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SIMULATION OF BEAM EXTRACTION FROM TR24 CYCLOTRON AT IPHC

N. Kazarinov#, I. Ivanenko, JINR, Dubna, Russia
F.Osswald, T. Adam, E. Traykov, IPHC/IN2P3/CNRS, Unistra, 67037 Strasbourg, France

Abstract

The CYRCé (CYclotron pour la ReCherche et l'Enseignement) TR24 cyclotron is used at IPHC (Institut Pluridisciplinaire Hubert Curien) for the production of radio-isotopes for diagnostics, medical treatments and fundamental research in radiobiology. The TR24 cyclotron produced and commercialized by ACSI delivers a 16-25 MeV proton beam with intensity from few nA up to 500 µA. The TR24 is a compact isochronous cyclotron with normal-conducting magnet and stripper foil for the beam extraction. The calculation model for OPERA 3D program code is described. The magnetic field map in the working region of the cyclotron is generated. The beam characteristics outside the cyclotron, that will serve as initial conditions for the design of future beam lines are determined.

INTRODUCTION

The study of beam extraction from TR24 [1] cyclotron is mandatory for the design of the future beam lines and the specification of the performances in regard of the different applications. The simulation of the ion trajectories for different azimuthal positions of the stripper, the influence of energy dispersion taking into account the 3D cyclotron fringe field and field of the combo magnet will help us to define the reference orbit, the best beam extraction and the optimal settings of the optical elements.

MAIN PARAMETERS OF PROBLEM

H⁻ ion beam is produced in the CUSP ion source [2] with kinetic energy of 30 keV The beam emittance is strongly dependent on beam current.

For H^- ion beam currents equal to 5 mA the initial beam emittance is equal to 50 π·mm·mrad. The main parameters of the TR24 cyclotron and H- ion beam are indicated in Table 1.

CYCLOTRON MAGNETIC FIELD

The main magnet of TR24 compact cyclotron is intended to produce the isochronous magnetic field with the level of 1.36 T at the cyclotron centre. Magnet has 170 x 170 x 110 cm closed yoke with pole diameter of 120 cm. Four azimuthally-profiled sectors provide the isochronous acceleration and focusing of the H^- beam up to the extraction radius of about 51 cm.

For analysis of the extraction efficiency and beam characteristics along the extraction trajectory a 3D computer model of the cyclotron magnet was created. Magnetic field calculations were performed with TOSCA OPERA 3D. The calculated average magnetic field and flutter distributions along cyclotron radius are presented in Fig. 1.

Table 1: Cyclotron and H^- Beam Parameters

Parameter	Value
Center magnetic field, T	1.36
RF frequency, MHz	85.085
Harmonic number	4
Dee voltage, kV	50
Number of dee	2
Maximum extraction radius, cm	51
Charge	-1
Mass number	1
Maximum current, mA	5
Injection energy, keV	30
Extraction energy, MeV	18-24
Injected Beam emittance, π·mm·mrad	50

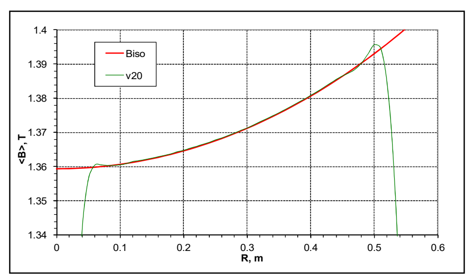

Figure 1: Isochronous (red line) and simulated (green line) average magnetic field.

The results of calculations are used for trajectory analysis of the extracted beam from the last orbits to the object point in the beam transporting line placed beyond the cyclotron at the entrance of the combo magnet at radius of 132 cm. The median plane distribution of the inner magnetic field, the field in the yoke and the field outside magnet up to 150 cm from cyclotron center is shown in Fig. 2.

CLOSED AND EXTRACTION ORBITS

In contrast to [3], closed orbits exist for the entire range of output energies without any correction of the average magnetic field.

The closed and extraction orbits for extraction energy W_{ex} range (Table 1) are shown in Fig. 3.

The main parameters of the closed orbits for various values of the extraction energy W_{ex} at extraction point are shown in Figs. 4-5.

#nyk@jinr.ru

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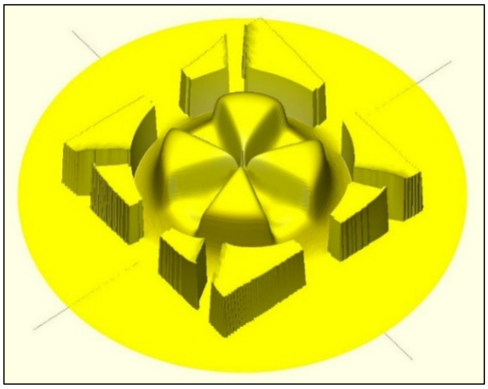


Figure 2: The distribution of the inner and outer magnetic field in median plane of the cyclotron.

