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The Extraction of Positively Charged Protons Beam from Cyclotron Due to Decreasing of the Energy at the Degrader

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Abstract
For modern medical cyclotrons, the acceleration of beams of negatively or positively charged protons is most widespread. As a rule, negatively charged ions are ex-traced from a cyclotron by recharging on a thin carbon foil. The method is easy in realization. However, to pro- duce negatively charged protons, a complex system of ex- ternal injection is usually used. Besides, the effect of Electromagnetic dissociation of an electron during acceleration limits the level of cyclotron magnetic field. Positively charged ions are produced by simple internal Penning type ion source and there are no limits in a magnetic field level. However, the extraction of such a beam from a cyclotron is possible only by a complex extraction system with an electrostatic deflector and passive or active focusing elements. At the paper the extraction of positively charged pro-ton beam by means of partial decreasing of energy at degrader is considered. The proposed method combines the positive features of described above schemes, such as easy of ions production, no limitation of the magnetic field level and an easy technical realization of extraction system. The obvious disadvantage of this method is the increasing of the beam emittance after passing through the degrader. As an example, a three-sector model cyclotron with a magnetic field level of 1 T to accelerate of positively charged protons to an energy of 15 MeV is proposed. The beam extraction is carried out due to 5 – 10% energy loss on a graphite degrader.

Keywords: Positively, Cyclotron Due, Degrader, Decreasing.

Introduction

Currently, accelerated beams of protons or deuterons are the main tool for solving applied tasks, especially in the field of medicine. Modern medicine cyclotrons generally use two main acceleration schemes, either for positively charged or negatively charged protons or deuterons [1]. Both acceleration schemes have as advantages and disadvantages. For instance, the advantage of negatively charged protons or deuterons acceleration is the simplicity and efficiency of their extracting from a cyclotron by re- charging on a thin foil [2]. However, in order to obtain negatively charged protons or deuterons, a complex external injection system is usually used. Additionally, the effect of electromagnetic dissociation of the electron in the process of acceleration limits the level of cyclotron magnetic field. The advantage of positively charged protons or deuterons acceleration is the fact that they are produced by a simple internal Penning type ion source with a cold or hot cathode. However, the extraction of positively charged ions beam from a cyclotron is only possible by means of a com- plex system with an electrostatic deflector and passive or active focusing elements. At the paper the extraction of positively charged proton beam by means of partial de- creasing of energy at the degrader is considered [3]. The proposed method combines the advantages of the de- scribed above schemes, such as the simplicity of ion pro- duction by inner ion source, no restriction of the magnetic field level and easy technical realization of the extraction system. Meanwhile, the extraction can be carried out simultaneously in several directions, the number of which is determined by the periodicity of cyclotron magnetic system. The disadvantage of this scheme is the fact that the beam emittance increases after passing through the de- grader. As an example, the proton acceleration in a three-sector model cyclotron with a field level of 1 T to energy of 15

MeV and the extraction due to 5 – 10% of energy losses at a graphite degrader is proposed.

Three-Sector Model Cyclotron

The proposed scheme for the extraction of a positively charged proton beam by means of partial decreasing of energy at the degrader is most easily realized by a cyclotron with a three-sector magnetic structure and high azimuthal variation. As an example, consider the widely used version of a medical cyclotron for proton acceleration up to energy of 15 MeV. Average cyclotron magnetic field is 1 T.

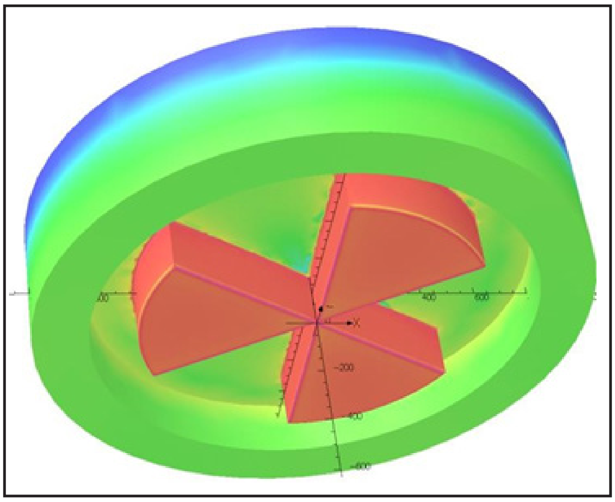

Figure 1: Computer model of the three-sector cyclotron for the proton acceleration up to the energy of 15 MeV.

