

Superconducting Accelerators for Proton Therapy: Overview and the Compact AVF Cyclotron SC230

 Sumitomo Heavy Industries, Ltd.

Yuta Ebara

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IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 63, Mar. 2026. Presentation given at ISS 2025, Nagasaki, Japan, Dec. 2025.

➤ Company

Sumitomo Heavy Industries, Ltd.

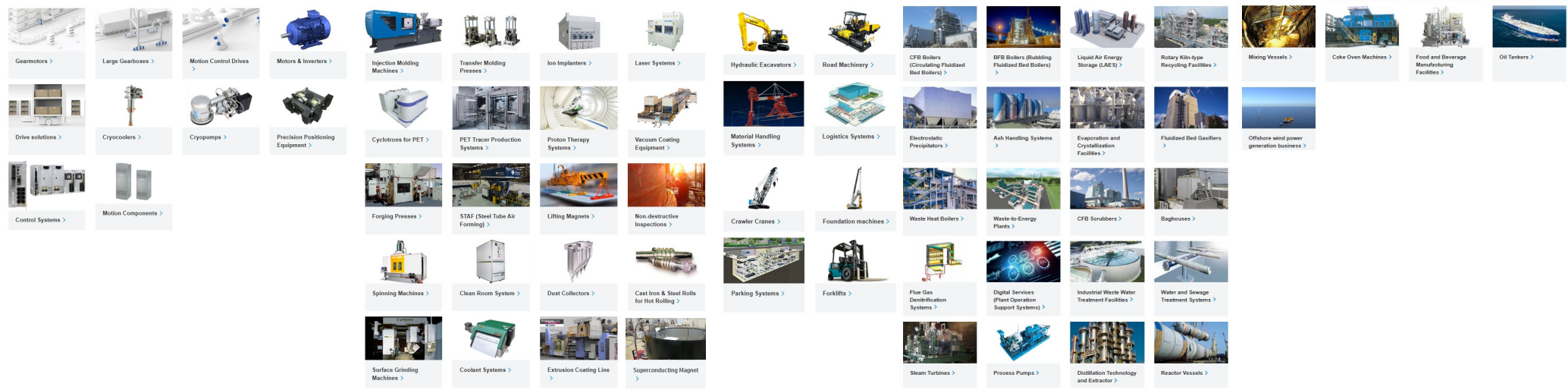


➤ Speaker

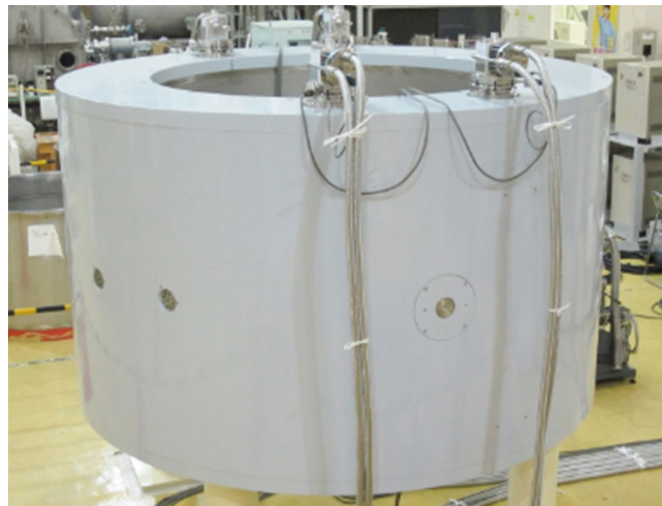
YUTA EBARA

- Technology Research Center
- Since 2015
- Engineer in superconducting & accelerator technologies





Accelerators



SC magnets



Cryocoolers



➤ Over 50 Years of Accelerator Manufacturing

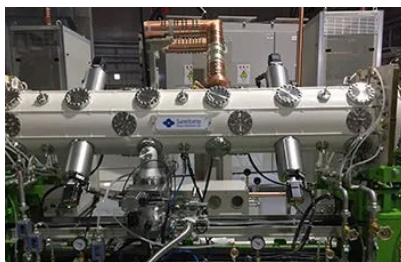
- 1972- Research accelerator
- 1981- PET cyclotron
- 1988- Injector for heavy ion radiotherapy
- 1996- Proton therapy system
- 2009- BNCT system

➤ Medical Accelerators

PET



Linac for carbon therapy



BNCT



Radionuclide therapy



Proton therapy



I N D E X

01

Proton Therapy

- Proton therapy, PT system
- Development needs

02

Proton Therapy Accelerators

- Superconducting accelerators
- Types of accelerators

03

“SC230” Compact High-Beam-Current Cyclotron

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Proton Therapy Accelerators

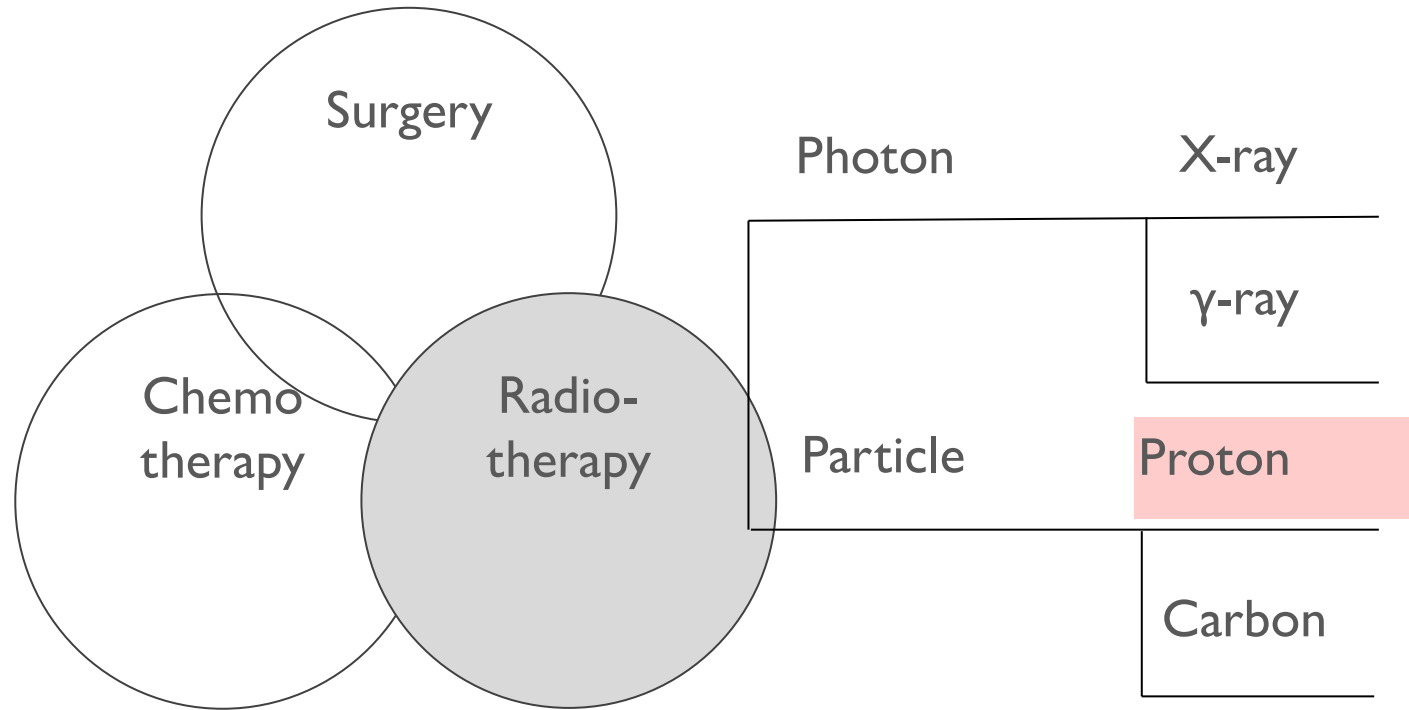
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“SC230” Compact High-Beam-Current Cyclotron

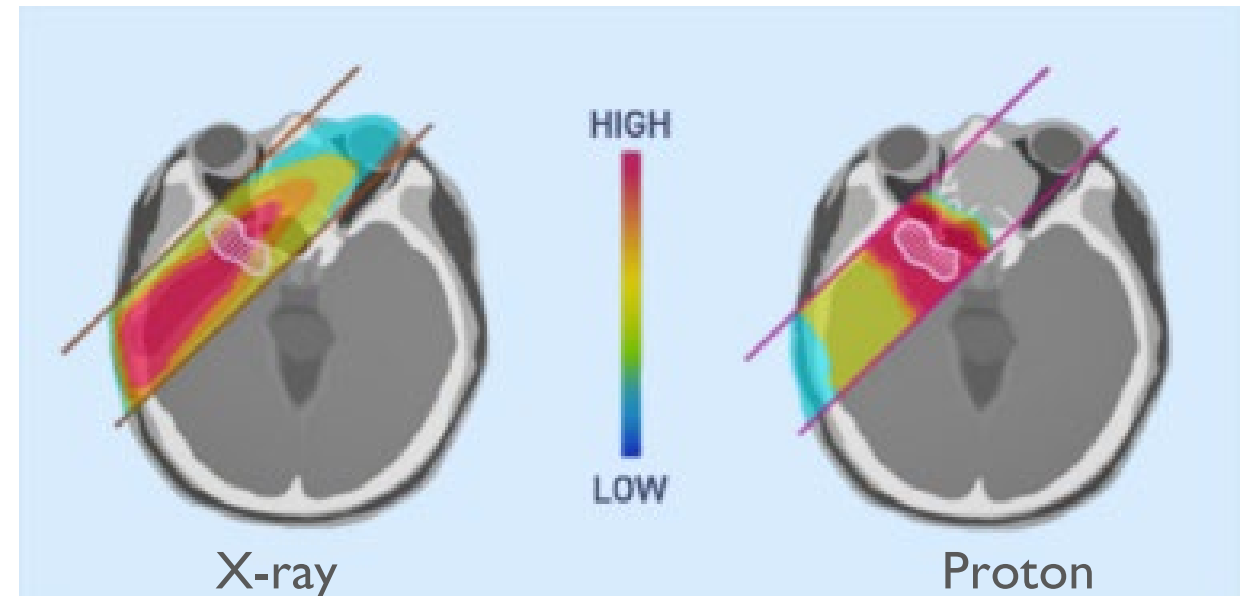


➤ **Proton therapy** is a type of radiation therapy that uses protons.

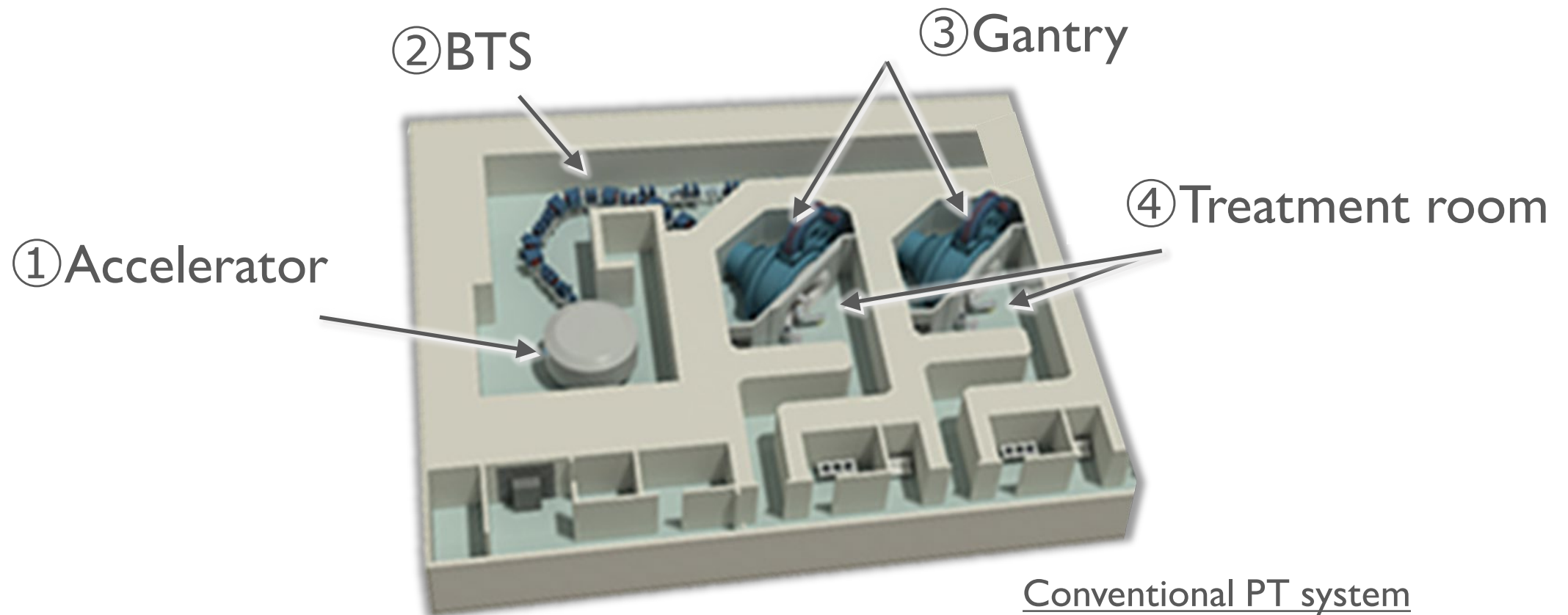


- **The proton beam enables pinpoint irradiation.**
 - X-rays deliver dose not only to the tumor, but also to the healthy tissues before and beyond the tumor.
 - Protons, because of the Bragg peak, deposit most of their energy at the tumor.
 - This advantage is even greater with multi-angle irradiation and IMPT.

Dose distributions



- Proton therapy system consists of four major components.



➤ 1. Accelerator

➤ It accelerates protons to high energies (typically 230MeV) which is enough to reach deep-seated tumors.

➤ 2. Beam transport system (BTS)

➤ It transports the beam from the accelerator to the gantry.

➤ It may have a degrader to reduce the beam energy.

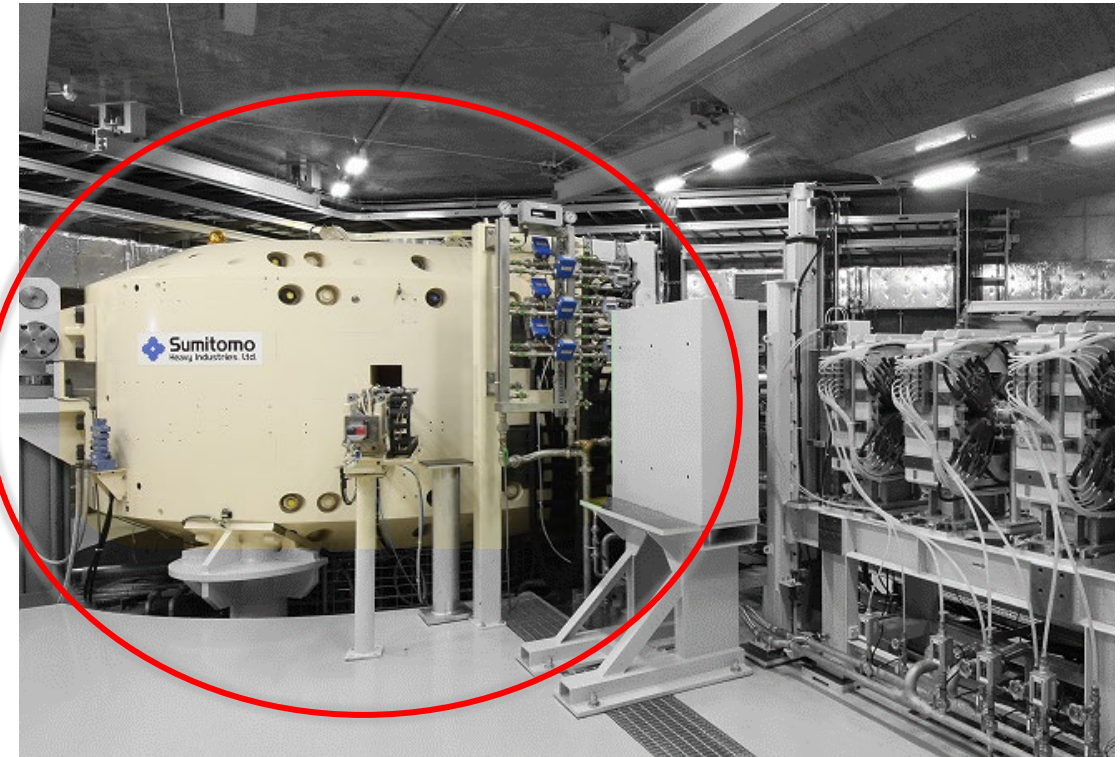
➤ 3. Gantry

➤ It delivers the beam from different angles around the patient.

➤ 4. Treatment room

➤ In this room, patient lies on a robotic bed.

➤ Proton beam is precisely aligned with the tumor.



This is one of the largest components in the system.
(Our conventional model weighs 220 tons!)

