BEAM DYNAMICS IN A CUSTOMS CYCLOTRON WITH AN INTERNAL ION SOURCE

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A project of a complex for explosives detection on a base of a gamma resonance method is developed in Russia. The search for explosives is based on the detection of high nitrogen concentrations in a luggage. The complex consists of a cyclotron, developed in Dubna, an original storage ring, a gamma rays producing ^{13}C target, and a detecting equipment. For purposes of simplification in the cyclotron design an internal source of H$^-$ ions instead of an external beam injection was introduced and examined. The computations have shown that the beam with an energy ~1.8 MeV and current 100…200 μA would be extracted from the cyclotron with efficiency ~95%.

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1. INTRODUCTION

A scheme of the installation and the main parameters of the required cyclotron with the external injection were considered earlier in [1, 2]. Since these cyclotron beam parameters did not satisfy to needed ones, the scheme of installation was changed. The storage ring was included in the installation and the cyclotron with internal ion source and essentially smaller beam current was proposed. All computations for this cyclotron described below were subdivided into 3 regions: central, main acceleration and extraction ones.

2. CENTRAL REGION OF THE CYCLOTRON

Geometry of the central region of cyclotron together with the trajectories of ions on the first turn is shown in Fig.1. All calculations of ion dynamics were done by our code PHASCOL [3] taking into account space charge effects and making use a preliminarily prepared map of the dees electric field. The electric field simulation of the selected electrode structure was performed with the help of the well-known code "Mermaid" [4]. Fig.2 shows the electrodes structure for the cyclotron. Axial dee aperture is 20 mm. Parameters of the model: ~8×10^6 nodes, run time ~10 min, mesh step in X-Y plane – 1mm.

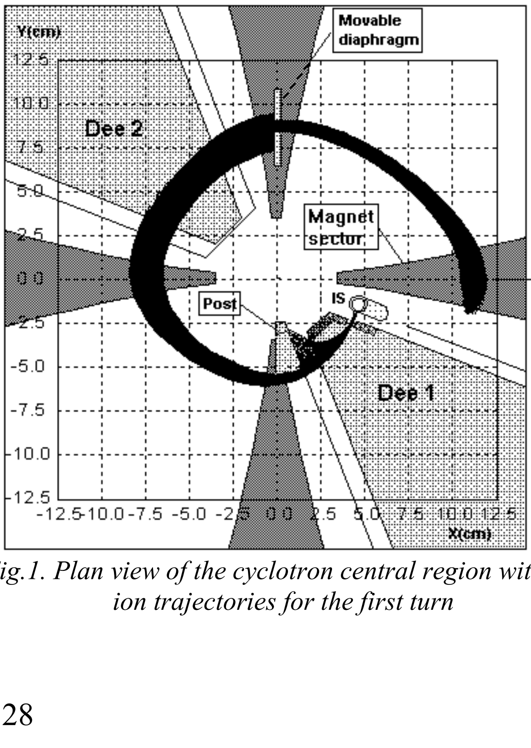

Fig.1. Plan view of the cyclotron central region with the ion trajectories for the first turn

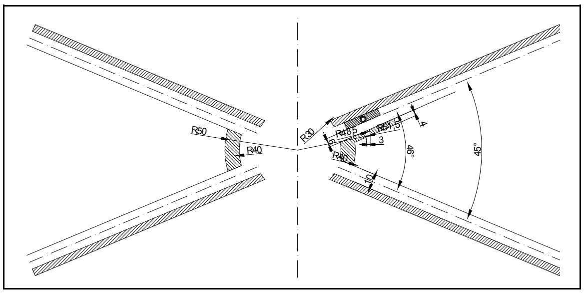

Fig.2. X-Y view of dee electrode structure

Total electric field map in the median plane of the cyclotron is illustrated in Fig.3. "Hot" spots are clearly visible near the corners of the dee tips and ground structure. The necessity for the rounding of the dee corners is quite obvious.

