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MAGNETIC FIELD OF THE 40–80 MEV H^- CYCLOTRON C-80: EXPERIMENTS AND CALCULATIONS

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Abstract

The paper concerns to the final parameters of the magnetic field distribution of the new H-minus isochronous cyclotron C-80 and results of 3D computer calculations and experimental measurements before the installation of the vacuum chamber into the cyclotron gap. The cyclotron C-80 with variably energy 40 - 80 MeV and current up to 100 µA is planned to be used as for applied physics program – for production of medicine isotopes, for therapy of eye melanoma and surface forms of cancer, for radiation resistance tests of electronic components – as well as for fundamental research in nuclear physics, solid state physics and biology.

GENERAL DESCRIPTION

The magnet and the magnetic system are the most important part of the cyclotron, and a considerable attention was paid to their design. The magnetic field of the cyclotron C-80 should meet several requirements. The magnetic field rigidity at the final orbit must reach Br = 13.2 kGs·m, which corresponds to 80 MeV energy of the proton beam. For insuring the isochronism, the magnetic field averaged over the azimuth when going from the centre of the magnet to the final orbit should increase by ~8.5%. The azimuthal variation of the magnetic field should provide the vertical and horizontal transversal focusing. Some room should be left for a high frequency system: the gap between the shims should be wider than 160 mm. In distinction from a standard cyclotron, there is an additional and essential requirement for an H^- machine – to keep H-minus losses due to dissociation less than some percent. Acceleration of H^- ions has obvious advantages: a possibility for 100 % extraction of the beam with high intensity and variable energy. On the other hand, it requires a special source of H^- ions, high vacuum, and what is most important, the magnetic field strength in the magnet sector should not exceed in our case 16.8 kGs to prevent H^- electromagnetic dissociation.

2D CALCULATION AND OPTIMIZATION

A few years ago, as a first approximation, the magnetic structure of the cyclotron was designed on the basis of 2D calculations by using the POISSON program and measurements on two small models [1-3]. The geometry and the key parameters of the magnetic system for the cyclotron were selected:

The major unit of the cyclotron, its electromagnet, was designed using the model of the magnet of the PNPI SC-1000 synchrocyclotron (SP-72). This electromagnet has been a traditional design with an E-shaped magnet yoke and a pole of 1.5 m in diameter with gap 289 mm. The calculations have showed that simple increasing of the pole radius from 0.75 m to 1.025 m causes not only the increasing of the magnetic flow up to more than1.6 of previous value but and the saturation the iron in the pole end. Therefore the cross section of the yoke has been increased by 16% and the height of the side pillar decreased by 0.5 m. These procedures allowed decrease the maximum field in the magnet yoke down to 23.5 kGs, decrease the excitation current down to 800 A and reduce the power consumption down to 120 kW.

Also the hill and valley gaps were chosen by the method of the filling factors [4] that was adapted to cyclotron. It was supposed that the initial height of each of the sectors would be equal to 90 mm, and during further optimization it was not changed. For obtaining the required isochronism, the height of the correction sector shims was varied. The initial heights of these shims were chosen equal to 20 mm. They were then optimized by 3D calculations to obtain an isochronous field. Besides, in the course of the optimization, special constrained conditions were imposed. It was required that the amplitude of the main 4-th field harmonic should not exceed ~3000 Gs, and the field near the extraction radius $r \approx 90$ cm should be $B \leq 16800$ Gs. To reduce H-minus dissociation losses, a magnetic structure of C-80 with high spiral angles was proposed [2]. Under these conditions, the H-minus dissociation should be below 5% [5]. For these purposes, additional valley shims were introduced into the magnetic system, and their geometrical parameters were also varied.

3D CALCULATION AND OPTIMIZATION

At the second stage, the main parameters of the cyclotron magnetic system were refined and optimized by computer simulations with the 3D MERMAID code [6,7], and the dynamics simulations were performed with the code in [8]. The main peculiarities and modifications of the preliminary design can be formulated as follows [9]:

The detailed 3D geometry of the magnet yoke, of the sectors (4 pairs), sector shims (17 correction shims in each sector), and the valley shims, the coils, and the external boundaries was introduced in the computer model. Because of a big angular extension of the spiral sectors in C-80, it was necessary to use in the calculations a half of the magnet with the corresponding symmetry boundary conditions. The external boundary of the area where the calculations were performed was chosen rather far to get rid of its influence on the magnetic field in the working region and to determine correctly the fringe field. The fringe field was taken into account for correct calculations of the extraction beam optics. Thus, for the

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description of the magnetic structure of C-80 using the MERMAID program, about 20.5 million direct prisms were required, which allowed to reach the necessary precision in the calculations of the magnetic field.

