The 8th Symp. on Accelerator Science and Technology, 1991, Saitama, Japan

COMPACT CYCLOTRON FOR PROTON THERAPY

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Abstract

The compact proton-theraphy system is being developed in collaboration between Sumitomo Heavy Industries, Ltd.(SHI) and Ion Beam Applications(IBA). This system comprises a 230-MeV high-field isochronous cyclotron and the beam-delivery equipments with rotating and/or fixed gantries. The cyclotron has a super-compact normal-conducting magnet realized by using the high magnetic field of 3.09 T at peak on the hill. The sufficient vertical-focusing and good extraction of the beam are confirmed by computer simulations of magnetic fields and beam optics. The cyclotron is 4.3 m in outer yoke diameter, 2.1 m in yoke height, and less than 200 tons in magnet weight. The total power consumption of the cyclotron is 350 kW.

Introduction

Proton or heavy-ion therapy is recognized to be one of the most effective method of cancer therapy at present. It is, however, not yet generally applied to patients because it needs a high energy accelerator and a huge beam delivery system. There are several accelerators used for the proton therapy, such as a synchrotron, a linac and a cyclotron. Each has merits and demerits. The synchrotron can accelerate the charged particle up to any high energy with variable mode, but the acceleration current, which is pulsed in low duty cycle and limited by the space charge at injection, has little margin for the proton therapy. In addition, it needs highly skilled specialists for the operation. The cyclotron can accelerate more current than the synchrotron and its operation can be much simpler than that of the synchrotron. The linac can accelerate the large current, but becomes too huge in dimension and consumes much more electric power than the others.

Sumitomo Heavy Industries, Ltd. (SHI) has long been studying accelerators for the proton therapy[1], and has recently proposed a compact FM cyclotron, which adopted a superconducting or normal conducting magnet[2]. Ion Beam Applications (IBA) proposed the proton therapy system with a novel compact isochronous cyclotron, using high magnetic field[3]. The isochronous cyclotron is designed with a fixed energy of 230-MeV to reduce the number of parameters and components, and an energy degrader is used to change the beam energy. This cyclotron can accelerate high current intensity of the beam. The fixed energy is very effective to simplify the cyclotron and to make it reliable. The FM cyclotron is designed with variable energies from 230 MeV to 140 MeV. The beam current from this cyclotron is not so high, but the radioactivity produced by the lost beam can be much reduced.

After carefull comparison between both the cyclotron, we selected the isochronous cyclotron as the best machine installed in hospital for the proton therapy, because this cyclotron is the simplerst and the most reliable. SHI and IBA have decided to collaborate on the development of this proton therapy system, based on the fixed-energy isochronous cyclotron. The birds eye view of the cyclotron is shown in Fig.1 and parameters are listed in Table 1.

The present paper describes the detail of the isochronous cychrotron, especially on the focusing property and the beam extraction.

Table 1. Parameters of The Compact High-Field Cyclotron

Beam		
type of ions	H^+	
fixed energy	230	MeV
maximum intensity		
-guaranteed	25	nA
-design value	100	nA
horizontal emittance	<15	π.mm.mrad
vertical emittance	<10	π.mm.mrad
energy spread	<0.3	percent
Magnetic structure		
number of sectors	4	
sector angle at the center	36	degree
sector angle at extraction	53	degree
spiral angle at the center	0	degree
at extraction radius	60	degree
max hill field	3.09	T
valley field	0.985	T
average field at extraction	2.165	T
average field at center	1.740	T
magnetic induction	5.248×10^5	A.t
apparent current density in coils	153	A/cm^2
actual current density in coils	214	A/cm^2
power per coil	92	kW
weight of one coil	13.3	tons
weight of the iron	185	tons
RF system		
resonating system	2 dees in opposite valleys	
harmonic mode	H=4	
dee voltage	100	kV
frequency	102.11	MHz
length of resonator	60	cm
estimated capacitance per resonator	58	pf
estimated RF power for 100 kV	65	kW
Power consumption		
beam on target	350	kW
magnet and vacuum	250	kW
vacuum only	25	kW
Ion source		
type of source	Hot filament P.I.G.	
filament power	1.5	kw
filament lifetime	>800	hours
time for filament changing	<30	min.
arc power	0.5	kW

