Design of the Central Region for a Compact Superconducting Cyclotron with Three-Dimensional Orbit Analysis.

F.Noda, R.Tsuneyoshi, K.Ogawa, N.Kikuzawa,
Y.Uozumi, T.Sakae and M.Matoba
Faculty of Engineering, Kyushu University
Hakozaki, Fukuoka-shi,Fukuoka 812, Japan

S.Matsuki
The Institute for Chemical Reserch, Kyoto University
Gokanosho, Uji-shi, kyoto 611, Japan

Abstract

Design of a central region is carried out for a compact superconducting AVF cyclotron for proton.

The superconducting cyclotron has a strong magnetic field which makes the central region smaller. After construction, therefore, the degree of freedom of adjustment is restricted within narrow limits. For high-precision design, the three-dimensional calculation is required at the central region.

A three-dimensional electric field produced by the central equipment, i.e. dees, ion source and reinforcement electrodes, is calculated by a relaxation method. The equation of particle motion in electromagnetic field is numerically solved by using the three-dimensional Runge-Kutta-Gill method. With sufficient energy gain, projection of trajectory on median plane is found to clear all electrodes and ion source. The vertical displacement is suppressed by electric focusing.

I. INTRODUCTION

In recent years there has been renewal of interest in applying a superconducting magnet for accelerators. Generally speaking, a superconducting magnet is mainly characterized by following two points: First superconducting magnetic field is stronger than a conventional one. Secondly it is able to use with a persistent current mode. For a cyclotron, the former plays an important role in making a compact and light machine, and the latter makes running cost economical.

A concept for designing a superconducting cyclotron is basically same as that for a conventional machine. The high magnetic field, however, makes extra difficulties of design: severe condition for the early a few turns and the beam extraction. The narrower pitch of turns at extraction radii should require a highly optimized extraction system, but it is not concerned in the present paper.

The scope of this paper is focused on the central region. Because of smaller central region, the design is more difficult and the degree of freedom of adjustment after constructed is smaller than conventional one. For these reasons, it is necessary to design with the optimum condition as much as possible.

The model machine[1] is a superconducting AVF cyclotron for proton. The acceleration system has three dees with peak voltage V_{max} = 50 kV and three dummy dees. The harmonics number h of the radio frequency is three. The center magnetic field B_0 is 3.2 T.

In the present paper, we deal with the design of central region with an internal PIG ion source, and are not concerned here with external ion source. Of course, we have to compare the two, and estimate which is better.

II. BEAM TRACE AND DESIGN OF CENTRAL REGION

A. ELECTRIC FIELD CALCULATION AND BEAM TRACING PROGRAM

A three-dimensional electric field produced by the central equipment was calculated by the relaxation method. The calculated region was 100×100×10 with a mesh step of 1.0 mm for x, y direction and 2.5 mm for z direction.

The equation of particle motion in electromagnetic field was numerically solved by using a three-dimensional Runge-Kutta-Gill method. We deal with the RF electric field approximately as $E=E_a\cos(\omega t+\theta_0)$, here ω is the radio frequency and θ_0 the initial phase of RF.

B. ORBIT CALCULATION AND DESIGN OF CENTRAL REGION

Central region design of cyclotron has been widely investigated for a long time. Now, under a high magnetic field, the first point to note is that accelerated beams clear the ion source. If enough acceleration efficiency is not obtained at each acceleration gap, beams are lost at ion source after one turn.

To begin with, we examine the acceleration efficiency at the first-gap: from ion source to puller, because it seems to be a serious problem at the first-gap. The acceleration efficiency at first-gap depends on the initial RF phase and τ / T (or d), here τ is a transit time for the first-gap, T the RF cycle, and d the distance of first-gap. This relation is shown in Fig.1. A first-gap length d is chosen as 2, 3 and 4 mm. This figure shows that a best acceleration efficiency 85% is obtained at θ_0 = -80 ~ -90 degree for d = 3 mm. Similarly, the calculated results from 2nd to 10th-gaps are shown in Fig.2. The $|\theta_n|$ is the deviation of phase from a peak phase of RF voltage to obtain a best acceleration efficiency. The $|\theta_n|$ is lager, the acceleration efficiency is the smaller in a general way. As Fig.2 shows, the effective acceleration mainly depends on acceleration at the early a few gaps, especially on at the first-gap.

