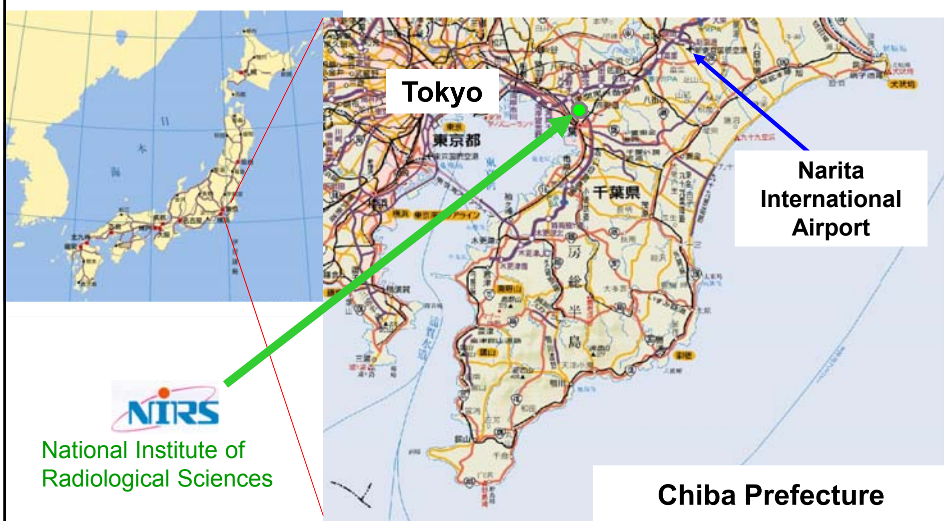
NIRS HIMAC

Extraction Methods

Koji Noda
National Institute of Radiological Sciences
Lecture in Accelerator for Medical Applications,
Voesendorf, Austria, 1st June, 2015

NIRS

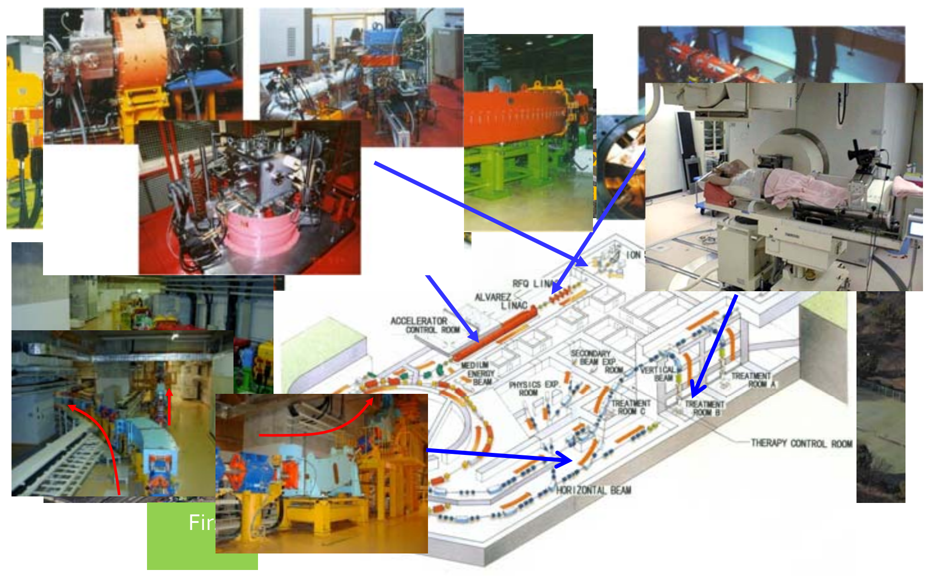
National Institute of Radiological Sciences



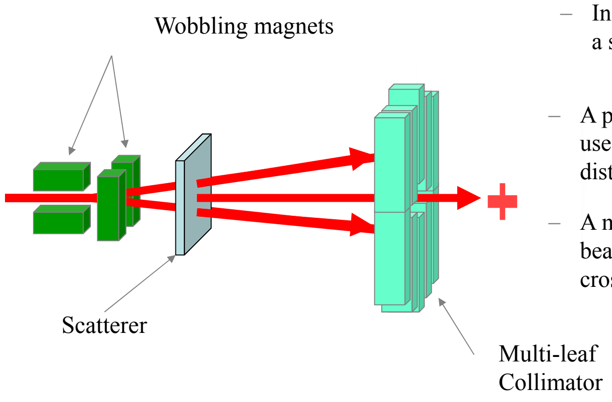
National Institute of Radiological Sciences

Contents

HIMAC
Heavy Ion Medical Accelerator in Chiba

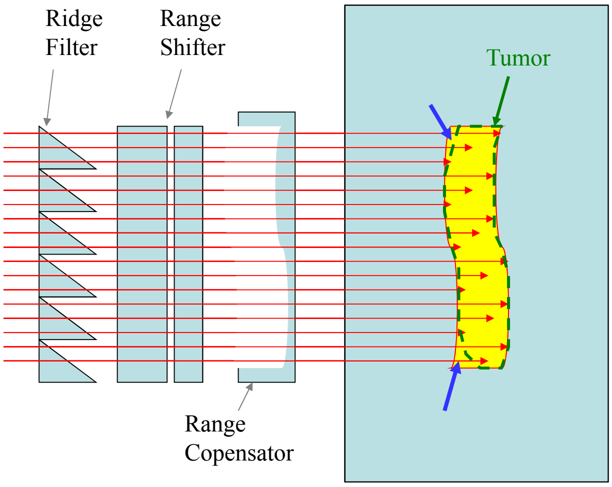


Wobbling Method for Lateral Field



- 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.

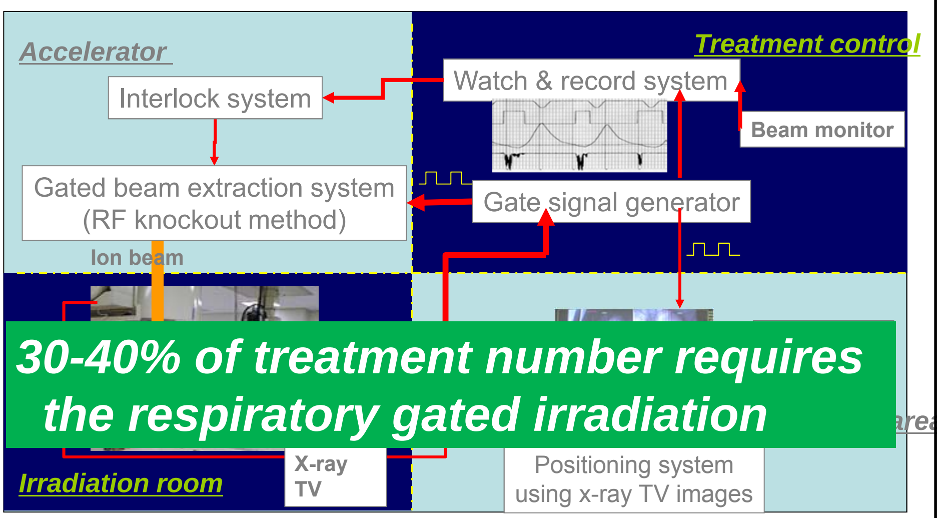
Ridge Filter Method for SOBP



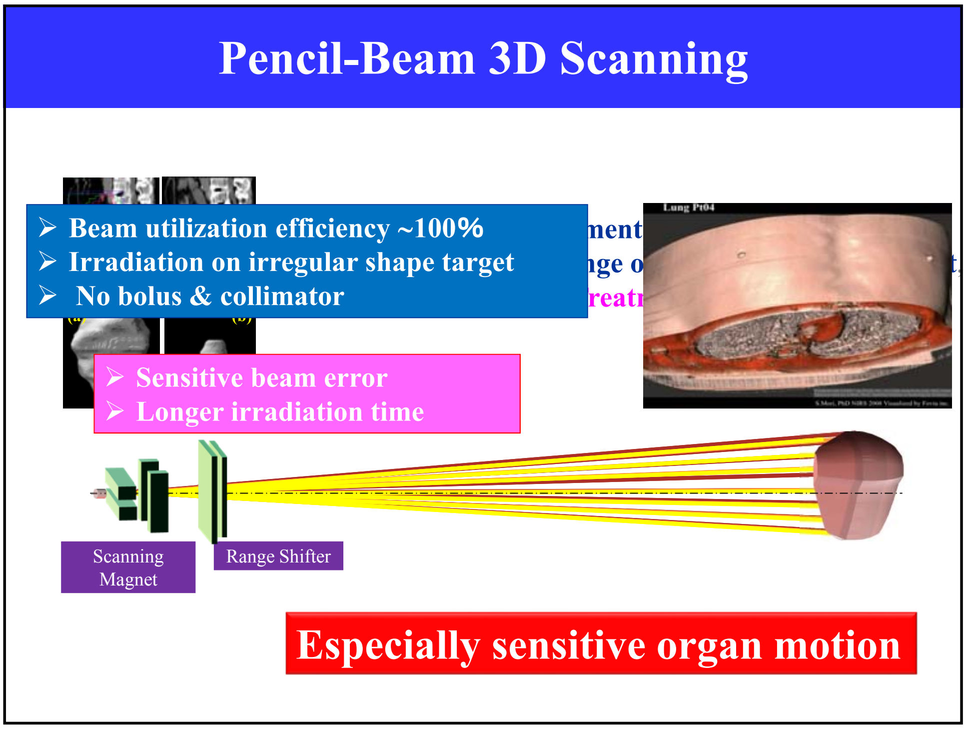
- The beam energy is originally monochromatic.
- Ridge filter is inserted in order to expand the beam energy so as to match with tumor thickness.
- A range shifter is used as energy absorbers for the fine tuning of the range.
- Range compensator is set in order to adjust the end-point to the curvature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

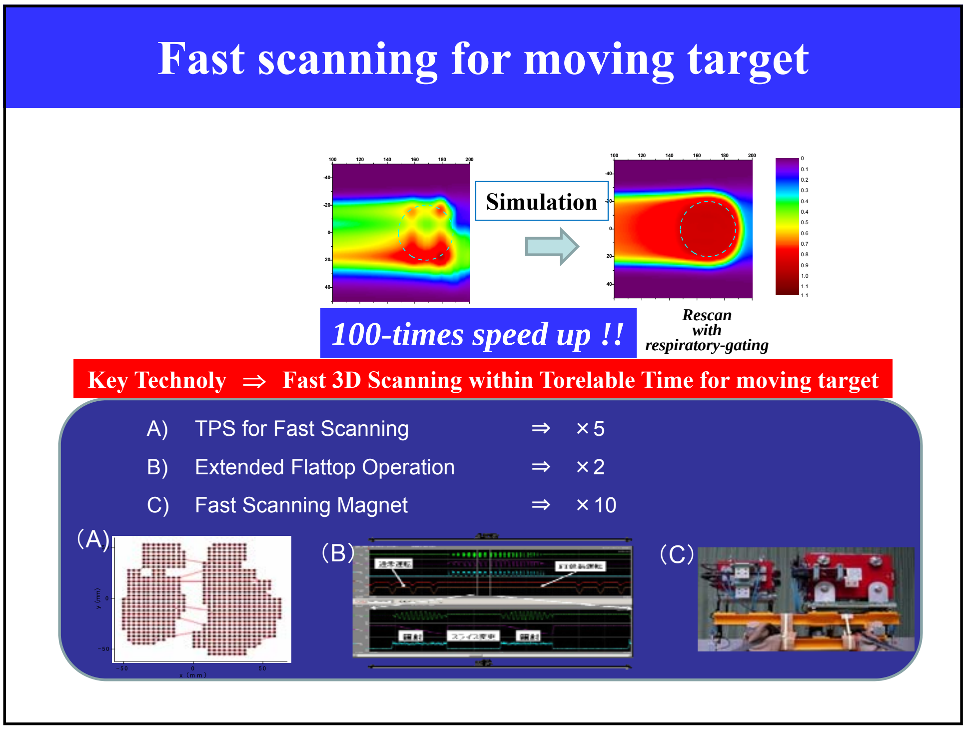
Respiratory Gated Irradiation

- Irradiation synchronized with a patient's respiratory motion -

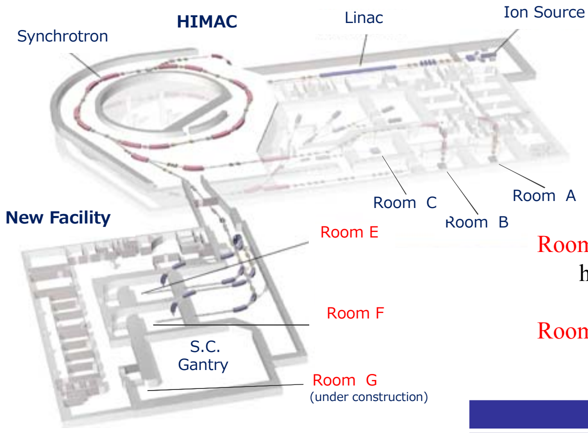


30-40% of treatment number requires the respiratory gated irradiation


Pencil-Beam 3D Scanning
➤ Beam utilization efficiency ~100%
➤ Irradiation on irregular shape target
➤ No bolus & collimator
Lung Pt04
➤ Sensitive beam error
➤ Longer irradiation time
Scanning Magnet
Range Shifter
Especially sensitive organ motion


Fast scanning for moving target
Simulation
100-times speed up !!
Rescan with respiratory-gating
Key Technoly ⇒ Fast 3D Scanning within Torelable Time for moving target
A) TPS for Fast Scanning ⇒ ×5
B) Extended Flattop Operation ⇒ ×2
C) Fast Scanning Magnet ⇒ ×10
(A)
(B)
(C)

HIMAC and New Facility



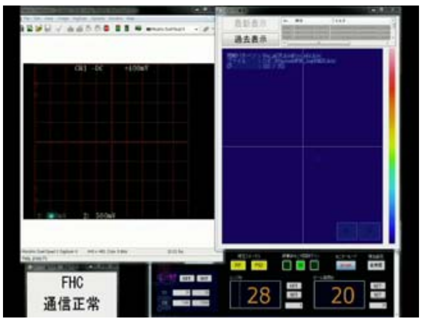
Room E & F with H/V scanning ports have treated more that 600 pts since 2011

Room G with rotating gantry is under development.

