Superconducting rotating gantry for carbon therapy at HIMAC

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NIRS HIMAC

Outline

- Introduction
- Gantry development
  - Design
  - Construction
  - Beam commissioning
- Future plans
- Summary

Cancer Treatment

1. Surgery
2. Chemotherapy
3. Radiotherapy
   - Advantage: no pain, no infection
   - Kinds of radiation
     - X-rays (γ-rays)
     - Protons
     - Carbon ions

     (particle beams)
   - Expectation for (particle) radiotherapy
     - QOL (Quality Of Life) after the treatment
     - Small physical burden (good for aged people)
     - Effective for radiation-resistant tumors (Carbon-ion radiotherapy)

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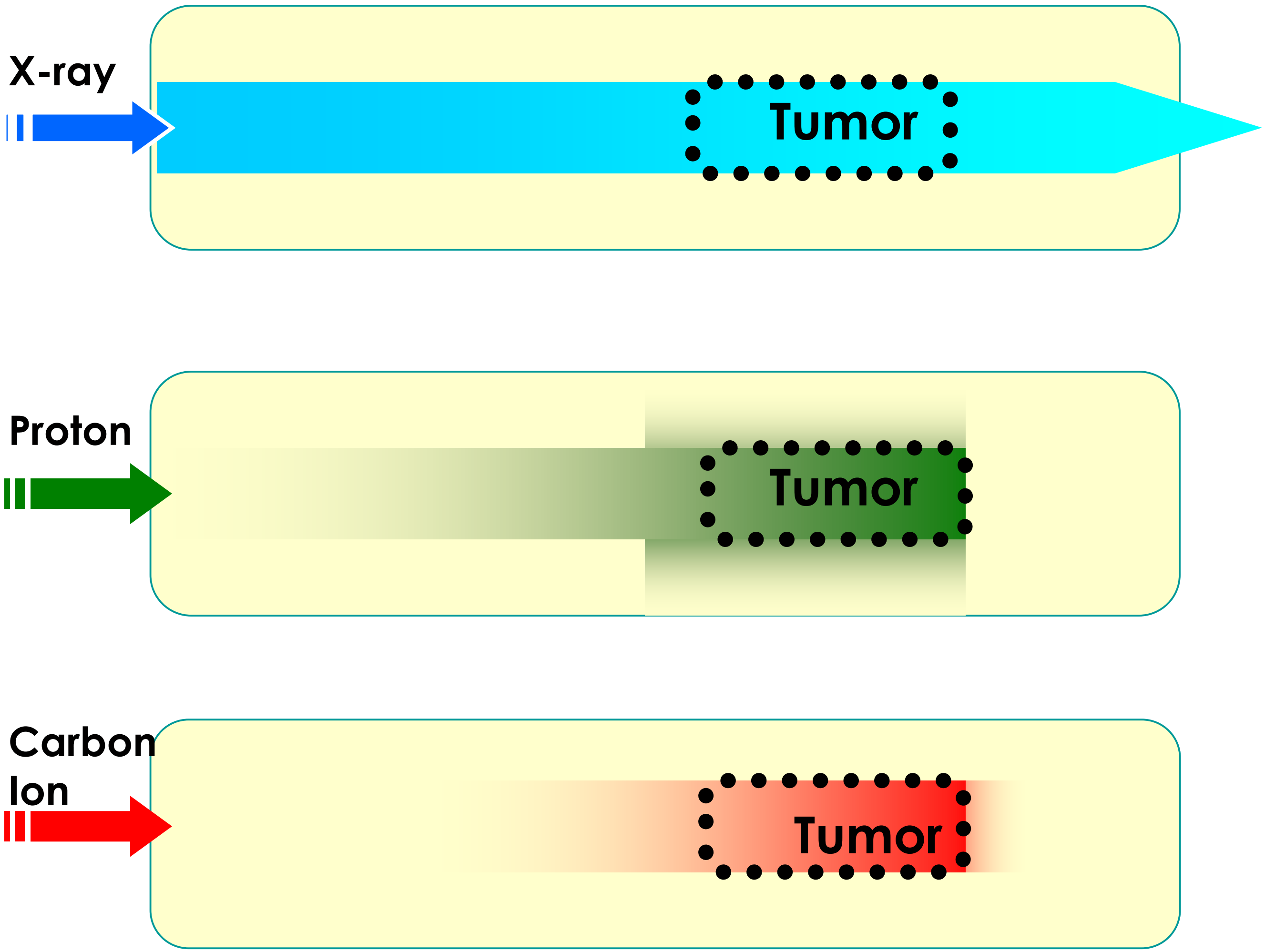
Comparison between X-ray and particle therapy



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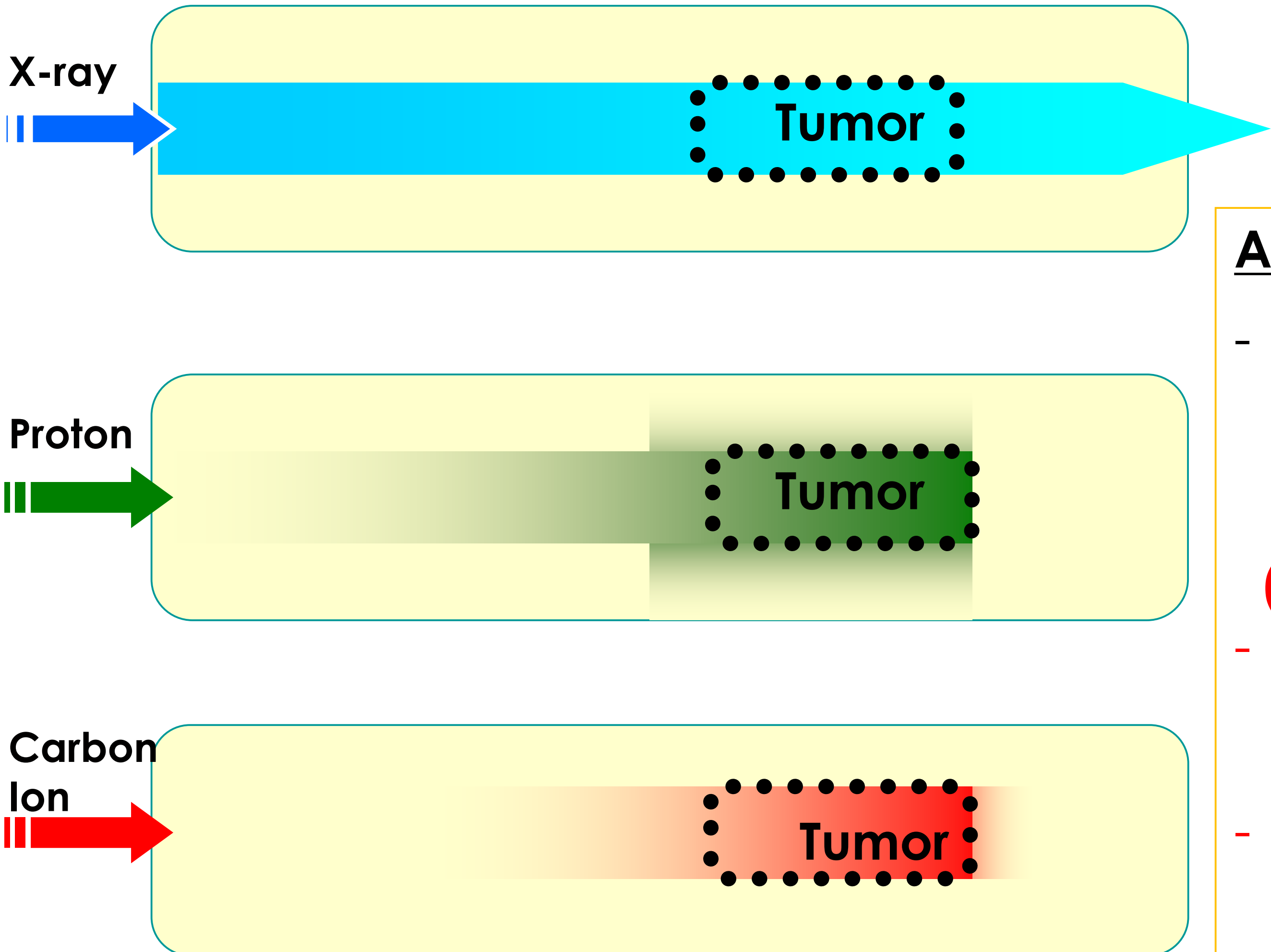
Comparison between X-ray and particle therapy



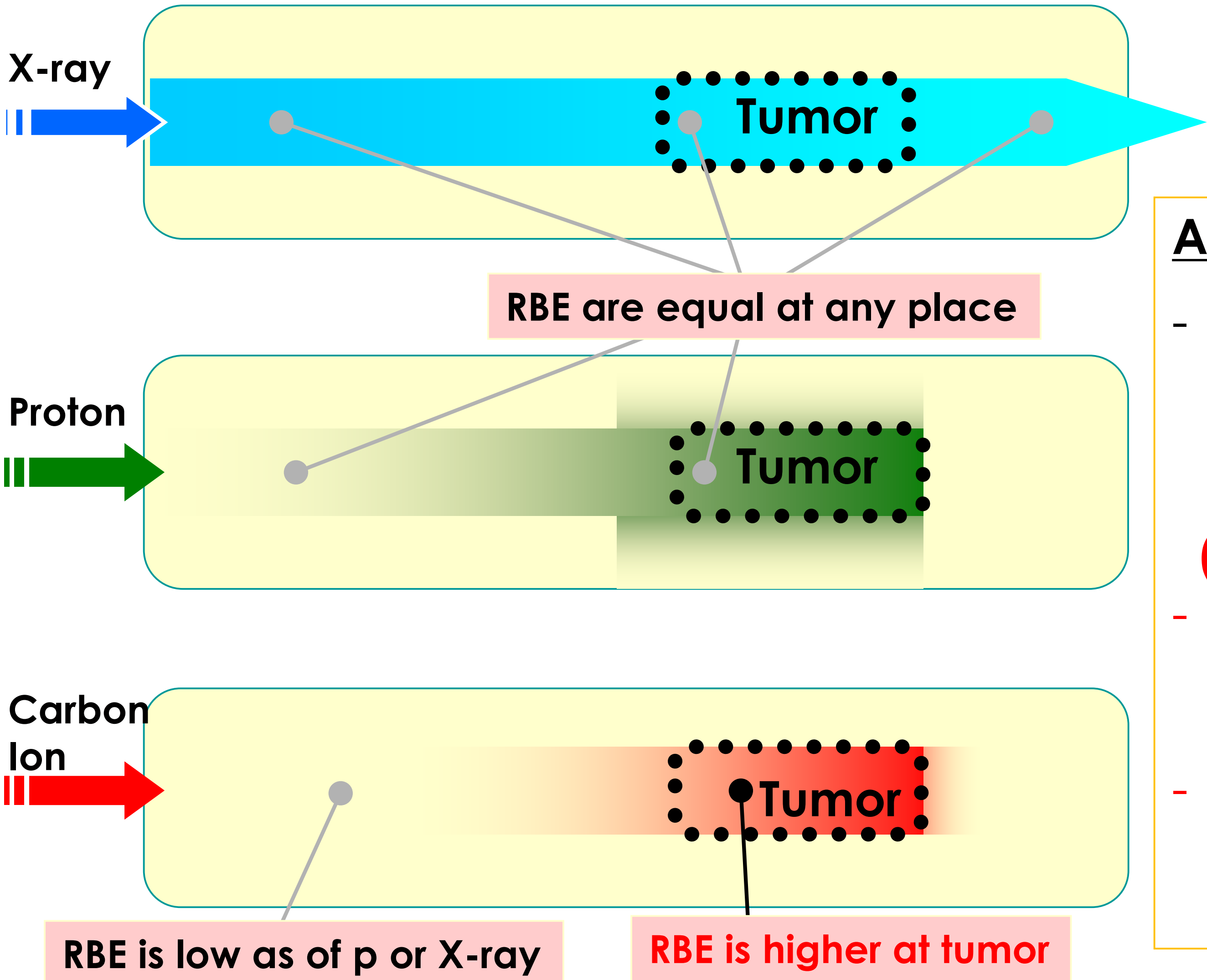
Advantage of ion therapy

- Physical dose can be concentrated due to Bragg peak

(Carbon therapy)

- Lower multiple scattering in the lateral direction
- RBE (Relative Biological Effectiveness) is 2~3 times higher around the tumor

Comparison between X-ray and particle therapy



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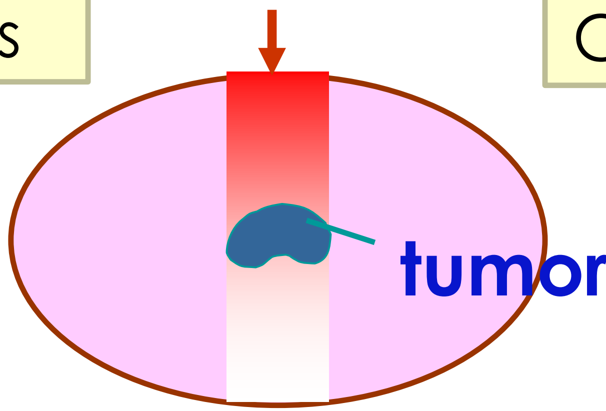
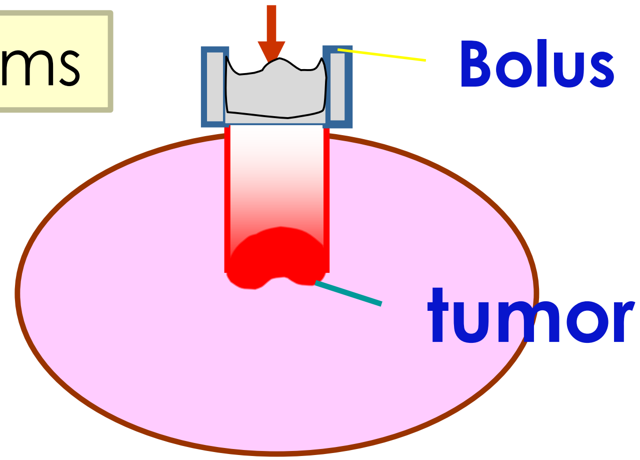
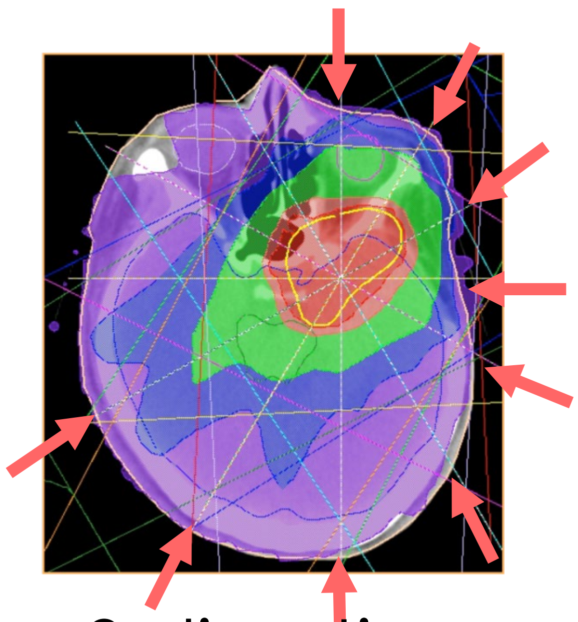
Dose distribution of X-ray and Carbon beams

