

DESIGN STUDY OF A SUPERCONDUCTING AVF CYCLOTRON FOR PROTON THERAPY

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Abstract

We have designed a 4 Tesla superconducting AVF cyclotron for proton therapy. Its yoke weight is about 55 tons, which is about one fourth of our normal conducting 230 MeV cyclotron. In order to reduce the size and the weight without deteriorating the beam stability, the hill gap around the outer pole radius should be made small. Calculated extraction efficiency is higher than 60%, by arranging the extraction elements properly. The low temperature superconducting coil using NbTi wire is conduction-cooled by 4K GM cryocooler. Three dimensional electromagnetic finite element codes have been used during all phases of basic design.

INTRODUCTION

Up to now, cyclotrons, synchro-cyclotrons, and synchrotrons have been designed and manufactured as accelerator for proton therapy. Since extracted beam stability by a cyclotron is the best among them, a cyclotron may be the best choice for proton therapy, especially for pencil beam scanning.

Sumitomo Heavy Industries, Ltd. (Sumitomo) started in 1991 with IBA developing a normal conducting azimuthally varying field (AVF) cyclotron named P235, which accelerate proton to 230 MeV, and Sumitomo installed a cyclotron-based proton therapy system at National Cancer Center in Japan in 1998 [1]. This system has two gantries and one fixed port, and its foot print is about 30 m×50 m.

In order to let the system widely accepted by more hospitals, it should be more compact so that it can be easily introduced in a small space. As for the beam delivery system, Sumitomo developed a compact one with a vertical beam transport line and a short-length type gantry, which was installed at Aizawa hospital in Japan in 2013.

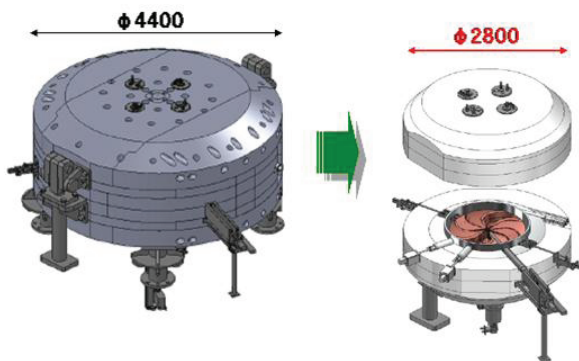


Figure 1: Schematic view of P235 and SC cyclotrons for proton therapy.

In this paper, we present a basic design study of a 4 T superconducting (SC) AVF cyclotron. Comparison between P235 and SC cyclotrons is shown in Fig. 1 and Table 1. It should be noticed that the yoke weight of SC cyclotron is about one fourth of that of P235. This makes the cyclotron transportation from our factory to a hospital, and reinstallation in the hospital much easier.

Table 1: Comparison Between P235 and SC Cyclotrons

	P235	SC Cyclotron
Main coil type	Normal	Superconducting
Diameter	4.4 m	2.8 m
Height	2.1 m	1.7 m
Yoke weight	200 t	55 t
Peak power consumption	440 kW	200 kW (RF) + 40 kW (cryocooler)

AVF CYCLOTRON DESIGN

Basic Parameters

Design concept of SC AVF cyclotron is the same as that of the P235, except there is a set of SC main coils in a cryostat. Some basic parameters are shown in Table 2.

Beam extraction radius is set to be 0.6 m, which is the smallest among the AVF cyclotrons for proton therapy. The average magnetic flux density at beam extraction radius calculated is 4 T. According to an approximated formula for the vertical tune,

$$v_z^2 \cong 1 - \gamma^2 + F^2(1 + 2 \tan^2 \xi), \quad (1)$$

where γ , F^2 , ξ are the Lorentz factor, flutter, and spiral angle, respectively, the flutter has to be large enough to make the spiral angle reasonably small. Therefore, hill gap is set as small as 12 mm in the outer region.

Magnetic Field

Magnetic field distribution of the magnet is calculated using Opera-3D code [2]. One example of the field calculation is shown in Fig. 2. In the design process, the hill span angle and the spiral angle for each radius are adjusted to get isochronism and vertical beam stability. The magnetic field map obtained has isochronism of 10^{-3} order and is not enough for beam tracking. So, the field map is fine adjusted artificially according to

$$\frac{B_{isochro}(\vec{r}, \theta) - B(\vec{r}, \theta)}{B(\vec{r}, \theta)} \cong \gamma^2(\vec{r}) \frac{T(\vec{r}) - T_0}{T_0}. \quad (2)$$

