HEAVY ION CYCLOTRONS DEVELOPMENT AT JINR

R.Ts.Oganessian
Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research
141980 Dubna, USSR

Introduction

For the last ten years heavy ion beams found an increasingly wide use in large-scale research along various lines of physics and technology. This fact has led to a need for a new generation of high-intensity accelerator facilities which be capable of accelerating the nuclei of practically all elements of the Mendeleev Table over wide ranges of masses and energies.

After considering various possibilities of producing intense heavy ion beams with energies of up to 10 MeV/amu and even 100 MeV/amu now we have given preference to the cyclotron method.

During more than 20 years this trend has been pursued at our Institute, covering a wide range of studies at the existing accelerators, the development of high-charge state ion sources, the formation of magnetic fields, tests of different systems for beam extraction, etc. At the Laboratory of Nuclear Reactions three heavy-ion cyclotrons are presently in operation which produce beams for physics experiments (the U200, the U300 and the U400) and one cyclotron specially constructed for applied purposes and put into operation in 1985.

The cyclotron U400

Autonomous mode of operation

The U400 cyclotron is designed for producing ions with masses ranging between 4 and 250 and energies from 35 to 1.8 MeV/amu, respectively [1]. The isochronous distribution of the magnetic field in the magnet gap with a pole diameter of 400 cm and with power consumption of 0.85 MW is obtained by means of iron shims and trimming coils at a level of 19-21.4 kG. Two dees with an angle of 42° and 100 kV r.f. potential provide the acceleration on the 1st, 2nd, 3rd and 4th harmonics of all particles characterized by the ratio $4 \leqslant A/Z \leqslant 20$. Ion beam extraction is performed by stripping on a carbon foil from different radii of acceleration[2]. The extraction efficiency is determined by the ion charge state distribution and varies between 20% and 80% depending on the atomic number and energy of the particles accelerated. The extracted beam is transported in any of the 12 transfer lines located at different levels with respect to the median plane. A vertical beam is intended for irradiation of a liquid target. The beam emittance is equal to 80 and 40 mm.mrad in vertical and radial directions, respectively. The energy spread of particles without monochromatization is equal to 1%. The maximum beam power is equal to about 3 kW. The main parameters of the presently accelerated beams are given in Table 1.

Table 1.

Ion	Energy (MeV/amu)	Intensity (pps)
$^{13}C^{2+}$	14,0	10^{13}
$^{14,15}N^{2+}$	12,6-8,5	$2\cdot10^{14}$
$^{16}O^{2+}$	8,0	$3\cdot10^{14}$
$^{20,22}Ne^{2,3+}$	3,9-13,5	$2\cdot10^{14}-10^{14}$
$^{24,26}Mg^{3+}$	7,9-6,7	$10^{14}-5\cdot10^{13}$
$^{40}Ar^{4,5+}$	5,5-8	$10^{14}-9\cdot10^{13}$
$^{42,44,48}Ca^{4,5+}$	5,3-6,7	$5\cdot10^{12}-2\cdot10^{13}$
$^{48-50}Ti^{5+}$	5,0-5,5	$4\cdot10^{13}-10^{13}$
$^{51}V^{5+}$	5,5	$5\cdot10^{13}$
$^{52-54}Cr^{5,6+}$	5,3-6,8	$10^{13}-5\cdot10^{12}$
$^{55}Mn^{6+}$	5,5	$6\cdot10^{13}$
$^{56,58}Fe^{6+}$	5,3	$2\cdot10^{13}$
$^{58,64}Ni^{6+}$	5,3	10^{13}
$^{59}Co^{5,7+}$	3,6-7	$2\cdot10^{13}-10^{12}$
$^{64,70}Zn^{7,8+}$	5,2-6,2	$10^{12}-5\cdot10^{11}$
$^{76}Ge^{8+}$	5,3	$2\cdot10^{12}$
$^{84}Kr^{9+}$	6,0	$5\cdot10^{11}$
$^{90}Zr^{11+}$	9,0	10^{10}

Injector mode

In this mode of operation the cyclotron accelerates ions ranging from ^{16}O to ^{238}U with A/Z=16-20. We carried out bench tests of an arc ion source for generating high-charge (A/Z=10) and relatively low-charge (A/Z=20) state ions. The results presented in fig.1 indicate that a beam of the heaviest particles with an energy of 1.8 MeV/amu and with an intensity of more than 10^{13} pps is producible on the fourth harmonic. The turn separation on the final radius will be equal to 10 mm thus permitting the efficient beam extraction with the aid of an electrostatic deflector without ion charge changes prior to ion introduction into the second stage of acceleration.

