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EXTRACTION OF PROTONS WITH THE ENERGY OF 35 MeV FROM THE UPGRADED AIC-144 CYCLOTRON[1]

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The first experimental results on AIC-144 isochronous cyclotron new extraction system are described. The cyclotron will be able to generate beams of protons, deuterons, and α-particles. One of the principal goals of the upgraded facility is to extract beams of protons and deuterons (proton energy 60 MeV, deuteron energy 30 MeV) for proton radiotherapy and for fast neutron beams. The precession method for particle extraction was chosen as the best one. It is the first time that the proton beam of energy 35 MeV has been extracted from the cyclotron with the efficiency above 50 %. More careful adjustment of the extraction system parameters (better control of the 1st harmonic of the magnetic field and the position of the deflectors) will permit an increase in the extraction efficiency to the design value of 70 %.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

Вывод протонов с энергией 35 МэВ из циклотрона АИЦ-144 после его реконструкции

Бакевич Э. и др.

Приводятся результаты экспериментов по запуску новой системы вывода изохронного циклотрона АИЦ-144. Циклотрон предназначен для ускорения пучков протонов, дейтронов и α-частиц. Одной из важнейших задач реконструкции машины является обеспечение вывода пучков протонов и дейтронов (с энергиями 60 и 30 МэВ соответственно) для протонной радиотерапии и для получения пучков быстрых нейтронов. Для вывода частиц был выбран метод прецессии как наиболее соответствующий поставленным требованиям. Впервые был получен выведенный пучок протонов с энергией 35 МэВ с эффективностью вывода свыше 50 %. Более тщательная настройка параметров системы вывода (регулирование первой гармоники магнитного поля и положений дефлекторов) позволит увеличить эффективность вывода до проектного значения 70 %.

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BEAM CENTERING AND AMPLITUDES OF BETATRON OSCILLATIONS

In order to meet the requirements to the amplitudes of betatron oscillations ($a_r \leqslant 5$ mm, $a_z \leqslant 3$ mm) some modifications were done to the central cyclotron region geometry. Two diaphragms with an angular distance 180° between them were installed on the 1st and 2nd turns of the beam. The dimensions of the slits intended for the beam pass were $(\Delta r, \Delta z) = (1 \times 10)$ mm^2 and (2×10) mm^2. Figure 1 shows current distribution at the centre of the cyclotron obtained by means of the differential probe with lamellas of radial thickness 1 mm. These current measurements and their comparison with the results of computations demonstrate that the beam is centered with an accuracy of 1÷2 mm and has an incoherent radial amplitude $\leqslant$ 2.5 mm.

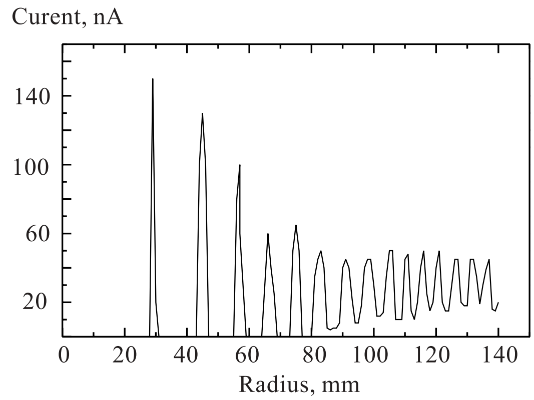

Fig. 1. Current distribution at the centre of the cyclotron after installation of two diaphragms

The 1st harmonic with the amplitude ~5 G, which exists in the main acceleration region of the cyclotron, leads to beam decentering up to 7 mm near the radius 50 cm. But a smooth decrease in the 1st harmonic to 2 G, which is ensured by special B1 coils at the radius 60 cm, causes a corresponding decrease down to 2 mm of beam decentering. This effect of the 1st harmonic (which is due to a quite large number of beam turns (~150) between the radii 50 and 60 cm) was computed and confirmed by the beam shadow measurements at the cyclotron. These measurements also proved that incoherent radial oscillations did not exceed 2 mm. Thus, the sum of radial oscillations had the amplitude not more than 4 mm. Axial amplitudes were decreasing during acceleration from 5 mm to 3 mm because of betatron axial frequency increasing from 0.15 ($r = 10$ cm) to 0.4 ($r = 60$ cm).

MEASUREMENT OF RADIAL GAIN ENHANCEMENT

In order to measure the radial gain enhancement a special 5-lamellas probe was used. This probe was installed at the azimuth 118°, i.e., 2° upstream the entrance of the ESD-2, the first element of the extraction system for the beam energy considered. Radial thickness of the 1st lamella was 0.5 mm, the thickness of others was 2 mm. The vertical dimension of the lamellas was 20 mm. Figure 2 shows the results of measuring the current distributions between the lamellas. An increase in radial gain just before the extraction is clearly seen. The absolute current value was somewhat higher in this experiment as compared with the intensity value in the beam centering measurements, Figure 1.