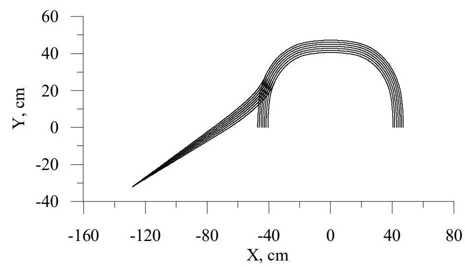
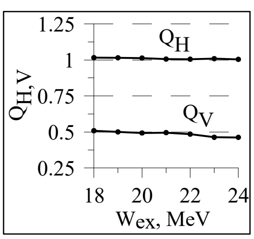


Figure 3: Closed and extraction orbits for extraction energy range 18 MeV ≤ W_{ex} ≤ 24 MeV.



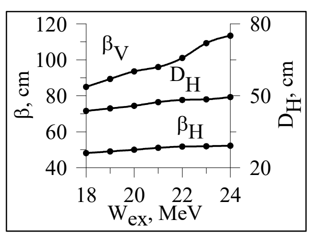
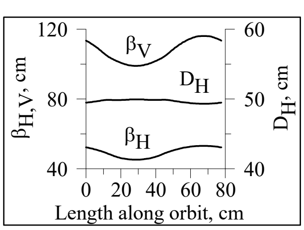


Figure 4: Frequencies $Q_{H,V}$.

Figure 5: Horizontal (H) and vertical (V) β-functions. Dispersion function D_H.

Periodic solutions for betatron functions $\beta_{H,V}$, and dispersion function D_H can be obtained by using the calculated values and its derivative with respect to length along the orbit as initial conditions. These solutions for the closed orbit corresponding to the extraction energy W_{ex} = 24 MeV are shown in Fig. 6.



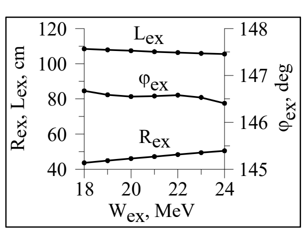


Figure 6: Periodic solutions for $\beta_{H,V}$ and D_H, W_{ex}=24 MeV.

Figure 7: Extraction radius R_{ex}, angle φ_{ex} and orbit length L_{ex}.

The extraction orbit begins at the point with the coordinates (R_{ex}, φ_{ex}) of the closed orbit corresponding to extraction energy W_{ex}. The angle φ_{ex} and the length of the extraction orbit L_{ex} have to be fitted to provide the coincidence of the radial and angular position of the final point in focusing plane with the position of the object point of the beam line. The dependencies of extraction radius R_{ex}, angle φ_{ex} and orbit length L_{ex} on energy W_{ex} are shown in Fig. 7.

STRIPPING FOIL POSITIONING

The angular position of the stripping foil coincides with extraction angle φ_{ex}. Its radial position depends on extraction energy W_{ex}, extraction radius R_{ex} and the energy gain per turn ΔW. For TR24 cyclotron the value ΔW is equal to 0.2 MeV. The energy gain ΔW leads to the increasing of the extraction radius by amount $\Delta R = 2$ mm. With this definitions the inner bound of the stripping foil is defined as $R_f = R_{ex} - \Delta R/2$.

ION DISTRIBUTION AT STRIPPING FOIL

The ion distribution at the stripping foil is dependent on the horizontal dimension a_H of the beam. The value of the horizontal dimension a_H is approximately constant in the extraction energy range and may be evaluated as $a_H = 5$ mm. The ratio $a_H/\Delta R$ define the number of turn N_t that is needed for 100% beam extraction:

$$N_t = \lceil a_H/\Delta R \rceil = 3 \ ; \ N_{sh} = N_t - 1 = 2 \qquad (2)$$

The number Nsh defines the value of the shift from initial radius R_i and energy W_i of the beam to the extraction ones R_{ex} and W_{ex}:

$$R_{ex} = R_i + N_{sh}\Delta R \ ; \ W_{ex} = W_i + N_{sh}\Delta W \qquad (3)$$

The distribution of the ions accumulated at stripping foil was found by macro particle simulation. The coordinates of each particle in five-dimensional phase space was transformed by means of one turn transfer matrix for each N_t extracted turns. The particle that had radius greater than R_f was accumulated and do not consider in the calculations of the next turns. The distributions of the ion with extraction energy of 24 MeV in the various phase space planes are shown in (Figs. 8, 9).

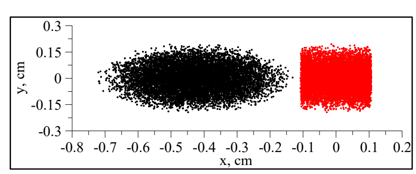


Figure 8: Plane (x,y). Accelerated beam – left, beam at stripping foil – right.

