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Accelerators system for production of medical isotopes ^{18}F for PET

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The production of medical isotope ^{18}F for Positron Emission Tomography using the irradiation of an enriched water target by proton beam from isochronous cyclotrons is the standard approach in radiopharmaceutical industry. The question of increasing the efficiency for the production of ^{18}F is critical for cyclotrons. The novel concept of using a cyclotron and a post-acceleration of the beam for additional irradiation of ^{18}O water targets is considered in this presentation. The main advantage of this concept is to maximize the use of the proton beams for nuclear reactions, which increases the yield of ^{18}F. The physical analysis of this system is given. The comparison of the proposed system with the standard system is discussed.

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1. Introduction

Positron Emission Tomography (PET) is an imaging functional technique for nuclear medicine that produces a 3-dimensional image of the human body processes [1]. This approach is based on the detection of pairs of gamma rays indirectly emitted by a positron-emitting radionuclide that is introduced through the body on a biologically active molecule. This positron emitting isotope ^{18}F is produced using a cyclotron. The ^{18}F is paired with a glucose analog to form fluorodeoxyglucose (^{18}F-FDG), which is injected into patient's body and the PET scan provides the required information for the doctor to properly diagnose and treat the patient [2].

The production of medical isotope ^{18}F is based on the nuclear reaction of the proton beam with oxygen in enriched water [3]. The isochronous cyclotrons are used for these goals [4, 5]. The comparison of two types of accelerators shows that isochronous cyclotrons found large application for this technology. The radioactive yield of medical isotopes is the main parameter which characterizes the production efficiency. Increasing the production efficiency and overall yield of the cyclotron is demanded from many users of these high output PET isotope distributers. Thus, the search of novel approaches for increasing this production efficiency for medical isotope production is of great interest to these commercial providers.

The novel approach for production of medical isotopes is based on the combined proton accelerator system is presented in this paper.

2. Current system for production of ^{18}F medical isotopes at Siemens

The Siemens cyclotron system for production of ^{18}F medical isotopes is presented in Figure1 [6]. The system includes the following main sub-systems:

1. Isochronous cyclotron accelerator of negative hydrogen ions.

2. The system for converting of negative hydrogen ions to protons and the output of the proton beam from the vacuum chamber to the external target.

3. Target system.

4. The delivered system of irradiated enriched water with ^{18}F to radiochemistry units for preparation of the radioactive biomarker.

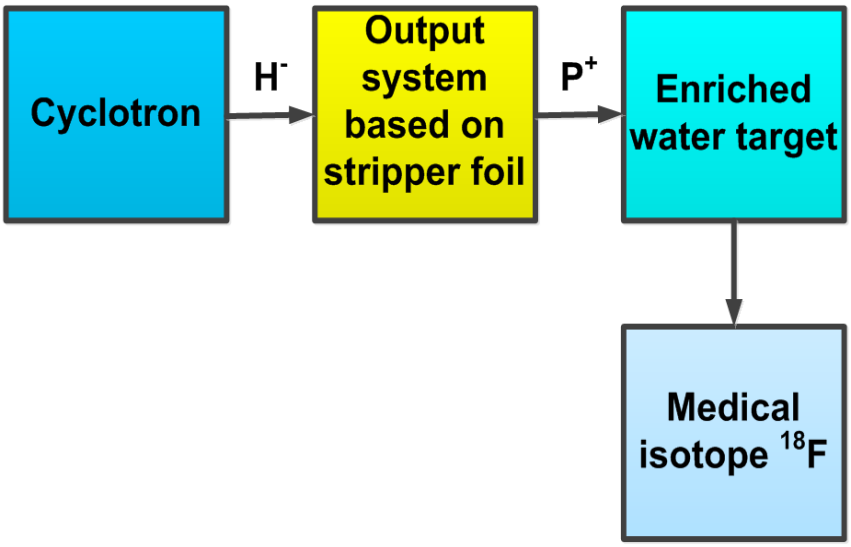

Figure 1. The structure of system for production of ^{18}F at Siemens.

The main parameters of Eclipse cyclotrons are following [6]:

- Kinetic energy is 11 MeV.
- Beam current is 120μA (2x60μA for dual beams).

The description of isochronous cyclotron is provided in the literature [7, 8]. The picture of the Eclipse Cyclotron is shown below in Figure 2. The beam size in cross section is given in Figure 3. The waveforms of beam current from the current integrator are shown in Figure 4.

The current yield of the Eclipse cyclotron is 7 Curies of ^{18}F output in 120 minutes [6].

The goal of increasing this yield of ^{18}F leads to the search for new approaches and concepts.

Figure 2. The picture of Eclipse cyclotron.

