INITIAL DESIGN OF A 13 MEV CYCLOTRON FOR POSITRON EMISSION TOMOGRAPHY: DESIGN OF THE DEE SYSTEM

S. Oh, W.Y. Yang, M. Yoon, Dept. of Physics, POSTECH, Korea
J.S.Chai, J.H. Ha, KCCH, Korea
J.W. Kim, RIKEN, Japan

Abstract

A design study of the main magnet for a 13 MeV cyclotron has been underway in a joint collaboration between the Korea Cancer Center Hospital and POSTECH. A maximum energy of 13 MeV has been chosen to produce radioisotopes such as ^{18}F. There are four magnet sectors, each with radial-ridged shape. The dees will be operated at the fourth-harmonic rf mode. In this presentation, we describe initial design parameters of this 13 MeV PET cyclotron as well as some features of the dee system.

1 INTRODUCTION

At the Korea Cancer Center Hospital (KCCH), design study of a 13 MeV cyclotron for Positron Emission Tomography (PET) has been in progress since July 1997. The study has been carried out in a joint collaboration between KCCH and the Pohang University of Science and Technology (POSTECH).

The KCCH has played a leading role in radiation medicine as well as in the treatment and research of cancer, since it was established as the Radiological Research Institute in 1963 to promote the medical application of atomic energy in Korea. For neutron therapy and radiation treatment, a 50 MeV medical cyclotron, built by Scanditronix, was installed at the hospital in 1986. The cyclotron has provided an in-house source of radio-isotopes such as ^{201}Tl, ^{123}I, ^{67}Ga, etc, and in particular, the shorter-lived radio-isotopes for diagnostic or clinical use. In addition to serving in-house duties, this cyclotron has also produced and supplied 15$\%$ of 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 in Korea. So far only two hospitals have 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 the Korea Cancer Center Hospital, increasing desire 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 pursuing the purchase of another 30 MeV medical cyclotron in the very near future. A decision has been made to design the PET cyclotron in Korea. This will not only ease the problems associated with maintenance during operation but also keeps the door open for continuous upgrading of the machine in the future. The project is supported by the Ministry of Science and Technology (MOST) of the government, as a part of the 2nd phase of the mid- and long-term nuclear energy research plan. The project was started in July 1997 and is to be completed in three years.

In this presentation, we introduce the initial parameters of this 13 MeV PET cyclotron with particular emphasis on the initial orbit calculation and the rf system design.

2 BEAM OPTICS

The first step of the cyclotron design is to obtain initial parameters for the beam optics. For this purpose, we employ a simple theory based on hard-edge approximation for cyclotron orbit.

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 and 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. The revolution time of a particle along the equilibrium orbit is

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

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.

The above two equations lead to

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

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

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

where

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

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 a 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 the 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 the 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 computer program which calculates the machine parameters and focusing frequencies. The input parameters of this program are the maximum energy, the hill and valley fields at that energy, and the hill and valley angles. The program then calculates the isochronous fields, orbit location and focusing frequencies at each energy.

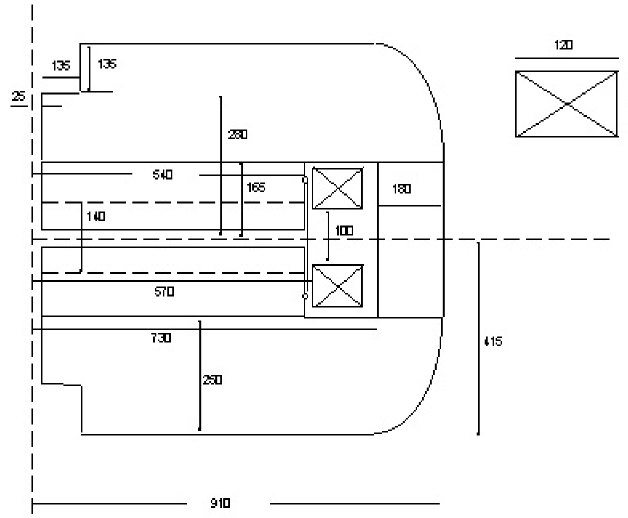

Figure 1: Side view of the 13 MeV cyclotron

Fig. 1 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.

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 ease of guiding the beam into the target. Accelerating negative ions has also an advantage in that the 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. The maximum average magnetic field is 1.19 T. The dee voltage is 50 kV and the harmonic number is four. 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}=40 kV, h=4, θ_{dee}=43.6°, the energy gain per turn is ΔE=159 kV. The total number of turns is therefore approximately 82.

Based on the analytical calculation above, detailed design study for magnet system is being carried out with the help of computer programs POISSON and TOSCA. Detailed design result of the magnet system and the equlibrium orbit analysis will be presented in the near future.

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
Ion source		Internal negative PIG
Hill angle	degrees	43.5
Valley angle	degrees	46.5
Maximum average magnetic field	T	1.19
Flutter		0.36
Harmonic number		4
Radio-frequency	MHz	71.5
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		0.59-0.62
Radial focusing frequency		1.04-1.06
Beam current	μA	$\sim$20

3 DEE SYSTEM

Design of the rf resonator system is being carried out with the help of the SOPRANO program. The rf system is conceptually similar to the LC resonator circuit, where the resonant frequency is given by

$$f = \frac{1}{2\pi\sqrt{LC}} \quad ,$$

where L is the inductance and C is the capacitance. In the calculation, we set f to be 73 MHz, which is approximately the fourth harmonic of the revolution frequency of a beam. Two 43.6° dees are located in two valleys. Total length of each dee is 54 cm. The distance between the dee and the liner is 1 cm. Applied voltage is 40 kV.

The operation mode of the cavity is TM_{01} and it consists of two concentric cylinders. The radii of the inner and outer cylinders are 10 cm and 15.3 cm and the length is 30 cm. The cavity is made of OFHC copper and the Q value is approximately 10^4. The coupling is inductive and the total rf power is 10 kW. Table II shows the major parameters of the rf system.

Table II : Main parameters of the rf system

Parameter	Unit	Value
Resonant frequency	MHz	73
Rf power	kW	10
Dee voltage	kV	40
Dee angle	degree	43.6
Dee length	cm	54
Harmonic number		4
Cavity inner radius	cm	10
Cavity outer radius	cm	15.3
Cavity length	cm	50
Cavity mode		TM_{01}
Rf coupling		inductive

4 CONCLUSION

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

5 ACKNOWLEDGMENTS

This work is supported by Ministry of Science and Technology, Republic of Korea.