UPDATE OF CLASSICAL CYCLOTRON U-150 MAGNETIC SYSTEM. SIMULATION AND EXPERIMENT

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Abstract

Classical cyclotron U-150 located in the Academy of Sciences of the Republic of Uzbekistan, Tashkent, was developed more than 50 years ago in Efremov's institute for acceleration various particles (p, d, He). For magnetic field re-tuning the current coils are used. Nowadays U-150 is used to accelerate only protons to energy of 15-22 MeV for producing isotopes for medical or industrial applications. In order to save the electrical energy and operating simplification it is proposed to create a decreasing average magnetic field in cyclotron only by means of ferromagnetic parts. To create a negative gradient of the magnetic field steel parts are made and installed in the magnet.

Analysis of measurement results showed the possibility of production of the required isotopes in updated U-150 with power economy of about 15%. Experimental irradiation of the target showed that the created field gradient did not provide an achievement of the required proton energy at radius of 64-65 cm. To achieve required energy one correction coil is kept in operation and measured magnetic field showed a satisfactory result. For estimation of possibility of creating the required magnetic field gradient without correction by coils the simulation of the cyclotron magnetic system were done and the results of calculations and its analysis are presented in this paper.

INTRODUCTION

On Fig.1 you can see a photo of the classical cyclotron U-150 which located in Tashkent in the Academy of Sciences of the Republic of Uzbekistan. Magnetic yoke of classical cyclotron U-150 has an E-type core.

Figure 1: Cyclotron U-150 during the measurements of the magnetic field.

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One sees in Fig. 2, 3 the pole, the vacuum chamber cover and the steel rings located inside the vacuum chamber. In the gap between the poles of magnet and the vacuum chamber of cyclotron (top and bottom), which is 25 mm in height, steel discs having varying thickness along the radius were installed.

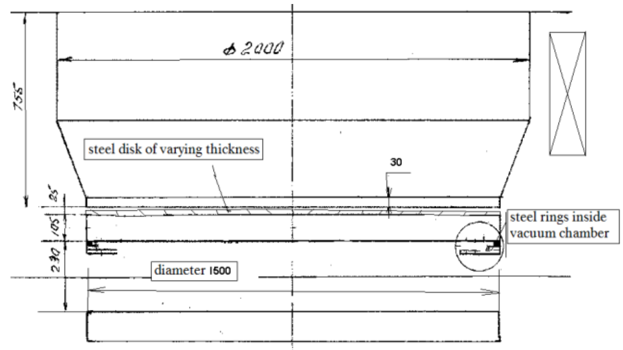

Figure 2: Size and cross section of the magnet SP-72 pole.

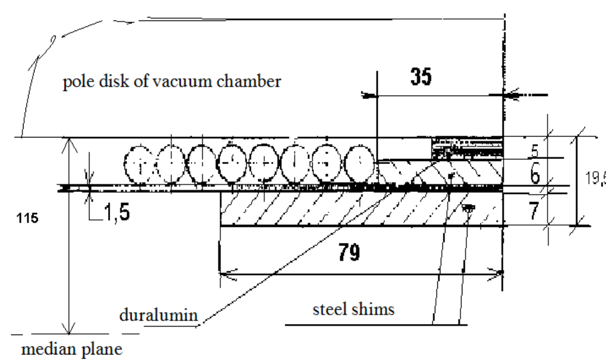

Figure 3: Cross section of the steel shims and coil located inside the vacuum chamber of the cyclotron.

Originally correction coils were included in the design of the cyclotron to provide a possibility of acceleration particles of various types. Nowadays U-150 accelerates only a proton beams and the need for using of the coils for forming of magnetic field is missing. Required profile of the magnetic field is possible to be obtained by the modification of the design of cyclotron's pole using additional iron components without the correction coils which allows saving the electric power for the operation of the cyclotron.

Overview of the modification of the magnetic system and its experimental results is presented in this write-up.

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SELECTION OF THE PARAMETERS FOR MAGNETIC SYSTEM

According to the requirements specification the chosen shape of the magnetic field has to provide acceleration of the protons at the parameters of the cyclotron shown in Table 1.

Table 1: Required parameters for U-150

Operating generator frequency	15.2 – 16.0 MHz
Radius of the target position	64 cm
Voltage on the dees	100 - 110 kV
Protons final energy	22 MeV

The magnetic field during first part of simulations was assumed of the next form:

- Within radii 0 – 10 cm magnetic field is constant.
- In the range of radii of 10 – 64 cm expected decline of the magnetic field had a constant value of the field index $n = r/B \cdot dB/dr$.

Two series of calculations of the magnetic field and beam dynamics that were consistent with the different values of B_0 and n have been performed. In the first case, the value of the field at the center has been chosen so that the initial frequency of the proton revolution was ~ 200 kHz greater than the maximum possible frequency of the generator, i.e. f_0 = 16.200 MHz. For a given value of f_0 the field in the center was determined by the formula:

$$B_0 = \frac{2\pi E_0 f_0}{ec^2} = 10633\,\text{G}. \qquad (1)$$

The second series of calculations concerned to opportunity to get protons with an energy of 22 MeV on the target (r = 64 cm), since the calculations for the first series showed that the energy of the protons cannot exceed 21.5 MeV at B_0 = 10633 G. Obviously, to increase the energy at the radius of target an increase of the magnetic field is required in this place and in the center of the cyclotron as well.