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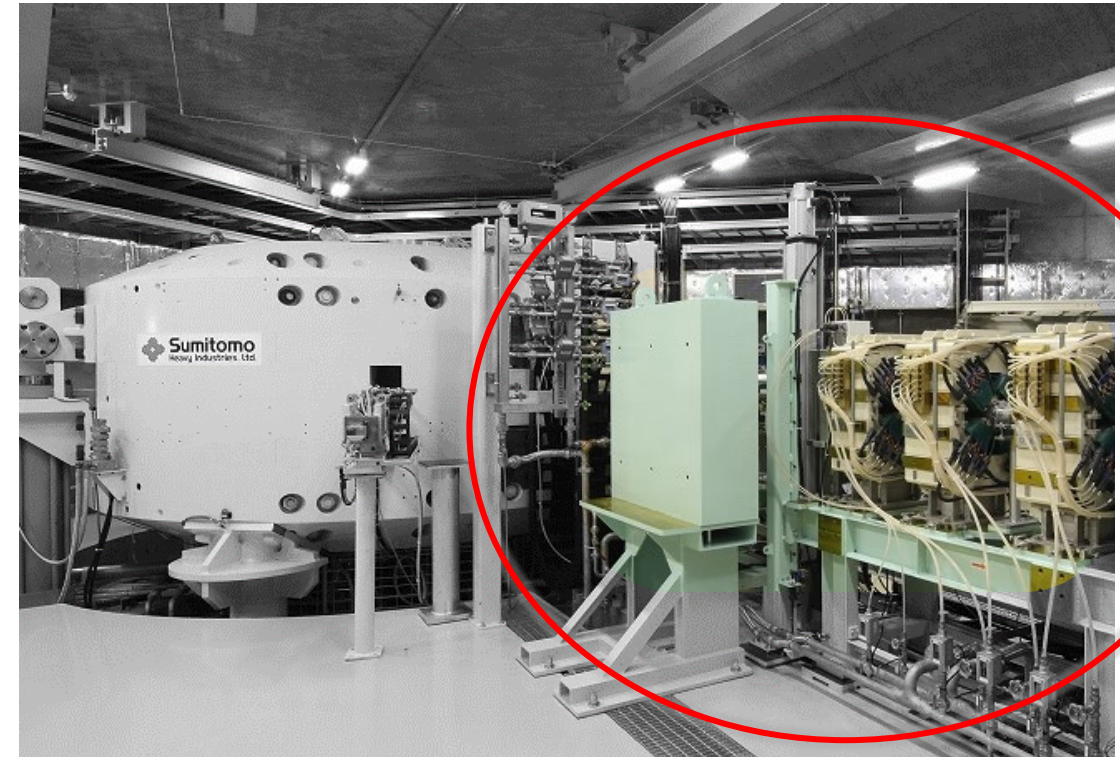
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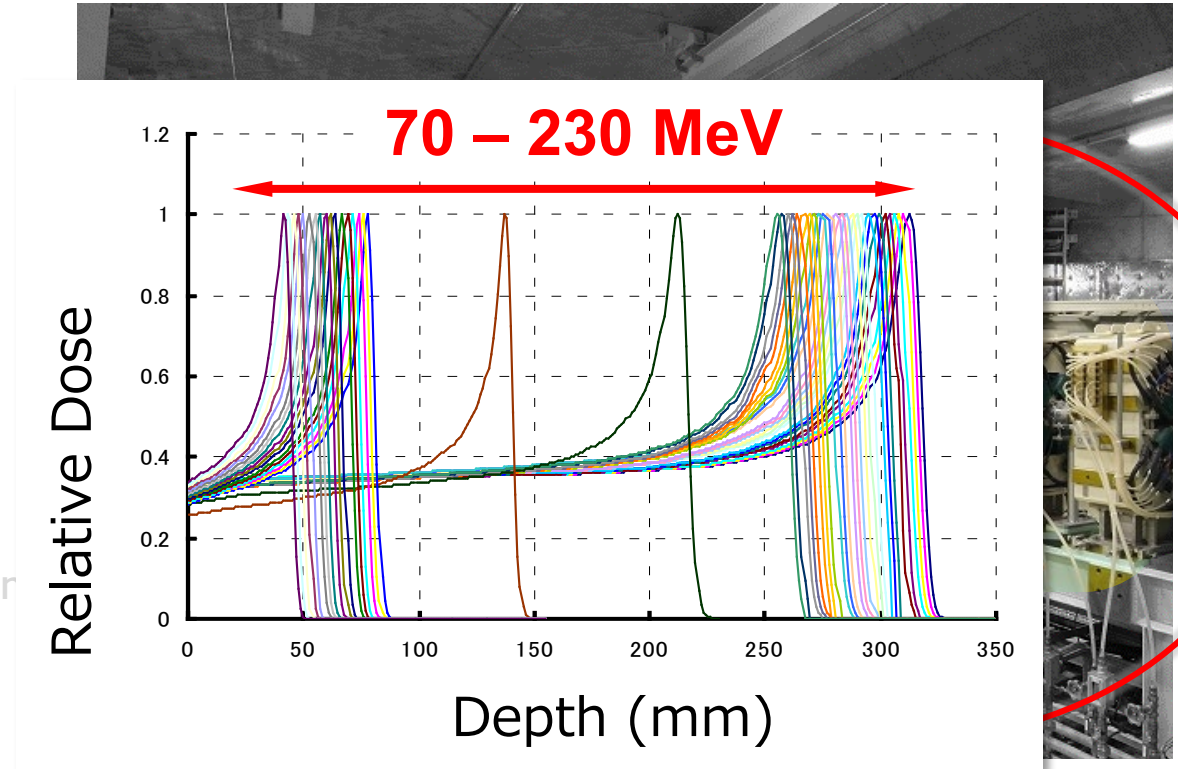
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➤ 4. Treatment room

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➤ Proton beam is precisely aligned with the tumor.



**By adjusting the proton energy,
we can control the depth-dose distribution.**

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➤ 2. Beam transport system (BTS)

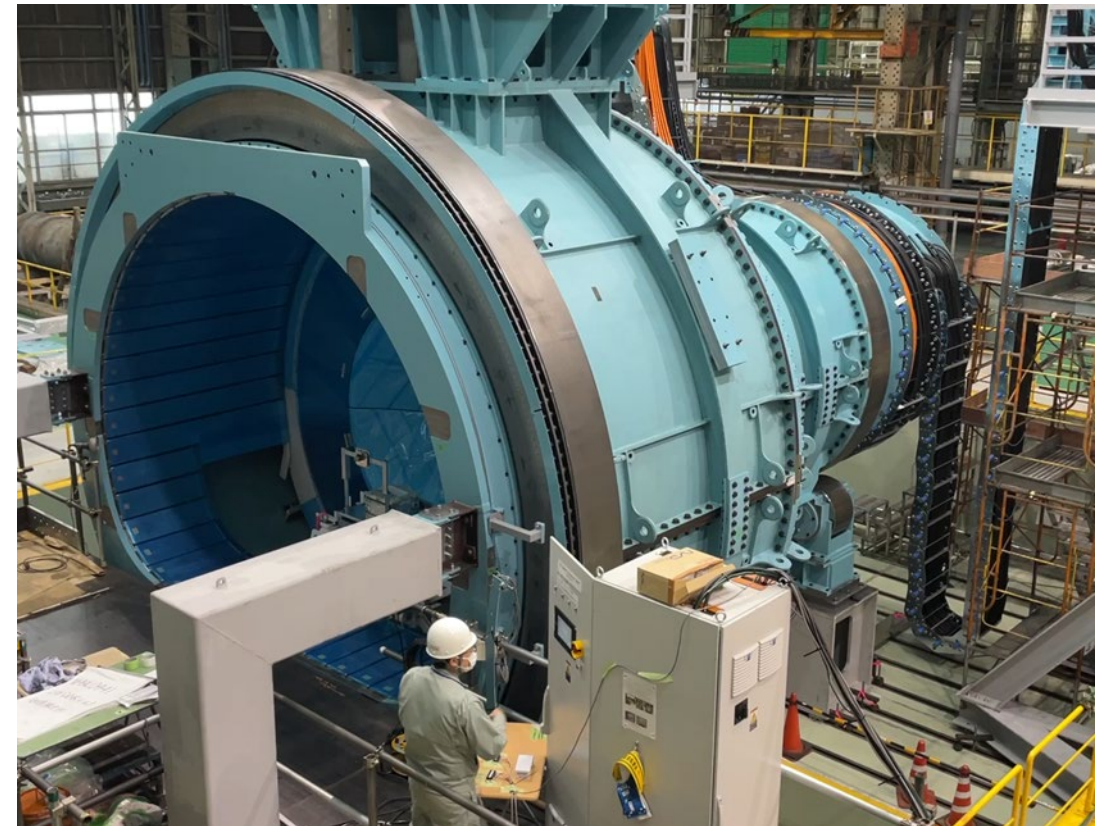
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➤ In this room, patient lies on a robotic bed.
➤ Proton beam is precisely aligned with the tumor.



It enables irradiation from multiple angles.

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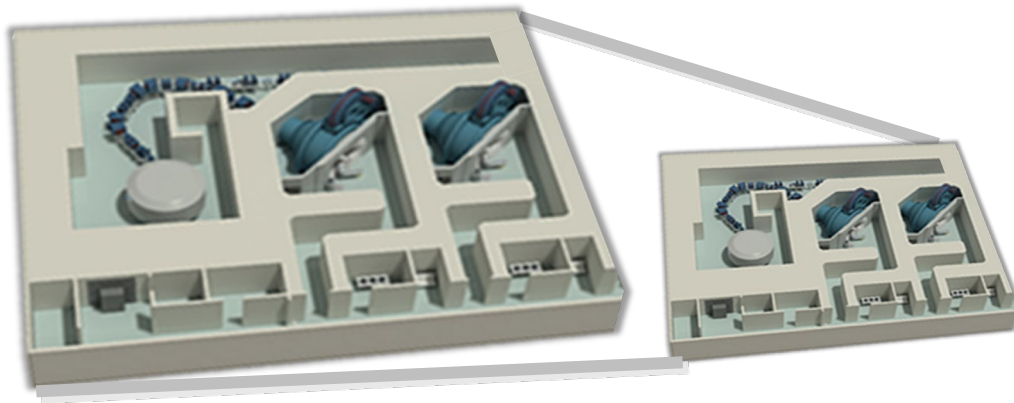
➤ In this room, patient lies on a robotic bed.
➤ Proton beam is precisely aligned with the tumor.



- What proton therapy systems need today to further expansion.

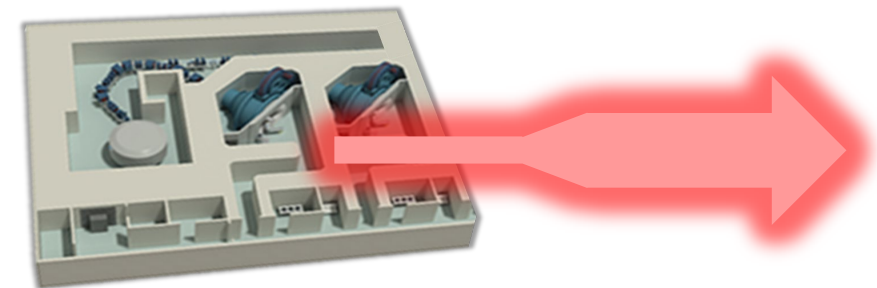
System Miniaturization

To reduce building size and cost.



High Beam Current

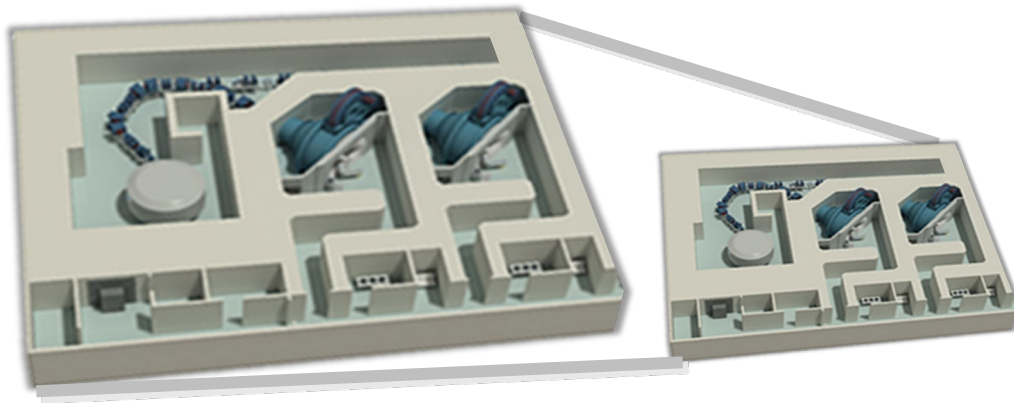
To enable faster treatment and higher patient throughput.



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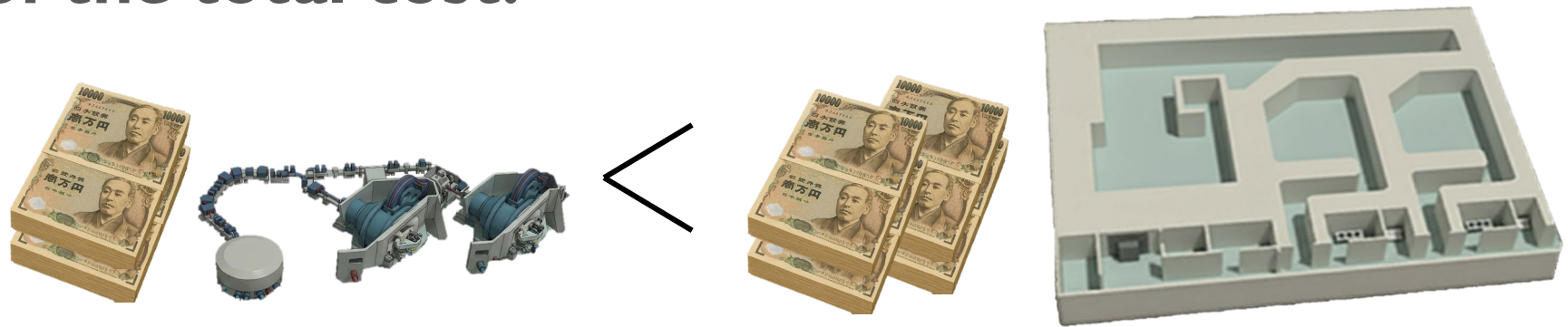


➤ **The initial cost is quite expensive.**

*“Current three to four treatment room proton therapy facilities cost of the order of **\$100–200 million**, whereas a single room facility costs about **\$30 million**”*

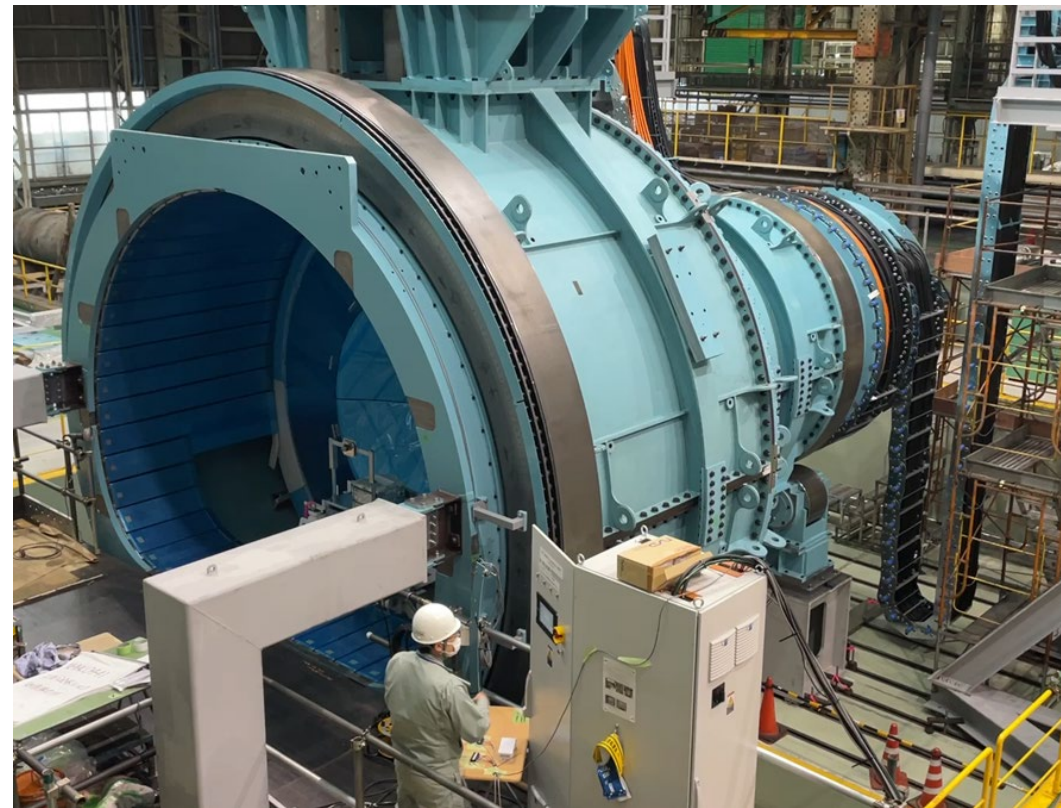
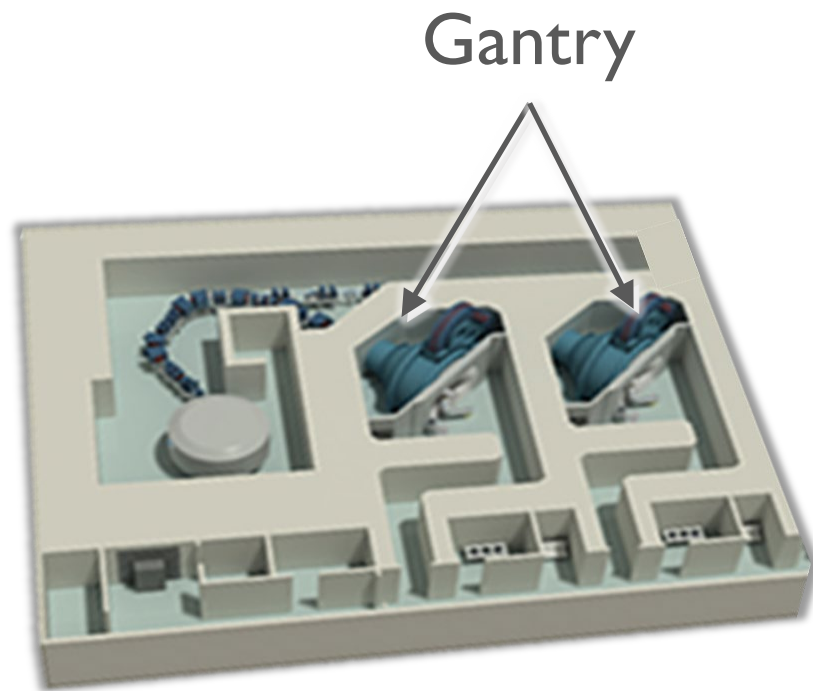
R. Mohan, Precision radiation oncology (2022)

➤ **In some facilities, the building itself accounts for half or more of the total cost!**



➤ **System miniaturization reduces initial costs!**

- A trend related to miniaturization.
 - There are several innovative solutions to reduce gantry size.



