INVESTIGATION OF MINIMIZED CONSUMPTION POWER ABOUT 10 MeV CYCLOTRON FOR ACCELERATION OF NEGATIVE HYDROGEN

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Abstract

SKKUCY-10 cyclotron with 10 MeV particle energy was designed with purpose of production about fluorodeoxyglucose (FDG). Design strategy was maximization of accelerating voltage in order to secure the turn separation. Magnet had deep valley type, RF cavity had four stems and one RF power coupler. There was internal ion source for compact design of cyclotron. Specification of cyclotron was analysed by simulating particle dynamics for central region and whole system. AVF cyclotron had 83.2 MHz of radio frequency, 1.36 T of average magnetic field, 40 kV of main accelerating voltage. Phase slip between RF and beam was less than 15 degrees, minimum turn separation was over 2 mm. Specifications of both single beam analysis of reference particle and multi-beam analysis of bunch of particles were calculated by using Cyclone v8.4 and CST-Particle studio codes.

INTRODUCTION

Cyclotron was one of main device to product medical radio isotopes such as ^{18}F, ^{13}N, ^{11}C, ^{15}O for PET and ^{64}Cu, ^{67}Ga, ^{99m}Tc, ^{123}I for SPECT and so on [1]. Since fluorodeoxyglucose(FDG) was useful for diagnosis of cancer by using positron emission tomography machine, cyclotron was started to developed rapidly for production of ^{18}F isotope. Production yield of ^{18}F was studied with many nuclear reaction, there were optimal condition, acceleration energy, type of particle. Main process was also discovered (p, n) reaction at ^{18}O liquid target with few MeV energy level.

Design strategy of cyclotron was affected by user, medical physicist and researcher of radio isotope, and cyclotron market. Most cyclotron was distinguished by accelerating energy. One of design goal is compact size or high current with low energy for production of medical isotope with 7~20 MeV, another is high efficiency with 30~100 MeV for research field. There also be higher energy 100, 250 MeV cyclotron in order to apply the proton therapy or production of neutron [1- 3].

Cyclotron of ^{18}F production was developed to maximize the beam current with optimal energy 9~11 MeV. Low energy cyclotron usually had sector focus magnet typed pan cake and internal penning ionization gauge ion source. There are two types low energy cyclotron, one is used 4 stems dee and deep valley magnet, other is 2 stems dee and shallow valley magnet [4, 5]. Deep valley design was known that it has advantage of increasing characteristic of vertical focus. It was affected to decrease the beam losses inside cyclotron, to maximize the emission current at the target. One of main limitation of emission current is performance of internal ion source, it is depended on number of particle in the plasma region inside of chimney. So there was high current cyclotron used two internal ion source in order to increase the emission current [6].

DESIGN OF MAIN STRUCTURE

Cyclotron focused production of ^{18}F isotope was designed for acceleration of negative hydrogen ion with 10 MeV peak energy. Main strategy of design was maximization of beam current keeping the small size of cyclotron. Design of cyclotron was performed by progressing four steps. First one is selected radio frequency 83.2 MHz, fourth harmonics considered specification of RF power, size of magnet and coil power.

Design Concept

Cyclotron for 10 MeV was consisted of sector focus magnet, coils, half wavelength resonator, PIG internal ion source and vacuum chamber. Scheme of structure was represented in Fig. 1, it is shown cross section view according to beam plane (z = 0). Magnet has 8 hills and shim bar, four side yokes, RF system was consisted of four dees and four liners, one power coupler and fine tuner. Vacuum chamber was positioned between coil and hill, one PIG ion source connected with chamber.

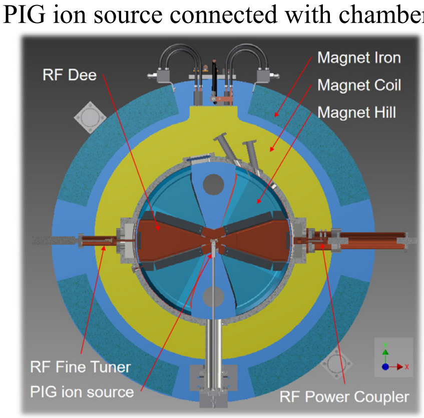

Figure 1: Cross section view of 10 MeV cyclotron.

