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PROGRESS REPORT ON THE JINR HEAVY ION ACCELERATORS

Yu.Ts.Oganessian

Laboratory of Nuclear Reactions
Joint Institute for Nuclear Research
Head Post Office, P.O.Box 79
101000 Moscow, USSR

The results and future perspectives of the development of the JINR heavy ion accelerators are briefly summarized. The main parameters of the isochronous cyclotron U400 presently in operation and of the proposed heavy ion facility for producing ion beams ranging from ^{4}He to ^{238}U with energies of 120 to 20 MeV/nucleon respectively, are given. The results of work aimed at accelerating nuclei to an energy of 4.5 GeV/nucleon at the Synchrophasotron are presented, and the main approaches to the construction of the superconducting heavy ion synchrotron NUCLOTRON are described.

Introduction

During the last decade heavy ion beams have found increasingly wide applications in large-scale research into various fields of physics and technology. This has led to the necessity to build high-intensity accelerator facilities of a new generation which would cover the entire range of masses of the elements of the Periodic Table and a wide energy range up to 10 GeV/nucleon. In the accelerator techniques this is a major problem of the nearest future and its solution can be achieved by different methods. In my talk I would like to touch upon the approaches developed at the JINR where heavy ion beams are traditionally used in many fields of research.

Low and Medium Energy Heavy Ion Accelerators

In analysing various possibilities of producing intense heavy ion beams with energies up to 10 MeV/nucl now we have given preference to the cyclotron method. This line of research has been pursued at our Institute during the last 20 years involving a wide range of studies to develop high charge state ion sources, to form magnetic fields in the region of high saturation, to test different systems of beam extraction, etc. These studies are underway in bench tests and in experiments using the existing accelerators. By the present time there have already been built 3 isochronous cyclotrons with an average level of magnetic induction B=2T. The beams provided by these cyclotrons are used in physical experiments. By the end of the present year another cyclotron will be put into operation for applied purposes /1/. Below are given some characteristics of the 400 cm cyclotron U400 and of the new heavy ion cyclotron facility.

The K=625 cyclotron U400

Independent operation

It is known that the main parameters of an accelerator system are determined by the possibilities of the multiply-charged ion source. In designing the U400 a plasma-type (PIG) ion source /2/ was chosen, of which the comparative characteristics are presented in fig. 1.

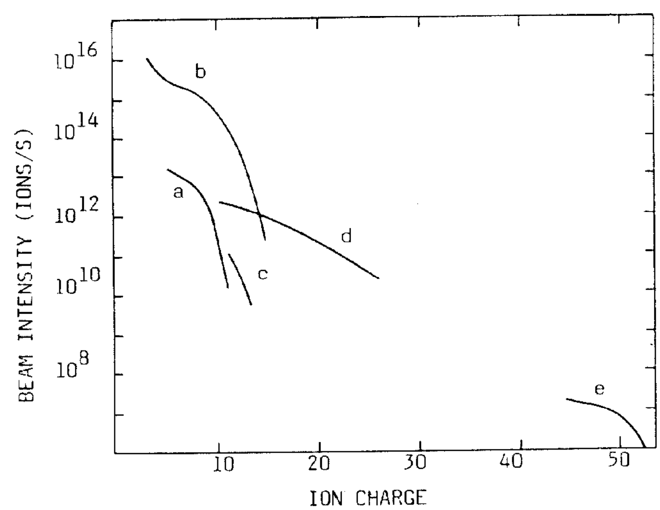

Fig. 1. The Xe ion beam intensity as a function of charge state, obtained at the input of the ion sources: (a) duoplasmatron; (b) PIG source; (c) laser ion source (data are given for Zr ions); (d) ECR; (e) electron-beam ion source.

This machine is designed for accelerating ions with masses from 4 to 250 to energies of 20 to 1.7 MeV/nucleon, respectively /3/. The isochronous distribution of magnetic induction is obtained using 4 sectors with straight boundaries ($\gamma = 0^{\circ}$) at a level of B=1.9-2.15 T with a maximum correction $B(r,0) < 5\times10^{-3}$T. Two dees with 42° angles and RF potential V_0=100 kV allow one to obtain beams of all particles with the ratio $4 \leqslant A/Z \leqslant 20$ on the first, second, third and fourth harmonics.

