All-ion Accelerators

- New Trend of Induction Synchrotron -

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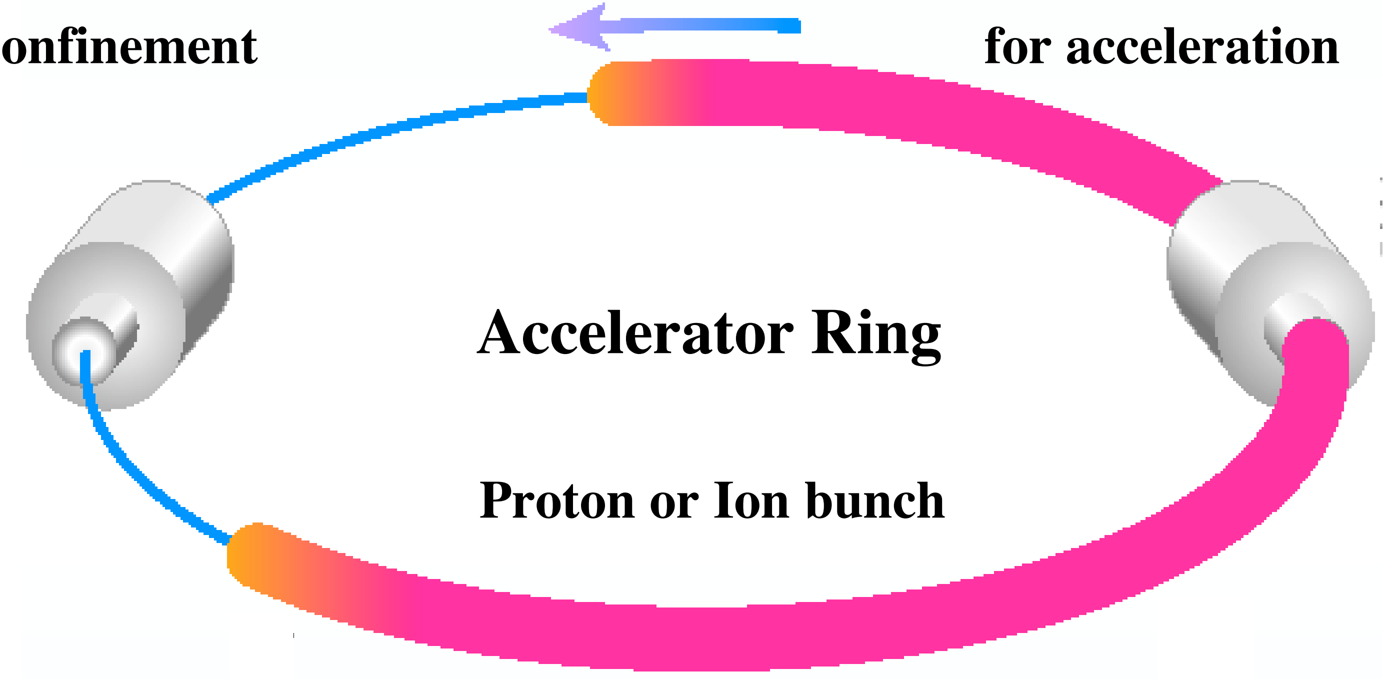
Experimental results of induction acceleration in the KEK 12GeV PS
Idea of all-ion accelerators
Its applications
Summary

