Wide-band Induction Acceleration in the KEK Digital Accelerator

T. Yoshimoto[1,2], M.Hirose[2,3], T.Arai[2], X. Liu[1,2],
T. Adachi[2,4],T.Kawakubo[2], H. Kobayashi[2,3], S.Takano[2], E.Kadokura[2],
K.Okamura[2,4], K.Takayama[1,2,4], Y. Okada[5], and H. Asao[5]

[1]Tokyo Institute of Technology,
[2]KEK,
[3]Tokyo City University,
[4]The Graduate University for advanced Studies,
[5]NEC Network and Sensor Systems

IPAC'14 9:50~10:10 Wednesday, 18 June, 2014

Contents

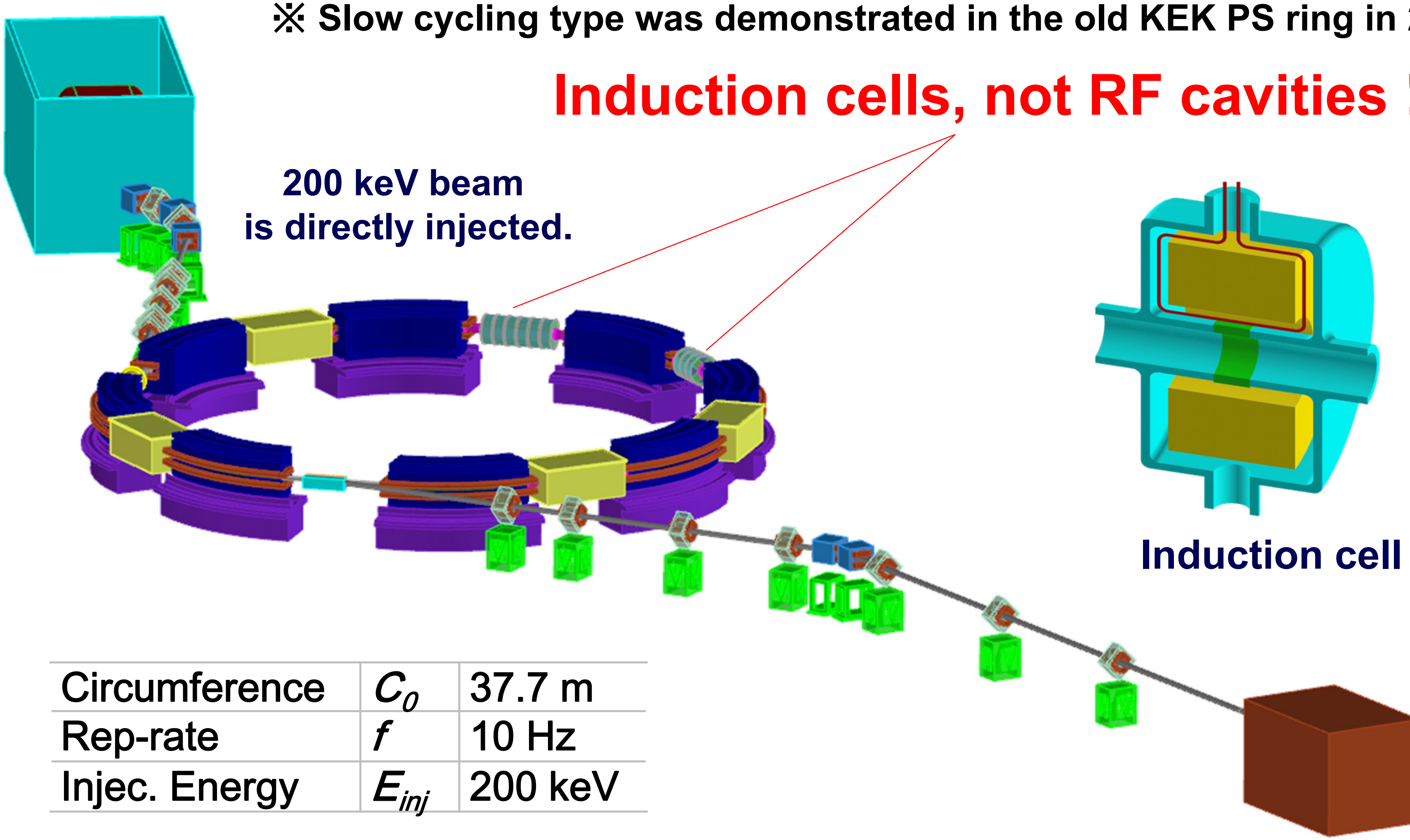
- What is induction synchrotron ?
- Three features of induction synchrotron
- Outline of KEK digital accelerator
- Wide band acceleration
- Novel beam handling
- Conclusion

What is Induction synchrotron ?

KEK digital accelerator (Wide-band fast cycling induction synchrotron)[1)]

※ Slow cycling type was demonstrated in the old KEK PS ring in 2006.[2)]

Induction cells, not RF cavities !!



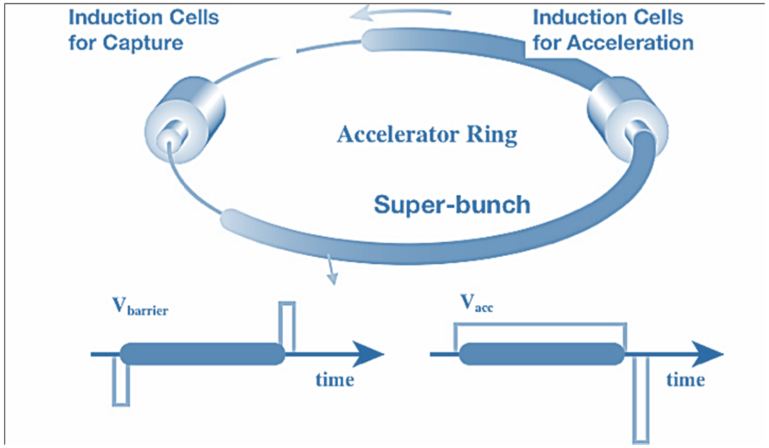
Induction cell

Circumference	C_0	37.7 m
Rep-rate	f	10 Hz
Injec. Energy	E_{inj}	200 keV

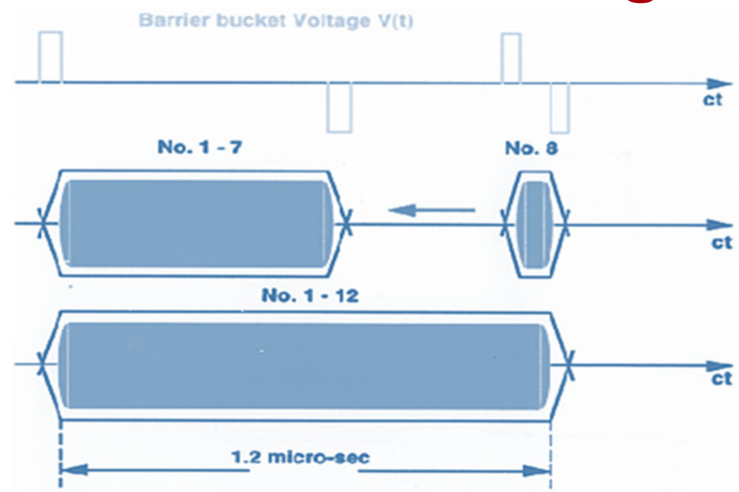
1) T. Iwashita, *et al.*, "KEK digital accelerator", *Phys. Rev. ST-AB* **14**, 071301(2011)
2) K. Takayama, *et al.* ,"Experimental Demonstration of the Induction Synchrotron" , *Phys. Rev. Lett.* **98**, 054801 (2007)

Three notable features of Induction synchrotron

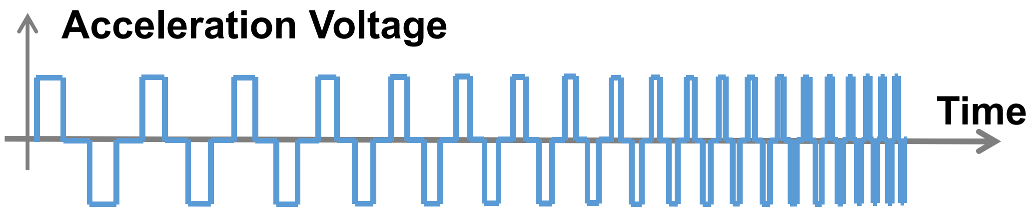
Super-bunch acceleration[1)]



Novel beam handling



Wide-band acceleration[2)]



Advantages

Rev. frequency: 0 ~ a few MHz

Wide variety of ion species can be provided in a broad energy range.

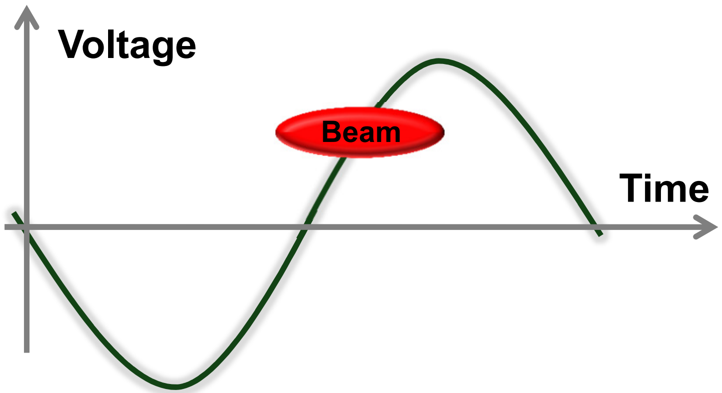
Disadvantages

- **Space charge limit & residual gas interactions in low energy region**
- **In small ring (~100 m), max. rev. frequency is limited by semiconductor switching of acc. volt..**

1) K.Takayama, *et al*, "Superbunch Hadron Colliders", *Phys. Rev. Lett.* **88**, 144801 (2002)
2) K.Takayama, *et al*, "All-ion accelerators: An injector-free synchrotron", *Journal of Applied Physics* **101**, 063304 (2007)

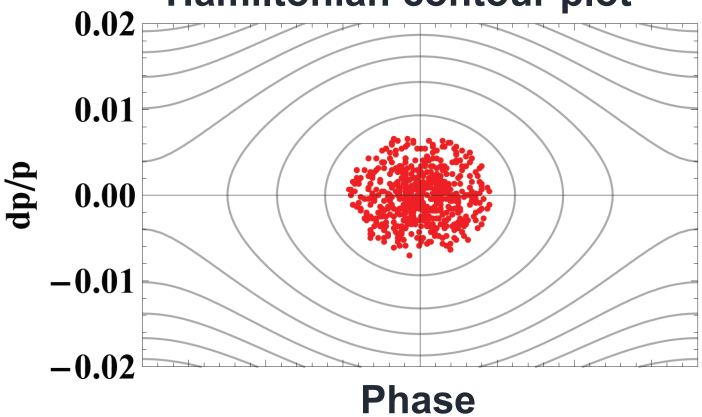
RF acceleration & Induction synchrotron

Conventional RF acceleration

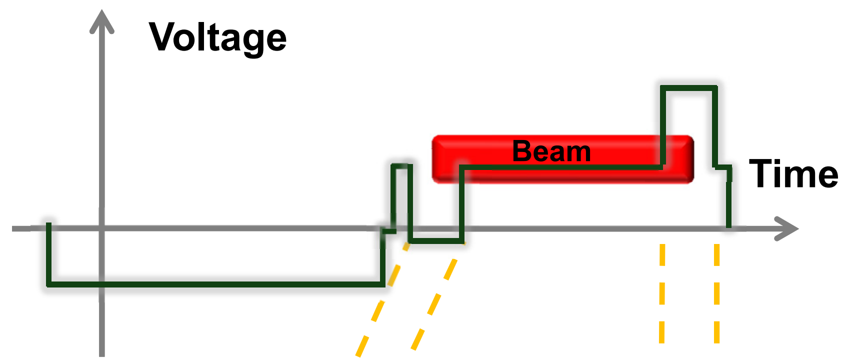


Confinement & Acceleration function are combined.

