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Compact Hadron Driver for Cancer Therapies using Energy Sweep Scanning

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and collaborators
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Content

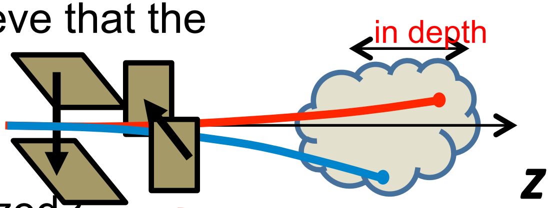
I. Motivation and Background (4 min)
II. Development of Key Technology (5 min)
(Induction Synchrotron)
III. Idea of Quick and Continuous Energy Sweeping
IV. Design of Dedicated Hadron Driver
V. Beam Extraction and Spill Control Simulation
VI. Summary and Prospect (1 min)

High light (10 min)

Motivations

Overview and our understanding:

- A cancer therapy has notably evolved through the last three decades.
- Various ideas have been explored and materialized in commercially available cancer therapies.
- Experts in research labs.and industry have been very eager to develop the related technology.
- We would like to appreciate their big efforts. However, we don't believe that the technology has already arrived at a **level of state of art**.



Our questions on the current cancer therapies:

1.Why is **continuous 3D spot scanning (*especially in depth*)** not realized?
2.Shooting of driver beams on a **moving target (*quick irradiation*)**is impossible?
3.Is a gigantic and very expensive **gantry** really necessary in order to concentrate the dose on the tumor?

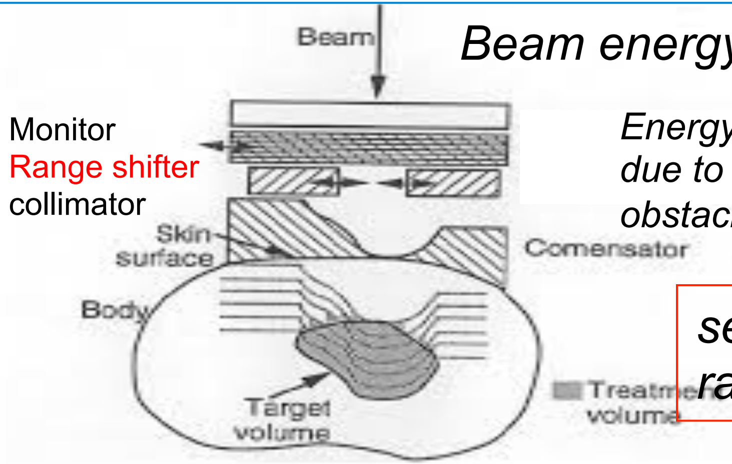
To accelerator physicists like us, **Present status of the technology** seems to result from the following facts;

A) Inherent characteristics of hadron drivers (RF synchrotron or RF cyclotron)
B) Limited diagnosis techniques to identify the position and shape of a tumor
C)Our blind acceptance that a patient lies in his serious condition and his tumor is a stationary target; in the other word, the position of patient can't be largely rotated nor moved for treatment **(This may be *a kind of mind control*.)**

Existing Technique: Energy Sweep using Range Shifter or Programmed Ramping of Bending

Energy sweep (1): Range shifter (most conventional)

Beam energy E is constant.

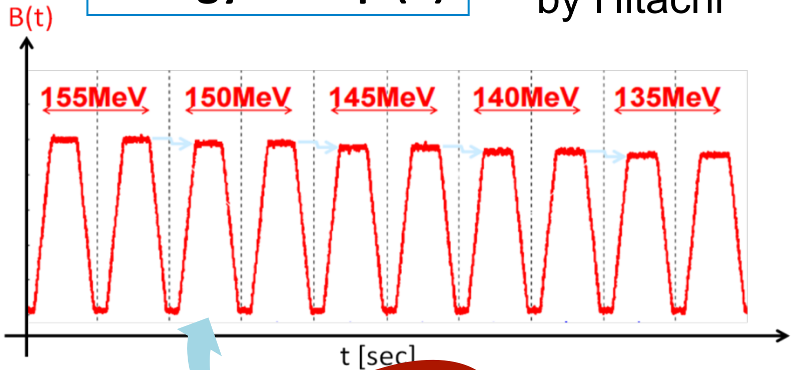


Energy loss due to physics obstacle

serious residual radiation

Energy sweep (2)

by Hitachi

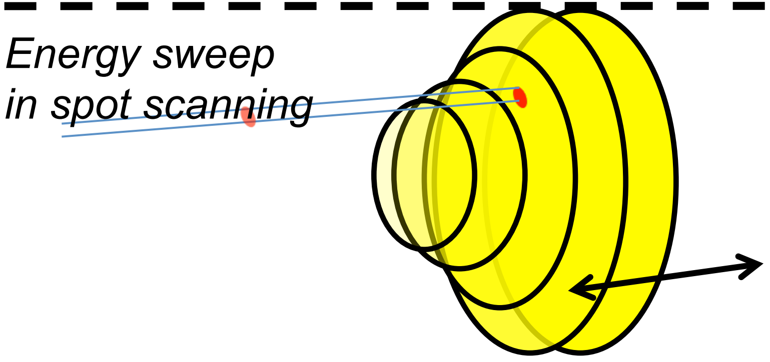


$E \sim B_{max}$

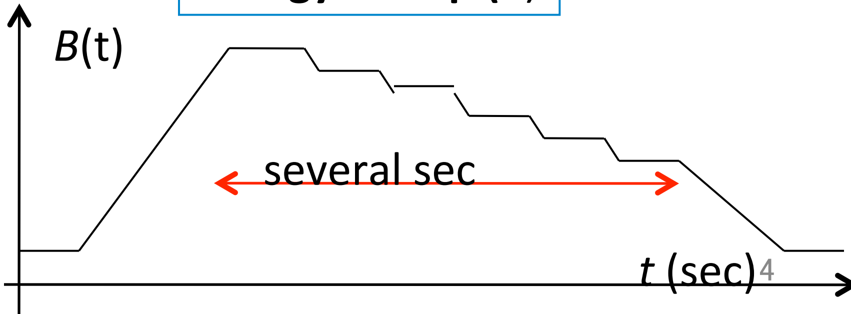
discrete

Energy sweep (3)

by NIRS

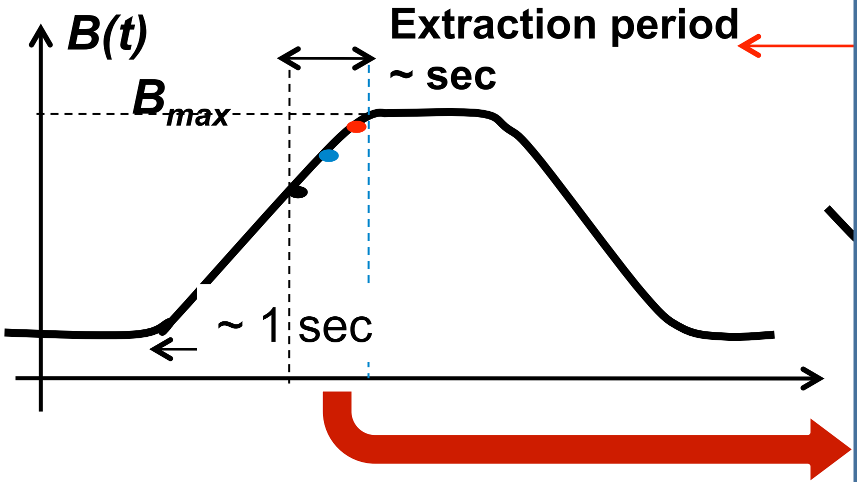


Sweep in depth → Energy sweep

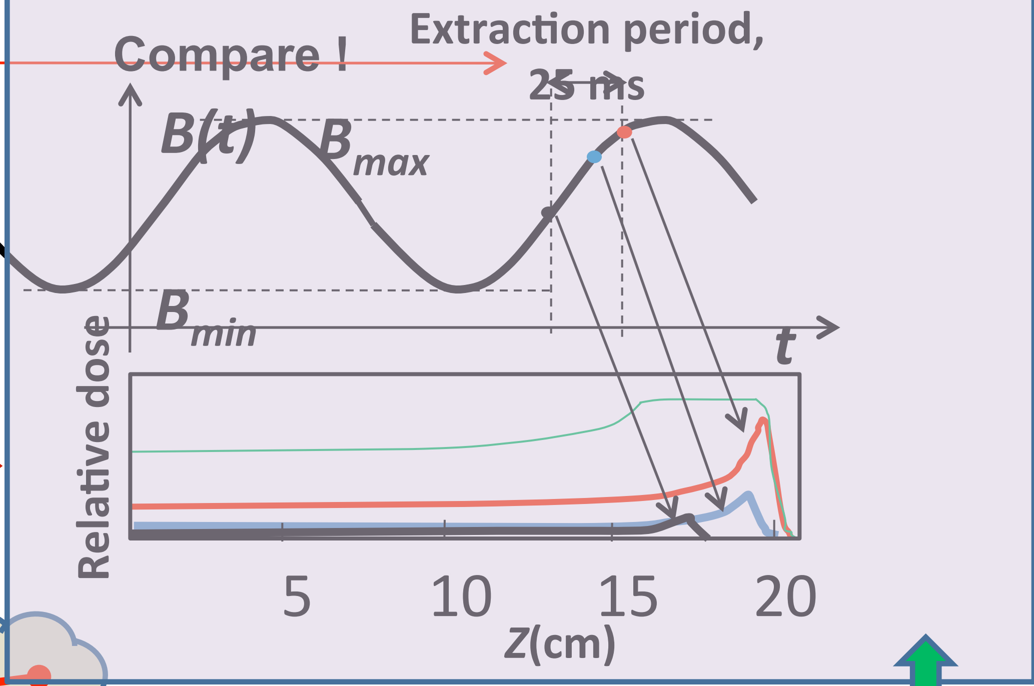


Proposed Technique: Continuous Energy Sweep

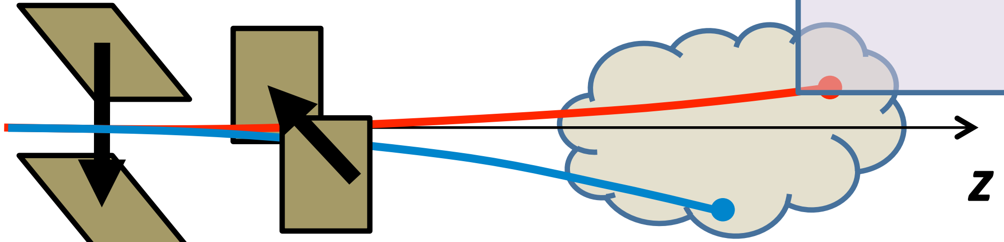
In Slow Cycling Synchrotron



In Fast Cycling Synchrotron



focused today



Horizontal scan **Vertical scan** **Depth scan due to energy sweep**

Summary of Characteristics of Hadron Drivers for Therapy

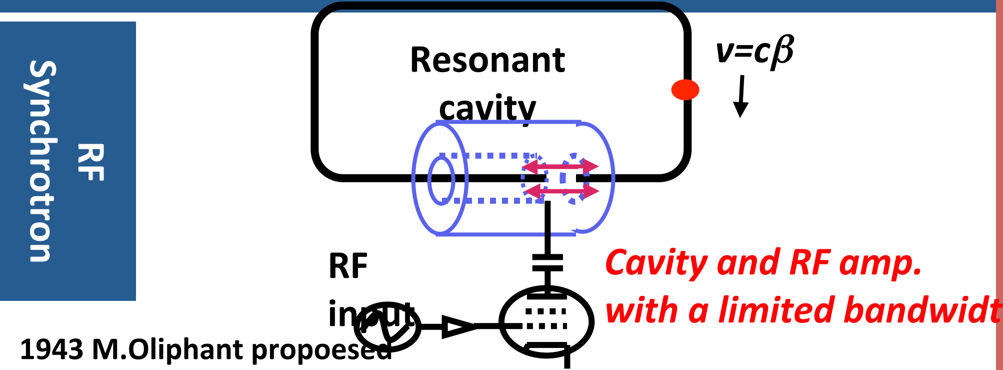
Classification	Acceleration/ Confinement	Bending field	Sweep in depth	3D continuous spot scanning (CSS)	Irradiation on moving target	3D CSS on moving target	Remark
Slow cycling synchrotron Current drivers 0.3 Hz – 1 Hz intensity per pulse is large by 10 times.	**RF** (Proposed in 1945, demonstrat-ed just after)	fixed B_{max}	○ (with range shifter*)	×	×	×	in most of currently working drivers
		variable B_{max}	○ (not continuous)	×	×	×	already demonstrat-ed by Hitachi, NIRS, GSI
	Induction (demonstrat-ed in 2006)	fixed B_{max}	◎ (continuous)	◎	×	×	reduced cost
Fast cycling synchrotron 10-20 Hz Beam intensity per pulse is lower.	**RF**	fixed B_{max}	○ (with range shifter*) **	×	◎	×	No example
	Induction (demonstrat-ed in 2013)	fixed B_{max}	◎ (continuous)	◎	◎	◎	reduced cost (recently designed by KEK)
Remark	Machine itself has been demonstrat-ed	technically not easy to change B_{max}	various ideas	better quality of irradiation	■Respiratory-gated Irradiation is not required, resulting in reduction of irradiation time-period ■allows Gantry-free cancer therapy, resulting in large Cost reduction	ideal therapy	

