AFAD2018 WG-3
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Toward the Next Hadron Therapy Driver

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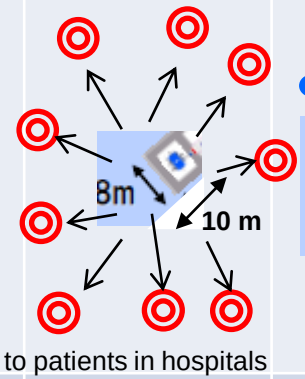
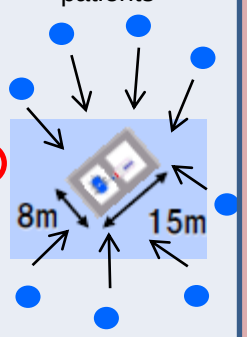
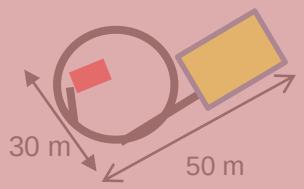
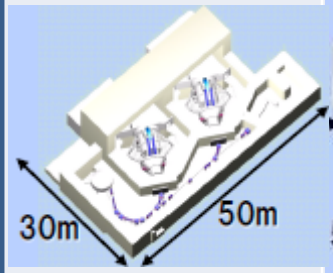
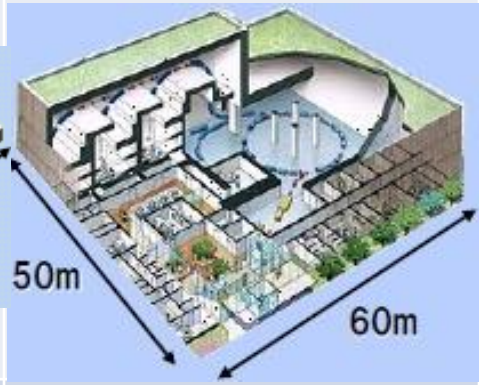
Content

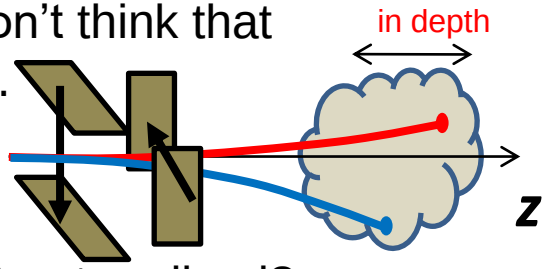
Comparison between Accelerator Driven Cancer Therapies

	Low Cost Therapy		Hadron Therapy		
	α-Therapy	BNCT	Next generation (p/He3/C)	Proton	Carbon
Space requirement			no injector no gantry 		
Energy (MeV)	30	30	250/300/200	230	400
Accelerator	Cyclotron	Cyclotron	Induction synchrotron	Cyclotron/ Synchrotron	Synchrotron
Cost (M$)	7	10-15	40 - 50	60 - 70	~ 150
Fee (k$)	3 ?	10 ?	20 ?	~ 30	> 30
status	under development	Clinical trial is going on.	under development	running	running

Our Motivations toward New Trend

Overview and our understanding:

- A cancer therapy has notably evolved through the last three decades.
- Various ideas such as spot scanning 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 think 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) Precise 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~~ dose on tumor?

To accelerator physicists like us**, Present status of the technology** appears 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 in real time.

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*.)**

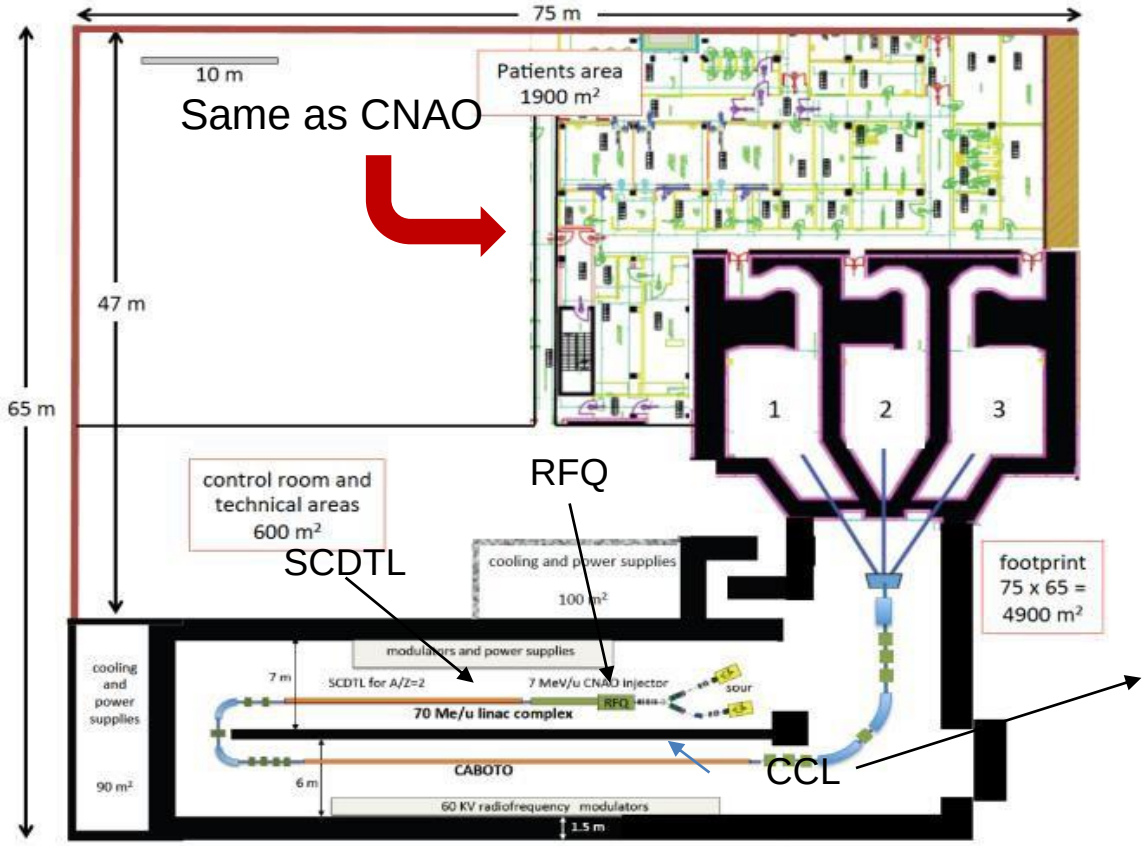
CArbon BOoster for Therapy in Oncology (CABOTO) by ADAM

Linac running at 200 Hz is composed of a large number of accelerating units (typically 10), which are singly powered by *independently* controlled klystrons, the final beam energy can be varied *continuously* from pulse to pulse, i.e. every 5 ms, by adjusting the amplitude and/or phase of the klystron signals [4]. This feature makes possible the implementation of the active *spot scanning technique* with tumour *multi-painting*, the best possible way for treating moving organs [11,12]. This is a unique feature of all linacs

Properties:

- 100 - 200 Hz operation
- Variable energy every 5 msec per pulse to pulse

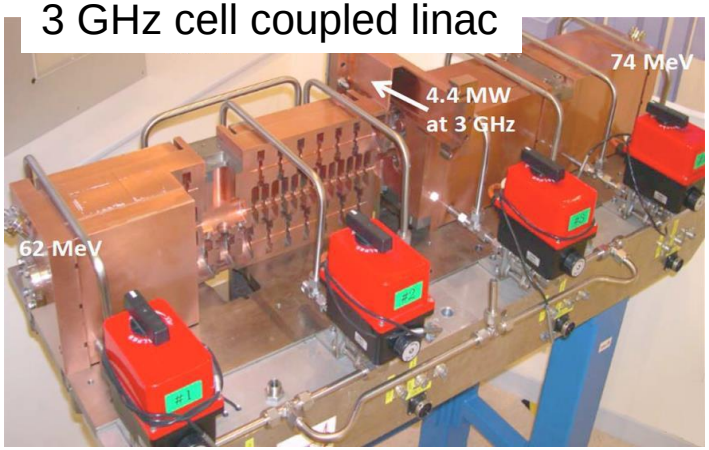
→ 3 D spot-scanning on moving organ



Size -> equivalent to existing C therapy

Cost (construction, operation) ?

3 GHz cell coupled linac



U. Amaldi and A. Degiovanni, "Protron and Carbon Linacs for Hadron Therapy", *Proc. of Linac 2014* (2014).

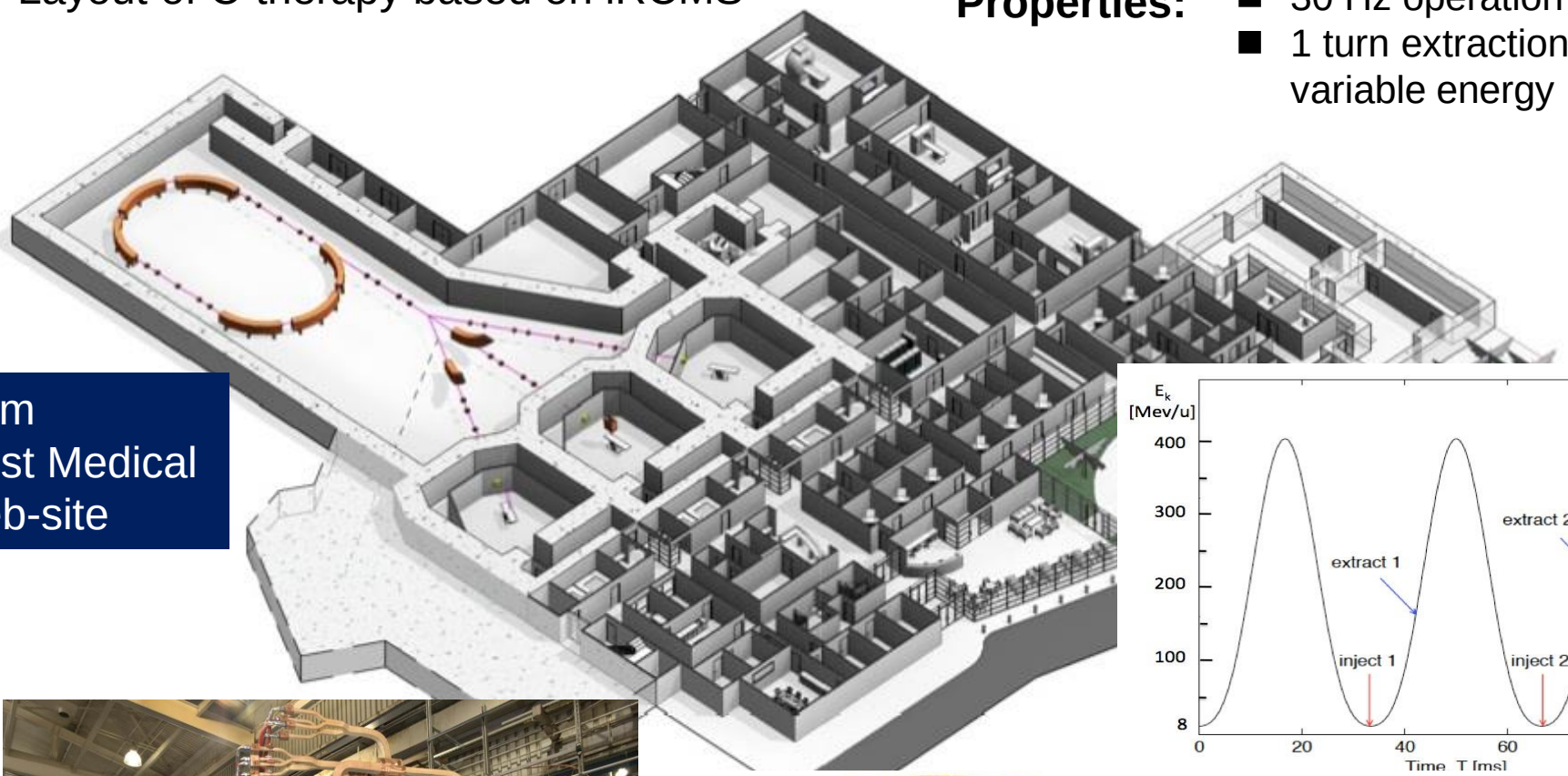
iRCMS (Ion Rapid Cycling Medical Synchrotron)

Layout of C-therapy based on iRCMS

Properties:

- 30 Hz operation
- 1 turn extraction with variable energy per pulse

m
st Medical
b-site



Field measurement of the combined-type magnet at BNL

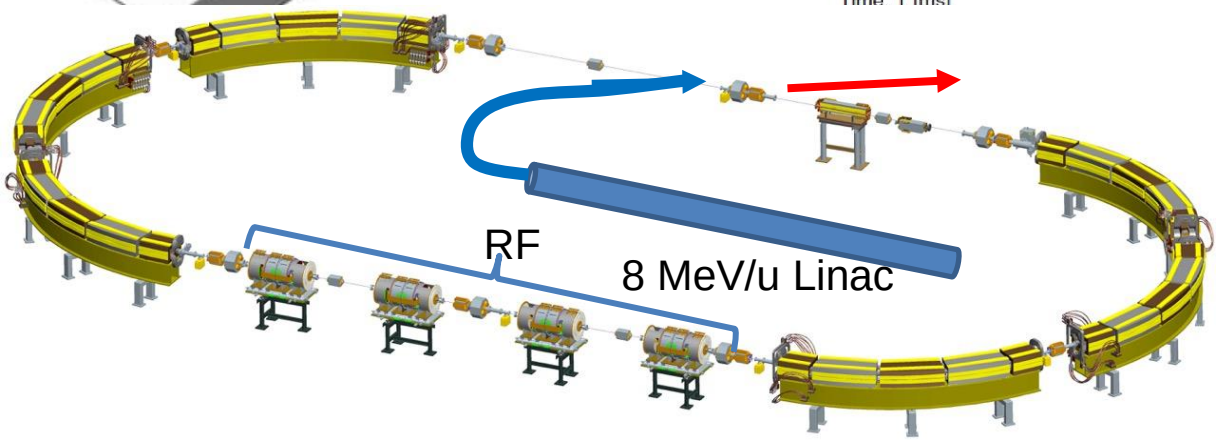


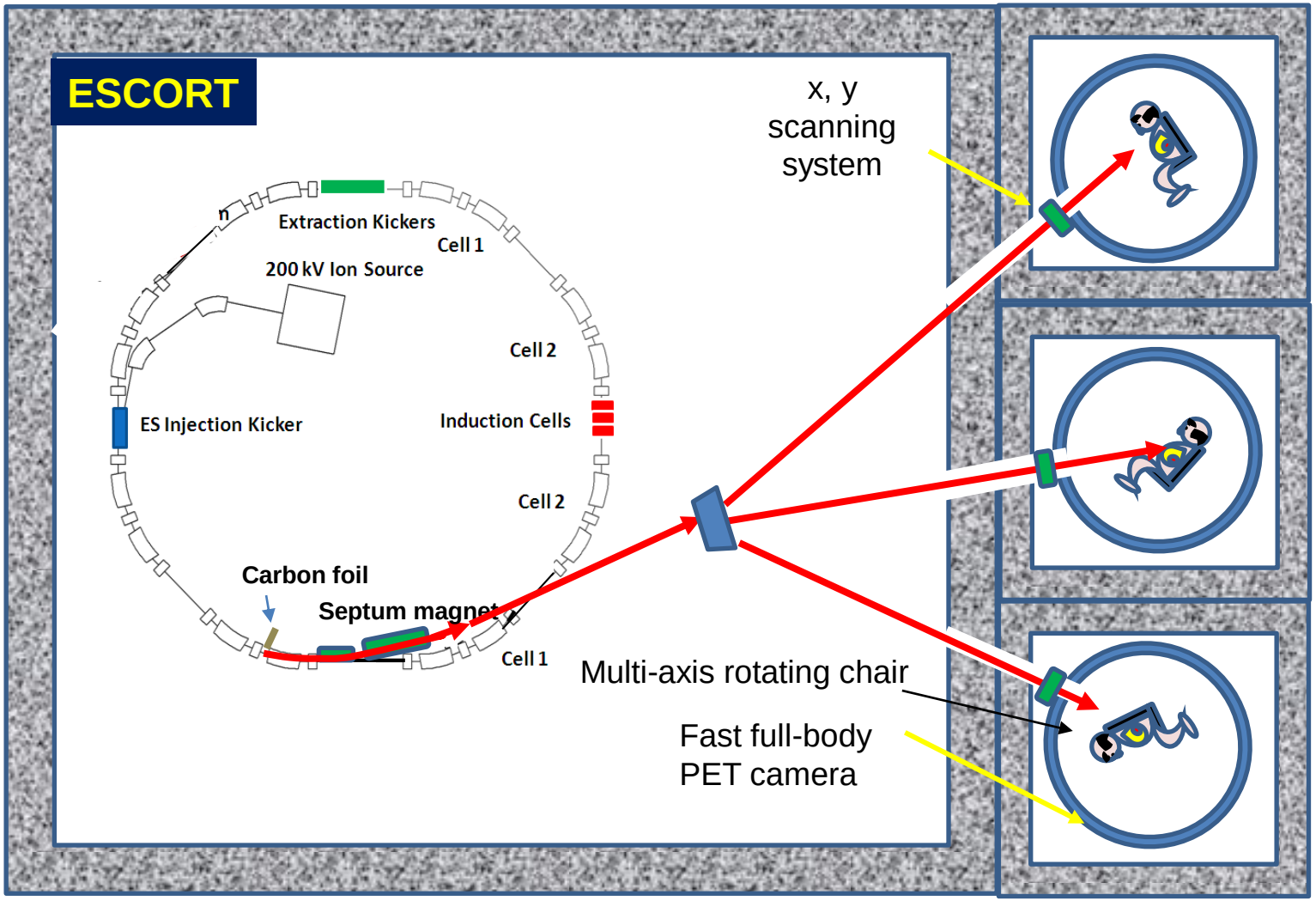
Image of the Next Generation of Hadron Therapy of gantry-free and injector-free, with continuous spot-scanning in the x,y and z directions from 4π angle

Properties:

- Injector-free
- 20 Hz Continuous energy sweep extraction

➡

- Low cost
- 3D spot scanning on moving target



Issues to be solved in the next generation of Hadron Therapy Driver

1. Demand of low cost → No injector or low energy injector, No RF

2. Demand of low cost → Gantry-free → Irradiation under the Natural condition of body

   → Fixed beam and Relocation of a patient

3. To avoid Respiratory-gated irradiation

   → ■ Quick irradiation (< respiratory time period of a few sec)
   ■ Precise real-time detection of the target position and profile

4. To avoid undesired irradiation on normal tissue → Spot scanning by a pensile beam with dose concentration on tumor

5. To avoid undesired residual radiation around energy degrader → use a non-destructive device
→ Extraction from the driver with energy sweep minimizing residual radiation of the extraction device

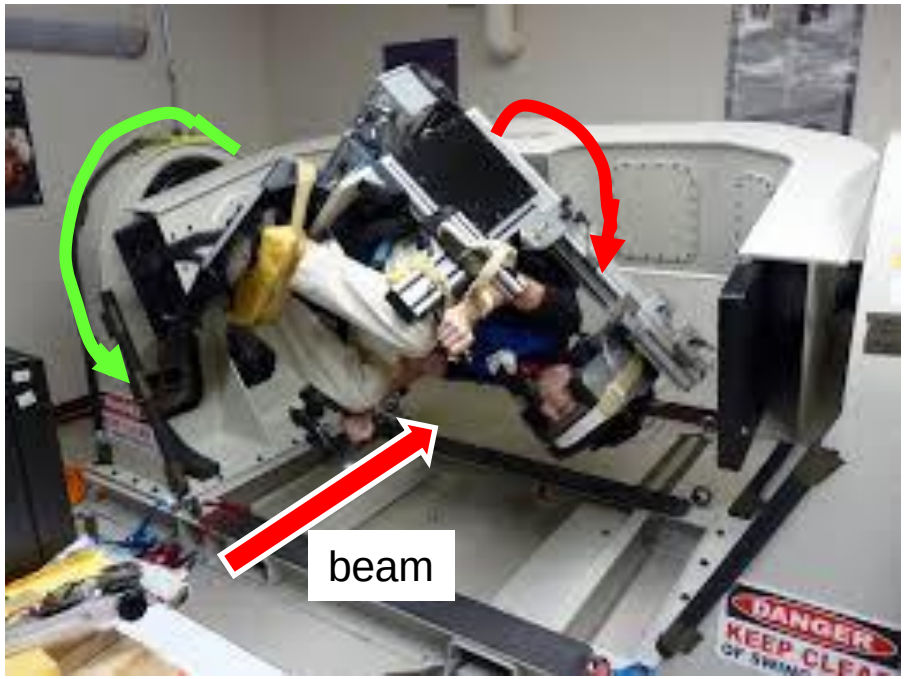
6. Smooth irradiation in depth

Issue			1	2	3	4	5	6
Fast cycling accelerator	Linac	LIGHT	×	possible	◎	○	○	?
	Fast cycling synchrotron	iRCMS	×	possible	○	○	○	△
		ESCORT	○	possible	○	○	◎	◎
	Cyclotron		△	possible	×	○	×	×
Slow cycling accelerator	Slow cycling synchrotron		×	×	×	○	×	×

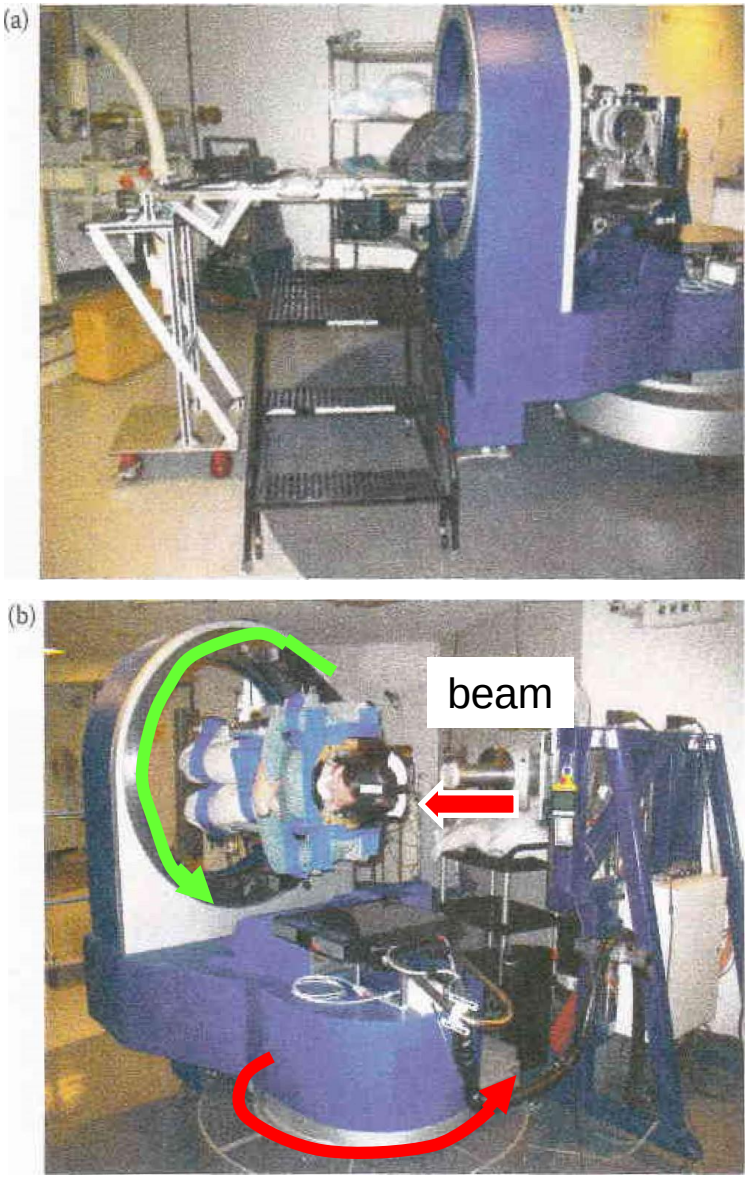
Multi-axis Irradiation Bed/Chair to allow Focused Irradiation on Moving Target without Gantry

Existing examples:

Multi-axis irradiation bed/chair

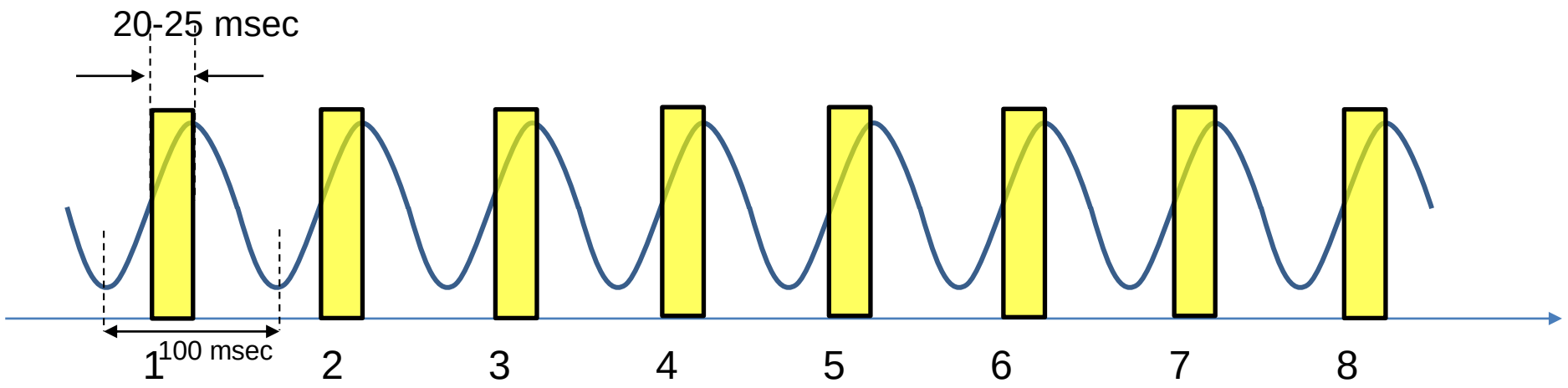


for training of astronaut
Multi-axis rotating chair of NASA



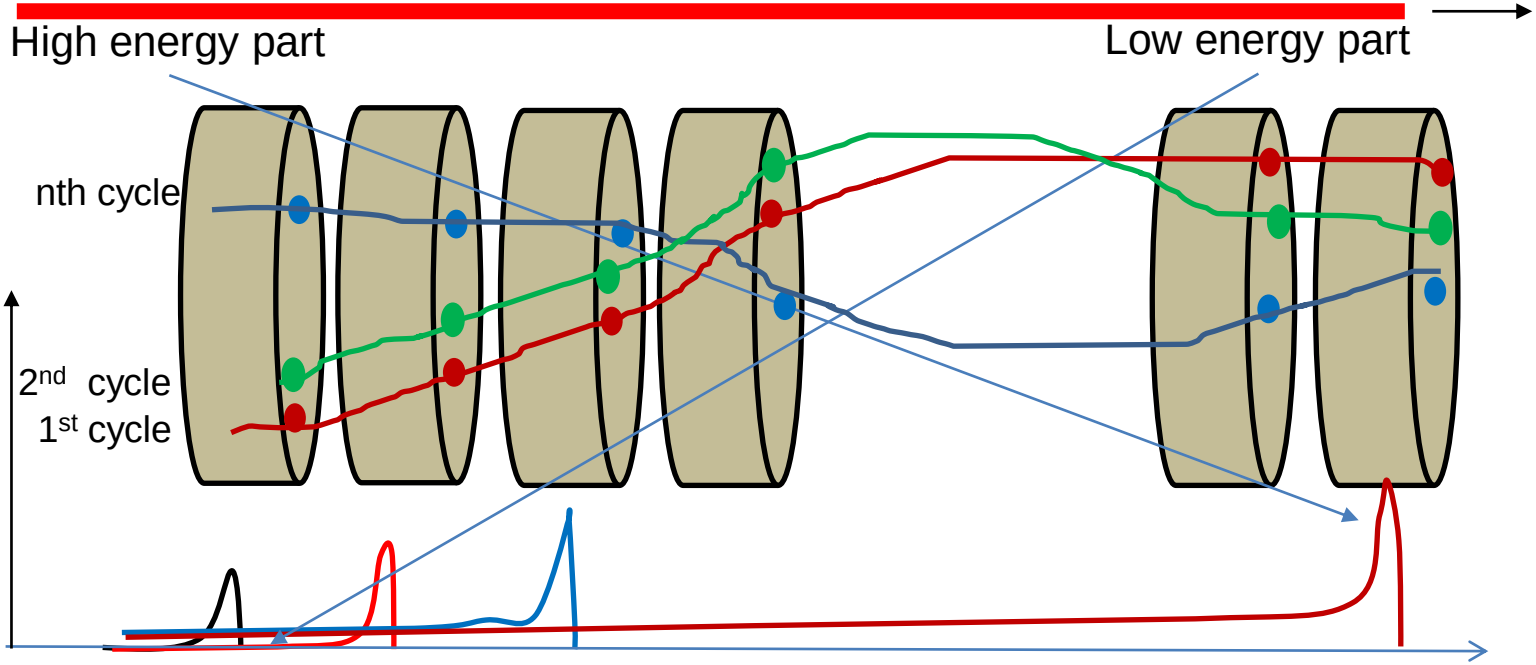
for Proton Beam Stereotactic Radiosurgery
Massachusetts General Hospital

Spot-scanning on the x-y plane with energy sweeping extraction from a fast cycling synchrotron



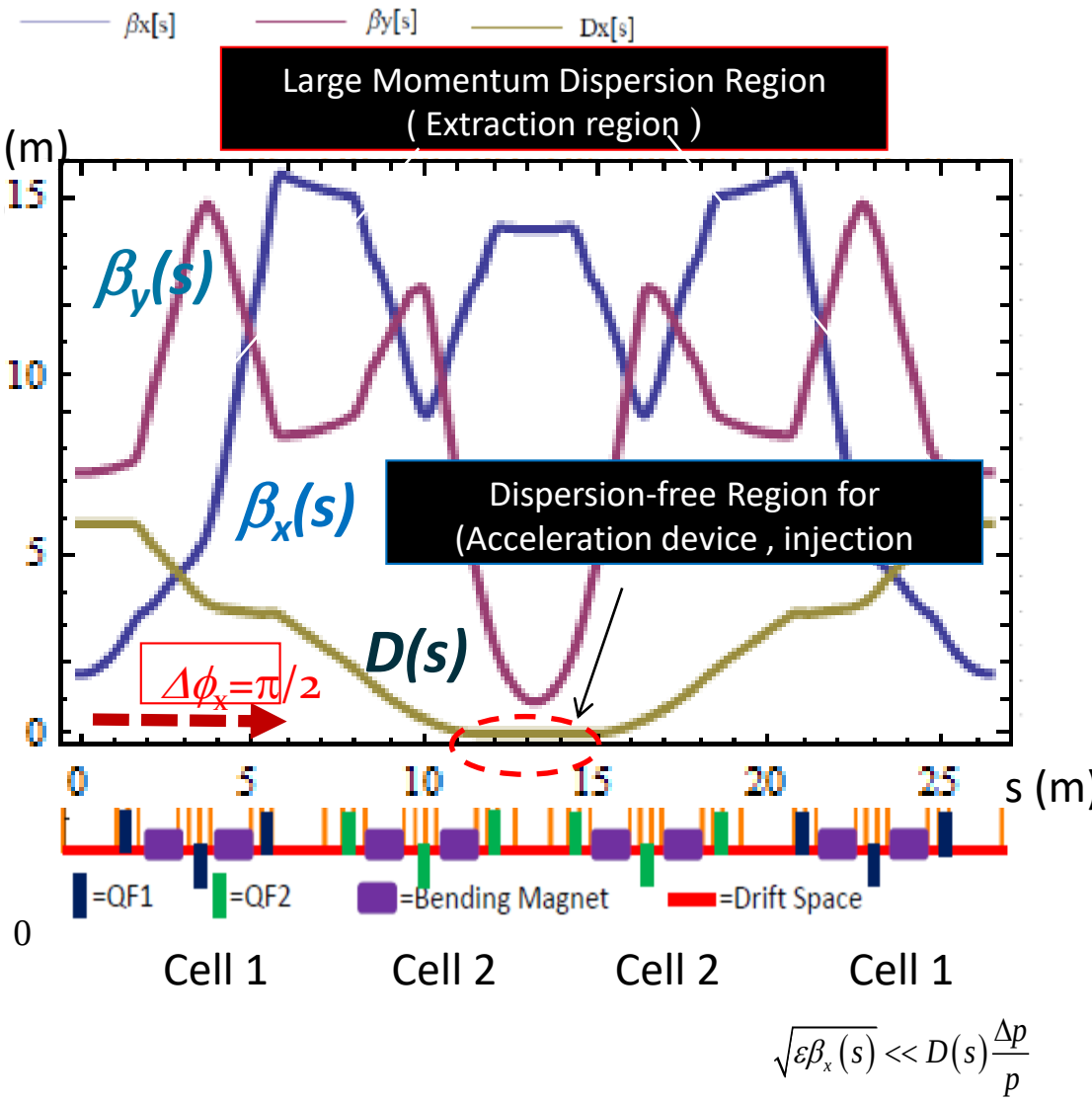
Extracted beam in a single cycle

20-25 msec long **(<< typical time period of motion of the human body)**



Machine parameters, Lattice function and Cell structure

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
	a_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

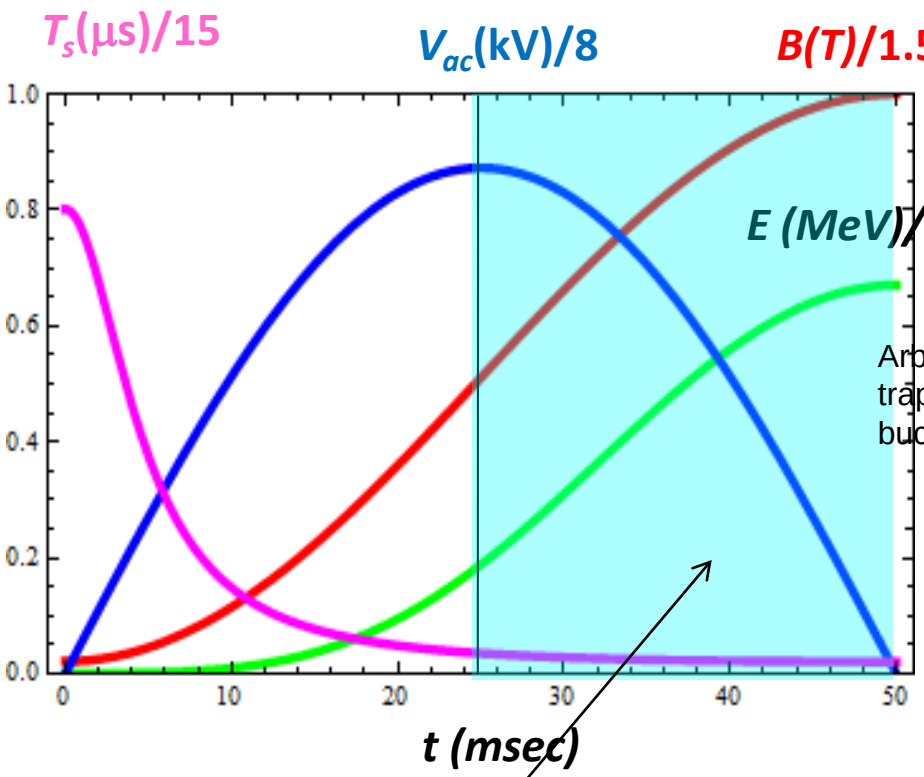


$$\sqrt{\varepsilon\beta_x(s)} << D(s)\frac{\Delta p}{p}$$

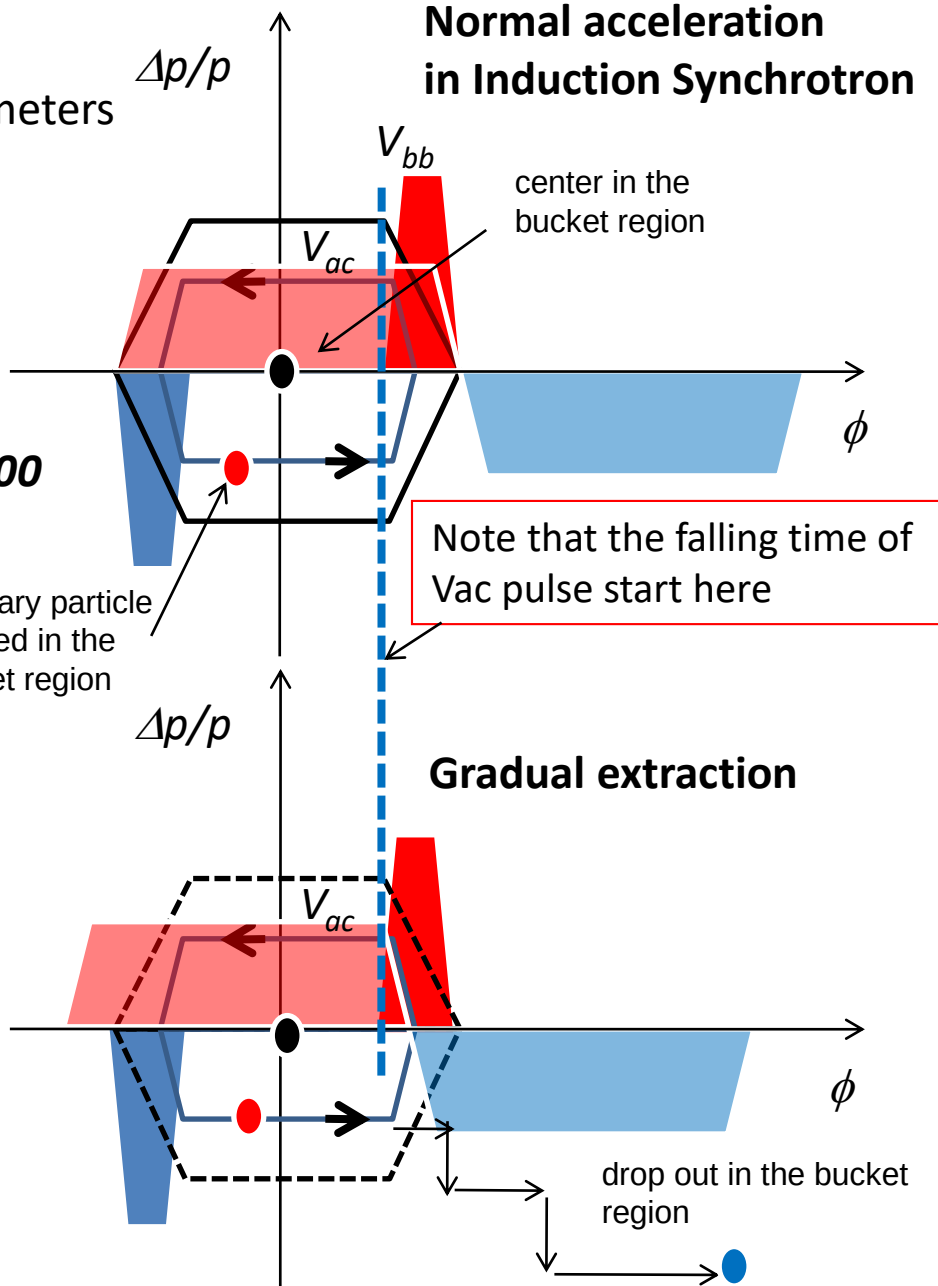
Leo K. W., K.Takayama *et al*., "Compact hadron driver for cancer therapies using continuous energy sweep scanning", *Phys. Rev. Accel. Beam* **19**, 042802 (2016).

