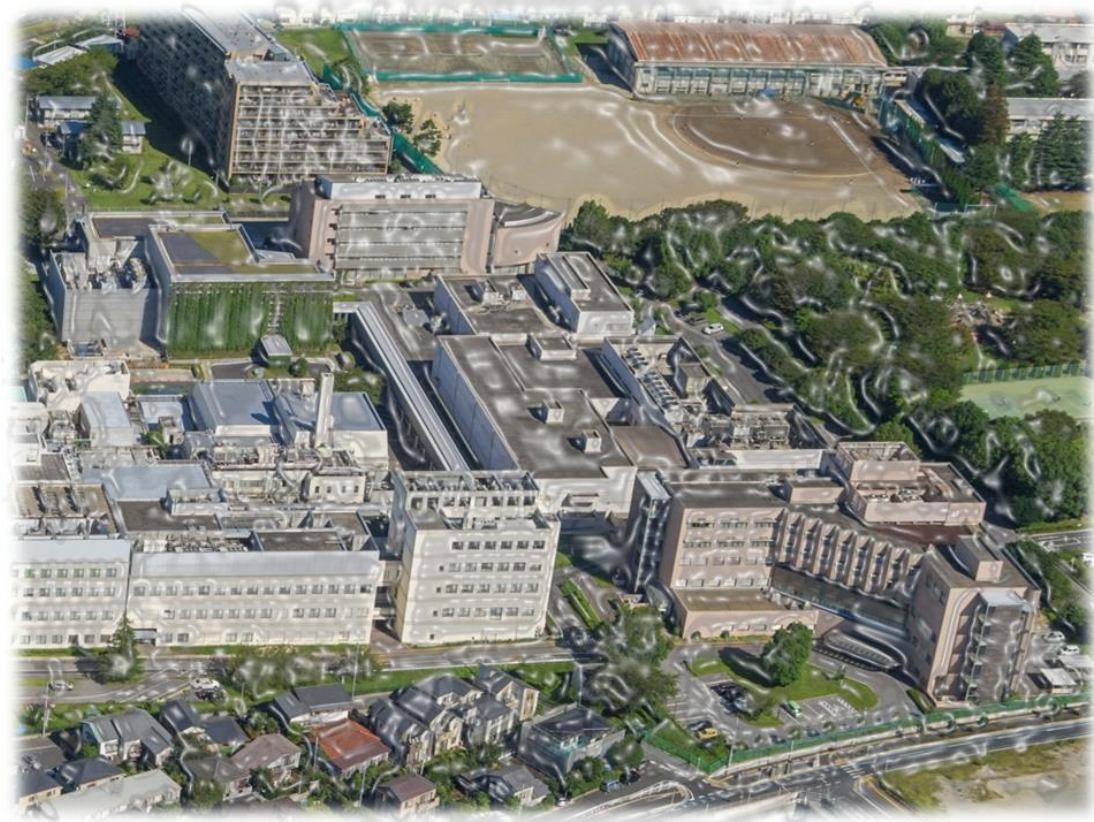
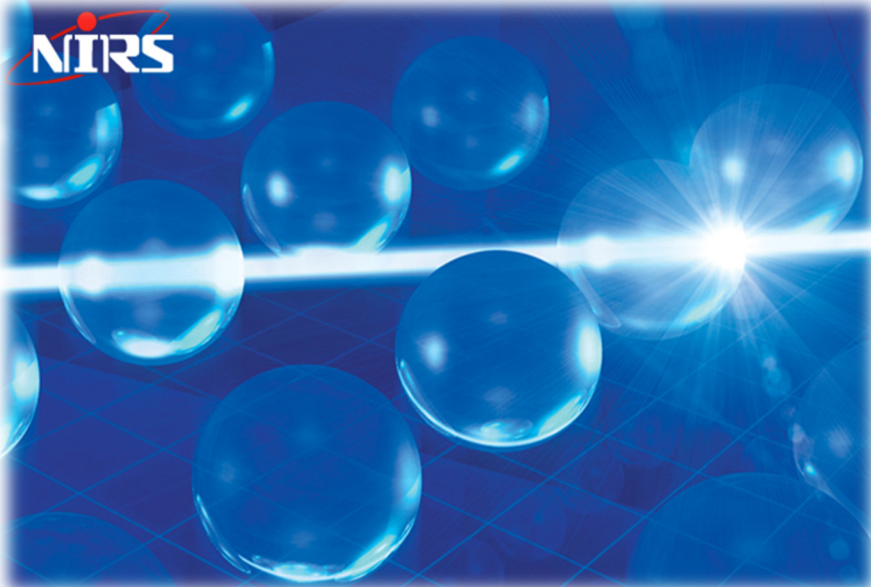


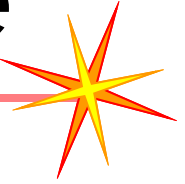
Superconducting Gantry for Carbon Ion Radiotherapy

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Department of Accelerator and Medical Physics,
National Institute of Radiological Sciences (NIRS)



2018/5/1



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



Introduction

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**

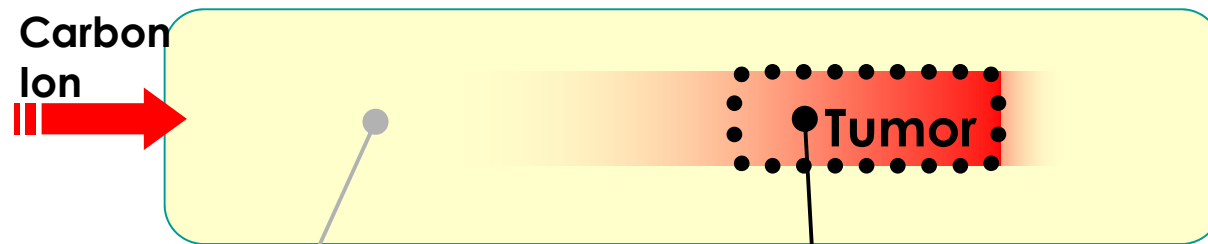
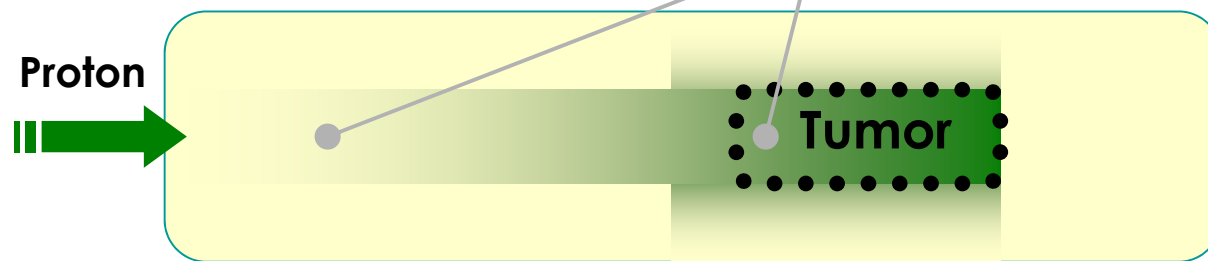
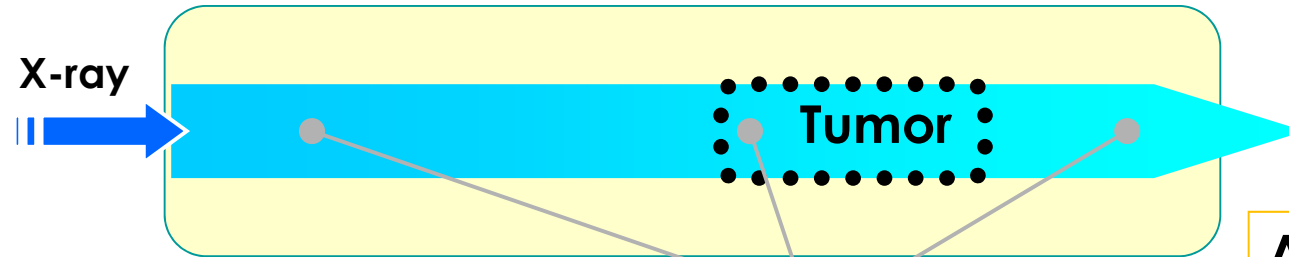
- QOL (Quality Of Life) after the treatment

- Small physical burden (good for aged people)

- **Effective for radiation-resistant tumors**

- (Carbon-ion radiotherapy)**

Comparison between X-ray and particle therapy



RBE is low as of p or X-ray

RBE is higher at tumor

Advantage of ion therapy

- Physical dose can be concentrated due to Bragg peak

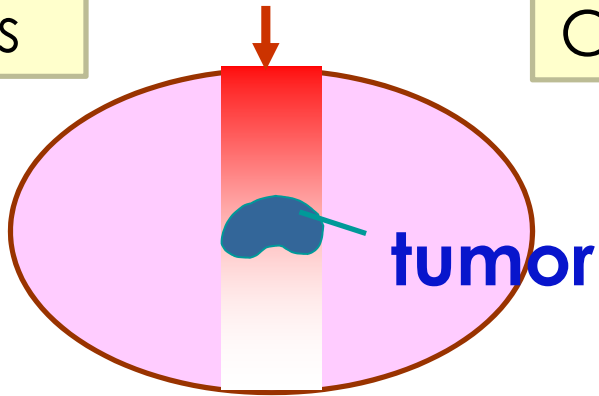
(Carbon therapy)

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

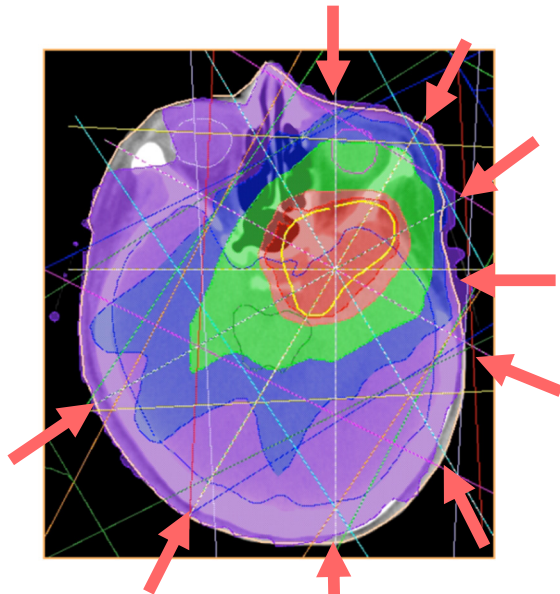
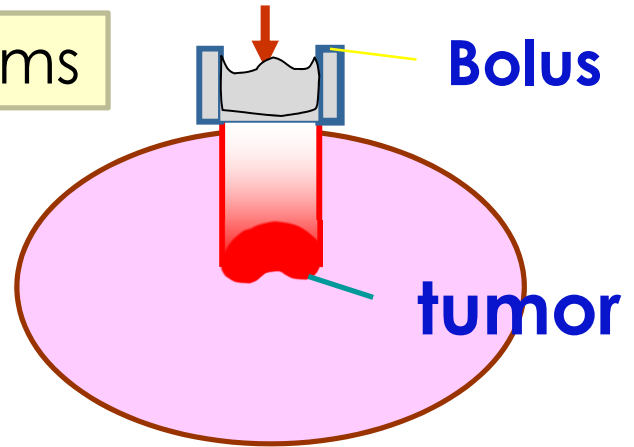
Dose distribution of X-ray and Carbon beams



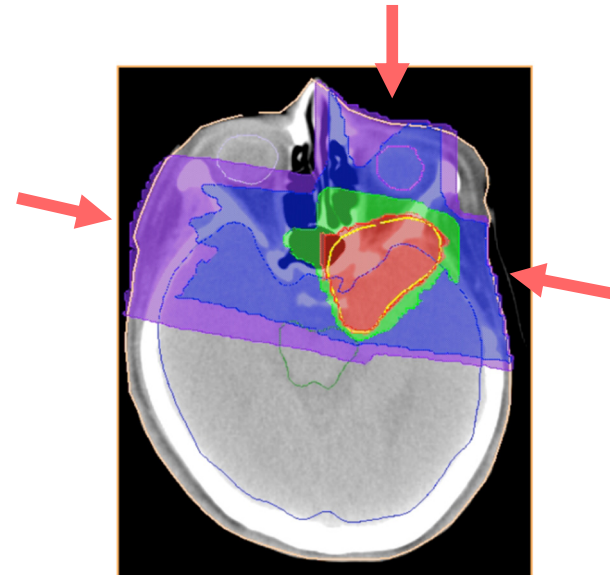
X-rays



Carbon beams



9 directions

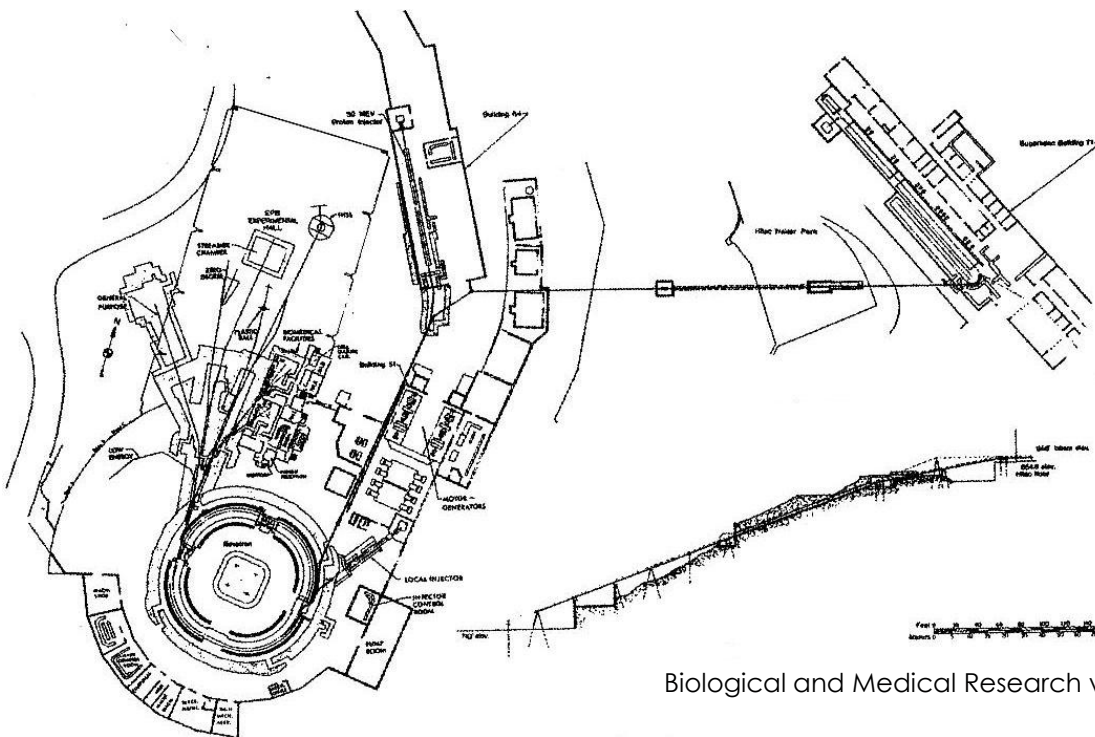


3 directions

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.

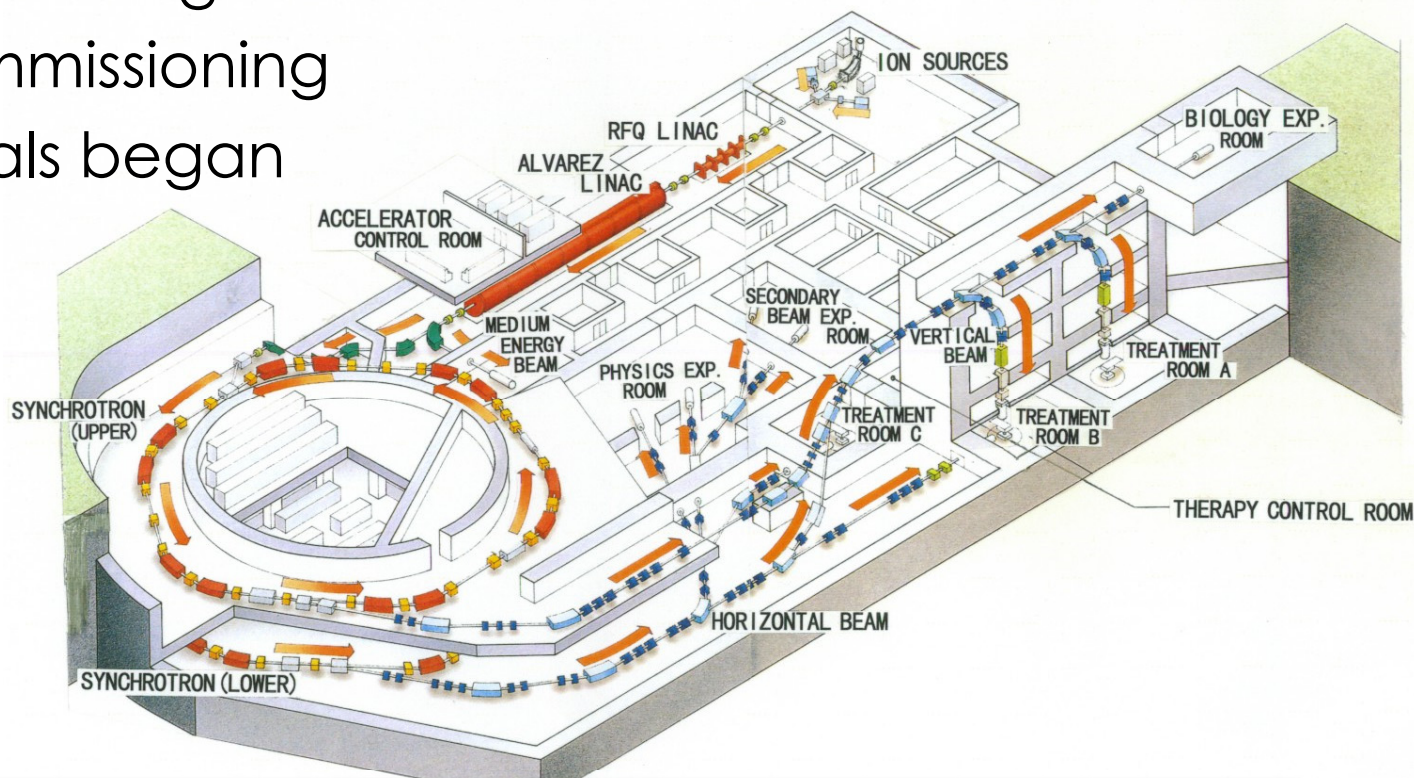


Biological and Medical Research with Accelerated Heavy Ions at the Bevalac, LBL-11220, UC-48 (1980).
E.A. Blakely *et al.*, *Adv. Radiat. Biol.* 11, 295 (1984).
W.T. Chu *et al.*, *Rev. Sci. Instrum.* 64, 2055 (1993).