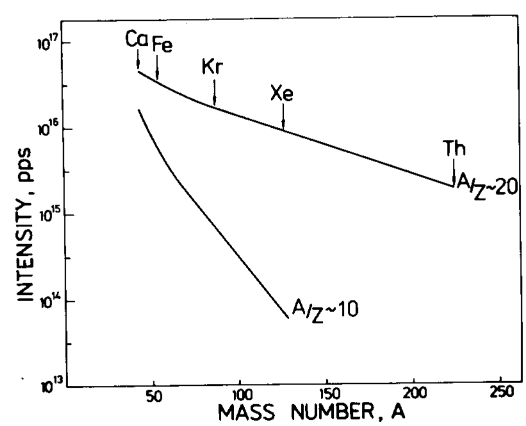

Fig. 1. Possibilities of the arc-type ion source of the U400 cyclotron.

Heavy ion cyclotron facility

The heavy ion cyclotron facility was constructed using as a basis the beam parameters of the U400 as an injector. In this facility another cyclotron with a 400 cm pole diameter (the U400M) serves as a post-accelerator designed on the basis of the existing accelerator U300 (ref. [3]). In 1971 this system was first tested in acceleration of Ge, Kr, and Xe ions at the U300 - U200 tandem [4]. The ions accelerated by the injector cyclotron U400 are extracted by an electrostatic deflector and transported via an 120-meter beam line into the cyclotron U400M. After a charge increase in passing through a stripping foil placed in the central part of the U400M cyclotron the ions are injected onto an equilibrium orbit and accelerated to the final energy. A schematic view of the cyclotron facility is shown in fig.2. The four dees located in valleys with an r.f. potential amplitude of 150-200 kV (a frequency range of 11.5-25 MHz) produce an acceleration rate providing orbit separation on the final radius of 4-7 mm. A system of electrostatic deflectors and magnetic channels will be used for beam extraction. The ion beam parameters expected at the U400M exit are presented in Table 2.

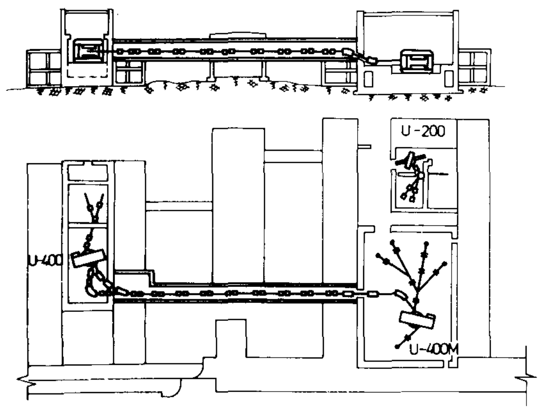

Fig. 2. Schematic view of the U400 + U400M heavy ion cyclotron facility.

Table 2.

	The U400	The U400M
Range of ion masses	16-238	16-238
Ion energy, MeV/amu	2.5-1.7	120-20
Ratio A/Z	16-20	2-5
Intensity, pps	10^{14}-10^{13}	5x10^{12}-10^{11}

A 1:3 model accelerator was designed to produce the magnetic fields required for the stable and isochronous acceleration of ions to energies of 120-20 MeV/amu. By using iron shims in magnetic fields of 16-19.5 kG distributions were obtained which differed from isochronous ones by ±100 G (in this range the magnetic field flutter lies between 0.16 and 0.09 at a sector spiral angle of 40°). The further field correction is performed by trimming coils placed on the sectors surface. An important phase of work at the construction of the cyclotron facility is a study of the modes of the ion acceleration and extraction of ion beams from the U400M. In our view, this problem can be solved most optimally if the U400M cyclotron is operated in an autonomous mode in combination with an arc-discharge ion source. This type of ion source will permit the production of accelerated ions ranging from $^{4}He^{2+}$ to $^{40}Ar^{8+}$ (A/Z=2-5) with energies of (120-20) MeV/amu and with intensities of 10^{13}-10^{11} pps.