➤ Superconducting gantry

- uses high magnetic fields to increase bending force.



➤ Non-rotating gantry

- uses multiple fixed beamlines.
- This requires several coils, but the rotating structure can be eliminated.



➤ Rotating bed (Upright system)

- Instead of rotating the beam, the patient is rotated.
- Therefore, a gantry is not required.



➤ These approaches will help make the system smaller!

- What proton therapy systems need today to further expansion.

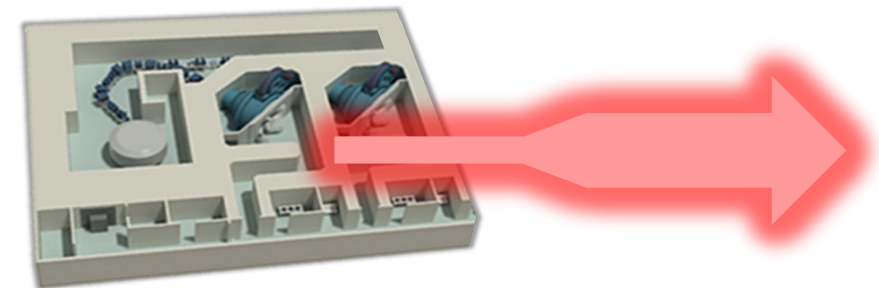
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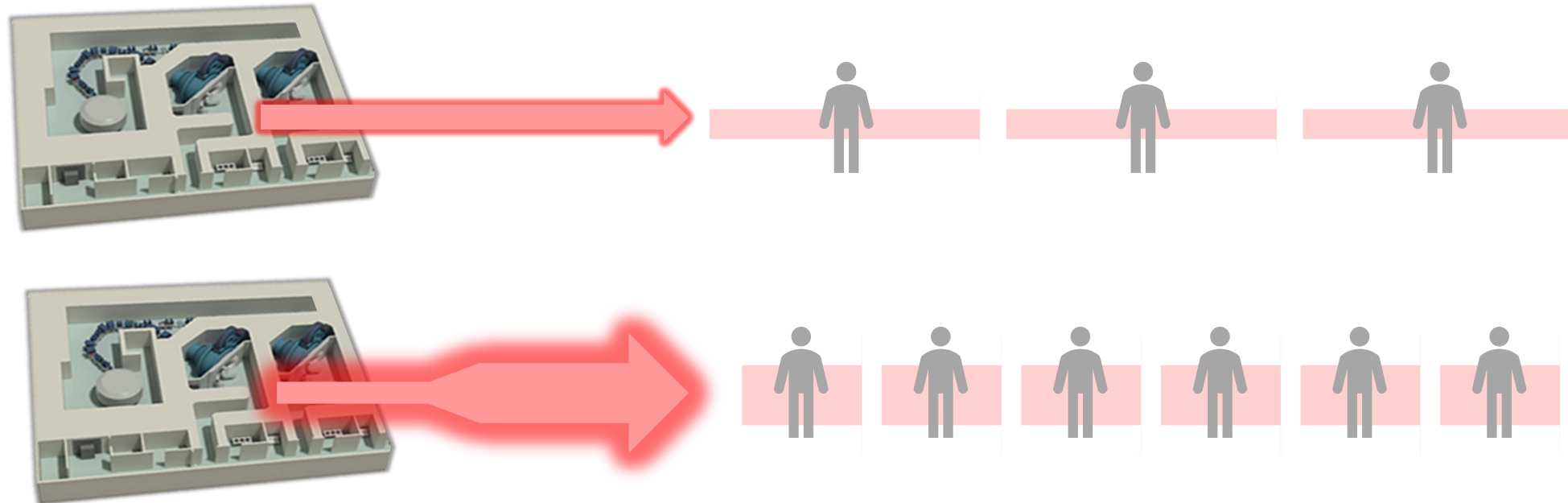


High Beam Current

To enable faster treatment and higher patient throughput.



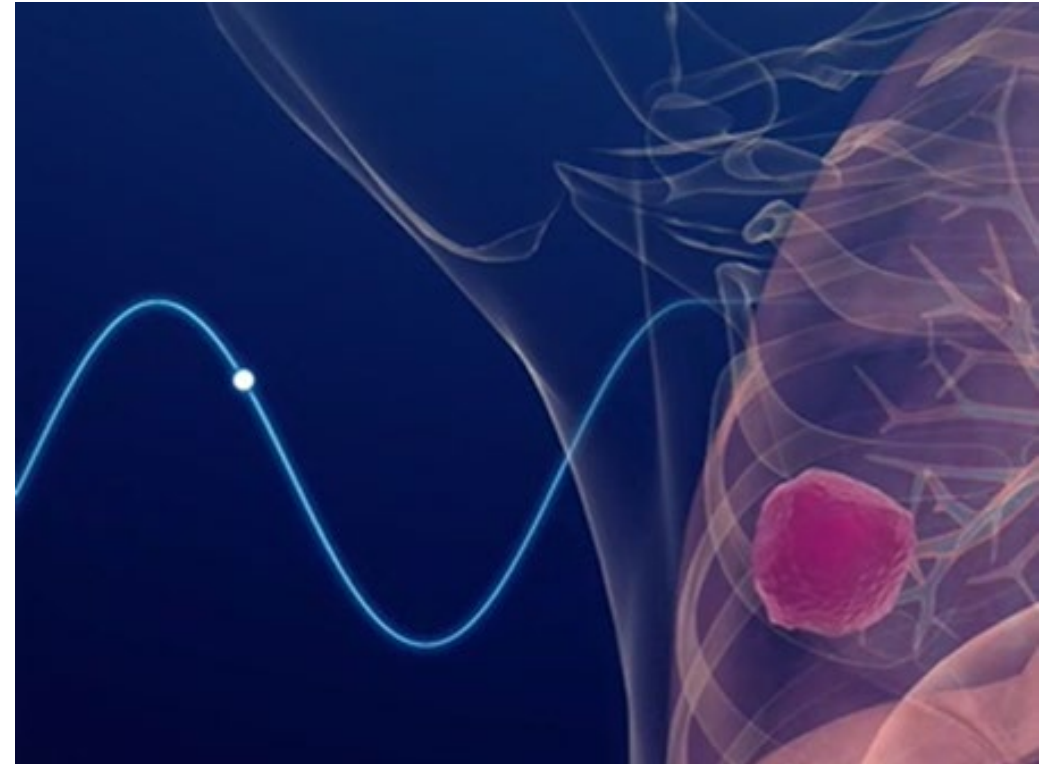
- A higher beam current allows the dose delivery in a **shorter time**.
- Shorter irradiation time **increases patient throughput**.



- High current beams shorten the payback period, making it easier for hospitals to adopt the system!

- High beam current enables advanced treatment techniques.
- **Breath-hold irradiation**
 - helps deliver dose to moving organs such as lung.
- **pFLASH-RT**
 - uses ultra-high dose rate beams.
 - It can further reduce damage to normal tissues.

Breath-hold irradiation

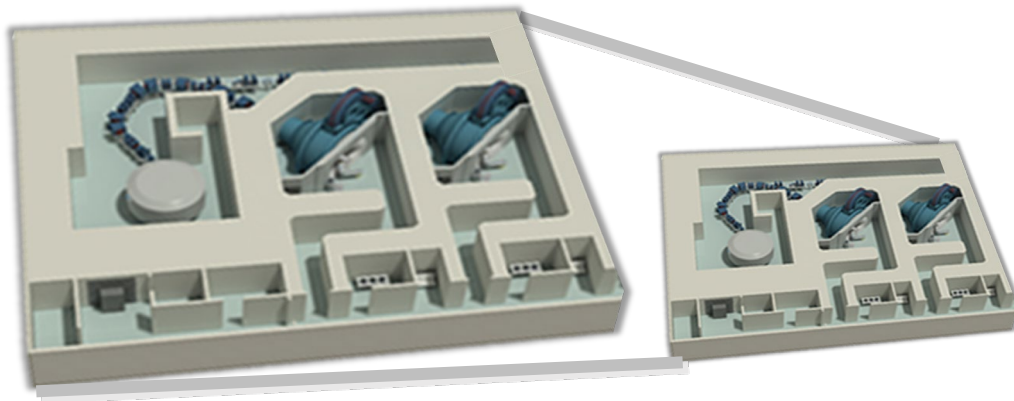


- These techniques require high current beams!

What proton therapy systems need today to further expansion.

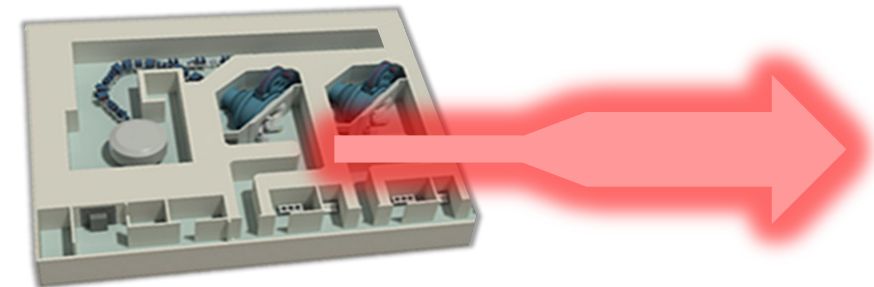
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To reduce building size and cost.



High Beam Current

To enable faster treatment and higher patient throughput.



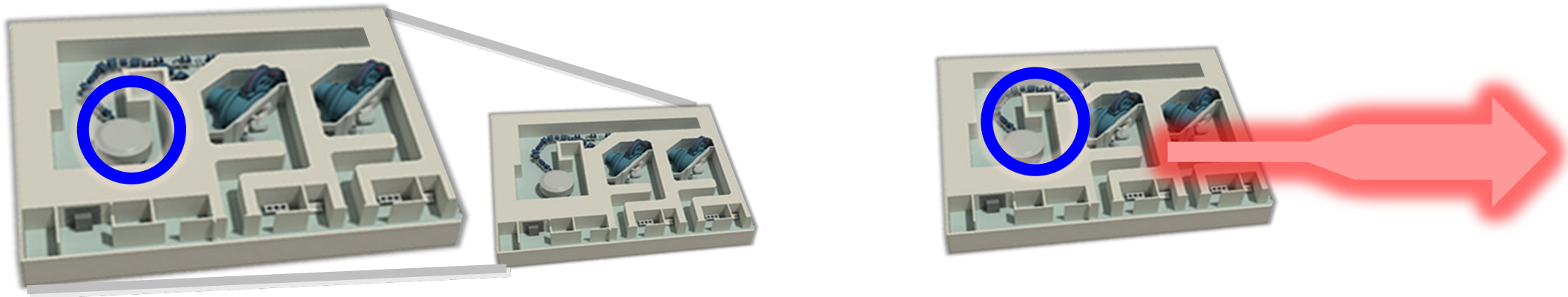
What proton therapy systems need today to further expansion.

System Miniaturization

To reduce building size and cost.

High Beam Current

To enable faster treatment and higher patient throughput.



“Accelerator” is central to achieving both goals.

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Proton Therapy Accelerators

- Superconducting accelerators
- Types of accelerators

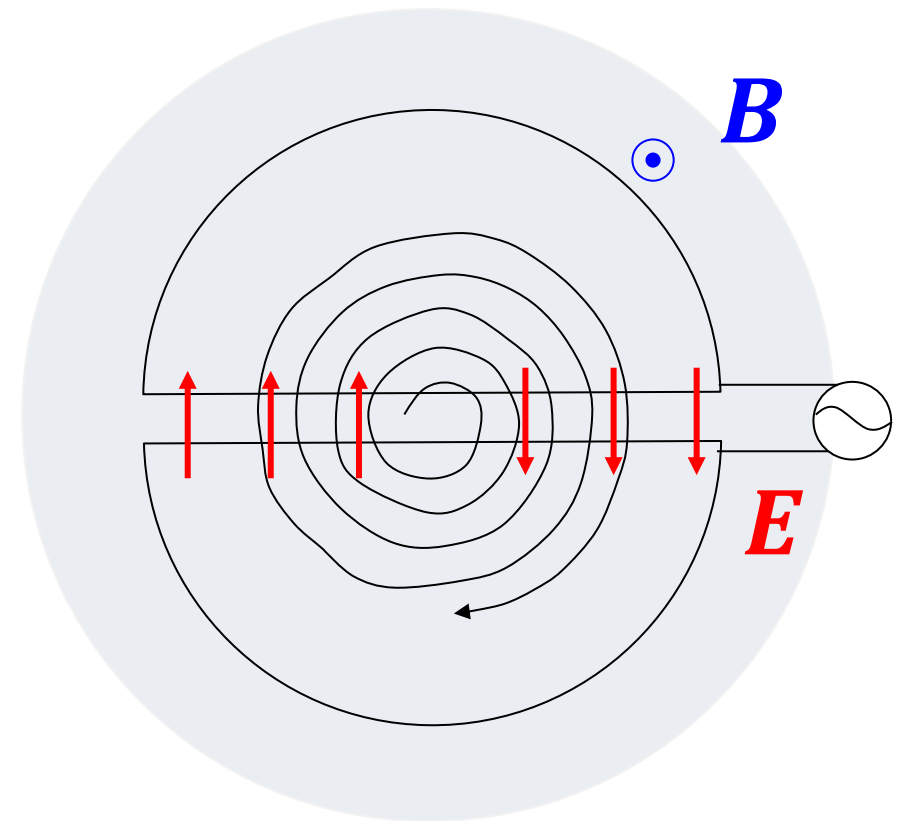
03

“SC230” Compact High-Beam-Current Cyclotron

- In circular accelerators, particles are bent by the magnetic field.
- The radius of the beam is inversely proportional to the field.

$$r = \frac{mv}{qB}$$

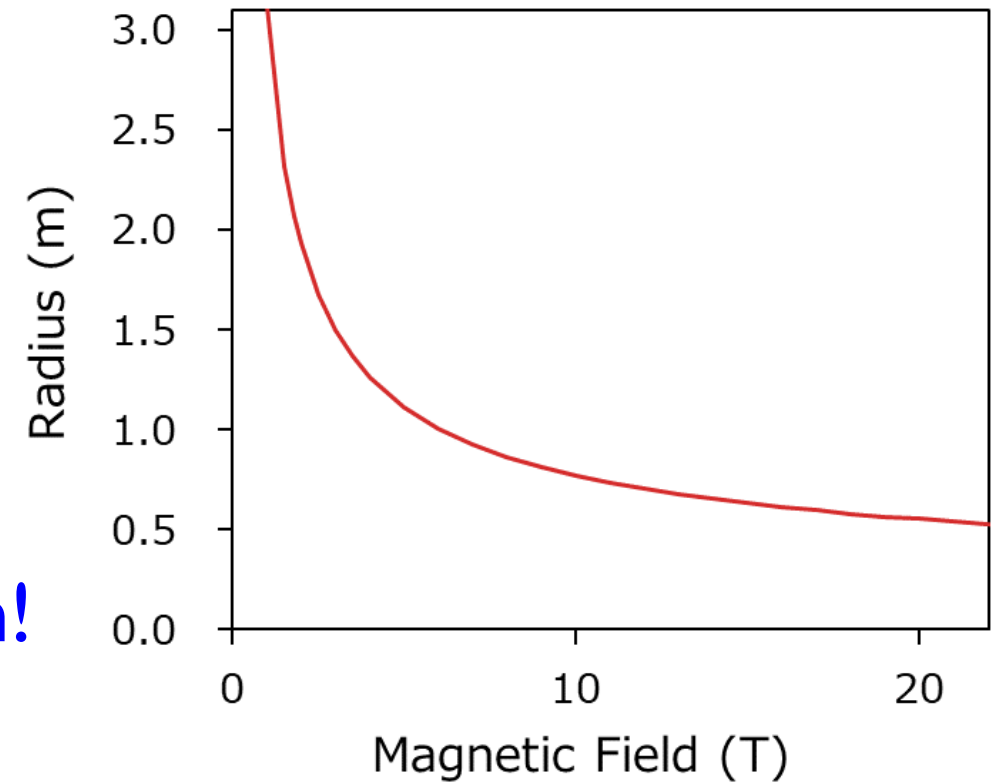
(Larmor radius)



- In circular accelerators, particles are bent by the magnetic field.
- The radius of the beam is inversely proportional to the field.
- If we want to make accelerators more compact, we need to apply higher fields.

