Conceptual Design Study of 13 MeV Proton Cyclotron

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ABSTRACT

A study to determine the conceptual design of a 13 MeV proton cyclotron for PET (Positron Emission Tomography) facility has been carried out. Based on studies on reactions of PET radioisotopes production, reaction cross-sections and some design references, a design of the proton cyclotron is proposed. The design criteria for the main components are decided using empirical and semitheoretical methods, as well as by referring to data regarding cyclotrons for PET production. The empirical method was carried out by using some data from operational experiences of BATAN cyclotron at Serpong, while the semitheoretical method was carried out by using the commonly used equations of cyclotron basic theory. The general layout of components and the main components, namely the ion source, the RF dees, the magnet, and the extractor are discussed. Based on the calculations and on the data used, the cyclotron is designed as a negative ion acceleration cyclotron with internal ion source. The designated proton energy and beam currents are 13 MeV and 50 μA. Its magnetic field is in the relativistic mode with sectors on the pole. The magnetic field intensity at the extraction radius is 12.745 kG and in the innermost radius is 12.571 kG. The magnetic poles consist of four sectors to make adequate space for components placement such as dees, ion source, extractor and beam probe. The dee angle is 43^0. The dee operates at 78 MHz on the fourth harmonic. A multifoil extractor is chosen to obtain an efficient operation.

INTRODUCTION

Currently, cyclotron accelerators are used not only as research tools but also as commercial instruments, especially in the field of nuclear medicine. Commercial cyclotrons offer more compact systems and lower residual radiations which reduce the economic costs of installation and radiation protection. These cyclotrons are usually used for producing short-lived radioisotopes, so they should be placed in site in diagnostic facilities such as Positron Emission Tomography (PET) facilities. PET uses radioisopes of elements found in living things such as carbon, oxygen, and nitrogen. This technique can quantize regional oxygen consumption on glucose metabolism in the brain or the heart [1]. Four important radioisotopes used in PET technique are ^{11}C, ^{15}O, ^{13}N and ^{18}F. For this purpose, targets enriched in ^{18}O, ^{15}N and ^{13}C, which can be obtained commercially, are used [2].

The cyclotron design study at BATAN was started at the Center for Accelerator and Material Process Technology at Yogyakarta (PTAPB) in response to the trends in the use of cyclotron diagnostic facility with PET techniques in hospitals in Indonesia. A group of activities has been established to create a Basic Engineering Design Package (BEDP) document of the 13MeV cyclotron for PET which began in early 2009 and is planned for completion in 2014 [3]. The determination of the conceptual design is an early stage of the activities. The conceptual design is the result of the first design iteration and was completed on time.

Here we discuss the determination of the design criteria, which is performed using empirical and semitheoretical methods, and the resulting conceptual design. The empirical method is based on the experiences from BATAN Serpong cyclotron operation and design references in the world, while the semitheoretical method directly uses the basic equations commonly used in the cyclotron. The purpose of this work is to obtain a starting point for creating the basic design of cyclotron for PET facility, while its goal is to obtain data about the type and general specifications of the main components of the cyclotron.

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The rest of this paper is organized as follows. In the second section, the procedures followed on the design and the data used as references are discussed. Then, in the third section, the decision taken in the design process is discussed deeply greater. Finally, the conclusions are presented in the fourth section.

EXPERIMENTAL METHODS

The scope of design

The parts discussed in the basic design are the main and specific components of cyclotron, namely ion source, magnets, RF dee systems and extractors. Other components, such as power supply systems, cooling system and others common systems, are not discussed here, although those systems also play very important roles. The problems in technical design and materials are also not discussed.

Methodology

The following methods were used for determining the specifications of main components:

1. Reference to the standards issued by the IAEA on the cyclotron technology for imaging facility with PET techniques [4].
2. Empirical method, based on the operating experience of BATAN's CS-30 cyclotron, information obtained from the literature on the operation of other cyclotron facilities, and results of personal communication with experts in cyclotron technology [5].
3. Semitheoretical method, based on basic equations used in the design of cyclotron; in this work, those equations were not analyzed in detail using the physical theory of cyclotron.

