Review of Ion Therapy Machine and Future Perspective

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National Institute of Radiological Sciences, QST
IPAC 2019, Melbouren, May 23, 2019

NIRS HIMAC

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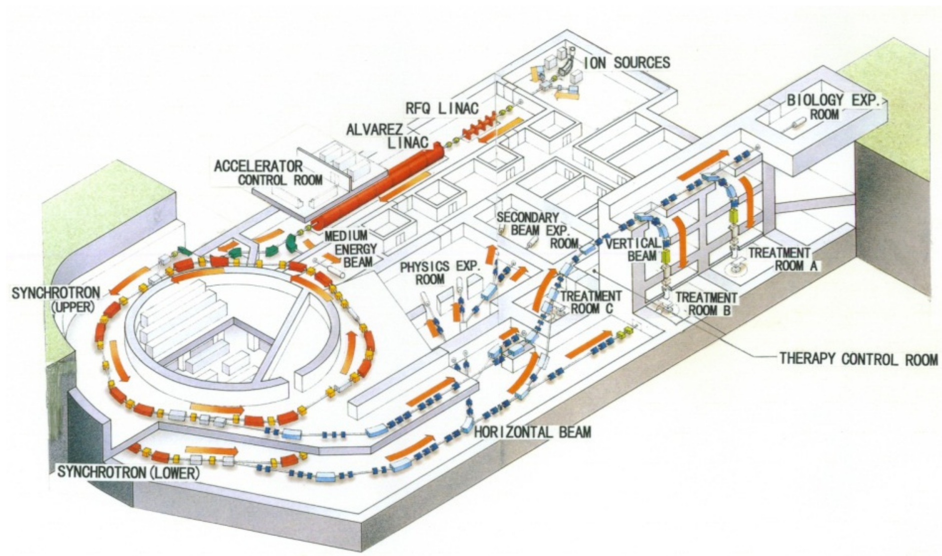
1. Introduction

2. Development for Ion RT

3. Future Plan

4. Summary



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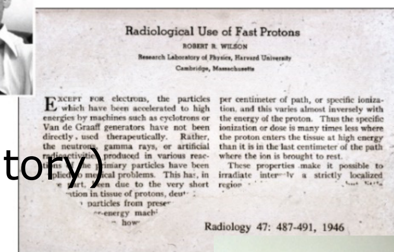
Heavy-Ion RT in Japan

R.R. Wilson, "Foreword to the Second International Symposium on Hadrontherapy," in Advances in Hadrontherapy, (U. Amaldi, B. Larsson, Y. Lemoigne, Y., Eds.), Excerpta Medica, Elsevier, International Congress Series 1144: ix-xiii (1997).


Radiological Use of Fast Protons
ROBERT R. WILSON
Research Laboratory of Physics, Harvard University
Cambridge, Massachusetts
Radiology 47: 487-491, 1946

1946- RR Wilson (USA) proposed applying accelerated ion beams to cancer therapy.

1975- Clinical research started using

an accelerator for physics research(Lawrence Berkeley Laboratory)

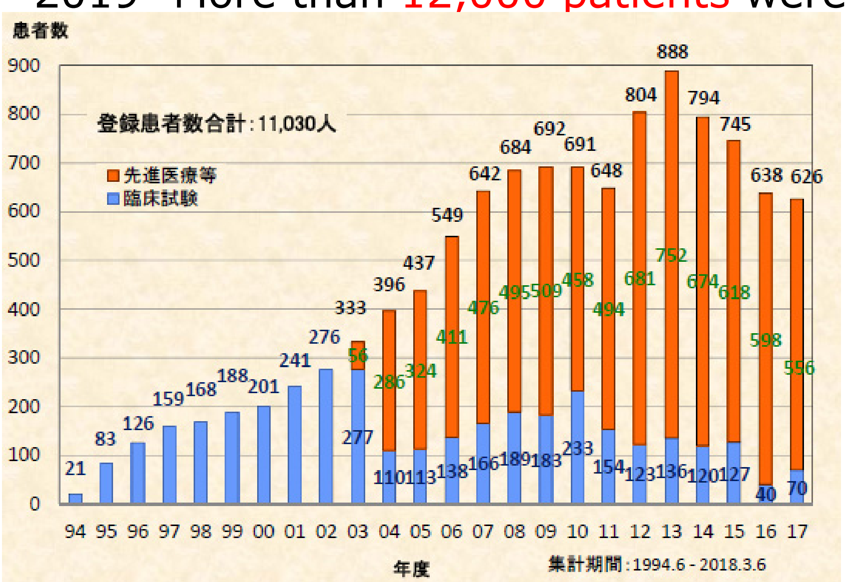
1984- R&D of heavy ion cancer radiotherapy started.

1993- We (QST-NIRS) succeeded in completing a Carbon-Ion cancer radiotherapy (HIMAC) machine for the first time in the world.

1994- Clinical study of Carbon-Ion Radiotherapy began.

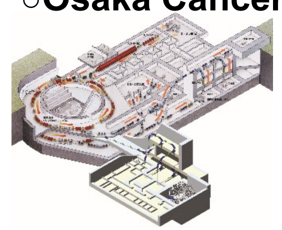
Yasuo Hirao

2019- More than 12,000 patients were treated.



Carbon-Ion Radiotherapy Facilities in Japan

- ○NIRS (1994)
- ○Hyogo HIRT Center (2002)
- ○Gunma University (2010)
- ○Kyushu International HIRT Center(2013)
- ○Kanagawa Cancer Center (2015)
- ○Osaka Cancer Center (2018)

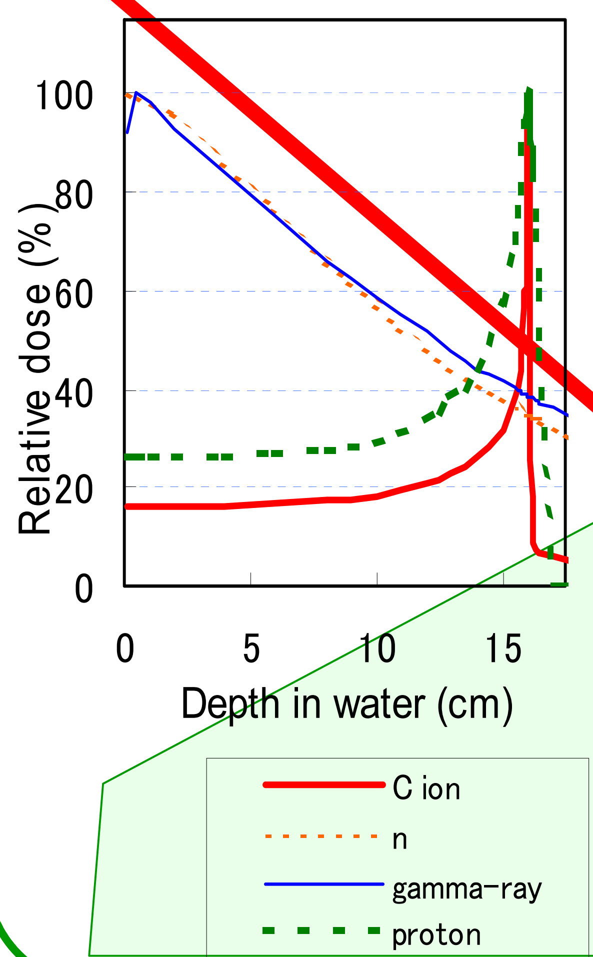


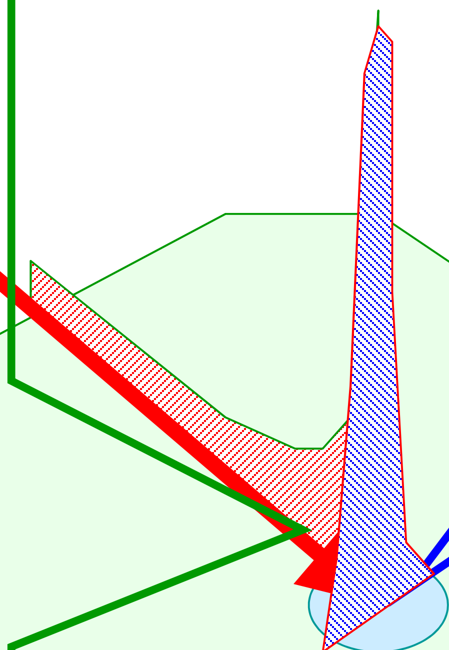
HIMAC(NIRS)

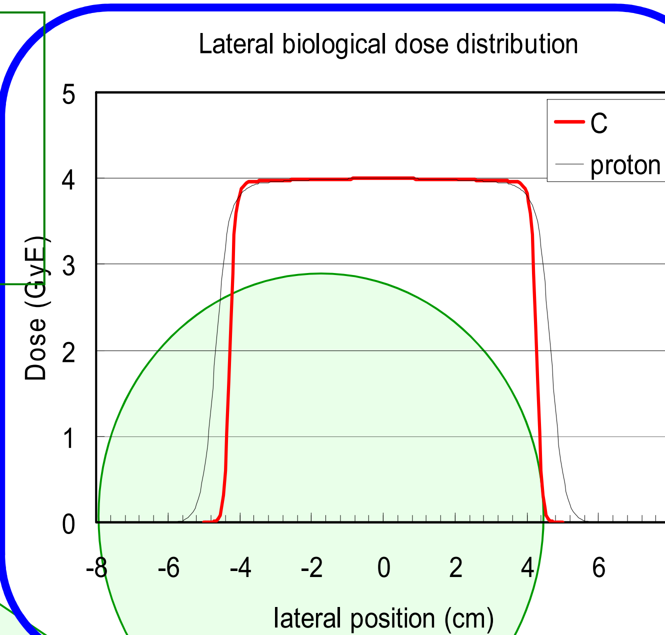
Gunma University

Physical Characteristics of Ion RT

High longitudinal dose localization owing to the Bragg peak.

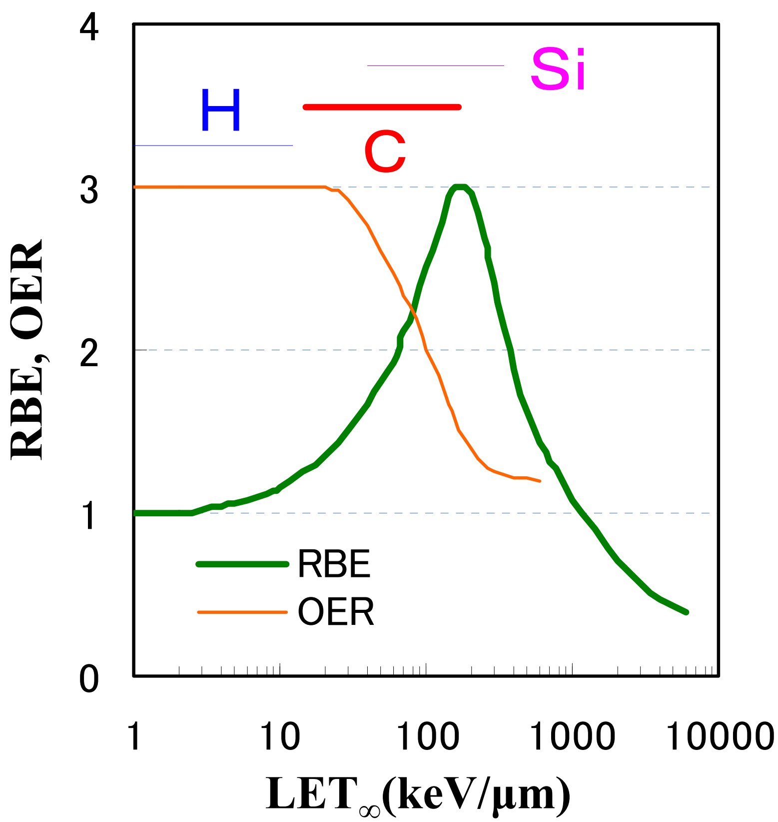




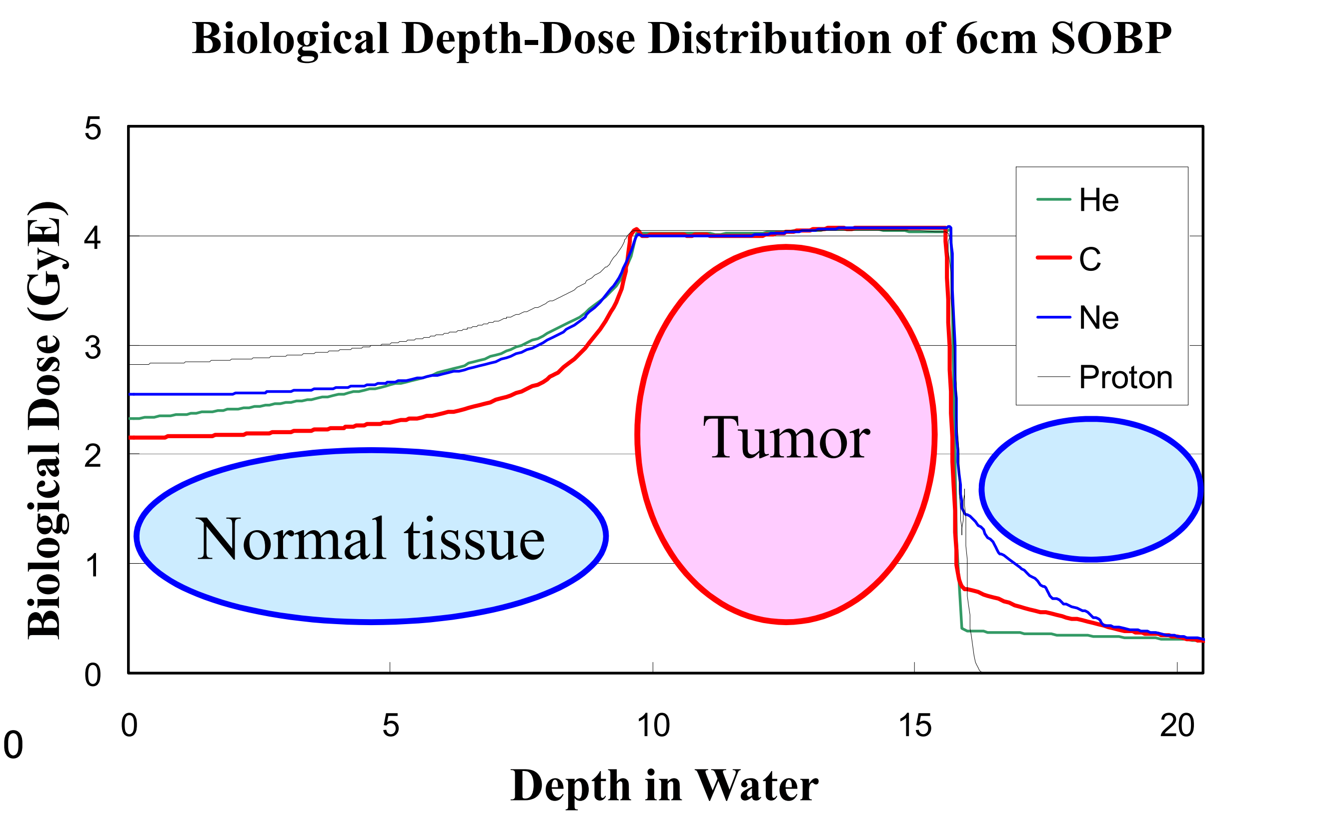


High transverse dose localization owing to the low multiple scattering.

Biological Characteristics of Ion RT



LET dependence of RBE & OER

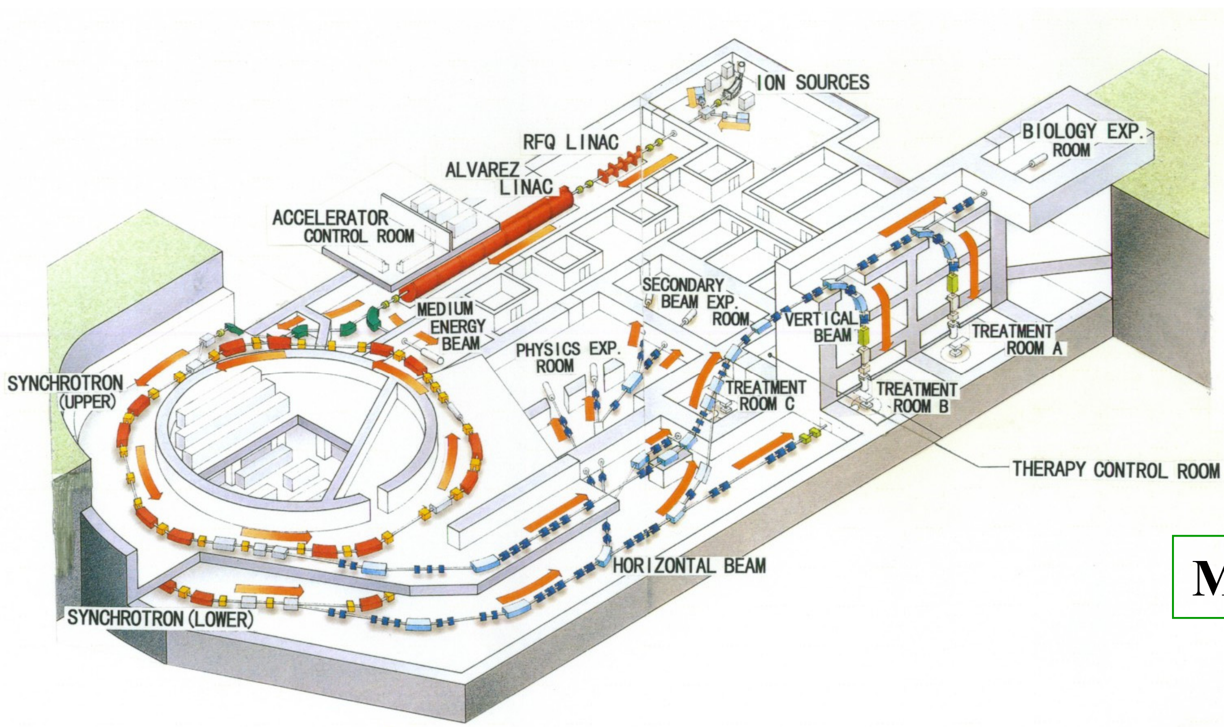


Biological dose should be higher in tumor than that in normal tissue
Carbon-ion has the highest bio-dose contrast.

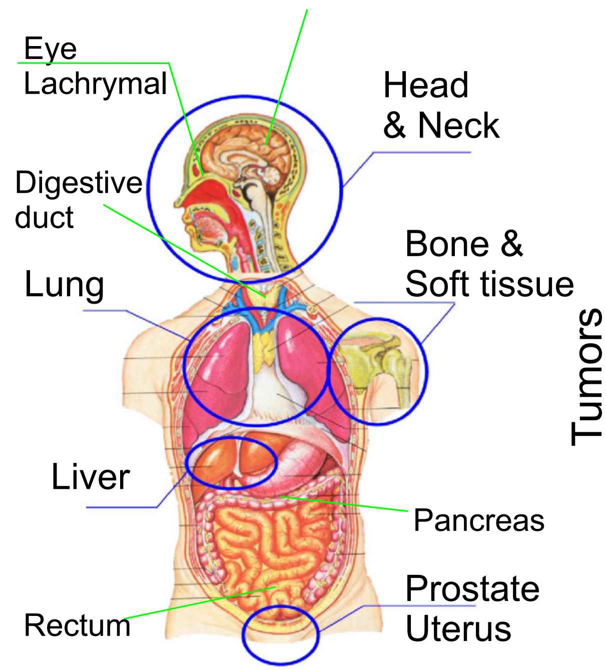
NIRS HIMAC

First Facility Dedicated to HI RT

- Ion species: High LET (100keV/μm) charged particles → He, C, Ne, Si, Ar
- Range: 30cm in soft tissue → 800MeV/u (Si)
- Maximum irradiation area: 22cmΦ
- Dose rate: 5Gy/min
- Beam direction: horizontal, vertical



HIMAC (Heavy Ion Medical Accelerator in Chiba)



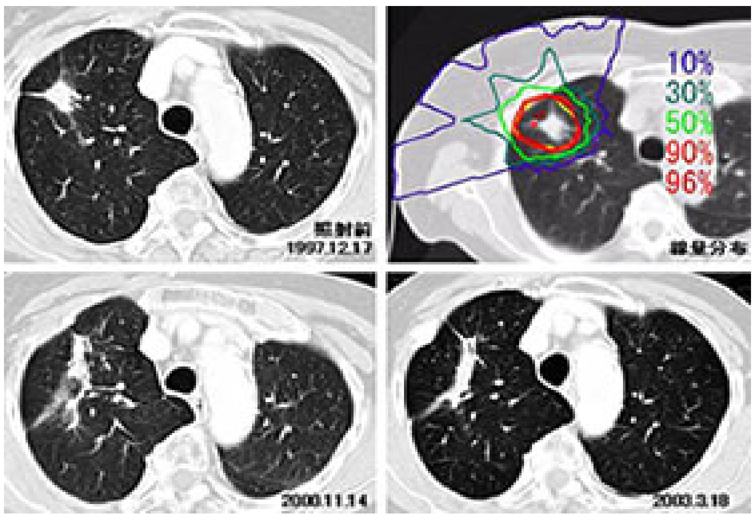
More than 12,000 pts treated since '94.