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



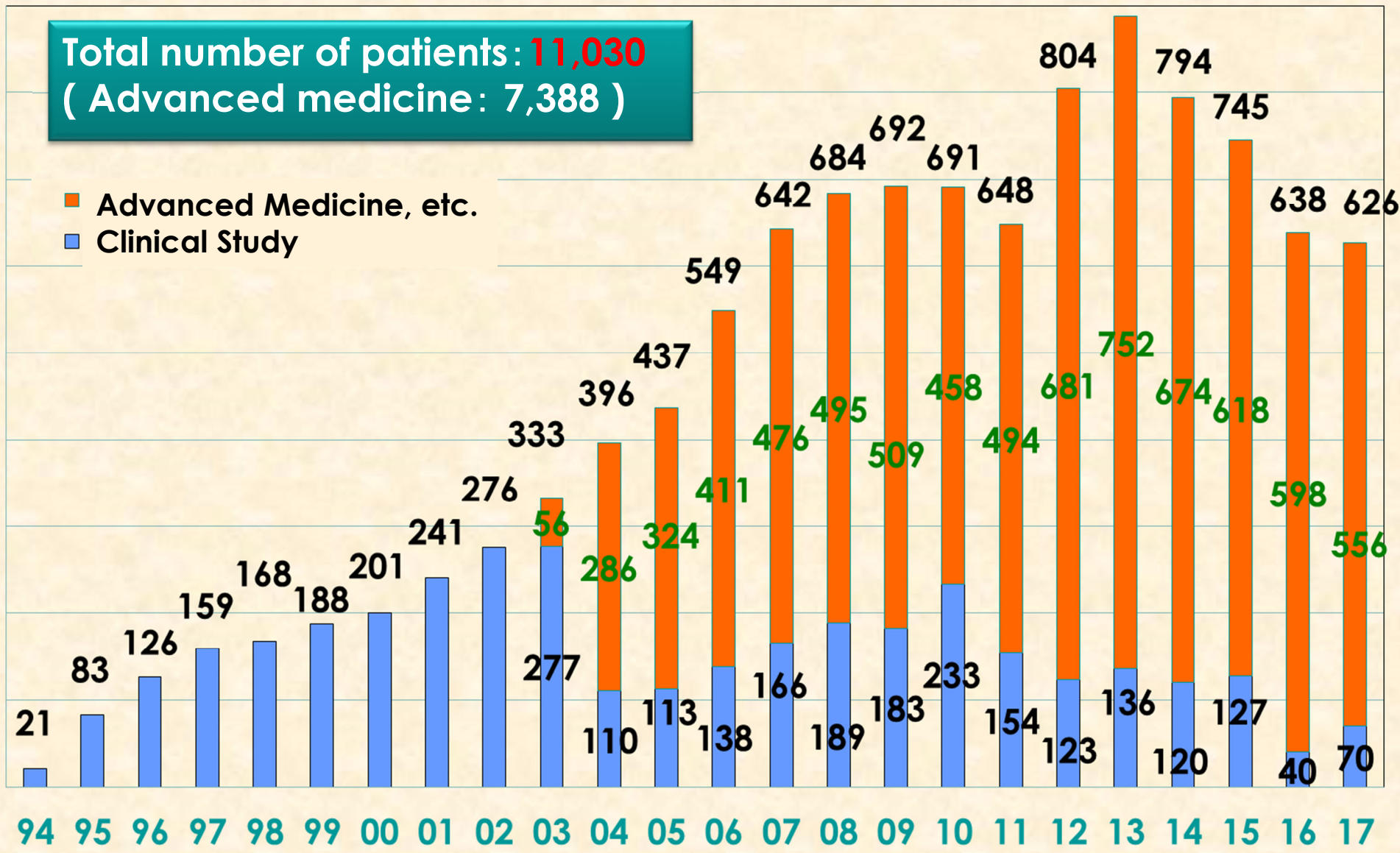
HIMAC can accelerate heavy ions having $q/m=1/2$ up to $E/A=800$ MeV

Patients treated with CIRT at NIRS

#patients

Total number of patients: 11,030
(Advanced medicine: 7,388)

- Advanced Medicine, etc.
- Clinical Study



Year

1994.6 - 2018.3.6



Gantry Development

New treatment facility



Construction completed in 2011

- **New development**

- **Fast 3D raster scanning**
- **Superconducting rotating-gantry**

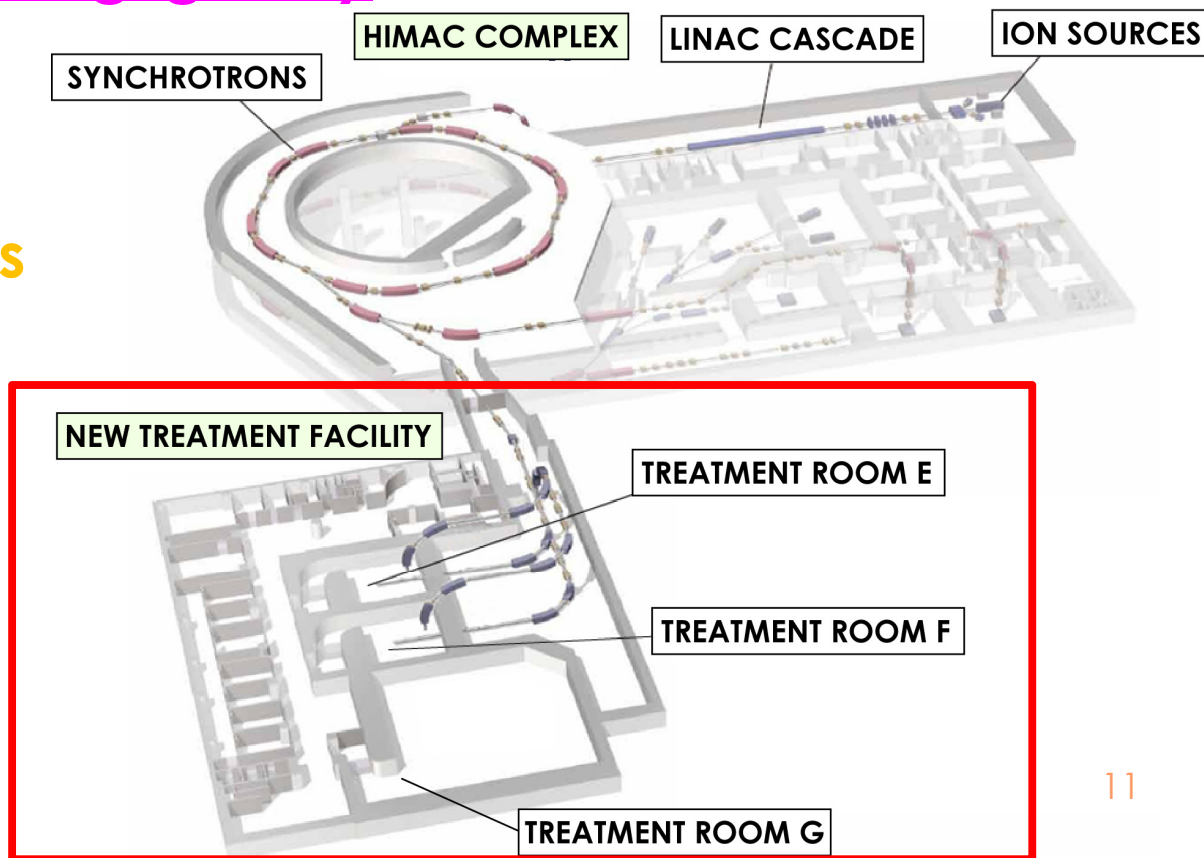
- **3 treatment rooms**

- **Room E & F**

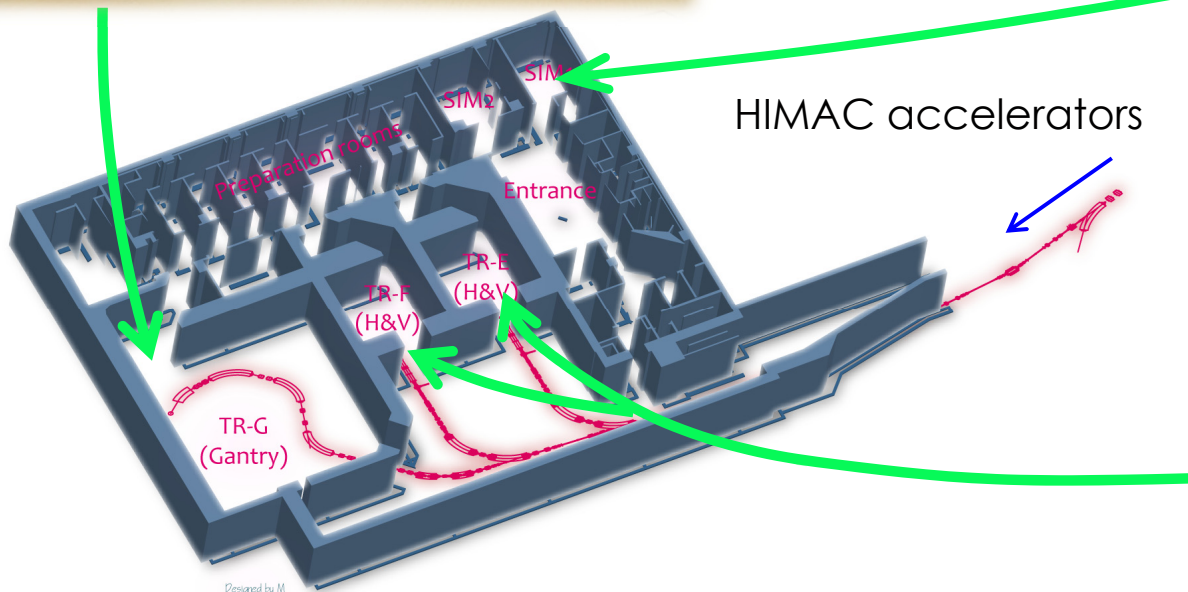
Fixed H&V scanning ports

- **Room G**

Rotating-gantry port



Treatment floor (B2F)



Irradiation using fixed irradiation ports



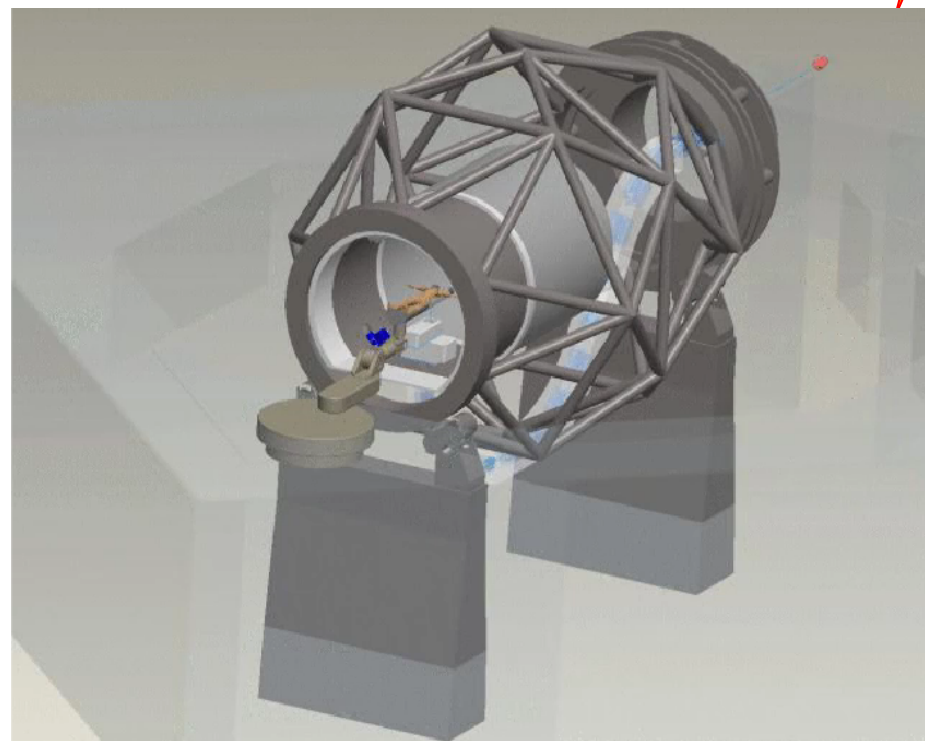
Treatment for a lung cancer with 4 directions

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 B_p is 3 times higher
 - Magnets will be very large and heavy
- Difficult to
 - Design
 - Construct



Rotating gantry for carbon therapy

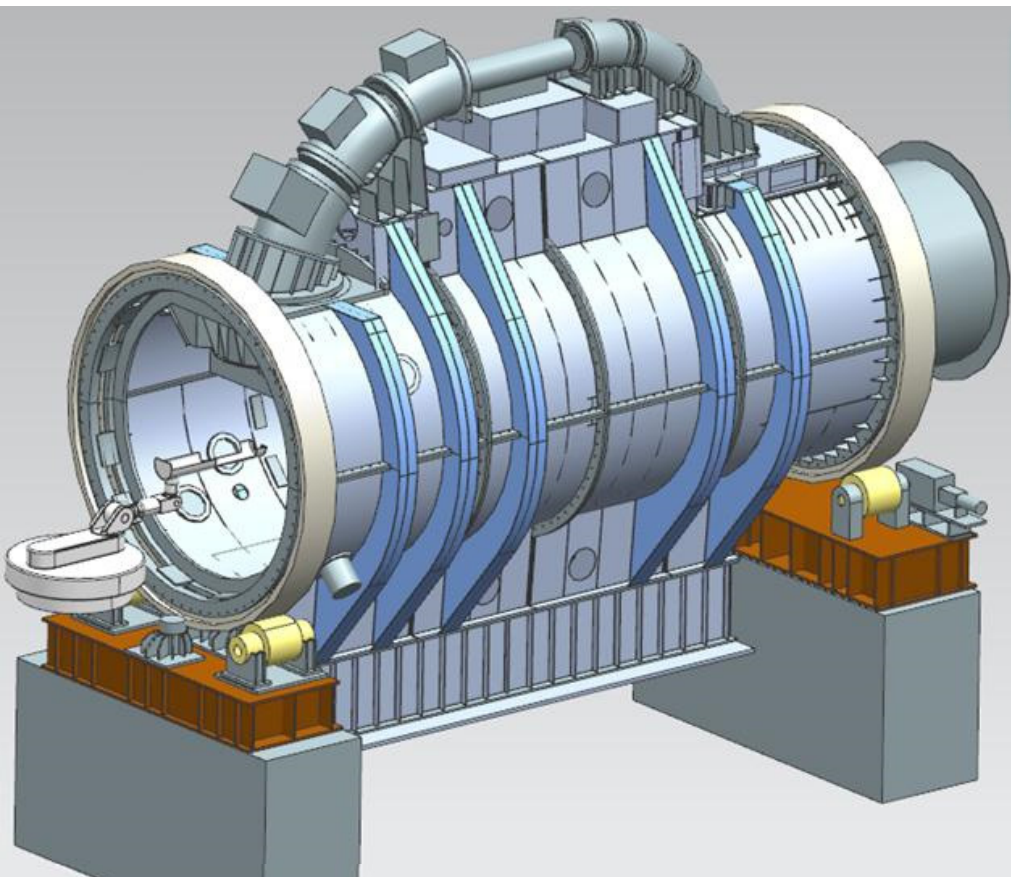
- **World-first carbon-gantry**
 - HIT @ Heidelberg, Germany
 - Clinical use since Nov. 2012
 - Weight: **600 tons** (rotating part)





Design of SC rotating-gantry

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

Weight: order of 300 tons

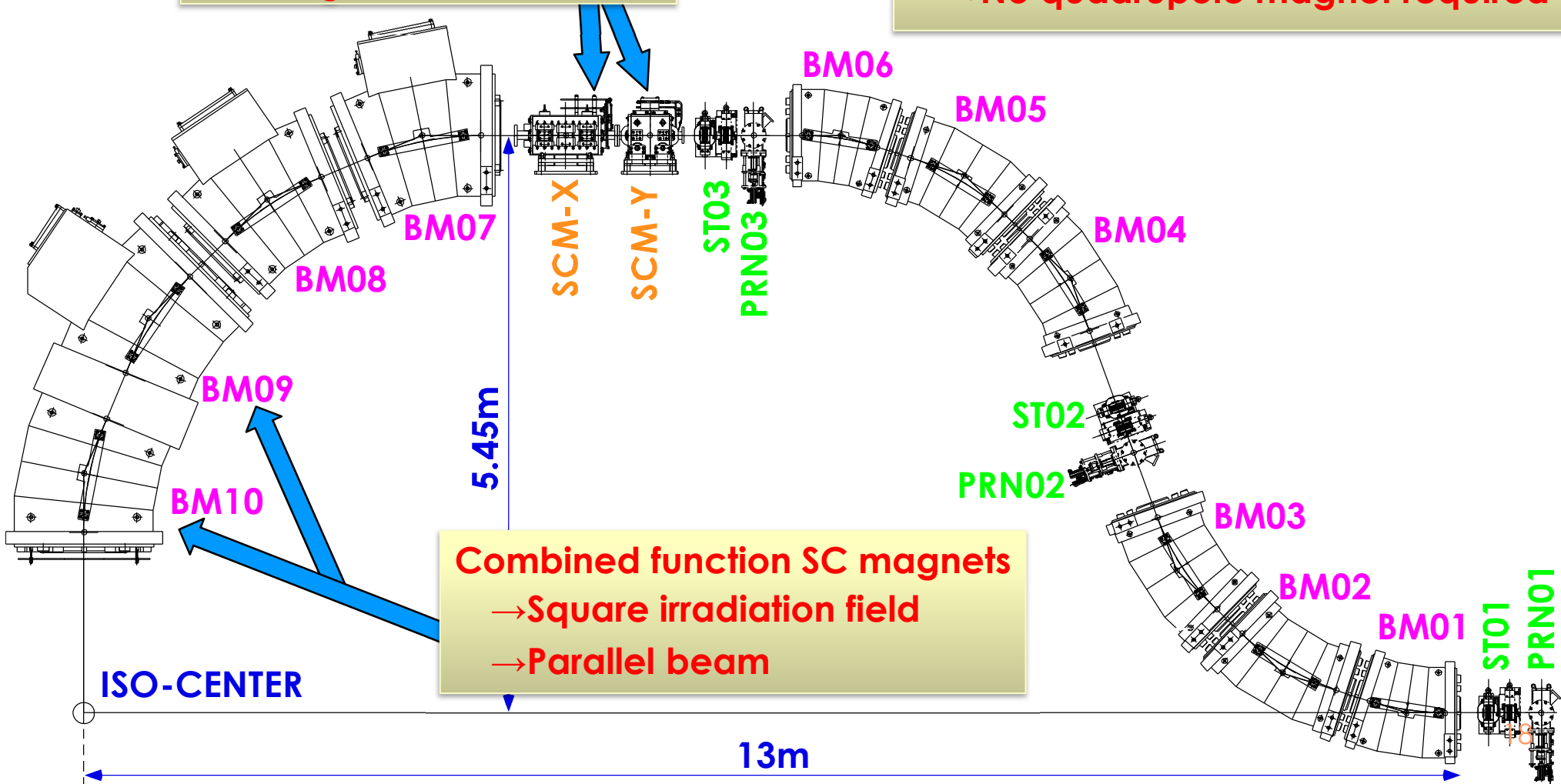
The size and weight are considerably reduced

