ACCELERATION OF HEAVY IONS AT THE TOHOKU UNIVERSITY CYCLOTRON

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ABSTRACT

A small internal heavy ion source of the cold cathode type has been in operation at the Tohoku University compact cyclotron. Beams of carbon, nitrogen, oxigen and neon have been accelerated and used in experiments in the energy range 3∿6 MeV/nucleon. External beam intensities are 0.5∿5 eμA for most of carbon, nitrogen, and oxigen beams. About 40∿50 percent of extracted-beam intensities has been transported to a target position by means of the achromatic beam transport.

INTRODUCTION

In heavy ions acceleration with a compact cyclotron the yield of highly-charged ions from an ion source is very important since the energy of accelerated ions increases quadratically with the charge. As an internal heavy ion source, in general, the cold cathode PIG source is still one of the practical sources for producing highly charged ions. The ion source of this type is suitable for the compact cyclotron because of its simple structure. At the Tohoku University cyclotron of K = 50 MeV, an internal cold cathode PIG heavy ion source was developed for heavy ions acceleration. In achieving heavy ion acceleration with the compact cyclotron we encounter several problems to solve. These are 1) the design of an ion source which can easily replace the ordinary hot cathode ion source of axial insertion for p, d, h and α, 2) the production of highly charged ions in the ion source under a condition of low arc power application due to a limited capability of water cooling, 3) effective ions extraction from the exit slit of the ion source for a fixed beam-extraction puller system at the central region of the cyclotron, 4) heavy ions acceleration with different harmonics numbers (H = 2, 3 and 4) of the high-frequency RF acceleration, and 5) the lifetime of the cathodes which are smaller in comparison with those of an ordinary-size heavy ion source. In particular, the production of highly charged ions in the ion source depends primarily on the operation of electrical arc power applied to the ion source and the accuracy and stability of the gas-feed system. For heavy ions acceleration with a compact cyclotron little experience has been obtained with respect to these problems. Recently, however, Antaya et al.[1] have developed a small PIG heavy ion source of axial insertion for the Michigan State University K = 500 MeV superconductive cyclotron. The body diameter of 35 mm of their ion source is just the same as that of our heavy ion source.

In this report general characteristics of our heavy-ion PIG source will be described with emphasis on those features mentioned above.

ION SOURCE DESIGN

In designing the present ion source we generally followed the previous achievements of cold cathode PIG sources. However, we needed to take special considerations for the compact cyclotron, namely; 1) the maximum body size of the ion source, 2) the shape of the exit slit facing the puller, and 3) the counter-measures against the material sputtered from the cathodes. The maximum body size was limited to be 35 mm due to a rather complex geometrical arrangement of the central electrodes of the cyclotron consisting of two dee's, dummy dee's, a puller and pillars. A cross section view of the ion source is shown in Fig. 1. The anode block (chimney) is made of copper and is cooled by water. The water pipe is made of stainless steel and is covered by a piece of thin tantalum sleeve to protect itself from sputtering by discharge. This pipe supports the upper cathode holder and provides an electrical connection between the both cathodes. As counter-measure against the sputtered material, an insulation fence made of boron nitride is fitted between the bottom cathode and the inside wall of the anode block. This fence prevents electric discharge between the cathode and the anode at the bottom and also prevents the dust of the sputtered material from forming an electrical short circuit.

The arc bore diameters of the anode block were designed to be 6, 7 and 8 mm. By inserting a sleeve of different thickness into the arc bore, the effective bore diameter can be varied without any difficulty. In most experiments, the anode block of 7-mm bore diameter has been used by inserting a 6-mm diameter sleeve. This idea turned out quite convenient for removing together with the sleeve the sputtered material depositing inside the anode. The exit slit is made of tantalum, and fitted to the anode along the grooves shown in Fig. 1 and then fixed with two tantalum spacers. This idea is also very useful for taking out the exit slit on which the sputtered material deposits firmly. We did not adopt the electron dump behind the ion source nor the bent water pipe against discharge of the E × B mode, but instead used a thin tantalum cover pipe to protect the straight water pipe.