SC technology enables miniaturization!

Radius vs Magnetic field



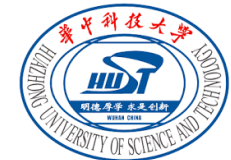
Superconducting Accelerators

➤ In recent years, several commercial SC accelerators have been developed.



Name	AC250	S250	S2C2	SC240
Manufactures	Siemens(Germany)	Mevion(US)	IBA(Belgium)	CIM(China)
Extracted Field	3.0 T	8.2 T	5.0 T	3.0 T
Yoke Weight	90 t	17 t	50 t	90 t
Superconductor	NbTi	Nb ₃ Sn	NbTi	NbTi
Coil Cooling	LHe	Cryocoolers(?)	Cryocoolers	LHe

➤ Several projects are proposed/underway as well.



K250(MIT)

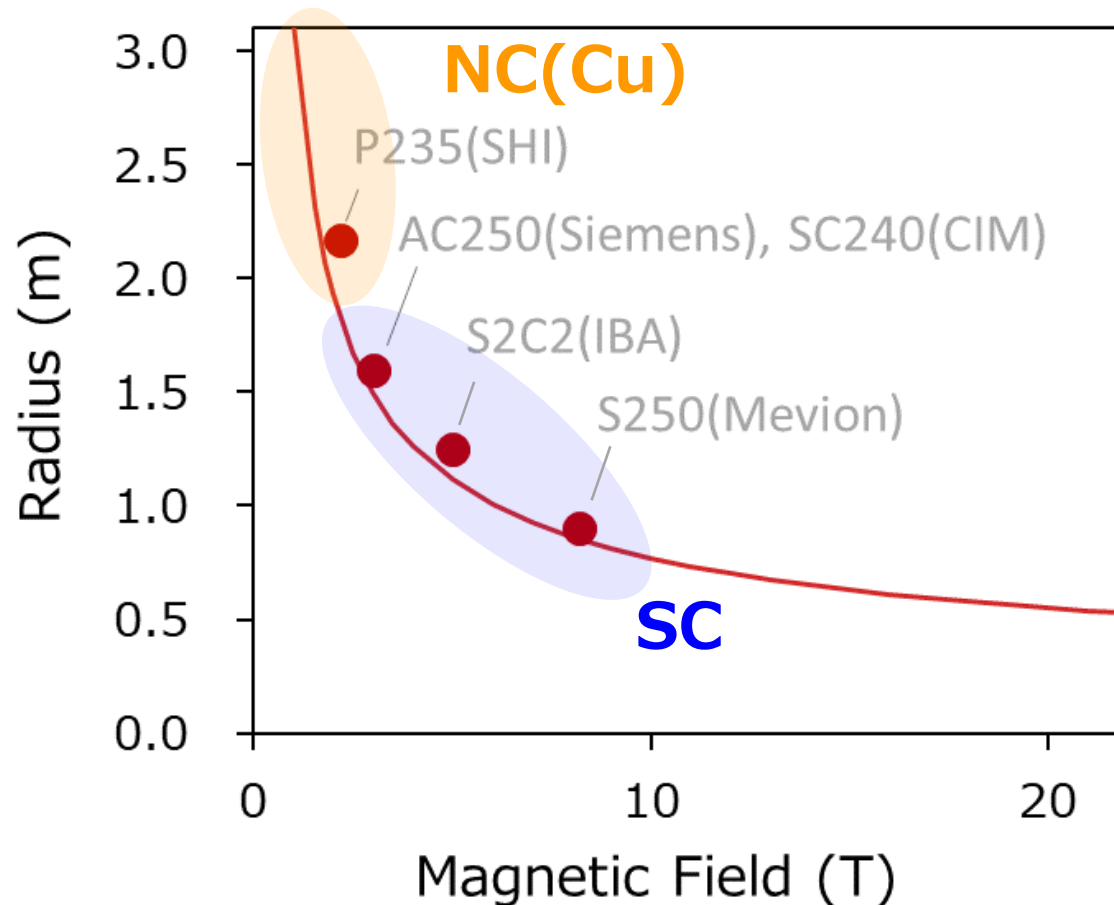
K230(Inetix&JINR)

TAAC(Antaya)

SCIC(Pronova)

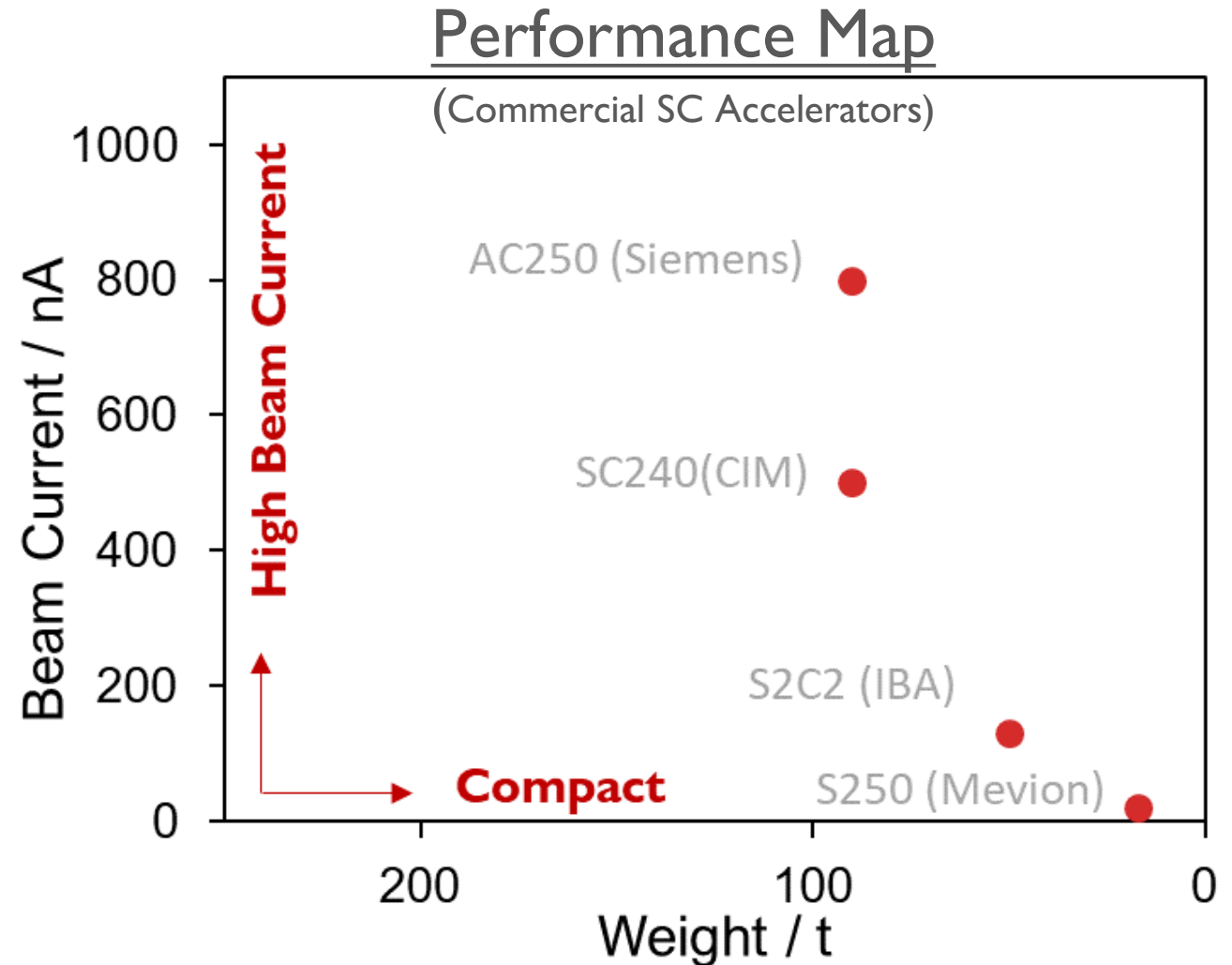
SCC250(HUST)

- When we plot existing accelerators in the graph, we can find that SC coils enable smaller accelerators than NC coils can achieve.

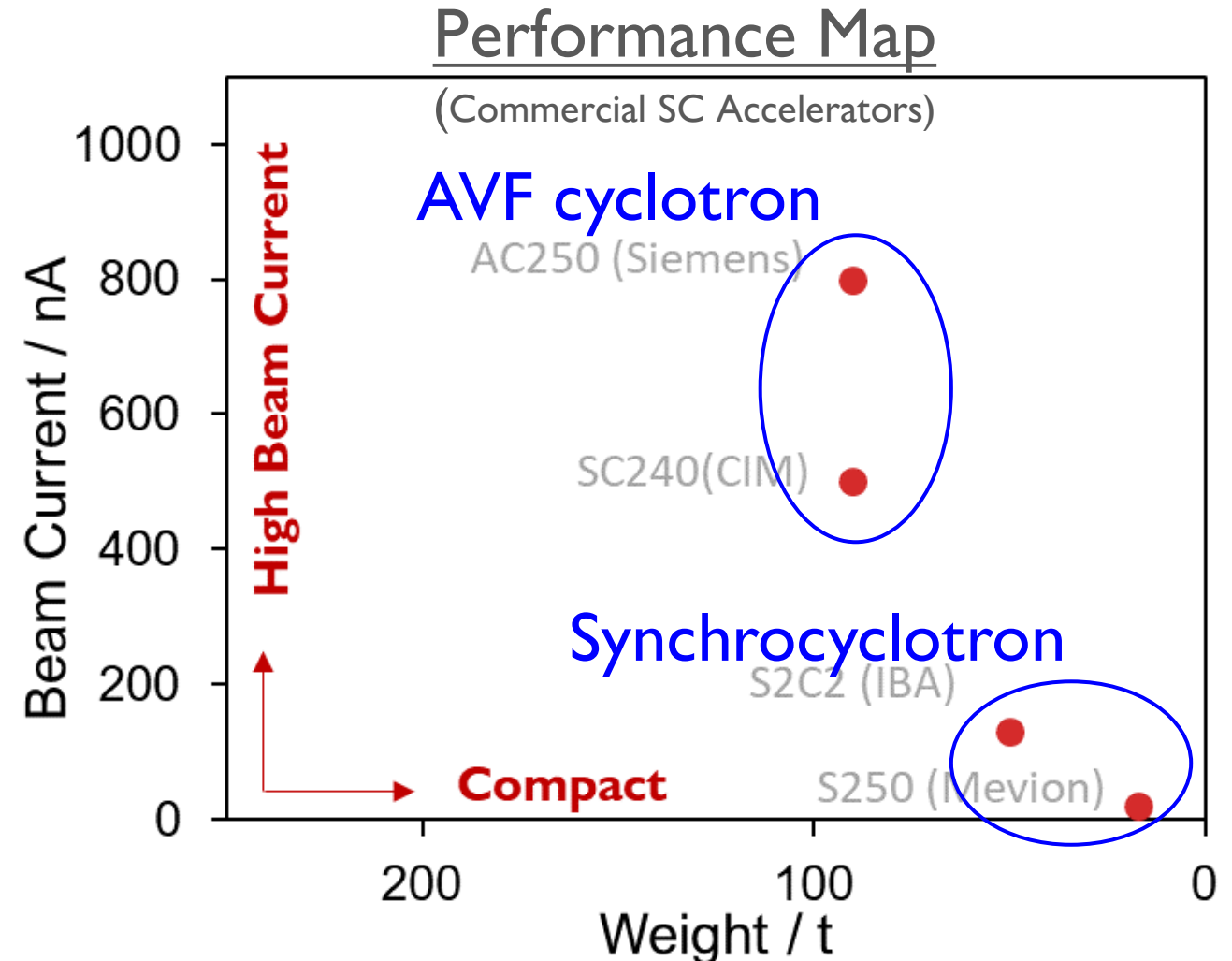


Don't forget:
a high beam current is also required.

- **The focus is on the two needs.**
 - When we plot existing commercial SC accelerators, they form two groups.
 - These groups correspond to different accelerator types.



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 - When we plot existing commercial SC accelerators, they form two groups.
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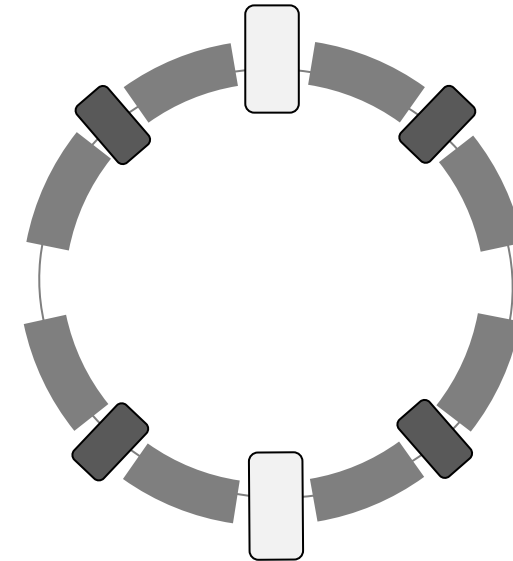
➤ There are three major types of accelerators.

Type	Synchrotron	Synchrocyclotron	AVF cyclotron
Magnetic Field	Varying	Fixed	Fixed
RF Frequency	Varying	Varying	Fixed
Superconducting type	Does not exist	Exist	Exist
Size	△ >5m	⊙ 1.5-3 m	○ 3-5m
Current	△ 10 ⁻¹ -10 ⁰ nA Pulse (10 ⁻¹ Hz/10 ⁻¹ ~10 ⁰ s)	△ 10 ¹ -10 ² nA Pulse (10 ³ Hz / 10 ⁻⁵ ~10 ⁻⁶ s)	⊙ 10 ² -10 ³ nA Continuous

Type	Synchrotron
Magnetic Field	Varying
RF Frequency	Varying
Superconducting type	Does not exist
Size	△ >5m
Current	△ 10^{-1} - 10^0 nA Pulse (10^{-1} Hz/ 10^{-1} ~ 10^0 s)

The advantage of a synchrotron is that the accelerator itself can change the energy (no degrader required).

Synchrotrons maintain the orbit by varying both the magnetic field and the RF frequency.



- Synchrotrons are widely used in HEP.
- There are **no SC synchrotrons** for PT.
- They have **low beam current**.

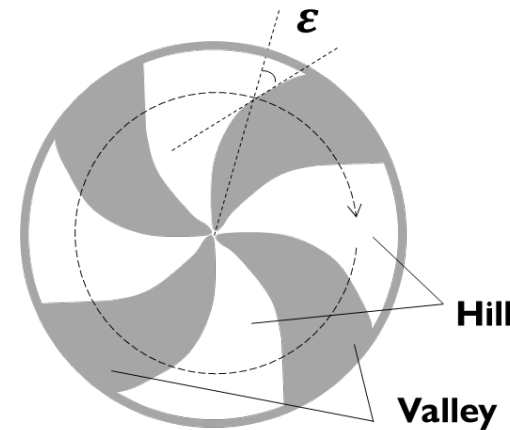
Type	Synchrocyclotron
Magnetic Field	Fixed
RF Frequency	Varying
Superconducting type	Exist
Size	◎ 1.5-3 m
Current	△ 10 ¹ -10 ² nA Pulse (10 ³ Hz / 10 ⁻⁵ ~10 ⁻⁶ s)

Synchrocyclotrons modulate the RF frequency but fix the magnetic field.

- They can be miniaturized by adopting SC coils. They are highly compact.
- They have **low beam current**.

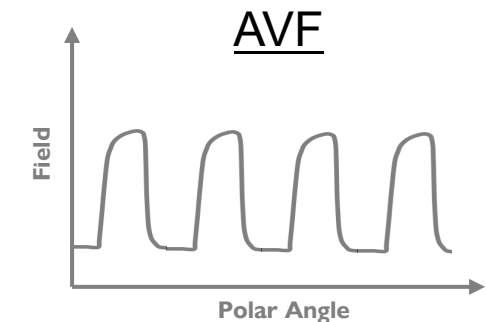
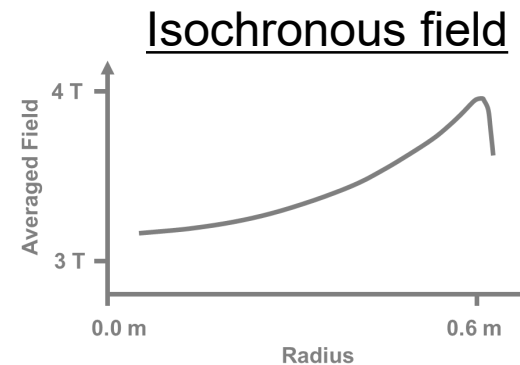
Type	AVF cyclotron
Magnetic Field	Fixed
RF Frequency	Fixed
Superconducting type	Exist
Size	○ 3-5m
Current	⊙ 10 ² -10 ³ nA Continuous

➤ Magnetic field distribution is complex for beam stability.



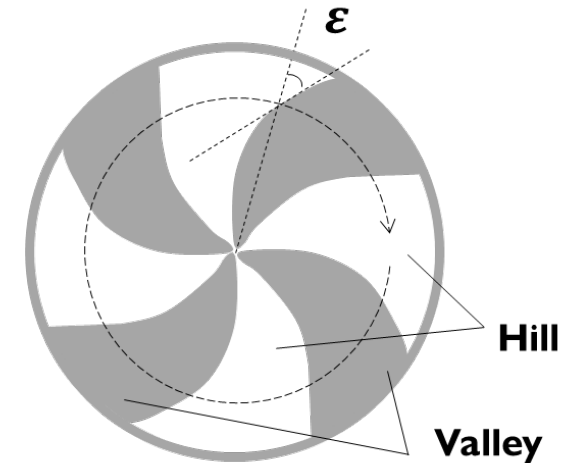
➤ **Isochronous field** is formed, and the magnetic field increases with radius.