X-rays

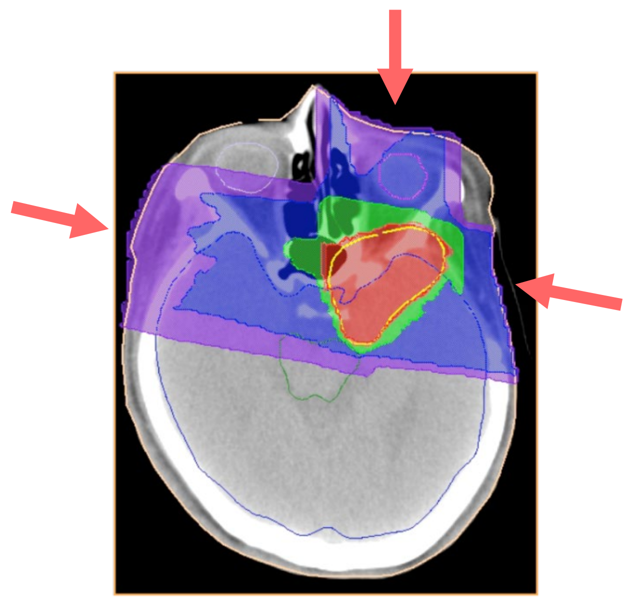


Carbon beams





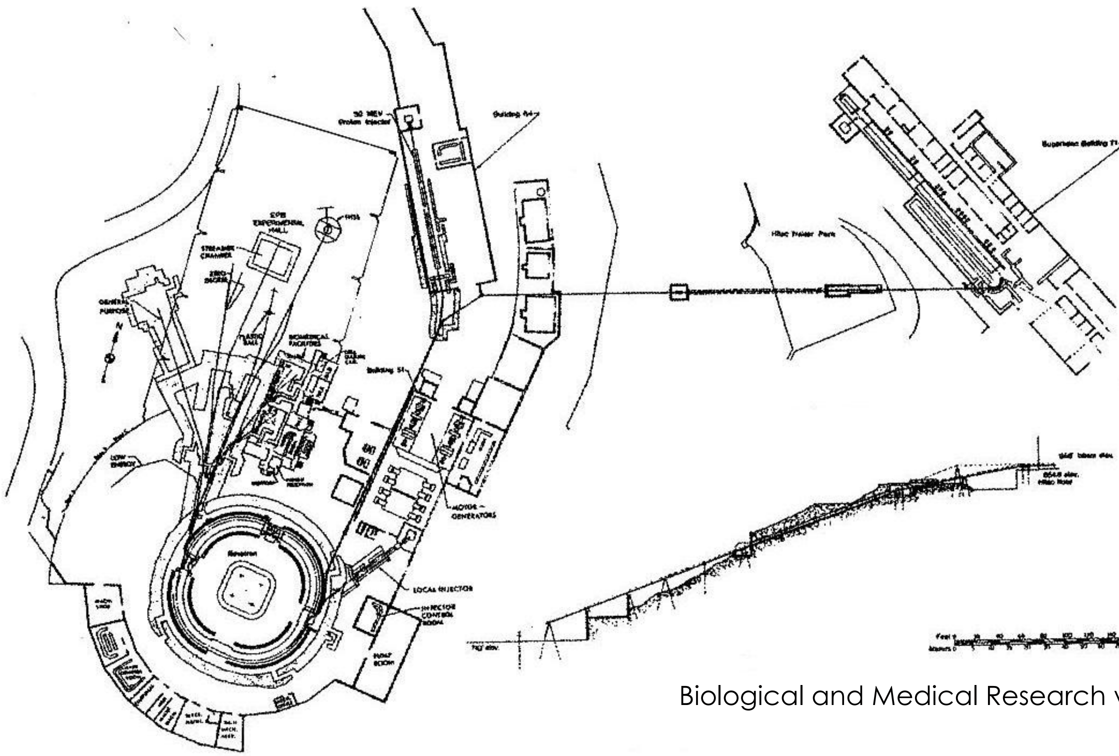
9 directions



3 directions

Pioneer's work at LBL

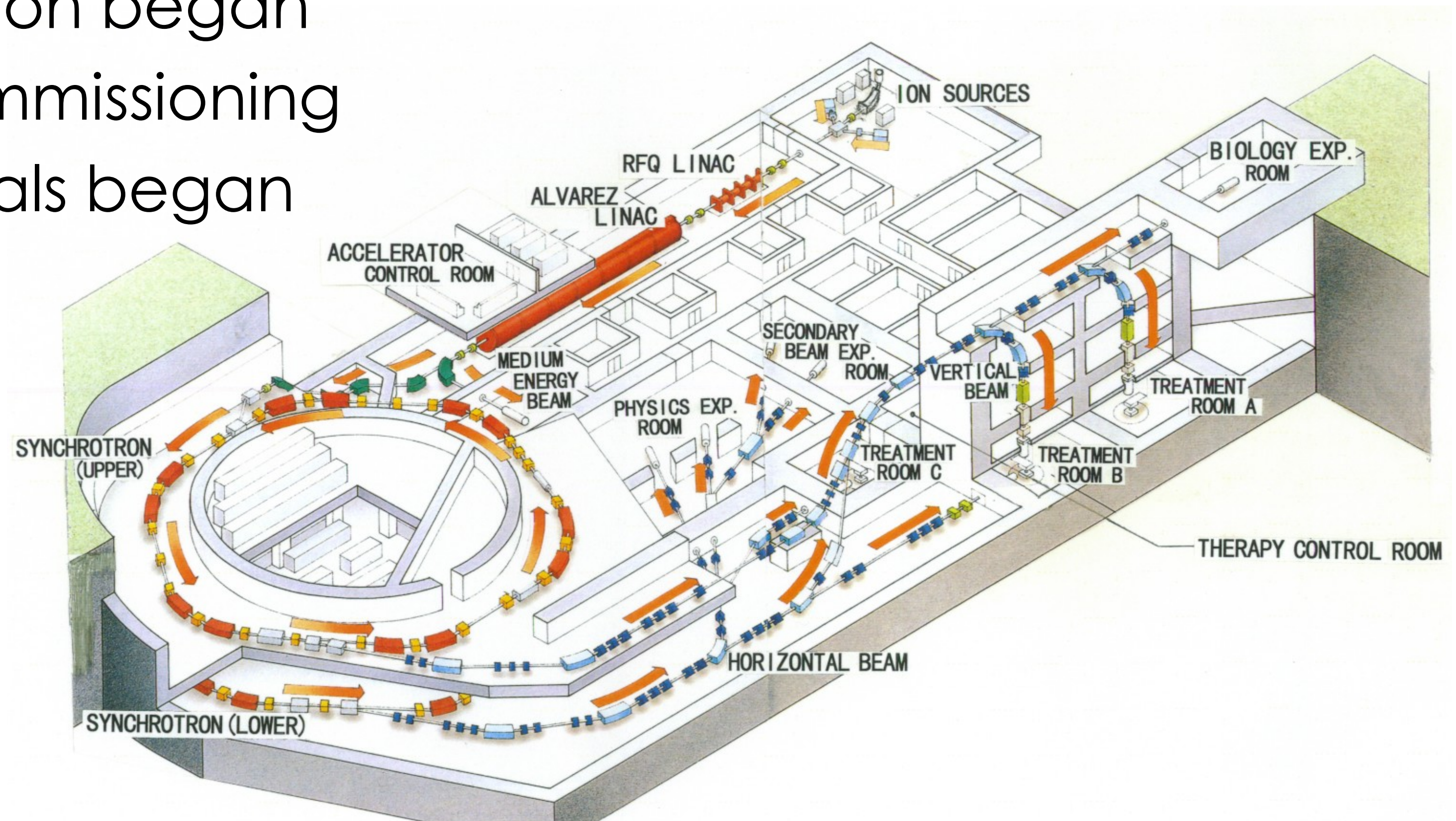
- **1940's: R. Willson proposed the medical application of heavy-ion beams.**
- **1957: LBL started clinical trials with Helium ions (2054 patients)**
- **1975: Treatment with Neon ions was made (433 patients).**
- **1992: The research had been aborted, due to the shutdown of Bevalac.**



Biological and Medical Research with Accelerated Heavy Ions at the Bevalac, LBL-11220, UC-48 (1980).
E.A. Blakely *et al.*, Adv. Radiat. Biol. 11, 295 (1984).
W.T. Chu *et al.*, Rev. Sci. Instrum. 64, 2055 (1993).

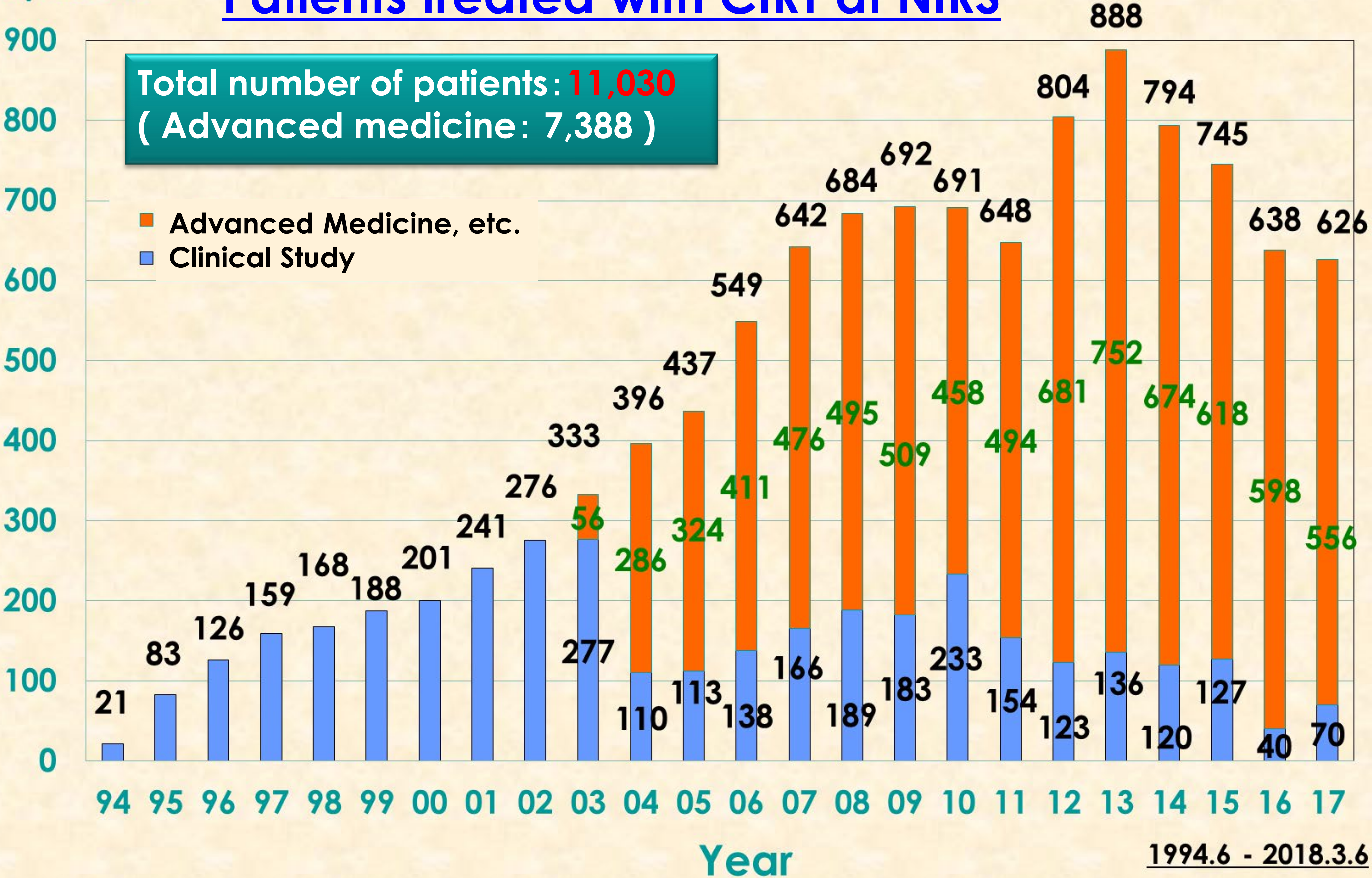
World-first heavy-ion medical accelerators

- **HIMAC（Heavy Ion Medical Accelerator in Chiba）**
  - 1984: Project was funded by Japanese Government
  - 1987: Construction began
  - 1993: Beam commissioning
  - 1994: Clinical trials began



HIMAC can accelerate heavy ions having q/m=1/2 up to E/A=800 MeV

Patients treated with CIRT at NIRS

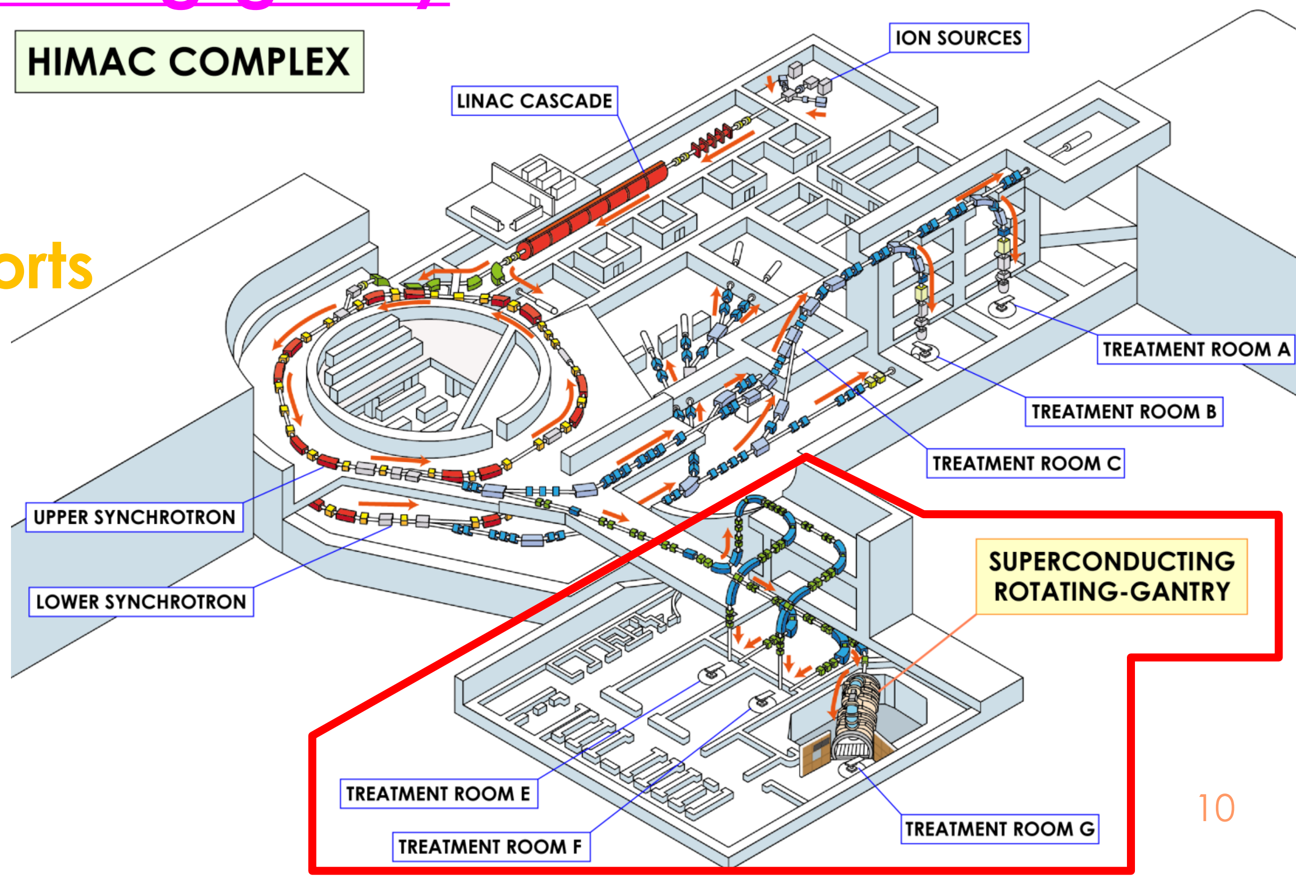


Gantry Development

New treatment facility

Construction completed in 2011

- **New development**
  - Fast 3D raster scanning
  - Superconducting rotating-gantry
- **3 treatment rooms**
  - Room E & F
    Fixed H&V scanning ports
  - Room G
    Rotating-gantry port



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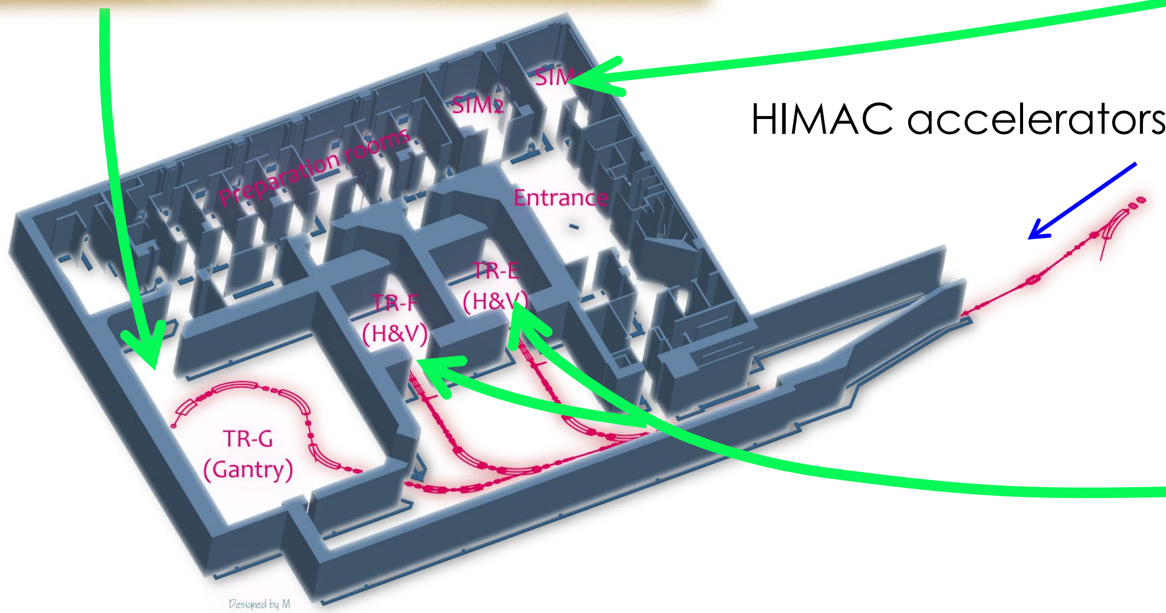
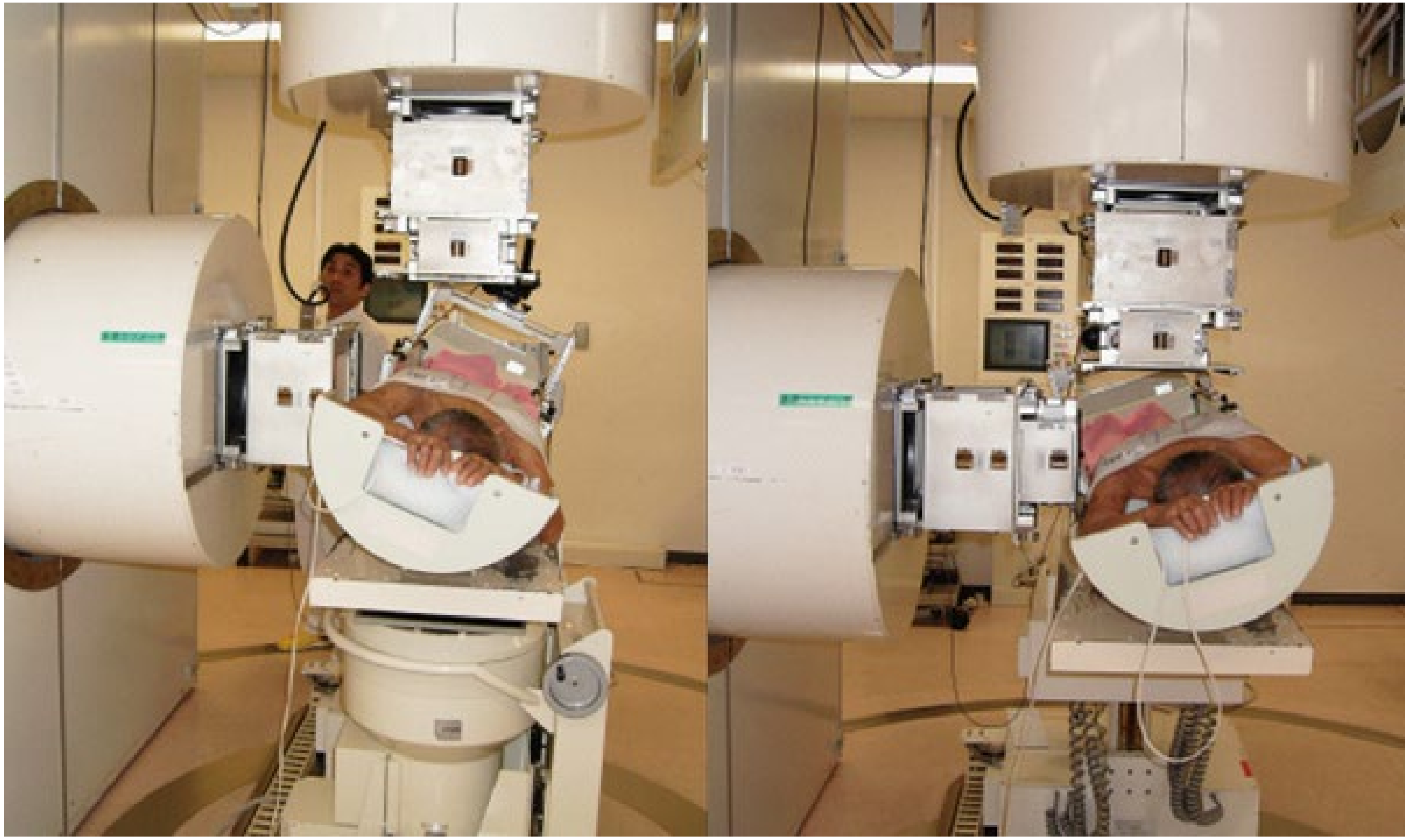
Treatment floor (B2F)



Irradiation using fixed irradiation ports



Treatment for a lung cancer with 4 directions

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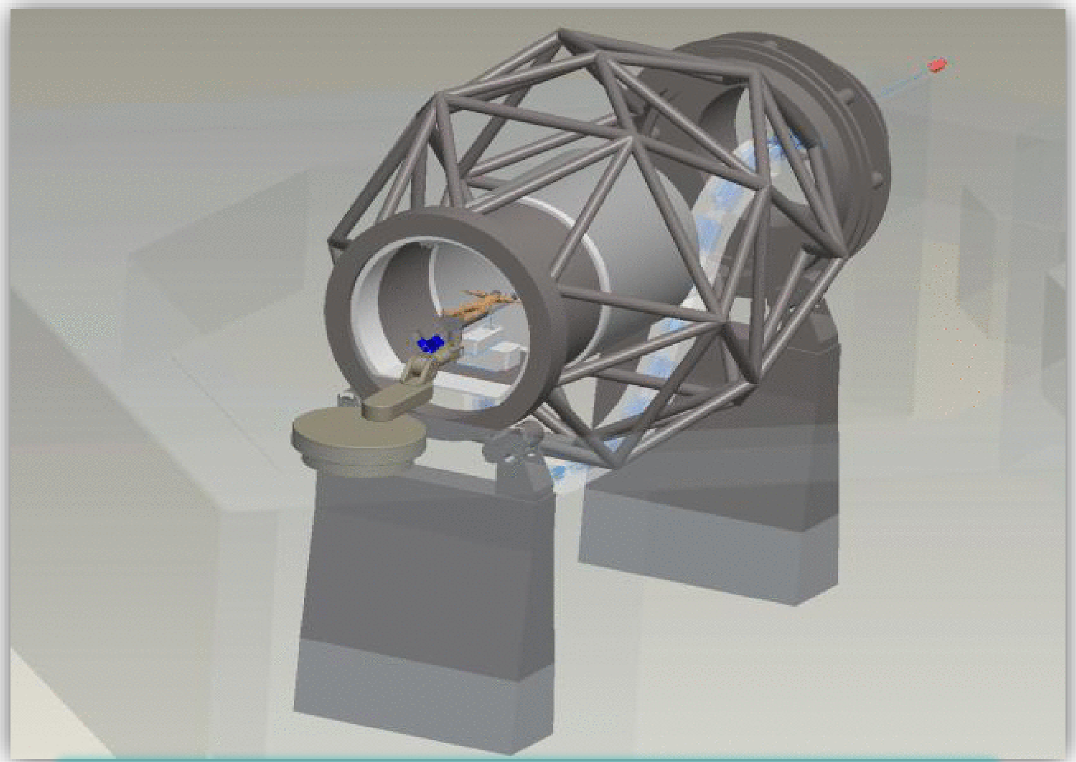
By using a rotating gantry

