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Development of Carbon-Ion Radiotherapy Facilities at NIRS

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Outline

- Introduction
- Development of a compact facility
- Recent developments
- Future plan
- Summary

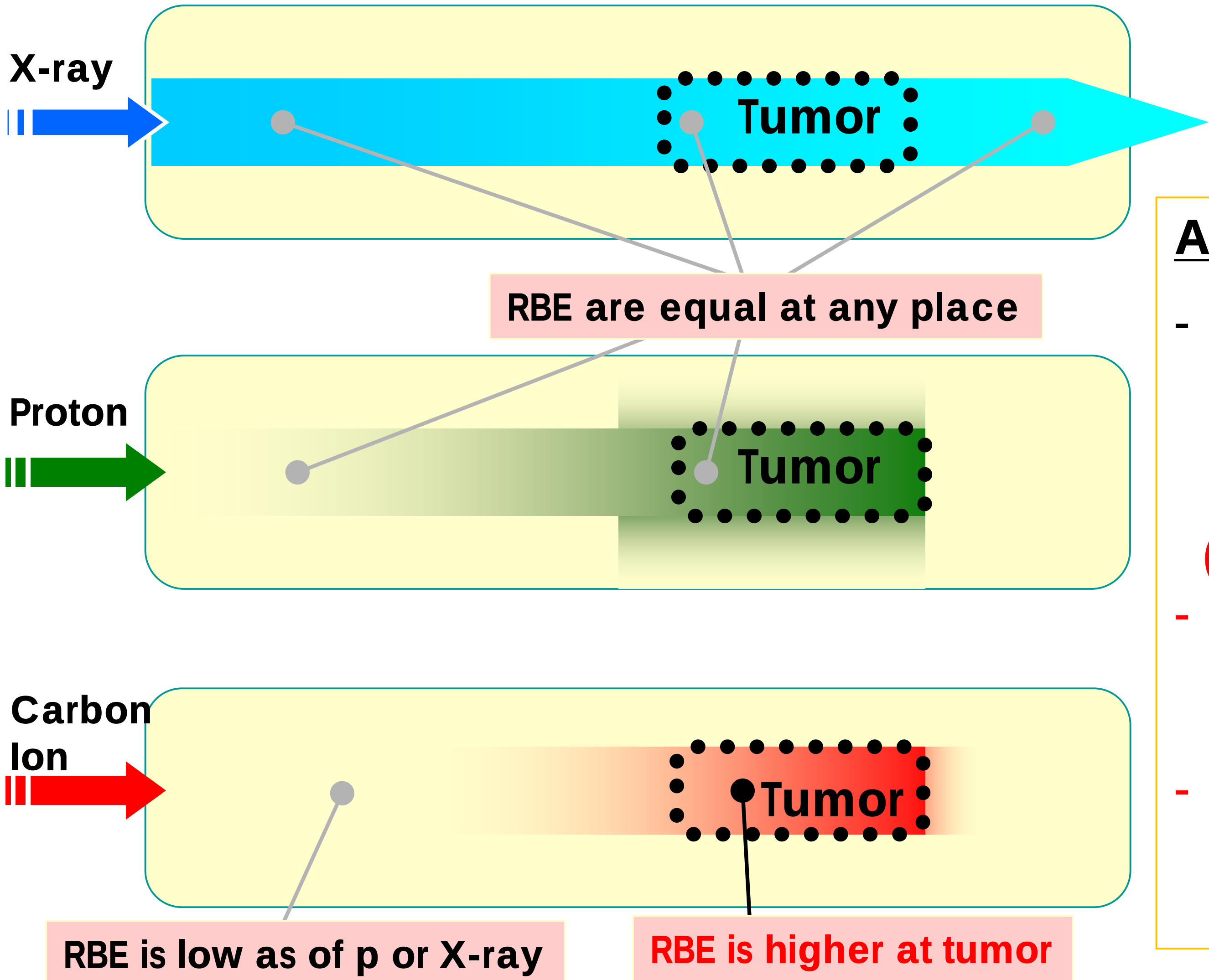
Introduction

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) — Protons, Carbon ions
   - 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



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

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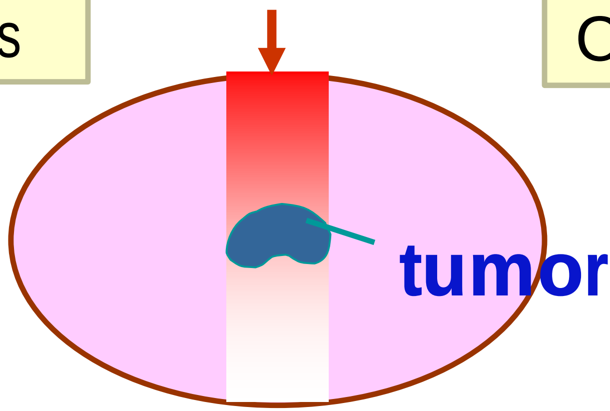
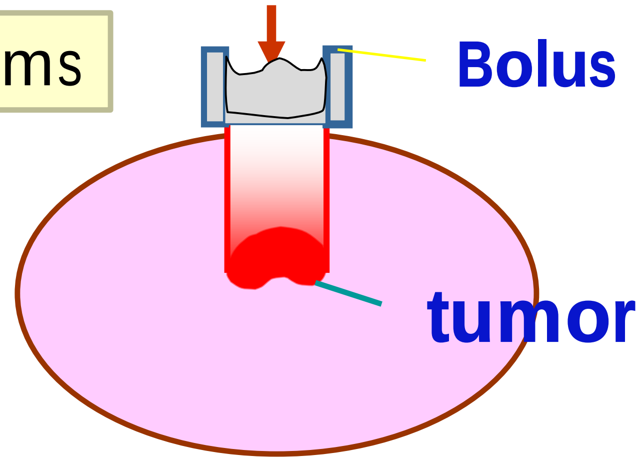
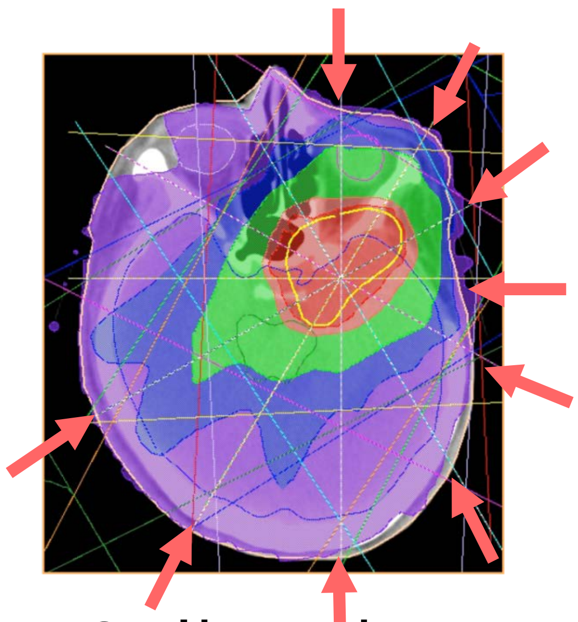
Dose distribution of X-ray and Carbon beams

X-rays

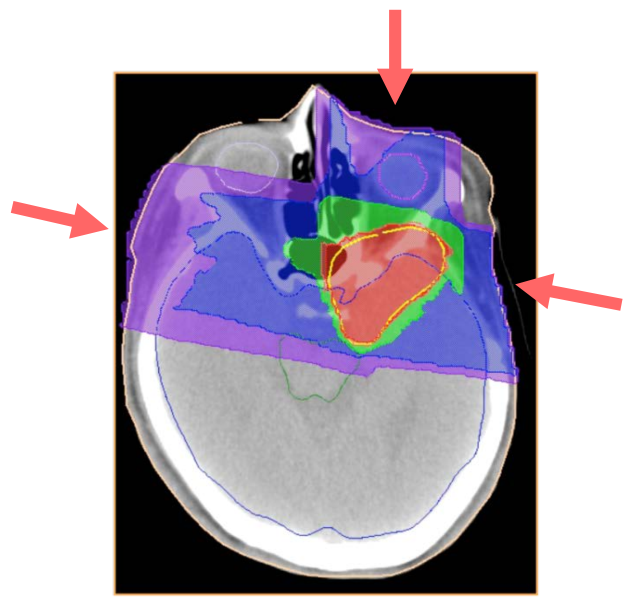


Carbon beams





9 directions



3 directions

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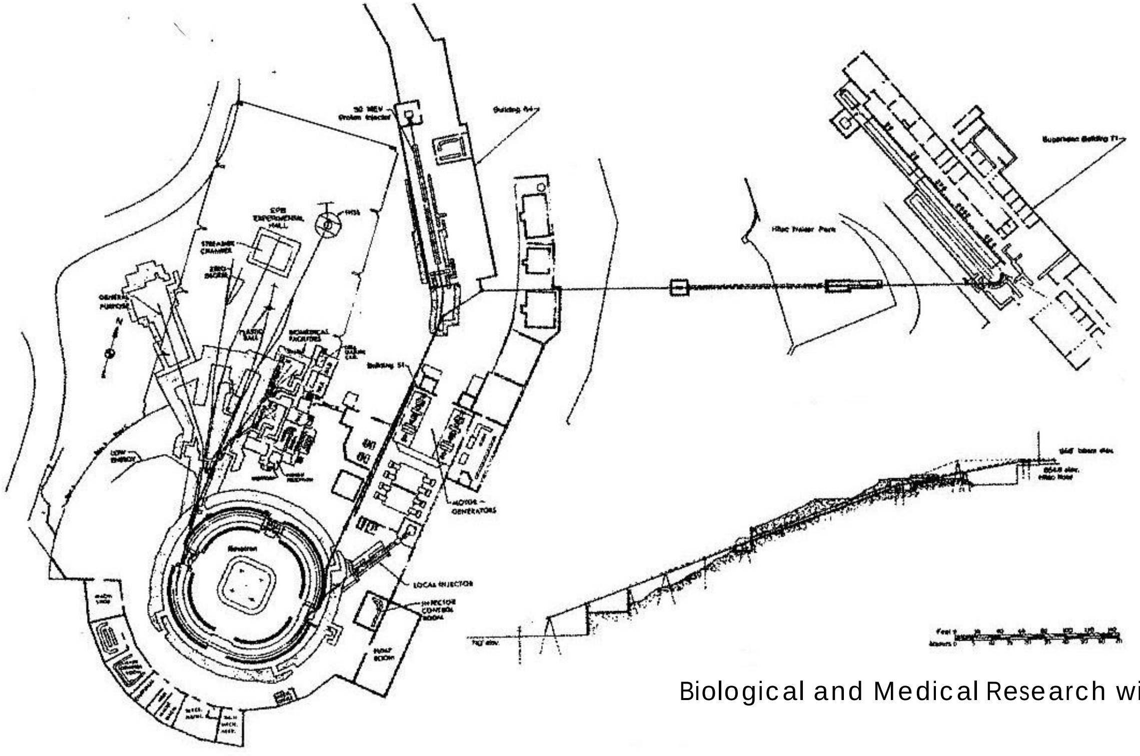
Pioneer's work at LBL

- **1940's: R. Willson proposed the medical application of heavy-ion beams.**

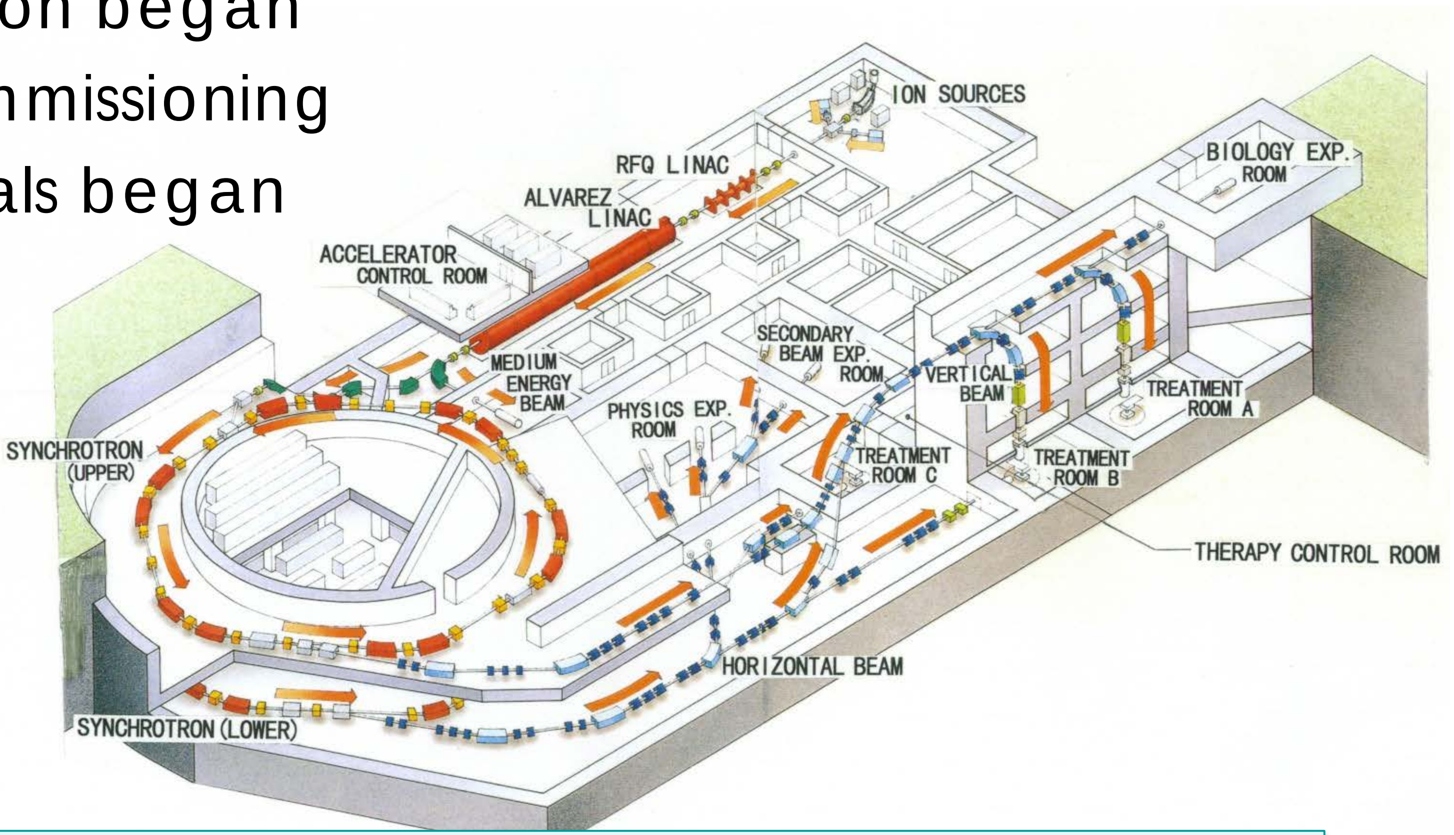
- **1957: LBL started clinical trials with Helium ions (2054 patients)**
- **1975: Treatment with Neon ions was made (433 patients).**
- **1992: The research had been aborted, due to the shutdown of Bevalac.**



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).

