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Extraction of the Carbon Ion Beam from the U-70 Accelerator into Beamline 4a Using a Bent Single Crystal

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Abstract—A beam of six-charged carbon ions with an energy of 24.8 GeV/nucleon is extracted from the U-70 synchrotron by means of a silicon crystal bent through 85 mrad. A total of 200 000 particles are observed in beamline 4a upon forcing 10^9 circulating ions to the crystal. The geometrical parameters, timing structure, and composition of the beam have been measured. It has been shown for the first time that, using a bent single crystal, an ion beam with required parameters can be extracted from the accelerator ring and formed for regular use in physics experiments.

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Bent single crystals have long been used to good effect to extract proton beams from accelerators, in particular, from large modern colliders [1–3]. The use of single crystals for extracting a portion of the proton beam with energies of 50–70 GeV into various beamlines has become customary practice at the Institute for High Energy Physics (IHEP) [4, 5]. Carbon ions, along with protons, have been accelerated lately at the U-70 synchrotron [6]. The mode of extraction of the six-charged carbon ion beam with an energy of 24.8 GeV/nucleon into beamline 4a was investigated in the U-70 run in the spring of 2015. It should be noted that the possibility of using crystals for deflecting and extracting ion beams was demonstrated about 20 years ago [7, 8], and collimation of heavy ions on the circulating beams of the RHIC and SPS accelerators was investigated in later experiments [9, 10].

The purpose of this work was to produce and study a stable ion beam with the aid of particle extraction by a crystal for use in regular U-70 runs.

The layout of carbon ion beam extraction by means of a crystal deflector and its transport in beamline 4a is shown in Fig. 1.

The crystal deflector *CD* was installed in the vacuum goniometer inside the 27th magnetic unit of the U-70. The oblong silicon crystal wafer with orientation (111) and dimensions of 0.3 × 3 × 60 mm (thickness, height, and length downstream of the beam) was bent through an angle of 85 mrad with the aid of a metal holder (Fig. 2). The bending angle as large as this is explained by the specific features of beamline 4a. Nominally, it is used to obtain negative particles on the internal amorphous target of the U-70 accelerator. Negative particles are ejected by the magnetic field of the accelerator into the outer side of the ring, whereas protons or ions deflected by the crystal are turned inward.

Bump magnets were used for forcing the circulating beam onto the crystal. Two bending magnets M_1 and M_2 ejected the beam that had been channeled and deflected by the crystal into beamline 4a and thereafter was formed by two quadrupole lenses *HL* and *VL*. Beam collimators *HC* and *VC* were fully opened. The

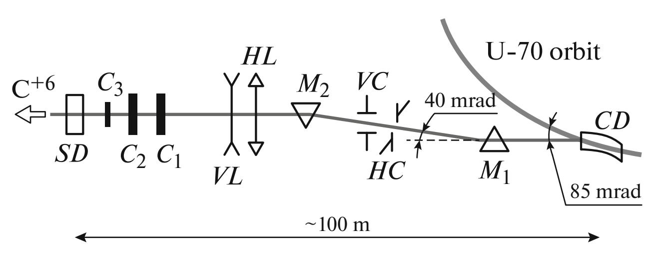

Fig. 1. Diagram of carbon ion beam extraction into beamline 4a: (*CD*) crystal deflector, (M_1, M_2) deflecting magnets, (*HC*, *VC*) horizontal and vertical collimators (*HL*, *VL*) horizontal and vertical quadrupole lenses, (C_1, C_2, C_3) scintillation counters, and (*SD*) semiconductor detector.

