OPERATION MODE OF AIC-144 MULTIPURPOSE ISOCHRONOUS CYCLOTRON FOR EYE MELANOMA TREATMENT *

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Abstract

Computational and experimental results concerning acceleration and extraction of the 60 MeV proton beam at AIC-144 cyclotron of the Institute of Nuclear Physics (Krakow, Poland) are considered. A proton beam of the AIC-144 cyclotron is accelerated without large losses in the radial region of 12-62 cm and is extracted from the cyclotron with a pretty good overall efficiency of ~35%. The beam was used for successful treatment of 15 patients in 2011-2012.

INTRODUCTION

The AIC-144 cyclotron is used at the Institute of Nuclear Physics, Polish Academy of Sciences, mainly as a source of deuteron and proton beams for isotope production on the internal target. In the past years several systems of the cyclotron have been modified in order to provide parameters of the external proton beam with an energy of 60 MeV necessary for eye melanoma radiotherapy which has been conducted at the INP since 2011 [1].

Important efforts have been made to increase reliability of the RF system operation at a frequency of 26.26 MHz and dee voltage of 60 kV. Stable operation of the RF system in this regime essentially increased the extraction efficiency of 60-MeV protons [2].

Magnetic field measurements were fulfilled in order to shape the specified level of the isochronous field with a required accuracy and to limit the 1st harmonic of the field imperfections to ~ 5 Gs [3].

Particle dynamics computations show that the beam is accelerated up to extraction system with tolerable phase drift and amplitudes of transverse oscillations. Main losses of the protons (~40%) occur at the radius ~62 cm (energy ~59.5 MeV) due to the action of the coupling resonance Q_r-$2Q_z = 0$ and the parametric one $2Q_z = 1$.

Experimental study of the beam acceleration and extraction confirms the main results of the computations. The RF phase of the beam just before the extraction is close to 10°RF, as measured using the Smith and Garren method [4].

The experimental extraction efficiency is ~50% after two electrostatic deflectors in comparison with the internal circulating beam intensity and approaches ~35% at a point out of the cyclotron.

IMPROVEMENT OF RF SYSTEM OPERATION

Between 2005 and 2007 the high-frequency system was revamped. The modernization included reduction of the contact resistance at the power stage of the generator, the acceleration chamber, the resonator, and the chamber connecting the resonator with the acceleration chamber.

After ten year of operation some high-frequency elements became stale. These elements, in the form of sheets, were connected by bolts, and the contact impedance between them was not sufficiently low. It resulted in unstable power output and accelerating voltage in the cyclotron.

In order to improve the connectivity and prevent future degradation, copper elements were covered with copper sheets. Welded joints were used in place of the screwed ones. The contact force was increased and the contacts in the areas where welding was not possible were cleaned.

Reduction of the contact resistance for high-frequency current resulted in a 50% decrease in power loss and an increase in the amplitude of the high-frequency voltage at the accelerating electrode from ~50 kV to 65 kV.

LATEST SHAPING OF MAGNETIC FIELD

The latest AIC-144 magnetic field mapping and shaping campaign was conducted in 2011-2012 [3]. The main goals of that campaign were the following:

- verification of the cyclotron magnetic field in comparison with the 2006 mapping;
- shaping of the new magnetic field regime in view of the new requirements to the central magnetic field bump and an increase in the final energy of the accelerated proton beam;
- correction of the 1st harmonic of the magnetic field in the extraction region of the cyclotron.

Verification of the Magnetic Field

A small (~5 Gs) change was observed in the average magnetic field against the previous (2006) one at the same conditions of the magnet. This difference was corrected by a small change, ~(5-10) A, in the excitation current in the cyclotron trim coils. Fig. 1 shows the initial deviation of the average magnetic field from the required one and the deviation after the correction of the trim coil current.

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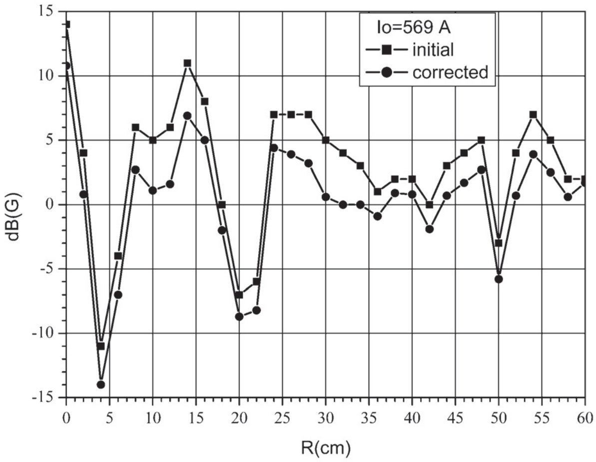

Figure 1. Deviation of the average magnetic field from the required one, the main coil current Io=569 A.