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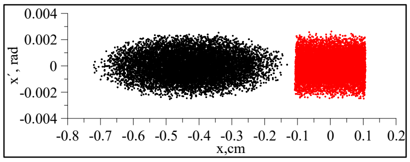

Figure 9: Horizontal plane (x, x′). Accelerated beam - left, beam at stripping foil – right.

The beam distribution in vertical plane (y, y′) (see Fig. 10) does not differ significantly from accelerated one.

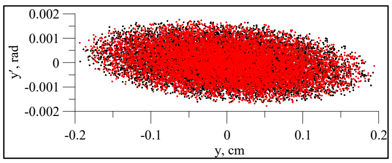

Figure 10: Plane (y, y′). Accelerated beam – black dots, beam at stripping foil – red dots.

ION DISTRIBUTION AT OBJECT POINT

The betatron functions $\beta_{H,V}$ and dispersion function D_H along the extraction orbit from the stripping foil to object point of the beamline are shown in Fig. 11.

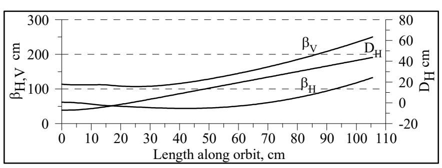

Figure 11: The betatron $\beta_{H,V}$ and dispersion D_H functions along the extraction orbit at 24 MeV.

The changing of the rms beam emittance along the extraction orbit is shown in Fig. 12. Due to the influence of the momentum spread, the horizontal rms emittance changes in the presence of a non-zero bending magnetic field of the cyclotron.

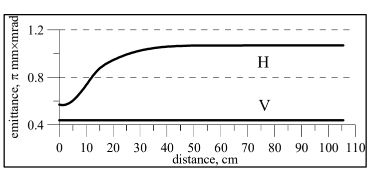

Figure 12: The horizontal (H) and vertical (V) rms beam emittance along the extraction orbit at 24 MeV.

The ion distributions in horizontal (x, x′) and vertical (y, y′) planes at the object point of the beamline are shown in (Figs. 13, 14).

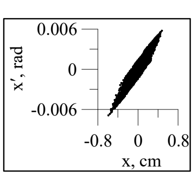

Figure 13: Plane (x,x′).

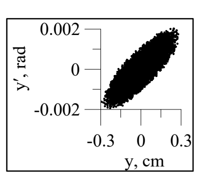

Figure 14: Plane (y,y′).

TRANSPORT IN BEAMLINE

The initial part of experimental beam-line [4] is shown in Fig. 15. The betatron functions $\beta_{H,V}$ and dispersion function D_H along the beamline from the object point to DIAG2 are shown in Fig. 16 (quads are switched off).

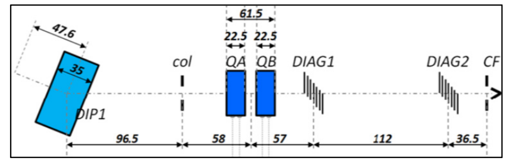

Figure 15: Experimental beam line [4]. *DIP1* – combo magnet; *QA*, *QB* – quadrupole lenses; *DIAG1,2* – diaphragms, *CF* – Faraday's cap.

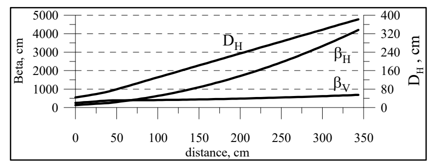

Figure 16: The betatron $\beta_{H,V}$ and dispersion D_H functions along the experimental beamline at 24 MeV.

The changing of the rms beam emittance along the experimental beamline is shown in Fig. 17. The horizontal rms emittance changes in the presence of a non-zero bending magnetic field of the combo magnet.

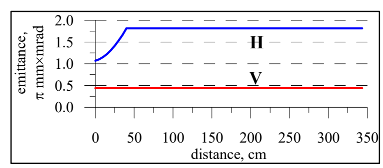

Figure 17: The horizontal (H) and vertical (V) rms beam emittance along the experimental beamline.

The ion distribution in the plane (x, y) at the DIAG2 is presented in Fig. 18. The horizontal ion density at the same point is given in Fig. 19.

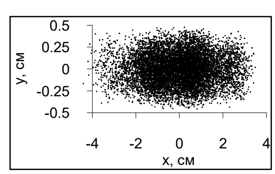

Figure 18: The ion distribution at DIAG2.

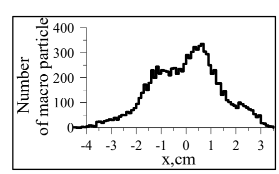

Figure 19: The horizontal ion density at DIAG2.

The horizontal ion density has a multi-peak form as it was observed in [4]. This is explained by presence in the extracted beam of three groups of the ions with energies of $W_{ex} - \Delta W$, W_{ex} and $W_{ex} + \Delta W$.

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