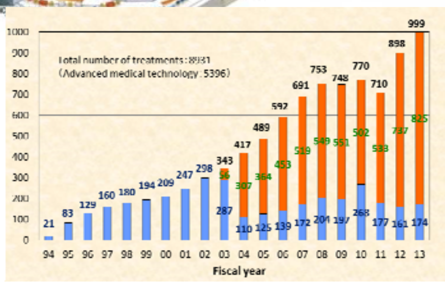
Main specifications	
Ion species	^{12}C
Irradiation method	3D Scanning
Beam Energy	430 MeV/n (max.)
Maximum Range	30cm in water
Maximum Field	22×22 cm² (E, F)

Treatment with 3D Scanning

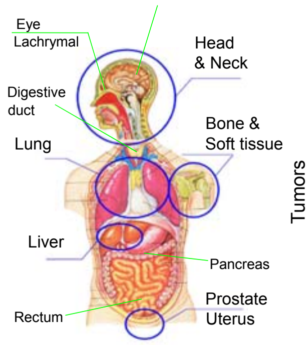
- **Operation**
  - Daily QA (MU calibration, range check etc) ～ 15min/course
  - Treatment irradiation (except positioning) ～ 2min
  - 30 patients/day under 3hr operation of 2 rooms



HIMAC Treatment



- ✓ More than 10 000 pts treated since '94.
- ✓ ≈1 000 pts/y, ≈100 shots/day @180 d/y
- ✓ Downtime rate < 0.5%



Summary of Clinical Results

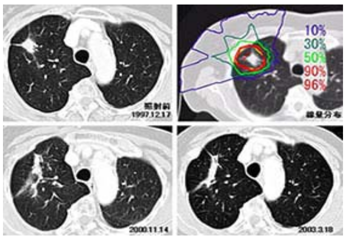
The HIMAC clinical trial with carbon-ion has proven

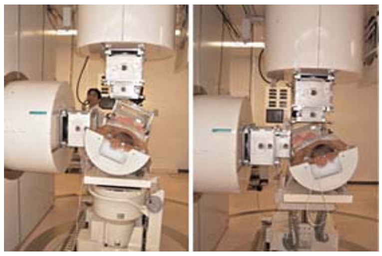
- ➢ **a short course treatment, such as one fractional treatment of lung cancer, is possible.**
- ➢ **very effective against radio-resistive cancer.**

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 – 95.4GyE (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 (2)

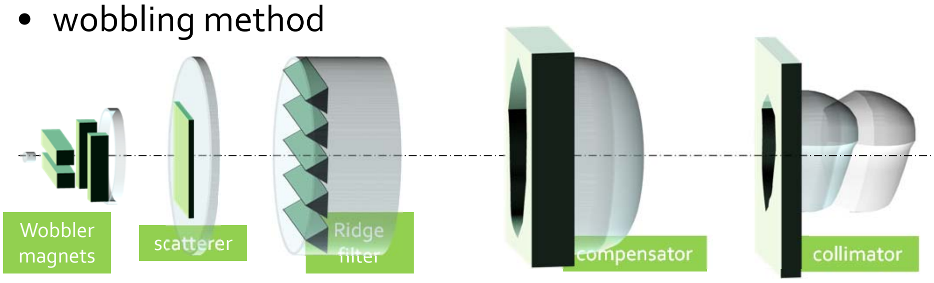
Treatment against Radio-Resistive tumor

Before treatment

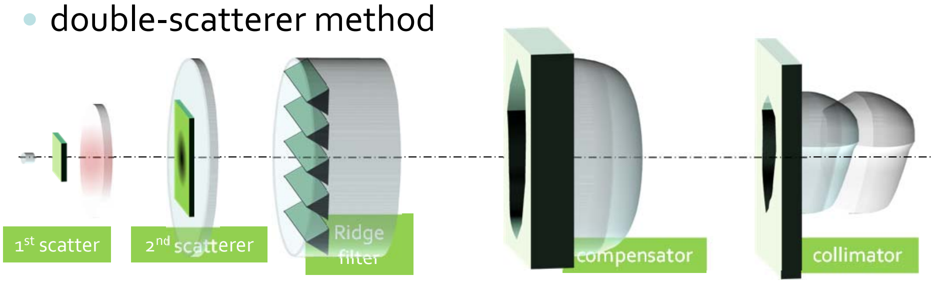
Contents

Broad Beam Delivery

- wobbling method

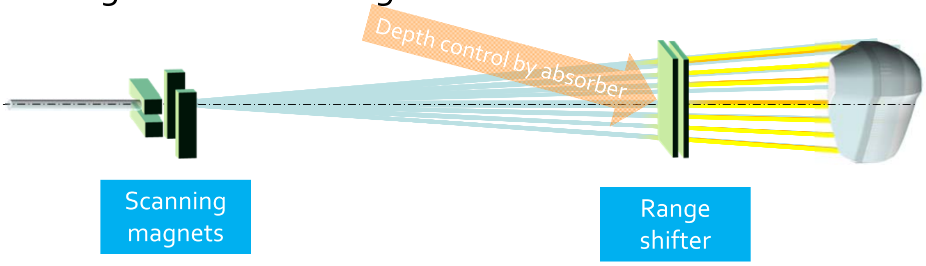


- double-scatterer method

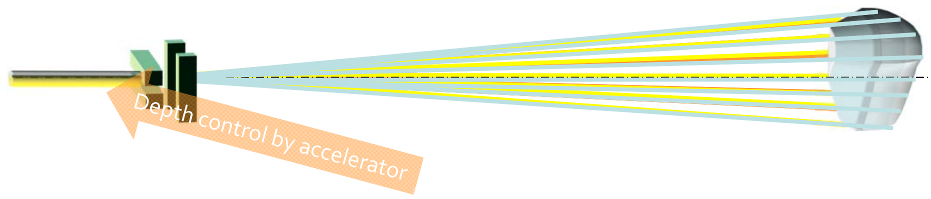


Pencil beam delivery (scanning)

- range-shifter scanning



- energy scanning



Requirements from Static Tumor Treatment

	Double Scatterer	Wobbler	3D Scanning
Pos. Error	<±0.5 mm @ 2nd Scatterer	<±2.5 mm	<±0.5 mm $\Delta\sigma/\sigma < 10\%$
Spill Ripple	No effect	Avoid ripple with around wobbling freq.	Suppress ripple with kHz-order
Low dose-rate control	No	No	Necessary
Intensity Modulation	No	No	Necessary
Energy Scan	Fixed	Fixed	Full energy scan

Koji Noda,
Dept. Accelerator and Medical Physics, NIRS

Requirements from Moving Tumor Treatment

	Double Scatterer	Wobbler	3D Scanning
Beam ON/OFF	< 1 ms	< 1 ms	< ~ 0.1 ms @ spot scanning
Intensity Modulation	No	No	Necessary
Low dose-rate control	No	No	Necessary
Energy scan	Fixed energy	Fixed energy	Full energy scan (Hybrid scan)

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.

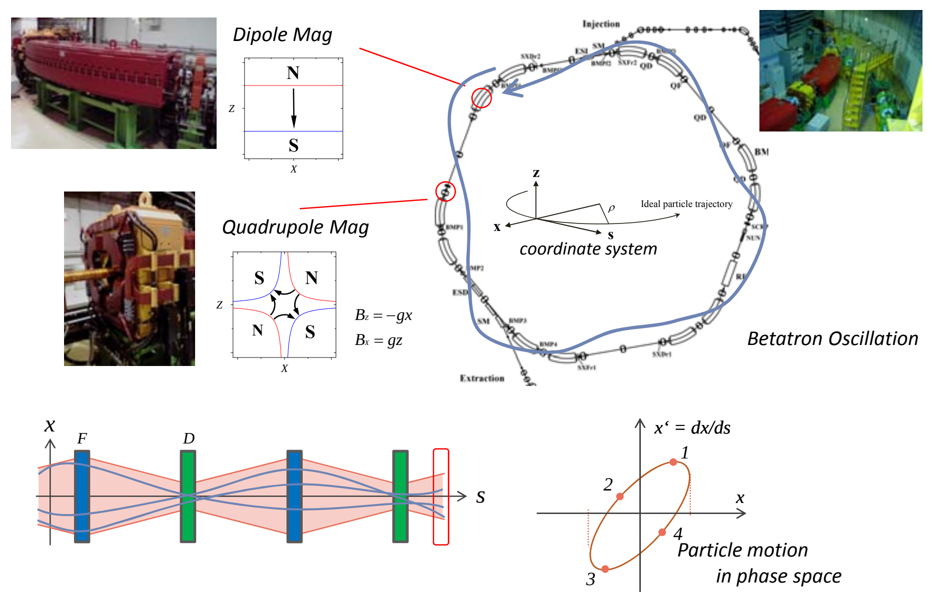
VI. Precise position control for double scattering and 3D scanning

VII. Precise beam-size control for 3D scanning

3D scanning has required higher performance of slow extraction compared with broad beam methods.

Contents

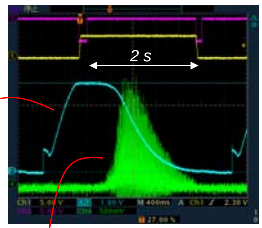
Transverse Motion in Synchrotron

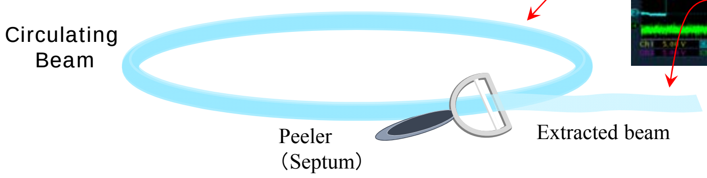


Slow Extraction from Synchrotron

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

⇒ Slow Extraction



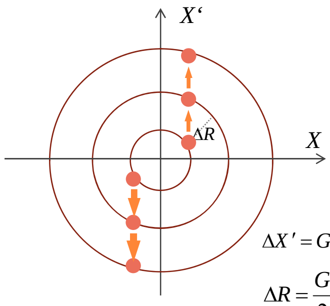


The HIMAC synchrotron has employed a slow extraction method combined the third-order resonant extraction and the beam heating through transverse RF electric field.

Resonance of Betatron Oscillation - Integer Resonance -

$\boldsymbol{Q = p + q; betatron\ tune}$

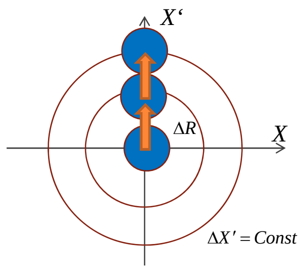
$\boldsymbol{p; positive\ integer,\ |q| \ll 1}$



$\Delta X' = GX = GR\cos(2\pi Qn + \phi_0)$

$\Delta R = \frac{G}{2}\sin\{2\pi(2Q)n + 2\phi_0\}$

Driving term
⇒ Quadrupole component



Driving term
⇒ Dipole component

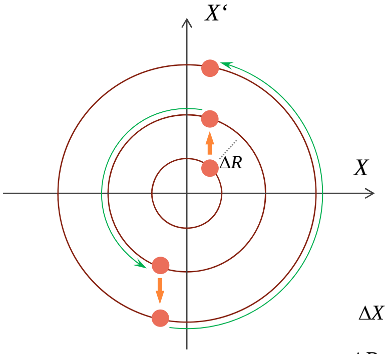
Koji Noda,
Dept. Accelerator and Medical Physics, NIRS

Resonance of Betatron Oscillation - Half-Integer Resonance -

$Q = \frac{p}{2} + q$, ***Betatron tune***

p; ***positive integer***, $p \neq 2n$

$|q| \ll 1/2$



Driving term

⇒ Quadrupole field

$$\Delta X' = GX = GR\cos(2\pi Qn + \phi_0)$$

$$\Delta R = \frac{G}{2}\sin\{2\pi(2Q)n + 2\phi_0\}$$

Resonance of Betatron Oscillation - Third-Integer Resonance -

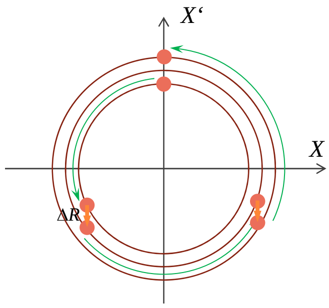
$Q = \frac{p}{3} + q$; ***betatron tune***

p; ***positive integer***, $p \neq 3n$

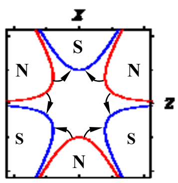
$|q| \ll 1/3$

Driving term

⇒ Sextupole field



Sextupole



$B_z \propto (x^2 - z^2)$

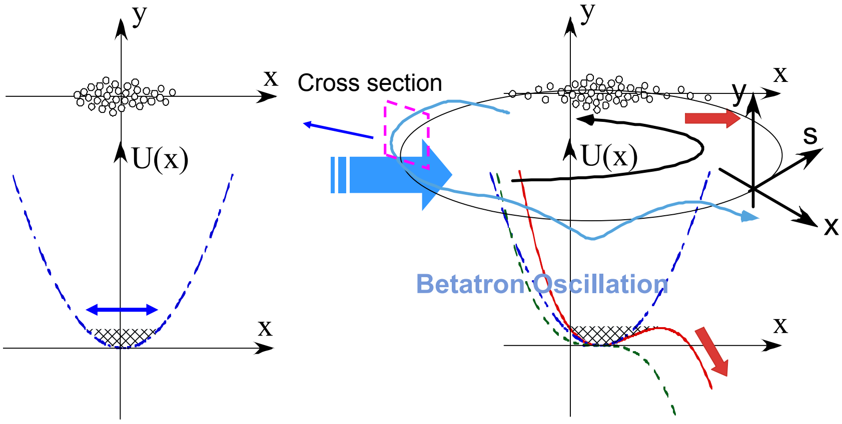
$$\Delta X' = SX^2 = SR^2\cos^2(2\pi Qn + \phi_0)$$

$$\Delta R = \frac{SR}{4}[\sin\{2\pi(3Q)n + 3\phi_0\} + \sin(2\pi Qn + \phi_0)]$$

Third-Integer Resonant Slow Extraction

$F = -Kx \Rightarrow U = \frac{K}{2}x^2$

$F = -Kx + Sx^2 \Rightarrow U = \frac{K}{2}x^2 - \frac{S}{3}x^3$



Stable Oscillation
in Parabolic Potential

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

Third-Integer Resonant Slow Extraction

Kobayashi Hamiltonian

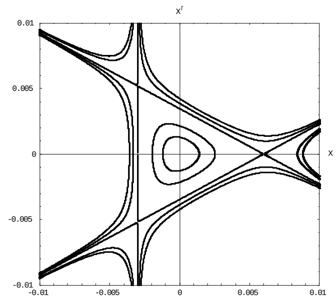
(Y. Kobayashi, NIM, 83,1970)

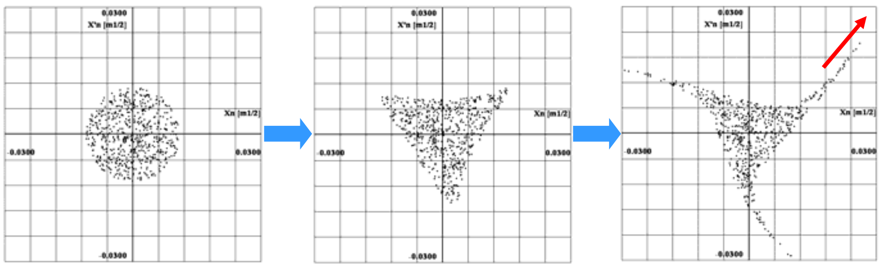
$$H = \frac{\varepsilon}{2}\left(X^2 + X'^2\right) + \frac{S}{4}\left(3XX'^2 - X^3\right)$$

Sextupole Term

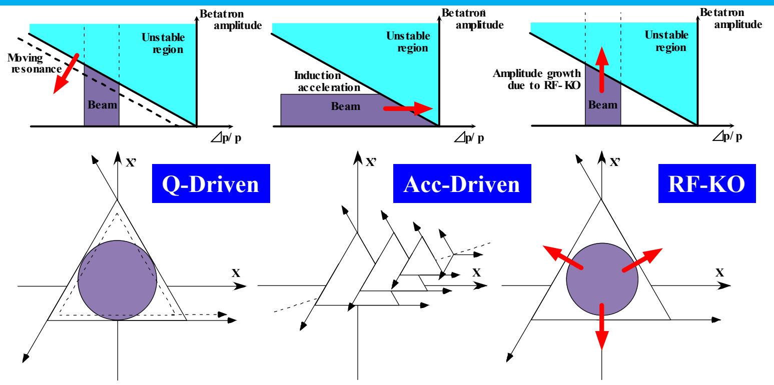
$$Q = \frac{p}{3} + q, \varepsilon = 6\pi q$$

$$A = 48\sqrt{3}\pi^2\frac{q^2}{S^2}$$





Third-Integer Resonant Slow Extraction



(1) The Q-driven method extracts the beam slowly by shrinking the separarix 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 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.

