23rd Int. Conf. Cyclotrons Appl. CYCLOTRONS2022, Beijing, China JACoW Publishing
ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEBO04

COMMISSIONING OF THE SUMITOMO SUPERCONDUCTING AVF CYCLOTRON SC230

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Abstract

A 230-MeV superconducting azimuthally varying field (AVF) cyclotron SC230 was developed by Sumitomo Heavy Industries, Ltd. This is the world's smallest isochronous cyclotron for proton therapy, and its weight is 65 tons, which is 0.3 times that of our previous cyclotron model. The size is reduced by generating high magnetic fields using NbTi superconducting coils cooled without cryogen. In addition, this cyclotron features the maximum beam current >1 μA and low power consumption <200 kW. The beam-commissioning test was started at the end of 2020. The first extracted beam was observed in July 2021. Subsequently, and the basic performance of the beam was measured. The processes and results of the beam commissioning are reported.

INTRODUCTION

Proton therapy was proposed in 1946 and first used to treat patients in 1954 [1, 2]. No incision is required, and the characteristic depth dose distribution with a Bragg peak minimizes damage to normal cells. Afterward, patients can receive outpatient treatment while continuing their daily lives, contributing to the maintenance of their quality of life (QOL). Therefore, proton therapy is becoming more prevalent in cancer treatment, and the number of proton therapy facilities is increasing. More than 100 facilities are in operation worldwide [3], and further growth is expected in the future. However, the large device size limits its use in hospitals. Therefore, miniaturization of the device size is one of the issues in proton therapy. Manufacturers have been promoting the development of miniaturization of equipment, and in recent years, the miniaturization of the accelerator, which is one of the primary mechanisms, has been conducted with superconducting coils. Commercial superconducting accelerators for proton therapy were developed by Varian, Mevion, and IBA [4-6].

Miniaturization of accelerators with superconducting coils has the following merits:

- Reduction of building cost
- Shorter delivery times
- Lower operating costs
- Reduced daily downtime

Downsizing is expected to lower the building cost by reducing the construction site area and lowering load-bearing requirements. Moreover, because the large assembly can be transported as it is, disassembly and reassembly times are reduced, and delivery times are shortened. Furthermore, with superconducting coils, the power consumption of coils and running costs can be reduced. In addition, as the power consumption of coils can be reduced, continuous energization at night is possible, which eliminates the daily coil excitation and demagnetization time in hospitals and contributes to the reduction of downtime. Hospitals benefit from a variety of services. Many superconducting accelerators for proton therapy are being designed and developed to provide such benefits.

Sumitomo Heavy Industries developed the superconducting cyclotron SC230. The weight of the yoke is 65 tons, equivalent to 3/10 times that of the conventional model [7]. Additionally, it is not only compact but also consumes low energy and offers a high beam current. Energy saving is not only a countermeasure against recent issues, such as unstable energy supply and global warming but it is also expected to reduce operating costs. The power consumption is ≤200 kW, equivalent to 3/5 times that of conventional models. Its high-current beam contributes to shortening the treatment time. The maximum beam current of the cyclotron is ≥1 μA, which is 3.3 times that of the conventional machine, which is the maximum for proton therapy accelerators. It reduces patient burden, increases patient throughput, and allows for more patients to be treated. In the future, it can be applied to treatment methods that require high-current beams, such as FLASH treatment and the breath-hold irradiation method.

The basic design of the cyclotron was reported in 2013 [8]. The design and fabrication of each component including the superconducting magnet have been completed thus far, and the mapping and formation of the magnetic field have been completed [9-13]. A new test site was established in 2020. The cyclotron was relocated to this site and conditioned. Commissioning tests started at the end of the same year and the beam was extracted in July 2021. Additionally, the extracted beams met the performance requirements, and the development of SC230 was completed. Here, we report on the commissioning.

SC AVF CYCLOTRON SC230

The developed superconducting AVF cyclotron SC230 for proton beams is a four-spiral sector-type AVF cyclotron. Figure 1 shows an image of the external appearance of the cyclotron. The main specifications for its components are presented in Table 1.

It produces a fixed-energy proton beam required for proton therapy. The cyclotron was miniaturized by using a superconducting magnet to generate a high magnetic field of 3–5 T. The average magnetic field was approximately 3.9 T at the extraction radius of 0.6 m.

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Figure 1: Sumitomo superconducting AVF cyclotron SC230.