The nonlinear magnetic properties of the used electro technical steels (3 types) were taken into account. To increase the vertical focusing in the central region, the zero and low spiral sectors were prolonged from the radius of 27 cm to the radius of 40 cm.

In the preliminary version of the magnet structure, four valley shims in each valley were used to provide isochronisms on the last radii. To cut down the number of the valley shims from four to one, the azimuthal width of the sectors was expanded on ~20 mm from the radius of 70 cm to the final radius of 102.5 cm. Under these conditions, the H-minus dissociation is below 3 % [7].

Only the 3D field calculations made possible to perform the central region design taking into account the axial injection system geometry and the design of the magnetic field bump for the beam focusing at the first turns.

MAIN RESULTS

Main parameters of the C-80 magnetic structure are presented in Table 1.

Table 1: Parameters of C-80 cyclotron

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 centre	1.352 T
Flatter (max.)	0.025
Extraction radius	0.65-0.90 m
Ampere-turns	$3.4 \cdot 10^5$
Power	120 kW
Wight	250 t
EXTRACTED BEAMS	
Energy (varied)	40 - 80 MeV
Method	stripping

At the final stage of the magnetic field formation, the computer calculations and the magnetic field measurements were performed in parallel. The magnetic field in the full scale magnet was measured using a system based on twenty NMR calibrated Hall probes and an automated coordinate system, which could position probes in the cylindrical coordinate system with an accuracy of 0.1 mm along the radius at each azimuthal angle (with steps 0.5°, 1°, 1.5°, 2° or 2.5°) at the radii from zero up to 100 cm (with steps 0.5, 1, 1.5, 2 or 2.5 cm). The time of the magnet topography measurements on the super period was ~6–8 hours and on the periodicity element was about 2 hours. The local field defects were corrected by using iron shims. The necessary shim thickness was predicted by 3D calculations, and then refined experimentally. Disagreements between the computer predicted and measured fields did not exceed some Gs.

As a result, a magnetic field (see Fig.1) was obtained, which ensures stable acceleration of the beam in the working region of the cyclotron.The isochronism of the magnetic field was provided with the accuracy of 2–5 Gs.

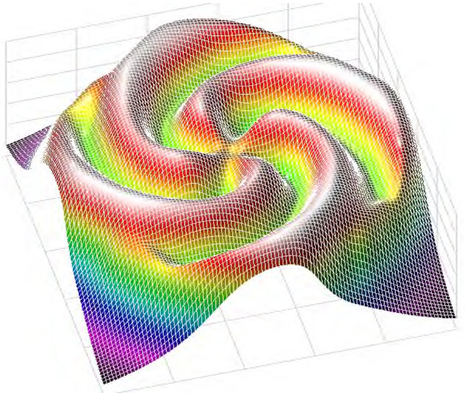

Figure 1: Final magnetic field distribution of C-80.

The measured main harmonics of the magnetic field versus the radius are shown on Fig. 2:

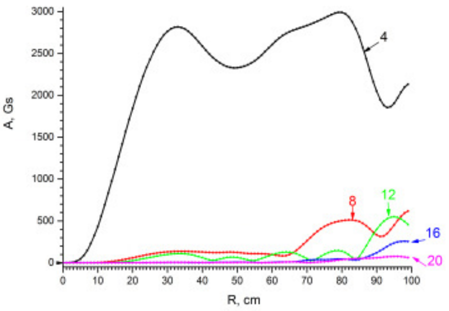

Figure 2: Main harmonics of the magnetic field C-80.

A special attention was paid to reduce the lower harmonics. They are shown on Fig. 3. The most dangerous harmonics A_1, A_2, A_3 lead to strong distortions of the accelerated orbits.