assumed
realtime monitoring of tumor
fast feedback to beam control

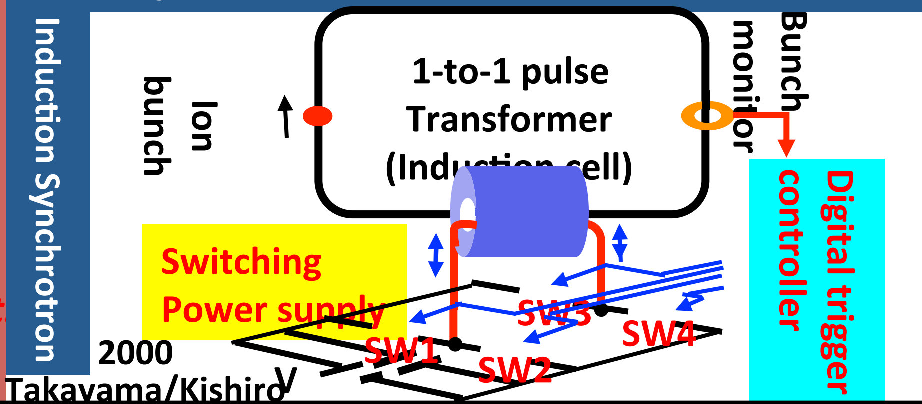
* Problems in Use of Range Shifter:
causing secondary emission and serious residual radiation around the beam handling devices along the beam line

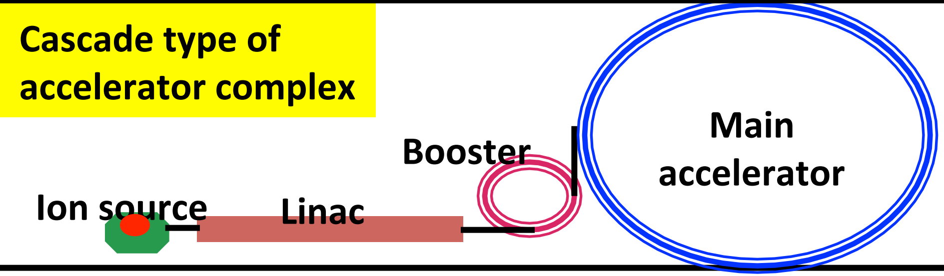
** BNL and Best Medical has proposed energy sweep extraction. Technical details are unknown.

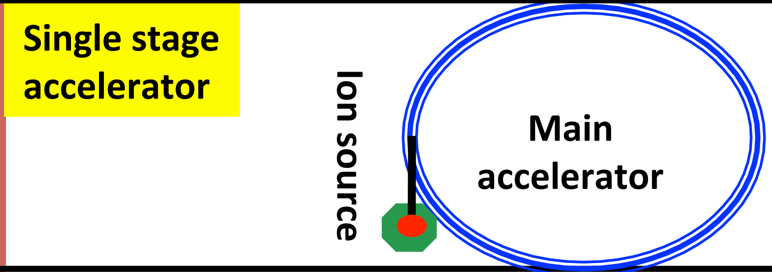
Characteristics of Induction Synchrotron



1943 M.Oliphant propoesed the first proton synchrotron, 1945 E.M.McMillan, V.Veksler (publication)

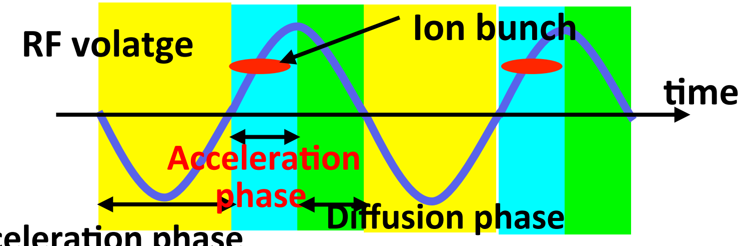


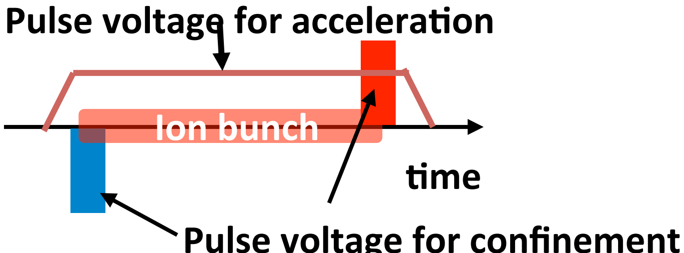




Functionally combined acceleration/confinement -> increase in the local density -> limit on a beam current

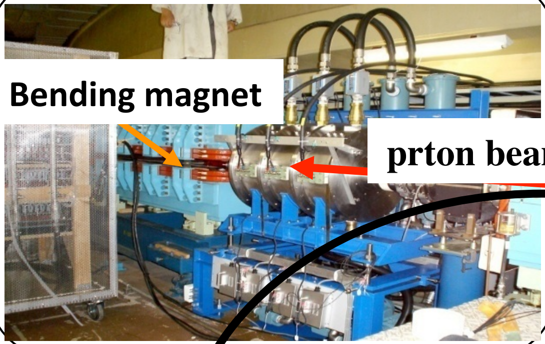
Functionally separated acceleration/confinement -> increasing a freedom of beam handling





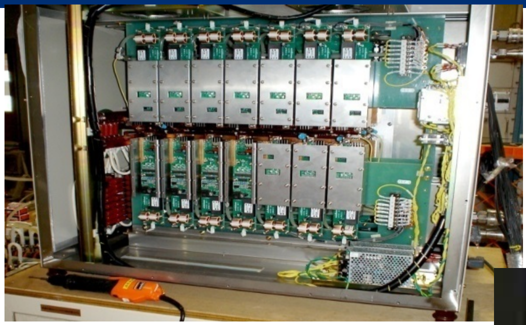
Complete Demonstration of the Induction Synchrotron Concept (2006, March)

ion : H^+
500 MeV -> 6 GeV
$N = 2.5 \times 10^{11}$



Bending magnet

prton beam



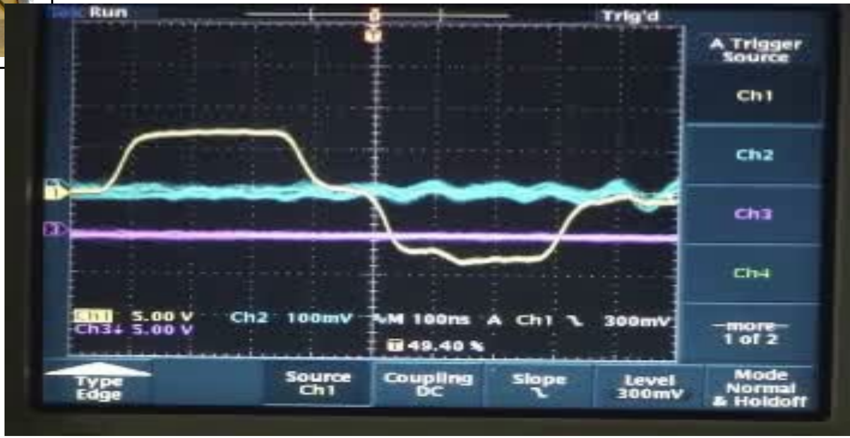
Switching Power Supply
(40kW、Max f_{rep}=1MHz)

500 MeV → 6 GeV

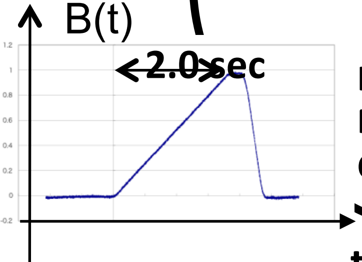
Pulse voltage for confinement

Pulse voltage for acceleration

Proton bunch signal



Induction cell
10 cells
V_{out}= 2kV/cell



KEK 12GeV
Proton Synchrotron
C_0=340m

500MeV
Booster Synchrotron
C_0=37m

40MeV H-Linac

750keV
Cockloft-Walton

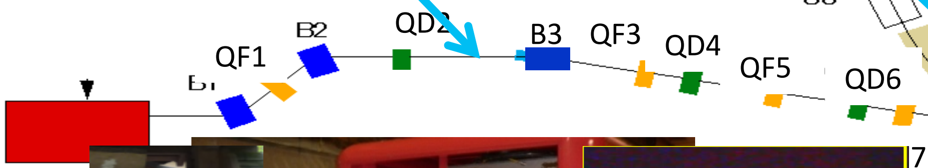
K.Takayama *et al.*, *Phys. Rev. Lett.* 94, 144801 (2005)
Phys. Rev. Lett. 98, 054801 (2007)

KEK Digital Accelerator (Fast Cycling Induction Synchrotron)

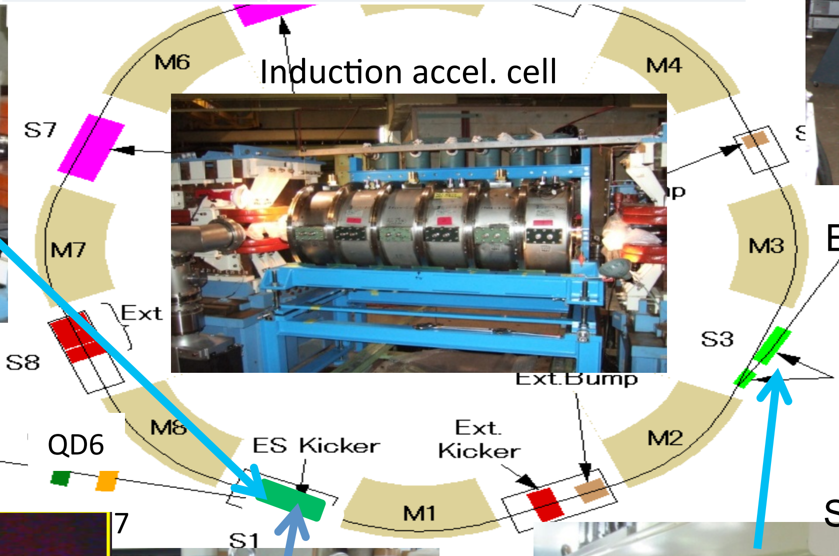
T. Iwashita *et al.*, *"KEK Digital Accelerator", Phys. Rev. ST-AB 14, 071301 (2011).*

Circumference	37.7 m
B_{mx} / Rep-rate	0.84 Tesla / 10 Hz
Mximum energy	315 MeV (p), 2.15 GeV（Gold）

