HIGH EFFICIENCY STRIPPING EXTRACTION
IN THE 80-MeV H^- ISOCHRONOUS CYCLOTRON AT PNPI

S.A. Artamonov, A.N. Chernov, E.M. Ivanov, G.A. Riabov, V.A. Tonkikh

1. Introduction

The start up of a new high intensity isochronous cyclotron with the design beam energy from 40 up to 80 MeV and beam current of 100 μA was announced in November 2016. The cyclotron is intended for production of high quality medicine isotopes, organization of eye melanoma treatment facility, treatment of surface forms of cancer and radiation resistance tests of the electronics for the aviation and space research [1].

The H^- cyclotron has the advantage that the high intensity internal beam can be extracted from the acceleration chamber with practically 100% efficiency by transformation of H^- ions into H^+ ions by using a thin foil. The extraction system consists of a probe with a stripping foil, an extraction window in the vacuum chamber and two aligning magnets to match the extracted beam with the beam transport line. The beam optics calculations in the measured magnetic field make it possible to find the optimal relative position of the extraction system elements as well the parameters of the extracted beam with the energy 40–80 MeV. At present, the beam is extracted from the chamber with the efficiency about 100% and there is good agreement with the optic calculations.

The external view of the cyclotron and the first part of the beam transport line are presented in Fig. 1. Basic parameters of the cyclotron are summarized in Table 1.

Fig. 1. The external view of the C-80 cyclotron and the beginning part of the transport line

Table 1

Characteristics of the C-80 cyclotron

Parameter	Value
Magnet	
Pole diameter	2.05 m
Valley gap	386 mm
Hill gap (min)	163 mm
Number of sectors	4
Spiral angle (max)	65°
Magnetic field in the centre	1.352 T
Flatter (max)	0.025
Extraction radius	0.65–0.90 m
Extracted beams	
Energy	40–80 MeV
Method	Stripping

A 3D sketch of the cyclotron and the extraction system are presented in Fig. 2. A schematic view of the extraction system is presented in Fig. 3.