Advantage of a rotating gantry

1. No need to rotate a patient
2. Precise dose distribution
3. IMPT (Intensity Modulated Particle therapy)



Beam can be directed to a target from any of medically desirable directions

Rotating gantry for hadron therapy

- **Proton therapy**
  - Gantries are commonly used
  - Commercially available
- **Carbon therapy**
  - Required Bρ is 3 times higher
    - Magnets will be very large and heavy
  - Difficult to
    - Design
    - Construct

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Rotating gantry for carbon therapy

- **World-first carbon-gantry**
  - HIT @ Heidelberg, Germany
  - State-of-art gantry
  - Clinical use since Nov. 2012

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Design of SC rotating-gantry

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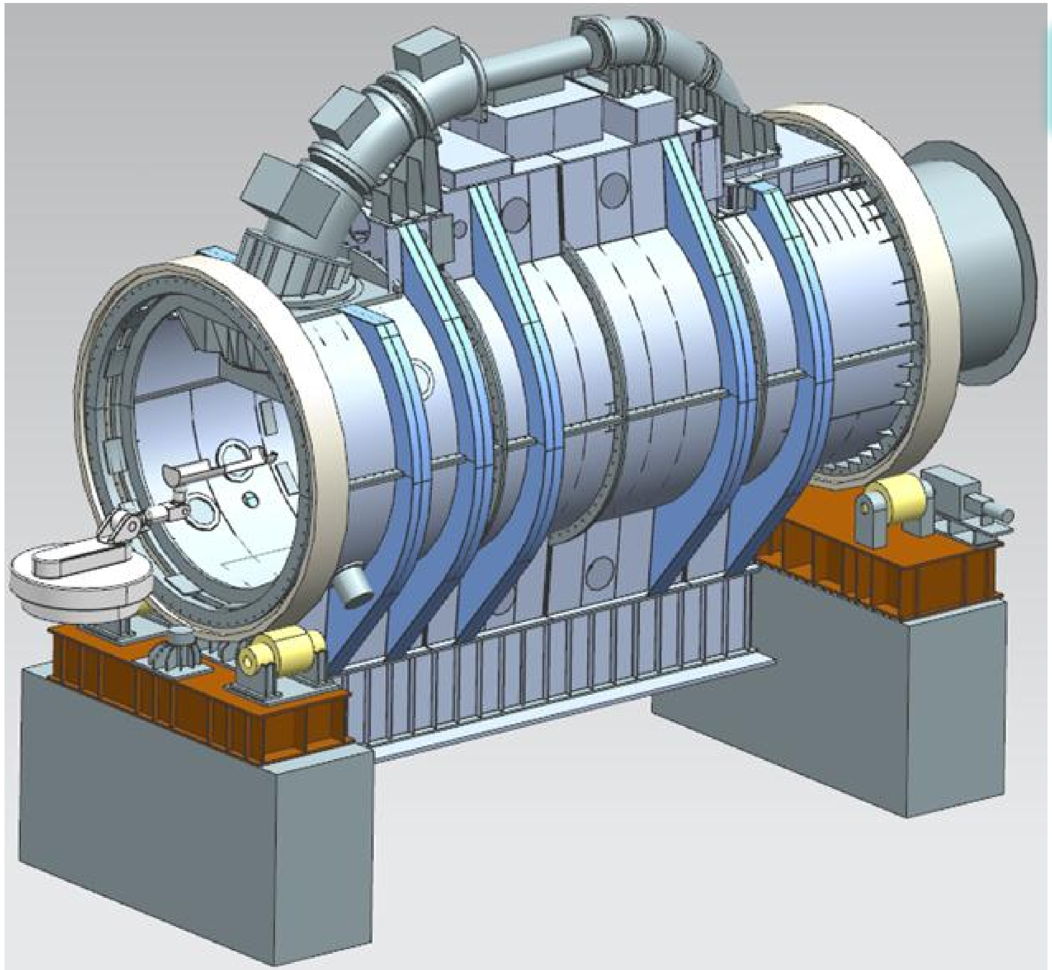
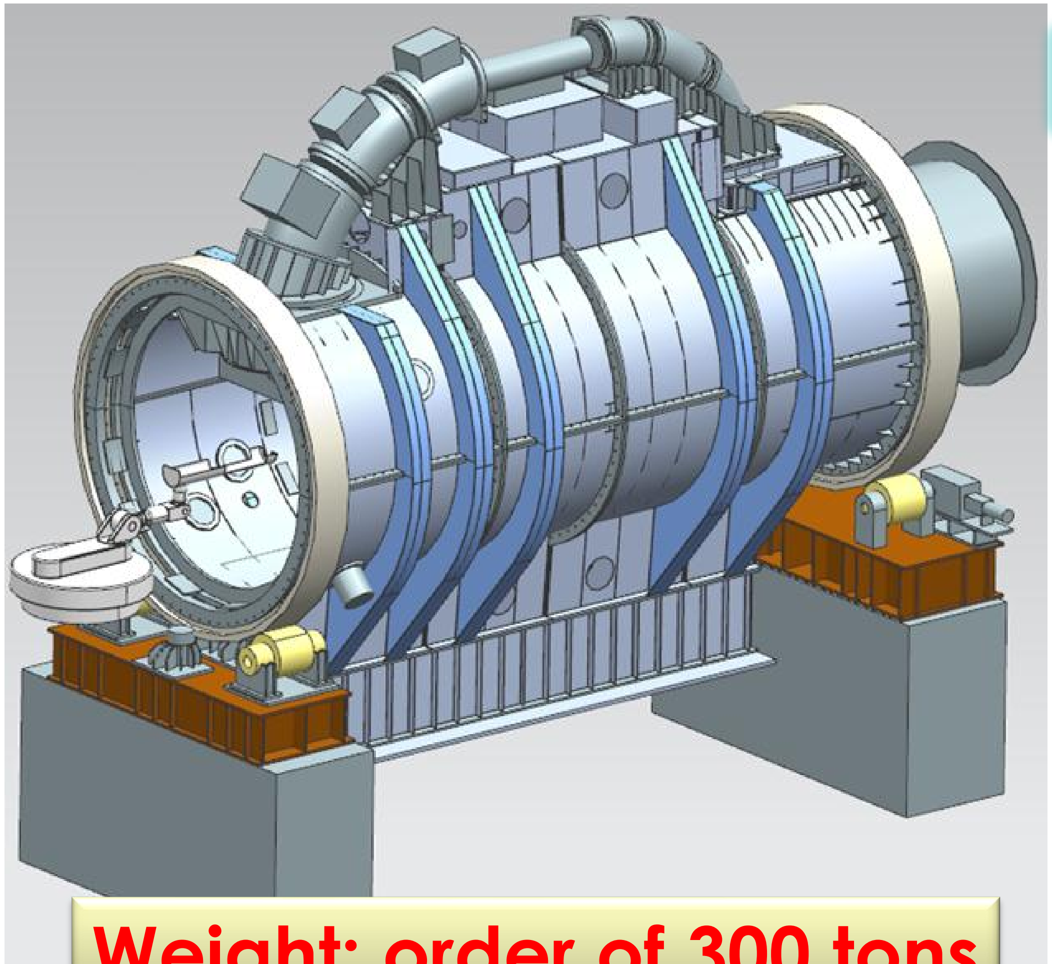
Superconducting rotating-gantry



Use of superconducting (SC) magnets

Ion kind	: ^{12}C
Irradiation method	: 3D Scanning
Beam energy	: 430 MeV/n
Maximum range	: 30 cm in water
Beam orbit radius	: 5.45 m
Length	: 13 m

Superconducting rotating-gantry



Weight: order of 300 tons

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Length	: 13 m

The size and weight are considerably reduced

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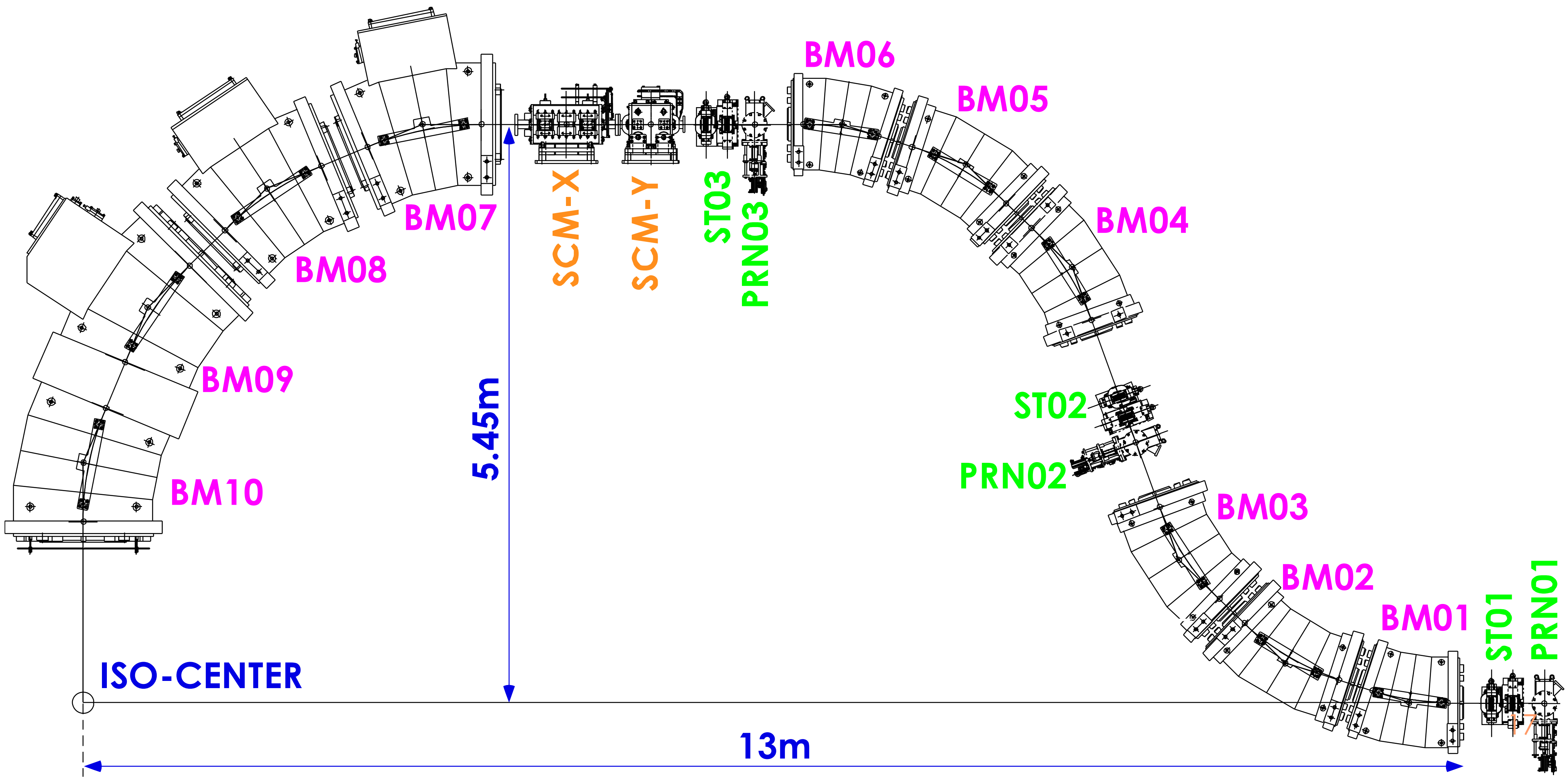
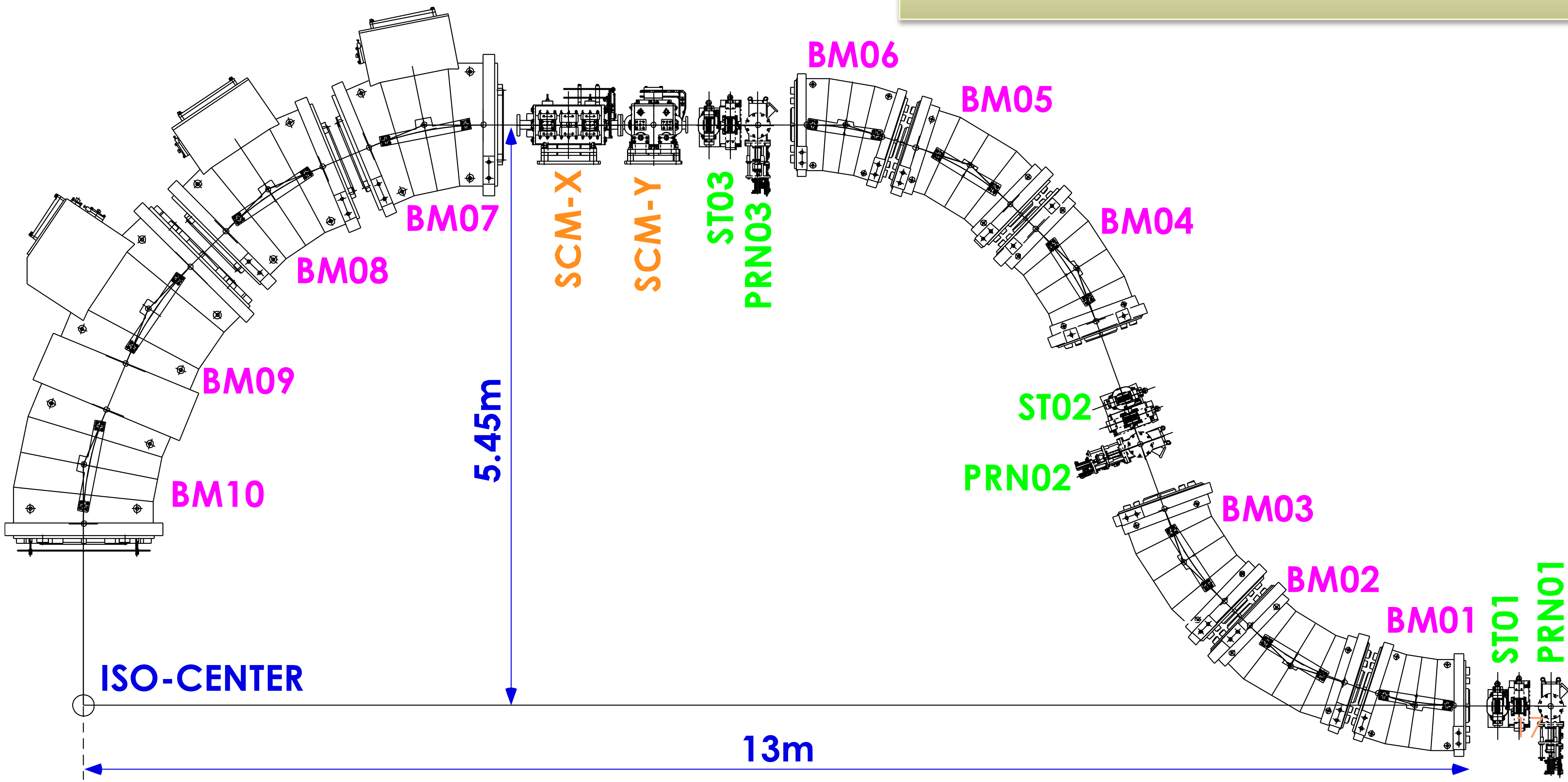
Layout of the SC gantry



Layout of the SC gantry

Combined function SC magnets
→No quadrupole magnet required



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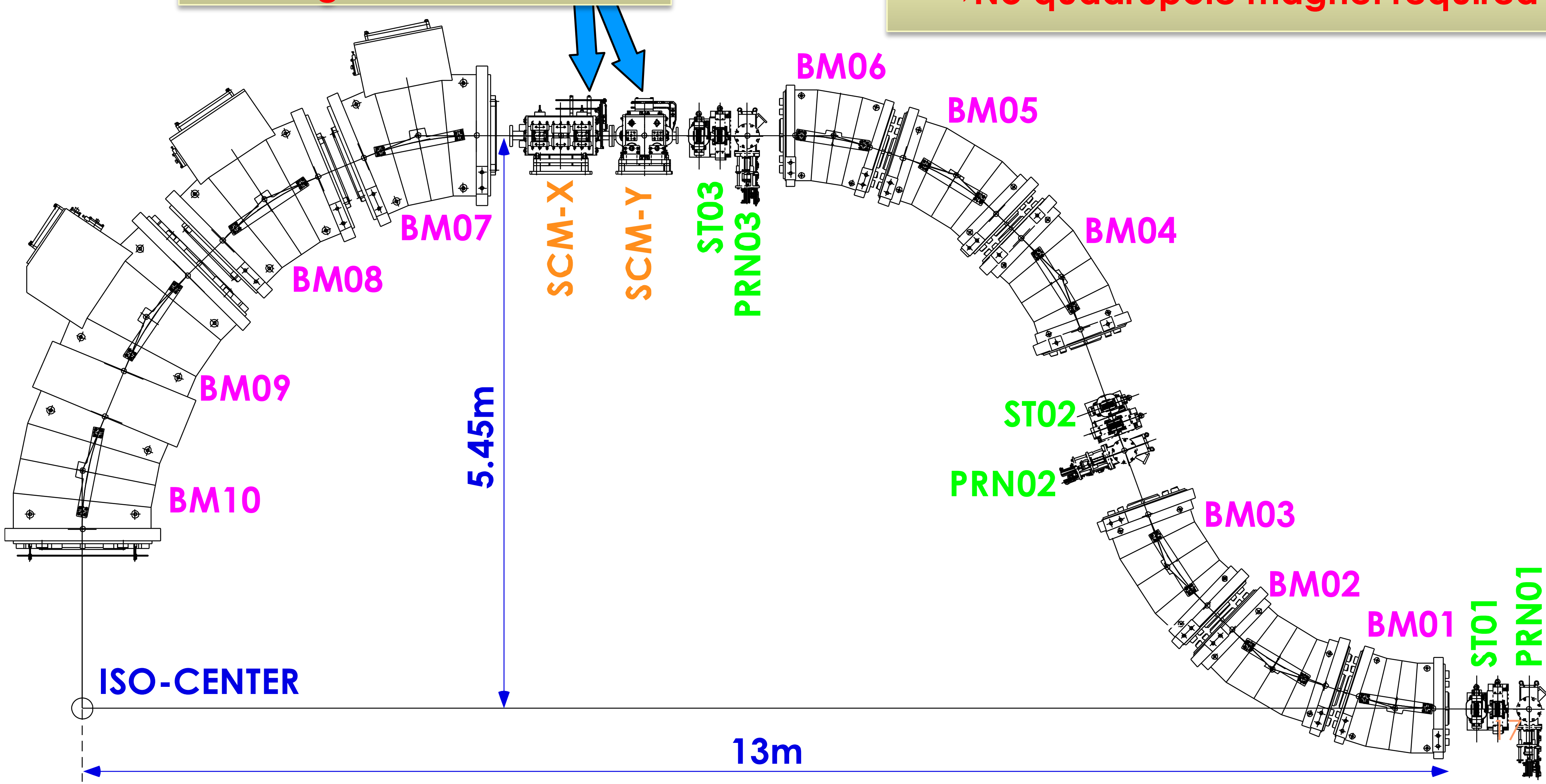
Layout of the SC gantry