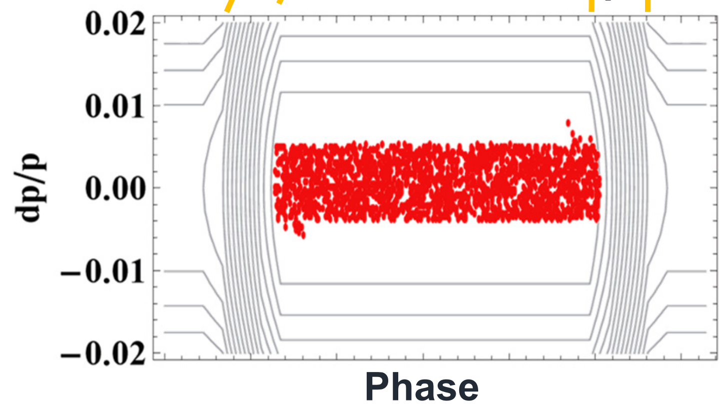
Hamiltonian contour plot



Induction acceleration

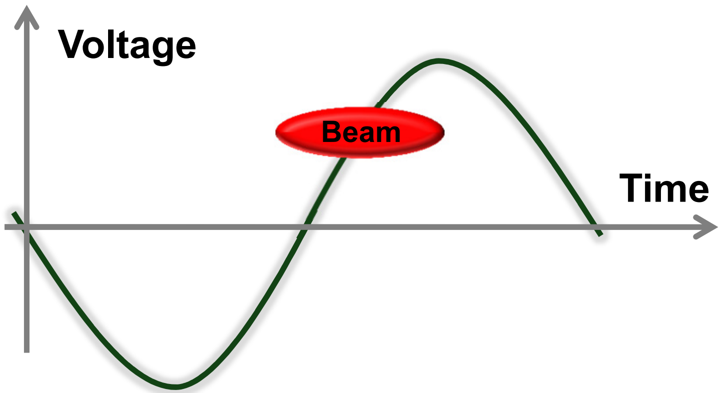


Hamiltonian contour plot

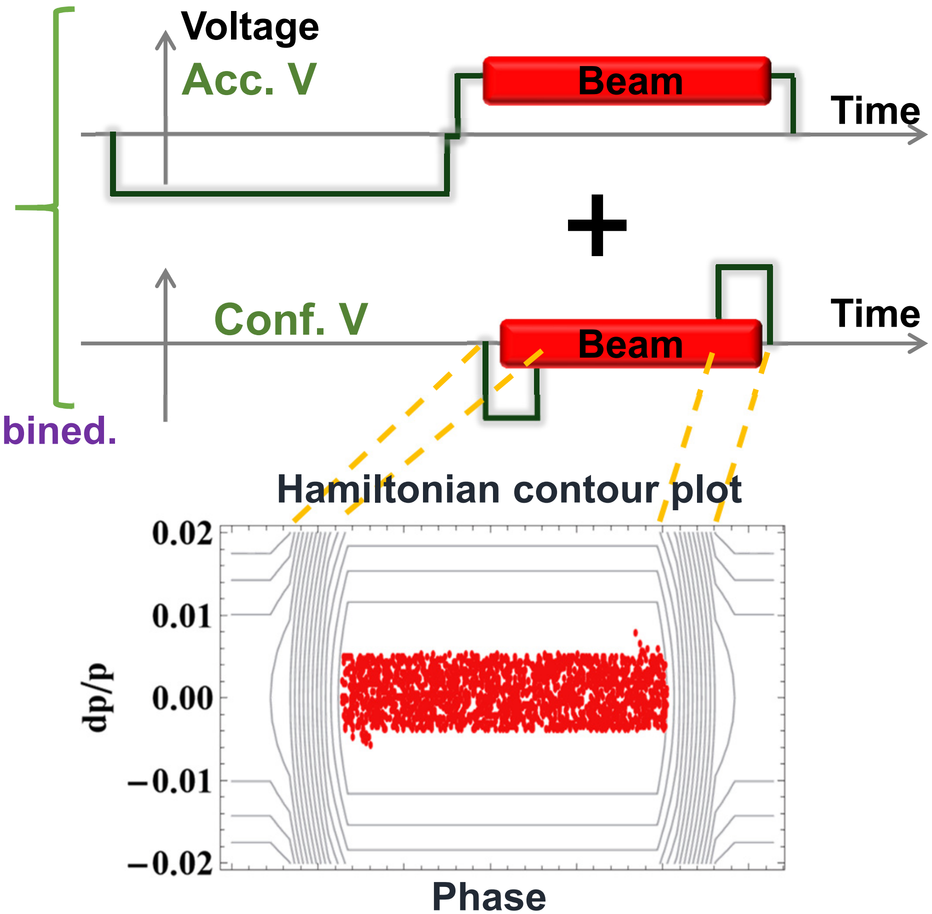


RF acceleration & Induction synchrotron

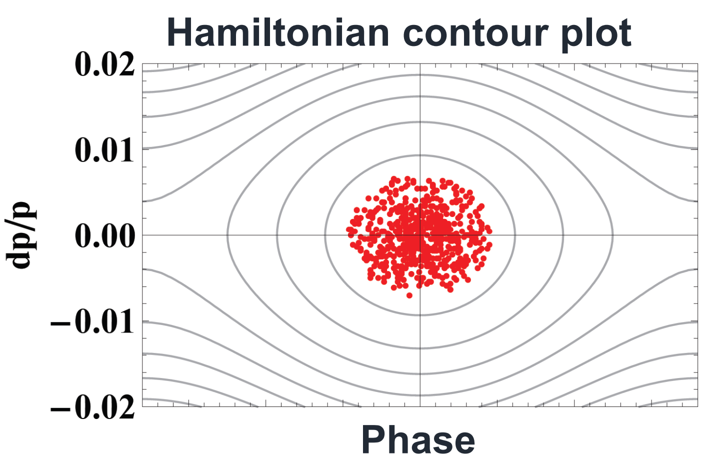
Conventional RF acceleration



Induction acceleration

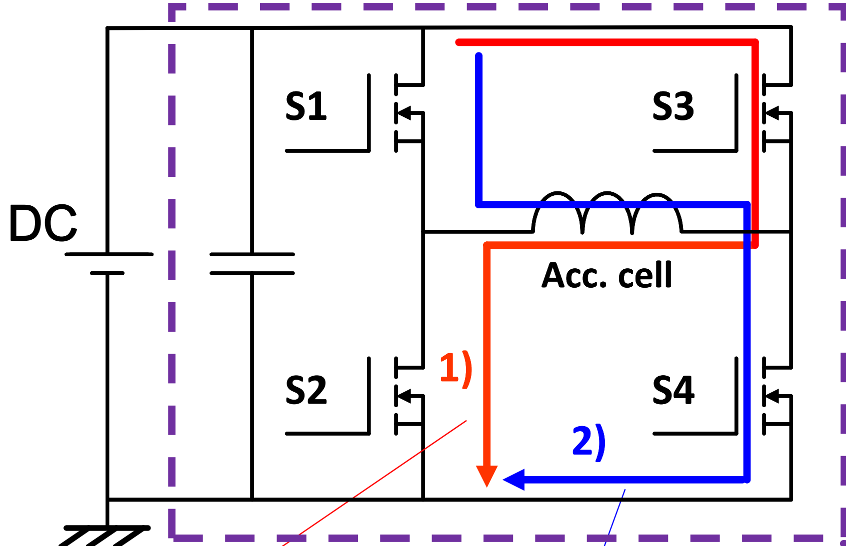


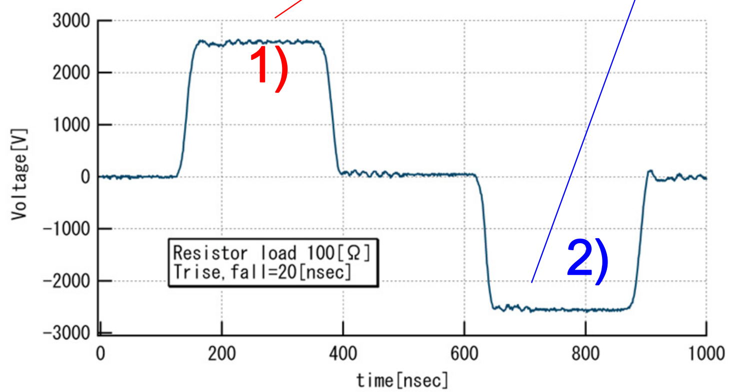
Confinement & Acceleration function are combined.



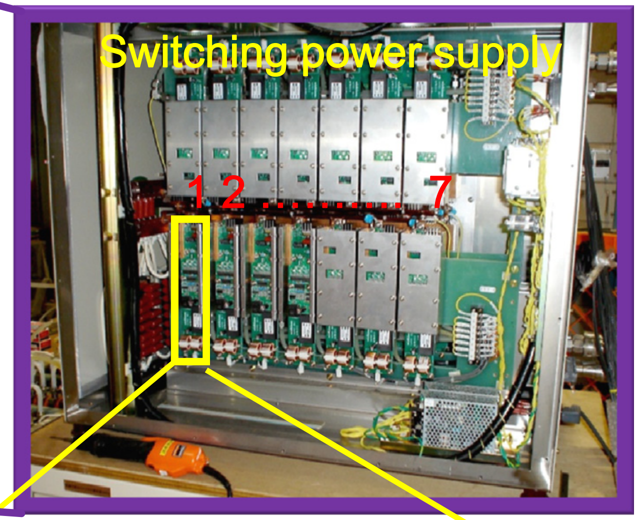
Separate function can creates a longer bucket ⇒ mitigating space charge effect.

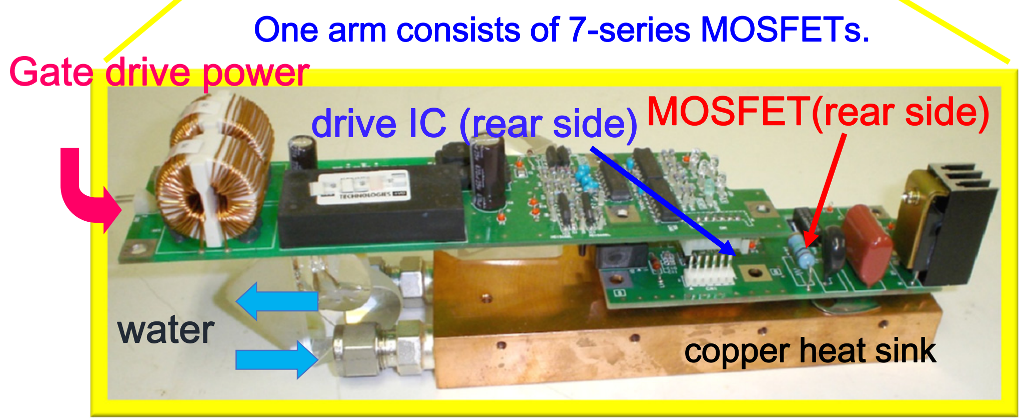
Switching Power Supply for Induction cells





Waveform generated by switching power supply
(2.5kV, 20A, 1MHz)

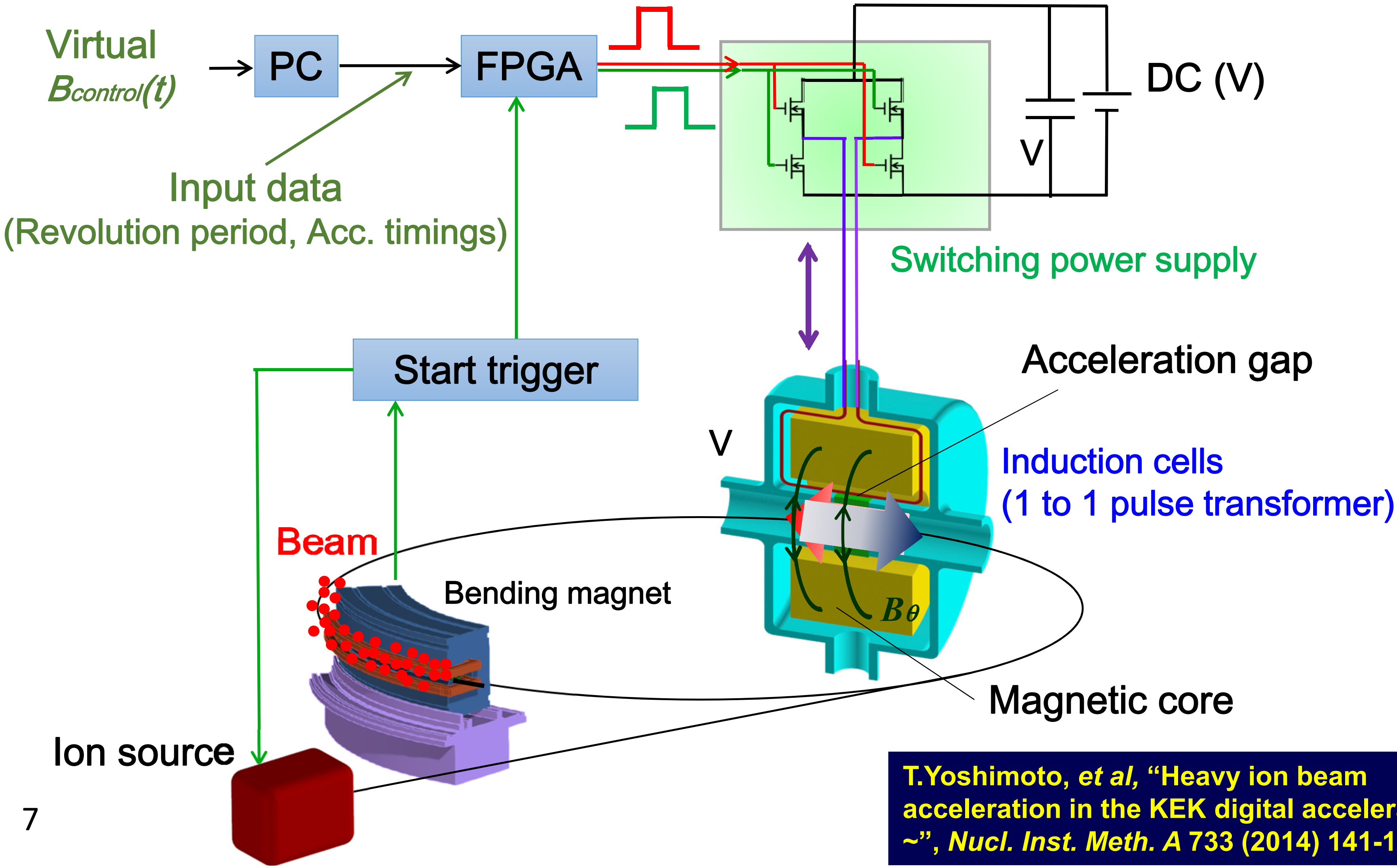




Next generation of SPS: K.Okamura, *et al*, MOPME068 in IPAC'14
"SiC-JFET Switching Power Supply toward for Induction Ring Accelerators"

Fully programmed control of KEK digital accelerator

In advance, all information for acceleration timings is load to FPGA.
Virtual *B(t)* decides ideal revolution period and acc. timings.



