DECY-13 cyclotron equilibrium orbit verification using CYCLONE

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Abstract. A cyclotron is a machine that accelerates a charged particle in a circular trajectory using electric and magnetic fields. The technical development of 13 MeV cyclotron in PSTA (Pusat Sains dan Teknologi Akselerator) BATAN was started in 2010 which eventually will be used for radioisotope production. A cyclotron consists of various technologies such as an electromagnetic, RF (Radio Frequency), ion source, and vacuum systems. Among them, the electromagnetic creates a magnetic field for particles to accelerate in a stable circular orbit. A particle within a uniform magnetic field moves along a closed trajectory, and that is called an equilibrium orbit. The stability of particle acceleration refers to the movement along the equilibrium orbit with oscillation. This paper deals with the equilibrium orbit verification using CYCLONE. We calculated and analyzed the magnetic and electric fields using Opera, then used them as input data in CYCLONE. The CYCLONE analysis provides several beam parameters such as beam energy, tune diagram, and beam trajectory. The analysis result shows that the beam was accelerated until the desired energy (13 MeV).

1. Introduction
A cyclotron is a machine that accelerates a charged particle in a circular trajectory. It was invented by E.O. Lawrence in 1929, then he developed the first cyclotron, which could accelerate proton energy up to 80 keV in 1932 [1]. Initially, the cyclotron was mainly used for nuclear physics experiments, but in the 1980s, due to the development of Positron Emission Tomography (PET) technology, the cyclotron started to be used for medical purpose. Currently, 1283 cyclotrons are used worldwide as a medical device for radioisotope production, neutron cancer therapy, and also for proton and heavy ion therapy [2]. In Indonesia, the number of cyclotron facility for radioisotope production is limited in Jakarta (3 facilities), and those are brought from overseas.

A technical development of DECY-13 MeV cyclotron in PSTA (Pusat Sains dan Teknologi Akselerator) BATAN was started in 2010. A DECY-13 cyclotron consists of various technologies such as an electromagnetic, RF (Radio Frequency), ion source, and vacuum systems. Among them, the electromagnetic creates a magnetic field for particles to accelerate in a stable circular orbit. A particle within a uniform magnetic field moves along a closed trajectory, and that is called an equilibrium orbit. Meanwhile, a particle moves in longitudinal and transverse directions with oscillation, and this is called betatron oscillation. Therefore, the stability of particle acceleration does not refer to a collection of particles at one point but to the movement along the equilibrium orbit with oscillation.

CYCLONE is a common program in the cyclotron technology to verify the equilibrium orbit. This code was developed in the mid-1960s at MSU as part of the K50 cyclotron project [3]. The program has
since been used to design central regions for the MSU K500, K1200, and K100 cyclotrons, and the Milan K800 cyclotron. The program was brought to TRIUMF from MSU and has been modified to make it more flexible for simulation in TRIUMF cyclotrons [4]. The code is popular in scientific organizations around the world and is useful for study all regions of a cyclotron, especially for central region design work. Orbits are calculated using Runge-Kutta type integration in a variety of magnetic and electric field maps. The equations of motion in CYCLONE are fully relativistic [5].

This paper deals with the equilibrium orbit verification using CYCLONE. We calculated and analyzed the magnetic and electric fields using Opera, then used them as an input data in CYCLONE. The CYCLONE analysis provides several beam parameters such as beam energy, tune diagram, integrated phase error, and beam trajectory.

2. Methodology
In general, the cyclotron electromagnetic design process is shown in Figure 1, it consists of two stages, initial and precision designs. The DECY-13 was designed to accelerate H− from ion source through the trajectory until reach 13 MeV at the extraction. At the initial parameter, the cyclotron magnet was designed as 1.96 m × 1.30 m × 1.21 m with the total weight and magnetic field at centre are ∼17.3 ton and 1.27479 T, respectively [6]. The number of magnet sector is four with pole and extraction radius are at 48 cm and 41 cm, respectively [6]. An internal PIG ion source and ∼77 MHz RF are applied in DECY-13. An OPERA-3D is used to gain information on the magnetic field [7]. Then the magnetic field from simulation and the isochronous field from calculation are compared. In the next stage, CYCLONE is used to examine the beam stability.

![Figure 1. Cyclotron electromagnetic design flowchart, it consists of two stages, initial and precision designs using OPERA-3D and CYCLONE codes.](image)

The beam parameters are analyzed, and simulation is repeated to secure stability. At this stage, iterative design of sector structure is needed, it is called soft shimming process. The structure of the DECY-13 magnet sector (median plane) is shown in Figure 2, it consists of hill and valley structures with the shimming process was applied at the hill sides.

![Figure 2. Median plane of sector magnet of DECY-13, consist of hill and valley structure with shimming process was applied at the hill sides.](image)
3. Result and Discussion

3.1 OPERA-3D Magnetic field simulation

Magnetic field calculation was done by OPERA-3D, in terms of magnetic field characteristics, the low carbon steel is adapted for cyclotron electromagnetic. The properties of low carbon steel to be used in the electromagnetic are expressed by a B-H curve that indicates the relationship between the flux density and the intensity of the applied magnetic field. In the initial electromagnetic design, the maximum magnetic field was calculated as 1.9 T [6]. Meanwhile, the maximum magnetic field for our sample low carbon steel in Figure 3 is \( \sim 1.85 \) T. Therefore, since the maximum magnetic field of the design electromagnetic is in the magnetic saturation region, then we used this material for DECY-13 with the B-H curve as shown in Figure 3.