Leakage of Particles from the Barrier Bucket

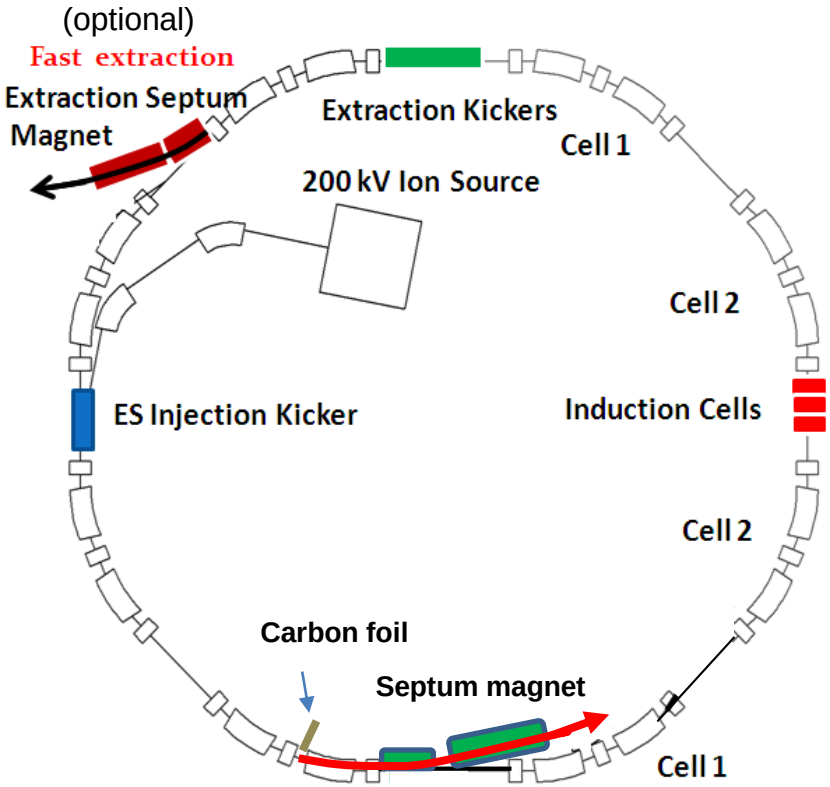
Time variation of the accelerator and beam parameters

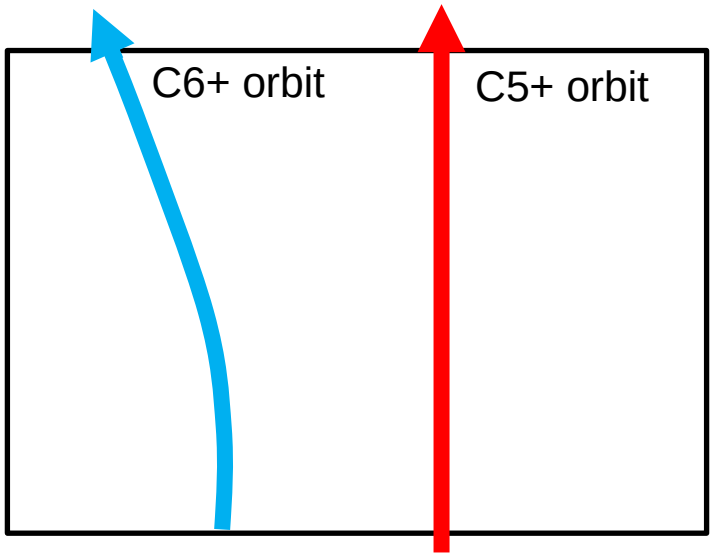


Extraction time region
（starting/stopping is flexible.）

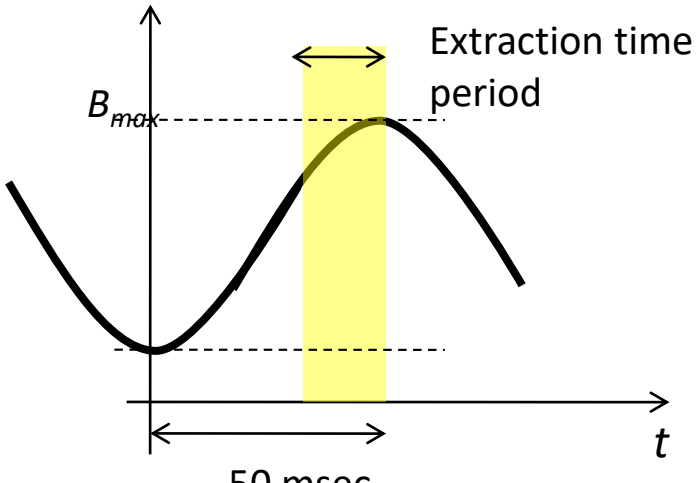


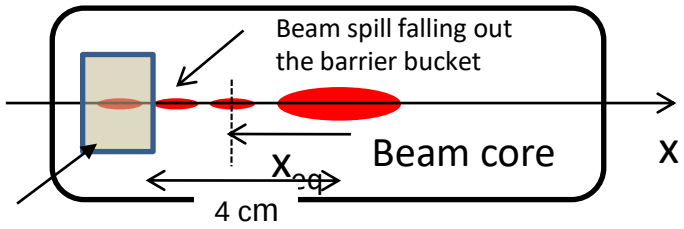
Continuous and Energy Sweep Extraction using Carbon Foil Stripping in ESCORT





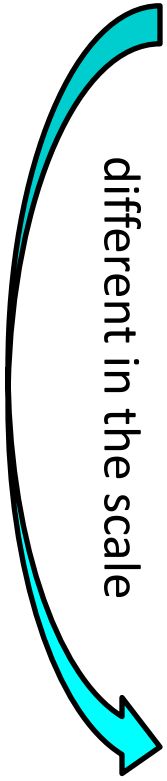
Vacuum chamber in the bending mag.
(top view)