T.Yoshimoto, *et al*, "Heavy ion beam acceleration in the KEK digital accelerator: ~", *Nucl. Inst. Meth. A* 733 (2014) 141-146

How to generate confinement voltages

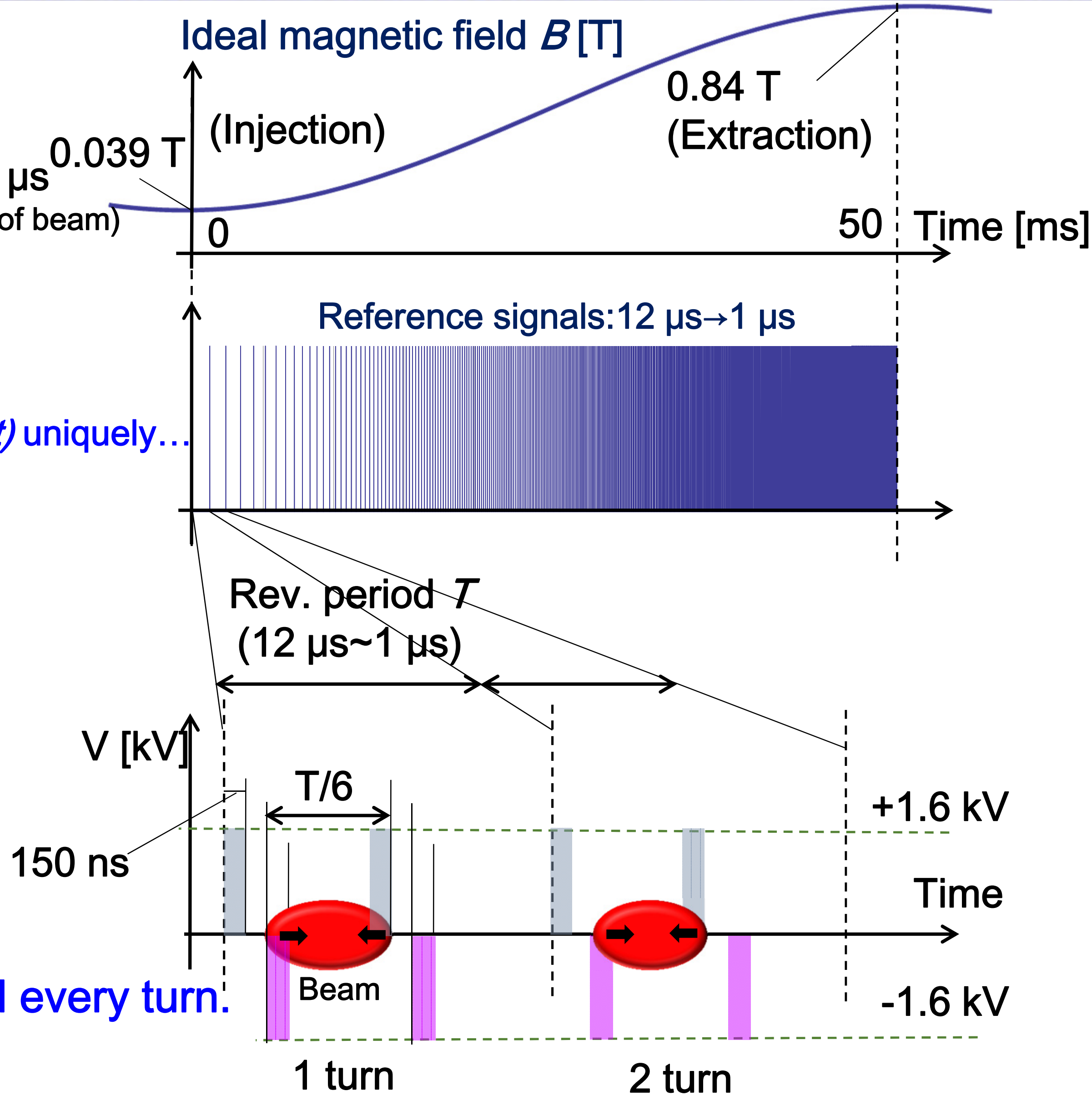
Reference signals:12 μs→1 μs
(which generate every ideal rev. period of beam)

$$T(t) = \frac{C_0}{c}\sqrt{\frac{1+D}{D}}$$

B(t) determines *T(t)* uniquely…

$$D = \left\{ \left(\frac{Q}{A}\right)\left(\frac{e\rho}{m_0 c}\right) \right\}^2 B^2$$

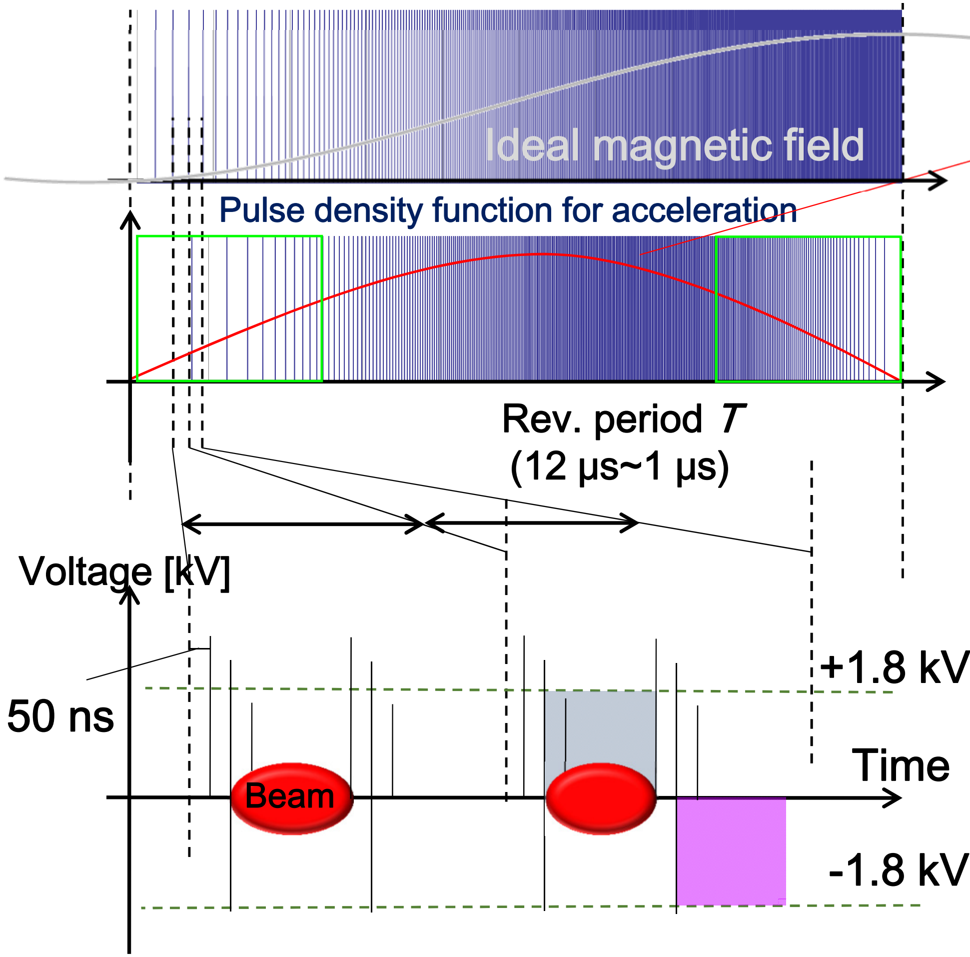
Here,
ratio of charge to mass : *Q/A*
charge element : *e*
bending radius: *ρ*
unit mass: m_0
ideal magnetic field : *B(t)*



Conf. voltages are generated every turn.

How to generate acceleration voltage

Reference signals (signals of ideal rev. period) :12 μs→1 μs



Required acc. voltage per turn *V(t)*:

$$V(t) = \rho C_0 \frac{dB(t)}{dt}$$

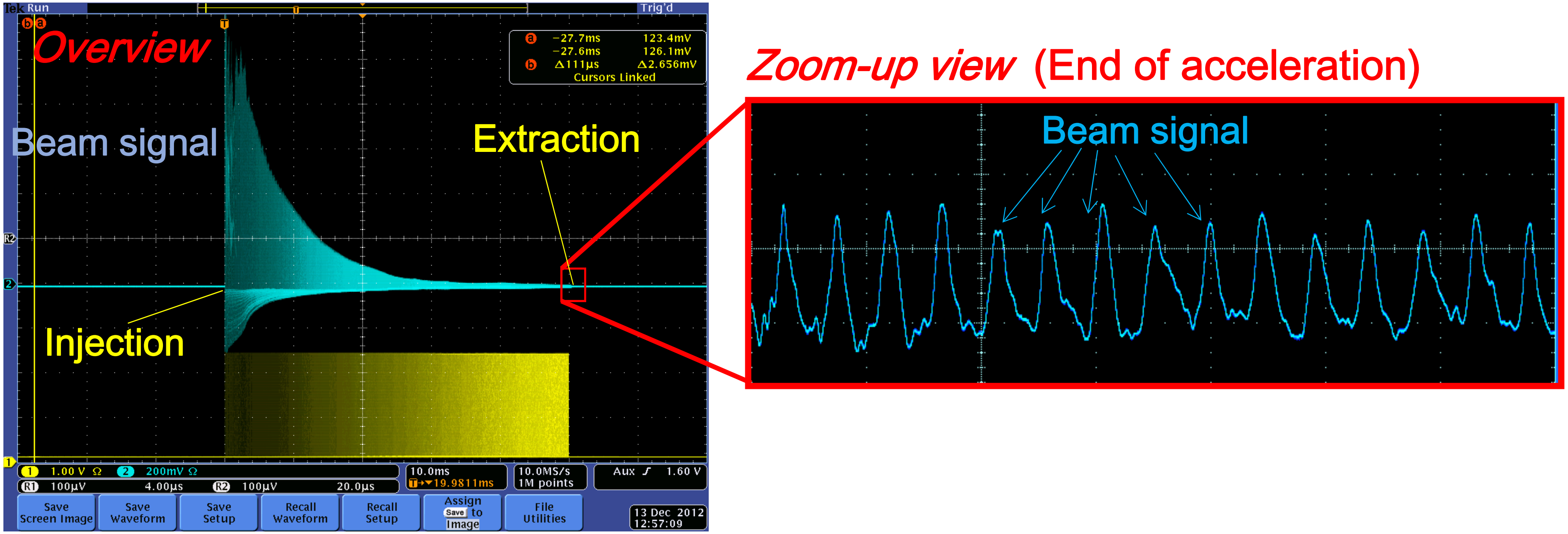
ρ : bending radius
C₀ : circumference
B(t): ideal magnetic field

$$\delta(N+1) = \begin{cases} 1 & \cdots \left(\sum_{n=1}^{N+1} V(n) - V_0 \sum_{n=1}^{N} \delta(n) > V_0\right) \\ 0 & \cdots \left(\sum_{n=1}^{N+1} V(n) - V_0 \sum_{n=1}^{N} \delta(n) < V_0\right) \end{cases}$$