➤ **Azimuthally Varying Field (AVF)** is formed with a hill and valley structure.



Type	AVF cyclotron
Magnetic Field	Fixed
RF Frequency	Fixed
Superconducting type	Exist
Size	○ 3-5m
Current	◎ 10 ² -10 ³ nA Continuous

- AVF cyclotrons fix both the magnetic field, and the RF frequency.



- They **can be miniaturized** by adopting SC coils.
- They can generate **a high beam current**, because they can produce a continuous beam.

Type	Synchrotron	Synchrocyclotron	AVF cyclotron
Magnetic Field	Varying	Fixed	Fixed
RF Frequency	Varying	Varying	Fixed
Superconducting type	Does not exist	Exist	Exist
Size	△ >5m	⊙ 1.5-3 m	○ 3-5m
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The “**AVF cyclotron**” is unique in its ability to be both compact and high-current.

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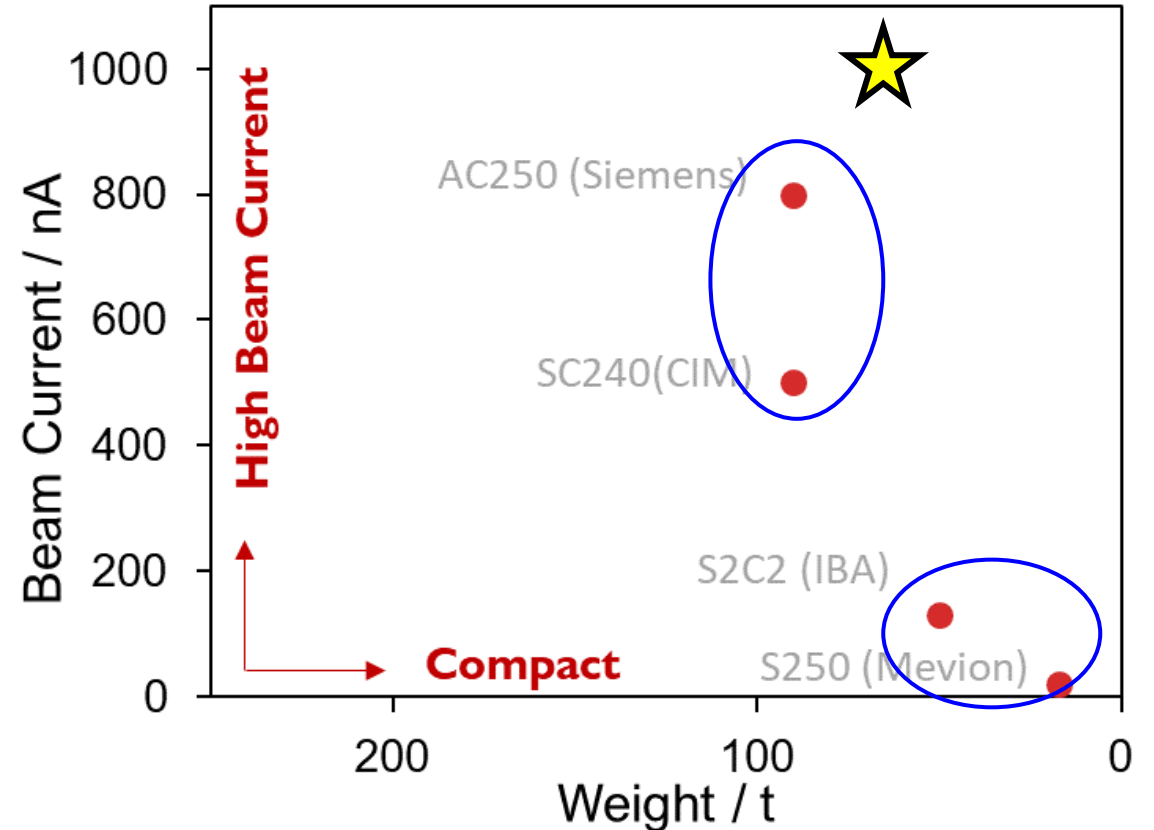
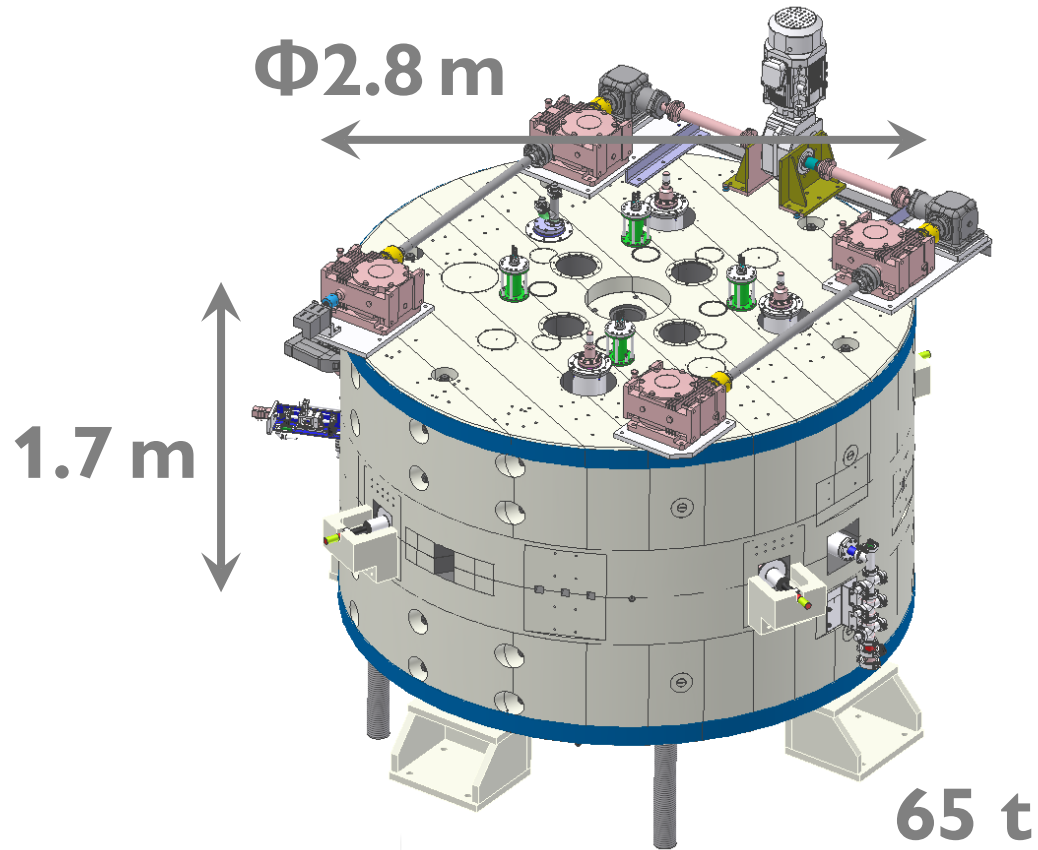
03

“SC230” Compact High-Beam-Current Cyclotron



SC230 – Compact and High Current Cyclotron –

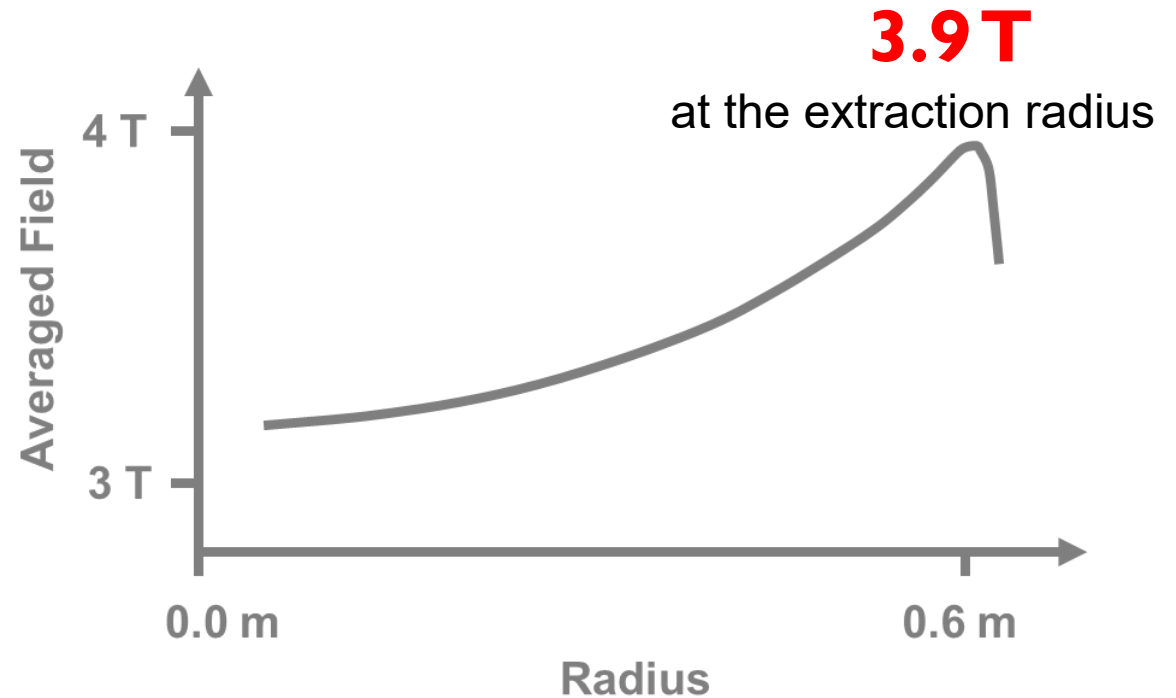
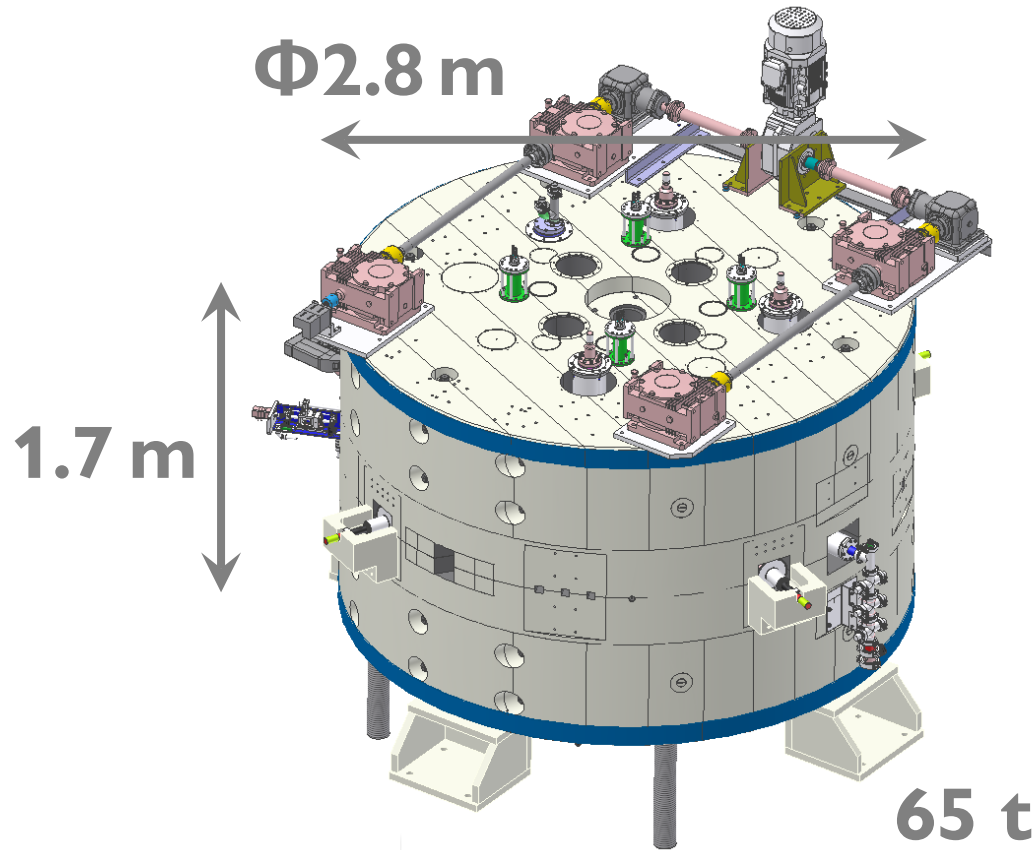
- Type: **AVF cyclotron** – to achieve both compactness and high beam current
- Weight: **65 tons** – the smallest AVF cyclotron for PT
- Max beam current: **1 μA** – the highest among all accelerators for PT



SC230 – Compact and High Current Cyclotron –

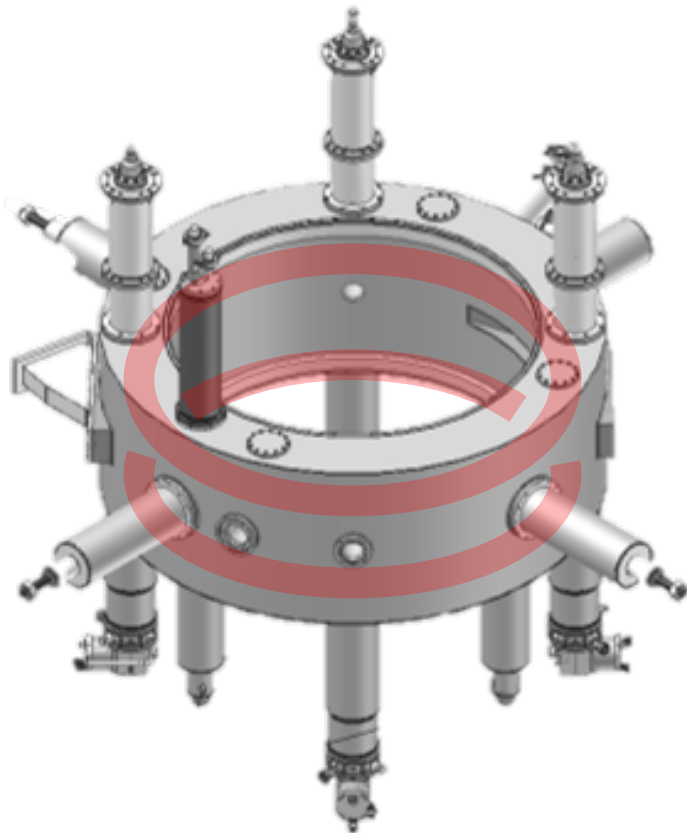
AP1-01-INV Yuta Ebara
Tue. Dec 2, 2025

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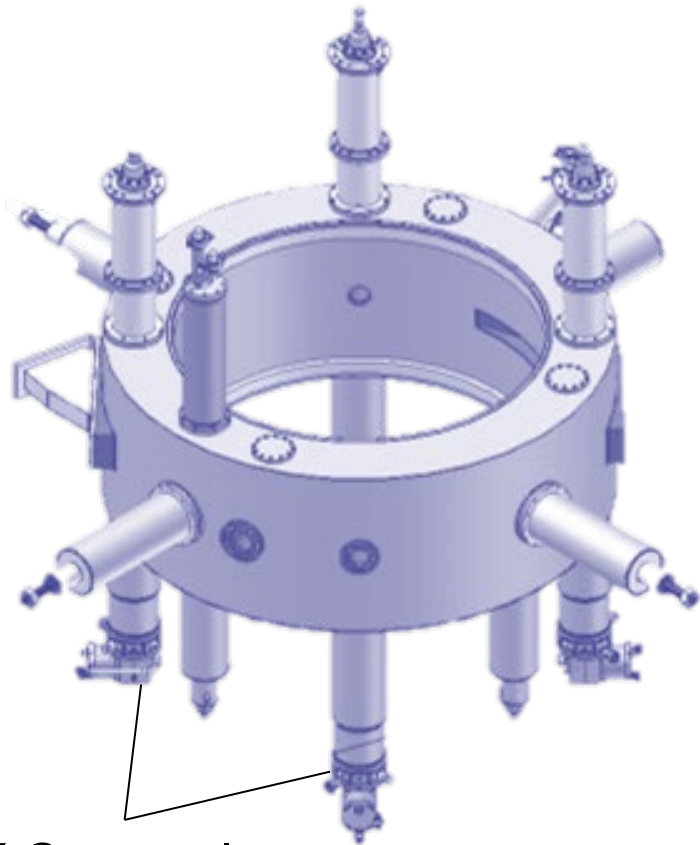
➤ NbTi superconducting coils

Cryostat for SC230



Parameters		Specifications
SC wire	Material	NbTi/OFC
	Thickness	2.10 mm
	Width	3.40 mm
Coil	Configuration	Two circular coils with axial gap
	Diameter	1380/ 1580 mm (Inner/ Outer)
	Number of turns	2208 Turns/Coil
Coil current		~ 440 A (Max. 488 A)
Stored energy		5.3 MJ

- **Cooled by four cryocoolers** (no liquid helium required)
- Coils are cooled to temperatures **below 5 K** ($T_c \sim 7.4$ K)