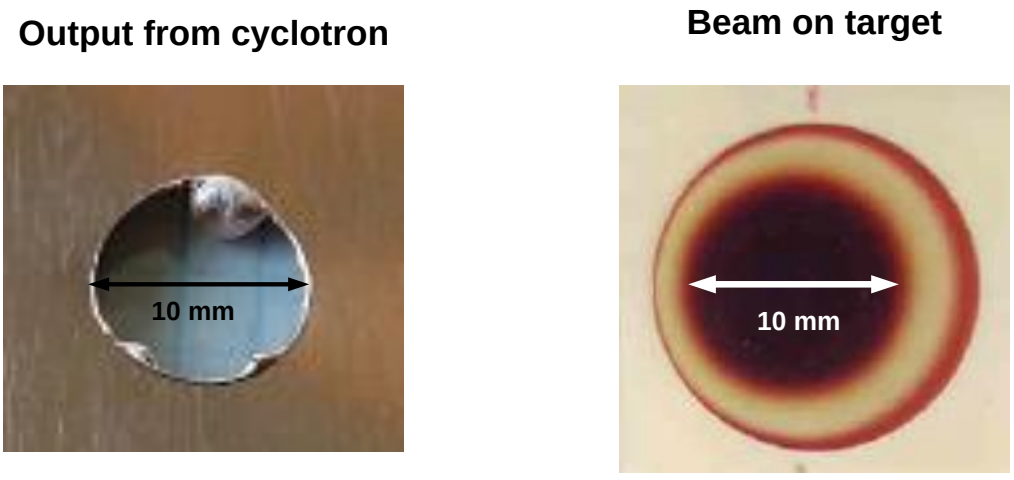

Figure 3. Autograph of proton beam from Eclipse cyclotron.

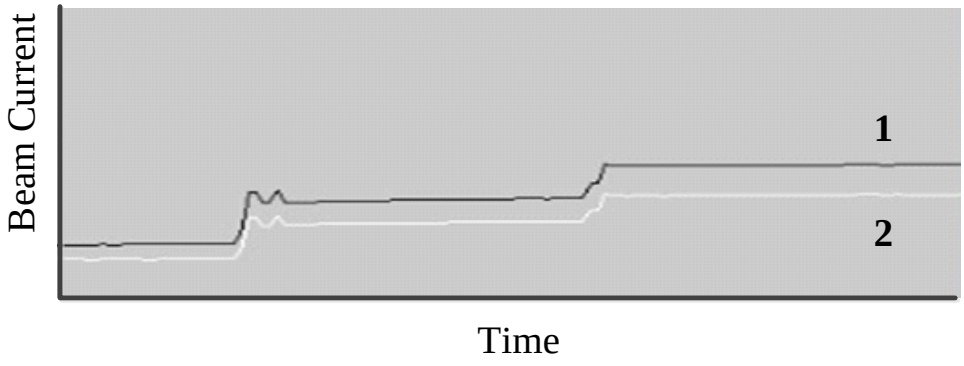

Figure 4. Example of beam current waveforms for beam lines 1 and 2.

3. Physical processes in irradiated target

The two physical processes are in the irradiated enriched water:

1. Ionization of the enriched water by proton beam (Figure 5a).
2. Nuclear reaction of protons with oxygen (Figure 5b).

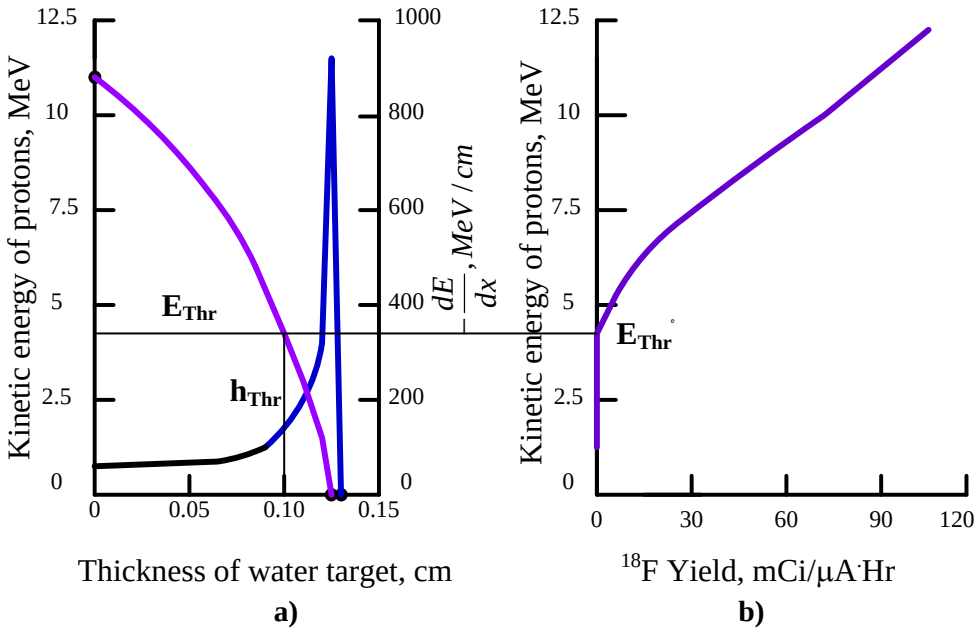

Figure 5. The physical processes in the irradiated water.

