The measurement results of carbon ion beam structure extracted by bent crystal from U-70 accelerator

A G Afonin[1], E V Barnov[1], G I Britvich[1], Yu A Chesnokov[1], P N Chirkov[1], A A Durum[1], M Yu Kostin[1], V A Maisheev[1], V I Pitalev[1], S F Reshetnikov[1], A A Yanovich[1], R M Nazhmudinov[2], A S Kubankin[2] and A V Shchagin[2,3]

[1]Institute for High Energy Physics in National Research Centre "Kurchatov Institute", Protvino 142281, Russia;
[2]Belgorod State University, Belgorod 308015, Russia;
[3]Kharkov Institute of Physics and Technology, Kharkov 61108, Ukraine.

E-mail: chesnokov@ihep.ru

Abstract. The carbon ion $^{+6}$C beam with energy 25 GeV/nucleon was extracted by bent crystal from the U-70 ring. The bent angle of silicon crystal was 85 mrad. About 2×10^5 particles for 10^9 circulated ions in the ring were observed in beam line 4a after bent crystal. Geometrical parameters, time structure and ion beam structure were measured. The ability of the bent monocrystal to extract and generate ion beam with necessary parameters for regular usage in physical experiments is shown in the first time.

The bent monocrystals are successfully used long time for proton beam extraction in circular accelerators included large modern colliders [1, 2, 3]. The usage of monocrystals to extract the part of a proton beam with energy 50 – 70 GeV in various beam lines is usual practice in IHEP [4, 5]. The carbon ions instead of protons were recently accelerated in the U-70 synchrotron [6]. The mode of extraction of six-charged carbon ions with energy 25 GeV on a nucleon in the beam line 4a was investigated in spring-2015 operating run of U-70. It is necessary to note that the opportunity of deflection and extraction of ion beams by the crystals has been demonstrated about twenty years ago [7, 8] and collimation of circulated heavy ions was investigated at the RHIC and the SPS in later experiments [9, 10]. The main purpose of our work is a creation and study of stable ion beam extracted by a silicon crystal to apply in regular U-70 beam runs.

The scheme of extraction of carbon ions by the crystal deflector and beam transportation in beam line 4a is shown in figure 1.

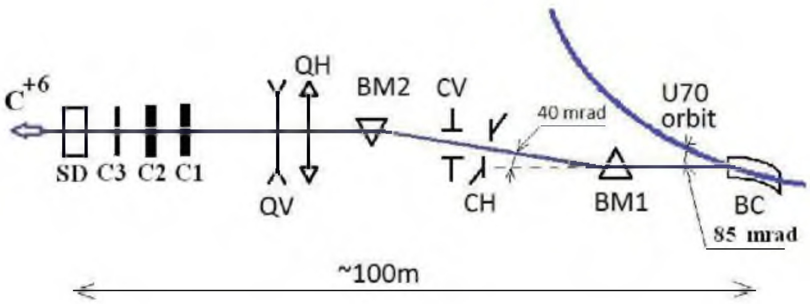

Figure 1. The scheme of crystal extraction of ions in the beam line 4a. BC is the bent crystal, BM1 and BM2 are the dipole magnets, QH and QV are the quadrupole lenses, CH and CV are the beam collimators, C1 - C3 are the scintillation counters, SD is semiconductor detector.

The crystal deflector BC has been installed in vacuum goniometer inside the 27th magnetic block of U-70. The lengthened silicon crystal plate with orientation (111) was bent by 85 mrad angle by the metallic holder (see figure 2) and had dimensions 0.3×3×60 mm (thickness, height, length along a beam). Such significant angle of the crystal bend is determined by the specificity of the beam line 4a. Nominally, this beam line is used for negative particles production, which is formed on internal amorphous target in U-70. Negative particles are pushed out by a magnetic field of the accelerator in the external side of a ring, but the protons or ions deflected by a crystal are turned inside the ring. Circulating beam is tuned on the crystal by slow increasing field in bump-magnets. The ion beam from bent crystal was directed on an axis of 4a beam line by two dipole magnets BM1 and BM2 and then formed by two quadrupole lenses QH and QV. The copper collimators CH and CV have been opened completely. A couple of big scintillation counters C1 and C2 measured the beam intensity.

