ELECTROSTATIC AND MAGNETIC ELEMENTS OF THE NEW EXTRACTION SYSTEM FOR THE ISOCHRONOUS CYCLOTRON AIC-144

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On the isochronous cyclotron AIC-144 the beam extraction is realized with the help of a new extraction system. As extraction system elements three electrostatic deflectors and three passive magnetic channels are used. The parameters and features for all elements are given. The particularities and details of the constructive decisions applying under their realization are described.
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1 INTRODUCTION

The AIC-144 isochronous cyclotron [1] designed and constructed at the Institute of Nuclear Physics in Krakow will be able to generate beams of protons and deuterons. One of the principal goal of the new facility is to extract the beams of protons and possibly, deuterons (proton energy 60 MeV, deuteron energy 30 MeV) for proton radiotherapy and for horizontal and vertical fast neutron beams [2].

It was extremely important to select the best and the most efficient extraction system for the cyclotron [3, 4]. The problem of the effective beam extraction was found difficult considering constrains of the existing cyclotron. The precession method for extraction was agreed as the right one. One of the most important issues was the control of the 1-st harmonic of the magnetic field distortion due to the deflection system in the area of the internal circulating beam. It was important to measure the effect of such a magnetic field distortion and to introduce the measured data into the computer codes for beam dynamics calculations. Requirement to have the realistic fringe field maps, including the field inside of the magnetic channels, stimulated the necessary measurements of the field. The means to correct the possible field distortion due to the removal of ferromagnetic material from the valley between sectors for installation of the new harmonic coils were foreseen. Optimization of the various parameters of the proposed extraction system, e.g. positions, field, gradients, etc… were included into the upgrade program. It was useful to organize a field modification in order to shift the position of the coupling resonance to limit the axial blow-up of the beam by including the corresponding valley shims and other available means. The central region structure has been investigated in details to obtain the necessary beam quality in the pre-extraction region. The non-linear effects inside extraction elements have been taken into account to prevent deterioration of the beam emittance. Matching of the extraction beam to the downstream beam transport system acceptance has been performed. Designing of the electrostatic channels was done with special care.

Beam extraction experiments were carried out for the proton of 35 MeV final energy. This regime has the following parameters: main coil current of 169.2 A, optimal radio frequency of 19.995 MHz, a corresponding isochronous magnetic field at the machine center was 13.250 kG, accelerating dee voltage was 45 kV. Intensive simulation of particle motion and necessary alignments of the extraction system structure elements accompanied beam measurements.

The layout of the cyclotron chamber with the new extraction system installed is given in Fig. 1.

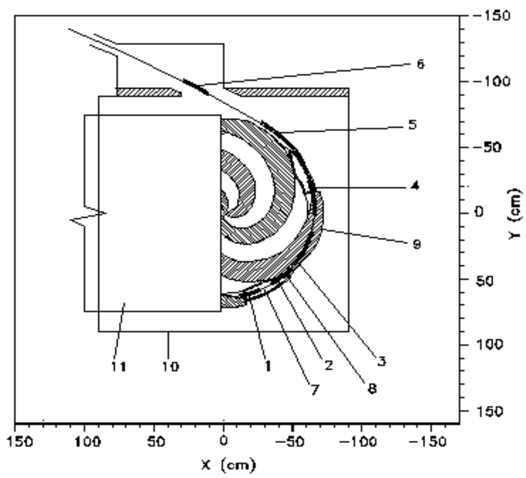

Fig. 1. Cyclotron chamber with extraction system layout. 1, 2, 3 - electrostatic deflector sections ESD-1,2,3; 4, 5, 6 - magnetic channel sections MC-1,2,3; 7 - valley shim; 8 - harmonic coil; 9 - spiral shim; 10 - vacuum chamber; 11 – dee.