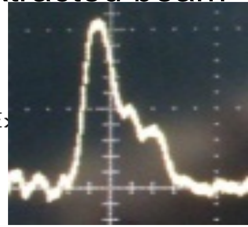
LEBT & ES Kicker



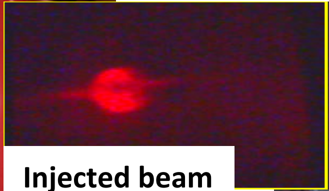
Induction accel. cell



Extracted beam



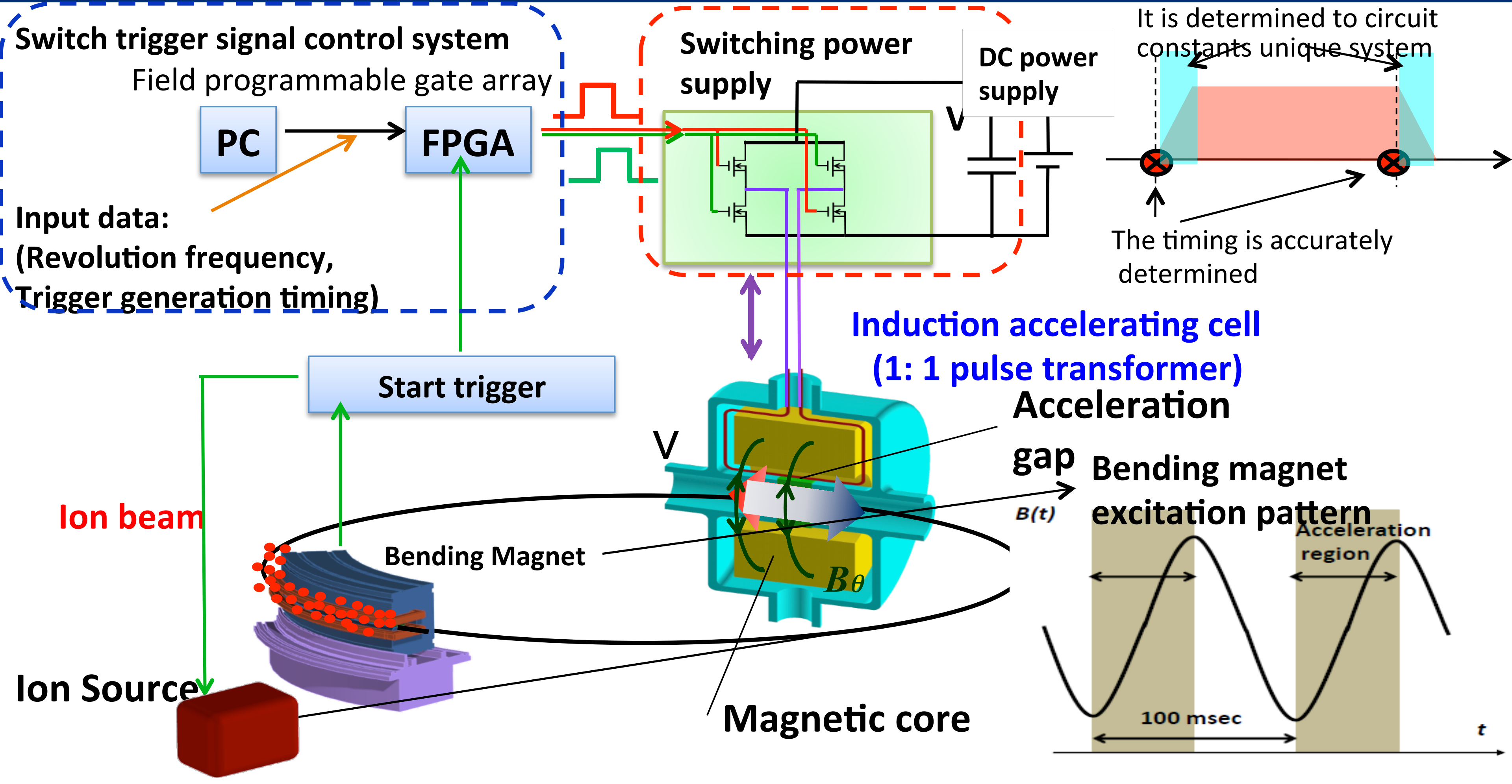
ECRIS & 200 kV HVP



Injected beam

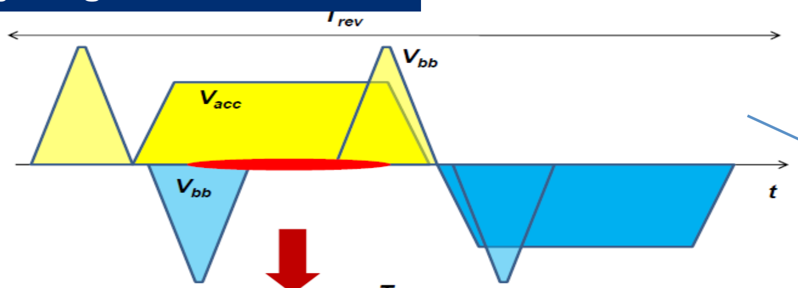
Septum magnet

Schematic View of KEK Digital Accelerator (fast cycling IS) Operation

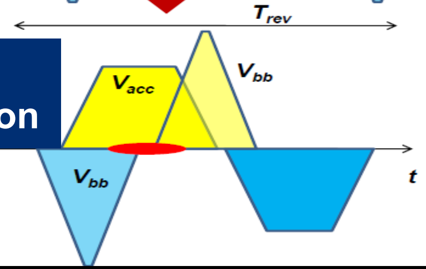


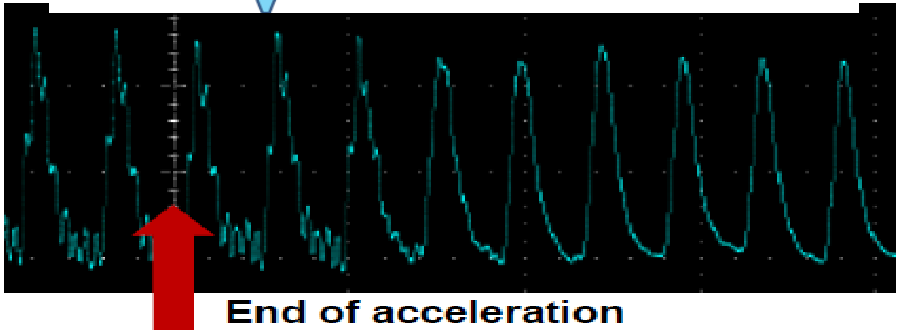
Acceleration of A/Q=4 Ions

1) Early stage of acceleration

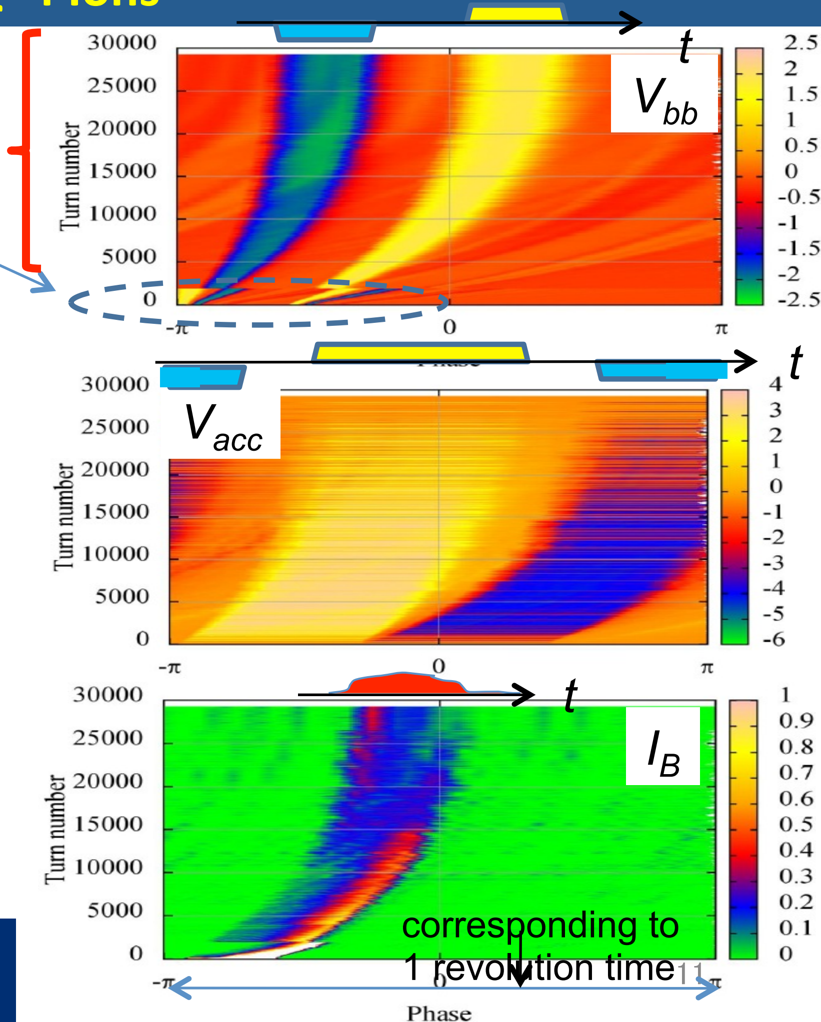


2) Late stage of acceleration





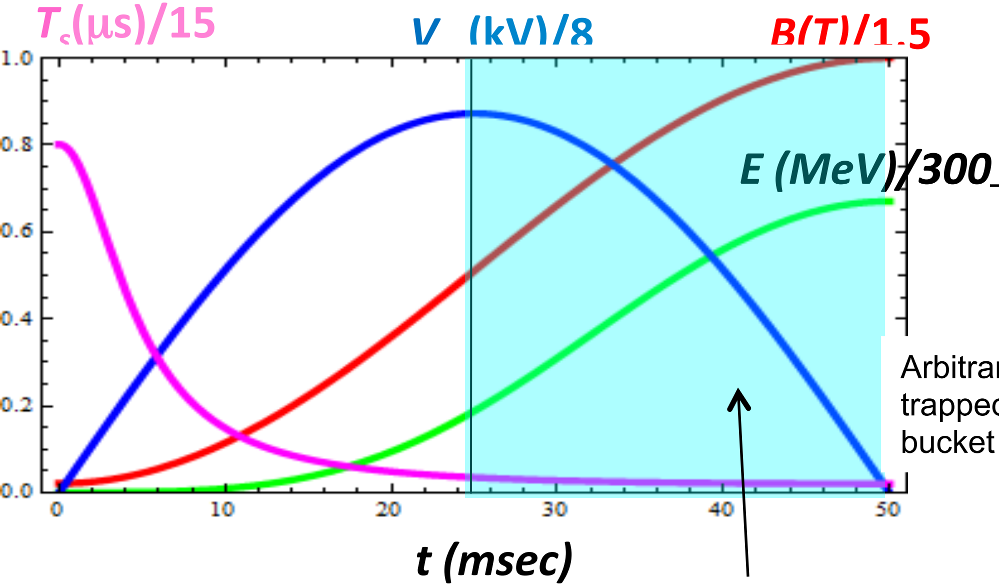
End of acceleration



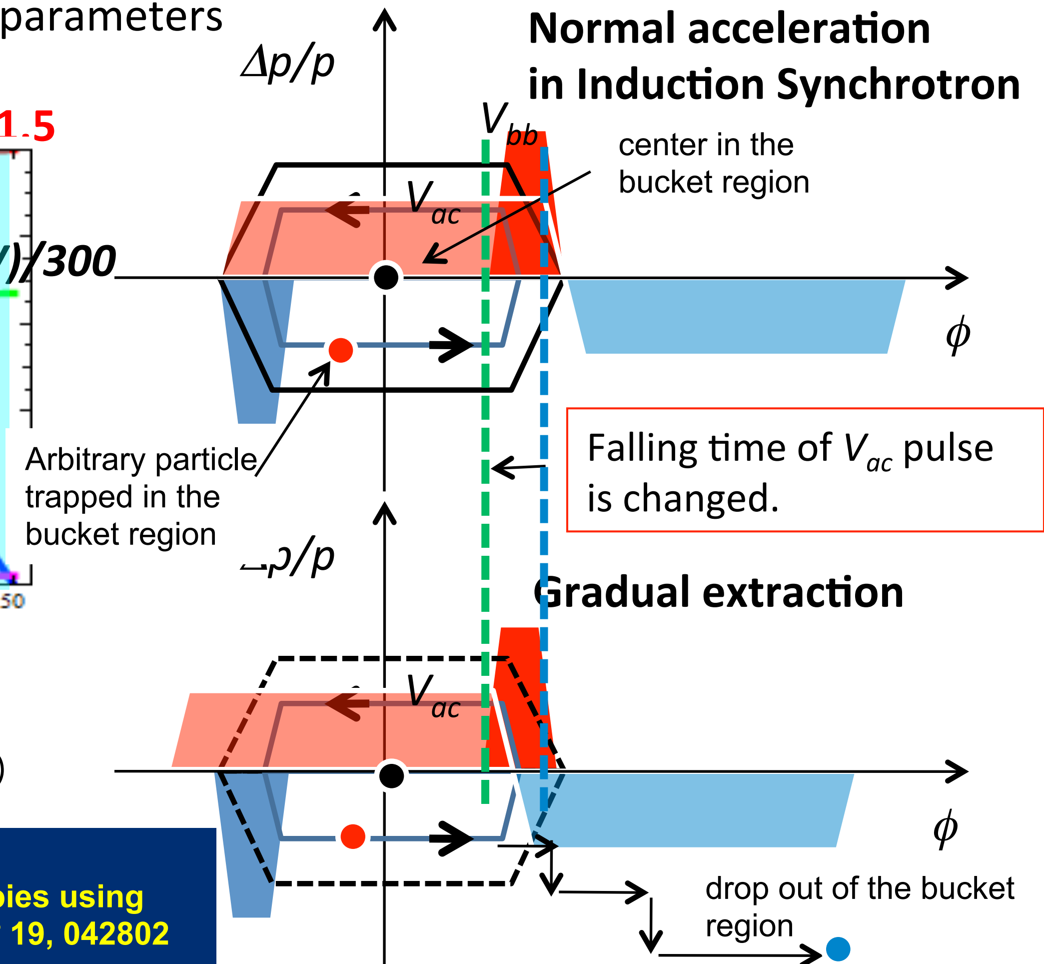
K.Takayama, T.Yoshimoto *et al*., "Induction Acceleration of Heavy Ions in the KEK Digital Accelerator", *Phys. Rev. ST-AB* 17, 010101 (2014)