Magnet system

When the field level is optimized to make the cyclotron as small as possible, the magnetic field strength becomes 3.09 T on the hill, 0.985 T in the valleys, 2.165 T averaged field at extraction radius, 1.74 T averaged field at the center. Such field levels are mostly dictated by the requirement of obtaining adequate vertical focusing without having to use excessive spiraling of the sector. However, when the magnetic field in the pole is highly saturated, the magnetic excitation current is usually very large and only the superconducting coil can give such a high current. The advantage of a superconducting system is a reduction of the electrical power required by the cyclotron, in particular when the coil is excited with permanent current mode. On the other hand, disadvantages include the mechanical complexity of a split-coil cryostat with very large forces involved, the potential problems associated with the liquid helium supply and the very long thermal time constants. For such a large mass, marm-up or cool-down times are in excess of one week, yielding excessive repair downtime for a medical device.

IBA has found, however, a solution with normal conducting coil using the deep-valleys concept pioneered by IBA with the CYCLONE 30 series. The problems such as how to reduce the magnetic excitation current, how to extract the beam efficiently and how to get large flutter are solved by adopting small hill gap which varies from 9.6 cm at the center to 0.6 cm at extraction. The magnetic field is simulated by computer code 'TOSCA' which can simulate the three dimensional nonlinear magnetic field. The magnetic excitation current becomes 5.248×10^5 A.t which can be given by convensional coils with current density of 214 A/cm^2 and power consumption of 190 kW. The design of sector shape is now in the process of optimization. From the computer simulation using 'TOSCA' and 'ORBLA', which is the computer code for the study of optical property, we are expecting the flutter and ν_r, ν_z at present design stage as shown in Fig.2 and Fig.3, respectively. The gap decreases to zero at extraction to provide a very sharp radial field fall-off in order to simplify the beam extraction. The azimuthal shape of the hills is not rectangular but trapezoidal. The wider base of the hills reduces magnetic saturation, resulting in an improved flutter and a low power in the coils. The gap in the valleys is 60 cm, a good compromise between the reduction of coil power and a convenient dimensioning of the RF system in the vally.

To facilitate maintenance, the upper half can be quickly (15 minites) raised by one meter above the median plane by means of hydraulic jacks. The cyclotron can be opened, closed, pumped down and restarted for operation in less than two hours.

RF acceleration system

Two dees are located in opposite valleys and resonate on the 4-th harmonic of the ions' orbital frequency, i.e. 25.527x4=102.11 MHz. Each dee is supported by four vertical pillars, located symmetrically about the median plane. This design optimizes the simplicity, the mechanical stability and the cooling. Optimization of the diameter and length of each pair of opposite pillars allows for the shaping of the amplitude of dee voltage versus radius.

The dee voltage of 100 kV gives the energy gain of 400 keV/turn which makes easy the design of central region and the radial gain of 0.72 mm/turn at the extraction radius. This radial gain is sufficient to place the septum of deflector. The other parameters are listed in the Table 1.

Vacuum system

The vacuum system consists of four 2000 l/s oil-diffusion pumps located below the cyclotron and four 3000 l/s valved cryopumps located above the cyclotron. These pumps are connected .to the acceleration chamber through holes in the valley. The operational pressure of 5×10^{-6} can be reached with this system.

Injection system

The ion source is a hot filament P.I.G. source introduced axially at the center of cyclotron through an air lock. Considering the very small arc currents required, the lifetime of an ion source filament is expected to exceed one month.

Extraction

The beam extraction is one of major problems in the high field cyclotron which must be solved carefully. The proton of 230 MeV has large field rigidity which will generally require a long deflector with a strong electric field. Sparks in a deflector will make a serious dose error for the medical use. Therefore, the field strength of the deflector must be designed well under the voltage and field strength product criterion for the stable operation, resulting small gap between the septum and the deflector electrode.