For the trajectory analysis the simple three-sector computer model of cyclotron magnet has been created (see Fig. 1). The main dimensions of the model are shown in Figure 2. The sector structure of the magnet has an external diameter of 1260 mm in order to achieve the required pro- ton energy of 15 MeV. To increase the magnetic field azimuthal variation, the model has no poles. The sectors have the height of 145 mm and are placed on the upper and lower beams of the yoke. The model cyclotron magnetic field flutter has a value of about 0.8, and betatron frequencies are or □ 1.1 and Qz □ 0.9.2000

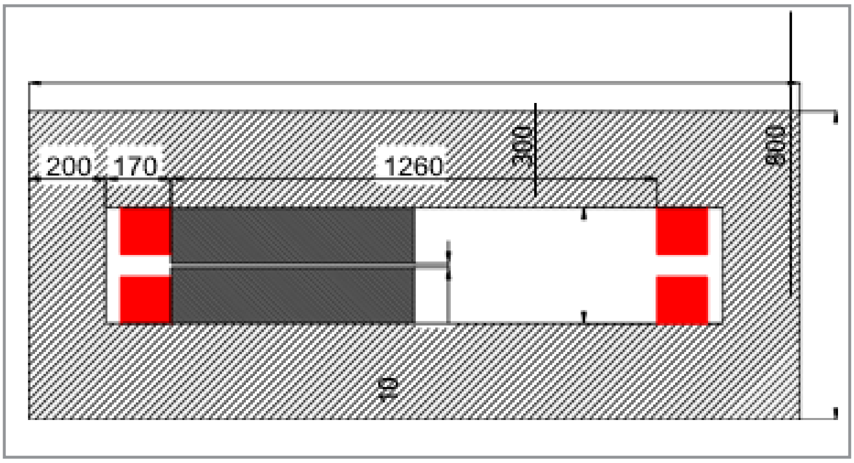

Figure 2: Main dimensions of the three-sector model cyclotron magnet.

Beam Parameters Estimation

For the trajectory analysis, the beam parameters before and after degrader, where the beam receives both angular and energy dispersion, has been estimated. This transformation has been estimated by the LISE++ programmed [4].

Figure 3 shows how the angular dispersion of the proton beam with an energy of 15 MeV depends on the energy losses when the beam pass through degraders which are made of graphite or other suitable materials. The best material for degrader is available, spray-resistant and heat-resistant graphite.

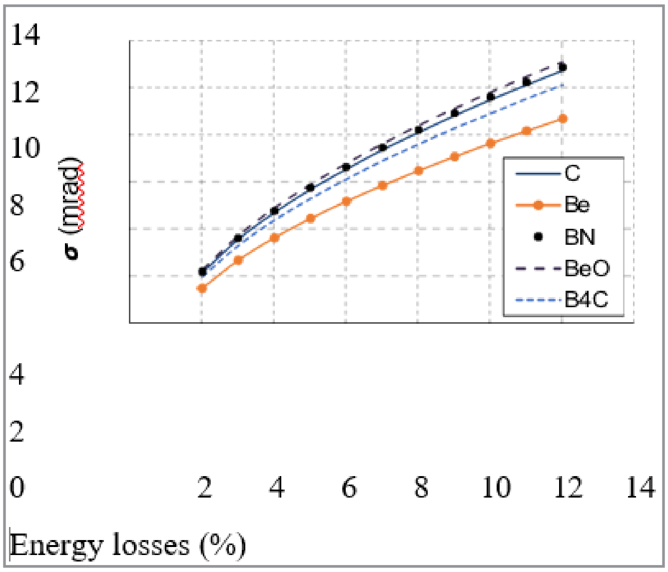

Figure 3: Dependence of the angular dispersion of the pro- ton beam with the initial energy of 15 MeV on the losses of energy at the degraders of various materials.

