Overview of NIRS Accelerator Activity

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Workshop on Hadron Beam Therapy April. 27 ’09, Erice, Italy
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1. Introduction

2. HIMAC Tour

3. Development of Technologies at HIMAC

4. Compact Carbon-Therapy Facility

5. New Treatment-Facility Project
1. Introduction

HIMAC
Heavy Ion Medical Accelerator in Chiba

National Institute of Radiological Sciences

Tokyo
Narita international airport
Chiba Prefecture
HIMAC facility

- Ion species: High LET (100keV/μm) charged particles
- Range: 30cm in soft tissue
- Maximum irradiation area: 22cm Φ
- Dose rate: 5Gy/min
- Beam direction: horizontal, vertical

→ He, C, Ne, Si, Ar
→ 800MeV/u (Si)

Size: 7200 m² (60 x 120 m)
Cost: 320 M US$ (32,600 M JPY)
135 M$ for building
165 M$ for machine

HIMAC (Heavy Ion Medical Accelerator in Chiba)
Progress of treatment number

1. Introduction

Total: 4504 (Jun 1994 – Feb 2009)

Treatment Period: 43 wks
1st Term (Apr〜Aug): 18.5wks
2nd Term (Sept〜Feb): 24.5wks
Treatment: 4 days per week

advanced medicine.
clinical study
The histogram shows the number of tumors treated from June ‘94 to Feb. ’09. Total number is 4,502, and treatments of more than 30% are utilized with irradiation gated with respiration.
### 1. Introduction

**Typical operation**

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**Treatments:**
- Daytime on weekday

**Experiment (Phys.&Bio):**
- Night and daytime on weekend.

**Machine maintenance:**
- Daytime on Monday.

**Operation time:** 8300h/2ring

**Breakdown ratio:** 0.6% @’04
1. Introduction

Result of clinical trials

Lung

T2N0M0  stage IB
28GyE (1 fraction)

before 1 year after

Treatment planning
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HIMAC tour

- Linac cascade
- Synchrotron
- Ion source
- Treatment room
- Irradiation system
- Transport line
2. HIMAC Tour

Ion source

10GHz-ECR source

18GHz-ECR source

PIG source
There are a cascade of linear accelerators consists of RFQ-linac and Alvarez linac. Both are operated with 100MHz RF power. RFQ first accelerates up to 800keV/n, then the Alvarez linac accelerates up to 6MeV/u. They have ability to accelerate ions with charge-mass ratio of 1/7.
The pre-accelerated ions are injected into synchrotrons. There are two synchrotron rings on the lower level and upper level. Circumference is about 130m. Their optical design is normal FODO. The synchrotron can accelerates ions with q/m=1/2 up to 800 MeV/n at the maximum.
Beam transport line

- Vertical beam line
- Horizontal beam line
2. HIMAC Tour

Irradiation system

- Ridge Filter
- Wobbling Magnet
- Multi Leaf Collimator
- Bolus
- Controller
- Dose monitor
- Scattering material
- Cancer Tumor
- Irradiation area
- Range Shifter
Treatment room

Horizontal port

Vertical port
Positioning patient

A patient must be positioned precisely before the treatment by comparing x-ray radiography image to digitally reconstructed radiography image (DRR).

Almost cases, it takes about 15 minutes.

On the other hand, irradiation takes about 1~2 minutes.
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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
Intensity Upgrade

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

Laslett tune shift

\[ \Delta Q_y = -\frac{N R r_p z^2}{\pi b (a + b) \beta^2 \gamma^3 Q_y B_f} \frac{1}{A} \]

Under several $10^{10}$ c-ions, the vertical tune is spread across a few resonance lines, which decreases beam intensity and lifetime!!
Transverse Gymnastics
- Resonance Correction -

Resonance correction by using additional sextupoles

Before correction

After correction

Qx+2Qy=10

Longer lifetime is realized!!
We can obtain beam intensity more than $2 \times 10^{10}$ carbon ions in one cycle.

