NIRS accelerator
present and future activities

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1. Introduction

2. Development of HIMAC Accelerator

3. New Treatment-Facility Project

4. Summary
HIMAC Tour

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

Introduction
Irradiation system

Ridge Filter

Scattering material

Dose monitor

Controller

Wobbling Magnet

Multi Leaf Collimator

Range Shifter

Cancer Tumor

Irradiation area

Bolus
As a result, about 10000 irradiation per 180 days in one year were available.
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R&D for Upgrade of HIMAC Accelerator

1. For increasing irradiation accuracy
   - Gated Irradiation with Patient’s Breathing: RF-KO Slow Extraction
   - Improvement of time structure of extracted beam (Reduction of Spill Ripple)
   - Intensity Modulation
     - Delivering high duty beam

2. For increasing efficiency of treatment and study
   - TSA of Injector
   - Automatic beam-axis alignment
   - Intensity Upgrade
     - Development of Ion Source
     - Development of Electron Cooler

3. Development of key technologies of medical accelerator
   - Step-wise variable energy for Injector
   - Development of non-destructive monitors
   - Development of APF-IH Linac
   - Development of Compact ECR Ion Source  ⇒ Compact Carbon-Therapy Machine
   - Development of Compact Un-tuned RF Cavity
1) **Optical Matching between Injection Line and Ring**

2) COD Correction at Injection level

3) Optimization of Bump-orbit for Multiturn Injection

4) **Resonance Correction**

5) Multi-harmonics Operation of Acceleration

More than $2 \times 10^{10}$ carbon-ions can be stored, accelerated and extracted from synchrotron.
We carried out beam-optics matching between injection line and ring in the vertical direction, by using SBPM.
Intensity Upgrade: Resonance Correction

Intensity should be increasing by suppressing space charge effect, which is effective for the compact synchrotron.

Laslett tune shift

\[ \Delta Q_y = - \frac{N R r_p Z^2}{\pi b (a + b) \beta^2 \gamma^3 Q_y B_f} \]

Under several \(10^{10}\) c-ions, the vertical tune is spread across a few resonance lines, which decreases beam intensity and lifetime!!
Intensity Upgrade: Resonance Correction

Resonance correction by using additional sextupoles

Before correction

Intensity (10^10 ppp)

After correction

Intensity (10^10 ppp)

Vertical tune

Qx + 2Qy = 10

Longer lifetime is realized!!
Respiratory gated irradiation


Accelerator

- Interlock system
- Gated beam extraction system (RF knockout method)

Ion beam

Treatment control

- Watch & record system
- Gate signal generator
- Beam monitor
- Planning simulation

Positioning area

- Reference Image
- Compare
- Positioning Image
- Positioning system using x-ray TV images

Irradiation room

- PSD
- Respiration waveform
- X-ray TV
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”.
Original RF-KO Extraction

Single RF-KO Method

No problem for broad beam method because of much different ripple frequency

Response time $< 1 \text{ ms}!!$

Time structure of extracted beam

Advanced RF-KO Extraction

Double RF-KO Method for Spot Scanning

Advanced RF-KO Method

(A) Phase=0deg.

FM signal

Ripple < ±10%

(B) Phase=180deg.

(A)+(B)

Time Scale: 200 ms/div

Time Scale: 500 µs/div

K. Noda et al., NIM-A492 (2002) 253

Development

The spill ripple is considerably reduced by summing up two rf-signals that are out of phase of 180 deg in each other.
Assuming radial distribution of particle diffused by RF-KO while keeping Reyleigh distribution, the AM function can be optimized so as to keep the extracted intensity constant. A deviation of the optimized AM function from the true one is corrected by the feedback. The right figure shows an experimental result. As a result, we can obtain the constant intensity in the spill.
Spill Controller

Function Generators

Voltage Controlled Amplifier RF Switch

RF Amp.

Kicker Electrode

Circulating beam

AM Function controller

Current Amp $10^{-6}$A/V, 100kHz

Spill

Beam gate

Intensity

S. Sato et al., NIM-A574 (2007) 226
T. Furukawa et al., NIM-B240 (2005) 32
R&D for Compact Facility

- Beam Study
- Compact RF-cavity
- Compact Injector RFQ + APF-IH
- Development Irrad. Tech.
- High-Precision MLC

Installation of local injector

Prototype injector for the Standard type facility

- It has been developed and tested in March 2006.
- It was installed for the local injector into HIMAC in FY2009.
- In April 2011, 4MeV/n-C beam from this injector was successfully accelerated and extracted from synchrotron.

