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CURRENT STATUS OF SUMITOMO'S SUPERCONDUCTING CYCLOTRON DEVELOPMENT FOR PROTON THERAPY

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Abstract

Sumitomo Heavy Industries, Ltd. is developing a compact superconducting isochronous 230 MeV cyclotron for proton therapy. It is designed to produce 1000 nA proton beams for high dose rate cancer treatment.

The cyclotron magnet, which includes a liquid-helium-free cryostat, has been fabricated and the magnetic field has been measured. Magnetic field distribution and parameters such as horizontal and vertical tunes agreed well with the original design. A 120 kW solid-state RF system is being tested. Other components such as the ion source and electrostatic deflector are being fabricated. After the testing of individual components, they will be assembled and beam testing will be scheduled at a new test site.

INTRODUCTION

Sumitomo Heavy Industries, Ltd. developed a normal conducting AVF proton cyclotron P235 in the 1990s [1]. Today, several P235 cyclotrons are in operation for cancer treatment.

In 2012, the basic design of a superconducting (SC) cyclotron [2] was established to reduce the size and cost of the system. The narrow pole-gap design makes the size smaller than existing isochronous cyclotrons for this purpose. Two h = 2 cavities and one supplementary h = 4 cavity are used to obtain large turn separation at the electrostatic deflector (ESD).

SC cyclotron components have been fabricated and tested since 2017. Figure 1 shows the magnet assembled in 2018. In the following sections, the current status of cyclotron component development and beam dynamics are discussed.

Figure 1: Superconducting cyclotron magnet. Diameter of the yoke is 2.8 m.

The detailed design started in 2015 [3]. The updated design parameters are listed in Table 1. Some parameters such as beam current have been changed to meet high dose rate therapy requirements. The supplementary h = 4 cavity has been removed to further reduce costs. To achieve turn separation with low acceleration voltage, a precessional extraction scheme was adopted.

Table 1: Main Design Parameters of the SC Cyclotron

Description	Parameter	Unit
Particle species	Proton	
Energy	>230	MeV
Beam current (max.)	1000	nA
RMS emittance	~ 1	π mm.mrad
RMS momentum spread	<0.1%	
Extraction efficiency	>70%	
Extraction radius	0.6	m
Average magnetic field	3.1–3.9	T
Yoke size	ϕ2.8 m × 1.7	m
Yoke weight	65 t	t
Coil material	NbTi/Cu	
Stored energy	5.1	MJ
Magnetic induction	9.7×10^5	AT/coil
Main coil current	442	A
Coil cooling time	14	days
Field ramp up time	<1.5	h
Quench recovery time	<24	h
RF frequency	95.2	MHz
Harmonic number	2	
Dee voltage	50–75	kV
RF wall loss	<120	kW

CYCLOTRON COMPONENTS

Cryogenic System

The cryostat [4], as shown in Fig. 2, was fabricated in 2018. Two NbTi coils are supported by four horizontal and four vertical structures. The coils are conduction cooled by four 4 K Gifford–McMahon cryocoolers (RDE-412). After the cryostat was assembled in the yoke, its performance was tested. The cooling time of the coils from room temperature to 4.2 K was 14 days, as shown in Fig. 3. Ramp-up time from 0 A to 488 A was 1.5 h. Quench protection of SC coils was done by a 1.1 Ω dump resistor. To date, we

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have not experienced a quench except during scheduled quench tests. The recovery time from a quench is 17 h.

Figure 2: Cryostat of the cyclotron.

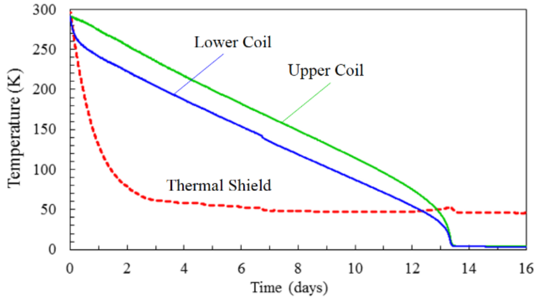

Figure 3: An example of SC coil cooling test.