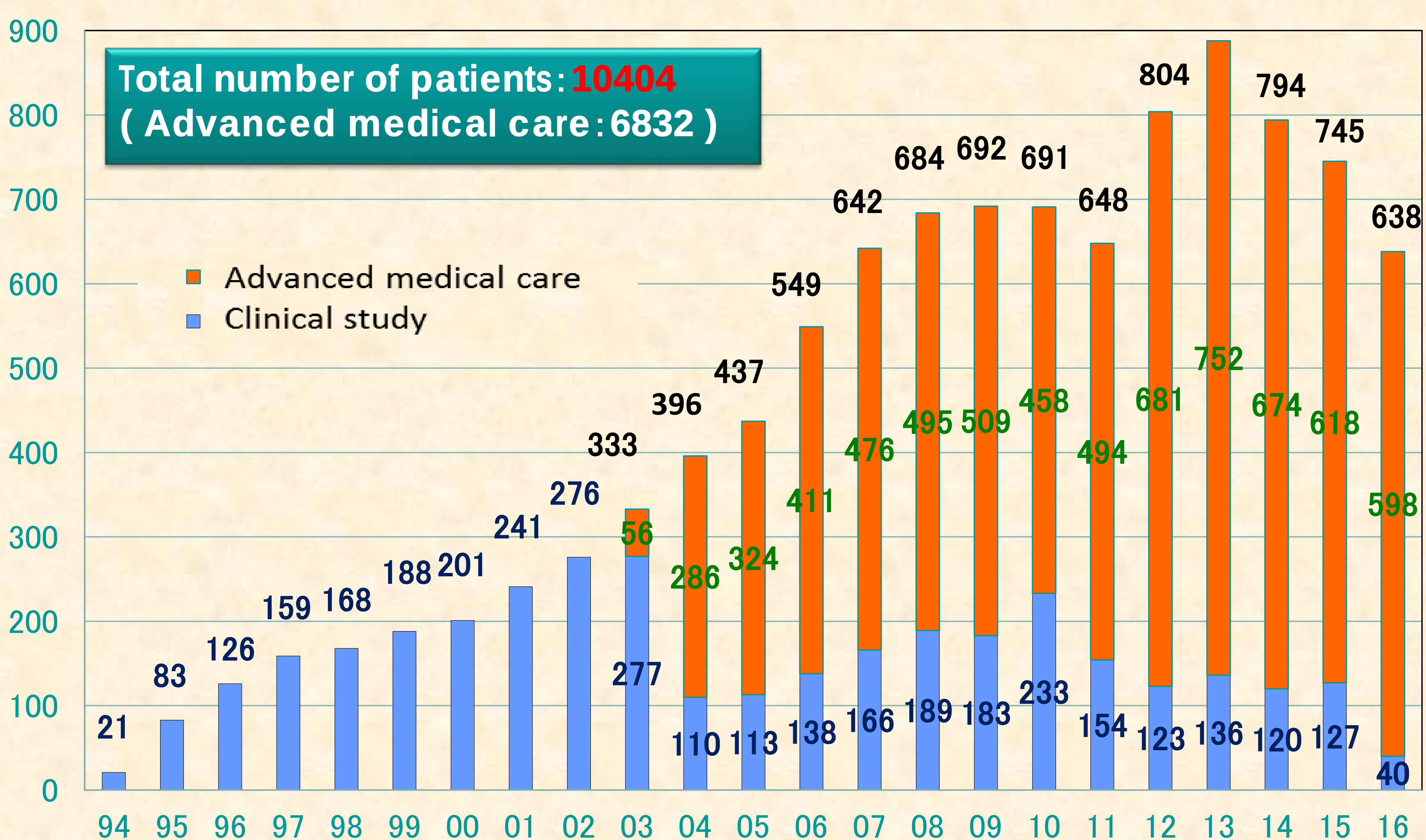
World-first heavy-ion medical accelerators

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



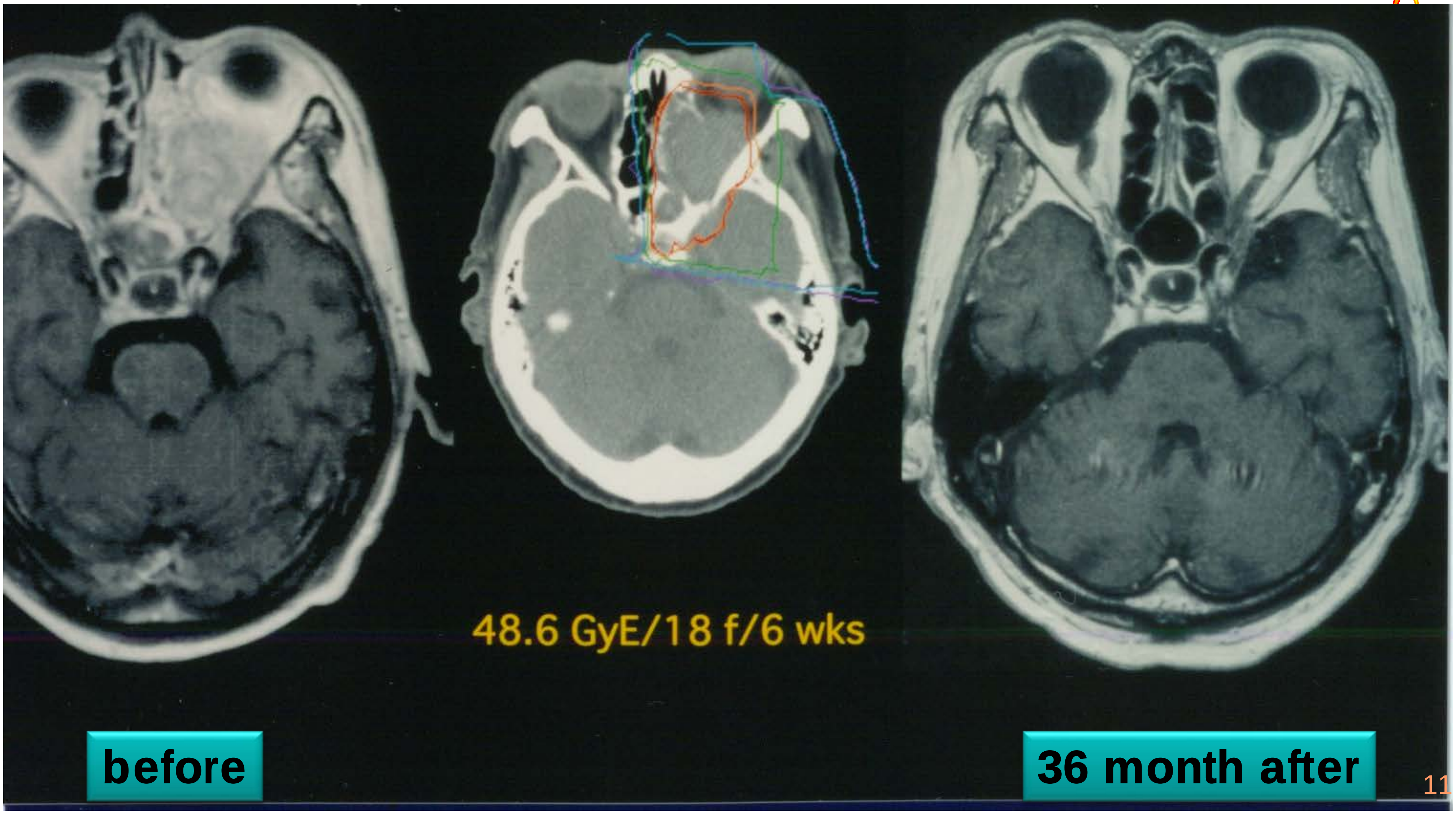
HIMAC can accelerate heavy ions having q/m=1/2 up to E/A=800 MeV

Patients treated with carbon-ion radiotherapy at NIRS

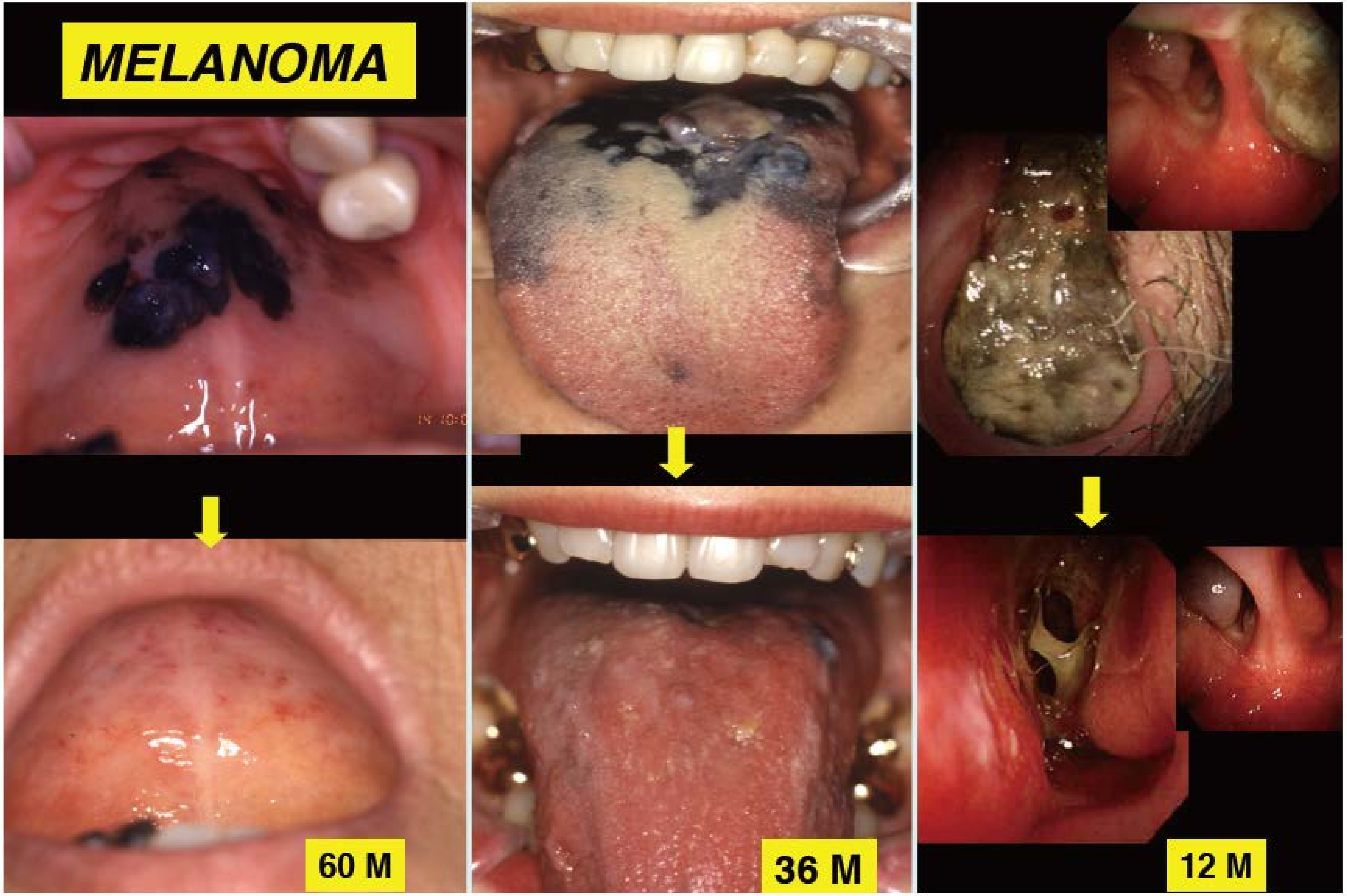


Some clinical results

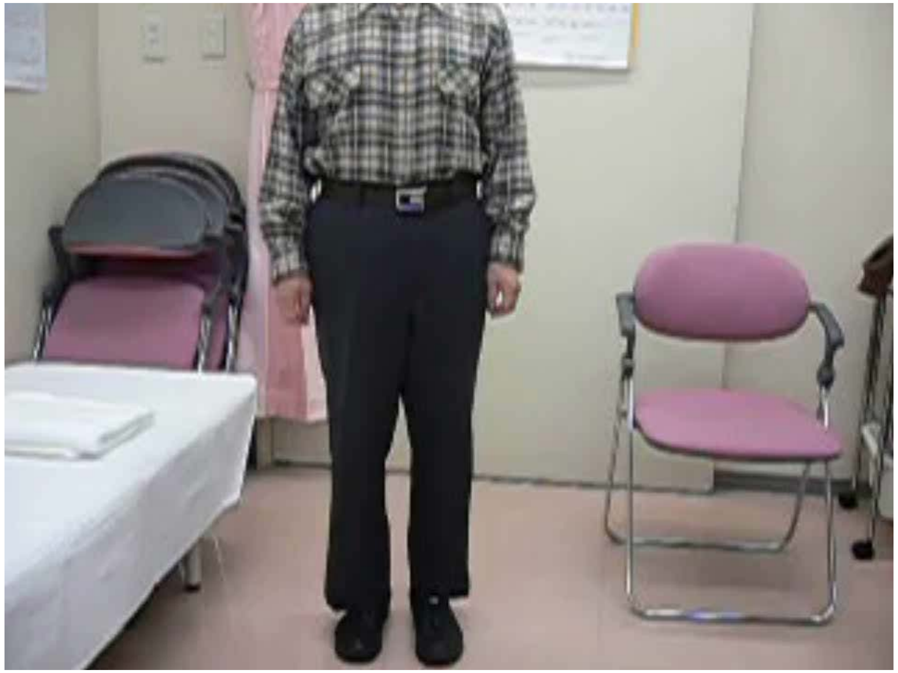
Head and Neck tumor

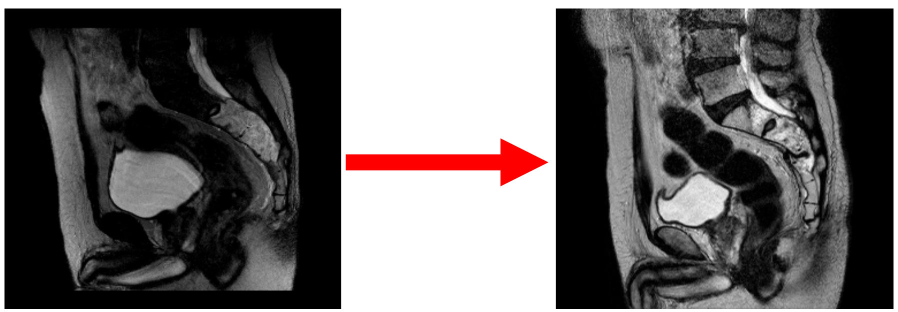


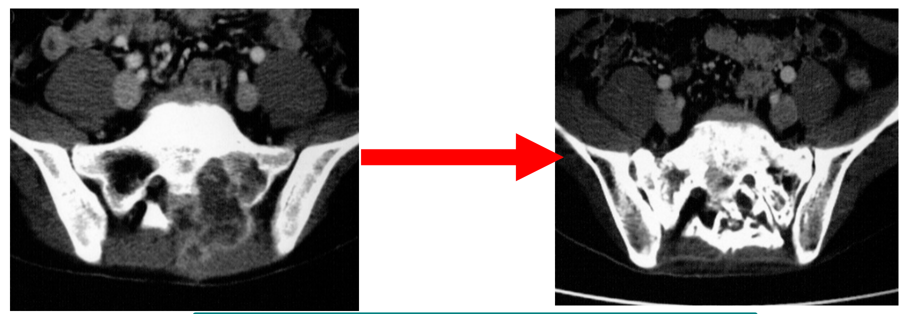
Malignant Head and Neck Tumors



Sacral chordoma, osteosarcoma







Unresectable sacral chordoma

5 years after C-ion RT

Sacral osteosarcoma

13 years after C-ion RT

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Local Control and Survival Rate in Chordoma

	No of Pts (new Pts/year)	Site S:sacrum Sp:mobile spine	Treatment	5 year Local Control	5 year Overall Survival
Sweden 1) 1963-1998	39 (1.1)	S+Sp	Surgery	44%	84%
MGH. 2) 1982-2002	27 (1.4)	S	Surgery + Proton	72%	82%
LBL 3) 1977-1989	14 (1.2)	S	Surgery + Helium	55%	85%
Mayo 4) 1980-2001	52 (2.5)	S	Surgery	56%	74%
NIRS 1996-2011	185 (12)	S+Sp	C-ion (unresectable)	78%	85%