Performance

		Q-Driven	Acc-Driven	RF-KO
Fast beam on/off		Several 100 ms	Several ms (?)	*<0.5 ms*
Time Structure	Fine	OK by FB	OK	***OK***
	Global	OK by FB	OK by FB	***OK by FB & FF***
Intensity Control		Not easy	Not easy	***OK***
Position Control		Complicate	Hardt condition	***Easy***
Profile Control		OK	OK	***Easy***
Variable Energy		Not easy	Not easy	***Easy***

Contents

RF-KO Slow Extraction

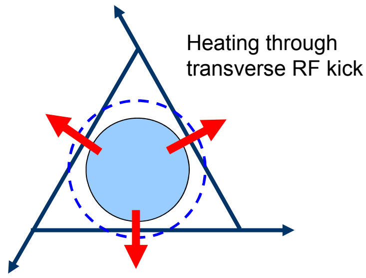
Under the constant separatrix, transverse heating can enlarge the amplitude of the circulating beam, and particles with larger amplitude than the separatrix can be extracted from the synchrotron. As a transverse-heating method, the RF-KO method has been utilized.

$$\frac{d^2X}{d\theta^2} + Q^2X = Q^2\beta^{\frac{3}{2}}g(X,\theta) + A \cdot \sin\{(q+\delta q)\theta + \varphi\}$$

$$Q = \frac{p}{3} + q, \qquad |q| \ll 1/3$$

RF-KO extraction

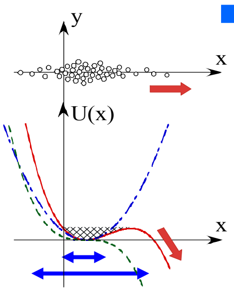
K.Noda et al., NIM-A 374, 1996



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

RF-KO Slow Extraction with FM & AM

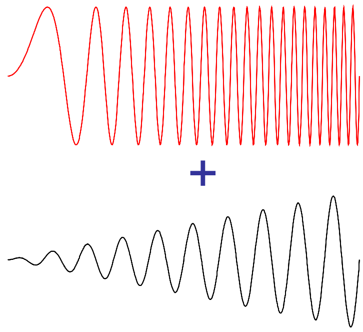
Amplitude dependence of the horizontal tune



Amplitude dependence of the tune

→ ***Frequency modulation (FM)***

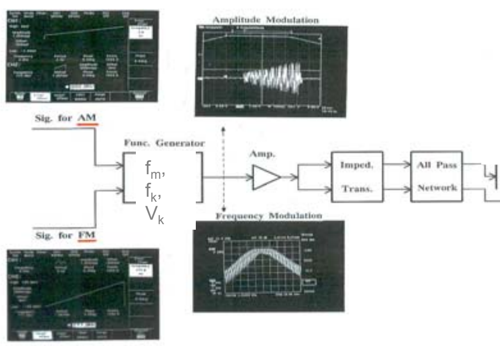
$$\frac{d^2X}{d\theta^2} + Q^2X = Q^2\beta^{\frac{3}{2}}g(X,\theta) + A\cdot\sin(q_k\theta+\phi)$$

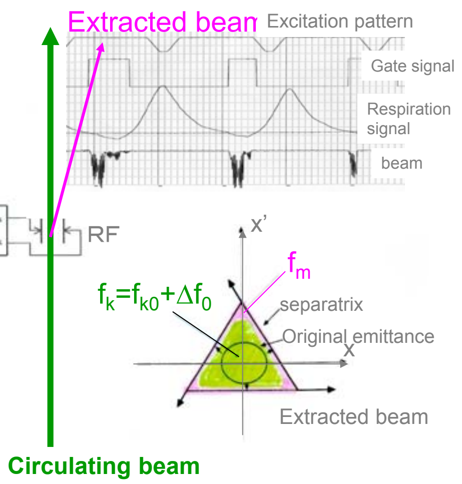


Global spill control

→ ***Amplitude modulation (AM)***

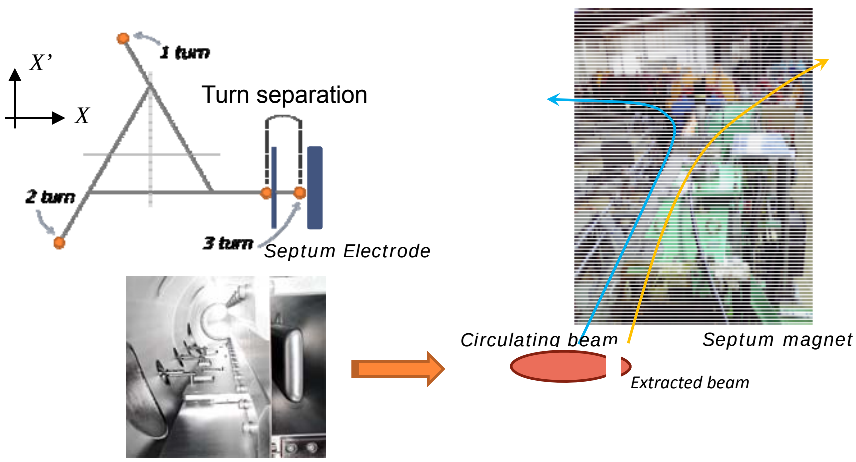
RF-KO Slow Extraction with FM & AM



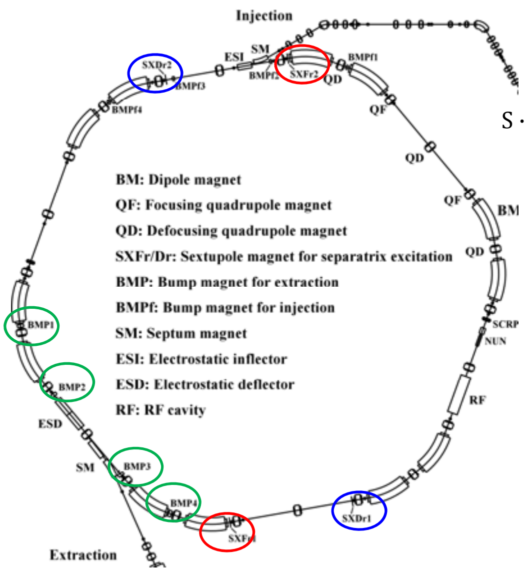


RF-KO Slow Extraction System

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

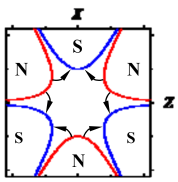


Slow Extraction System
- Separatrix Eciter; Sextupole -



$$S \cdot e^{ip(\theta-\theta_0)} = \sum_j S_j \cdot e^{jp(\theta-\theta_j)}\,\delta(\theta-\theta_j)$$

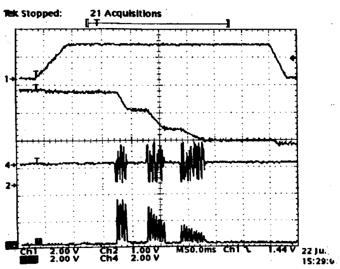
Sextupole



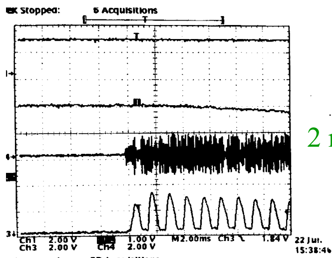
$B_z \propto (x^2 - z^2)$

Ⅱ. Fast Beam ON/OFF

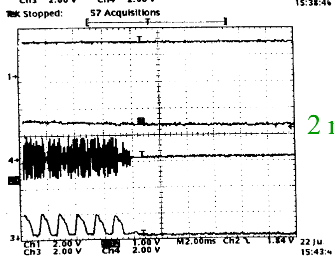
Response time < 1 ms !!



Time Scale: 50 ms/div



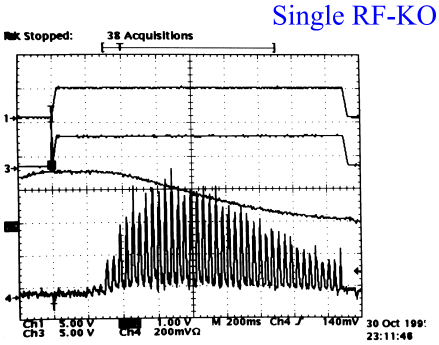
2 ms/div



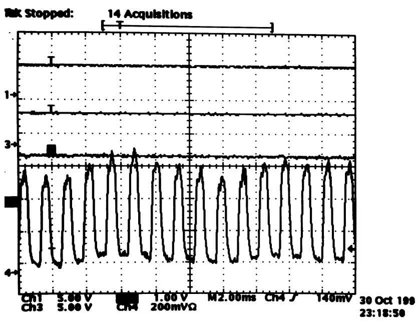
2 ms/div

Ⅲ. Time Structure Control
Spill Ripple of Original RF-KO

Single RF-KO Method



Time Scale:200 ms/div

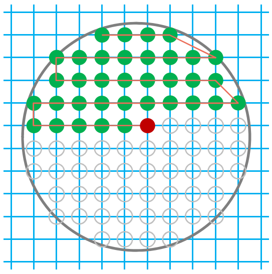


Time Scale:2 ms/div

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

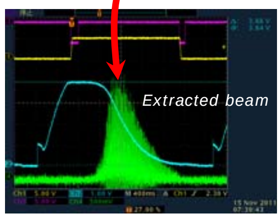
Such huge ripple brings huge non-uniformity in 3D scanning.

Ⅲ. Time Structure Control
- Dose Distribution and Spill Ripple -

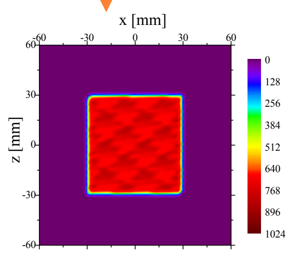


Spot assign

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



Uniform distribution cannot be obtained



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

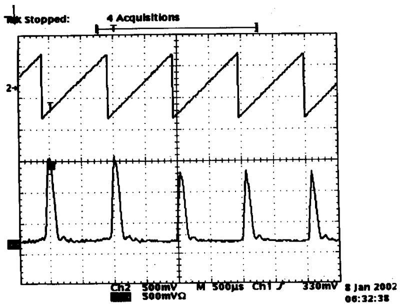
Study on Spill Ripple in RF-KO Method

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

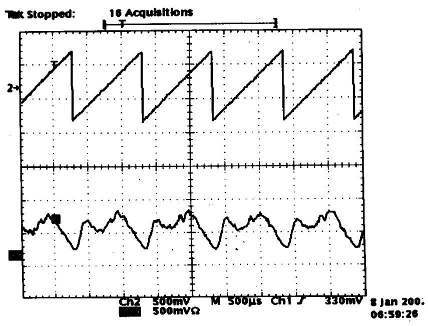
1. Time Structure for One FM Period
1.1. Chromaticity Dependence

$\xi_x \sim 0$



Time Scale: 500 μs

$\xi_x \sim -3.2$

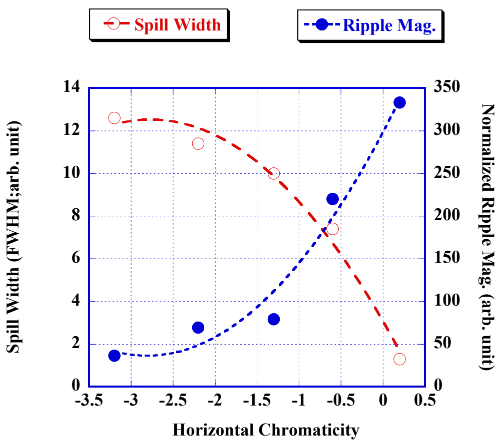


Time Scale: 500 μs

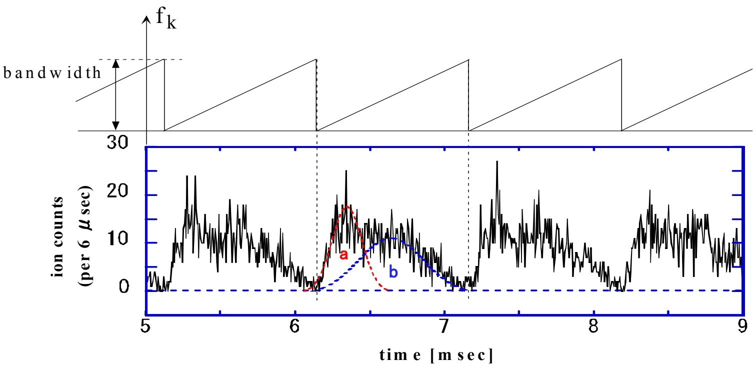
1.1. Chromaticity Dependence

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

The spill width and the ripple magnitude increases and decreases as a quadratic function of the chromaticity, respectively.



1.2. Dual Peaks for FM Period



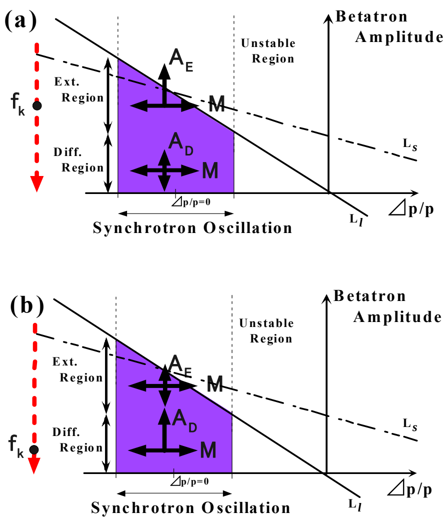
Peak (a) is the beam extracted mainly due to the transverse RF field, while peak (b) mainly due to the synchrotron oscillation.

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.