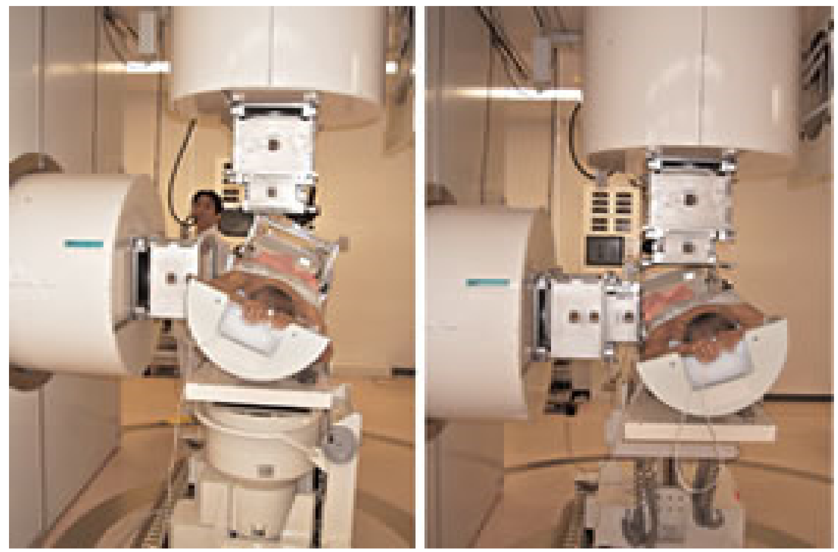
NIRS HIMAC

Clinical Results

Single Fraction Treatment with Respiratory Gated Irradiation

A single fraction treatment against Stage I NSCLC has been carried out since 2003. The treatment result shows 3-y OS rate of 94% with 50 GyE irradiation, which is almost comparable to surgery while keeping high QOL.





59.4 – 95.4GyE (18 fraction)
94/10 ~ 97/8

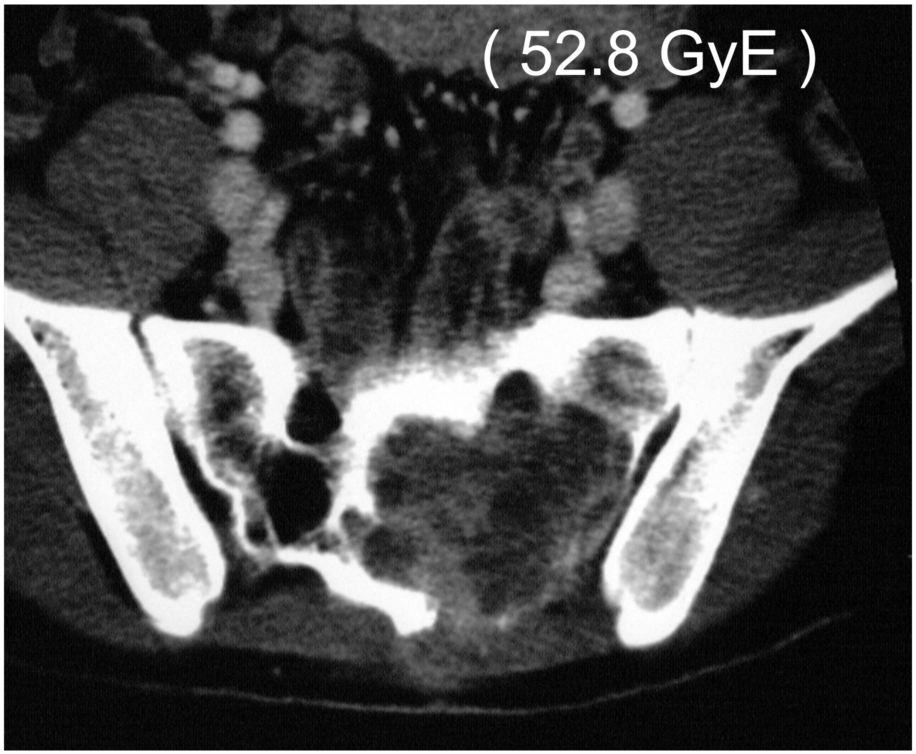
→ **54 – 79.2GyE (9 fraction)**
97/9 ~ 00/12

→ **52.8 - 60GyE (4 fraction)**
00/12 ~ 03/11

→ **28 - 32GyE (1 fraction)**
03/4 ~ 06/3

Clinical Results

Treatment against Radio-Resistive tumor



Before treatment

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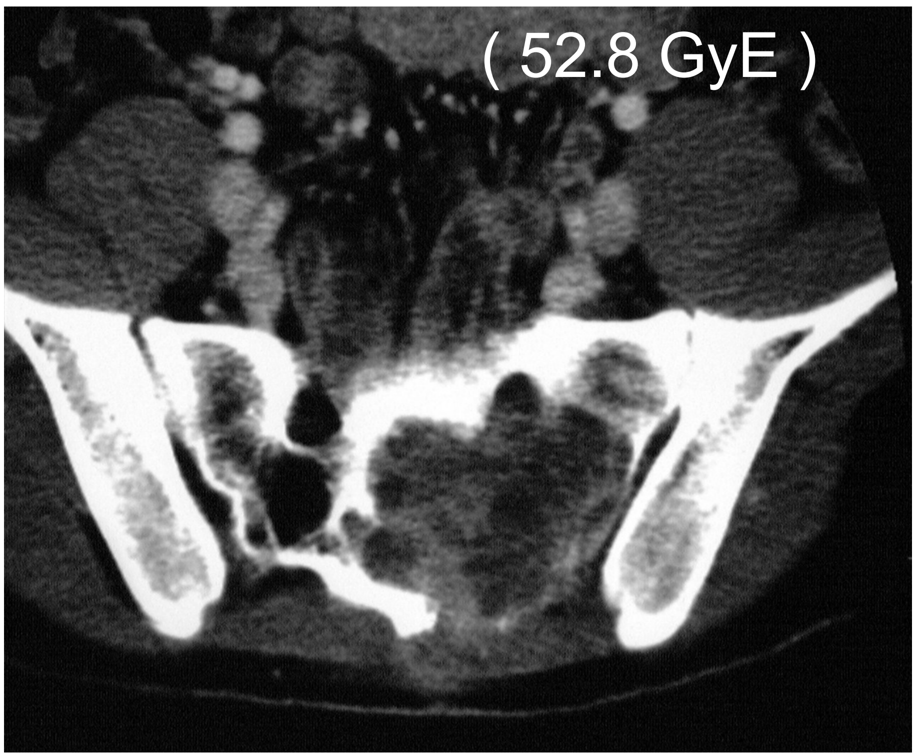
Clinical Results

Treatment against Radio-Resistive tumor



Before treatment

Summary of Clinical Results

The HIMAC clinical trial with carbon-ion has proven

- a short course treatment, such as one fractional treatment of lung cancer, is possible.
- very effective against radio-resistive cancer.

National Insurance covers the followings since 2016:
Prostate and Bone&Soft tissue for Carbon-ion RT
Prostate and Pediatrics for Proton RT

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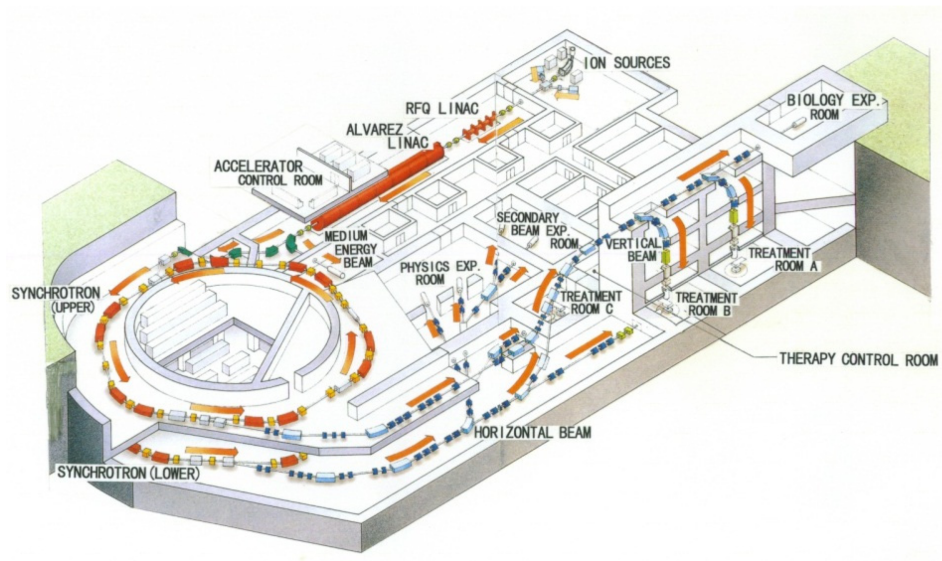
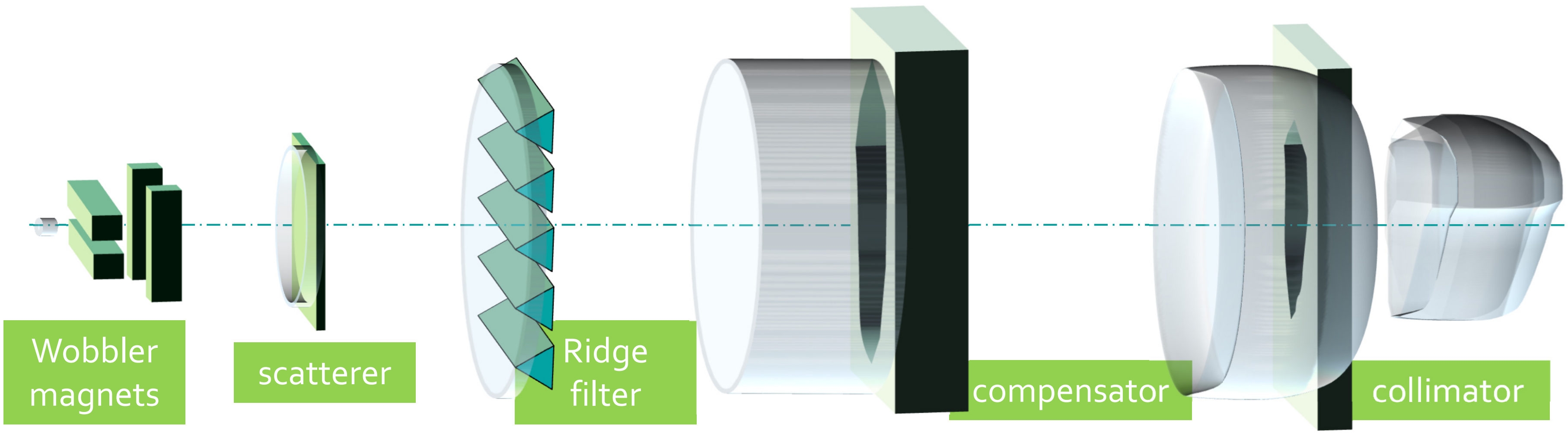


NIRS HIMAC

Passive Beam-Delivery Method

Wobbling Method with RF, since1994



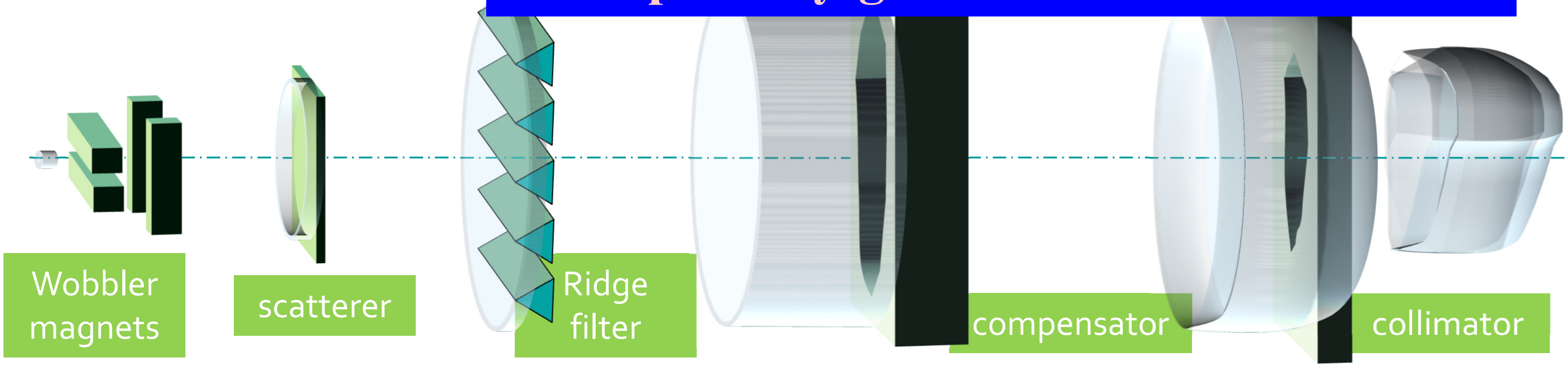
◎ Easy dose management
◎ Relatively low beam-position accuracy
× Low beam-utilization efficiency
× Require bolus and patient collimator

Passive

Passive Beam-Delivery Method

Wobbling Method

Innovations in HIMAC passive method are
- **Layer stacking method**
- **Respiratory-gated irradiation**



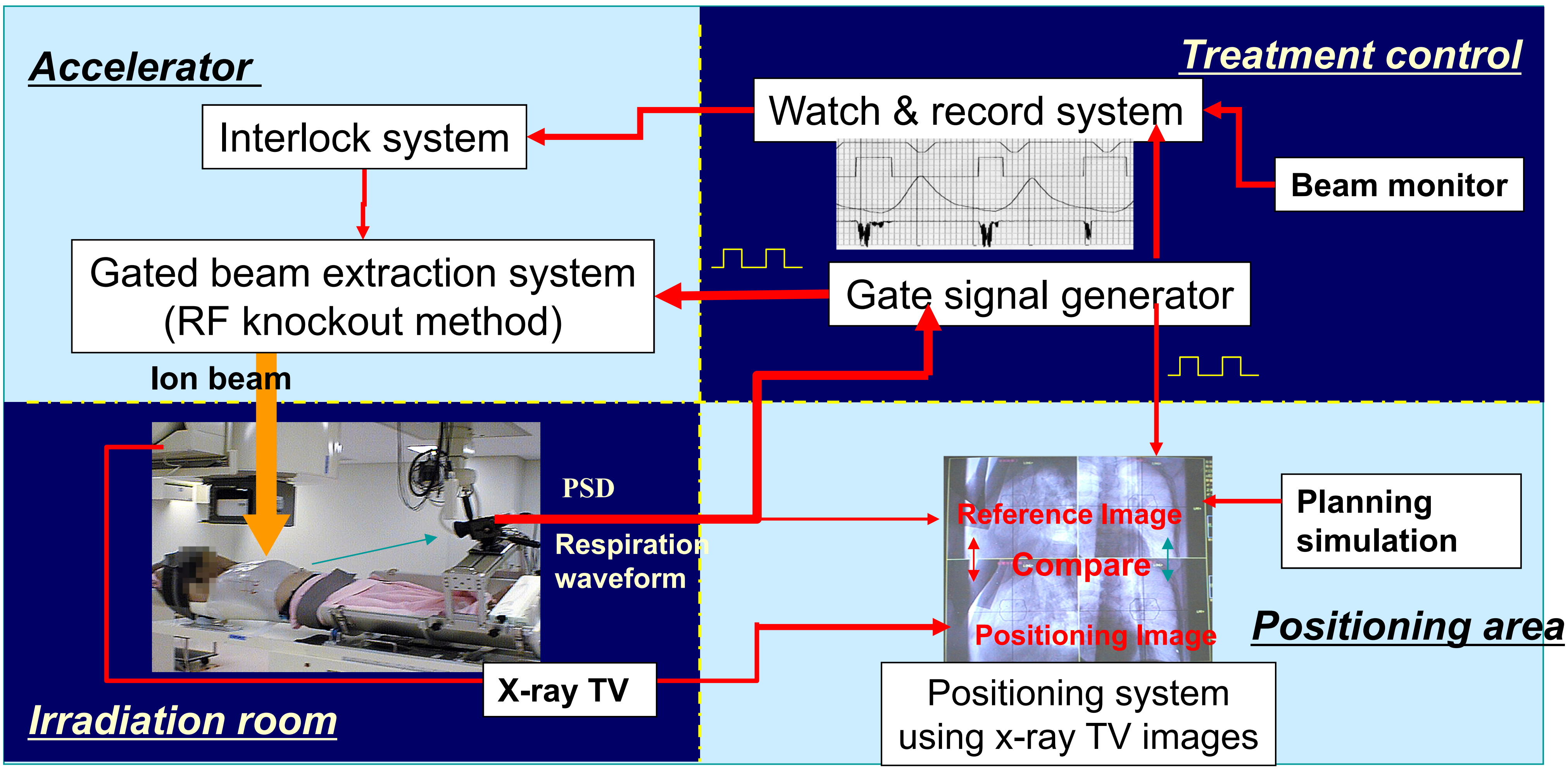
◎ **Easy dose management**
◎ **Relatively low beam-position accuracy**
× **Low beam-utilization efficiency**
× **Require bolus and patient collimator**

NIRS HIMAC

Passive

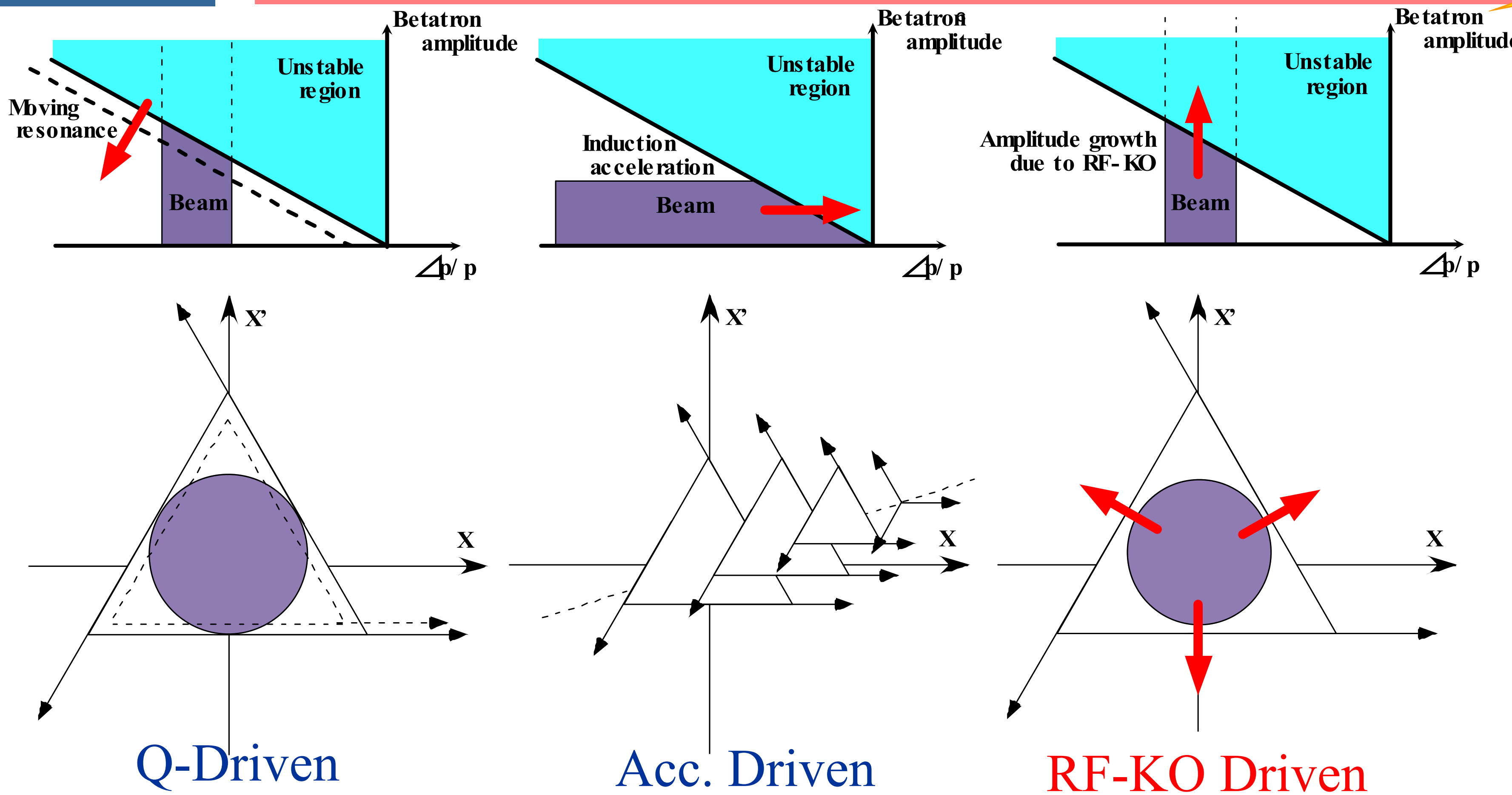
Respiratory gated irradiation

- Irradiation system of coincident with a patient ‘s respiratory motion -



Passive

RF-KO Slow-Extraction



There are three kind of slow-extraction methods from synchrotron: Q-Driven. Acc-Driven and RF-KO-Driven. The RF-KO extraction has been employed at HIMAC, because of quick response to beam "ON/OFF".