Magnet

The pole and yoke were assembled in 2018. Figure 4 shows the inside of the magnet. The span angles of four sectors were designed to be as small as possible to achieve large acceleration voltage by h = 2 cavities. The average magnetic field was 3.1 T in the center region, and 3.9 T at the extraction radius. Magnetic field maps were measured by a newly developed mapping system [5]. It took approximately 2.5 h to complete one full map without magnetic channels (MC) with six Hall probes.

Figure 4: Cyclotron pole and extraction harmonic coils.

After adding the calculated magnetic field perturbation induced by MCs, the field map shown in Fig. 5 was used to calculate the field error from the isochronism. The error was adjusted three times by pole machining. The machining dimensions were determined using "saturated iron" approximation. The discrepancy between the measured and calculated values was approximately 10%. After machining, the isochronism was obtained as shown in Fig. 6.

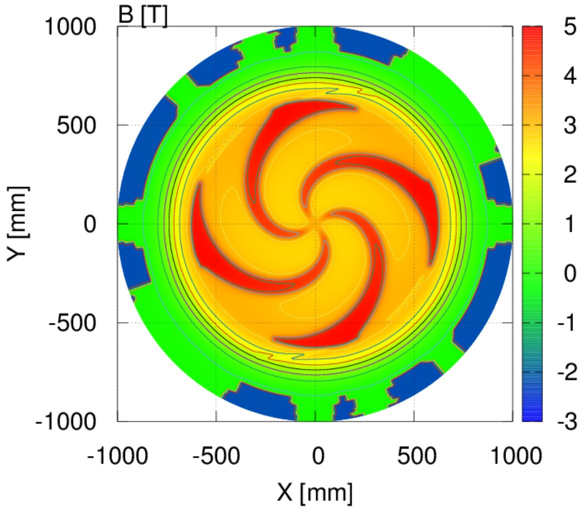

Figure 5: Magnetic field map. R < 630 mm region was measured by Hall probes [5]. The outside region was obtained by 3D calculation [6].

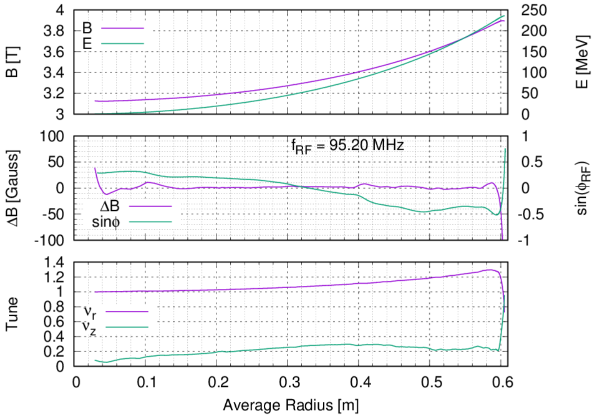

Figure 6: Parameters during acceleration.

RF System

Two opposite valleys will be occupied by RF cavities. The average Dee voltage is 50 kV in the center region, and greater than 75 kV in the outer region. The estimated total wall loss was below 100 kW by 3D calculation. Mock-up cavity low-level testing was completed in 2018. Now, the outer walls of actual cavities are being built. Simultaneously, a 120 kW, 95.2 MHz solid-state amplifier is being tested. After the cavities are installed in valleys, low-power testing will begin in early 2020.

Ion Source and Center Region

Hot-cathode-type Penning ionization gauge (PIG) ion source will be used. The ion source was tested in a 3 T magnetic field, and sufficient beam current was extracted. A vertical chopper will be equipped to perform fast beam on/off. Two sets of center harmonic coils (C-HC) are used to perform beam centering [7]. Modifiable phase slit and vertical slit are positioned to obtain high extraction efficiency.