Scanning magnets on top
→Large scan size

Combined function SC magnets
→No quadrupole magnet required



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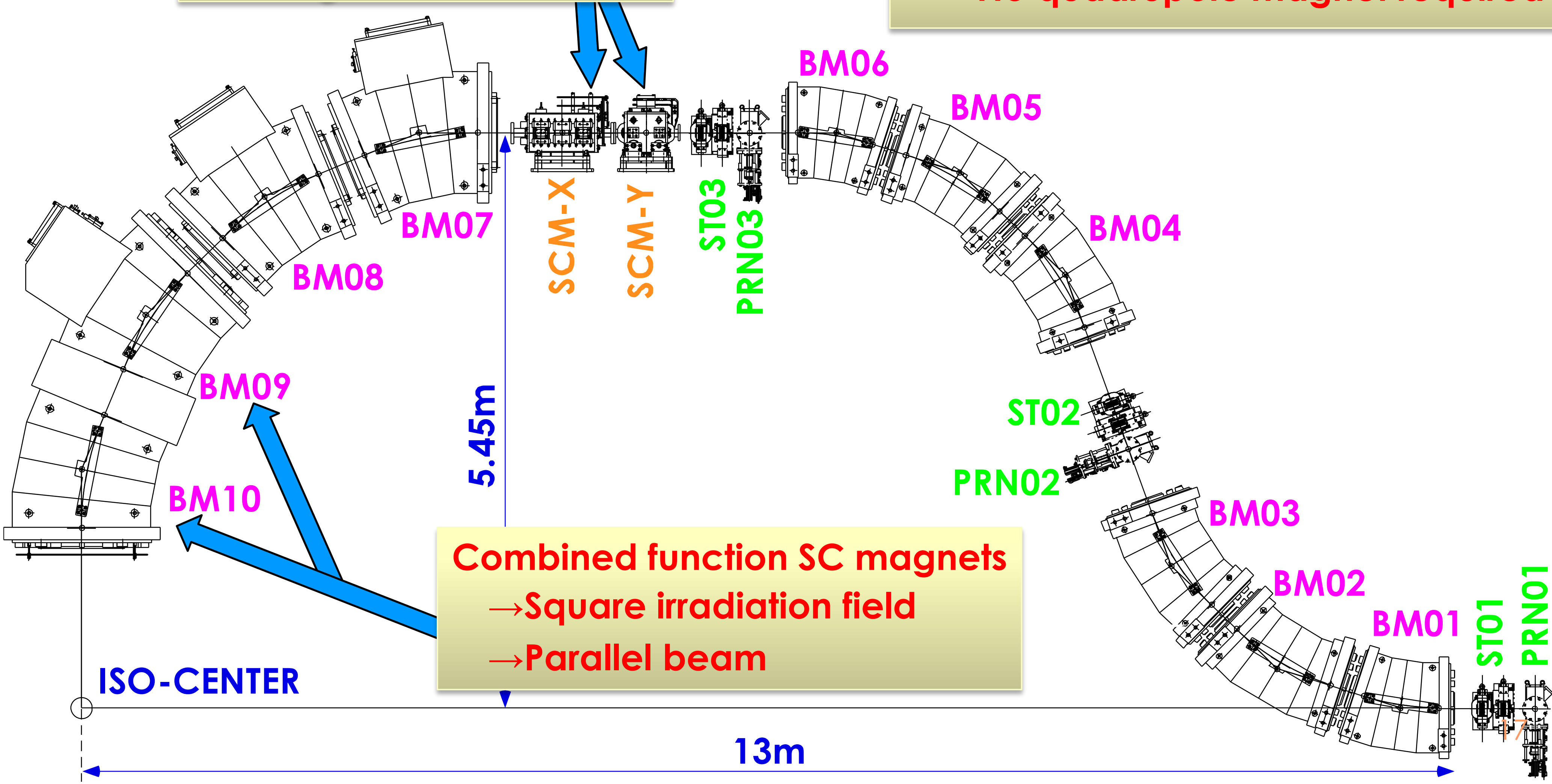
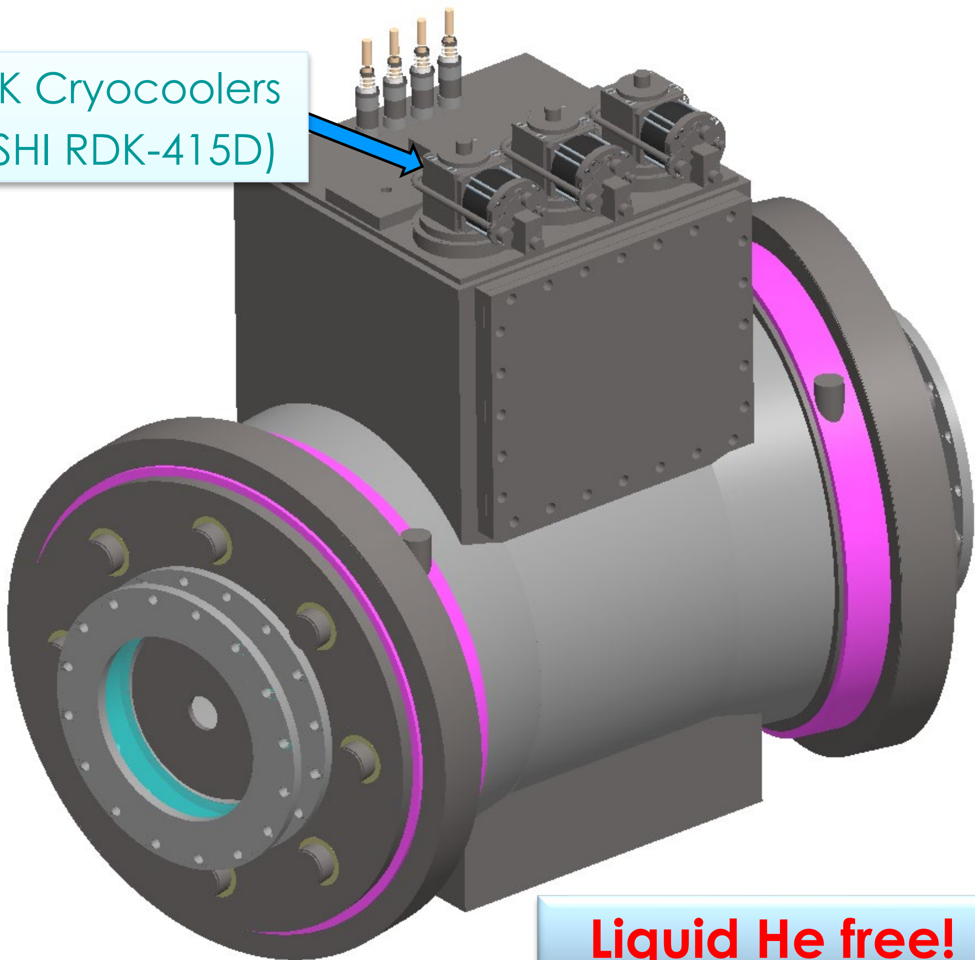


Combined function SC magnets
→Square irradiation field
→Parallel beam

Curved SC magnets for gantry

SC magnet (BM02-05)

4K Cryocoolers
(SHI RDK-415D)



Liquid He free!

Curved SC magnets for gantry

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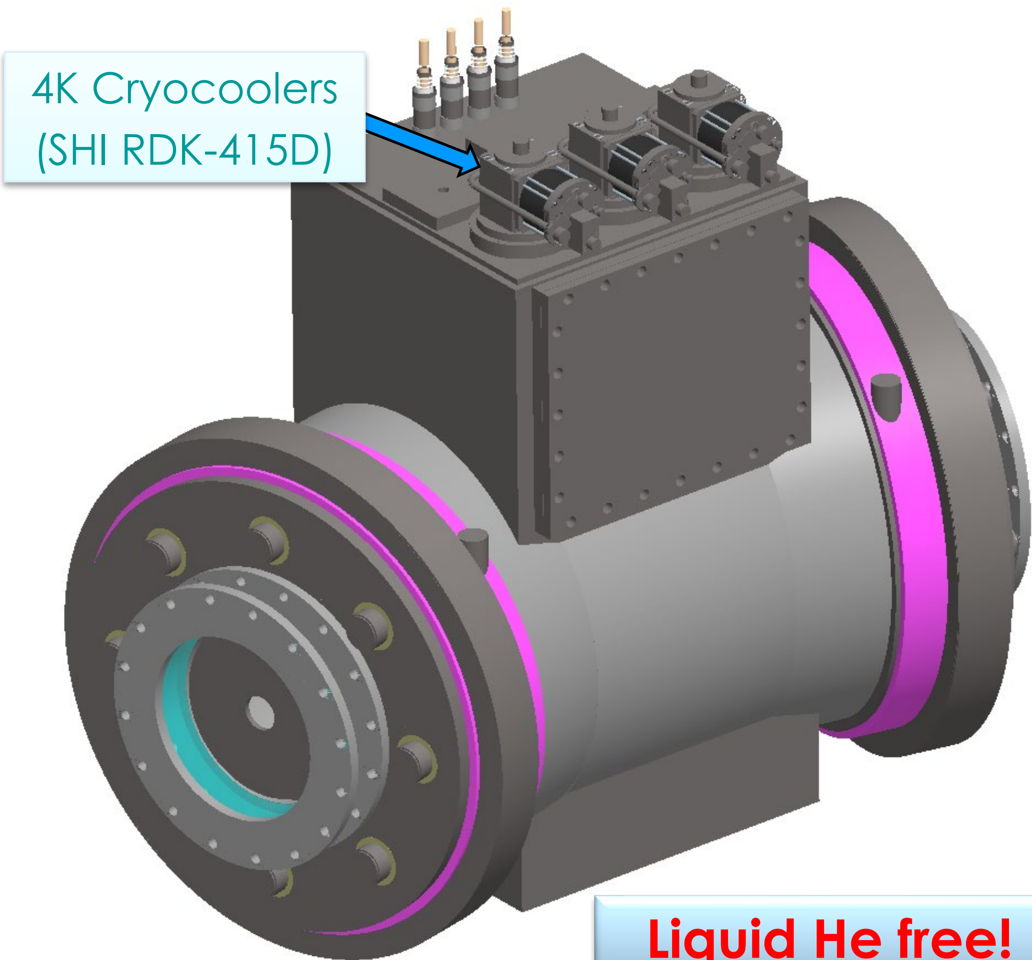
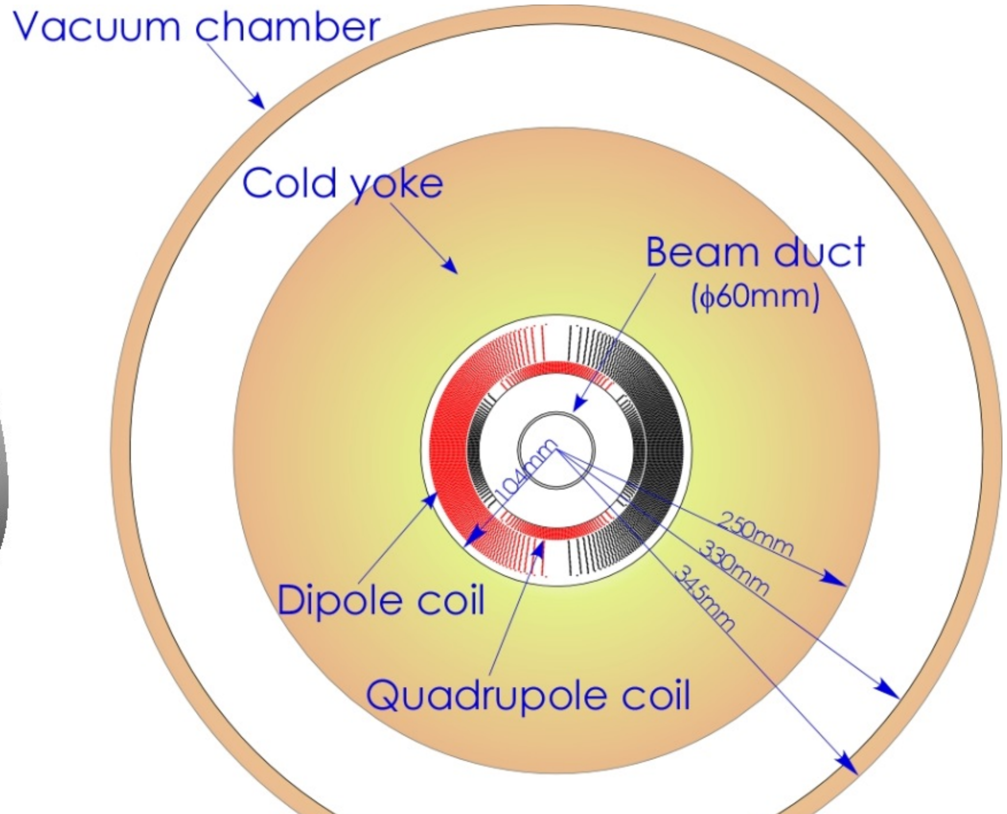
SC magnet (BM02-05)



Liquid He free!

Cross-sectional view



Dipole and quadrupole coils can be independently excited

Specifications of SC magnets

Parameters	Symbol	Unit	BM01	BM02	BM03	BM04	BM05	BM06	BM07	BM08	BM09	BM10
Type	□	□	Superconducting sector magnet									
Coil	□	□	Dipole+Quard.						Dipole		Dipole+Quard.	
Bending angle	θ	deg	18	26				18	22.5			
Bending radius	ρ	m	2.3						2.8			
Maximum field	B_{dipole}	T	2.88						2.37			
Maximum field gradient	G_{max}	T/m	10						□		1.3	
Bore size	D_{bore}	mm	ϕ60						□ 122	□ 170	□ 206	
Effective radius or area	D_f or A_f	mm	ϕ40						□ 120	□ 160	□ 200	
Uniformity (dipole)	$\Delta BL/BL$	□	$\pm 1\times 10^{-4}$									
Uniformity (quadrupole)	$\Delta GL/GL$	□	$\pm 1\times 10^{-3}$									
Inductance (dipole)	L	H	6.2	9.1				6.2	5.2	8.9	12	
Stored Energy (dipole)	P	kJ	57	84				57	133	225	319	

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Construction of SC rotating-gantry

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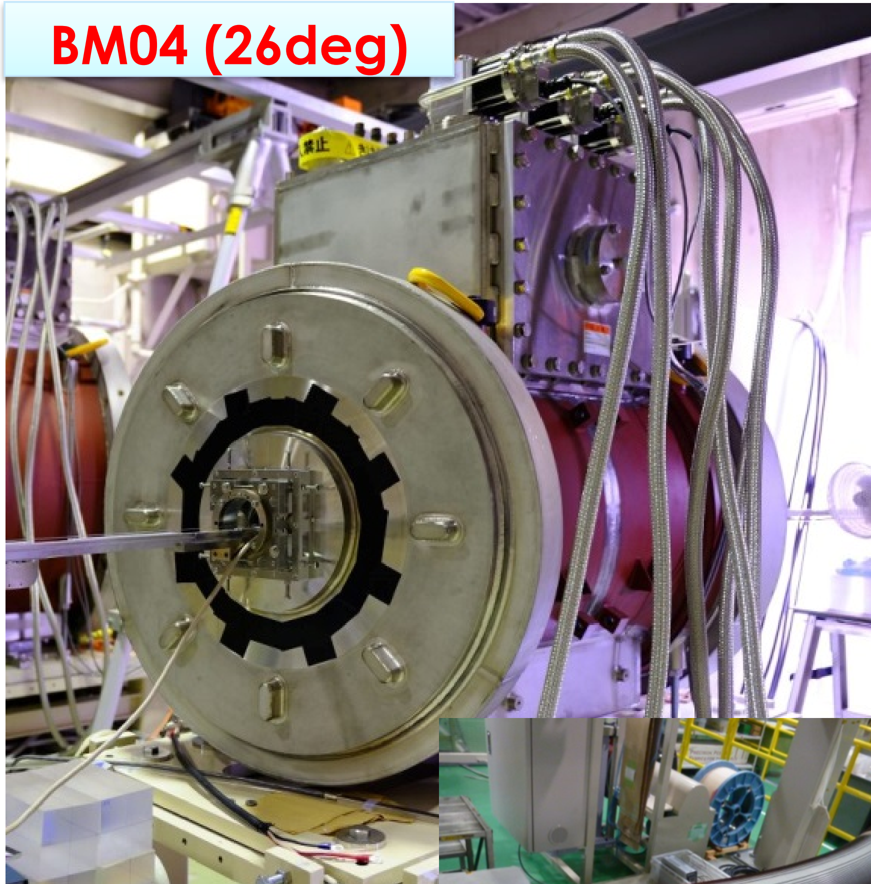
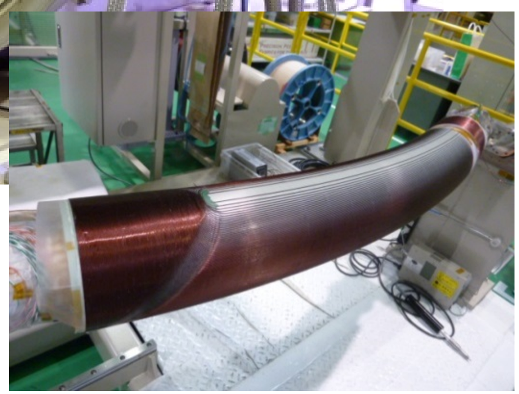
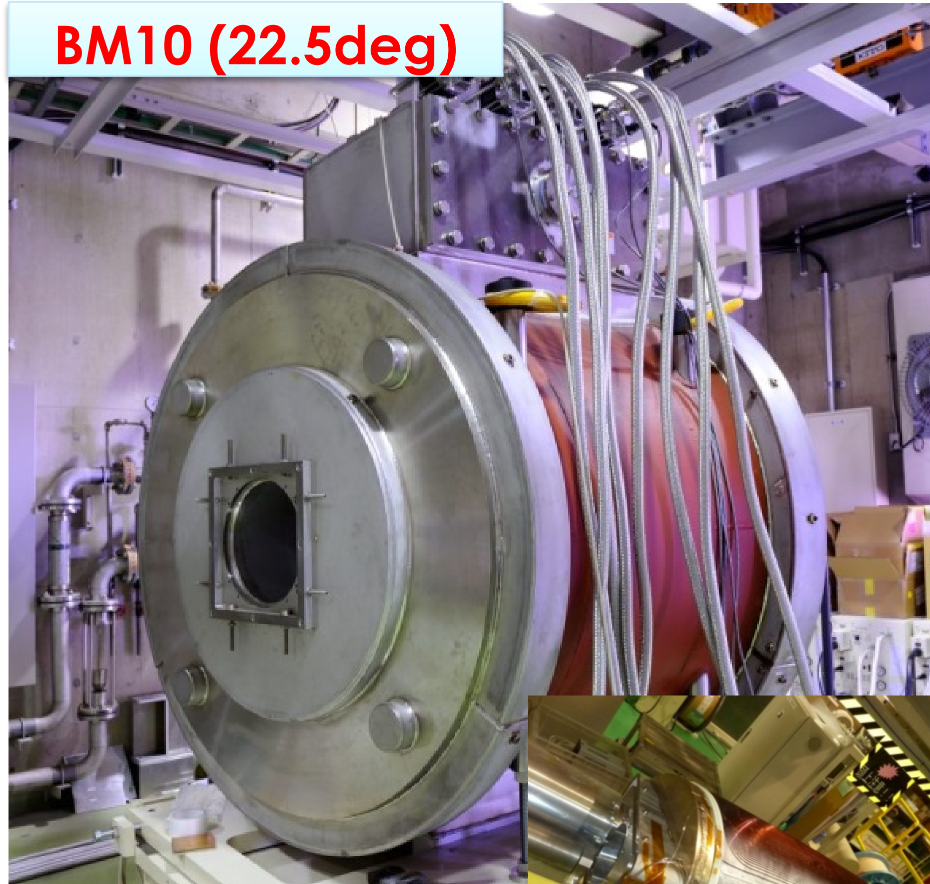
Construction of SC magnets

