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Review of Heavy Ion Accelerators for Hadrontherapy

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National Institute of Radiological Sciences

11th Int'l Conf. on Heavy Ion Accelerator Technology,

June 10 '09, Venice, Italy

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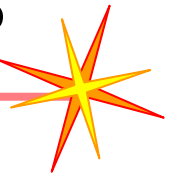
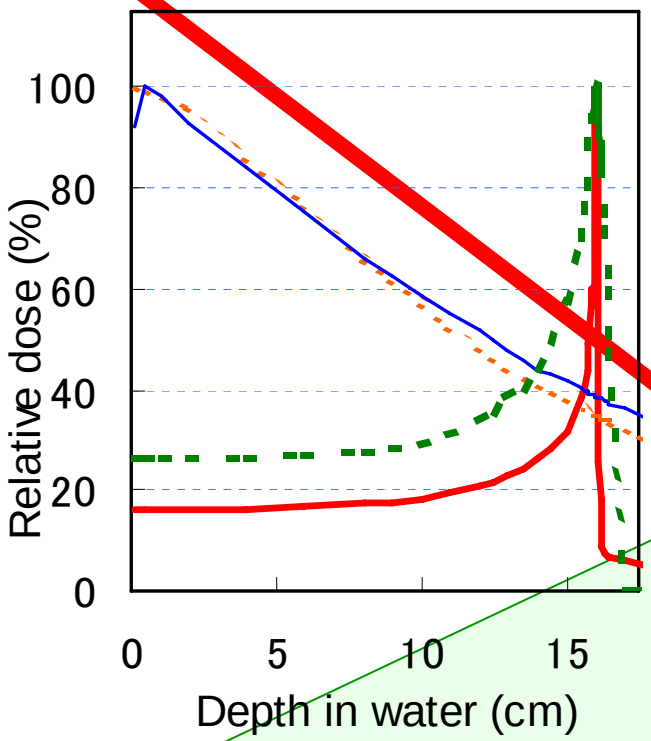
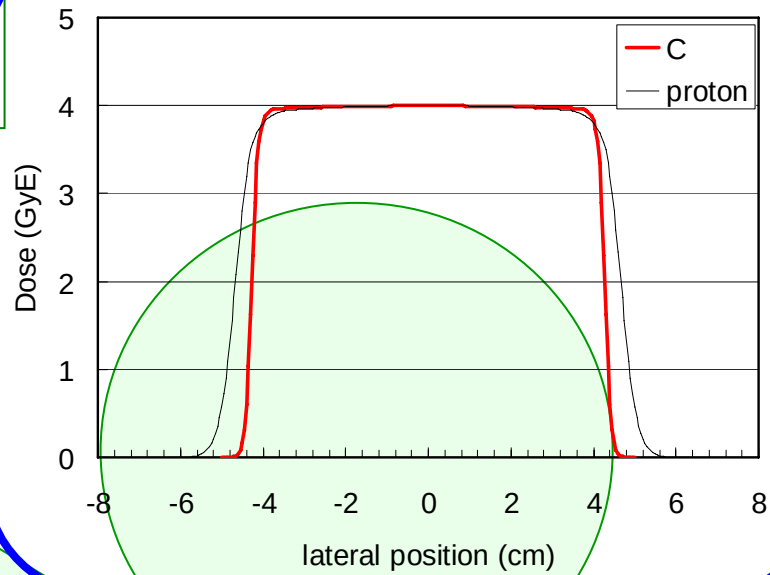
Contents



Feature of Ion Radiotherapy

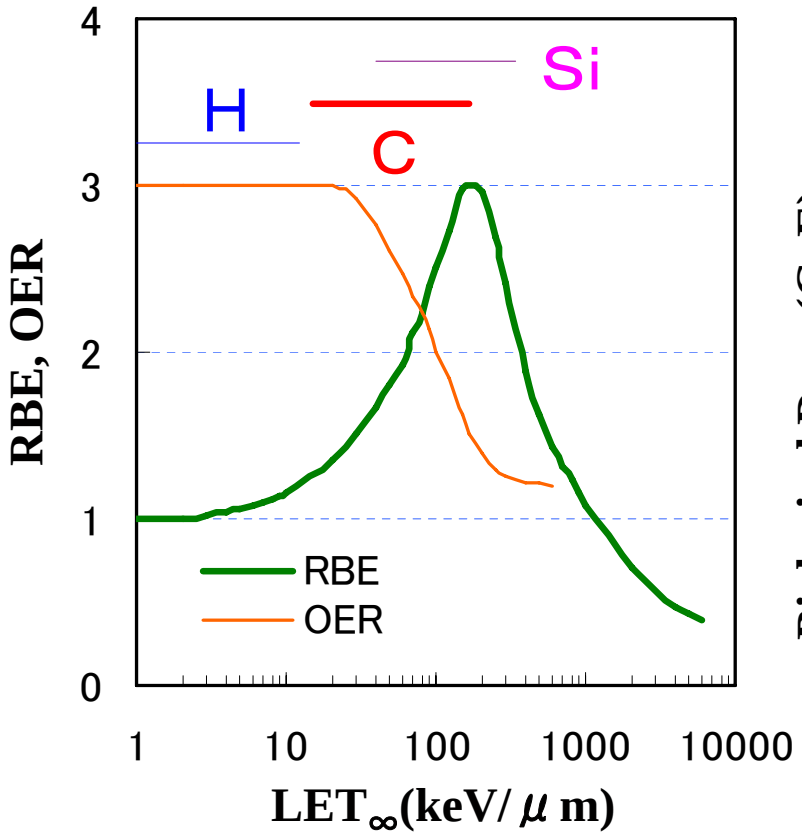
Good longitudinal dose localization due to the Bragg peak.



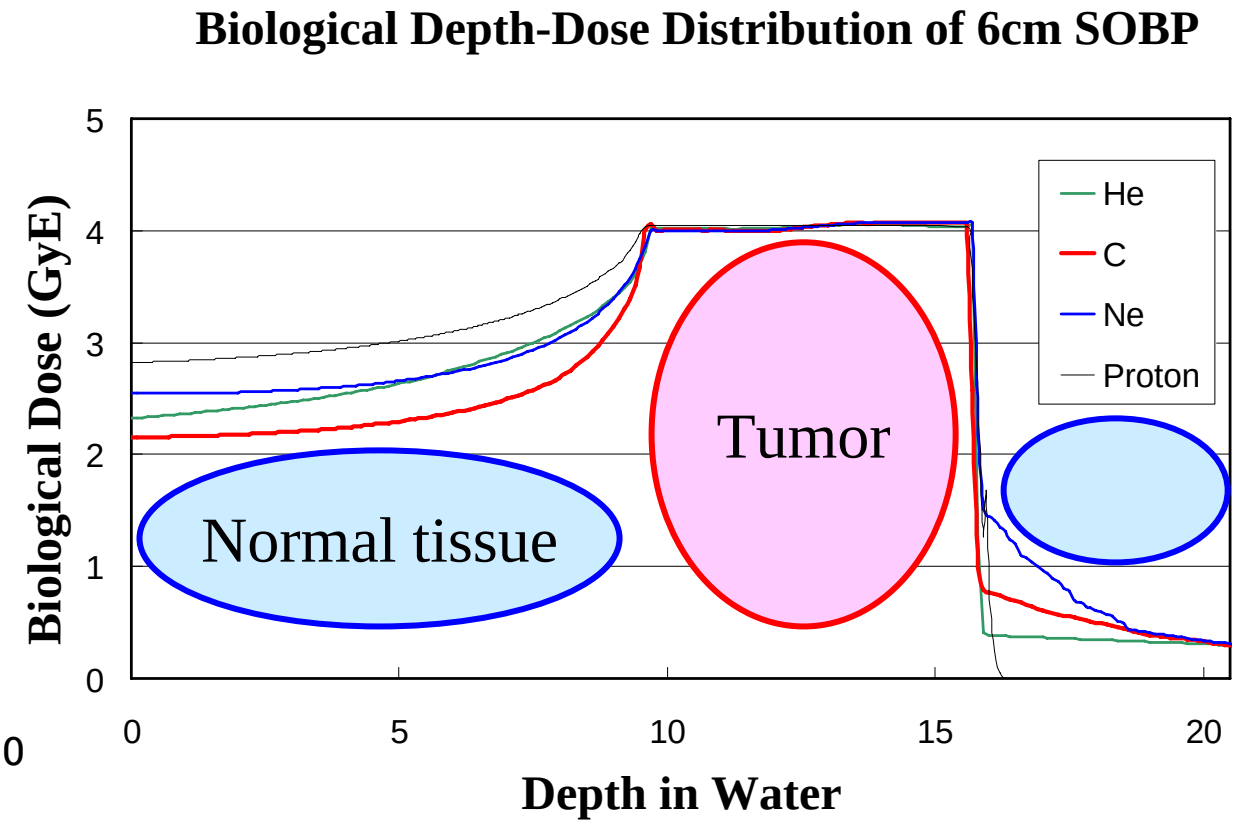


Good transverse dose localization due to the low scattering.

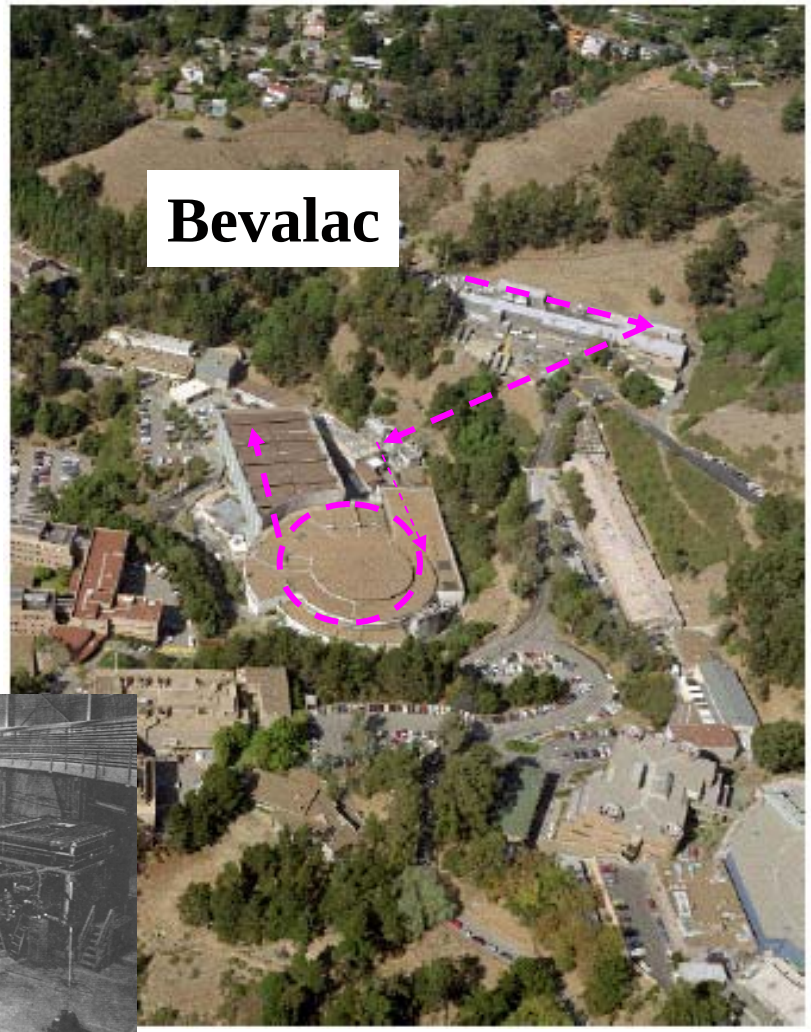
Biological Effect of Ion beams

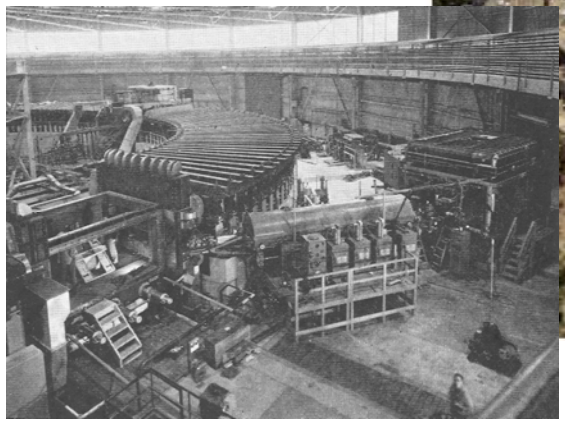


LET Dependence of RBE & OER



Pioneering Work at LBL





June ’75: 1st He patient
May ’77: 1st C patient
Nov. ’77: 1st Ne patient
Mar. ’79: 1st Ar patient
Nov. ’82: 1st Si patient