The ionization of enriched water determines ionization losses and the decreasing of kinetic energy of protons see Figure 5a. The Bragg peak is the threshold kinetic energy for starting the nuclear reaction (E_{Thr}). The nuclear reaction is shown in Figure 6.

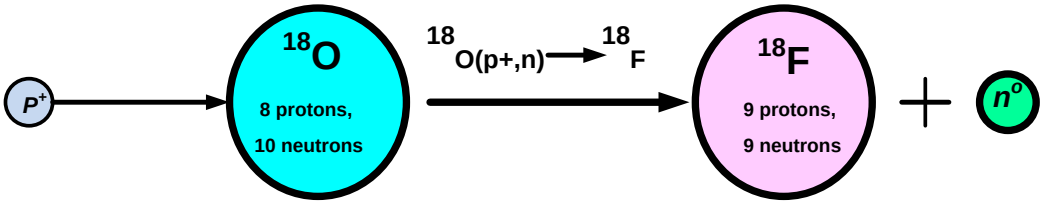

Figure 6. The nuclear reaction for the production of ^{18}F.

Analysis of physical processes in the target shows next:

1. Brag peak in the ionization processes leads to high dissipation of energy in the water that determines the high heating of water and components of the target with processes of increasing pressure and bulb forming in water.
2. Efficiency for production of isotope ^{18}F depends on the kinetic energy of protons.
3. Relative low efficiency for the production of ^{18}F from the partial use of the proton beam.

This analysis opens the potential ways for new concepts of increasing the efficiency for production of ^{18}F. One concept for increasing the production of ^{18}F is considered below.

4. Novel concept of accelerator system for production of ^{18}F medical isotope

The novel concept of accelerator system for production of ^{18}F medical isotopes is based on the following innovations:

1. An accelerator system based on the cycling of a single proton beam through multiple targets.
2. The irradiation of the target by protons with high kinetic energy threshold for nuclear reactions.
3. The separation of proton beams for the irradiation of an enriched water (target) with a partial target.
4. Post-acceleration of the proton beam after the initial cyclotron external target.

5. Accelerator system based on the cyclotron as an injector to the target and linear post-accelerators with bending magnets.

This concept is explained in Figure 7, where the selected level of the proton kinetic energy beams after water target. The primary kinetic energy is 11 MeV, taken from the Siemens Eclipse Cyclotron. But this concept of the accelerator system is acceptable for any PET cyclotron.

The technical solution of this novel concept is given in Figure 8.

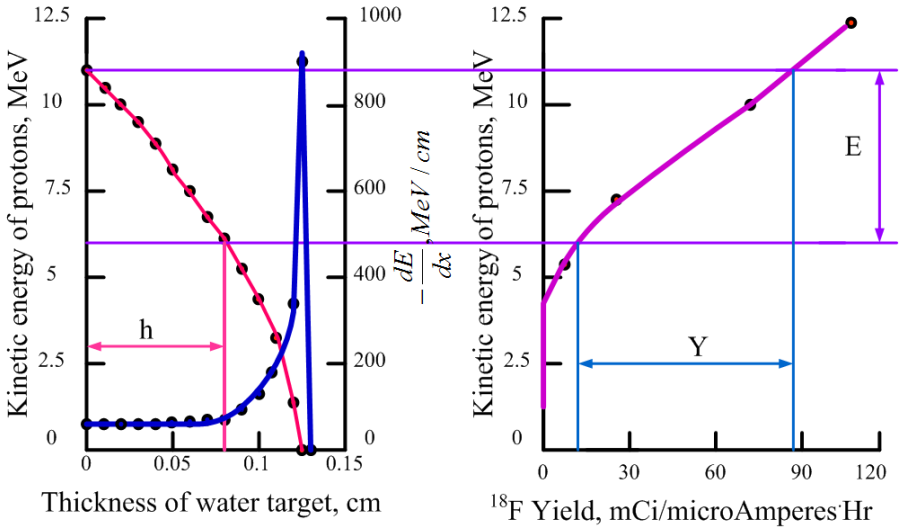

Figure 7. The physical processes in the target under proton irradiation.

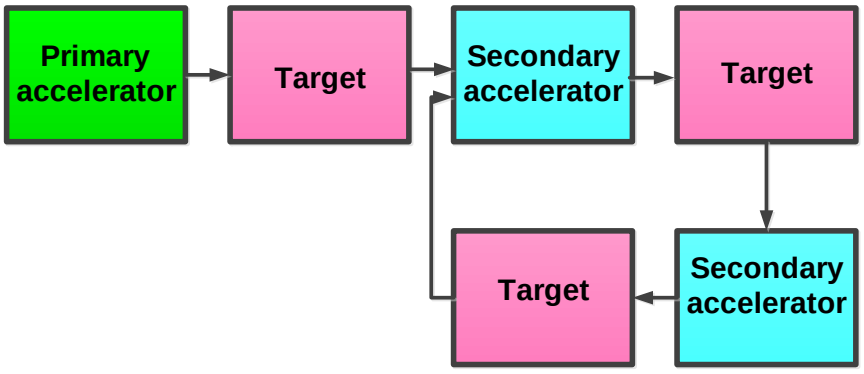

Figure 8. The technical solution of novel concept for production of medical isotopes.