US-Japan Inertial Fusion Workshop 28/9/2005 at Utsunomiya University

Schematic View of Induction Synchrotron

Separated function in the longitudinal direction

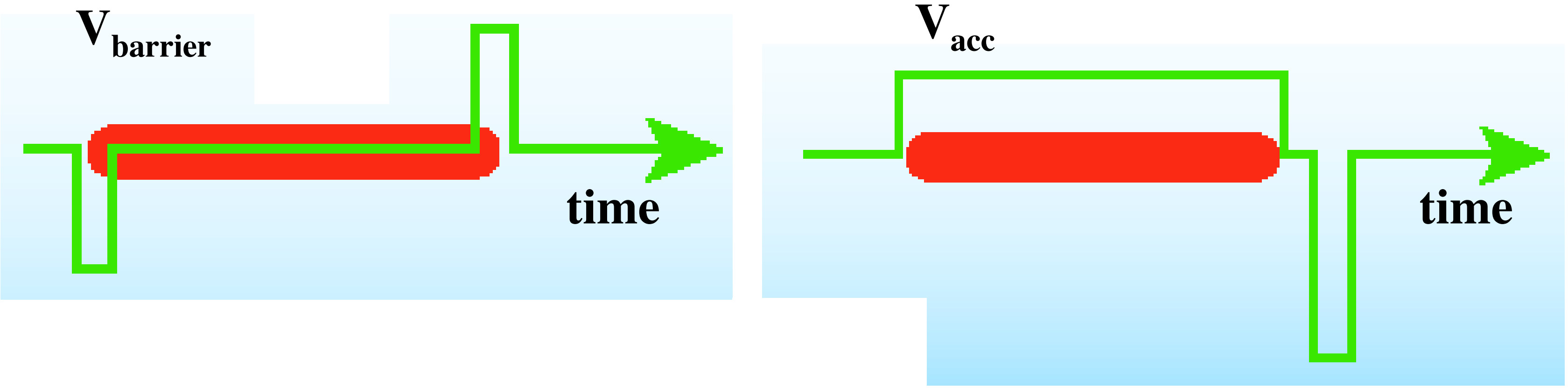


Induction acceleration cell
for confinement

Induction acceleration cell
for acceleration

Accelerator Ring

Proton or Ion bunch



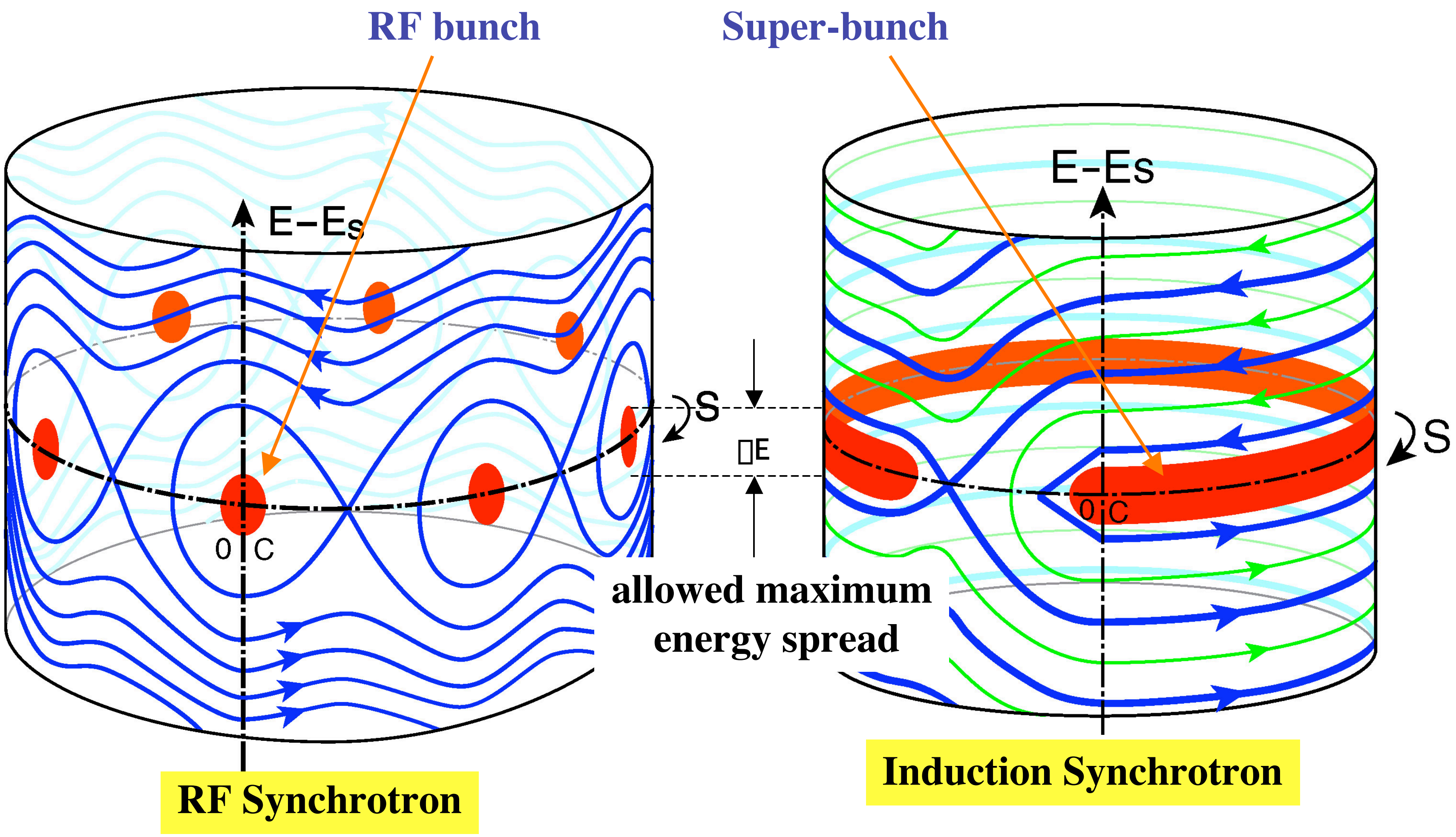
$V_{barrier}$

time

V_{acc}

time