Development of ion sources

As is known, the parameters of heavy ion beams produced by cyclotrons are determined to a considerable extent by the possibilities of ion sources. Therefore, during the last several years we at the Laboratory of Nuclear Reactions carry out work aimed at improving the existing arc ion sources and at creating new types of ion sources. A series of studies performed at the U300 cyclotron have made experiments with the accelerated ^{14}C a hermetically sealed ion source incorporating a special system for gas inlet into the discharge chamber [5] has been designed. The consumption of $^{14}CO_2$ in the ion source is equal to 0.03 cm^3/min. The ion beams of $^{14}C^{2+}$ and $^{14}C^{3+}$ have been accelerated to energies of 5.1 MeV/amu and 11.5 MeV/amu, respectively, and with an energy resolution of 0.8%. The intensity of the external beams is equal to 3 uA and 1 uA, respectively. Studies of the behaviour of laser plasma in the transverse magnetic field have been carried out and a variant of a laser ion source has been developed, which produced the ions of $^{12}C^{3+}$, $^{24}Mg^{8+}$, $^{28}Si^{7+}$, $^{40}Ca^{10+}$, $^{48}Ti^{12+}$, and $^{52}Cr^{13+}$ for acceleration in the U200 cyclotron [6] (see fig. 3). In the experiments a commercial CO_2 laser served as a radiation source. It allowed one to obtain a laser radiation power density of 1.5 x 10^9 W/cm^2 on the target surface with a pulse repetition rate of about 1 Hz. The internal beam intensity ranged between 10^7 and 10^{10} ppp for an accelerated ion pulse duration of 1-10 us depending on the ion charge state. These results have been obtained with a laser source having a normal directed at an angle of about 45° to the magnetic field lines. The $^{12}C^{3+}$ ions were produced and accelerated using another variant of a laser source in which the direction of the plasma jet is parallel to the magnetic lines of force. In this case there was a possibility of using a low-energy laser with a frequency rate of up to 100 Hz. The average intensity of the accelerated beam was 20 nA at a frequency rate of 25 Hz and the pulse duration was equal to 2 us. At present work is underway to develop a compact source of multiply-charged ions in which plasma heating would be performed at the frequency of the cyclotron electron resonance [7]. As the new types of sources cannot be placed inside the cyclotron vacuum chamber a system for external beam injection should be constructed [8,9]. It has been decided to make such a system for operation at the U200 cyclotron. On the basis of calculations and taking into accout the experimentally measured distribution of the magnetic field in the vertical channel we have chosen the system shown schematically in fig. 4. The results obtained at the U200 cyclotron form a basis for designing similar systems for use with other cyclotrons of the Laboratory of Nuclear Reactions.

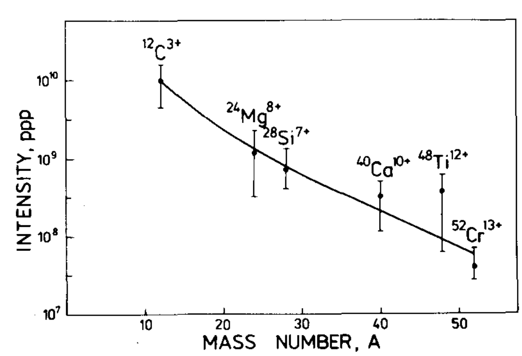

Fig. 3. The beam intensity per laser pulse as a function of the atomic number of target material.