The example of this technical solution for accelerator system with a single beam from the cyclotron is presented in Figure 9. The analysis of the beam losses is given in Figure 10. Decreasing of the beam current after the target is compensated by the increasing kinetic energy of the protons. The dependence of the yield of ^{18}F on the kinetic energy of the protons (Figure 11) from [3] allows for this compensation.

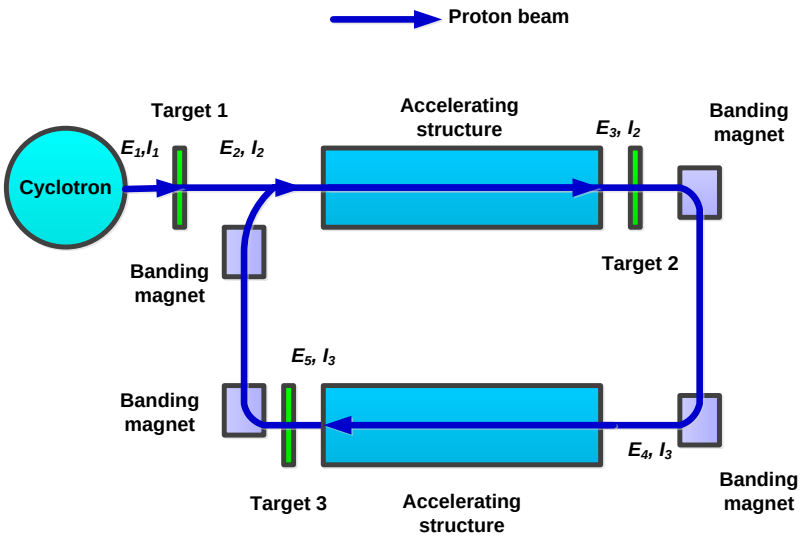

Figure 9. The example of technical solution with single beam from cyclotron.

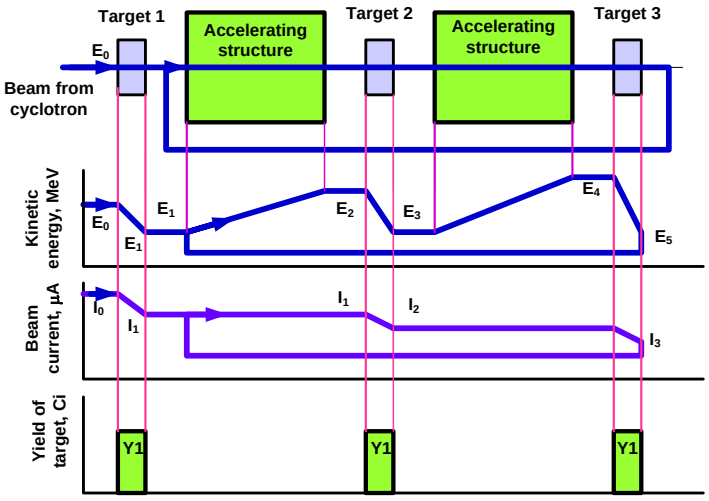

Figure 10. The distribution beam parameters after cyclotron.

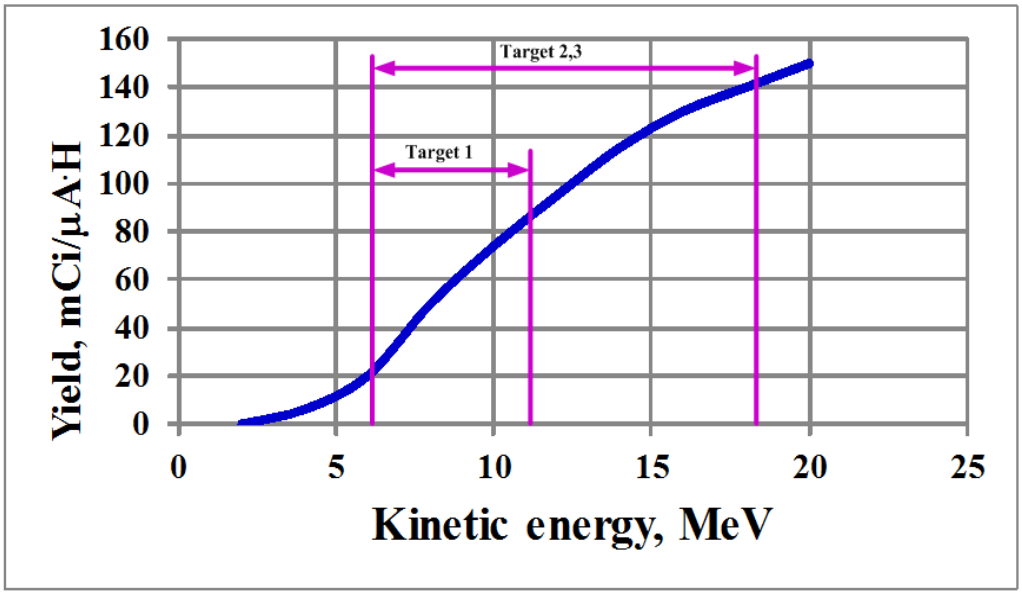

Figure 11. The dependence of yield of ^{18}F on kinetic energy of protons.