Table 2: Main Specifications of SC Cyclotron

Beam	Particle species	Proton
	Extraction energy	230 MeV
	Beam current	> 300 nA
	Emittance	$\sim 3 \pi$ mm-mrad
	Momentum spread	$\pm 0.2 \%$
	Extraction efficiency	> 60 %
	Extraction radius	0.6 m
	Circulating frequency	48.15 MHz
Magnet	Size	$\phi 2.8\text{m} \times 1.7\text{m(H)}$
	Yoke weight	55 t
	B at extraction radius	4 T
	B at center region	3.2 T
	Number of sectors	4
	Coil material	NbTi/Cu
	Stored energy	4.6 MJ
	Magnetic induction	10^6 AT/coil
	Main coil current	445 A
	Ramping up time	30~60 min
	Cryostat cooling time	17 days
RF	Number of dees	2 + 1
	RF frequency	96.3 MHz, 192.6 MHz
	Dee voltage	50-100 kV, 180 kV
	Total wall loss	120 kW

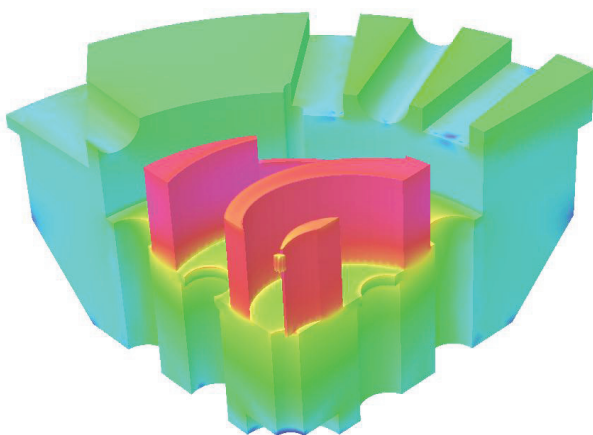


Figure 2: Magnetic field of SC cyclotron calculated by Opera-3d code (1/8 model).

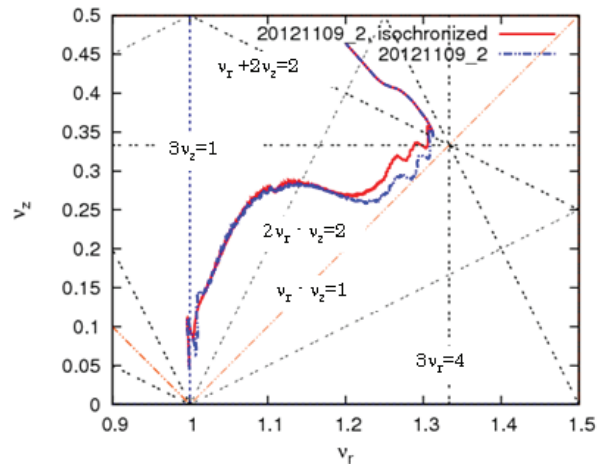


Figure 3: Tune diagram.

The tune diagram is shown in Fig. 3. Some harmful resonances such as $v_r - v_z = 1$, $3v_r = 4$, should be avoided. A particle tracking with a resonance driving term $B_{1r} \sim 5$ Gauss was made, and no $v_r - v_z = 1$ resonance excitation was found in the tracking. The horizontal tune at outer radius is set around $1.1 \sim 1.2$ to enlarge the turn separation.

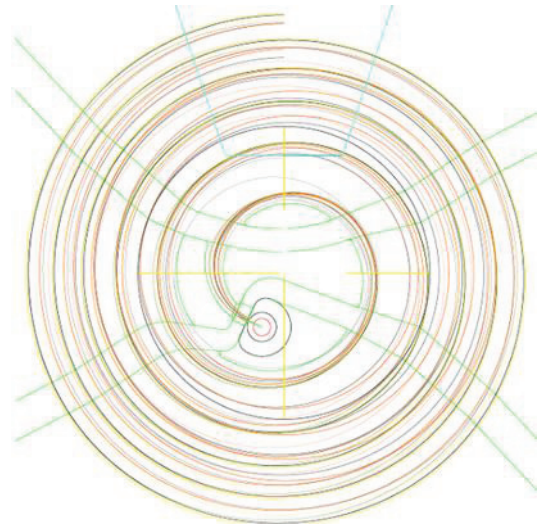


Figure 4: Beam orbit simulation in a center region.

Center Region

The center region has essentially the same structure as that of P235. It has an internal ion source. The proton beam is accelerated by 96.3 MHz ($H=2$), 50 kV dee electrodes. There is a set of electrodes to chop the beam within 50 μsec .

Figure 4 shows an example of beam orbit simulations in the center region. Since the vertical focusing by the electric field is strong in the center region, three dimensional electric field distributions were calculated using Opera-3D and used in the particle tracking.

RF Acceleration

Figure 5 shows a structure of RF cavity. The structure and parameters of the RF cavities were determined using Microwave studio code [3]. The average dee voltages are 50 kV in the center region, and 100 kV in the extraction region, respectively. Wall loss per cavity is 40 kW.