Shaping of the New Cyclotron Regime

The new cyclotron regime was simulated with the aim of increasing the energy of extracted protons and accordingly the penetrability of the beam in the eye therapy room

The f=26.26 MHz, Io=591.5 A regime was simulated on the basis of a new technique [5] using the Cyclotron Operator HELP Program Complex 2004-2012 and the main magnetic field maps measured for Io=570, 585, and 600 A. This regime was simulated with the central magnetic field bump ~360 Gs, relatively isochronous field, and 230 Gs field (Fig. 2). The latter bump was experimentally found to be most optimal for the extraction efficiency.

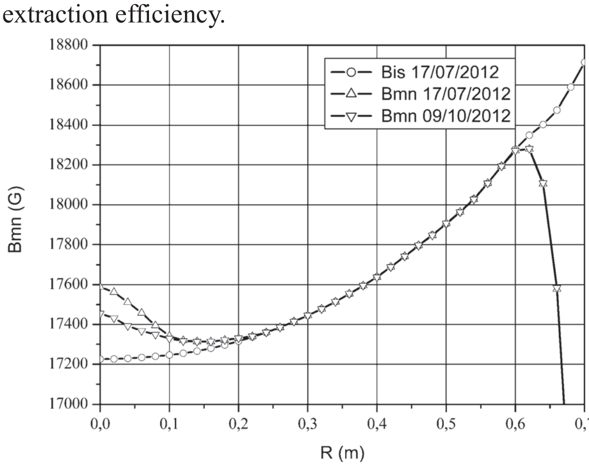

Figure 2. Average magnetic field for the f=26.26 MHz, Io=591.5 A regime with the increased bump (Bmn 17/07/2012) and the optimal one (Bmn 09/10/2012).

Correction of the 1st Harmonic of the Magnetic Field

The initial value of the 1st harmonic of the magnetic field measured in 2011 was ~12-13 G at R = 62 cm. It was decreased to ~2 G by the three iterations of the horizontal shift of the vacuum chamber with iron pole sectors . The vacuum chamber was shifted by 0.46 mm.

EXPERIMENTAL RESULTS

Phase motion of the beam was measured with the Smith and Garren method [4]. To implement this procedure, the beam current was measured at different radial positions of integral probe N3 at four main coil currents which were decreased step by step. The first point is the working current in the main coil, the second corresponds to the moment when the beam current begins to decrease, the third is fixed when the beam current is equal to the half of the maximum at the radius described, and the forth is taken when the beam becomes equal to zero. An example of this series of the Smith and Garren curves is shown in Fig. 3.

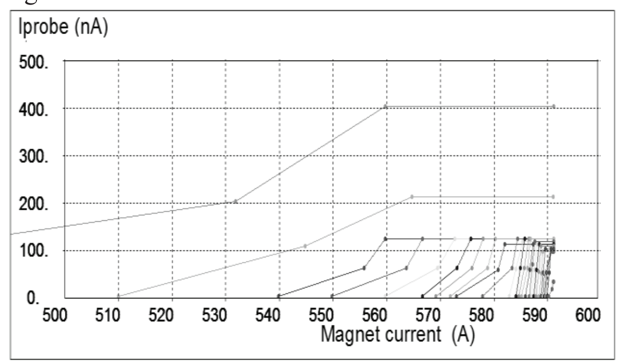

Figure 3. Smith and Garren curves measured for a radial range of probe positions 6-62 cm.

This simple method after using the appropriate mathematical procedure made it possible to achieve the phase motion of the beam center with quite good accuracy. Two phase curves obtained by this method for the initial magnetic field with a bump at the center region 360 Gs and for the one decreased by 130 Gs are compared in Fig. 4. Both phase curves were obtained after the main coil current was experimentally optimized to achieve the maximal extraction efficiency. It occurs if the phase of the beam just before the extraction is ~10°RF.

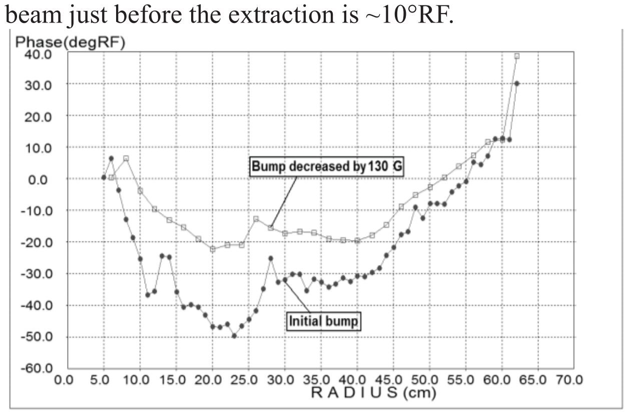

Figure 4. Comparison of two phase curves obtained for different distributions of the average field shown in Fig.2.