The first consideration for the partial target was the selection of the kinetic energy for the separation of chemical processes in the purification of lubricants and oil [9]. This paper is the development of this concept for proton beams. The concept of the partial target contains the target with the enriched water. This target has a smaller thickness in comparison to the standard water target (see Figure 12).

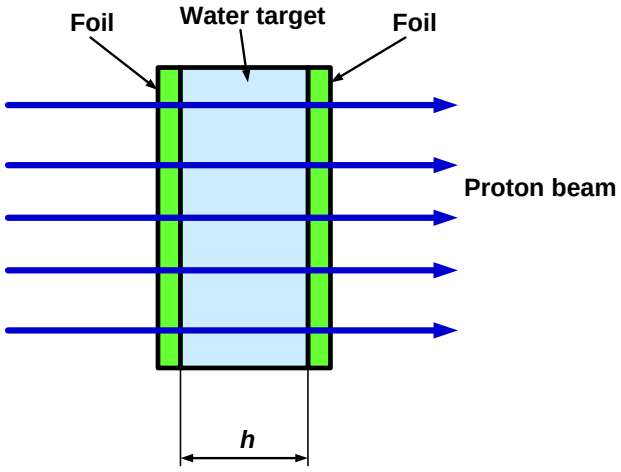

Figure 12. The concept of partial target.

The computer simulation on the SRIM program [10] for ionization of water by the proton beam with an injected kinetic energy of 11 MeV showed the low ionization losses in water (see Figure 13).

The proton beam after the partial target injects to the linear accelerator for post acceleration. The reasonable kinetic energy after the partial target is 6 MeV. The beam after the partial target has an increase of emittance and in the diameter of proton beam. According simulation the diameter of beam will increase from 10 mm to 15-20 mm. The example of the trajectories of the 11 MeV proton beam injected into the water and 6 MeV after it is injected into air according to the SRIM program is shown in Figure 14.

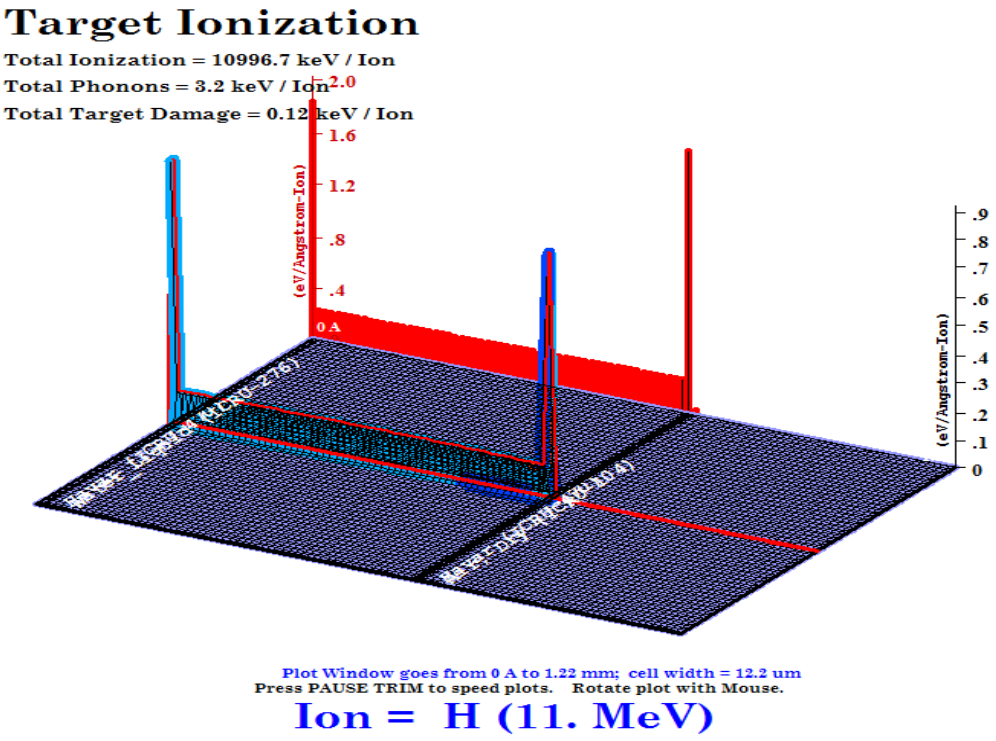

Figure 13. The simulation of ionization of the partial target from water and the two havar foils.