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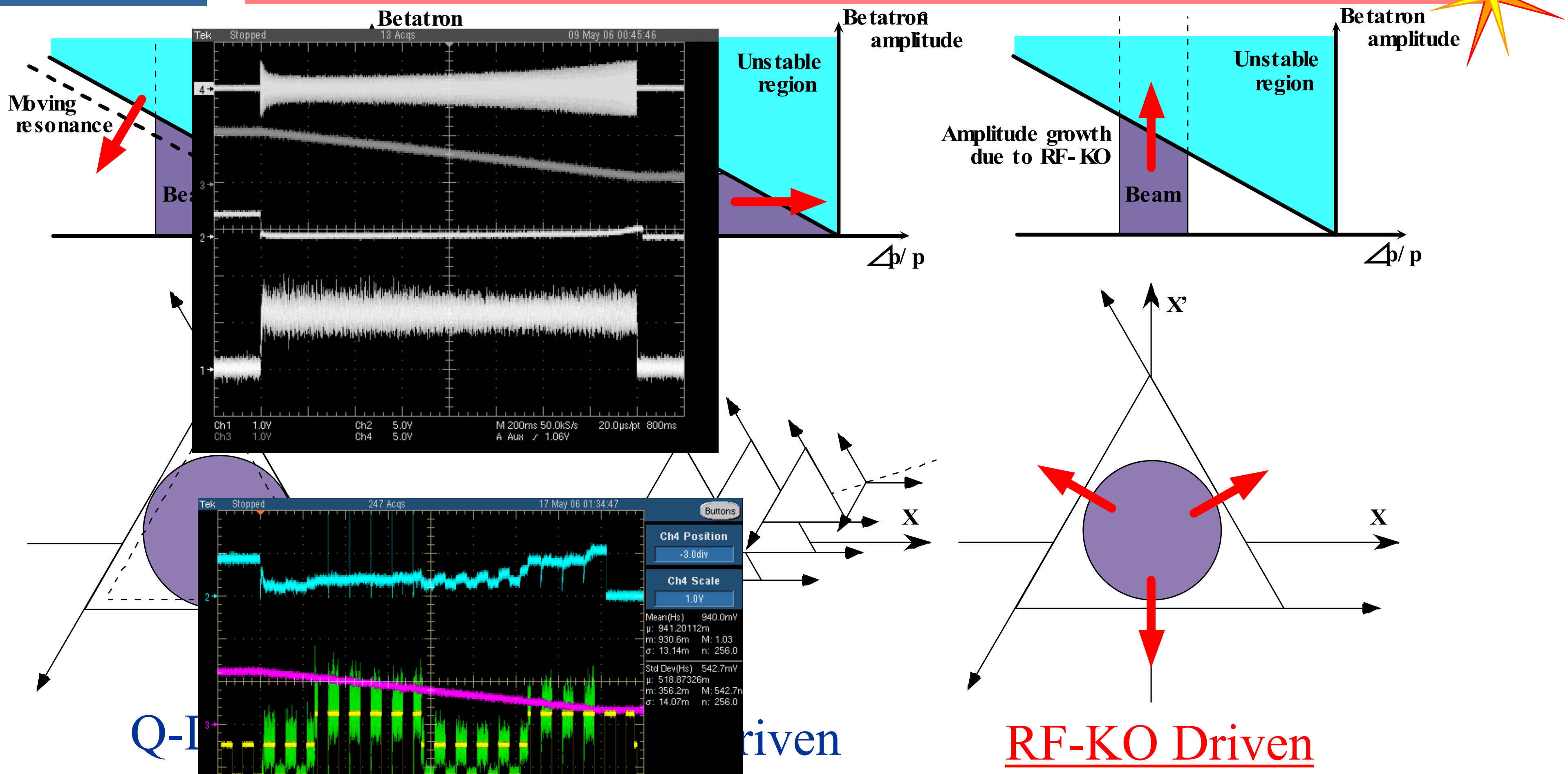
RF-KO Slow-Extraction



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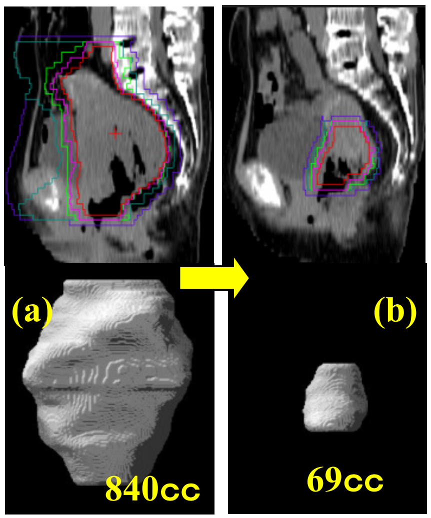
Pencil-Beam 3D Scanning



We should modify a treatment planning corresponding to change of target during treatment,

⇒ Adaptive Cancer Treatment

- 3D Scanning (Active method)1

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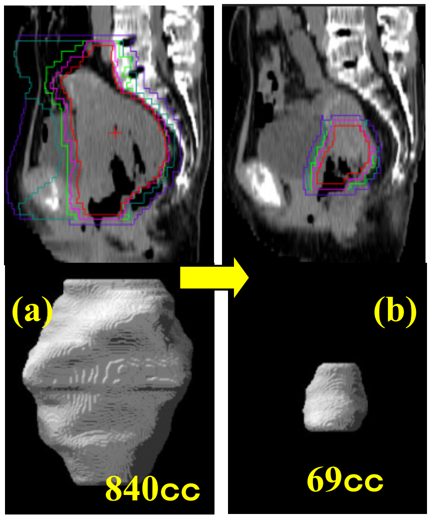
Pencil-Beam 3D Scanning



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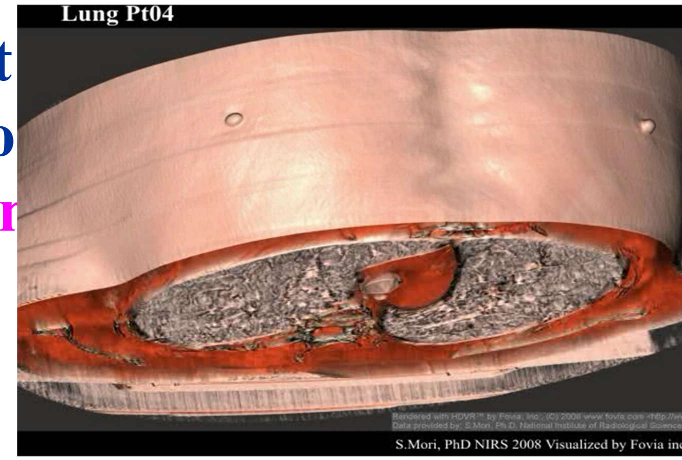
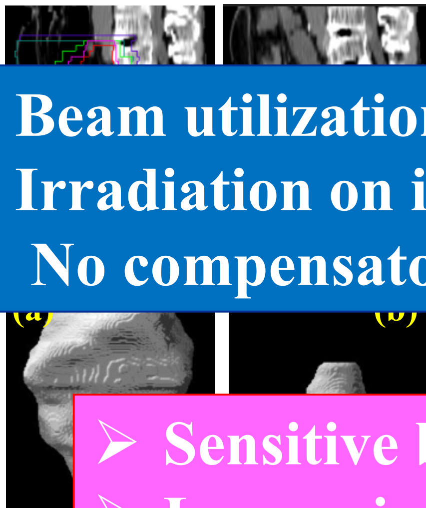
⇒ Adaptive Cancer Treatr

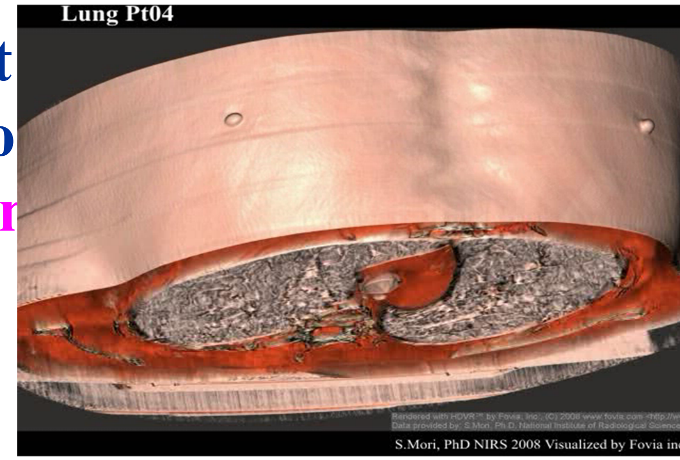


- 3D Scanning (Active method)1

Pencil-Beam 3D Scanning



- Beam utilization efficiency ~100%
- Irradiation on irregular shape target
- No compensator & patient collimator



- Sensitive beam error
- Longer irradiation time

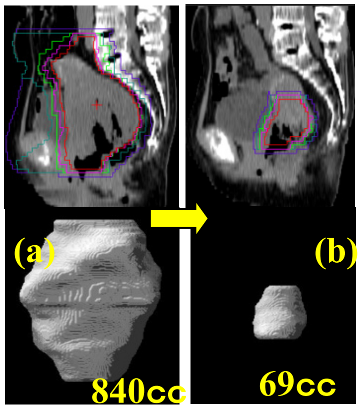
- 3D Scanning (Active method)1

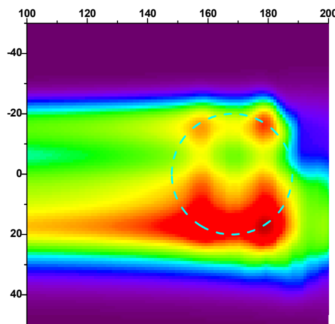
Especially sensitive to organ motion

NIRS HIMAC

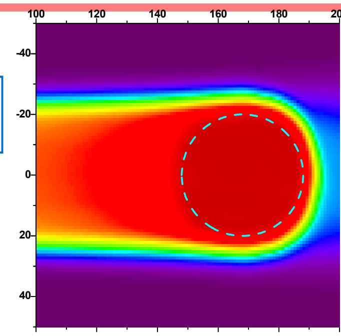
3D Scan

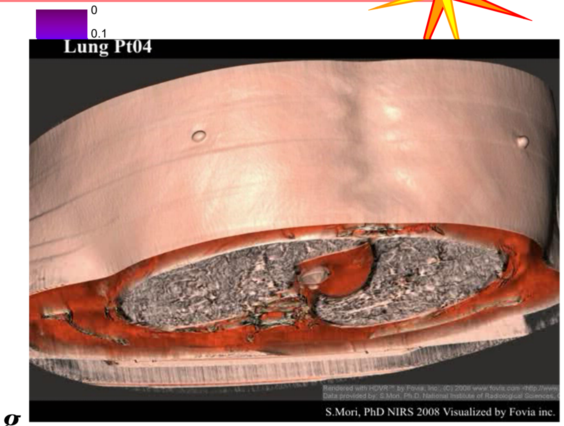
Fast Scanning for Moving Target





Simulation





100-times speed up !!

escan with tory-gating

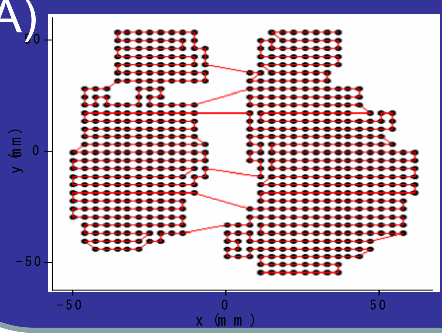
Key Technology ⇒ Fast 3D Scanning within Torelable Time for Moving Tumor Treatment

A) TPS for Fast Scanning ⇒ ×5

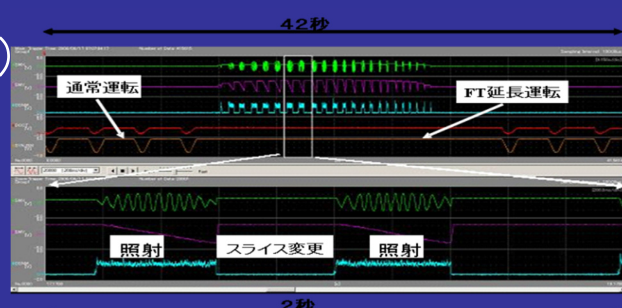
B) Extended Flattop Operation ⇒ ×2

C) Fast Scanning Magnet ⇒ ×10

(A)



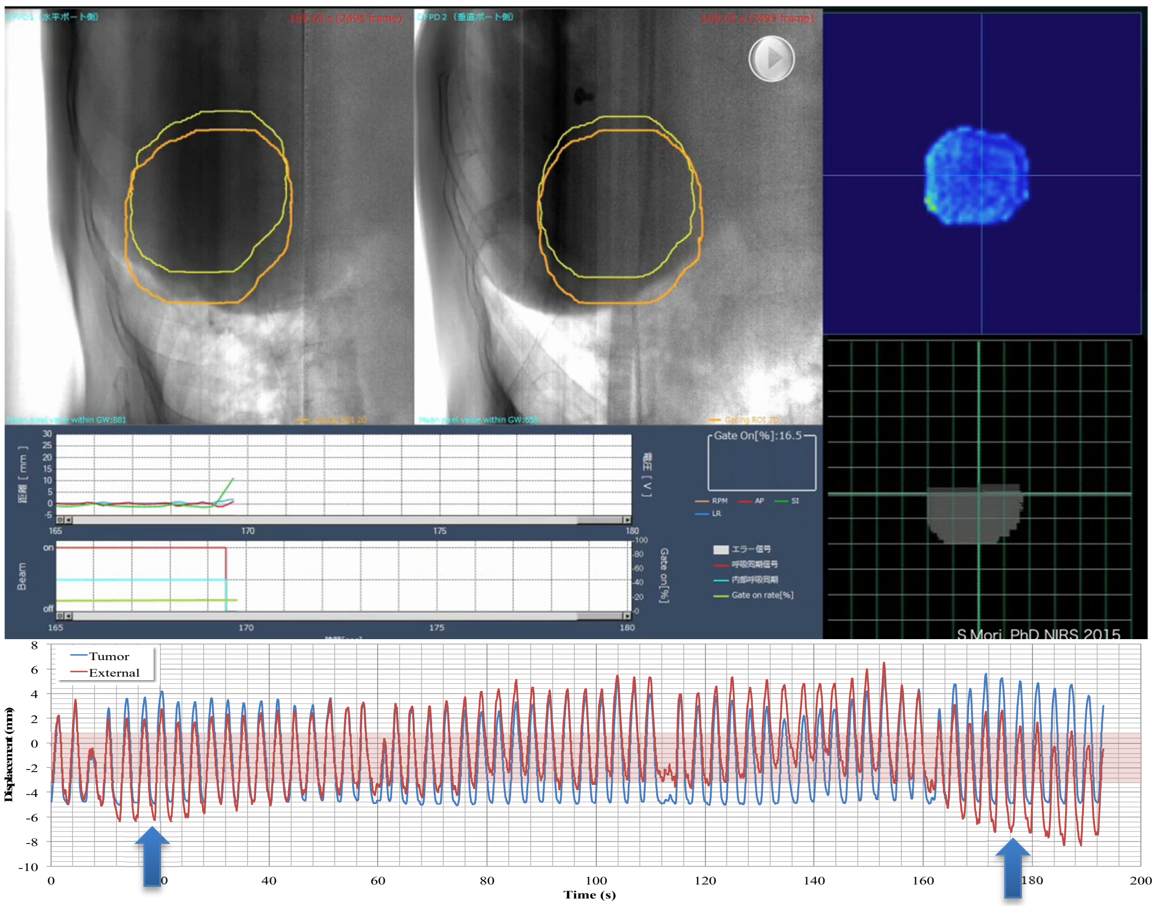
(B)



(C)

IGRT

Moving Tumor Treatment by Fast 3D Rescanning



- External and tumor positions were good correlation.
- But external gating could cause < 3mm gating error.

- Setup: 6.0 min
- Treatment: 3.5min/field
- Beam on rate: 38.4%

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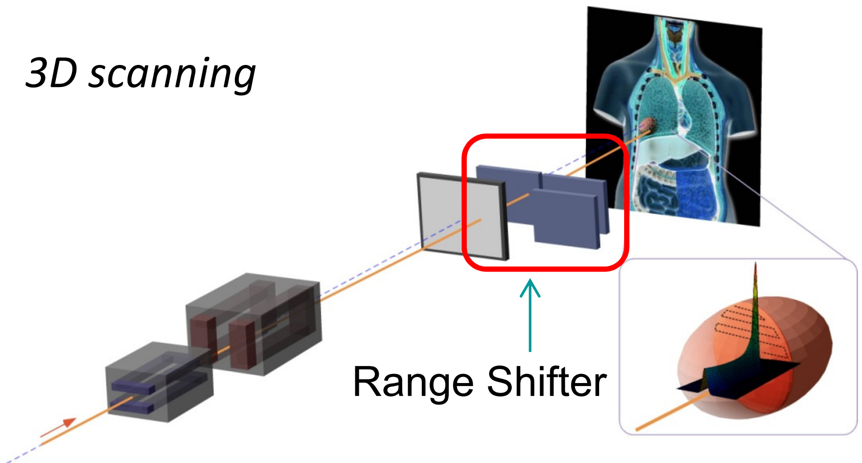
Depth- Scan

Variable-Energy Operation

3D scanning



Beam-size growth due to Multiple scattering

⇒ *Penumbra growth*

NIRS HIMAC

Variable-Energy Operation

3D s

Variable-Energy Operation

- High speed slice change
- Suppressing beam-size growth
- Reduction of 2nd neutron

NIRS HIMAC

Depth- Scan

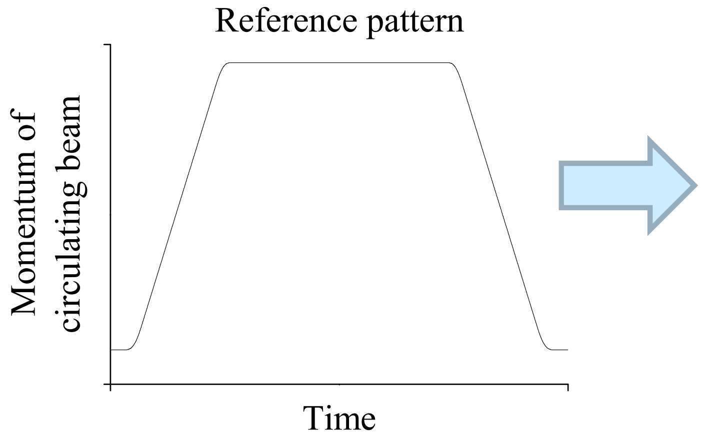
Variable-Energy Operation

3D s

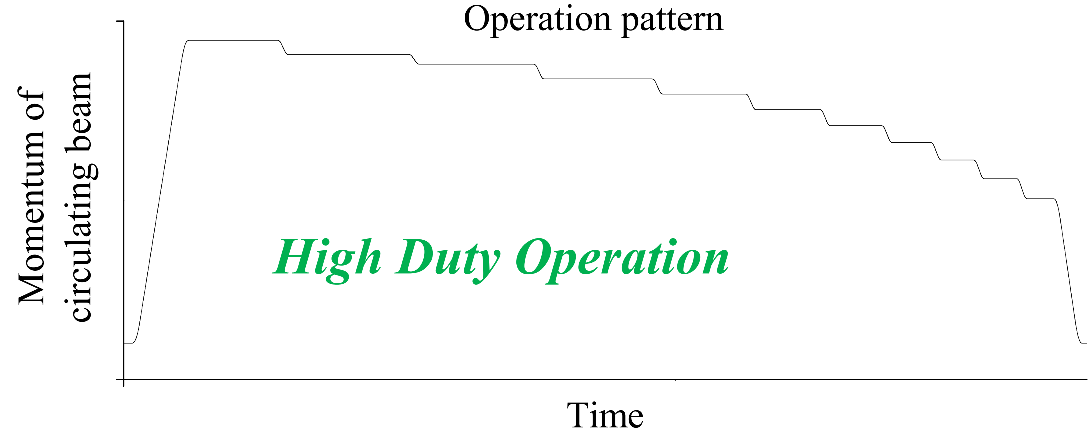
Variable-Energy Operation

- High speed slice change
- Suppressing beam-size growth
- Reduction of 2^{nd} neutron

Standard Operation Pattern



NIRS ⇒ Variable-E operation in one cycle !