Idea 1: Particles Dropping out of the Barrier Bucket

Time variation of the accelerator and beam parameters

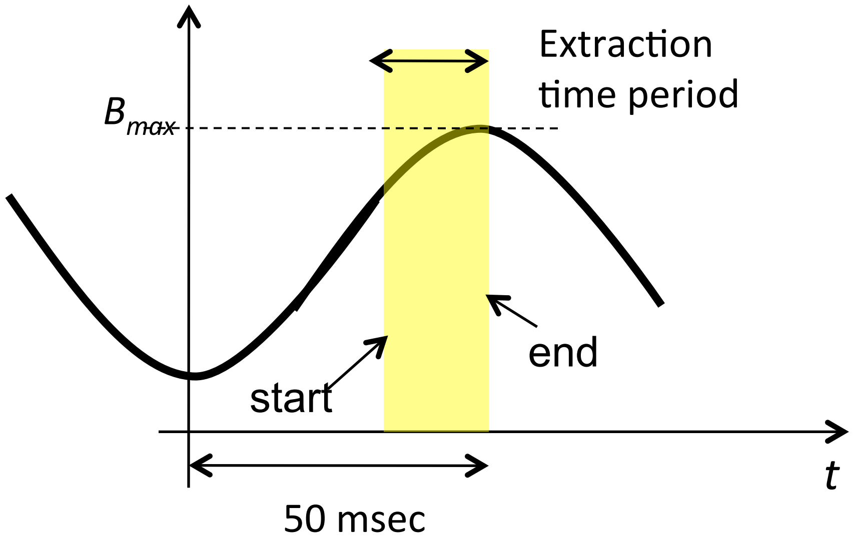


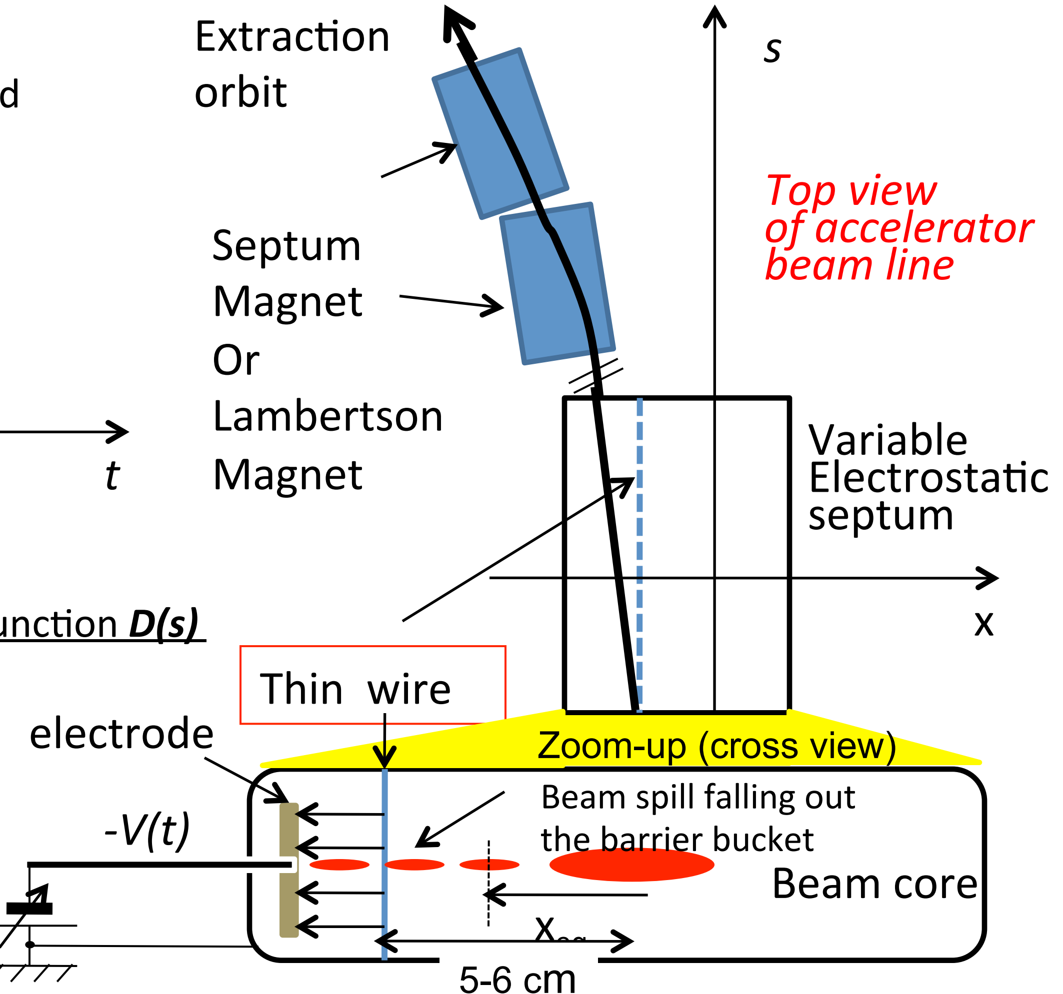
Extraction time region
(starting/stopping is flexible.)



Leo K.W., T. Monma, T. Adachi, T. Kawakubo, T. Dixit, and K.Takayama, “Compact Hadron Driver for Cancer Therapies using Continuous Energy Sweep Scanning”, *Phys. Rev. ST-AB* 19, 042802

Idea 2: Extraction with Energy Sweeping





Extraction method:

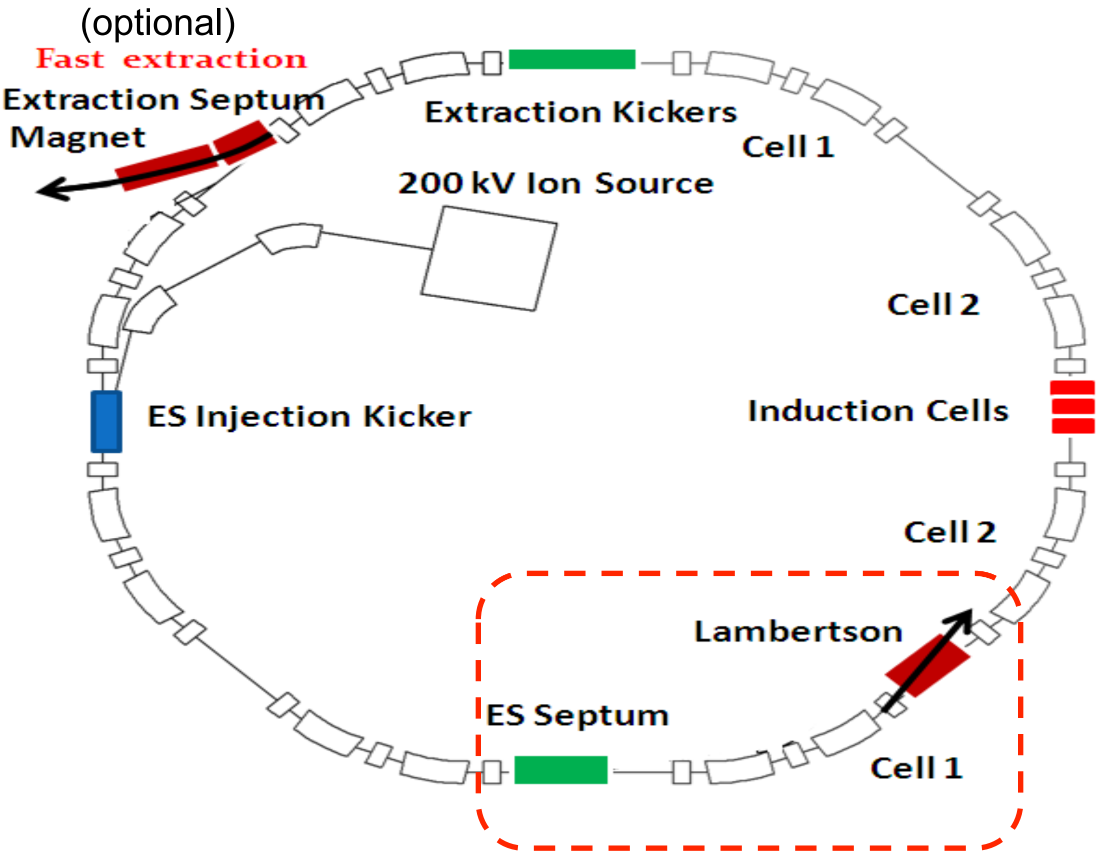
This relies on a <u>finite momentum dispersion function ***D(s)***</u> and <u>large momentum deviation ***Δp/p***</u>

$\boldsymbol{x_{eq}}$: Center of betatron oscillation of particles left from the confinement region (barrier bucket)

