$	89	1
$^{37}Cl^{6+}$	95	0.3
$^{36}Ar^{2+}$	17	1 enA
$^{38}Ar^{2+}$	16	60 epA
$^{38}Ar^{3+}$	33.5	0.01
$^{40}Ar^{2+}$	15	0.5
$^{40}Ar^{3+}$	32	8
$^{40}Ar^{4+}$	58	3.5
$^{40}Ar^{5+}$	83	7
$^{40}Ar^{6+}$	120	1.2
$^{40}Ar^{7+}$	164	0.35
$^{40}Ar^{8+}$	240	0.6
$^{40}Ar^{9+}$	286	~0.5 epA
$^{40}Ca^{5+}$	81	1
$^{40}Ca^{6+}$	121	0.1
$^{40}Ca^{7+}$	120	5 enA
$^{40}Ca^{8+}$	240	0.15
$^{52}Cr^{5+}$	70	0.3 enA
$^{53}Cr^{5+}$	68	50 epA
$^{55}Mn^{5+}$	68	0.5 enA

Ion	Energy (MeV)	External Beam Current (eμA)[a]
$^{54}Fe^{6+}$	84	0.075
$^{54}Fe^{7+}$	116	0.3 enA
$^{56}Fe^{5+}$	67	0.017
$^{56}Fe^{6+}$	81	0.035
$^{56}Fe^{8+}$	148	0.02
$^{63}Cu^{3+}$	22	5 enA
$^{63}Cu^{4+}$	33	3 enA
$^{63}Cu^{5+}$	65	0.03
$^{63}Cu^{6+}$	82	0.017
$^{63}Cu^{7+}$	112	0.01
$^{63}Cu^{8+}$	130	4.5 enA
$^{65}Cu^{5+}$	55	0.01
$^{65}Cu^{6+}$	80	6 enA
$^{65}Cu^{7+}$	109	2 enA
$^{65}Cu^{8+}$	126	1.7 enA
$^{64}Zn^{3+}$	21.5	0.6 enA
$^{64}Zn^{4+}$	32	2 enA
$^{64}Zn^{5+}$	55.5	4 enA
$^{64}Zn^{6+}$	81.5	0.01
$^{64}Zn^{7+}$	111	1.5 enA
$^{66}Zn^{5+}$	54	1 enA
$^{66}Zn^{6+}$	79	4 enA
$^{66}Zn^{7+}$	107	0.4 enA
$^{80}Kr^{7+}$	83	0.7 enA
$^{82}Kr^{7+}$	85	6 enA
$^{83}Kr^{7+}$	86	6 enA
$^{84}Kr^{7+}$	84	0.025
$^{86}Kr^{7+}$	89	0.01
$^{129}Xe^{8+}$	64	0.07
$^{131}Xe^{8+}$	63	0.025
$^{132}Xe^{8+}$	62.5	0.025
$^{134}Xe^{8+}$	61.5	0.01
$^{136}Xe^{8+}$	60	6 enA

[a] Electrical microamperes except as noted.
[b] Enriched isotopic abundance source feed.

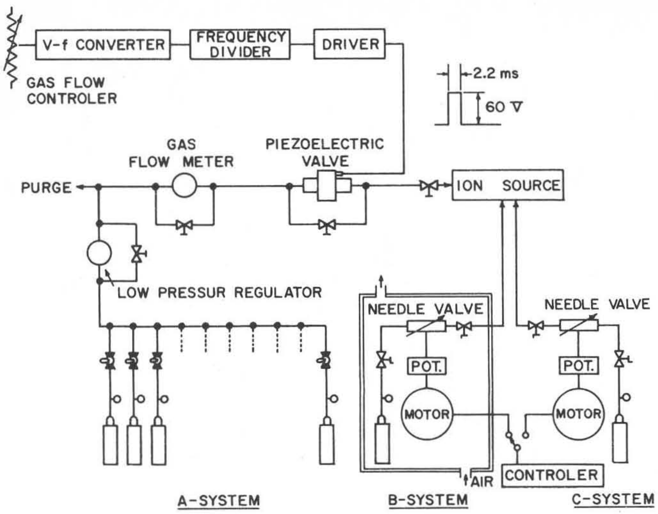

Fig. 3 Block diagram of the Texas A&M cyclotron gas handling system.