Total: 1,314 @’77-92
He patients 858
Heavier ions 456

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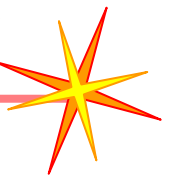

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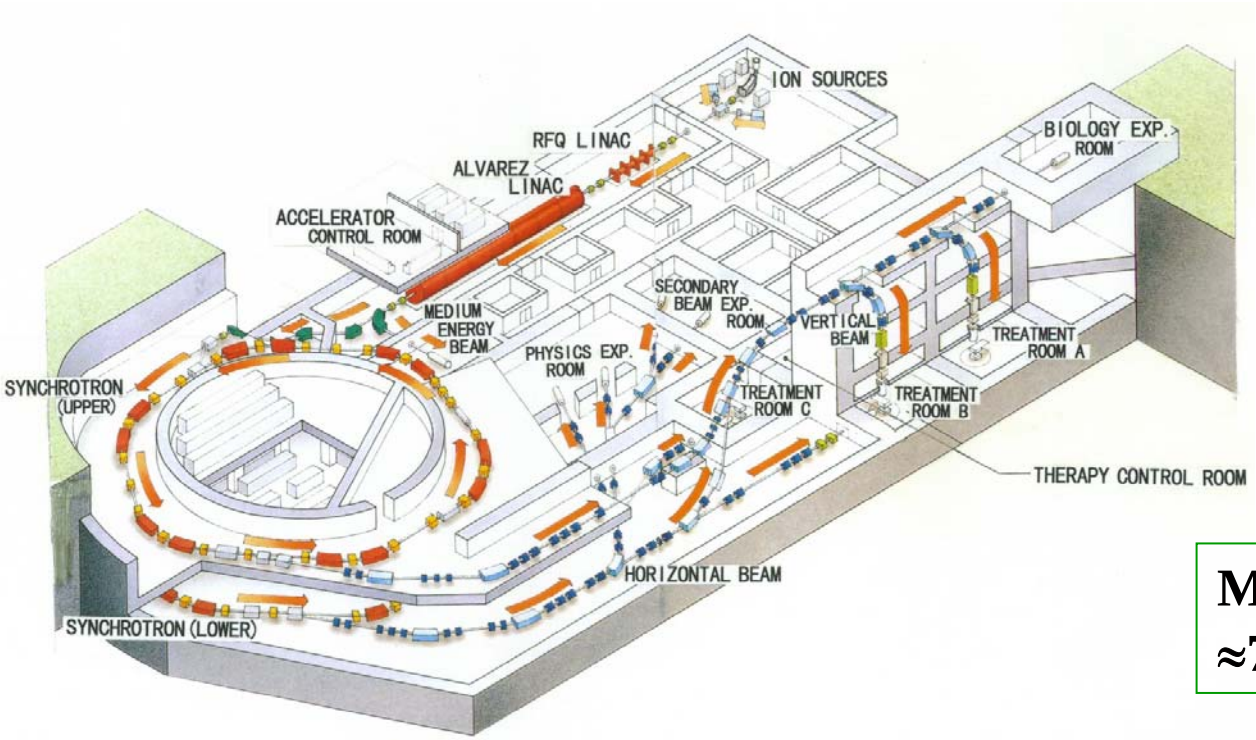
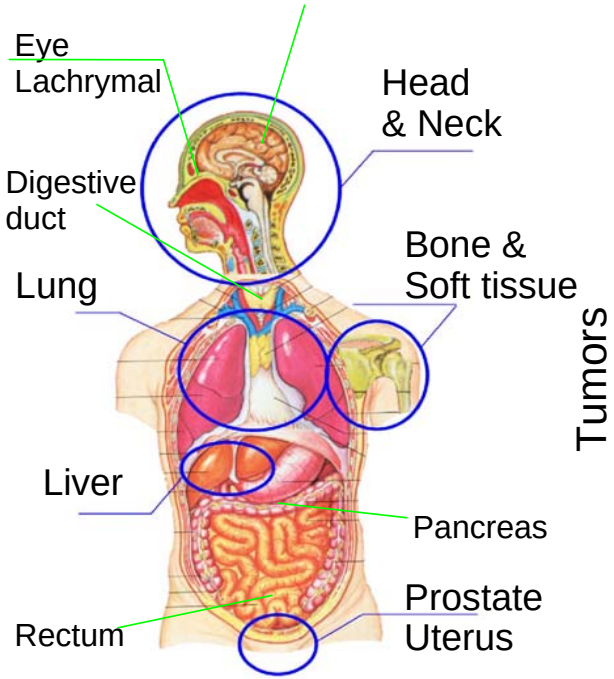
HIMAC facility

- 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

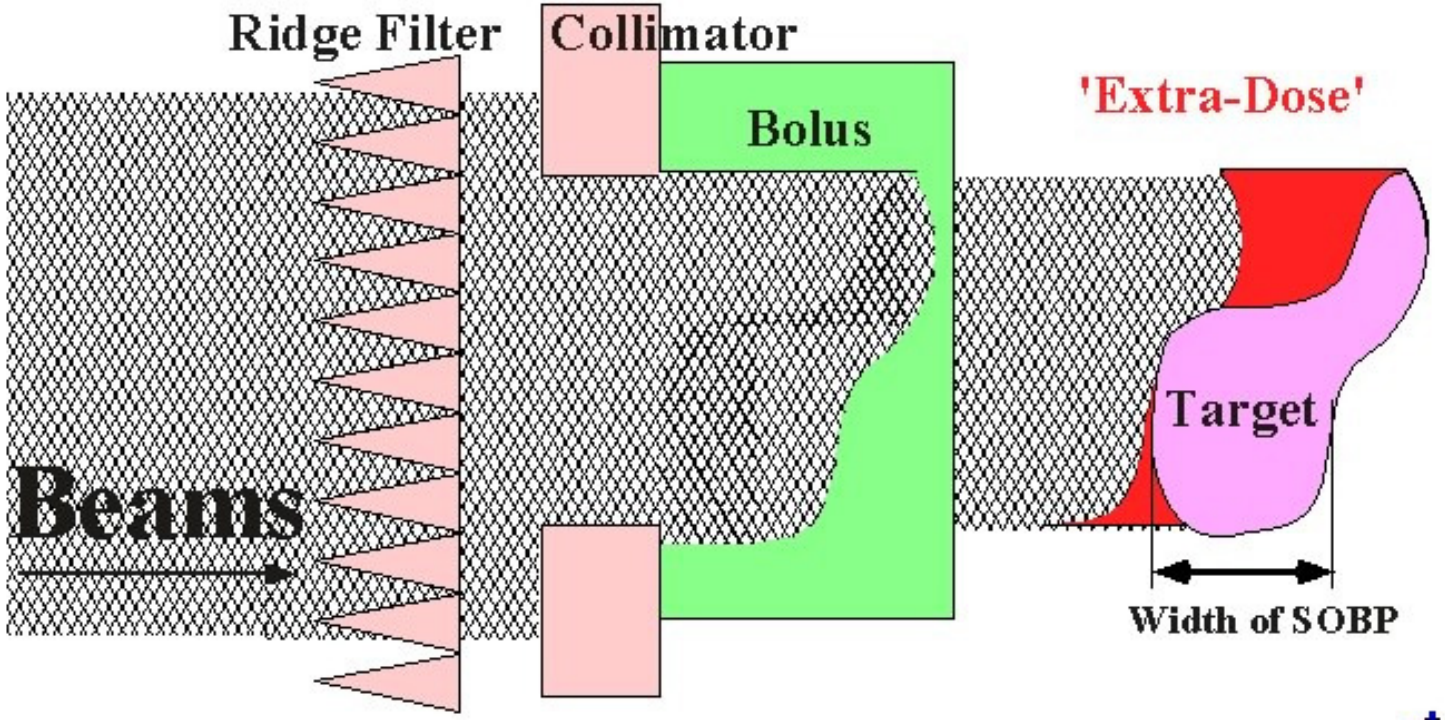




More than 4,500 pts treated since ‘94.
≈750 pts/y, ≈70 shots/day @180 d/y

HIMAC (Heavy Ion Medical Accelerator in Chiba)

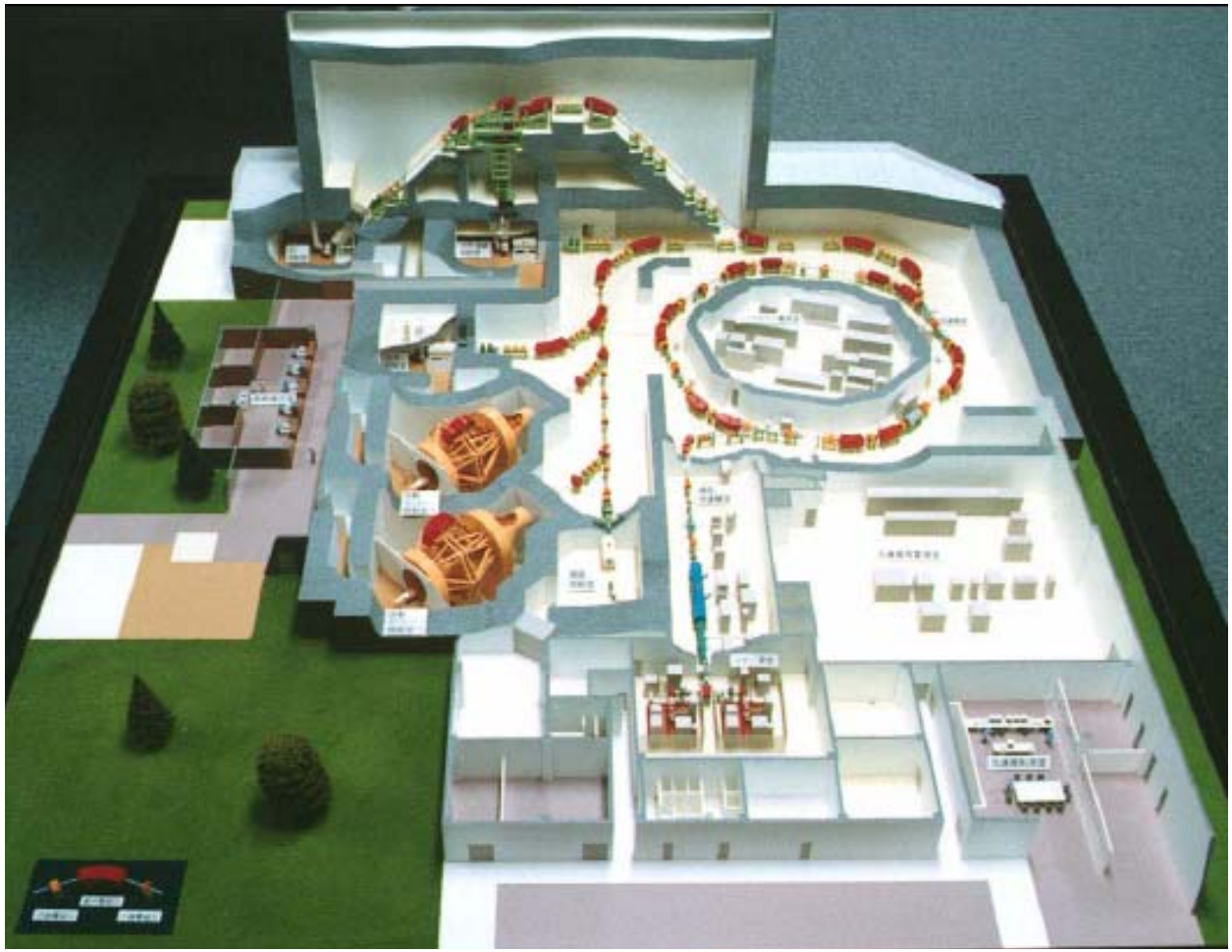
Present HIMAC Method



Broad Beam Method with Wobbler and Scatterer

- ○ **Dose distribution is independent of beam quality**
- ○ **Easy dose management**
- △ Low beam-utilization efficiency
- × **Extra-dose is given on normal tissue when irregular shape**
- × **Require Bolus and patient collimator**