1) Cancer.2000 2)IJROBP.2006 3) IJROBP.1993 4) J Bone Joint Surg. 2005

Development of a compact facility

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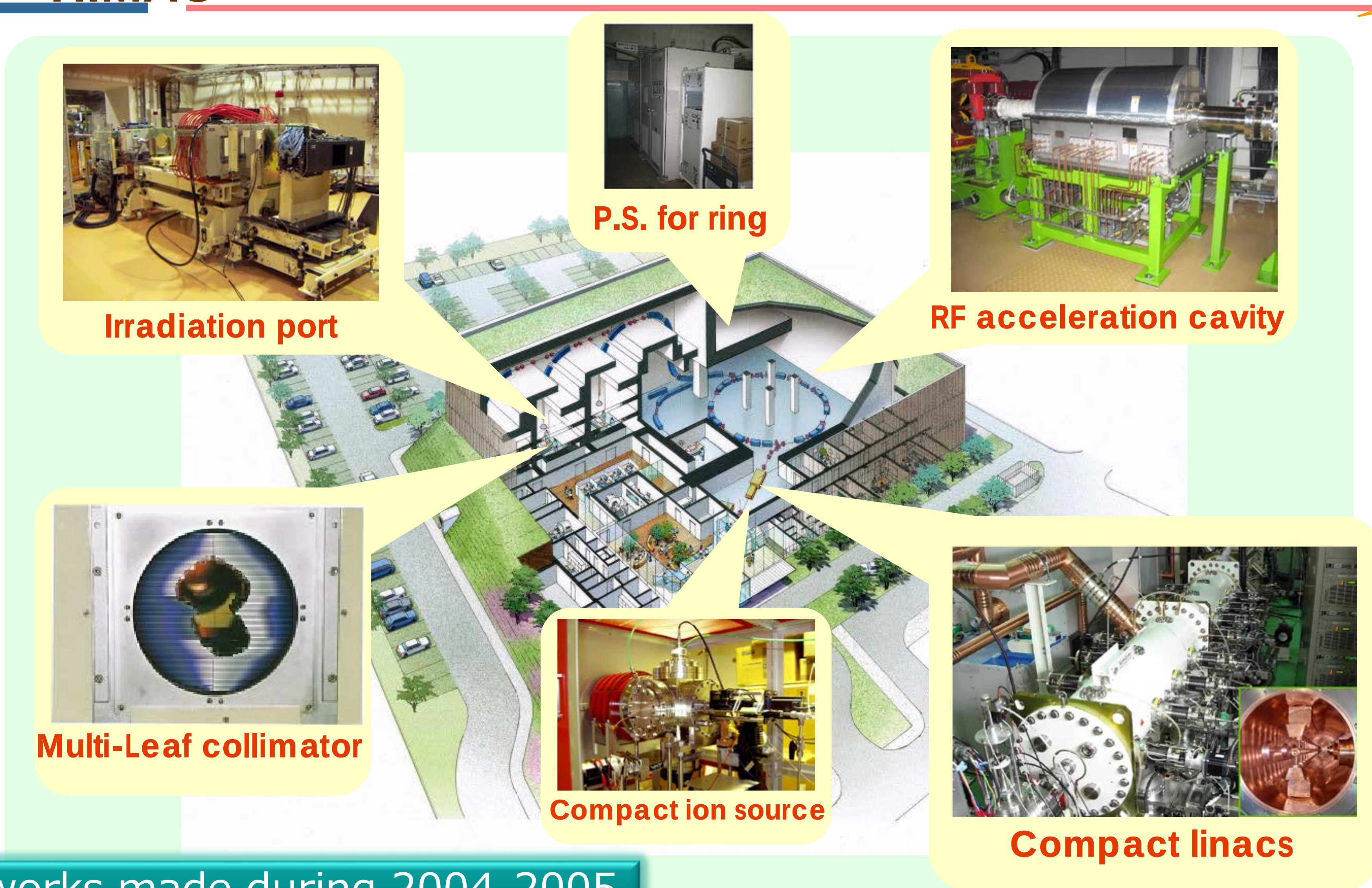
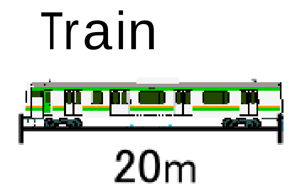
Design of a compact facility and Related R&D works

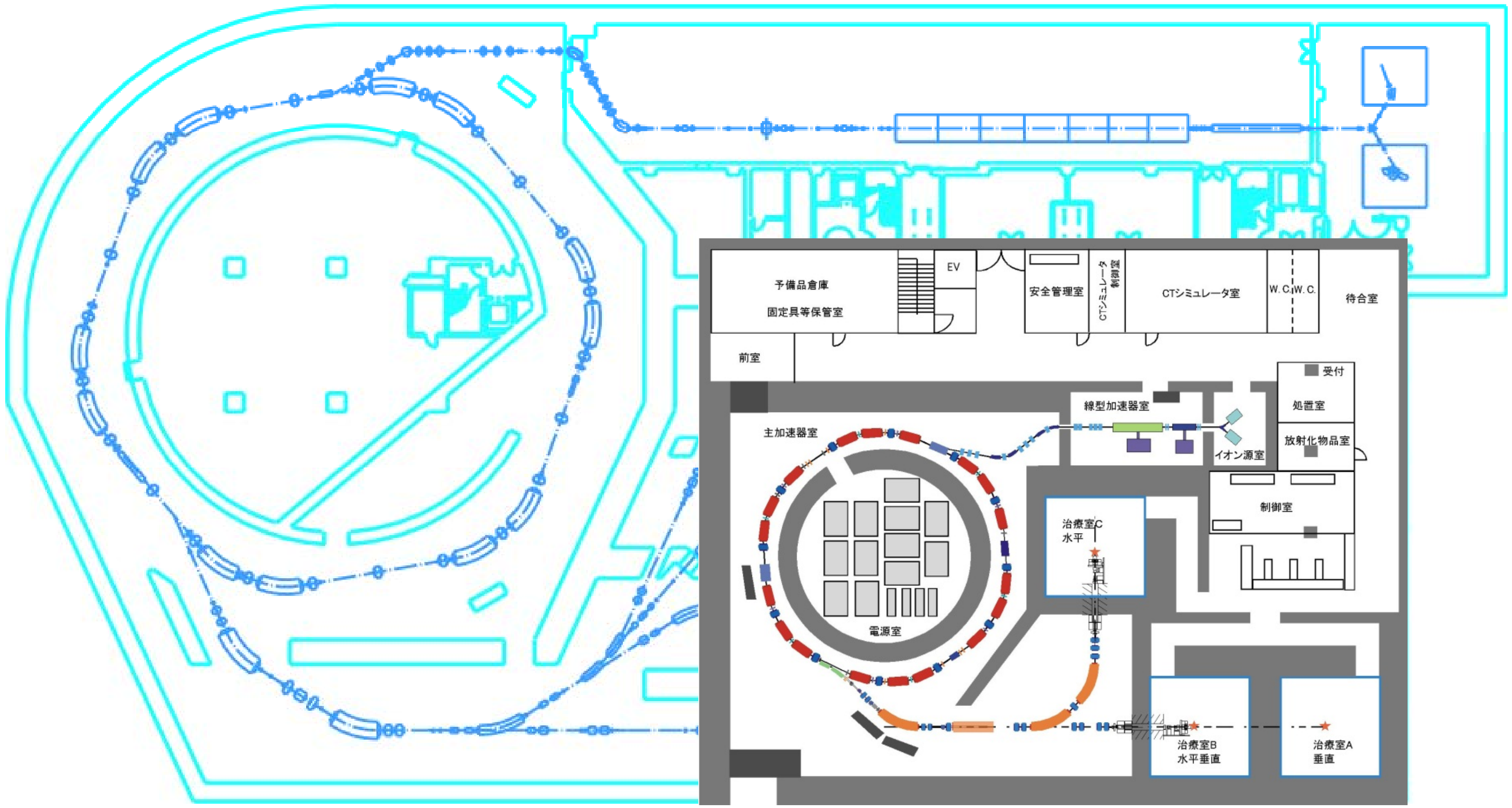


R&D works made during 2004-2005

Compact facility for carbon-ion radiotherapy (CIRT)

As a result of R&D works and design studies, we could design the compact accelerator facility, dedicated for CIRT





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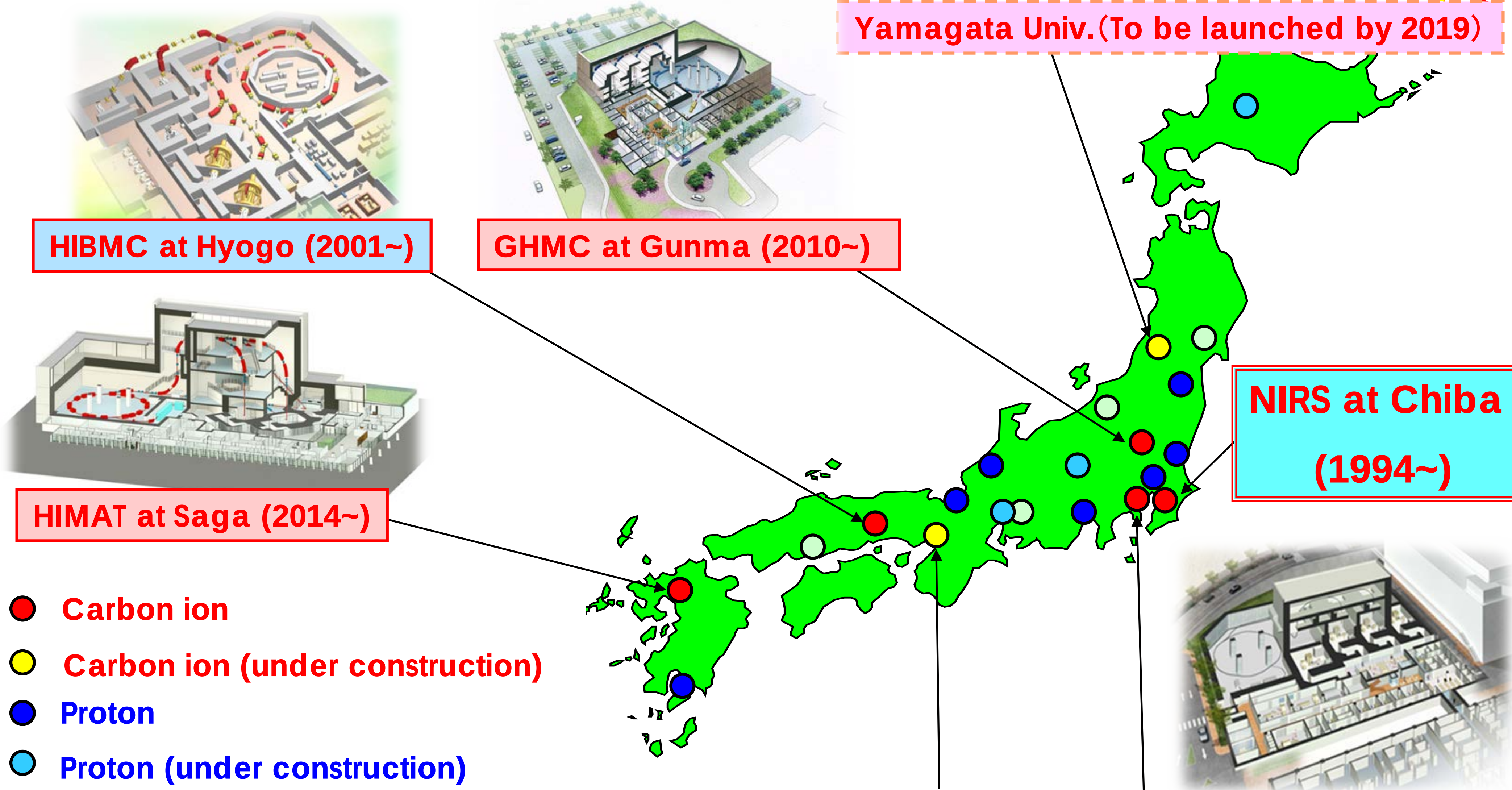
Particle radiotherapy facilities



- Carbon ion
- Carbon ion (under construction)
- Proton
- Proton (under construction)
- Planning

Osaka（To be launched by 2018）

KCC at Kanagawa (2015~)

