ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK007

BEAM EXTRACTION FROM TR24 CYCLOTRON AT IPHC

N. Kazarinov#, I. Ivanenko, JINR, Dubna, Russia
F. Osswald, IPHC/IN2P3/CNRS, University of Strasbourg, France

Abstract

The CYRCé cyclotron (CYclotron pour la ReCherche et l'Enseignement) 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 18-24 MeV proton beam with intensity from few nA up to 500 µA. Field distribution in the region of the extraction performed with OPERA 3D as well as beam dynamics related with stripping are analysed. 3D calculation model and hypothesis about geometry and beam are described. The TR24 is a compact isochronous cyclotron with normal-conducting magnet and stripper foil. It is a challenge to fit the high intensity proton beam used for target irradiation to radiobiology and analytical applications due to requirements on beam quality and energy resolution. Our goal is to evaluate the extraction efficiency and the beam characteristics in the focusing plane outside the cyclotron, which will serve as inputs for the design of future beam lines and enable beam matching conditions. Therefore, different issues are discussed: energy dispersion, transverse dynamics and orbit separation.

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 fringe field will help us to define the reference orbit, the best beam extraction and the optimal settings of the optical elements.

CYCLOTRON AND ION BEAM PARAMETERS

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.

Table 1: Cyclotron and H^- Beam Parameters

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

#nyk@jinr.ru

CYCLOTRON MAGNETIC FIELD

The main magnet of TR24 compact cyclotron is intended to produce the isochronous magnetic field with the level of 1.36T 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 51cm.

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.

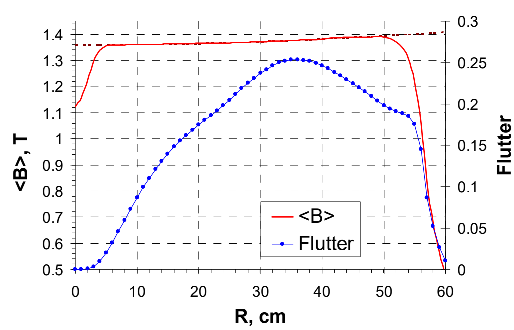

Figure 1: Average magnetic field and flutter.

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 radius of 120 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.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK007

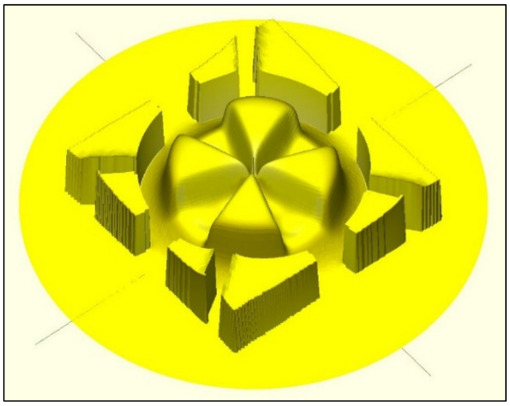

Figure 2: The distribution of the inner and outer magnetic field in median plane up to 150 cm from cyclotron center.

CLOSED AND EXTRACTION ORBITS

Unfortunately in the calculated field map $B(r,\varphi)$ the closed orbits of accelerated beam can be calculated for kinetic energy not greater than 23.5 MeV. Therefore the map $B(r,\varphi)$ has been modified to $B_{mod}(r,\varphi)$ for the range of radius 47 cm < r <55 cm by using the averaged $<B(r)>$ and isochronous $B_{is}(r)$ magnetic fields:

$$B_{mod}(r,\varphi) = B(r,\varphi) + (B_{is}(r) - < B(r) >) \qquad (1)$$

The closed and extraction orbits for extended extraction energy Wex range are shown in Fig. 3.

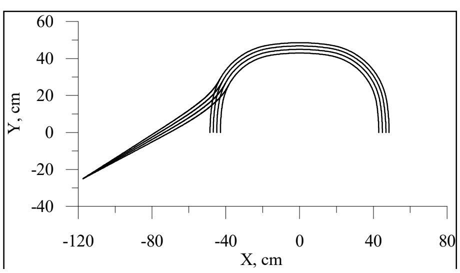

Figure 3: Closed and extraction orbits for extended extraction energy range 18 MeV < W_{ex} < 25 MeV.

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

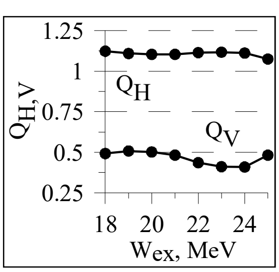

Figure 4: Betatron frequencies $Q_{H,V}$.

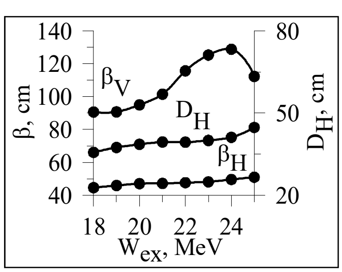

Figure 5: Horizontal (H) and vertical (V) β-functions. Dispersion function D_H.