Hyogo Facility



1) **Proton:**
   Energy: 230 MeV
   2 Gantry + 1 H
2) **Carbon**
   Energy: 320 MeV/n
   1 H&V, 45º line

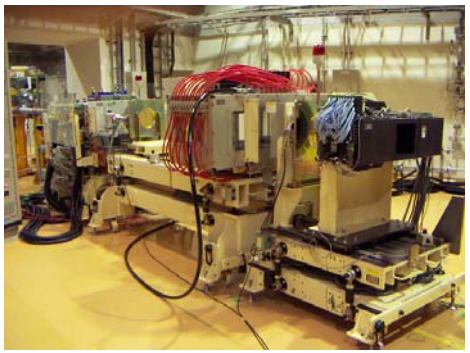
- **10GHz-ECR IS: 2**
- **200MHz RFQ+DTL: 5MeV/n**
- **Synchrotron(96m)**
  Multiturn Injection
  RF-KO extraction

2,339 pts treated from May ’01 to Oct ‘08

Design and R&D by NIRS

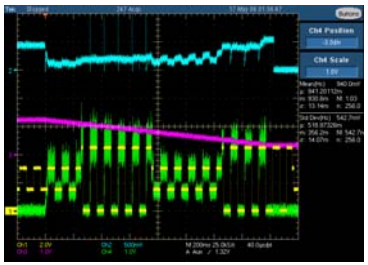
Compact RF-cavity

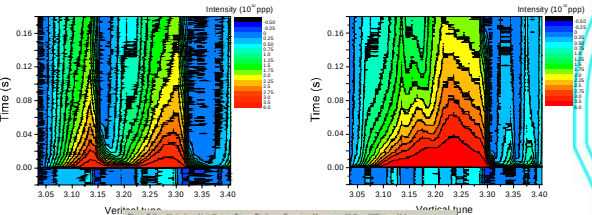
Compact Injector
RFQ + APF-IH

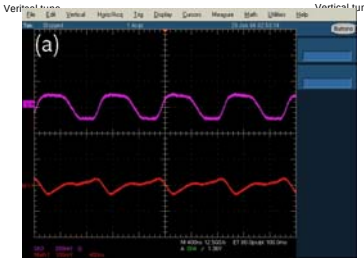


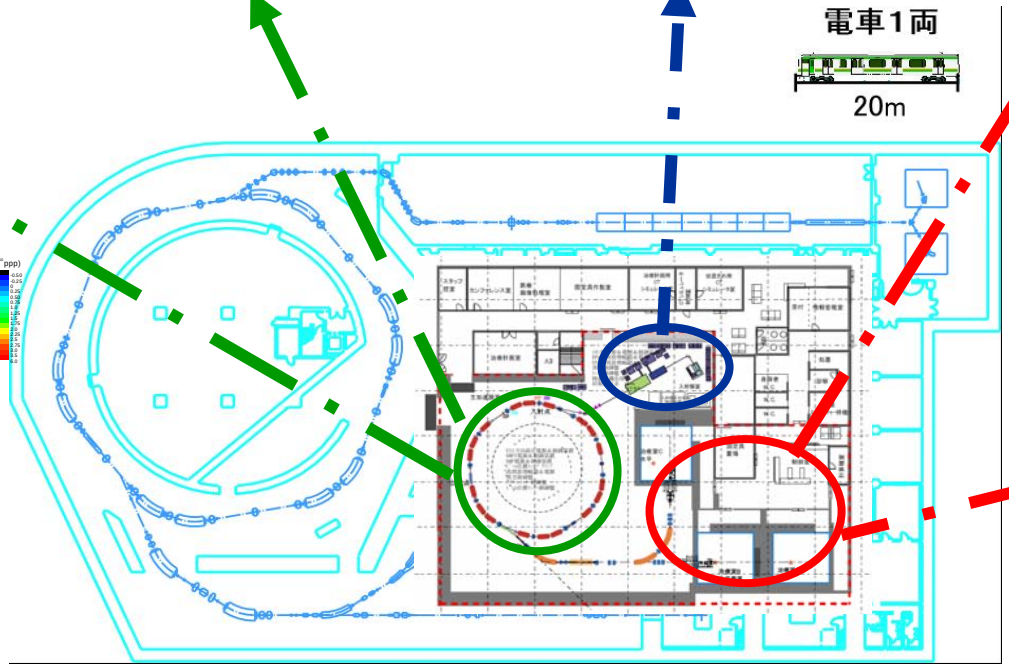
Development Irrad. Tech.

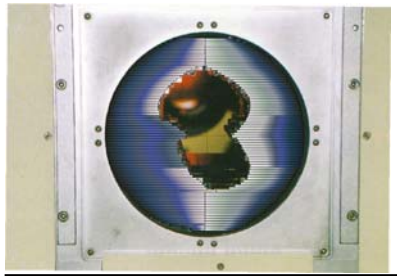
Beam Study









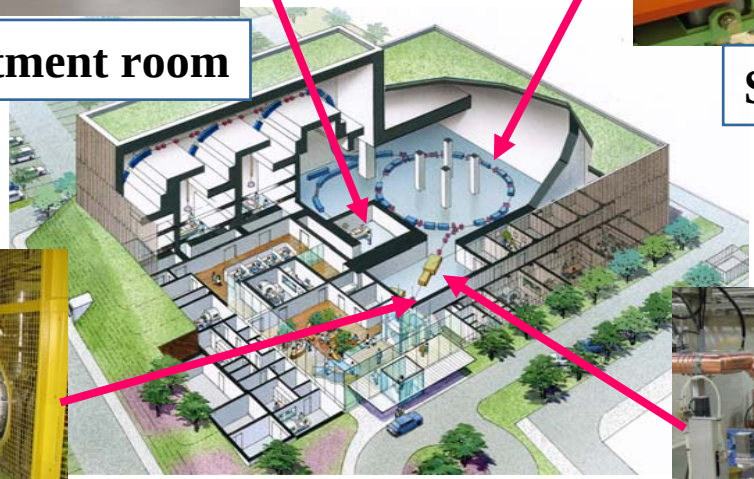


High-Precision MLC

Gunma University

Treatment room

Synchrotron



10GHz-ECR

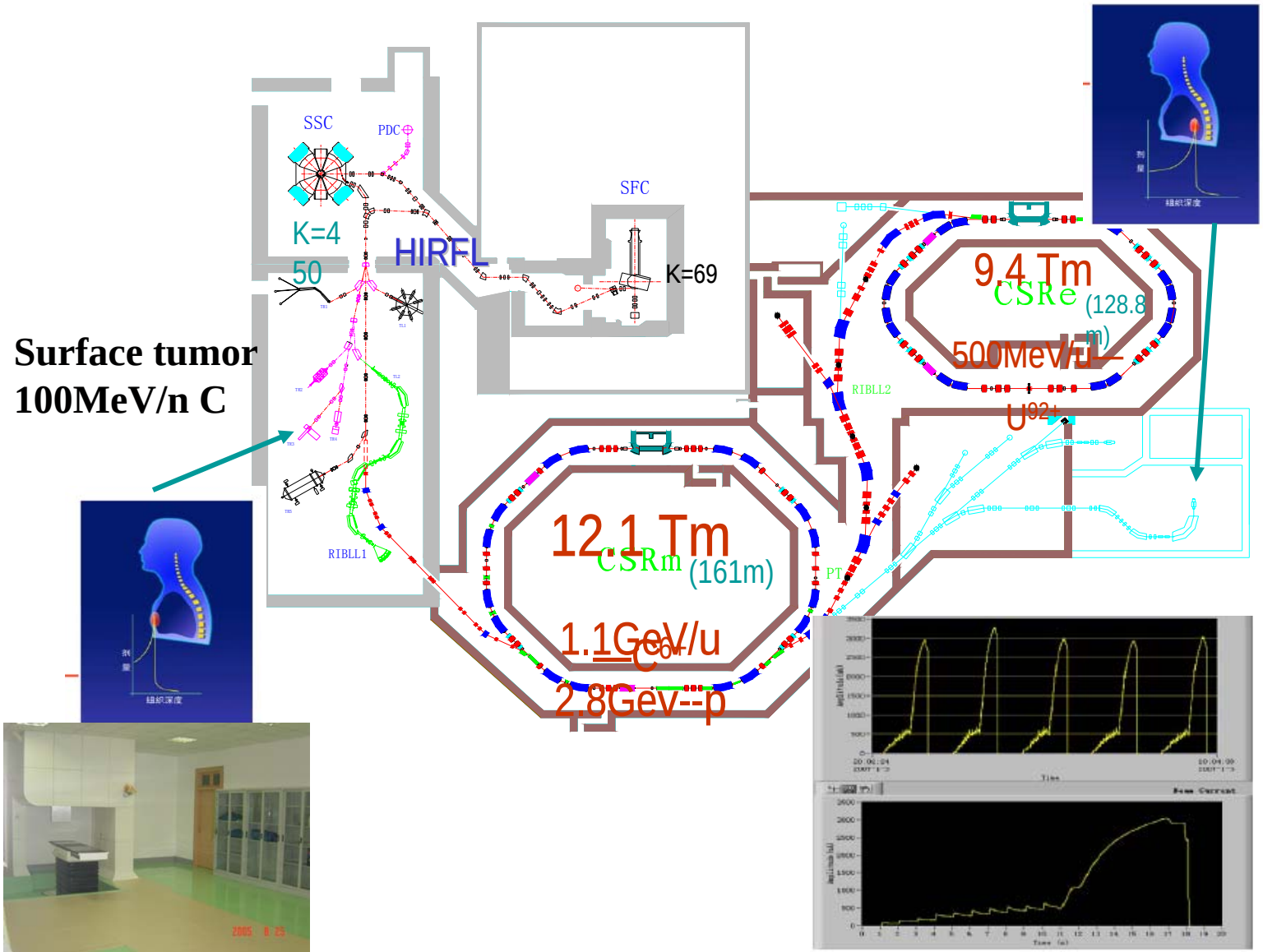
RFQ+APF-IH Linac

- **Carbon:**
  Energy: 140-400 MeV/n
  H&V, H, V and R&D room

- **10GHz-ECR IS**
- **200MHz RFQ+APF-IH:**
  0.6 – 4MeV/n
- **Synchrotron(~62m)**
  Multiturn Injection
  RF-KO extraction
  Acc. Driven extraction

- **Spiral Wobbling**
  Respiratory-Gated Irrad.
  Layer-stacking Irrad.