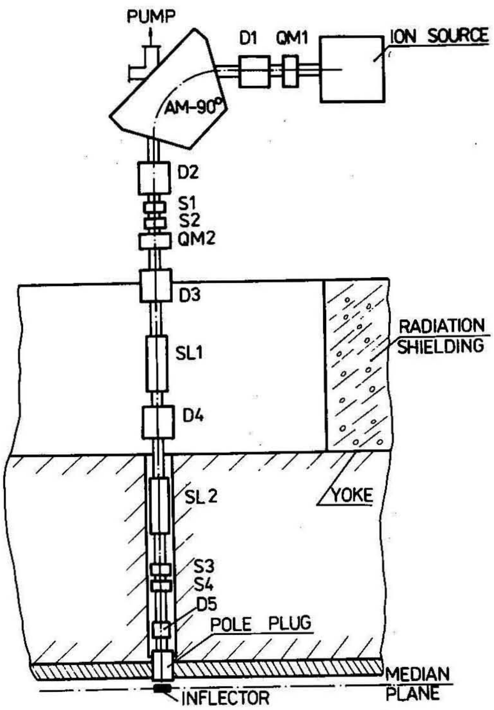

Fig. 4. Scheme of external beam injection in the U200 cyclotron. QM - quadrupole magnets, D - diagnostics, AM - analysing magnet, S - steerings, SL -solenoid lenses.

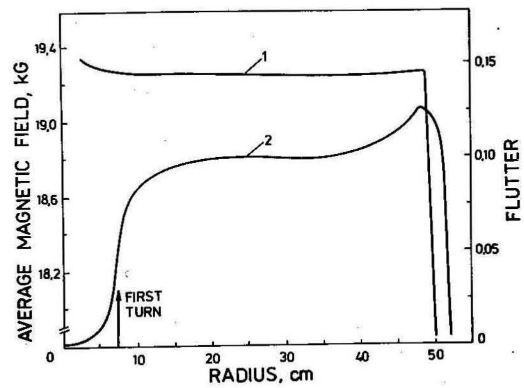

Fig. 5. Radial distribution of average magnetic field and flutter in the cyclotron CI-100.

The cyclotron for applied research

The unique properties of heavy ion beams (the specific losses of heavy ions are many times higher than those of light particles) make them an excellent tool for investigating a wide range of fundamental and applied problems [10]. Owing to these properties, heavy ions can be used in many topical areas of science and technology (e.g. production of nuclear filters, studies of radiation effects on materials, high energy implantation, atomic physics, etc) [11-12]. Therefore, during the last ten years, at the Laboratory of Nuclear Reactions research is underway in these directions, along with the studies aimed at synthesizing new elements and exotic nuclei and with the nuclear reaction mechanism studies. The need for 5-10 MeV/nucleon heavy ions for physical experiments leads to the necessity to build big accelerators. On the other hand, the problem is significantly simplified by the fact that a heavy ion energy of 1-2 MeV/amu is enough for the majority of the abovementioned trends of research. An analysis has shown that the most optimal solution is the construction of a special-purpose accelerator. On the basis of the possibilities of the existing ion sources of the arc-discharge type and taking into account the experience of constructing heavy ion cyclotrons we have chosen the accelerator of the cyclotron type - the cyclic implanter CI-100. The CI-100 is designed for producing beams of heavy ions with $A/Z=5.3-6$ and for accelerating them to a maximum energy $E=40\ Z^2/A^2$ MeV/amu [13]. The implanter is a four-sector isochronous cyclotron with a pole diameter of 105 cm. The CI-100 magnetic field was formed with the aid of iron masses without using trim coils. The isochronism of the mganetic field in the working region provides a small phase shift in the acceleration process while magnetic field flutter (fig.5) provides enough vertical focussing from the first turns ($\Delta \sin \varphi \sim 0.05$ and $\nu_z = 0.3-0.35$).