Basic equations

The basic parameters of cyclotron components consist of particle energy, magnetic field, RF frequency, and extraction radius. Those parameters are related to the following two equations [6]. The first equation, relating proton revolution frequency, f_p with the magnetic field B, is

$$f_p = 1.53\,B \tag{1}$$

The second equation, relating proton energy E_p, magnetic field B and radius R is as follows:

$$E_p = 0.48\,B^2 R^2 \tag{2}$$

where f_p is in MHz, B in kG, E_p in MeV and R in meters. The RF frequency depends on the harmonics used in the RF operation. In our case, the fourth harmonics is used; consequently, the RF frequency is $4\,f_p$.

Design requirements

Design of the use: radioisotopes to be produced

The main radioiotopes used in PET imaging techniques is listed in Table 1 [7].

Table 1. The main radioisotopes for PET imaging technique

Radioisotopes	Half-life, minutes	Gamma energy, MeV
^{18}F	109.8	0.633
^{11}C	20.4	0.959
^{13}N	9.96	1.194
^{15}O	2.04	1.738

Because its half-life is not too short and its gamma energy is the lowest, ^{18}F is the most commonly used radioisotope, in the form of a compound called fluorodeoxy glucose (FDG). Typical activities of FDG injected into the patient's body are 185-555 MBq (5-15 mCi) for whole body imaging [7].

Requirements of energy and beam current of proton

Table 2 shows the nuclear reactions, beam currents, and the yields of radioisotopes for the cyclotron producing radioisotopes for PET designed by TRIUMF at Vancouver, Canada [2].

Table 2. Proton beam current needs for the production of positron emitter

Reactions	Radioactivities	Beam current (E_p =11 MeV)
^{15}N(p,n)^{15}O	500 mCi ($T_{1/2}$=2 minutes)	8 μA
^{16}O(p,α)^{13}N	200 mCi ($T_{1/2}$=10 minutes)	30 μA
^{14}N(p,α)^{11}C	1 Ci ($T_{1/2}$ =20 minutes)	25 μA
^{18}O(p,n)^{18}F	1 Ci ($T_{1/2}$=110 minutes)	15 μA

The KIRAMS-13 cyclotron at the Korean Institute of Radiological and Medical Science (KIRAMS) operates at a proton energy of 13 MeV and a beam current of 20 μA [8]. The first hospital in Indonesia to set up a PET cyclotron is the Gading Pluit Hospital, which uses a GE Minitrace baby cyclotron operating at a proton energy of 9.6 MeV and a beam current of 50 μA [9]. To determine the proton energy required for producing ^{18}F, the cross section data shown in Fig. 1 is used.

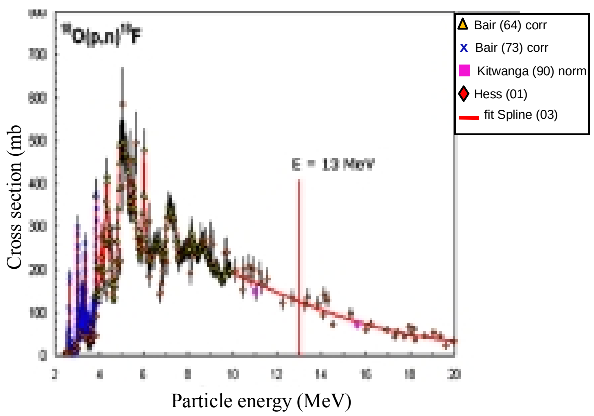

Fig. 1. Reaction cross section of ^{18}O reaction ^{18}O (p,n) ^{18}F [10].

Since radioisotope production uses a relatively thick target, the thick target yield equation is used. In this equation, the radioisotope yield is calculated by integration from the energy of zero up to the incoming proton energy. From the reaction cross section data on Fig. 1, it can be seen that the chosen proton beam energy of 13 MeV is adequate to obtain sufficient yield energy. For energies above 13 MeV, the reaction cross-section is sufficiently low that its contribution to the integration is not significant.

Based on the references and observations above, it was concluded that a setting of a proton energy of 13 MeV and a beam current of 50 μA is feasible.

Requirements for the layout

When a non-self-shielded cyclotron is in operation, the negative ion machine accelerates H^- ions to 13 MeV. At the extraction radius, the negative particles are stripped of their electrons by passing through a very thin carbon foil, resulting in positively charged H^+ ions. These ions are bent outwards to the target ports by the magnetic field. Up to 50 μA of proton beam intensity can be extracted onto a single target or divided between two oppositely mounted targets. This necessitates a radiological shielding which is designed in such a way that the doses at several locations in a positron emission tomography facility would not exceed 2.5 μSv/h during cyclotron operations.