IMP at Lanzhou, China

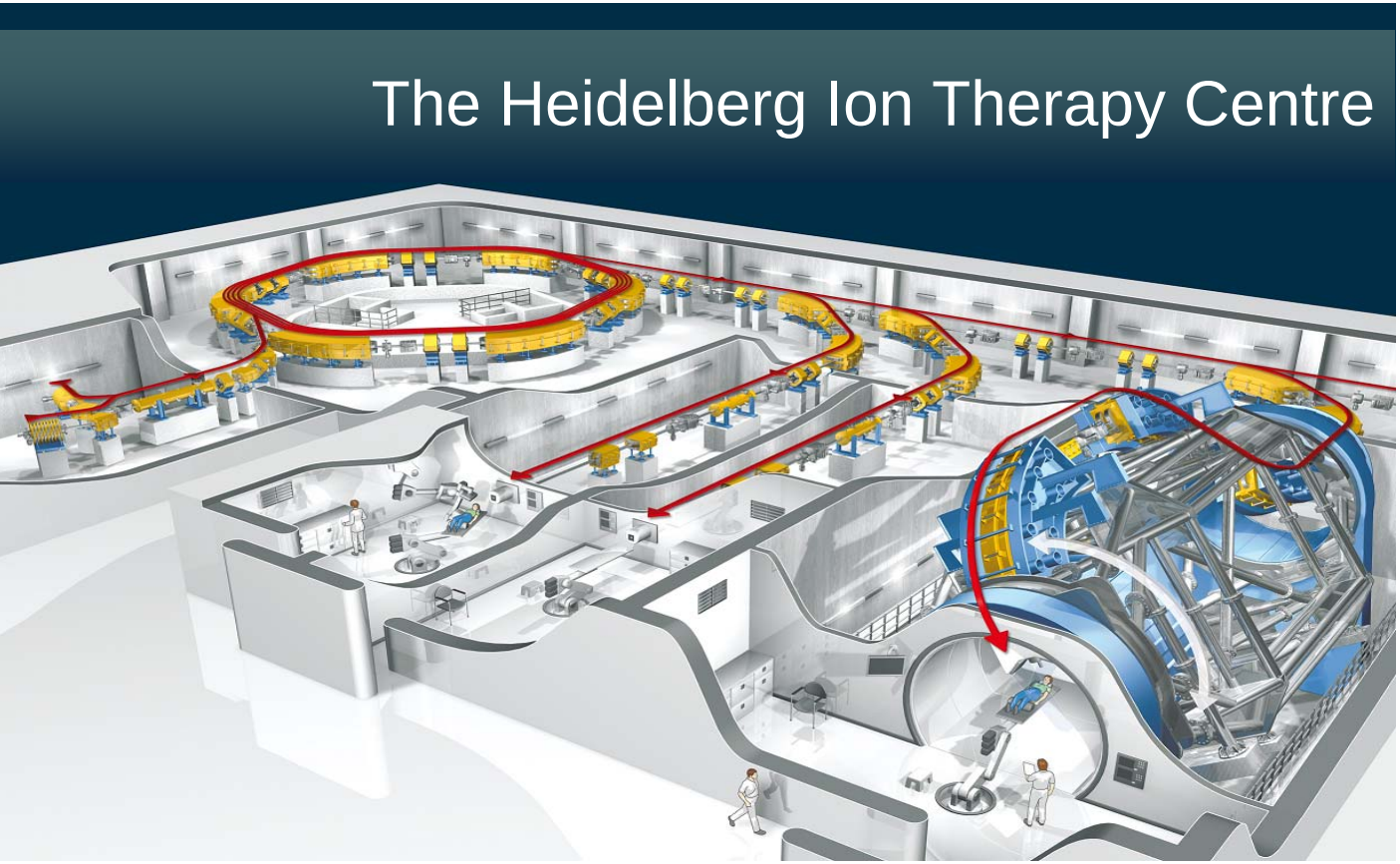


Deeply seated tumor
430MeV/n C
Cooler-Synchrotron

Surface tumor
100MeV/n C

- **Injector: SFC**
- **Cooler Synchro**
  Charge Ex. Inj.
  Cool Stacking

HIT Facility



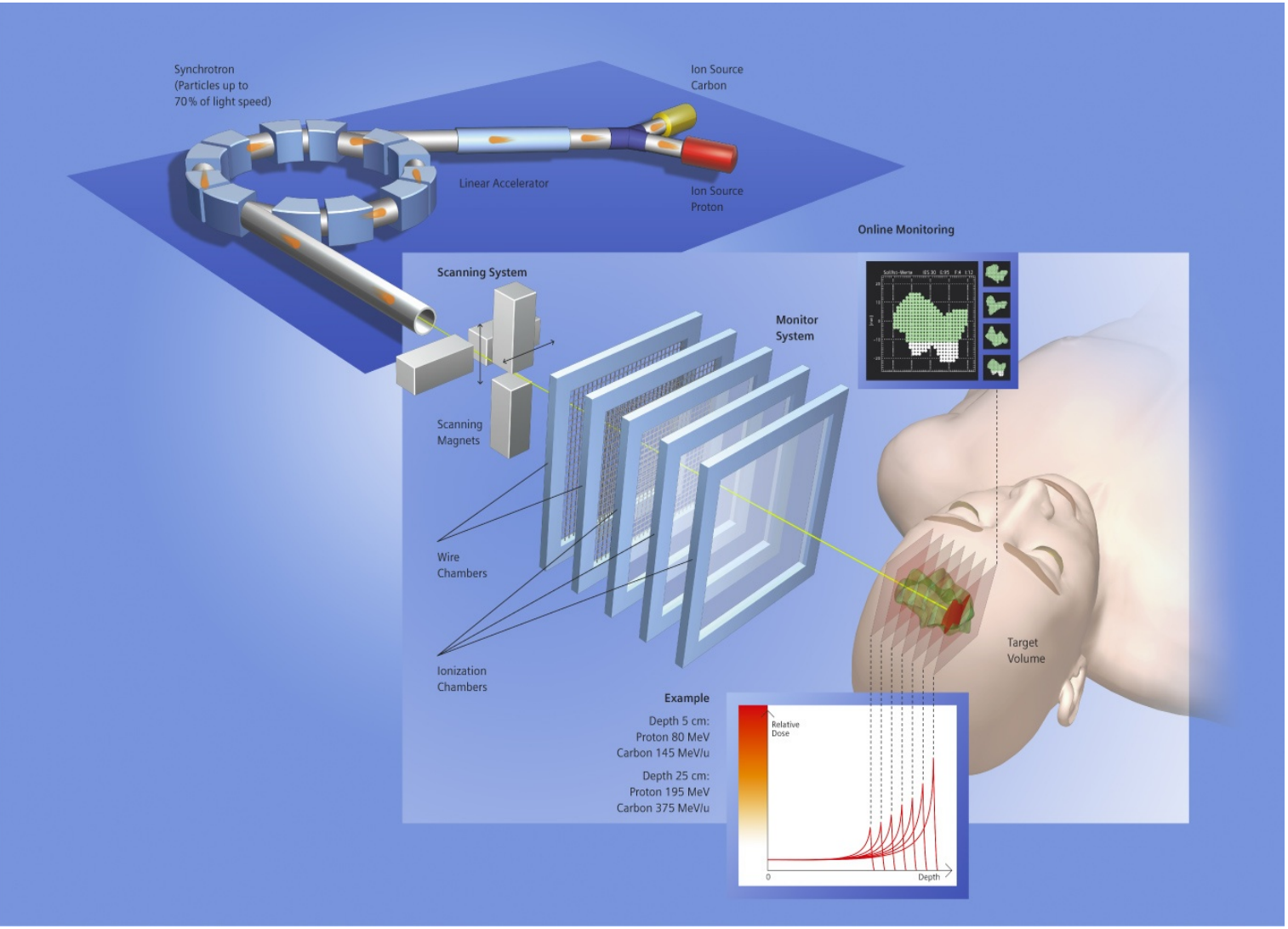
- **p, He, C, O:**
  Energy: 50-430 MeV
  1 Gantry + 2 H

- **ECR IS: 2**
- **216MHz RFQ+IH: 7MeV/n**
- **Synchrotron(~60m)**
  Multiturn Injection
  RF-KO extraction

- **Variable Energy Operation**
- **Variable FT (1-10s)**
- **Variable Intensity**
- **Variable Beam Size**

Based on GSI treatments of 400pts since’97,
HIT has been constructed.

Raster Scanning Developed by GSI



- **Variable Energy Operation**
- **Variable Intensity**
- **Variable Beam Size**

Revised HIT Accelerator Design by Siemens

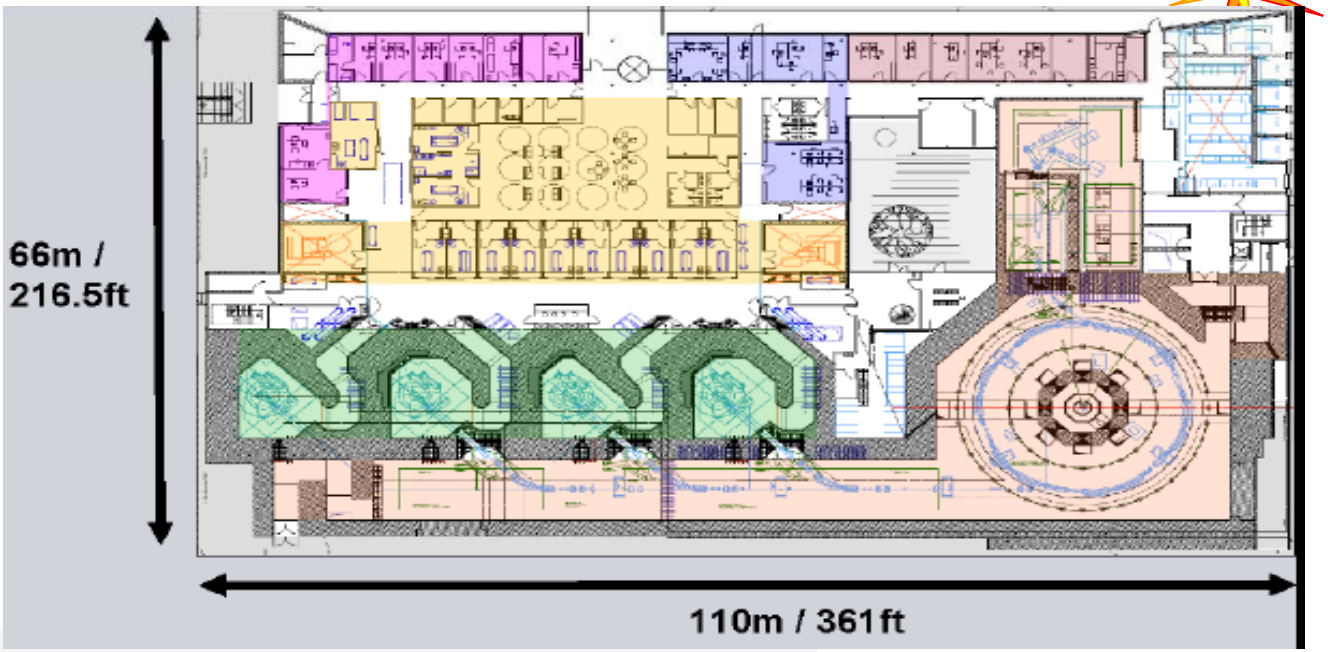
The HIT accelerator design has been modified
To improve technical capabilities
To reduce const ruction and operating costs
Examples