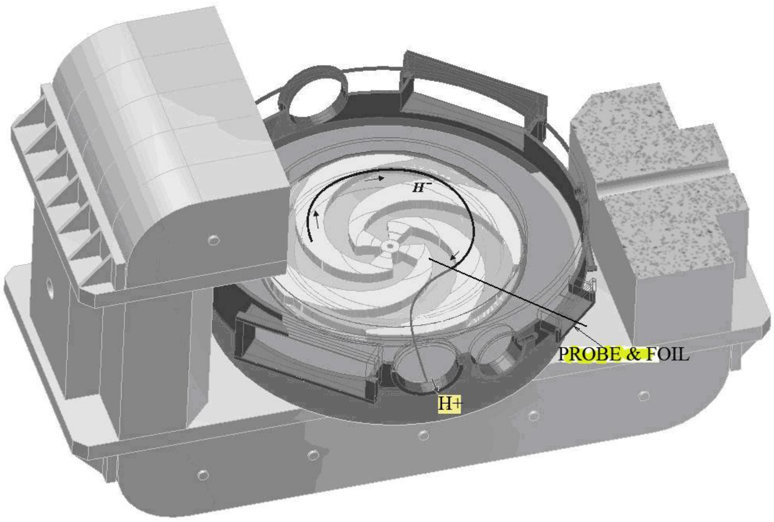

Fig. 2. 3D sketch of the C-80 cyclotron and the extraction system

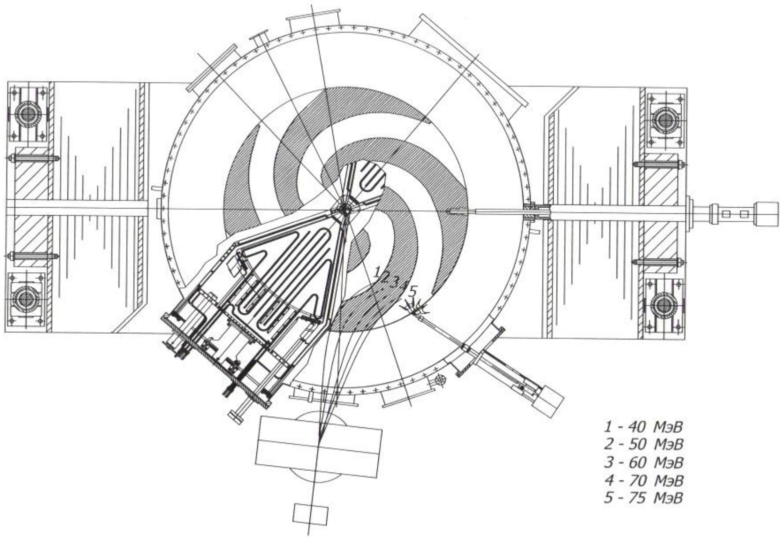

Fig. 3. Schematic view of the extraction system of the C-80 cyclotron

2. Magnetic field

To design the extraction system, it is necessary to know the magnetic field as in the acceleration region, so on the edges. For that reason, the residual magnetic field was measured up to the radius of 230 cm.

The C-80 cyclotron has some specific features in the magnetic structure. As can be seen from Table 1, the magnetic structure with very low flatter and very high spiral angles (up to 65°) is used in the cyclotron. Such a structure makes it possible to decrease the magnetic field in the hill region to avoid beam losses due to electro-dissociation of H^- ions. As a result, it permits acceleration of H^- ions up to an energy of 80 MeV using a magnet with the pole diameter of 2 m and keeping the beam losses below 3%. A detailed description of the magnetic structure can be found in RUPAC-2014 report [2]. The final magnetic field of the C-80 cyclotron is presented in Fig. 4.

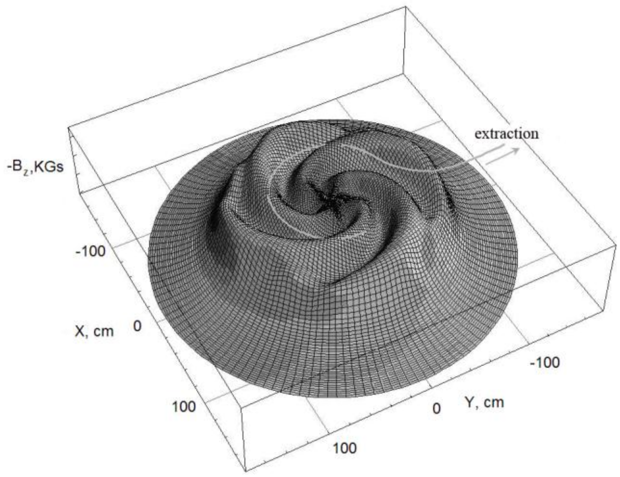

Fig. 4. Magnetic field of the C-80 cyclotron

3. Reference trajectories

One of the problems in designing of the extraction system is to determine the relative positions of the stripping foil and the extraction window in the vacuum chamber. As a first approximation, the positions of the foil and the window were estimated on the basis of simulated closed orbits in the calculated magnetic field. The particle trajectories started from the closed orbits. It was necessary to provide that the participles of different energies pass throw the extraction window and enter the entrance of the aligning magnet. This was achieved by varying the stripper position along the radius and azimuth. Trajectories of the extracted particles are shown in Fig. 5.