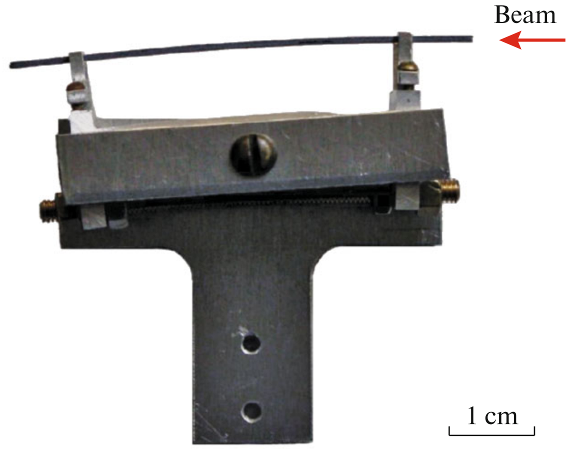

Fig. 2. Design of the crystal deflector with a bending angle of 85 mrad.

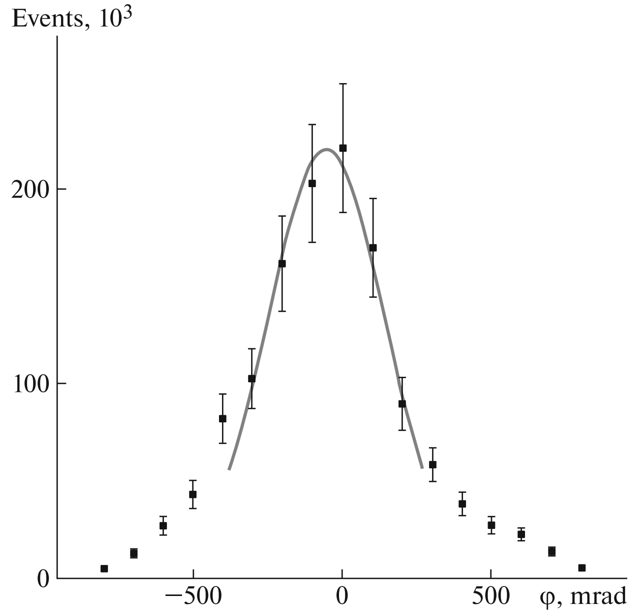

Fig. 3. Number of particles in the beamline vs. crystal orientation φ with respect to the beam direction.

beam intensity was measured by large scintillation counters C_1 and C_2.

A direct proof that the extracted beam is channeled consists in the so-called orientation curve—the dependence of the extracted beam intensity on the crystal angle with respect to the incident beam direction. The results of the angular scanning of the beam by the crystal are shown in Fig. 3.

At a maximum, $(2.2 \pm 0.3) \times 10^5$ particles were observed in beamline 4a when 10^9 ions were incident on the crystal deflector. Full width at half-maximum of the curve $\sigma = 0.2$ mrad corresponds to the angular beam spread in the accelerator. The obtained beam extraction efficiency complies with the theoretical expectations.

In Fig. 4, the theoretical point (an asterisk) for carbon fits the theoretical curve well [11]. The figure also presents the theoretical curve and experimental points

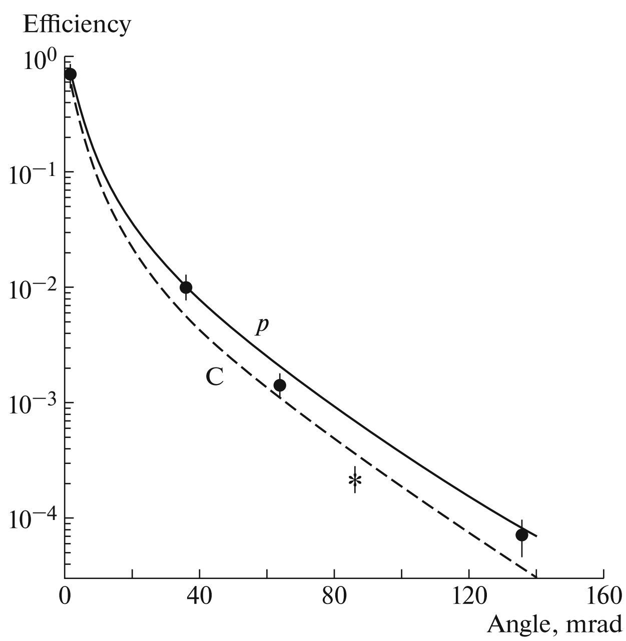

Fig. 4. Efficiency of carbon (C) and proton (p) circulating beam extraction by crystals as a function of the bending angle. The calculation results are shown with curves, the solid circles present the experimental values for protons, and the asterisk is the experimental value for carbon.