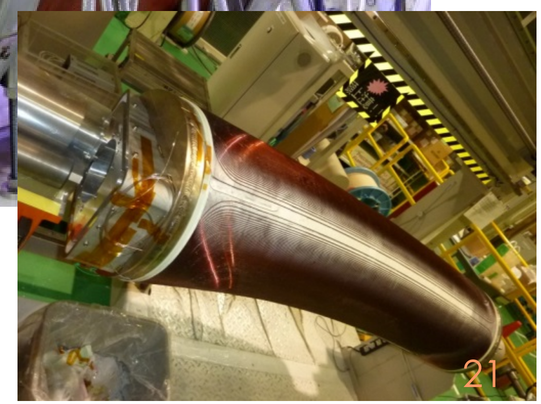
BM04 (26deg)





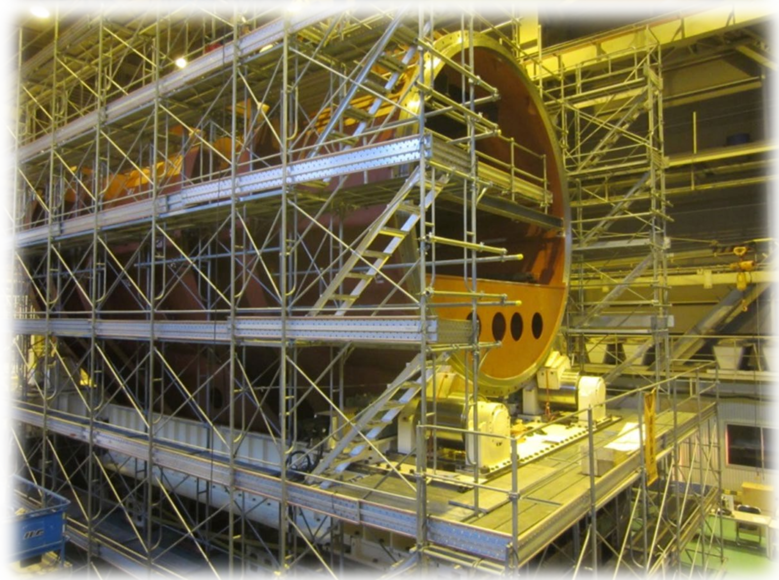
BM10 (22.5deg)





Construction of structure

Construction and tests



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Construction and tests

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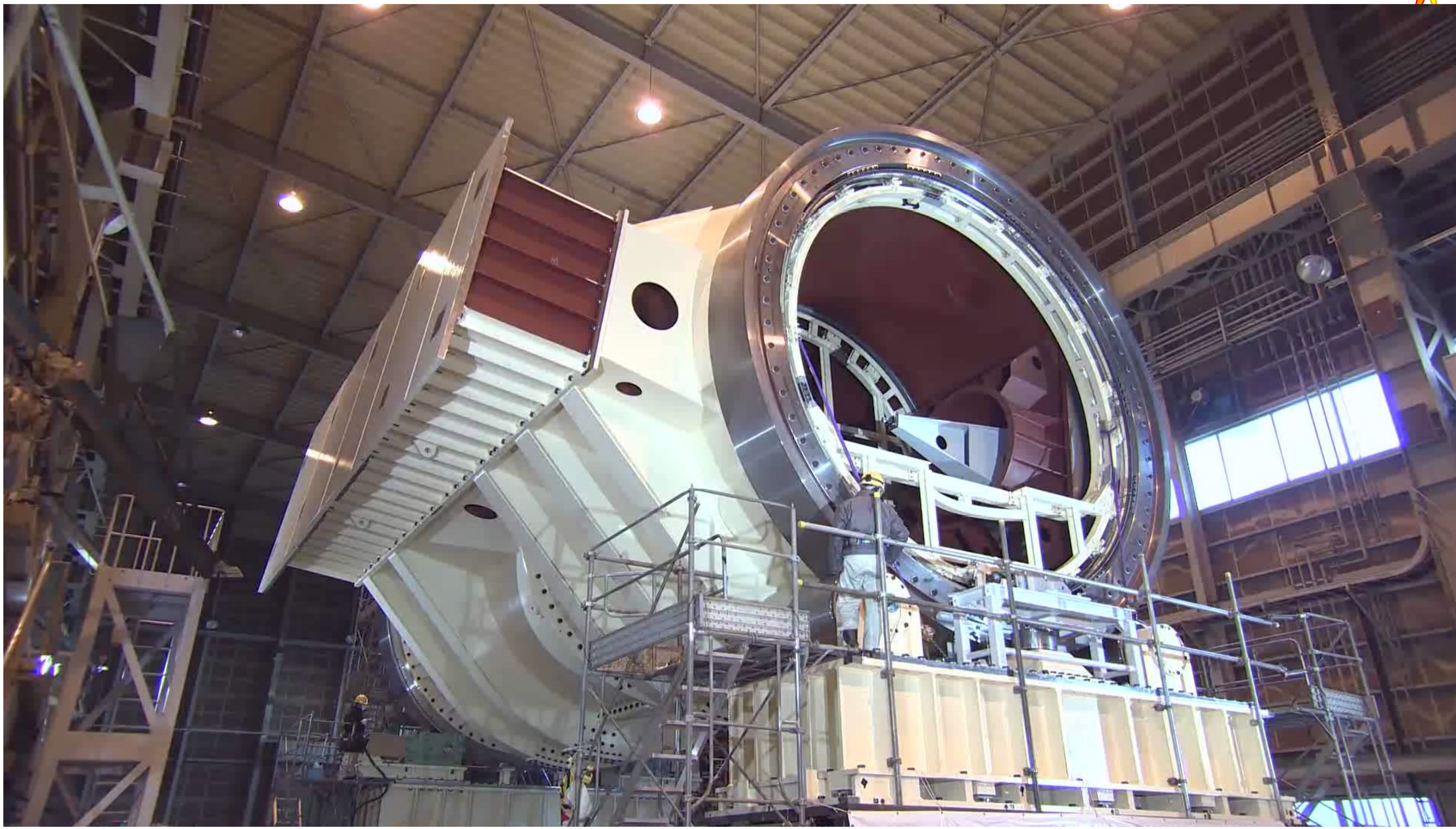
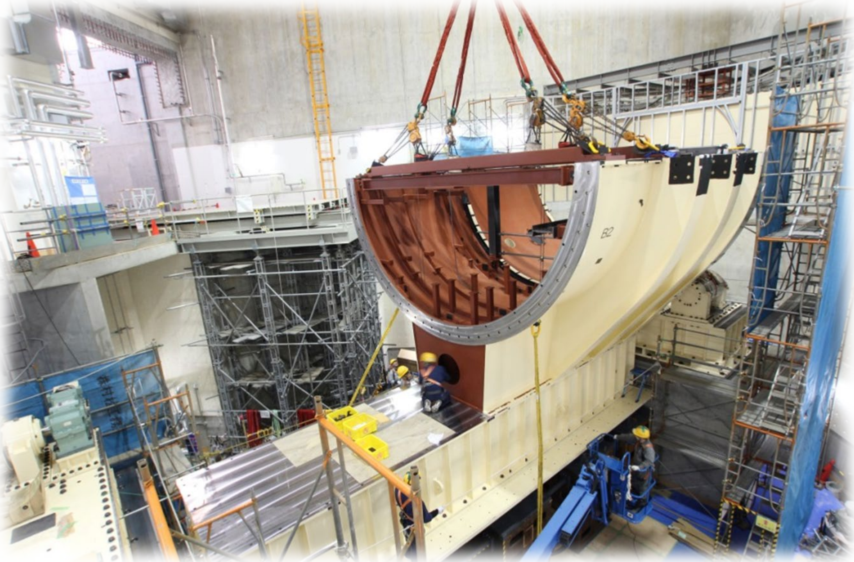
Rotation tests at Toshiba



Transportation#1

Transportation#2

Installation to NIRS



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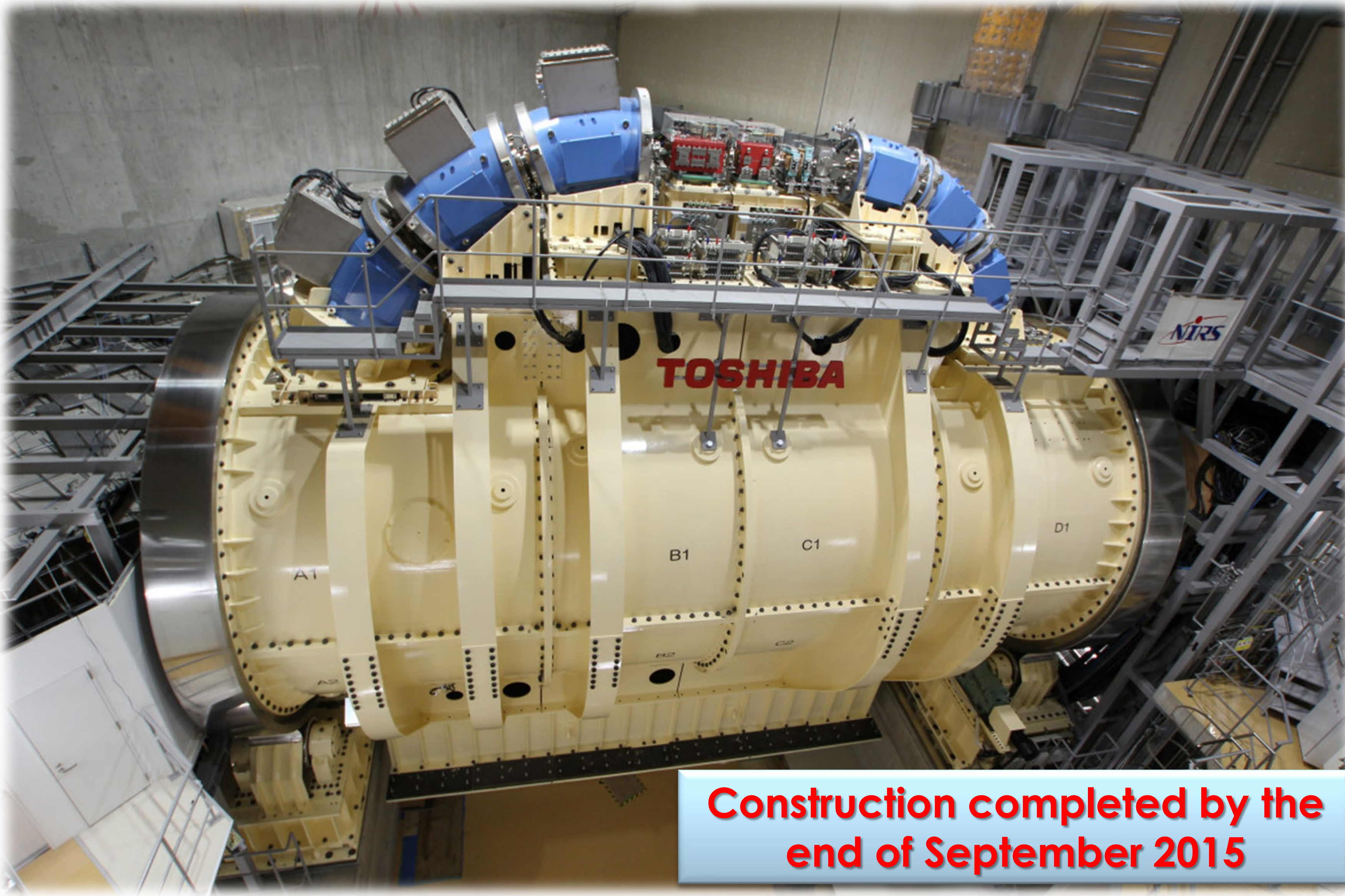
Installation to NIRS



Construction completed by the end of September 2015

Treatment room

Treatment room G

SC gantry

Beam commissioning

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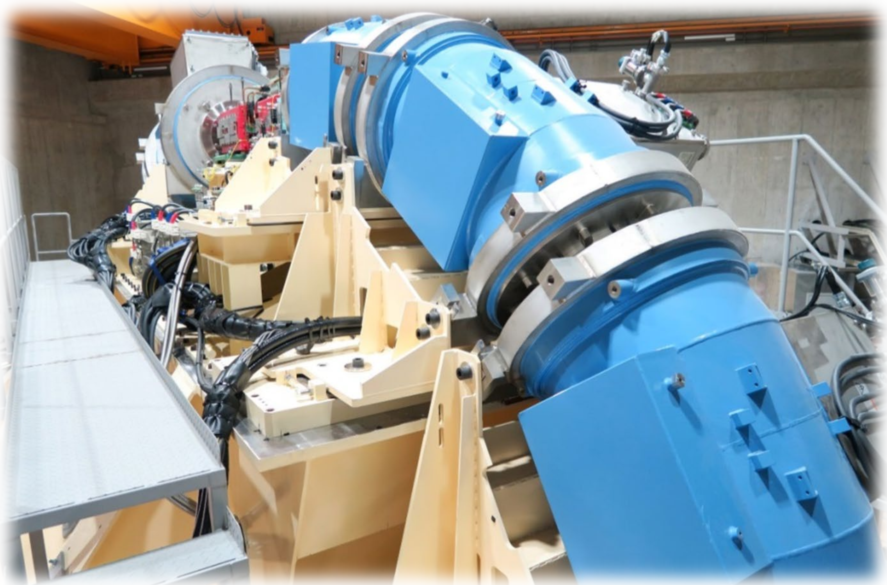
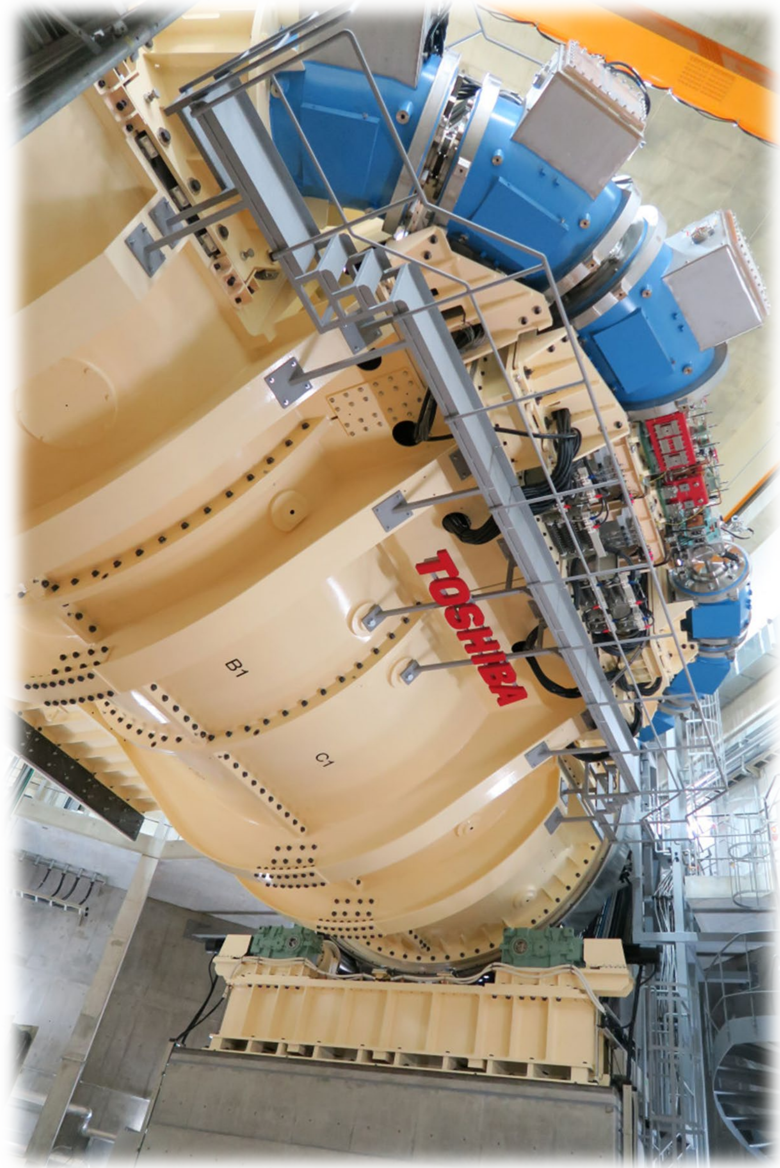
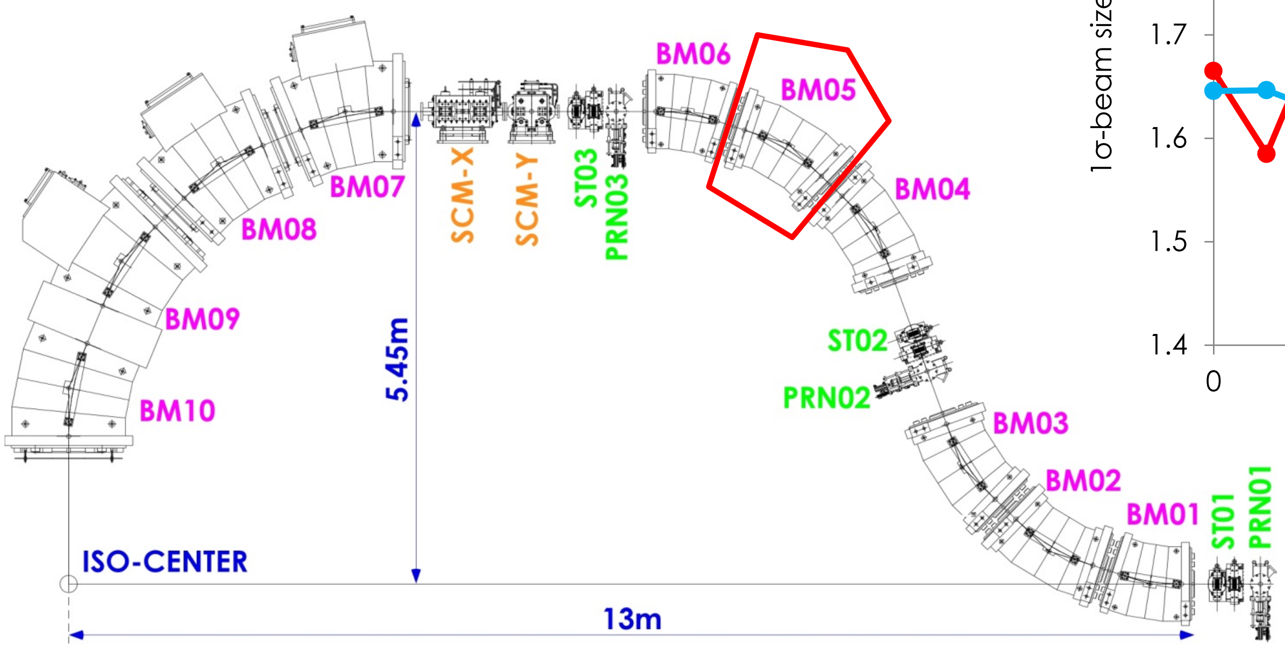
Beam commissioning began since Oct. 2015

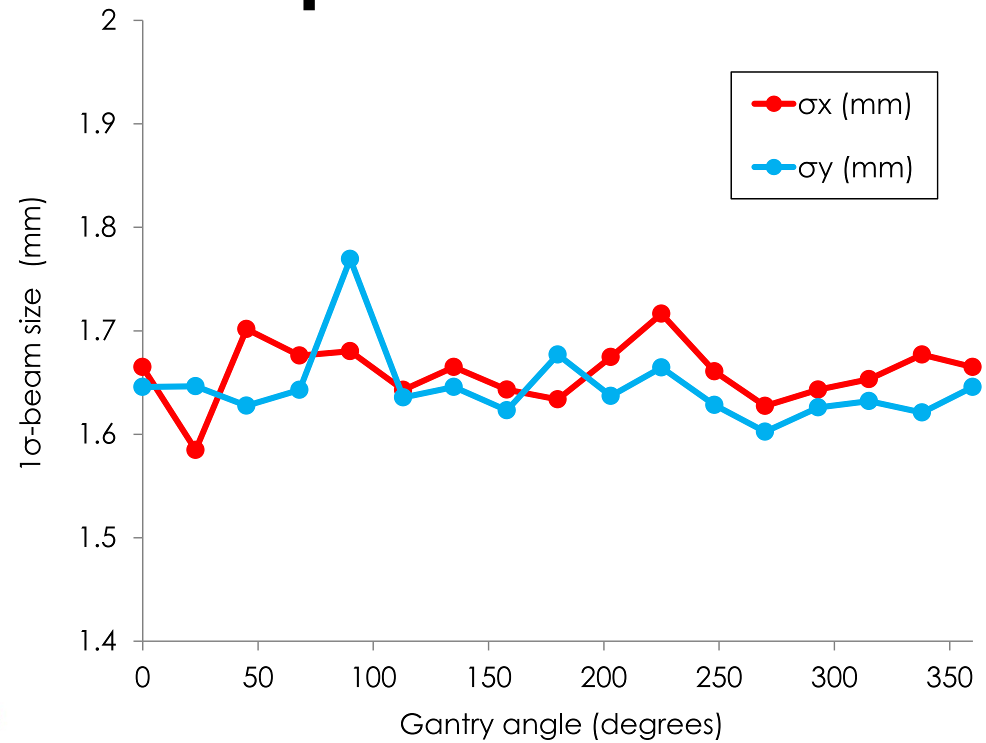




Angular dependence

- The SC quadrupole of BM05 was finely tuned, so as to obtain circular beam spots at the isocenter.