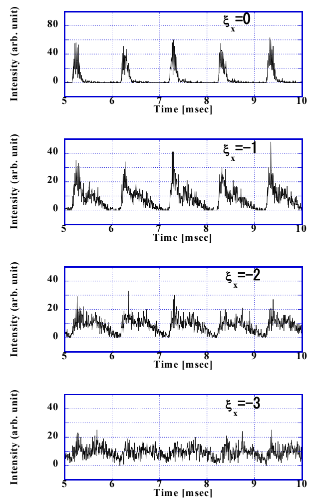
The slope of the L increases with increasing the chromaticity.



1.4. Spill-Structure Control by Chromaticity

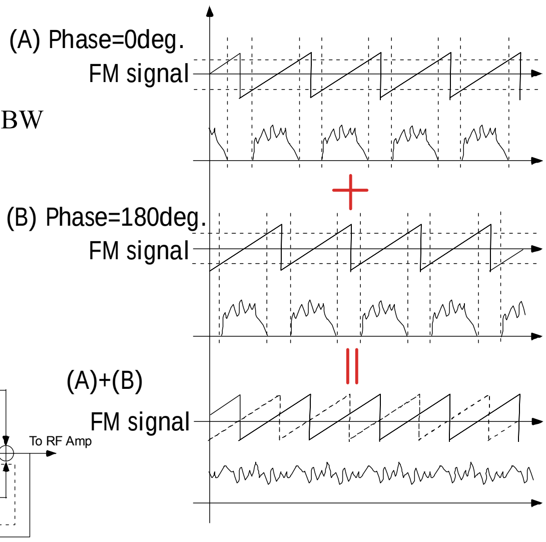
Simulation Result:

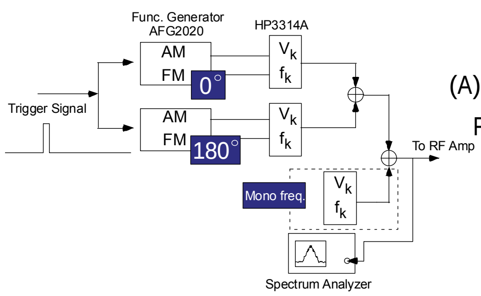
With increasing the chromaticity, both peak (a) and (b) are widened.
It is considered as follows:
Peak (A): the extraction region is increased with increasing the chromaticity.
Peak (B): The average distance from the particles in the extraction region to the boundary is to be long with incasing the extraction 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)

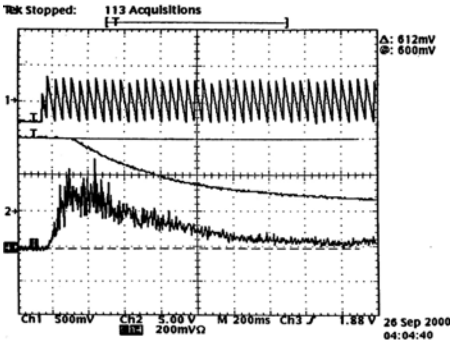
- ✓ Chromaticity Control
- ✓ Spill-shape Control by narrow BW
- ✓ FM + FM with 180 deg
- ✓ Utilizing same AM to dual FM



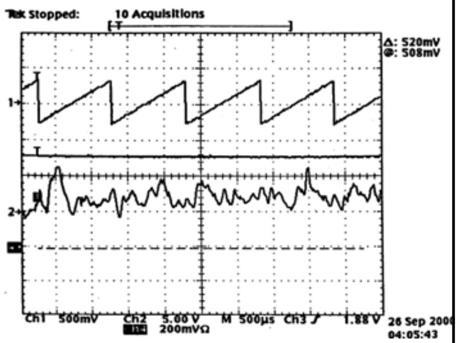


2. Dual FM Method (2)

Ripple < ±30%

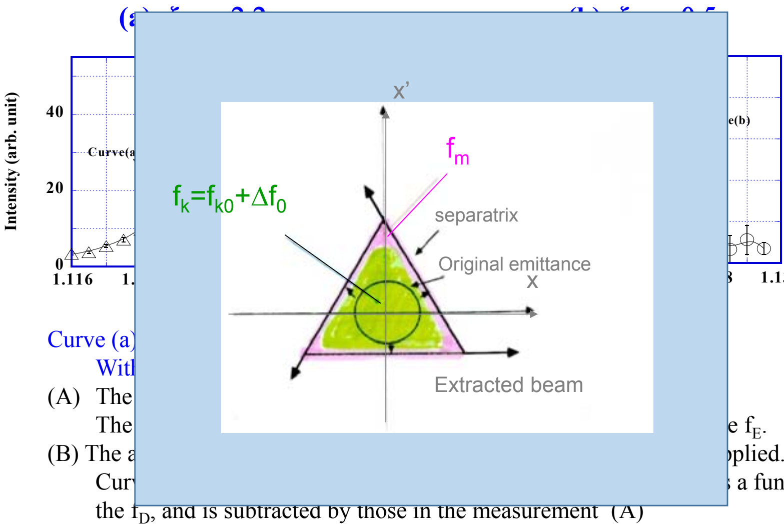


200 ms/div



500 μs/div

3. Separate Function Method (1)
- Extraction and Diffusion Regions -

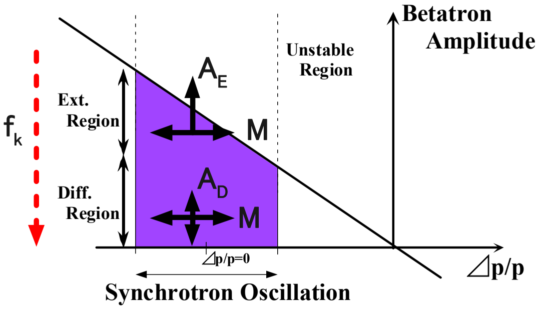


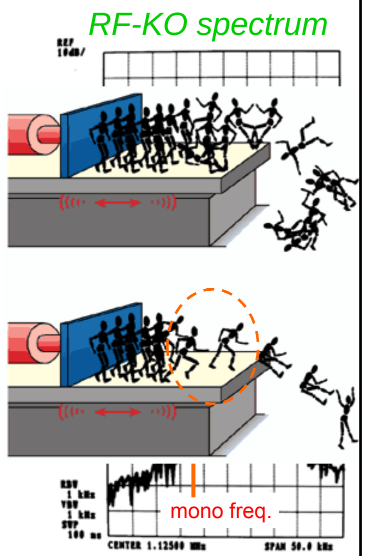
Curve (a) ...
Wit...
(A) The ... The ... e f_E.
(B) The a... ...plied.
Cur... ...s a function of the f_D, and is subtracted by those in the measurement (A)

3. Separate Function Method (2)

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

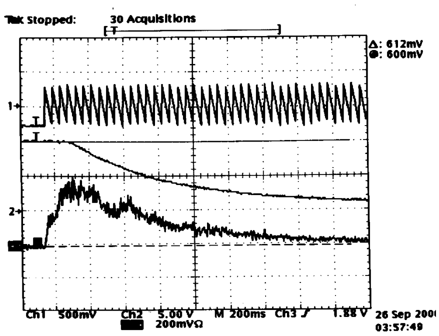
➡ Increasing sweep velocity !!



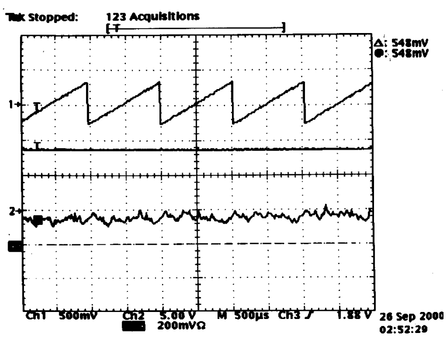


3. Separate Function Method (3)

Ripple < ±20%



200 ms/div

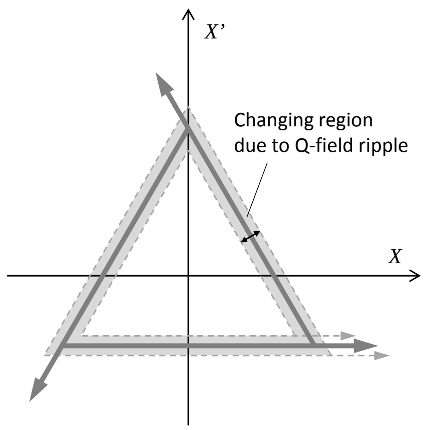


500 μs/div

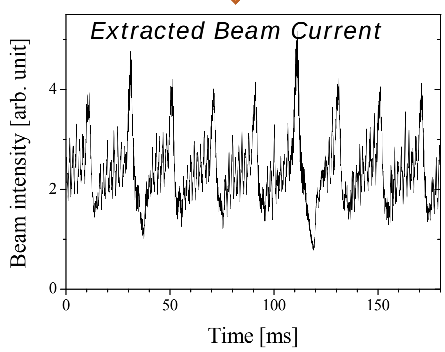
kHz-order ripple can be significantly suppressed.

Koji Noda,
Dept. Accelerator and Medical Physics, NIRS

4. Robust against Q-Field Ripple
4.1 Ripple Source



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



4.2. Proposed Method

Q-field ripple suppression

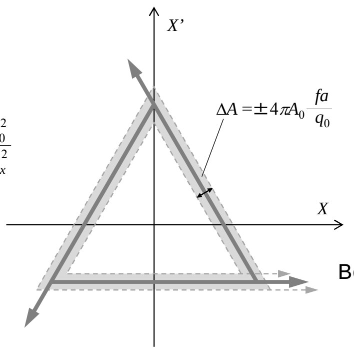
- Improvement of PS
- Feed Back
- Feed Forward

Another method?

Stable region area

$$A_0 \equiv 48\sqrt{3}\pi^2 \frac{q_0^2}{S_x^2}$$

$Q = p/3 + q_0$
S_x : SX field



$$\Delta A = \pm 4\pi A_0 \frac{fa}{q_0}$$

Tune ripple due to Q-PS ripple

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

Extracted beam current

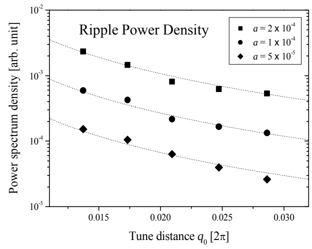
$$N(t) \approx ne\left(b - 4\pi\sigma A_0 \frac{fa}{q_0}\cos(2\pi f t)\right)$$

Beam current ripple term

Beam ripple magnitude $\propto \left(\sigma a \frac{A_0}{q_0}\right)$

Increase q_0 under constant A_0

4.3. Optimization (1)

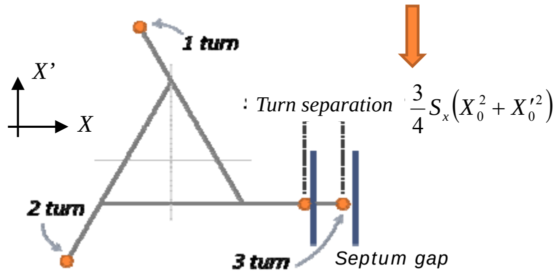


Limit of this method?

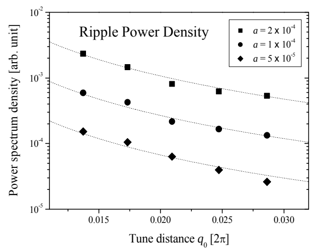
→ *Turn separation &*
Septum electrode gap

To keep stable region $A_0 \equiv 48\sqrt{3}\pi^2 \frac{q_0^2}{S_x^2}$

S_X field is increased

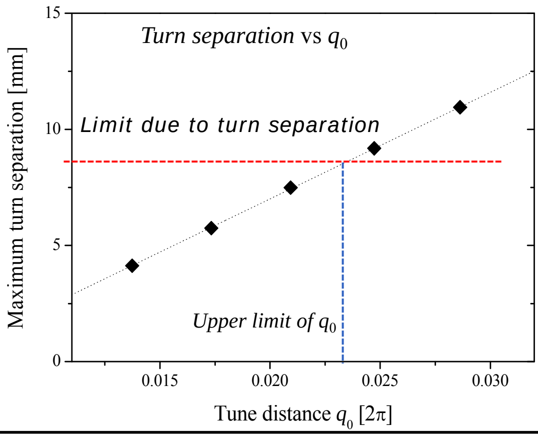


4.3. Optimization (2)



Limit of this method?

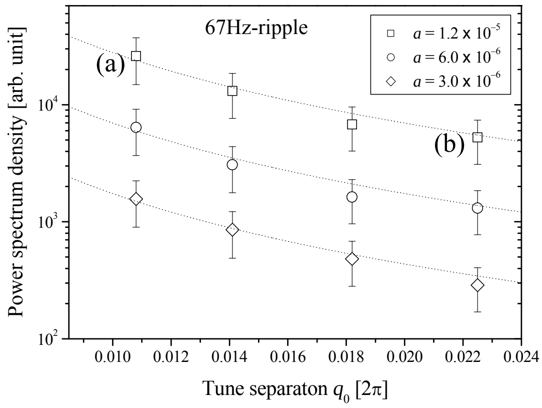
→ *Turn separation &*
Septum electrode gap

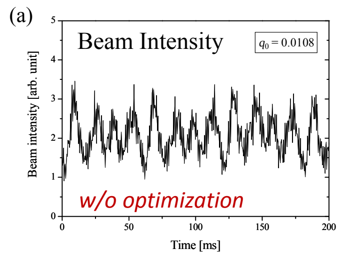


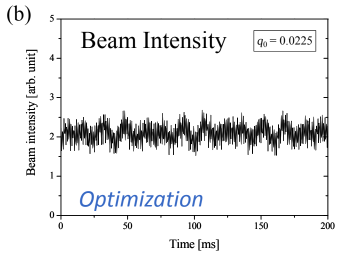
Koji Noda,
Dept. Accelerator and Medical Physics, NIRS

4.4. Experiment Result (1)

Additional Q-field ripple with 67Hz of frequency



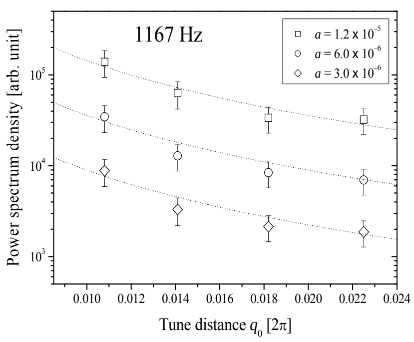




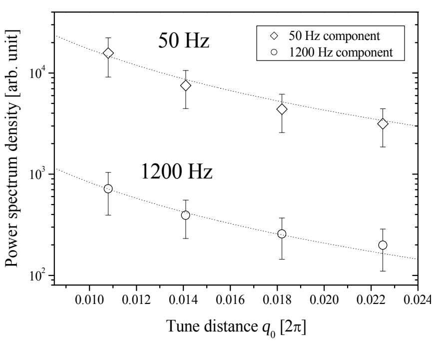
Ripple amplitude can be reduced to 44% of w/o this method !