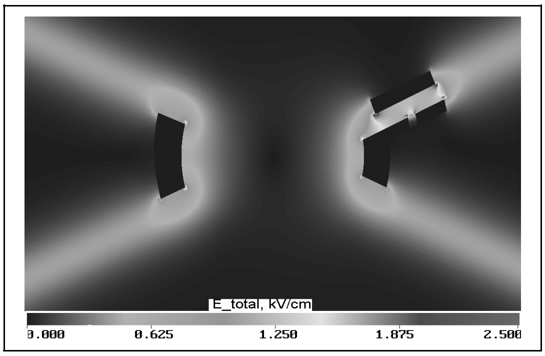

Fig.3. Contour plot of the computed electric field distribution

To be used in computation of dynamics, the map was transformed on the grid with the steps along a radius ΔR=1 mm and along the azimuth Δφ = 0.5° in the limits R= (4…30) cm, φ = (0-360)°. In the median plane two horizontal components of electric field were calculated: radial E$_r$ and azimuthal E$_φ$. Out of the median plane three components of electric field were calculated by the following formulas obtained on the basis of Maxwell's equations:

$$E_z(z) = -\frac{z}{r}\left(E_r + r\frac{dE_r}{dr} + \frac{dE_\varphi}{d\varphi}\right),$$

$$E_r(z) = E_r(z=0) - \frac{z}{r}\left[E_z + z\left(2\frac{dE_r}{dr} + r\frac{d^2E_r}{dr^2}\right)\right],$$

$$E_\varphi(z) = E_\varphi(z=0) - \frac{z^2}{r^2}\left(\frac{dE_r}{d\varphi} + \frac{d^2E_\varphi}{d\varphi^2}\right).$$

Size of the ion source (IS) output slit was supposed equal Δr×Δz=0.5×5.0 mm. Optimum position of the slit along the radius and azimuth was selected from the condition of approaching the orbits of ions to the accelerated equilibrium orbit which corresponded to the dee voltage ~50 kV.

The first accelerating gap for the extraction of ions from IS is shaped between the IS and puller. The puller overlaps the aperture of the first dee in its nose and has a window with the dimensions Δr×Δz=3.0×5.0 mm. The center of puller window is located on radius 50 mm. A width of source-puller gap is equal to 5 mm.

Selection of the optimum position of the diaphragms, which form a beam, was carried out so that to fulfill the following conditions:

- The current of the formed beam must be not less than 200 mkA, using the assumption that IS ensures 6 mA of current in the continuous regime.
- The smallest possible values of the transverse emittances of beam and energy spread in it were necessary to attain.
- The radial position of the beam on reaching the required energy must be matched with the position of the septum of electrostatic deflector of the beam extraction system.

A starting bunch of ions was formed by injecting the series of micro bunches with the energy 100 eV from the IS slit. The longitudinal dimension of each micro bunch was equal to 1°, and the transverse emittances ε_r=150 (0.06) π mm·mrad, ε_z=1000 (0.45) π mm·mrad. (Normalized values of emittances are shown in brackets). Each micro bunch contained 500 macroparticles distributed normally on the transverse phase planes and uniformly along a longitudinal direction. First micro bunch was injected when a zero voltage was on the first accelerating gap. Then, with the interval of 0.14 ns, to which corresponded ~2°RF, the injection of 32 additional microbunches was simulated. A total number of injected macroparticles was equal to 16500.

The selected position of diaphragms is shown in Fig.1. The first diaphragm is located after the yield of beam from the first dee and it occupies the azimuthal region (70…90)°. This diaphragm overlaps the part of the ion beam that has in this region a radius less than 55 mm. The second diaphragm is arranged on azimuth 270° and has a radial width of gap 6.6 mm. A center of diaphragm is located on radius 87 mm. If we accept as 100% – number of ions which started from the IS in the period of injection 4.62 ns, then 7% ions will fall on the first dee nose, 64% will be delayed by the post (1-st diaphragm), 12% will remain on the walls of the second diaphragm and 17% will be obtained for further acceleration. Calculations showed that the following power of beam will be set down on the diaphragms: 1-st diaphragm ~100 W, 2-nd diaphragm ~30 W. Approximately 3000 macroparticles were accelerated up to final energy.