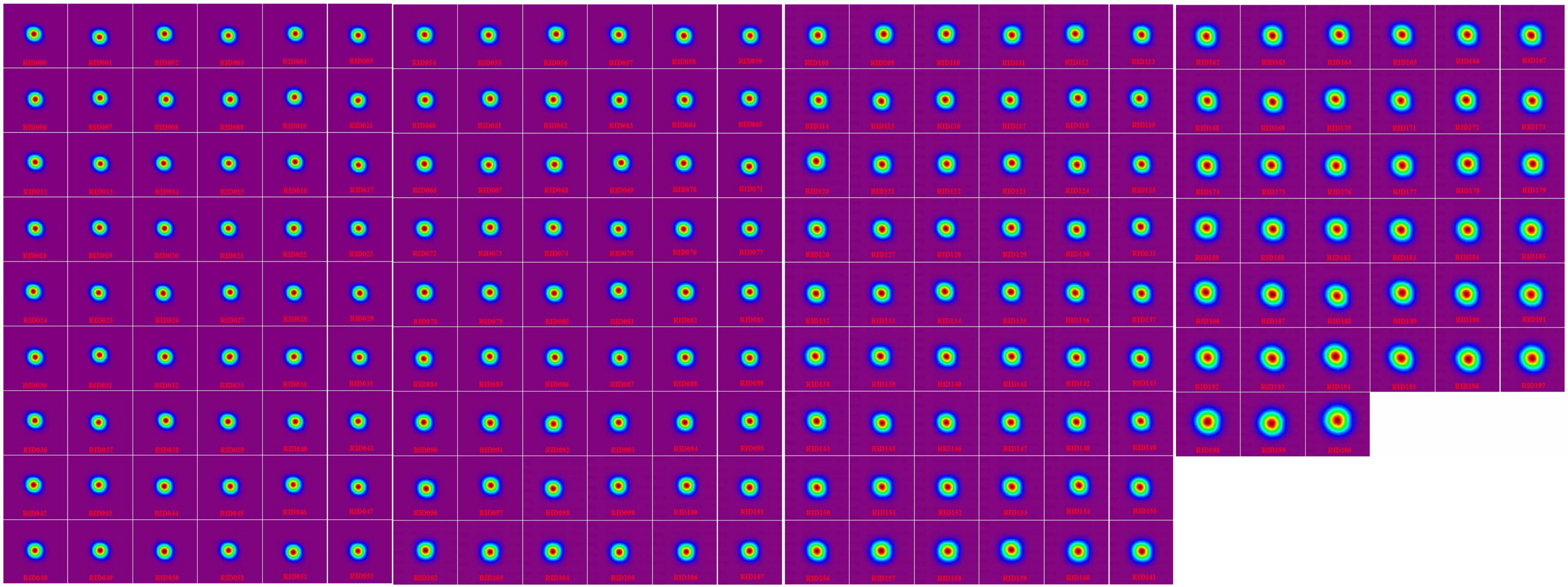




Angular dependence of beam sizes at isocenter (E=430 MeV/u)

Energy dependence

- Beam tuning was made for 201 kinds of beam energies for *E*=430~55.6 MeV/u.



Energy dependence

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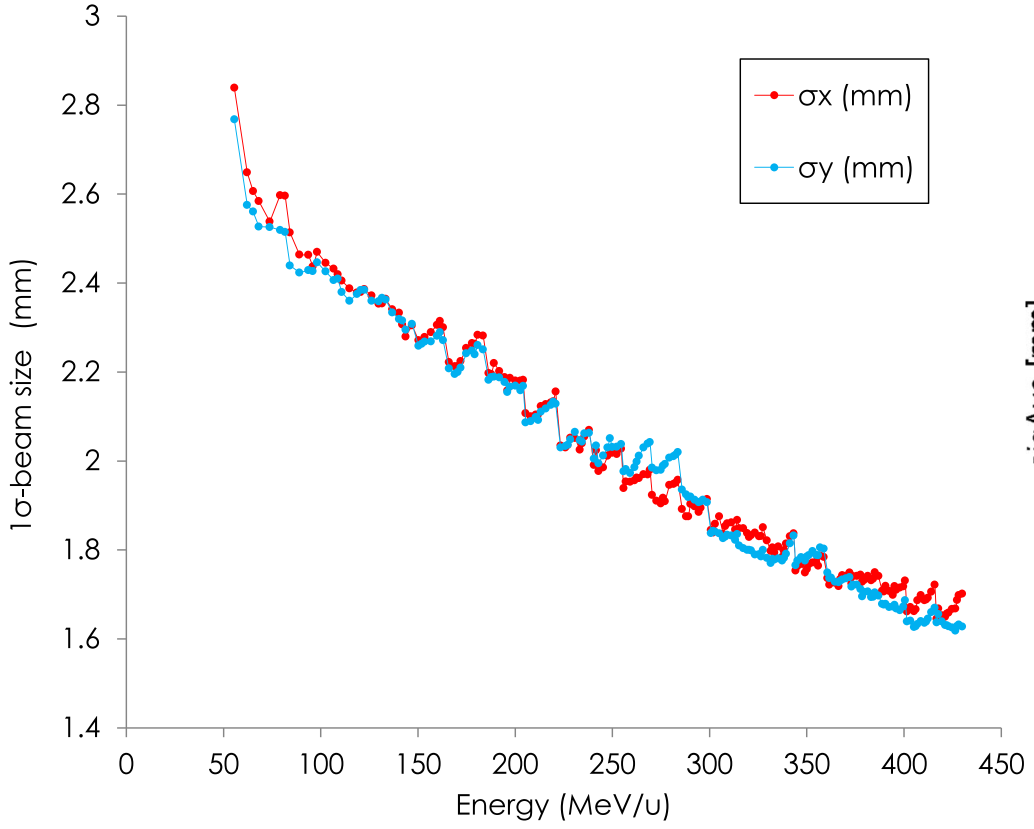
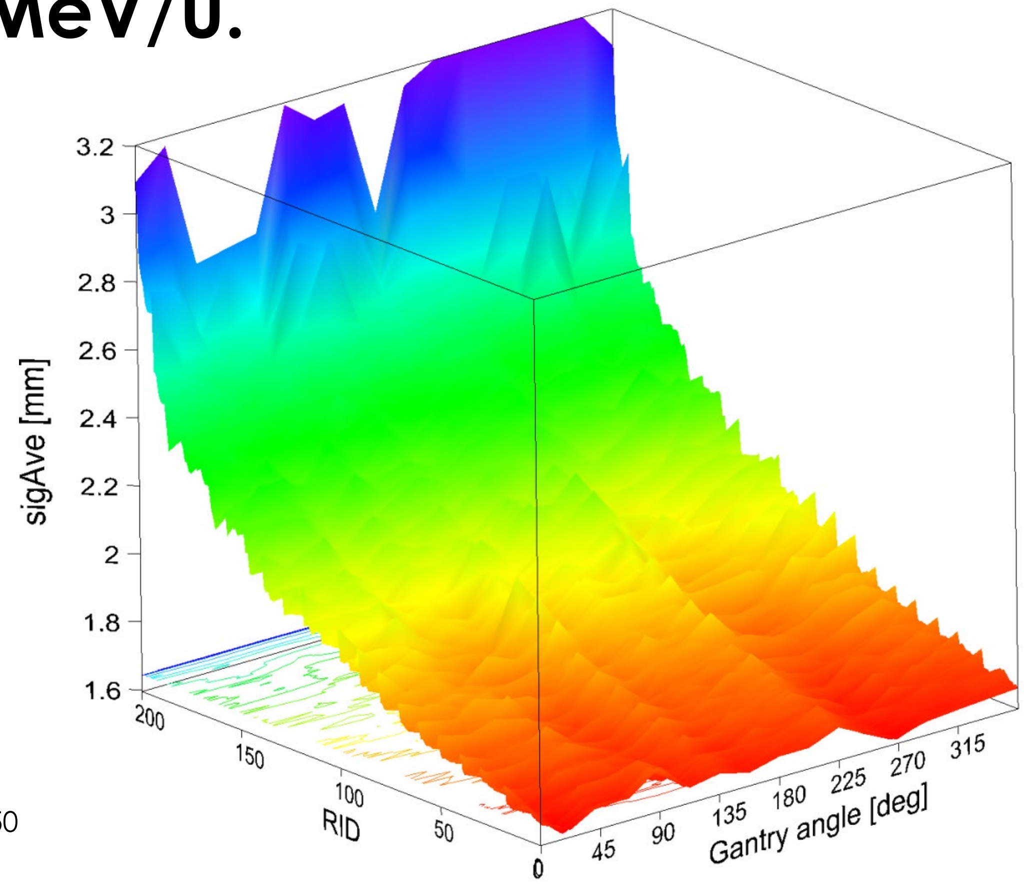


Energy dependence of beam sizes at isocenter (45 degrees)



Average beam sizes as a function of gantry angle and RID

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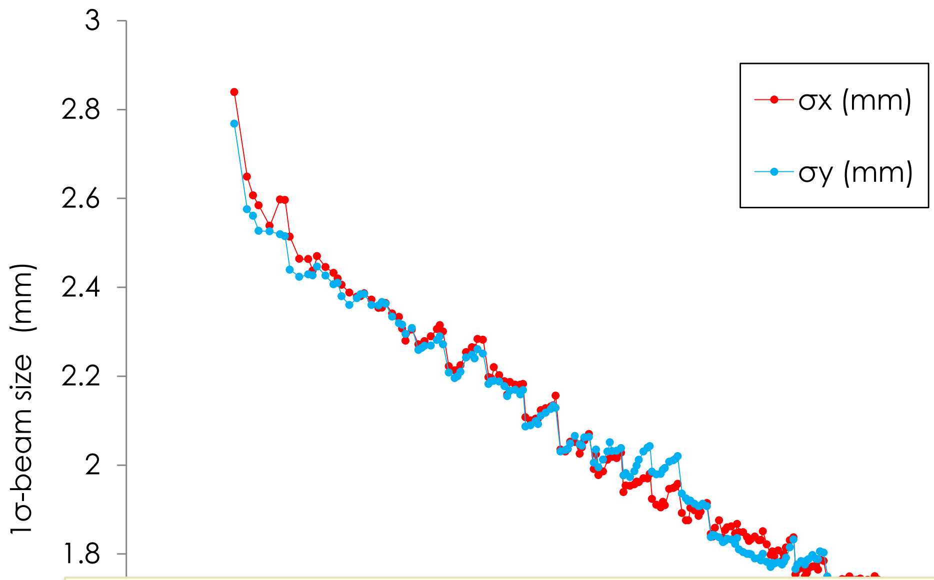
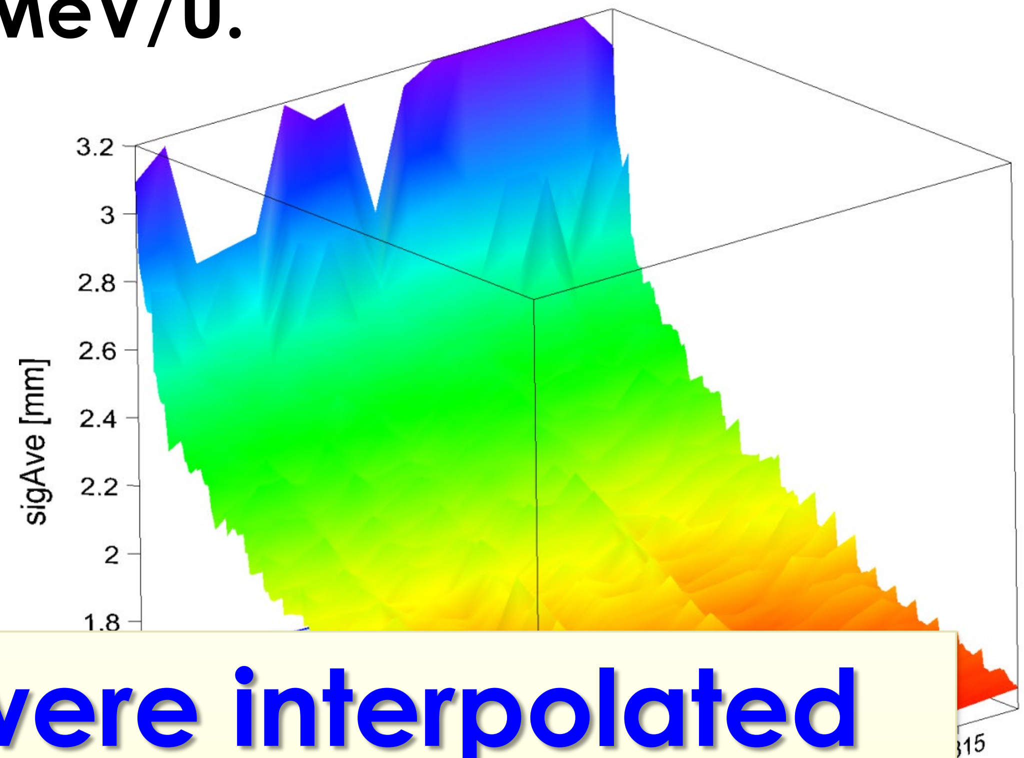
Energy dependence

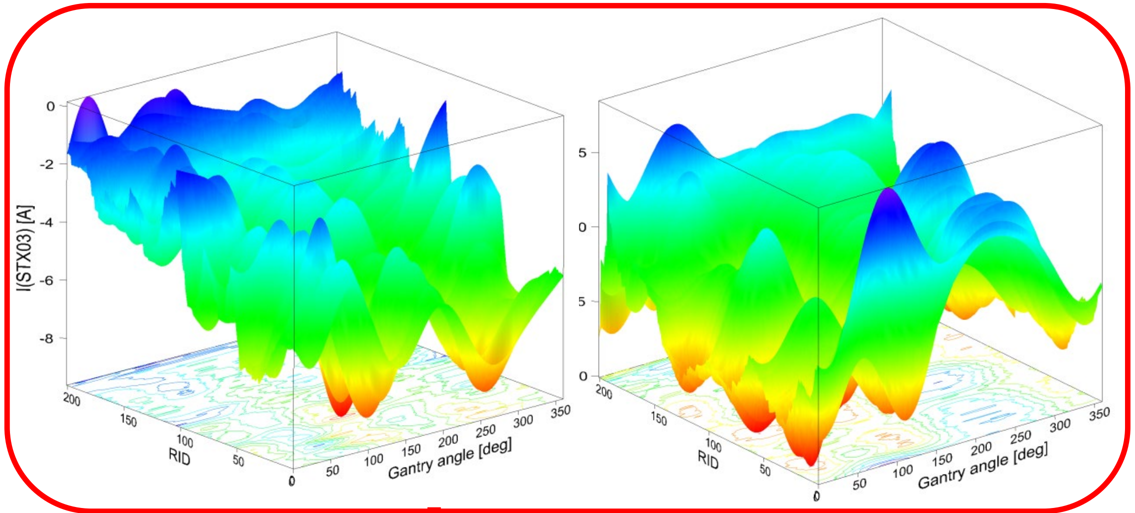
- Beam tuning was made for 201 kinds of beam energies for *E*=430~55.6 MeV/u.

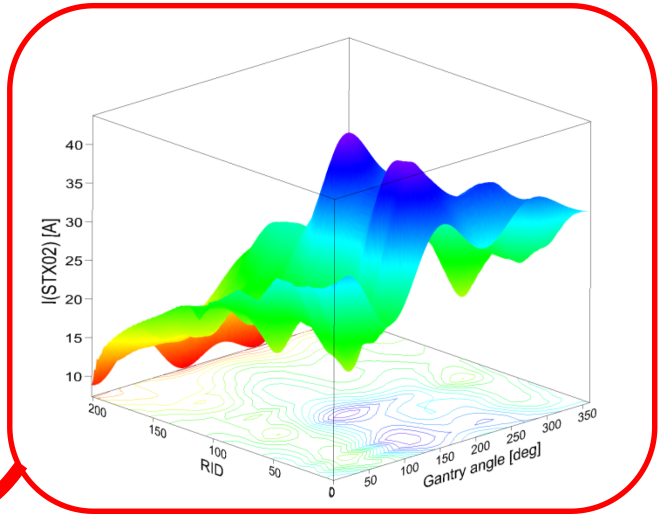


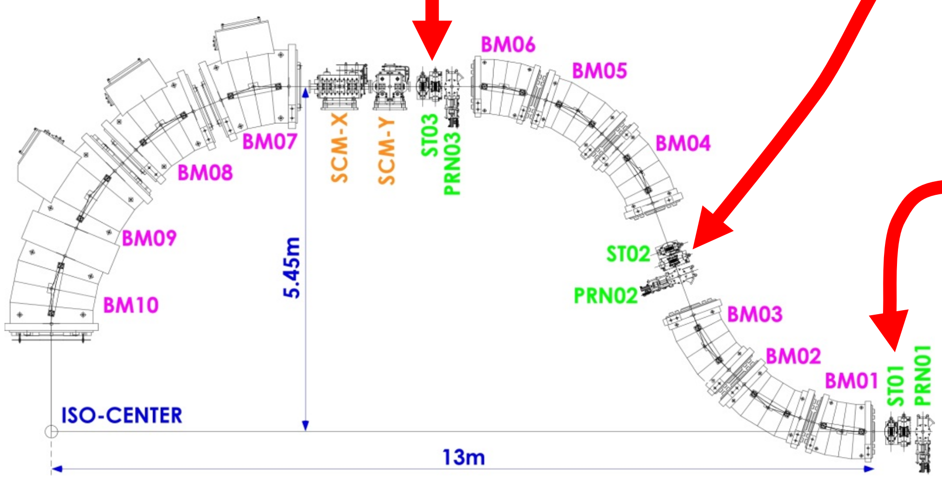


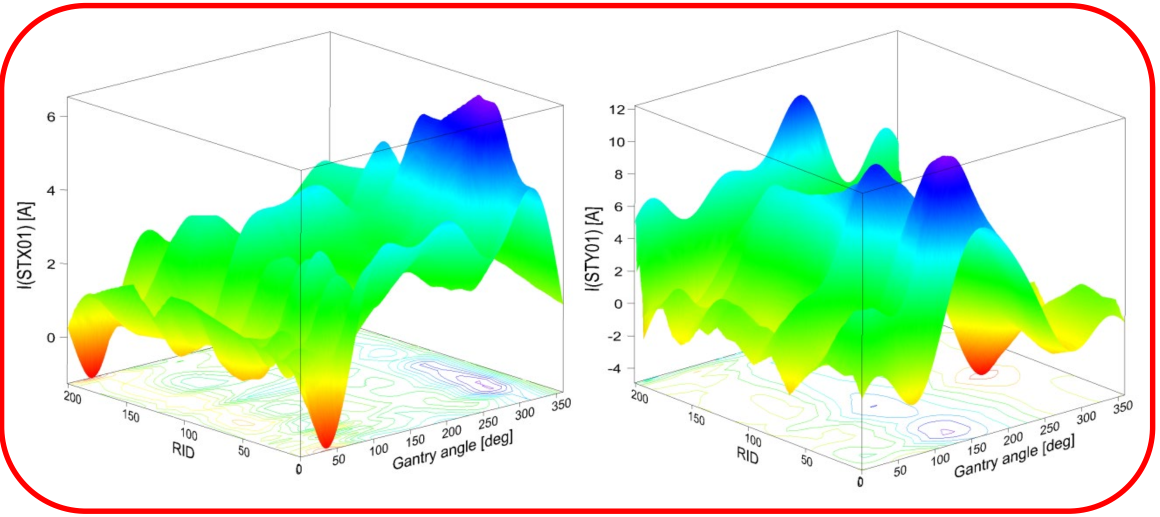
Parameter sets were interpolated to provide beams by angular step of Δθ=1 degree.