The r.f. system of the CI-100 is a half-wave resonator consisting of two coaxial lines. The acceleration is performed by two dees with an angle of 34°,which are placed in opposite valleys. Owing to a high wave resistance of the resonance line both the geometric size and loss power have been decreased thus permitting elimination of water cooling for the cavities. Power is supplied from the output of the r.f. generator, via two coaxial feeder lines (ρ = 140 Ohm) to coupling loops located in one of the resonators. The connection with the resonance system is inductive and controllable.

To produce ions at the CI-100 use is made of a vertical arc-type source with indirect cathode heating. The main components of this source are shown in fig. 6. The source is introduced into the central region of the cyclotron through an axial slit available in the yoke and in the magnet pole. The source design envisages a transfer chamber which allows one to replace the source without disturbing the vacuum in the chamber. The life-

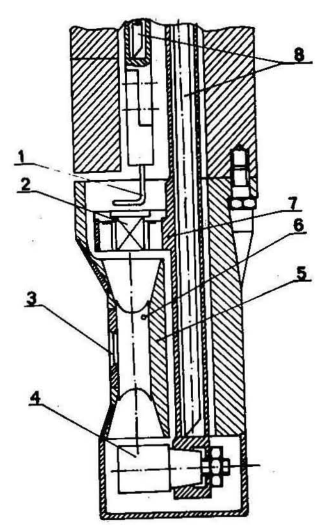

Fig. 6. Main components of the CI-100 ion source: 1 - filament, 2 - cathode, 3 - emission slit, 4 - anticathode, 5 - gas discharge chamber (anode), 6 - gas inlet, 7 - cathode and anticathode holder, 8 - channels for cooling the filament and cathodes holder.

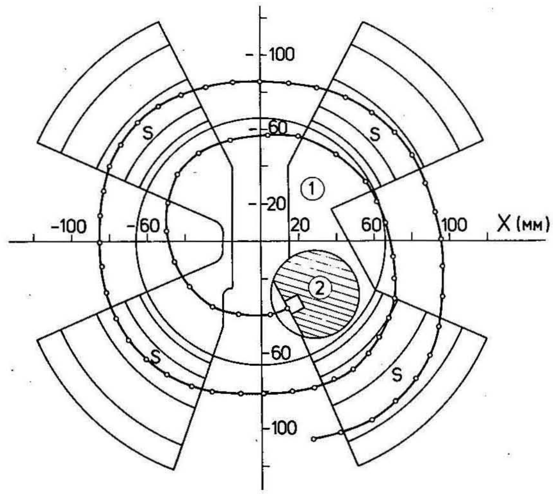

Fig. 7. Plan view of the central region of the CI-100 and the $^{40}Ar^{7+}$ ion trajectory on the first turns. B = =19.2 kG, R_{source} = R_{puller} = 40 mm, U_g = 50 kV. 1 - removable plug 130 mm diam., 2 - vertical ion source.

time of the ion source operated in the mode of generation of multiply-charged ions ($^{40}Ar^{7+}$) is equal to 20-22 hours. The geometry of the central region of the CI-100 is presented in fig. 7. The evacuation system of the CI-100 1500 liters in volume consists of one diffusion pump mounted on the chamber and two pumps on resonance tanks, with a total pumping speed of 5250 1/s for nitrogen. These pumps provide a pressure of $1x10^{6}$ torr in the cyclotron chamber without gas supply into the ion source (leakage and desorption are equal to $2x10^{-4}$ 1 torr s^{-1}). The operating pressure during beam acceleration is $(5-10)x10^{-6}$ torr. Beam extraction is performed using an electrostatic 28° deflector placed in the valley. The aperture of the deflector is 10 mm and voltage applied to the potential plate does not exceed 40 kV. As an additional method of beam extraction, ion stripping on a thin carbon foil is used. The lay-out of ion beam extraction is shown in fig. 8. The main parameters of the CI-100 are presented in Table 3.

Table 3.

