Extraction Methods

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National Institute of Radiological Sciences
Lecture in Accelerator for Medical Applications,
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1. Introduction
2. Requirements from Beam Delivery
3. Resonant Slow Extraction
4. Development of RF-KO
5. Summary
HIMAC
Heavy Ion Medical Accelerator in Chiba

• Ion species: High LET (100keV/μm) 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

Wobbling Method for Lateral Field

- The beam profile is originally sharp.
- In order to enlarge the beam size, a scatterer is inserted.
- A pair of orthogonal magnets is used to form a uniform dose distribution in the lateral direction.
- A multi-leaf collimator tailors the beam so as to match with the cross-sectional shape of the tumor.
Ridge Filter Method for SOBP

- The beam energy is originally monochromatic.
- Ridge filter is inserted in order to expand the beam energy so as to match with tumor thickness.
- A range shifter is used as energy absorbers for the fine tuning of the range.
- Range compensator is set in order to adjust the endpoint to the curvature of tumor.

Respiratory Gated Irradiation

- Irradiation synchronized with a patient’s respiratory motion -

30-40% of treatment number requires the respiratory gated irradiation
Pencil-Beam 3D Scanning

- Beam utilization efficiency ~100%
- Irradiation on irregular shape target
- No bolus & collimator
- Sensitive beam error
- Longer irradiation time

Especially sensitive organ motion

Fast scanning for moving target

100-times speed up !!

Key Technology ⇒ Fast 3D Scanning within Torelable Time for moving target

A) TPS for Fast Scanning ⇒ x5
B) Extended Flattop Operation ⇒ x2
C) Fast Scanning Magnet ⇒ x10
HIMAC and New Facility

Room E & F with H/V scanning ports have treated more than 600 pts since 2011

Room G with rotating gantry is under development.

<table>
<thead>
<tr>
<th>Main specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion species</td>
</tr>
<tr>
<td>Irradiation method</td>
</tr>
<tr>
<td>Beam Energy</td>
</tr>
<tr>
<td>Maximum Range</td>
</tr>
<tr>
<td>Maximum Field</td>
</tr>
</tbody>
</table>

Treatment with 3D Scanning

- **Operation**
  - Daily QA (MU calibration, range check etc) ~ 15min/course
  - Treatment irradiation (except positioning) ~ 2min
  - 30 patients/day under 3hr operation of 2 rooms
HIMAC Treatment

- More than 10,000 pts treated since 94.
- ≈1000 pts/y, ≈100 shots/day @180 d/y
- Downtime rate < 0.5%

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.
Clinical Results (1)

Single Fraction Treatment with Respiratory Gated Irradiation

LCR > 95%, a 5 year OSR ~ 50-60% and a cause-specific SR ~ 70-80%. These results correspond to those obtained with surgery. The treatment period and the number of fractions have been successively reduced from 18 fractions over 6 weeks to single fraction in one day. It has been carried out since April 2003.

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

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

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

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

Clinical Results (2)

Treatment against Radio-Resistive tumor

Before treatment

After 8 Year

(52.8 GyE)
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Broad Beam Delivery

- wobbling method
- double-scatterer method
Accelerators for Medical Applications,
Vienna, June 1st, 2015

Pencil beam delivery (scanning)

- range-shifter scanning

- energy scanning

Requirements from Static Tumor Treatment

<table>
<thead>
<tr>
<th></th>
<th>Double Scatterer</th>
<th>Wobbler</th>
<th>3D Scanning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pos. Error</td>
<td>&lt;±0.5 mm @ 2nd Scatterer</td>
<td>&lt;±2.5 mm</td>
<td>&lt;±0.5 mm ( \Delta\sigma/\sigma &lt; 10% )</td>
</tr>
<tr>
<td>Spill Ripple</td>
<td>No effect</td>
<td>Avoid ripple with around wobbling freq.</td>
<td>Suppress ripple with kHz-order</td>
</tr>
<tr>
<td>Low dose-rate control</td>
<td>No</td>
<td>No</td>
<td>Necessary</td>
</tr>
<tr>
<td>Intensity Modulation</td>
<td>No</td>
<td>No</td>
<td>Necessary</td>
</tr>
<tr>
<td>Energy Scan</td>
<td>Fixed</td>
<td>Fixed</td>
<td>Full energy scan</td>
</tr>
</tbody>
</table>
### Requirements from Moving Tumor Treatment