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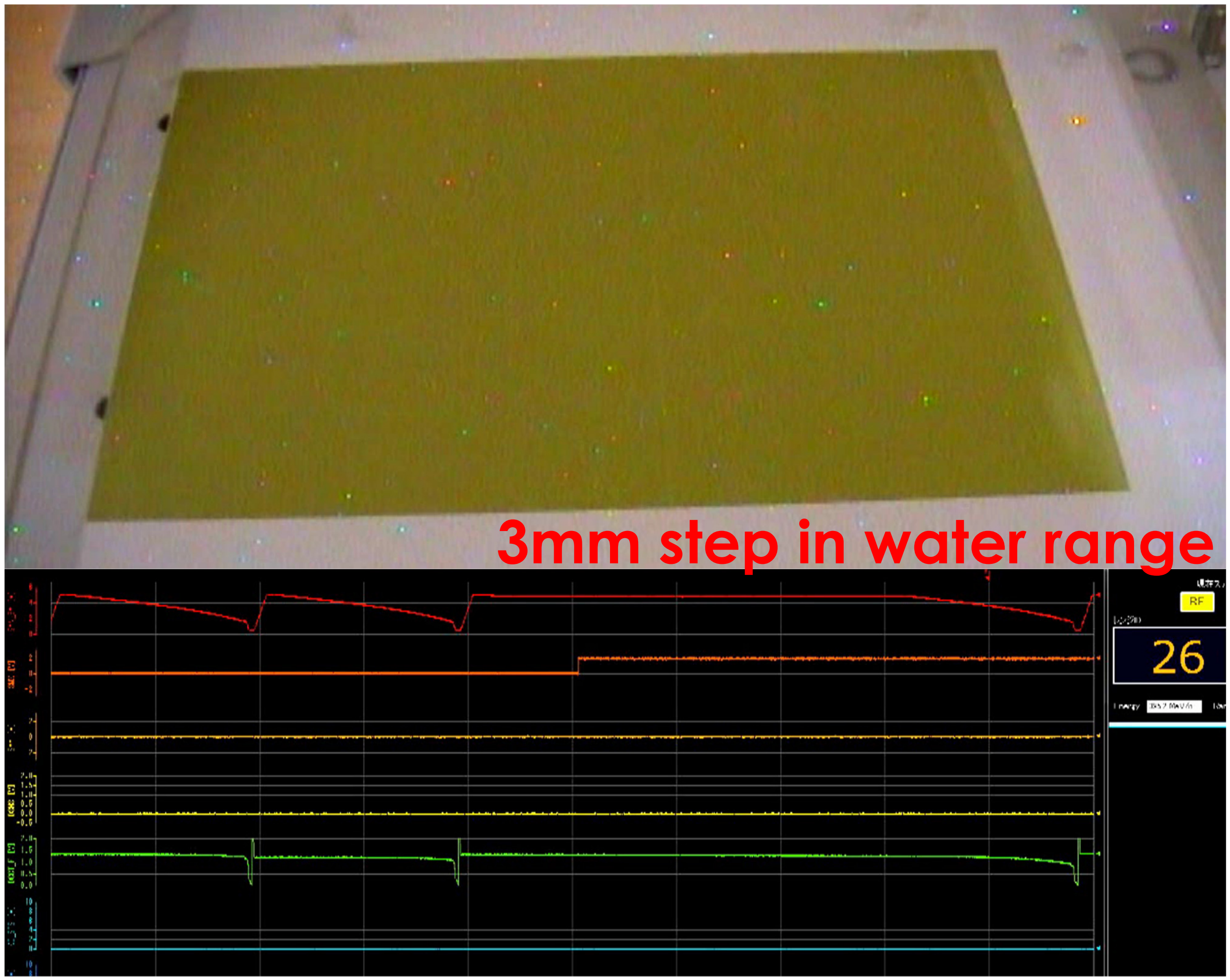
Full Energy Depth Scan

Lower energy

Beam direction

Higher energy



Current pattern of BM

Scanning magnet (X)

Scanning magnet (Y)

Extracted beam

Beam current in ring

Irradiation gate

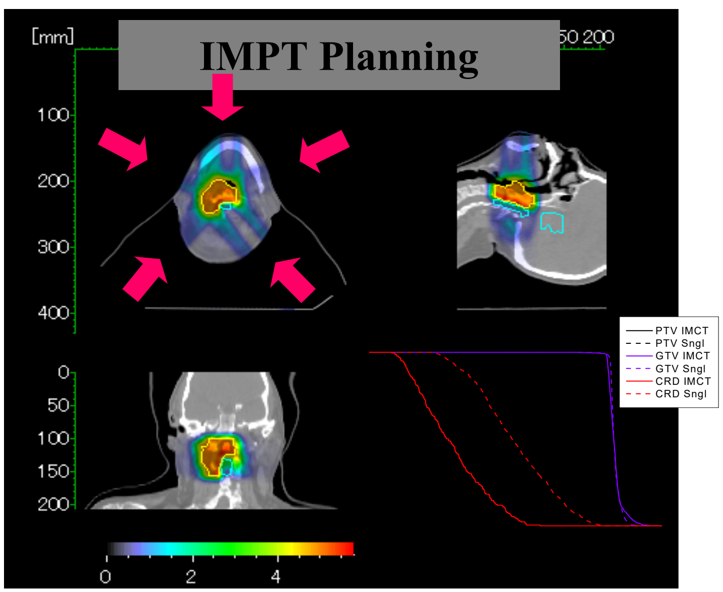
Energy ID

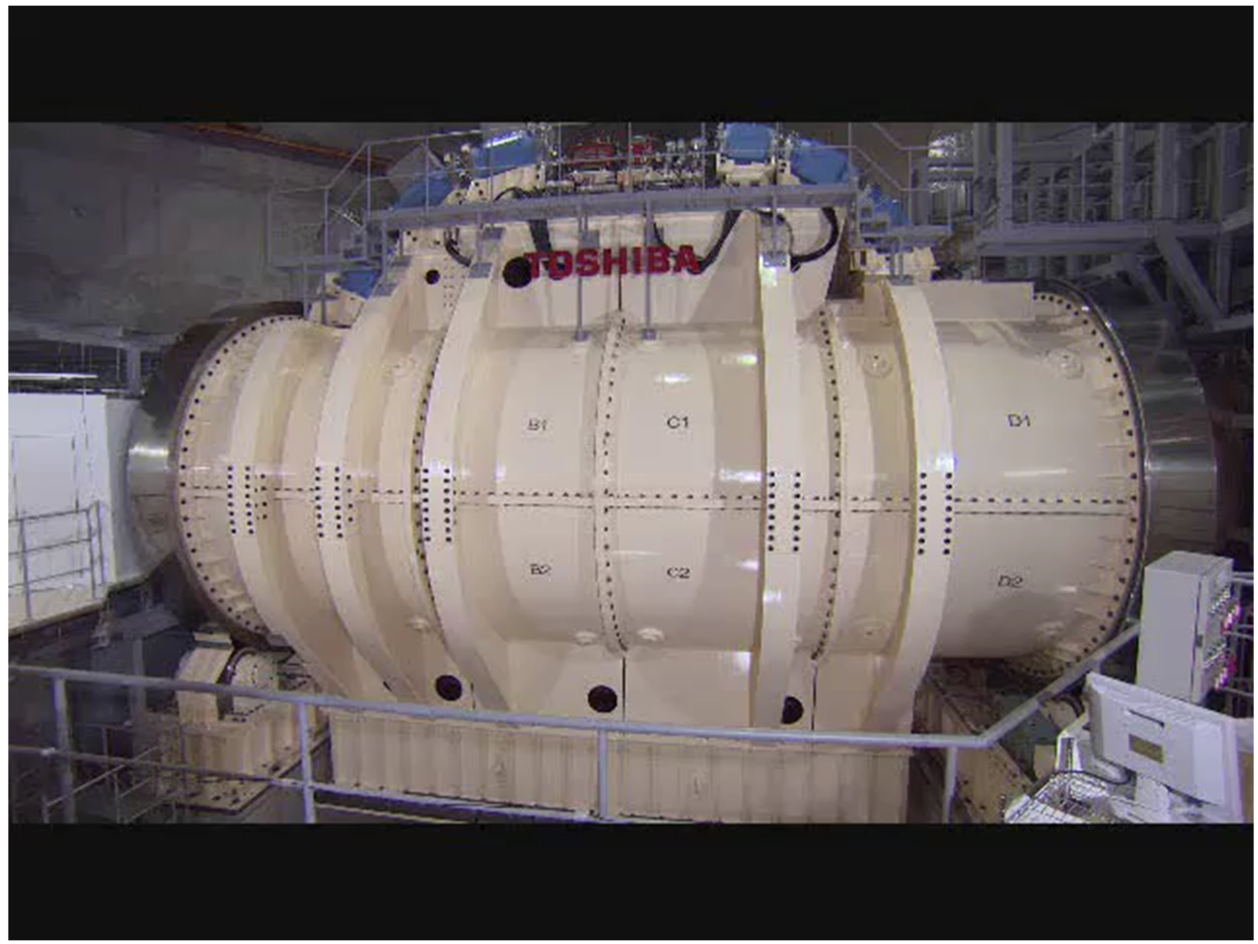
NIRS HIMAC

Rotating Gantry

3D Scanning + R-Gantry
- **Reduction of Patient's Load**
- **High accurate treatment**

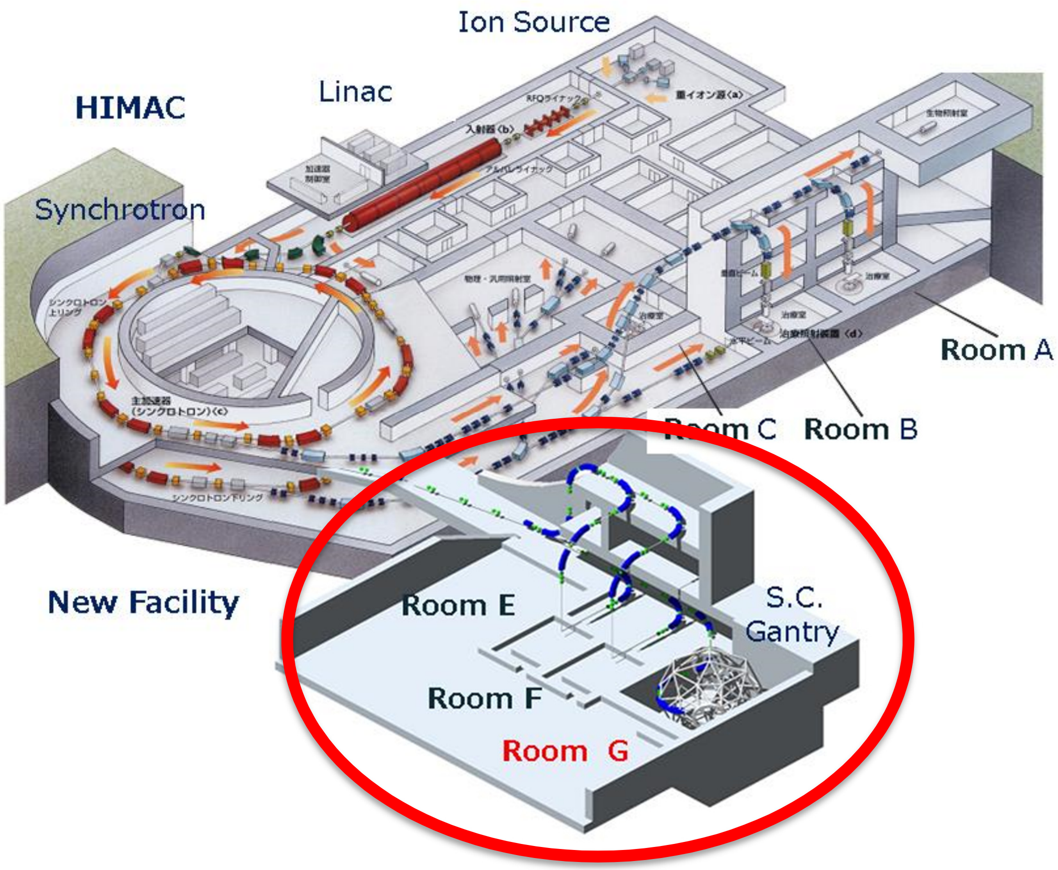
Shorter Course Treatment





New Treatment

HIMAC and New Treatment Facility



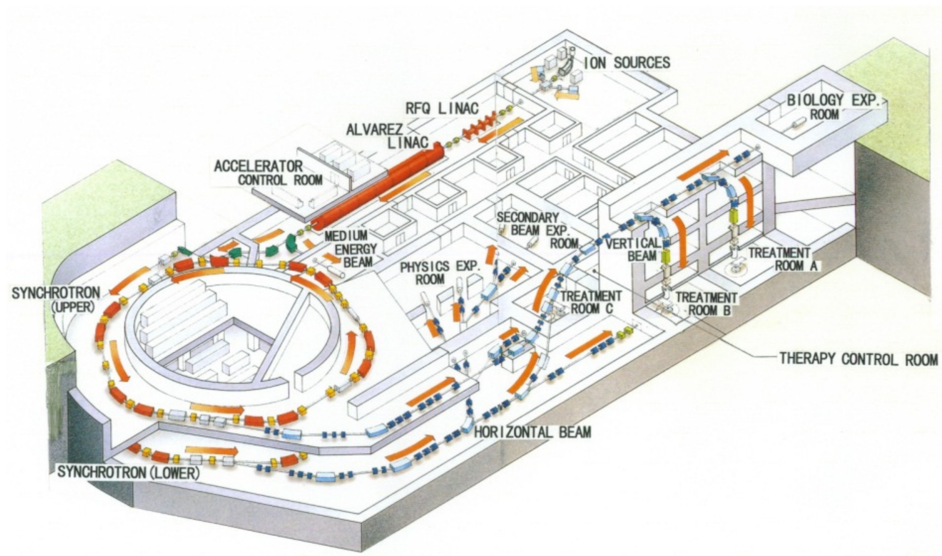
Treatment in a day (Oct. 10, 2018)

Treatment site	Number of patients
Prostate	23 pat.
Head & neck	14 pat.
Bones & soft tissues	10 pat.
Uterus	6 pat.
Lung	4 pat.
Recurrent rectal cancer	9 pat.
Pancreas	6 pat.
etc. (lymph node…)	3 pat.
	75 patients

Repainting & Respiration Gating : ~1/3 of pts.

All patients are treated in the new treatment facility in the present.

Contents

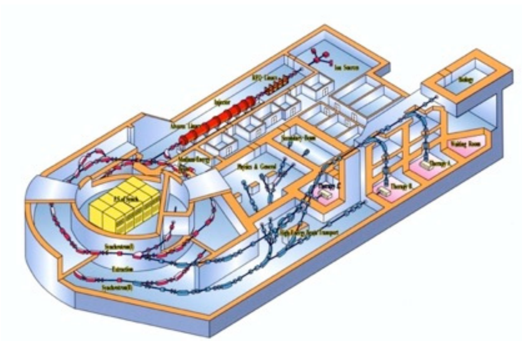


ION SOURCES
RFQ LINAC
ALVAREZ LINAC
ACCELERATOR CONTROL ROOM
BIOLOGY EXP. ROOM
MEDIUM ENERGY BEAM
SECONDARY BEAM EXP. ROOM
PHYSICS EXP. ROOM
VERTICAL BEAM
TREATMENT ROOM A
TREATMENT ROOM B
TREATMENT ROOM C
SYNCHROTRON (UPPER)
THERAPY CONTROL ROOM
HORIZONTAL BEAM
SYNCHROTRON (LOWER)

NIRS HIMAC

Current C-ion Radiotherapy

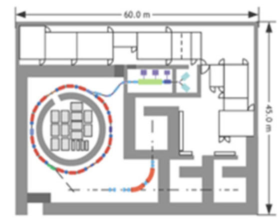
1st Generation



1994-NIRS
120x65m, 300M USD

1/3

2nd/3rd generation



2010 – Gunma Univ.
60x45m、100M USD

1) Facility is still huge and expensive.

→Cost and size now 1/3rd the HIMAC, but still high!

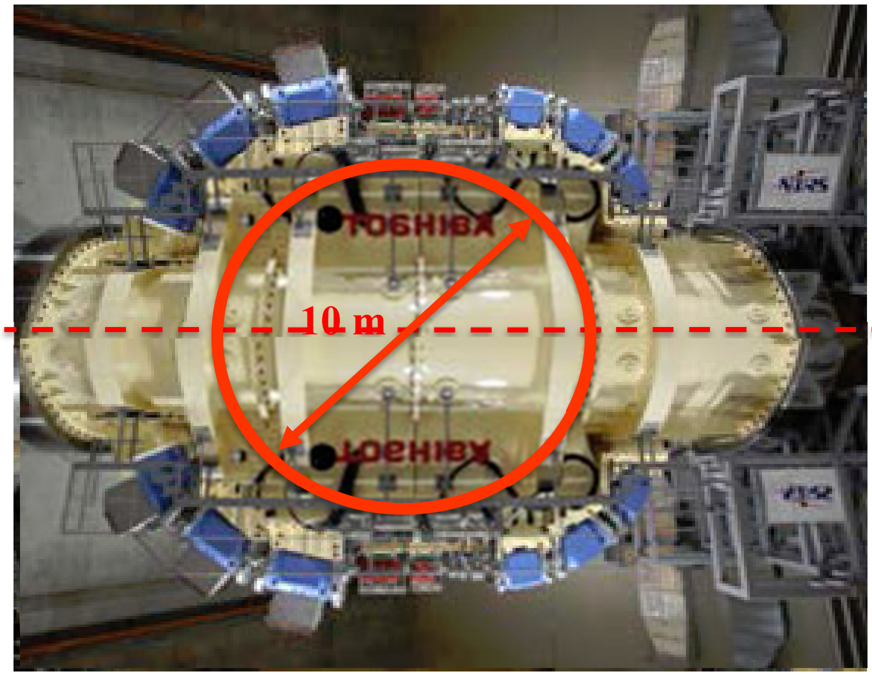
2) Currently, not always satisfactory in tumor control.

→Higher performance is required.

"Quantum Scalpel" Project

NIRS HIMAC

Superconducting Technology

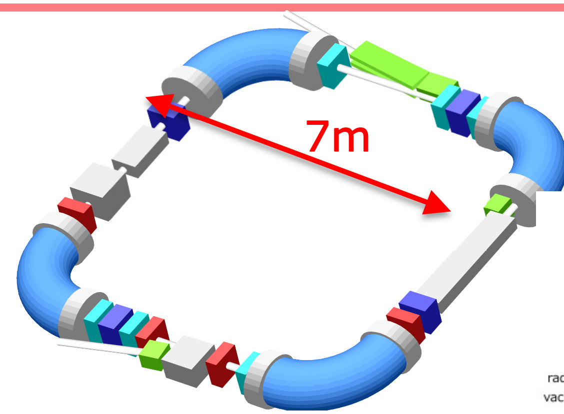


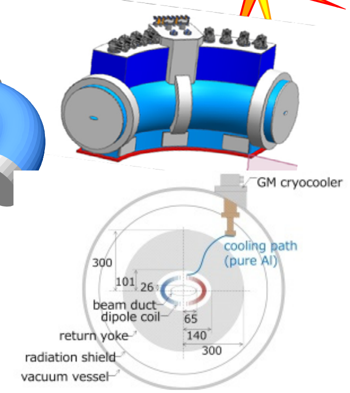
Number of the quench of super-conducting magnets for rotational gantry is only one time in this year.

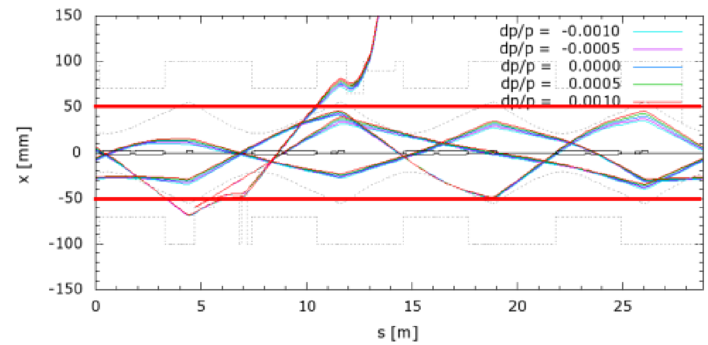
- Differences between rotational gantry and synchrotron.
  - Maximum field : 2.9 T (G) -> 4.0 T (S)
  - Excitation time : 60 sec (G) -> <10 sec (S)
    → Fine NbTi cable with low AC loss

Design of SC Synchrotron

- Superconducting magnet
  - Number : 8
  - Bending angle : 45 degree
  - Magnetic field : 4 T
  - Excitation rate : ~0.5 T/s
  - Cooling : GM cryocooler w/o Liq.He
- Synchrotron
  - Circumference : ~28 m
  - Energy : 4 ~ 430 MeV/u







Takayama S, et al., Proc. of Accel. Soc. of Japan, p.1223, 2018.
Mizushima K, et al., Proc. of Accel. Soc. of Japan, p.1243 2017.

