Development of Compact Proton Synchrotron with Combined Function Dedicated for Cancer Therapy

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Abstract

A compact proton synchrotron with combined function lattice has been developed to be dedicated for cancer therapy. Its maximum energy and the circumference are 250 MeV and 23.9 m, respectively. A ring with 6-fold symmetry composed of 6 identical combined function magnets of the focusing structure of FDF has been adopted in order to avoid the effect of sector resonances. By the calculation with use of 3 dimensional code TOSCA, the operation point of the betatron oscillations is expected to remain well close to the desired value of (1.70, 1.75) in the wide excitation level up to 1.35 T.

1 Introduction

Recently cancer therapy has become one of the most important item for human welfare because about one third of the people die for cancers. In Japan, group of University of Tsukuba has achieved good results with proton therapy and in these few years, heavy ion therapy has become available after the completion of world first dedicated heavy-ion synchrotron, HIMAC in Chiba. The number of patients who fortunately receive such benefit, however, is limited to rather smaller value compared with those who need such charged particle therapy.

In Kyoto University, efforts to realize particle cancer therapy has been continued succeeding the will of late Prof. Hideki Yukawa who wanted to utilize the attainment of physics for human welfare and at the first stage, pion therapy has also been pursued together with proton and neutron therapies[1]. In recent years, however, a proton facility called KUMPF has been proposed for the merit of compactness both in size and cost[2]. On the basis of such approach, we are aiming at establishing a prototype design of dedicated proton synchrotron for cancer therapy, which can be operated in hospitals without experts of accelerator.

Main difficulty in operation of synchrotron resides in control of RF system and tracking of excitation currents between dipole and quadrupole magnets. From the point of view of easy daily routine-operation, we do not need much flexibility, but the fewer the freedom of operation, the better. So as to respond such requirement, we have already constructed a real power untuned-RF cavity well suited for daily routine operation[3]. So as far as synchrotron ring is concerned, the operation will become very easy if the combined function lattice works well because no tracking between dipole and quadrupole is needed, although its design is somewhat difficult. From this point of view, we are making main efforts to establish reliable design of combined function lattice. In Fig. 1, the proposed lattice with 6-fold symmetry is shown. Each magnet deflect proton as large as 60° and has focusing

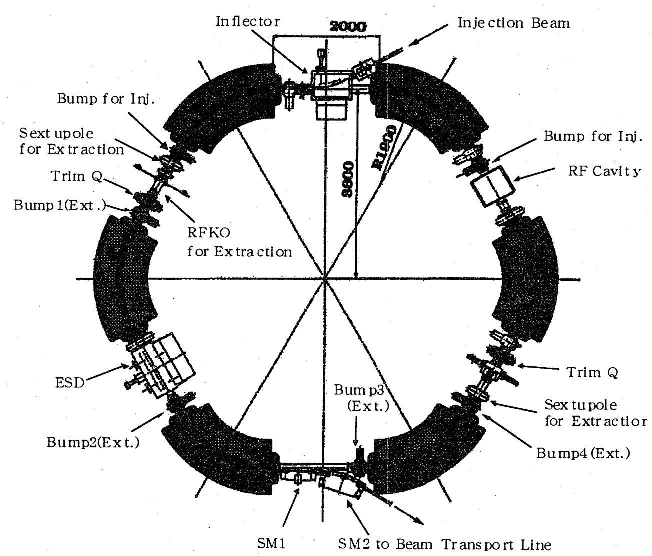


Fig. 1 Combined Function Proton Synchrotron.

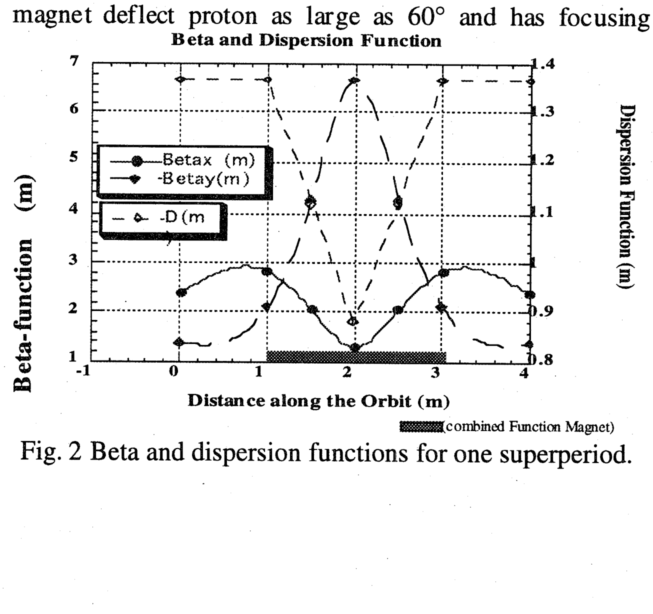


Fig. 2 Beta and dispersion functions for one superperiod.