$x_{eq}=D(s)\Delta p/p$

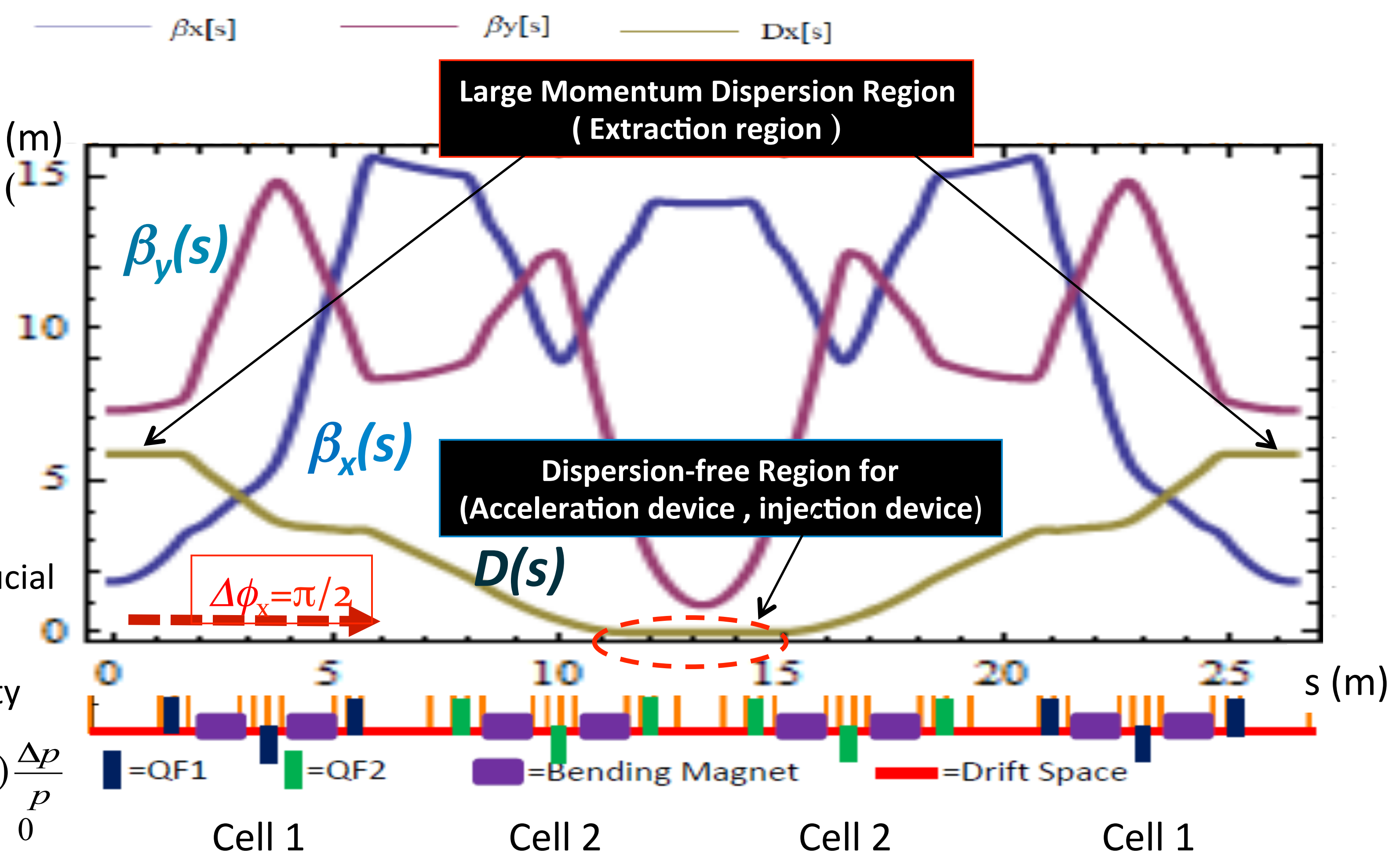
Dedicated Hadron Driver System

Energy	656 MeV for proton 200 MeV/nucleon for $A/Q = 2$ ion
C_0	52.8 m
Ion species	Gaseous/metal ions
Ion source	Laser ablation IS ECRIS
Injector	200 kV (electrostatic)
Ring	Fast cycling (10 Hz)
	$B_{max} = 1.5$ T
	$\rho = 2.8662$ m
	FODOF cell with edge focus of B
	Mirror symmetry
	$\nu_x/\nu_y = 1.3143/1.4635$
	2m long dispersion-free region 3m long flat large dispersion region
	α_p=0.273088 γ_T=1.92, E_T=864.7 MeV
Acceleration	Induction cells driven by SPS employing SiC-MOSFET $V_{acc} = \rho C_0 dB/dt$ (max 7 kV)
Vacuum	10^{-8} Pa



Quick and continuous extraction region of concern

Lattice Function and Cell Structure



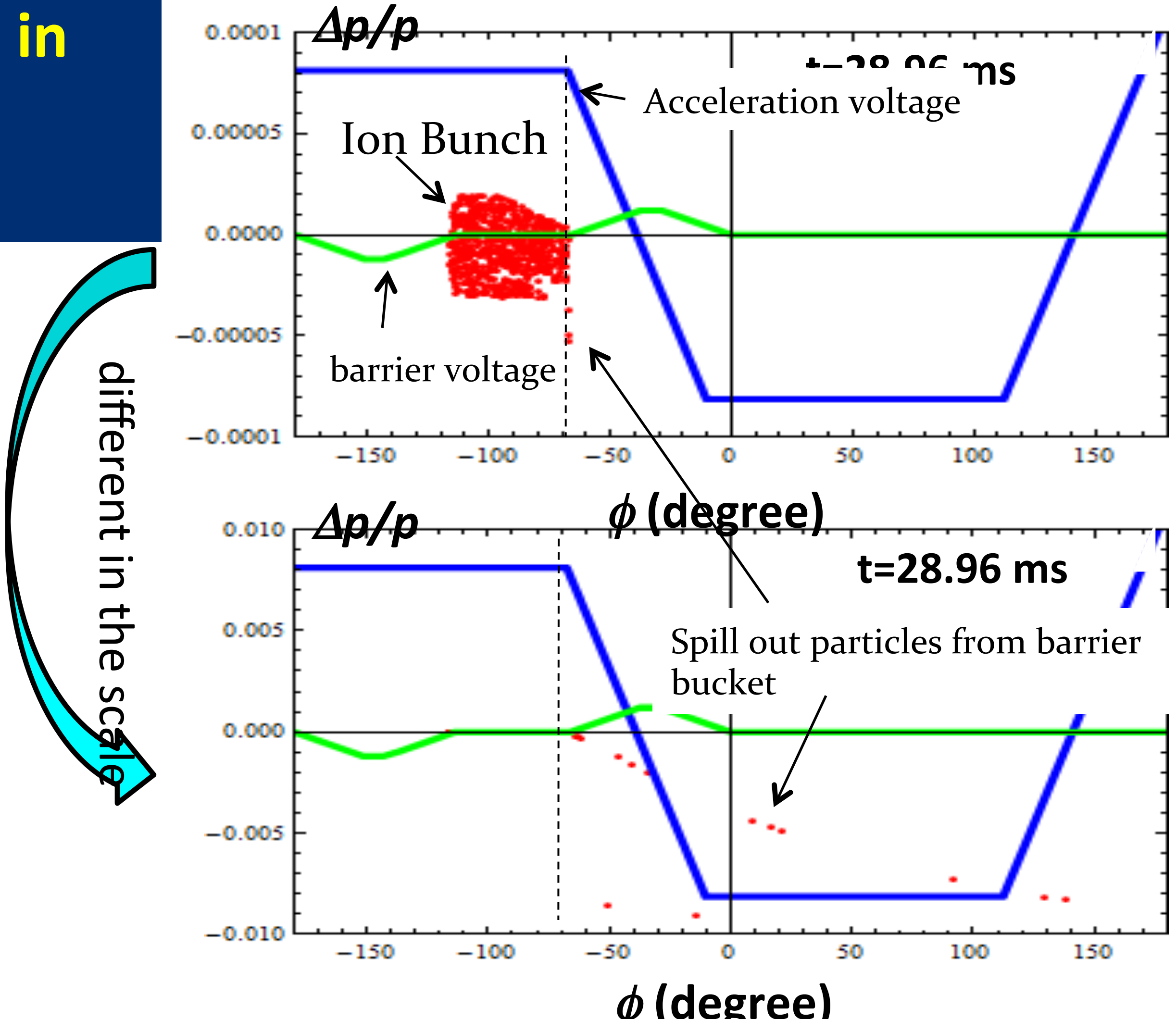
Small $\beta_x(s)$ is crucial

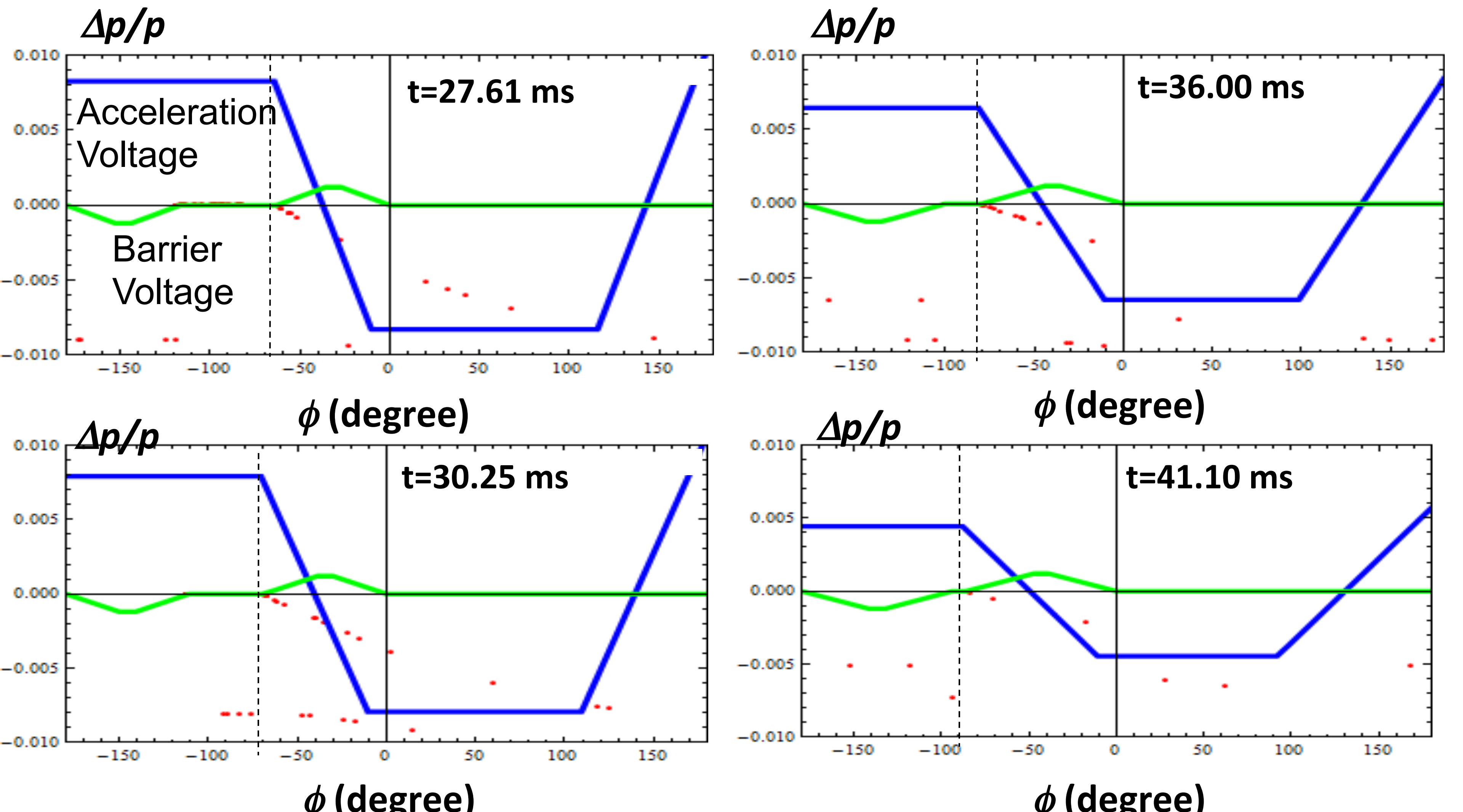
for small

Momentum purity

$$\sqrt{\varepsilon\beta_x(s)} << D(s)\frac{\Delta p}{p_0}$$

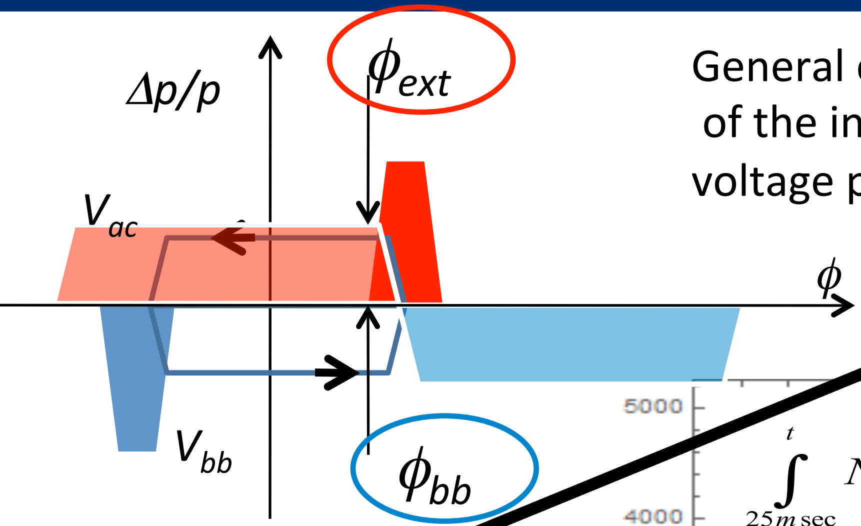
Behaviour of particles in the phase space during the extraction