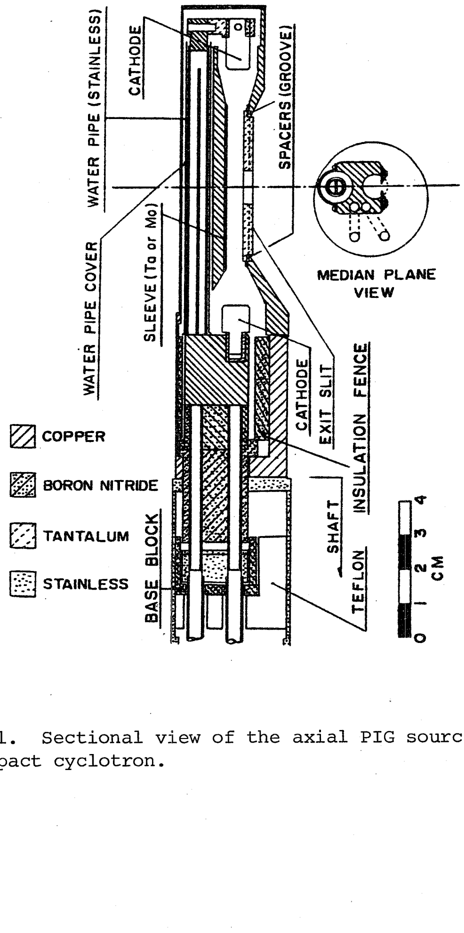


Fig. 1. Sectional view of the axial PIG source for a compact cyclotron.

ION-BEAM TRAJECTORIES FROM THE EXIT SLIT TO THE PULLER

For designing the exit slit of the heavy ion source the gradient of the slit surface and the thickness of slit aperture edge are important parameters. On the other hand, the pertinent characteristics of cyclotron beam-time structure, the radial and axial emittance, the particle intensity and energy spread are to a large degree determined by acceleration conditions in the central region. For heavy ion extraction from the ion source the space charge force should be more considerable, but this effect is not considered in the present calculations.

The computer program "CALTRA"[2] is developed in which the accelerating gap is covered by an electric field depending sinusoidally on time and the magnetic field is uniformed. Beam trajectories were calculated for a uniform magnetic field of $H = 13$ kG, the amplitude of RF electric field of 35.46 kV with a frequency of 23.9889 MHz. These parameters correspond to the acceleration of $^{14}N^{5+}$ at $E = 84$ MeV. The dependence of beam trajectories on the slit surface gradient θ and the slit aperture edge thickness t has been studied. Some typical examples of the calculated beam trajectories are shown in Fig. 2, where Figs. a), b) and c) show the trajectories for the case of $\theta = 0°$, 15.26° and 28.61° as a function of the thickness of the exit slit aperture edge $t = 0$, 0.25 and 0.5 mm. It is suggested that the thickness of the exit slit aperture edge, t, should be designed as small as possible, if a parallel-beam situation is required as a good initial condition for the optimum beam acceleration. In other words, a strong beam divergence is caused by the thickness of the slit aperture edge rather than the gradient of the slit surface. The beam trajectories of the ions emitted from the plasma surface in the ion source were also calculated as a function of the start time relative to the phase of the RF field. A duty factor that ions extracted from a plasma surface are possible to pass through the puller is calculated to be about 30 %, and 70 % of these ions are calculated to have nearly equal trajectories. On the basis of these results, the parameters of the exit slit were determined.

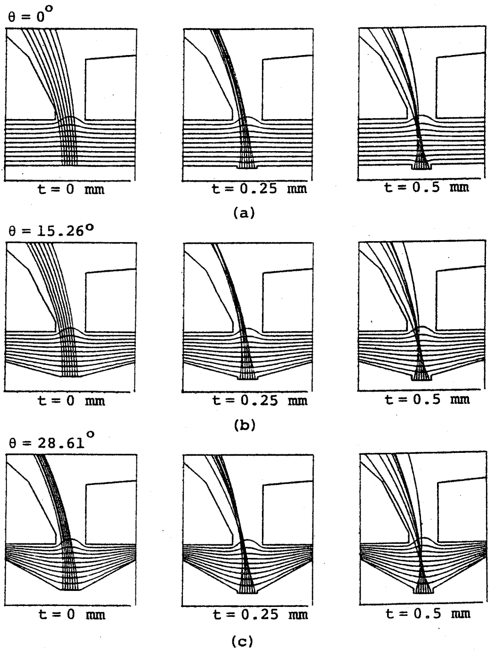


Fig. 2. Equipotential lines and $^{15}N^{5+}$ trajectory in the case of two-dimensional ion source structure. The parameter θ of the exit slit is the gradient of the slit surface; a) $\theta = 0°$, b) $\theta = 15.26°$, and c) $\theta = 28.61°$, and t denotes the thickness of the exit slit aperture edge.