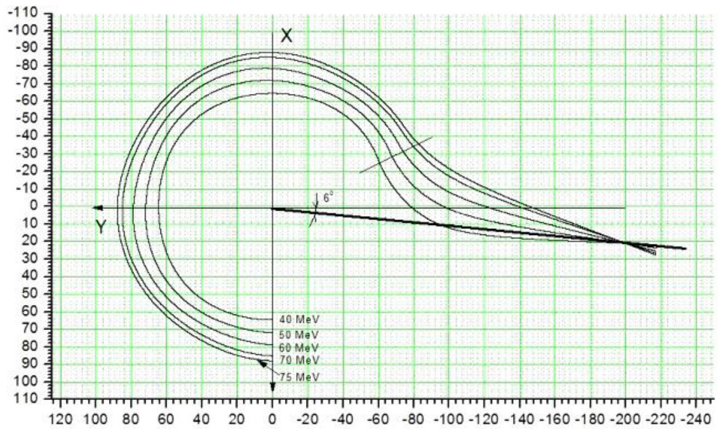

Fig. 5. Trajectories of the extracted particles

As a result of these calculations, it was established that the full energy in a range from 40 up to 80 MeV can be obtained when the stripper foil is moved along a nearly straight line in the coordinate system shown in Fig. 5 (the line equation is $y = 0.88857x – 36.27$). The maximal deviation from the straight line does not exceed a few centimeters.

An original stripper probe with three stripper foils was designed for the C-80 cyclotron. The probe can be moved along the straight line, and in addition each foil can move along the azimuth by 5 cm. As a result, it permits to obtain the whole energy range by moving the probe along the straight line. The reference trajectory calculations made possible to estimate the main parameters of the extraction system: the position of the extraction window in the vacuum chamber, the position and movement ranges of the stripper foil, the arrival points of particles with different energies at the aligning magnet entrance, the direction of the extracted beam and the necessary angle range for the aligning magnet. The direction of the extracted beam is ~ 6° with respect to the longitudinal axis of the cyclotron magnet as it is shown in Fig. 5. The deviation angle in the aligning magnet is varied from 15 up to –4°.

4. Beam optics calculation

Besides the reference trajectory, it was necessary to determine the size and divergence of the beam near the reference trajectory to design the beam transport line.

The computer simulations [3] were used to determine both the reference trajectory and the beam optics. In the linear approximation, the movements in the vertical and horizontal planes are independent, and the beam behaviour can be described by two independent phase ellipses. The starting ellipse size at the stripper in the vertical plane is defined assuming that the maximum beam size in the cyclotron is about 6 mm. The divergence and orientation of the ellipse in the phase space of the vertical plane repeat these parameters of the matched with the magnetic structure ellipse at the radius and azimuth of the stripper. The beam spot at the stripper is supposed to be 3 mm in the horizontal plane and the divergence and orientation of the phase space ellipse corresponds to the matched ellipse. An example of evolution of the phase ellipses in the extraction process for 70-MeV beam is shown in Fig. 6.

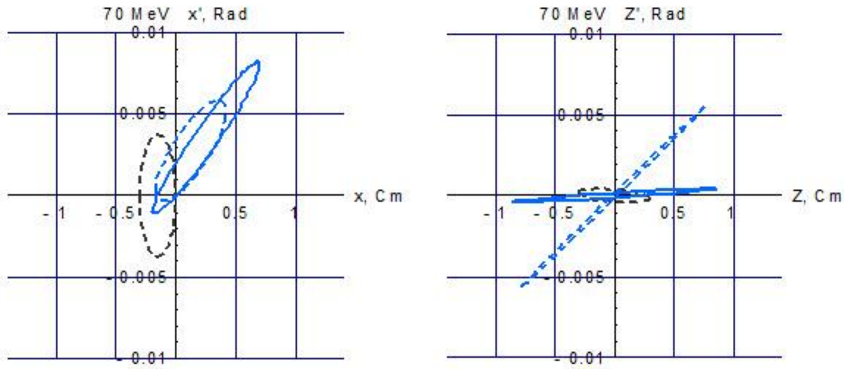

Fig. 6. Phase ellipses for 70-MeV beam in the extraction process: the *black dotted line* corresponds to the stripper position; the *blue dotted line* corresponds to the entrance of the aligning magnet and the *blue solid line* corresponds to the exit of the magnet

Figure 7 shows the evolution of the beam envelopes from the stripper foil up to the exit of the aligning magnet for the 70-MeV beam. After the stripper foil, the beam is exposed to defocusing forces in the horizontal and vertical planes.