4.4. Experiment Result (2)

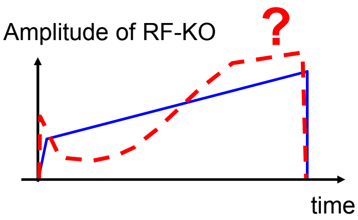
Additional Q-field ripple with 67Hz



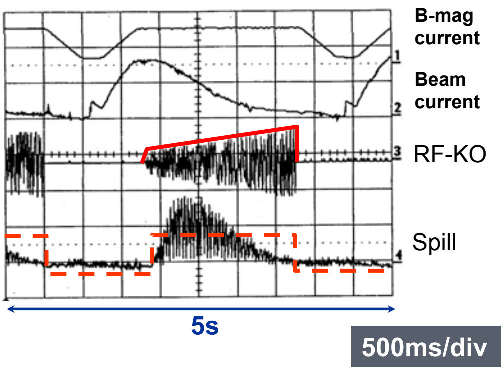
Original 50&1200Hz ripple



5. Global Spill-Structure Control
5.1. Requirement

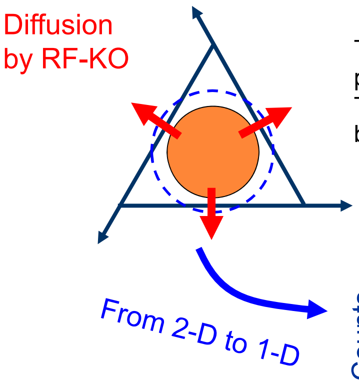


In the RF-KO slow-extraction, global time-structure can be controlled by the amplitude modulation (AM) of transverse RF-field
Originally, we have used linear AM function to expand the spill length

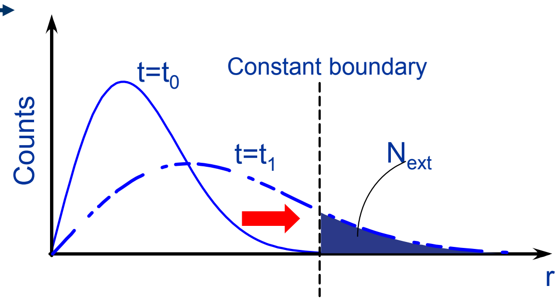


In order to obtain square shaped spill, suitable AM function is necessary!!

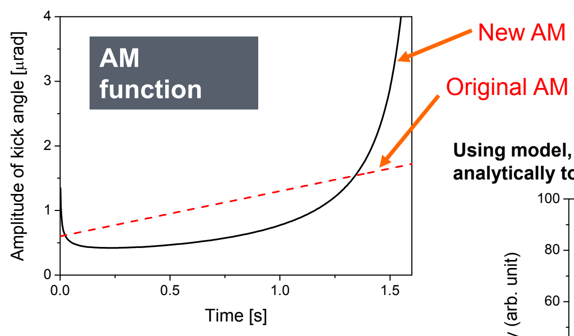
5.2. Simple Model



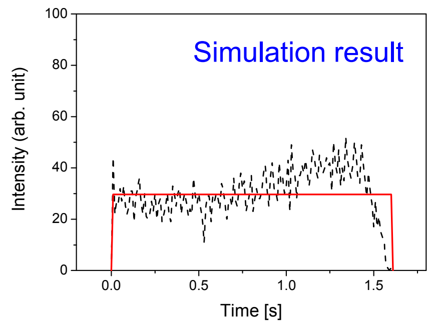
To obtain suitable AM function analytically, we proposed simple 1-D model.
The radial distribution of particles is assumed to be Rayleigh distribution under diffusion by RF-KO.



5.3. Simulation



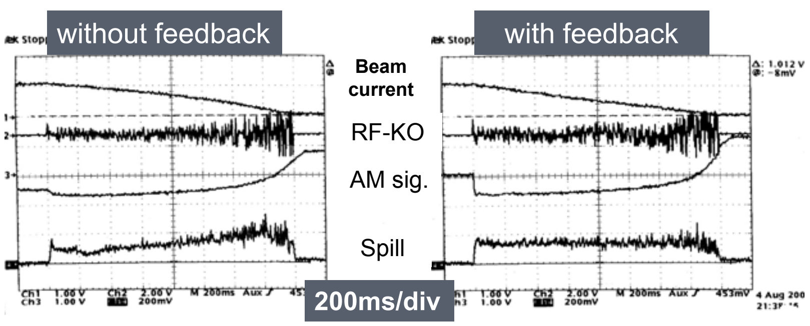
Using model, new AM function can be calculated analytically to keep the extracted intensity constant.



$$\theta(n)=\left[\frac{d}{dn}\left(\frac{\sigma^2(n)}{k}\right)\right]^{1/2}$$

$$\sigma^2(n)=-r_0^2\cdot\left[\ln\left[\frac{n}{f_{rev}\cdot\tau_{ext}}\cdot\left\{1-\exp\left(-\frac{r_0^2}{\sigma_0^2}\right)\right\}+\exp\left(-\frac{r_0^2}{\sigma_0^2}\right)\right]\right]^{-1}$$

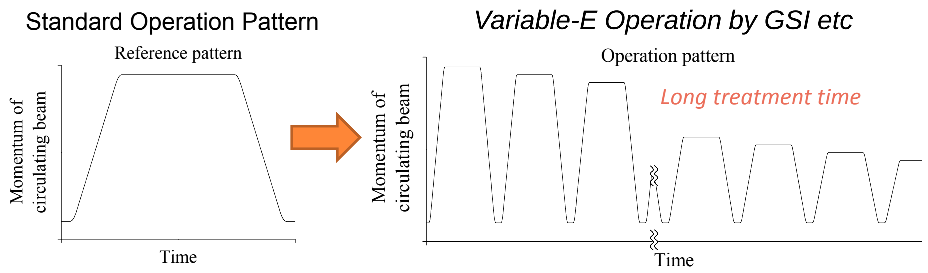
5.4. Experimental Result



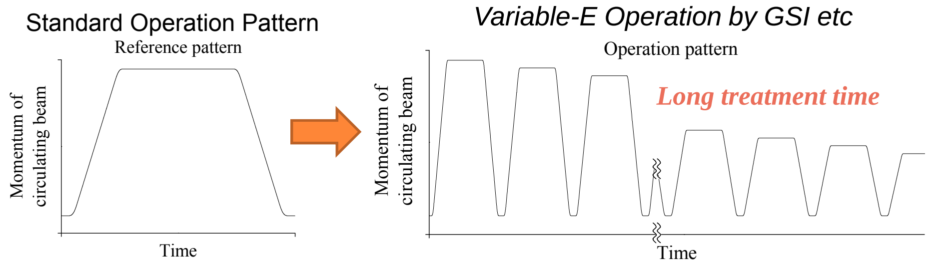
1) Without feedback: the result is in good agreement with the simulation one.
2) With feedback system: square shaped spill is realized.

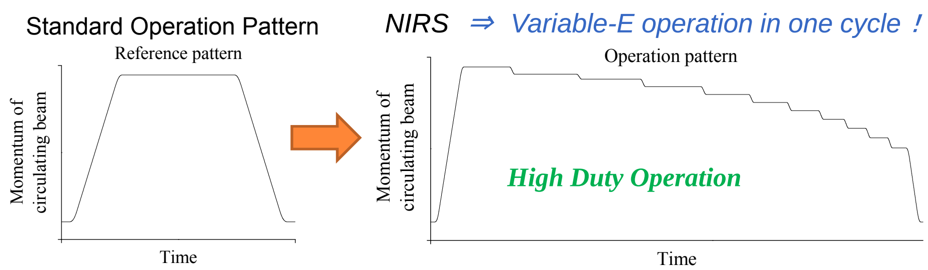
Ⅳ. Variable Energy Operation

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



NIRS Approach

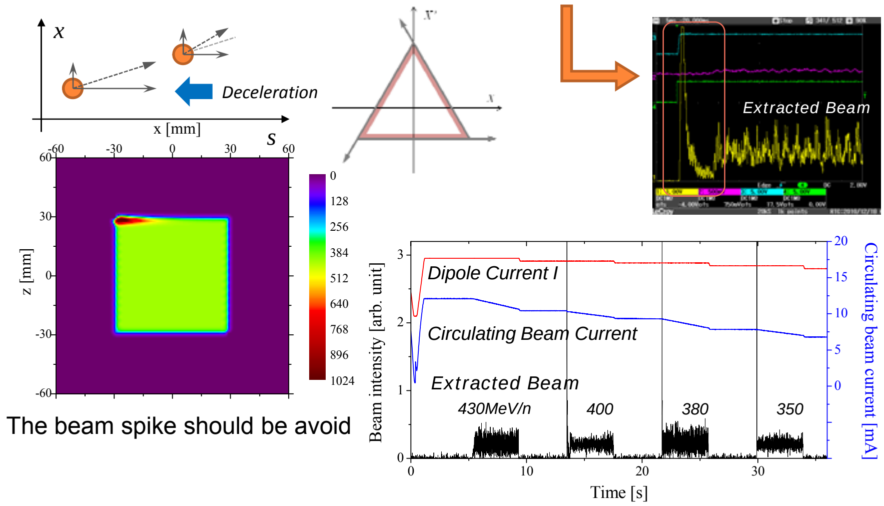




Problem in Deceleration Operation

Emittance growth due to deceleration

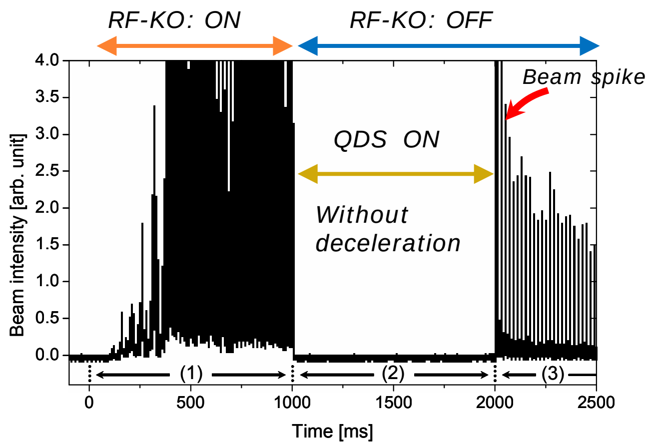
Beam Spike after Deceleration



The beam spike should be avoid

Beam Spike Problem

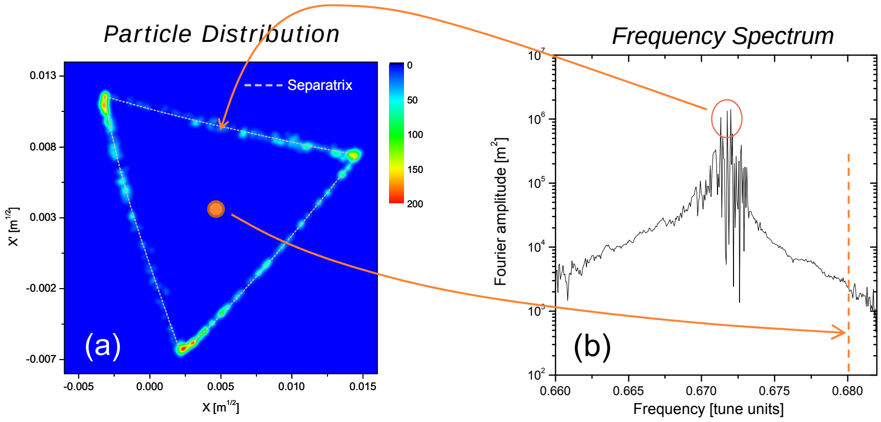
Beam spike is observed not only just after deceleration, but also just after turning QDS off.



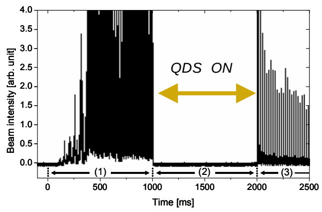
Source of Beam Spike

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

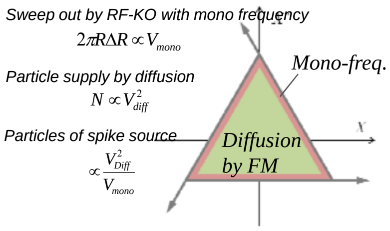


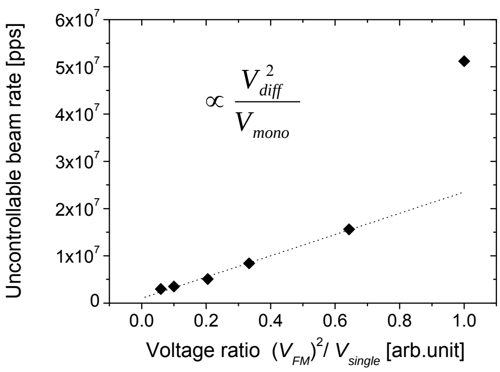
Beam-Spike Suppression



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

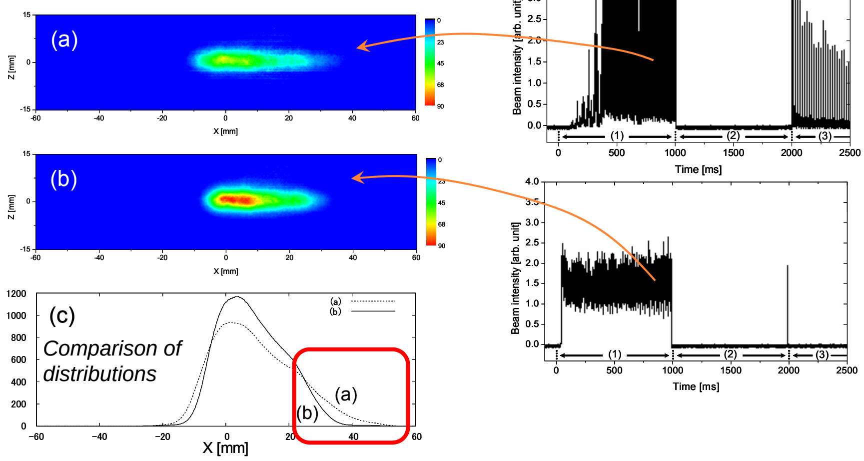
Increasing the ratio V_{mono}/V_{diff}, beam spike can be suppressed.