Centering beam spots

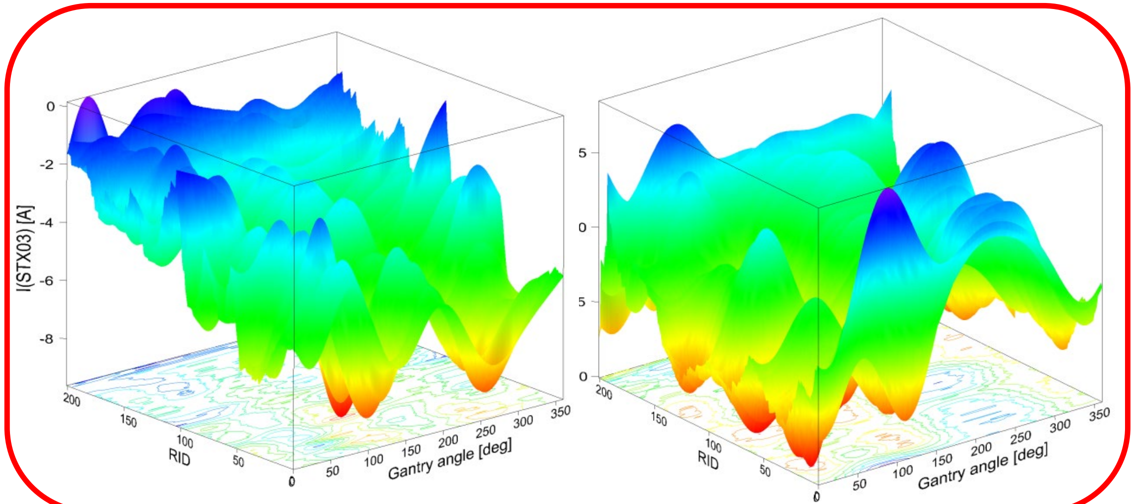


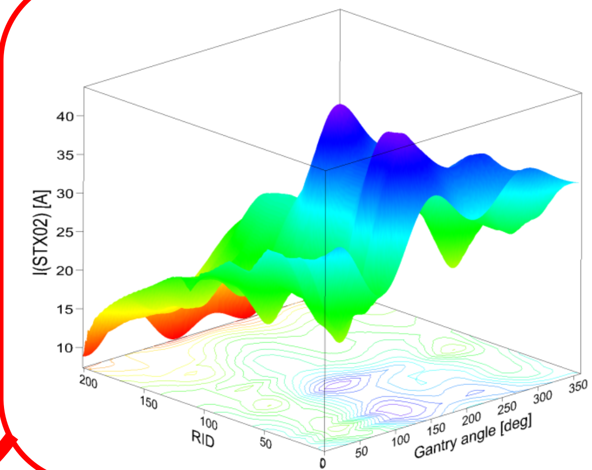




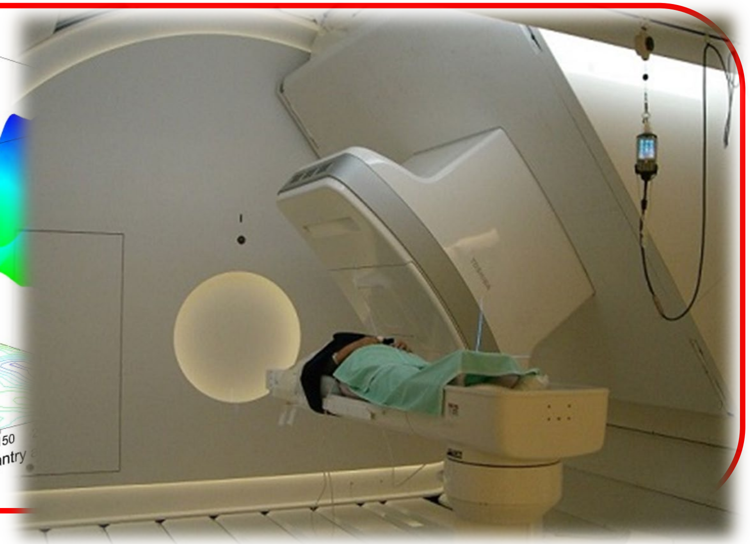


Centering beam spots





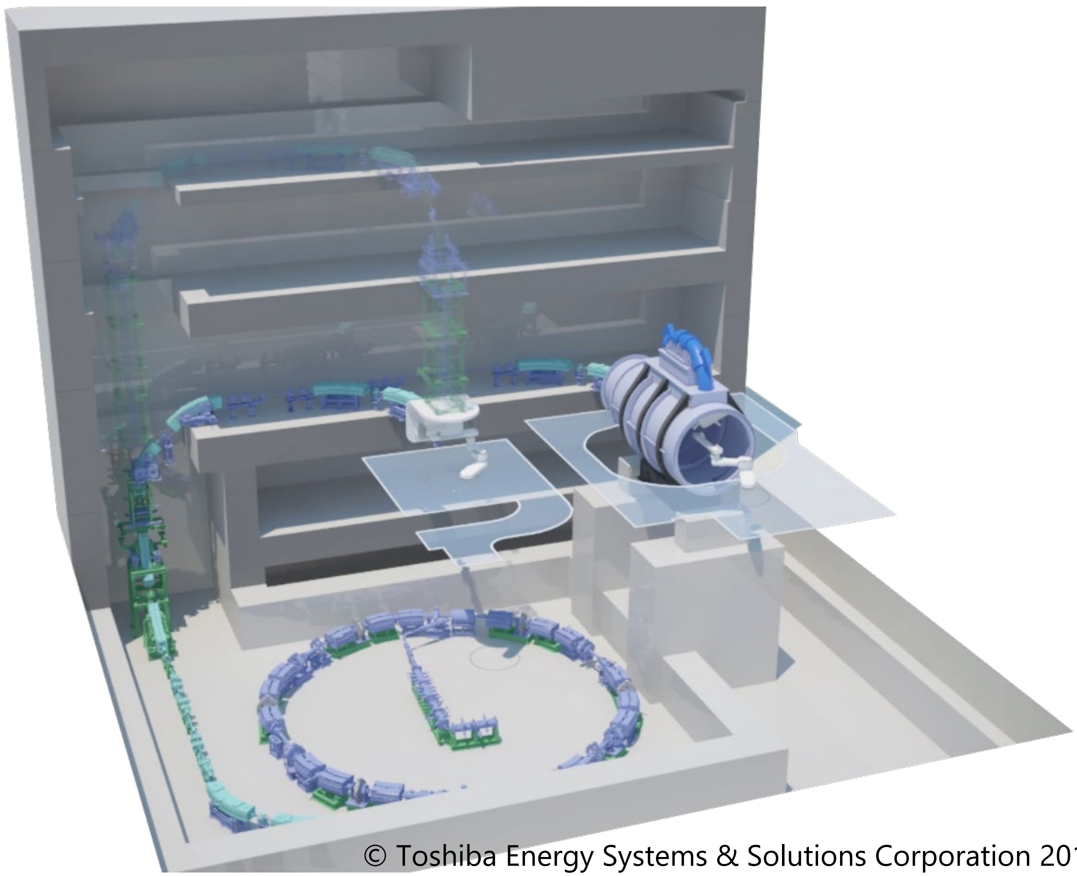
After series of beam commissioning, treatment using the gantry began since May 2017!



Future plans

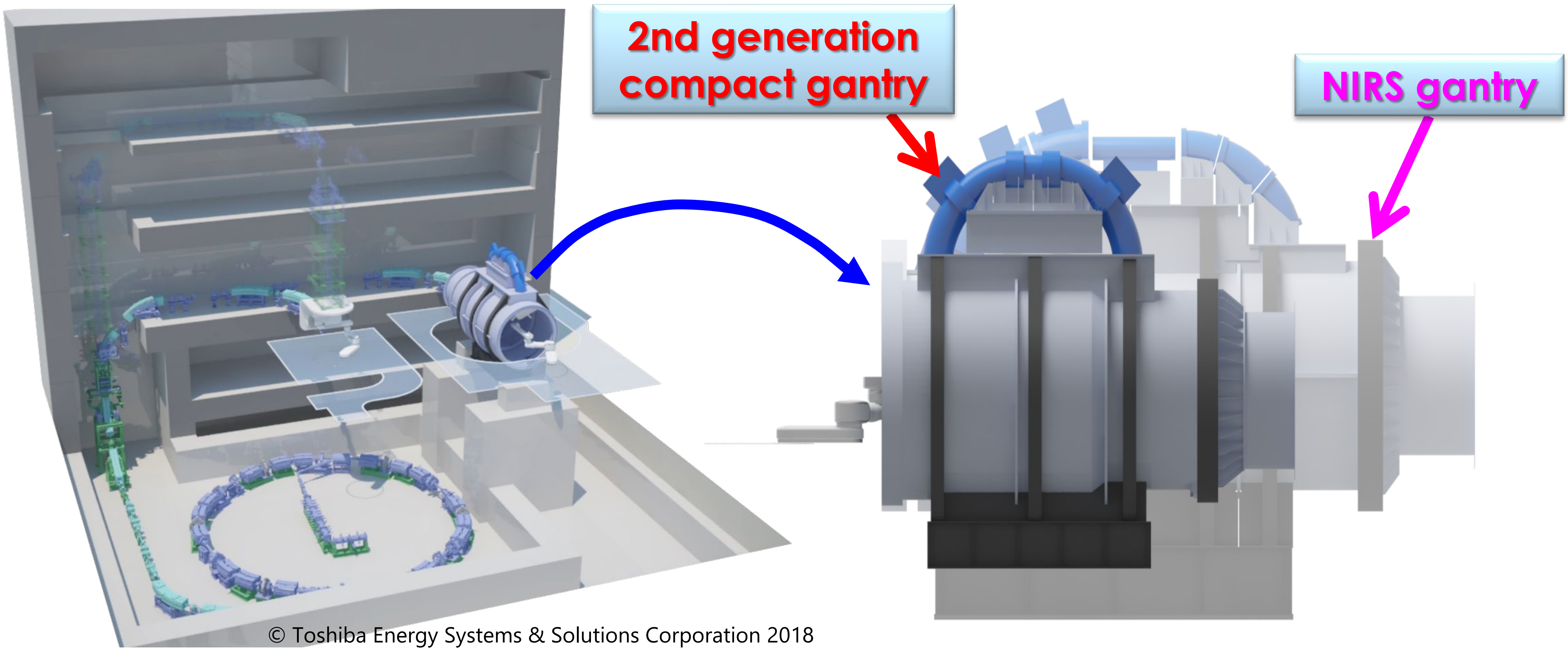
2nd-generation SC gantry

- A compact facility for CIRT is being constructed at Yamagata University.



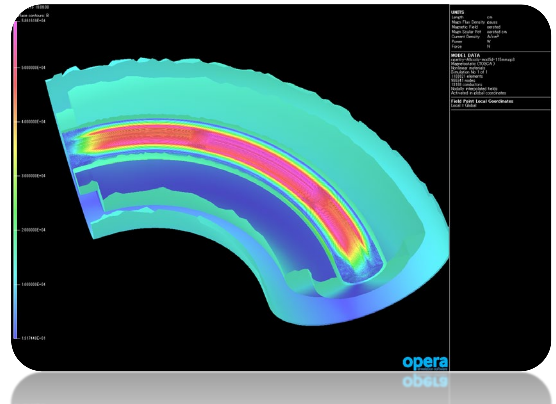
2nd-generation SC gantry

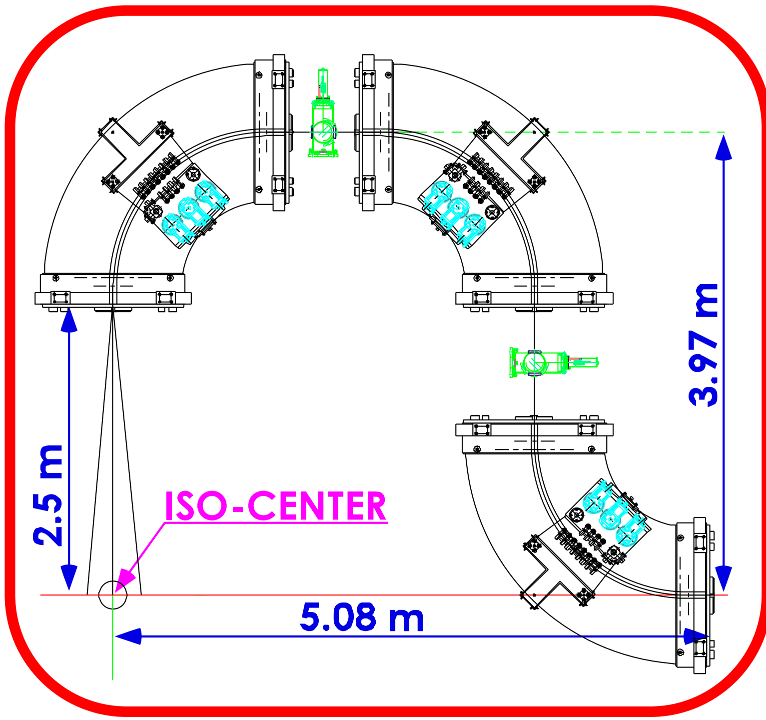
- A compact facility for CIRT is being constructed at Yamagata University.
- <u>2nd-generation compact gantry</u> will be installed.

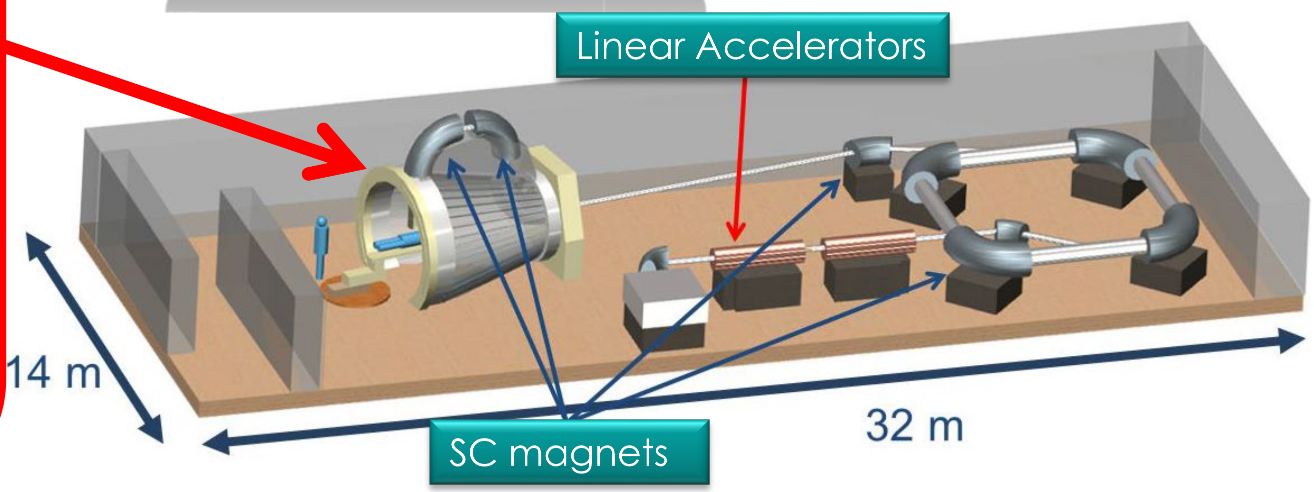


3rd-generation SC gantry

- Combined function SC magnets **(B_{max}~5 Tesla)**
- A size and weight will be **smaller than those of proton gantries**







Summary

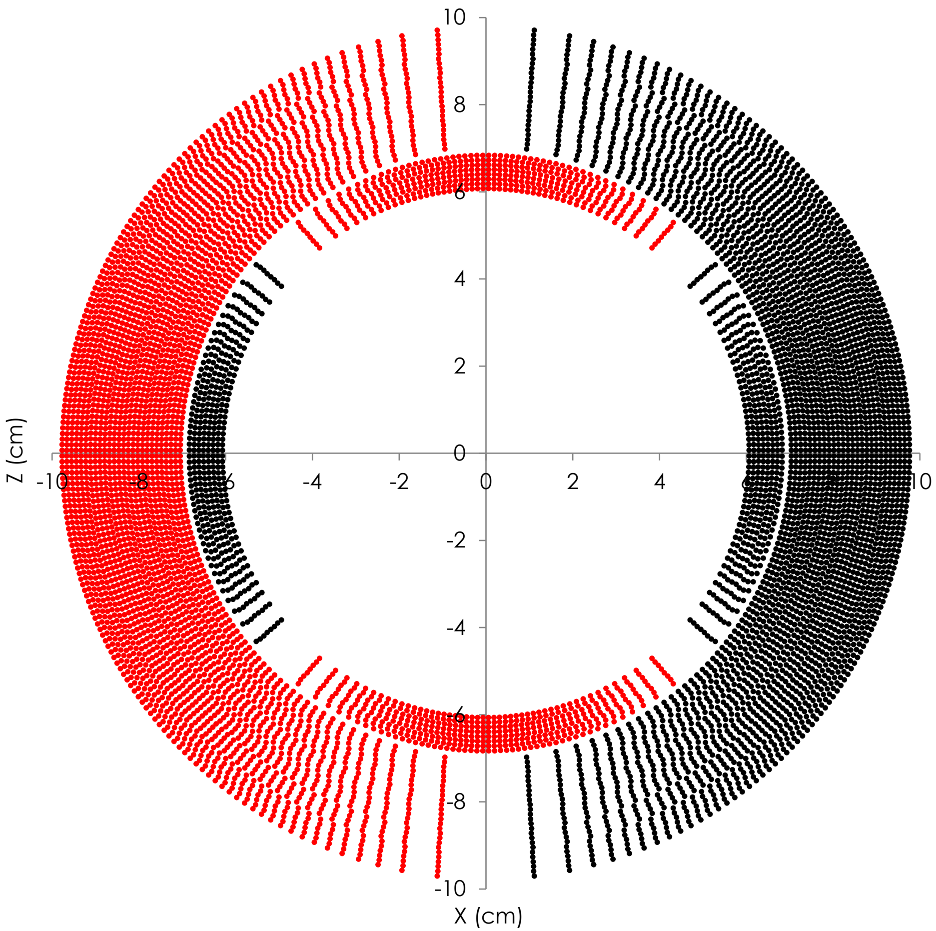
- CIRT using HIMAC has been performed since 1994, and more than 11,000 patients were treated at NIRS.
- The SC gantry as well as the fast 3D raster-scanning irradiation, were developed.
- After series of the commissioning works, cancer treatment using the SC gantry began since May 2017.
- The next-generation compact gantries are being developed.