To suppress space-charge effect, we can obtain beam intensity more than $2 \times 10^{10}$ carbon ions in one cycle.
Respiration gated irradiation

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

**Accelerator**
- Interlock system
- Gated beam extraction system (RF knockout method)
- Ion beam

**Irradiation room**
- X-ray TV
- PSD
- Respiration waveform

**Treatment control**
- Watch & record system
- Gate signal generator
- Beam monitor

**Positioning area**
- Reference Image
- Compare
- Positioning Image
- Planning simulation
- Positioning system using x-ray TV images

**Positioning system using x-ray TV images**

3. R&D
RF-knockout extraction (1)

Diffusion by *transverse RF-field*

- Constant separatrix
- Fast response of beam on/off
- Easy operation

Frequency modulation (FM)

Amplitude modulation (AM)
We have developed the RF-KO slow extraction method, since 1994. As a result, we can almost suppress the spill ripple by the dual FM and Separate function methods.
Global Spill Control for RF-KO

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.
Global Spill Control and Intensity Modulation

3. R&D

- NIRS
- HIMAC

Circulating beam

Function Generators

Voltage Controlled Amplifier
RF Switch

Kicker Electrode

RF Amp.

AM Function controller

VCA

V_{AM}

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

Spill

Beam gate

Intensity

Ionization Chamber

Scanning Magnets

Range Shifter

Extracted Beam

Scanning Irradiation System

Intensity Modulation controller
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Specification

1. Ion species: high LET (100keV/μm) charged particle - Carbon
2. Range: Max. 25cm in water
3. Maximum irradiation area: 15cm square
4. Dose rate: 5Gy/min $\rightarrow 1.2 \times 10^9$ pps (C ions)
5. Irradiation direction: horizontal, vertical
6. Treatment rooms: 3 (H&V, H, V)
7. Irradiation technique: gating & layer stacking irradiation

1. Accelerator systems and Irradiation systems:
   High reliability, stability, reproducibility, easy operation, easy maintenance and absolute safety
2. The other requirements:
   - Precise beam delivering
   - Easy beam tuning in a short time
   - Accurate dose measurement and control
   - Fail-safe system
Design and R&D for Compact Facility

Beam Study
Compact RF-cavity
Compact Injector RFQ + APF-IH
Development Irrad. Tech.
High-Precision MLC
Gunma University Heavy-Ion Medical Center

- Treatment Room
- Synchrotron
- 10Ghz-ECR
- Injector Linac APF-IH

4. Compact Facility
1. Introduction

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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
Present HIMAC Method

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

Broad Beam Method with Wobbler and Scatterer

Ridge Filter
Collimator
Bolus
Target
'Extra-Dose'

Width of SOBP

5. New Project
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
3D organ motion with breathing
Simulation of moving tumor irradiation

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

Moving Tumor Irradiation

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

Example:

- **Non-gating**
  - $\Phi 40\text{mm}$ spherical target
  - $s(t) = 1.7 - 31.3 \cdot \cos^4\left(\frac{\pi t}{3.2s - \phi}\right)$
  - Motion: 7mm in gate

- **Gating**
  
In order to avoid hot/cold spot due to target motion, we decided to employ “gating method” with rescanning.
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
(1) Planning for fast scanning

Optimization including the contribution of extra dose in raster scanning

Without $U_i$

$U_i \propto$ Beam intensity
Fast scanning with beam of high intensity
EDR cause dose distortion

Cost function: $f(w)$

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

Predict EDR

Extra dose in raster scanning (EDR): $U_i$
(2) Extended FT in Synchrotron

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

Since $2 \times 10^{10}$ c-ions is enough high to complete single-fraction, we have employed the extended FT to save the dead time of synchrotron operation.
(3) Fast Scanning Magnet

Since 29 December 2008

100mm/ms in H
50mm/ms in V
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 Variable-Energy Operation Pattern

11-steps Energy Operation

Flattop

Accel

Decel

Inj

Operation Pattern

430 MeV

140 MeV

5. New Project
11-steps Energy Operation

$C^6$, 290 MeV/n

Operation Pattern (SX)

Stored Beam

Beam Spill

11-steps Beam Extraction
Phase-Controlled Raster Scanning

Average position of target in each slice is to be “Zero”

⇒ one slice with rescanning in one gate

This method needs intensity modulation.
PCR method ~ experiment

Fabrication of moving phantom

- XY moving stage
- Wedge for range variation
- It is possible to operate arbitrary waveform.
- Screen+CCD system is set on the stage.

**Specification**

X and Y direction : ±20mm
Range direction    : ±17mm (WEL)
Max. speed: 40 mm/s
In this stage, we only tested 2D uniform scanning without gating. Next step is 3D scanning test including non-periodic irregular motion!
New Treatment Facility: Specification

1. Ion species: $^{12}$C, $^{16}$O ($^{11}$C, $^{15}$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
5. New Project

New Treatment Facility (1)

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

Ground-Breaking Ceremony

Construction

6 Feb, ‘09

19 Feb, ‘09
The construction of the new treatment facility will be completed at March 2010.

Thanks for your attention!!