4K Cryocoolers



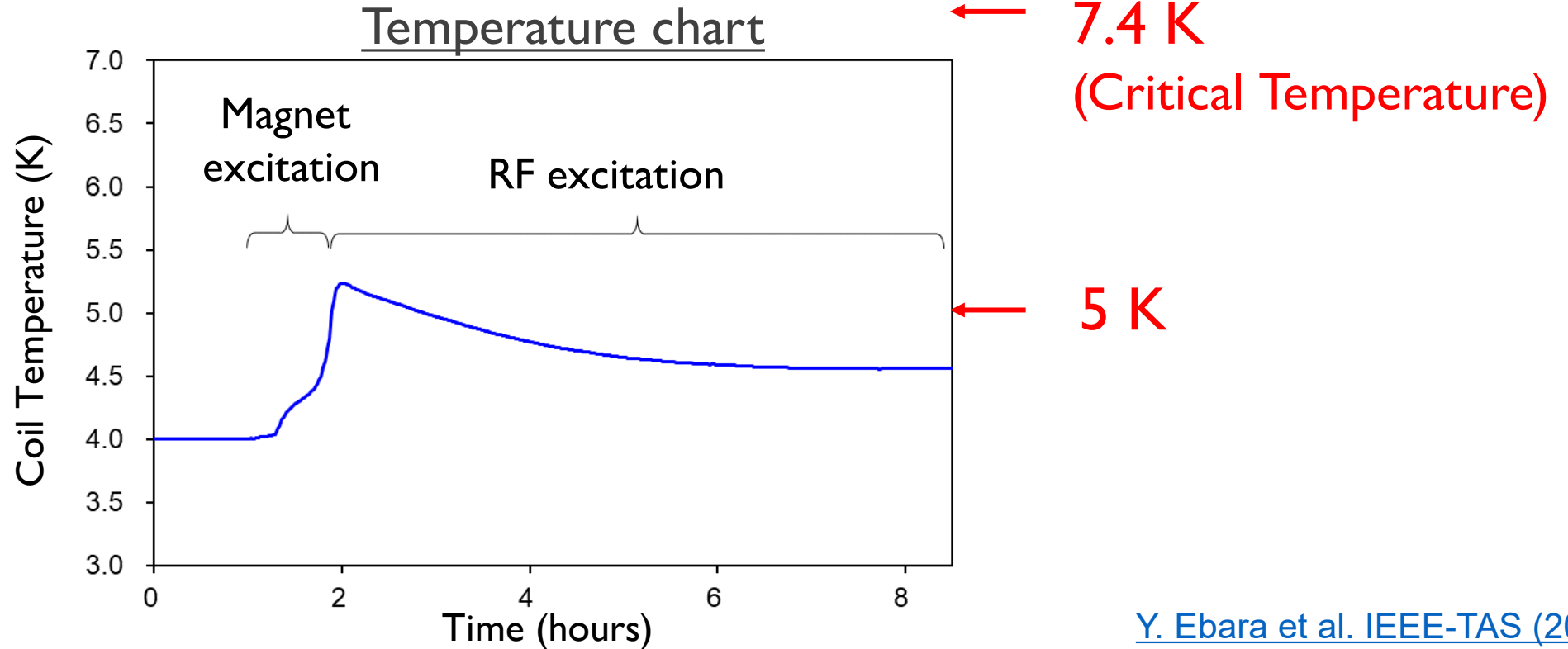
Parameters		Specifications
Coil cooling	method	Conduction cooling
	cryocooler	Four 4K-GM cryocoolers
Coil temperature		< 5 K
Cooling time from RT		14 days
Recovery time from quench		17 hours

- **Cooled by four cryocoolers** (no liquid helium required)
- Coils are cooled to **below 5 K** (The critical temperature : 7.4 K)

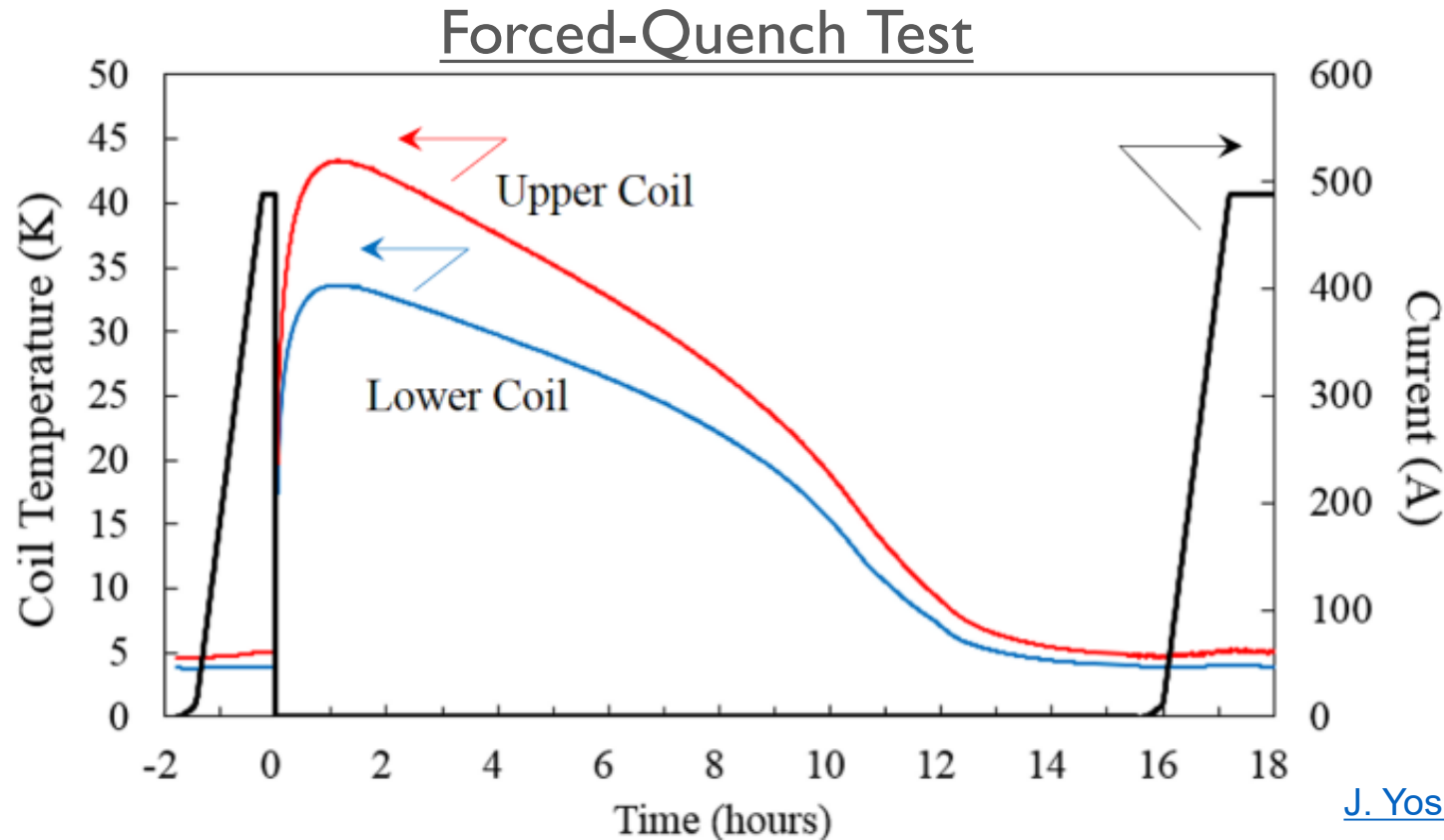


➤ Coil temperature during operation

- Temporary temperature rise occurred during excitation.
- Even during RF operation, temperature remained below 5 K.



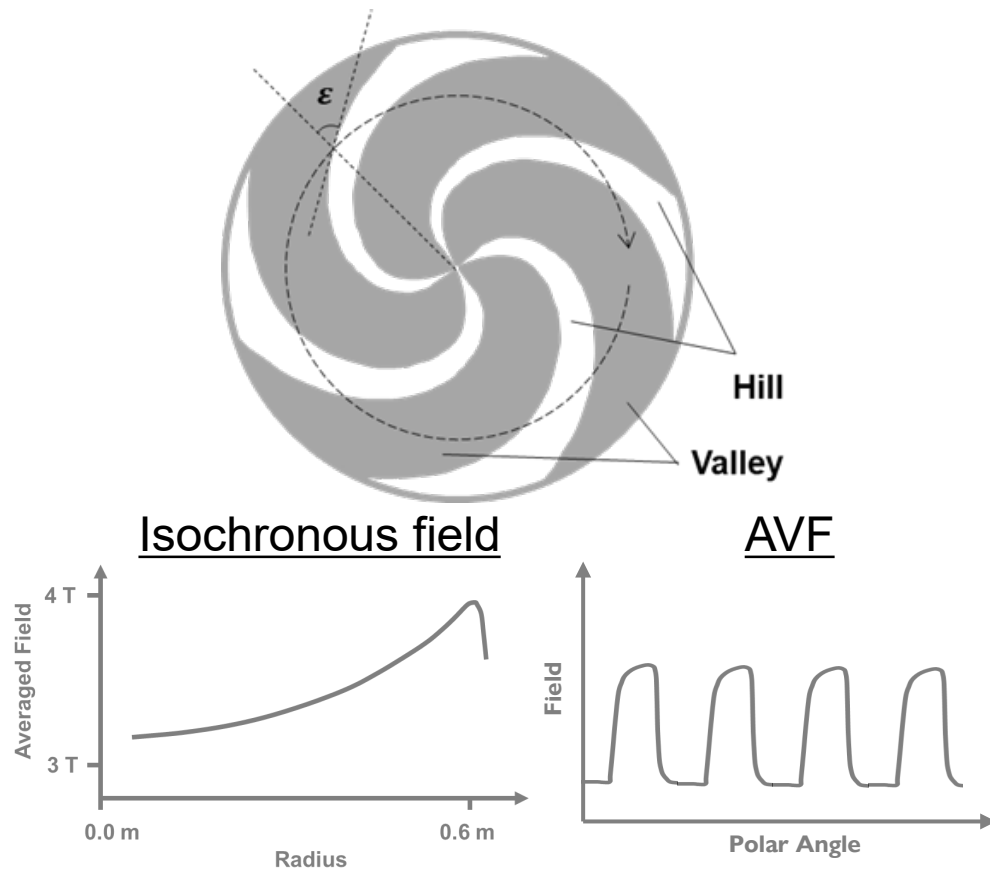
- **Quench detection and protection system.**
 - Detects by balance voltage, protects using external dumper.
 - Forced-quench test confirmed that the system works properly.



[J. Yoshida et al. IEEE-TAS \(2019\)](#)

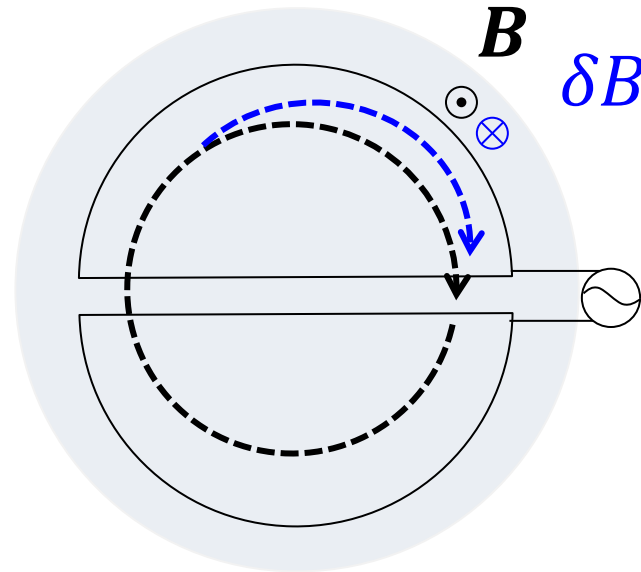
- AVF cyclotrons use complex pole shapes for beam stability

Inside structure of SC230



[Y. Ebara et al. NIM A \(2023\)](#)

- Accurate field distribution is extremely important.
- Error fields cause orbit shifts, which create phase mismatches between RF and particles.



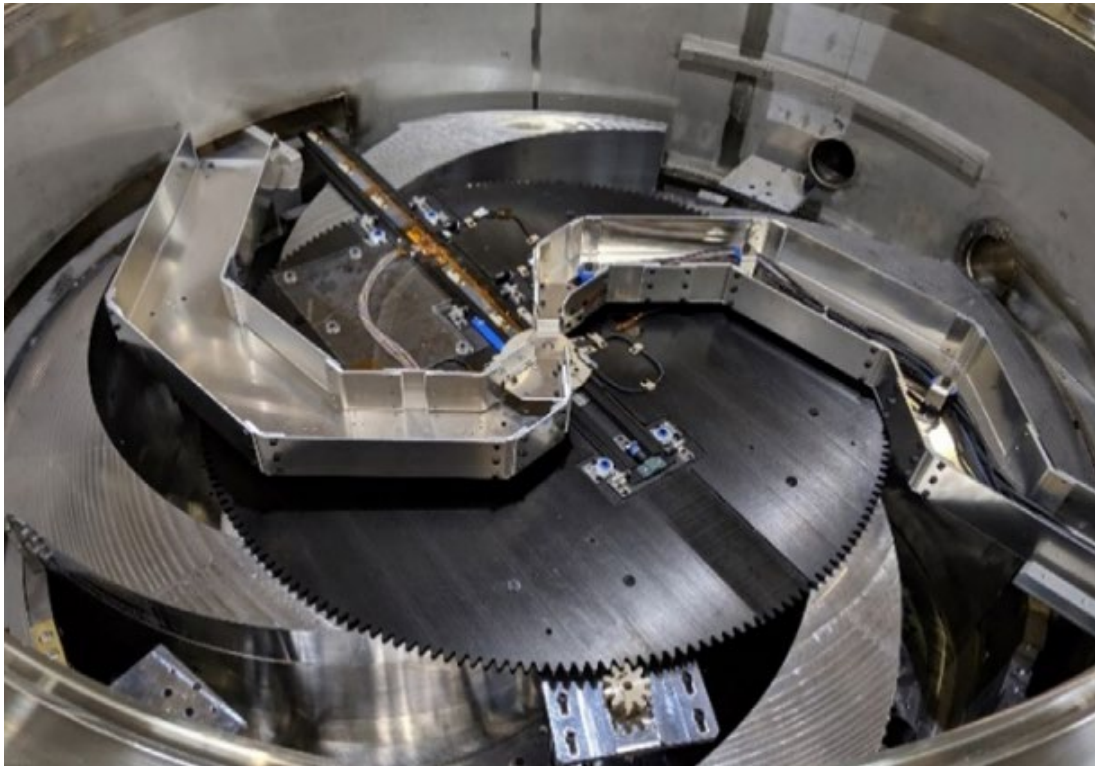
Error fields
→ Orbit shifts
→ Phase shifts

$$\sin(\delta\phi) \sim -\frac{\omega_{\text{RF}}}{V_{\text{acc}}} \int dS \delta B$$

- In AVF cyclotrons, error fields must be less than 100ppm.
For SC230, the allowable error was 50ppm.

➤ Field Mapping

- A mapper was developed to measure the field distribution in high accuracy.