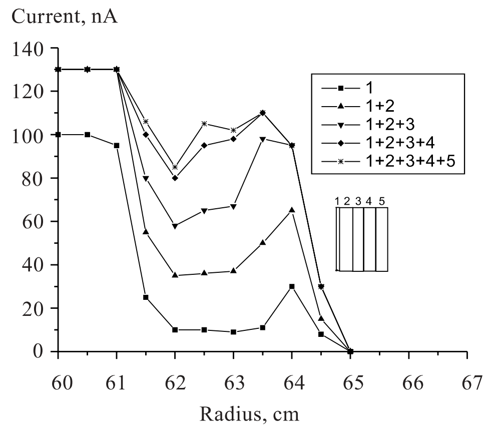

Fig. 2. Measurement of current distribution between probe lamellas

EXTRACTION SYSTEM

The extraction system of the AIC-144 cyclotron consists of 6 elements located inside the vacuum chamber: 3 electrostatic deflectors and 3 magnetic channels. They have the following denotations and azimuth positions: ESD-1 — (98÷117)°, ESD-2 — (120÷140)°, ESD-3 — (140÷177)°, MC-1 — (183÷205)°, MC-2 — (215÷250)°, MC-3 — (273÷283)°. The 2nd and 3rd electrostatic deflectors are mounted on the same case and are powered by one high-voltage unit. This set of elements is proposed to be used for extraction of 60 MeV protons. For extraction of 35 MeV protons the 1st electrostatic deflector was removed from the vacuum chamber. The remaining elements are able to extract the beam to the matching point. The matching point, where beams of various energies and type of particles should be extracted to is located just in front of the first element of the transport line.

In the Table the required parameters of the extraction system that correspond to proton energy of 35.1 MeV are presented. The focusing gradients of the electric and magnetic fields are used inside ESD-3, MC-2, and MC-3 in order to compensate the defocusing effect (in horizontal plane) of the fringe magnetic field. The elements ESD-2 and MC-1 have a uniform field inside their working apertures.

Parameters of the extraction system for proton energy of 35.1 MeV

Element	φ_1 (°)	φ_2 (°)	r_1 (cm)	r_2 (cm)	ΔB (kG)	ε (kV/cm)	dB/dx (kG/cm)	$d\varepsilon/dx$ (kV/cm^2)
ESD-2	120	140	63.85	64.60	—	58.3	—	0.0
ESD-3	140	177	64.60	65.69	—	48.9	—	−20.4
MC-1	183	205	65.66	65.99	−1.582	—	0.0	—
MC-2	215	250	66.83	75.17	−2.153	—	0.8	—
MC-3	273	283	88.37	98.33	0.0	—	1.0	—

EXTRACTION EFFICIENCY

The following procedure to make the extraction system operational has been applied:

• measurement of the radial gain enhancement without the extraction system inside the vacuum chamber;

• the same but with ESD-2, 3 at their working position in order to measure probable particle losses on the outer side of the septum;

• beam passage through ESD-2, 3, measurement of the particle losses inside them;

• step by step installation of the magnetic channels MC-1, 2, 3, the corresponding tuning of the radial gain enhancement, and measurement of the beam transport efficiency at each step.

We observed a very high efficiency (∼85 %) of the beam deflection at the exit of ESD-3 when no magnetic channels were installed inside the vacuum chamber. Installation of the magnetic channels required additional efforts to compensate the 1st harmonic in order to improve the process of radial gain enhancement. This procedure was not very long. As a rule, 1÷2 hours were enough to obtain the extracted beam with efficiency above 50 %. No particle losses were detected inside the magnetic channels. It is interesting to note that in the previous experiments (before the upgrading program was fulfilled) on 18.6 MeV deuteron beam extraction from the machine by methods other, than the given above, the extraction efficiency was not greater than 7 % [1].

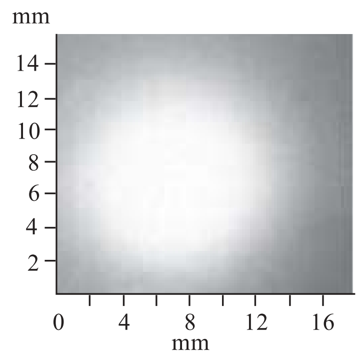

Fig. 3. Television image of the beam spot in the window of the vacuum chamber

We believe that longer and more accurate adjustment of the extraction system parameters (mainly careful control of the 1st harmonic of the magnetic field and the position of ESD-2, 3) will permit us to increase the extraction efficiency up to the design value of 70 %.

To visualize the extracted beam in the window of the vacuum chamber we used a luminescent target and a television camera. Figure 3 shows the beam spot on this target. The position and the size of the beam closely agree with the computational results.

CONCLUSIONS

It is the first time that the proton beam of energy 35 MeV has been extracted from the AIC-144 cyclotron with efficiency above 50 %. More careful adjustment of the extraction system parameters (better control of the 1st harmonic of the magnetic field and the position of ESD-2, 3 as major factors) will permit an increase in the extraction efficiency to the design value of 70 %.

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