Particle Distribution during Extraction

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



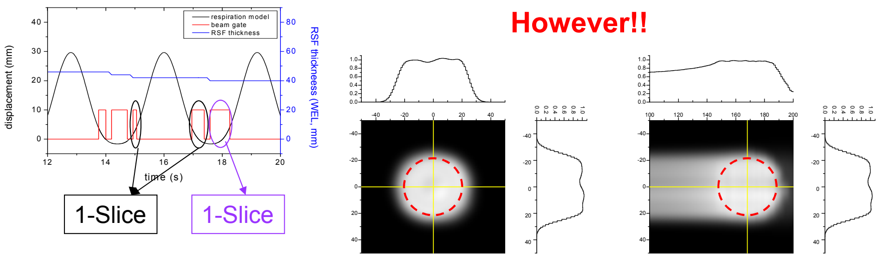
Particle-density reduction was verified in the tail region

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



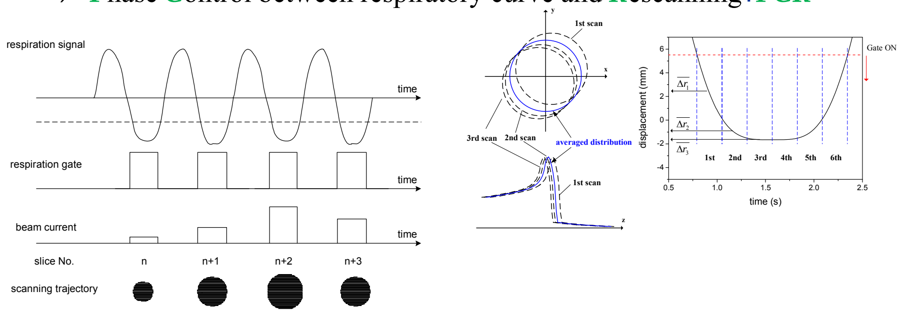
Why?
Different position in each slice

We could not obtain uniform distribution.

Phase Control Rescanning

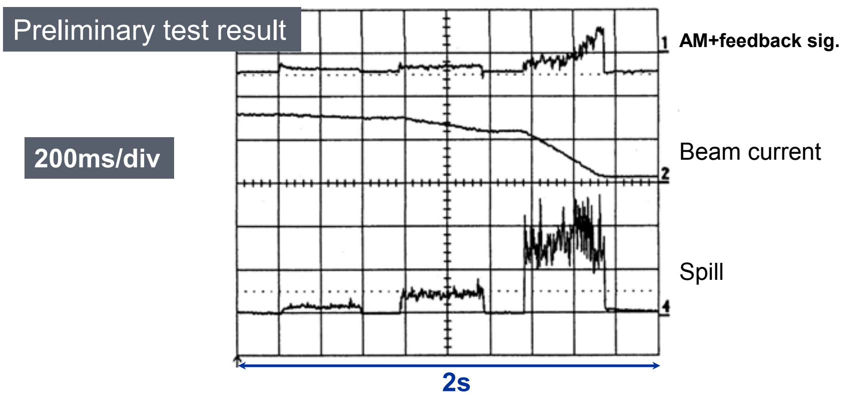
Target position should be closed to "ZERO" on average during one slice irradiation

⇒ ***P***hase ***C***ontrol between respiratory curve and ***R***escanning : ***PCR***



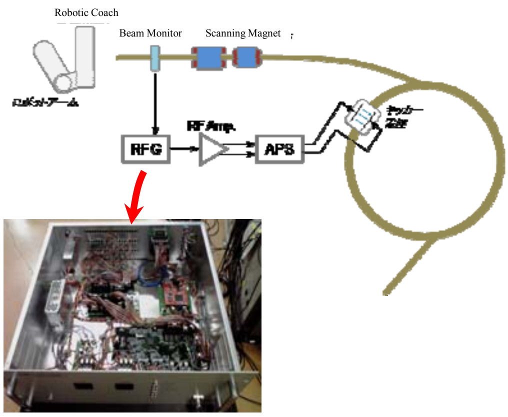
Intensity modulation should be required, because almost same irradiation time is required in each slice irradiation even in different cross section in each slice.

Intensity Modulation by applying global spill control



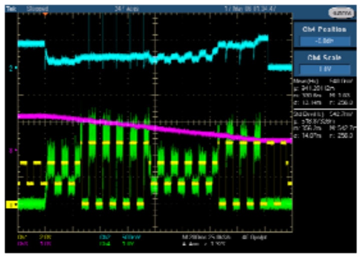
Now, we develop intensity control system during a single flattop. Based on simple model, AM function is analytically calculated to control intensity. Dynamic range of more than 10 is expected.

Prototype Spill-Control System



RF Signal Generator with amplitude feedback control

Applying PI feedback control, the system can modulate the **intensity range of 4 times** with less than 20% ripple.

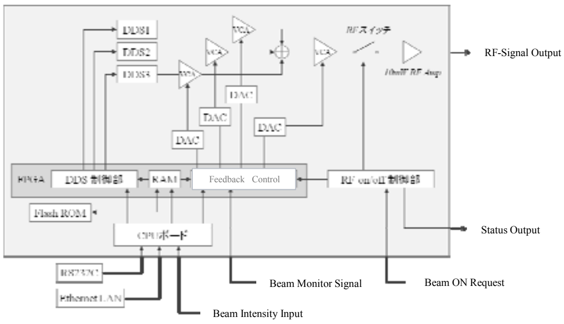


This system was required the intensity modulation range of 20 times with less than ripple magnitude of 20%, which is realized by suppression method for both spill ripple and beam spike !!

New Spill-Control System

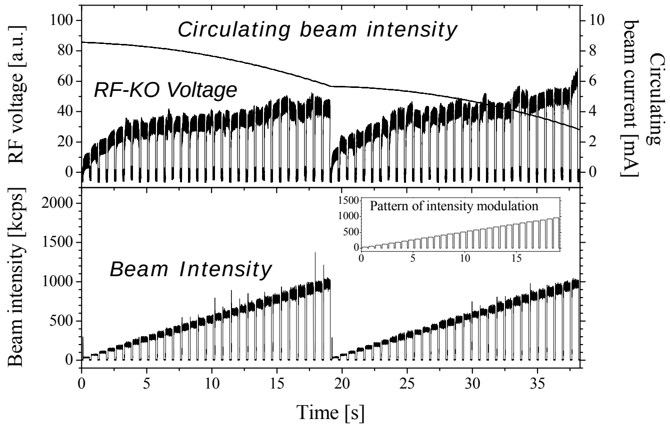
RF Signal Generator

- 3 waves synthesizer applied with DDS
- Amplitude feedback modulation with 10kHz-period
- Intensity control trough PI-control



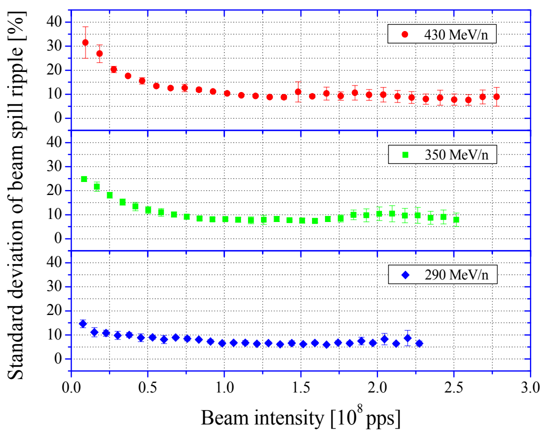
Intensity Modulation Experiment

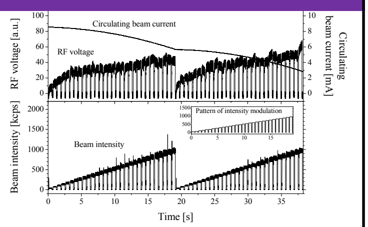
- Intensity modulation ranging from 2 times of routinely delivered intensity to 1/15 of that, corresponding to the total modulation range of 30 times
- Estimating spill-ripple magnitude in each intensity

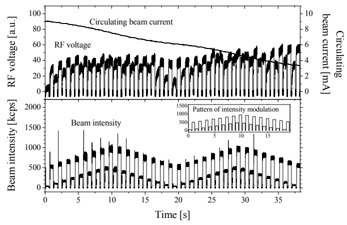


Intensity Modulation Experiment

- Measurements in 430,350,290MeV/n
- Intensity modulation with 30 times

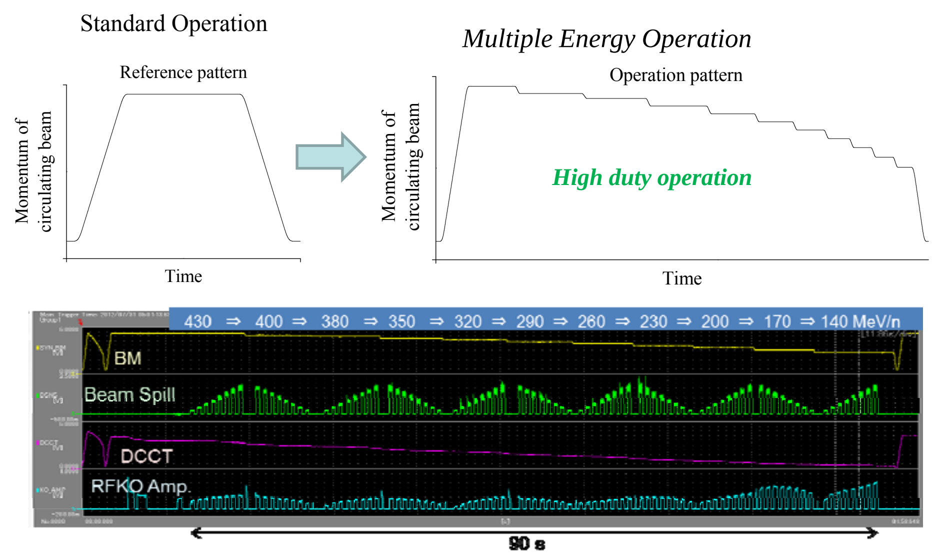




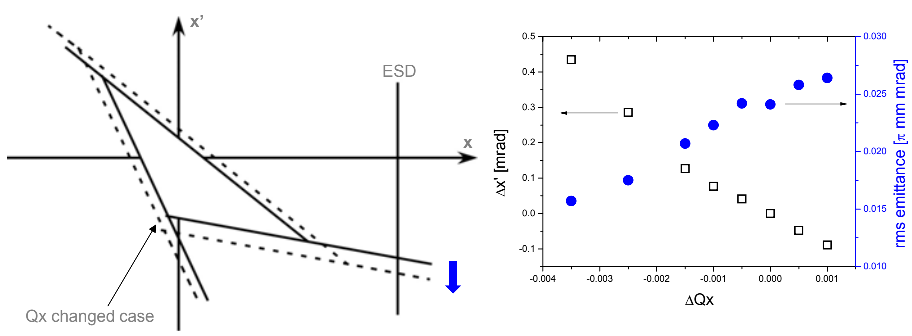


Intensity modulation with more than 20 times was successfully achieved with less that 20% of spill-ripple magnitude !!

Multistep Energy Operation with Intensity Modulation



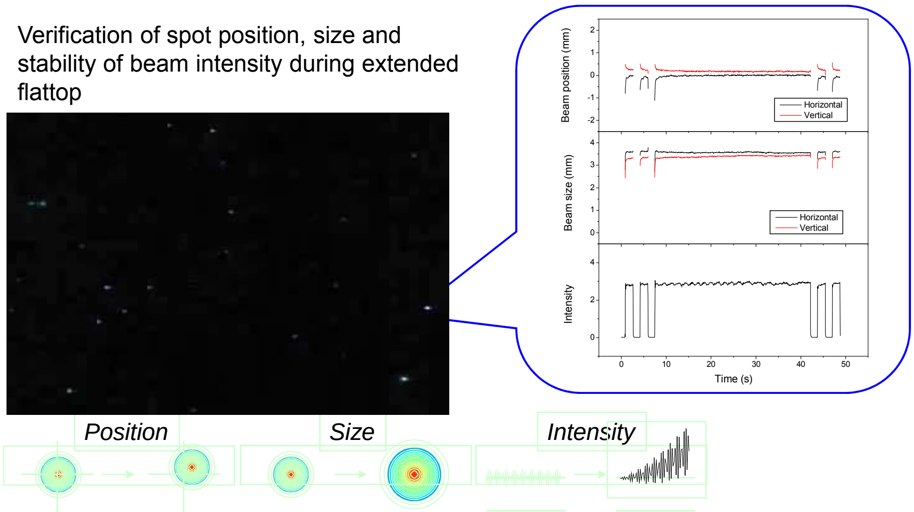
Ⅵ. Precise Position Control



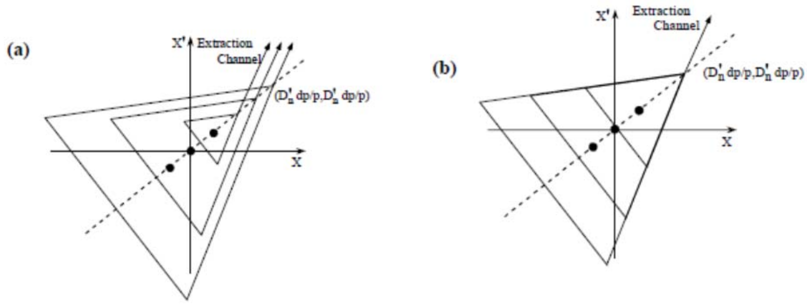
1. Small deviation of magnet field brings tune difference.
2. Slow-extraction is very sensitive to tune difference.
3. It brings change of the extraction angle and emittance.
4. Beam position and size is change at iso-center.

Stability of Beam Position and Profile

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



Hardt Condition

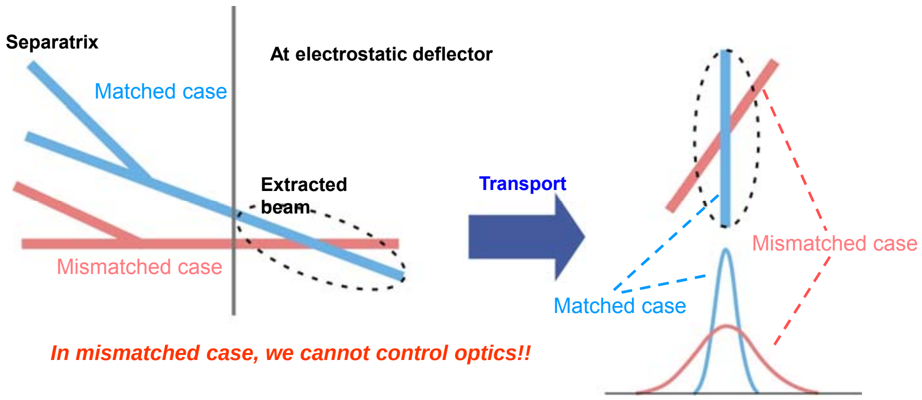


$$D_n \cos(\Delta\mu) + D_n' \sin(\Delta\mu) = -\frac{4\pi}{S_n}\xi_x \qquad -\tan\left(\Delta\mu + \frac{2n\pi}{3}\right) = \frac{D_n'}{D_n}$$

$$S_n = \frac{l_s}{2B\rho}\beta^{3/2}B''$$

D_n, D_n’; Normalized dispersion function
Δμ: Phase advance from the separarix exciter to extraction channel.
S_n: Normalized sextupole field
ξ: Chromaticity

Ⅶ. Precise Beam-Profile Control



In mismatched case, we cannot control optics!!