The required level of beam energy losses is determined by the degrader thickness. On the other hand, the degrader thickness affects the angular and energy dispersion. Ac- cording to estimation, to obtain 5% energy losses for a pro- ton beam with the energy of 15 MeV, the thickness of the graphite degrader should be 117mkm. At this case, after passing through the degrader, the transverse beam size re- mains almost unchanged, while the angular spread shows a considerable increasing from 2□r □ 0.5mrad and 2□z’□1mrad before degrader up to 2□r □ 2□z □ 16mrad after degrader passing (see Fig. 4). In addition, the beam at the output of the degrader receives an energy dispersion of about 0.048 MeV (0.3%), as shown in Table 1.

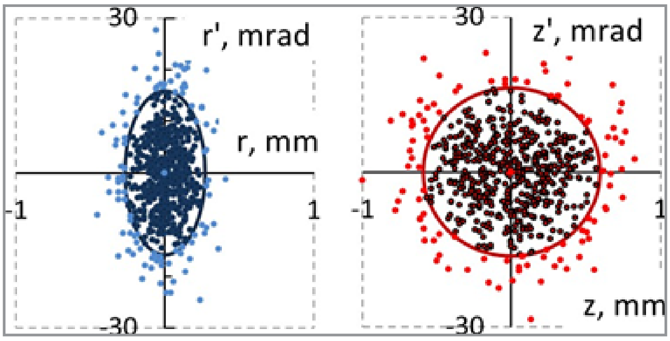

Figure 4: Radial and vertical emittances of the proton beam after passing the degrader for 2□ and 3□ normal transverse distribution of the ions in the beam.

The Extraction of the Beam Due To 5 – 10% Energy Losses

In order to extract a positively charged proton beam, the degrader is installed in the cyclotron magnet “valley” at the maximum acceleration radius.

Figure 5: The extraction of the 15 MeV proton beams due to 5% energy losses at the degrader.

Figure 6: The extraction of the 15 MeV proton beams due to 10% energy losses at the degrader

The beam extraction can be carried out simultaneously in several directions, the number of which is determined by the number of elements of the periodicity of the cyclotron magnetic system. Thus, a three-sector cyclotron can use maximum three extraction lines.

After passing the degrader the proton beam with reduced magnetic rigidity goes along a partial rotation inside cyclotron magnet and is extracted from the cyclotron at an angle, which depends on the level of beam energy losses (see Figs. 5 and 6). The higher the beam energy losses at the degrader are, the larger the angle of the beam extraction from the cyclotron is. It is important because the larger the extraction angle is, the less is the effect of the negative radial gradient of the magnetic field in the area of the sector edge on the extracted beam. And, accordingly, the less is the extracted beam defocusing in this negative radial gradient.

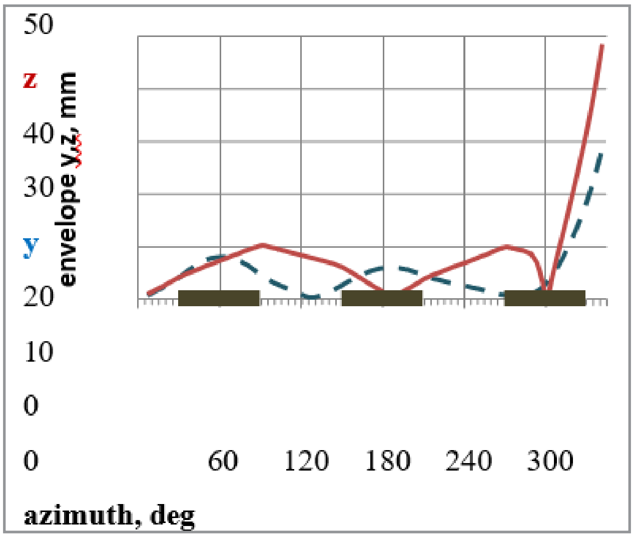

Figure 7: Proton beam envelopes during the extraction with an energy loss of 5% on the degrader.