Table 1
Main Parameters of Combined Function Proton Synchrotron

Maximum Energy	250 MeV
Radius of Curvature	1.9 m
Circumference	23.9 m
Maximum Magnetic Field at the Central Orbit	1.28 T
Lattice Structure	OFDFO
Operating Point	(1.70, 1.75)
Bending Angle of the Magnet	60°
n-values	F: -5.855, D:6.164

structure of FDF. In Fig. 2, beta- and dispersion functions of this lattice are shown for one superperiod. Main optics is solely based on these 6 magnets, while two trim quadrupoles are added considering correction of operation point. These trim quadrupoles are expected to become

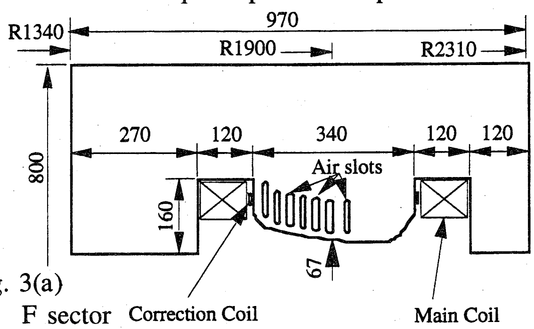


Fig. 3(a)
F sector

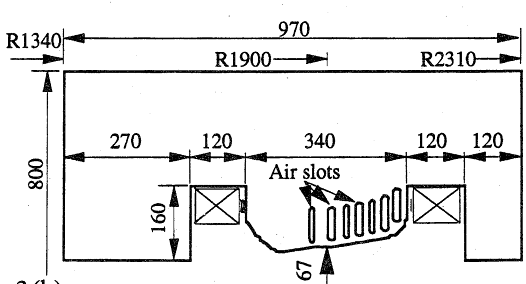


Fig. 3(b)
D sector

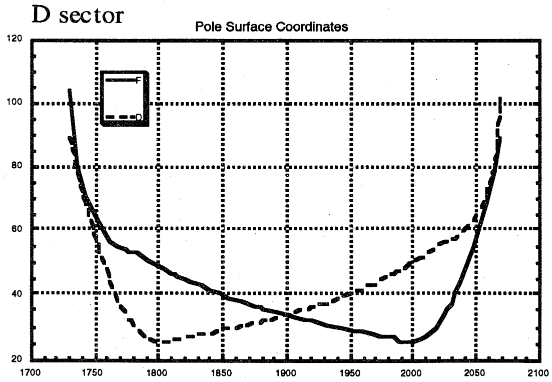
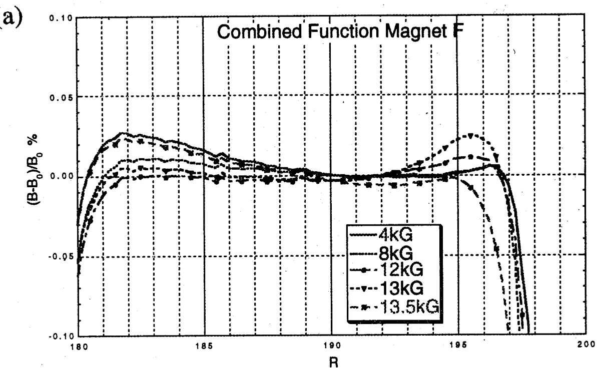


Fig.3(c) Pole profiles of F (solid line) and D (dashed line).

(a)



(b)

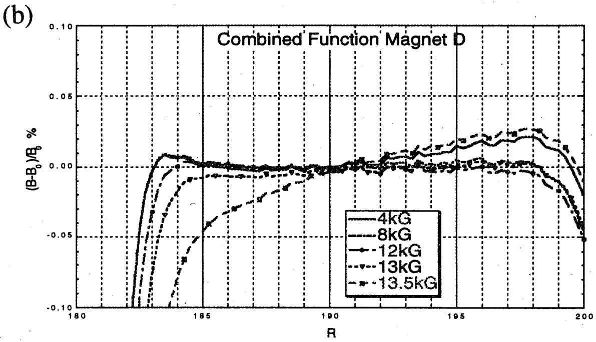


Fig. 4 Calculated Field Distribution in F (a) and D (b) sectors.

unnecessary once the final good design is fixed by construction of the prototype machine, hopefully at Kyoto University. The budget for the whole ring, however, is not approved yet, but we are now constructing only one of the six identical combined function magnets in order to fix the design. Main parameters of the ring are listed up in Table 1. In the following sections, design of the model magnet are described.

