Verification of DECY-13 cyclotron magnet design using cyclotron particle tracking codes

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Abstract. In order to increase a capacity building of an accelerator development, Center for Accelerator Science and Technology (CAST) – BATAN Yogyakarta, is developing DECY-13 Cyclotron for Positron Emission Tomography (PET) radioisotope production. One of the main components of the cyclotron, a magnet has been designed based on equilibrium orbits analysis of each increase in energy. To assure the designed magnet can guide a particle up to 13 MeV, a particle tracking is important to be carried out using simulation codes that have been benchmarked. Here, the designed magnetic field data and electric field data of the Dee were used in particle tracking simulation. The particle tracking results show that particles in the pass acceptance range can pass the central region and be accelerated up to 13 MeV. These results are consistent with the previous result of our particle tracking code. The range of phase acceptance of accelerated particle is around 110 degrees and the maximum initial axial excursion of the accelerated particles is ±1.5 mm. These results verify that the designed magnet can guide particles up to 13 MeV.

1. Introduction
A cyclotron has been widely used in many fields of application. Mostly, the cyclotron is used to produce radioisotopes for positron emission tomography (PET), single-photon emission computed tomography (SPECT), or other area of science [1]. The high energy particle beams can also be used to produce neutron beams or be used directly for material science [2] and medical application such as cancer therapy [3]. Even though, the role of cyclotrons is quite important, the use of cyclotron in Indonesia is relatively small. To date, there are only four operating cyclotrons in Indonesia and all of them are installed in the hospitals for PET [4]. Thus, to increase the use of cyclotron in Indonesia, understanding of the cyclotron technology is needed. Preparing human resources on cyclotron technology, increasing of capacity building, and developing cyclotron for application that may require a specific beam current or energy in the future are also needed. For this purpose, Center for Accelerator Science and Technology (CAST) – BATAN Yogyakarta, is developing 13 MeV cyclotron named DECY-13 [5].

A magnet which is one of the main components of a cyclotron has a crucial function as a beam guide so that the beam has a circular path. In addition, the magnet also has a function for focusing the beam by shaping hill-valley azimuthally on the magnet pole surfaces. The DECY-13 cyclotron magnet has been designed by using 3D magnetic field simulation code based on finite element method. The magnet parameters such as average magnetic field, vertical and horizontal tunes have been calculated using well known GENSPEO code based on static equilibrium orbit (no acceleration) analysis [6]. Verification the
designed magnet by applying it to the particle tracking simulation with acceleration is important to do to see how the dynamic behavior of the particle trajectories. Particle tracking simulation with acceleration using our own code has been performed by applying DECY-13 designed magnetic and electric field data, and the tracking result shows that the particle can be accelerated up to 13 MeV [7,8]. However, the particle tracking code has not been benchmarked with experiment result or others established codes. Thus, the particle tracking simulation using benchmarked tracking codes is needed in order to convince the designed magnet can guide the beam up to 13 MeV.

There are many particle tracking codes that have been built for cyclotron trajectory and have been benchmarked with experiment results [9]. Two of them, that are OPAL and SNOP codes were used for DECY-13 designed magnet verification. OPAL (Object Oriented Parallel Accelerator Library) is an open source code for general accelerator particle tracking simulation, including space charge calculation [10]. The code has been used for cyclotron particle trajectory such as in PSI Ring Cyclotron and superconducting skeleton cyclotron [11,12]. Meanwhile, SNOP is a particle dynamic simulation code specifically for complex structure of cyclotron [13]. This code has been used for beam analysis in the extraction system of the AVF cyclotron RCNP and in the modified TRIUMF PETtrace 800 cyclotron [14,15].