In the case of superconducting cyclotron with constant Hill gap, the difficulty arises from the strong fringing field in which the extracted beam has a long path or requires strong deflection force. By giving an elliptical profile to the hill gap, the contribution to the magnetic induction of the highly saturated iron of the hill remains constant until the maximum pole radius. While its derivative is discontinuous at this point creating a highly rapid drop-off of the outside field. Thus it becomes possible to keep the isochronous condition up to the extraction radius which is a few mm inside of the magnet edge. Fig.4 shows the field distribution at the azimuthal center of hill simulated by 'TRIM'. By this design, the fringing field problem is completely removed. The beam which is accelerated with the isochronous codition to the extraction radius is easily extracted by conventional extraction devices. The deflector, which has the length of 57 cm, the field strength of 140 kV/cm and is located at the extraction radius in the valley, will deflect the beam more than 10 mm from the equilibrium orbit near the center of hill, where it will enter a special window, feel a sharply decreasing fringing field and go out the cyclotron. The equilibrium orbit and the extraction orbit are shown in Fig.5.

The optical property of the magnet edge, although partly corrected by the special window mensioned above, is a strong radial divergence and a strong vertical focussing force; a passive gradient corrector, therefore, will be located in the extraction orbit in order to optimize the beam envelope.

Conclusion

The proton therapy system using the compact, high-field isochronous cyclotron becomes the very simple, reliable and low cost facility. The feasibility study of the cyclotron has proved that the performance such as the beam focussing and the beam extraction is quite satisfactory.

References

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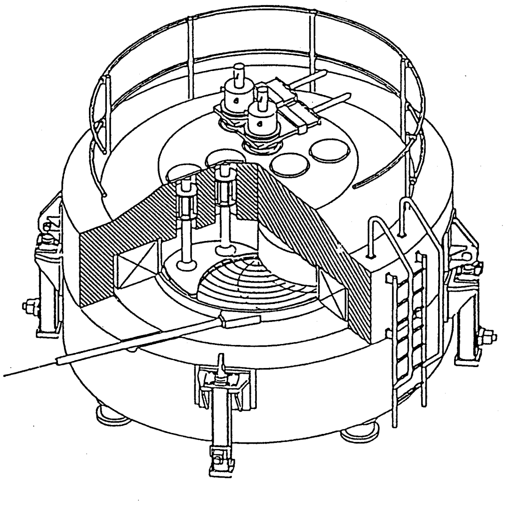

Fig.1 The birds eye view of the 230-MeV isochronous cyclotron.

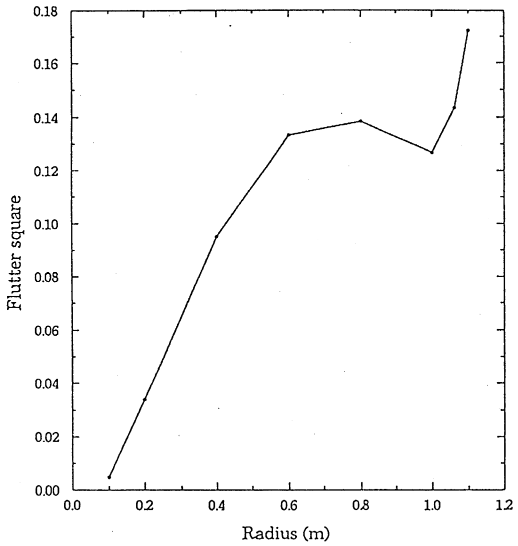

Fig.2 The flutter of the cyclotron magnet, which is expected from 'TOSCA' simulation.