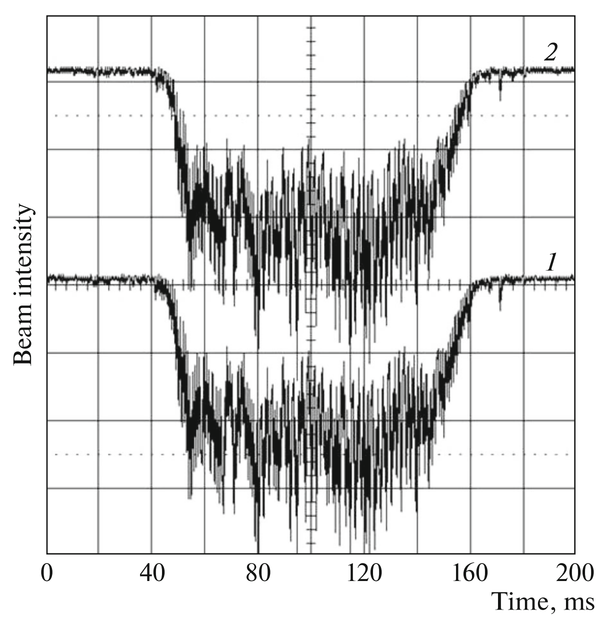

Fig. 5. Timing structure of the ion beam incident on the crystal, which was measured by monitors *1* and *2*.

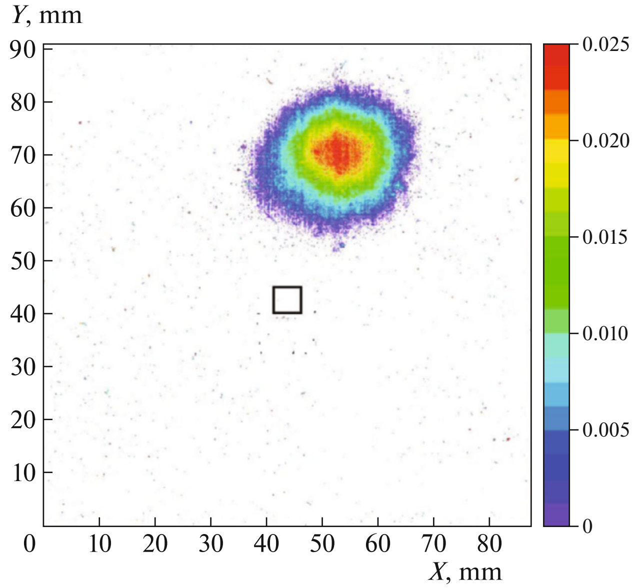

Fig. 6. Image of the particle distribution in the extracted beam.