V_0: constant induction acc. voltage
δ(n): acc. density table
N: turn number

Induction acc. voltages are generated discretely in order to give required acc. voltage spuriously. ➡ **Pulse density control**

Result of beam acceleration

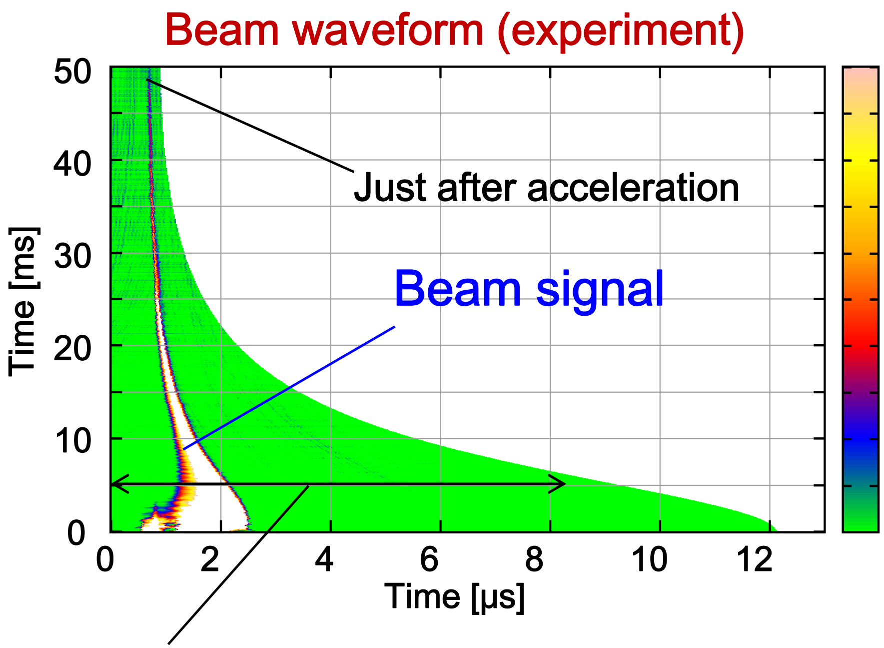


Beam and machine parameters:

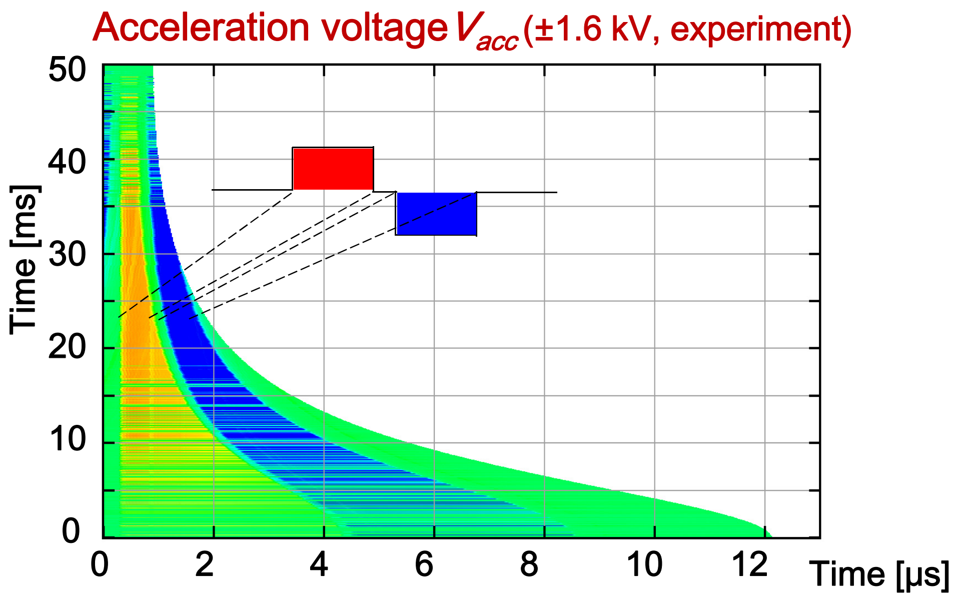
Bending magnetic flux density	0.039 → 0.51 [T]
Mass to charge ratio A/Q	4/1
Energy	0.05→8 [MeV/u]
Injection current	~100 μA

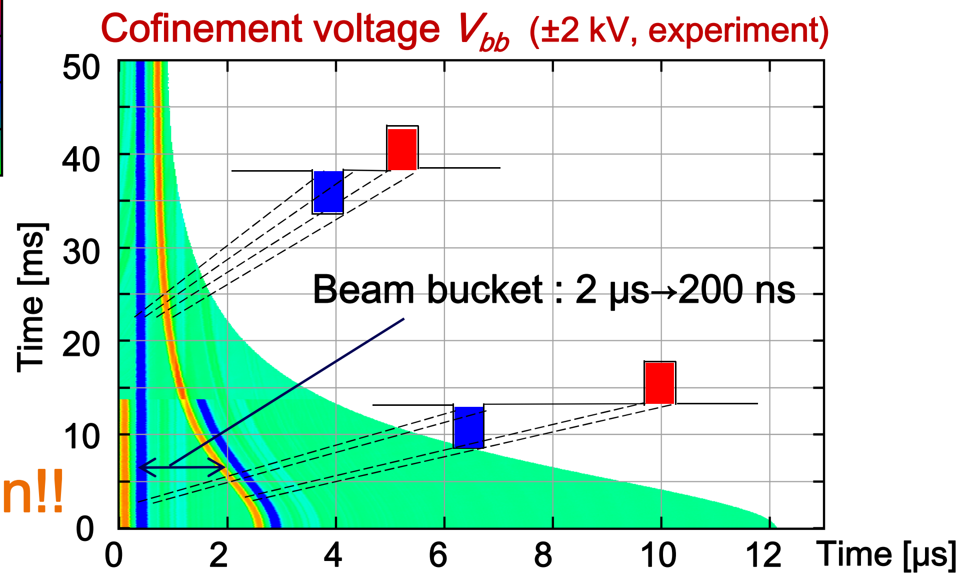
*K.Takayama, T.Yoshimoto, *et al* ,“Induction acceleration of heavy ions in the KEK digital accelerator”, *Phys. Rev. ST-AB* **17**, 010101(2014)

Wide-band acceleration (experiment)



Rev. period: 12 μs→1 μs !!





Success of wide-band acceleration!!

Beam survival & discussion

Beam survival: ~ 10%

Reasons

- **Vacuum (~ 10^{-6} Pa)**

Strong interaction with residual gas in low energy (200 keV ~)

- **Non-zero dispersion optics (D = 1.4 m at Induction cell region)**

Unfortunately, present optics was designed for the PS booster ring 40 years ago.

- **Discrete acceleration**

In our case, acc. voltages are constant because of fixed output of DC power supply. Therefore we do not generate acc. voltage every turn.

Solution:

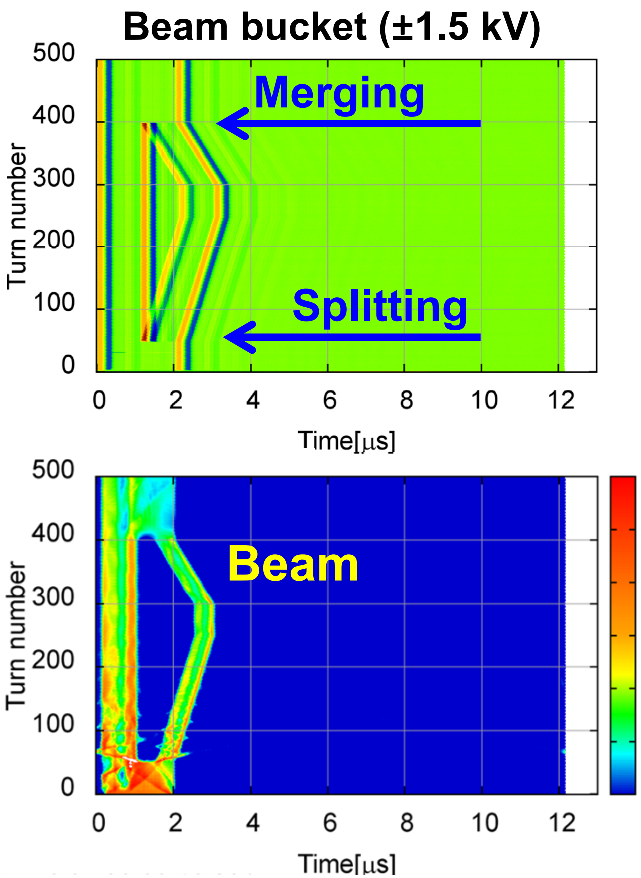
DC power supply with time varying output voltage may be ideal to meet required acceleration voltage demand.

These three reasons are not issues for brand-new future induction synchrotrons.

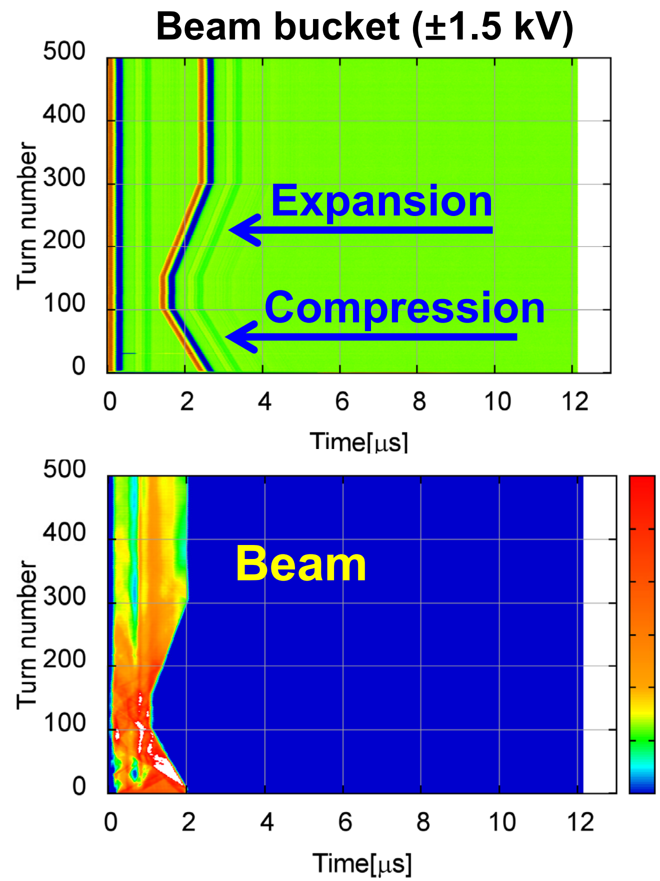
Novel beam handling (Experiment, E = 200 keV, A/Q = 4)

※ **preliminary experiment**

Splitting & Merging



Compression & Expansion



Combination of these technique makes various operations.

Ex. 1: Separated beams can be provided to different lines at different energies.

Ex. 2: It is easy to stack bunches at injection.

Conclusion

We have demonstrated:

- **wide-band acceleration** **(Rev. *f* : 82 kHz ~ 1 MHz)**

  A wide variety of ion species can be provided in a broad energy range for various applications, where high intensity is not required.

  ## There is space charge limit in low energy !!

- **beam handling** **techniques with induction synchrotron.**

  Various useful operations are expected soon.

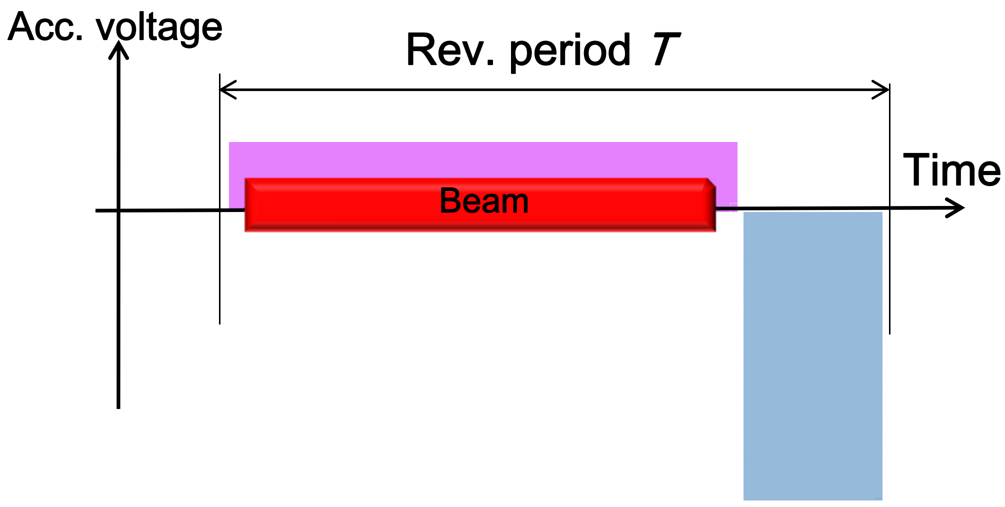
Future works …

We try to establish the super bunch (very long beam) acceleration.

