# INITIAL DESIGN OF A 13 MEV CYCLOTRON FOR POSITRON EMISSION TOMOGRAPHY : DESIGN OF THE MAIN MAGNET

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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 radio-isotopes such as $^{18}F$. There are four magnet sectors, each with radial-ridged shape. Maximum magnetic fields are 1.9T and 0.48T at hill and valley centers, respectively. The total size of the cyclotron is less than 2 m in diameter. In this presentation, we describe initial design parameters of the 13 MeV PET cyclotron, with emphasis on the beam optics calculation and main magnetic field shape.

## 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 main magnet 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 $\rho_0$ 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 $B_h, B_v, \rho_h, \rho_v$ 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 $\theta_h$ and $\theta_v$ 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 $\theta_h, \theta_v$ 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

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

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

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

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

$$n = -\frac{r}{B_0}\frac{\partial B_0}{\partial r} = -\beta^2\gamma^2. \tag{8}$$

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:

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

Accurate $\nu_r$ and $\nu_z$ 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

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

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.

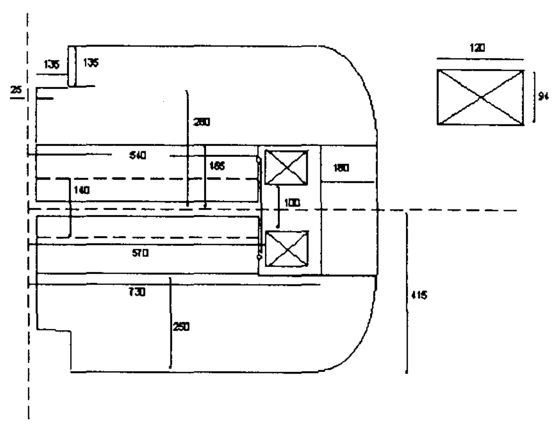


Figure 1: Side view of the 13 MeV cyclotron

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.

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 |
| Dee angle | degrees | 43 |
| Dee voltage | kV | 50 |
| Beam current | $\mu$A | ~20 |

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 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 $\theta_{dee}$ is the dee angle. With $V_{dee}$=50 kV, $h$=4, $\theta_{dee}$=43°, the energy gain per turn is $\Delta E$=199.5 kV. The total number of turns is therefore approximately 70.

## 3 Magnet System

In order to determine the pole gap of the main magnet, the program POISSON [1] has been utilized. This program provides a good basis to determine the approximate starting geometry of the yoke. The result showed that when the full gap heights of the hill and valley are 3 cm and 14 cm, the magnet fields at maximum radius are 1.9 T and 0.48 T, respectively, when $NI$=46000 Ampere-turns. However, in order to properly reflect the effect of the azimuthally non-symmetrical nature of the geometry, a three- dimensional magnetic field calculation program is required. For this purpose, the TOSCA program has been used and and we are now in the process of optimizing the detailed geometry of the magnet using this program.

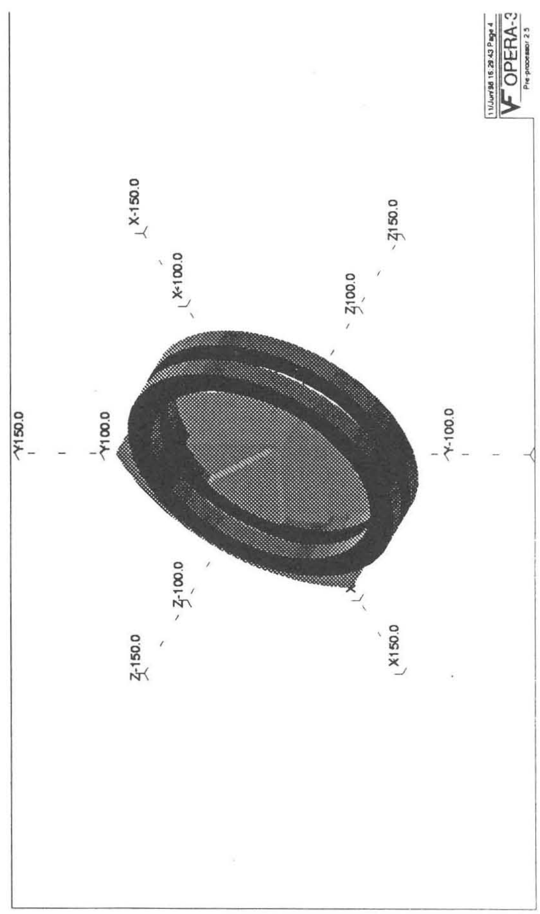


Figure 2: View of the magnet system obtained with TOSCA program

Fig. 2 shows a preliminary plan view of the magnet system obtained by the TOSCA program. Not shown in the figure are the central holes with 20 cm diameter. These holes at four valley regions will be used for pumping ports. It is expected that the presence of these holes will significantly disturb the magnetic field shape in the region near the hole, and thus a careful optimization process for pole tips shape will be necessary. This process is still underway.

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 specializing in high quality magnets. 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 complete magnets will be forged from ingots. Special forging will be required to assure uniformity. The forged steel will then be annealed for homogeniety. At the present time, we are in the process of purchasing the materials for the magnet.

## 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, this cyclotron will serve to produce short-lived radio-isotopes.

## 5 Acknowledgments

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## References

[1] User's Guide for the POISSON/SUPERFISH Group of Codes, LA-UR-87-115, Los Alamos Accelerator Code Group