Heavy-ion radiotherapy worldwide

Recent Developments

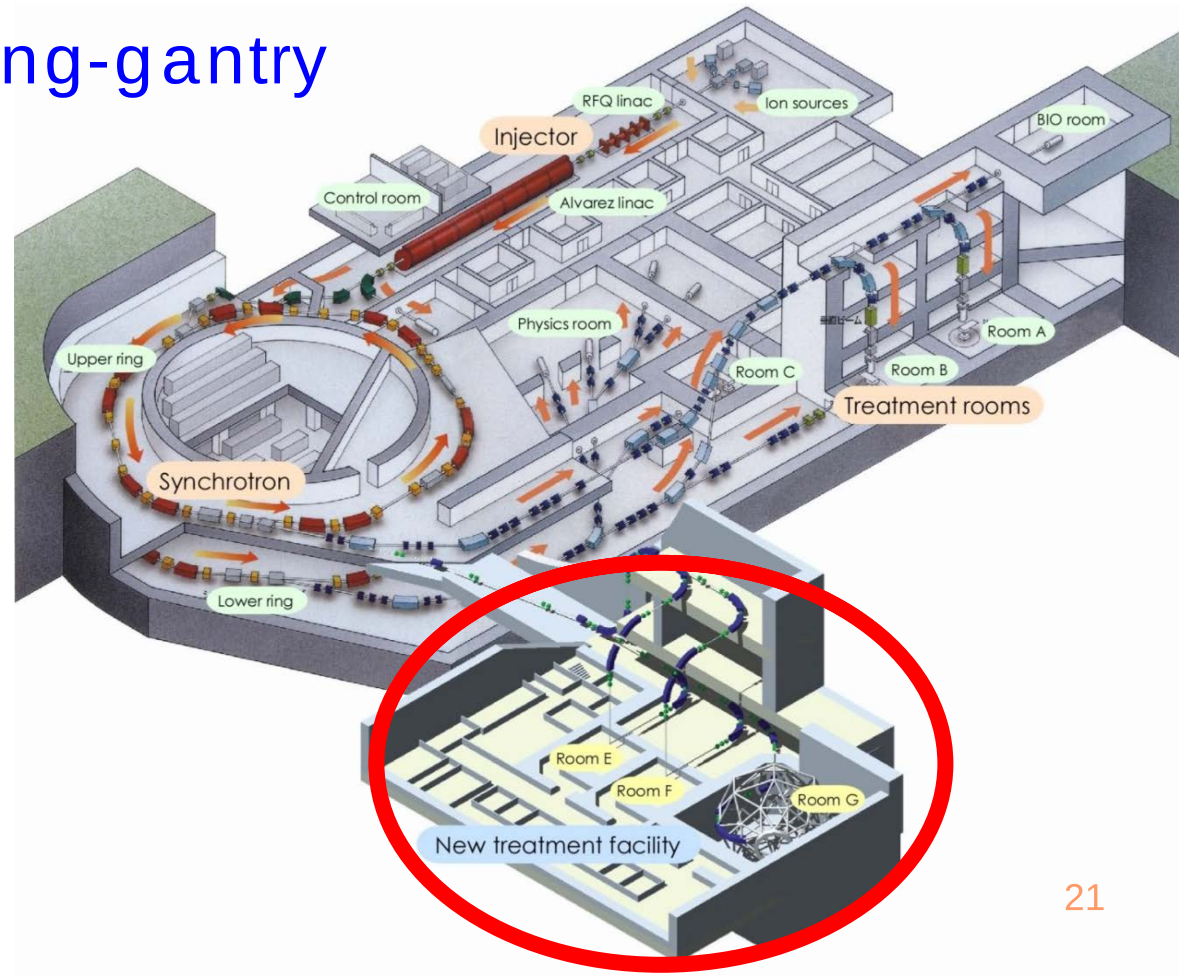
New treatment facility

Construction completed in 2011

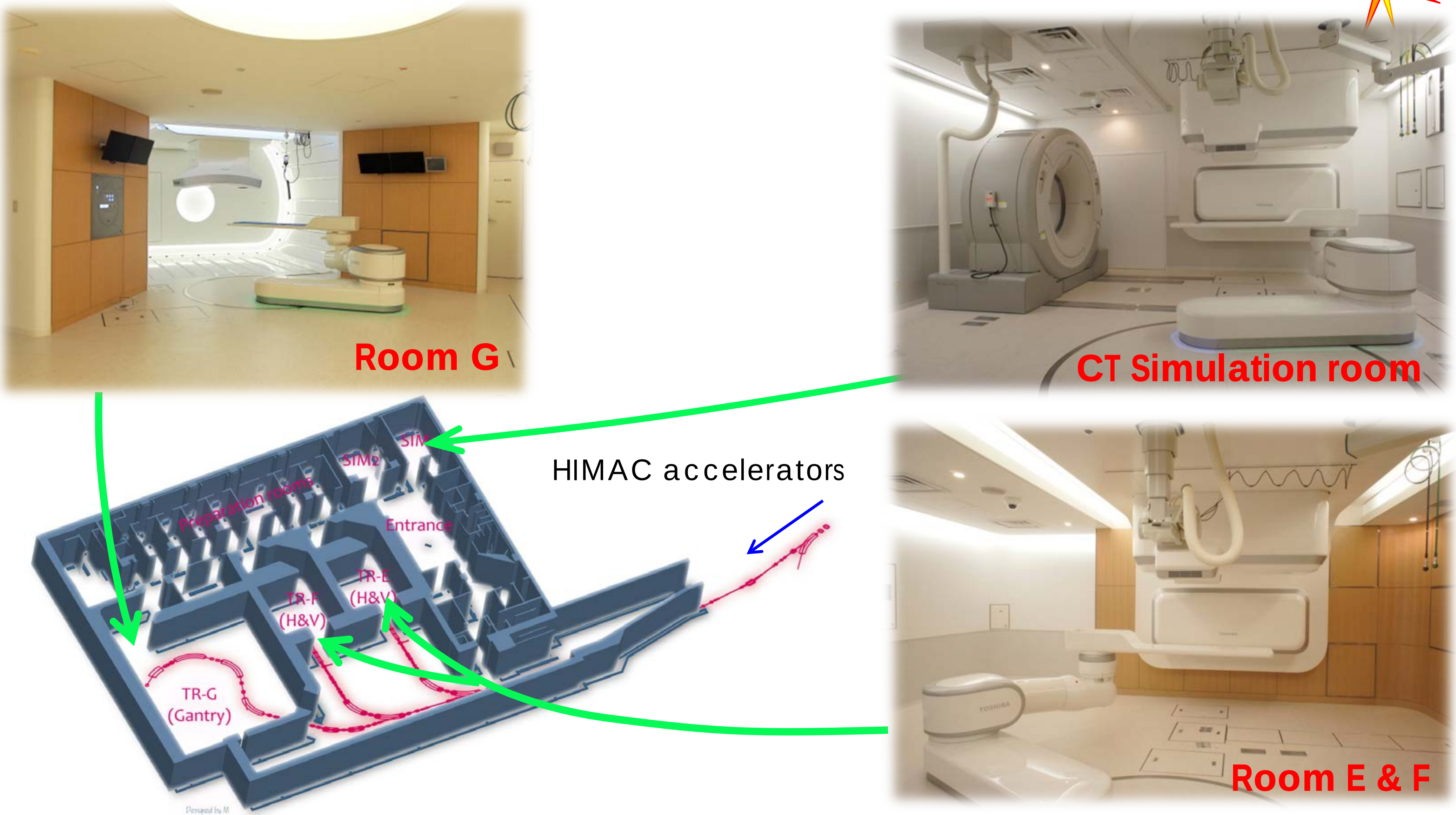
- New development
  - 3D raster scanning
  - Superconducting rotating-gantry
- 3 treatment rooms
  - **Room E & F**

    Fixed H&V scanning ports
  - **Room G**

    Rotating-gantry port

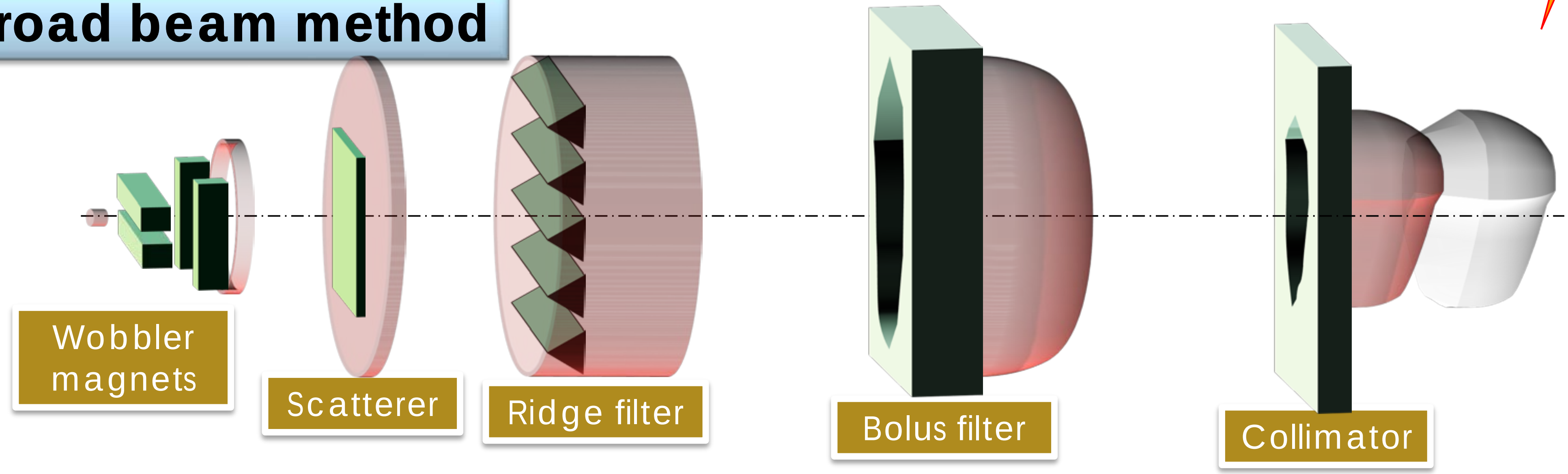


Treatment floor (B2F)



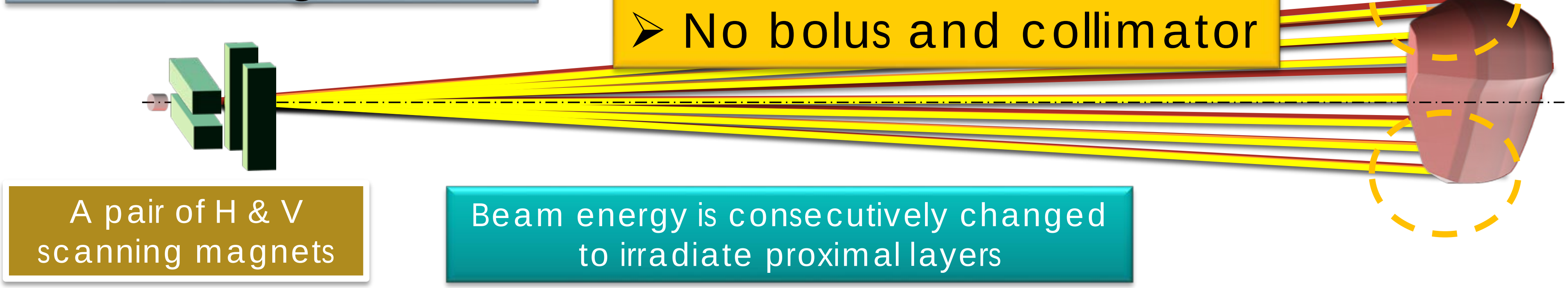
Irradiation methods

Broad beam method



3D scanning method

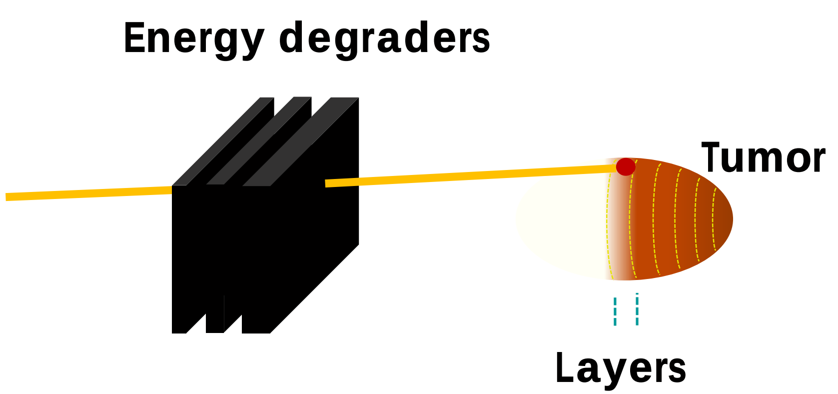
- Precise dose distribution
- Efficient irradiation
- No bolus and collimator

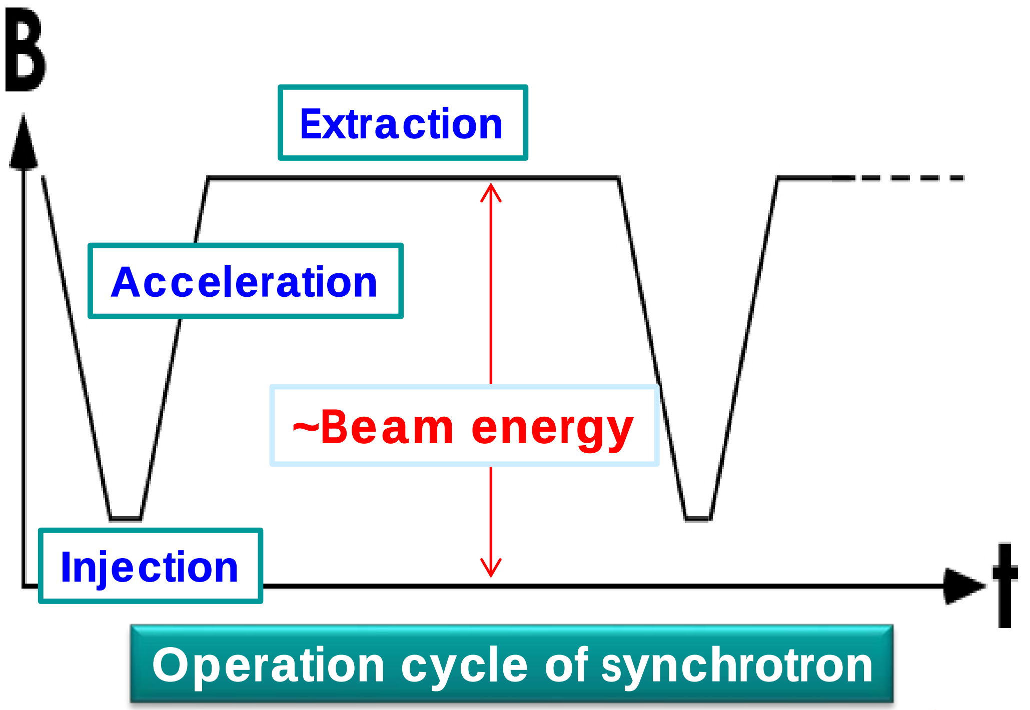


Depth-dose distribution

- **Synchrotron operation**
  - Fixed operation cycle (period: ~3 sec)
  - Fixed extraction energy
- **Use of energy degraders**
  - Enlarges a beam size
  - Produces fragments

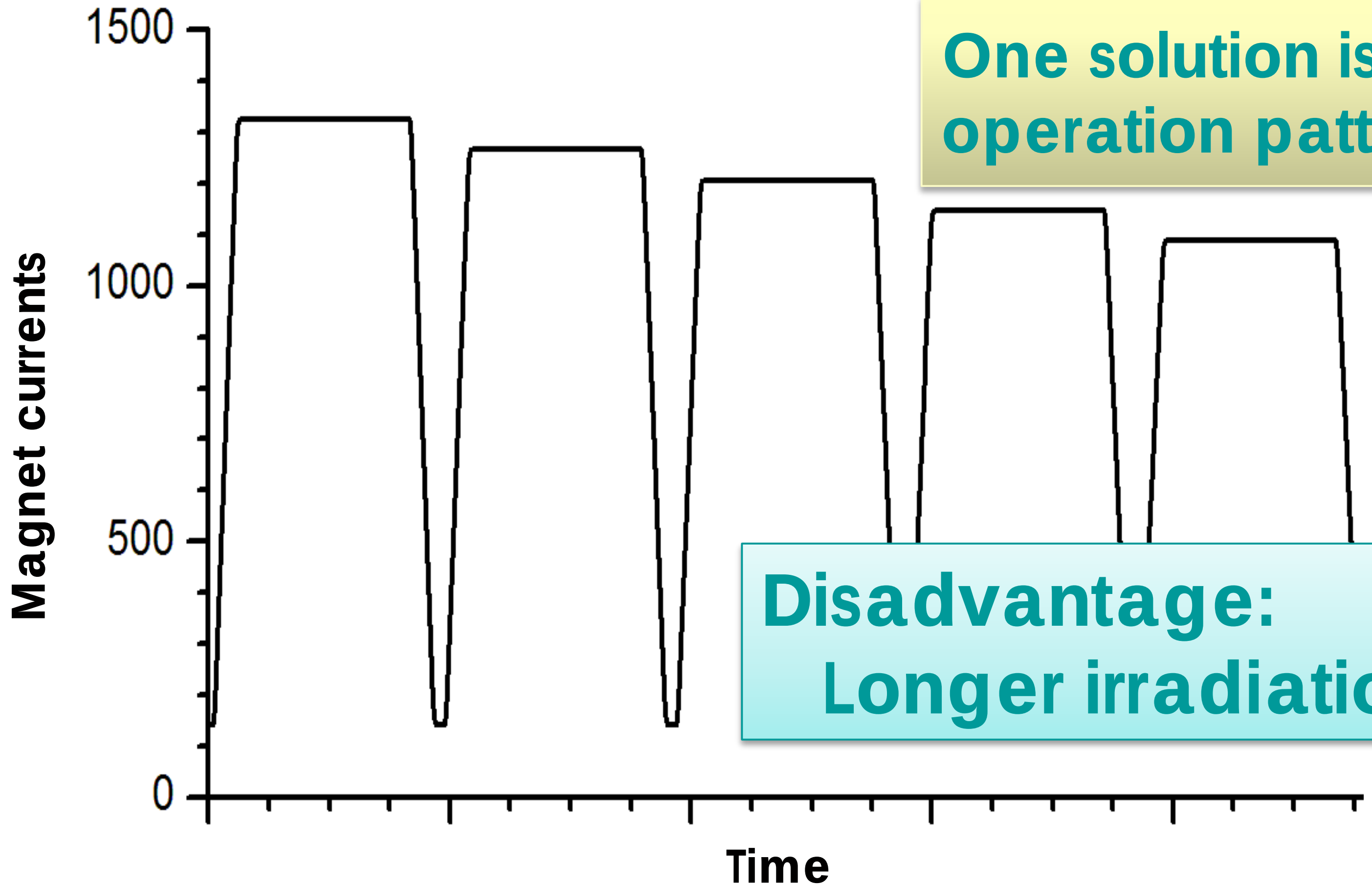
deteriorates dose distribution





For 3D scanning irradiation

- **To take advantage of 3D scanning irradiation,**
  - Beam energy must be changed by accelerators



One solution is to change operation patterns

Disadvantage:
Longer irradiation time!