<table>
<thead>
<tr>
<th></th>
<th>Double Scatterer</th>
<th>Wobbler</th>
<th>3D Scanning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam ON/OFF</td>
<td>&lt; 1 ms</td>
<td>&lt; 1 ms</td>
<td>&lt; ~ 0.1 ms @ spot scanning</td>
</tr>
<tr>
<td>Intensity Modulation</td>
<td>No</td>
<td>No</td>
<td>Necessary</td>
</tr>
<tr>
<td>Low dose-rate control</td>
<td>No</td>
<td>No</td>
<td>Necessary</td>
</tr>
<tr>
<td>Energy scan</td>
<td>Fixed energy</td>
<td>Fixed energy</td>
<td>Full energy scan (Hybrid scan)</td>
</tr>
</tbody>
</table>

### Requirement from Medical System

I. Precise and easy dose management
   ⇒ Slow extraction

II. Fast beam ON/OFF for respiratory gating irradiation

III. Time structure control for beam wobbling and 3D scanning method

IV. Beam control under variable energy operation for 3D scanning

V. Intensity control for 3D scanning with respiratory gating.

VI. Precise position control for double scattering and 3D scanning

VII. Precise beam-size control for 3D scanning

3D scanning has required higher performance of slow extraction compared with broad beam methods.
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Transverse Motion in Synchrotron
**Slow Extraction from Synchrotron**

Requirements from Radiotherapy
- Beam duration for a few hundreds micro-seconds to a few seconds
- Precise dose management

⇒ Slow Extraction

The HIMAC synchrotron has employed a slow extraction method combined the third-order resonant extraction and the beam heating through transverse RF electric field.

**Resonance of Betatron Oscillation - Integer Resonance**

\[ Q = p + q; \text{betatron tune} \]
\[ p; \text{positive integer}, \ |q| \ll 1 \]

\[ \Delta x' = Gx = GR \cos(2\pi Qn + \phi) \]
\[ \Delta R = \frac{G}{2} \sin[2\pi(2Q)n + 2\phi] \]

Driving term ⇒ Dipole component

Driving term ⇒ Quadrupole component
Resonance of Betatron Oscillation
- Half-Integer Resonance -

\[ Q = \frac{p}{2} + q, \text{ Betatron tune} \]
\[ p; \text{positive integer, } p \neq 2n \]
\[ |q| \ll 1/2 \]

Driving term  \( \Rightarrow \)  Quadrupole field

\[ \Delta X' = GX = GR \cos(2\pi Qn + \phi_i) \]
\[ \Delta R = \frac{G}{2} \sin(2\pi Qn + 2\phi_i) \]

Resonance of Betatron Oscillation
- Third-Integer Resonance -

\[ Q = \frac{p}{3} + q; \text{ betatron tune} \]
\[ p; \text{positive integer, } p \neq 3n \]
\[ |q| \ll 1/3 \]

Driving term  \( \Rightarrow \)  Sextupole field

\[ \Delta X' = SX' = SR \cos^2(2\pi Qn + \phi_i) \]
\[ \Delta R = \frac{SR}{4} \left[ \sin[2\pi(3Q)n + 3\phi_i] + \sin(2\pi Qn + \phi_i) \right] \]
Stable Oscillation in Parabolic Potential

Driving particles to unstable region, beam is slowly extracted from ring

Kobayashi Hamiltonian
(Y. Kobayashi, NIM, 83, 1970)

\[ H = \frac{p}{2} (X^2 + X'^2) + \frac{S}{4} (3X^2X'^2 - X'^4) \]

\[ Q = \frac{p}{3} + q, \epsilon = 6\pi q \]

\[ A = 48\sqrt{3}\pi^2 \frac{q^2}{S^2} \]
(1) The Q-driven method extracts the beam slowly by shrinking the separatix through approaching the tune to the resonance, which is controlled by changing the Q-field of the synchrotron. $q \Rightarrow 0$

(2) Owing to the chromaticity effect, the tune can be approached to the resonance while changing the momentum through beam acceleration or deceleration. $q = q_0 + \xi \Delta p / p \Rightarrow 0$

(3) Under the constant separatix, transverse heating can enlarge the amplitude of the circulating beam, and particles with larger amplitude than the separatix can be extracted from the synchrotron. As a transverse-heating method, the RF-KO method has been utilized.