Difference between RF Synchrotron and Induction Synchrotron seen in Phase-space



RF bunch

Super-bunch

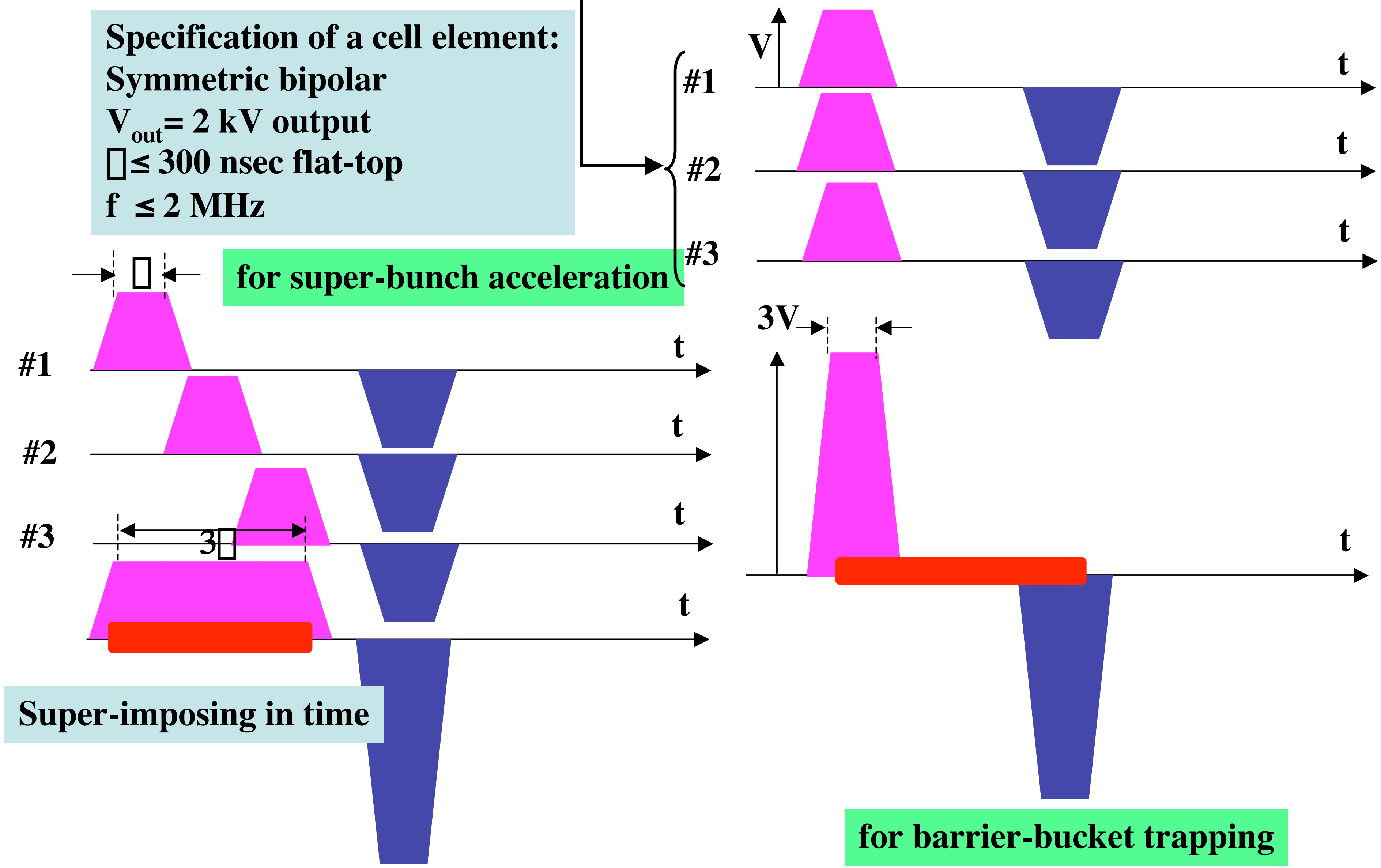
allowed maximum energy spread

RF Synchrotron

Induction Synchrotron

Possible scheme to generate induction step-voltage for a barrier bucket and super-bunch acceleration assuming the basic flip-flop operation of an single unit

Specification of a cell element:
Symmetric bipolar
V_{out}= 2 kV output
□≤ 300 nsec flat-top
f ≤ 2 MHz