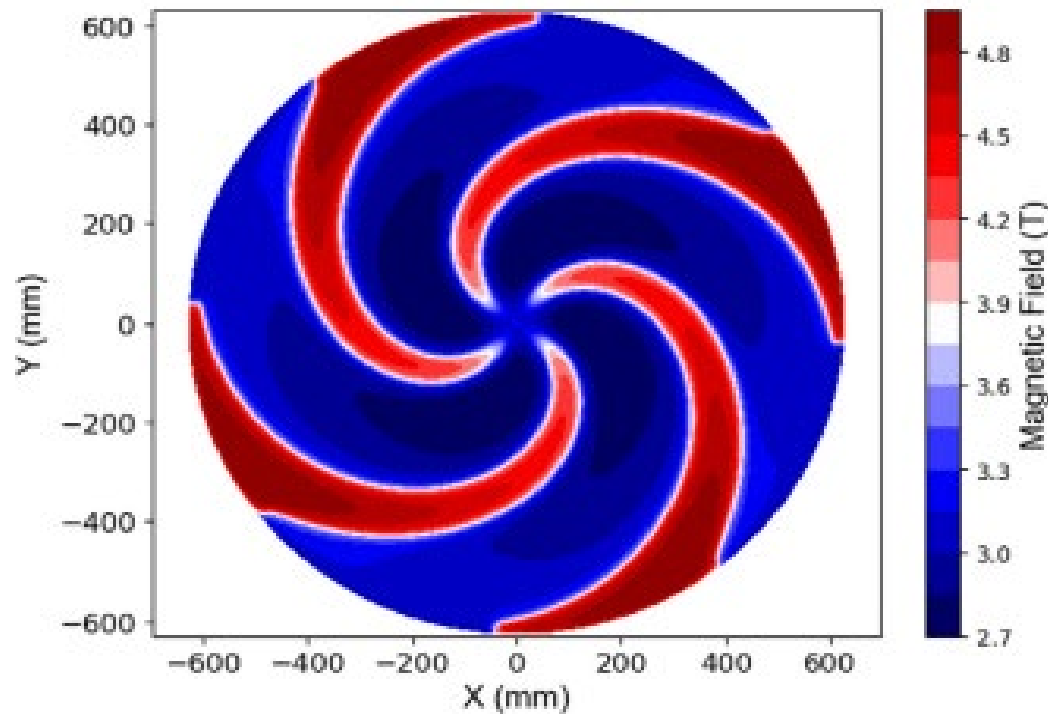
Parameters	Specifications
Sensor type	Hall probes
Number of sensors	6
Type of stages	Linear and rotate stages
Material of stage	CFRP
Actuators	USMs
Measurement points	~52 000
Measurement area	$\phi 1,260$ mm
Measurement time	2.5 hours
Adjustment methods	Pole machining Shimming Coil centering

[Y. Ebara et al. NIM A \(2019\)](#)

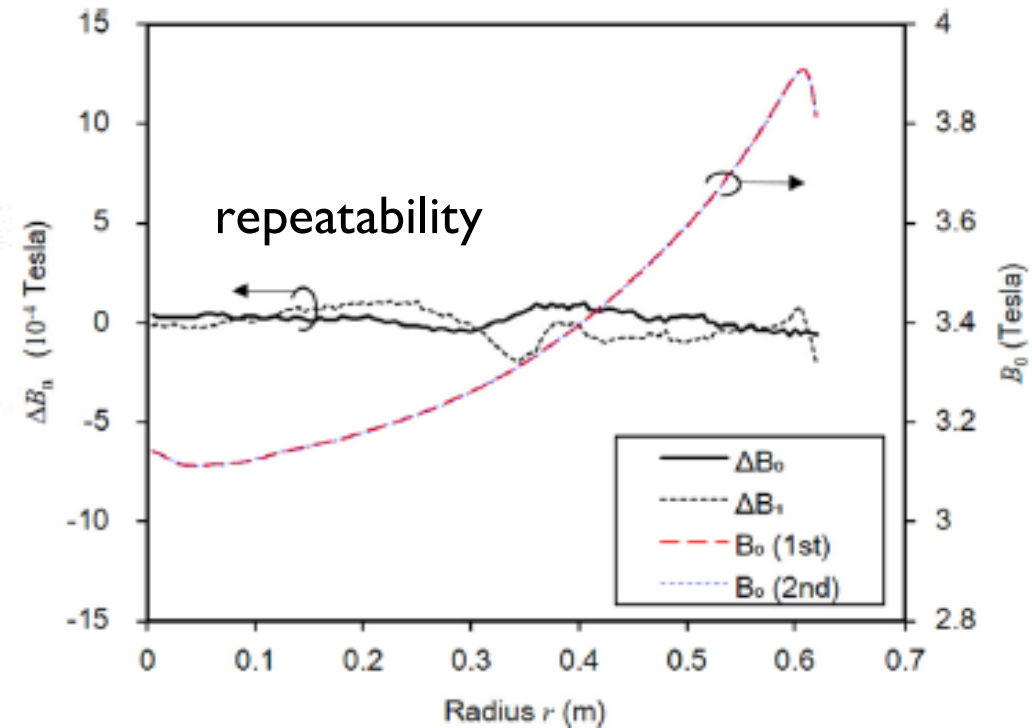
➤ Field Mapping

- A mapper was developed to measure the field distribution in high accuracy.

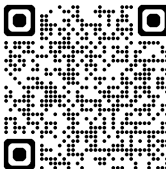
Measured field (2D-map)



Measured Isochronous field



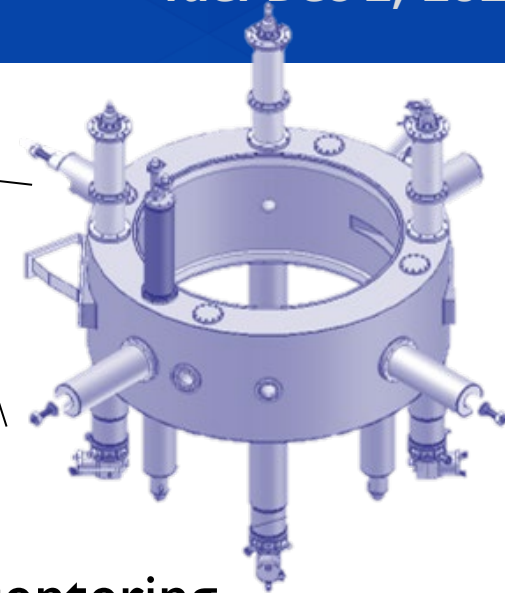
[Y. Ebara et al. NIM A \(2019\)](#)



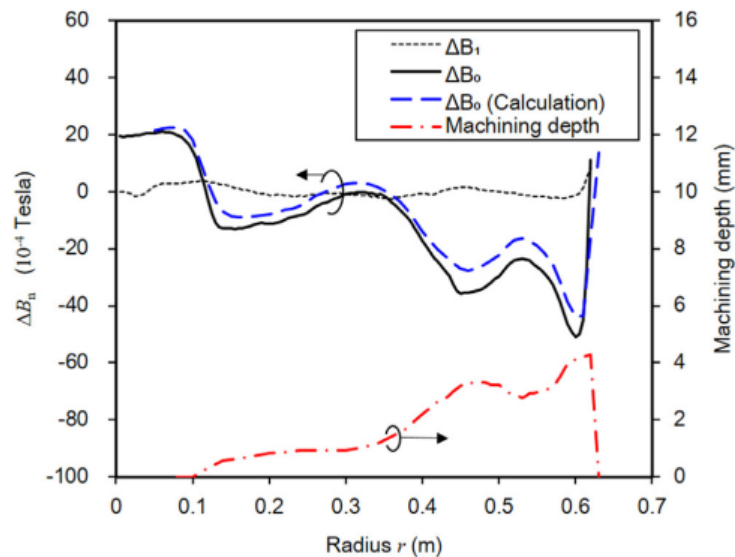
➤ Field Adjustment

- We have three techniques to adjust the field:
 - Pole Machining – for coarse adjustment of B_0
 - Shimming – for fine adjustment of B_0
 - Coil centering – to adjust field harmonics (B_1)

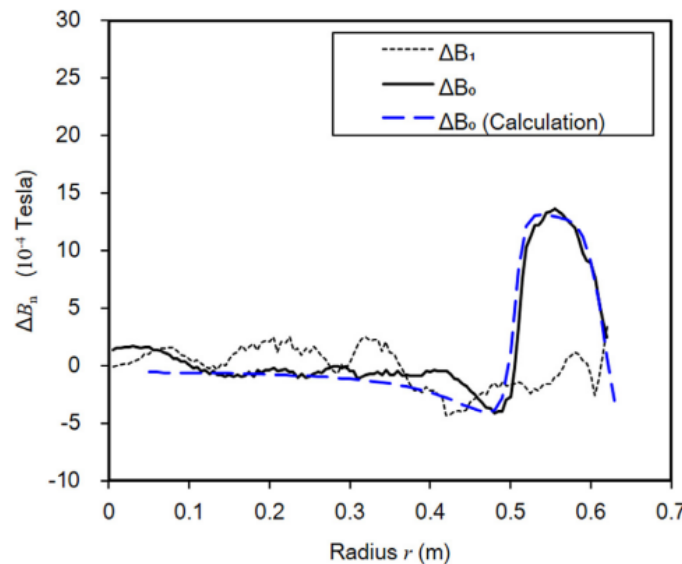
Coil supports



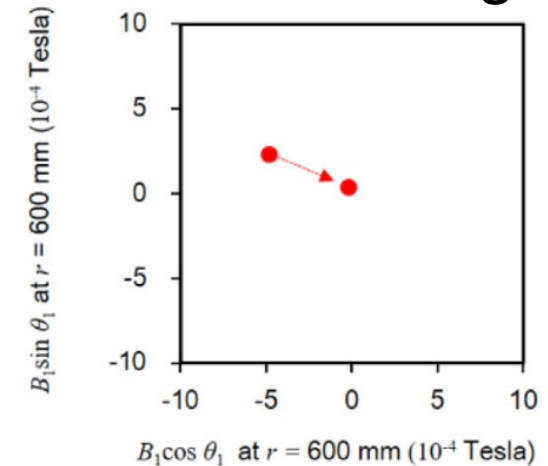
Pole Machining



Shimming



Coil centering



➤ Finally, the field distribution was adjusted as designed.

- SC230 was installed at the new test site.
- Then, commissioning began.

APDC (APplication Development Center)

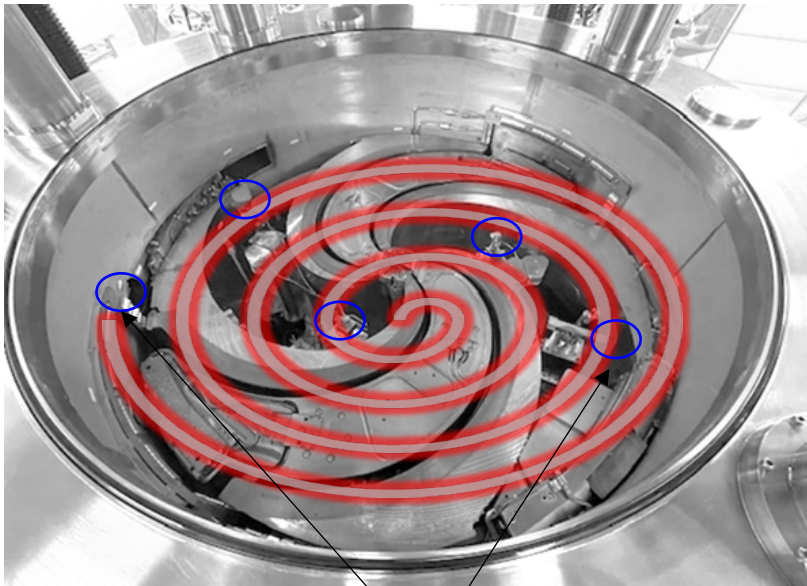


SC230 Installation



- Probes were used to monitor beam conditions.
- Parameters were tuned based on probe measurements.

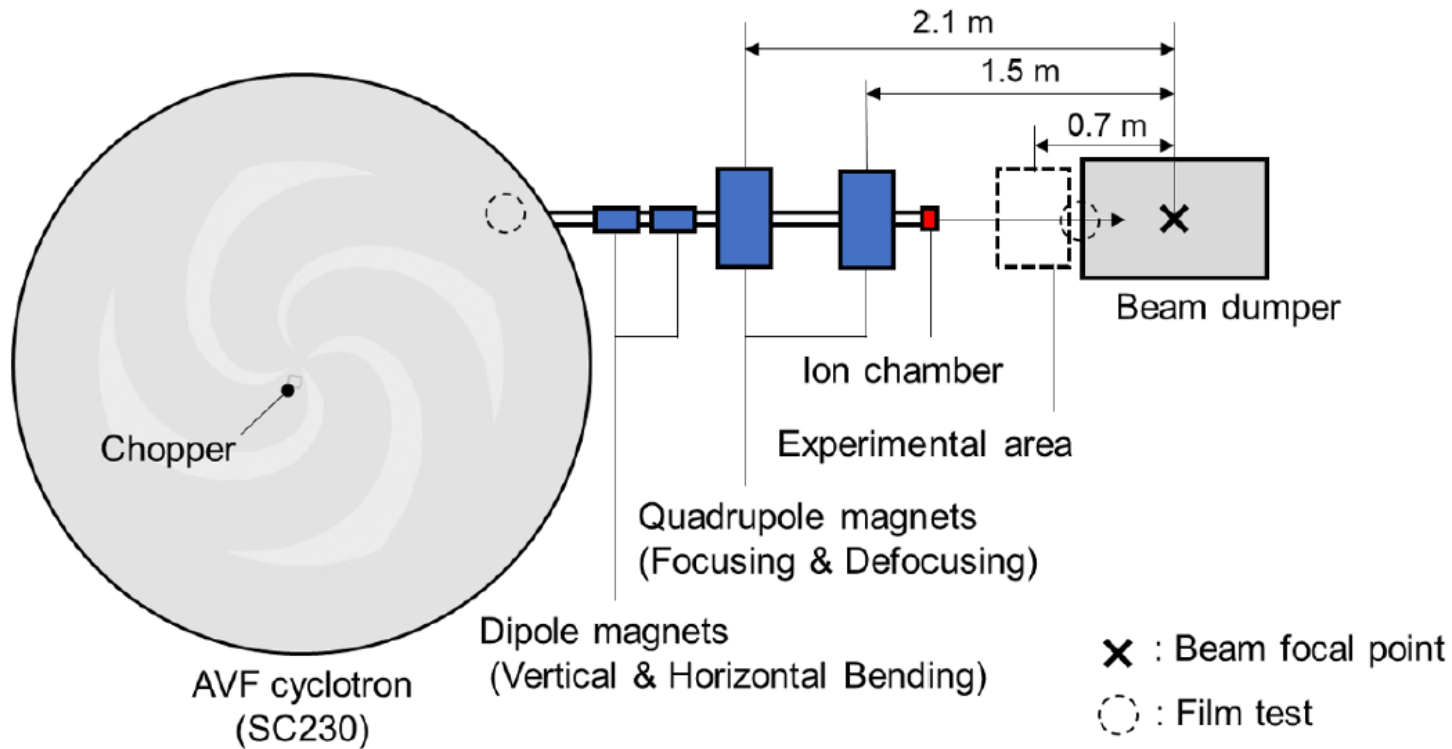
We worked in three shifts, 24 hours a day!



Probes



➤ First beam was observed!

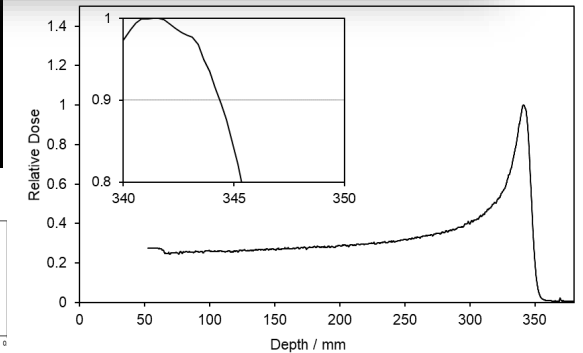
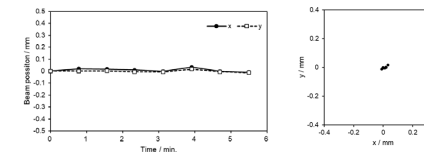
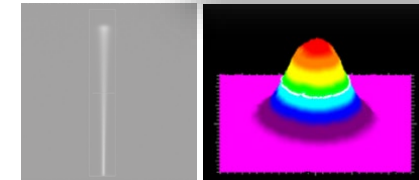
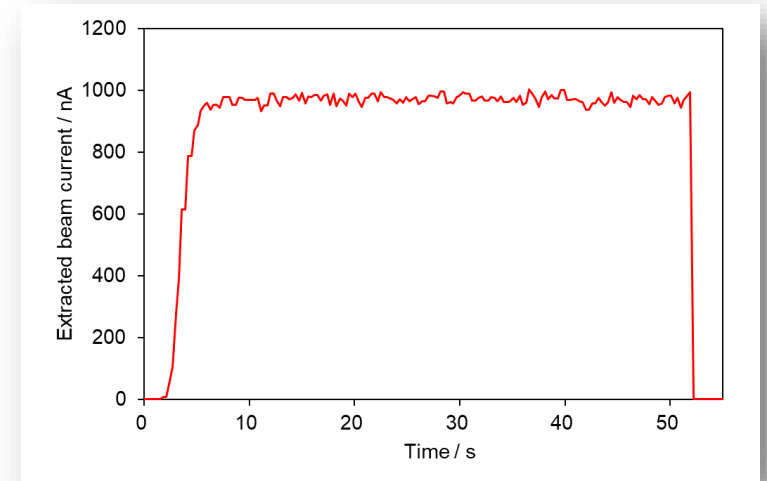


*Beam mark
produced by the extracted beam*

[Y. Ebara et al. NIM A \(2023\)](#)

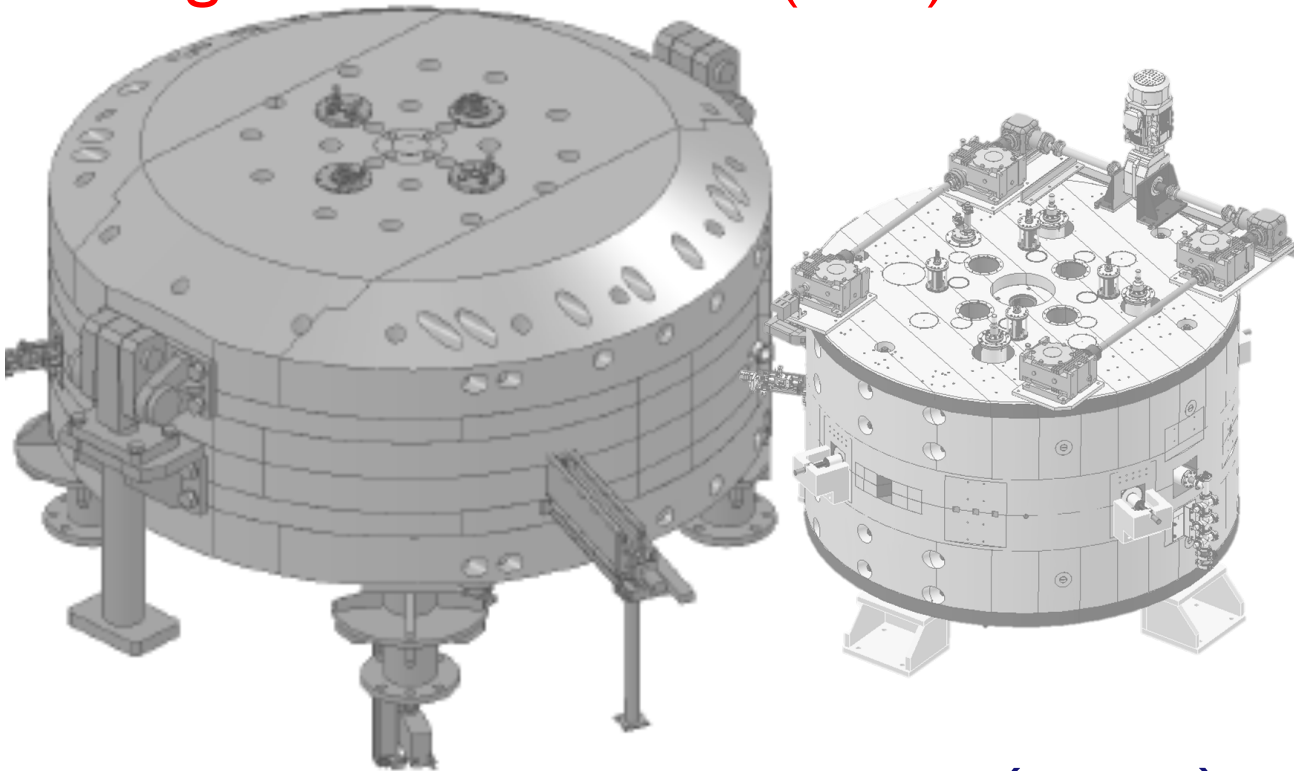
- After extracting the beam, we measured the properties of the beam.
- All beam specifications were successfully met.