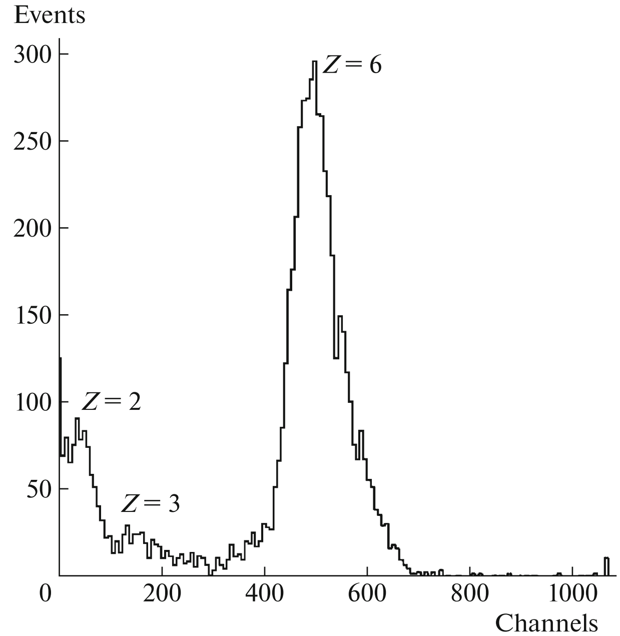

Fig. 7. Ionization loss spectra of beam particles in scintillator C_3.

for the proton beam [11]. The efficiency of beam extraction by the crystal was calculated using the SCRAPER program [12]. Both particle passage through the crystal in view of nuclear interactions and multiturn movement in the U-70 accelerator were taken into account in the calculation. It should be noted that the extraction efficiency for carbon ions is several times lower than the respective value for the proton beam, though the channeling properties of crystals are identical for ions with equal values of the magnetic rigidity (the ratio of the particle momentum to its charge p/z), which was established in [7, 8]. The lower (relative to protons) extraction and collimation efficiency for the circulating ion beam was also observed in [8–10]. It is explained by the higher-intensity nuclear interaction of ions with the crystalline target in comparison with protons in multiturn particle movement in the accelerator.

The signals from the scintillation monitors of beam guidance toward the crystal in the accelerator are depicted in Fig. 5. Analysis of the signals shows that the uniformity of guidance and the timing structure of the beam are good, though the intensity of circulating particles is low.

Figure 6 presents the image of the extracted beam at the site of the detectors, which was obtained using the EVT3 radiation monitoring film. The full width at half-maximum of the carbon ion beam is ~10 mm in both planes. This corresponds to the size of the proton beam extracted earlier.

The beam composition was measured at its center by the ionization loss in thin scintillator C_3. The results are shown in Fig. 7. Ions with different charges were identified by the quadratic dependence of the ionization loss. It is apparent that the carbon peak with a charge STATE of 6 dominates (~80%). At the beam periphery, i.e., at a level of 1% of the main intensity, the beam composition was measured with semiconductor surface-barrier detector *SD* (the detector position with reference to the beam center is shown with a square in Fig. 6).

The spectra of ionization losses on the detector are presented in Fig. 8. One can see that there are 30% of carbon and numerous fragments. The presence of these fragments is mainly caused by interactions of the

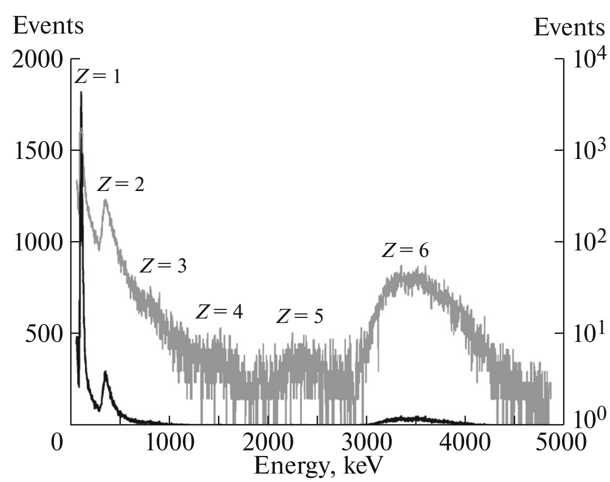

Fig. 8. Ionization loss spectra of beam particles in the semiconductor (the black line is in the linear scale and the gray line is in the logarithmic scale).

extracted carbon beam with vacuum-tight partitions and other substances in beamline 4a (~5 g/cm^2).

As a result, the investigation has shown that, using a bent single crystal, it is possible to extract an ion beam from the accelerator with acceptable parameters (beam intensity, timing structure, and composition) for physics experiments scheduled for regular runs of the U-70 accelerator.

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