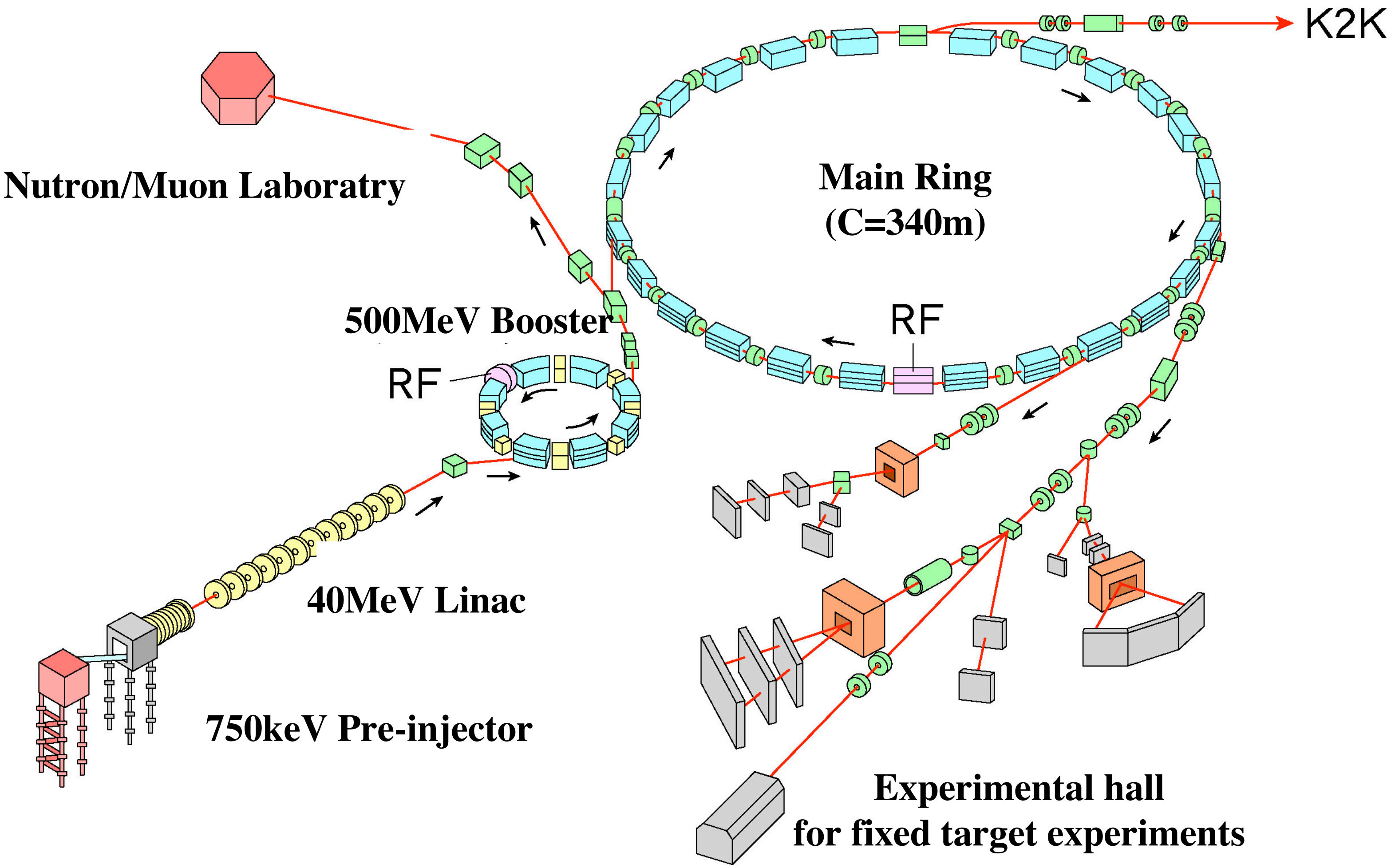


for super-bunch acceleration

Super-imposing in time

for barrier-bucket trapping

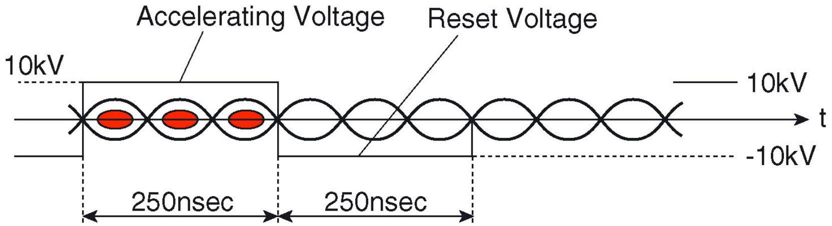
KEK 12GeV PS


K2K
Nutron/Muon Laboratry
Main Ring
(C=340m)
500MeV Booster
RF
RF
40MeV Linac
750keV Pre-injector
Experimental hall
for fixed target experiments

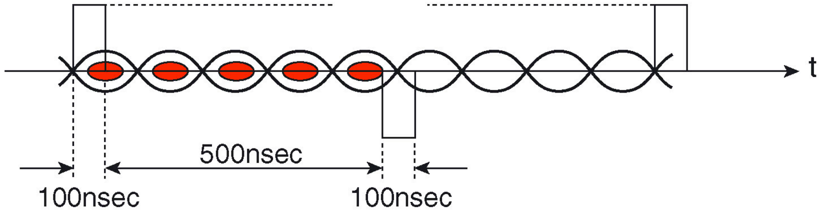