1) 12dipoles（each8tons）instead of 6（each25tons）
   cost reduction, easier installation and handling
2) Smaller and lighter quadrupoles
   cost reduction, less power consumption
3) Optimized injection and extraction system
   Higher intensity, Shorter treatment times
4) 3sources
   more flexibility, Other ions species

Courtesy of HIT and Danfysik

New Projects by Siemens

Marburg



Kiel

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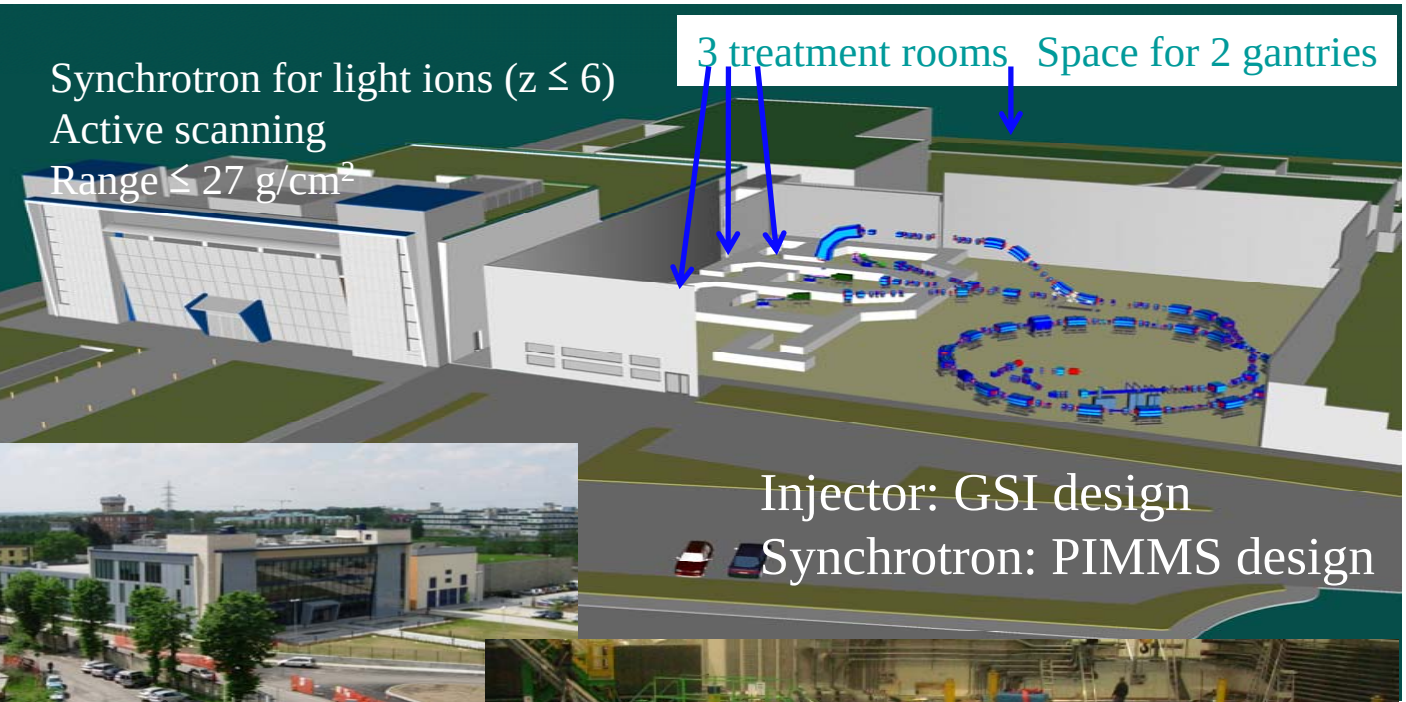
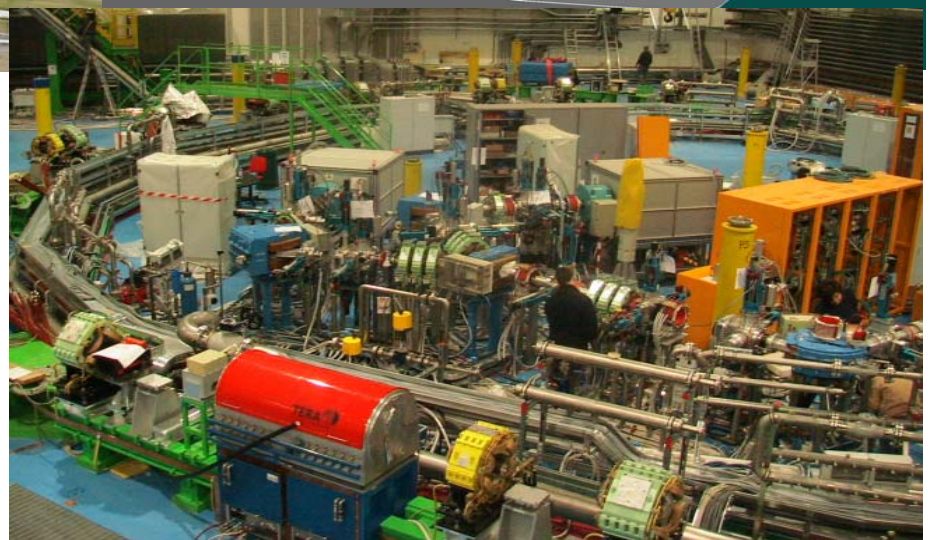
CNAO Facility





- **p, He, C, O:**
  Energy: p 7-250 MeV
  C 7-400 MeV/n
  2 H + H&V

- **ECR IS: 2**
- **216MHz RFQ+IH: 7MeV/n**
- **Synchrotron(~78m)**
  Multiturn Injection
  Acc Driven extraction
  RF-KO extraction

- **Active scan**

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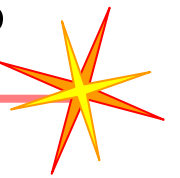
Contents



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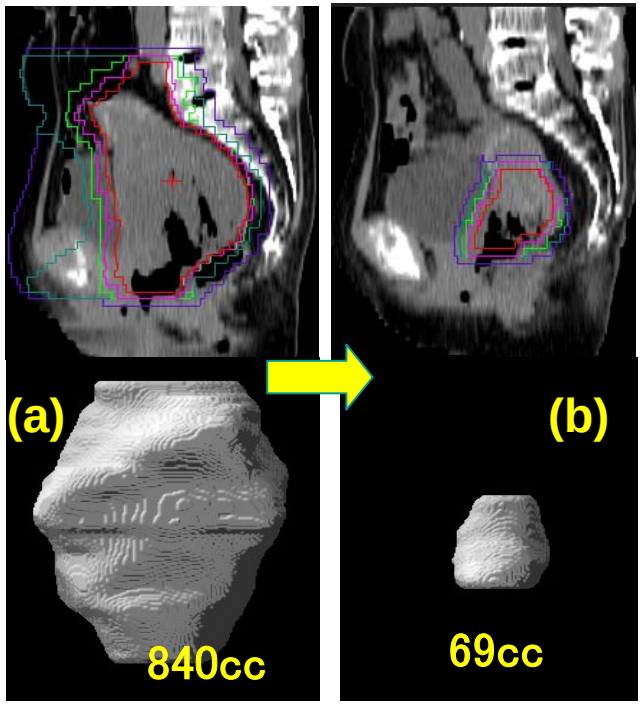
New Project

Motivation of New Treatment Facility



Large changing target shape and size

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

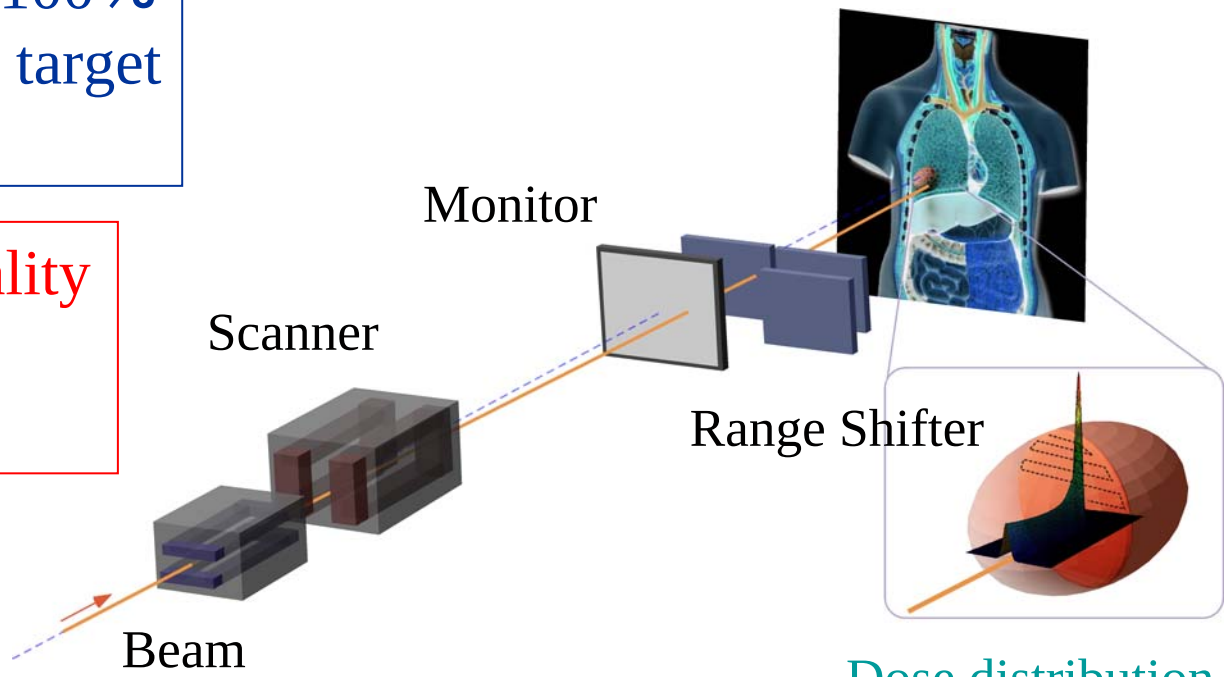
⇒ Adaptive Cancer Treatment

3D Scanning Method

Adaptive Therapy by 3D Scanning

1) Beam utilization efficiency ~100%
2) Irradiation on irregular shape target
3) No bolus & collimator

1) Depend directly on beam quality
2) Not easy dose management
3) Sensitive to organ motion