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

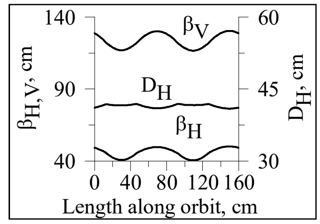

Figure 6: Periodic solutions for $\beta_{H,V}$ and D_H. W_{ex}=24 Mev.

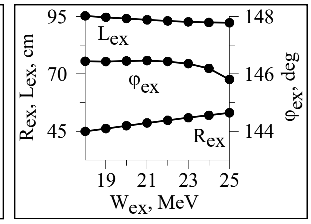

Figure 7: Extraction radius R_{ex}, angle φ_{ex} and orbit length L_{ex}.

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 ΔR=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 $a_H/\Delta R$ defines 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 N_{sh} 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 was transformed

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK007

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.

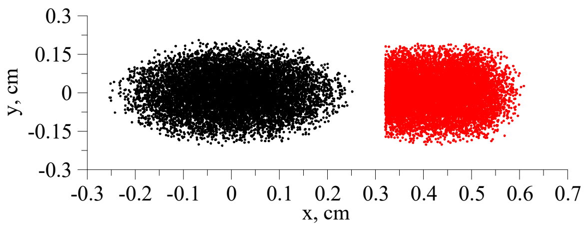

Figure 8: Plane (x,y). Accelerated beam – left, beam at stripping foil – right.

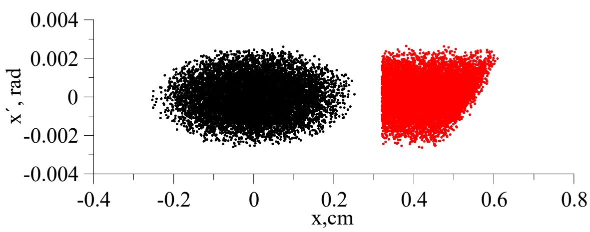

Figure 9: Plane (x,x′). Accelerated beam – left, beam at stripping foil – right.

The accumulated beam distribution in plane (y,y′) does not differ significantly from accelerated one.

The horizontal betatron functions at stripping foil position was changed to values β_H =46.0 cm, α_H = 0.18, ε_{rmsH} = 0.38 π mm×mrad. The dispersion function D_H = 32.9 cm, D'_H = 0.15, momentum spread $(\Delta p/p)_{rms}$ = 1.6 10^{-3}.

The coherent displacement and energy spread have negligibly small values for the chosen foil inner bound R_f. This position is optimum and its changing lead to increasing of the coherent displacement and energy spread. The coherent horizontal angle was not changed and equal to about 1 mrad in spite of the small variation of R_f.

The vertical betatron functions and emittance approximately coincide with the ones of accelerated beam and are equal to: β_V =128.5 cm, α_V = 0.16, ε_{rmsV} = 0.44 π mm×mrad.

ION DISTRIBUTION IN 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 beam line are shown in Fig.10.

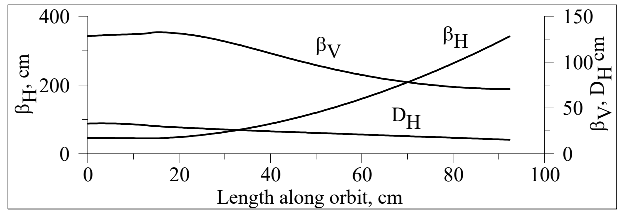

Figure 10: The betatron $\beta_{H,V}$ and dispersion D_H function along the extraction orbit.

The ion distributions in plane (x,y) and plane(x,x′) at the object point of the beam line are shown in Fig.11,12.

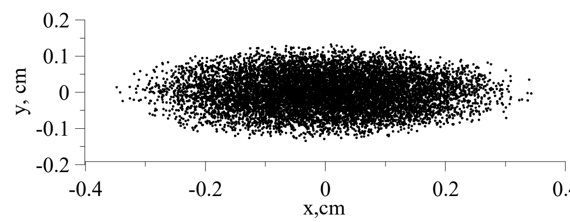

Figure 11: Ion distribution at object point in plane (x,y).

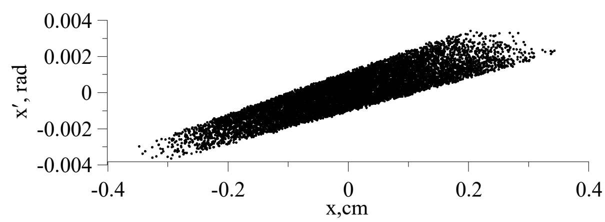

Figure 12: Ion distribution at object point in plane (x, x′).

REFERENCES

[1] Advanced Cyclotron Systems Inc., http://www.advancedcyclotron.com/cyclotron-solutions/tr24/.

[2] K. Jayamanna, M. McDonald, P. W. Schmor, D. H. Yuan, "The TRIUMF Compact DC H-/D- Ion Source", in *Proc. EPAC'90*, 12-16 June 1990, Nice, France, pp. 647-649. http://www.JACoW.org/