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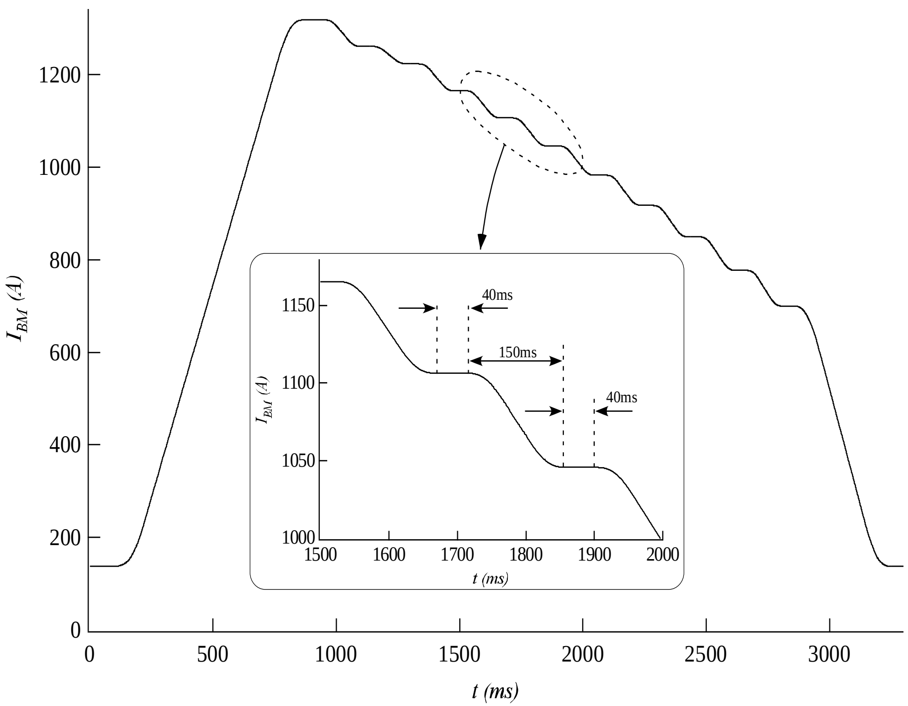
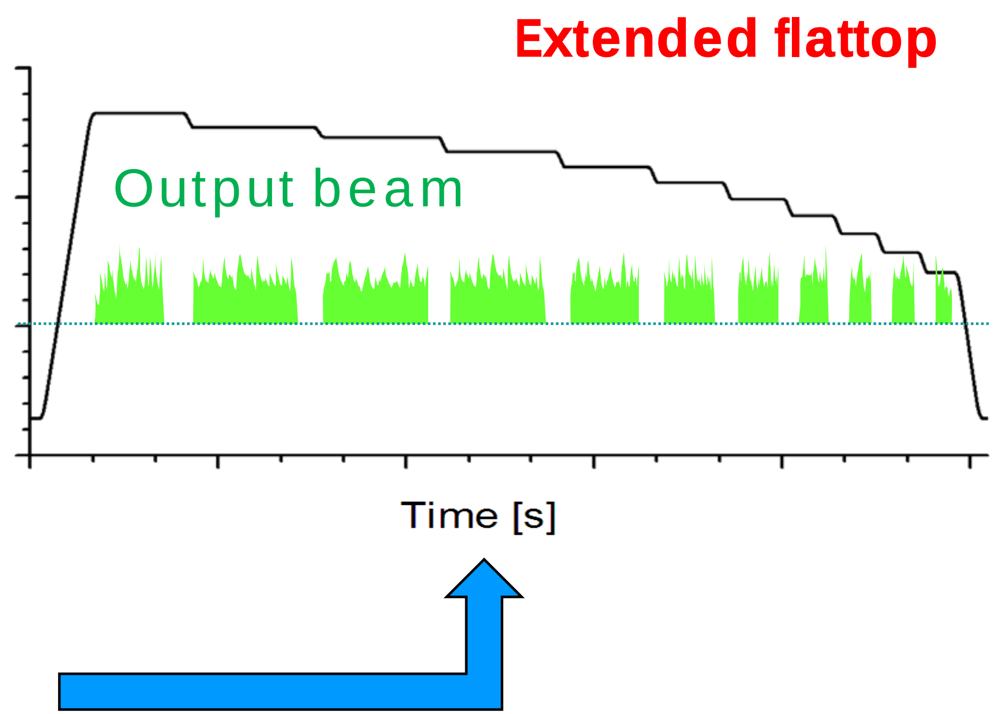
Variable energy operation

- Operation pattern having various flattops
- Each flattop can be extended
- **This operation enables to extract beams having various energies quickly!**





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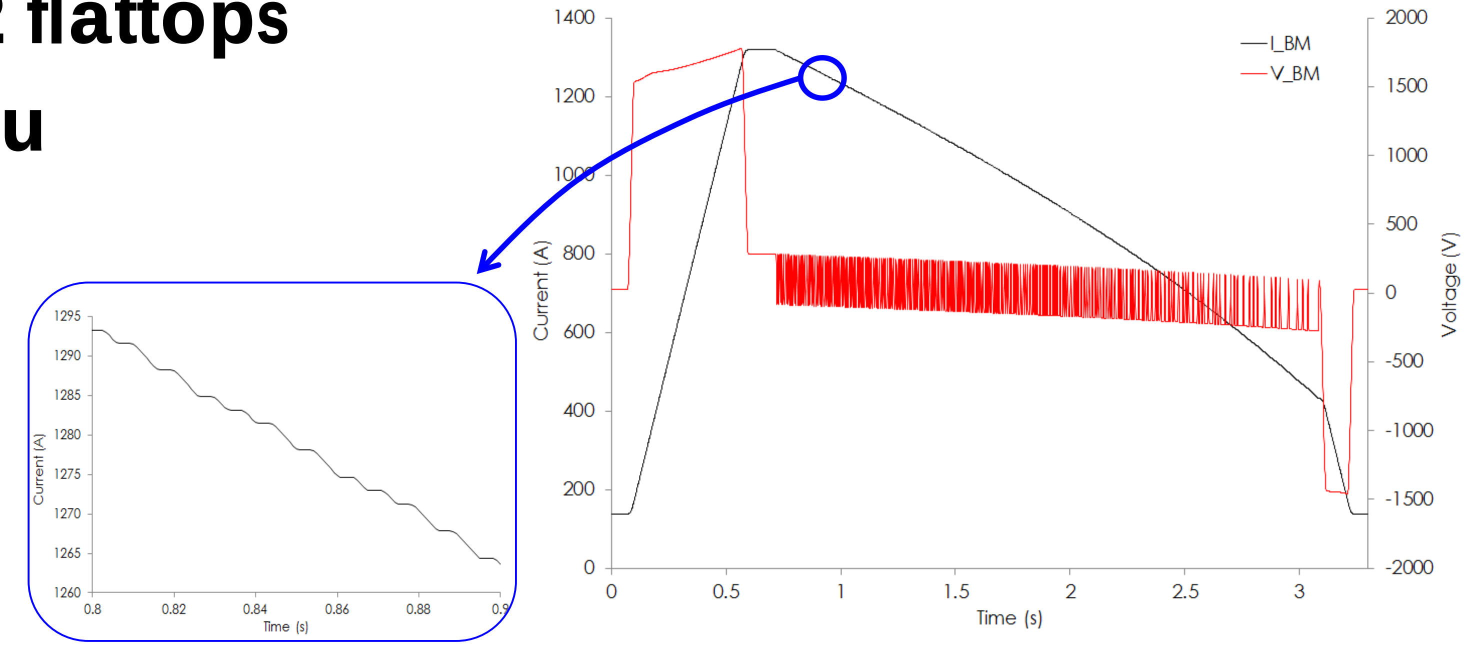
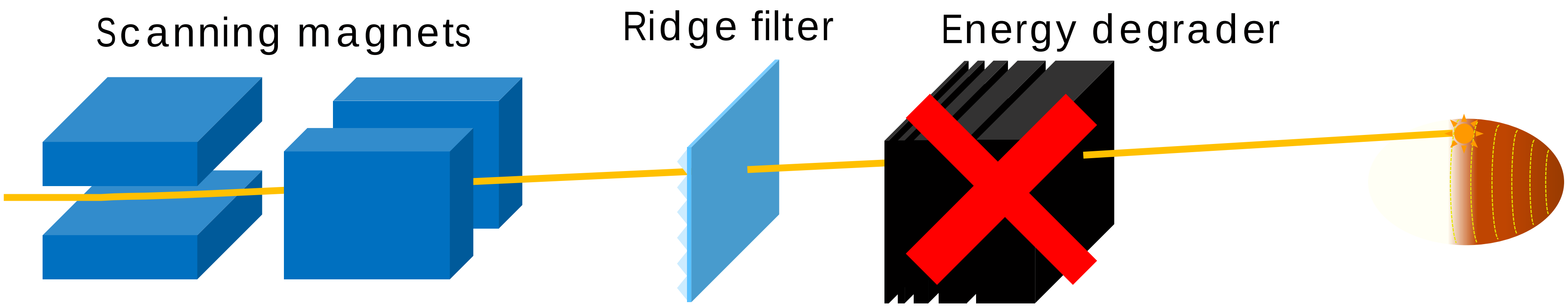
Full energy scanning

- **Pattern with 202 flattops**
- **E=430~50 MeV/u**
- **No degrader**





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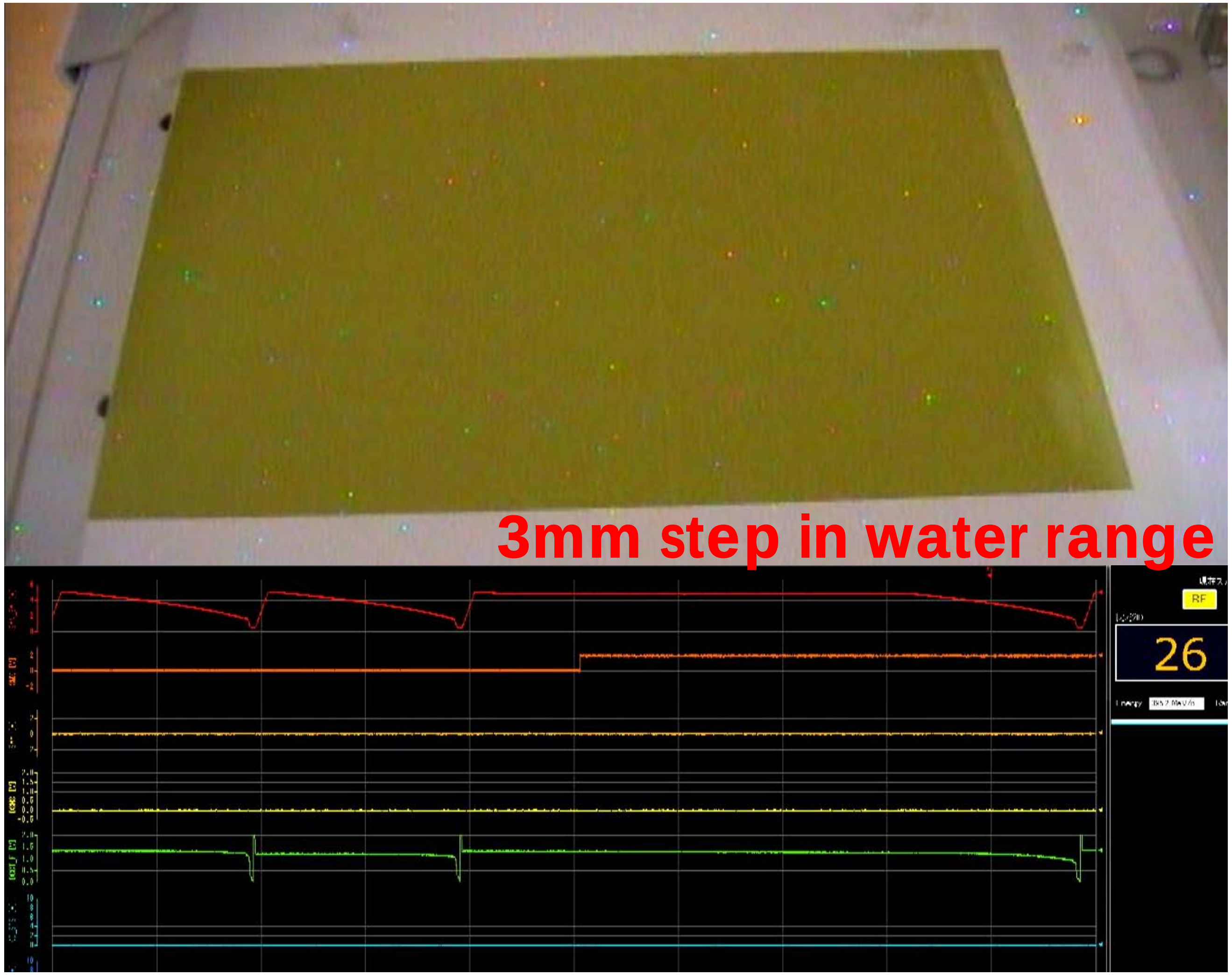
Beam acceleration and extraction tests

Lower energy

Beam direction

Higher energy



Current pattern of BM

Scanning magnet (X)

Scanning magnet (Y)

Extracted beam

Beam current in ring

Irradiation gate

Energy ID

Superconducting rotating-gantry

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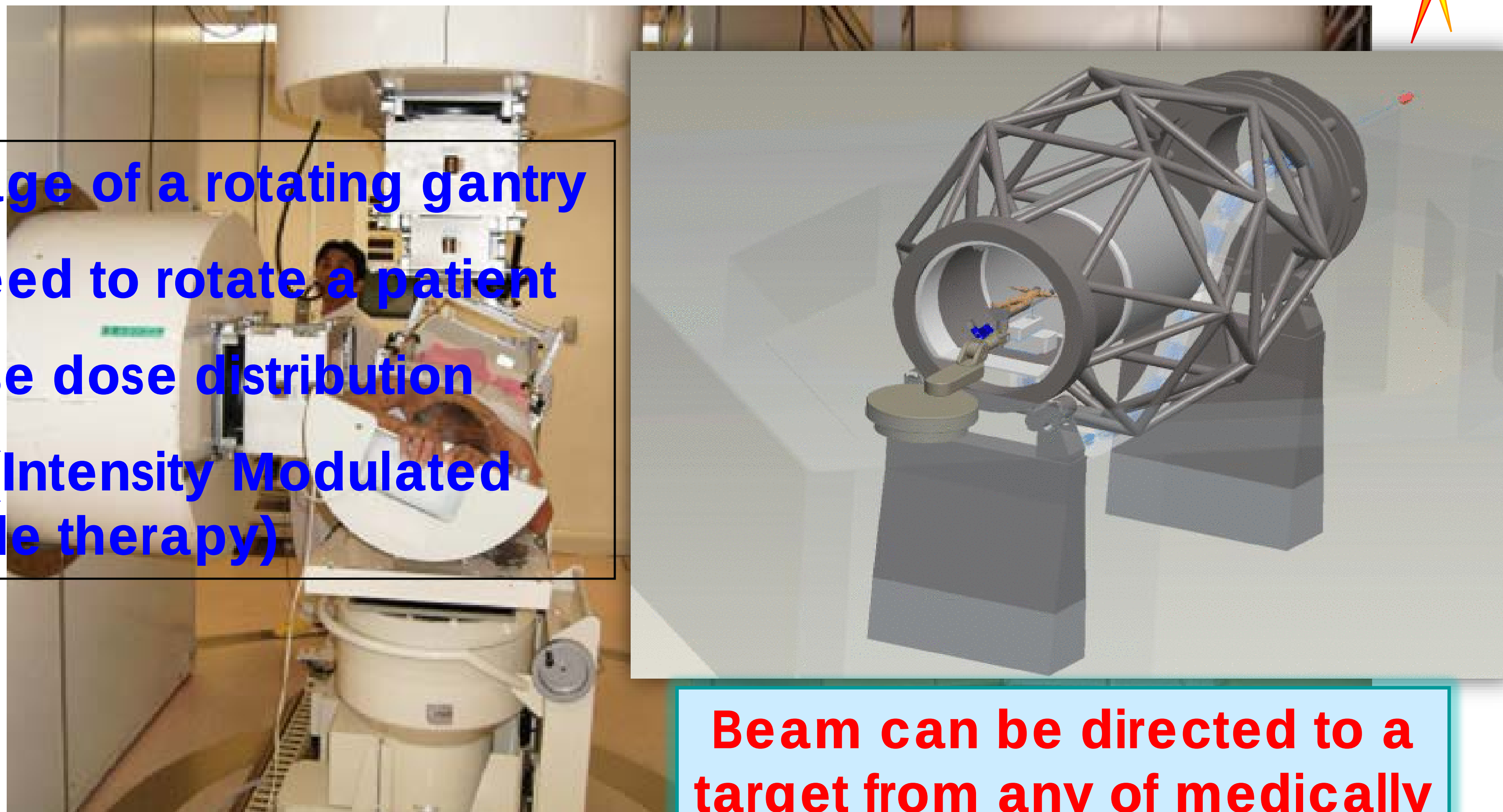
Irradiation using fixed irradiation ports