Dose distribution of pencil beam

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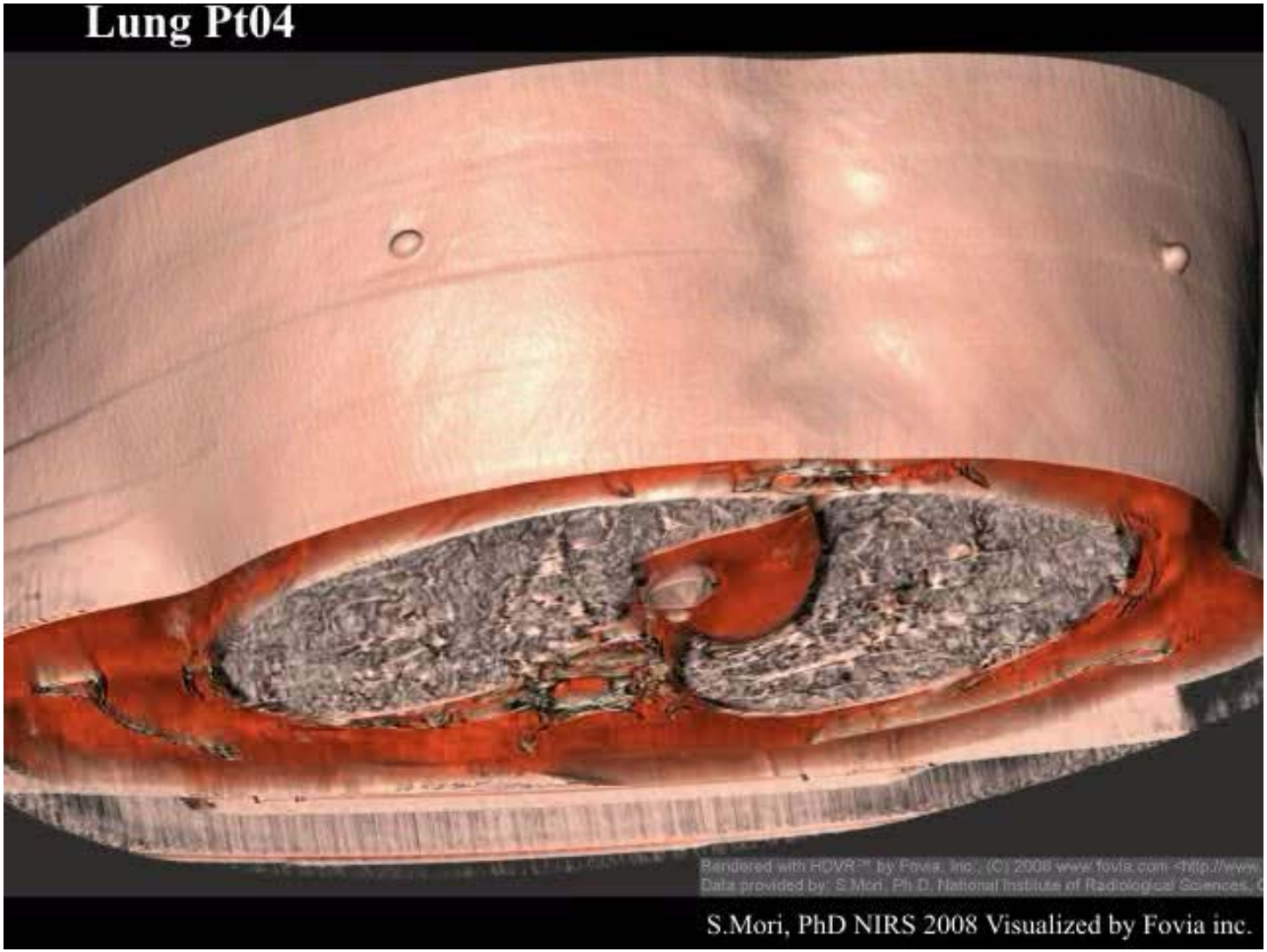
3D organ motion with breathing



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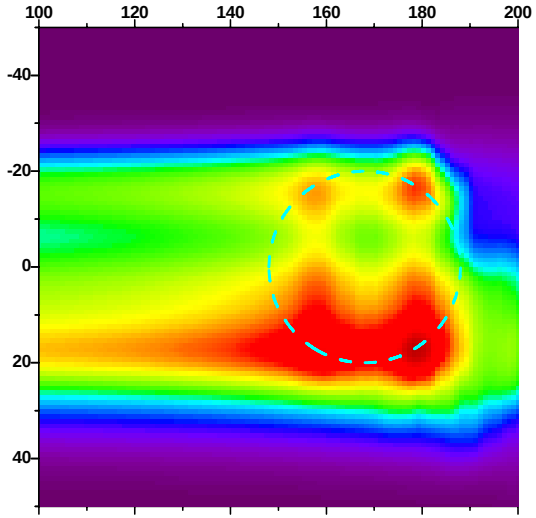
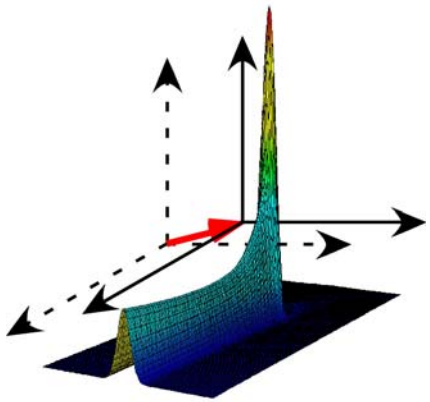
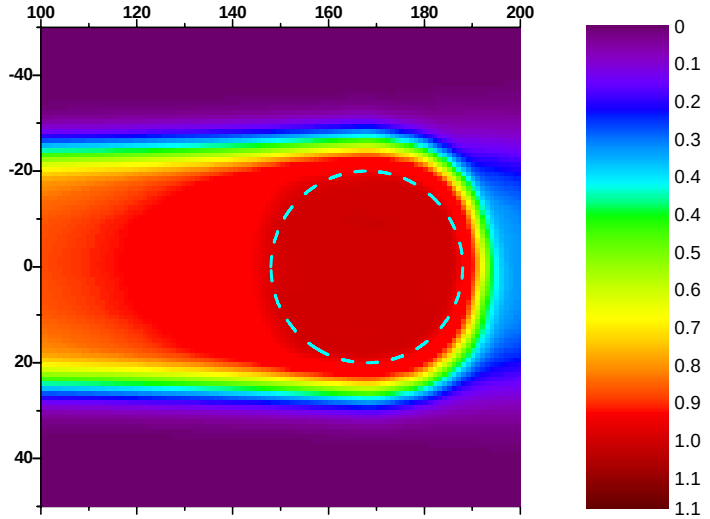
New Project

Moving Tumor Irradiation

Simulation of moving tumor irradiation

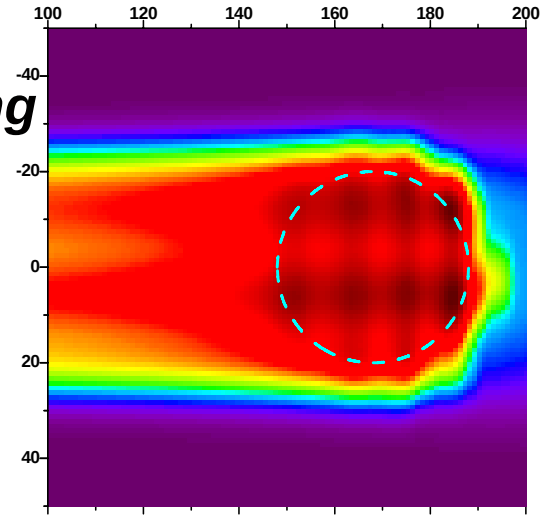






Non-gating

Gating



Gating with rescanning (8 times)

Example:
Φ40mm
spherical target

$$s(t) = 1.7 - 31.3 \cdot \cos^4\left(\pi t / 3{,}2 s - \phi\right)$$

Motion : 7mm in gate

In order to avoid hot/cold spot due to target motion, we decided to employ "*gating method*" with rescanning.

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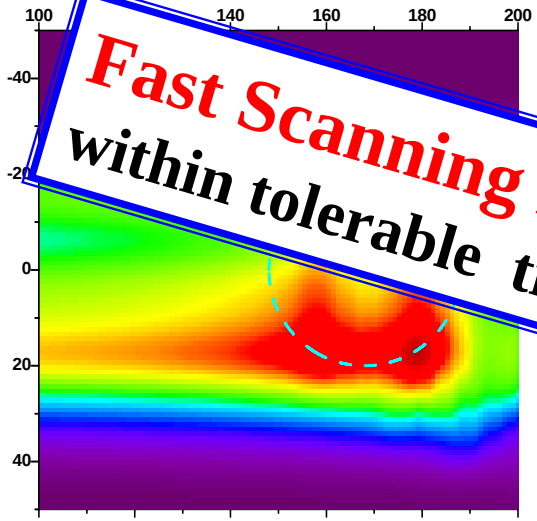
New Project

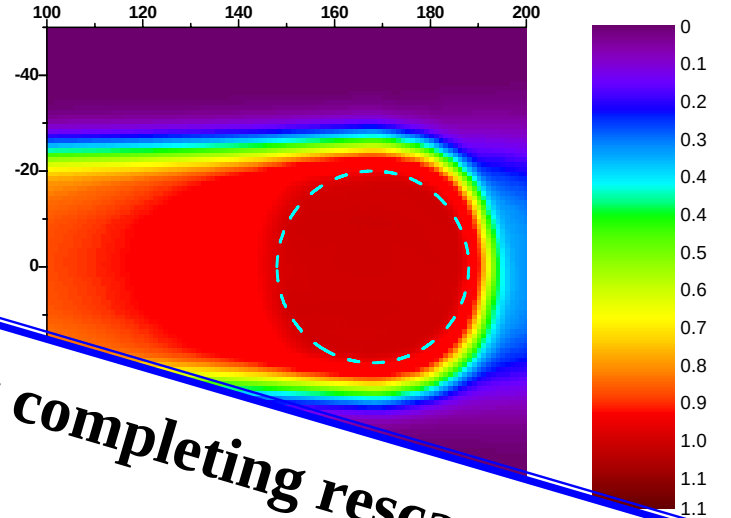
Moving Tumor Irradiation

Simulation of moving tumor irradiation

Fast Scanning is the key technology for completing rescanning within tolerable time.

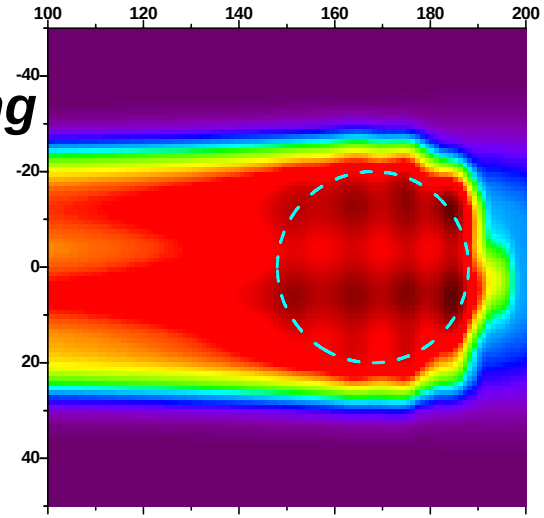


Non-gating



With

Gating



Example:
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Motion : 7mm in gate

In order to avoid hot/cold spot due to target motion, we decided to employ "*gating method*" with rescanning.

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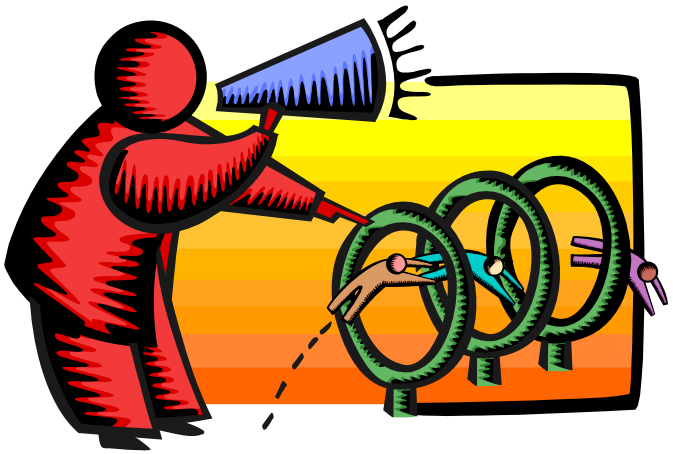
New Project

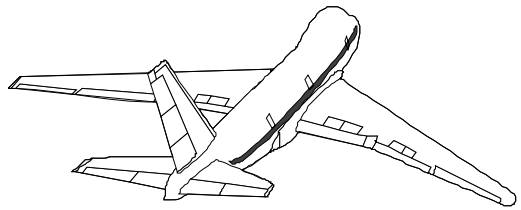
Fast scanning for moving target

In order to realize the rescanning with gating within acceptable irradiation time, we have studied following strategy.