Monte Carlo and discrete ordinate calculations have to be performed to determine the doses at several locations in a positron emission tomography (PET) facility, i.e. the bulk shielding assessments will be performed for cyclotron concrete as well as target system concrete. Experimental measurements data indicates that the cyclotron shielding together with the 60 cm thick concrete wall of the vault is sufficient to keep the radiation dose level.

RESULT AND DISCUSSIONS

Type of cyclotron

To produce protons with a cyclotron, one can use positive ion acceleration (abbreviated as PIA) or negative ion acceleration (NIA). The following subsections discuss the advantages and disadvantages of both types.

Overview of stability

Operation stability is essential for a cyclotron installed in a hospital, for two reasons: First, human resources having expertise in cyclotron are in limited number, and second, prime services have to be given to the patients.

In PIA tuning, the extraction process takes at least 30 minutes. This is because extraction system using high voltage that causes the spark of electricity. The sparks cause the extractor voltage to fall frequently. Extractor positions far from the beam port also cause the settings of extracted beam direction to be rather difficult. Both conditions cause a long tuning time. The sparks also cause instabilities in the dee voltage. If high intensity sparks occured, they can cause a trip on the high voltage source of the RF oscillator. Operating experiences of CS-30 showed that the high voltage source of the RF system failed every hour [11], so even if the specification of the cyclotron state that a proton current of 60 μA can be produced, the average current operation is only of 33.8 μA [12].

If NIA is instead used to produce protons, an H^- ion beam is accelerated and extracted to target. The extraction process in NIA is performed not by using the electrostatic deflector but by using carbon foil. This process does not use high voltage electrostatic at all, so there is no disturbance which causes high voltage instability.

Extraction efficiency

Highly efficient beam current production will contribute to the economical feasibility for the hospital facilities. Also, high beam production efficiency allows lower radiation exposure, which confirms to the principle of minimum radiation "as low as reasonably achievable" (ALARA).

The extraction process in PIA uses a pair of electrodes as high voltage deflectors, one held at a negative potential to attract positive ions and the other is grounded. The two electrodes are separated by a gap of about 3 mm at the end of the gap where the beam enters, widening to approximately 5 mm at the other end. Through this gap the extracted beam is passed to the beam port. Because of this narrow gap, many parts of the beam are caught in the wall, reducing the intensity of the extracted beam and activating the deflector wall. The disadvantages are low extraction efficiency and high radiation intensity in the cyclotron tank, especially in parts of this extractor. Experiences with BATAN cyclotron facility's CS-30 cyclotron show that exposure to radiation in these parts is as high as 4000 mR. The extraction efficiency with PIA is no more than 70% and for old facilities can even be less than 50% [13].

The extraction process in NIA uses a carbon foil which is passed through by the negative ion beam. An H^- ion will lose both of its electrons and be transformed into H^+ ions or protons, which will then be deflected by a magnetic field at the cyclotron edge toward the beam port. Operating experiences show that the extraction efficiency of this model is almost 100% [5,14]. The high efficiency of NIA increases the efficiency of the production process. As an illustration, the IBA Cyclone-30 produces extracted beam power of 15 kW at 100 kW power consumption [13]. Another advantage is that the radiation exposure is lower for the personnel.

Table 3. Qualitative comparison of PIA and NIA characteristics.

Parameters	PIA	NIA
1. Stability	lower	higher
2. Vacuum requirement	lower	higher
3. Extraction efficiency	lower	higher
4. Residual radiation	higher	lower

Table 3 qualitatively compares the characteristics of NIA and PIA. NIA is chosen as it was found to be superior in three out of four criteria for comparison.

Main components parameters

Ion source

Internal and external systems

There are two methods for injecting ions into the acceleration chamber, namely internal and external ion sources. An internal ion source is placed in a vacuum tank and the main component of the ionization is in the central part of acceleration. This component is supported by a holder that connects to the drive components outside the vacuum tank. Gas injected into the ionization space, and cooling water lines are attached to this holder.

All components of an external ion source are located outside the vacuum tank. The resulting ion beam is then injected with early acceleration to several tens of kV through an inflector into the acceleration chamber of cyclotron. The inflector changes the direction of the vertical injection into the horizontal direction of movement in the cyclotron chamber. Table 4 shows a qualitative comparison between the internal and the external ion source systems.