**Performance**

<table>
<thead>
<tr>
<th></th>
<th>Q-Driven</th>
<th>Acc-Driven</th>
<th>RF-KO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast beam on/off</td>
<td>Several 100 ms</td>
<td>Several ms (?)</td>
<td>&lt;0.5 ms</td>
</tr>
<tr>
<td>Time Structure</td>
<td>Fine</td>
<td>OK by FB</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td>Global</td>
<td>OK by FB</td>
<td>OK by FB &amp; FF</td>
</tr>
<tr>
<td>Intensity Control</td>
<td>Not easy</td>
<td>Not easy</td>
<td>OK</td>
</tr>
<tr>
<td>Position Control</td>
<td>Complicate</td>
<td>Hardt condition</td>
<td>Easy</td>
</tr>
<tr>
<td>Profile Control</td>
<td>OK</td>
<td>OK</td>
<td>Easy</td>
</tr>
<tr>
<td>Variable Energy</td>
<td>Not easy</td>
<td>Not easy</td>
<td>Easy</td>
</tr>
</tbody>
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RF-KO Slow Extraction

Under the constant separatrix, transverse heating can enlarge the amplitude of the circulating beam, and particles with larger amplitude than the separatrix can be extracted from the synchrotron. As a transverse-heating method, the RF-KO method has been utilized.

\[
\frac{d^2X}{d\theta^2} + Q^2X = Q^3 \beta z g(x, \theta) + A \cdot \sin(q + \delta q + \phi)
\]

\[
Q = \frac{p}{3} + q, \quad |q| \ll 1/3
\]

RF-KO extraction

K. Noda et al., NIM-A 374, 1996

- Easy control
- Stable position & profile
- Easy and Fast beam ON/OFF

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RF-KO Slow Extraction with FM & AM

Amplitude dependence of the horizontal tune

Frequency modulation (FM)

\[ \frac{d^2X}{d\theta^2} + Q^2X = Q^2\beta^2g(X, \theta) + A \cdot \sin(qX + \phi) \]

Amplitude dependence of the tune

Global spill control

Amplitude modulation (AM)

RF-KO Slow Extraction with FM & AM

Extracted beam

Excitation pattern

Gate signal

Respiration signal

beam

Circulating beam

\[ f_k = f_{k0} + \Delta f_0 \]
RF-KO Slow Extraction System

Particles, driven to unstable region, jump into the gap of septum electrode.

Slow Extraction System
- Separatrix Eciter; Sextupole -

\[ S \cdot e^{jp(\theta - \theta_0)} = \sum S_j \cdot e^{jp(\theta - \theta_j)} \delta(\theta - \theta_j) \]
### Ⅱ. Fast Beam ON/OFF

Response time < 1 ms !!

- Time Scale: 50 ms/div
- Time Scale: 2 ms/div
- Time Scale: 2 ms/div

### Ⅲ. Time Structure Control

**Spill Ripple of Original RF-KO**

**Single RF-KO Method**

- Time Scale: 200 ms/div
- Time Scale: 2 ms/div

*No problem in beam-wobbling method, because the ripple frequency is much far from wobbling frequency*

*Such huge ripple brings huge non-uniformity in 3D scanning.*
### III. Time Structure Control
- **Dose Distribution and Spill Ripple**

- Dose management in each spot
- Assuming constant intensity while moving position
- When large spill ripple

When uniformity less than ±1%
⇒ Spill ripple magnitude < ±20%

#### Study on Spill Ripple in RF-KO Method

In order to improve the time structure of the extracted beam for the fast 3D scanning, the ripple source was studied.

1. Time Structure for one FM period
2. Dual FM method
3. Separate function Method
4. Robust RF-KO method against Q-field ripple
5. Global Spill-Structure Control
1. Time Structure for One FM Period

1.1. Chromaticity Dependence

Dependency of the spill width during FM period and of the ripple on the chromaticity.

The spill width and the ripple magnitude increase and decrease as a quadratic function of the chromaticity, respectively.
1.2. Dual Peaks for FM Period

Peak (a) is the beam extracted mainly due to the transverse RF field, while peak (b) mainly due to the synchrotron oscillation.

1.3. Steinbach Diagram for RF-KO

(a) The RF frequency matches tune in the extraction region.
(b) It matches that in the diffusion region.