Layout of the SC gantry



Scanning magnets on top
→ Large scan size

Combined function SC magnets
→ No quadrupole magnet required



ISO-CENTER

5.45m

13m

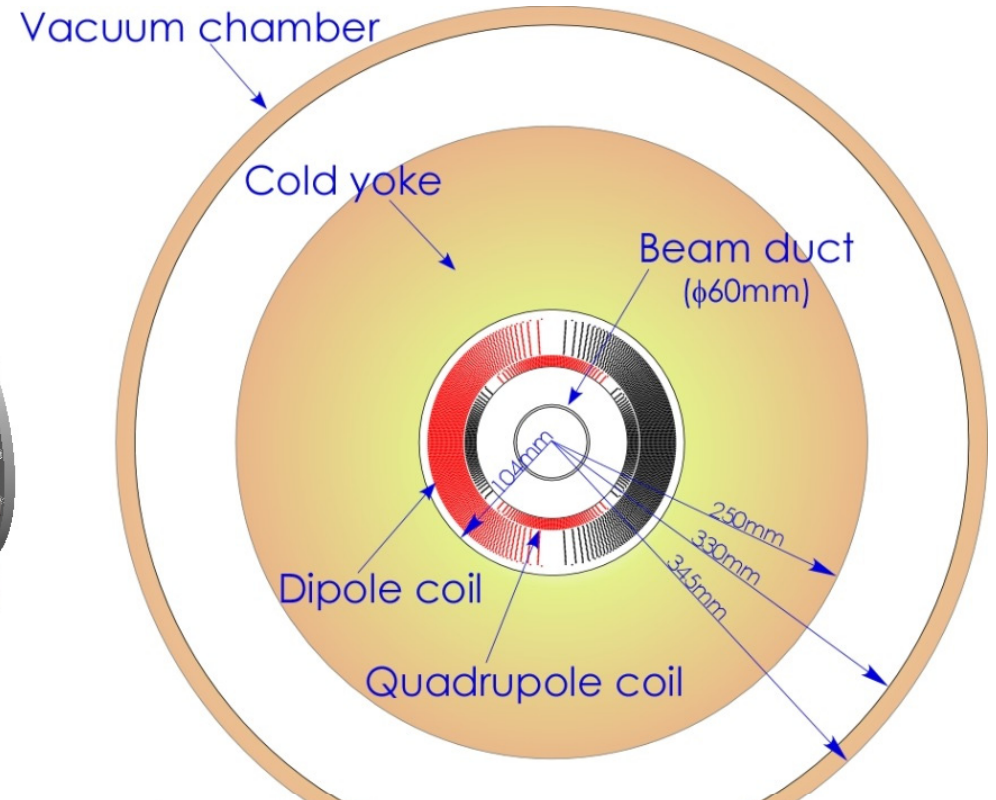
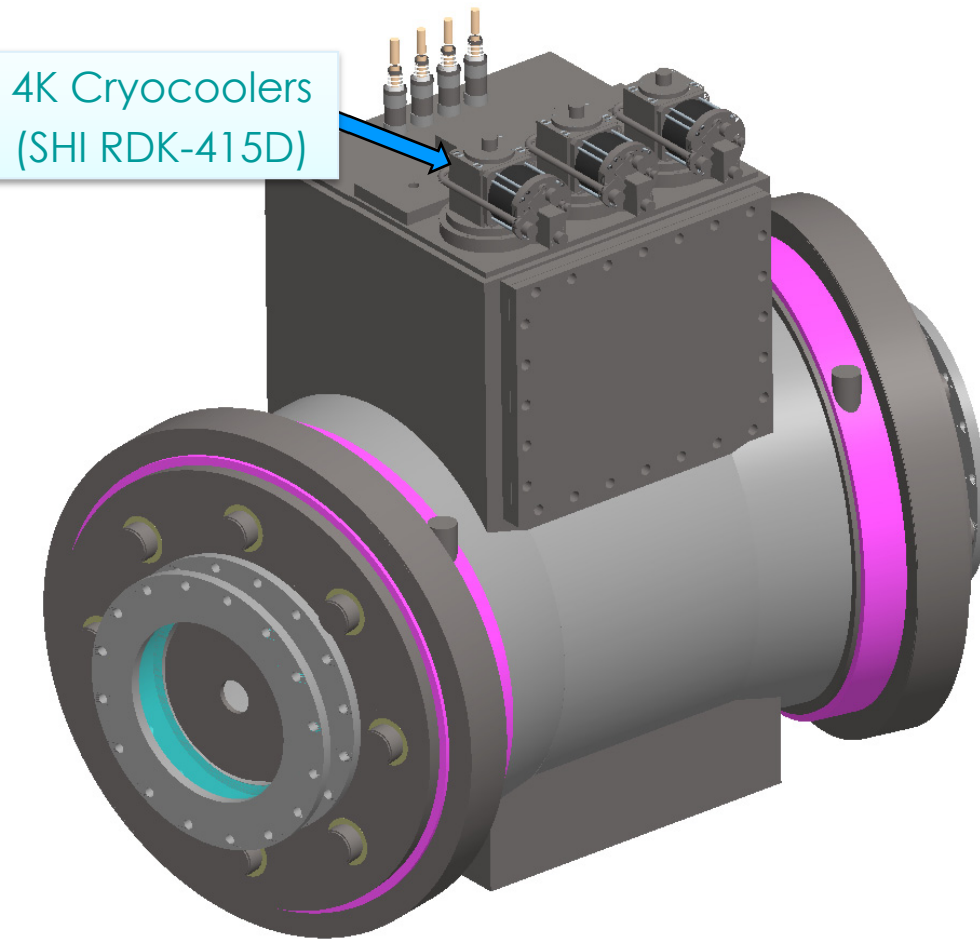
Combined function SC magnets
→ Square irradiation field
→ Parallel beam

Curved SC magnets for gantry



SC magnet (BM02-05)

Cross-sectional view

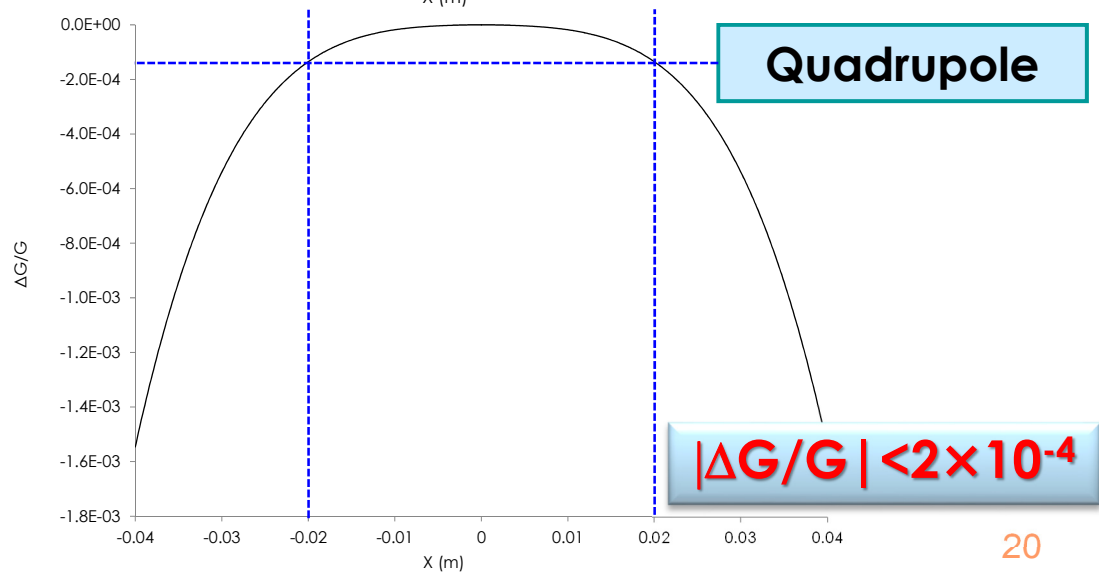
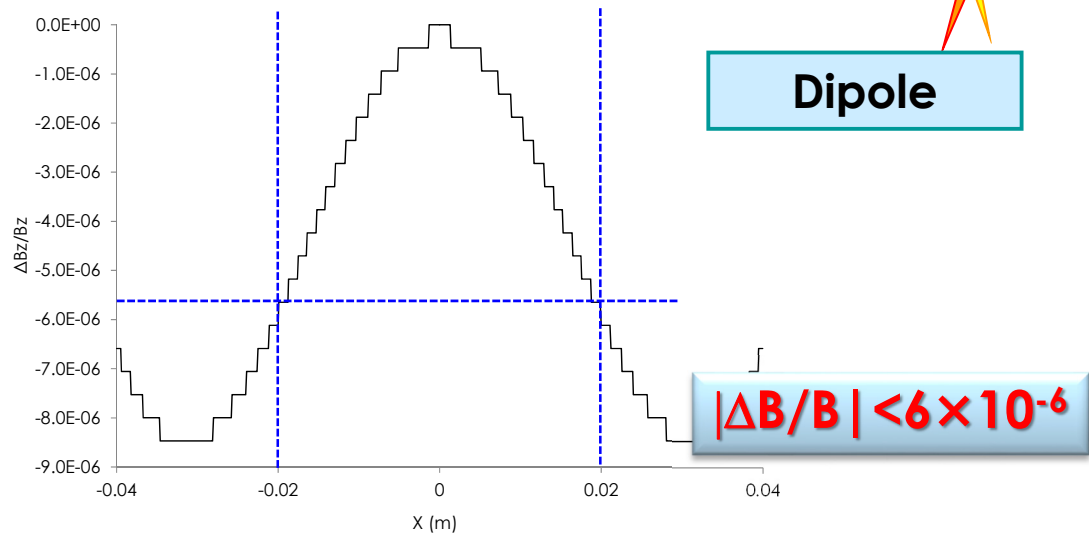
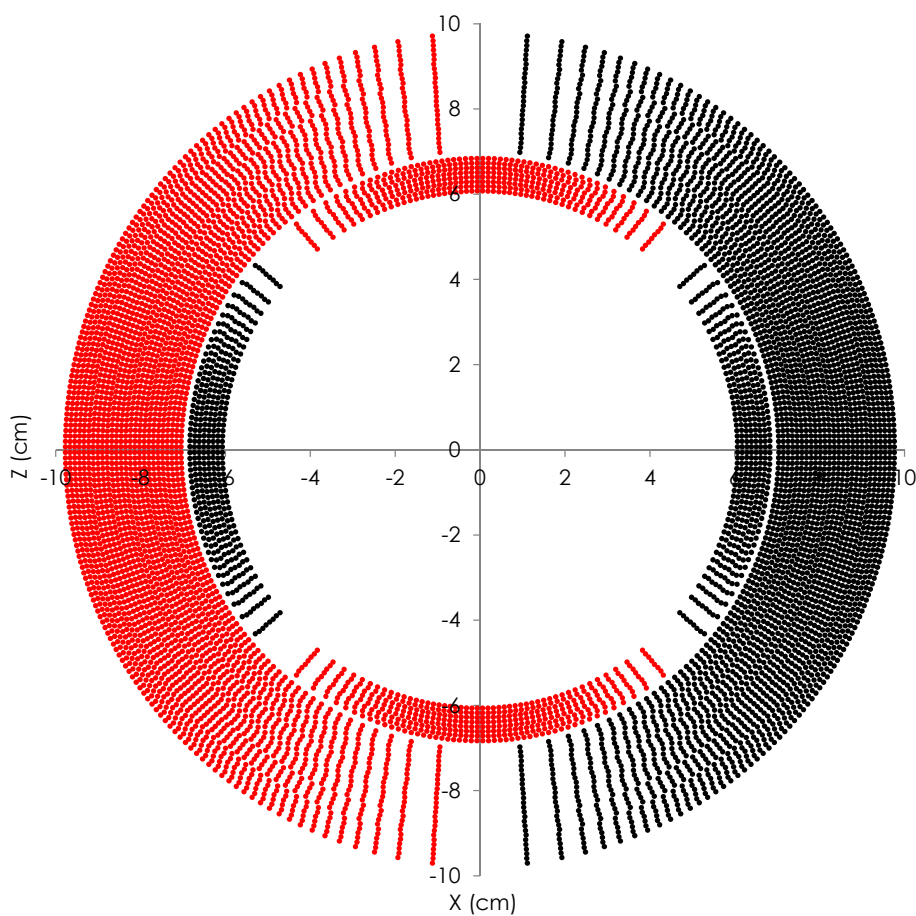


Dipole and quadrupole coils can be independently excited

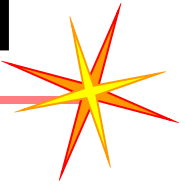
Design of SC coils



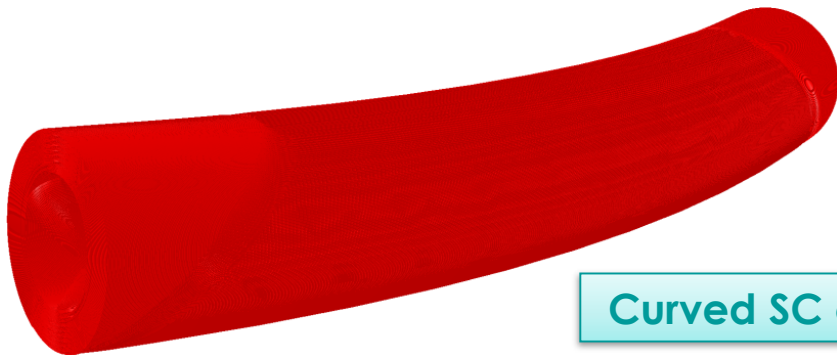
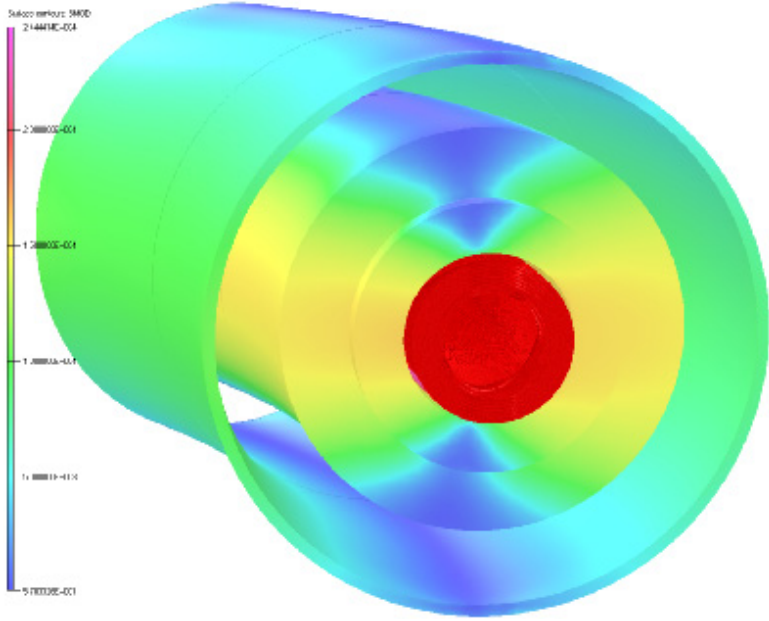
2D field calculation