Pole diameter, cm	105
Extraction radius, cm	46
Average magnetic field, kG	19.2 - 19.4
Number of sectors	4
Valley gap, cm	11
Hill gap, cm	2
Number of dees	2
Dee voltage, kV	50 - 70
R.f. power input, kW	25
Frequency range, MHz	20.4 - 20.9
Harmonic number	4
Operating pressure, Torr	$(5-10)x10^{-6}$
Extraction system	(i) electrostatic deflector (ii) stripping on carbon foil

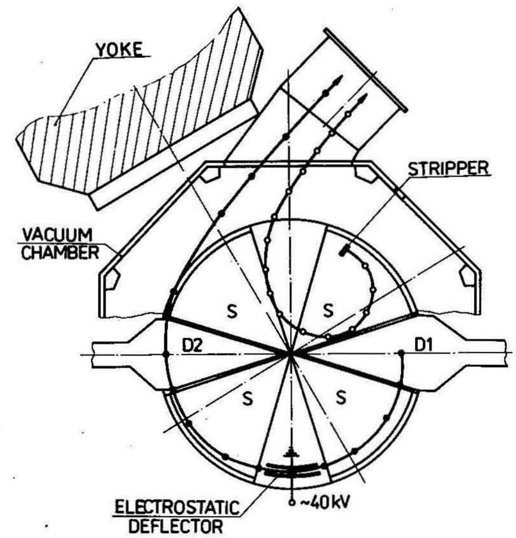

Fig. 8. Schematic of ion extraction from the CI-100 using an electrostatic method (solid points) and by stripping on a thin carbon foil (open points).

The construction of the cyclotron CI-100 was begun in 1984 and it was put into operation in May 1985. At present the accelerator produces the ions of the gaseous elements $^{12}C^{2+}$, $^{16}O^{3+}$, $^{22}Ne^{4+}$, and $^{40}Ar^{7+}$ with energies of (1-1.2) MeV/amu and intensities ranging between $7x10^{13}$ and 10^{12} pps. The modification of the ion source using solid material sputtering allows one to obtain $^{23}Na^{4+}$ and $^{35}Cl^{4+}$ ions from a NaCl crystal and to accelerate them to energies of 1.20 and 0.5 MeV/amu with intensities of $3x10^{11}$ and $4x10^{12}$ pps, respectively. Ion extraction from the vacuum chamber has been performed using the two methods with 50% efficiency. Figure 9 shows the signature of the beam at several radii. In the entire region of acceleration the beam lies in the median plane and has a vertical dimension not exceeding half the working aperture of the cyclotron. The radial size of the beam at final radii ranges between 5 and 7 mm. As the CI-100 magnetic field is close to the isochronous one, the radial intensity losses are determined mainly by ion stripping on residual gas (fig. 10). Figure 11 shows the relative 40Ar7+ beam intensity as a function of pressure in the cyclotron chamber. From this figure one can see that for 50% of the beam to reach the final radius it is necessary to have a residual gas pressure of not worse than $1x10^{-5}$ torr in the chamber. The depend-

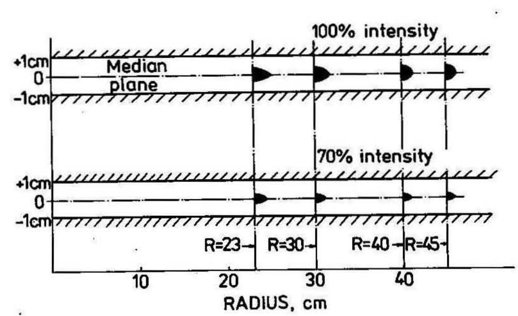

Fig. 9. Signature of the $^{40}Ar^{7+}$ ion beam at different radii of acceleration.

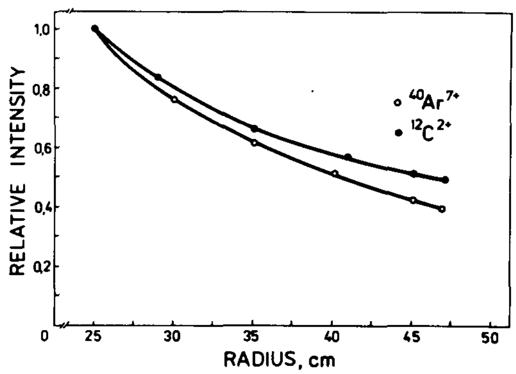

Fig. 10. Relative ${}^{12}C^{2+}$ and ${}^{40}Ar^{7+}$ ion beam intennities as functions of the radius.