ARC POWER SUPPLY AND GAS FEEDING SYSTEM

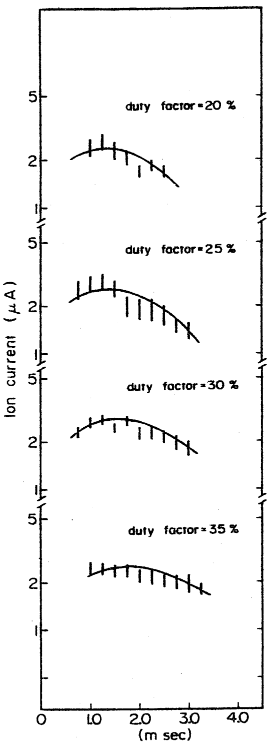
As mentioned above, for the production of highly charged ions for a small ion source such as the present one, the use of arc pulsing is necessiated because the permissible average arc power is limited.

The arc power supply can be operated in either DC mode or pulsing mode, and it can provide up to 6 A of average arc current and up to 5 kV of output voltage; a peak current of e.g. 20 A can be supplied in a pulsing mode of 30 % duty factor. The power supply generates current-regurated square-wave pulses having a width of 0.5 — 4.0 msec with a duty factor of 0 — 100 %. The effect of arc pulsing on the production rate of multiply charged ions will be described in a later section.

On the other hand the production of highly charged ions in the arc plasma and the lifetime of the cathodes are quite sensitive to the gas flow rate and the gas feed stability. For small-sized ion sources these are especially important and therefore a good gas control system of high stability at low gas flow rate is required. Two kinds of gases (main- and support-gases) can be fed independently to the ion source. Each gas system consists of a piezoresistive pressure sensor and two piezoelectric values for the primary gas pressure regulation and the gas flow rate control. The stability of the pre-pressure regulation is about 0.4 % in the pressure range from 100 to 500 torr. The absolute gas flow rate was measured and calibrated for nitrogen gas by the pressure-buildup method using another vacuum system. The gas flow rate can be controlled down to the minimum rate of 0.02 cc/min at a stability of 1%. The details of the gas control system have been described elsewhere.[3]

ION SOURCE OPERATION AND HEAVY ION ACCELERATION

The present heavy ion source was tested with N_2, CO_2, CH_4, O_2, Ne and Ar gases and is used in nuclear physics experiments.[4] Argon gas was used as a support gas for CO_2, CH_4 and O_2. The ions extracted from the source were accelerated in the Tohoku University cyclotron. The maximum beam energy of ions at the extraction radius of 680 mm is given by $E_{max} = 50\ q^2/A$ (in MeV), where q and A are the charge state and the mass number of the ion, respectively. Due to the limited arc power consumption the ion source was operated at an average arc power of about 0.4 kW. This necessitated the use of arc pulsing for obtaining highly charged ions because the pulsed source can be operated at a higher instantaneous power than the continuously operated source. The pulse width was varied from 0.75 to 4.0 msec keeping the same duty factor. The variation of the N^{5+} ion current with the pulse width is plotted for duty factors of 20, 25, 30 and 35 % in Fig. 3. The length of the vertical bars denotes an error estimated from the fluctuation of the N^{5+} ion beam intensity that was measured at a fixed duty factor. Fig. 3 shows that the ion current has a maximum around 1.5 ms pulse width. In order to explain qualitatively such a dependence of ion production on the pulse width, the time dependence of the number of nitrogen ions in the plasma column of a pulsed discharge was calculated[4], using an ionization model of stepwise mechanism in an arc plasma. The parameters used in the calculation are correlated with gas pressure, arc voltage, and magnetic field. The electron temperature is also one of the parameters depending on gas pressure, arc voltage and arc current. The parameters adjusted for fitting the calculated curves to the data are the electron density $N_e = 5 \times 10^{12}\ \text{cm}^{-3}$ and the electron temperature $T_e = 20$ eV. These curves are generally in agreement with the experimental data as seen from Fig. 3. In Fig. 4 values of the pulse width corresponding to the maxima of the N^{5+} ion current are plotted versus the pulse duty factor. The result of the calculation is denoted by a solid curve, which increases smoothly with the duty factor. Although the calculated curve mostly reproduces the experimental data relatively, there seems to be a maximum in the experimental data at a duty factor of about 30 %. It is suggested that the arc plasma may be



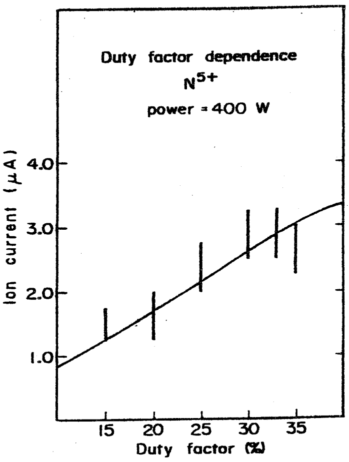


Fig. 4. Pulse widths corresponding to the maximum values of N^{5+} ion current for different duty factors in comparison with the result of calculation.