Thank you for attention !!

Preparatory Slides

Super bunch (very long beam) acceleration



Method 1:Half Bridge SPS

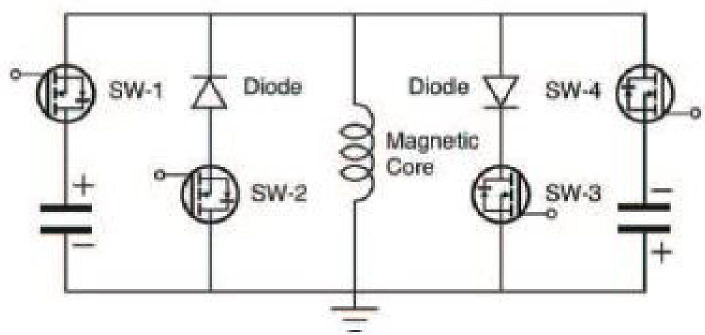
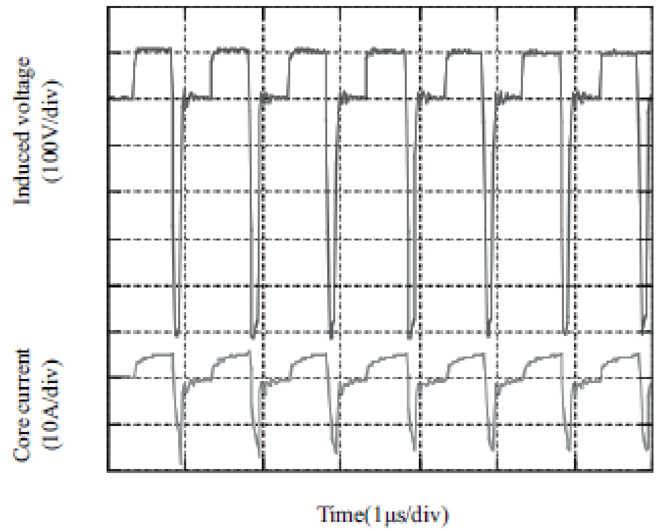
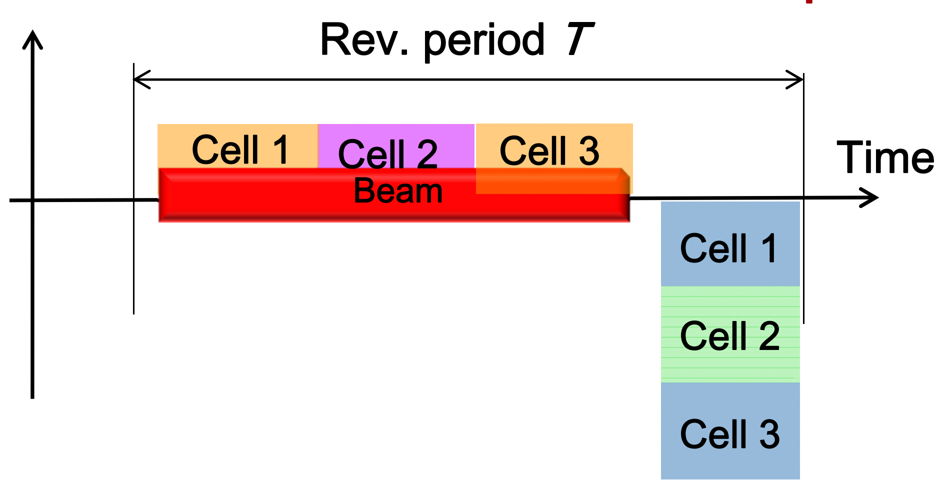


Fig. 11.16. Half bridge modulator.

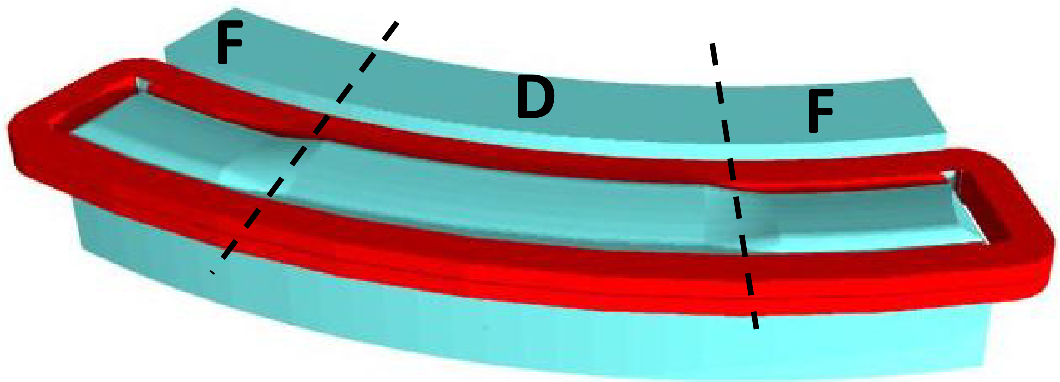


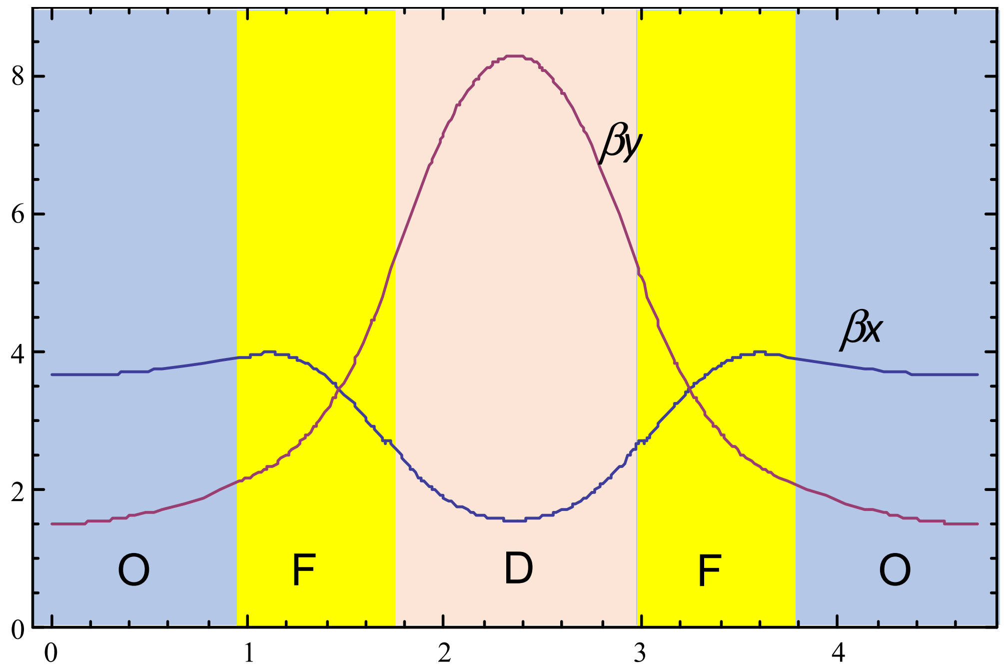
(experimental demonstration by Dr. Watanabe of Tokyo Tech.)

Method 2: combined acceleration pulse



The ring lattice in the KEK digital accelerator

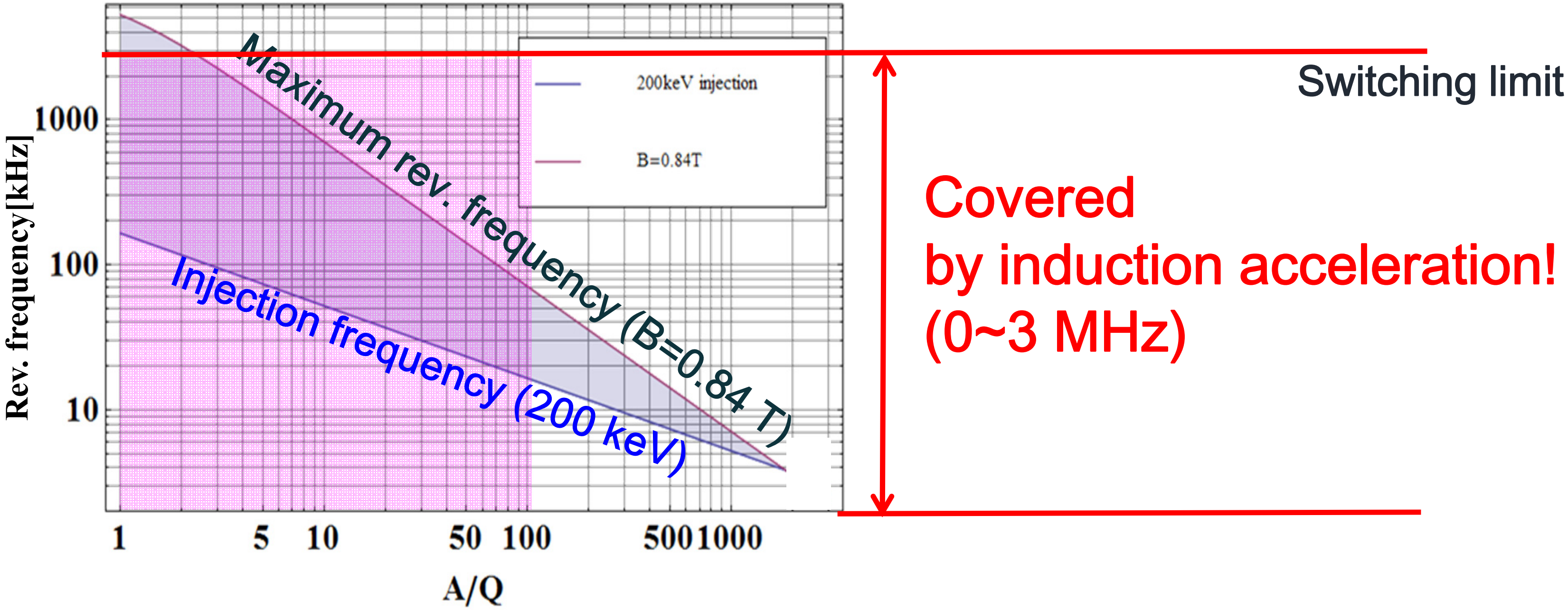




Which ion species can be accelerated ?

◆ Mass-to-charge ratio of many ions are 1~100.

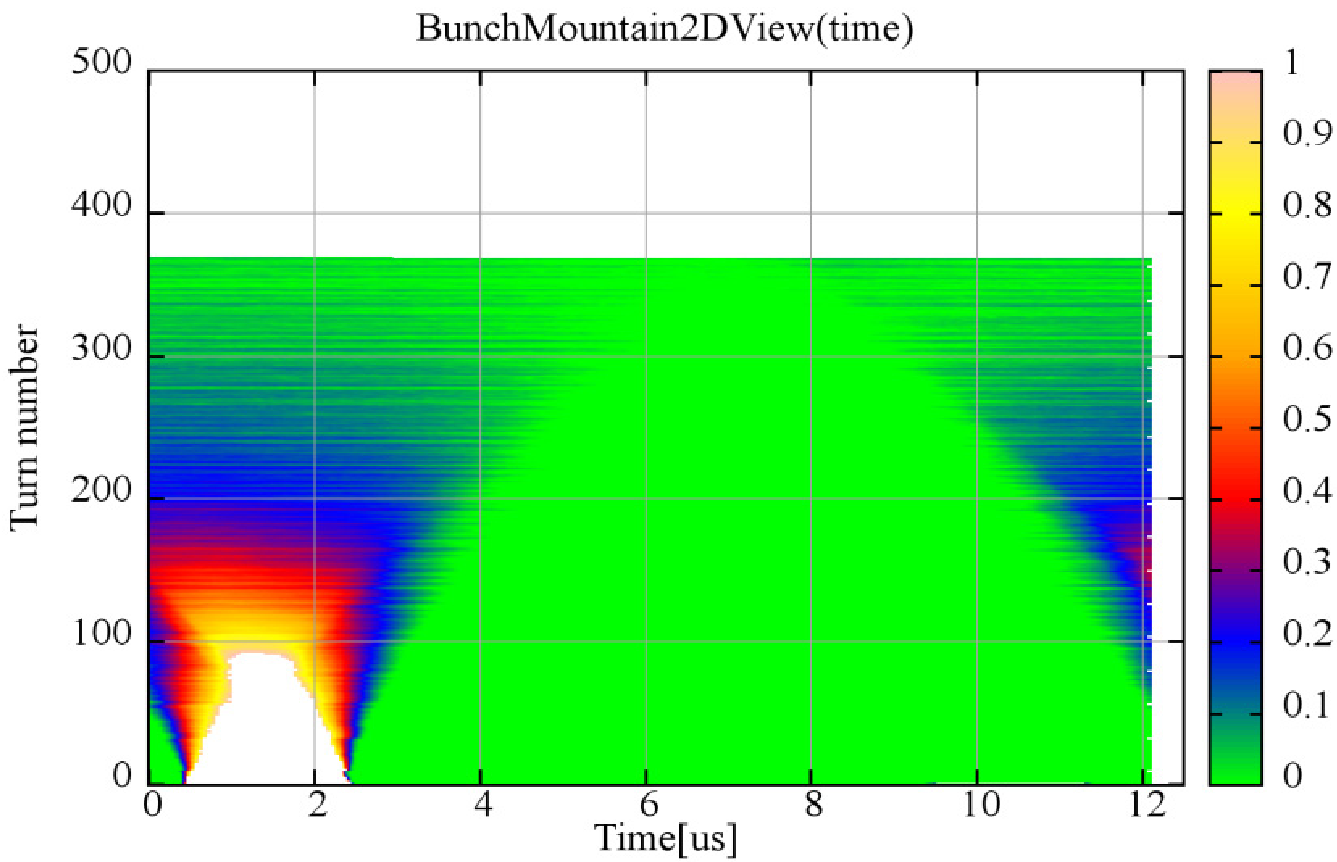
➡ Most ions species with any charge state can be directly accelerated.