$A_E$ and $A_D$ are the amplitude-growth rate in the extraction region and that in the diffusion region, respectively.
$M$ is the momentum-growth rate through the synchrotron oscillation.

The slope of the $L$ increases with increasing the chromaticity.
1.4. Spill-Structure Control by Chromaticity

Simulation Result:

With increasing the chromaticity, both peak (a) and (b) are widened. It is considered as follows:
Peak (A): the extraction region is increased with increasing the chromaticity.
Peak (B): The average distance from the particles in the extraction region to the boundary is to be long with increasing the extraction region. Further, the particles move obliquely toward the boundary due to amplitude beat through the RF-KO and due to momentum growth through the synchrotron oscillation. For a large chromaticity, thus, it takes the long time to reach to the boundary, compared with for a small chromaticity.

2. Dual FM Method (1)

- Chromaticity Control
- Spill-shape Control by narrow BW
- FM + FM with 180 deg
- Utilizing same AM to dual FM (B) Phase=180deg

![Dual FM Method Diagram]
2. Dual FM Method (2)

Ripple < ±30%

200 ms/div

500 μs/div

3. Separate Function Method (1)

- Extraction and Diffusion Regions -

(A) The RF-KO with the mono-frequency \( f_E \) is applied. The intensity of the extracted beam is measured as a function of the \( f_E \).

(B) The another RF-KO with the mono-frequency \( f_D \) is additionally applied. Curve (b) is obtained as follows: The intensity is also measured as a function of the \( f_D \), and is subtracted by those in the measurement (A).
3. Separate Function Method (2)

RF-KO with mono-frequency is added to Extraction Region

Increasing sweep velocity!!

3. Separate Function Method (3)

Ripple < ±20%

kHz-order ripple can be significantly suppressed.
4. Robust against Q-Field Ripple

4.1 Ripple Source

Q field ripple brings Spill ripple under $\Delta I/I < 2 \times 10^{-6}$

$X'$

Changing region due to Q-field ripple

$X$

Extracted Beam Current

Beam intensity [arb. unit]

Time [ms]

4.2. Proposed Method

Q-field ripple suppression
- Improvement of PS
- Feedback
- Feed Forward

Another method?

Stable region area

$A_0 = 4\sqrt{3}a^2 \frac{q_0^2}{S_f}$

$Q = \rho/3 + q_0$; SK field

$\Delta t = \pm 4\alpha_0 \frac{A_0}{q_0}$

Tune ripple due to Q-PS ripple

$q(t) = q_0 + a \sin(2\pi ft)$

Extracted beam current

$N(t) = n \left[ b - 4\alpha_0 A_0 \cos(2\pi ft) \right]$ q_0

Beam current ripple term

Beam ripple magnitude

$\propto \left| \alpha_0 \frac{A_0}{q_0} \right|$
4.3. Optimization (1)

Limit of this method?

- Turn separation & Septum electrode gap

To keep stable region

\[ A_0 = 4k_S \pi \frac{q_{0}}{S_k} \]

- Ripple Power Density

\[ \text{Turn separation} = \frac{3}{4} S \left( x_0^2 + x_0' \right) \]

4.3. Optimization (2)

Limit of this method?

- Turn separation & Septum electrode gap

Turn separation vs \( q_0 \)

- Maximum turn separation vs \( q_0 \)

Limit due to turn separation

Upper limit of \( q_0 \)
4.4. Experiment Result (1)

Ripple amplitude can be reduced to 44% of w/o this method!

4.4. Experiment Result (2)
In the RF-KO slow-extraction, global time-structure can be controlled by the amplitude modulation (AM) of transverse RF-field. Originally, we have used linear AM function to expand the spill length.

In order to obtain square shaped spill, suitable AM function is necessary!!

To obtain suitable AM function analytically, we proposed simple 1-D model. The radial distribution of particles is assumed to be Rayleigh distribution under diffusion by RF-KO.
5.3. Simulation

Using model, new AM function can be calculated analytically to keep the extracted intensity constant.

\[ \theta(t) = \left[ \frac{d}{dt} \left( \sigma^2(t) \right) \right]^{\frac{1}{2}} \]

\[ \sigma^2(t) = \sigma_0^2 \left[ \frac{\mu}{\nu} \exp \left( 1 - \exp \left( \frac{-1}{\nu} \right) \right) + \exp \left( \frac{-1}{\nu} \right) \right] \]

5.4. Experimental Result

1) Without feedback: the result is in good agreement with the simulation one.
2) With feedback system: square shaped spill is realized.
IV. Variable Energy Operation

Variable-Energy Operation
- High speed slice change
- Suppressing beam-size growth
- Reduction of 2\textsuperscript{nd} neutron

Standard Operation Pattern
- Reference pattern

Variable-E Operation by GSI etc
- Operation pattern
- Long treatment time

NIRS Approach

Standard Operation Pattern
- Reference pattern

Variable-E Operation by GSI etc
- Operation pattern
- Long treatment time

NIRS ⇒ Variable-E operation in one cycle !