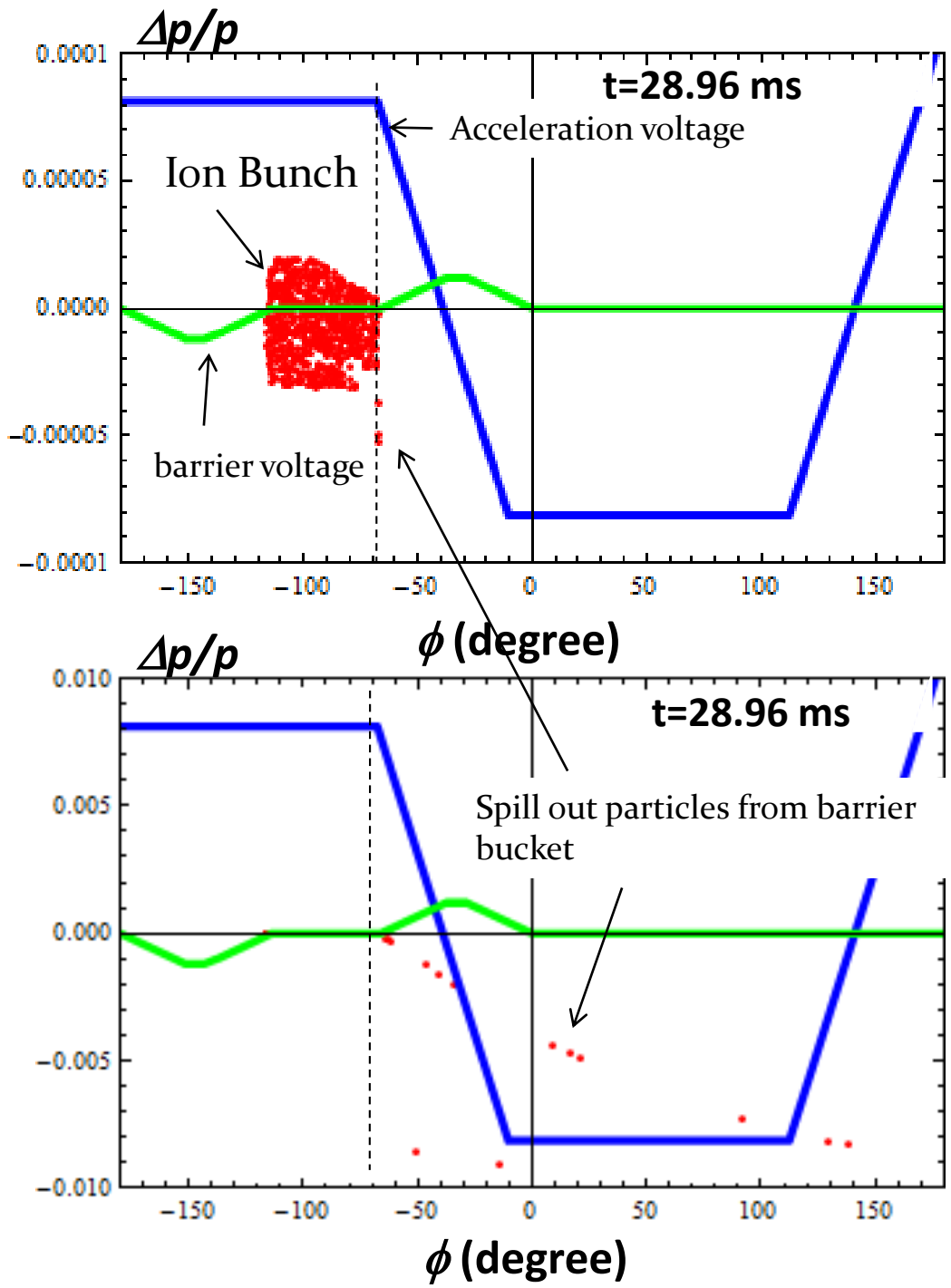


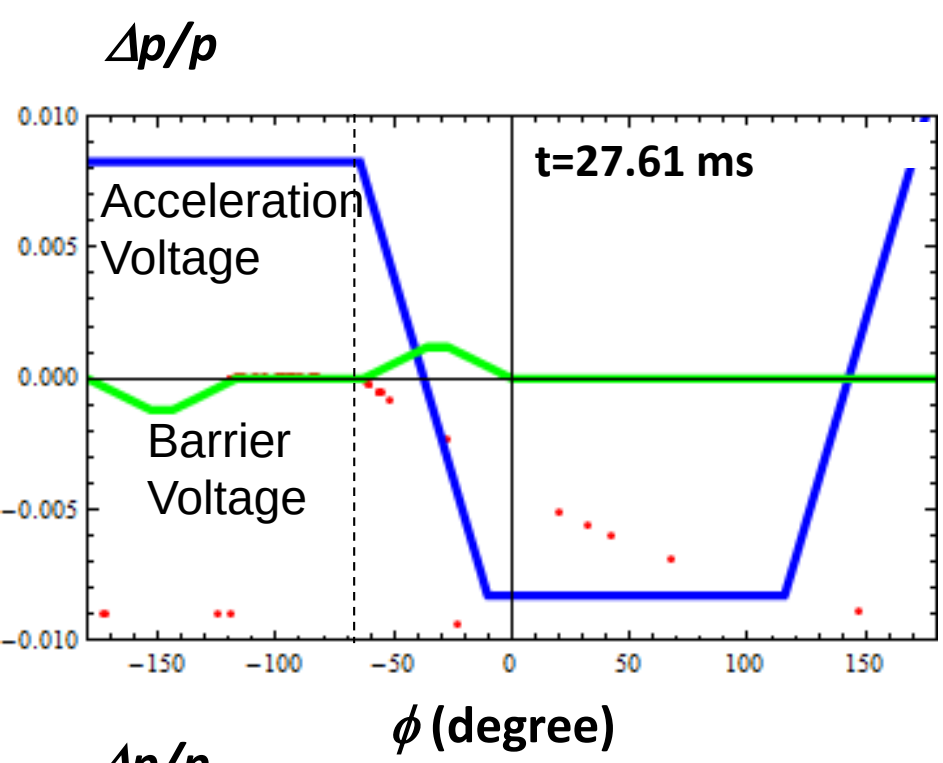


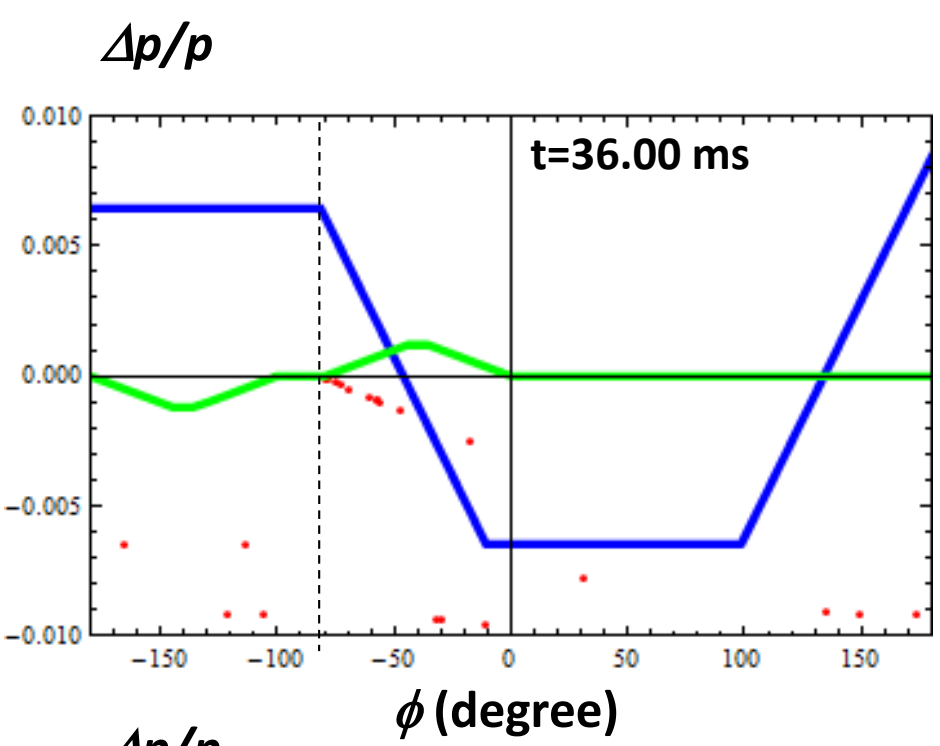
Carbon foil

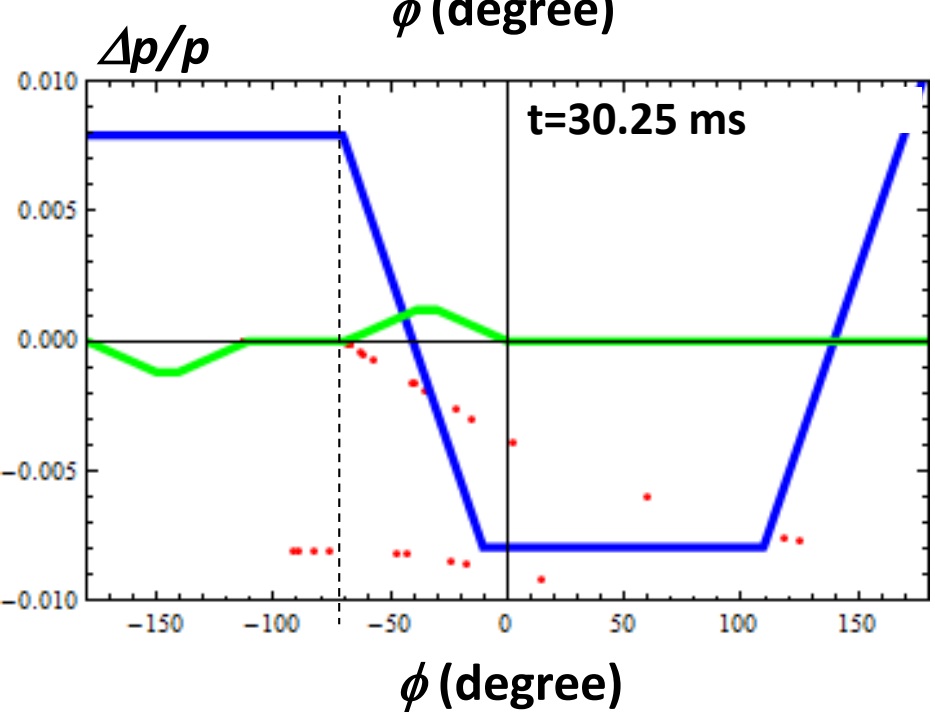
Behaviour of particles in the phase space during the extraction

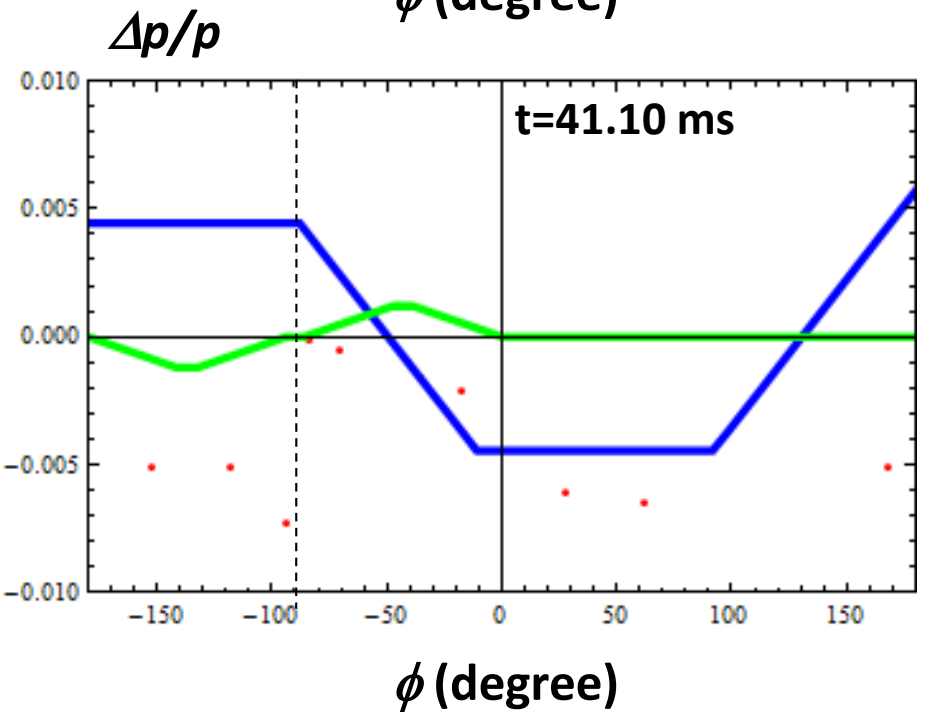




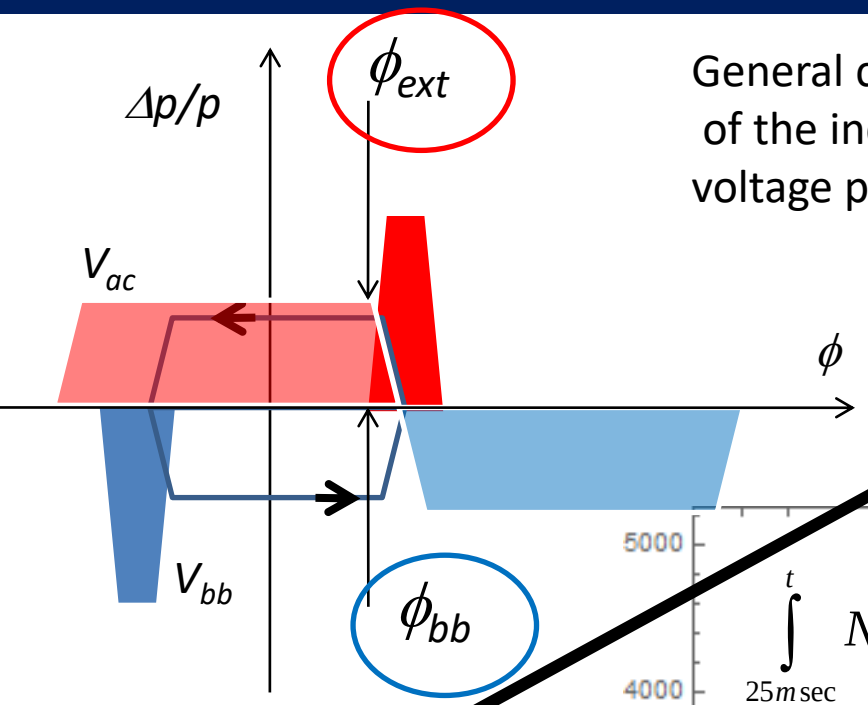

Δp/p
t=27.61 ms
Acceleration Voltage
Barrier Voltage
0.010
0.005
0.000
−0.005
−0.010
−150
−100
−50
0
50
100
150
ϕ (degree)


Δp/p
t=36.00 ms
0.010
0.005
0.000
−0.005
−0.010
−150
−100
−50
0
50
100
150
ϕ (degree)


Δp/p
t=30.25 ms
0.010
0.005
0.000
−0.005
−0.010
−150
−100
−50
0
50
100
150
ϕ (degree)

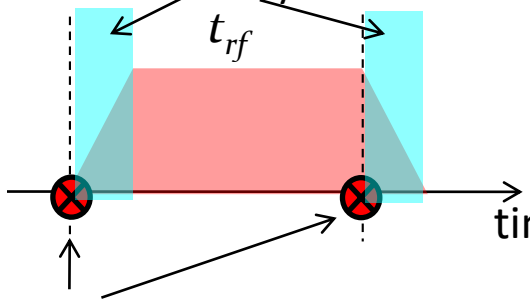

Δp/p
t=41.10 ms
0.010
0.005
0.000
−0.005
−0.010
−150
−100
−50
0
50
100
150
ϕ (degree)

Controlled Spill Structure and Spill Control Parameter



General characteristics of the induction pulse voltage profile control

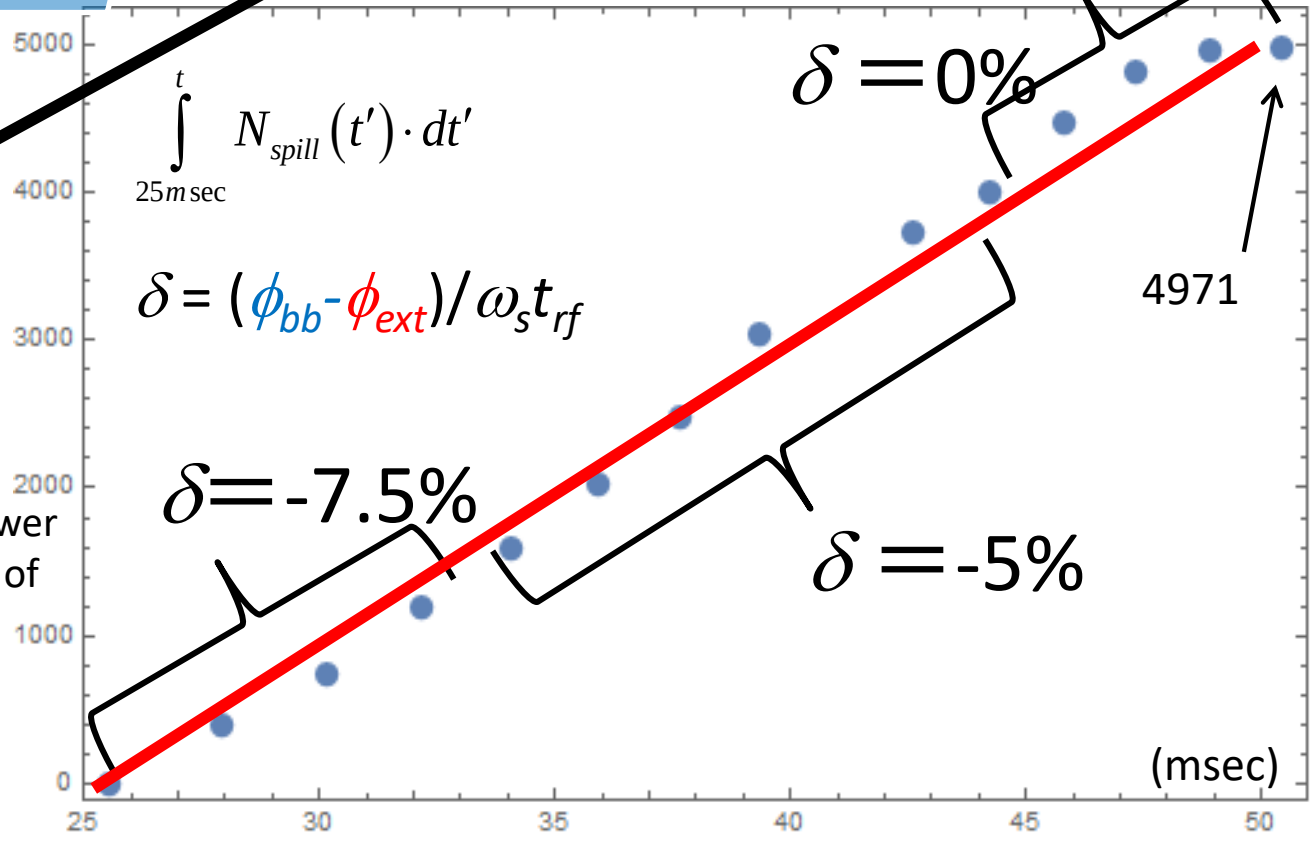
It is determined uniquely by the circuit constants of the system



This timing is accurately determined

$$\int_{25msec}^{t} N_{spill}(t') \cdot dt'$$

$$\delta = (\phi_{bb} - \phi_{ext}) / \omega_s t_{rf}$$



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

- Possible drivers for the next generation have been introduced, with a comparison among them *for ESCORT*
- Novel scheme of energy sweep extraction in the fast cycling synchrotron, based on the induction synchrotron concept, was introduced.
- Ideal lattice has been designed for a hadron beam driver for cancer therapies.
- Related activities at KEK have been introduced.

Prospect

Continuous and uniform 3D spot scanning on a target — *Low intensity operation*

↓ In future

3D spot scanning on a moving target
integrating real time diagnosis of the target position such as Liq. Xenon PET camera

↓

- 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 tumor.