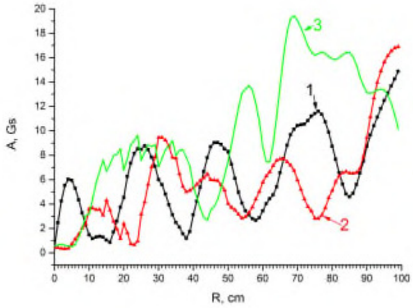

Figure 3: Measured lower harmonics of C-80.

For an improvement of the accelerated beam orbits centering and reducing lower magnetic field harmonics, four pairs of azimuthal correcting coils were installed between the sectors at the radii 85–1025 mm. In the every valley (see Fig.4) A, B, C, and D there are four types of the correction coils I, II, III, IV:

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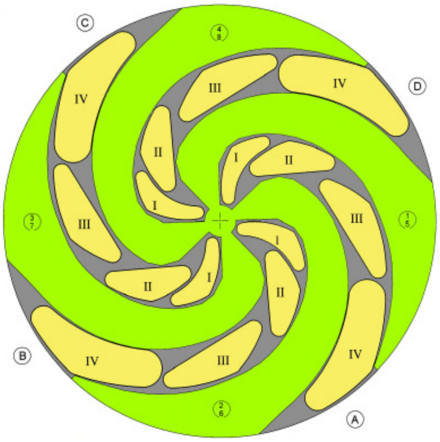

Figure 4: Top view of the pole tip of C-80.

The magnetic fields of these four harmonic coils were measured and examined. They are shown on Fig. 5:

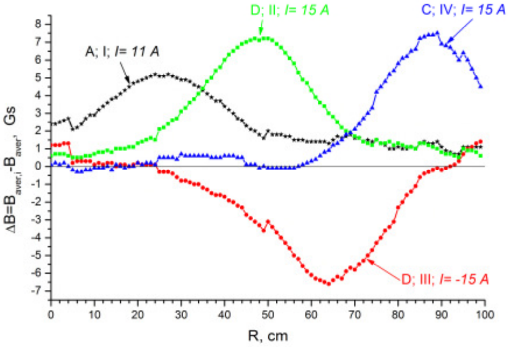

Figure 5: Contributions of the harmonic coil magnetic fields into the measured average field of the cyclotron.

The nominal currents in the harmonic coils of cyclotron C-80 were selected as follows: I: $I = \pm 25$ A, II: $I = \pm 25$ A, III: $I = \pm 25$ A, IV: $I = \pm 42$ A.

A special attention was paid to avoid dangerous resonances (see Fig.6). Detailed dynamics simulations were performed to be sure that the resonances which are crossed during the acceleration do not cause a significant harmful effect on the beam.

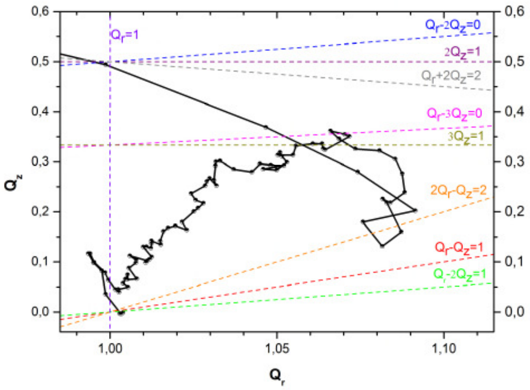

Figure 6: Working diagram of the cyclotron.

The number of ion turns in C-80 is about 400.

The extraction of the beam of variable energy 40–80 MeV in the C-80 cyclotron is performed by changing the radial position of the stripping foils [10].

CONCLUSION

Results of the final magnetic field distribution of the 80 MeV H-minus isochronous cyclotron at Gatchina are presented. Main features and problems are connected with applying the high spirality magnetic structure for acceleration of H^- ions. The formed structure permits to accelerate H^- ions up to energy 80 MeV using a rather small two-meter magnet, the beam losses due to the ion dissociation being less than 3%. As far as H-minus cyclotron operates at the fixed magnetic field, the necessary field distribution was obtained by using iron correction shims only. To obtain the necessary field distribution, 3D-computer calculations and successive magnetic measurements were very helpful.

In June 2016, a physical start-up of the C-80 cyclotron system was realized. The design parameters of the cyclotron were obtained in November 2016.

Currently, intensive work is underway to develop and build a new ophthalmological tract. It will focus on the treatment of melanoma of the eye on a beam of protons with energy of 70 MeV, and will be used for the treatment of superficial forms of skin cancer.

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