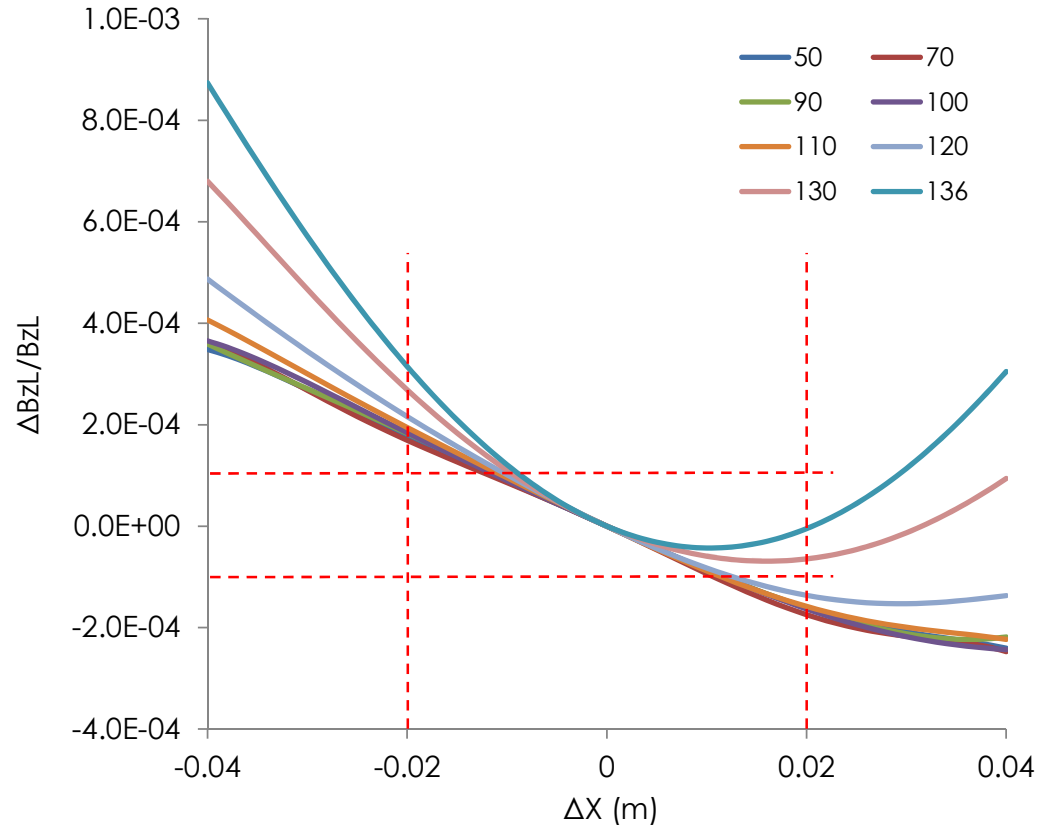
3D field calculation with Opera-3d



SC coils were precisely modelled



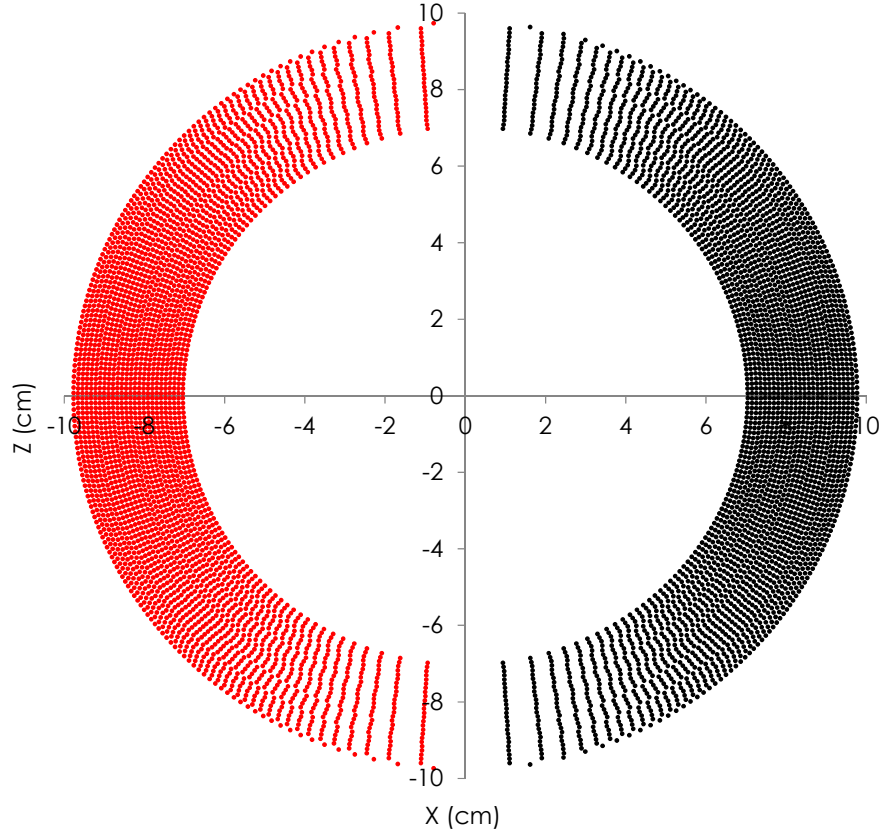
Curved SC coil



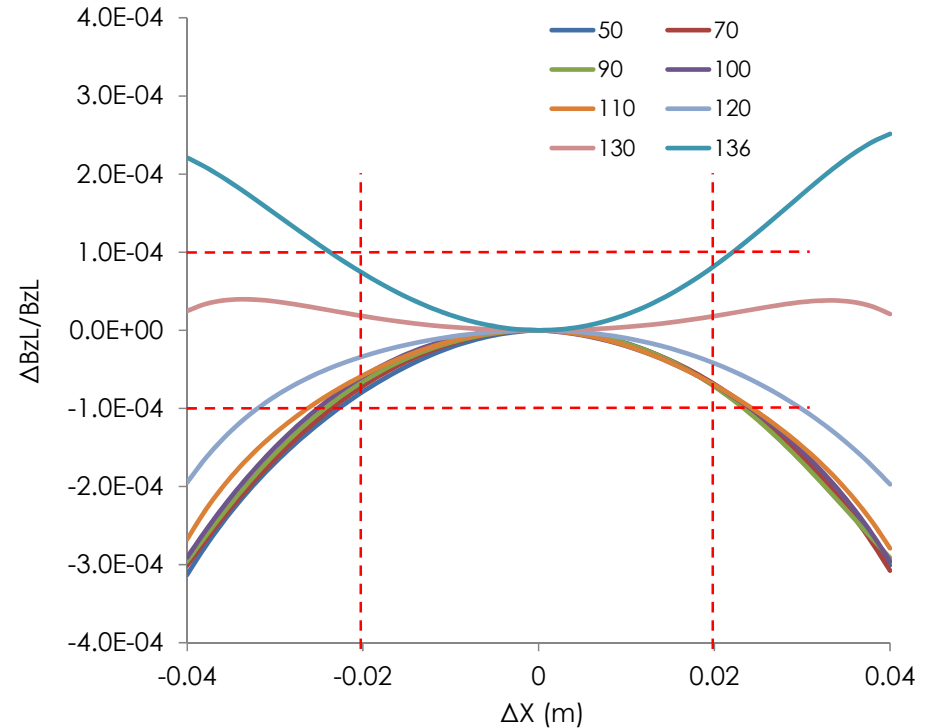
$|\Delta BL/BL| < 4 \times 10^{-4}$

Corrections with the outermost layer

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

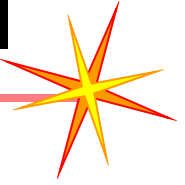


Corrected uniformity



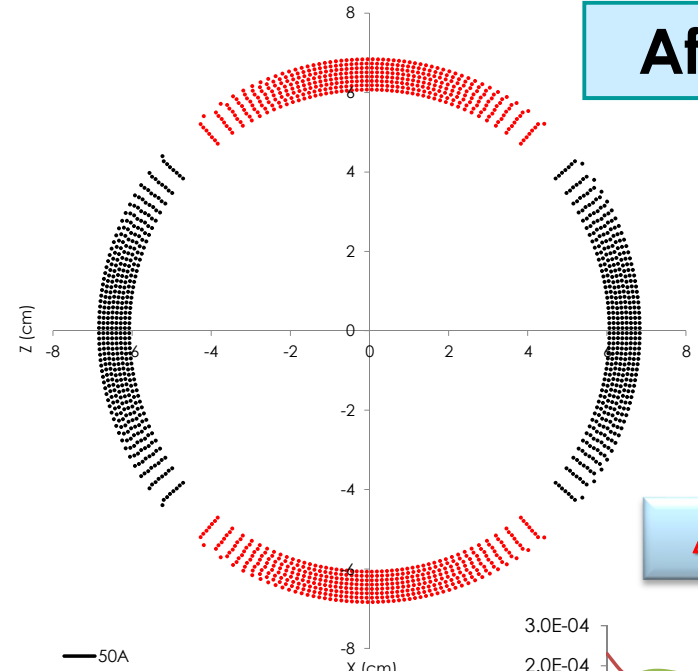
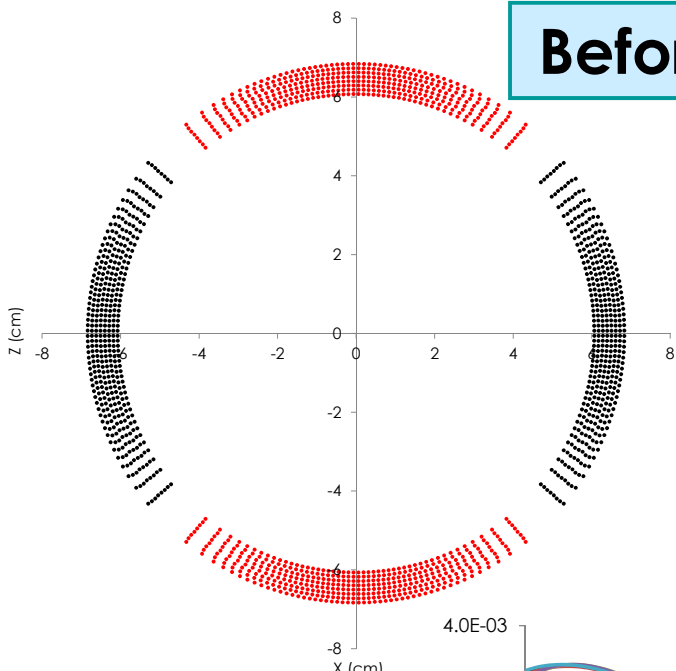
$|\Delta B_L/B_L| < 1 \times 10^{-4}!$

Design of the quadrupole coil

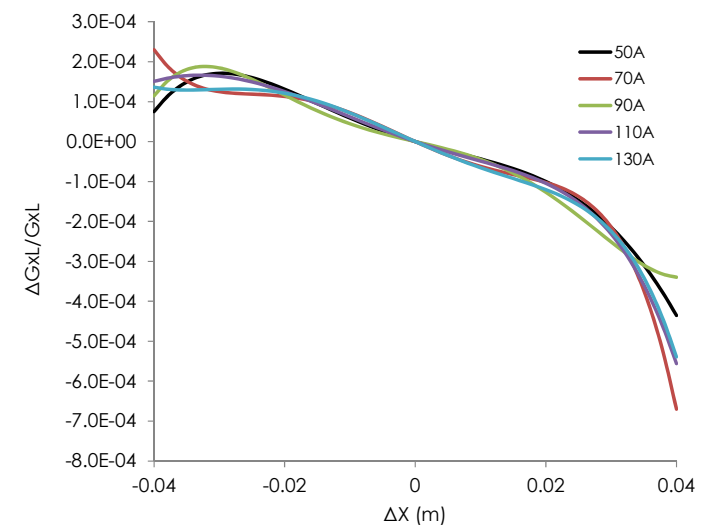
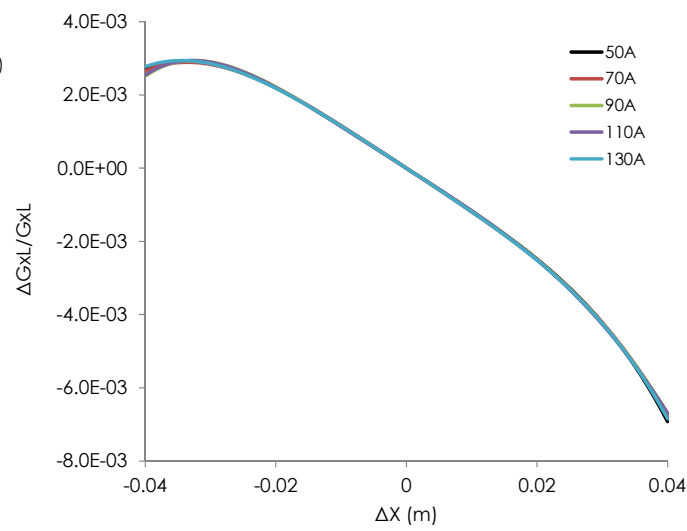


Before

After



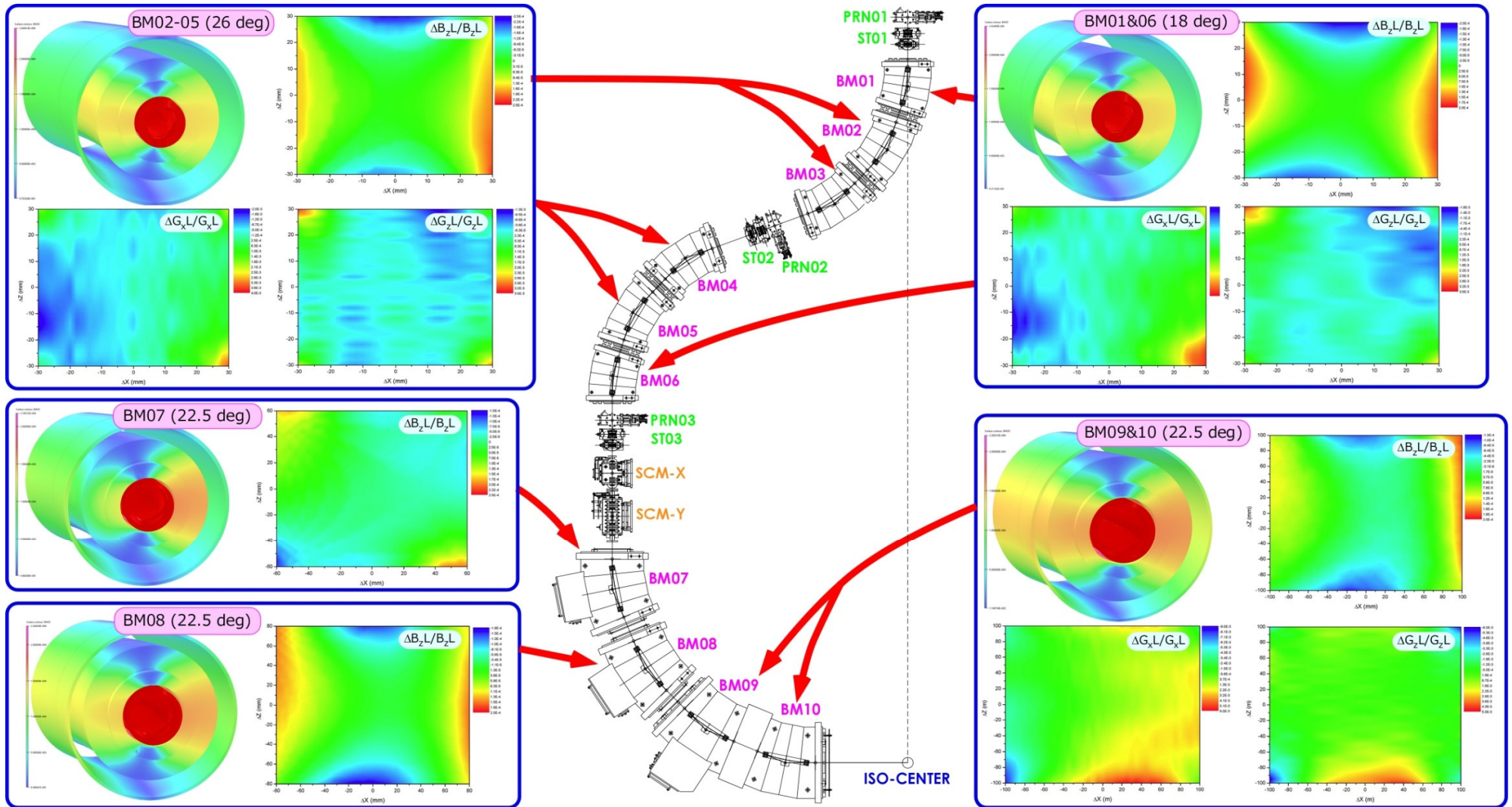
$\Delta GL/GL < 2 \times 10^{-4}$!



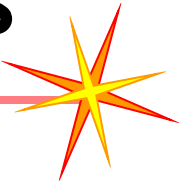
Design of SC magnets



All the SC magnets were designed by using a 3D magnetic field solver

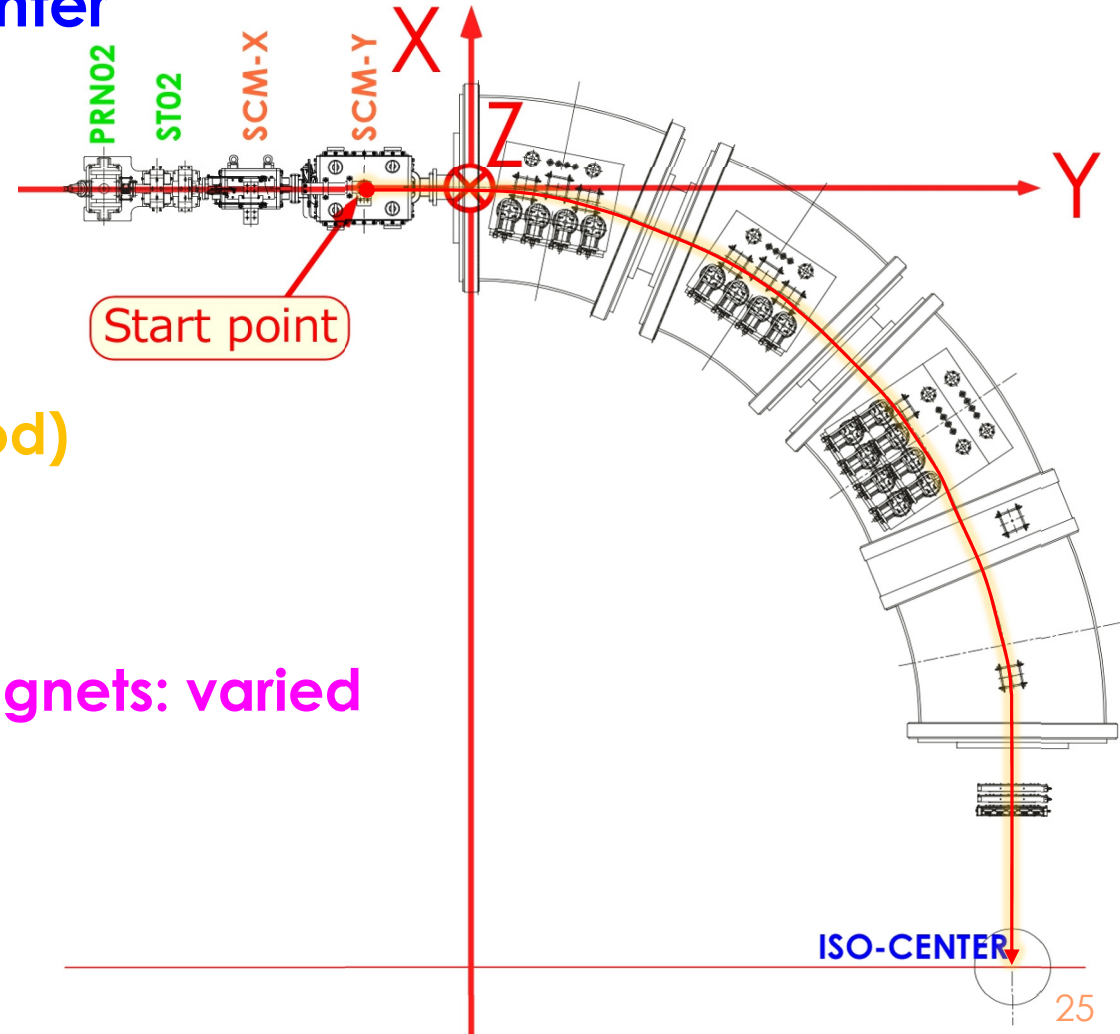


Beam tracking simulations

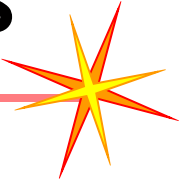


- **Beam tracking to the isocenter**
 - Field map data
(3D field calculations)
 - Numerical integration of
equation of motion
(4th order Runge-Kutta method)