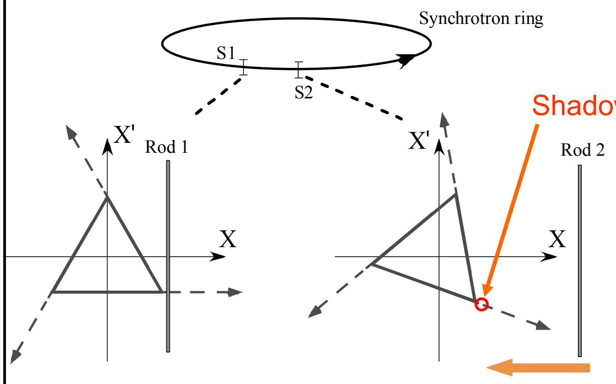
In order to control beam size at HEBT, it is necessary to define optical parameters of extracted beam at the extraction channel as initial condition of HEBT.

Measurement method of outgoing separatrix was proposed and verified.

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.

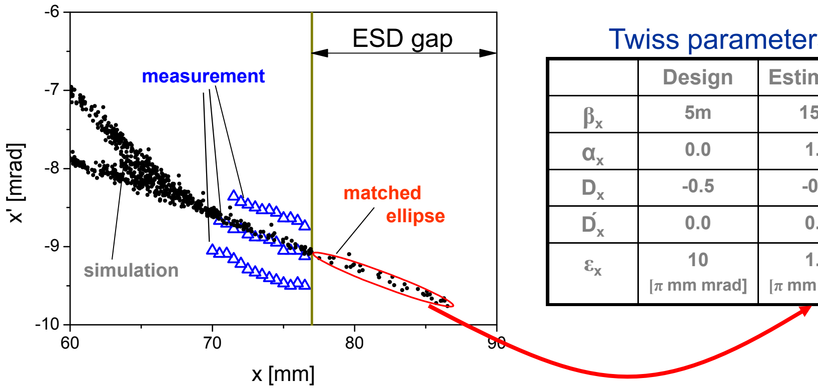
$$x_1' = \frac{x_2 - x_1}{\Delta L}$$



In this way, outgoing separatrix can be measured owing to constant separatrix.

Estimation of Twiss Parameters

Comparing simulation with measurement, twiss parameters was defined.

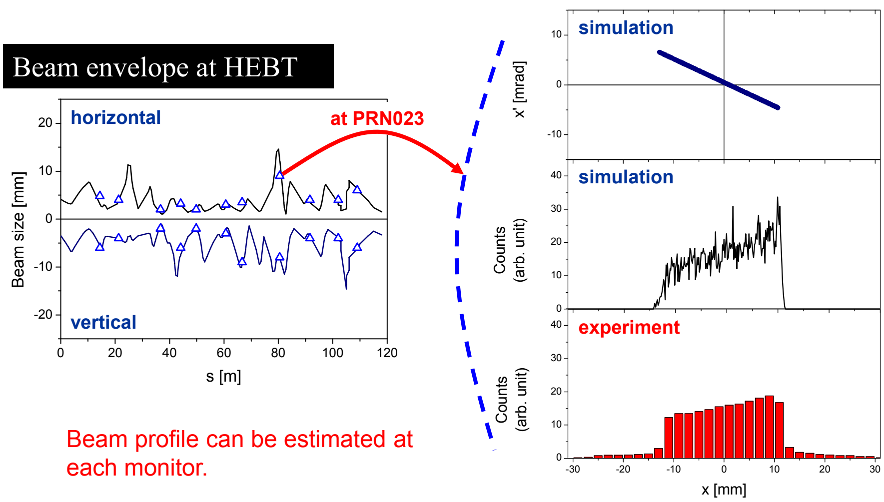


Twiss parameters

	Design	Estimated
β_x	5m	15m
α_x	0.0	1.0
D_x	-0.5	-0.5
D'_x	0.0	0.2
ε_x	10 [π mm mrad]	1.5 [π mm mrad]

Optics was redesigned to match the extracted beam.

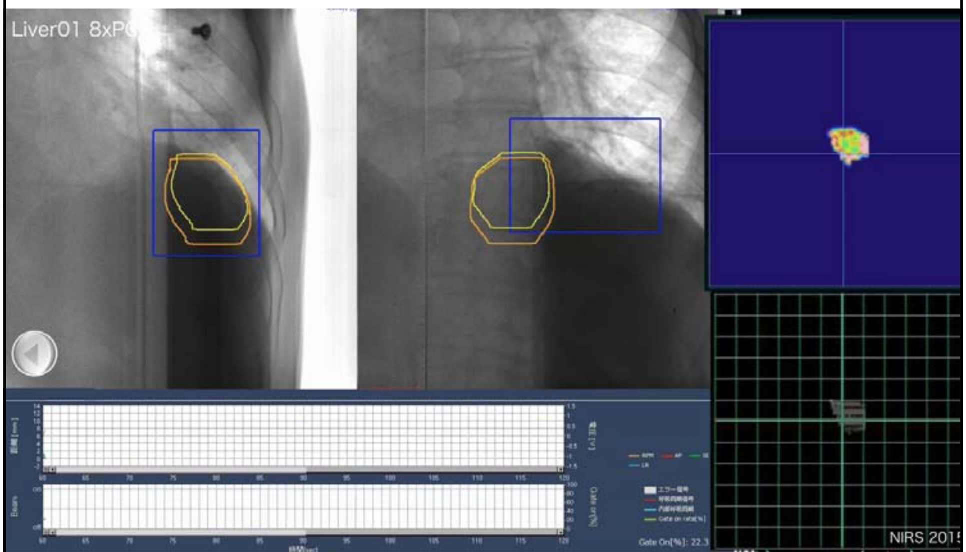
Matching with Transport System



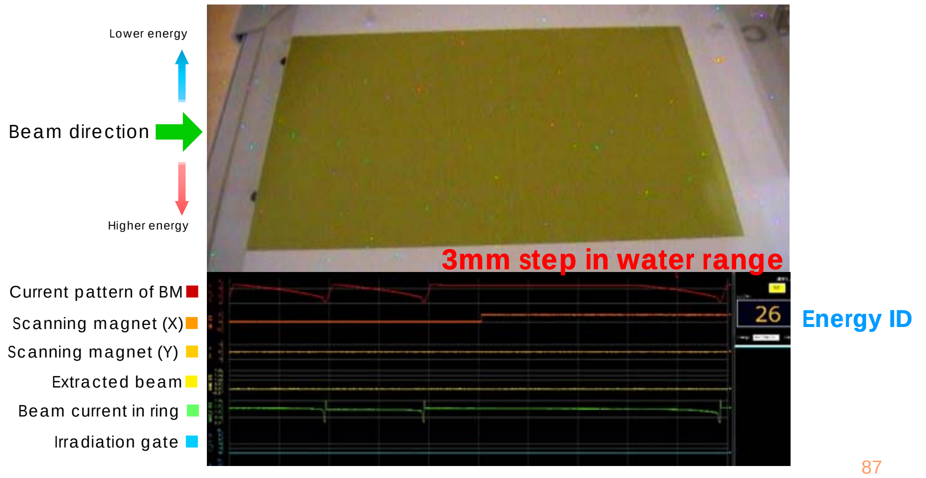
Beam profile can be estimated at each monitor.

Contents

3D Scanning for Moving Tumor



Full Energy Depth Scan



87

Superconducting Rotaing Gantry

88

Superconducting Rotaing Gantry

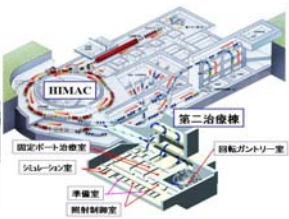
39

NIRS Technology Development

HIMAC

Standard-version@Gunma

New Treatment System



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

1994~

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

+

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

Advanced Standard Version

3rd Integer Resonant Slow Extraction - Analysis -

$$\frac{d^2x}{ds^2} + K(s)x = g(x,s)$$

$$\frac{d^2X}{d\theta^2} + Q^2X = Q^2\beta^{\frac{3}{2}}g(X,\theta)$$

$$X = \frac{x}{\sqrt{\beta(s)}}, \theta = \int \frac{ds}{Q\beta}$$

$$X = \mathrm{r}\cdot\cos(Q\theta + \phi) \equiv r \cdot cos\Phi$$

$$X' = \mathrm{r}\cdot sin(Q\theta + \phi) \equiv r \cdot sin\Phi$$

$$r = \sqrt{X^2 + X'^2}$$

$$\binom{X}{X'} = \frac{1}{\sqrt{\beta}}\begin{pmatrix}1 & 0\\ \alpha & \beta\end{pmatrix}\binom{x}{x'}$$

$$\frac{dr}{d\theta} = -Q\beta^{\frac{3}{2}}rg(X,\theta)sin\Phi$$

$$\frac{d\Phi}{d\theta} = Q - \frac{Q\beta^{\frac{3}{2}}g(X,\theta)cos\Phi}{r}$$

$$g(x,s) = \sum_j S_j x^2 \delta(s - s_j)$$

$$g(X,\theta) = \sum_j S_j \beta X^2 f(\theta - \theta_j)$$

$$\frac{dr}{d\theta} = -\frac{r^3}{4\pi}\sum_j S_j\,\beta^{\frac{3}{2}}\sin(3\Psi + p\theta_j)$$

$$\frac{d\Psi}{d\theta} = q - \frac{r}{8\pi}\sum_j S_j\beta_j^{3/2}\cos(3\Psi + p\theta_j)$$

$$\Psi = \Phi - \frac{p}{3}\theta = \left(Q - \frac{p}{3}\right)\theta + \phi = q\theta + \phi$$

Koji Noda,
Dept. Accelerator and Medical Physics, NIRS

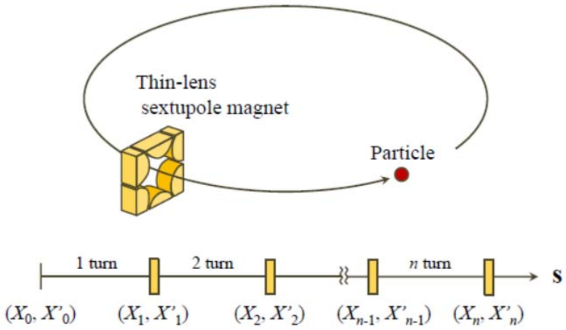
Characteristics of Third-Integer Resonant

$$\begin{pmatrix} X \\ X' \end{pmatrix} = \frac{1}{\sqrt{\beta}} \begin{pmatrix} 1 & 0 \\ \alpha & \beta \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}$$

Normalized phase space

$$M = \begin{pmatrix} cos2\pi Q & sin2\pi Q \\ -sin2\pi Q & cos2\pi Q \end{pmatrix}$$

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



$$\begin{pmatrix} \tilde{X}_n \\ \tilde{X}'_n \end{pmatrix} = M_X^n \begin{pmatrix} X_0 \\ X'_0 \end{pmatrix} + S_X \sum_{m=1}^{n} M_X^{n-m} \begin{pmatrix} 0 \\ X_m^2 \end{pmatrix}.$$

Third-Integer Resonant Slow Extraction

$$Q = \frac{p}{3} + q, \varepsilon = 6\pi q \qquad \begin{pmatrix} X \\ X' \end{pmatrix} = \frac{1}{\sqrt{\beta}} \begin{pmatrix} 1 & 0 \\ \alpha & \beta \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}$$

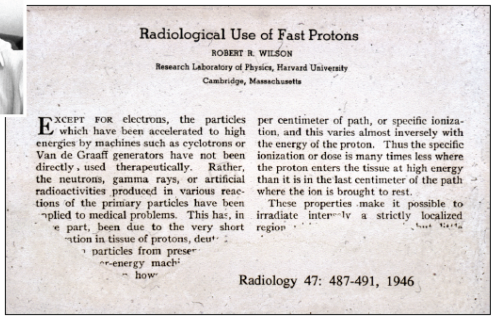
1) After 3 turns

$$\begin{pmatrix} X \\ X' \end{pmatrix} = M^3 \begin{pmatrix} X_0 \\ X'_0 \end{pmatrix} = \begin{pmatrix} 1 & \varepsilon \\ -\varepsilon & 1 \end{pmatrix} \begin{pmatrix} X_0 \\ X'_0 \end{pmatrix} \quad \begin{pmatrix} cos6\pi Q & sin6\pi Q \\ -sin6\pi Q & cos6\pi Q \end{pmatrix} = \begin{pmatrix} 1 & \varepsilon \\ -\varepsilon & 1 \end{pmatrix}$$

$$M = \begin{pmatrix} 1 & \varepsilon \\ -\varepsilon & 1 \end{pmatrix} \begin{pmatrix} X_0 \\ X'_0 \end{pmatrix}$$

Hadron RT proposed by R. Willson

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

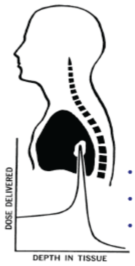
Cambridge, Massachusetts

EXCEPT FOR electrons, the particles which have been accelerated to high energies by machines such as cyclotrons or Van de Graaff generators have not been directly, used therapeutically. Rather, the neutrons, gamma rays, or artificial radioactivities produced in various reactions of the primary particles have been applied to medical problems. This has, in e part, been due to the very short ation in tissue of protons, deu particles from prese r-energy mach how

per centimeter of path, or specific ionization, and this varies almost inversely with the energy of the proton. Thus the specific ionization or dose is many times less where the proton enters the tissue at high energy than it is in the last centimeter of the path where the ion is brought to rest.

These properties make it possible to irradiate inter ly a strictly localized region

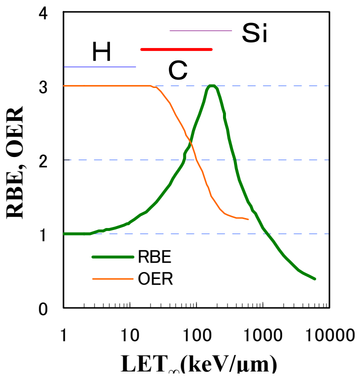
Radiology 47: 487-491, 1946



- Dose localization
- Low entrance dose
- No or low exit dose

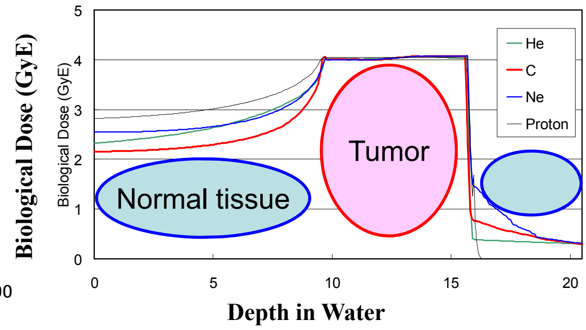
In 1946, R. Willson proposed the hadron RT owing to excellent physical characteristics

Biological Characteristics



LET Dependence of RBE & OER

Biological Depth-Dose Distribution of 6cm SOBP



Carbon-ion has highest contrast between bio-dose in normal and tumor tissue

Photo of New Treatment Research Facility


Building facade with green curtain

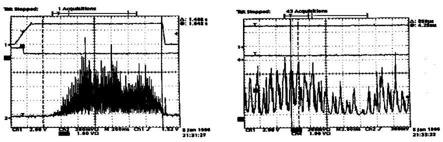

Entrance hall (1F)


Waiting hall (B2F)


Treatment Room E (B2F)

Adverse Dose Distribution Effect by Spill Ripple

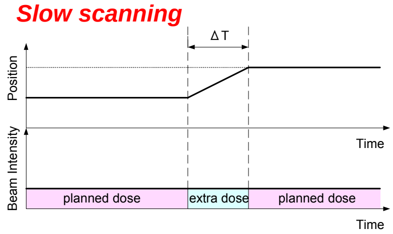
T. Inaniwa et al., Med. Phys. 34(8), 3302

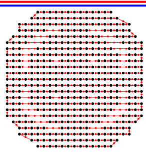

Time Scale:200 ms/div   Time Scale:2 ms/div

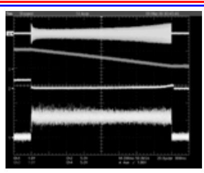
Extra-dose cannot be controlled ⇒

Because of huge spill ripple

Slow scanning

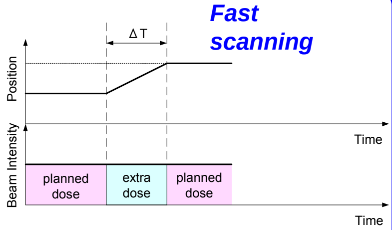






Flat spill structure:
⇒It is possible to predict extra-dose during moving between spot positions.