Table 1: Main Specifications of SC230

Parameter	Specification
Accelerator type	AVF cyclotron
Number, shape of sector	Four, spiral
Particle species	Proton
Beam energy	233–238 MeV (Fixed)
Maximum beam current	≥1000 nA
Beam structure	CW
Extraction diameter	0.6 m
Yoke size	Diameter: 2.8 m Height: 1.7 m
Yoke weight	65 t
RF frequency	95.3 MHz （h = 2）
Dee voltage	50 kV (Inside) 75 kV (Outside)
Number of dees	2
RF power	<70 kW
Total power consumption	<200 kW

Two upper and lower NbTi superconducting coils were used as magnetomotive force sources. The superconducting coils were installed inside a cryostat for vacuum insulation and cooled below 5 K by a conduction cooling method using four cryocoolers. With the conduction cooling method, the coils have improved maintainability. They were accessible from outside the cyclotron, and maintenance was allowed while keeping the coil cool. The operation of the cryocoolers is simple, with a simple button operation. Furthermore, since it is cryogen-free and does not use liquid helium, it does not emit helium even during quenching that can occur during a long-term power outage. Furthermore, it is an effective countermeasure against the instability of helium supply, which has become an issue in recent years. Its cooling time is 14 days. With a damper protection, quench recovery time is 17 hours [11].

When an AVF cyclotron is miniaturized by a high magnetic field, flutter becomes smaller because it is inversely proportional to the square of the average magnetic field. Therefore, to prevent beam divergence, the gap between the magnetic poles should be shortened to increase the difference between the hill and valley magnetic fields, thereby suppressing flutter reduction. Additionally, countermeasures should be obtained such as a large spiral angle, which increases the complexity of the magnetic field distribution. In SC230, to realize a compact AVF cyclotron, a magnetic pole gap is ±10 mm in a wide area, and ±6 mm at the nearest point, and a maximum spiral angle of approximately 70 degrees. The magnetic pole shape required complex and high dimensional accuracy, and the magnetic pole was manufactured by precision machining on the order of 0.01 mm. In addition, mapping and adjustment were performed to produce the average magnetic field at 50 ppm or less. Finally, it was confirmed that the isochronous magnetic field satisfying the requirements was formed.

The power consumption of the coils was low owing to their conductivity; therefore, RF power consumption was dominant in this cyclotron and must be kept low. To reduce the RF power consumption, the number of dees was two, which is minimum for commercial use, and the applied dee voltages were designed to be 50 kV on the inside and 75 kV on the outside. The total power consumption was below 200 kW owing to the small number of dees and the low dee voltage. However, the energy saving dees reduce not only its power consumption but also the energy gain per turn. Small turn separation reduces the beam extraction efficiency. Therefore, the precessional extraction method, which increases the turn separation by resonance, was adopted.

The maximum beam current was 1 μA, which is the highest among commercial accelerators for proton therapy. Because it is an AVF cyclotron, it had achieved a large beam current that could be regarded as continuous. In addition, the beam current upper limit in the conventional machine was set such that the electrostatic deflector (ESD), which was one of the extraction components, would not be damaged by beam loss. In SC230, the beam loss in the ESD was reduced to realize a large current beam. The turn separation increased, and the passage efficiency of the ESD improved by adopting the precessional extraction method described above. The $\nu_r = 1$ resonance was used for the method. The first harmonic component of the axial magnetic field B_{Z_1} should be precisely adjusted. B_{Z_1} was almost zeroed by the vertical coil position adjustment in advance [12]. In the commissioning, B_{Z_1} was adjusted by the horizontal coil position adjustment, and extraction harmonic coils (EHCs). The EHCs, which are facing two sets, can increase the B_{z1} to 8×10^{-4} T around the beam-extraction radius. In addition, owing to the feature of the narrow pole gap, the fringe field was attenuated with a high gradient in the extraction region, which contributed to efficient beam extraction.

Table 2: Design Specifications of the Components

Parameter	**Specification**
Ion source type	Hot cathode-type PIG ion source
Cryostat outer diameter	1.74 m
Cryostat height	0.64 m
Number of coils	2
Superconducting wire	Monolith NbTi/Cu
Coil current	442 A (488 A Max.)
Maximum stored energy	5.3 MJ
Coil temperature	<5 K
Cooling method	Conduction-cooling
Cryocoolers	4K-GM cryocoolers
Number of cryocoolers	4
Cooling time	14 days
Quench recovery time	17 hours
Coil supports	4 (vertical) 4 (horizontal)
Vacuum pumps	Two cryocoolers, dry pump
Operable vacuum	$< 1 \times 10^{-2}$ Pa
Extraction method	Precessional extraction
Extraction components	EHCs, ESD, MC1, MC2

COMMISSIONING

Parameters were adjusted along the beam flow from the ion source to the extraction components. Regions from the center to the exterior were named the central, isochronous, and extraction regions.

In the central region, the parameters of the ion source were adjusted primarily. The source was a Penning ionization gauge ion source using a hot cathode, and its electrical parameters were adjusted. The position and angle was adjusted from outside the cyclotron to maximize the beam current.

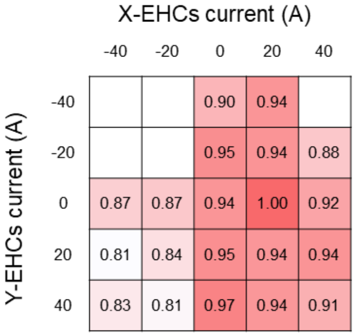
In the isochronous region, the isochronous field was formed by mapping and adjustment performed in advance. No adjustment mechanism was available. During commissioning, the beam was confirmed to pass through the isochronous region without any parameter adjustment. The formation of a distinct isochronous field was observed.