1. Treatment planning for fast scanning ⇒ ×5
2. Modification of acc. operation ⇒ ×2
3. Fast scanning magnet ⇒ ×10



100-times speed up of irradiation time



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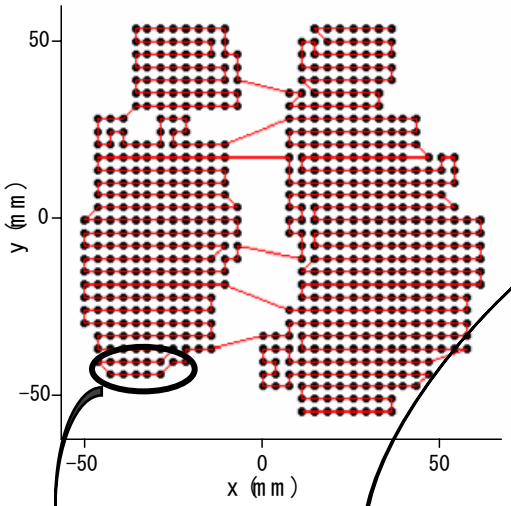
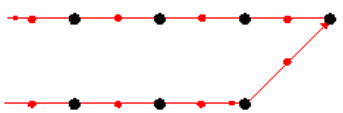
New Project

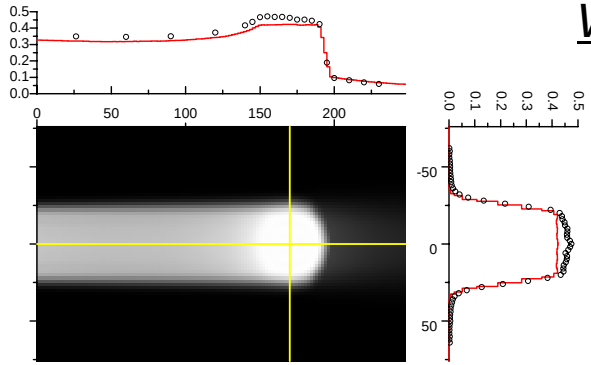
(1) Planning for fast scanning

Optimization including the contribution of extra dose in raster scanning





Extra dose in raster scanning (EDR) : U_i



Without U_i

$U_i \propto$ Beam intensity

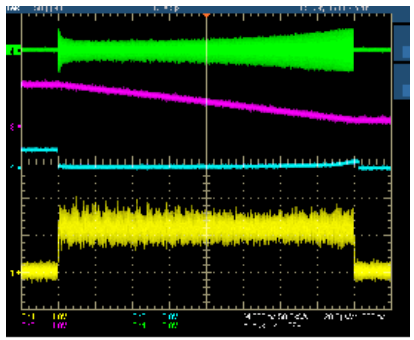
Fast scanning with beam of high intensity

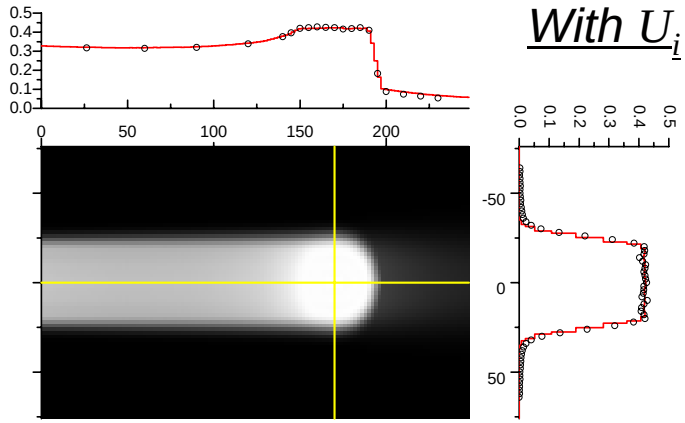
EDR cause dose distortion

Cost function : $f(w)$

$$f(w)=\sum_{i\in \mathrm{T}}\left(Q_{\mathrm{P}}^{\mathrm{o}}\left[D_{biol,i}(w)+U_i-D_{\mathrm{P}}^{\max}\right]_+^2+Q_{\mathrm{P}}^{\mathrm{u}}\left[D_{\mathrm{P}}^{\min}+U_i-D_{biol,i}(w)\right]_+^2\right)+\sum_{i\in \mathrm{O}}Q_{\mathrm{O}}\left[D_{biol,i}(w)+U_i-D_{\mathrm{O}}^{\max}\right]_+^2$$

Predict EDR

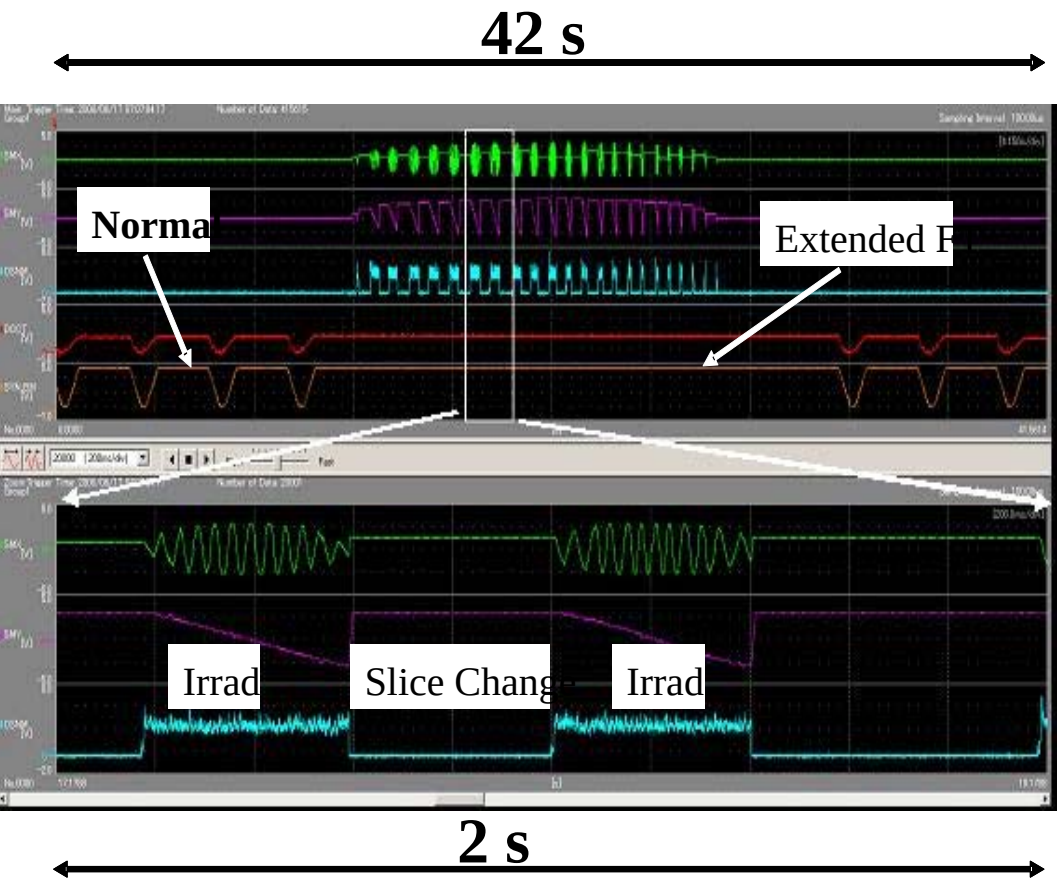




With U_i

New Project

(2) Extended FT in Synchrotron



Since 2×10^{10} c-ions is enough high to complete single-fraction, we have employed the extended FT to save the dead time of synchrotron operation.

1. Treatment planning for fast scanning ⇒ ×5
2. Modification of acc. operation ⇒ ×2
3. ~~Fast scanning magnet ⇒ ×10~~

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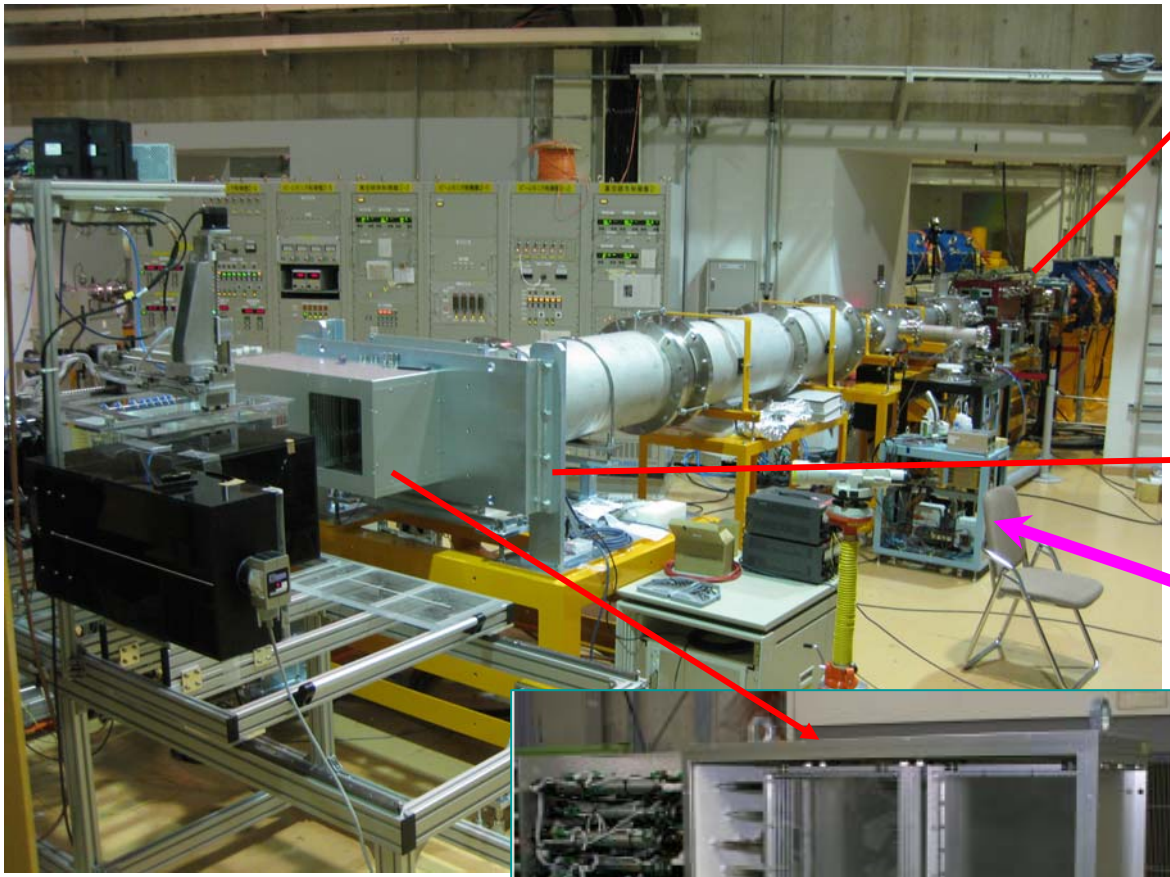
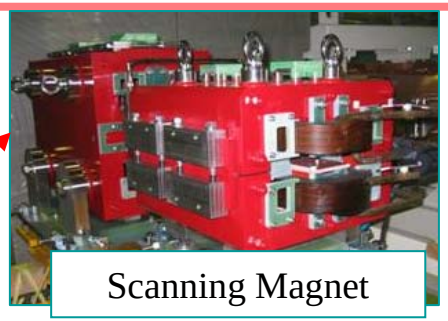
New Project