Hence, experimental optimization of the beam extraction was finally fulfilled by slightly tuning the main coil current in each investigated regime.

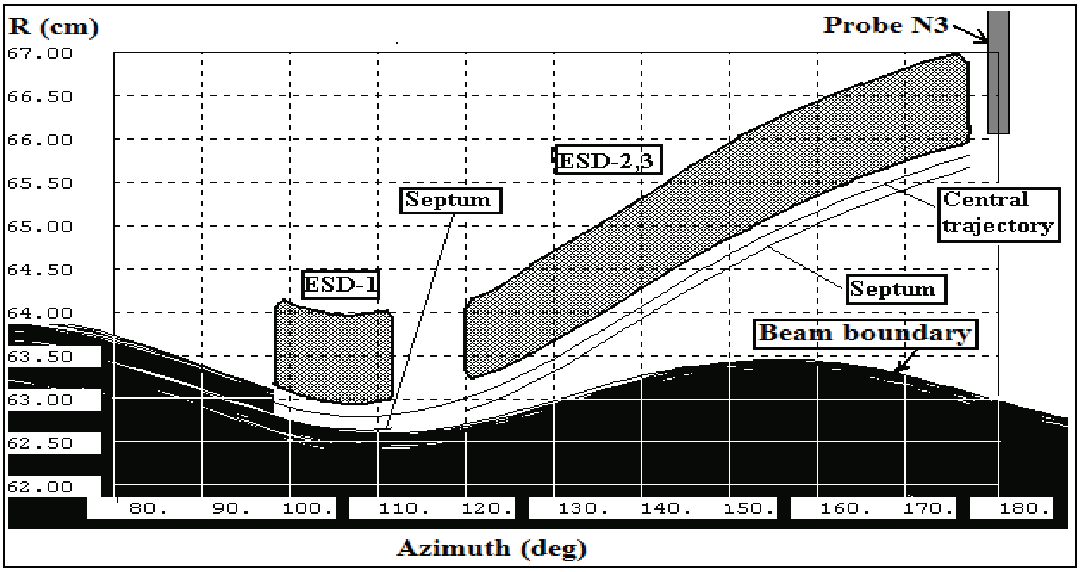

Figure 5. Schematic view of the first part of extraction system.

Extraction

The first part of the extraction system is schematically shown in Fig. 5. It consists of three electrostatic deflectors ESD1, ESD2, and ESD3. The latter two are located in a common body but have electrodes of different cross section. ESD2 has flat electrodes while ESD3 electrodes are vertically profiled to provide additional focusing of the beam in the horizontal plane. ESD1 has flat electrodes.

The best extraction efficiency was experimentally achieved by tuning the following parameters:

- bump of the magnetic field at the center of cyclotron;
- distance between the ion source and the puller;
- position of all elements of the extraction system;
- currents in the harmonic coils.

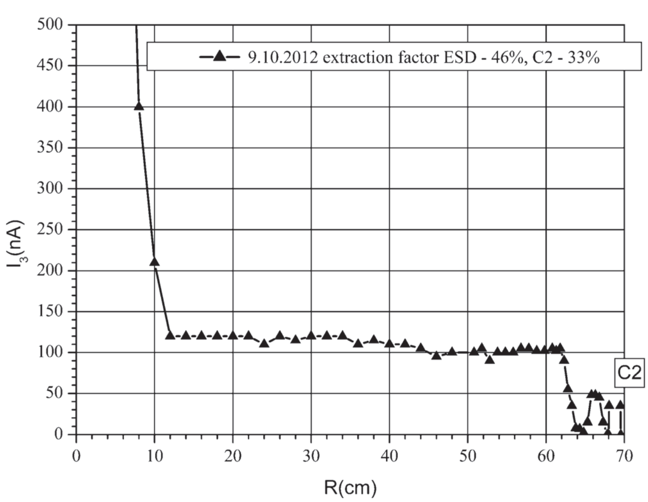

Figure 6. Beam current measured by probe N3.

Main beam current probe N3 was used in those optimization procedures to measure the radial distribution of the beam intensity through the entire acceleration region and the extraction region as well. Since the probe is located just behind the ESD3 exit, it can be used for direct estimation of the extraction efficiency after the first part of the extraction system. Fig. 6 shows the beam current measured by probe N3 beginning with the radius of 6 cm.

It is seen that the extraction efficiency after the deflectors is close to 50%. This value is in very good agreement with the results of the beam simulation. The overall efficiency was estimated at point C2 at a distance of ~2 m from the cyclotron This efficiency ~35% is also indicated in Fig. 6. Approximately 15% of the protons are lost in three magnetic channels.

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