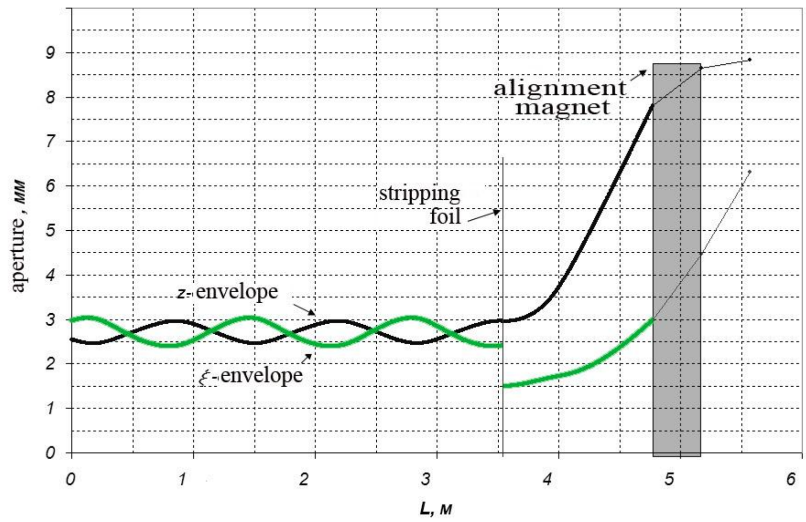

Fig. 7. Transformation of the beam envelopes in the extraction process

The calculated parameters of the beam ellipses at the aligning magnet are presented in Table 2.

Table 2

Twiss beam ellipse parameters at the alignment magnet entrance*

T, MeV	40		70	
	ξ	*z*	ξ	*z*
α	–1.793	–5.079	–3.562	–3.123
β, mm/mrad	5.801	5.010	3.559	62.220
γ, mrad/mm	0.727	5.348	3.845	0.173
ε, mm · mrad	5.4	3.8	5.6	1.2
D, cm	105		51	
D^1, rad	1.03		0.52	

* For details see Ref. [3].

5. Trajectory calculations in the experimentally measured magnetic field

At the final stage, 500 particle trajectories were calculated with random start conditions in the experimentally measured magnetic field map from the inflector exit up to the entrance of the aligning magnet. These calculations confirmed to a great extent the previous results for the positions of the stripper foil and the extraction window, the direction of the extracted beam and the beam parameters. In addition, it was found that the beam spot in the horizontal plane on the stripper foil is 3 mm, as it was assumed in the previous calculations. The energy uncertainty is about 1%. Furthermore, it was found that the internal beam quality strongly depends on the cyclotron tuning, in particular on the central optics tuning, and on the first and third harmonics of the magnetic field. It is interesting to note that the second and fifth harmonics have no effect on the beam emittance.

6. Experiment

The physical start up of the C-80 cyclotron was in summer of 2016. The design beam parameters were achieved in November 2016. The extracted beam was obtained in the energy range from 40 up to 78 MeV. The extraction efficiency estimated as a ratio of the current on the first in beam line Faraday cup and the current on the internal probe was 80–100%. The beam was directed into the beam line, which position was defined from computer simulations. The beam energy could be changed by moving the stripper probe along the calculated line. The results of computer simulations were confirmed by experiment.

Optimization of the beam line and the tuning of the cyclotron regime are planned for the near future.

Acknowledgment

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References

1. Yu.N. Gavrish *et al.*, in *Proc. of XXV Russ. Particle Accelerator Conf. (RuPAC 2016), St. Petersburg, 21–25 Nov., 2016*, TUCASH04, pp. 176–178.
2. S.A. Artamonov *et al.*, in *Proc. of XX Int. Conf. Beam Dynamics & Optimization, BDO-2014, St. Petersburg, 30 June – 04 July, 2014*, pp. 18–19.
3. N.K. Abrossimov *et al.*, Preprint PNPI-2851 (2010).
4. N.K. Abrossimov *et al.*, Preprint PNPI-2858 (2011).