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

Treatment for a lung c

Rotating gantry for particle 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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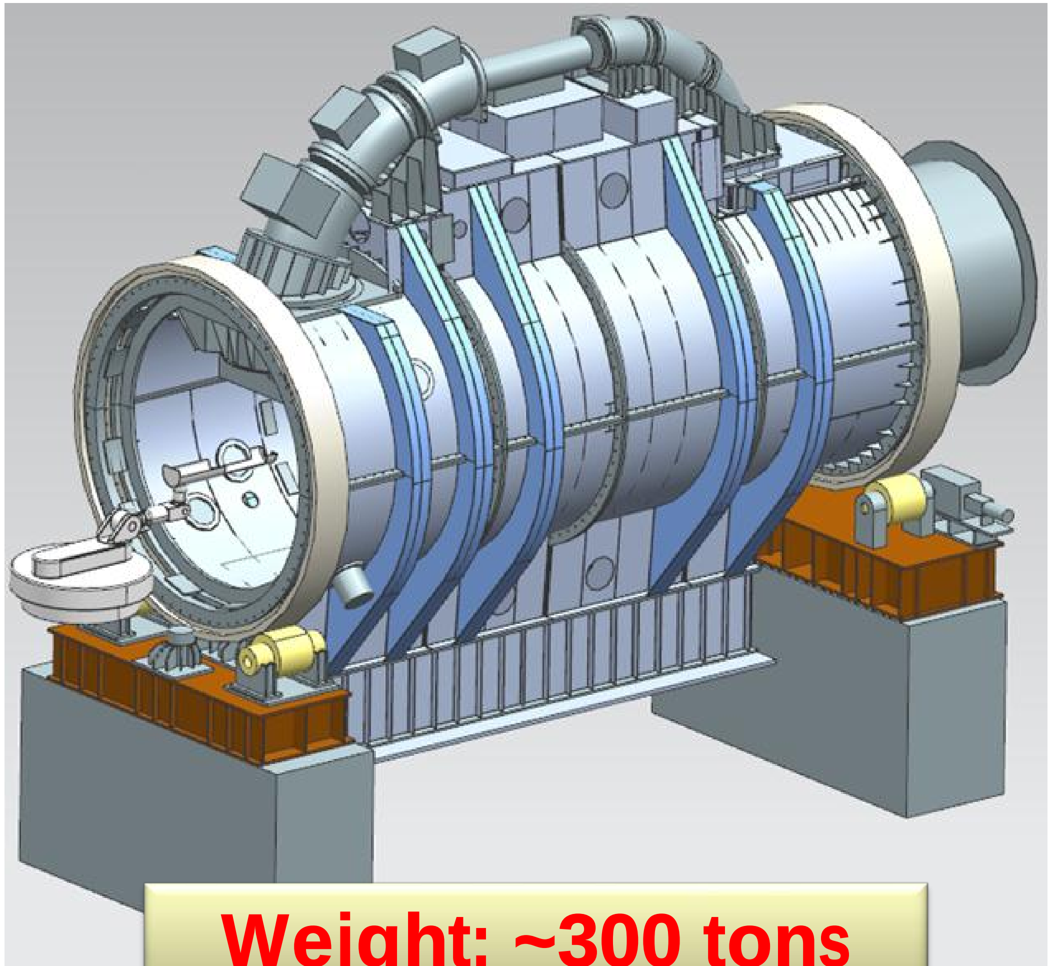
Superconducting rotating-gantry



Use of combined-function SC magnets

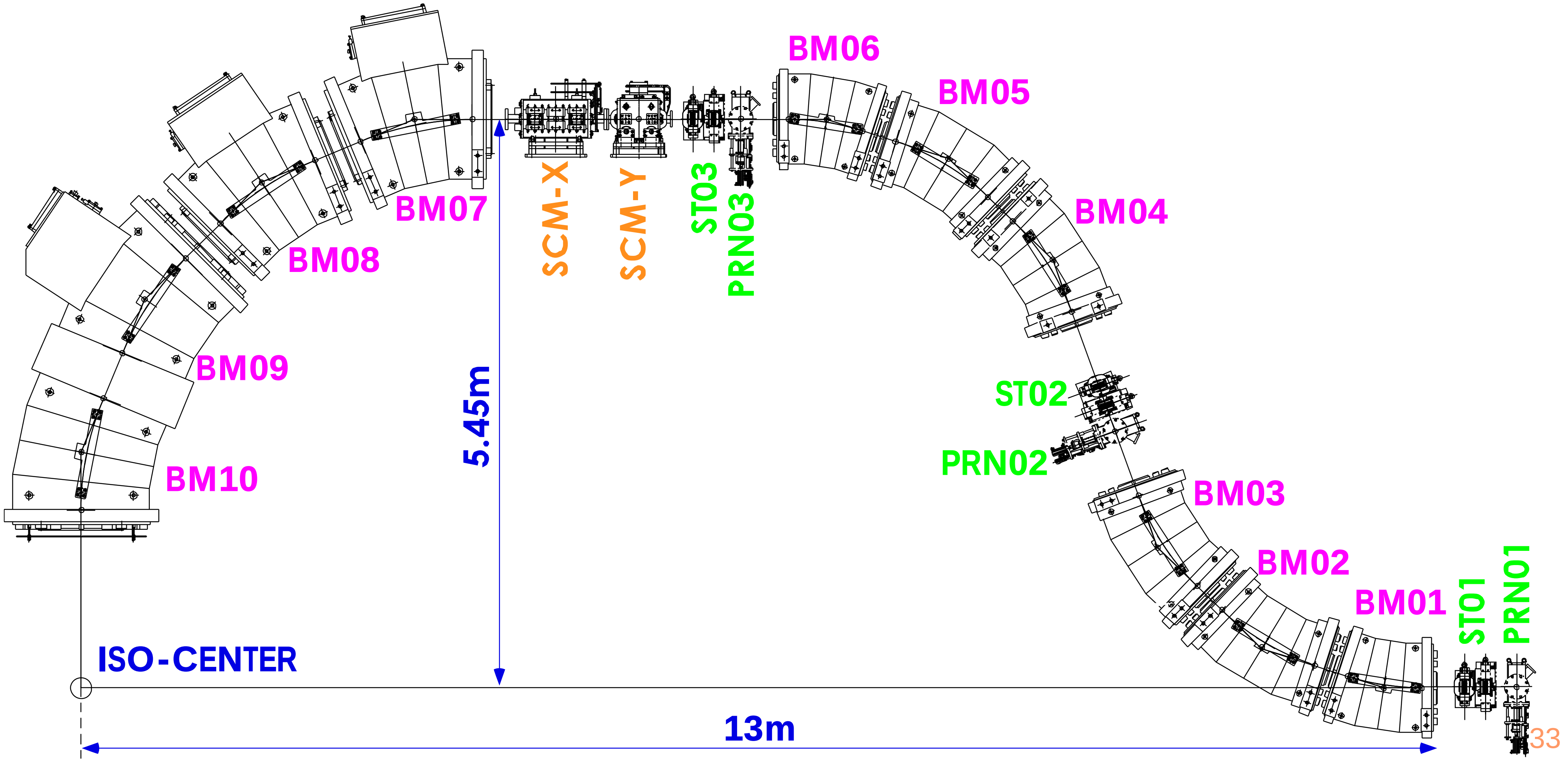
Ion kinds	: Carbon ions
Irradiation method	: 3D scanning
Maximum energy	: 430 MeV/n
Beam range	: 30 cm in water
Beam orbit radius	: 5.45 m
Length (ring to ring)	: 14 m

Weight: ~300 tons

Size and weight are considerably reduced

Layout of the SC gantry

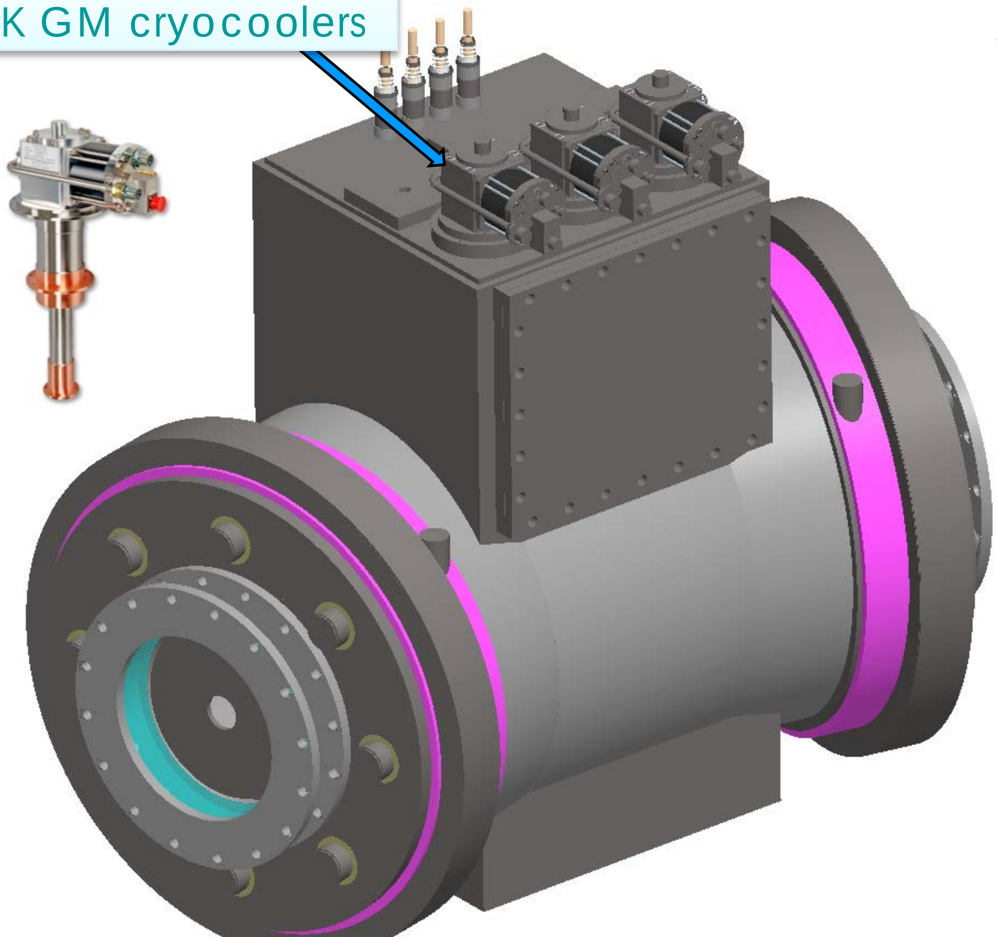
Combined-function SC magnets→No quadrupole magnet required



Development of SC magnets

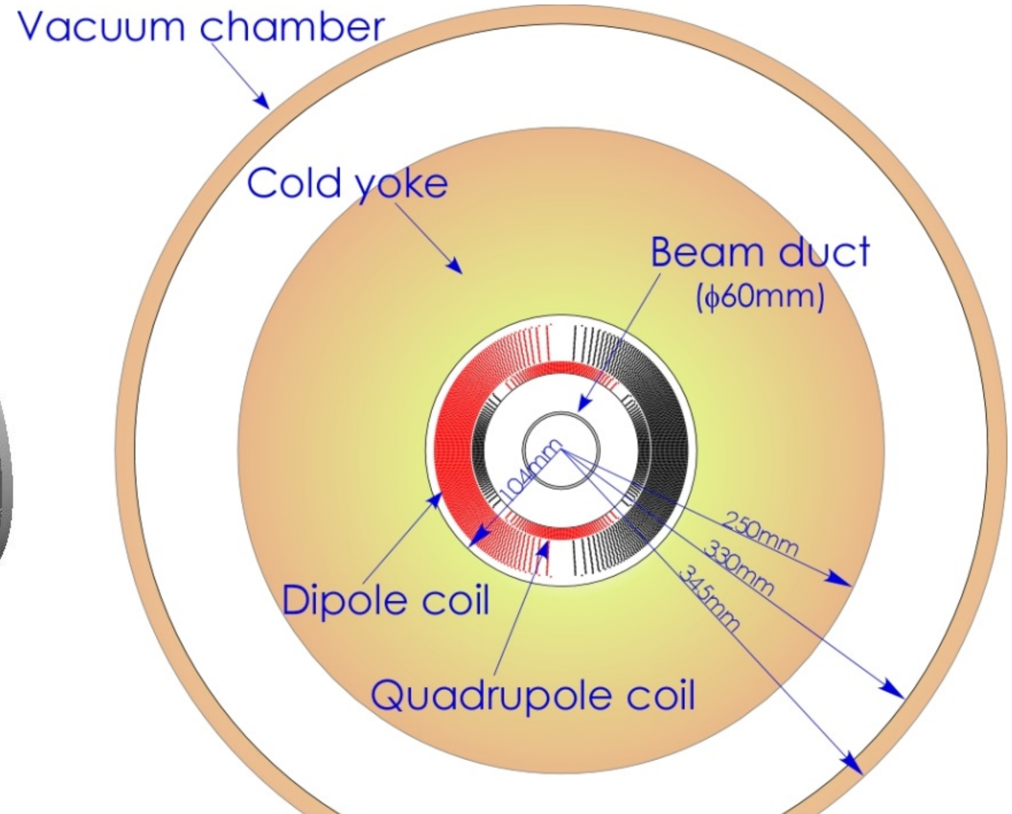
SC magnet (BM02-05)

4K GM cryocoolers



Liquid He free!