NIRS HIMAC

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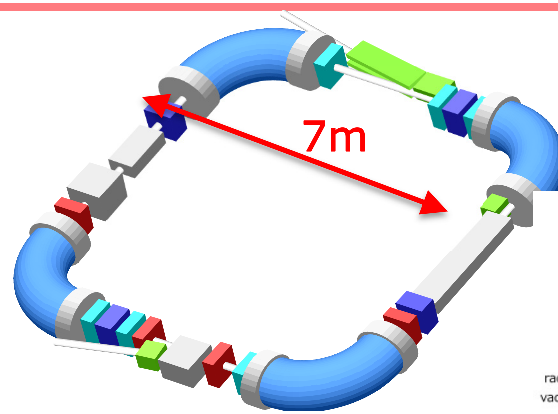
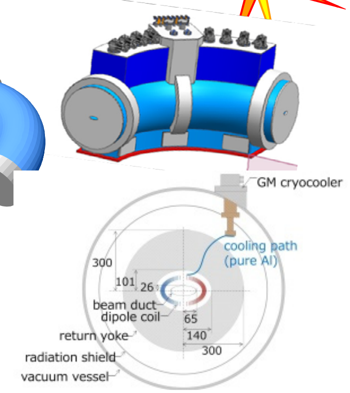
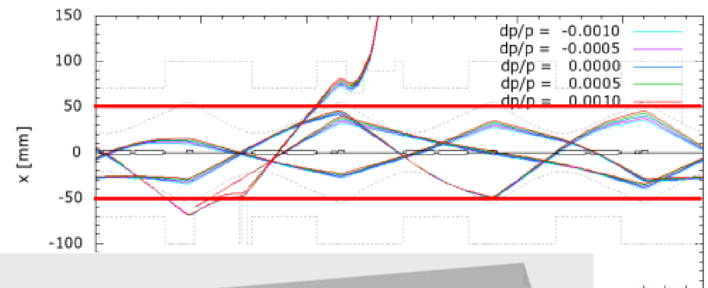
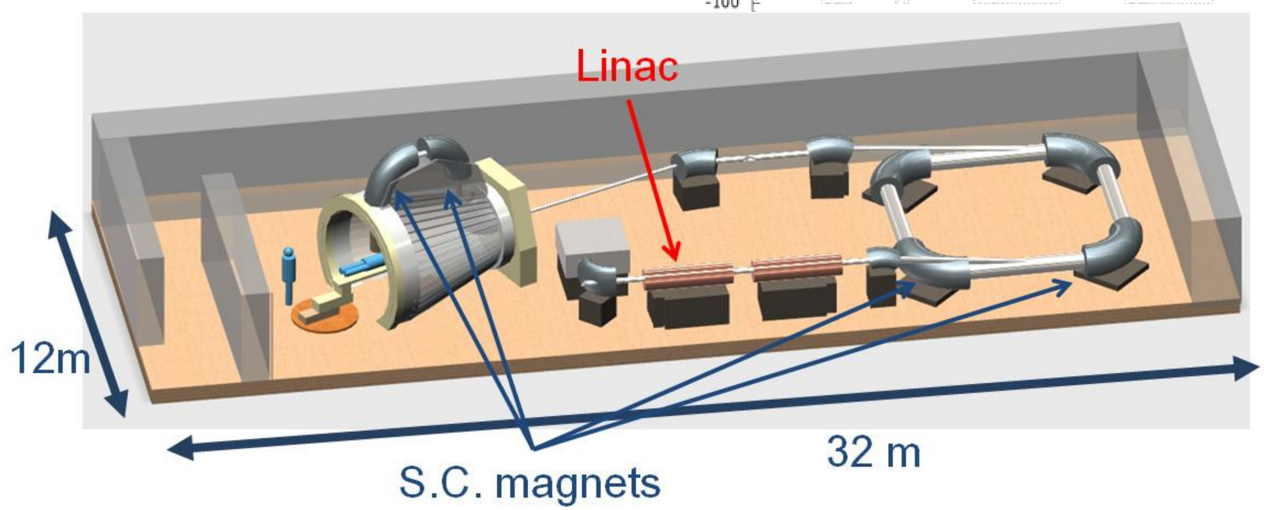




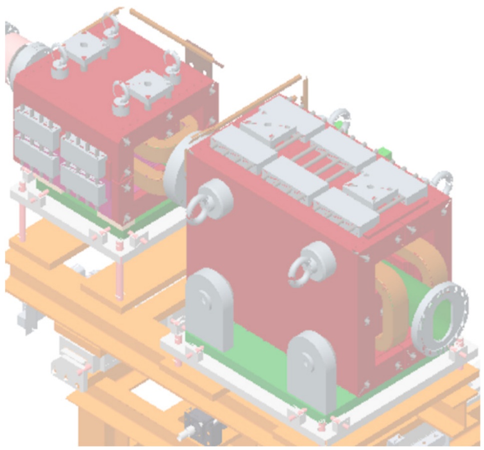


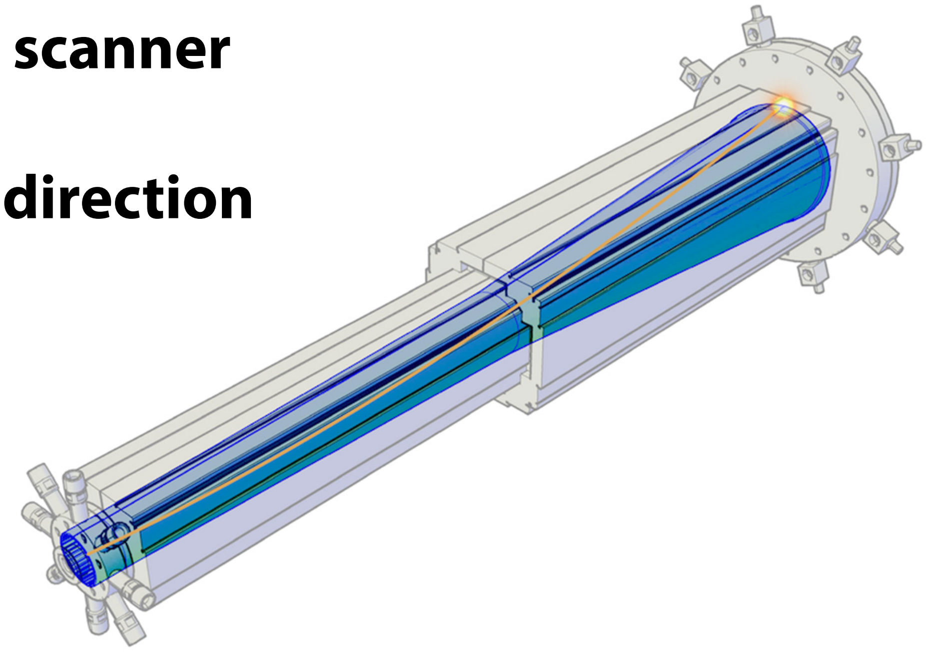
3, 2018.
43 2017.



Compact 3D-scanner

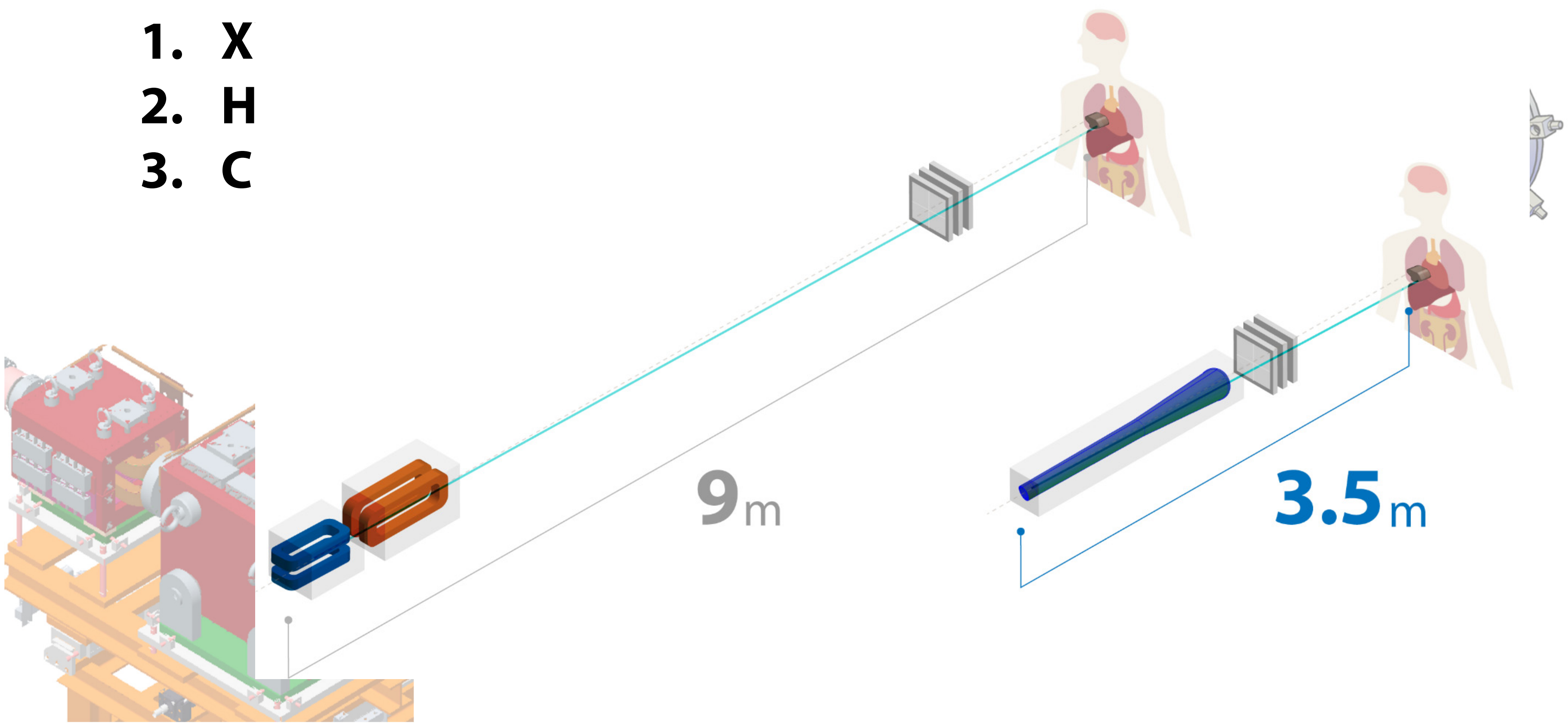
1. XY combined type new scanner
2. High magnetic field
3. Changing gap in beam direction



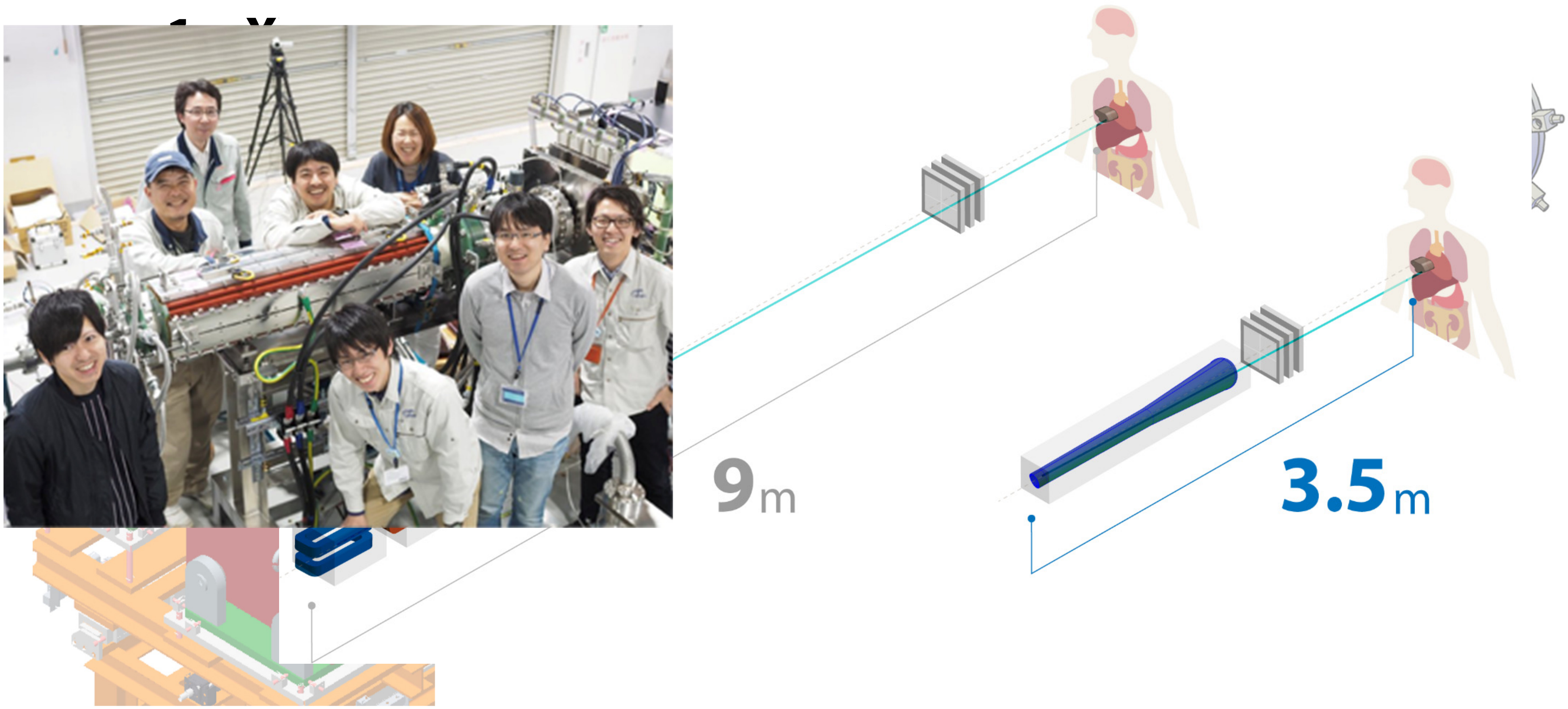


Compact 3D-scanner

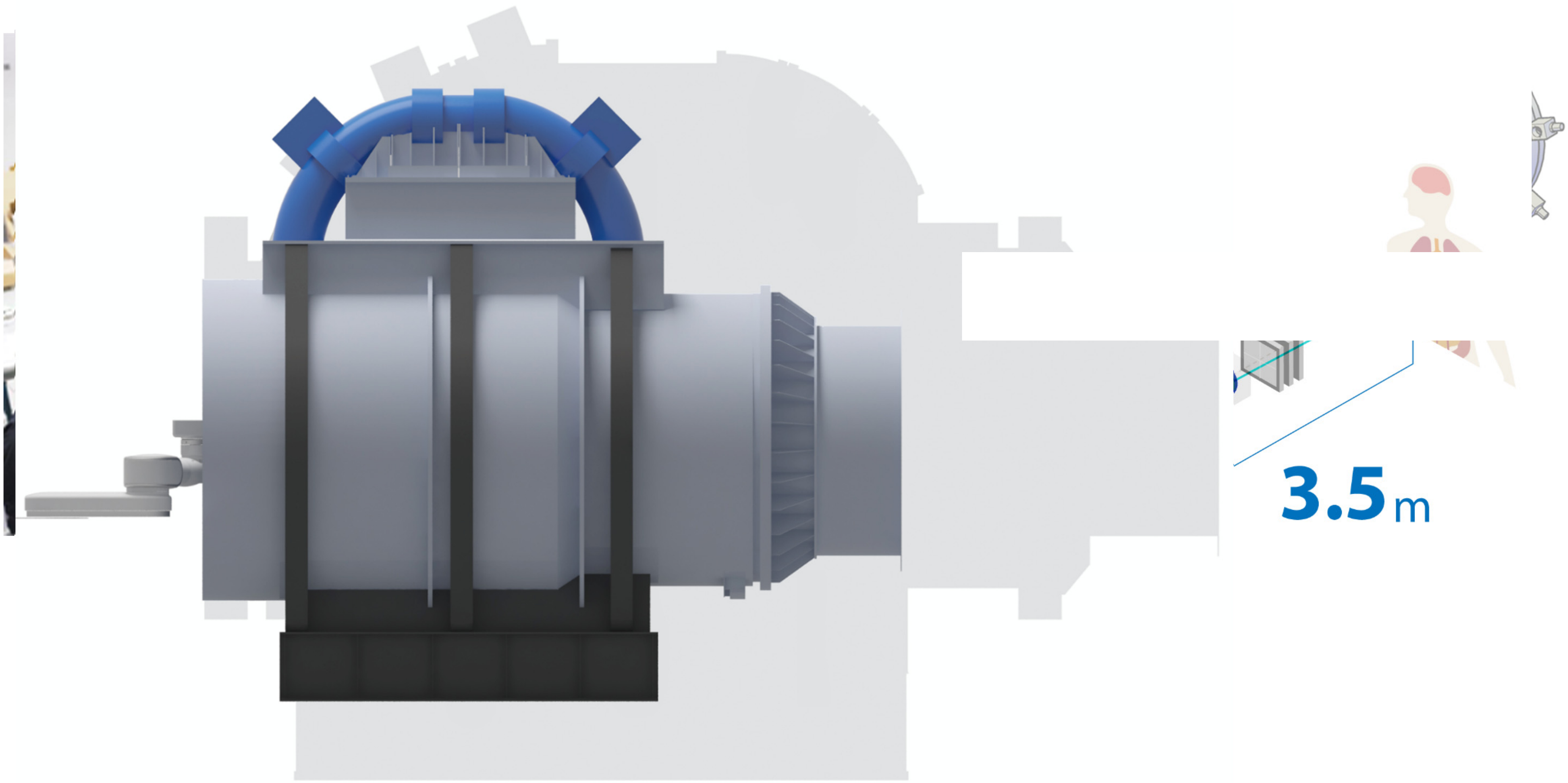
1. X
2. H
3. C



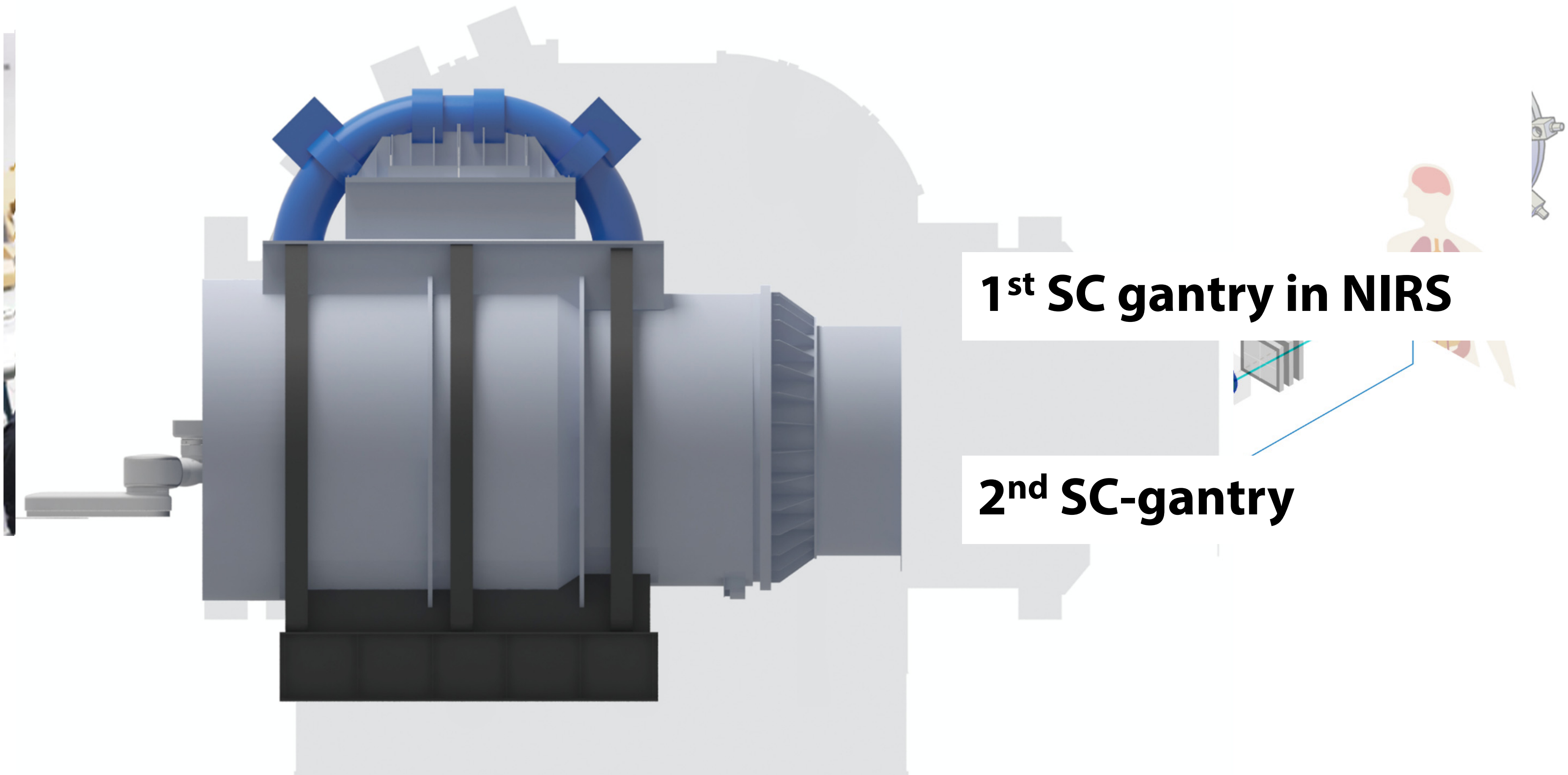
Compact 3D-scanner



Compact 3D-scanner



Compact 3D-scanner

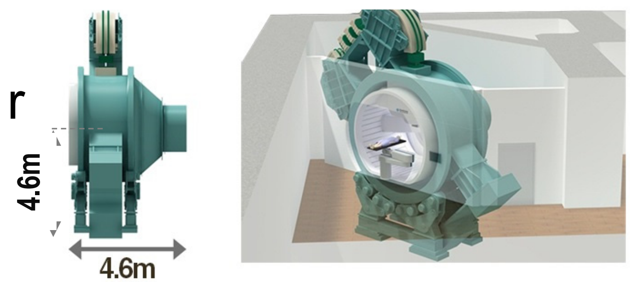


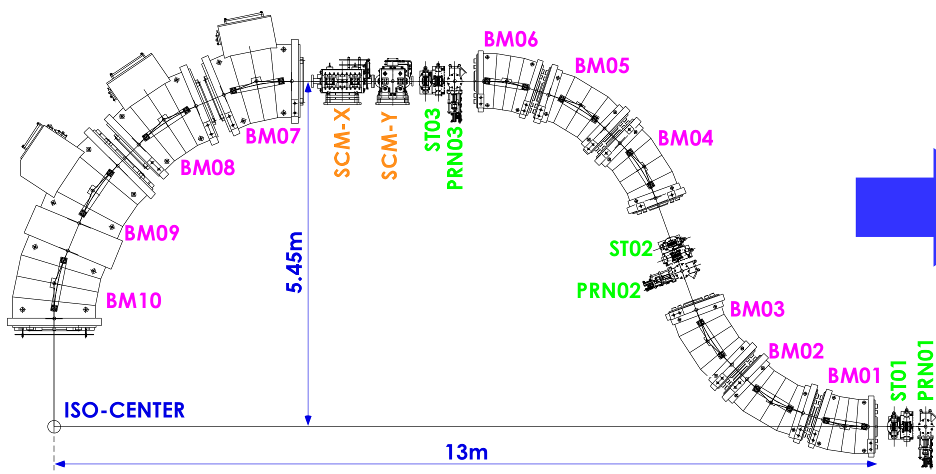
Design of Rotating Gantry

Design Considerations

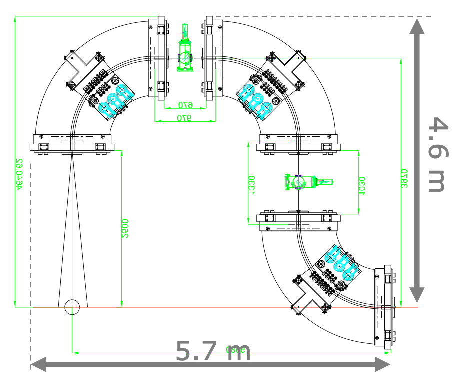
- ✓ Beam matching to keep beam-size independent
- ✓ Set the compact 3D-scanner
  in the downstream of the SC magnets to r
- ✓ SC magnet of 5 T will be employed