In table 1 there are given the intensities of ion beams of the isotopes of various elements ranging from ^{14}N to ^{84}Kr /4/. To my knowledge, these are the highest intensities so far achieved in this energy

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region.

Table 1

Ions	Energy* (MeV/nucl)	Intensity (ions/s)
$^{14,15}N^{2+}$	8.5-12.6	3×10^{14}
$^{16}O^{2+}$	8.0	3×10^{14}
$^{20,22}Ne^{3+}$	8.2-13.5	2×10^{14}
$^{40}Ar^{4+5+}$	5.5-8.0	1×10^{14}
$^{48-50}Ti^{5+}$	5.0-6.0	3×10^{13}
$^{51}V^{5+}$	5.5	5×10^{13}
$^{52-54}Cr^{5+6+}$	5.3-6.8	1×10^{13}
$^{55}Mn^{6+}$	5.5	6×10^{13}
$^{56,58}Fe^{6+}$	5.3	2×10^{13}
$^{58,64}Ni^{6+}$	5.3	1×10^{13}
$^{64,70}Zn^{8+}$	5.2-6.2	1×10^{12}
$^{76}Ge^{8+}$	5.3	2×10^{12}
$^{84}Kr^{9+}$	6.0	5×10^{11}

* The energy required to satisfy the conditions of the physical experiment.

Ion beam extraction is performed from different radii by stripping on a carbon target /5/. The extraction efficiency is determined by the ion charge distribution and varies from 20% to 80% depending on the atomic number and energy of the bombarding particle.

The external beam can be transported via one of the 12 beam lines located at different levels with respect to the median plane. A vertical beam line is intended for irradiating a target in the liquid phase. Beam emittance is equal to 50 mm-mrad, the particle energy spread is about 1%. The maximum beam power is about 3 kW.

Operation as injector

In this mode of operation the cyclotron should be capable of accelerating ions ranging from ^{16}O to ^{238}U characterized by the ratio A/Z=16-20. We have carried out the bench tests of a plasma ion source to generate high charge state (A/Z=10) and relatively low charge state (A/Z=20) ions. The results presented in table 2 indicate that on the fourth harmonic (n=4) it is possible to obtain beams of the heaviest particles with an energy of 1.7 MeV/nucl and with an intensity of more than 10^{13} part/s.

The separation of the neighbouring orbits will be 10 mm at the final radius, this allowing effective beam extraction using an electrostatic deflector. Thus the ion charge remains constant until the ions reach the central region of the post-accelerator.

Table 2
Intensities (ions/s) of ion beams from a PIG source.

A/Z = 10		A/Z = 20	
^{4+}Ca	2×10^{16}	^{2+}Ca	7×10^{16}
^{5+}Cr	1×10^{16}	^{3+}Cr	2×10^{16}
^{6+}Fe	3×10^{15}	^{3+}Fe	3×10^{16}
^{7+}Ge	4×10^{14}	^{4+}Ge	2×10^{16}
^{8+}Se	2×10^{15}	^{4+}Se	4×10^{16}
^{14+}Xe	7×10^{13}	^{7+}Xe	2×10^{16}
		^{11+}Th	3×10^{15}

Heavy Ion Cyclotron Facility

Based on the beam parameters of the U400 cyclotron as an injector there has been designed a cyclotron facility including as a post-accelerator the cyclotron U400M /6/ with a pole diameter of 400 cm.

In 1971 this system was first tested in accelerating Kr and Xe ions by the tandem system of the U300 and U200 cyclotrons /7/.

The spatial distribution of magnetic induction in the cyclotron U400M was investigated using a model 1/3 of its natural size. In the four-sector variant with a spiral angle $\gamma = 40^{\circ}$ an isochronous field has been obtained for B=1.6-1.95 T with a flutter of 0.12 and 0.07 respectively. Such parameters provide strong beam focussing over the entire range from 20 to 120 MeV/nucl (fig. 2).

The four dees located in valleys with an r.f. potential amplitude V_o=150-200 kV (f=15-25 mHz) permit the acceleration rate $E = 8zV_o$ MeV/turn with orbit separation R = 4-9 mm at the final radius. Ion beam extraction will be performed using a system of electrostatic and magnetic deflectors.