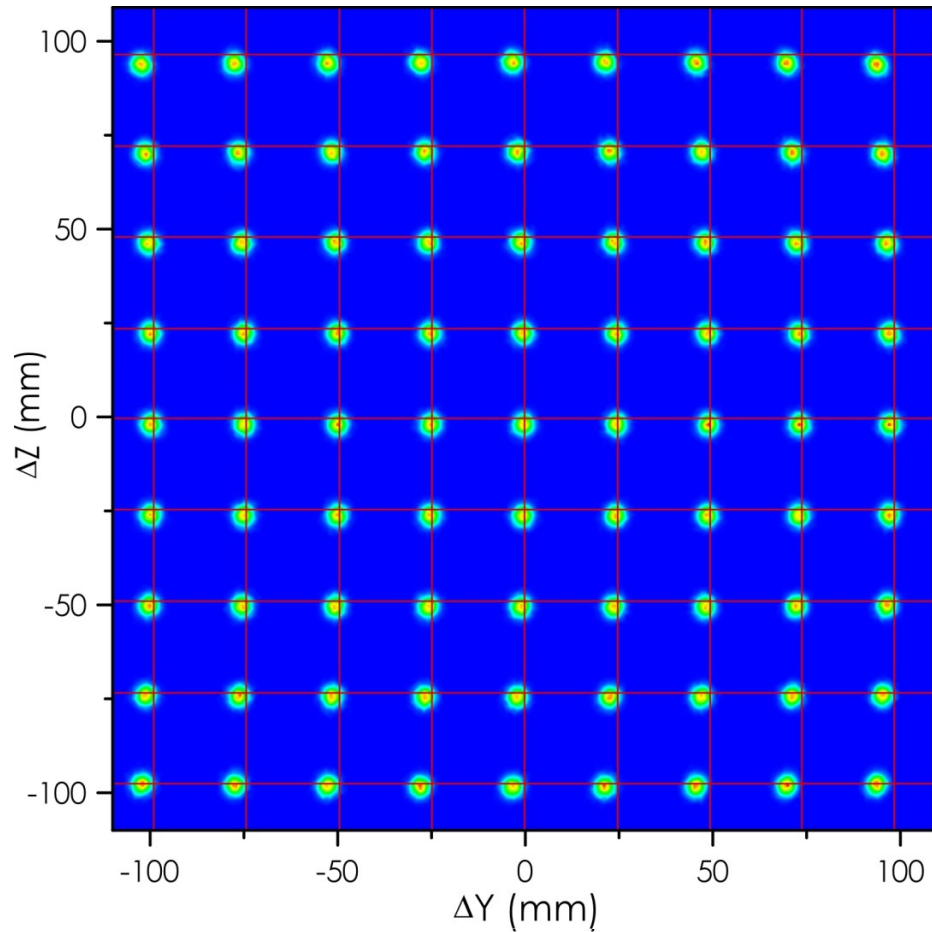
- **Beam profile at isocenter**
 - Kick angle of scanning magnets: varied
 - 81 spots at isocenter



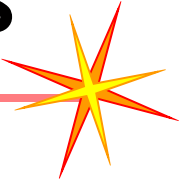
Beam tracking simulations



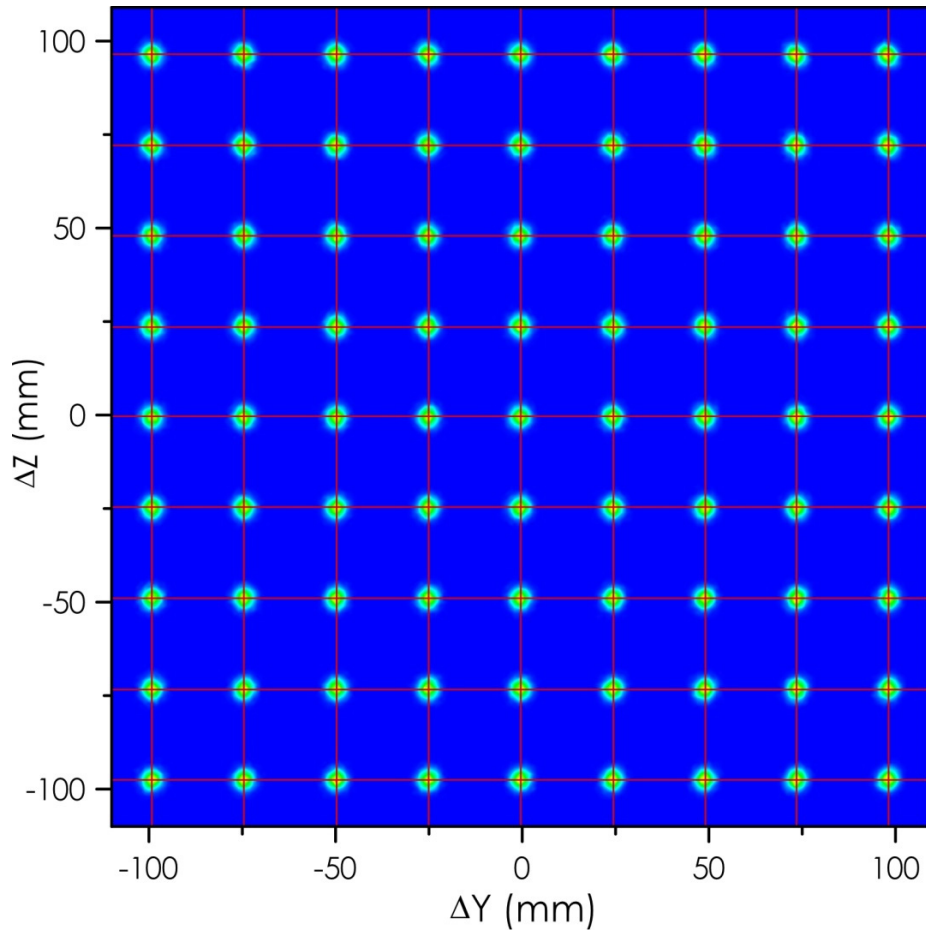
Calculated profile at isocenter
($E=430$ MeV/u)



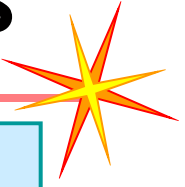
Beam tracking simulations



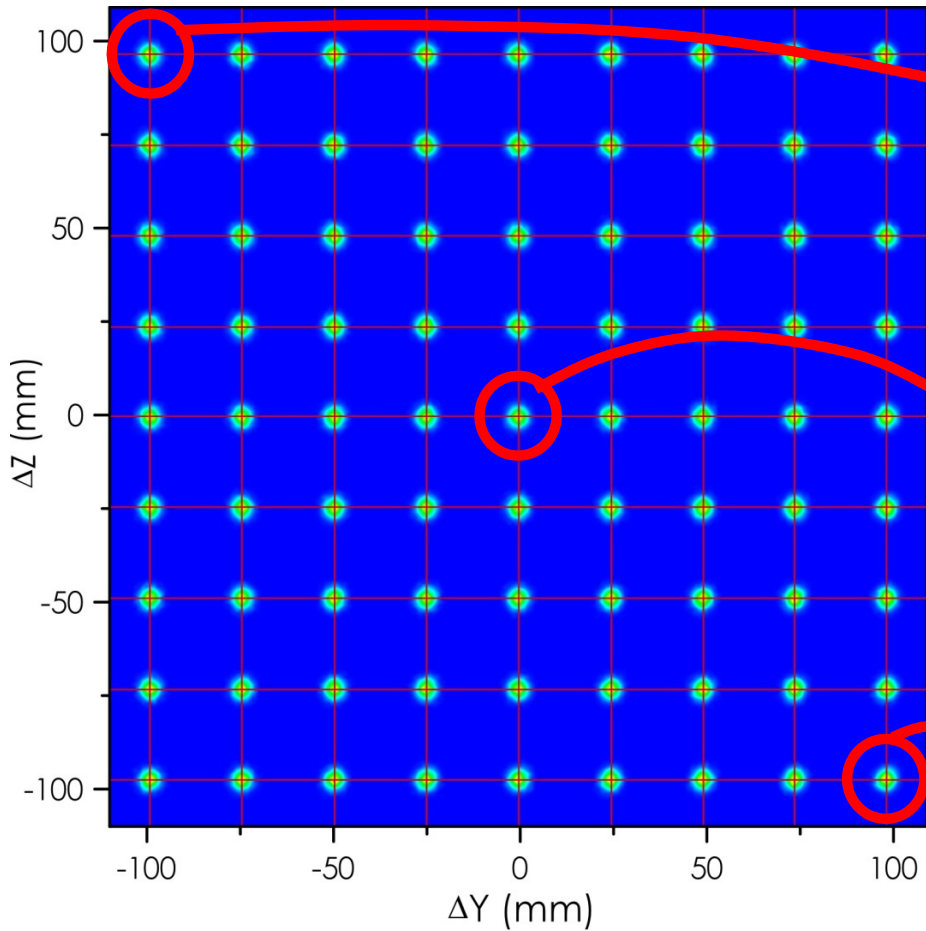
Calculated profile at isocenter
(with corrections of scanning magnets)



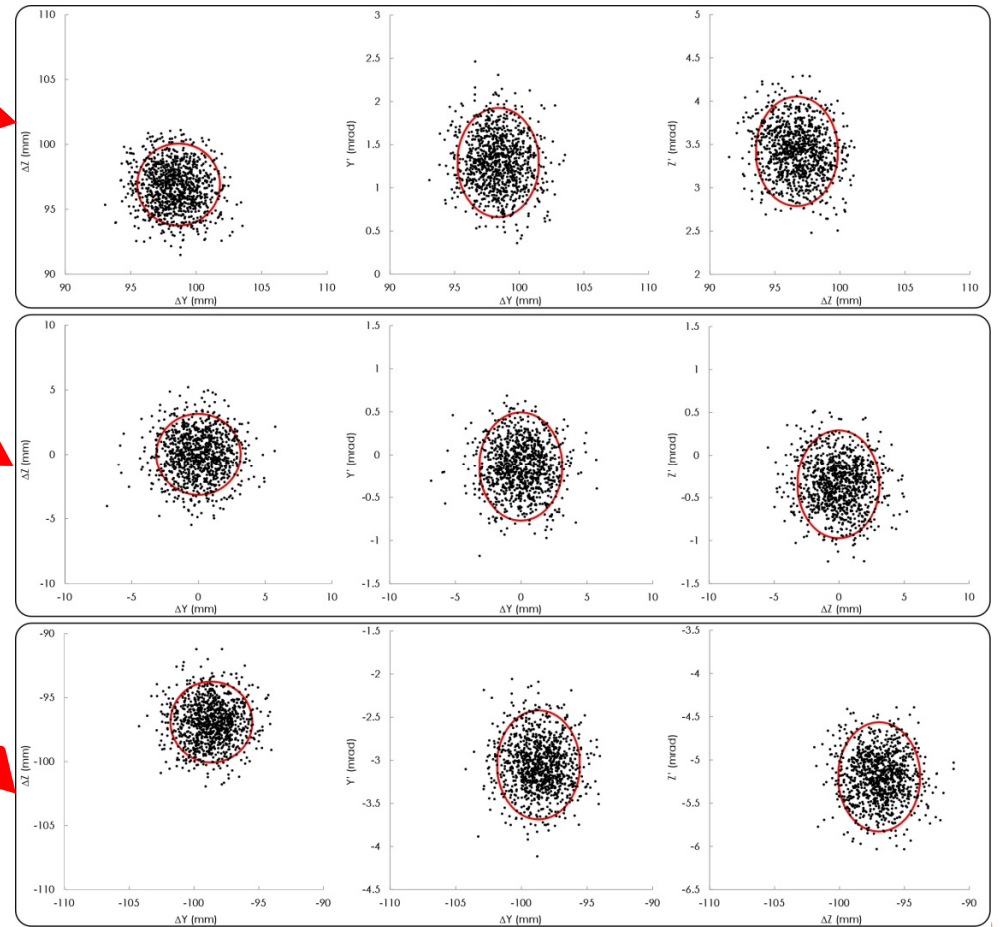
Beam tracking simulations



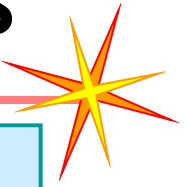
Calculated profile at isocenter
(with corrections of scanning magnets)



Phase space distributions of
the beam spots

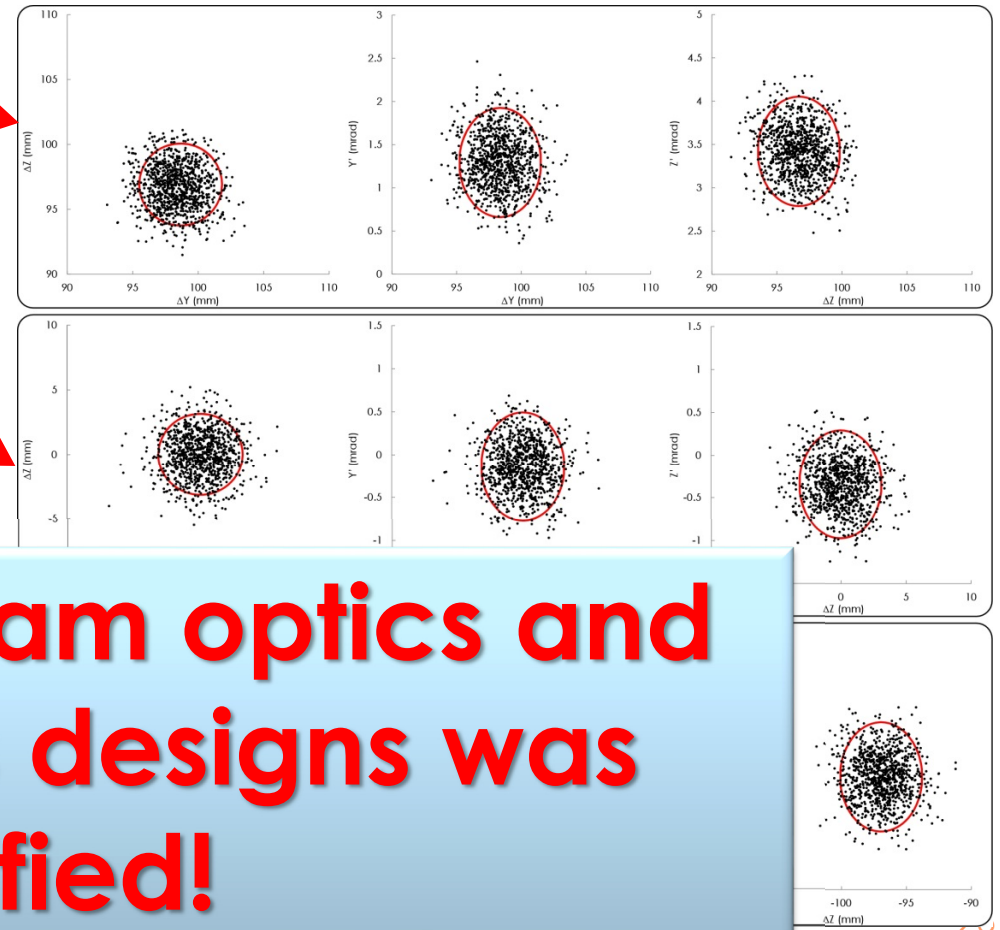
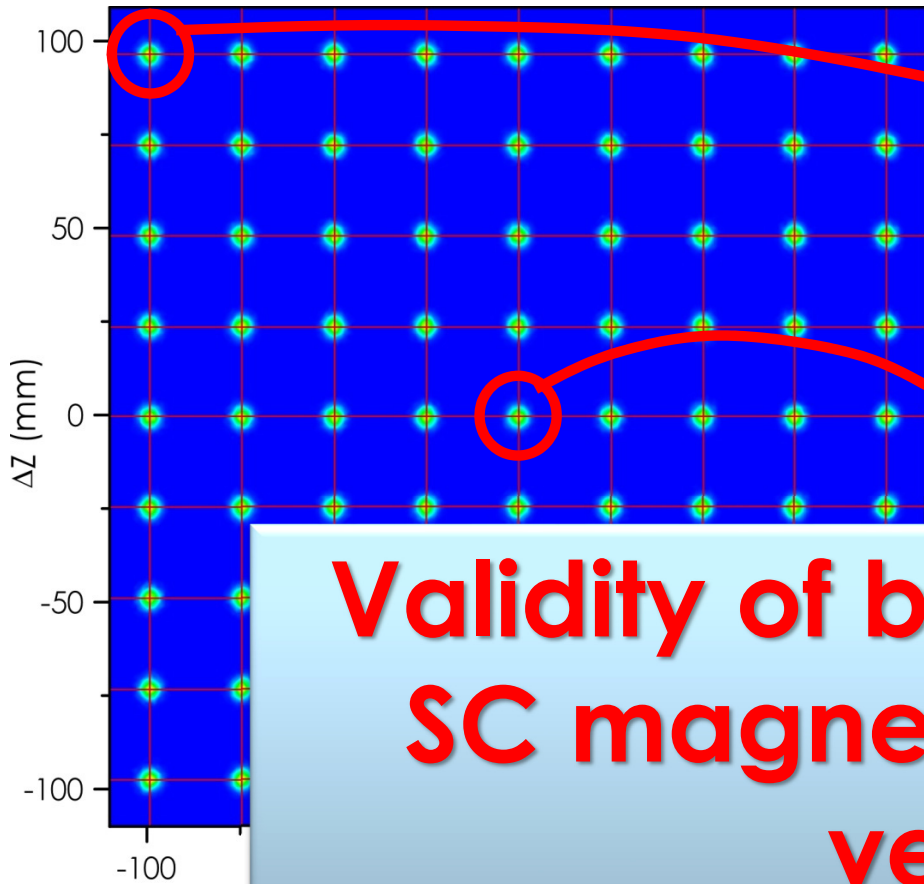


Beam tracking simulations

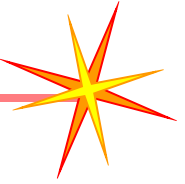


Calculated profile at isocenter
(with corrections of scanning magnets)

