NEW HEAVY-ION CYCLOTRON

Yu. A. Lazarev

On the last day of Dec. 1978 at Dubna, a new heavy-ion accelerator was started up – the 4-meter isochronous cyclotron U-400. This unique facility for nuclear-physics research was planned and constructed in three years by a team of scientists, engineers and workers under the direction of Academician G. N. Flerov and Doctor of Physicomathematical Sciences Yu. Ts. Oganesyan.

The new accelerator is intended for the production of intense beams of fast ions of almost all elements of the Mendeleev table. The main range of mass numbers of the accelerated particles is $20 \leq A \leq 140$. Ions of this mass range can be accelerated to an energy of 10 MeV/nucleon or less. The requirement for applied research for an energy of 1-2 MeV/nucleon can be met for all ions with mass number $12 \leq A \leq 240$. Light particles with $A \leq 20$ can be accelerated to an energy of 30-40 MeV/nucleon.

When planning the accelerator, the main attention was devoted to the achievement of a high beam intensity of the particles in the main mass range. For this, the design was optimized from the point of view of simplicity of accelerator construction, a high operating reliability, and a low operating cost. As a result of analyzing different versions, the choice of the machine type was made in favor of the cyclotron: this trend of technology for the acceleration of heavy ions is traditional for the Nuclear Reaction Laboratory of the Joint Institute of Nuclear Research. The U-400 accelerator project, developed in the Nuclear Reaction Laboratory of the Joint Institute of Nuclear Research, is based on the results of 20 years of experimental research by specialists of the Laboratory in the field of accelerator physics and technology. The significant stages of these researches were the development of ion sources of the arc type, the construction and operation of the U-300 classical cyclotron (operating since 1960), the building of the 2-meter U-200 isochronous cyclotron, which came on stream in 1968, and was the prototype of the U-400 accelerator (scale 1:2), the construction of the U-300–U-200 tandem cyclotron and the accelerated ions of Xe, Kr and Ge obtained on it.

The decision on the construction of the U-400 was made in 1974. The first components of the future cyclotron started development on July 7, 1975. Assembly of the accelerator was completed in Aug. 1978, and in November operation with the beam started. A month later, the beam was reduced to the final radius and heavy ions were extracted from the accelerator chamber.

The electromagnet of the cyclotron, with a mass of 2000 tons, is assembled from individual stacks of plates of ordinary steel. The manufacture and assembly of the stacks of the magnet framework was carried out directly in the cyclotron hall. The assembly of the electromagnet as a whole was accomplished in parallel with this. The unique tools for assembling and machining the stacks of the framework were supplied to Dubna from Czechoslovakia.

The design of the electromagnet allows a magnetic field strength of 2.13 T to be obtained in the air gap. The distinctive feature of the U-400 is that on the final radius of the accelerator (180 cm), the energy of the accelerated ions amounts to $\sim 700(z_i^2/A)$ MeV/nucleon. The azimuthal field variation is created by four pairs of sectors with straight borders. A drop from 2.7 T (hill) to 1.6 T (valley) provides a stable focusing of the beam up to an energy of 30-33 MeV/nucleon. The isochronous shape of the central magnetic field is provided by stepped annular shims and correcting windings.

The high-frequency system of the cyclotron consists of two coaxial resonators, loaded by two dees with an angular length of 42°, which are arranged in two oppositely placed valleys. Over the frequency range 6-12 MHz, the potential on the dees was about 100 kV. This system has a Q-factor of 5000 and allows ions to be accelerated efficiently at the 2nd, 3rd and 4th harmonics of the high-frequency potential (the energy increase of the ions during revolution is equal to 2.83; 3.7 and $4z_ieV_0$, respectively). The average power of the high-frequency generator is ~30 kW. The vacuum space of the accelerator amounts to 25 m^3 and is pumped-out by seven oil–vapor pumps with an output of 4200 liter/sec each. The working vacuum with the beam of accelerated