Main parameter of cyclotron structure was listed up at Table 1. There were four sectors in the magnet iron, pole radius was 750 mm. When radio frequency is 83.2 MHz, isochronous radius for 10 MeV is calculated about 335

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mm, average magnetic field is 1.365 T. Hill radius was selected 365 mm, it was considered size and power consumption of coil. Resonator also was designed with consideration about magnet, and power consumption. Since this cyclotron was used internal ion source, electric field and RF was matched and optimized with PIG source structure. Main goal of design was increase of beam current with keeping the emission energy. Beam energy was calculated 9.8 MeV, beam current was analysed 197 µA having 2.15 pC charge in a one bunch at the one turn in central region.

Table 1: Main Specification for 10 MeV Cyclotron

Main parameter	Value
Pole Height [mm]	815
Pole Diameter [mm]	1500
Weigh [t]	9
Number of Sector	4
Coil Consumption Power [kW]	26
RF [MHz]	83.2
Harmonic	4^{th}
Number of Dee	2
RF Consumption Power [kW]	14
Type of Ion Source	Internal PIG
Ion Source Power [kW]	1.5

Magnetic Field Design

Magnet was consisted of return yoke, hills, center poles and coils in the Fig. 2. Design of magnet structure was started firstly for cyclotron, and magnetic field distribution was analysed by using TOCSA in OPERA3D code [7]. Optimization steps were that isochronous magnetic field was calculated, phase error analysis, and correction of magnetic field by using single beam dynamics code, CYCLONE v8.4 [8]. Correction magnetic field was ideal state for accelerating single particle until 10 MeV, so the structure of magnet was changed to satisfy the simulation result compared correction magnetic field with many iterations of simulation.

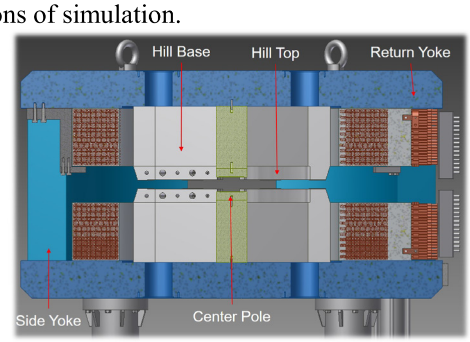

Figure 2: Mechanical scheme of magnet structure in vertical plane direction.

Optimal magnetic field was represented in Fig. 3. In order to get the result rapidly, symmetry of one-eighth was applied. Magnetic field was shown on the centre region of coil, radius was 365 mm. The range of field value was from 0.34 to 2.0 T, and higher field was calculated on the hill.

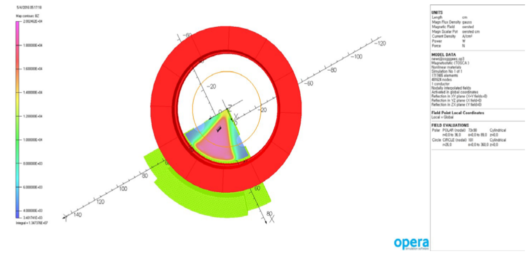

Figure 3: Magnetic field distribution at beam plane by using TOSCA in OPERA3D code. Red color is high magnetic field, almost 2 T, on the hill.

Electric Field Design

Electric field is performed acceleration of particles, resonator was designed by applying the coaxial cable structure. Resonator was consisted of four main dees, four liners and one power coupler and RF tuner in the Fig. 4. Dee and liner were connected with stems, it was played role of inner conductor in coaxial cable. All component is connected vacuum chamber, dees and liners on the left and right side are connected central dee, center liner and puller. Magnet of 10 MeV cyclotron had deep valley structure, so resonator was designed like connected two coaxial cables. Dee angle was selected 35°, stem position and radius was optimized for matching the radio frequency and electric field distribution. Power coupler and RF tuner was designed by applying capacitive coupling.

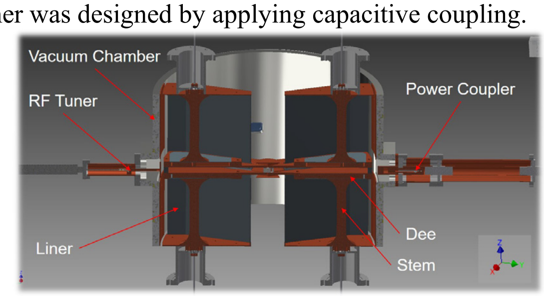

Figure 4: Mechanical drawing of RF resonator on view of vertical cross section, there are four dees and liners, one power coupler and RF tuner.