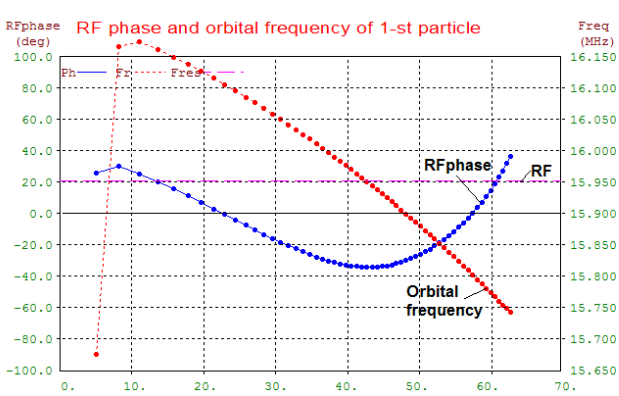

Figure 4: Results of calculation of the phase and orbital frequency of proton in magnetic field with n = -0.004 and at a voltage of 100 kV on the dees.

Dynamics calculations showed that from a set of curves of the field the best is one which corresponds to $n = -0.004$. In this case, the phase of the proton in the acceleration is in the range of ± 40 °HF. One can see in Fig. 4 the results of the phase motion in this field at dee voltage 100 kV. Frequency of the accelerating field 15.95 MHz was selected to optimize the phase motion, the energy of the central proton on the target was equal to 21.5 MeV.

Consider the results of the second cycle of calculations, which concerns the possibility of obtaining energy of 22 MeV at a radius of 64 cm. Magnetic field, which corresponds to the radius R of proton energy W, can be estimated using the following formula

$$B = \frac{\sqrt{W(2E_0 + W)}}{ecR}. \qquad (2)$$

For radius 64 cm and energy 22 MeV, this formula gives a value of 10644 G. Curves of the magnetic field passing through the R = 64 cm with a value of B_0 = 10644 G, but with different values of the index field in the range from -0.002 to -0.010 were calculated.

The results of the dynamic calculation of the acceleration of protons to an energy of 22 MeV in the magnetic fields with the values of field index -0.002, -0.004 and -0.006 have shown that if the respective frequencies of the accelerating field 16.04, 16.08 and 16.09 MHz, the protons are accelerated to 22 MeV, and their phase motion are only slightly different from that shown in Fig.4.

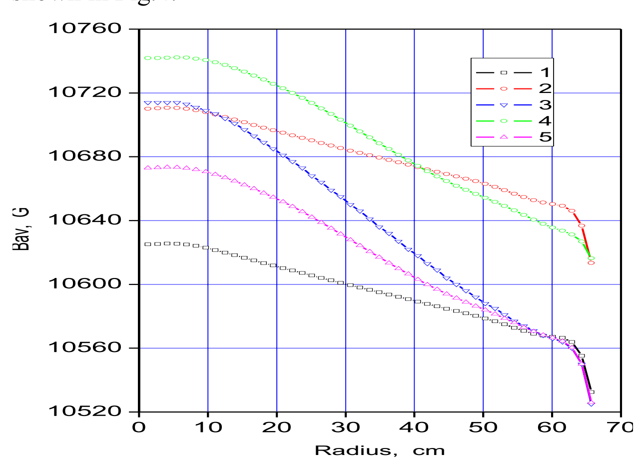

Figure 5: Five variants of calculated magnetic field, corresponding to the three disk geometry. Magnet excitation current 1 – 662.46 A, 2 – 669.21 A, 3 – 663.43 A, 4 – 667.28 A, 5 – 661.5 A.

As follows from estimation above the required decrease of the magnetic field is desirable within 0.75 – 1.1%. In Figure 5 the results of magnetic field calculation for the three types of discs are shown. At the center the discs had a thickness 13 mm, 14.5 mm and 16 mm, the thickness of the disks is reduced to 9 mm at a radius of 700 mm, a full disks radius is 750 mm. These discs placed in the gap,

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provide a decline of the magnetic field along the radius by 0.5%, 1.0% and 1.5%. To obtain field decline in the range of 550-650 mm radius steel ring size 74×7 mm in thickness had to be reduced to 4 mm. Real distribution of the magnetic field corresponds to approximately constant derivative dB/dr from 10 cm to 64 cm.

EXPERIMENTAL RESULTS

As a result of simulation it was decided to form the field using the disc 1. This disk were manufactured (Fig.6) and installed in the magnet of the accelerator.