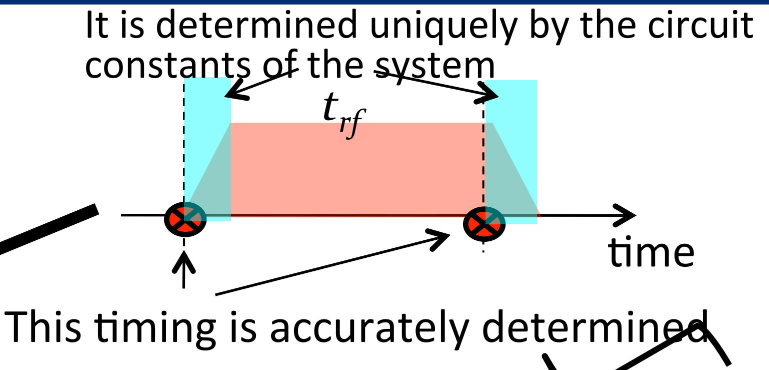


Δp/p
t=27.61 ms
Acceleration
Voltage
Barrier
Voltage
ϕ (degree)
Δp/p
t=36.00 ms
ϕ (degree)
Δp/p
t=30.25 ms
ϕ (degree)
Δp/p
t=41.10 ms
ϕ (degree)
0.010
0.005
0.000
−0.005
−0.010
−150
−100
−50
0
50
100
150

Spill Control Parameter and Controlled Spill Structure

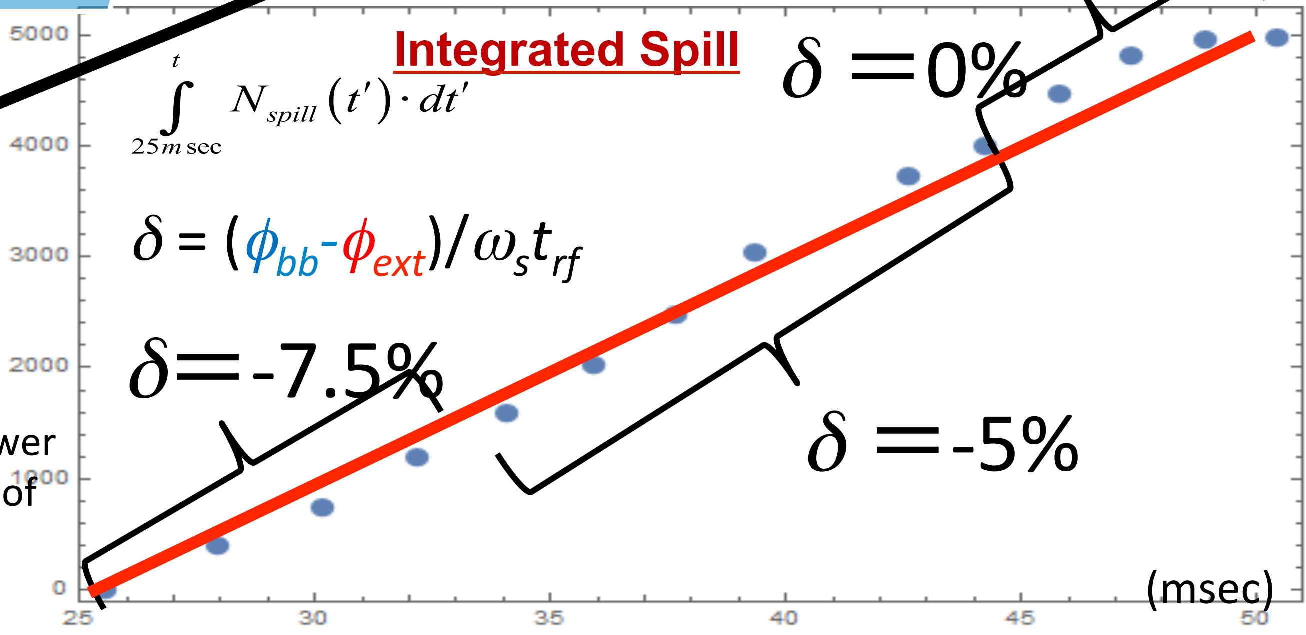


General characteristics of the induction pulse voltage profile control



Control of ϕ_{ext} with ϕ_{bb}:

Realized by the FPGA to manage timing of the gate signal of the power semiconductor switching element of the switching power supply that drives the accelerating cell



Summary and Prospect

Summary

- Novel scheme of energy sweep extraction in the fast cycling synchrotron, based on the induction synchrotron concept, was introduced.
- Ideal lattice has been designed as a hadron beam driver for cancer therapies.
- Continuous energy sweep extraction simulation was shown but the designed extraction system and beam loss estimation were not introduced due to a limited time of presentation. (refer our publication)

Prospect

Continuous and uniform 3D spot scanning on a target

Low intensity/pulse operation

In future

3D spot scanning on a moving target integrating real time diagnosis of the target position

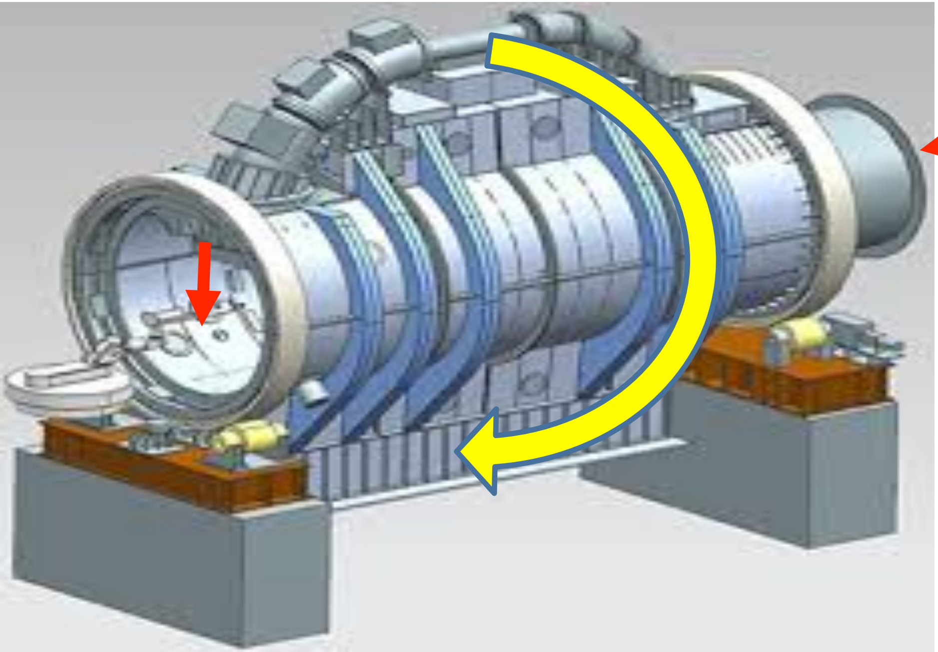
Low cost Therapy

- Like Medical examination of stomach cancer by X-ray, where a patient is turned round and his cancer part is modified or moved by gravitation.
- Require monitoring the 3D real time image of the cancer part.

→ **Gantry free 3 D spot scanning**

from Gigantic Heavy-Ion Gantry to Multi-axis Rotating Irradiation Chair

Gigantic Gantry



40 M$ and running cost (4 M$/year)

Multi-axis rotating chair of NASA

Pencil beam for 3D spot scanning

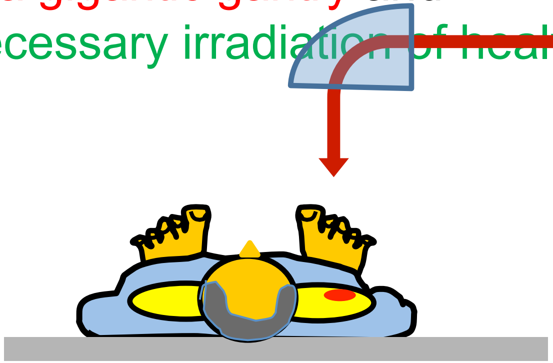
1 M$ and running cost (0.1 M$/year)

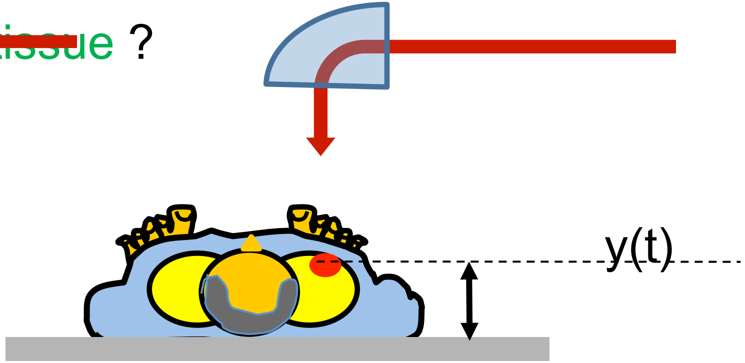
Multi-axis rotating tool at Play Ground

Moving Target and Shooting Hadron Beam

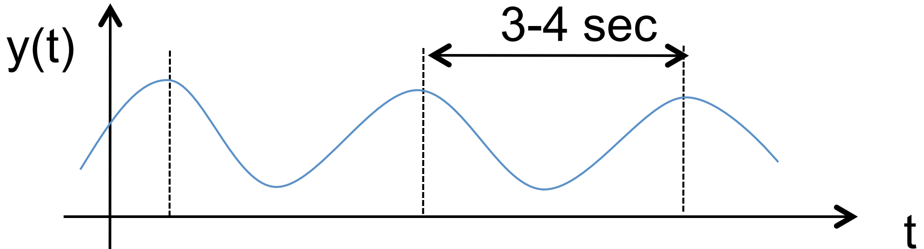
Typical moving target ➡ Lung cancer

Crucial query: How are **shooting hadron beams**
focused on this **lung tumor**
in a continuous spot scanning method
without using a gigantic gantry and
avoiding unnecessary irradiation of healthy tissue ?