Table 4. Qualitative comparison of internal and external ion sources

Parameters	Internal System	External System
1. Construction	simpler	more complicated
2. Efficiency of ion beam	higher	lower
3. Vacuum loading	major	small
4. Radiation exposure	higher	lower
5. Investment costs	lower	higher
6. Maintenance costs	lower	higher

Considering its advantages of simpler construction, higher ion beam efficiency, and lower investment and maintenance costs, the system type with internal ion sources is chosen.

Type of ion source

Several types of ion source have the necessary high intensity to produce H^- which can be used externally, such as the duoplasmatron type, the Ehlers source, the cold cathode PIG (Penning Ion Gauge) and the multicusp. However, internal ion sources types available are limited to the cold cathode PIG and the Ehlers sources. Both types of ion sources are similar in terms of their work principles, the only difference being that a hot cathode is needed on the Ehlers ion source.

Since the PIG ion source is simpler than the Ehlers ion source, it can be estimated that the costs required for a PIG type ion source would be cheaper. Therefore, the PIG ion source is chosen for this design.

The position of the ion source

The internal ion source can be installed radially from the sides of the cyclotron tank or axially from the top of the magnet, requiring a hole in the magnet pole. Because of its simplicity, the radial installation of the ion source is selected.

Output of ion beam current

The amount of the ion beam generated by cyclotron is obtained from the extracted ion beam from ion source multiplied by the beam acceleration efficiency. The acceleration efficiency is determined by the amount of ion beam collisions with the components in the tank, especially with the dees, and with molecules of residual gas. Based on the operating experiences of the CS-30 BATAN Serpong cyclotron, the efficiency is at the range of 60% [5]. The GE cyclotron at Gading Pluit hospital also operates at this value [14]. To obtain a 50 μA extracted beam current from a cyclotron, an ion source output current of 100 μA is adequate.

Magnet

Magnetic field strength

The determination of the magnetic field strength is based on the equation (1) by first determining the value of the frequency f of the RF system. RF tubes which operate at the 100 MHz region can be obtained in the market, but the chosen value of f must not be within the frequency band of radio communication broadcast to avoid leaks which could interfere with public communications. If the RF frequency is taken as 78 MHz and if the RF system operates in the fourth harmonic, the proton revolution frequency is f = 19.5 MHz. Using equation (1) to determine the value of the magnetic field strength,

$$B = \frac{19.5}{1.53} = 12.745\, kG \qquad (3)$$

If B_{max} = 12.745 kG is determined as the average magnetic field at the outermost radius (the radius of the particle beam extraction) where the expected proton energy is 13 MeV, then based on equation (2) extraction radius is R = 40.8 cm.

If B_{max} = 12.745 kG corresponds to the maximum kinetic energy E ($r_{\max}$) = 13 MeV, and by including the proton rest mass E_0 = 938.256 MeV, then using relativistic equation

$$B_{\max} = B_c\,(1 + \frac{E_o}{E_{\max}}) \qquad (4)$$

The magnetic field strength in the central region will be B_c = 12.571 kG.

Magnet sectors

Magnetic field intensity measured above is anisochronous magnetic field in average. To obtain focusing and stability of beam during acceleration, a magnetic pole is made in the form of sectors of low (valley) and high (hill) magnetic fields. The number of sectors is determined by considering the placement of components: two pieces of dee, an ion source, an extractor, and beam probes. The two dees require space on two valleys. The extractor which extracts beam to the three target directions requires free azimuth motion; thus, one valley is provided for extractor. Then the ion source and beam probes can occupy a single valley. So, a total of four valleys are required in the magnetic pole. With four sectors (N = 4) of symmetry, each hill and valley has an angle of 45^0. For the dees to enter fully into the valleys, the valley angle has to be slightly larger than dee angle namely 46.5^0 and the hill angle is 43.5^0.