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Extraction

Beam extraction will be performed by one ESD and two MCs (MC1, MC2). In order to remove the B_{z1} component produced by MCs, dummy MCs (C-MC1, C-MC2) are placed in the counter positions. Harmonic coils (E-HC), as shown in Fig. 4, were placed in the valleys to create adequate B_{z1} components for precessional extraction. The structure of MC1 is shown in Fig. 7. MC2 consists of three iron bars. The average field gradients of MC1 and MC2 are 21.8 T/m and 26.1 T/m, respectively. MC1 and MC2 were fabricated before magnetic field measurements. Magnetic field distributions induced by MCs were measured at several points near the MCs, which is consistent with the calculations by Opera-3D [7].

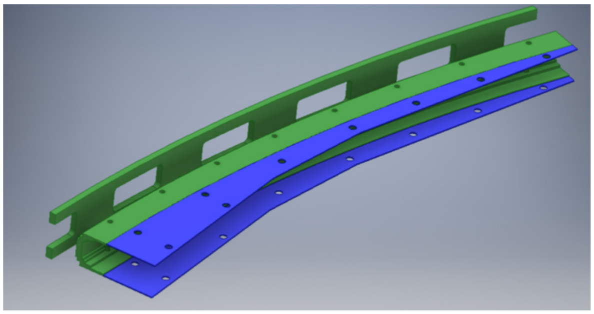

Figure 7: Magnetic channel 1.

Diagnostics

Since the sector spiral angle is large, it is difficult to insert one straight radial probe into the cyclotron center. Instead, several vertically movable probes will be set in a valley for measuring beam current and checking isochronism. A radial probe will be placed between MC1 and MC2 to optimize the beam extraction efficiency. Horizontal and vertical collimators will be set downstream of MC2. Beam loss current will be monitored on each side of the collimator.

Vacuum

The vacuum chamber consists of upper and lower poles, and the inner wall of the cryostat. Two 10-in aperture cryopumps (Canon-Anelva P-101C) will be installed to achieve better than 0.7 mPa within 2 h. The system will be tested in 2020.

BEAM DYNAMICS

In order to gain enough turn separation and reduce RF phase slippage during the precessional extraction process, the structures of sectors and MC1 were optimized. Figure 8 shows the tune diagram. The horizontal tune at extraction was determined to be $\nu_r = 0.9$. The turn separation was in the mm order R = 602 mm, as shown in Fig. 9. In this simulation, B_{z1}= 0.4 mT was applied by E-HCs. The RF phase excursion during $\nu_r = 1.3$ to 0.9 was $\delta\sin(\phi) = 0.5$, which might be allowable. The vertical tune near the extraction region is always larger than 0.2, which may be preferable for reducing beam loss. The best simulated extraction efficiency was approximately 80% by careful tuning of C-HC and E-HC parameters.

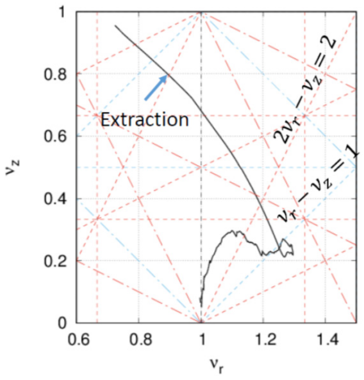

Figure 8: Tune diagram.

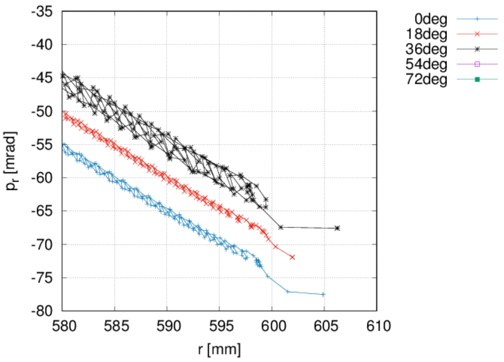

Figure 9: (r, r') phase plot around the extraction radius. ESD is placed at R = 602 mm. An offset of 5 mrad is artificially added to avoid overlapping.

CONCLUSION

Most SC cyclotron components have already been designed and are currently being built. The SC magnet was built and the specified magnetic field was successfully excited. Isochronous field was obtained by pole machining.

At Ehime Works' Saijo plant, a new building for cyclotron beam testing is under construction. Whole components of the SC cyclotron will be assembled at the new site and beam testing will start in 2020.

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