Phase space distributions of
the beam spots



**Validity of beam optics and
SC magnets designs was
verified!**

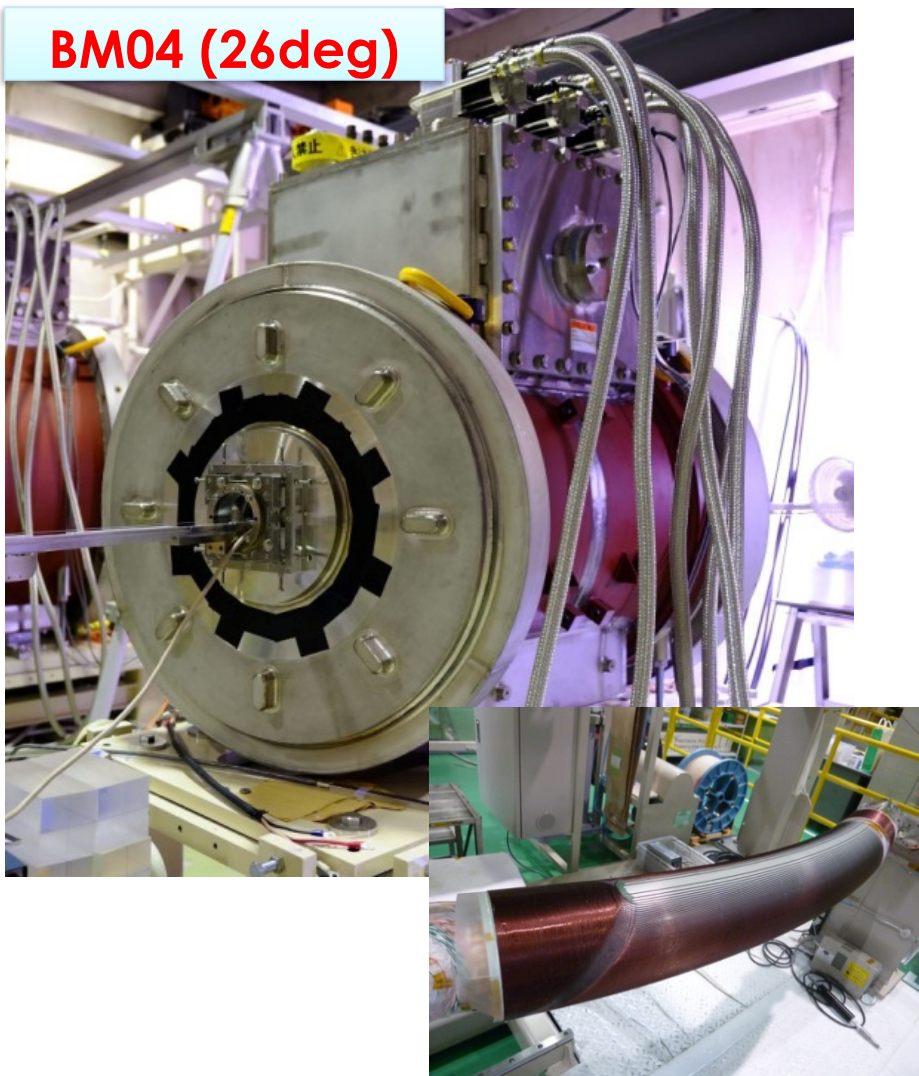


Construction of SC rotating-gantry

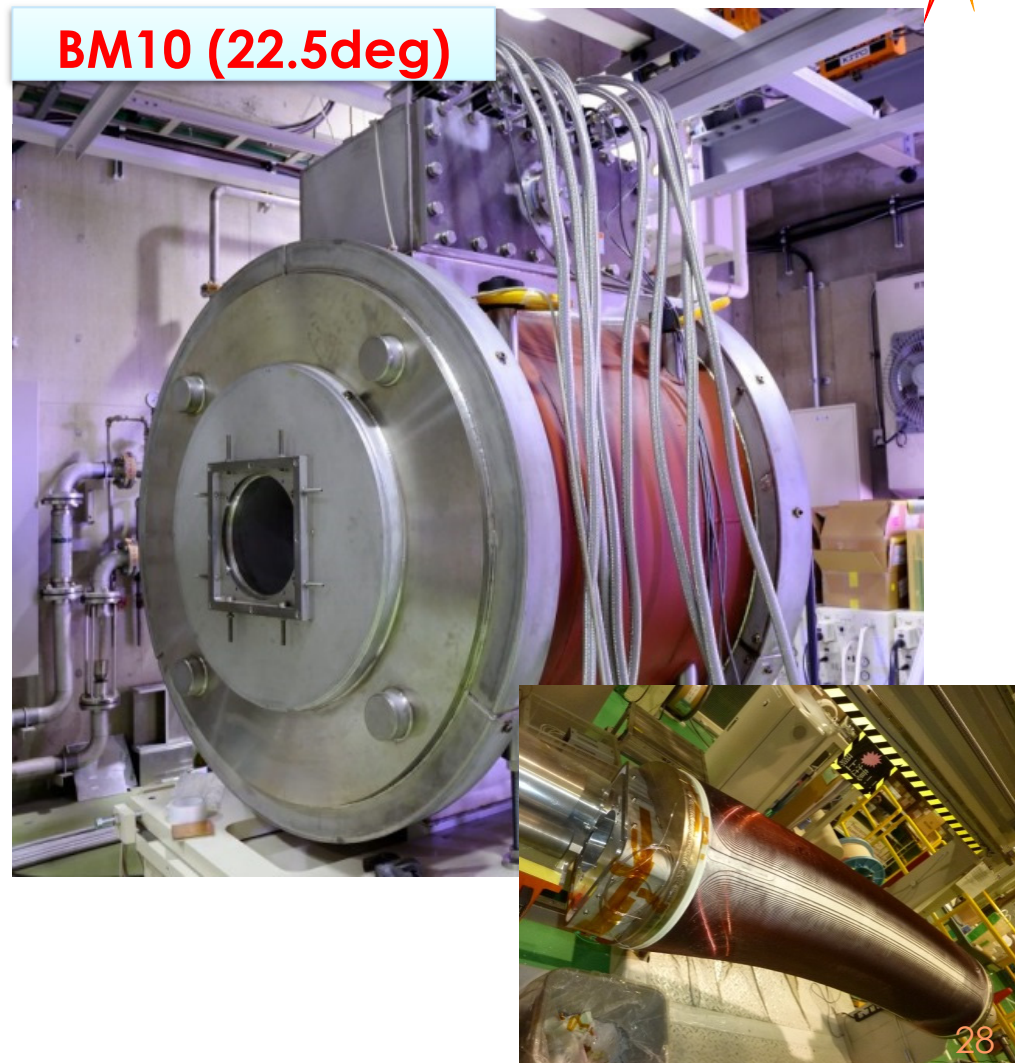
Construction of SC magnets



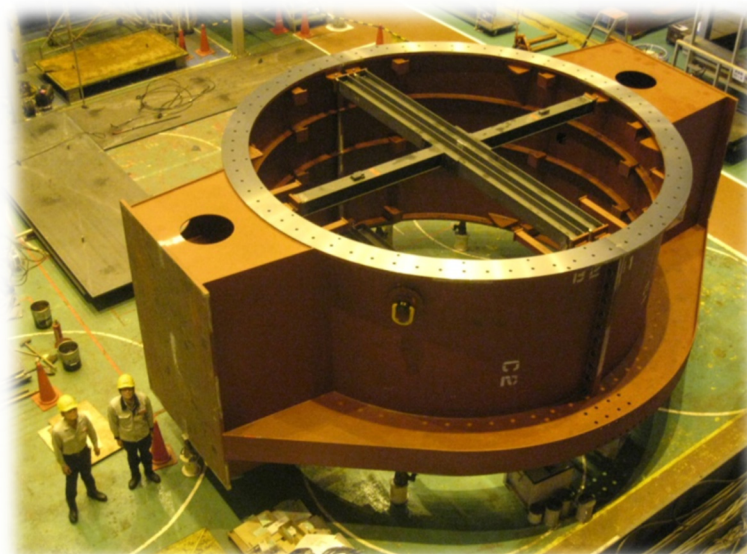
BM04 (26deg)



BM10 (22.5deg)



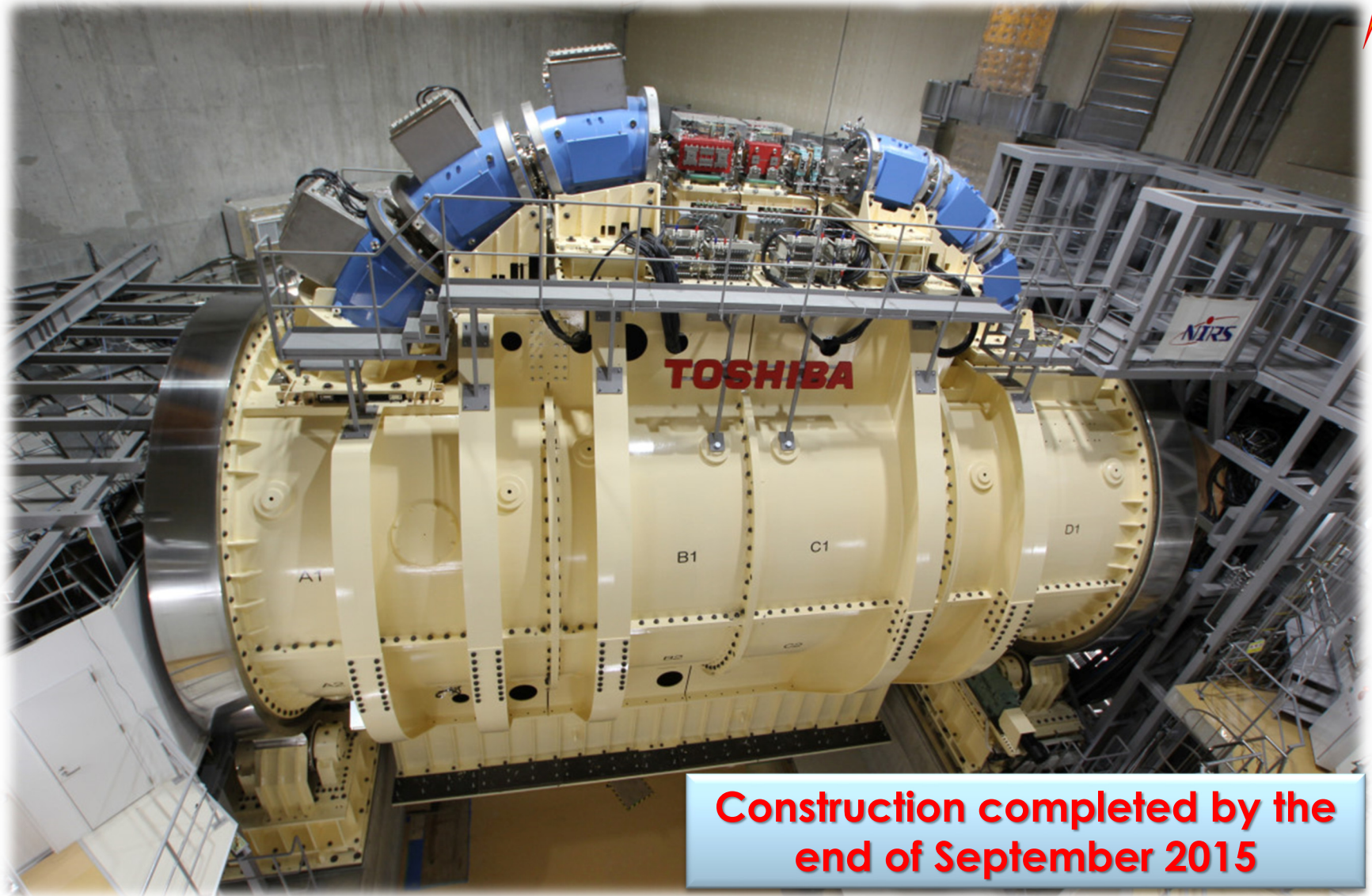
Construction of structure



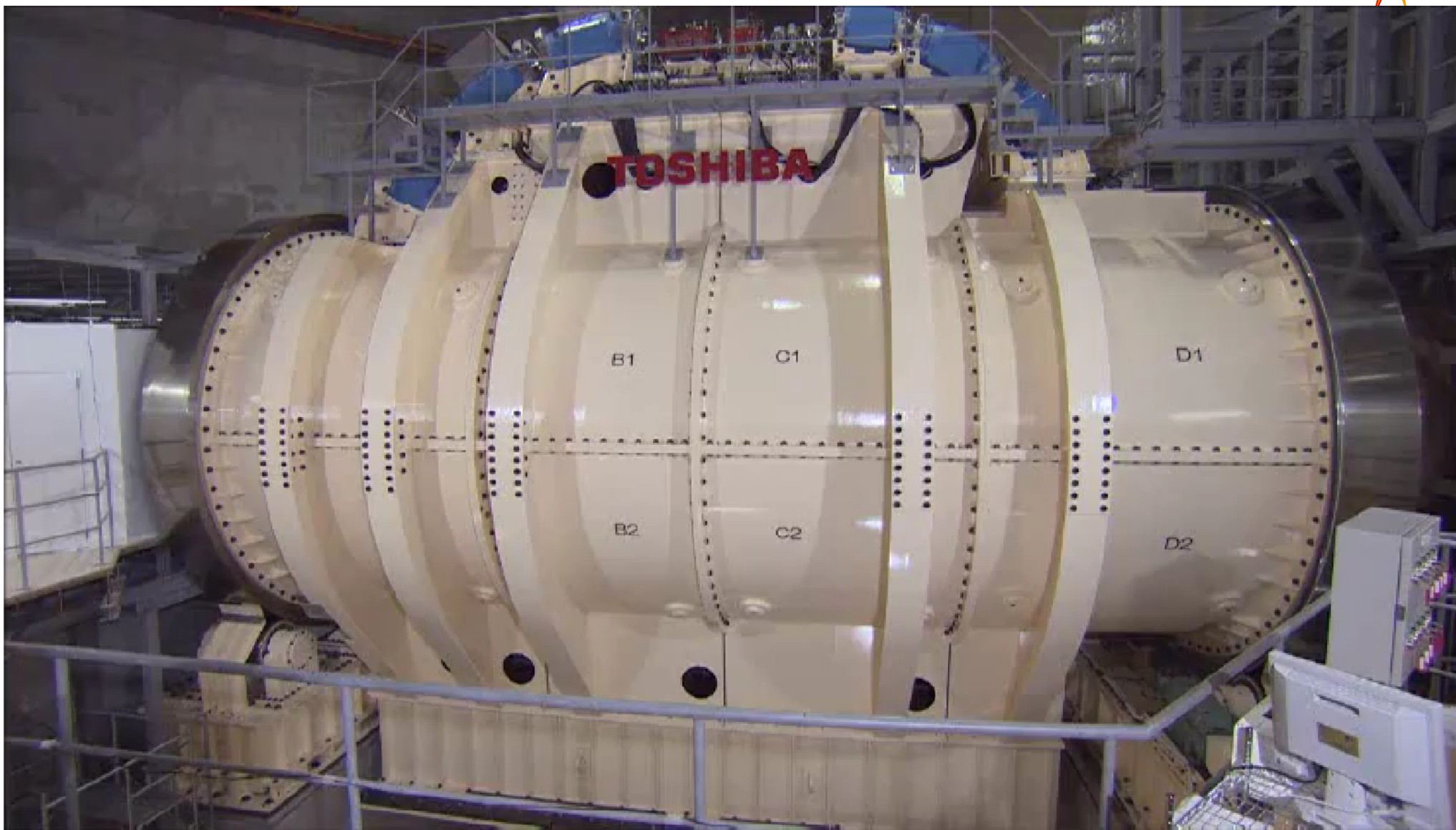
Construction at NIRS



Construction at NIRS



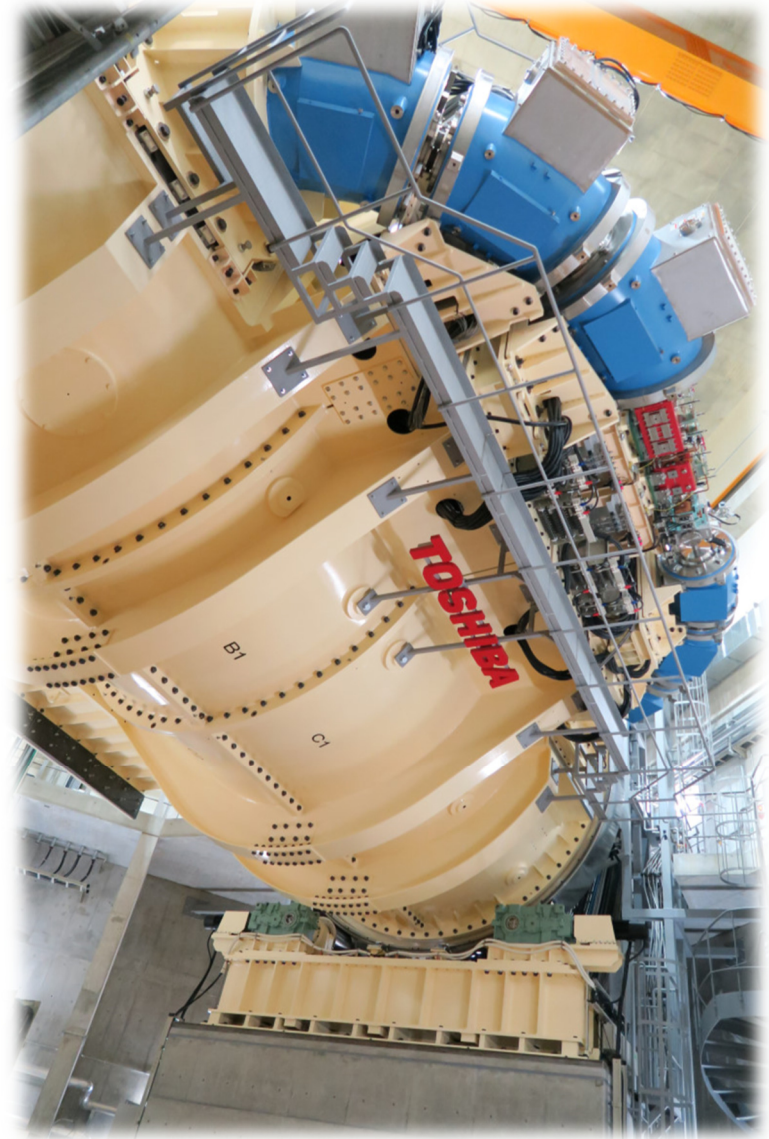
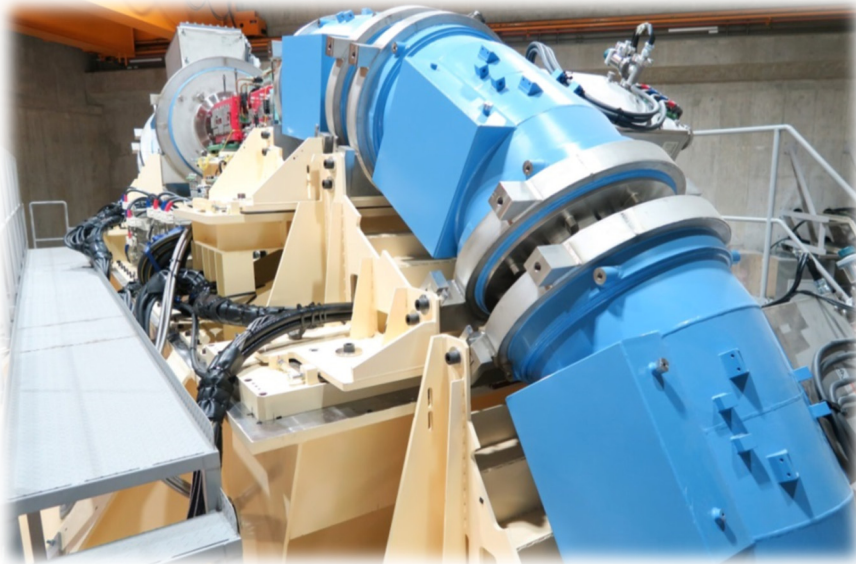
Construction completed by the end of September 2015