Physical parameters for the change in its position and its shape :



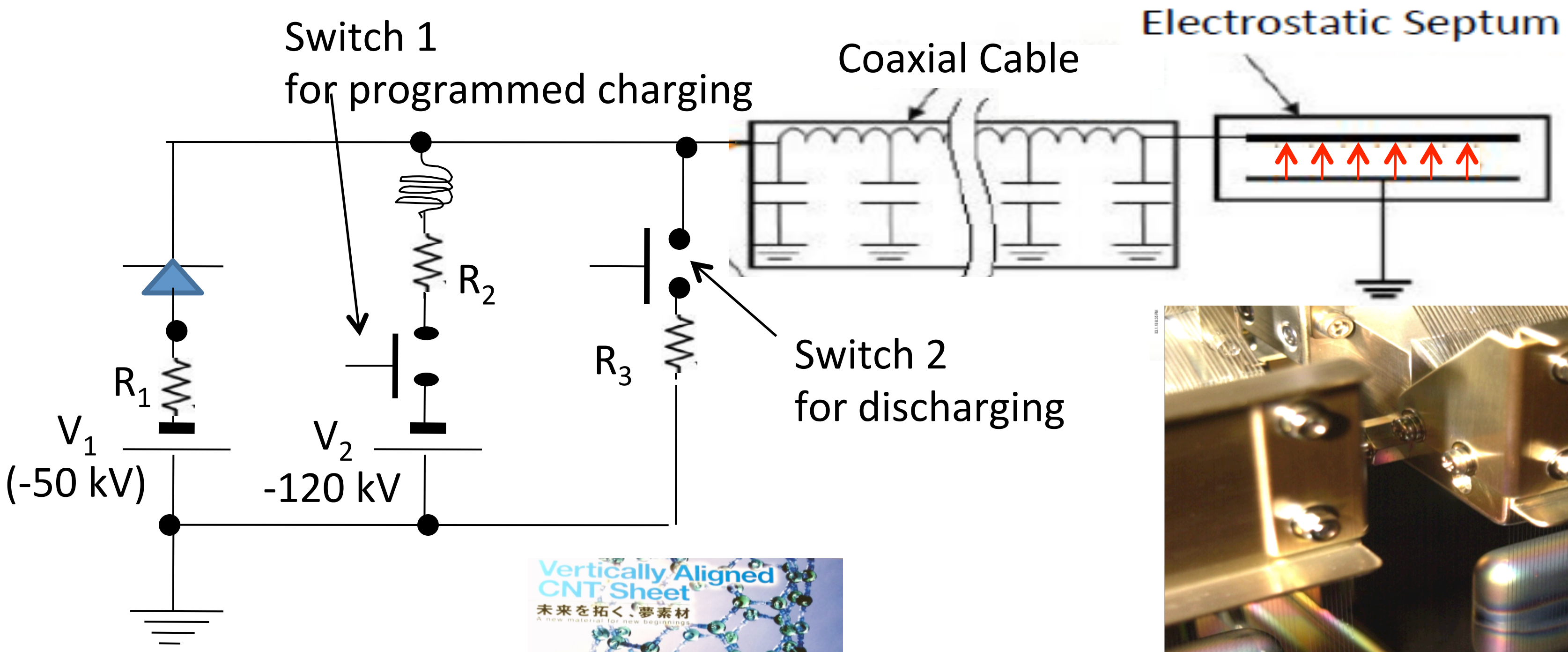
Extraction Devices: Electrostatic Septum and Lambertson Magnet

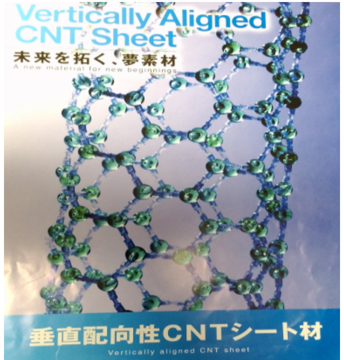
Strong demand → Extraction orbit must be same.
It should not depend on energy.

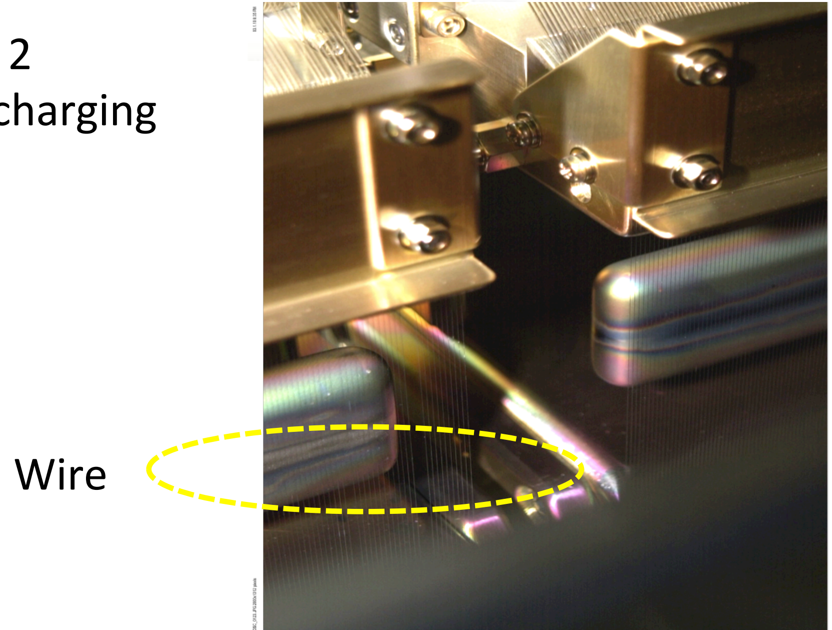
How must the extraction device perform?

$$\boldsymbol{B} \sim \beta\gamma, \quad \boldsymbol{E} \sim \beta^2\gamma$$

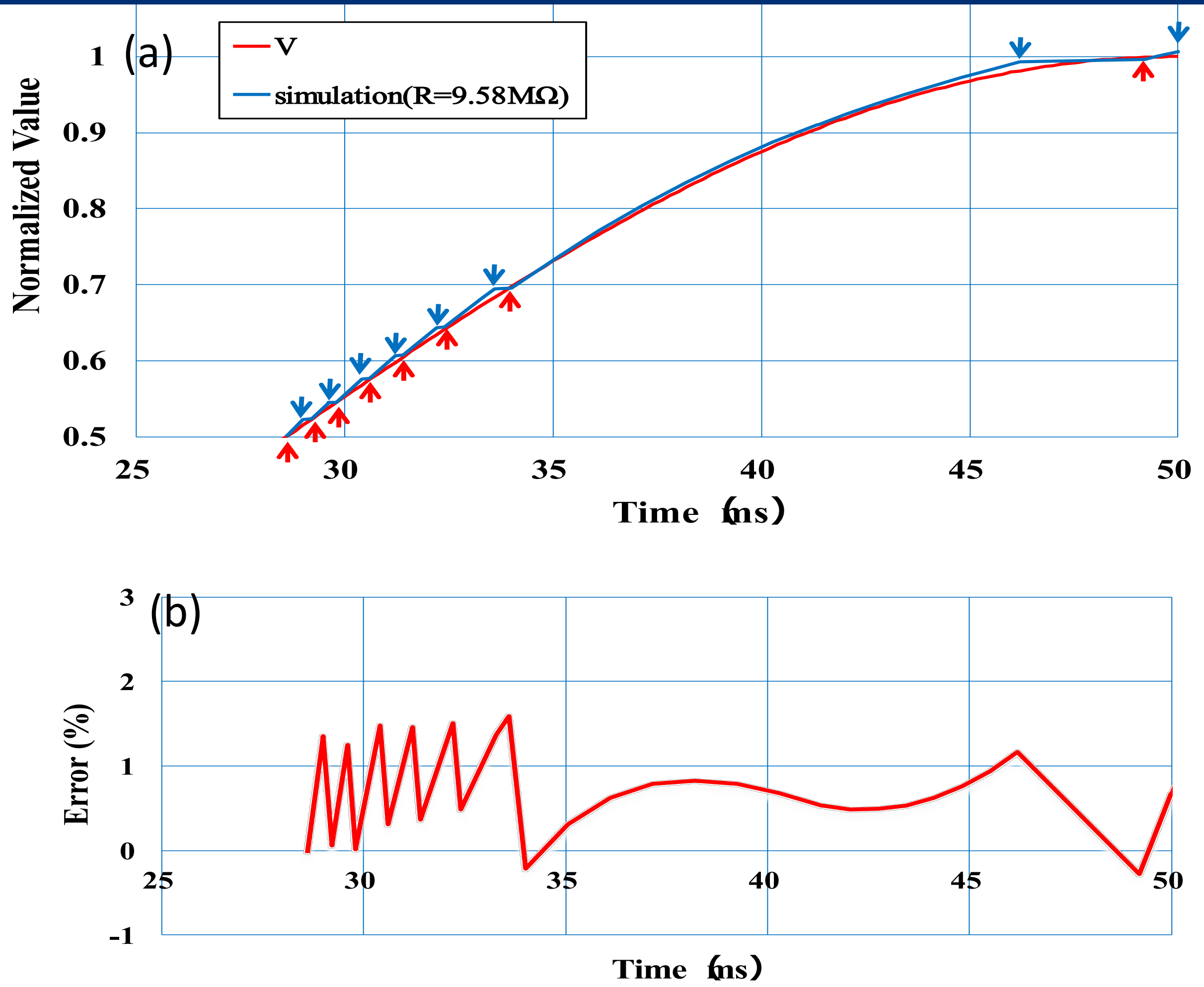
Variable Voltage Electrostatic Septum (Equivalent Circuit)



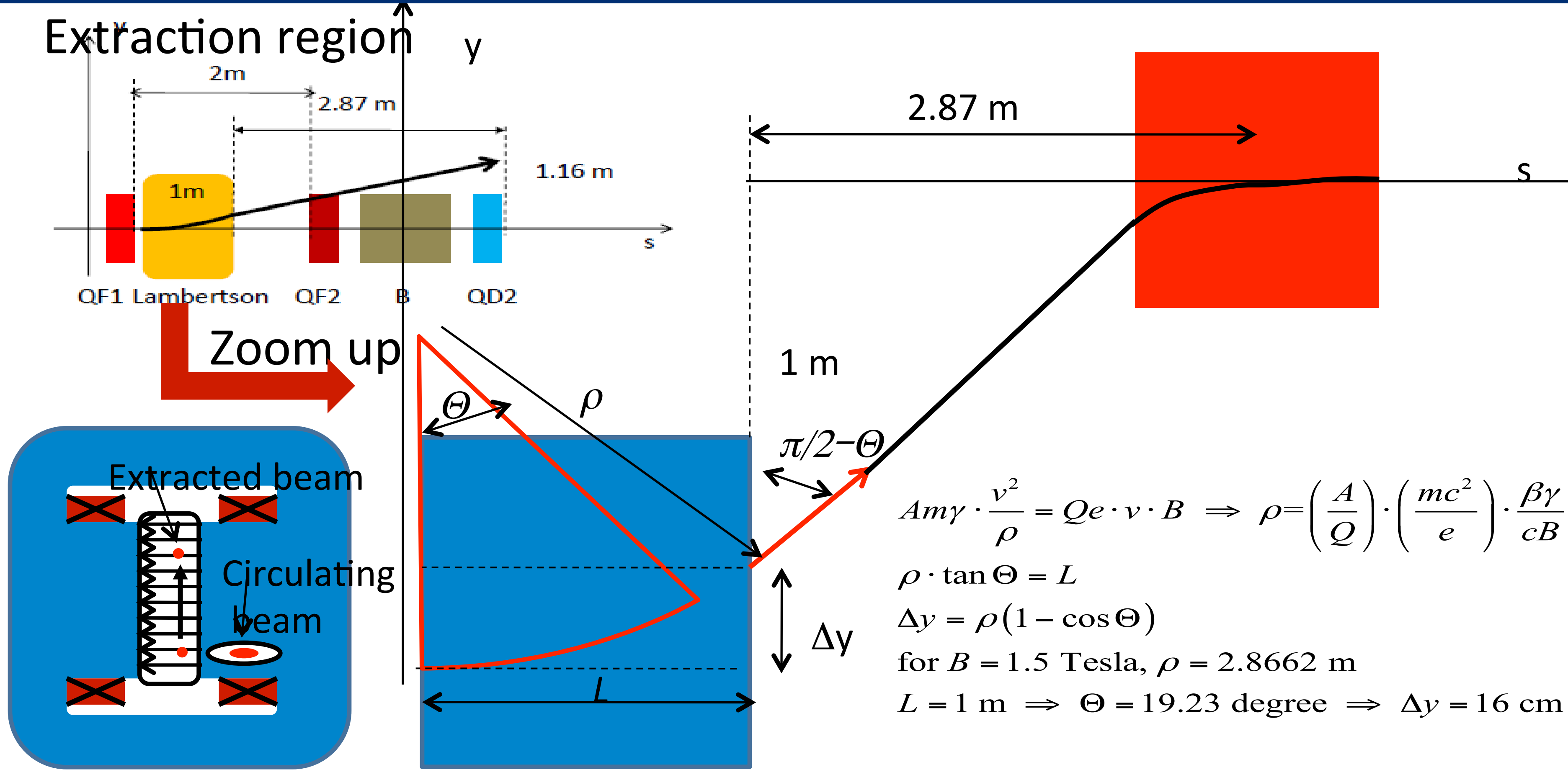




Extraction Voltage in the ES-Septum (Ideal/simulation)