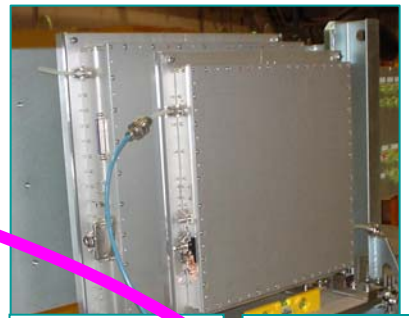
(3) Fast Scanning Magnet

100mm/ms in H
50mm/ms in V



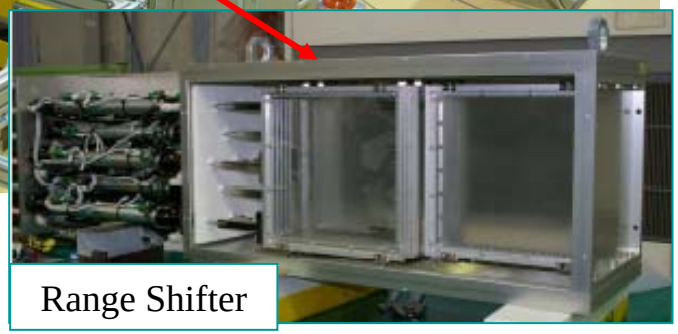


Scanning Magnet

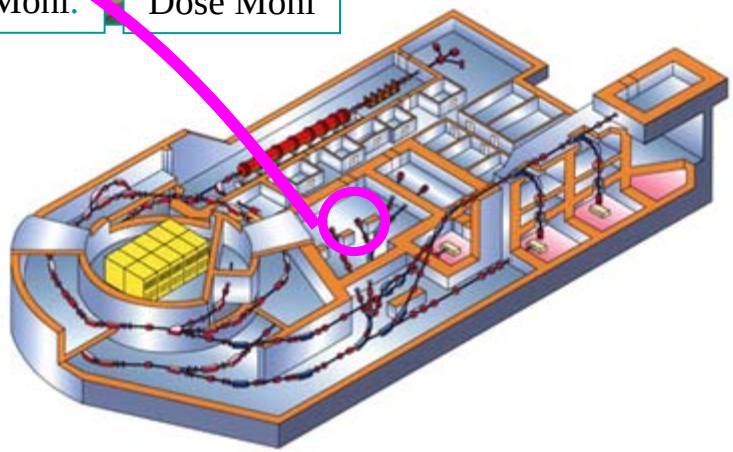


Pos. Moni.

Dose Moni



Range Shifter



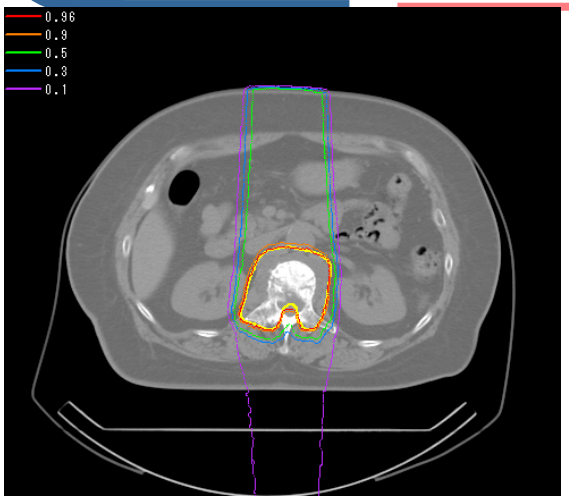
Since 29 December 2008

NIRS

HIMAC

New Project

Fast 3D-Scanning Experiment



(1)+(2)

Total time: 76 s

Scanning time: 64 s

Range-shifter time: 12 s

(1)+(2)+(3)

Total time: 18.5 s

Scanning time: 6. 5 s

Range-shifter time: 12 s

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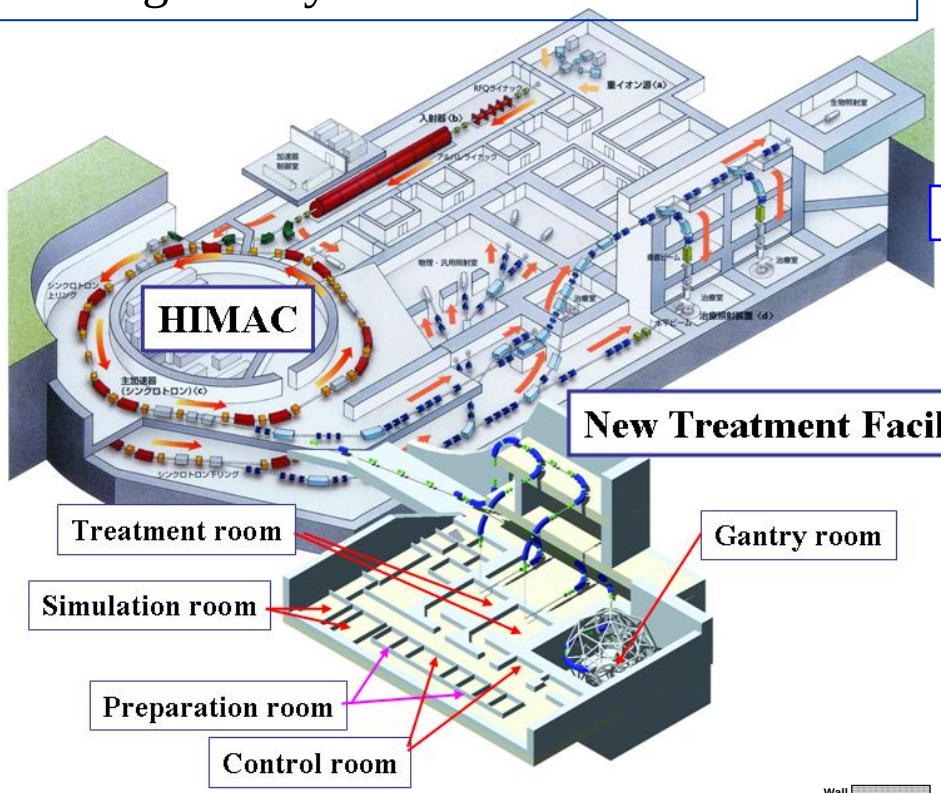
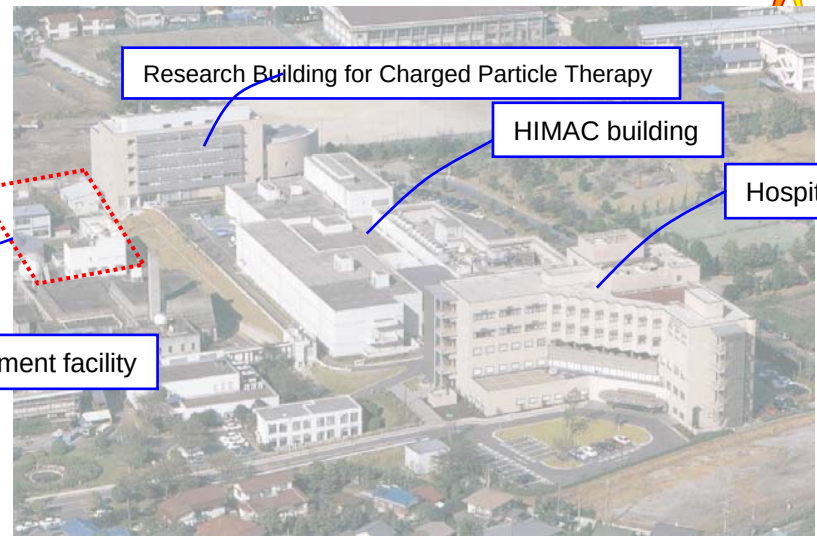
New Project

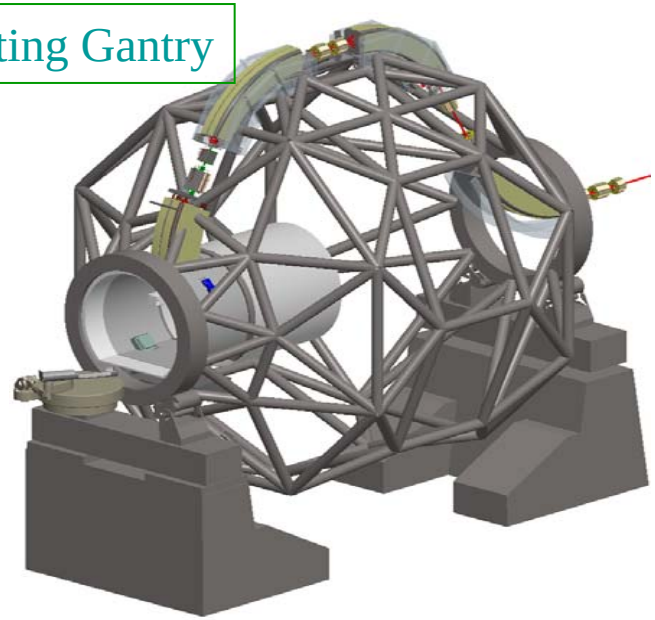
New Treatment Facility (1)

○3D Scanning with Gating (H&V): 2 rooms
○Rotating Gantry : 1 room

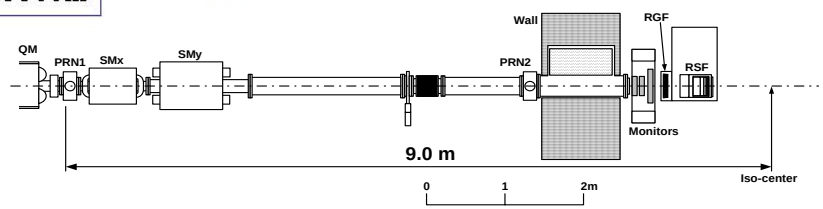




Rotating Gantry



3D Scanning



New Treatment Facility (2)

Ground-Breaking Ceremony

Construction

NIRS

HIMAC

New Project

New Treatment Facility (3)

New facility building

The construction of the new treatment facility will be completed at March 2010.

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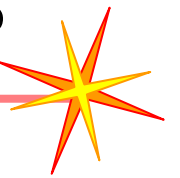
Contents



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Summary

1) In Asia
   - HIMAC, Hyogo and IMP facilities have been well going on hadrontherapy
   - Saga and Kanagawa prefectures just approved the facility construction.
   - China has several plans of the hadrontherapy facility
   - Taiwa also is preparing

2) In Europe
   - HIT facility has completed the full beam commissioning and will start the treatment of 1st patient soon.
   - CNAO facility has been being constructed, and the beam commissioning of the injector has been being carried out.
   - Siemens has constructed Marburg and Kiel facilities and made a contract with Shanghai project
   - Lyon and Med-Austron projects will start the construction
   - ARCHADE and INF projects have designed superconducting cyclotron.

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Heavy Io Therapy in the World

- Carbon
- Carbon (under construction)
- Carbon (Approved planning)
- Carbon (Shutdown)

XXX : has an official collaboration with NIRS