2. MAIN ACCELERATION REGION

The ions reach the final energy ~1.8 MeV through 9 turns. In Fig.4 the trajectories of ions during entire cycle of acceleration are shown. The dependence of the bunch phase width on the azimuth is shown in Fig.5. In the beginning of acceleration the bunch phase width increases up to 110°RF. As a result of acting the diaphragms on the first turn the width of bunch decreases to ~15°RF and remains similar to the end of acceleration.

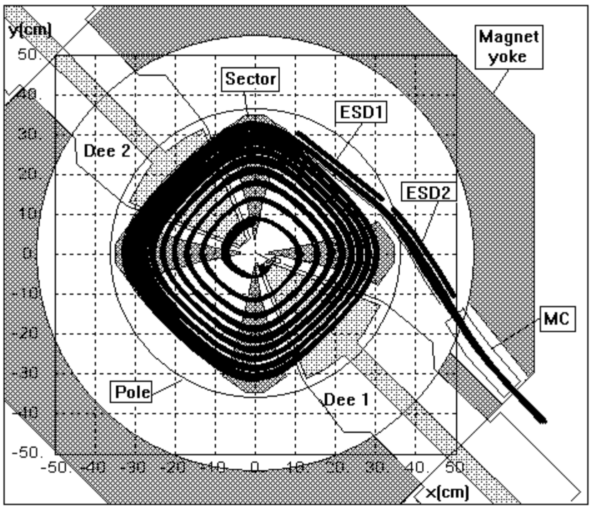

Fig.4. Plan view of the whole acceleration region of the cyclotron with extraction system

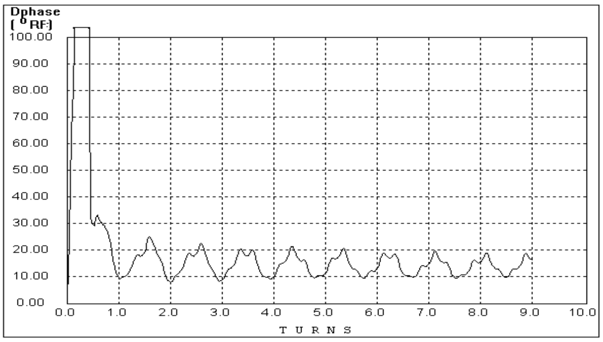

Fig.5. Bunch phase width versus turn number of acceleration

Axial motion of ions is demonstrated in Fig.6. Amplitude of the axial oscillations of ions does not exceed 5 mm within the whole region of acceleration.

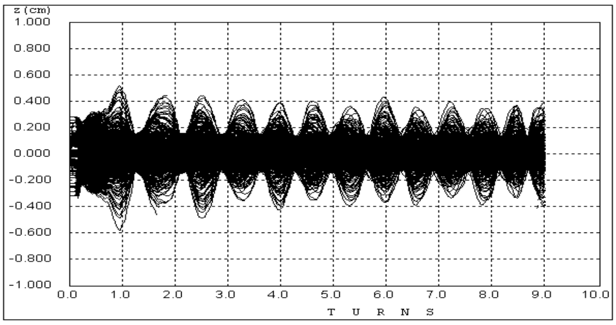

Fig.6. Ion axial motion versus turn number of acceleration

Position of ions on the phase planes and on the plane radius-energy is shown in Figs.7, 8. The final rms values (±2σ) of the beam transverse emittances are equal: ε_r=50 π mm·mrad, ε_z=9 π mm·mrad. The ions are distributed inside an angle range of the transverse impulses ±10 mrad and ±5 mrad in horizontal and vertical planes, respectively. The average energy of beam is equal 1.82 MeV, energy spread is ±2.5%.

