INITIAL DESIGN OF A 13 MEV CYCLOTRON FOR POSITRON EMISSION TOMOGRAPHY

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Abstract

Since July, 1997, design studies for a 13 MeV H$^-$ cyclotron have been underway. This is a collaboration between the Korea Cancer Center Hospital(KCCH) and POSTECH. The choice of 13 MeV for the energy is expected to allow efficient production of β^+ emitter isotopes for PET (Positron Emission Tomography) applications while keeping the machine cost reasonably low. The design calls for a four-sector radial-ridge geometry with the magnetic field ranging between 1.9 T in the hill and 0.48 T in the valley. The overall size of the cyclotron is less than 2 meters in diameter. In this presentation, we describe the outline of the machine together with the design parameters.

1 INTRODUCTION

The Korea Cancer Center Hospital, which was founded in 1968, has been involved in the business of nuclear medicine and radiation therapy. The hospital was actually established in 1963 as an Institute for Radiation Medicine, which was affiliated to the Office of Atomic ENERGY OF Korea. It started service at first by utilizing gammas form Co and later, the radio-isotopes produced by a research nuclear reactor at the Korea Atomic Energy Research Institute. In 1986, a 50 MeV medical cyclotron, built by Scanditronix, was installed in a site of the Cancer Hospital for neutron therapy and services in nuclear medicine. This provided an in-house supply of cyclotron-based radio-isotopes such as ^{201}Tl, ^{123}I, ^{67}Ga, etc, and in particular, the much shorter-lived radio-isotopes, for diagnostic or clinical use, although so far they have mainly been used for research purposes. In addition to serving in-house duties, this cyclotron has also produced and supplied 15$\%$ of the all cyclotron based radio-isotopes in Korea. This service has greatly contributed towards awareness of the potential benefits of nuclear medicine afforded by particle accelerators and evoked calls for similar services in other hospitals thereby prompting purchase of particle accelerators for in-house use in these hospitals. Two hospitals have so far installed dedicated cyclotrons for PET (Positron Emission Tomography) applications. where the isotopes of interest are the four clinically significant positron emitters ^{15}O, ^{13}N, ^{11}C, and ^{18}F in particular.

At Korea Cancer Center Hospital, mounting desires for an uninterrupted, reliable and timely supply of the isotopes to customers has prompted obtaining a dedicated 5-13 MeV cyclotron for PET applications and at the same time pursuing the purchase of a second (30 MeV) medical cyclotron in the very near future. The PET cyclotron is to be designed by us. This will not only ease the problems associated with maintenance during operation but also keeps the door open for a continuous upgrading of this machine in the future. The design and construction are planned to be completed in three years. At the time of writing this paper we are in the process of purchasing the materials for the cyclotron magnet.

2 BEAM OPTICS

In order to obtain initial parameters for beam optics, we utilize a simple theory for cyclotron optics. Fig. 1 shows one sector of a radial-ridge cyclotron where the shaded area is the hill. In the figure, the origin 0 denotes the geometrical center of the cyclotron. The parameters B_h, B_v, ρ_h, ρ_v represent the magnetic fields and the radius of curvatures at the center of hill and valley, respectively.

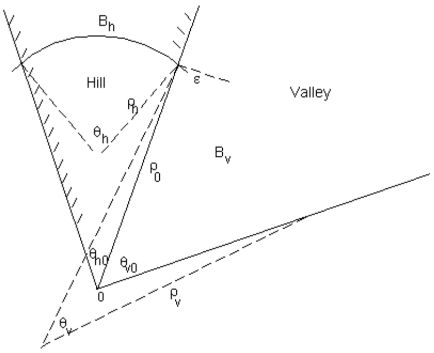

Figure 1: Top view of one sector of the cyclotron

Denoting B_0 as the time-averaged magnetic field and ρ_0 as the radius of curvature along the equilibrium orbit, the magnetic rigidity is given by

$$\frac{p}{q} = B_0\rho_0 = B_h\rho_h = B_v\rho_v \quad , \tag{1}$$

where p and q are respectively the momentum and the charge of the particle. The revolution time of a particle along the equilibrium orbit is

$$T_0 = \frac{N\rho_h\theta_h}{v} + \frac{N\rho_v\theta_v}{v}. \qquad (2)$$

Here N is the total number of sectors, v is the particle velocity, and θ_h and θ_v are the bending angle at the hill and the valley with respect to the center of curvature, respectively (see Fig. 1).