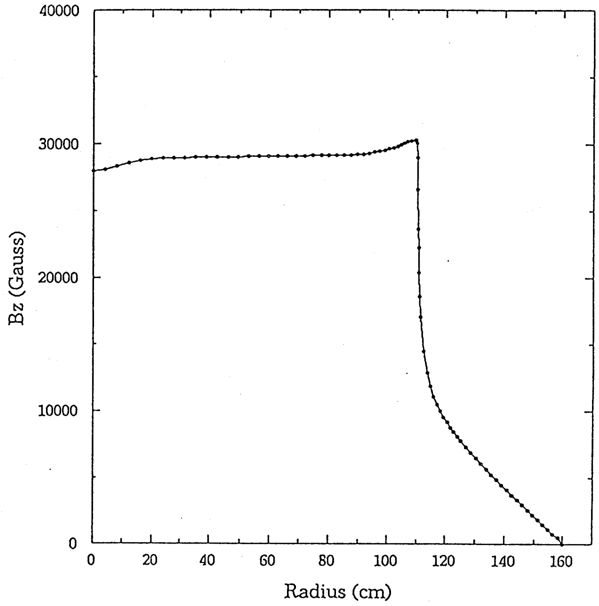

Fig.4 The radial field distribution at the azimuthal center of hill simulated by 'TRIM'.

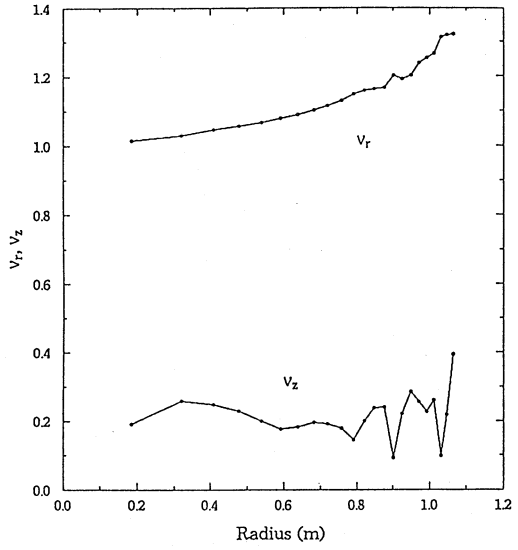

Fig.3 Horizontal (ν_r) and vertical (ν_z) tunes of the betatron motion in the cyclotron magnet, which are expected from 'TOSCA' and 'ORBLA' simulation.

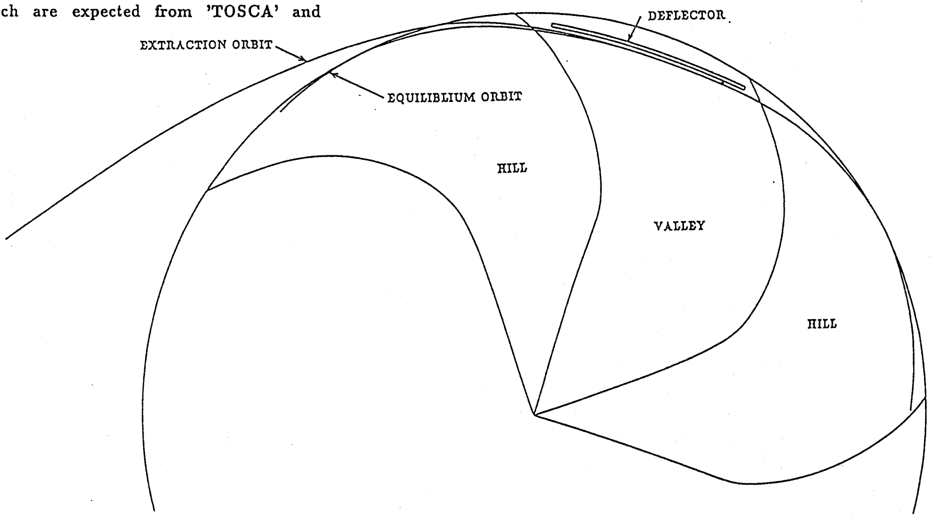

Fig.5 The extraction orbit of the 228.5-MeV proton and the equiliblium orbit of the 228.0-MeV proton.