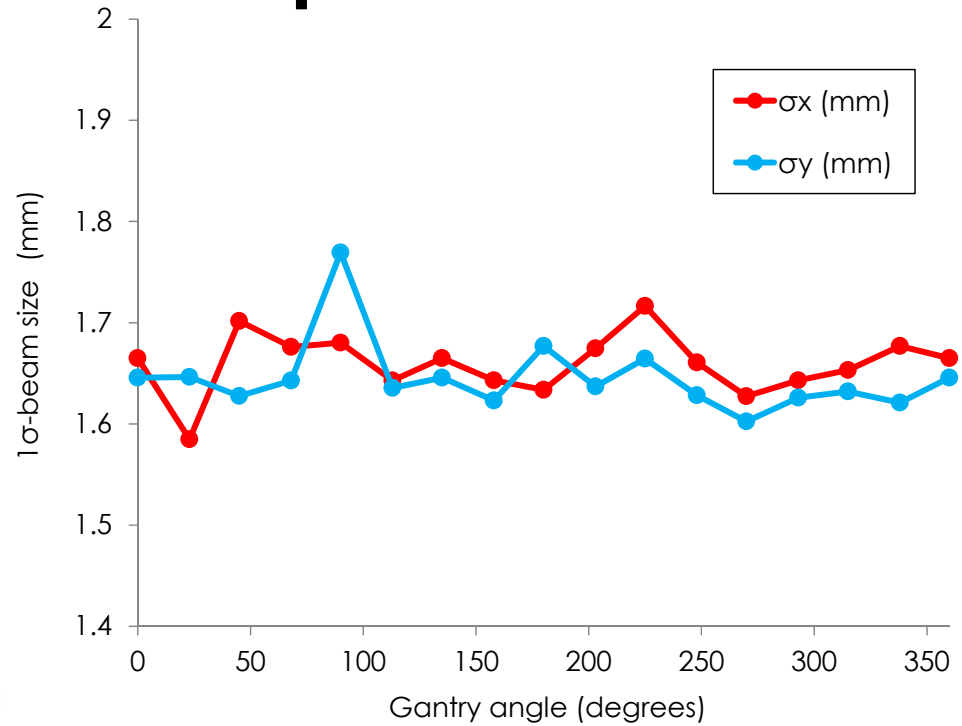
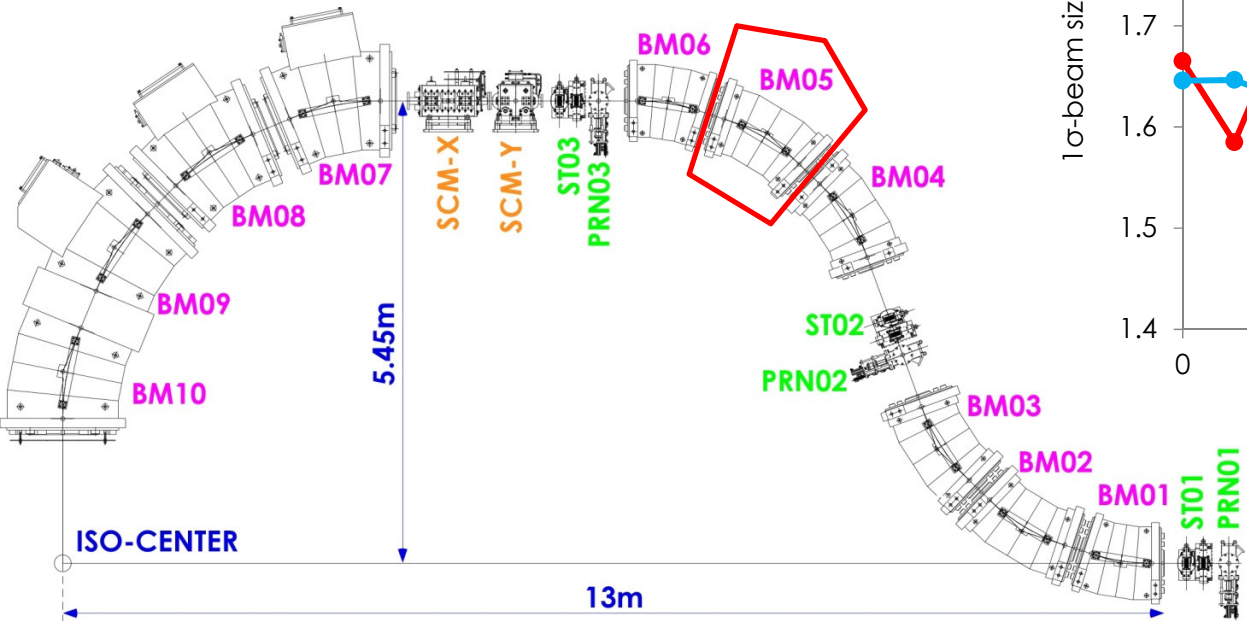
Beam commissioning

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.

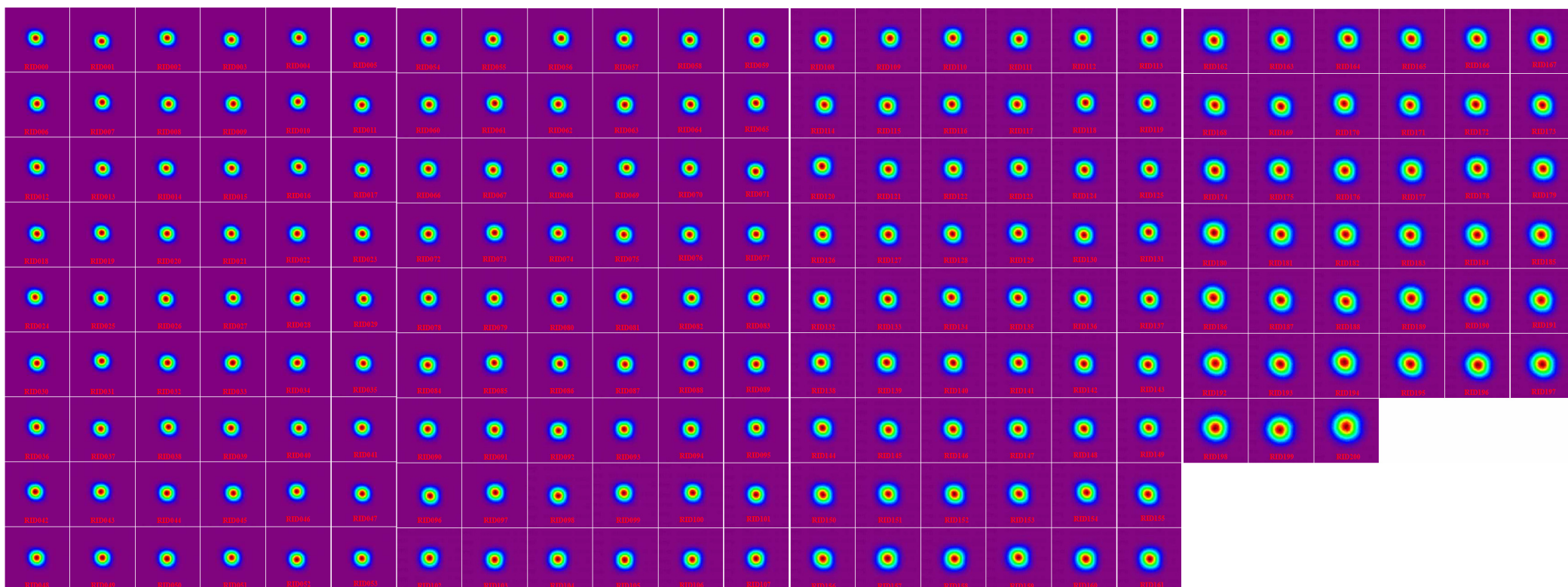


Angular dependence of beam sizes at isocenter (E=430 MeV/u)

Energy dependence



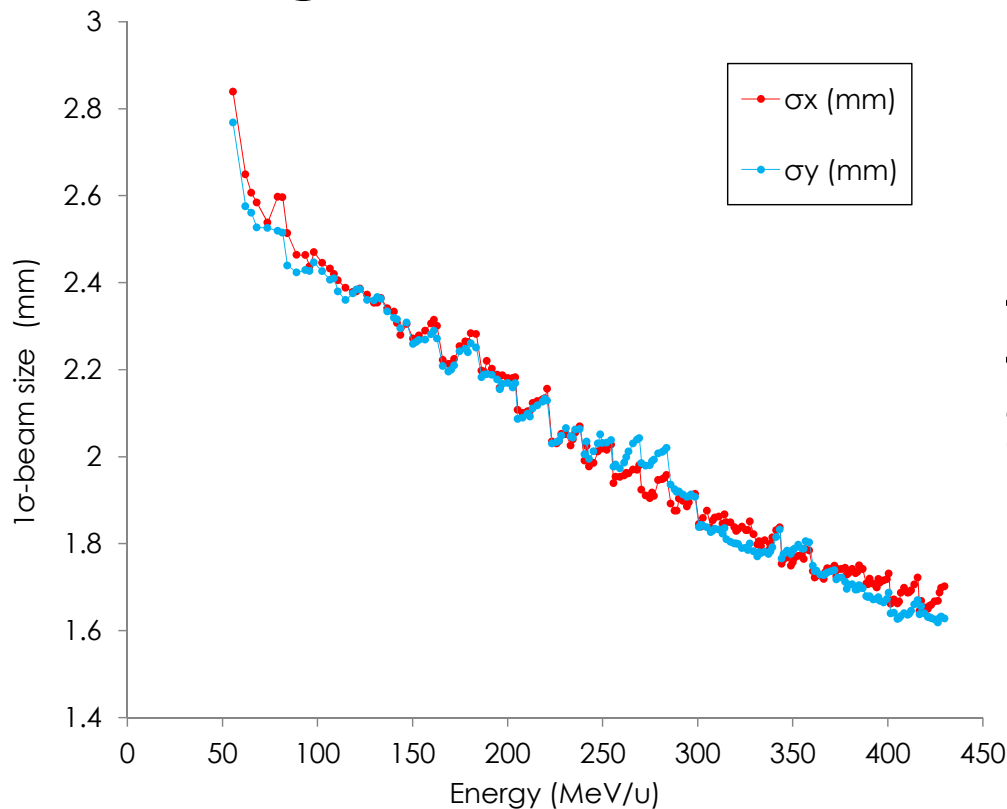
- Beam tuning was made for 201 kinds of beam energies for $E=430\sim 55.6$ MeV/u.



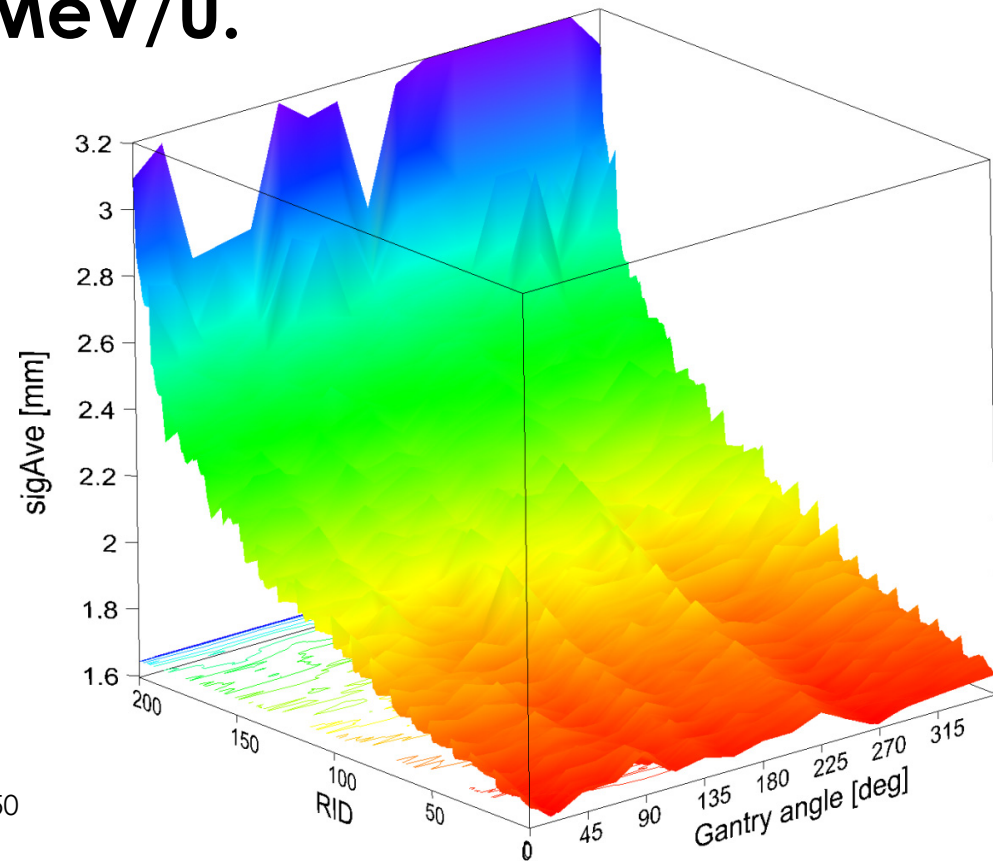
Energy dependence



- Beam tuning was made for 201 kinds of beam energies for $E=430\sim 55.6$ MeV/u.



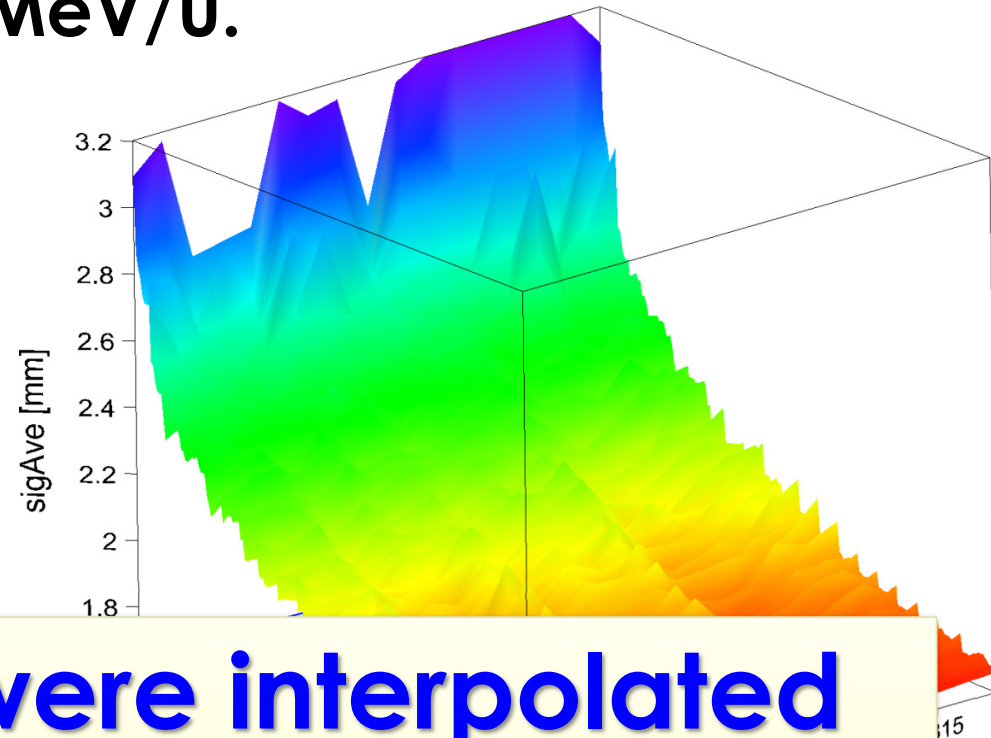
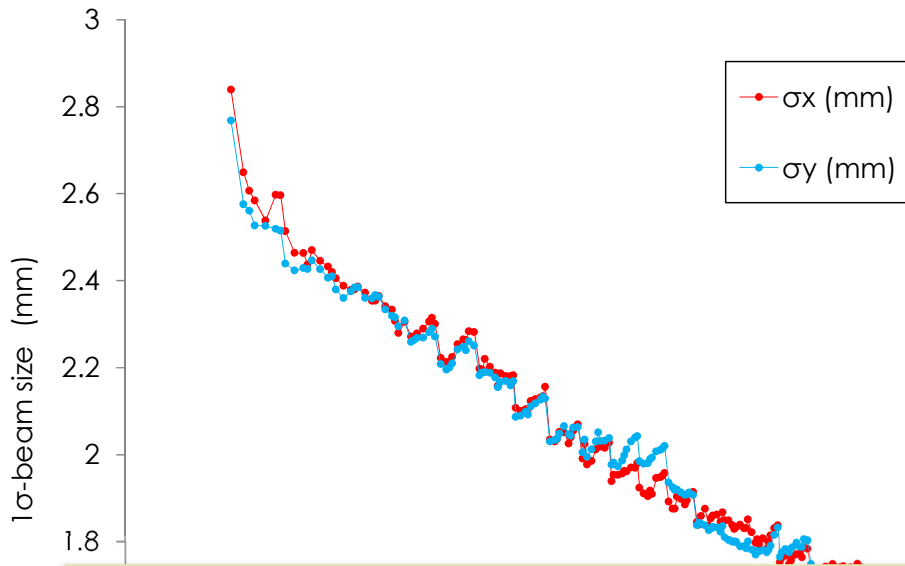
Energy dependence of beam sizes at isocenter (45 degrees)