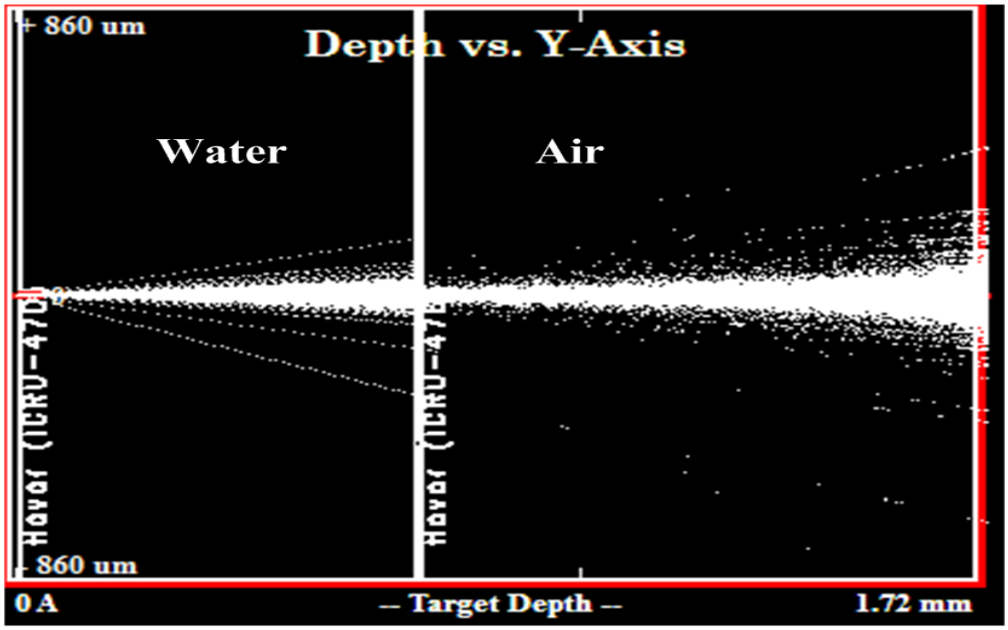

Figure 14. The simulation of trajectories of proton beam with 11 MeV injected to water and 6 MeV proton beam in air.

The 3 structures for linear accelerators [11, 12] can potentially be used in the proposed concept:

1. High voltage accelerating structure.
2. Room temperature radiofrequency resonator structure.
3. Superconducting radiofrequency resonator structure.

The main criteria, which determines the length of accelerating structure is the gradient of the electrical field for the acceleration of protons. The more effective approach is the use of a radiofrequency superconducting structure with a gradient of electrical field about ~25-33 MV/m [13]. It is necessary to point out that the variant of the racetrack FFAG accelerator for high energy was discussed in [14] at the XX International Cyclotron Conference in Vancouver in 2013. The question of the type of the linear accelerator and the efficiency of the acceleration is complex and will be considered in future work.

The bending magnet presents standard magnet with radius determines magnetic field, see Figure 15.

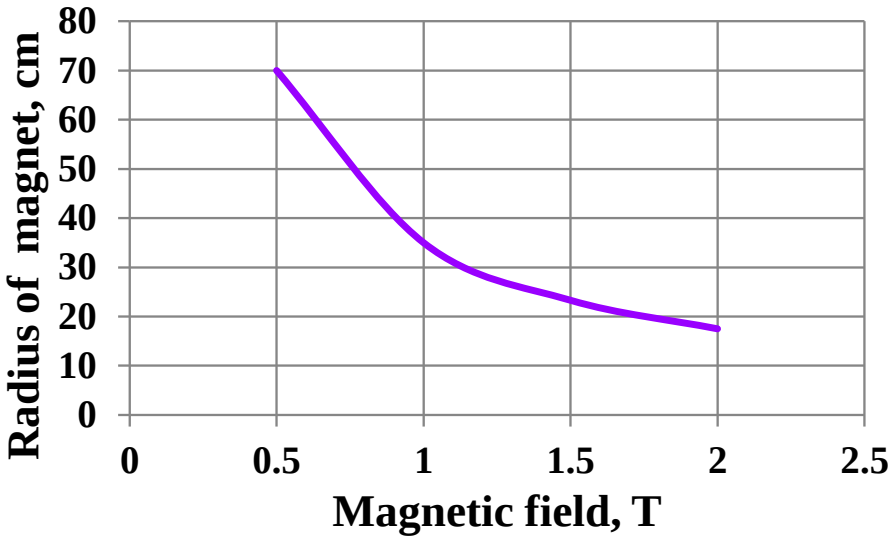

Figure 15. Dependence of radius of banding magnet on magnetic field.

The preliminary consideration of physical aspects for the novel concept shows that this concept allows for the increasing of the total yield of radioactive isotope.

5. Variants of accelerator system

The two variants of accelerator structures can be used for the production of medical isotopes. The first variant addresses single beam acceleration from the cyclotron (Figure 16). The second variant uses dual beam acceleration (Figure 17).

The main parameters of proposed systems are the following:

1. Kinetic energy of proton beam from cyclotron is 11 MeV.
2. Proton beam current from cyclotron is 60 μA for single beam and 120 μA for dual beam.
3. Kinetic energy of the proton beam after targets is 5-6 MeV.
4. Kinetic energy from accelerating structure (linac) is 13-18 MeV.
5. Total number of target is 3 for single beam and 6 for dual beam.
6. Total yield from 3 targets for single beam is 6 Ci/Hr and 12Ci/Hr for dual beam.