High Duty Operation
The beam spike should be avoided. Beam spike is observed not only just after deceleration, but also just after turning QDS off.
Source of Beam Spike

Source of beam spike is particles in boundary area of separatrix
Simulation observed particles spilled out from separatrix through momentum increase due to synchrotron oscillation

Particle Distribution
Frequency Spectrum

Beam-Spike Suppression

RF-KO, having mon-frequency resonated with tune in extraction region, is applied in order to sweep out those particles.

Increasing the ratio $V_{\text{mono}}/V_{\text{diff}}$ beam spike can be suppressed.

Sweep out by RF-KO with mono frequency
Particle supply by diffusion $N \times V_{\text{diff}}$
Particles of spike source $V_{\text{mono}}^2$

Mono-freq.

Diffusion by FM

Uncontrollable beam rate [pps]
Particle Distribution during Extraction

2D profile during RF-KO extraction measured by non-destructive monitor in HIMAC synchrotron

Particle-density reduction was verified in the tail region

V. Intensity Control

NIRS Strategy for Moving Target Treatment
A) Minimizing moving amplitude for irradiation:
   Several mm by respiratory gating
B) Reducing hot/cold distribution by repainting

Why?
Different position in each slice

However!!
We could not obtain uniform distribution.
**Phase Control Rescanning**

Target position should be closed to “ZERO” on average during one slice irradiation

\[ \Rightarrow \text{Phase Control between respiratory curve and Rescanning: PCR} \]

Intensity modulation should be required, because almost same irradiation time is required in each slice irradiation even in different cross section in each slice.

**Intensity Modulation**

by applying global spill control

Now, we develop intensity control system during a single flattop. Based on simple model, AM function is analytically calculated to control intensity. Dynamic range of more than 10 is expected.
Applying PI feedback control, the system can modulate the intensity range of 4 times with less than 20% ripple.

This system was required the intensity modulation range of 20 times with less than ripple magnitude of 20%, which is realized by suppression method for both spill ripple and beam spike!!

New Spill-Control System

- 3 waves synthesizer applied with DDS
- Amplitude feedback modulation with 10kHz-period
- Intensity control through PI-control
Introducing an innovative approach to medical applications, Koji Noda presented his research at the Accelerators for Medical Applications conference in Vienna, June 1st, 2015. His focus was on intensity modulation, a technique that allows for precise control over the intensity of beams used in medical treatments.

The first diagram illustrates intensity modulation ranging from 2 times the routinely delivered intensity to 1/15 of that, corresponding to a total modulation range of 30 times. This method enables a comprehensive understanding of spill-ripple magnitude in each intensity level.

A subsequent graph details measurements taken at 430, 350, and 290 MeV/n, showcasing intensity modulation with 30 times. The data confirms that intensity modulation with more than 20 times was successfully achieved with less than 20% of spill-ripple magnitude, highlighting the precision and efficacy of this technique in medical applications.

Koji Noda’s work underscores the potential of advanced accelerator technologies in enhancing medical procedures through precise beam control.
**Multistep Energy Operation with Intensity Modulation**

1. Small deviation of magnet field brings tune difference.
2. Slow-extraction is very sensitive to tune difference.
3. It brings change of the extraction angle and emittance.
4. Beam position and size is change at iso-center.

**VI. Precise Position Control**
Stability of Beam Position and Profile

Verification of spot position, size and stability of beam intensity during extended flattop.