The above two equations lead to

$$\frac{N\theta_h}{B_h} + \frac{N\theta_v}{B_v} = \frac{2\pi}{B_0}. \qquad (3)$$

These equations provide the maximum average magnetic field and the revolution time of a particle when B_h and B_v are given.

With given hill and valley angles $\theta_{h_0}, \theta_{v_0}$ and the fields B_h and B_v, the bending angles θ_h, θ_v can be obtained from

$$\theta_h = 2\cos^{-1}\left(\frac{A}{\sqrt{1+A^2}}\right), \quad \theta_v = \frac{2\pi}{N} - \theta_h, \qquad (4)$$

where

$$A = \cot\frac{1}{2}\theta_h = \cot\frac{\pi}{N} + \frac{B_v}{B_h}(\cot\frac{\theta_{h_0}}{2} - \cot\frac{\pi}{N}). \qquad (5)$$

The maximum orbit deviation from the center of the cyclotron is at the center of the hill and is an important factor in determining the size of the cyclotron. It is given by

$$R_{max} = \rho_h(1 - \cos\frac{\theta_h}{2}) + \rho_0\cos\frac{\theta_{h_0}}{2}. \qquad (6)$$

Similarly the distance from the center of the cyclotron to the orbit at the center of the valley is given by

$$R_{min} = \rho_0\cos\frac{\theta_{v_0}}{2} + \rho_v(1 - \cos\frac{\theta_{v_0}}{2}). \qquad (7)$$

As is well known, in order to satisfy the isochronous condition, the field index must be

$$n = -\frac{r}{B_0}\frac{\partial B_0}{\partial r} = -\,\beta^2\gamma^2. \qquad (8)$$

The above simple relations provide a good basis for the initial design of the cyclotron. One of the important beam dynamical parameters are the radial and axial focusing frequencies. Magnetic fields must be carefully designed to avoid harmful resonances during the whole acceleration process. For four-sector cyclotron that we are considering here, the following perfect resonances must be avoided:

$$\begin{aligned} 4\nu_r &= 4 \\ 3\nu_r &= 4 \\ 2\nu_r &= 4 \\ \nu_r - 2\nu_z &= 0 \\ 2\nu_r + 2\nu_z &= 4 \quad . \end{aligned} \qquad (9)$$

Accurate ν_r and ν_z must be obtained through three-dimensional magnetic field calculation, measurement and analysis of the equilibrium orbit calculation. In the initial design stage no such data are available and therefore we resort to first-order beam optics using hard-edge model. If we assume that a cyclotron is composed of a series of dipole gradient magnets, we can then construct transfer matrices for the hill and the valley together with those for edge effects. Focusing frequencies are then obtained through

$$\begin{aligned} \cos(\nu_r\frac{2\pi}{N}) &= \frac{1}{2}Tr(M_r) \\ \cos(\nu_z\frac{2\pi}{N}) &= \frac{1}{2}Tr(M_z), \end{aligned} \qquad (10)$$

where M_r and M_z are the transfer matrices for one sector of a cyclotron in radial and vertical planes and N is the number of sectors. The symbol Tr means the trace of the matrix.

Based on the above, we wrote a program which calculates the machine parameters and focusing frequencies. The input parameters of this program are the maximum energy, hill and valley fields at that energy, and hill and valley angles. The program then calculates isochronous fields, orbit location and focusing frequencies at each energy. The results are shown in the following section.

3 RESULTS

Fig. 2 shows the side view of the half of the 13 MeV cyclotron. The system has a cylindrical shape. The height is approximately 93 cm and the diameter is 182 cm, respectively.