→ **Gantry free 3 D spot scanning** → Low cost Therapy

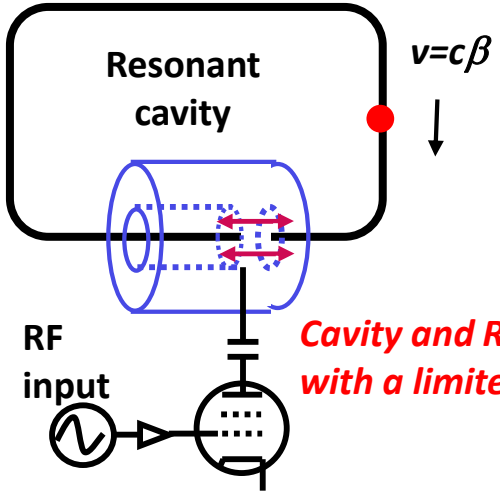
Demonstration of the pilot facility somewhere in South Asia is expected now.

Appendix

Induction Synchrotron and Current Activities related to ESCORT at KEK

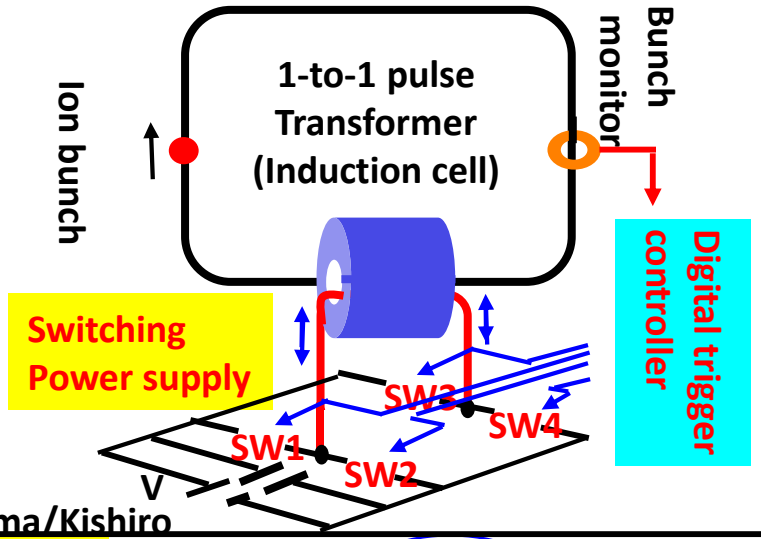
Characteristics of Induction Synchrotron (Digital Accelerator)

RF Synchrotron



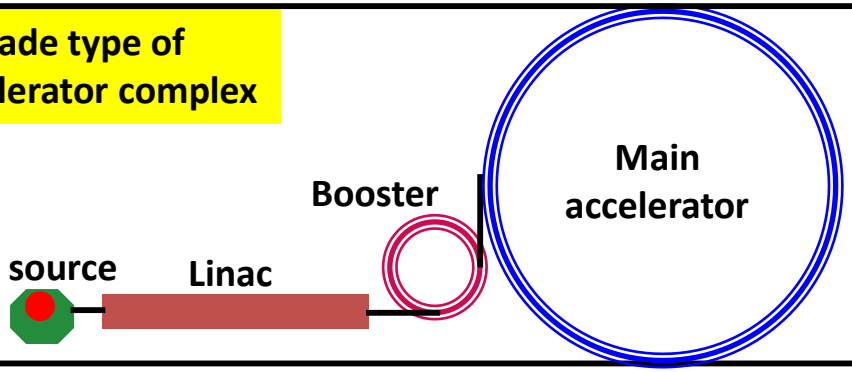
1945 E.M.McMillan, V.Veksler

Induction Synchrotron

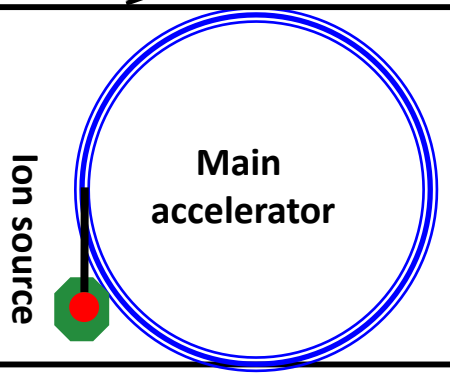


2000 Takayama/Kishiro

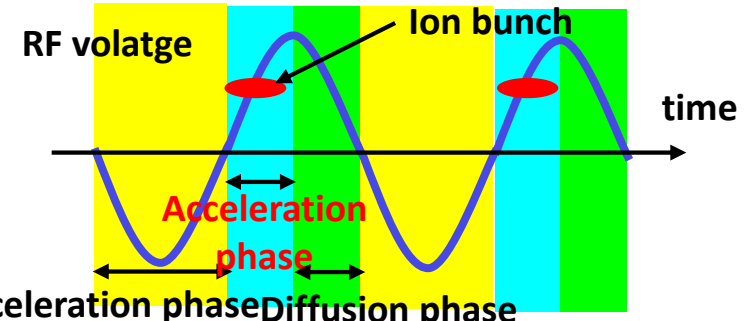
Cascade type of accelerator complex



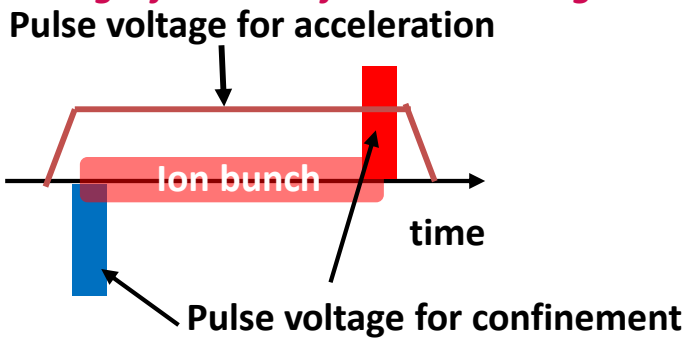
Single stage accelerator



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

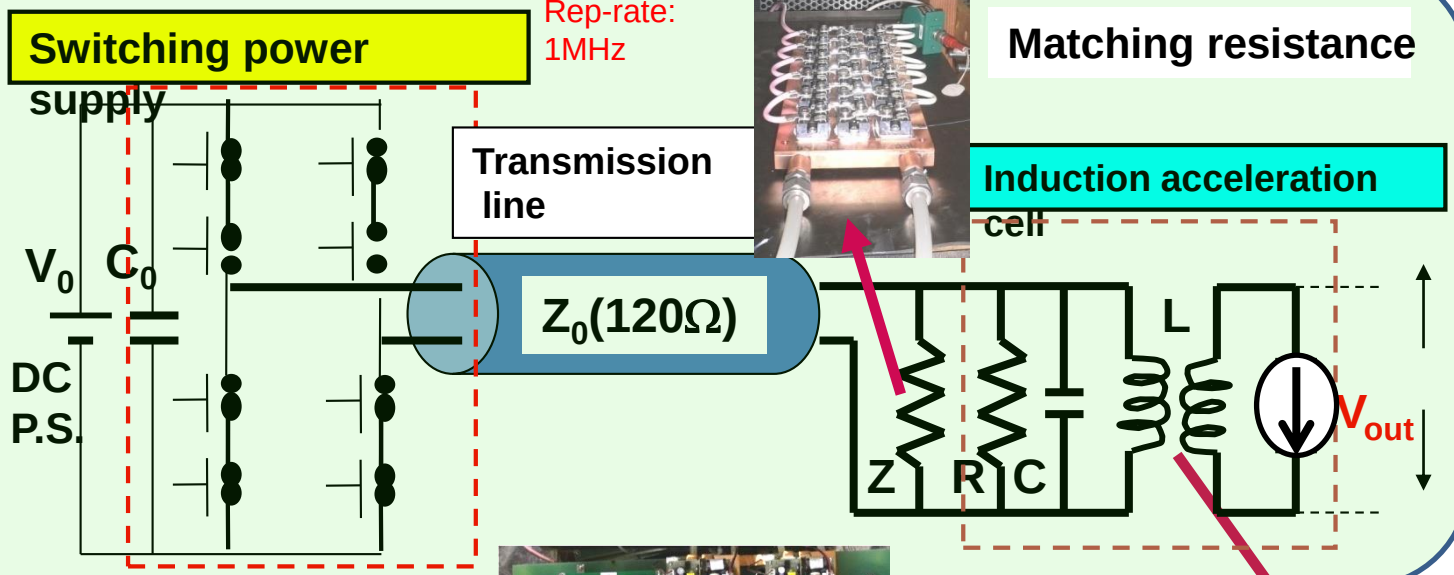


Functionally separated acceleration/confinement -> increasing a freedom of beam handling



Heart of Digital Accelerator : Evolutional Induction Accelerator System

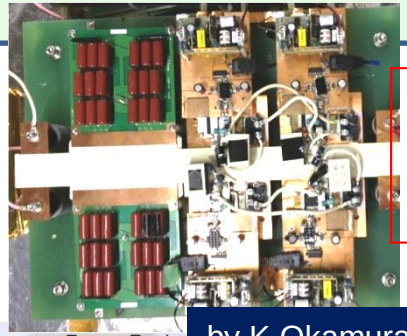
Equivalent Circuit



Swtiching arm S1
(7 MOSFETs in series)

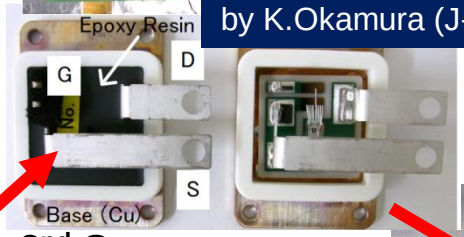
1st Gen. : 0.7 kV Si-MOSFETboard

by Koseki (now J-PARC), Tokuchi (now PPJ) *et al.*

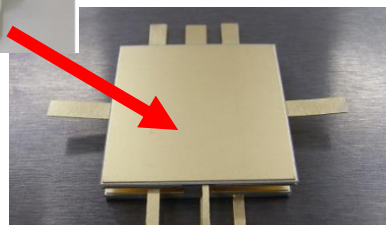


4th Gen.
3.3 kV
SiC-MOSFET
by Rohm

by K.Okamura (J-PARC) *et al* .

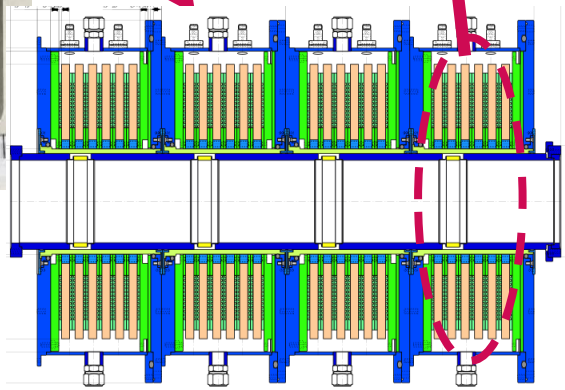


2nd Gen. :
SPS and
1.2 kV SiC-JFET
(custom package)



3rd Gen. : 2.4 kV SiC-JFET (custom package)

Magnetic material: nanocrystoline



Stack of 4 cells
V_{out}=3 kV/cell

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

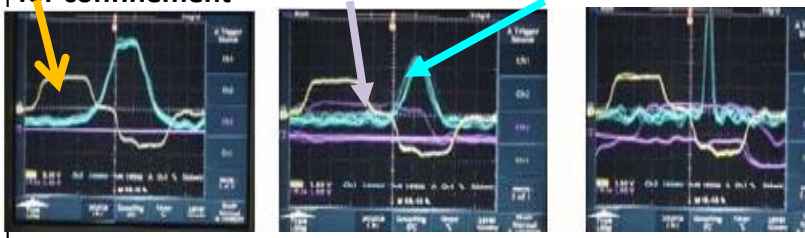
ion : H^+
500 MeV -> 6 GeV
$N=2.5 \times 10^{11}$