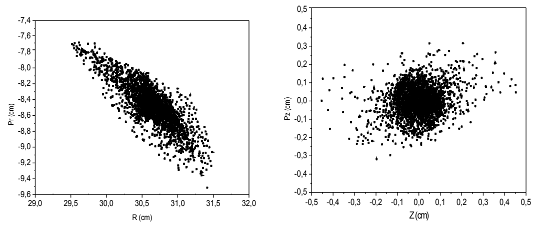

Fig.7. Position of 3000 ions on the transverse phase planes at azimuth of the deflector entrance. To the left – radial plane, to the right – axial one

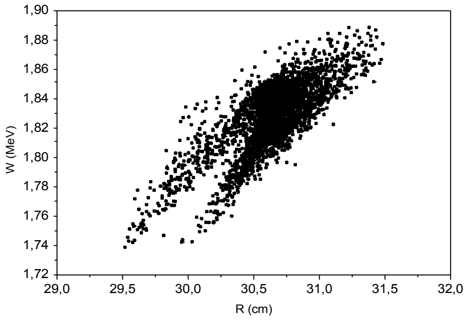

Fig.8. Position of ions on the plane radius-energy at azimuth of the deflector entrance

2.3. BEAM EXTRACTION SYSTEM

The position of the extraction system elements was schematically drawn in Fig.4. The system of extraction consists of two electrostatic deflectors ESD1 and ESD2 with the strength 26 kV/cm of electric field and permanent magnet MC with magnetic field -0.2 T at the center of their apertures. To compensate the beam defocusing in the horizontal plane arisen by the action of edge magnetic field the deflectors ESD1 and ESD2 must have the gradients of electric field -3.7 and -14.8 kV/cm^2, respectively. The magnetic field gradient in the horizontal plane of the MC is 0.03 T/cm. RMS beam envelopes (2σ) are shown in Fig.9.

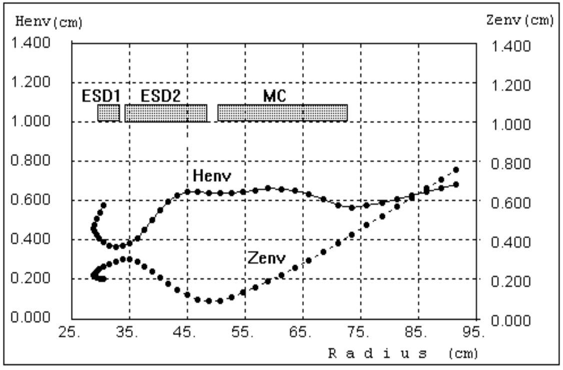

Fig.9. Horizontal Henv and vertical Zenv beam envelopes inside extraction system versus radius of central ion

Computations have shown that an extraction efficiency is about of ~95%. The basic losses of particles are observed at the entrance into the first deflector of the extraction system.

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ДИНАМИКА ПУЧКА В ТАМОЖЕННОМ ЦИКЛОТРОНЕ С ВНУТРЕННИМ ИСТОЧНИКОМ ИОНОВ

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Проект комплекса для обнаружения взрывчатых веществ на базе гамма-резонансного метода разрабатывается в России. Поиск взрывчатки основан на детектировании высоких концентраций азота в объектах багажа. Установка состоит из циклотрона, который разрабатывается в Дубне, небольшого накопительного кольца, гамма-мишени и детектирующей аппаратуры. В целях упрощения конструкции циклотрона используется внутренний источник H$^-$ ионов вместо их аксиальной инжекции. Расчеты показывают, что пучок с энергией ~1.8 МэВ и током 100...200 мкА может быть выведен из циклотрона с эффективностью ~95%.

ДИНАМІКА ПУЧКА В МИТНОМУ ЦИКЛОТРОНІ ІЗ ВНУТРІШНІМ ДЖЕРЕЛОМ ІОНІВ

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Проект комплексу для виявлення вибухових речовин на базі гамма-резонансного методу розробляється в Росії. Пошук вибухівки заснований на детектуванні високих концентрацій азоту в об'єктах багажу. Установка складається із циклотрона, що розробляється в Дубні, невеликого накопичувального кільця, гамма-мішені і апаратури для детектування. З метою спрощення конструкції циклотрона використано внутрішнє джерело H$^-$ іонів замість їхньої аксіальної інжекції. Розрахунки показують, що пучок з енергією ~1.8 МеВ і струмом 100...200 мкА може бути виведений із циклотрона з ефективністю ~95%.