Y. Iwata et al., NIM-A572 (2007) 1007
M. Muramatsu et al., RSI 76 (2007) 113304
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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
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

With respiratory-gating has been proposed for treatments of both moving and fixed targets. 3D-rescanning with respiratory-gating is a key technology for rescanning within tolerable irradiation time.
Fast scanning technique was proposed in order to realize the rescanning with gating within acceptable irradiation time.

(A) Treatment planning for fast scanning ⇒ ×5
(B) Modification of acc. operation ⇒ ×2
(C) Fast scanning magnet ⇒ ×10

100-100 times speed up of irradiation time!!

Test Port for Fast 3D Scanning

- Scanning Magnet
- Range Shifter
- Pos. Moni.
- Dose Moni

Since 29 December 2008

T. Furukawa et al., Med Phys. 37 5672-5682
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
Toward Energy Scan

Variable-Energy Operation

Operation Pattern

430 MeV/u

80 MeV/u

Flattop

Accel

Decel

Inj
11-steps Energy Operation

Tune: \((Q_h, Q_v) = (3.68, 3.11)\)
5. New Project

Toward Energy Scan

Energy Range: 430 $\Rightarrow$ 80 MeV/u, corresponding Range: 309 $\Rightarrow$ 17 mm in WEL
$\Delta R$ = 2mm $\Rightarrow$ 147 Energies
Interpolating 11-step pattern, 147-step pattern is obtained.
As an first stage, 47-step pattern was successfully tested.
Experiment of NIRS system ~ Biol.

Biological Dose Planning

Depth-Survival Curve: $1 \times 2 \times 4$

Physical Dose Planned/Measured
Experiment of moving target

Gating + fast rescanning test

Dose deviation

- W/o rescanning
- 8 times rescanning

<±2.5%!

T. Furukawa et al., Med Phys. 37 4874-4879
New Treatment Facility: Specification

1. Ion species: $^{12}\text{C}$, $^{16}\text{O}$ ($^{11}\text{C}$, $^{15}\text{O}$)
2. Irradiation method: PCR with Gating
3. Range: > 25cm in water
4. Maximum irradiation area: 22cm square for Fixed Port, 15cm square for Gantry
5. Delivered Intensity: $10^7$ - $10^9$ pps (C ions)
6. Treatment rooms: 2 (H&V), Rotating gantry
New Treatment Facility

- 3D Scanning with Gating (H&V): 2 rooms
- Rotating Gantry: 1 room
New Treatment Research Facility

Mar. 2010, new treatment building construction was completed.
**Commissioning of New Facility**

Design and R&D work were carried out. Room E was equipped with scanning systems.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
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<tbody>
<tr>
<td>3D scanning irradiation</td>
<td></td>
</tr>
<tr>
<td>Max field size</td>
<td>220 mm</td>
</tr>
<tr>
<td>Max SOBP</td>
<td>150 mm</td>
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<tr>
<td>Max energy</td>
<td>430 MeV/u</td>
</tr>
<tr>
<td>Moving target</td>
<td>OK</td>
</tr>
<tr>
<td>beam size</td>
<td>3~6 mm (1σ)</td>
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<tr>
<td>Ene. change</td>
<td>RSF</td>
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</table>
Image View of Treatment

Specifications

Long. : ±1m
Vertical : ±25cm
Lateral : ±30cm
Rotation : ±180deg
Rolling : ±25deg
Pithing : ±5deg
Iso-center pos. accuracy: ±0.5mm
Fast 3D scanning treatment was successfully carried out since May 17, 2011.

The First Treatment

Just before treatment

Just after treatment completed
The First Treatment

Verification by Auto-activation just after treatment
Summary

1. The HIMAC accelerator has been improved in order to improve the original HIMAC treatment.

2. Based on the development of the HIMAC, we carried out design study and R&D works for standard type C-RT facility. As a result, a pilot facility of a standard one was constructed by Gunma University.

3. NIRS has also constructed the new treatment research facility, based on the development of fast 3D scanning. Since May 17 2011, the first patient has been successfully treated. We also challenge to SC R-Gantry with scanning.

Thank you for your attention