Figure 2. The crystal device with 85 mrad bends.

There is orientation curve, which describes a dependence of particle beam intensity in the beam line versus crystal alignment angle with respect to direction of accelerator orbit. It is a direct proof of beam channeling in crystal when the experimental points are fitted by this curve. The results of angular scanning are shown in figure 3.

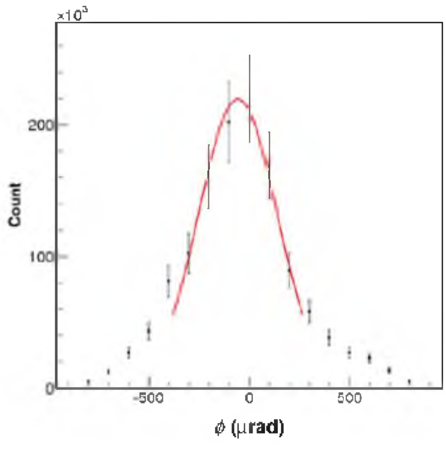

Figure 3. Dependence of particles quantity in the beam line versus crystal alignment angle ϕ with respect to direction of beam orbit in accelerator.

Maximum of (2.2 ± 0.3) $\times 10^5$ particles in the beam line 4a were observed at 10^9 ions on crystal deflector. The curve width is 0.2 mrad. It corresponds to angular divergence of a beam at the accelerator. The obtained results for efficiency of carbon ion extraction correspond to theoretical expectations, as shown below.

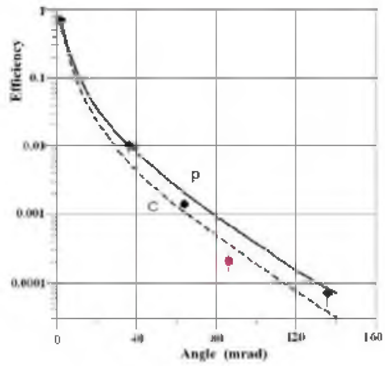

Figure 4. Efficiency of crystal extraction for a circulating beam versus crystal bend angle.

The experimental point (red color in figure 4) for carbon falls on a theoretical curve [11]. The data for a proton beam (a theoretical curve and experimental points [11]) are shown also. The calculations of crystal efficiency for beam extraction were done by the program SCRAPER [12]. This program described the processes of particle channeling and dechanneling in crystal. And also the nuclear interactions during particles penetration in a crystal material and multi-turn movement in accelerator ring were taken into account. It is necessary to note, the extraction efficiency of carbon ions is below in few times for corresponding value of a proton beam, although the channeling properties of crystals are identical to protons and ions with identical magnetic rigidity (p/z), which is the ratio of particle momentum to its charge [7,8]. The crystal extraction efficiency for ions is much smaller than for protons, which was described early [8, 9, 10]. It is well explained by a more intensive nuclear interaction of ions with a crystal target compare to protons during the particles multi-turn movement at accelerator.

The signals from scintillation monitors near the point of beam prompting on a crystal are shown in figure 5. It is visible, that uniformity of beam tuning and time structure is satisfactory in spite of the small intensity of circulating particles.

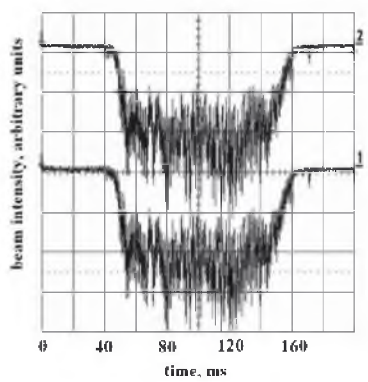

Figure 5. The time structure of ion beam directed on a crystal, on monitors 1 and 2 (the picture with the oscilloscope).