![Figure 3. BH curve of low-carbon for DECY-13.](image)

Local mesh with 1/8 boundary condition was used for fast and accurate calculation in OPERA-3D. Calculated vertical magnetic field component data in mid-plane is used as an input in the CYCLONE. Figure 4 shows field distribution in the magnet pole as a result of OPERA-3D simulation.

![Figure 4. Magnetic field analysis of 3-dimensional electromagnetic model using OPERA-3D (1/8 model).](image)
To satisfy isochronism, magnetic field is corrected by [8]

$$\frac{\Delta B(r)}{B(r)} = y^2(r) \frac{\Delta f_p(r)}{f_p(r)}$$ (1)

where $\Delta B(r)$ is the magnetic field error, $B(r)$ is the magnetic field value, $\Delta f_p(r)$ is frequency error, and $f_p(r)$ is the rotation frequency of particles in the cyclotron. Isochronous field acquired by numerical calculation is the reference for magnet shimming and this process is an iterative work. Using those equation, when $\Delta B(r)$ is added with the average magnetic field obtained from simulation, the reference magnetic field value, which enables particles to go up to 13 MeV, can be obtained.

At the final iteration, the $\Delta B(r)$ and $\Delta f_p(r)$ are small enough as we can see it as a comparison of reference and average magnetic fields. Figure 5 shows the magnetic field (B) after 4th iterations (soft shimming) with the discrepancy between Breference and Baverage is less than 0.02 kG, and this value is acceptable.

![Figure 5](image_url)

**Figure 5.** Comparison of reference and average magnetic fields, discrepancy between these parameters indicates $\Delta B(r)$ and $\Delta f_p(r)$.

Figure 5 shows that initially, the reference field decreases then increases correspond to the radius. This can be determined through the focusing method during the process of particle acceleration. In a region where the beam energy is low, the design is performed to decrease the magnetic field intensity along the radius. This is a method that uses weak focusing to vertically focus the beam. Moreover, in a region where the beam energy is high, the beam is focused on the hill and de-focused on the valley repeatedly. This is called strong focusing. Therefore, to vertically focus the beam in a region where beam energy is low, the center pole of a dipole form is located in the center of the cyclotron. The magnetic field at a flat dipole decreases as the radius increases.

### 3.2 CYCLONE equilibrium orbit verification

To verify the magnetic field data result, CYCLONE was used for beam orbit analysis. Equilibrium orbit analysis was done by CYCLONE simulation using Breference with an electrical potential difference between the two dees is 40 kV. The beam will be accelerated up to 13 MeV at radius ~ 41 cm as shown in Figure 6a, with average energy gain is 145 keV per turn [9]. This gain is comparable with KIRAM-13 that has an average energy gain 170 keV per turn at 45 keV of dee voltage [10].
Figure 6. Beam orbit analysis of final magnet model using CYCLONE: (a) Beam energy according to radius and (b) Horizontal ($v_r$) and vertical ($v_z$) tunes.

Transverse beam stability which is horizontal and vertical betatron oscillation numbers are represented as $v_r$ and $v_z$ in Figure 6b. Resonance occurs when $v_r$ and $v_z$ become integers, so this should be avoided. The $v_r$ from the tune graph shows a horizontal tune concerning energy, indicating horizontal betatron focusing. Resonance occurs from initial and final energy, but the initial energy is not considered, because it is low. In the final energy region, the beam obtains the required energy, so the stability is reasonable.

The $v_z$ from the tune graph is a vertical tune concerning energy, indicating vertical betatron focusing. When the beam is on the accelerating energy region, the $v_z$ value should be between 0 and 0.5 so that resonance can be avoided [11]. Figure 6b shows that $v_z$ remains within 0.1 when accelerating to 13 MeV, which satisfies the stability of the beam. Finally, the beam-rotating orbit is shown in 7, which was obtained by Orbit data. It showed that beam acceleration was stable. Dense trajectories are found in some regions of Figure 7 (e.g., at radius 30 – 40 cm). The turn separation of beams at each radius is shown in Figure 8, the dense trajectory region indicates that the trajectories of the neighbouring energy are close to each other but not overlapping. This result comparable with another simulation using snob and opal particle tracking [12]. The vertical movement of the beam is ± 4 cm as in Figure 9, while the dee gap is ± 10 cm, so this vertical movement is acceptable.

Figure 7. Beam trajectory of particles from ion source to the extraction, orbit accelerating to 13 MeV.
Figure 8. Turn separation of beams as function of radius at $\theta = 26^\circ, 90^\circ$, and $270^\circ$.

Figure 9. Vertical movement of particle according to the radius.

4. Conclusion
In this study, the magnetic field data of the final magnet model was inputted into the CYCLONE, which was an equilibrium trajectory program, thereby enabling the determination of the stability of its beams and trajectory of the accelerated beam. The simulation results show that the particles can be accelerated up to 13 MeV. The CYCLONE simulation result is comparable with other simulation codes i.e., snob and opal particle tracking.

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