Fig. 3. Comparison between the calculated curves and the experimental data of the pulse width dependence of the ion current. The calculated curves are qualiatively in agreement with the data.

disturbed by an application of the arc power exceeding the ability of the ion source.

The beam intensity of various ions of mass number up to 20 was measured with the integral beam probe at R = 650 mm for the 6 mm arc bore; the ions of $^{12}C^{4+,5+}$, $^{14}N^{4+,5+,6+}$ and $^{20}Ne^{5+}$ were accelerated. The ion source position relative to the puller electrode was set to be similar to that of the ordinary ion source for light ions. The necessary cyclotron parameters for heavy ion acceleration were numerically calculated. The observed beam intensities are listed together with beam energies in Table 1.

LIFETIME OF THE CATHODES

The lifetime is one of the most important subjects for an internal heavy ion source. The lifetime of a cold cathode heavy ions source is usually limited by the cathode wearing and cratering, because a deep cratering inhibits striking the arc discharge. In the present ion source tantalum was used as cathode material, because the sputtering rate of tantalum is nearly constant for different gases. No electrical shortening due to the building-up material across the insulators was experienced during the ion source operation. After 6 to 8 hours of operation the arc discharge becomes unstable and the beam current decreases. In the acceleration of the lower charge state ions such as $^{14}N^{4+}$, however, the lifetime of the ion source could be extended to 10 – 13 hours.

Recently, it has been reported by Antaya et al.[1] that the cathode lifetime of a cold cathode heavy ion source has been increased to $\sim$25 hrs by the use of hafnium cathodes when accelerating a carbon beam in the Michigan State University cyclotron. According to their experimental results, hafnium cathodes would melt at a lower arc power in comparison with tantalum and, as a result, the beam intensity was diminished. The cathode lifetime, however, was increased. We have measured the lifetime of cathodes made of hafnium and tantalum-carbide with the ion source test bench operated by a DC arc power. Argon gas was supplied and an arc power applied to the ion source was 0.35 kW with the arc current of 2 A and the voltage of 150 V. The lifetimes of the hafnium and the tantalum-carbide cathodes are 2 times and 4 times longer than that of the tantalum cathodes, respectively. For the hafnium cathodes the arc plasma impedance was one half of that of the tantalum cathodes. This fact can be interpreted in terms of the low work function of hafnium resulting in an easier emission of the thermal electrons as well as the secondary electrons from the cathodes. Furthermore, the sputtering rate of hafnium metal in ions collision is 1/3 $\sim$ 1/5 of that of tantalum.[5] We continue the study of the cathode material.

Table 1. Current intensity of accelerated ions. The current was measured at the radius R = 650 mm, where the extraction radius is 680 mm. The beam extraction efficiency was 40 – 60 %.

Gas	Ions	Energies (MeV)	Harmonics	Current (e A)
CO_2 + Ar	$^{12}C^{4+}$	65	4th	2.0
CH_4 + Ar	$^{12}C^{4+}$	65	4th	0.6
CO_2 + Ar	$^{12}C^{5+}$	105	3rd	0.03
N_2	$^{14}N^{4+}$	54	4th	5.0
N_2	$^{14}N^{5+}$	84	3rd	2.5
N_2	$^{14}N^{6+}$	120	3rd	0.17
CO_2 + Ar	$^{16}O^{5+}$	75	4th	1.0
CO_2 + Ar	$^{16}O^{6+}$	115	3rd	0.1
Ne + Ar	$^{26}Ne^{5+}$	50	4th	5.5[a)]

a) The ion current in this case may contain $^{12}C^{3+}$ ions.

SUMMARY

The most critical problem in designing a small PIG heavy ion source for a compact cyclotron is a special restriction in the central region. This limits the body size of the ion source and hence the arc power consumption. For this reason we necessarily accepted a small space in the anode chimney and narrow cooling lines.

Another feature revealed in the present work is that the shape of the exit slit is fairly sensitive for an efficient ions extraction from the ion source. When we used another shape of the slit, we could not obtain sufficient intensity of heavy ion beams.

The lifetime of the cathodes is another important problem, particularly, for the small ion source such as the present one whose cathodes are correspondingly small. In the present ion source the consumption of the cathodes is more rapid in comparison with larger ion sources. However, the present ion source having a moderate lifetime is actually being used in heavy ion experiments. For extending the cathode lifetime a study of cathode material is in progress.

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