Hardt Condition

\[ D_n \cos(\Delta \mu) + D'_n \sin(\Delta \mu) = -\frac{4\pi}{S_n} \xi_x \]

\[ -\tan\left(\Delta \mu + \frac{2\pi}{3}\right) = \frac{D'_n}{D_n} \]

\[ S_n = \frac{l_x}{2B_\rho} B^{3/2} B'' \]

\[ D_n, D'_n: \text{Normalized dispersion function} \]

\[ \Delta \mu: \text{Phase advance from the separatrix exciter to extraction channel.} \]

\[ S_n: \text{Normalized sextupole field} \]

\[ \xi_x: \text{Chromaticity} \]
In order to control beam size at HEBT, it is necessary to define optical parameters of extracted beam at the extraction channel as initial condition of HEBT. Measurement method of outgoing separatrix was proposed and verified.

In mismatched case, we cannot control optics!!

Measurement of Outgoing Separatrix

1) Inserted and fix position of rod1 at x = x1.
2) Search a shadow of rod1 at s2 by changing the horizontal position of the rod2 every operation cycle of the synchrotron.

In this way, outgoing separatrix can be measured owing to constant separatrix.
Estimation of Twiss Parameters

Comparing simulation with measurement, twiss parameters was defined.

Optics was redesigned to match the extracted beam.

Matching with Transport System

Beam profile can be estimated at each monitor.

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3D Scanning for Moving Tumor
Full Energy Depth Scan

Beam direction

Lower energy

Higher energy

Current pattern of BM
Scanning magnet (X)
Scanning magnet (Y)
Extracted beam
Beam current in ring
Irradiation gate

3mm step in water range

Energy ID

Superconducting Rotating Gantry
Superconducting Rotating Gantry

- He~Ar
- Max. 800 MeV/n
- Beam-Wobbling Method
- Respiratory-Gated Irrad.
- Layer Stacking Irrad.
- 1994~

NIRS Technology Development

- HIMAC
- Standard-version@Gunma
- New Treatment System

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

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

Advanced Standard Version
3rd Integer Resonant Slow Extraction
- Analysis -

\[
\begin{align*}
\frac{d^2x}{ds^2} + K(s)x &= g(x,s) \\
\frac{d^2X}{d\theta^2} + Q^2 X &= Q^2 \frac{3}{\beta^2} g(X,\theta) \\
X &= \frac{x}{\sqrt{\beta(s)}}, \theta = \int \frac{ds}{Q\beta} \\
x &= r \cdot \cos(Q\theta + \phi) \equiv r \cdot \cos\Phi \\
x' &= r \cdot \sin(Q\theta + \phi) \equiv r \cdot \sin\Phi \\
r &= \sqrt{x^2 + x'^2} \\
\begin{pmatrix} x' \\
x'' \end{pmatrix} &= \frac{1}{\sqrt{\beta}} \begin{pmatrix} 1 & 0 \\ \alpha & \beta \end{pmatrix} \begin{pmatrix} x \\
x' \end{pmatrix} \\
\frac{dr}{d\theta} &= -Q\beta^2 r g(X,\theta) \sin\Phi \\
\frac{d\Phi}{d\theta} &= Q - \frac{Q\beta^2 g(X,\theta) \cos\Phi}{r} \\
g(x,s) &= \sum S_j x^2 \delta(s - s_j) \\
g(X,\theta) &= \sum S_j \beta X^2 f(\theta - \theta_i) \\
\frac{dr}{d\theta} &= -\frac{r^3}{4\pi} \sum S_j \beta^2 \sin(3\Psi + p\theta_j) \\
\frac{d\Psi}{d\theta} &= q - \frac{r}{8\pi} \sum S_j \beta^{3/2} \sin(3\Psi + p\theta_j) \\
\Psi &= \Phi - \frac{p}{3} \theta = \left(\frac{Q - p^2}{3}\right) \theta + \phi = q \theta + \phi
\end{align*}
\]
Characteristics of Third-Integer Resonant

\[ \left( \begin{array}{c} X' \\ X'' \end{array} \right) = \frac{1}{\sqrt{\beta}} \left( \begin{array}{cc} 1 & 0 \\ \alpha & \beta \end{array} \right) \left( \begin{array}{c} X \\ X'' \end{array} \right) \]

Normalized phase space

\[ M = \left( \begin{array}{cc} \cos 2\pi Q & \sin 2\pi Q \\ -\sin 2\pi Q & \cos 2\pi Q \end{array} \right) \]

\[ Q = \frac{p}{3} + q, \varepsilon = 6\pi q \]