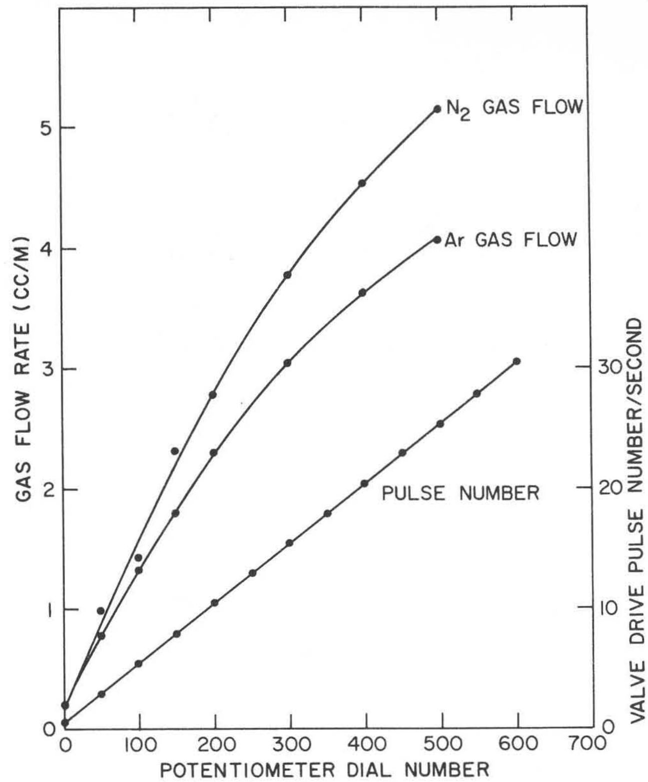

Fig. 4 Gas flow vs drive pulse rate of the piezo-electric valve used in the present ion source.

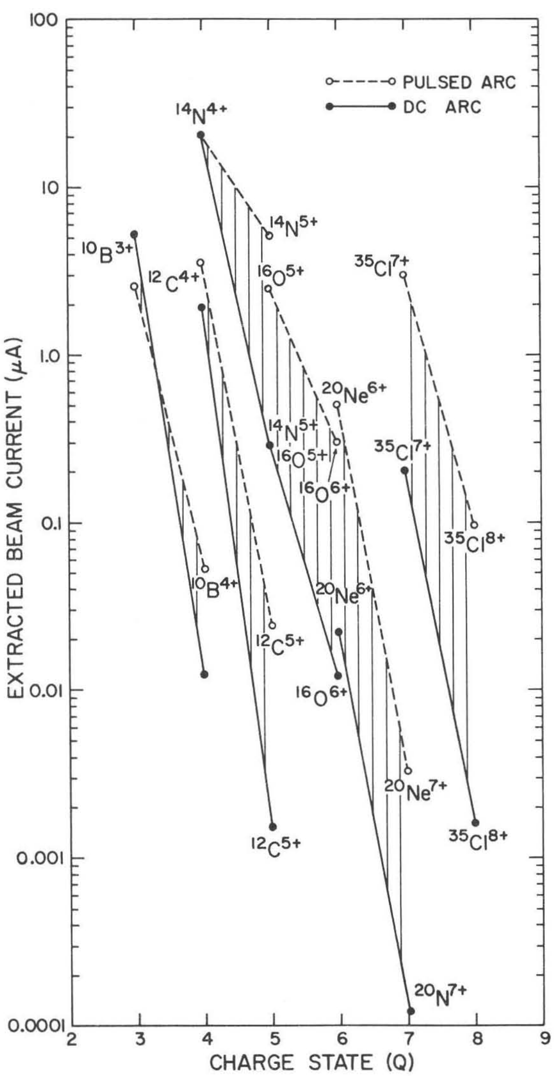

Fig. 5 Comparisons of the beam intensities of representative ions in pulse mode and dc mode.

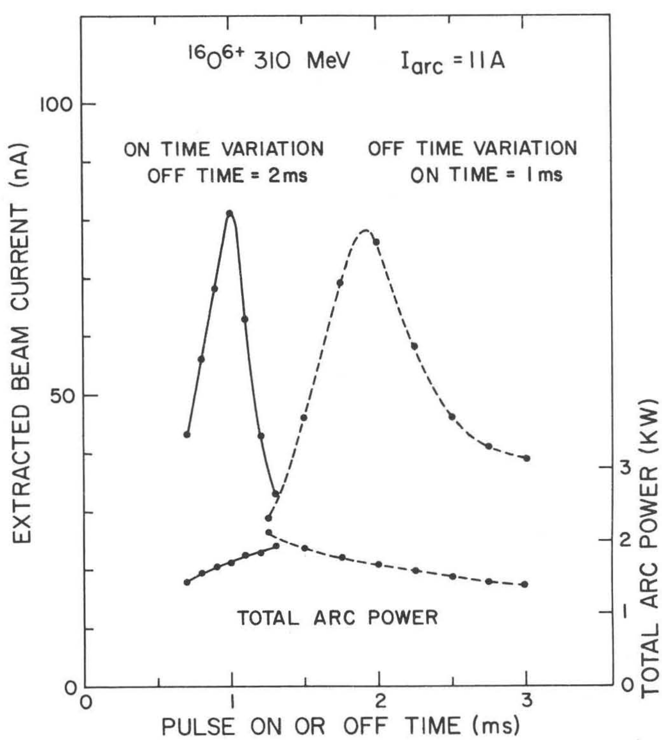

Fig. 6 Variations of the intensity of $^{16}O^{6+}$ beam as function of on-time and off-time in the pulse mode.

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