Average beam sizes as a function of gantry angle and RID

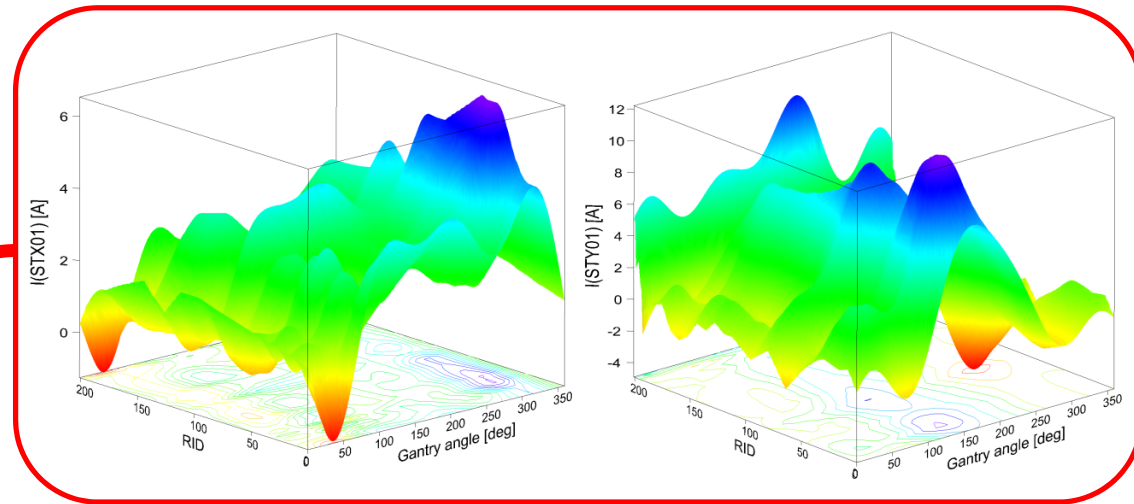
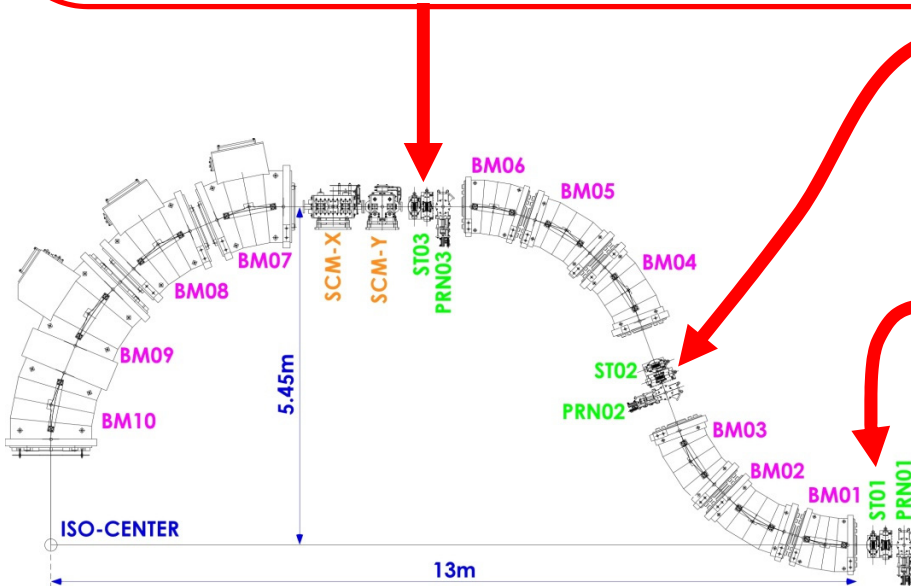
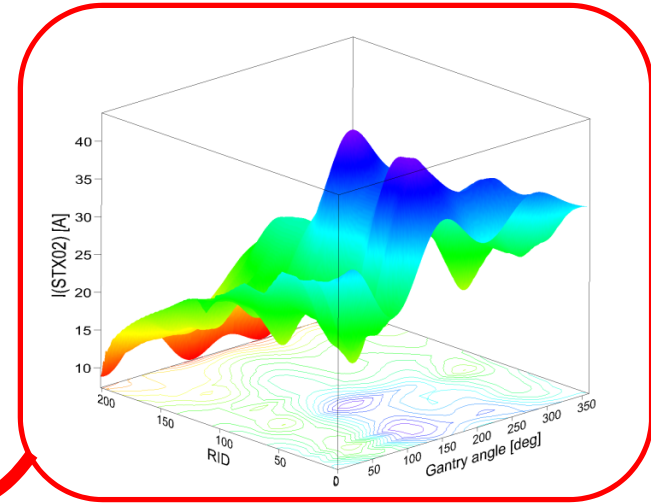
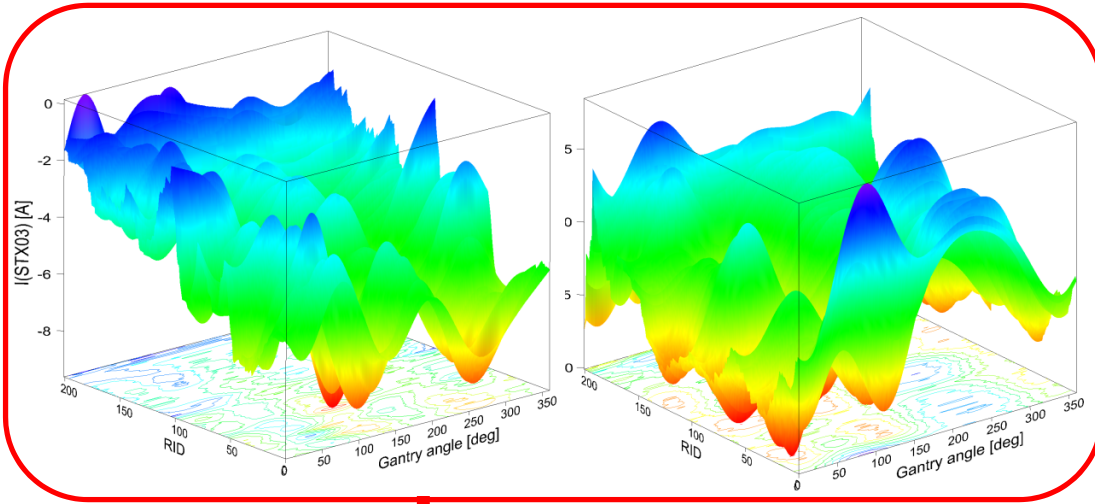
Energy dependence

- Beam tuning was made for 201 kinds of beam energies for $E=430\sim 55.6$ MeV/u.

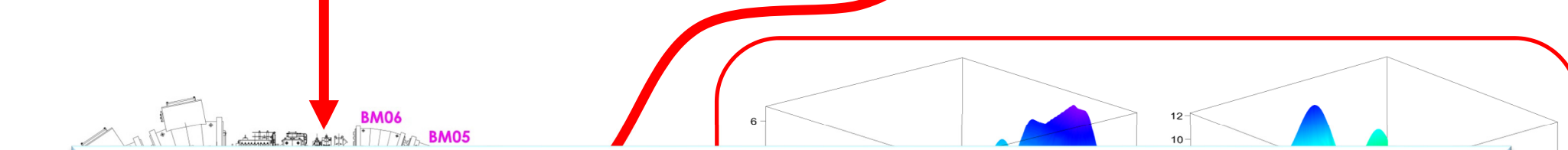
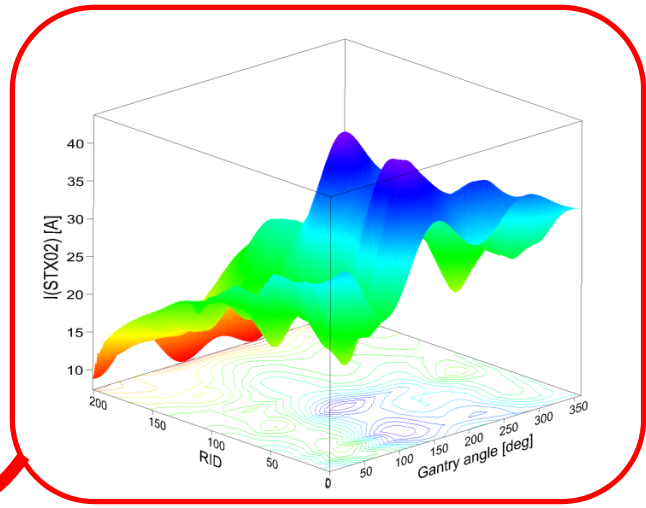
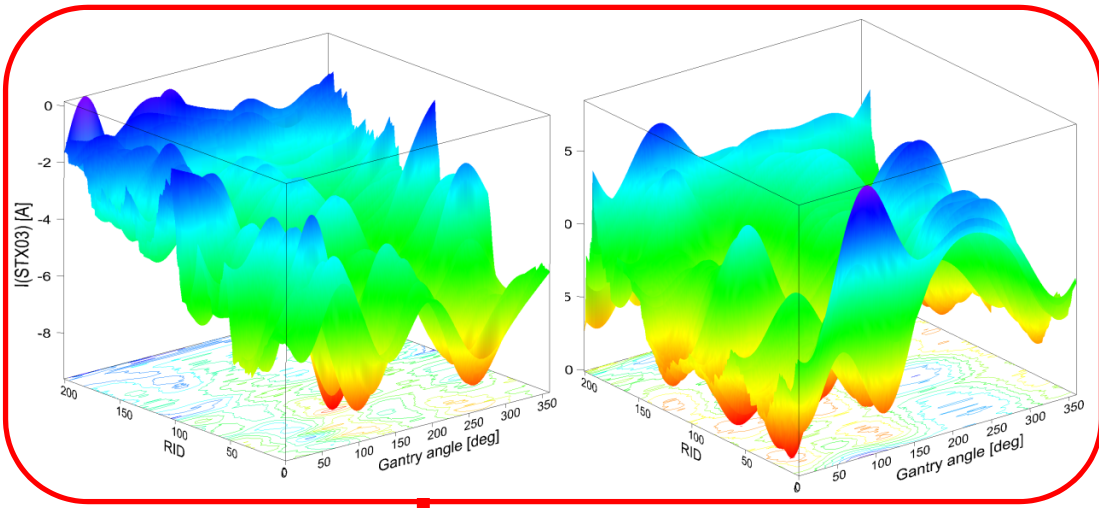


Parameter sets were interpolated to provide beams by angular step of $\Delta\theta=1$ degree.

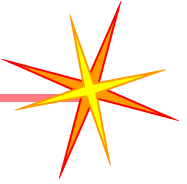
Centering beam spots



Centering beam spots



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

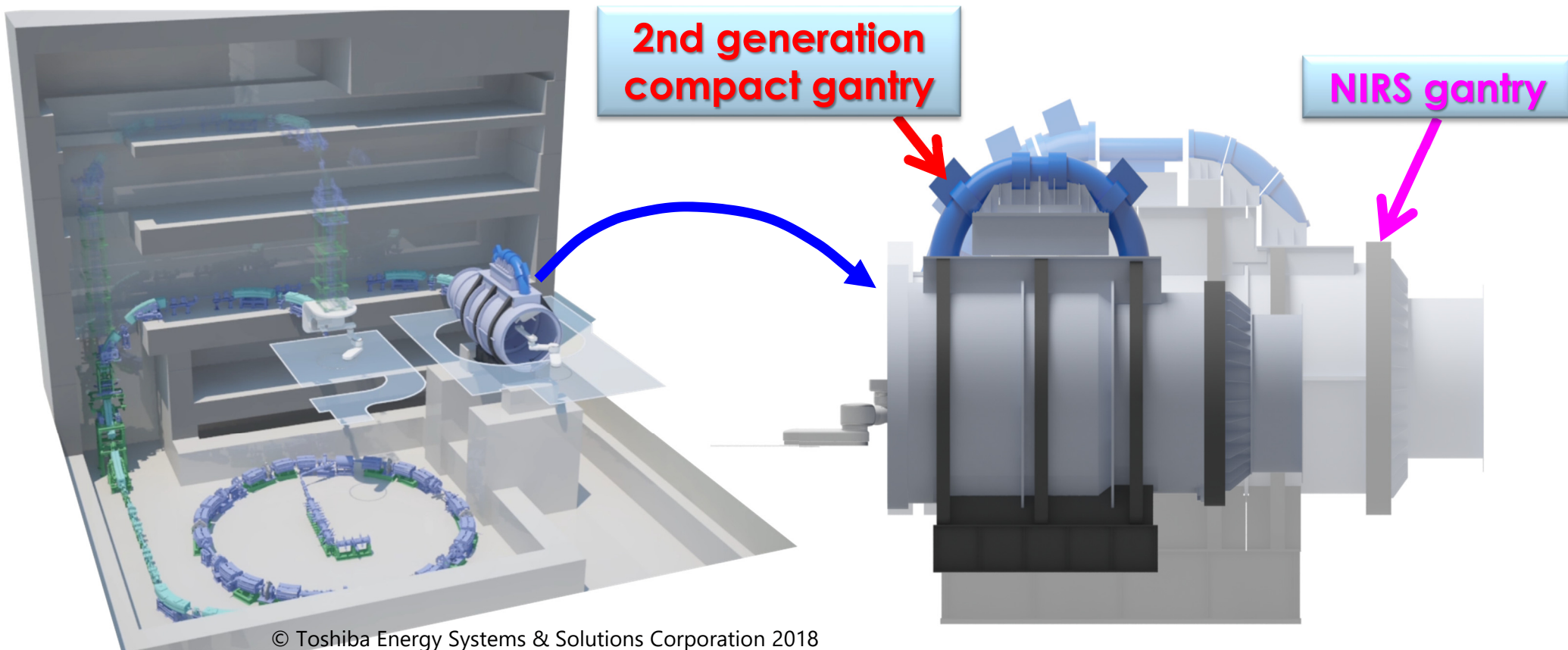


Future plans



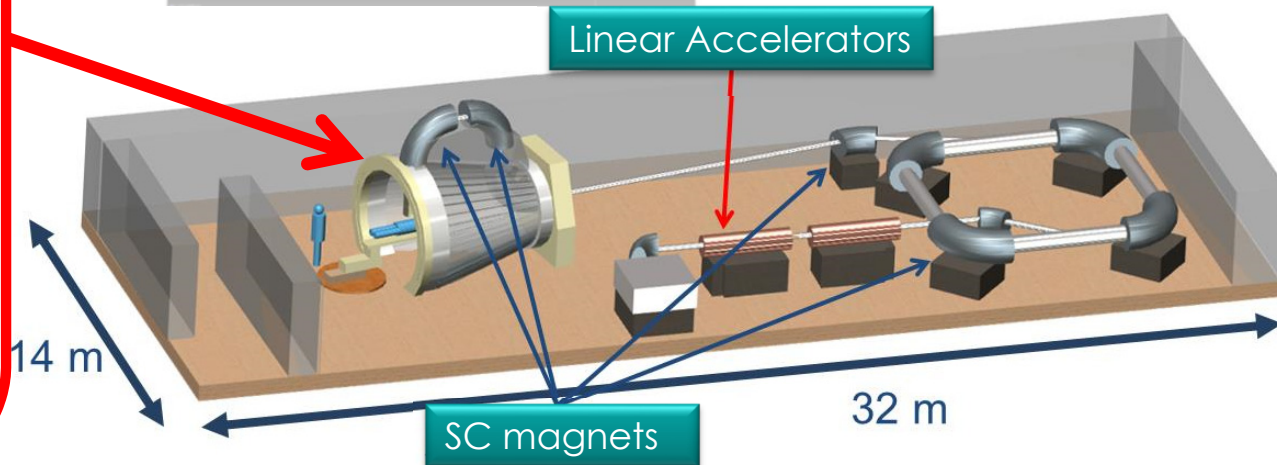
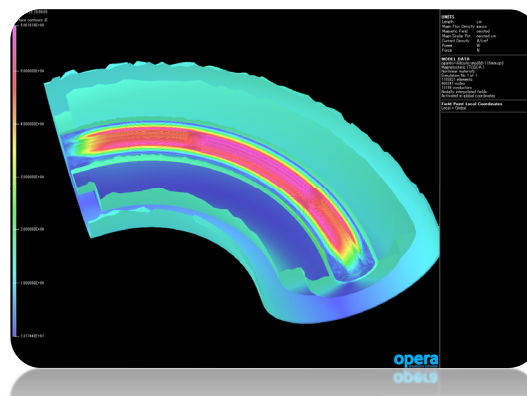
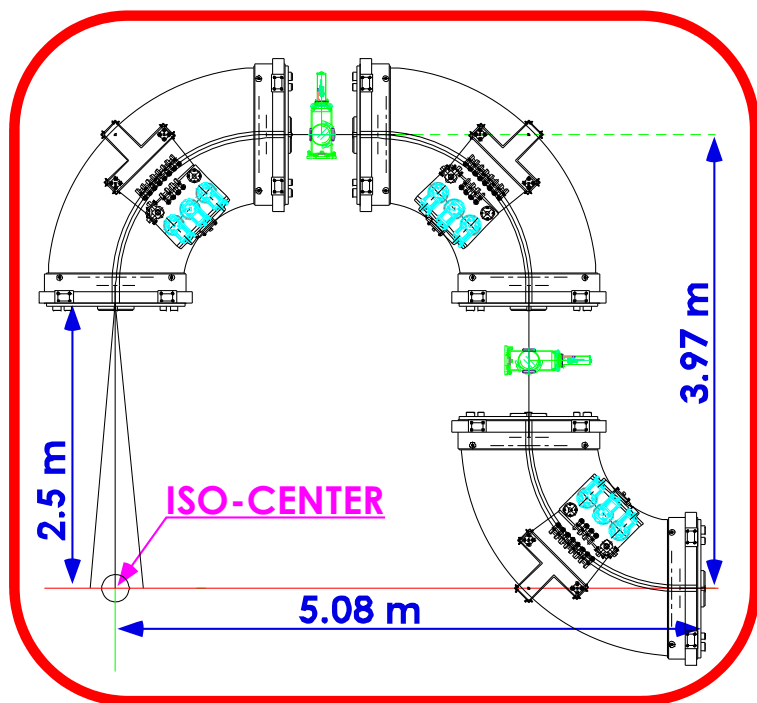
2nd-generation SC gantry

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



3rd-generation SC gantry

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

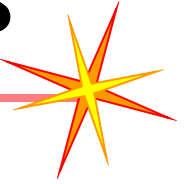


Summary



- 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.





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