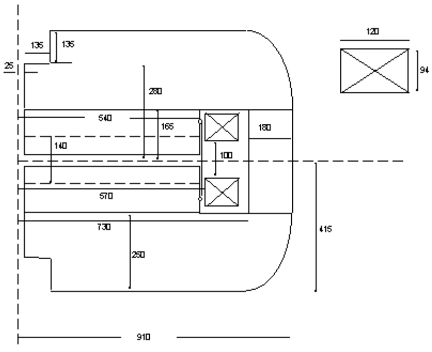

Figure 2: Side view of the 13 MeV cyclotron

Table I shows the main parameters for the 13 MeV PET cyclotron. The negatively charged hydrogen ion will be used for acceleration because of the easiness of guiding the beam into the target. Accelerating negative ion has also an advantage such that maximum extracted energy can be varied easily. The ion will be produced by an internal PIG source. The maximum energy of 13 MeV was chosen with particular emphasis on the production of ^{18}F isotopes. The fields at 13 MeV are 1.9 T and 0.48 T at the hill and valley centers, respectively. Thus the maximum average magnetic field is 1.19 T. The dee voltage is 50 kV and the harmonic number is four. The radio-frequency is 71.49674 MHz. The energy gain per turn is given by

$$\Delta E = 4qV_{dee} \sin \frac{h\theta_{dee}}{2}, \qquad (11)$$

where V_{dee} is the dee voltage h is the harmonic number and θ_{dee} is the dee angle. With V_{dee}=50 kV, h=4, θ_{dee}=43°, the energy gain per turn is ΔE=199.5 kV. The total number of turns is therefore approximately 70.

Table I : Main parameters of the 13 MeV PET cyclotron

Parameter	Unit	Value
Maximum energy	MeV	13
Beam species		Negative hydrogen
Number of sectors		4 (radial ridge)
Ion source		Internal negative PIG
Hill angle	degrees	43.5
Valley angle	degrees	46.5
Maximum average magnetic field	T	1.1896
Flutter		0.3562
Harmonic number		4
Radio-frequency	MHz	71.49674
Maximum average radius of a beam	cm	42.76
Maximum orbit distance from the cyclotron center	cm	44.66
Maximum magnetic field at the hill center	T	1.9
Maximum magnetic field at the valley center	T	0.48
Axial focusing frequency		0.595-0.624
Radial focusing frequency		1.041-1.062
Dee angle	degrees	43
Dee voltage	kV	50
Beam curent	μA	$\sim$20
Extraction		by stripping foil

The variation of focusing frequencies for the designed cyclotron with parameters given in Table I shows in Fig. 3. This figure shows the tune diagram with perfect resonances up to fourth order. Dotted lines are difference resonances while solid lines indicate sum resonances. The line on the lower left shows the variation of focusing frequencies throughout the accelerating region.

The magnet pole tips will be made of ultra-low carbon steel with 0.003% content of Carbon and Nitrogen, respectively. It will be supplied by a manufacturer specialized in a high quality magnet. Precision isochronism throughout the radius is achieved by shaping the hill radial thickness thus avoiding the use of concentric trim coils. Such a feature is especially important for hospital-based cyclotrons, because of operational simplicity. The yoke steel coming from the ingots will be precrushed with a press and then cold rolled. The whole magnets will be forged from ingots.

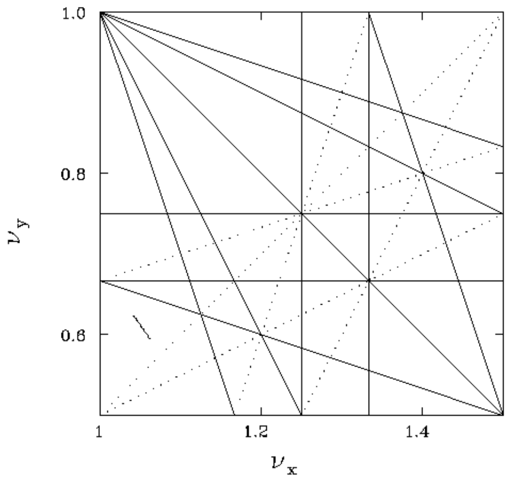

Figure 3: Tune diagram for perfect resonances up to fourth order. The line in the lower left shows the variation of focusing frequencies for the 13 MeV cyclotron.

Special forging will be required to assure the uniformity. The forged steel will then be annealed for homogetization. At the present time, we are in the process of purchasing the materials for the magnet. Details of the magnet system will be reported elsewhere [1, 2].

4 CONCLUSION

In Korea, design studies for a 13 MeV PET cyclotron have been in progress. Currently, design of the main magnets and the poles are being carried out. When completed in 2001, this cyclotron will serve to produce short-lived radioisotopes.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[1] M. Yoon et. al, Proceedings of the International Cyclotron Conference, Caen, 1998

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