2. Material and methods

The DECY-13 cyclotron was designed to accelerate $H^-$ particles up to 13 MeV energy. After reaching the final energy, the $H^-$ particles will be converted to protons by stripping their two electrons when collided with a stripper (carbon foil). The design specification of the DECY-13 cyclotron is shown in Table 1.

| Parameters          | Value  |
|--------------------|--------|
| Maximum energy     | 13 MeV |
| Accelerated particle | $H^-$ ion |
| Ion source type    | Internal (PIG type) |
| Harmonic number ($h$) | 4 |
| RF Dee frequency   | 77.64 MHz |
| $B_{\text{average}}$ | 12,747.9 gauss |
| Dimensions         | $1.96 \text{ m} \times 1.3 \text{ m} \times 1.21 \text{ m}$ |
| Magnet weight (without coil) | $\sim 17.3 \text{ ton}$ |
| Max Dee voltage    | 40 kV |

Particle tracking simulation requires magnetic and Dee electric field data. In this study, the particle tracking code used designed magnetic field data in the median plane and designed Dee electric field data in three-dimensional space which were calculated using finite element method program. The DECY-13 magnetic and electric field data are shown in Fig. 1. The distance of the ion source to puller is assumed to be 3 mm in the Dee electric field calculation. In this study the simulation is performed in a single particle tracking. Thus, the space-charge effect that is the effect of the interaction among the particles is neglected. The initial condition of the particle was adjusted to find the acceptable particles.
3. Results and Discussions

3.1. OPAL particle tracking
The result of OPAL particle tracking simulation indicates that the particle in a certain range of the RF phase can be accelerated up to 13 MeV. This result is consistent with the typical RF acceleration where only particles in the range of phase acceptance will be accelerated and form a bunch beam. In this simulation, the range of phase acceptance of the beam is 110 degrees. All particles within the phase acceptance range can pass the central region without any collision with central region components as shown in Fig. 2. A dense trajectory is found in some regions as shown in Fig. 3. The dense trajectory region means that the trajectories of the neighboring particle energy are close each other or even overlapping. The overlap trajectories can be seen in the particle energy graph with respect to the particle radius as shown in Fig. 4. Here, the overlap trajectories occur when the higher energy particle has smaller radius. In this simulation, most of the particles in the range of phase acceptance have smooth trajectories without any overlapping. Even though the overlapping occurs in the radial direction, the particles position in axial direction may be different.

The particle excursion in the axial direction was analyzed within the phase acceptance range of 110 degrees with a variation of the initial axial (z) position. From the particle tracking simulation, as the
initial z position increases, the axial excursion increases. The axial excursions at the initial $z = -1.5$, $z = 0$, and $z = 1.5$ are shown in Fig. 5 and the maximum excursion is -10 mm. The axial excursion is limited by $\pm 10$ mm dee plate gap. Thus, the particle will hit the plate while the excursion larger than the dee plate gap.

Figure 2: Central region components and particle trajectories in the phase acceptance range.

Figure 3: Particle trajectory calculated by OPAL.

Figure 4: Particle energy graph with respect to the trajectory radius from OPAL calculation.

Figure 5: Trajectories excursion in the axial direction calculated by OPAL.

3.2. SNOP particle tracking

The particle trajectory calculated by SNOP looks similar with those calculated by OPAL where some regions of the trajectory have a high density as shown in Fig. 6. The phase acceptance range of the particle is found at 109 degrees. The phase acceptance is similar with those calculated by OPAL but much higher than those calculated by our Scilab program in Ref. 8. The discrepancy comes from the gap of the ion and puller which is set to 3 mm in this simulation, meanwhile the gap is set to 6 mm in the Scilab program. The phase acceptance will decrease if the gap increases. Most of the particle’s trajectories in the phase acceptance range are not overlapping with the pattern of the correlation of particle energy with respect to the trajectory radius is shown in Fig. 7.

The axial excursion of the particle trajectories calculated by SNOP is shown in Fig. 8 and looks like similar with those calculated by OPAL. The particles in the range of initial z position of -1.5 mm to 1.5 mm have a maximum axial excursion less than $\pm10$ mm.
Figure 6: Particle trajectory calculated by SNOP.

Figure 7: Particle energy graph with respect to the trajectory radius calculated by SNOP.

Figure 8: Axial particle excursion calculated by SNOP.

4. Summary
The simulation results show that the particles in the phase acceptance range and certain initial axial position can be accelerated up to 13 MeV. Both benchmarked particle tracking codes give almost similar result in the trajectory, phase acceptance, and the maximum initial axial position calculation. The simulation results verify that the designed magnetic field can guide the particle up to 13 MeV. Magnet optimisation are still required to minimize the dense trajectories.

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