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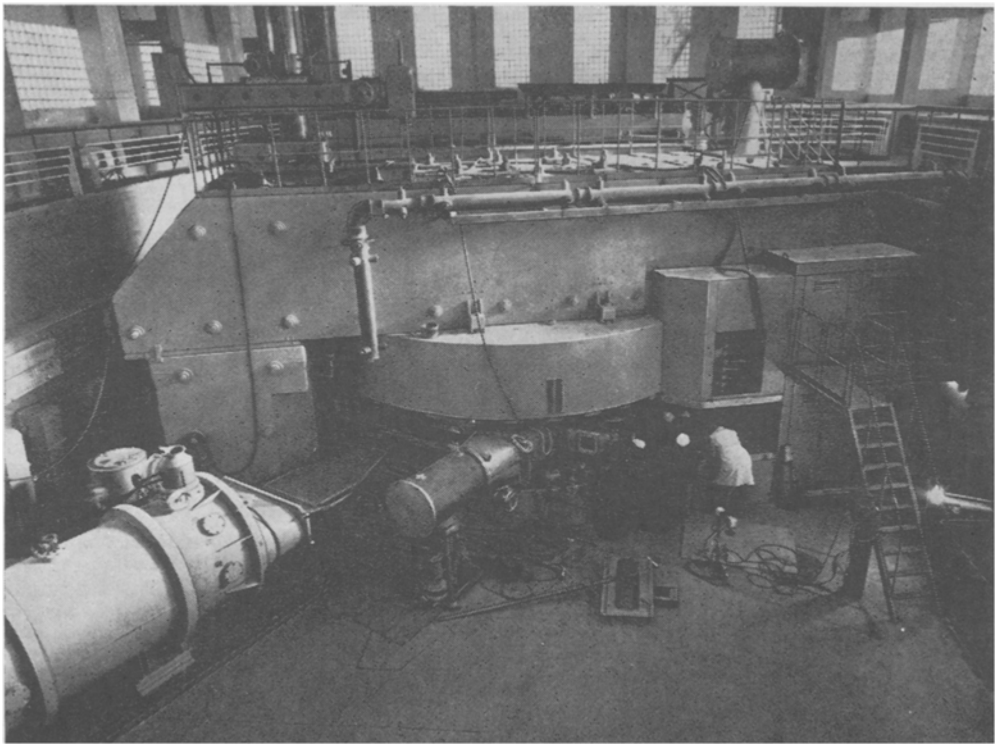

Fig. 1. General view of the U-400 isochronous cyclotron (Photo: Yu. Tumanov)

ions is equal to $2 \cdot 10^{-6}$ torr. It is assumed that in future the pressure will be reduced to $5 \cdot 10^{-7}$ torr, due to the introduction of cooled surfaces.

In order to extract the beam from the U-400 cyclotron, the method of charge transfer suggested by G. N. Flerov, Yu. Ts. Oganesyan, and G. N. Vyalov in 1964 will be used. The essence of this method consists in that for the ions passing through a thin carbon tape, the charge is increased as a result of which a strong radial instability of motion originates. Describing a sharply uncoiling spiral in the axially nonuniform magnetic field (deflection by 360 or ~700°), the particles exit from the accelerator chamber. Smooth tuning of the ions is achieved by movement of the carbon tape along the radius, and its movement in azimuth allows the beams of ions with different energy to be directed to the target, located at a fixed position. This method was investigated in 1965 on the CEVIL cyclotron (Orsay, France) and was used for the first time on the 200-cm isochronous cyclotron of the Joint Institute of Nuclear Research for extracting $^{4}He^{+1}$ ions and for a smooth variation of their energy from 27 to 41 MeV*. Two-revolution extraction is used in the U-400 cyclotron, which allows three beams to be obtained simultaneously, of which the charge differs by one or two units (e.g., $^{40}Ar^{+16}$, $^{40}Ar^{+17}$, and $^{40}Ar^{+18}$).

Powerful ion sources of the arc type with radial injection are used in the U-400 accelerator (the arc power for a pulse duration of 1 msec and an off-duty factor of 4 amounts to ~30-50 kW).

In Dec. 1978, a beam of $^{40}Ar^{+4}$ ions was obtained on the U-400 cyclotron, with a pulse intensity of $8 \cdot 10^{13}$ particles and an energy of 5 MeV/nucleon. The first experiments will start in the near future. In parallel with this, the intensity and energy of the ion beams will be increased, the selection of accelerated particles will be widened, systems for transporting the extracted beams will be developed, and rooms for experiments will be equipped.

The bringing on stream of the new accelerator opens up extensive prospects for conducting fundamental investigations in the field of heavy-ion physics, in particular, for experiments on the synthesis and study of the physical and chemical properties of the far transfermium and super-heavy elements ($Z \geq 108$) in nuclear reactions initiated by particles of mass $A \gtrsim 40$, including the rare isotopes ^{48}Ca, ^{54}Cr and ^{70}Zn, for studying the interaction mechanism of two complex nuclei, properties of nuclei remote from the region of β-stability, and certain urgent problems of atomic physics and quantum electrodynamics. The beams of heavy ions of the U-400 will significantly extend the possibilities for solving practical problems — the preparation of nuclear filters, simulation of radiation damage, ion implantation, etc.

* This method was used subsequently also for heavier ions up to ^{22}Ne.