Table 1. Parameters of extraction system for proton energy 35.1 MeV

Element	φ_1 (°)	φ_2 (°)	r_1 (cm)	r_2 (cm)
ESD-2	120	140	63.85	64.60
ESD-3	140	177	64.60	65.69
MC-1	183	205	65.66	65.99
MC-2	215	250	66.83	75.17
MC-3	273	283	88.37	98.33

Element	ΔB (кG)	ε (кV/cm)	dB/dx (кG/cm)	dε/dx (кV/cm^2)
ESD-2	-	58.3	-	0.0
ESD-3	-	48.9	-	-20.4
MC-1	-1.582	-	0.0	-
MC-2	-2.153	-	0.8	-
MC-3	0.0	-	1.0	-

In Table 1 the required parameters of the extraction system that correspond to proton energy 35.1 MeV are represented. The focusing gradients of electric and magnetic fields are used inside ESD-3, MC-2 and MC-3 in order to compensate 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.

2 BEAM DEFLECTION, EXTRACTION SYSTEM ELEMENT REQUIREMENTS

The extraction system of the AIC-144 cyclotron consists of 6 elements located inside the vacuum chamber (see Fig. 1): 3 electrostatic deflectors and 3 magnetic channels. They have the following notation and azimuth position: 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 2-nd and 3-rd electrostatic deflectors are mounted on the same case and supplied 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 1-st electrostatic deflector can be removed from the vacuum chamber. Possibilities of the rest elements are sufficient to extract beam to the matching point. The matching point, where beams of different type of particles and their energies should be extracted to, has the coordinates φ=308°, r=153 cm, and is situated just in front of the first element of transport line.

3 STRUCTURAL ELEMENTS

3.1 Electrostatic deflectors

The electrostatic sections are shown in Fig. 2. The septum parts of sections have water-cooling. The entrance part of the septum (thickness of 0.1 mm) is made of tungsten. Use in a deflectors design of C-shaped skeleton (stainless steel) allows to keep with a high accuracy required septum curvature at thermal loading on it due to losses of a beam up to several hundreds W.

The high-voltage electrode (titan) is not cooled by water, his entrance part is protected from hit of particles of a beam by special C-shaped diaphragm. Deflectors have a remote drive for radial moving and changing of the angle of an inclination in relation to a trajectory of a beam.

The gap between septum and a high-voltage electrode is adjusted within the limits of 4 – 15 mm without removing vacuum in the chamber of a cyclotron, the second kind of adjustment of a gap can provide its non-uniformity within the limits of 10 mm along the trajectory of a beam. Preliminary training of sections will be carried out by a high voltage within 12 hours. For the extraction of protons with the energy 35 MeV between a septum and a high-voltage electrode of the section ESD-2, 3 the gap of 5.5 mm at an entrance and 6.5 mm at an exit of the section were established, a working voltage was 45 kV (the calculation voltage was 40 kV).

3.2 Magnetic channels

The system of magnetic channels consists of three channels MC-1, 2 and 3. The design of MC-2 is shown in Fig. 3.

By means of the channel MC-1 a homogeneous decrease of a magnetic field by a value of ~0.18 T is carried out by means of steel plates with the cross sizes 2.5 × 30 mm. In the magnetic channel MC-2 by means of plates with the sizes (2.5-5) × 50 mm decrease of a magnetic field by a value of 0.18 - 0.22 T and radial focussing of a beam with a gradient 8 T/m are carried out. Additional steel plates in channels MC-1, 2 are placed in the aluminum C - shaped case and carry out the shimming of the magnetic field distortion brought by the channel in the area of the accelerated beam (the value of an average magnetic field distortion and the first harmonic is shimmed up to several Gs).

The magnetic channel MC-3 at the initial stage was designed as electromagnetic quadruple lens with the diameter of the aperture 30 mm which can provide a beam focusing in a radial direction with a gradient up to 20 T/m at a maximum level of its coil power dissipation of 1.9 kW. In area of accelerated beam the channel MC-3 creates the field perturbation not exceeding several Gs (for average field and the first harmonic). At the second stage the MC-3 was designed as a passive 3- ferromagnetic bar channel. All magnetic channels have remote adjustment of their radial position in the chamber of the cyclotron, the channel MC-3 has also additional adjustment of its angular position.