2 FDF Magnet with Combined Function

The magnet has the structure of FDF, where each section has deflection angles of 15°, 30° and 15°, respectively. With the calculation assuming sharp edge as the starting point, the n-values needed for F and D sections are calculated to be -5.855 and 6.164, respectively to realize the operation point of (1.75, 1.75). The pole shape has been determined to make the equipotential surface of the magnetic potential given as

$$\phi = -B_0 y\left[1 + k_1 x + \frac{k_2}{2}x^2 - \frac{1}{6}\left(\frac{k_1}{\rho} + k_2\right)y^2\right],$$

where x and y are the radial and vertical displacements from the central orbit, ρ is the radius of curvature of the central orbit and B_0 is the magnetic field at the central orbit[4]. In the present design, the sextupole component is desirable to

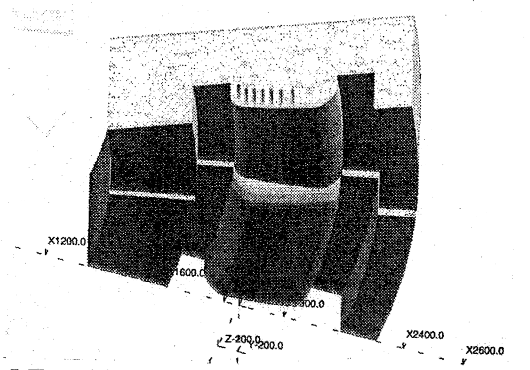


Fig. 5 Transition region assumed in the 3 dimensional calculation by TOSCA.

be as small as possible and we imposed the condition k_2 should be zero. In addition to this, several slots are made in the pole in order to keep the magnetic field strength constant in the whole pole region while the magnet field at the gap has large gradient. In Fig. 3(a) and (b), the cross section of F and D sectors are shown and the precise pole shape profiles are shown in Fig.3(c) for F and D sections by solid and dashed curves, respectively.

3 Field Calculation with 2 Dimensional Code

With this pole shape, the expected field distribution with cylindrical symmetry is obtained by 2 dimensional code PANDILA. In Fig.4, the field distributions are shown for full range of excitation levels. It is found that in the wide field levels between 0.4 and 1.35 T the good field region is realized for ±50 mm[5].

4 Three Dimensional Field Calculation with TOSCA

In order to avoid the saturation at the sharp edge of iron core, both ends of the magnet are designed to approximate the so called Rogowski's curve[6] by 5 steps in the region of ±70 mm length along the orbit. Further the transition regions between F and D sections also have such structure as illustrated in Fig. 5. Three dimensional field calculation has been performed with use of computer code TOSCA In Fig. 6, typical example of the field variation along the central orbit in the transition region between F and D sectors obtained with the three dimensional calculation is shown.

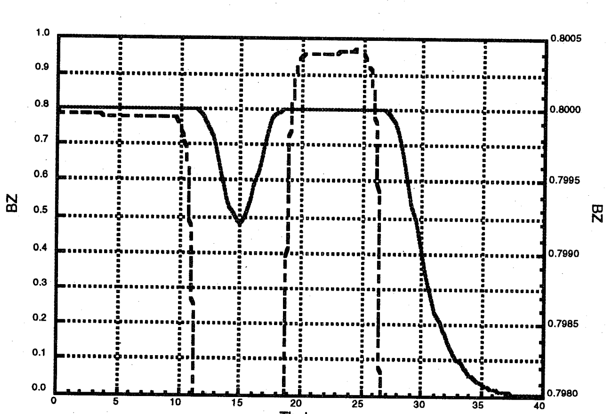


Fig. 6 Field variation along the central orbit in the transition region between F and D sectors..

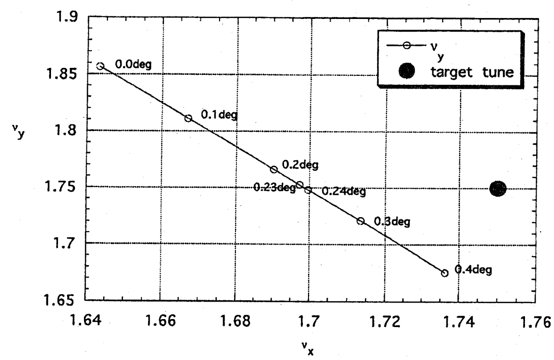


Fig. 7 Estimated betatron tune from field distribution.

5 Evaluation of Tune Values

Using the magnetic field map obtained by such calculations, two dimensional field distribution in the median plane is Fourier expanded, which is extrapolated to 3 dimensional distribution in the nearby region of the median plane with the relation $\nabla \times B = 0$. The equation of motion of proton beam is solved with this field distribution[8]. In order to realize desirable tune values for radial and vertical directions, the deflection angles of F and D sections are adjusted keeping the total deflection to be 60°. In Fig. 7, the result of such estimation is shown and it is known that the modified operating point of (1.70, 1.75) will be attained by selecting the deflection angles of 15.24° and 59.52° for F and D section, respectively.

Acknowledgment

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