The image of the extracted beam is shown in figure 6. This image was obtained by dosimetric film EBT3, which placed at the detectors position. The size of carbon ions beam (FWHM) is equal ~10 mm in horizontal and vertical planes. It corresponds to the size of proton beam, which was extracted earlier.

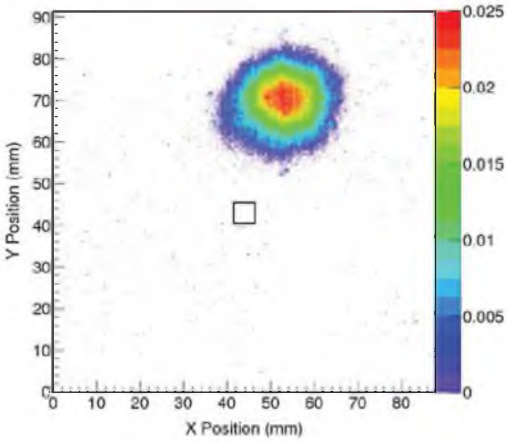

Figure 6. The image of particles density in the extracted ions beam.

The ionization energy losses in the thin scintillator C3 were used to determinate of beam composition in the center of beam spot. The results are shown in figure 7. The ions identification with a various charge was done by square-law dependence of ionization losses. It is visible, that the one peak dominates (approximately 80%). It matches carbon ion having charge 6.

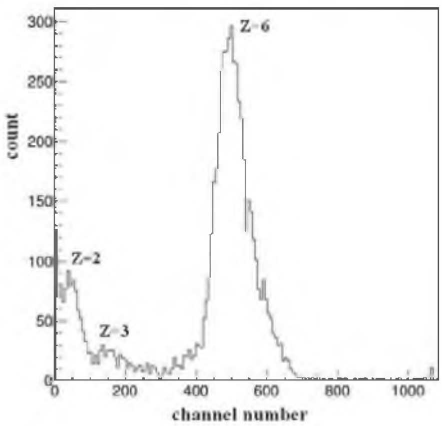

Figure 7. Ionization energy loss spectra of beam particles in the scintillator C3.

The semiconductor surface-barrier detector SD was used to measure the beam composition on periphery of the beam spot at 1% basic intensity level. The position of the detector with respect to the center of the beam is shown in figure 6 by a black square. Spectra of ionization losses in the detector are shown in figure 8. About 30% of carbon and the large quantity of fragments were there. The main reason of fragments is interaction of the extracted carbon beam with vacuum partition foils and other substance in the beam line 4a (about 5 g/cm^2).

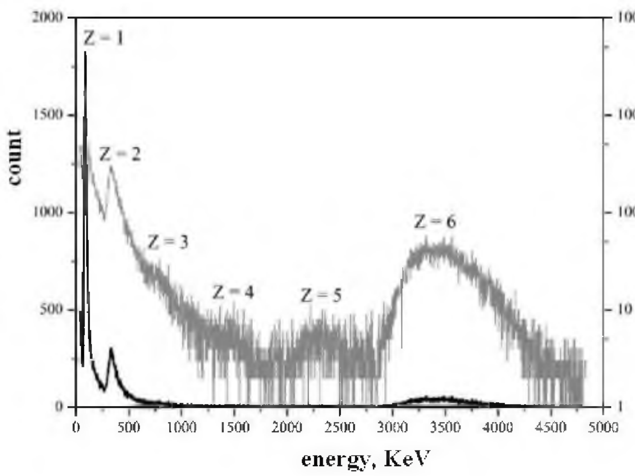

Figure 8. Ionization energy loss spectra of beam particles in the semiconductor detector (a black line – linear scale, a grey line – logarithmic scale).

Summary

Our investigation shown the possibility of bent monocrystal to extract the carbon ion beam from the accelerator with reasonable parameters (intensity, time structure and beam composition) for some physical experiments planned in regular U-70 runs.

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