Cross sectional view



Dipole and quadrupole coils can be independently excited

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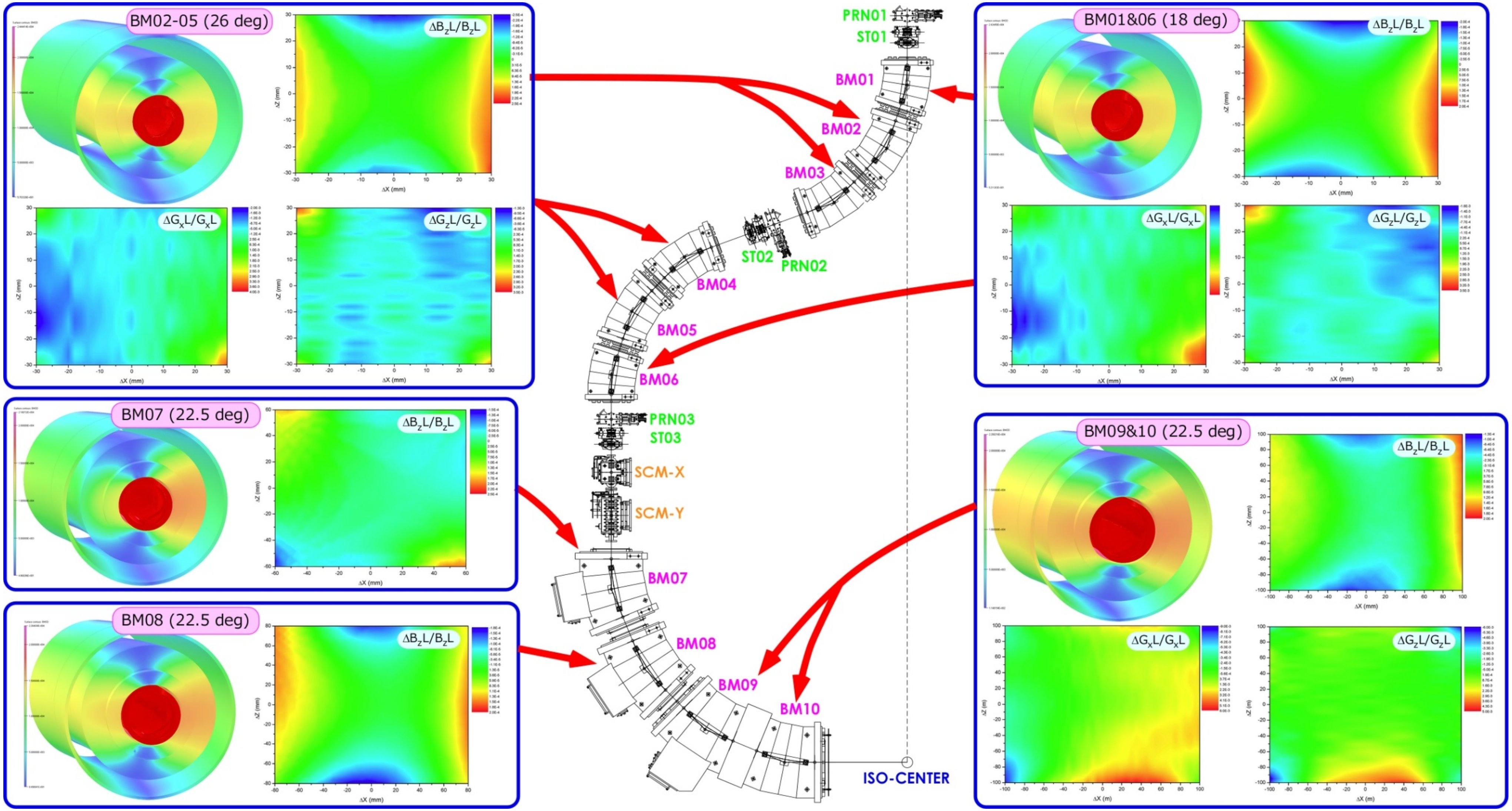
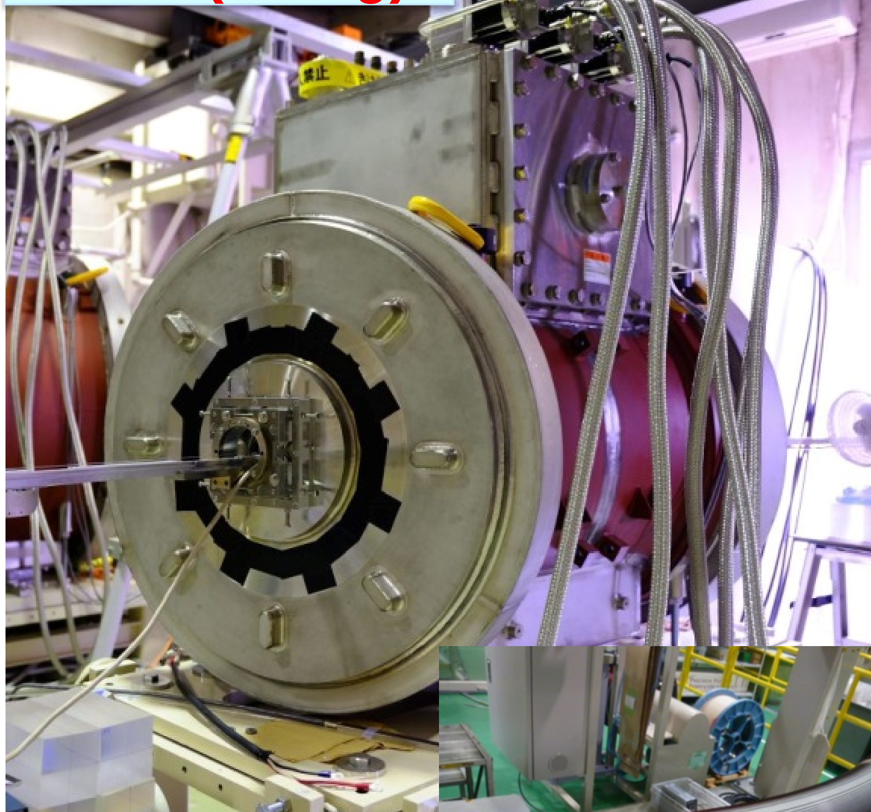
Design of SC magnets

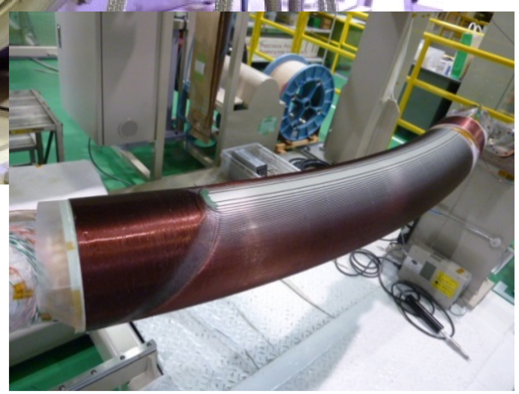
All the SC magnets were designed by using a 3D magnetic field solver



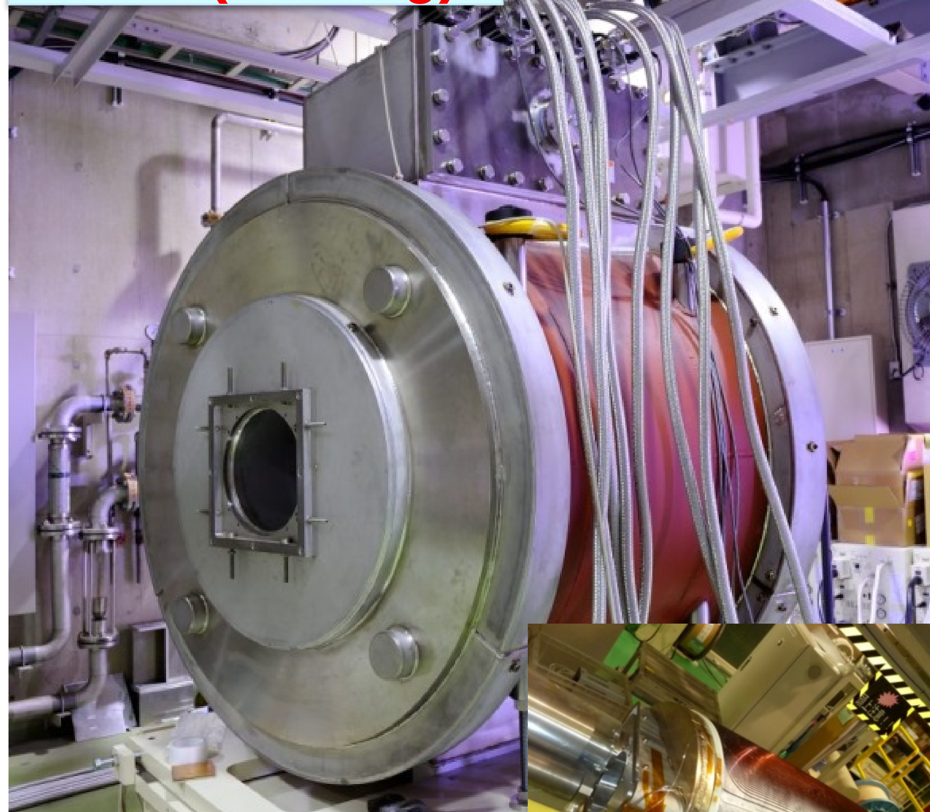
Construction of SC magnets

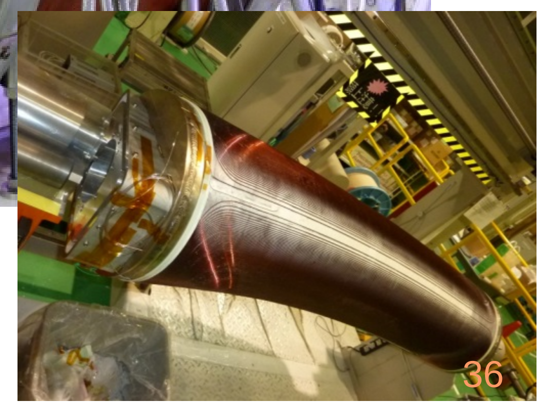
BM04 (26deg)



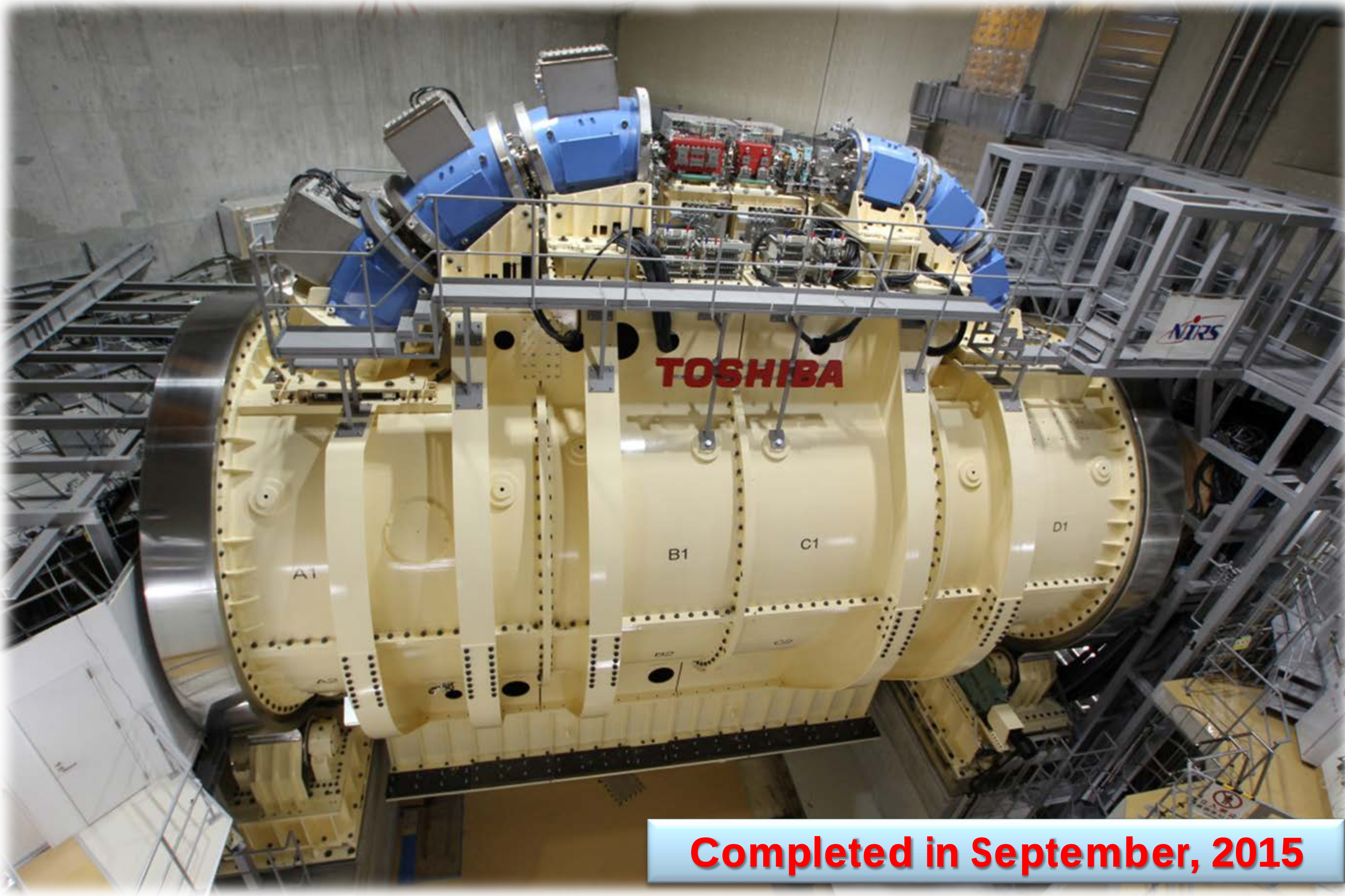


BM10 (22.5deg)