Lambertson Magnet



$$Am\gamma \cdot \frac{v^2}{\rho} = Qe \cdot v \cdot B \;\Rightarrow\; \rho = \left(\frac{A}{Q}\right) \cdot \left(\frac{mc^2}{e}\right) \cdot \frac{\beta\gamma}{cB}$$

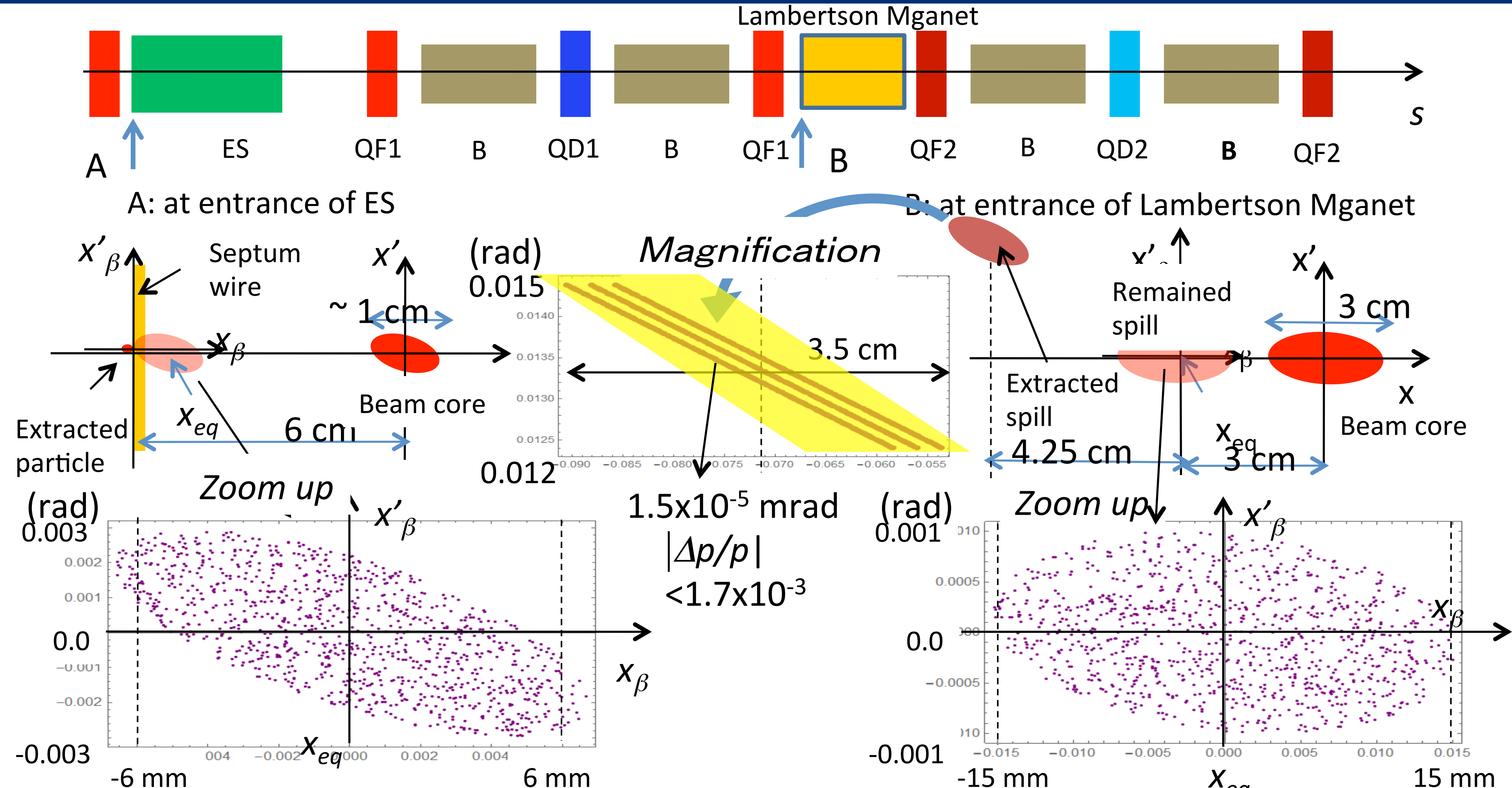
$$\rho \cdot \tan\Theta = L$$

$$\Delta y = \rho(1 - \cos\Theta)$$

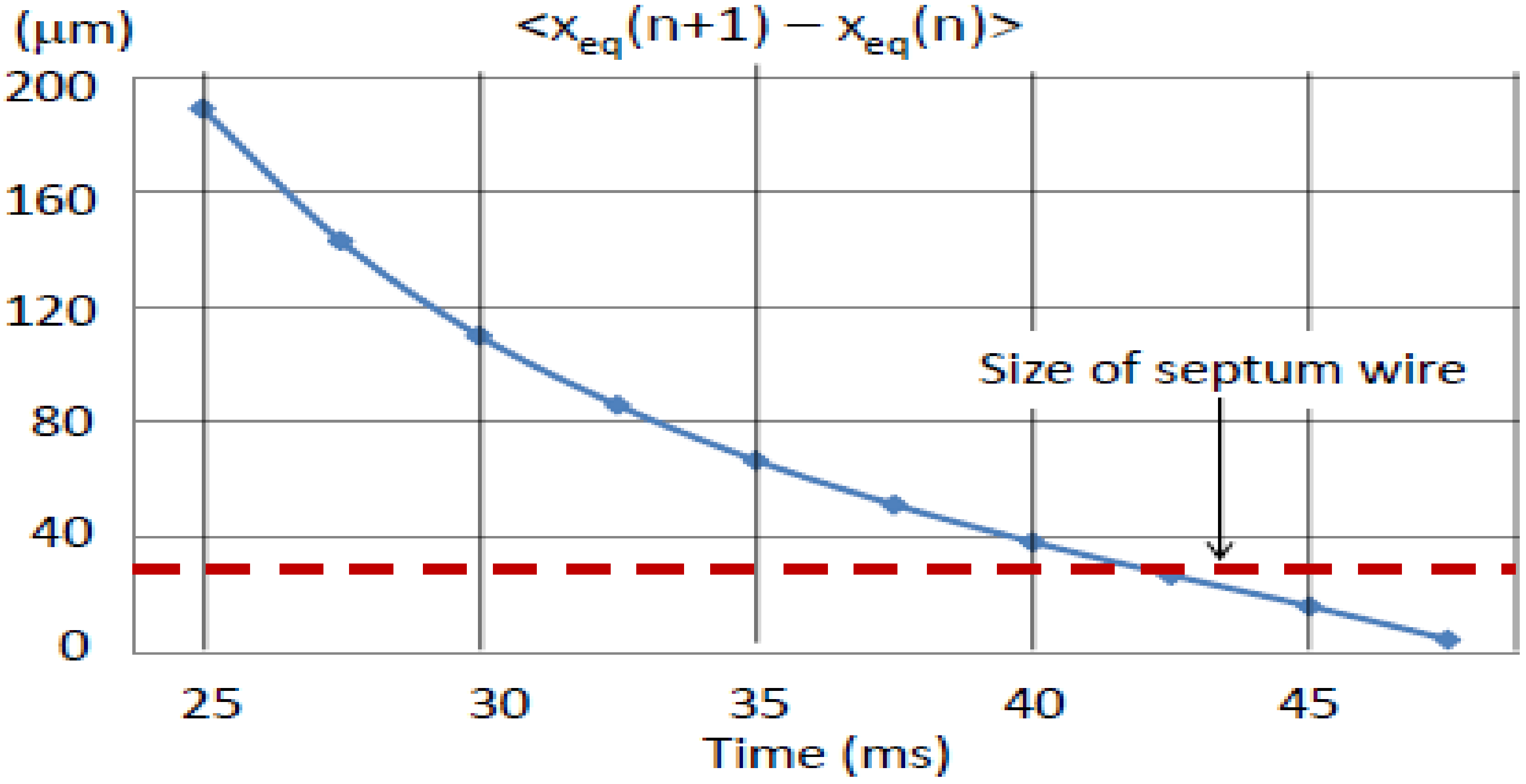
for $B = 1.5$ Tesla, $\rho = 2.8662$ m

$L = 1$ m $\Rightarrow$ $\Theta = 19.23$ degree $\Rightarrow$ $\Delta y = 16$ cm

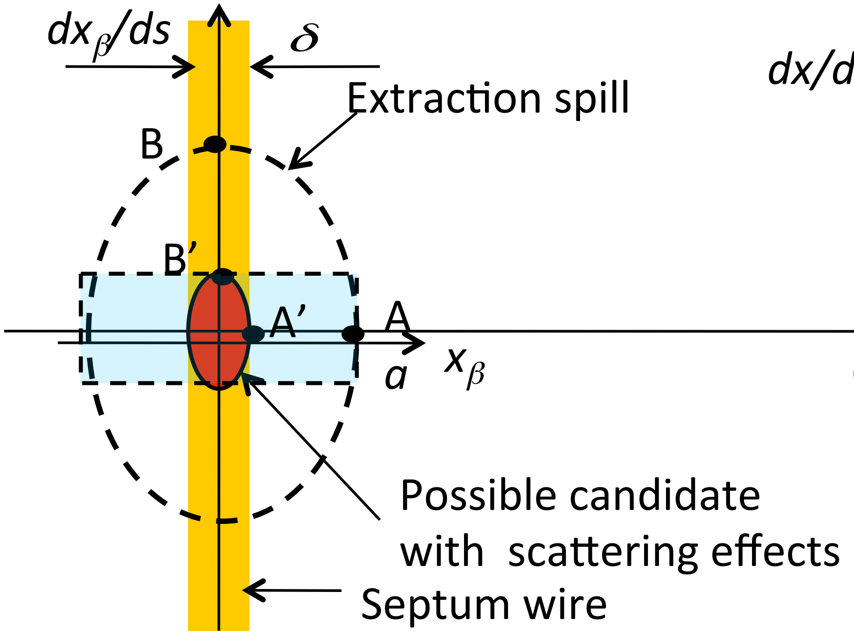
Phase-Space Profile of the Extracted Beam



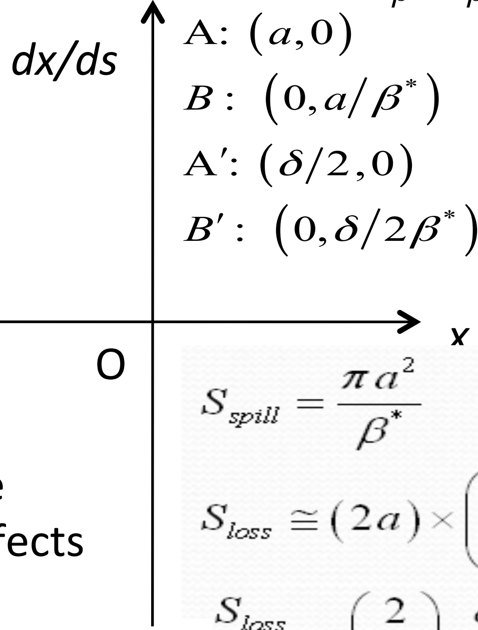
Turn Separation



Beam Loss Region in the Phase Space



in the space (x_β,dx_β/ds)



A: $(a,0)$

$B: \left(0, a/\beta^*\right)$

A': $(\delta/2,0)$

$B': \left(0, \delta/2\beta^*\right)$

$$S_{spill} = \frac{\pi a^2}{\beta^*}$$

$$S_{loss} \cong (2a) \times \left(2 \times \frac{\delta}{2\beta^*}\right)$$

$$\frac{S_{loss}}{S_{spill}} = \left(\frac{2}{\pi}\right) \cdot \frac{\delta}{a}$$

$=2 \times 10^{-3}$

Heart of Digital Accelerator : Evolutional Induction Accelerator System