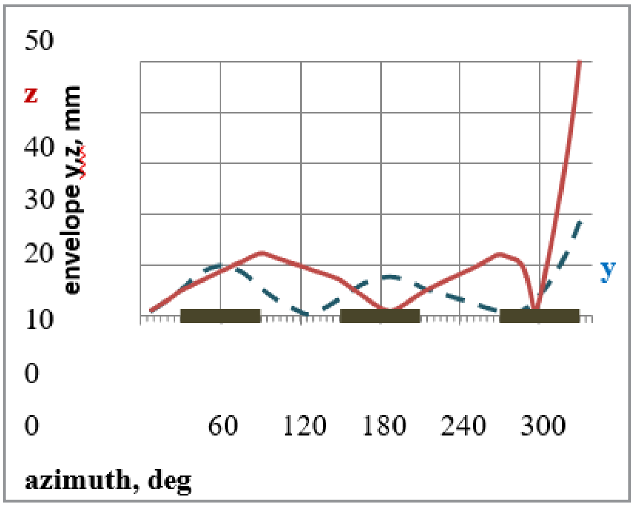

Figure 8: Proton beam envelopes during the extraction with an energy loss of 10% on the degrader.

On the other hand, the higher the energy losses at the degrader are the lager degrader thickness needs, which leads to the growth of the emittances of the beam after de- grader. The growth of the emittances leads to an increase of the aperture losses of the extracted beam when it moves inside the cyclotron magnet after degrader.

Table 1 presents the beam parameters after the degrader for two levels of the energy decrease in 5% and 10%, as well as the aperture losses in the three-sector model cyclotron magnet with a vertical gap between the sectors of 10 mm. The aperture losses are given for the cases of 2□ and 3□ of the normal particle transverse distribution in the beam after the degrader (Fig. 4).

Table 1: Beam Parameters after Degrader Passing

Energy losses %	Angular dispersion mrad	Energy dispersion MeV	Beam losses at 2□ or 3□ %
5	7.7	0.048	25 or 33
10	11.5	0.06	46 or 54

Figures 7 and 8 presents the extracted proton beam envelopes after the degrader, where the beam losses are 5% and 10% of the energy, respectively. Vertical envelopes are shown for the case of 3□ normal particle distribution in the beam immediately after the degrader and without taking into account the aperture losses during the extraction.

One way to reduce the aperture losses is to increases the vertical gap between the sectors. However, it leads to de- creasing of the magnetic field in the gaps between the sec- tors, which, in turn, leads to decreasing of the beam extraction angle. In order to keep the extraction angle value within the reasonable values, there is a plan to investigate the effects of the increasing of the magnetic field flutter by expanding the gap in the “valleys” or to find the proper sector profile, sector angular length or sector edge bevels.

Conclusion

The considered method of the extraction of a positively charged proton beam by partial decrease of energy at the degrader combines the advantages of known schemes, such as the use of a simple internal Penning type ion source, no restriction on the magnetic field level, an easy realization of extraction system and the ability to extract the accelerated beam simultaneously in several directions. The disadvantage of the proposed method is the increasing of the beam emittance after passing the degrader, which leads to a beam aperture loss during extraction. There is a plan to investigate the methods to decrease this loss. The implementation of the proposed method on the model cyclotron with the three-sector magnetic structure which accelerates protons to an energy of 15 MeV is considered.

References

1. Schmor, P. W. (2011). Review of cyclotrons for the production of radioactive isotopes for medical and industrial application. In Proceedings of the 19th International Conference on Cyclotrons and Their Applications (CYCLOTRONS’10) 419-422.
2. Gulbekyan, G. G., Borisov, O. N., & Kazacha, V. I. (2007). Extraction by stripping of heavy ion beams from AVF cyclotrons. In Proceedings of the 18th International Conference on Cyclotrons and Their Applications (CYCLOTRONS’07) 308-313.
3. Ivanenko, I. A., & Gulbekian, G. G. (n.d.). A method for extraction an accelerated beam of positively charged particles from a cyclotron (Patent No. RU2842003).
4. LISE++ group. (n.d.). LISE++. https://lise.frib.msu.edu