◆ Semiconductor switching capability of induction system limits maximum revolution frequency.

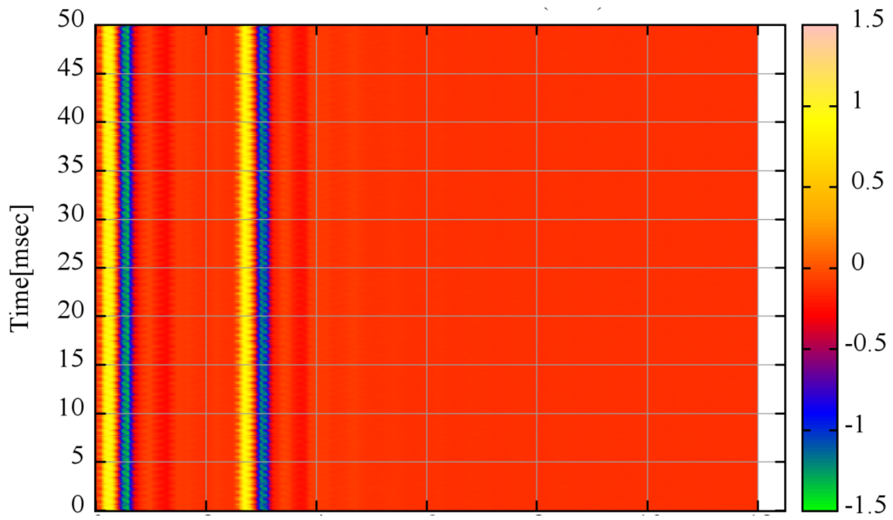
➡ In principle, large scale ring can eliminate this problem.

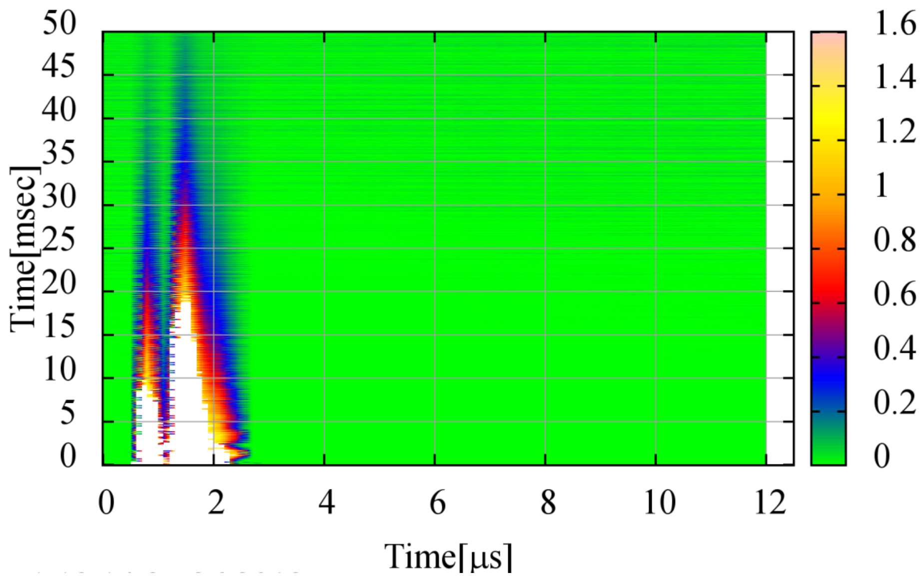
Free running (200keV A/Q = 4)

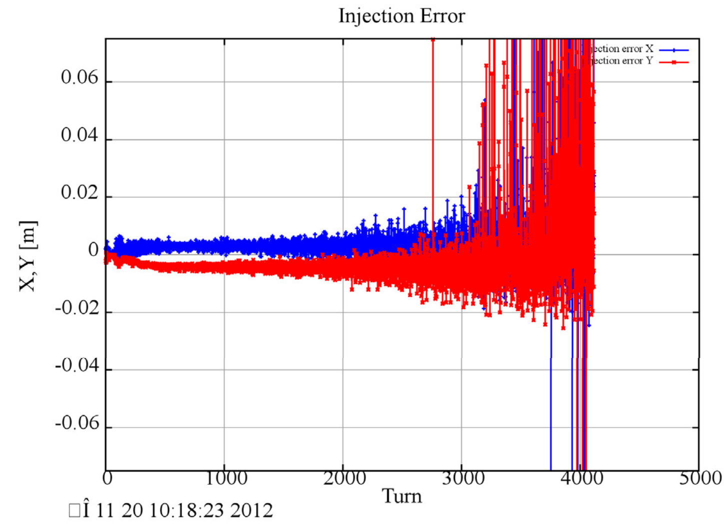


□Î 11 13 15:16:09 2012

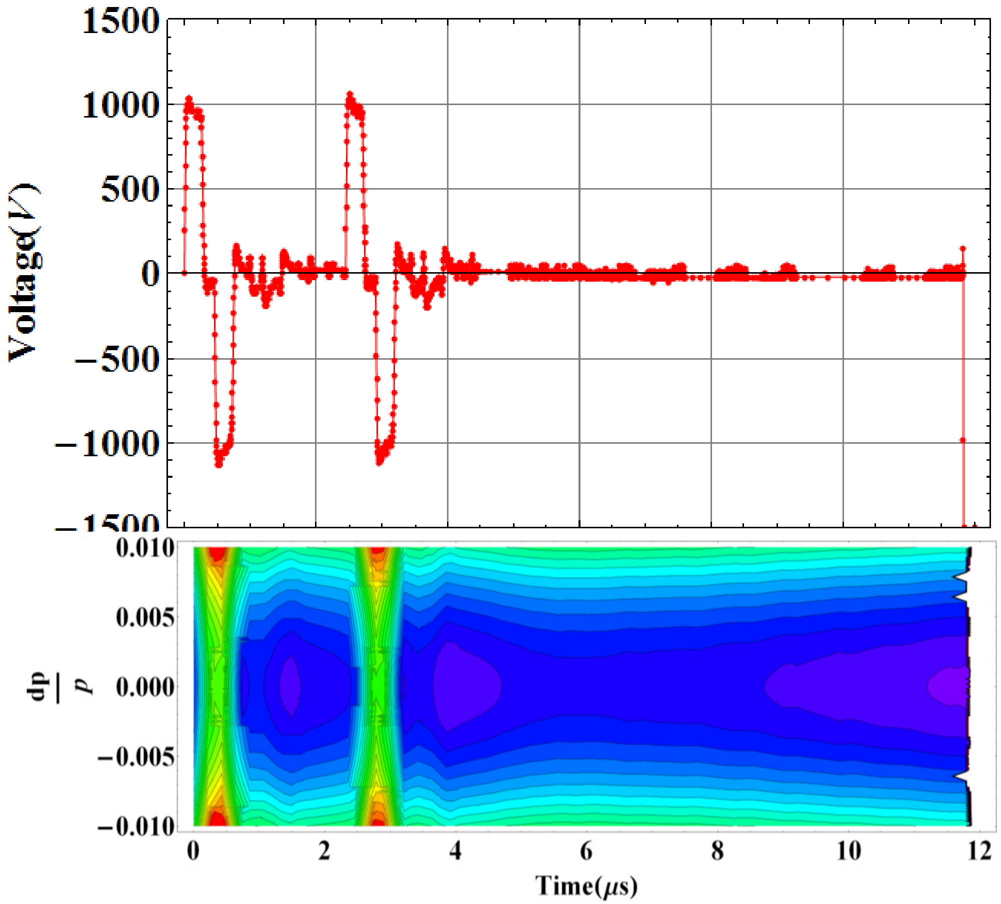
The Optimization of the barrier bucket position