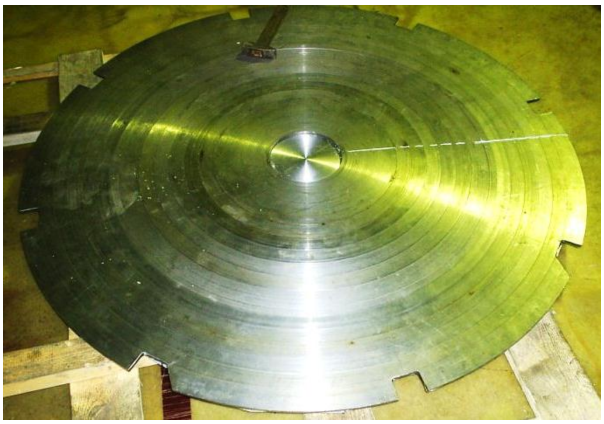

Figure 6: Steel disk for the forming of the magnetic field.

Measurements of the magnetic field showed that the decrease in the created field at target position leads to impossibility to achieve the required proton energy at radius of 64-65 cm. This fact makes impossible to irradiate the target evenly (Fig.7) causing its local overheating and an evaporation of the produced isotopes.

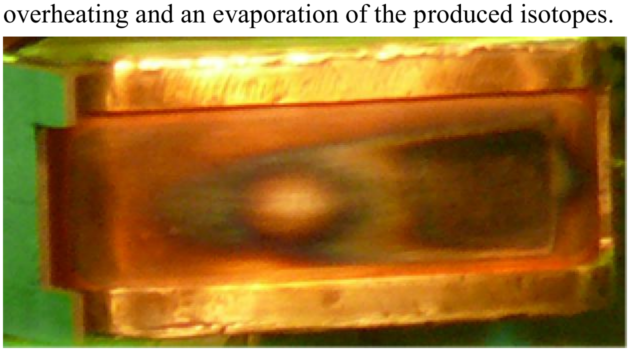

Figure 7: Target after irradiation.

Difference (Fig.8) between experimental and calculated results at radii 30-40 cm is explained by the fact that an error about 0.1 mm was made in the manufacture of discs (not counted in the calculations). The difference between the results near the radius of 60 cm is due to contradiction of drawings of the magnet (Fig.2,3) to its real design which can take place after several decades of operation. Also it can be explained by the absence of data about the B-H curve of the real material of cyclotron magnet.

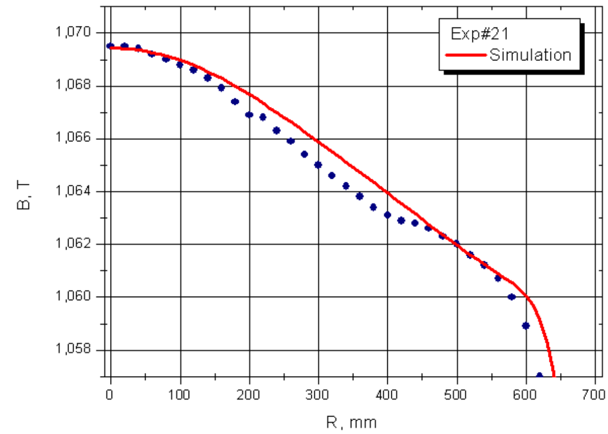

Figure 8: Calculated magnetic field in comparison with experimental measurements.

POSSIBILITY OF CORRECTION

Correction of the magnetic field at radii near the target position is possible by substitution of 6 mm outer ring by the shim of larger thickness. Calculations of the magnet with shims of different thickness were performed. To minimize the difference between simulation and experiment the following procedure were done:

- the difference of calculation results with 6 mm ring and ring with larger thickness was found;
- the resulting value of the difference was added to the experimental data.

The result is presented in Fig.9.

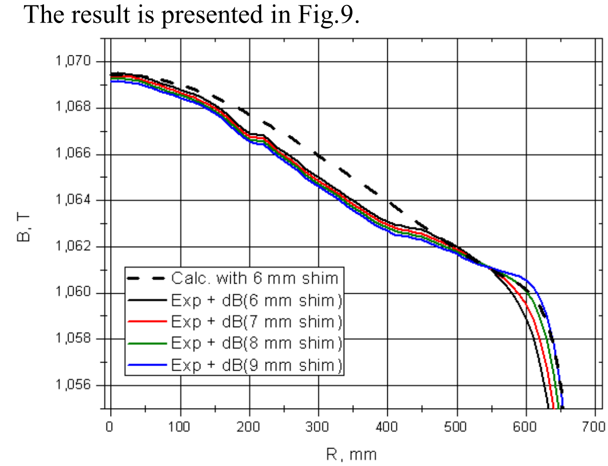

Figure 9: Calculation of the magnetic field with shims of different thickness based on experimental data.

One can see that the required magnetic field is obtained using a ring of 8-9 mm thickness.

CONCLUSSION

Nowadays cyclotron U-150 with modified magnetic system is successfully operated using only correction coils which are used for adjustment of the amplitude and phase of the first harmonic. Measured magnetic field provides energy savings of about 15%. Magnetic field correction is proposed and decision is waiting.

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