Construction of SC gantry



Completed in September, 2015

NIRS SC gantry for CIRT

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Future plan

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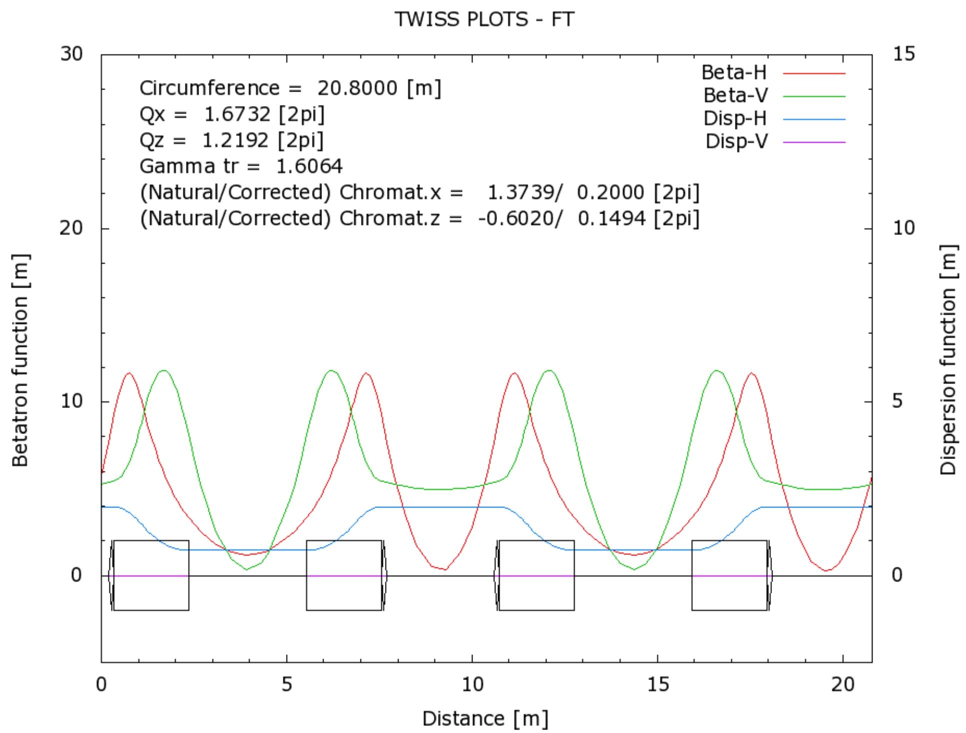
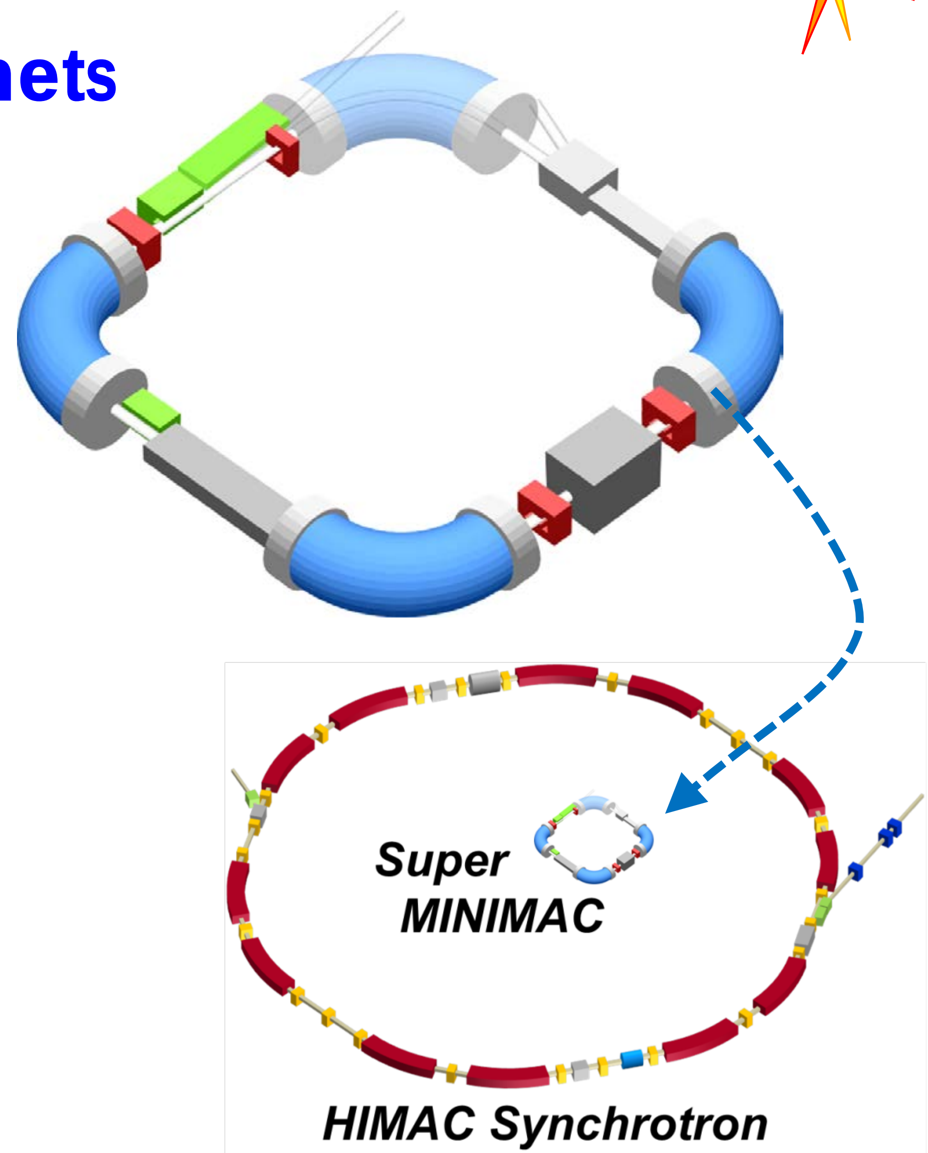
Superconducting synchrotron

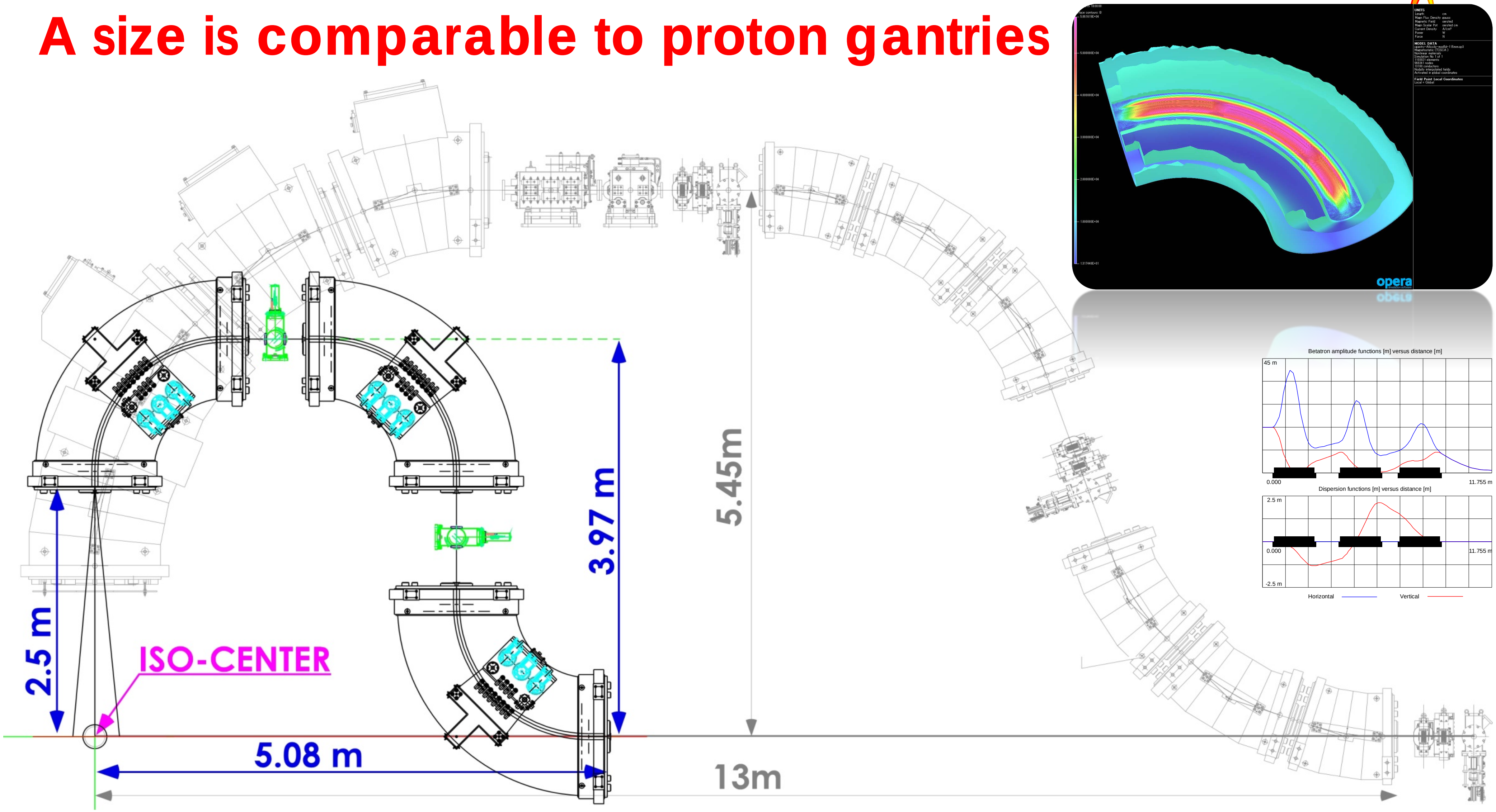
- **Combined-function SC magnets**
- **Max. dipole field: 4～5 Tesla**
- **Circumference: ~21 m**





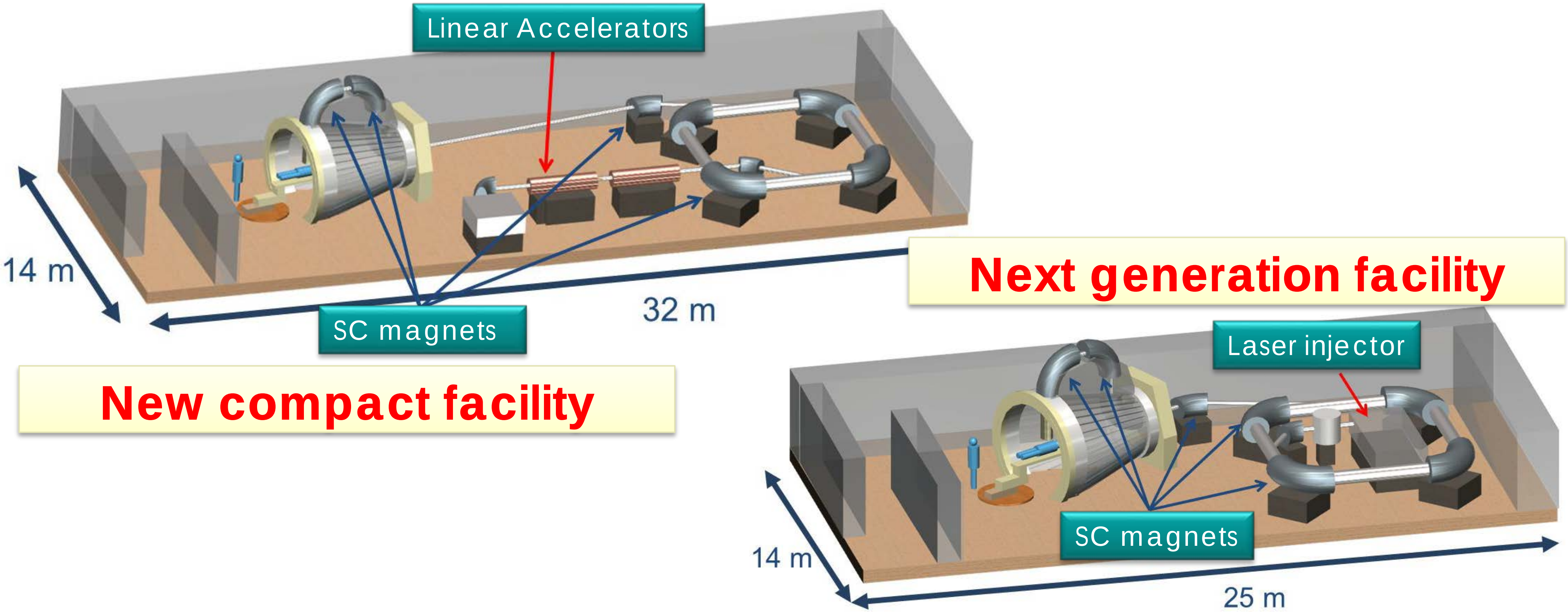
Compact SC gantry

- A size is comparable to proton gantries



Compact carbon facility

- Superconducting technology
- Multi-ion acceleration and irradiation (He, C, O)
- Laser-driven accelerator as an injector



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Summary

- CIRT has been performed since 1994, and more than 10,000 patients were treated at NIRS.
- With the R&D works, made during 2004-2005, a compact carbon facility was developed for widespread use of CIRT.
- Recently, the 3D scanning irradiation, as well as the SC gantry were developed.
- By using Superconducting and Laser technology, development of a compact facility is in progress.

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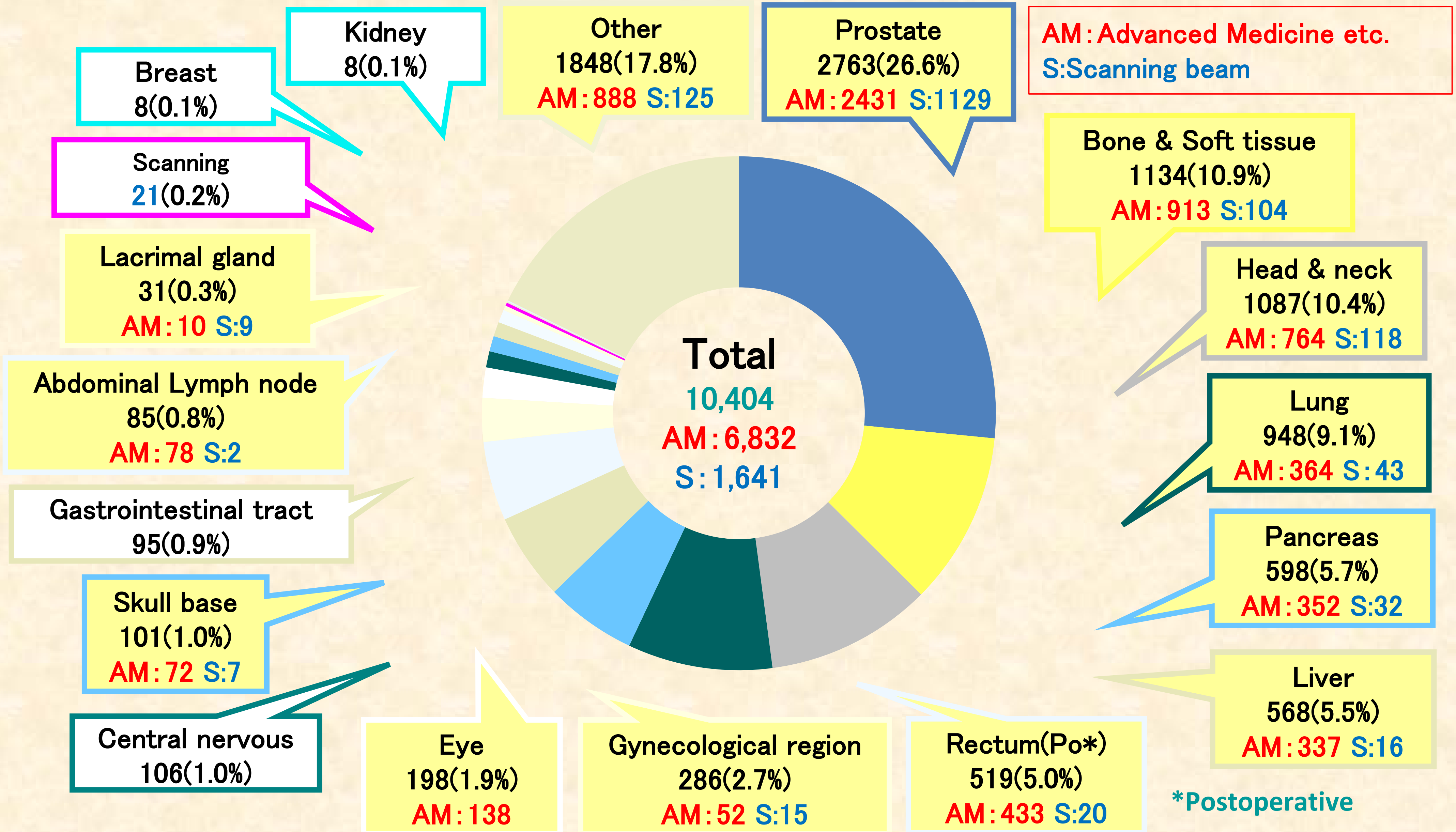
Collaborators

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

Patient Distribution Enrolled in Carbon Ion Therapy at NIRS
(June 1994～February 2017)



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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)	ΔBL/BL	–	$\pm 1\times10^{-4}$									
Uniformity (quadrupole)	ΔGL/GL	–	$\pm 1\times10^{-3}$									
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	

Fast slewing tests

- Tests with maximum slew-rate
- I=45~136 A (E=56~430 MeV/u)
- **No quench observed**
- **Average temperature converged below Tc~6.6 K**