The gap between the magnetic poles (hills) is determined based on the consideration that the distance should be as close as possible to obtain strong large magnetic field, but still be greater than the amplitude of vertical oscillation (betatron oscillation) of the beam. Based on references, the amplitude is 3 cm [15]. We set the gap between the hill to be d_h = 4 cm. The relation between the average magnetic field B_0 and the magnetic field in the center of hills B_h and in the center of valleys B_v is expressed by the equation [16]

$$\frac{2\pi}{B_0} = \frac{N\theta_h}{B_h} + \frac{N\theta_v}{B_v} \qquad (5)$$

where θ_h and θ_v are particle deflection angles on hills and valleys, respectively, and N is the number of sectors. The determination of θ_h and θ_v requires solving complex equations, and in approximations θ_h and θ_v are considered as hill and valley angles. If at the outer radius, the average magnetic field (B_0) is B_{max} = 12.745 kg, then from equation (5)

$$\frac{2\pi}{12.745} = \frac{4\pi\left(\frac{43.5^0}{180^0}\right)}{B_h} + \frac{4\pi\left(\frac{46.5^0}{180^0}\right)}{B_V} \quad (6)$$

or

$$0.157 = \frac{0.967}{B_h} + \frac{1.033}{B_v} \quad (7)$$

If B_h is set at 19.9 kG (which is still below the soft iron yoke saturation value at 21 kG), then the value of B_v is found to be 9.3 kG. Now, based on proportionality

$$\frac{B_v}{B_h} = \frac{d_h}{d_v} \quad (8)$$

Then the gap between the valley is d_v= 8.5 cm.

RF dee system

Dee geometry and frequency of operation

The geometry discussed here are the dee angle and the dee radius. The dee angle is determined the valley angle. If the construction symmetry is taken where there are four hills and four valleys, which are 2 dees can be installed in the 2 valleys and another 2 valleys to set the ion source and the beam probe. Valley angle is determined to be 46.5^o and dee angle (θ) should be less than 45^o. The particle revolution frequency has been selected on the magnetic system is of 19.5 MHz, means the operation of the RF dee voltage is 4$\times$ 19.5 MHz = 78 MHz.

The dee radius determines the maximum energy of protons of 13 MeV which is reached at a radius of 40.8 cm, and the radius of the dees should be slightly larger (42 cm). The size of the gap (the distance of upper and lower surfaces of the dee) is determined to be 3.5 cm. Accounting for the material thickness of the dees and water cooling conduit of about 0.75 cm, the total thickness of the dees is 5.0 cm. Since the gap in the magnetic valley has been set for 8.0 cm, the distance between the surface of the dees and the surface of the valleys is 1.5 cm.

Dee voltage

The dee voltage determines how many revolutions the particles have to complete in order to reach their maximum energy. The lower the dee voltage, the greater number of turns or revolutions will need to be and, consequently, the narrower the separation distance between neighboring turns according to the following approximation [17,18]

$$\Delta R \cong \left(\frac{R}{2}\right)\frac{2qV_0 \sin \varphi_s}{E} \quad (9)$$

where ΔR is the separation distance between turns, R is the dee radius, q is the ion charge, φ_s is the wide particle phase relative to the RF phase, V_0 is the peak dee voltage, and E is the particles' energy. From the equation, the separation distance is proportional to the radius and inversely proportional to the energy, but because energy is proportional to the radius square, so the separation distance is inversely proportional to radius. This means that while the maximum energy is achieved at the maximum radius, the separation will be the smallest at the maximum energy.

In theory, a high dee voltage is the choice, but the highest dee voltage feasible is determined by the required distance between the dee and the surfaces of the valleys to reduce electric sparks between the two surfaces. Operating experience with BATAN's CS-30 cyclotron, with a dee-valley distance of 1 cm, to avoid spark formation, the highest voltage allowable is limited to 25 kV and the normal operating voltage is 22 kV. Therefore, for this design, in which pre-determined distance is 1.5 cm, a safe value for dee voltage is 30 kV.

Beam extractor

Extractor position

In an isochronous cyclotron, the magnetic field is increased with increasing radius in order to compensate for the relativistic mass increase. Near the edge of the magnetic pole, the real magnetic field deviate far from the ideal magnetic field, at first rising to a maximum and then starting to decline sharply to zero. When the real field begins to fall away from ideal field, the particle phase begins to trail behind the phase of dee accelerating voltage. When the phases differ by 90^o, the acceleration stops; this point is called the acceleration limit. At a larger radius, the field index n = - (R /B)(dB/dr) reaches the value of 1 and this point is called radial focussing limit. Beyond this point, the magnetic field can no longer maintain the particle beam and the beam particles lose energy due to the influence of magnetic field. The radius where *n* reaches one is known as the independent extraction limit. In the region between the acceleration limit radius and the independent extraction radius, the extraction process is performed; the extractor foil is placed in this region.