Sumitomo
Proton gantry
(Aizawa Hospital Proton Therapy Center)





NIRS superconducting rotating gantry

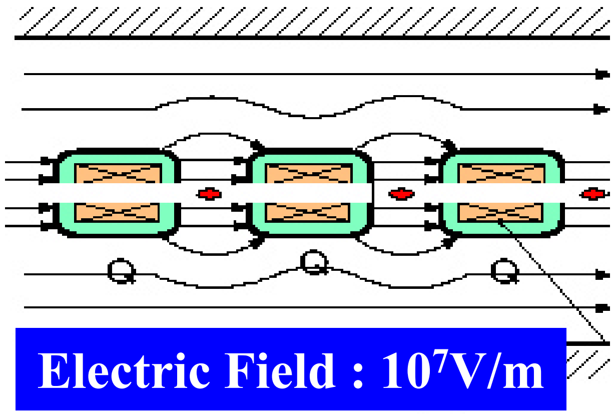


Compact SC gantry

NIRS HIMAC

Laser Acceleration Technology

Conventional linac : RF field



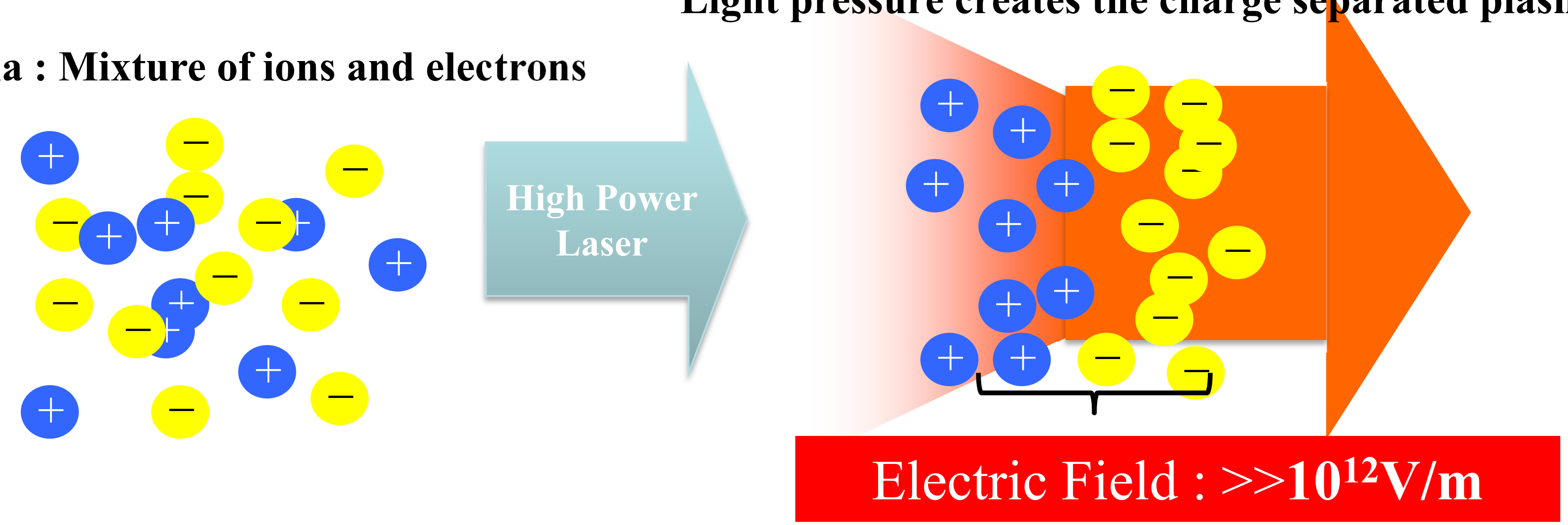
High electric field is required for compact linac.

There is a limitation due to discharge.

There is no discharge problem in plasma.

Plasma : Mixture of ions and electrons

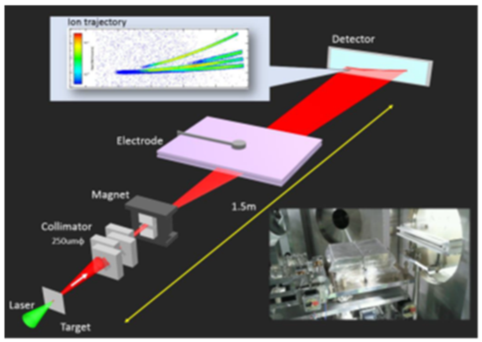
Light pressure creates the charge separated plasma

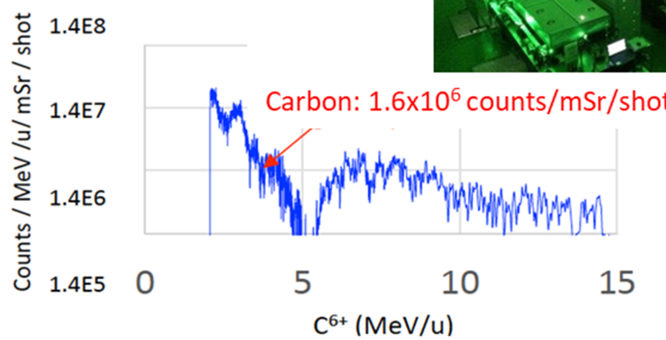


Development of Laser injector

✓ Determination of laser driven ion acceleration scheme

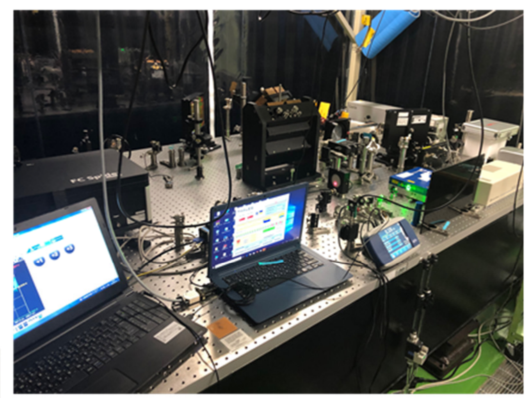
With J-KAREN-P etc., the acceleration scheme for generating 10^9 carbons/msr/sec @ 4 MeV/u in 10 % b.w. will be determined.





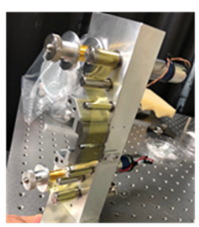
✓ Demonstration of high repetition rate laser driven ion acceleration over 10 Hz

Front end of over 10 Hz ion generation platform laser system has been developed.
100 Hz, 1 mJ, 2〜3 % stability achieved.

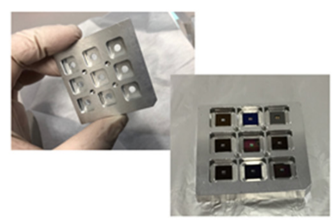


Over 10 Hz repeatable target systems are under preparation.

Tape type target
Merit:
Long time supply
Demerit:
Too thick target



Thin foil type target
Merit:
Submicron foil
Demerit:
limited supply



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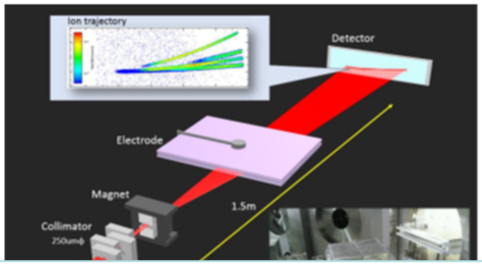
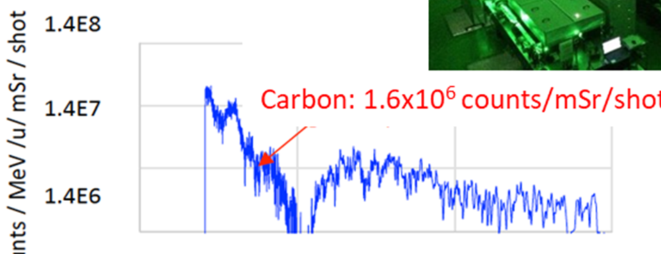
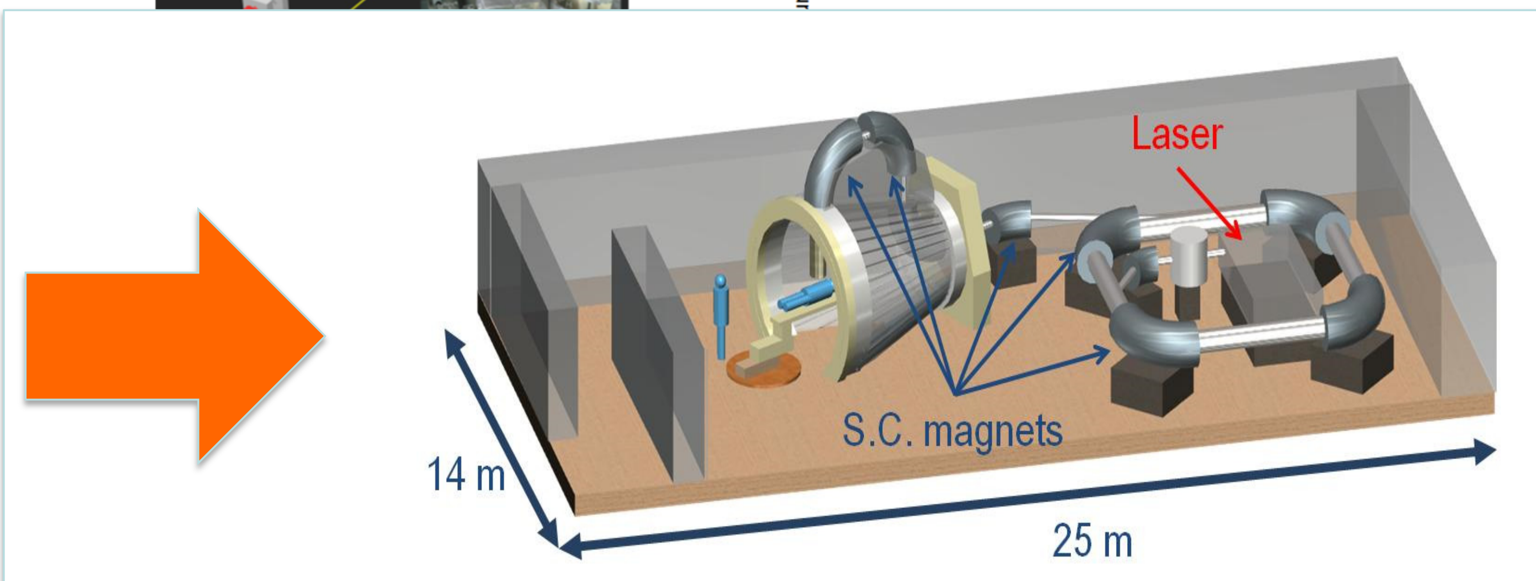
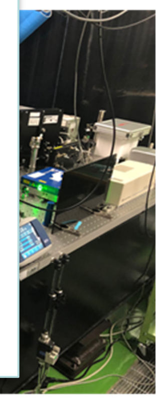


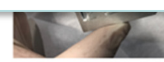


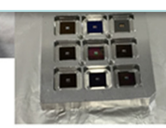




Too thick target

Demerit:
limited supply



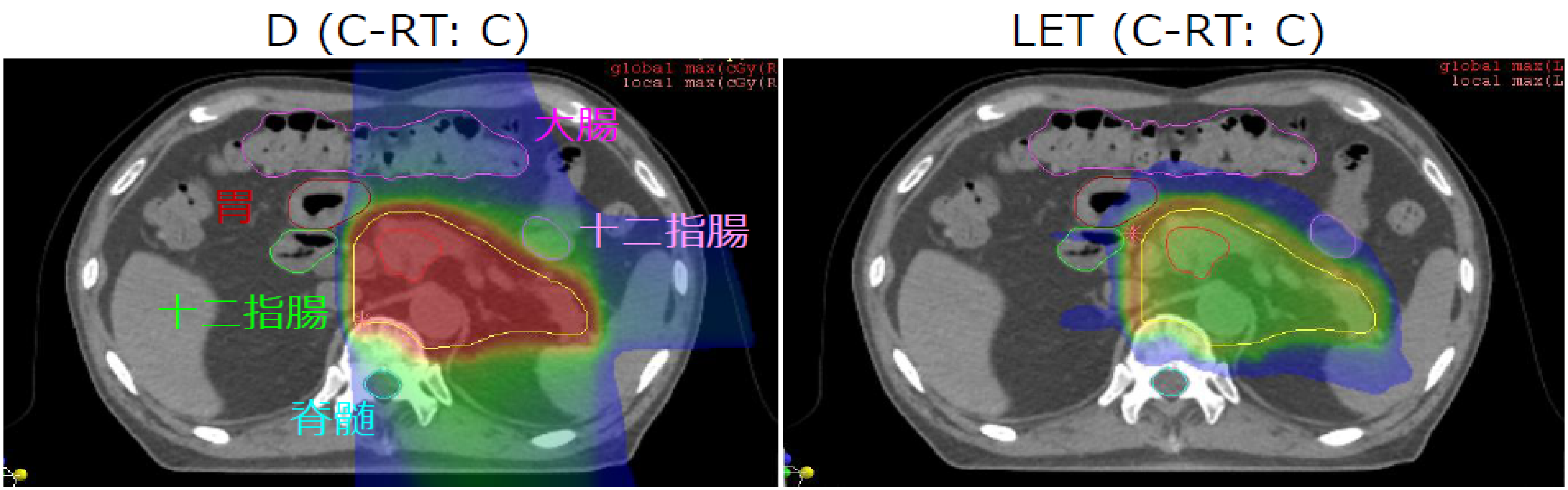


NIRS HIMAC

RBE Control

Multi-Ions Irradiation

C-ion RT with chemo-therapy has brought 2-y OS of 60% for pancreatic cancer treatment. On the other hand, 5-y OS is not improved due to insufficient dose, because it is difficult to increase the dose due to a tumor surrounded by radiosensitive organs.



Taku Inaniwa *et al.*, *Phys. Med. Biol.* 62 5180 (2017)

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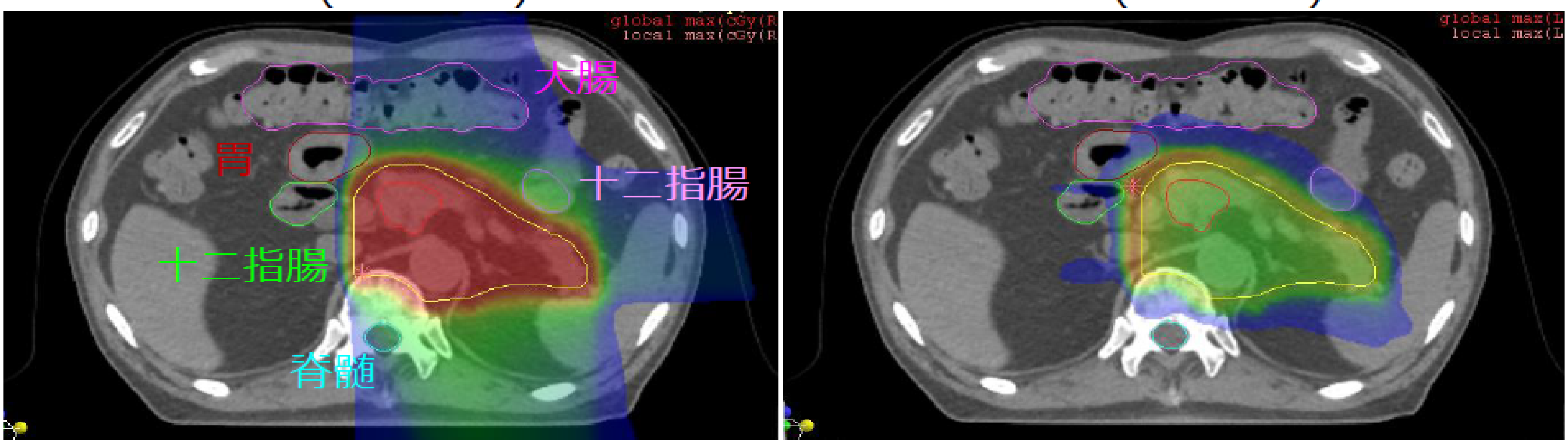
RBE Control

Multi-Ions Irradiation

- Multi-Ions Irrad. : Optimization of ion specifies for high performance
  - Malignant part → higher bio-effect than C-ion for Suppressing Recurrence
  - Boundary between tumor and normal tissue → Lower Bio-Effect for Reducing Toxicity
  - Other Part → C-ion owing to C-ion RT result

D (C-RT: C) LET (C-RT: C)



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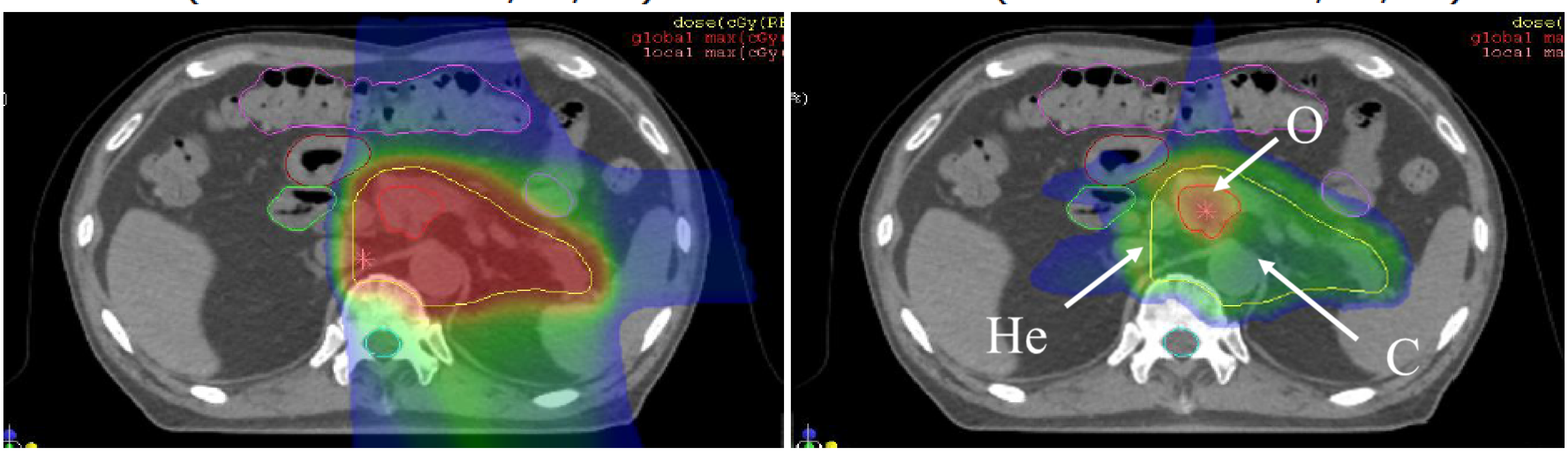
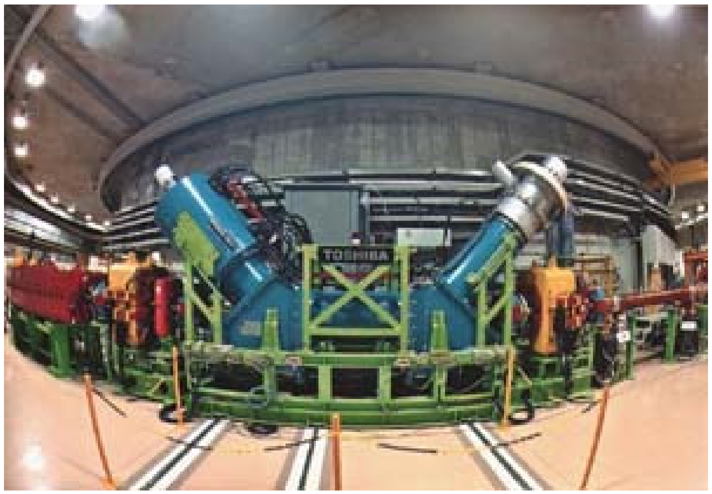


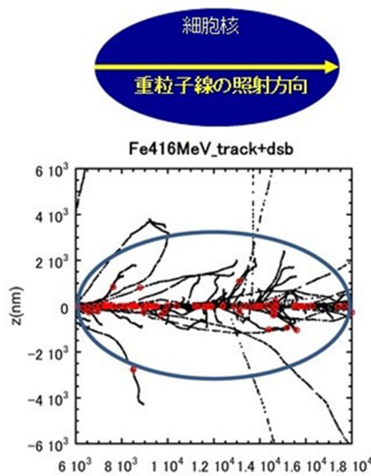
Taku Inaniwa *et al.*, *Phys. Med. Biol.* 62 5180 (2017)

External Magnetic Field on Tumor

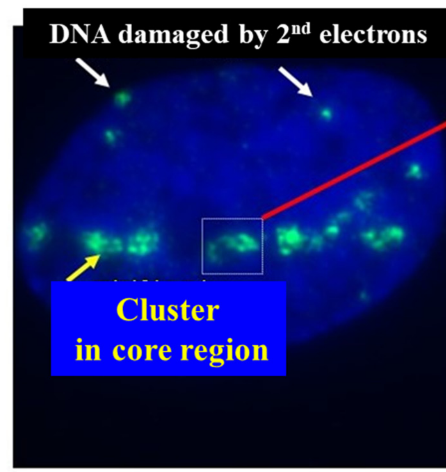


In the electron beam cooler,
electrons are constrained by a solenoid field
for efficient cooling.