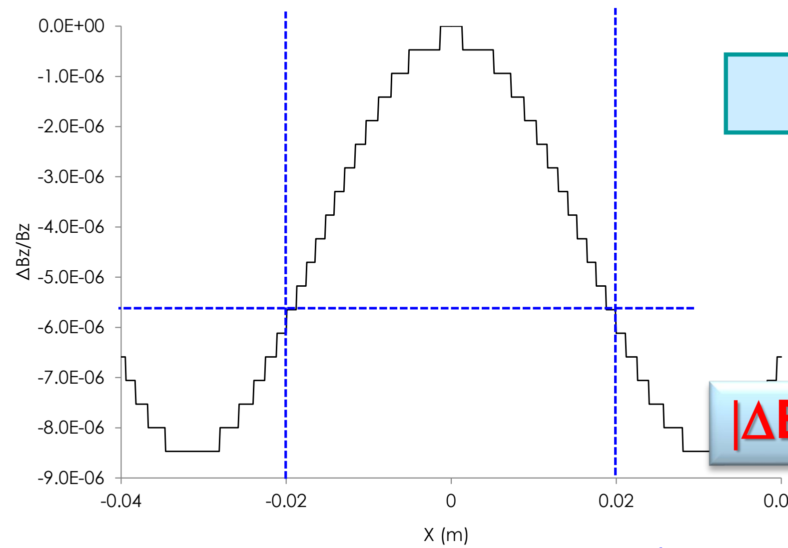
Collaborators

- T. Shirai, T. Fujita, T. Furukawa, Y. Hara, S. Matsuba, K. Mizushima, T. Murakami, K. Noda, N. Saotome, Y. Saraya, S. Sato, T. Shirai, R. Tansho (NIRS, QST)
- T. Fujimoto, H. Arai, et al. (AEC)
- T. Ogitsu (KEK)
- T. Obana (NIFS)
- N. Amemiya (Kyoto Univ.)
- T. Orikasa, S. Takayama, et al. (Toshiba Corp.)

Design of SC coils

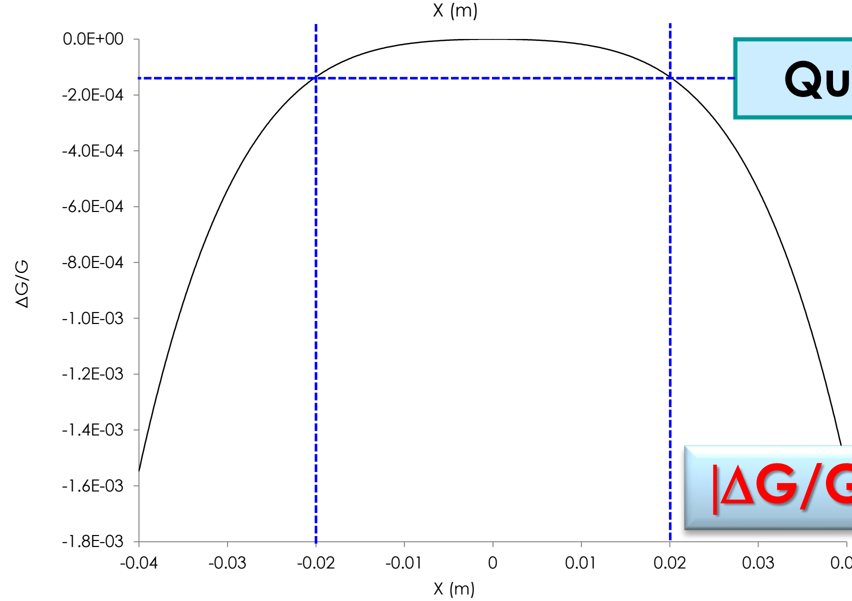
2D field calculation





Dipole

$|\Delta B/B| < 6\times10^{-6}$

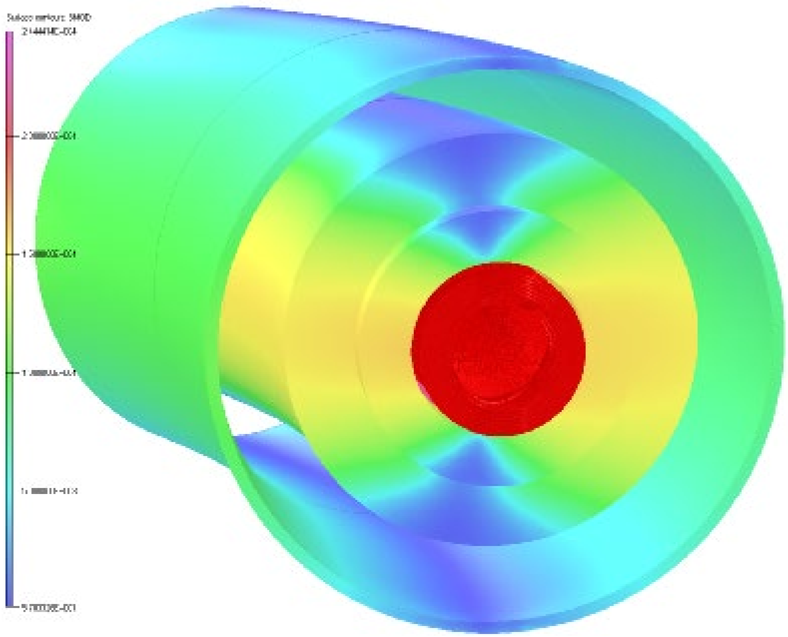


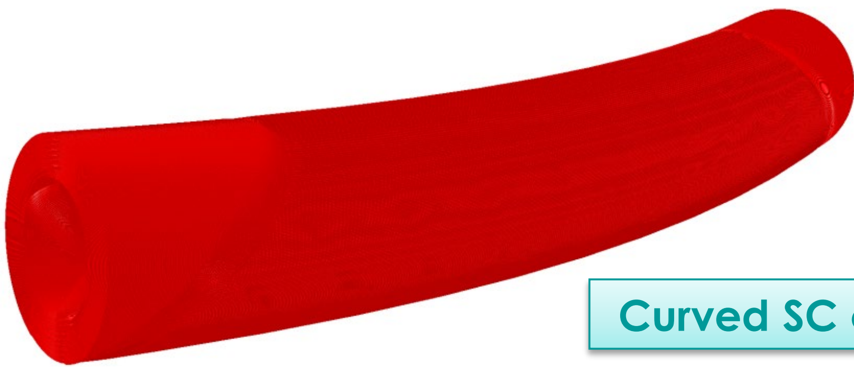
Quadrupole

$|\Delta G/G| < 2\times10^{-4}$

3D field calculation with Opera-3d

SC coils were precisely modelled



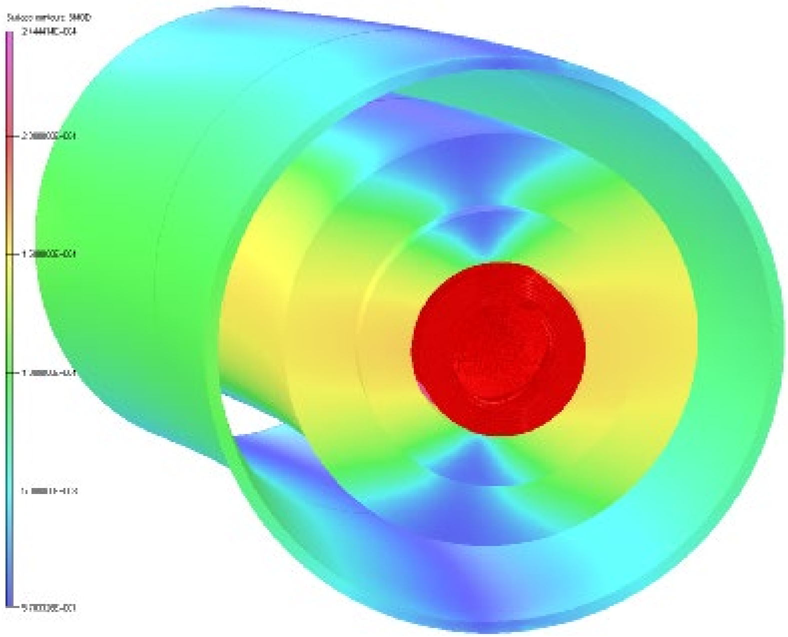


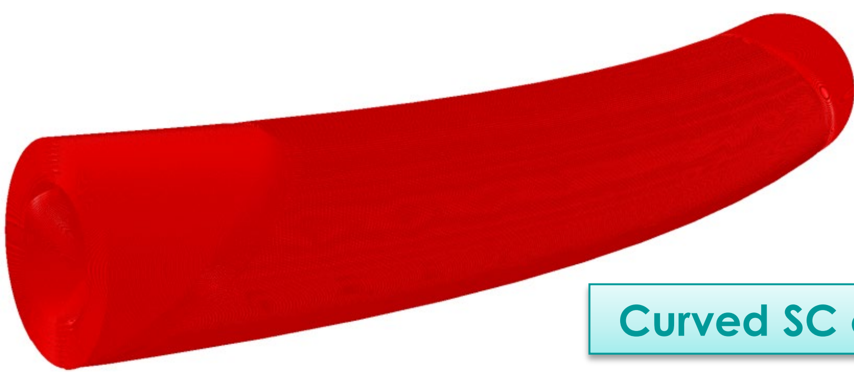
Curved SC coil

NIRS HIMAC

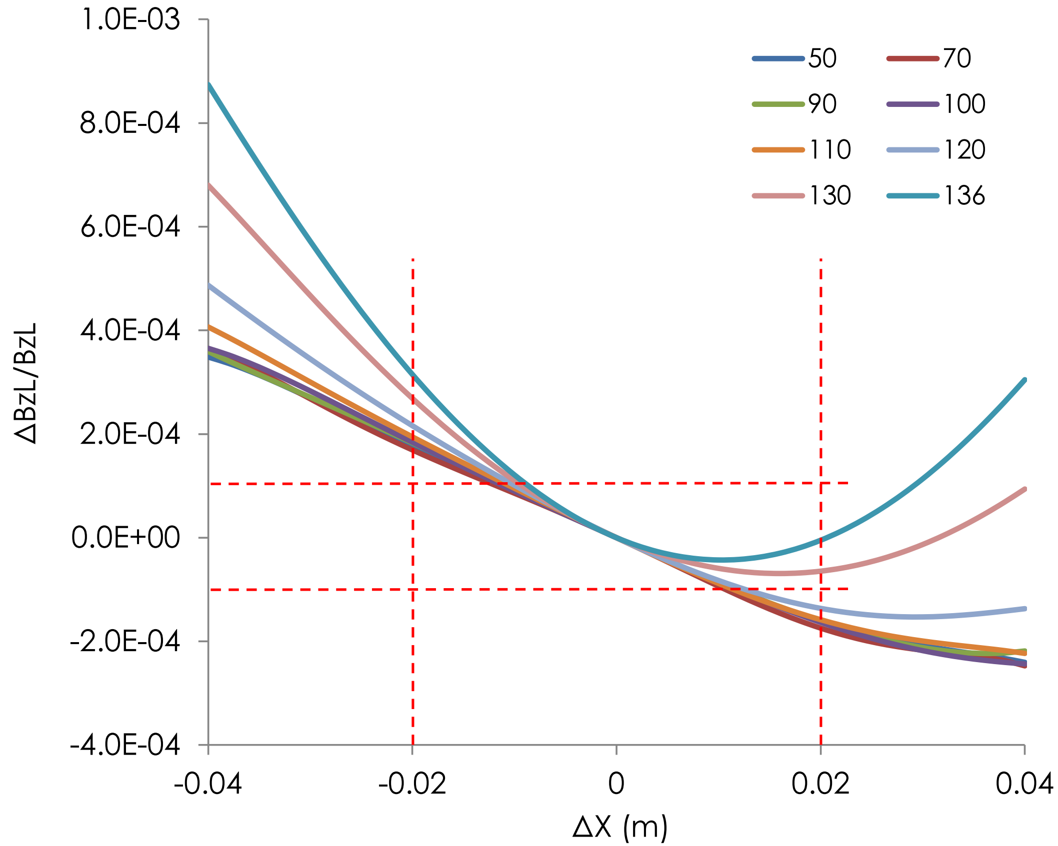
3D field calculation with Opera-3d

SC coils were precisely modelled





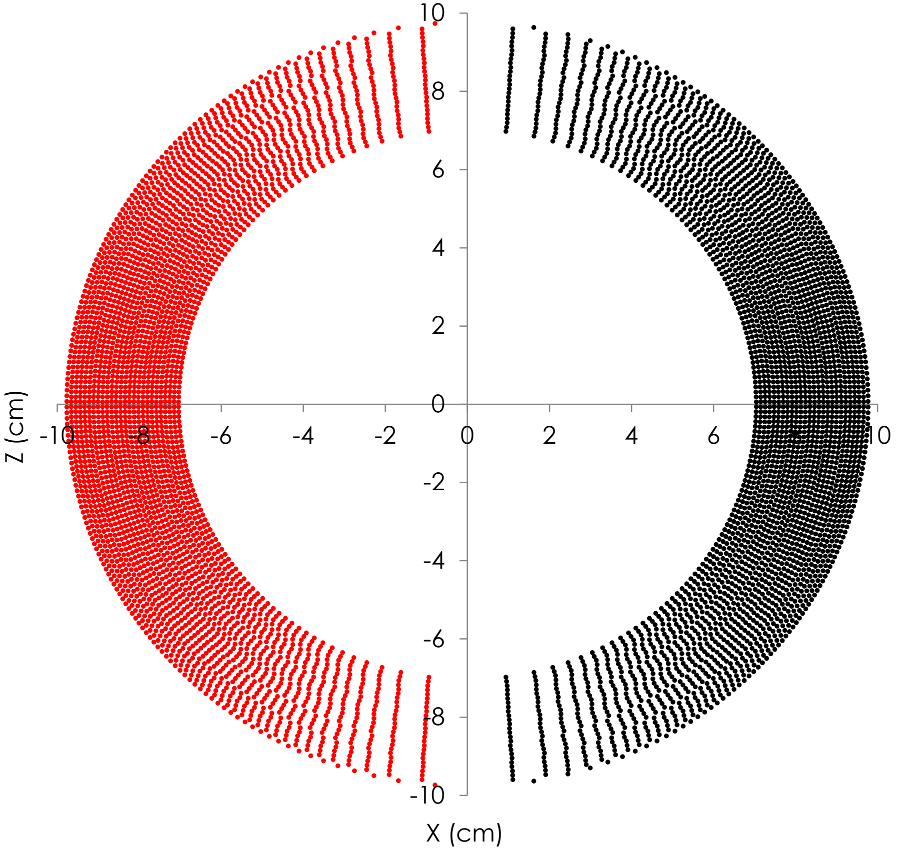
Curved SC coil



$|\Delta BL/BL| < 4\times 10^{-4}$

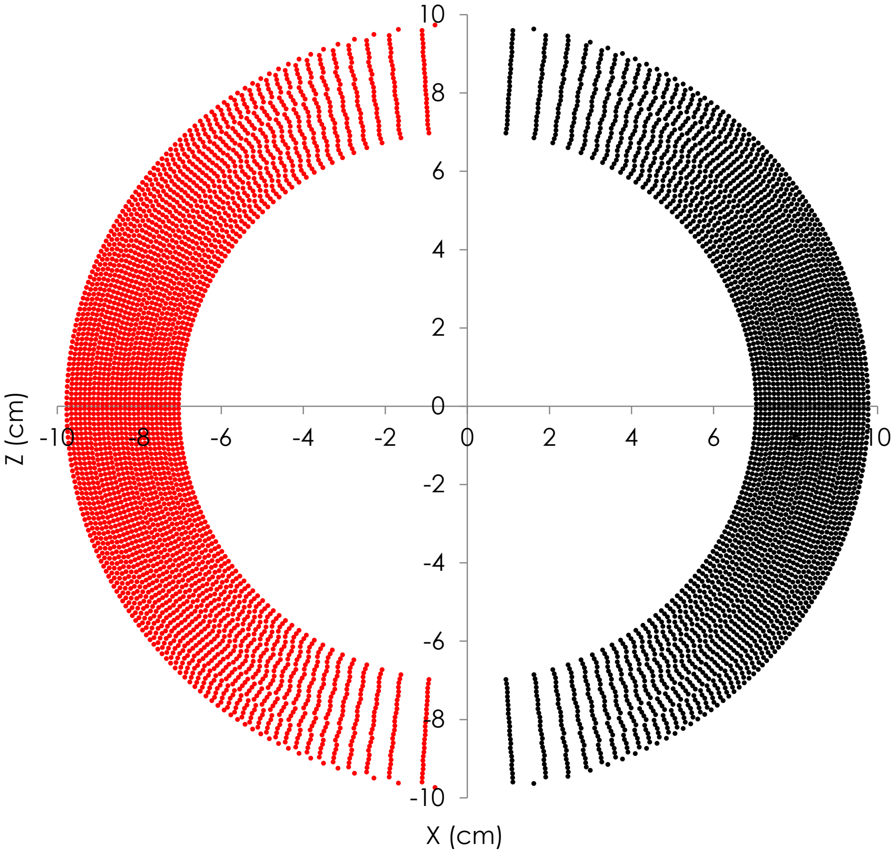
Corrections with the outermost layer

Coil positions of the outermost layer were modified to cancel out the measured multi-pole components

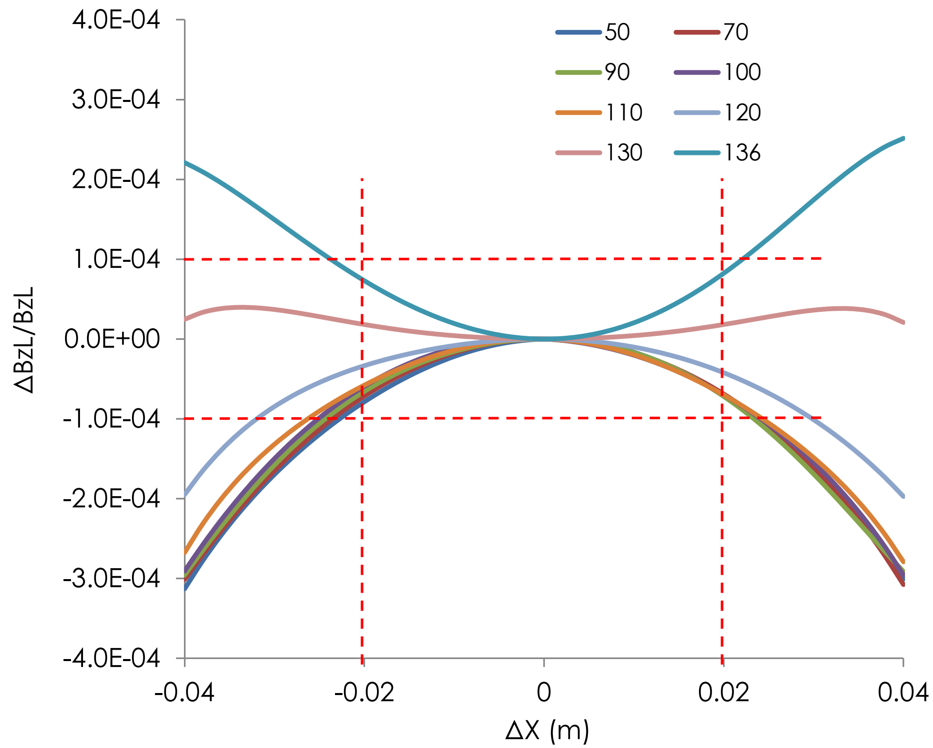


Corrections with the outermost layer

Coil positions of the outermost layer were modified to cancel out the measured multi-pole components



Corrected uniformity



$|\Delta BL/BL| < 1\times10^{-4}$!