The injection of the primary beam (Z_1) into the cyclotron U400M is performed so that the ions undergo charge exchange near the central region of the accelerating chamber (fig. 3). As the ratio of ion charges before and after stripping, Z_1/Z_2, varies over a wide range, the distance of the carbon foil from the centre of the magnet should also vary between 30 and 100 cm.

The correction of the trajectories of ions which have passed through the carbon foil to their equilibrium orbit is achieved by the smooth correction of the angle of entrance into the fringing field of the U400M magnet. The time coordination of the two accelerators is achieved by satisfying the condition $N = \frac{n_2 B_2 Z_2}{n_1 B_1 Z_1}$ (where the subscripts "1" and "2" refer to the injector and the post-accelerator respectively, and n is harmonic number).

This condition is fulfilled by choosing the values of B_1, B_2 and charge state Z_2. In accelerating ions ranging from Ar to U the N value is equal to 3 or 4.

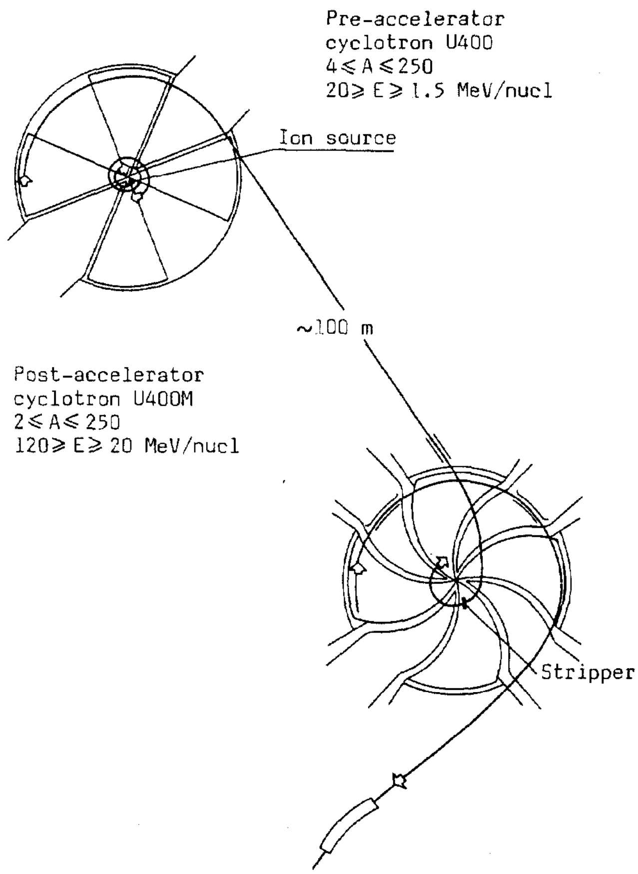

Fig. 2. Schematic view of the tandem U400 and U400M cyclotron system.

The expected parameters of external beams from the U400M are presented in table 3.

Table 3

	U400	U400M
Ion mass	16 - 238	16 - 238
Ion energy (MeV/nucl)	2.5-1.7	120-20
Ratio A/Z	16 - 20	2 - 5
Intensity (ions/s)	$10^{14}-10^{13}$	$5 \times 10^{12}-10^{11}$
Power consumption (MW)	1	1

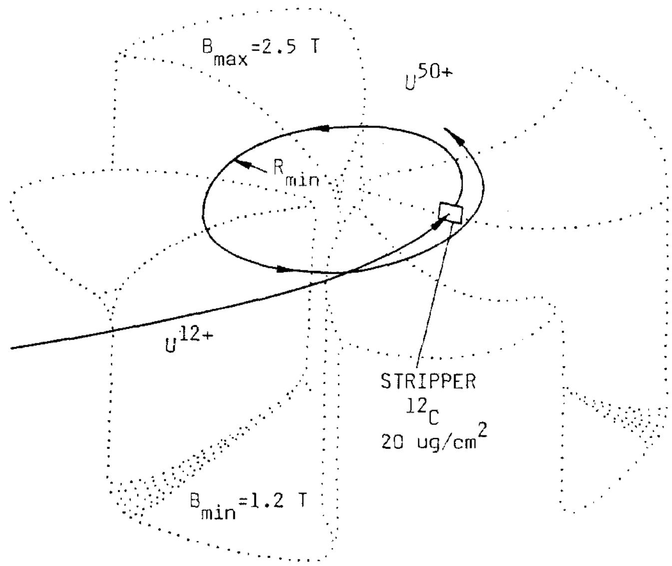

Fig. 3. Schematic view of the injection system of the U400M cyclotron.