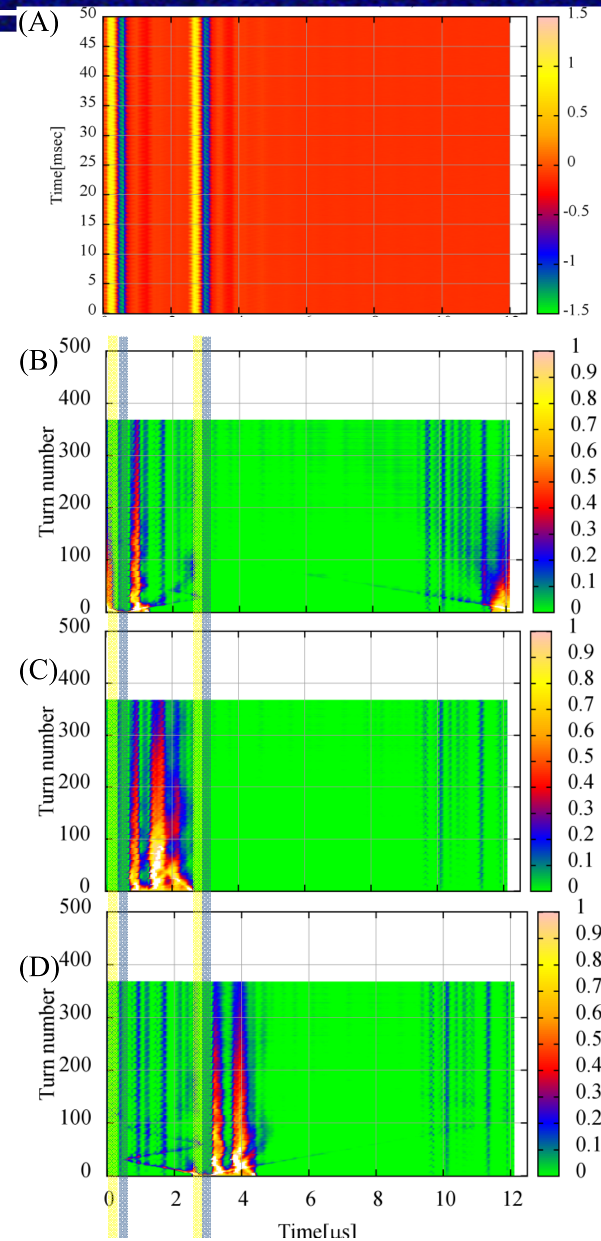




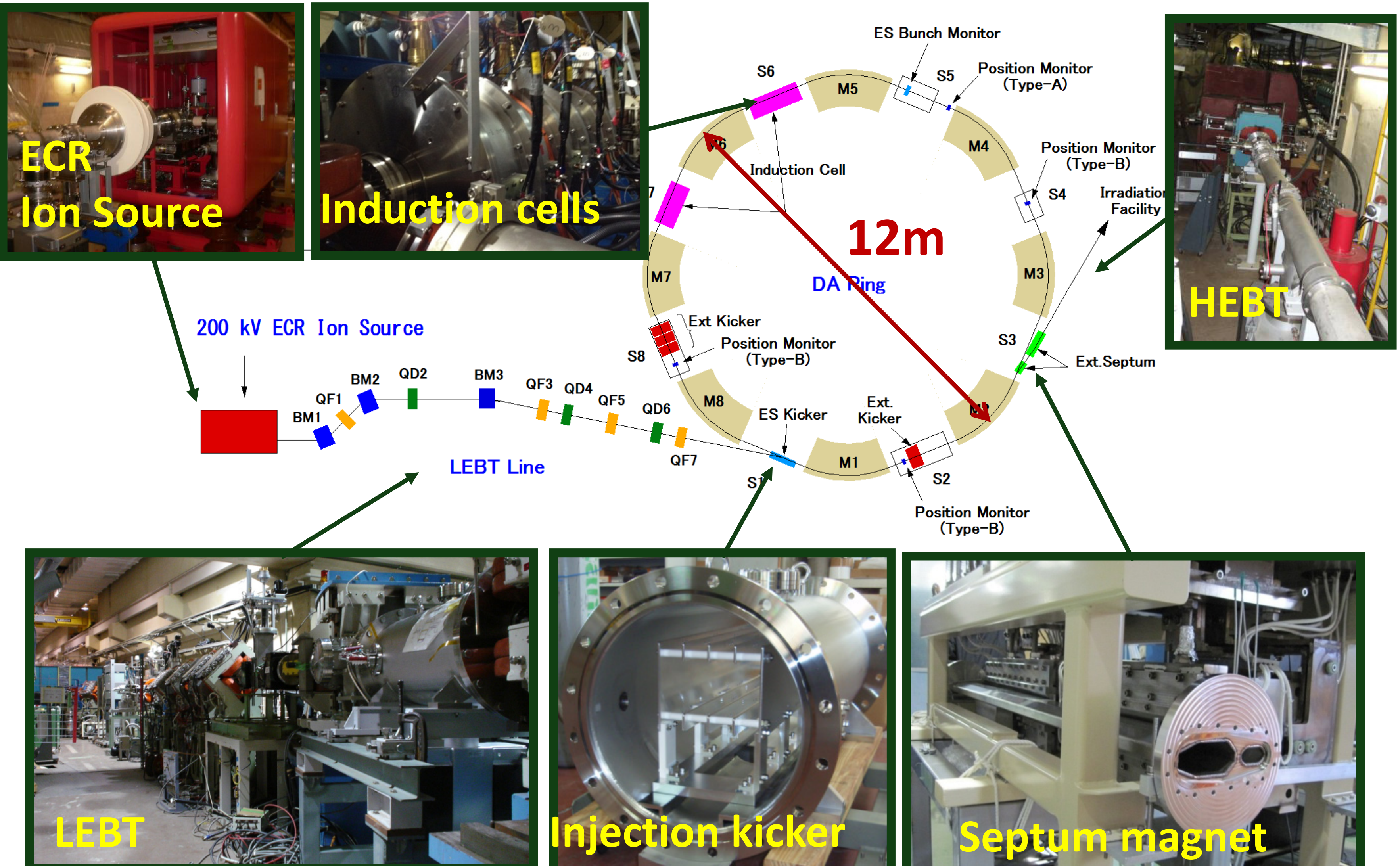
The Optimization of the barrier bucket position



$$H\left(\frac{dp}{p},t\right)=\frac{\eta E_s \beta_s^2}{2}\left(\frac{dp}{p_s}\right)^2+\frac{Z}{h\cdot T}\int_0^t V(t')dt'$$

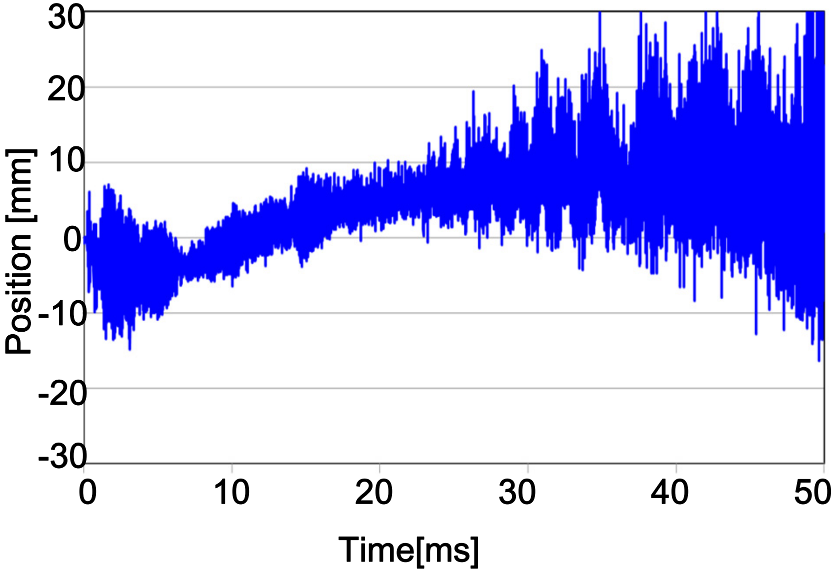


The Overview of KEK digital accelerator

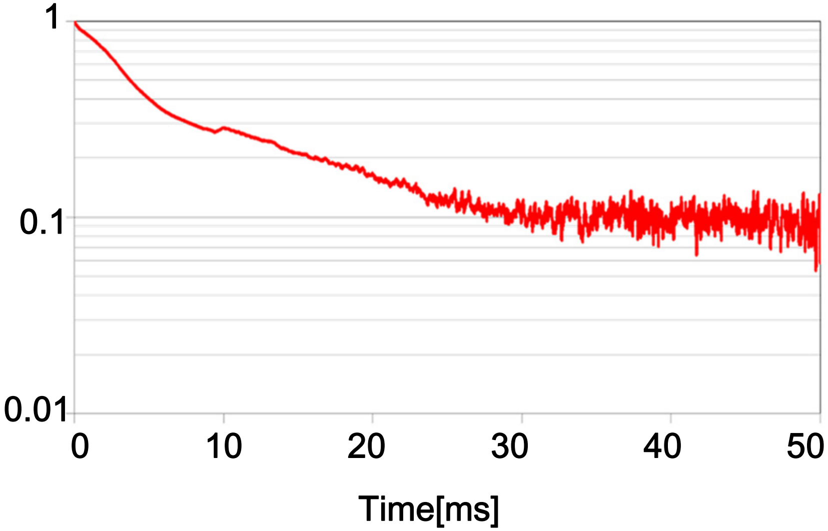


ビーム加速の解析結果 1

Horizontal beam position

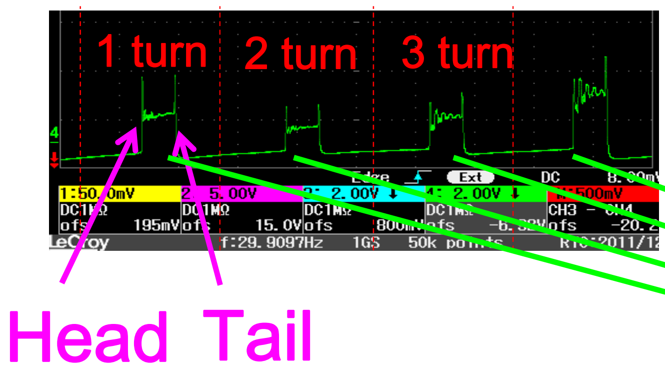


Beam survival: ~10%

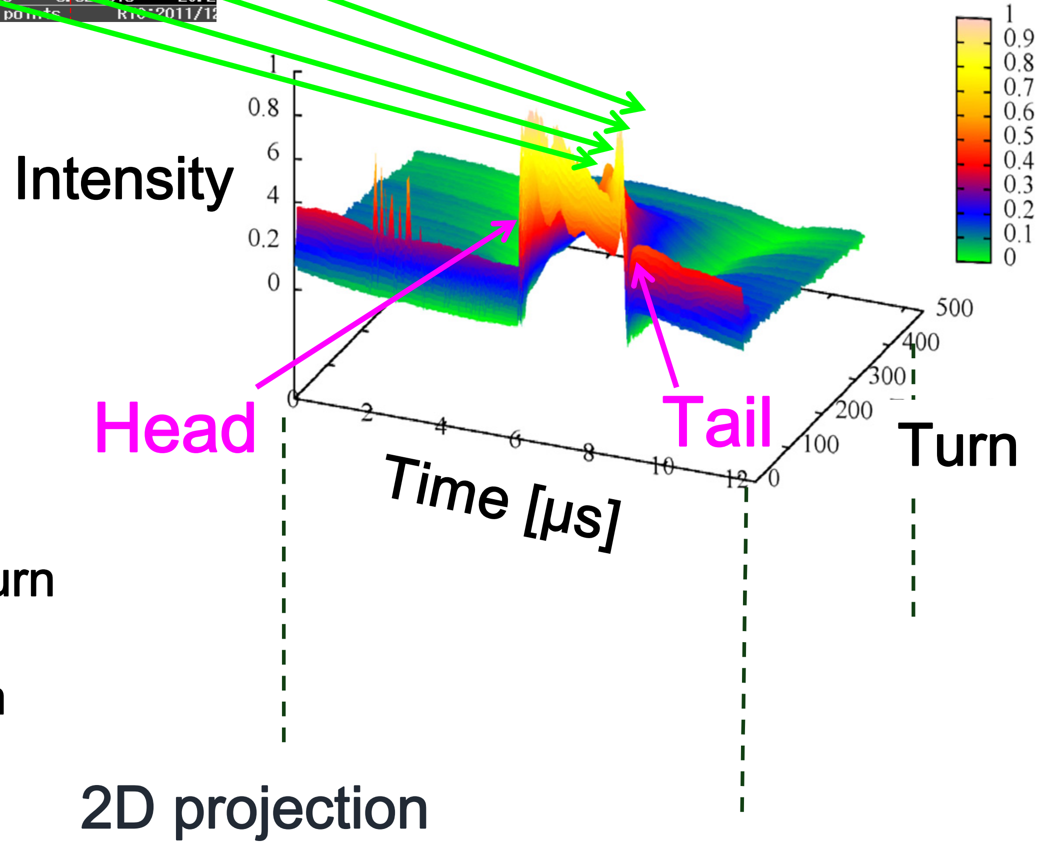


How to make mountain view

Monitor signal:



Mountain view:



Process:

1. Slicing oscilloscope view every ideal period

2. Arranging each graph in turn

3. Making 2D projection from the combined 3D graph

Adapting fully predictive control

It is difficult to construct feedback control because of the low S/N ratio of beam signal at present condition.

Method:

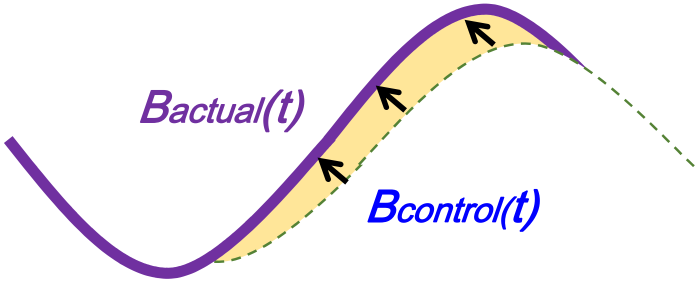
1. We set ideal magnetic flux density $B_{control}(t)$, calculate all required ideal periods and acceleration timings and write them in FPGA in advance.

2. We can modify ideal magnetic field $B_{control}(t)$ to correspond actual magnetic field $B_{actual}(t)$ from beam motion.

Actual magnetic field   Ideal magnetic field

$$B_{actual}(t) = B_{control}(t) \Leftrightarrow \begin{cases} B_{actual\_max} = B_{control\_max} & \text{(Max. B)} \\ B_{actual\_min} = B_{control\_min} & \text{(Min. B)} \\ \delta = 0 & \text{(Phase difference)} \end{cases}$$

It is essential for beam acceleration that Both magnetic fields are corresponded!!