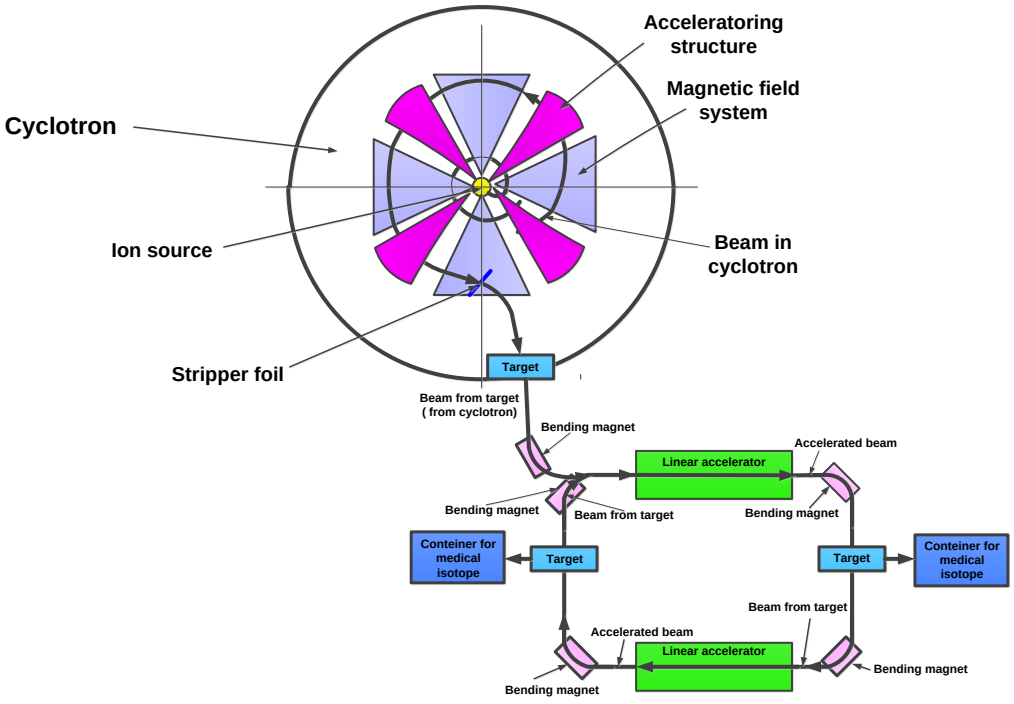

Figure 16. The accelerator system with single beam from cyclotron.