Fast scanning

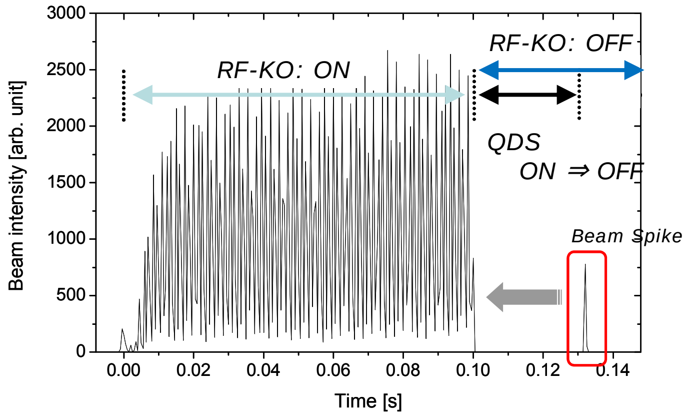


Experimental Condition

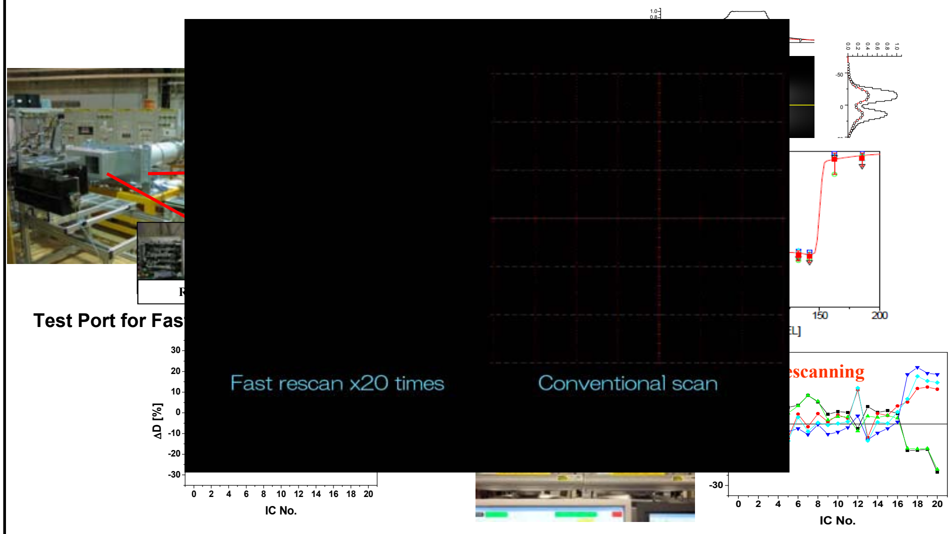
- Beam — C^{6+} 400 MeV/n
- Bare Tune — (3.681, 3.130)
- f_{rf} — 6.6118 (MHz) : Longitudinal RF Frequency
- f_{rev} — 1.6530 (MHz) : Revolution Frequency
- V_{rf} — ±4 (kV) : Longitudinal RF Voltage
- f_s — 1.46 (kHz) : Freq. of Synchrotron Oscillation
- f_k — 1.115 – 1.135 (MHz) : Transverse RF
- Δf_k — 4 – 28 (kHz) : Bandwidth (Typical value)
- V_k — 1200 (Vpp) : RF-KO Voltage (Typical value)
- ξ_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}) : *$K_2 = B''/(B\rho)$

Simulation Study for Beam Spike

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

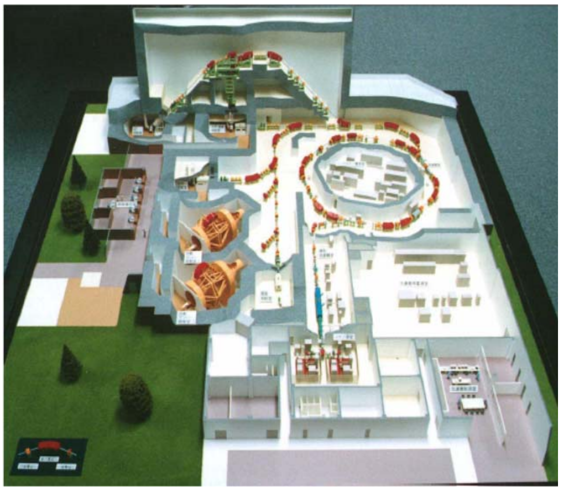


Verification of 3D Scanning for Moving Tumor



NIRS HIMAC

Hyogo Ion Beam Medical Center



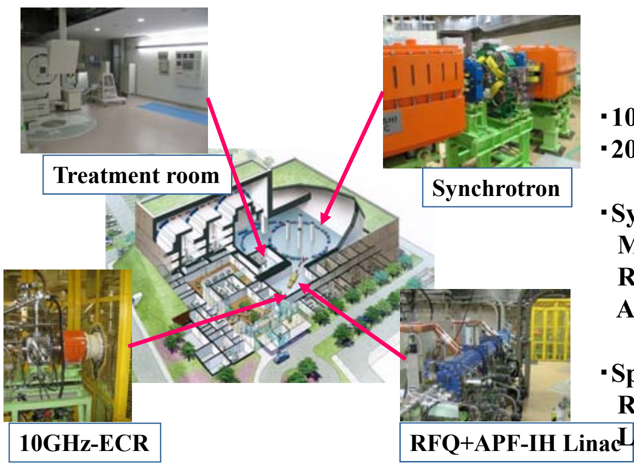
1) Proton:
   Energy: 230 MeV
   2 Gantry + 1 H
2) Carbon
   Energy: 320 MeV/n
   1 H&V, 45º line

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

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

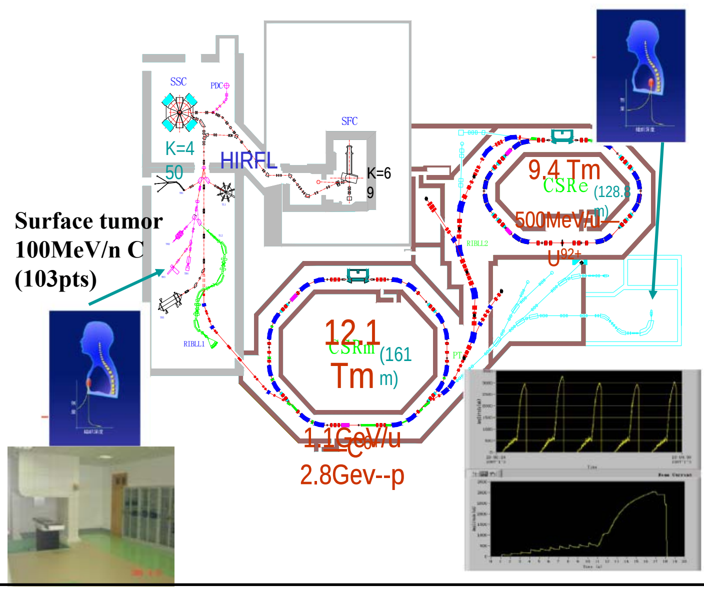
NIRS HIMAC

Gunma Uni. Heavy-Ion Medical Center



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

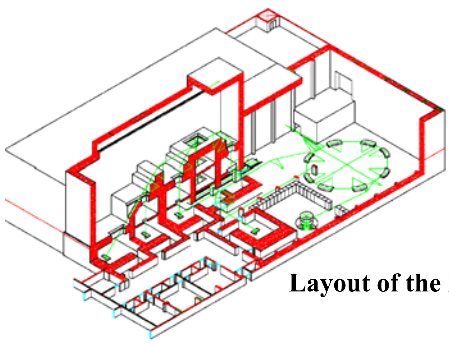


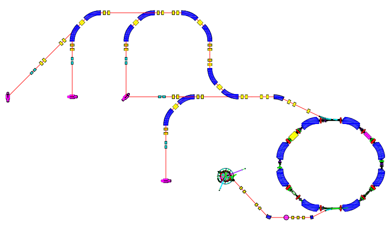
Deeply seated tumor
430MeV/n C (45pts)
Cooler-Synchrotron

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

HITFiL project

Heavy Ion Therapy Facility in Lanzhou (HITFiL)





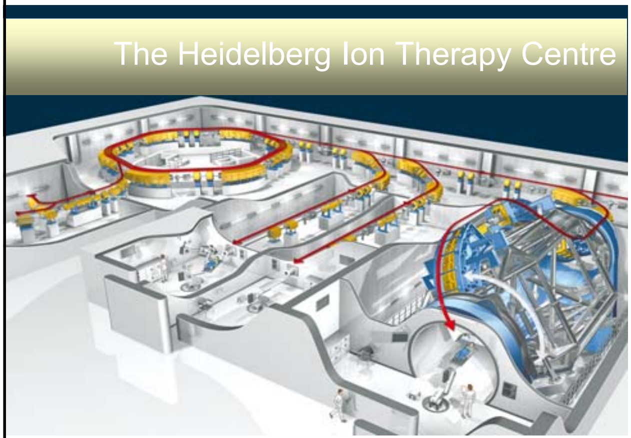
Layout of the HITFiL project

Four treatment rooms:

horizontal, horizontal+vertical, vertical and oblique beam lines

NIRS HIMAC

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

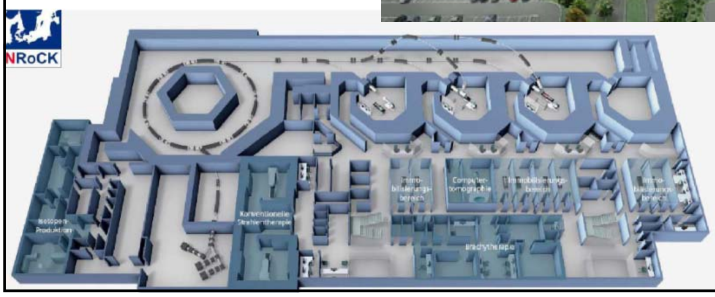
- Variable Energy Operation
- Variable FT (1-10s)
- Variable Intensity
- Variable Beam Size

Based on GSI treatments of 400pts since'97,
HIT was constructed and initiated carbon-ion RT.

NIRS HIMAC

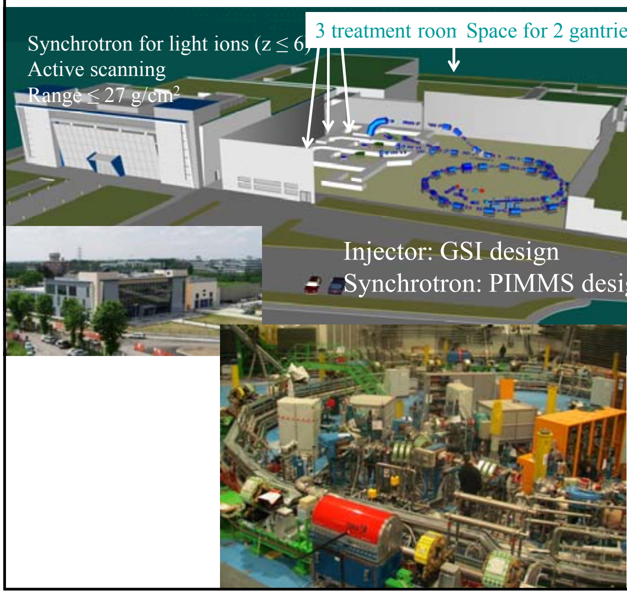
New Projects by Siemens

Shanghai



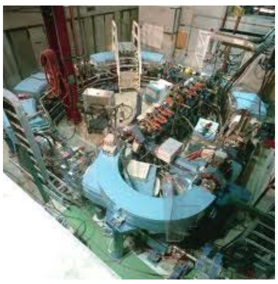
Kiel

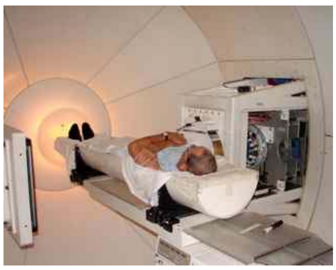
CNAO Facility



- 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

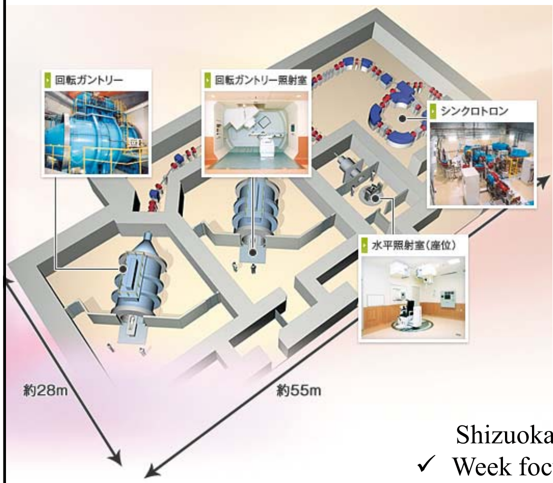




Loma Linda University Medical Center was opend in 1990

NIRS HIMAC

Proton RT Facility by MELCO



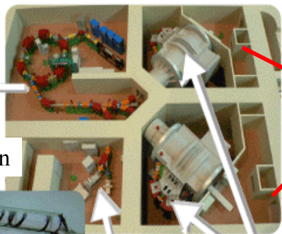
Shizuoka, S-Tohoku, Fukui, Ibusuki

- ✓ Week focusing: High intensity (17nA)
- ✓ Accel_driven extraction
- ✓ APF-IH Linac for proton

NIRS HIMAC

Proton RT Facility by Hitachi

Model



70-250MeV Synchrotron

Rotating Gantry

Beam Line for Reseach

U. Tsukuba, MDACC, Nagoya, Hokkaido

*Variable FT operation pre-triggered by respiration

* Variable energy operation for 3D scan