Possibilities of producing the beams of exotic nuclei.

The high intensity of beams from the injector cyclotron operated to accelerate ions with $A/Z \geqslant 10$ can be exploited for bombarding thin targets located in the place of the stripping foil. The recoil nuclei emitted at an angle close to 0° and within a solid angle not exceeding the acceptance of the cyclotron U400M (these nuclei include compound nuclei, direct reaction products, etc) can be caught to be accelerated and extracted as a beam of secondary particles lying beyond the region of stable isotopes.

The secondary beam intensity varies for different reactions; in each particular case it depends on the energy and angular distributions of the nuclei produced. In a number of cases, however, the intensity of fluxes of exotic ions, especially in the region of light nuclei, can amount to 10^5 - 10^8 part/s, thus presenting a certain interest for solving a wide range of nuclear physics problems.

On the other hand, if the lifetime of the nuclide being accelerated is sufficiently long it can be transferred to an ion source located outside the cyclotron and then, already in high charge state, injected into the central region of the accelerating chamber.

In the U400M cyclotron, for ion injection from an external ion source there is foreseen a vertical line for a beam turning by 90° in the magnet gap, as in the Louvain accelerator /8/.

High Energy Heavy Ion Accelerators

A further energy increase by using the cyclotron method will require the construction of an additional acceleration stage at a ring-type accelerator ($B R \sim 10$ Tm) for a particle energy of up to ~1 GeV/nucl. In principle, this line of development has been probed in the construction of meson factories (SIN, TRIUMPH) and in the projects of kaon factories for proton energies up to several GeV /9,10/.

However, along with the development of the cyclotron method, in 1971 at Dubna work was begun to produce the beams of relativistic nuclei at the Synchrophasotron. The proposed facility was designed for producing proton beams with an energy of 10 GeV and, therefore, its reconstruction for the acceleration of particles with $A/Z > 1$ required substantial changes in almost all the main units of the accelerator.

The development of the CO_2-laser-based/11/ pulsed source of fully ionized nuclei and electron-beam ion sources (KRION) /12/, together with the successful solution of all the technical problems, has allowed one to accelerate at this facility to an energy of 4.2 GeV/nucleon the ions of elements ranging from deuterons to ^{28}Si /13/.

The beam intensities for nuclei of various elements are presented in table 4.

Table 4

Beam intensities at the Synchrophasotron.

Particle	Number of ions/pulse
p	4×10^{12}
d	1×10^{12}
$\bar{d}$	5×10^{8}
$^{3}He^{2+}$	2×10^{10}
$^{4}He^{2+}$	5×10^{10}
$^{7}Li^{3+}$	2×10^{9}
$^{12}C^{6+}$	5×10^{8}
$^{16}O^{8+}$	5×10^{7}
$^{19}F^{9+}$	1.5×10^{7}
$^{22}Ne^{10+}$	10^{4}
$^{24}Mg^{12+}$	10^{5}
$^{28}Si^{14+}$	10^{2}

The development of this facility has enabled one to begin a wide range of studies in the field of relativistic nuclear physics, as well as to outline future prospects for high energy heavy ion accelerators at JINR.

An important stage in this field has been the design of economical dipole ($B = 2.23$ T) and quadrupole ($dB/dr = 87.5$ T/M) superconducting magnets in which the distribution of magnetic induction is shaped by iron masses /14/.

These elements served as a basis for the acting model synchrotron (SPIN) which is currently tested on a beam.

The SPIN magnetic system includes 2 superperiods each containing 12 regular FODO periods 1.5 m in length. The model is capable of accelerating protons to an energy of 1.5 GeV and ions to energies from 2 to 256 MeV/nucleon /14/.

The results of bench tests and operation in the acceleration mode have formed the basis for the project of the big accelerator "NUCLOTRON" designed to produce relativistic nuclei of virtually all elements and to accelerate them to an energy of 6 GeV/nucleon. The parameters of this accelerator and the expected intensities of relativistic beams have been presented in more detail in the Proceedings of the Conference held in Santa Fe /15/.

Work is currently underway to design and test separate systems of the future accelerator.

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