Parameters	Specifications	Result	Pass/Fail
Max. beam current	1000 nA	>1000 nA	✓ Pass
Beam energy	233-238 MeV	237 MeV	✓ Pass
Energy repeatability	< 0.2 MeV	0.18 MeV	✓ Pass
Extraction efficiency	≥ 60%	67%	✓ Pass
Min. controllable beam current	< 1 nA	< 1nA	✓ Pass
Ripple current	≤ 2 % (1σ)	0.6%	✓ Pass
Beam current stability	≤ 1 % (1σ) for 2 min.	1.0%	✓ Pass
Beam responsivity	≤ 50 μs	~30 us	✓ Pass
Beam position stability	< ±0.1 mm for 2 min.	< ±0.05 mm	✓ Pass
RMS emittance	< 2.2 μm (x) < 1.4 μm (y)	1.4 μm (x) 0.7 μm (y)	✓ Pass
Total power consumption	< 200 kW	193 kW	✓ Pass



[Y. Ebara et al. NIM A \(2023\)](#)

- **More compact (x0.3)** – Due to the superconducting coils
- **Lower power consumption (x0.6)** – Due to reduced losses in the coils
- **Higher beam current (x3.3)** – Due to the adoption of AVF type & upgrading of key components. (e.g., better thermal tolerance)



NC model (P235)

SC model (SC230)

Parameters	NC model	SC model
Yoke weight	220 t	65 t
Power consumption	330 kW	< 200 kW
Maximum beam current	300 nA	1000 nA

[Y. Ebara et al. NIM A \(2023\)](#)



Two additional topics related to cryogenics and superconductivity.

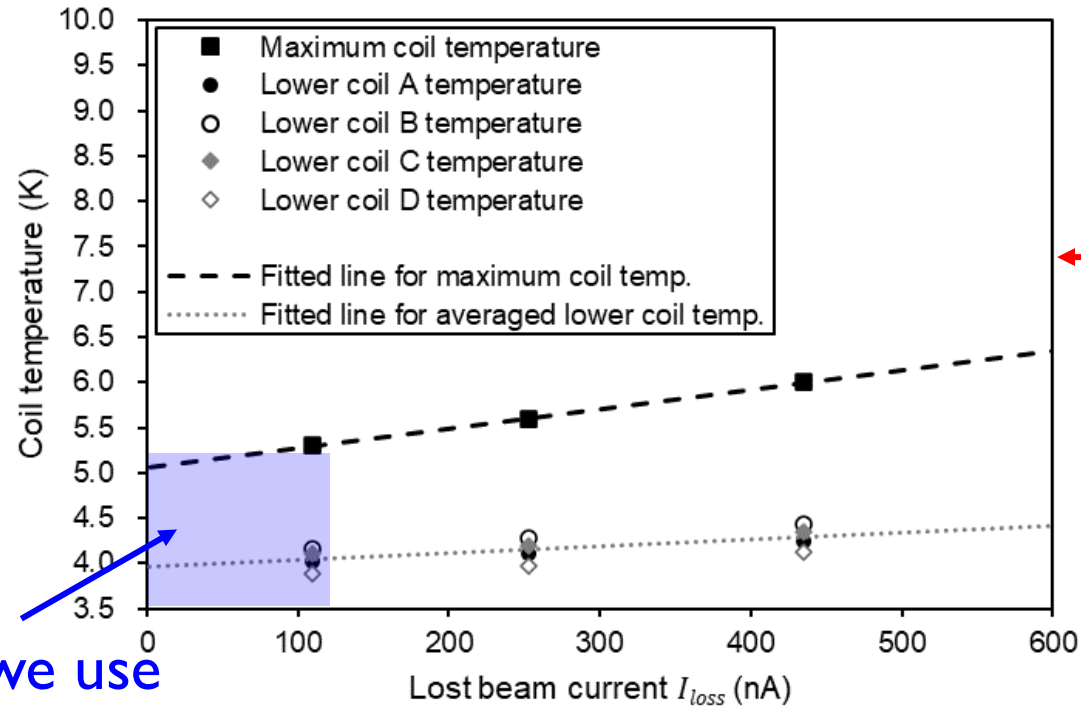
- There is a heat load specific to accelerators.
- **Beam loss** generates neutrons, which deposit heat in the coils.

Coil Temperature vs Beam Loss

Beam loss

→ Neutron generation

→ Coil heating



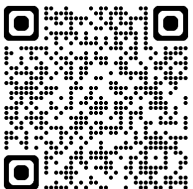
The area we use

← 7.4 K
(Critical Temperature)

Heat load: 2.3 W/ μ A

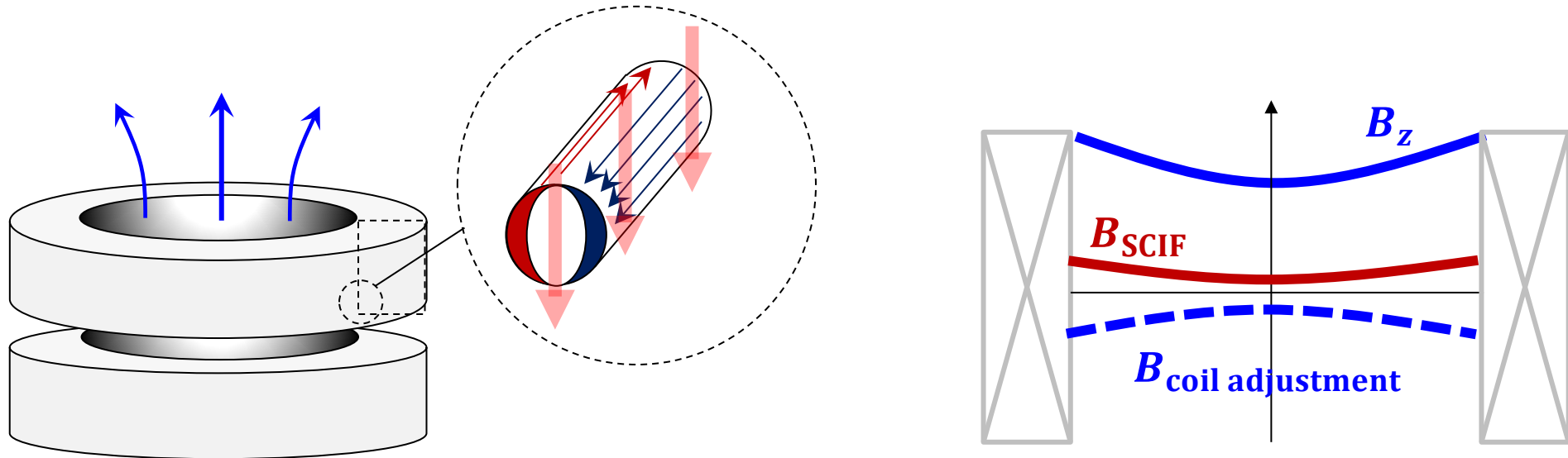
Please note that the driving duties are small.

[Y. Ebara et al. IEEE-TAS \(2023\)](#)



➤ SCIF: Screening Current Induced Field

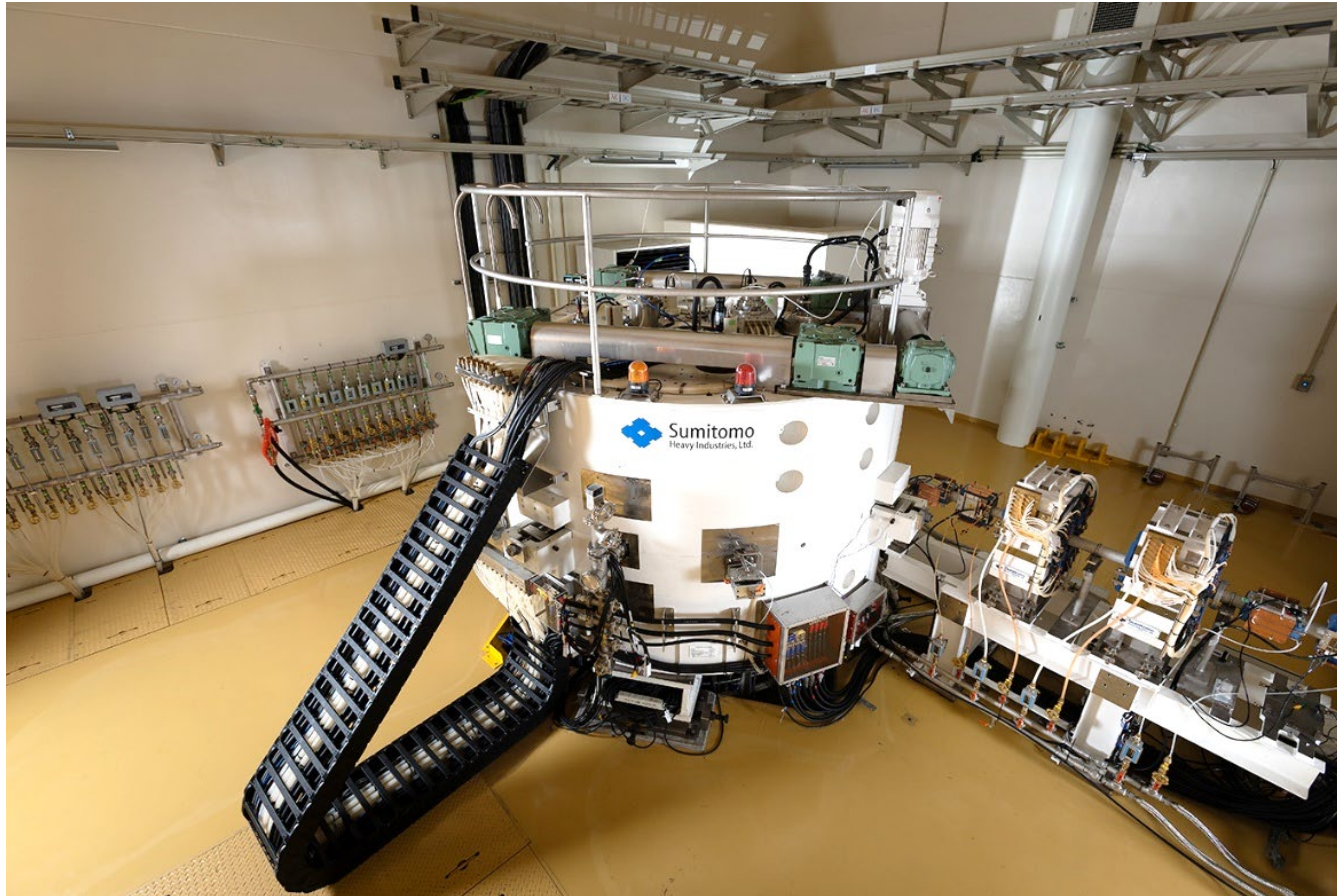
- Screening currents flow in the wires of superconducting coils.
- They have magnetic moments that **make error fields**.
- We must consider the effect of SCIF, even if the superconductor is LTS.



- SCIF distribution is similar to the distribution of the coil.
- The effect may be compensated by coil current.

- **SCIF-effect can be compensated by coil current correction**
 - Simulation showed that 0.05 A of correction current can compensate the effect of SCIF.
 - In experiments, the optimal coil current differed by 0.05 A between excitation and de-excitation.
 - The simulation and experimental results were in good agreement.
- **We confirmed that the SCIF effect does not pose a critical issue for operation.**

- **The development was completed.**
- **The system including SC230 has become commercially available.**

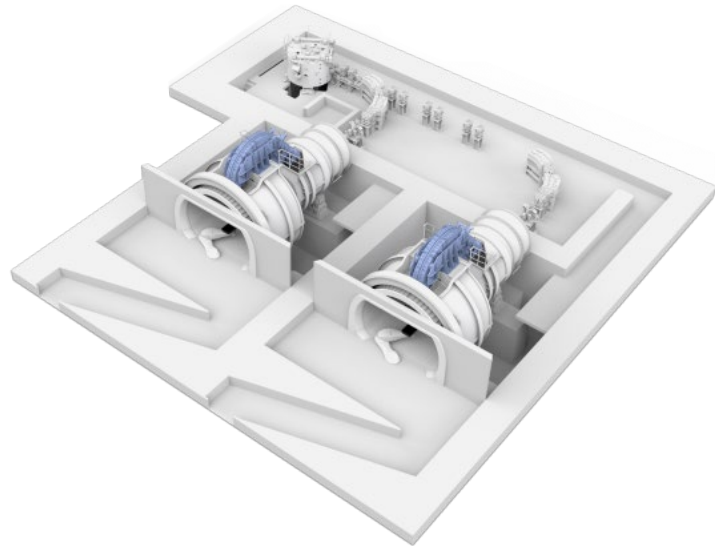


[Y. Ebara et al. NIM A \(2023\)](#)

- Proton therapy is radiotherapy that minimizes damage to healthy tissues.
- There are two major development needs;
 - System miniaturization
 - High beam current
- SC230 was developed.
 - AVF cyclotron with cryogen-free superconducting magnet
 - It is compact (65 t) and has high beam current (up to $1\mu\text{A}$).

— Products —

SHI receives first order for next-generation proton therapy system from Taichung Veterans General Hospital



[Taichung Veterans General Hospital]
Taichung Veterans General Hospital is a national hospital located in central Taiwan and provides safe and high-quality medical services with new medical technologies and outstanding talents. Taichung Veterans General Hospital plans to conduct research on new treatment technologies, such as FLASH, in collaboration with SHI.

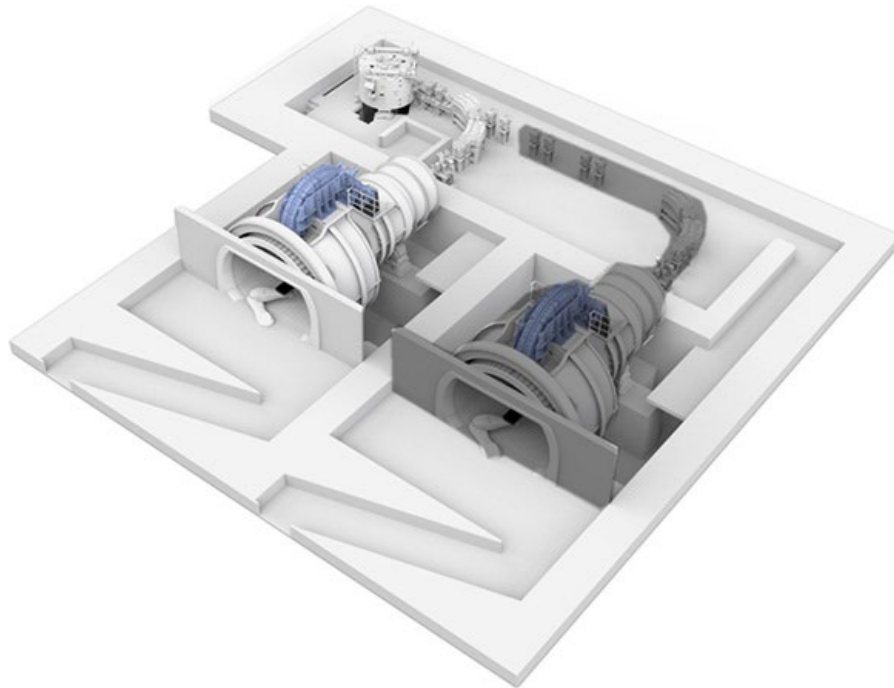
— Products —

Installation of a Next-generation Proton Therapy System Begins at Taichung Veterans General Hospital in Taiwan



— Products —

Order Received for Proton Therapy System for Bangkok Hospital—
First Order by a Southeast Asian Medical Institution, a Step Toward
Wider Adoption of Cutting-Edge Cancer Therapy —



[Wattanosoth Cancer Hospital]

Established in 2005, the hospital is a specialized cancer center within Bangkok Hospital Headquarter. The hospital is dedicated to delivering comprehensive cancer care through a multidisciplinary team of specialists, supported by advanced diagnostic tools and cutting-edge medical technologies.

[Bangkok Dusit Medical Services PCL]

This is the largest private hospital operating company in the Kingdom of Thailand. The company operates about 60 hospitals in Thailand, service a wide range of medical specialties, and provides international-standard medical services.



All forward-looking statements regarding the company's future performance are based on information currently available to Sumitomo Heavy Industries and determined subjectively. Future performance is not guaranteed and all information related to future performance contained herein is subject to changes in business environments.