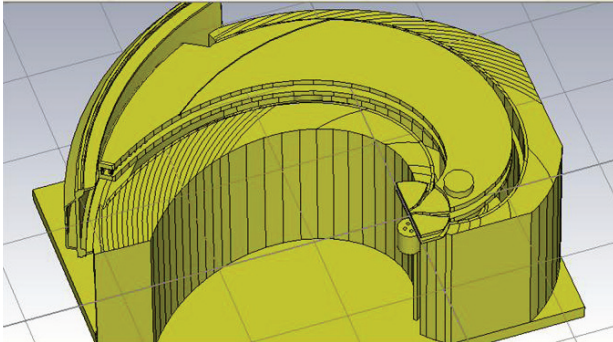


Figure 5: Electromagnetic field calculation of an RF cavity with Microwave studio code.

In order to get high beam extraction efficiency, another accelerating RF cavity may be installed locally around beam extraction radius. This cavity gives radial component of the electric field, which may excite beam instability. Some particle tracking simulations have been made to check this effect, and no problem of beam oscillation excitation has been found.

Beam Extraction

The proton beam is extracted to the outside of the cyclotron by one electrostatic deflector (ESD) and two passive magnetic channels (MC1, MC2). Since the hill gap is too small to admit MC1, it is placed inside of a dee electrode. Additionally, essentially the same structures (C_MC1, C_MC2) are placed to make 2-fold symmetry of the magnetic field distribution.

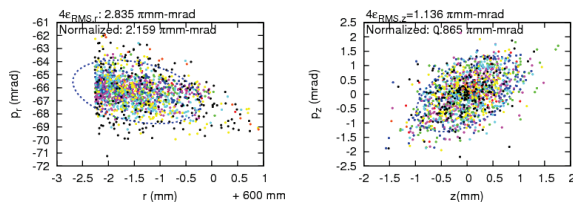


Figure 6: Extracted beam phase plot at ESD.

Phase space plot of the extracted beam at the entrance of ESD by a particle tracking code is shown in Fig. 6. The extracted beam emittance is around $3 \pi \text{mm-mrad}$ and the momentum spread is $\pm 0.2\%$, by cutting unwanted beams in the center region. The extraction efficiency will be 60~80 %, which depends on the effective thickness of the septum (0.3~0.1 mm).

Superconducting Coil and Cryostat

Figure 7 shows the cryostat of the SC coils. NbTi/Cu monolith wire (Cu/NbTi ratio of 2.4) is used. The maximum magnetic flux density in the coil space is 4.2 T.

The current density is 59 A/mm^2 . The current is supplied to the SC coils via HTS Bi-2223 current leads. The coils are conduction cooled by four two-stage 4K Gifford - McMahon (GM) cryocoolers. Therefore, no liquid Helium is needed, and high reliability can be expected. The cyclotron can be maintained without changing temperature of the cryostat so that maintenance can be finished in two days. A ramping up time of the magnetic field is 30~60 minutes.

The electromagnetic force between the SC coils and yoke/cryostat is supported vertically by four GFRP pipes, and horizontally by four GFRP straps, respectively. These eight supports can be used to adjust the position and the tilt of the coils.

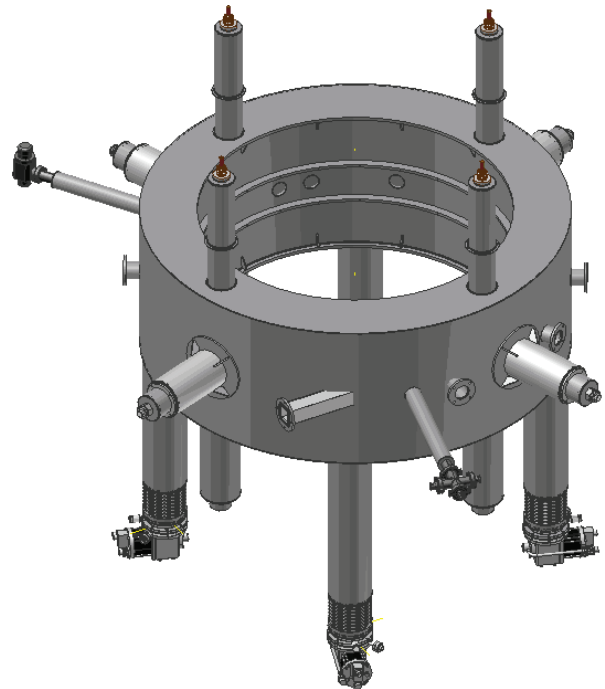


Figure 7: SC cryostat.

SUMMARY

A compact SC AVF cyclotron has been designed for proton therapy. It has been shown that its performance is enough for this purpose, and it can be manufactured in the existing technology.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] T. Tachikawa, et al., Radiat. Indust. 84, 48-53, 1999
- [2] Please see opera-3d pages in <https://www.cobham.com/about-cobham/>
- [3] <http://www.cst.com/Content/Products/MWS/Overview.aspx>