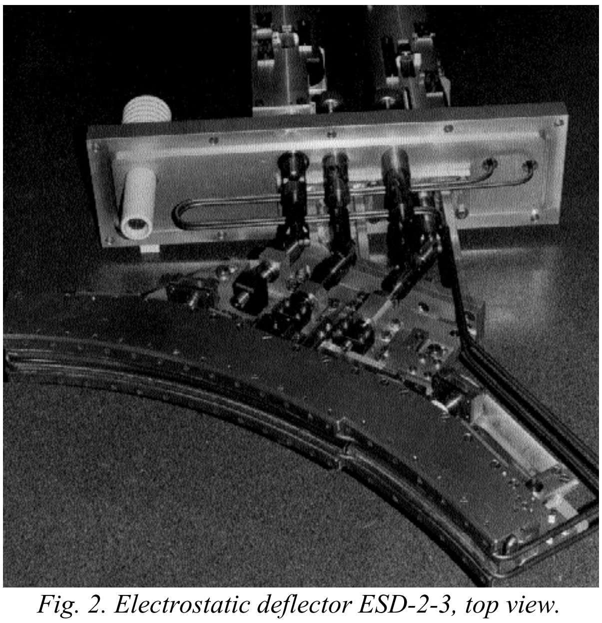

Fig. 2. Electrostatic deflector ESD-2-3, top view.

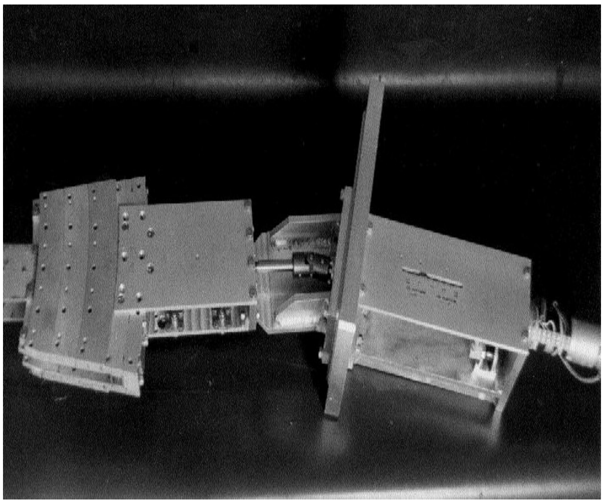

Fig. 3. Magnetic channel MC-2, entrance side.

3.3 Coils for the 1-st harmonic shaping

The value of amplitude and character of phase dependence of the magnetic field first harmonic near the radius R~60 cm are the parameters determining the characteristics of the beam turn separation enhancement in the electrostatic deflector mouth. The shaping of required characteristics of the magnetic field first harmonic (B1=2 Gs, φ_1 =0 - the phase is directed along the dee axis) was carried out by means of new cyclotron harmonic coils.

4 EXTRACTION EFFICIENCY

Commissioning of the extraction system has been done as follows:

- measurement of the radial gain enhancement without extraction system inside the vacuum chamber;
- the same but at presence of ESD-2, 3 at their working position in order to measure probable particle losses on the outer side of the septum;
- pass of the beam through ESD-2, 3, measurement of the particle losses inside them;
- step by step installation of the magnetic channels MC-1, 2, 3 together with corresponding tuning of the radial gain enhancement and measurement of the beam transport efficiency on each step.

We have observed a very high efficiency (~85%) of the beam deflection at the exit of ESD-3 when no magnetic channels had been installed inside vacuum chamber. Installation of the magnetic channels causes the necessity of additional efforts for 1-st harmonic compensation in order to improve the process of radial gain enhancement. This procedure was not very long. As a rule, 1-2 hours was enough in order to obtain extracted beam with efficiency no lower than 50%. No particle losses have been detected inside the magnetic channels.

After the accurate adjustment of the extraction system parameters (mainly careful control of the 1-st harmonic of magnetic field and position of ESD-2, 3) we have increased the extraction efficiency for 35 MeV protons up to the calculation value of 70%.

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