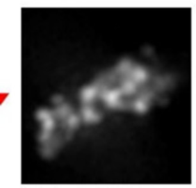
What happens
when solenoid field is applied on tumor
to constrain the secondary electrons induced by ions?



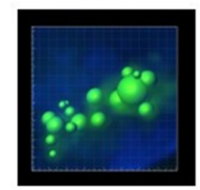
2^{nd} electrons
along ion orbit



DSB-marker after 30 min
by EOB of HI



Track in core region

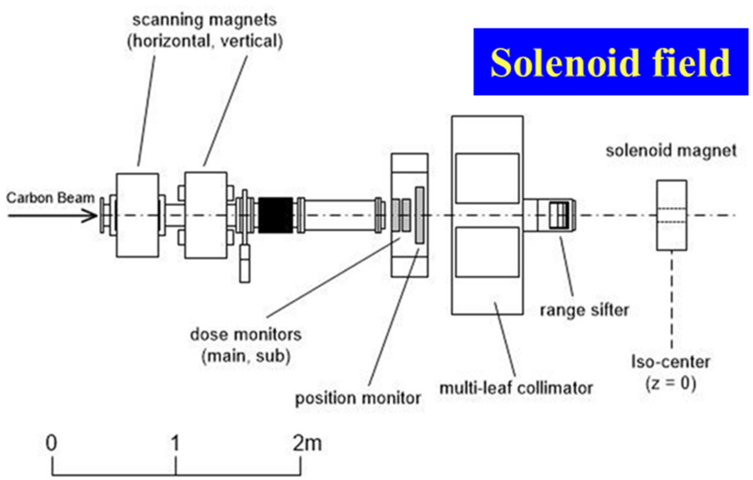


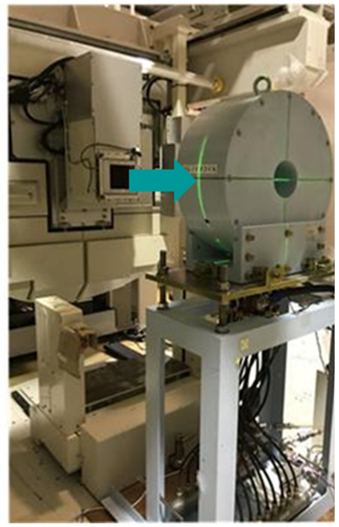
After image analysis

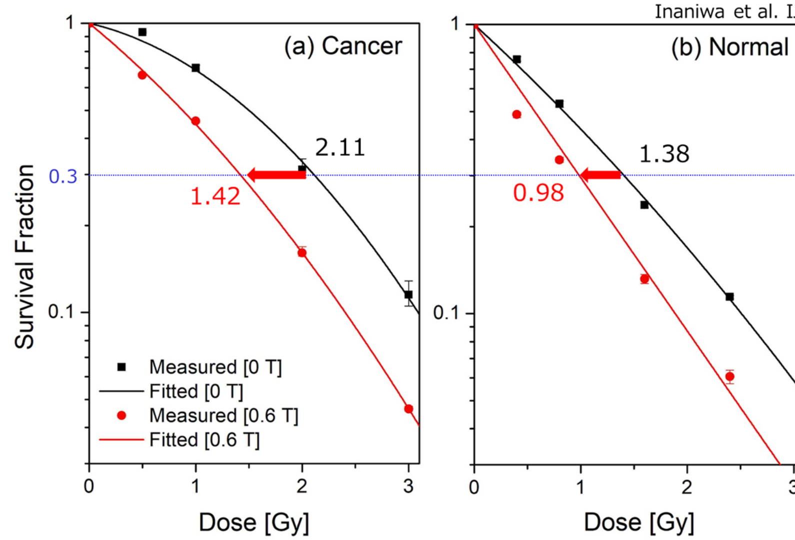
RBE Controlled by Mag. Field

Inaniwa et al. IJRB (20

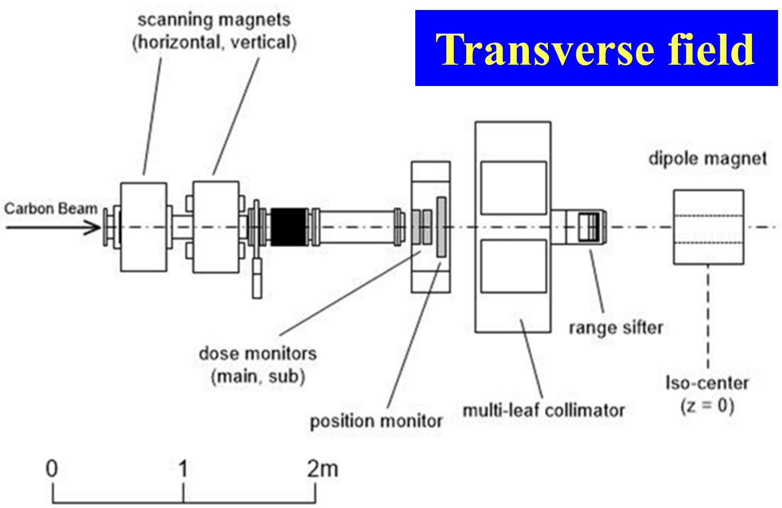
Solenoid field

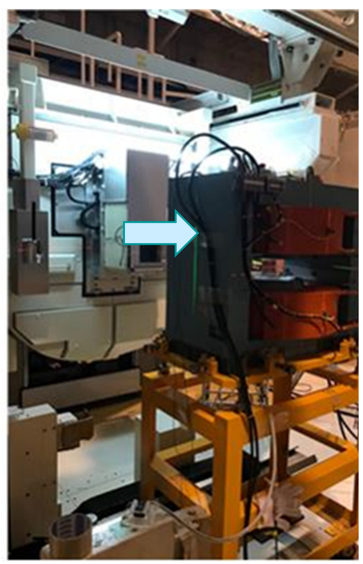


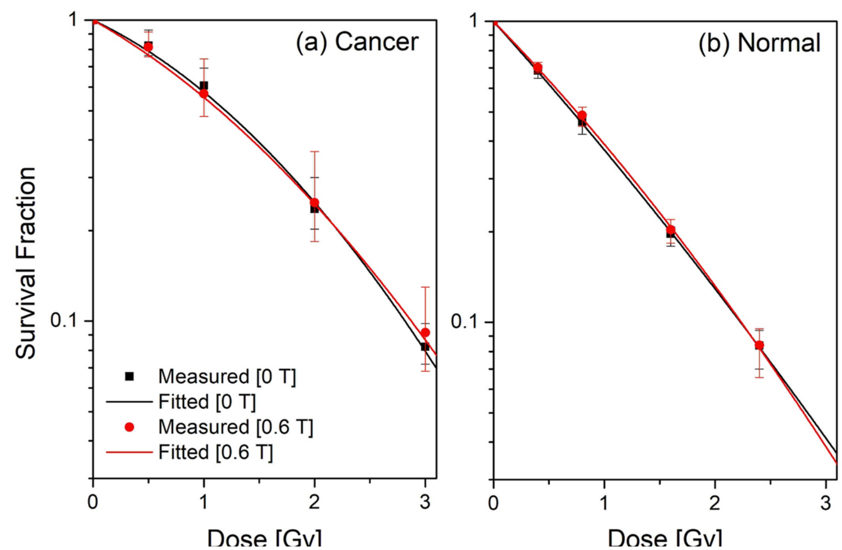




Transverse field



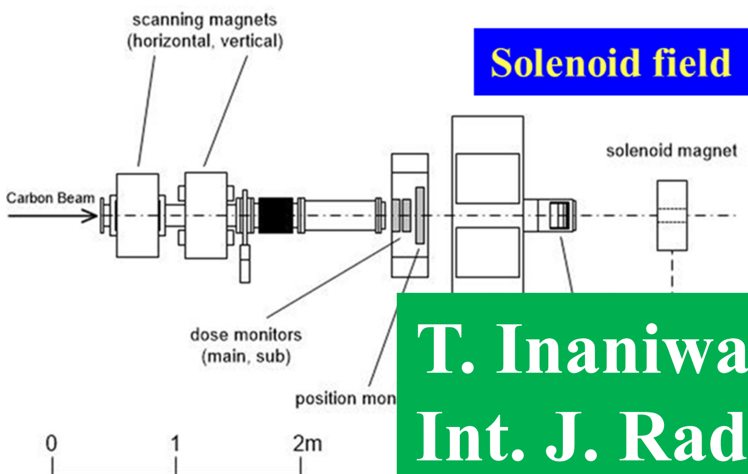


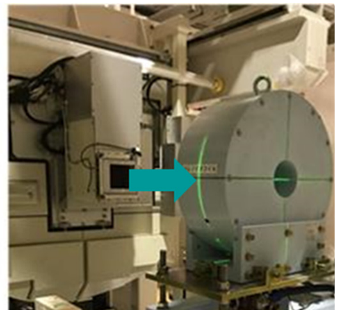


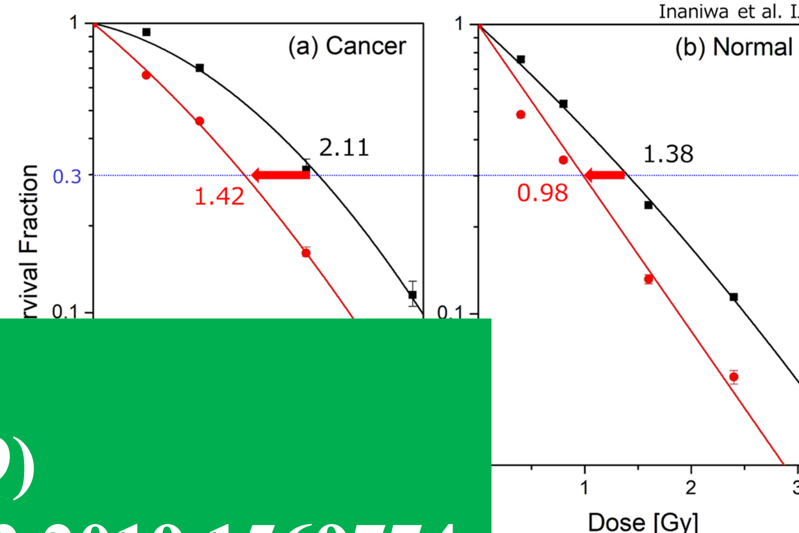
RBE Controlled by Mag. Field

Inaniwa et al. IJRB (20

Solenoid field







T. Inaniwa et al.,
Int. J. Radi. Bio., (2019)
DOI: 10.1080/09553002.2019.1569774

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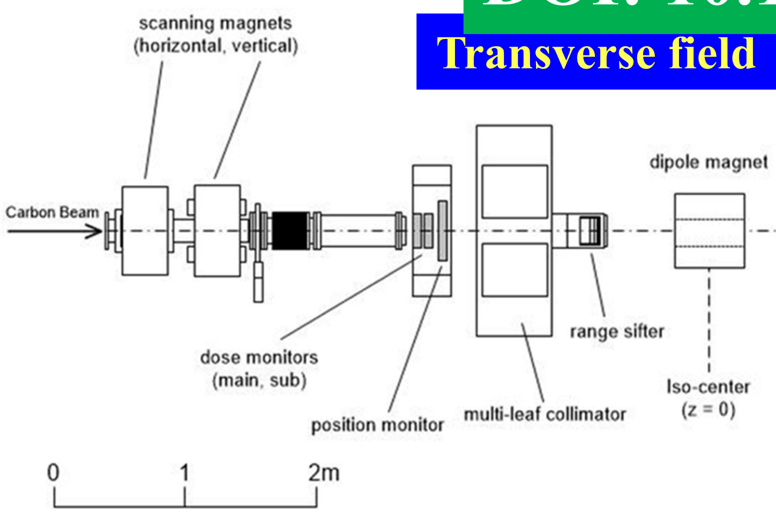
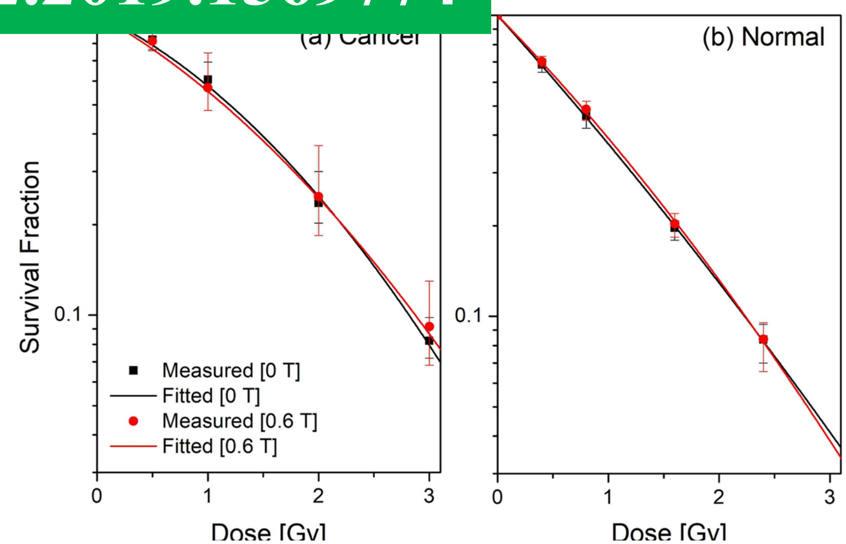
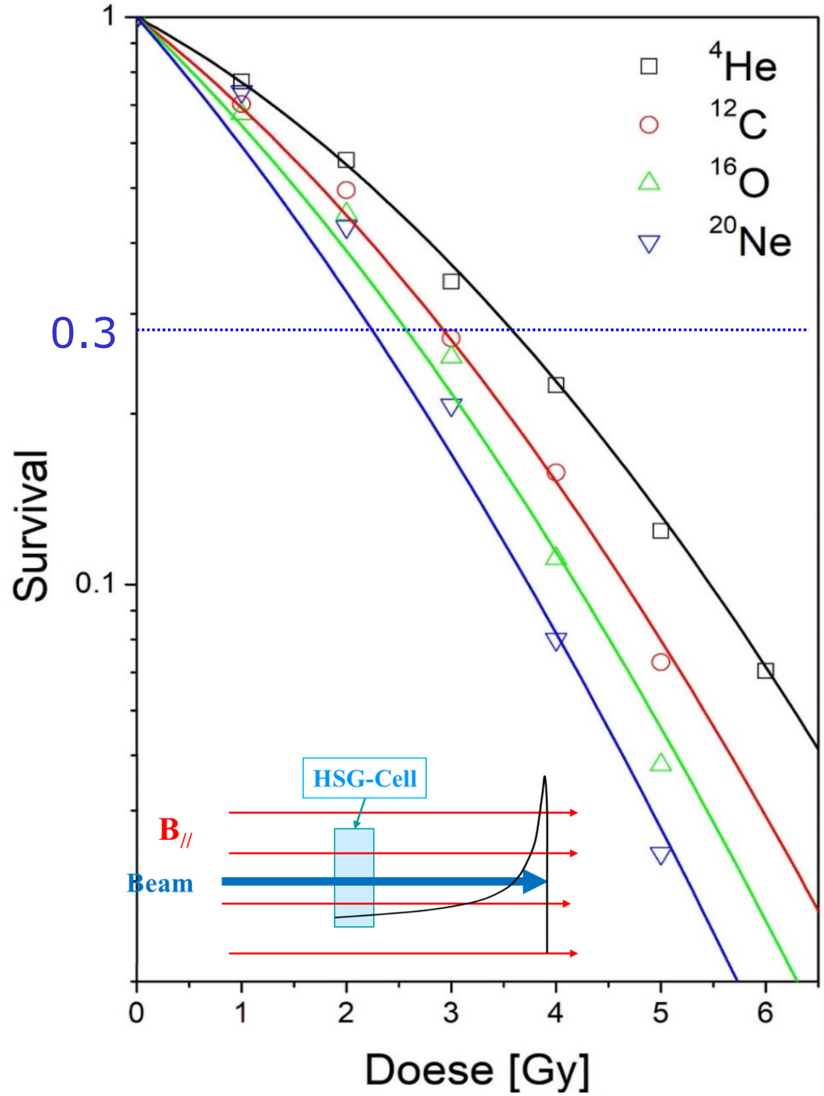




NIRS HIMAC

RBE Control

SR by $B_{//}$ and SR by Ion Species



Reference Data

Survival rates of cancer cells (HSGc-C5), irradiated by He, C, O and Ne-ions with the range of 15 cm WEL.