Resonator was generated accelerating electric field for negative hydrogen particles. Main resonant mode is TEM_{00}c in the coaxial cable. There were many methods to design accelerating voltage, assuming delta function of gap voltage, DC analysis and RF analysis. Cyclotron used PIG internal ion source had puller for extraction particles from chimney in the ion source. So main specification of emitted particle was decided at the central region, and then fine analysis of accelerating voltage should be considered in this position. Figure 5 shows electric field distribution by using eigen mode analysis by using CST-MWS code. The result of electric field fitted absolute value was plotted on the beam plane, and it was normalized to one joule stored energy. Radius 150 mm was selected for standard 40 kV acceleration at an acceleration gap because of unstable voltage distribution at the radius.

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Cavity loss power was calculated 12.7 kW to generate an electric field with 40 kV gap voltage at the gap on the 150 mm radius.

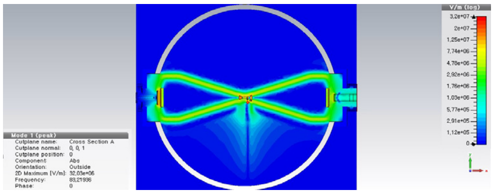

Figure 5: Electric field distribution on the beam plane by using eigen mode simulation in CST-MWS code [9], radio frequency 83.21 MHz and peak electric field was 32 MV/m at stored energy 1 joule.

ANAYLSIS OF BEAM SPECIFICATION

Magnetic and electric field was conformed after beam dynamics was considered by using the calculation code. The design of cyclotron affects two fields, so it is resulted beam specification. Analysis of beam characteristic was separated two parts, one was main accelerating part and other was bunching part. When the magnet structure was designed by correction magnetic field, main feature of acceleration was checked in the Fig. 6 by using CYCLONE v8.4 code. It could be calculated single particle tracking by using magnetic field and acceleration voltage. But it needed assumption about electric field and initial beam characteristics. So phase between beam and isochronous magnetic field was checked carefully, and then other code for more detail analysis was used.

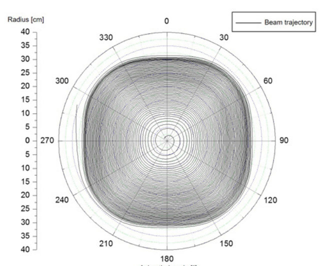

Figure 6: Single particle tracking for 10 MeV cyclotron, magnetic field was used simulation of structure, and electric field was brought assumption the constant voltage value. Initial beam position also was assumed until beam phase was fine result compared isochronous condition.

It was applied to analyse the beam specification by using multi particle calculation, especially central region. Analysis method of single particle tracking was benefit to design magnetic field quickly, but it could not calculate the beam efficiency and bunching effect. So Particle In Cell (PIC) solver was used for checking the particle specification. Electric field as well as magnetic field was imported from each simulation results, and input beam current was selected at an internal ion source. Beam energy and current was checked 190 keV, 197 µA after third accelerating gap because a bunch was formed after 3rd gaps. Figure 7 shows cross section view of particle distribution in the central region. Particles hit to the center dee surface, but they were not high charge density. Charge of a bunch was calculated 2.15 pC with 83.2 MHz frequency.

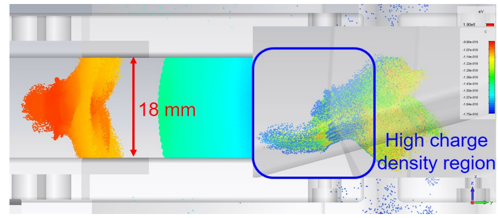

Figure 7: particle distribution, the color of left picture means that red is high energy 190 keV, and right picture shows charge density distribution, blue color means higher charge because of negative signal.

CONCLUSION

10 MeV cyclotron was designed for increase efficiency of beam current in terms of detail structure of magnet, resonator, and so on. Main specification of cyclotron was selected, 1.5 m pole diameter, 0.8 m pole height, 83.2 MHz radio frequency and 4th harmonics. Total consumption power was about 40 kW for beam power 1 kW (peak energy 9.8 MeV, peak current 90 µA). Magnetic and electric field were designed by using TOSCA in OPERA3D, Eigen mode solver in CST-MWS. These fields were possible to accelerate negative particles it was verified by beam dynamics specifications. Main acceleration was checked from analysis of single beam dynamics by CYCLONE v8.4 code, and low energy part, central region, was analysed as a bunch by using PIC solver in CST-PS. Especially initial beam bunch was analysed after cross to 3rd acceleration gap, peak beam energy 190 keV, charge of a bunch 2.15 pC.

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