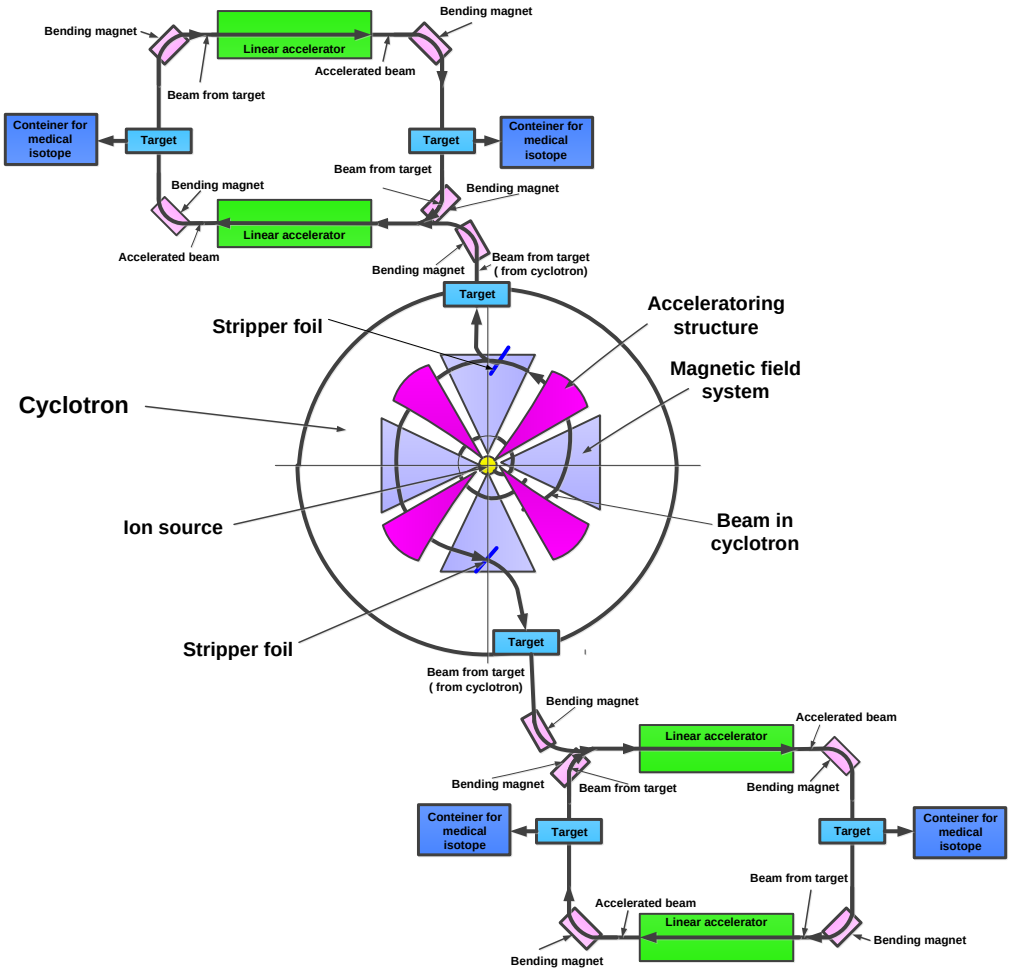

Figure 17. The accelerator system with double beam from cyclotron.

6. Comparison of current and proposed accelerator systems

The comparison of these systems is based on the two main parameters: beam efficiency and average activity of the radioactive isotope ^{18}F. The current and the proposed systems are shown in Figure 18.

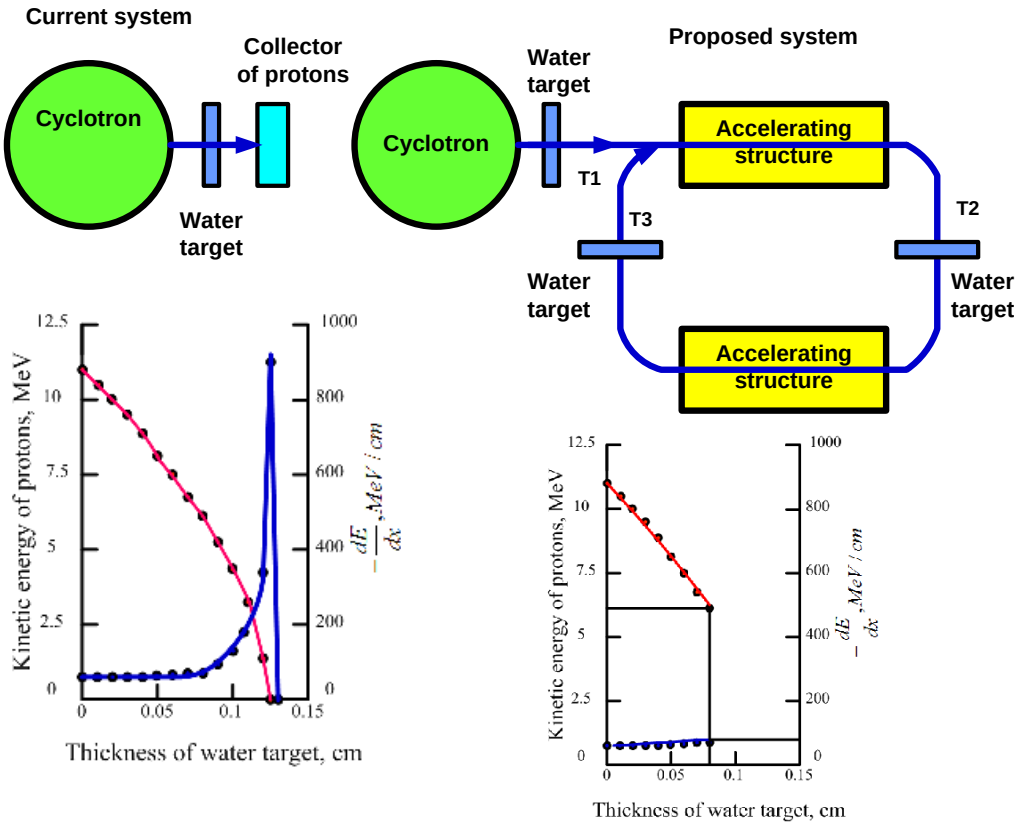

Figure 18. The comparison of current and proposed accelerator systems for production of ^{18}F.

The use of partial enriched water targets allows for the following physical process:

1. Ionization of water.
2. Nuclear reactions.

The absence of the Bragg peak allows for the decrease in the dissipation of energy in water, which leads to the low thermal loads. The nuclear reactions will be more effective for all beam propagated in the enriched water. This results in an increase (95-98%) in the efficiency of the use of the proton beam for the production of medical isotopes. The current system only allows for maximum 50% of beam for the same goals.

The factor of increasing of yield of radioactive isotope ^{18}F is 3 for single beam and 6 for dual beam. These factors correspond to the same accelerating structures. The variation of kinetic energy from each accelerating structure allows for the regulation of

the yield of the radioactive isotope ^{18}F. These comparisons allow for physical advantages of the proposed novel acceleration system. The economical questions are not considered in this paper.

7. Conclusions

1. The new concept of this accelerator system allows for a significant increase in the yield of radioactive isotope ^{18}F provided the use of the existing Eclipse cyclotron.
2. The detailed physical analysis of each sub-system for the accelerator system is required

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