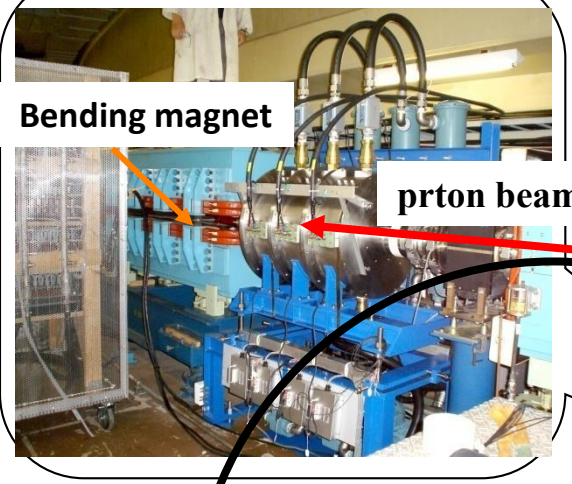
500 MeV → 6 GeV

Pulse voltage for confinement

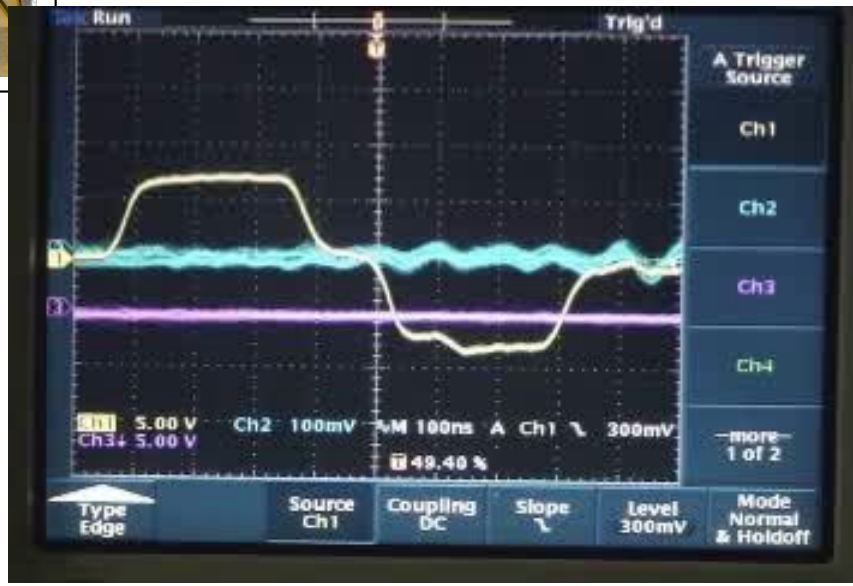
Pulse voltage for acceleration

Proton bunch signal

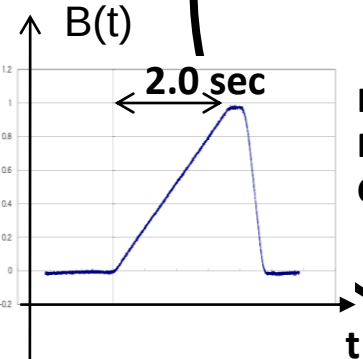




Switching Power Supply
（40kW、Max f_{rep}=1MHz）



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

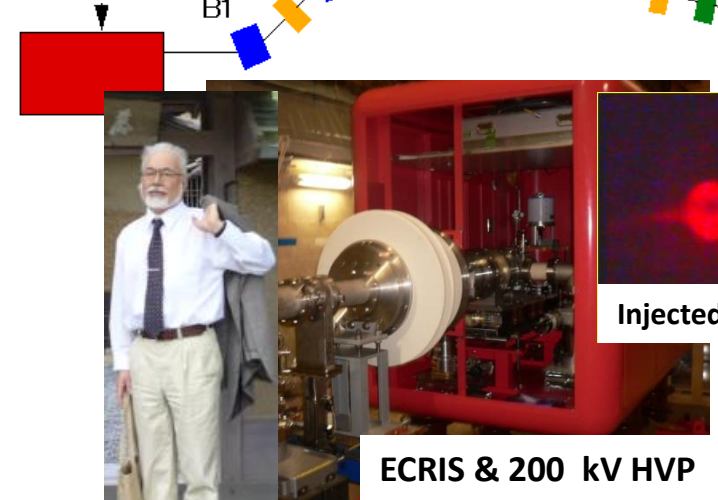
K.Takayama *et al.*, *Phys. Rev. Lett.* 94, 144801 (2005)
Phys. Rev. Lett. 98, 054801 (2007)

KEK Digital Accelerator (Fast Cycling Induction Synchrotron)

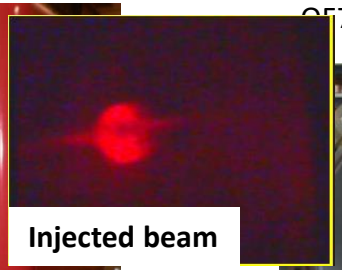
T. Iwashita *et al.*, *"KEK Digital Accelerator"*, *Phys. Rev. ST-AB 14, 071301 (2011).*