Model of extractor

When the particle beam hits the carbon foil, high heat occurs in the foil. This heat, combined with proton collisions, eventually changes the structure of the carbon foil. Therefore, the carbon foil will be damaged and must be frequently replaced. If there is only one foil attached to the extractor it has to be pulled out from the vacuum tank frequently, resulting in less efficient operations and the possibility of disturbing the vacuum. To avoid such disturbances, it is necessary to employ a multifoil extractor. Such an extractor, which typically contains four foils, is mounted on a carousel that can be adjusted from the outside, so that when a foil is no longer in an adequate condition, it can be replaced with the next one without disturbing the vacuum.

An extractor of this type can be moved both radial and azimuthally. The radial motion is needed to vary the energy of the particles, although in a small variation, whereas azimuthal motion is needed for steering of the extracted beam path to the correct direction to the target.

The target station

The number of stations needed depends on the PET isotopes that would be produced. For PET isotopes as listed in Table 1, a minimum of three target stations are required: the first target is for nitrogen gas targets in the production of ^{11}C and ^{15}O, while the second target is for CO_2 used in the production of ^{13}N, and the last one is for water enriched in ^{18}O for ^{18}F production.

Vacuum system

Two considerations determine the size of pumping system: ion source gas load and pressure dependent beam loss because of gas stripping. The gas flow through the ion source to generate the required H^- ions at the rate of about 3-8 cm^3/min [2,19]. If a value of 5 cm^3/min is taken, this is equivalent to 0.05 torr.litre/sec. The total area, including copper liners and dees, in the vacuum chamber is about 7×10^4 cm^2. If one assumes an outgassing rate typical for clean but unbaked copper and stainless steel surfaces of 2×10^{-4} torr.litre/sec, the total outgassing load is 1.4×10^{-4} torr.litre/sec [2]. Clearly, most gas load is due to ion source gas flow.

An equation to determine pumping speed is $Q = SP$, where Q is gas load, S is pumping speed and P is pressure to be achieved. If desired vacuum is obtained by $P = 1 \times 10^{-5}$ torr then a minimum pumping speed of 5000 litre/sec is required.

The layout of the cyclotron

Non-self-shielded cyclotron facilities should be placed inside a room enclosed by 70 cm thick concrete walls. Based on above discussions of the cyclotron's main components, the initial design layout of the main components of the 13 MeV cyclotron for the production of PET isotopes is as shown in Fig. 2.

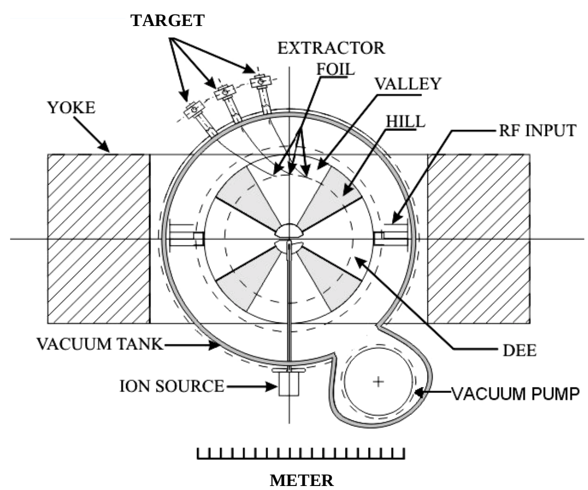

Fig. 2. The conceptual design of the 13 MeV Cyclotron: cross-section of the top view.

CONCLUSIONS

A conceptual design of the main components of a proton accelerator cyclotron with a proton beam energy of 13 MeV and a current of 50 μA for PET radioisotope production has been proposed. Based on considerations of operating stability, efficiency in producing an ion beam and ease of maintenance, a system of negative ion cyclotron accelerator with a radially mounted internal PIG ion source is chosen. A 100 μA beam current from the ion source is required. The magnet is a four-sector system, consisting of four hills and four valleys. Two of the valleys are used for placing the dees, while the other two valleys are for ion source and extractor placement respectively. By using a 78 MHz dee RF system running on the fourth harmonic, a 13 MeV proton energy will be achieved by a magnetic field of 12.745 kG and extraction radius of 40.8 cm. The criteria and specifications on this conceptual design and further developments in this work can be used as a reference for basic design cyclotron facility for PET.

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