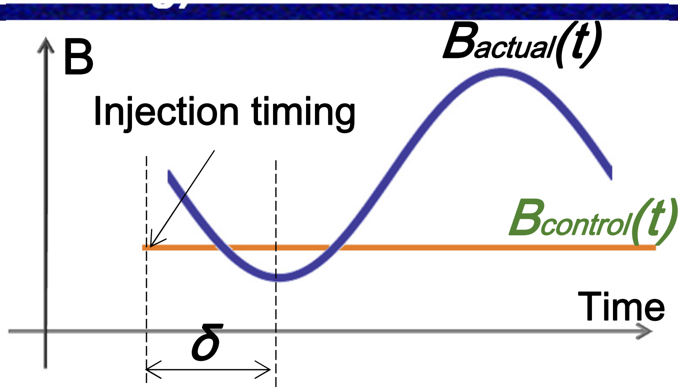


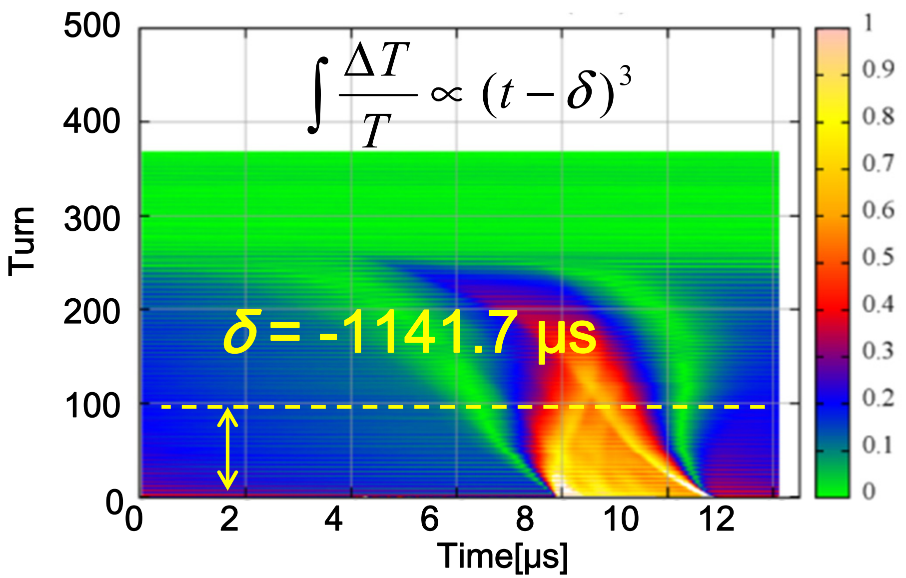
T. Yoshimoto, et al, "Heavy Ion Beam Acceleration in the KEK Digital Accelerator: Induction Acceleration from 200keV to a Few Tens MeV", NIM-A, 2013

Minimization of phase difference δ between ideal and actual magnetic field (Free running)

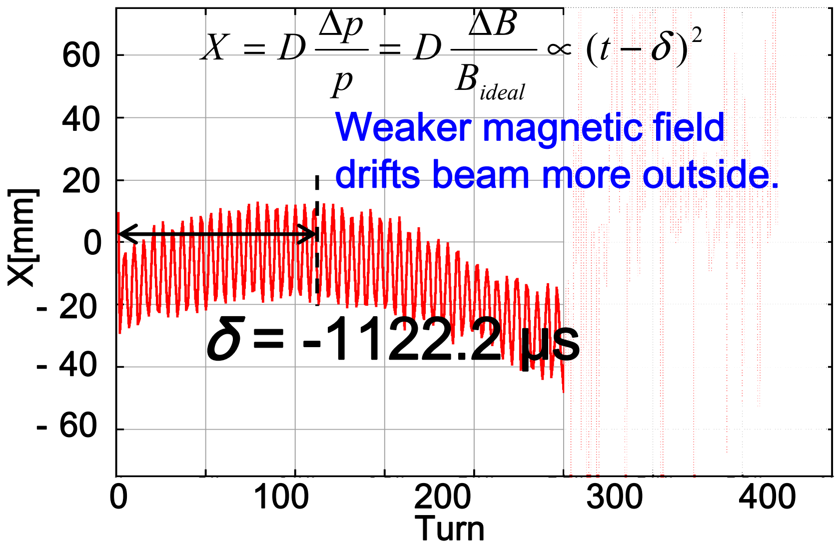
Method:

1. Injecting beam quite before actual injection timing arbitrary
2. Observing horizontal beam position and beam period in time





Beam period in time



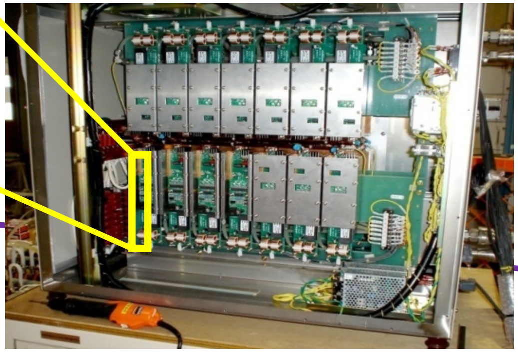
Beam position In time

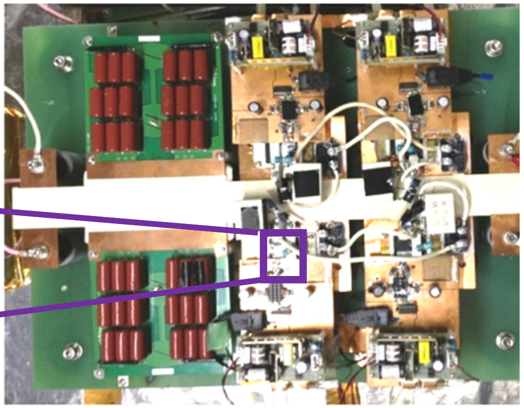
Using this method, we can minimize phase difference δ with the precision under one rev. period.

Development of Switching Power Supply (SPS)

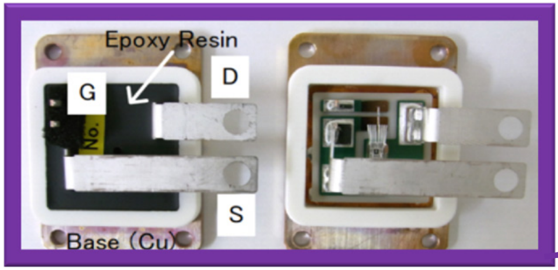
1st Gen.: 0.7 kV Si-MOSFET board

1st GEN. SPS(7 MOSFETs in series)

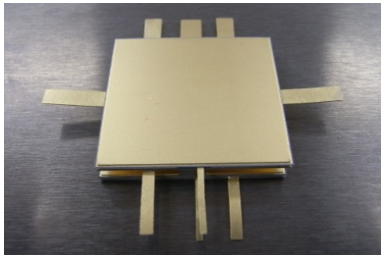




2 nd Gen.: SPS



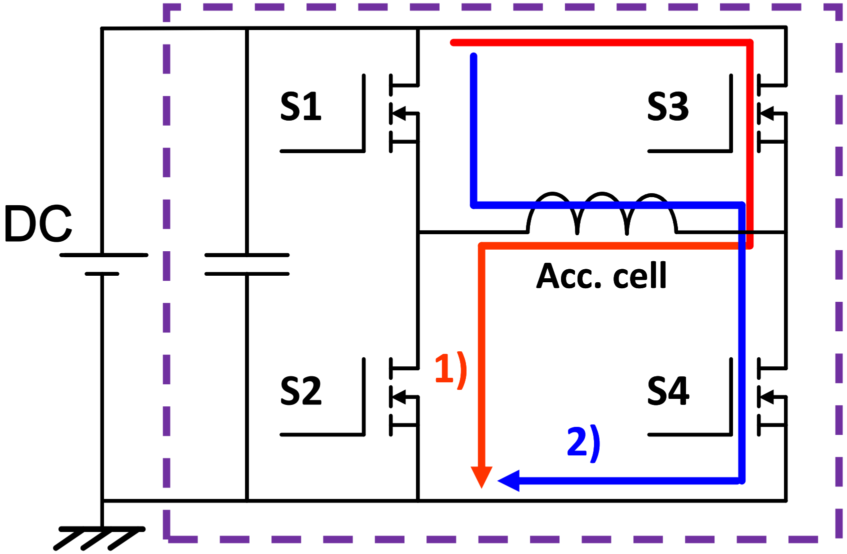
2 nd Gen.: 1.2 kV SiC-JFET (custom package)



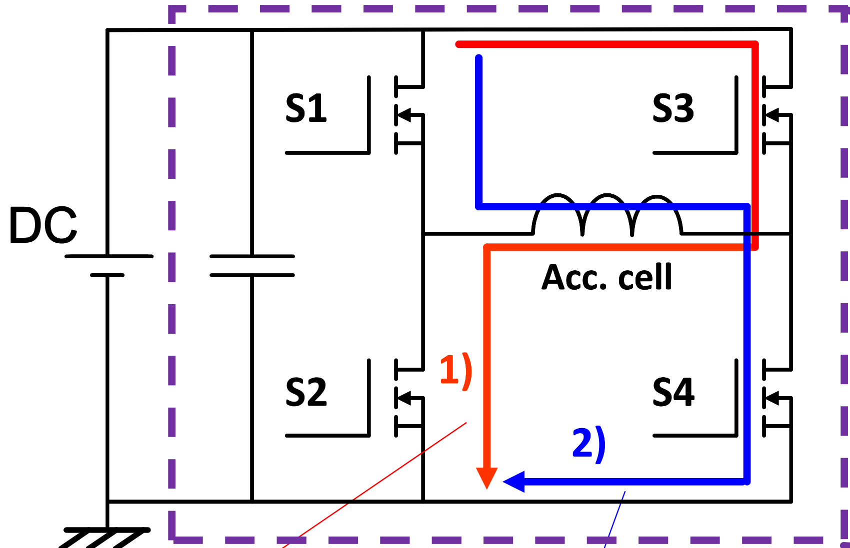
3rd Gen. 2.4 kV (custom package)

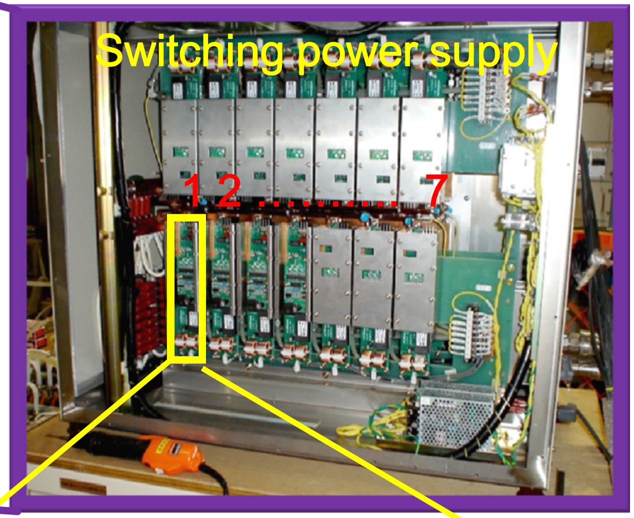
K.Okamura, *et al* , MOPME068 in IPAC'14

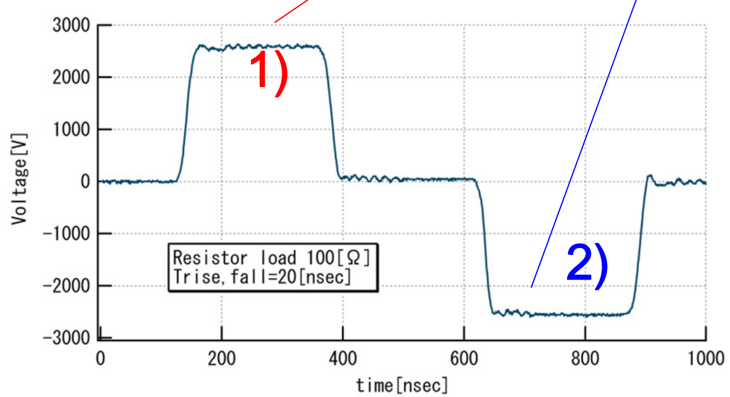
4th Gen. :3.3 kV SiC-MOSFET in 2015



Switching Power Supply for Induction cells

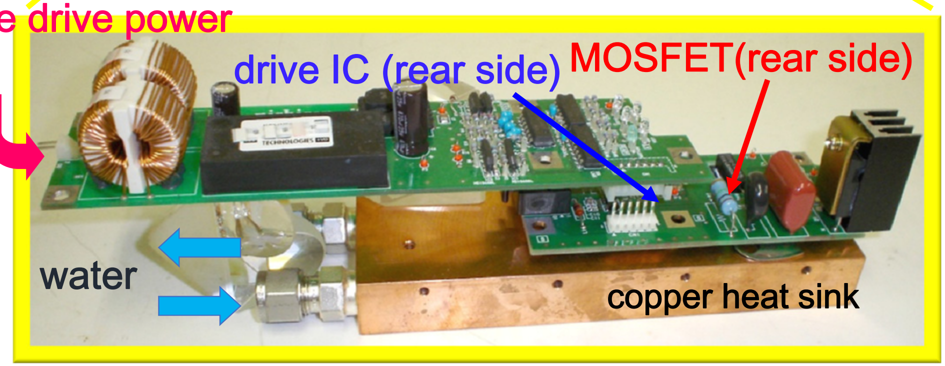






Waveform generated by switching power supply
(2.5kV, 20A, 1MHz)

One arm consists of 7-series MOSFETs.



Next generation of SPS: K.Okamura, *et al*, MOPME068 in IPAC'14
"SiC-JFET Switching Power Supply toward for Induction Ring Accelerators"

Possible Questions

- Applications of heavy Ions delivered from the KEK-DA?
- Applications as an accelerator technology?
- How is wake fields serious in an induction synchrotron?
  (What happens in high intensity drivers based
  on induction acceleration?)
- How is noise problem overcome?
  (Induction synchrotron is a fully pulse machine.)

KEK Evolutional Induction Acceleration System