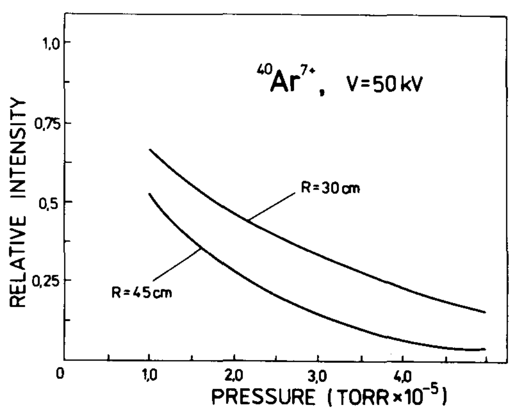

Fig. 11. The ${}^{40}Ar^{7+}$ ion beam intensity as a function of the average pressure in the cyclotron chamber.

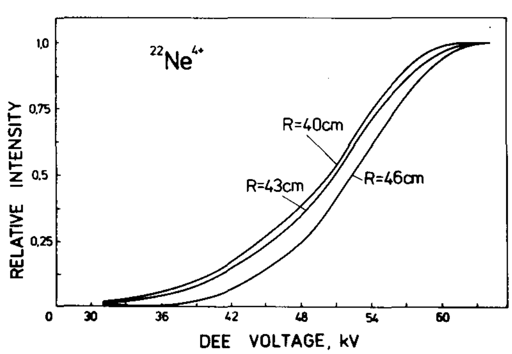

Fig. 12. The ${}^{22}Ne^{4+}$ ion beam intensity as a function of dee voltage for different radii of acceleration.

ence of beam intensity on the magnitude of accelerating voltage on the dees (fig. 12) indicates that ion loss on residual gas decreases with increasing acceleration rate. The "zero intensity" voltage corresponds to the value at which the ions do not pass round the region of the ion source.

In conclusion we note that the cyclotron constructed is simple to control, reliable in operation and absolutely safe with regard to radiation. This design may serve as a basis for similar machines which may occupy an area of not more than 150 m^2 without additional biological protection and with power consumption of about 150 kW.

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References

1. Yu.Ts.Oganessian et al. Proc. of the Xth Intern. Conf. on Cyclotrons and their Applications, East Lansing, Michigan, 1984, p.317.
2. I.A.Shelayev et al. JINR Comm. P9-4831, Dubna, 1969
3. G.N.Flerov et al. JINR Comm. 9-84-555, Dubna, 1984.
4. I.A.Shelayev et al. Proc. of the VIth Intern. Cyclotron Conference, New York, 1972, p.232.
5. A.A.Efremov et al. Proc. of the IXth All-Union Meeting on Charged Particle Accelerators, JINR, Dubna, 1985, v.1, p.85.
6. Yu.A.Bykovsky et al. Proc. of the IXth All-Union Meeting on Charged Particle Accelerators, JINR, Dubna, 1985, v.1, p.79.
7. K.S.Golovanivsky, Proc. of the Intern. School of Charged Particle Accelerators for Young Scientists, D9-84-817, Dubna, 1984, p.145.
8. G.H.Ryckewaert, Proc. of the IXth Intern. Conf. on Cyclotrons and their Applications, Caen, 1981, p.241.
9. D.J.Clark et al. Proc. of the Xth Intern. Conf. on Cyclotrons and their Applications, East Lansing, Michigan, 1984, p.133.
10. B.Fischer and R.Spohr, Reviews of Modern Physics, v.55, No 4, 1983, p.907.
11. G.N.Flerov, Vestnik AN SSSR, 1984, No 4, p.35.
12. D.Berenyi, Particles and Nuclei, 1979, v.10, issue 2, p.356.
13. A.M.Andriyanov et al. JINR Comm. 9-85-532, Dubna, 1985.