Next, a geometrical shape and configuration of reinforcement electrodes and ion source were determined from the typical beam trajectory which satisfied the condition shown in Fig.2. The gap length was chosen as 3 mm for first-gap, 4 mm for the gaps from second to sixth, and 6 mm for the gaps from seventh to tenth. For the later, gap length was 8 mm. The equipotential map and typical trajectory of proton projected on the median plane are shown in Fig.3 together with a schematic view of the equipment of central region. In this figure, the solid line shows the trajectory with a three-dimensional calculation and the broken line shows the trajectory with two-dimensional calculation. Here we employed an initial phase of the trajectory -85.0 degree.

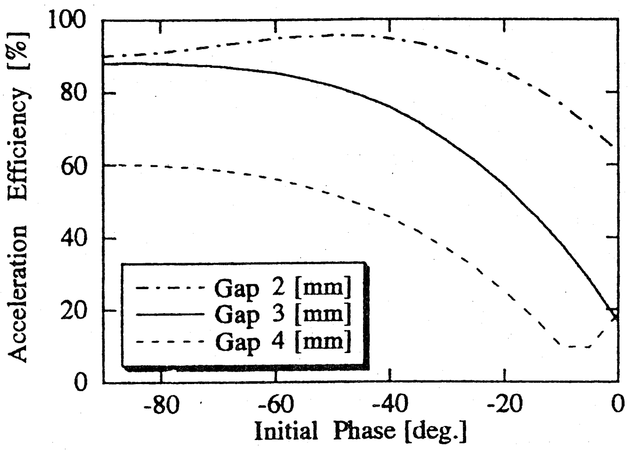

Fig.1 The acceleration efficiency at first-gap for different first-gap lengths, 2.0, 3.0 and 4.0 mm

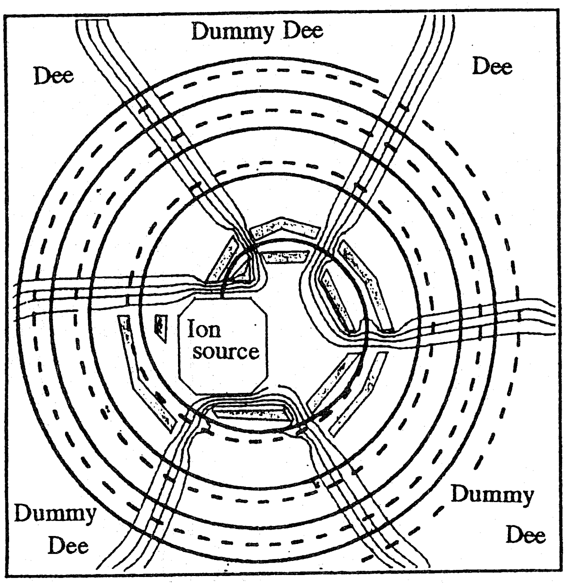

Fig.3 The equipotential map and typical trajectory of proton projected on the median plane with equipment in the central region.

The solid line shows a typical trajectory with three-dimensional calculation, and the broken line shows a typical trajectory with two - dimensional calculation.

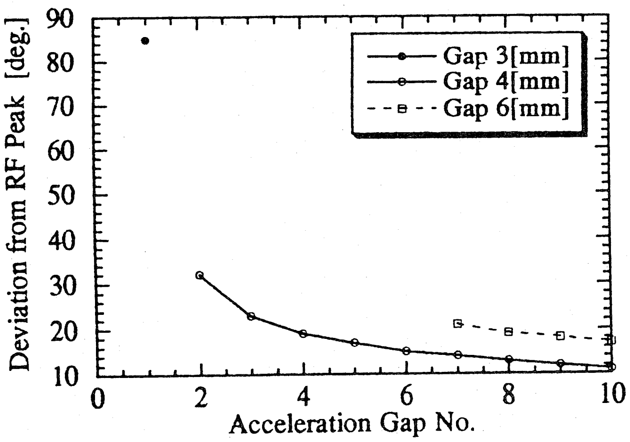

Fig.2 The deviation of phase from a peak phase of RF for each acceleration gap.

Furthermore, it is necessary to examine whether the center of trajectory converges. The center of a typical trajectory of a proton is calculated, and the converged point is considered as a machine center. The deviation of trajectory center in early a few turns from machine center is shown in Fig.4.