In the extraction region, parameters such as the central harmonic coils (CHCs), EHCs, ESD, and the position of the main coil were adjusted. The current of CHCs was tuned to adjust the orbital center. Additionally, to obtain an appropriate B_{Z_1} for precessional extraction, the horizontal-coil position and the currents of the EHCs were adjusted for coarse and fine adjustments of B_{Z_1}. The normalized beam current for each combination of EHCs-current values is shown in Fig. 2.

The ESD voltage adjusted the final extraction trajectory. After passing through the ESD, the beam passed through two passive magnetic channels and exited the cyclotron through a beam port located through the cryostat and yoke. Beam extraction was confirmed by observing using films.

The normalized beam current at each ESD voltage is shown in Fig. 3. Furthermore, the parameters were set to maximize the extracted beam current.

A beam extracted from the cyclotron was stopped by a damper after passing through two bending and two focusing magnets. An ion chamber was installed in front of the damper, and the beam current was measured. In addition, a measurement area was set up between the ion chamber and the damper, and key beam performances, including beam profile and energy, were measured using a beam profiler and a range measurement module. The SC230 supports fast scanning with 0.1 second energy switching and scan speeds of up to 100 m/s. Therefore, in addition to the maximum beam current, the current and position must be highly stable. Table 3 shows the required main beam specifications. During the commissioning, the maximum beam current was confirmed to exceed 1 µA, and the beam extraction efficiency was confirmed to be 67 %, which satisfy the specifications. In addition, current and position stabilities were measured, and the beam met all specifications.



Y \ X	-40	-20	0	20	40
-40			0.90	0.94	
-20			0.95	0.94	0.88
0	0.87	0.87	0.94	1.00	0.92
20	0.81	0.84	0.95	0.94	0.94
40	0.83	0.81	0.97	0.94	0.91

Figure 2: Normalized beam current for each combination of extraction harmonic coils (EHCs)-current values. The x and y directions are perpendicular to each other, and the relationship between the current and the first harmonic component of the axial magnetic field B_{Z_1} on MP is 7.6×10^{-6} T/A. The extraction beam current peaked under the conditions of the current set (0 A, 20 A), i.e., when B_{Z_1} of 1.5×10^{-4} T was generated in the x direction.

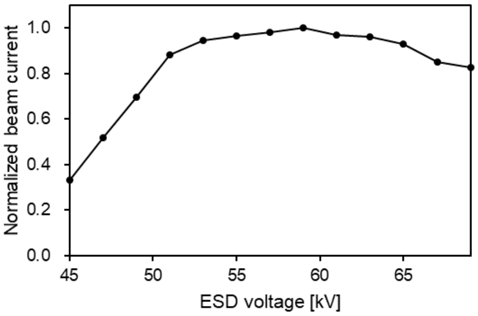


Figure 3: Normalized beam current at each electrostatic deflector (ESD) voltage. A broad distribution over 10 kV was confirmed. Finally, the voltage was set to 55 kV, a relatively low voltage within the flat peak area.

Table 3: Main Beam Specifications of SC230

Parameter	**Value**
Energy reproducibility	<0.2 MeV
Extraction efficiency	≥60 %
Minimum controllable beam current	<1 nA
Ripple current	≤2 % (1σ)
Beam current stability	≤1 % (1σ) for 2 min.
Beam responsivity	≤50 μsec
Beam position stability	<0.1 mm for 2 min.
RMS emittance	<2.2 μm (x), 1.4 μm (y)

Details of the commissioning and test results and the performance of the superconducting magnet were reported in Refs. [14, 15].

CONCLUSION

The world's smallest superconducting AVF cyclotron for proton therapy was developed. Challenging designs were adopted for each mechanism, including the complex yet precise magnetic-pole shape and energy saving dees. Each component adopting a design was realized through precise fabrication, assembly, and adjustment.

Transfer to the new test site and the assembly of the components were completed. The commissioning test was initiated in 2020. During the commissioning, the parameters were adjusted, and the results confirmed that the accelerated beam was extracted from the cyclotron through the central, isochronous, and extraction regions. The maximum extracted beam current was >1 μA, and the extraction efficiency was 67 %. In addition, all necessary specifications for proton therapy were satisfied. Through these tests, we observed that the performance requirements were reached. The development was completed in 2021.

The SC230 is compact and energy saving. Furthermore, its high beam current will improve patient throughput and enables treatment of more patients. In addition, the high-current beams should contribute to the expansion of treatment methods such as FLASH treatment and breath-hold irradiation. This cyclotron is expected to be installed in several hospitals and contribute to many treatments.

ACKNOWLEDGEMENTS

The commissioning was extensively supported by several engineers. We especially thank Dr. K. Taki, Mr. S. Hara, Dr. S. Nomura, Mr. K. Suga, Mr. H. Oda, and Mr. S. Fujita for their assistance with equipment adjustment and measurement.

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