Circumference	37.7 m
B_{mx}	0.84 Tesla
Mximum energy	315 MeV (p), 2.15 GeV（Gold）

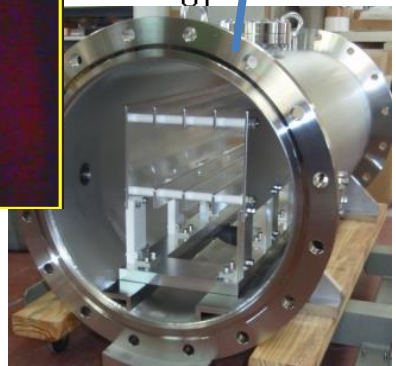
LEBT & ES Kicker

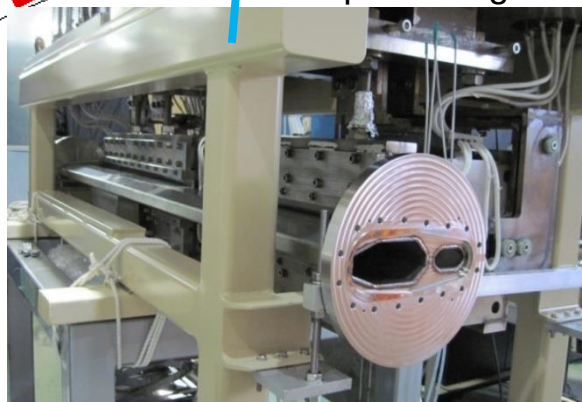


ECRIS & 200 kV HVP



Injected beam

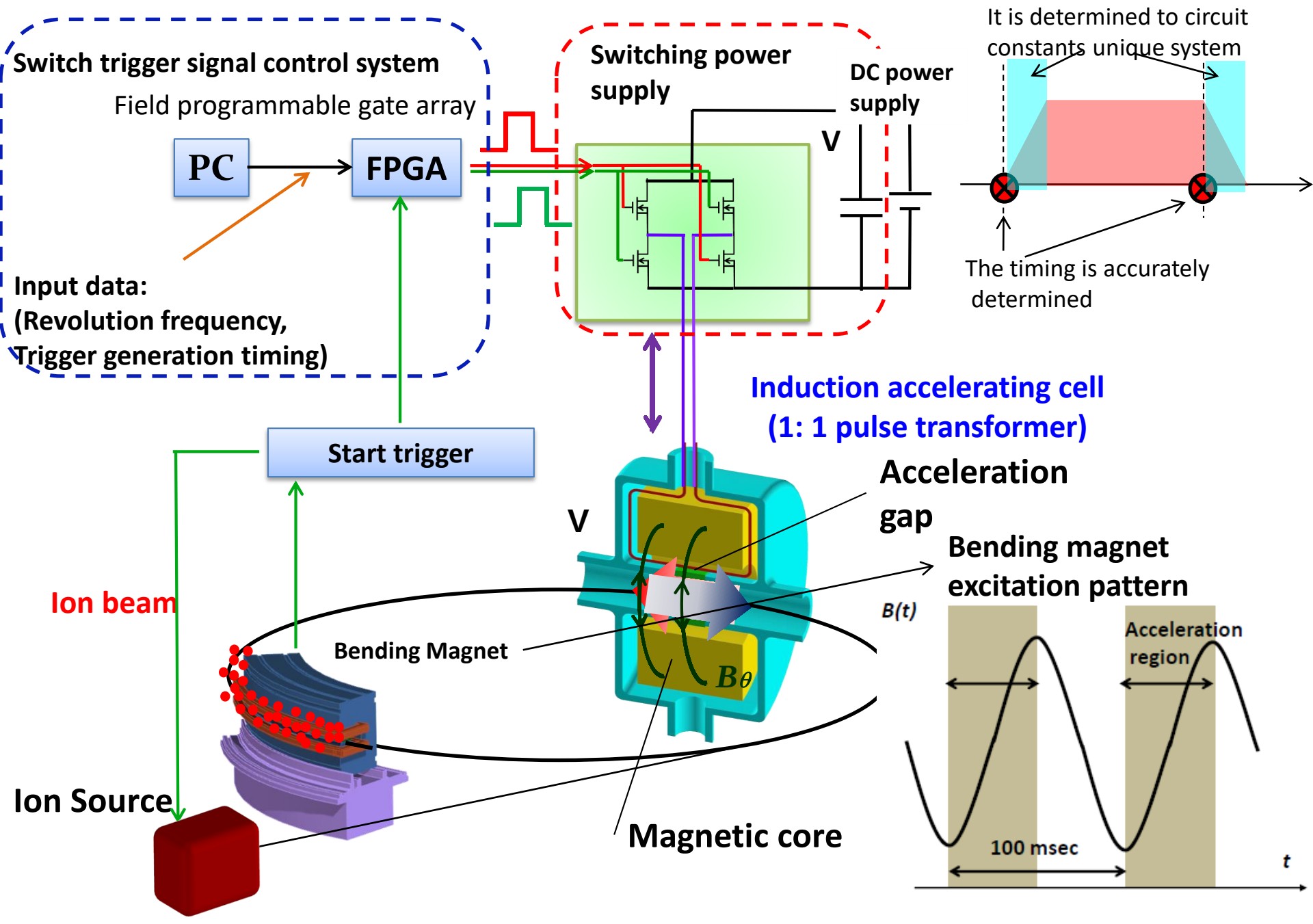




Extracted beam

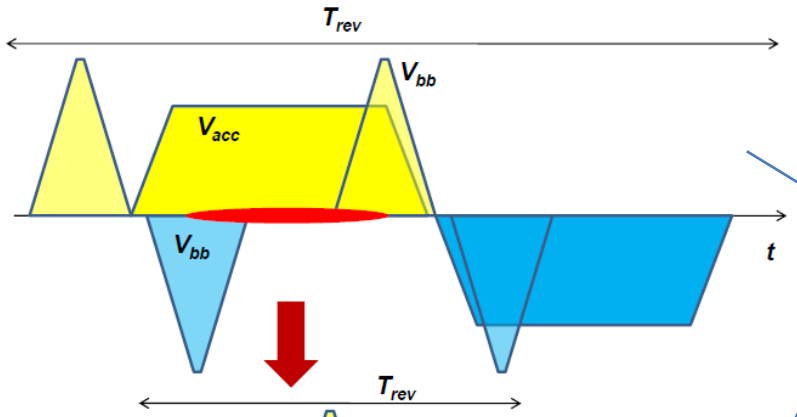
Septum magnet

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

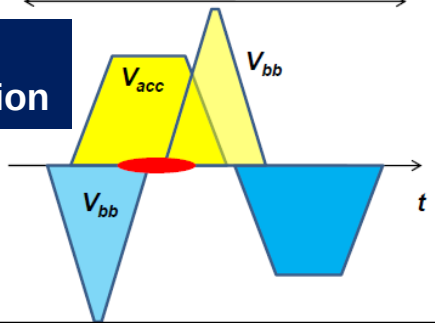


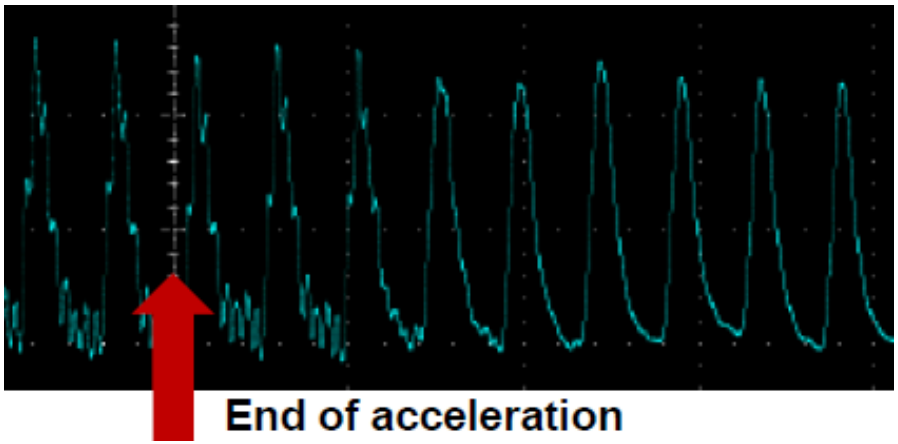
Acceleration of A/Q=4 Ions

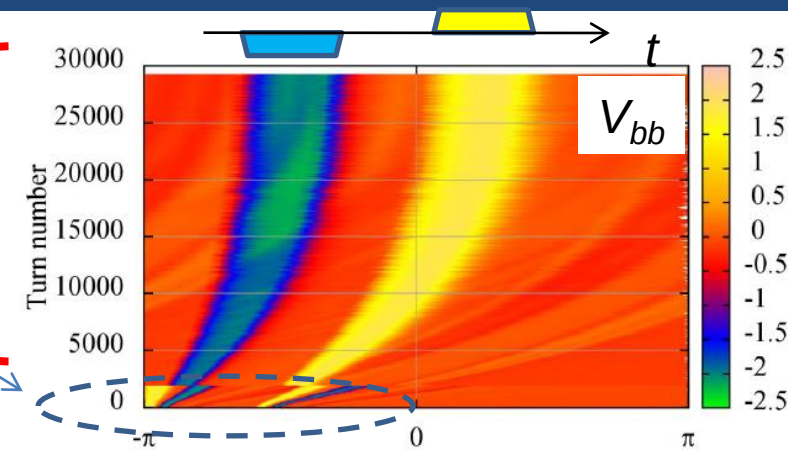
1) Early stage of acceleration

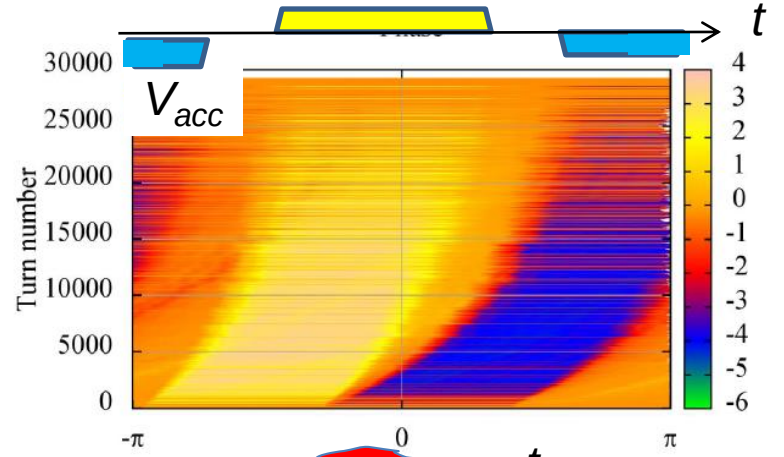


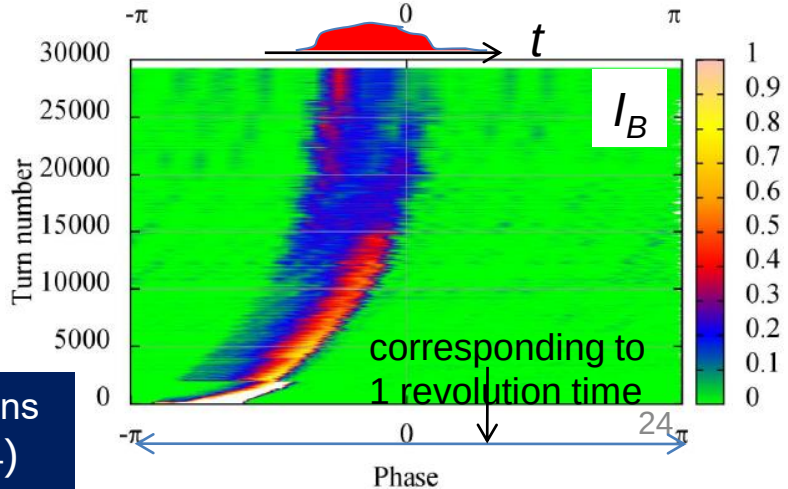
2) Late stage of acceleration









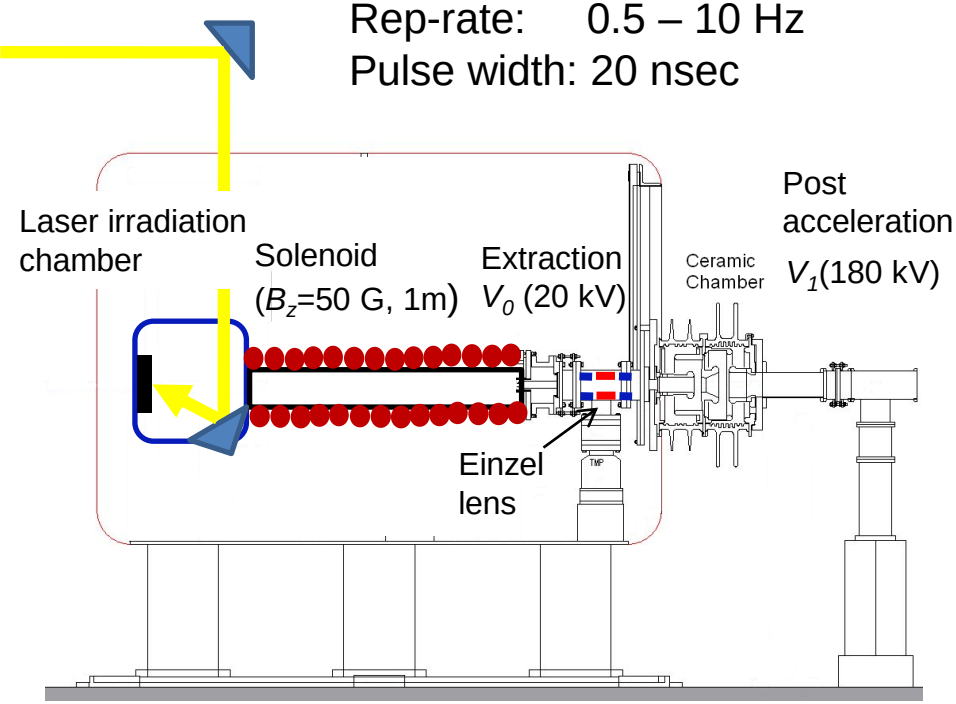


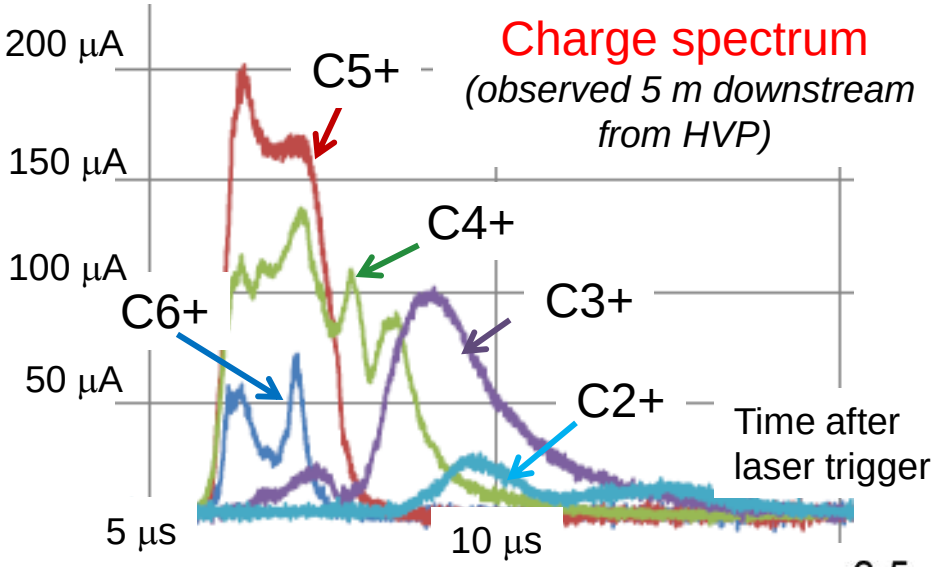
K.Takayama, T.Yoshimoto *et al*., "Induction Acceleration of Heavy Ions in the KEK Digital Accelerator", *Phys. Rev. ST-AB* 17, 010101 (2014)

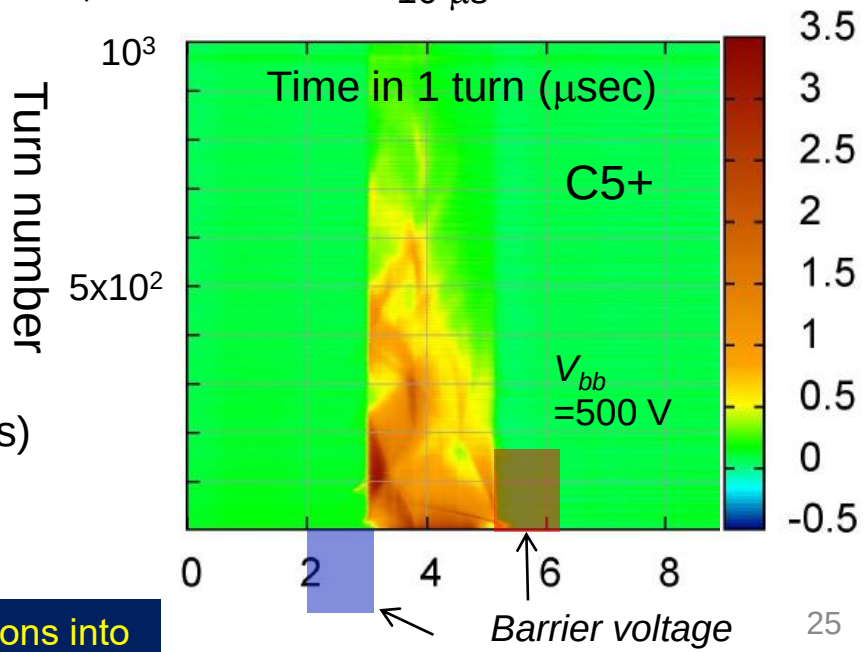
KEK-DA connected to Laser Ablation Ion Source

KEK Laser ablation ion source was initiated in the collaboration with Okamura Group (BNL) in 2013.

Nd-Yag Laser
Energy: 600 mJ
Rep-rate: 0.5 – 10 Hz
Pulse width: 20 nsec





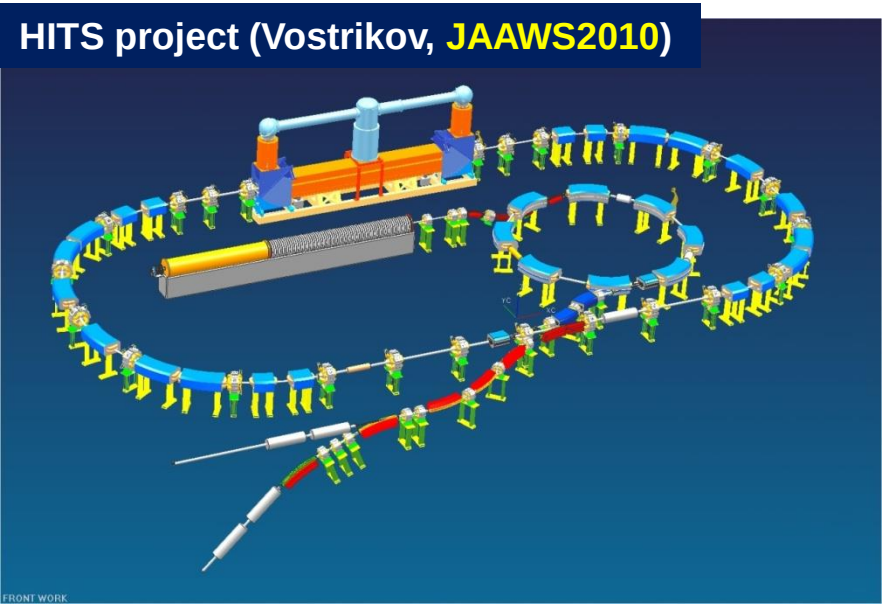


200 kV High voltage platform
in which the laser irradiation chamber with a graphite (for C ions) or metal target (for Al, Fe, Cu, Ag, Au ions) is embedded.

N. Munemoto *et al*., "Direct injection of fully stripped carbon ions into a fast-cycling induction synchrotron and their capture by the barrier bucket", *Phys. Rev. Accel. Beams* **20**, 080101 (2017).

Other Novel Accelerators for Medical Applications

HITS project (Vostrikov, JAAWS2010)



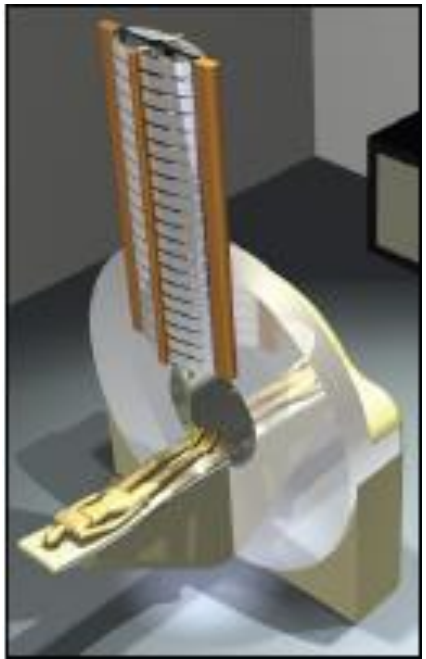
particle energy: p: 50 – 250 MeV,
C: 100 – 430 MeV/u

Intensity: p: 10^8 - 10^{11} part/cycle,
C: 10^7 - 10^{10} part/cycle

(Gantry-mounted proton accelerator)

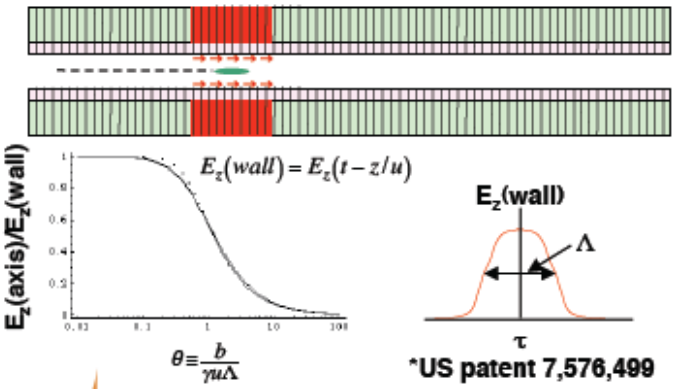
LLNL has already stopped its activity on DWA, because Industrial partner ran out of money.

MEVION S250 under operation



Dielectric Wall Accelerator
LLNL

Virtual travelig wave DWA for beams with arbitrary charge to mass ratios



*US patent 7,576,499