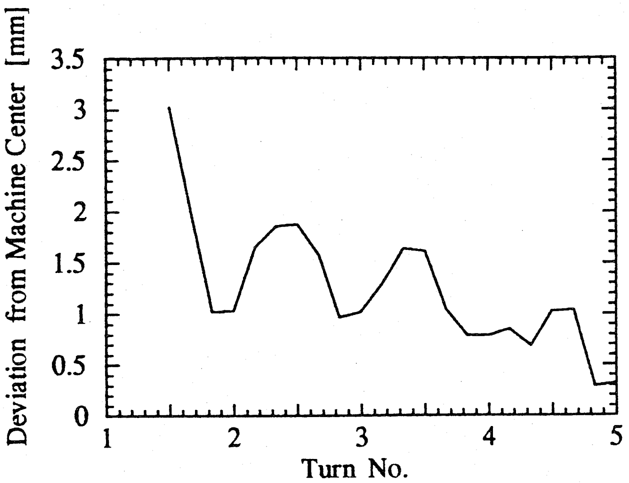

Fig.4 The deviation of a typical trajectory from the machine center with three-dimensional calculation

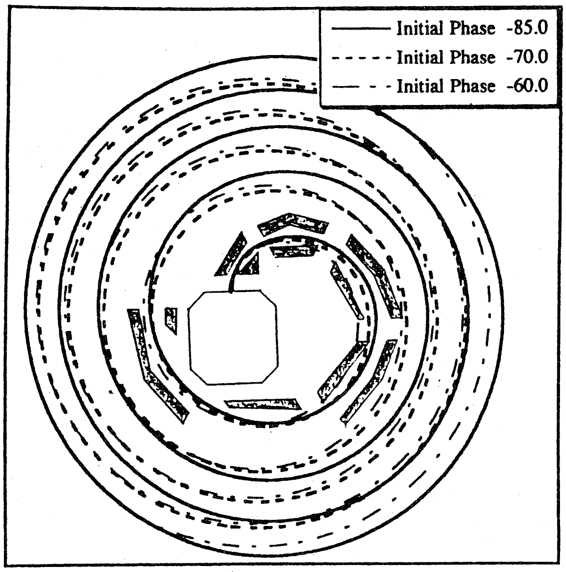

Fig.5 The trajectories of proton projected on medianplane for different initial phase, -85.0, -70.0 and -60.0 degree.

Finally a few trajectories of proton projected on the median plane are shown in Fig.5. This figure shows trajectories for the different initial phase, θ_0 = -85.0, -70.0 and 60.0 degree. The trajectories with sufficient energy gain, θ_0 = -85.0, -70.0 degree, clear all the electrodes and the ion source, but the trajectory for θ_0 = -60.0 degree can't clear becuse the acceleration efficiency is not sufficient. The vertical trajectory of proton is shown in Fig.6. In the central region the magnetic focusing is very small, and the effect of electrical focusing is large. The effect of magnetic focusing appears at r = 25 mm in the present model. The electric focusing is found to be effective on the vertical trajectory, and the maximum displacement from median plane d_z = 2.0 mm is smaller than the width of dee.

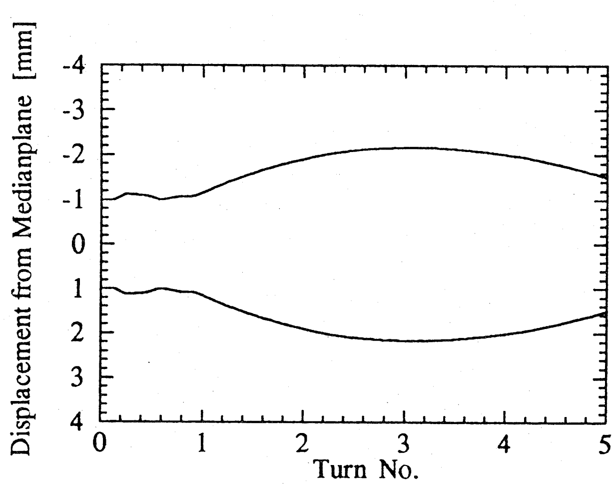

Fig.6 The displacement of a typical trajectory from the medianplane with three-dimensional calculation

III. SUMMARY

Three dimensional simulation codes were developed for designing central region of a superconducting AVF cyclotron. The result from comparison of two and three-dimensional calculation, we found out that it was necessary to use the three-dimensional calculation for especially a compact superconducting cyclotron which has narrow limits of adjustment after constructed. After series of calculations with these three-dimensional codes, the geometrical shape and configuration of reinforcement electrodes and ion source were determined by using a best initial RF phase θ_0 = -85.0 degree. The following results were obtained: The trajectories with a sufficient energy gain clear all the electrodes and the ion source, and the maximum displacement from median plane is smaller than the width of dee.

IV. REFERENCE

[1] Y. Uozumi et al., Proceedings of the 8th Symposium on Accelerator Science and Technology, Saitama, Japan, 1991