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Third-Integer Resonant Slow Extraction

\[ Q = \frac{p}{3} + q, \varepsilon = 6\pi q \]

\[ \left( \begin{array}{c} X' \\ X'' \end{array} \right) = \frac{1}{\sqrt{\beta}} \left( \begin{array}{cc} 1 & 0 \\ \alpha & \beta \end{array} \right) \left( \begin{array}{c} X \\ X'' \end{array} \right) \]

1) After 3 turns

\[ \left( \begin{array}{c} X' \\ X'' \end{array} \right) = M^3 \left( \begin{array}{c} X' \\ X'' \end{array} \right) = \left( \begin{array}{cc} 1 & \varepsilon \\ -\varepsilon & 1 \end{array} \right) \left( \begin{array}{c} X' \\ X'' \end{array} \right) \left( \begin{array}{cc} \cos 6\pi Q & \sin 6\pi Q \\ -\sin 6\pi Q & \cos 6\pi Q \end{array} \right) = \left( \begin{array}{cc} 1 & \varepsilon \\ -\varepsilon & 1 \end{array} \right) \]

\[ M = \left( \begin{array}{cc} 1 & \varepsilon \\ -\varepsilon & 1 \end{array} \right) \left( \begin{array}{c} X' \\ X'' \end{array} \right) \]
In 1946, R. Willson proposed the hadron RT owing to excellent physical characteristics.
Photo of New Treatment Research Facility

Building facade with green curtain

Entrance hall (1F)

Waiting hall (B2F)

Treatment Room E (B2F)

Adverse Dose Distribution Effect by Spill Ripple

Extra-dose cannot be controlled

Because of huge spill ripple

Flat spill structure:

⇒It is possible to predict extra-dose during moving between spot positions.

T. Inaniwa et al., Med. Phys. 34(8), 3302

Slow scanning

Fast scanning
Experimental Condition

- Beam: C\(^{6+}\) 400 MeV/n
- Bare Tune: (3.681, 3.130)
- \(f_s\) : 6.6118 (MHz) - Longitudinal RF Frequency
- \(f_{rev}\) : 1.6530 (MHz) - Revolution Frequency
- \(V_{rf}\) : \(\pm 4\) (kV) - Longitudinal RF Voltage
- \(f_s\) : 1.46 (kHz) - Freq. of Synchrotron Oscillation
- \(f_k\) : 1.115 – 1.135 (MHz) - Transverse RF
- \(\Delta f_k\) : 4 – 28 (kHz) - Bandwidth (Typical value)
- \(V_k\) : 1200 (Vpp) - RF-KO Voltage (Typical value)
- \(\xi_x\) : -3.2 – +0.2 - Horizontal chromaticity
- \(K_2(SXFr1, SXDr1)\) : 1.978 (m\(^{-3}\)) - Separatrix Ecitor
- \(K_2(SXFr2, SXDr2)\) : -1.644 (m\(^{-3}\)) - *\(K_2 = B''/(Bp)\)

Simulation Study for Beam Spike

Beam spike is observed not only just after deceleration, but also just after turning QDS off.

![Beam Spike Simulation](image-url)
Verification of 3D Scanning for Moving Tumor
Accelerators for Medical Applications,
Vienna, June 1st, 2015

Koji Noda,
Dept. Accelerator and Medical Physics, NIRS

1) Proton:
   Energy: 230 MeV
   2 Gantry + 1 H

2) Carbon
   Energy: 320 MeV/n
   1 H & V, 45° line

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

3,020 pts treated from May ’01 to Nov. ’09

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Gunma Uni. Heavy-Ion Medical Center

- 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.
HITFiL project

Heavy Ion Therapy Facility in Lanzhou (HITFiL)

Layout of the HITFiL project

Four treatment rooms:
horizontal, horizontal+vertical, vertical and oblique beam lines
Based on GSI treatments of 400pts since’97, HIT was constructed and initiated carbon-ion RT.

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

New Projects by Siemens

- Shanghai
- Kiel

Koji Noda,
Dept. Accelerator and Medical Physics, NIRS
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

First Facility Dedicated to Proton RT

Loma Linda University Medical Center was opened in 1990
Shizuoka, S-Tohoku, Fukui, Ibusuki
✓ Week focusing: High intensity (17nA)
✓ Accel driven extraction
✓ APF-IH Linac for proton

U. Tsukuba, MDACC, Nagoya, Hokkaido
*Variable FT operation pre-triggered by respiration
* Variable energy operation for 3D scan