Decrease of D_{30} by Ion-Species

^{4}He : 3.43 Gy

^{12}C : 2.80 Gy (-18%)

^{16}O : 2.46 Gy (-28%)

^{20}Ne : 2.13 Gy (-38%)

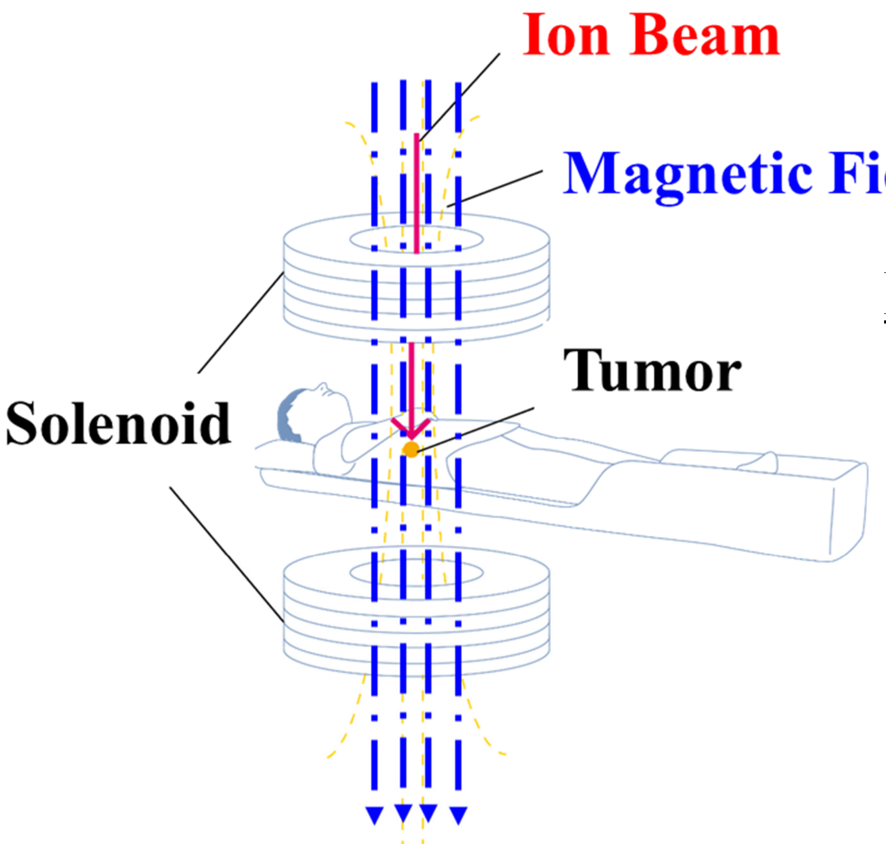
Decrease of D_{30} by $B_{//}$

2.11 Gy → 1.42 Gy (-33%)

NIRS HIMAC

RBE Control

SR by $B_{//}$ and SR by Ion Species



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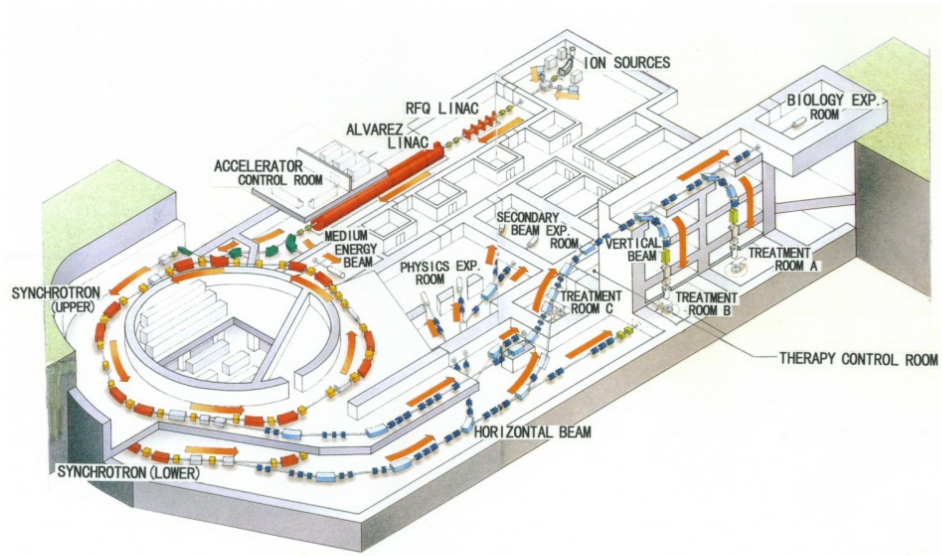
Contents



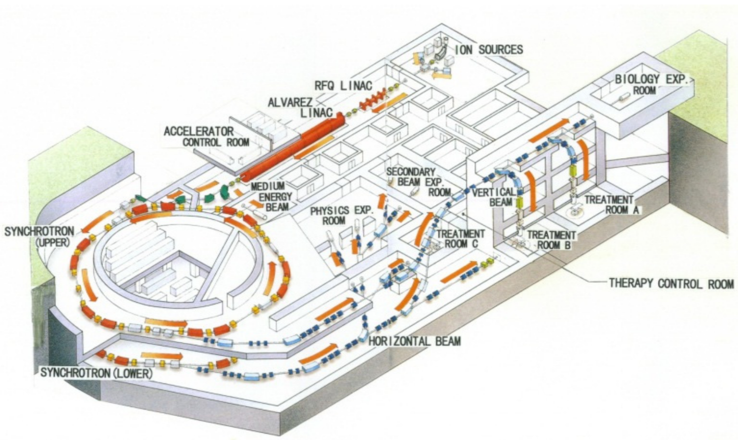
ION SOURCES
RFQ LINAC
ALVAREZ LINAC
ACCELERATOR CONTROL ROOM
BIOLOGY EXP. ROOM
MEDIUM ENERGY BEAM
SECONDARY BEAM EXP. ROOM
PHYSICS EXP. ROOM
VERTICAL BEAM
TREATMENT ROOM A
TREATMENT ROOM B
TREATMENT ROOM C
THERAPY CONTROL ROOM
SYNCHROTRON (UPPER)
SYNCHROTRON (LOWER)
HORIZONTAL BEAM

NIRS HIMAC

Summary

Technology Development

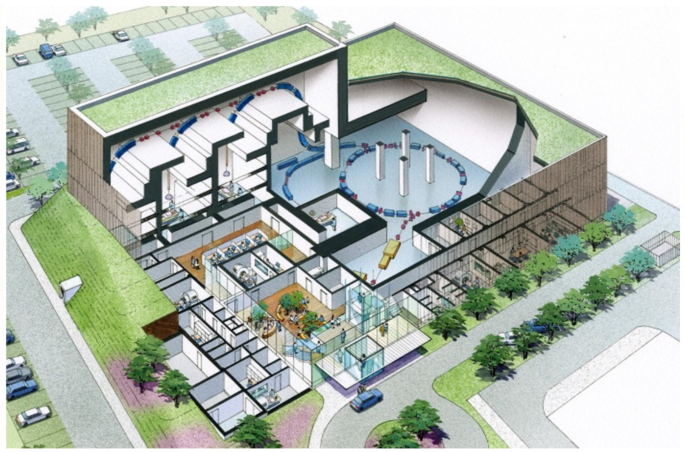
HIMAC



He〜Ar
Max.800MeV/n
Beam-Woblling Method.
Respiratory-Gated Irrad.
Layer Stacking Irrad.

1994~

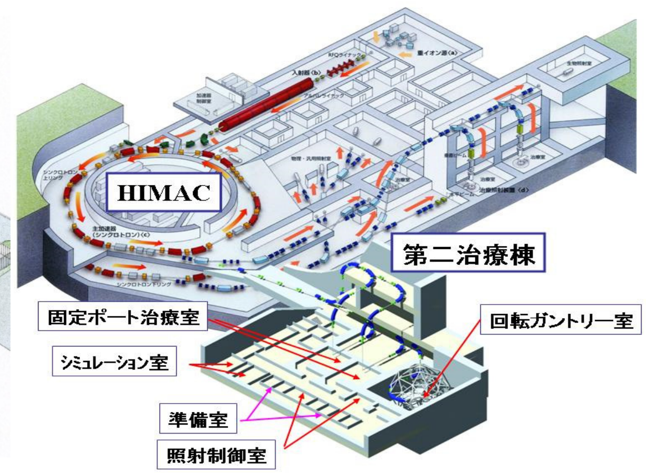
Standard-version@Gunma



C
Max. 400MeV/n
Spiral Wobling Method
Respiratory-Gated Irrad.
Layer Stacking Irrad.

+

New Treatment System

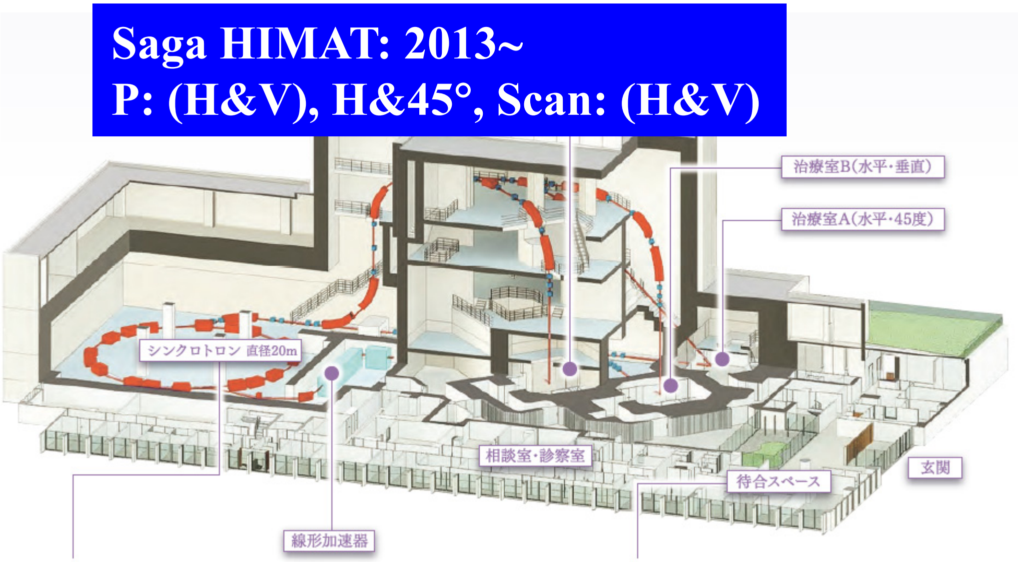


C, O
Max. 430MeV/n
Fast 3D-Scanning
Respiratory-Gated Irrad.
Rotaing Gantry

Advanced Standard Version

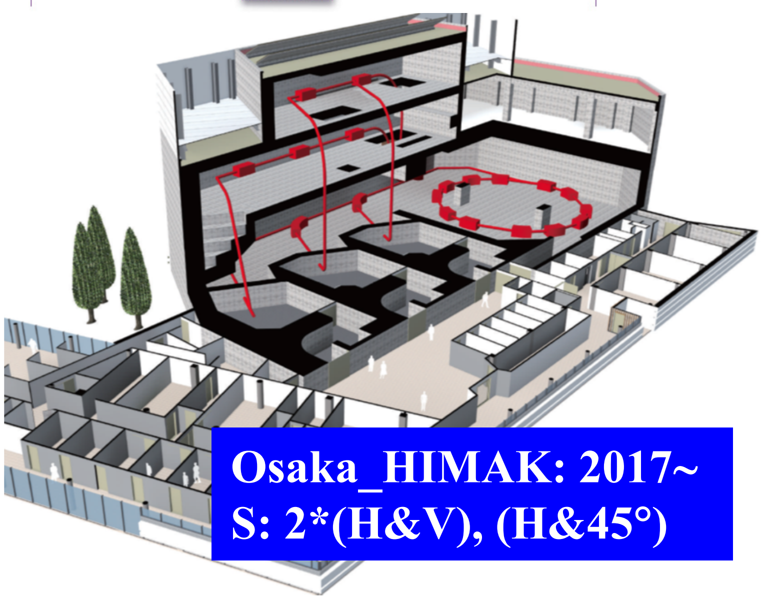
Advanced Standard Version

Saga HIMAT: 2013~
P: (H&V), H&45°, Scan: (H&V)



KCC_iROCK: 2015~
S: 2*(H&V), 2*H

Osaka_HIMAK: 2017~
S: 2*(H&V), (H&45°)



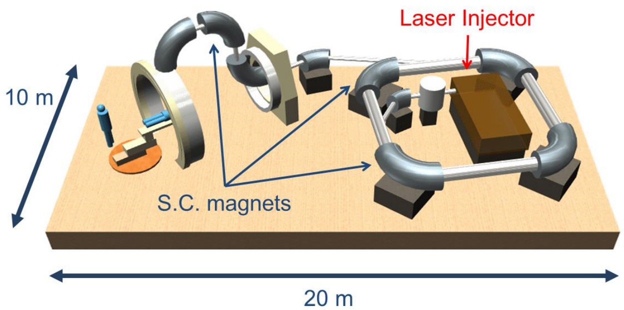
Yamagata: 2020
S: Gantry, H

NIRS HIMAC

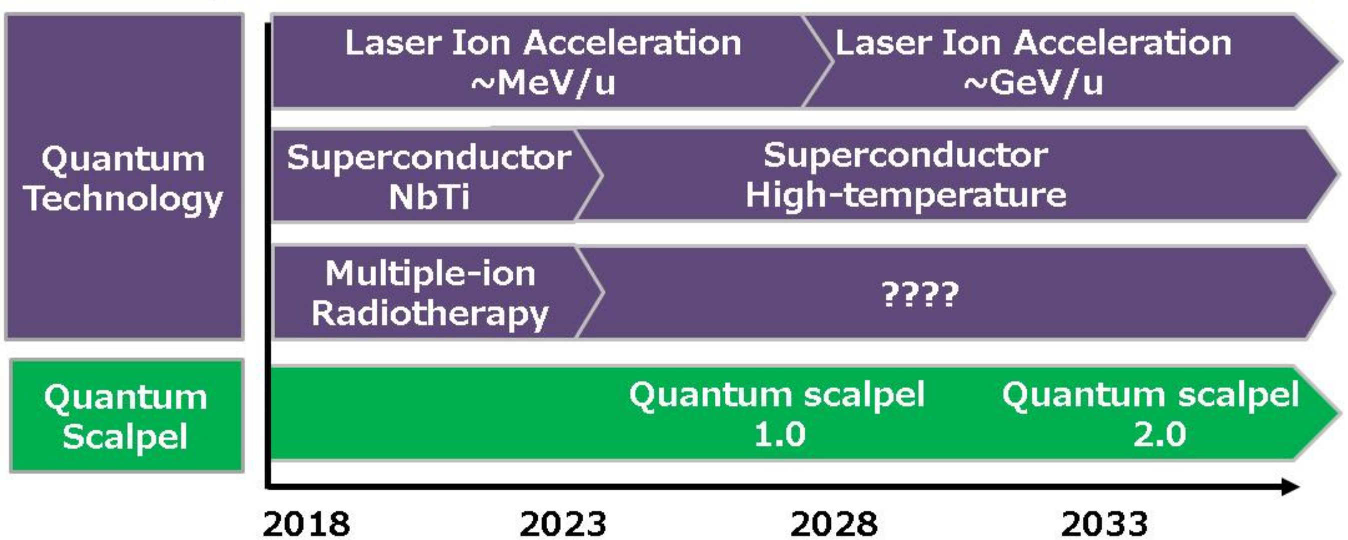
Advanced Standard Version

HiRT+ Compact Machine + RBE Control

= Quantum Scalpel



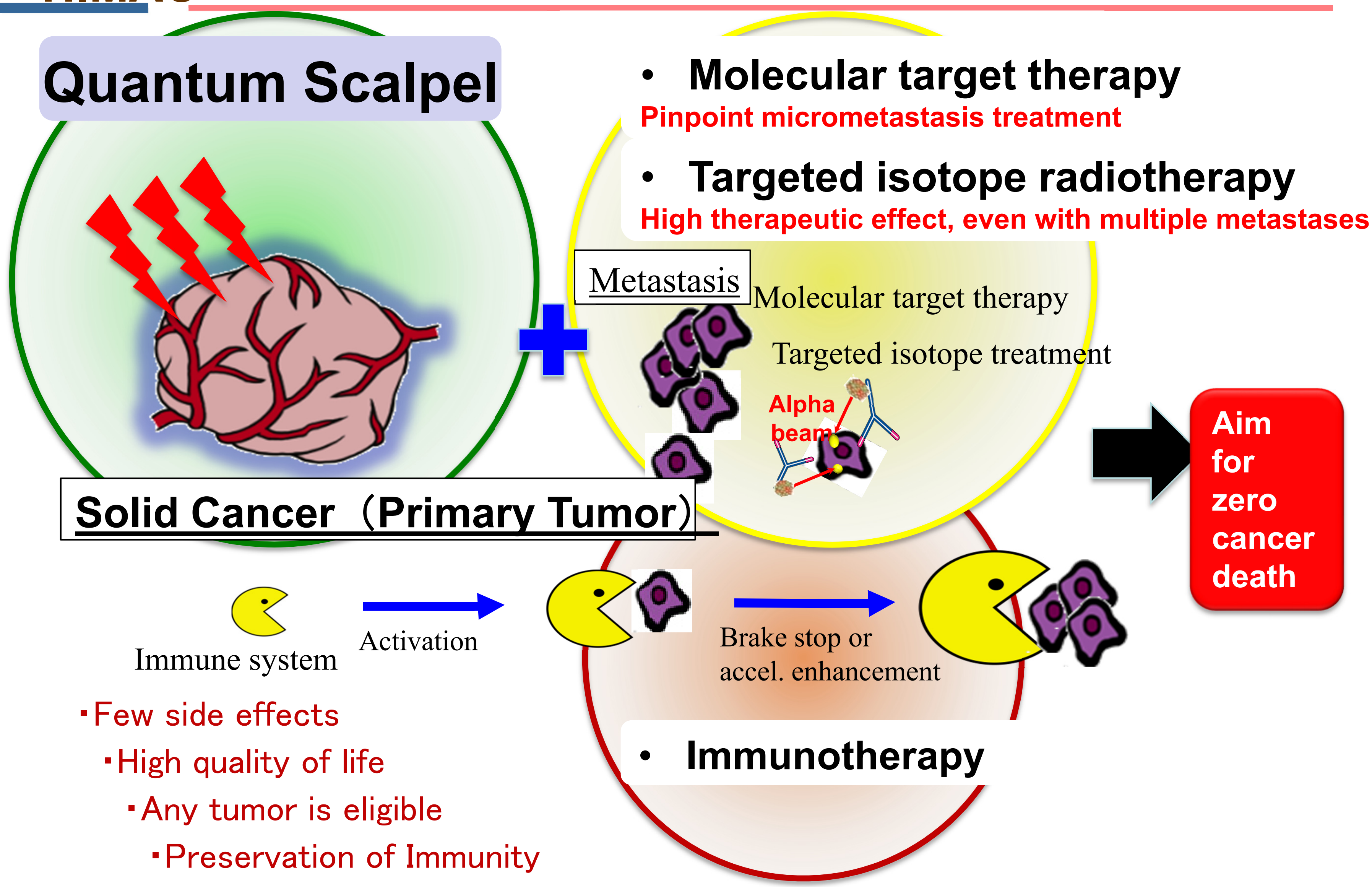
Roadmap



Summary

NIRS HIMAC

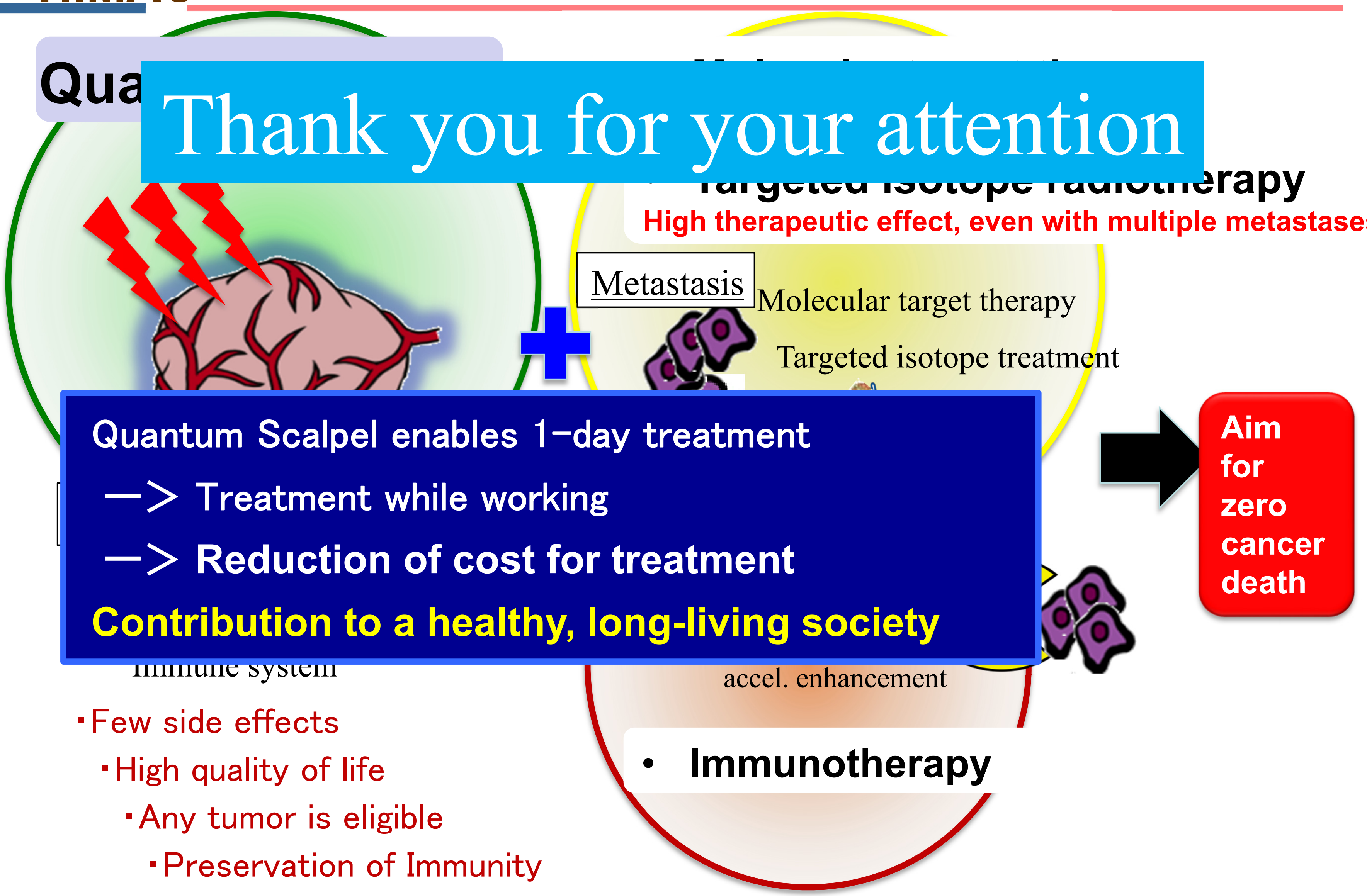
A Healthy, Long-living Society with Zero-Cancer-Death



Summary

A Healthy, Long-living Society with Zero-Cancer-Death

Thank you for your attention



Quantum Scalpel enables 1-day treatment

—> Treatment while working

—> **Reduction of cost for treatment**

Contribution to a healthy, long-living society

- Few side effects
- High quality of life
- Any tumor is eligible
- Preservation of Immunity