Scenario of POP Experiment

Induction acceleration system: output voltage 2kV/set

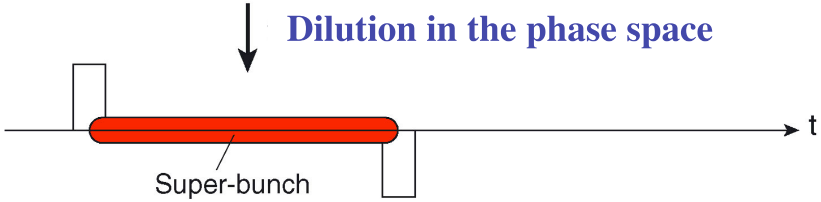
Step 1 Acceleration: Induction (500MeV->8GeV)
Confinement: RF with 3 sets



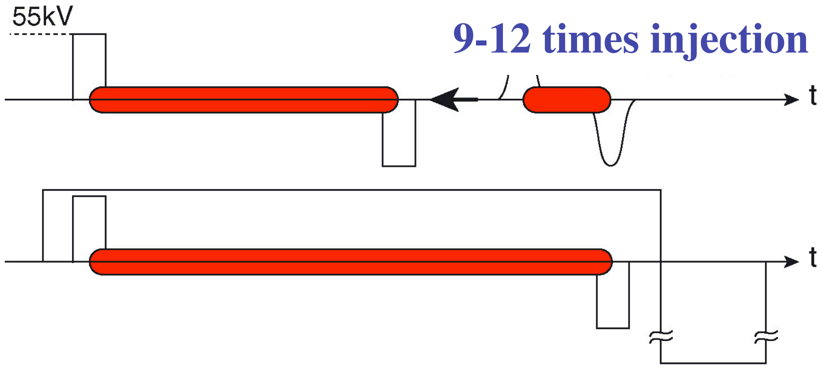
Step 2 Super-bunch formation at 500MeV with 3/6 sets



Dilution in the phase space



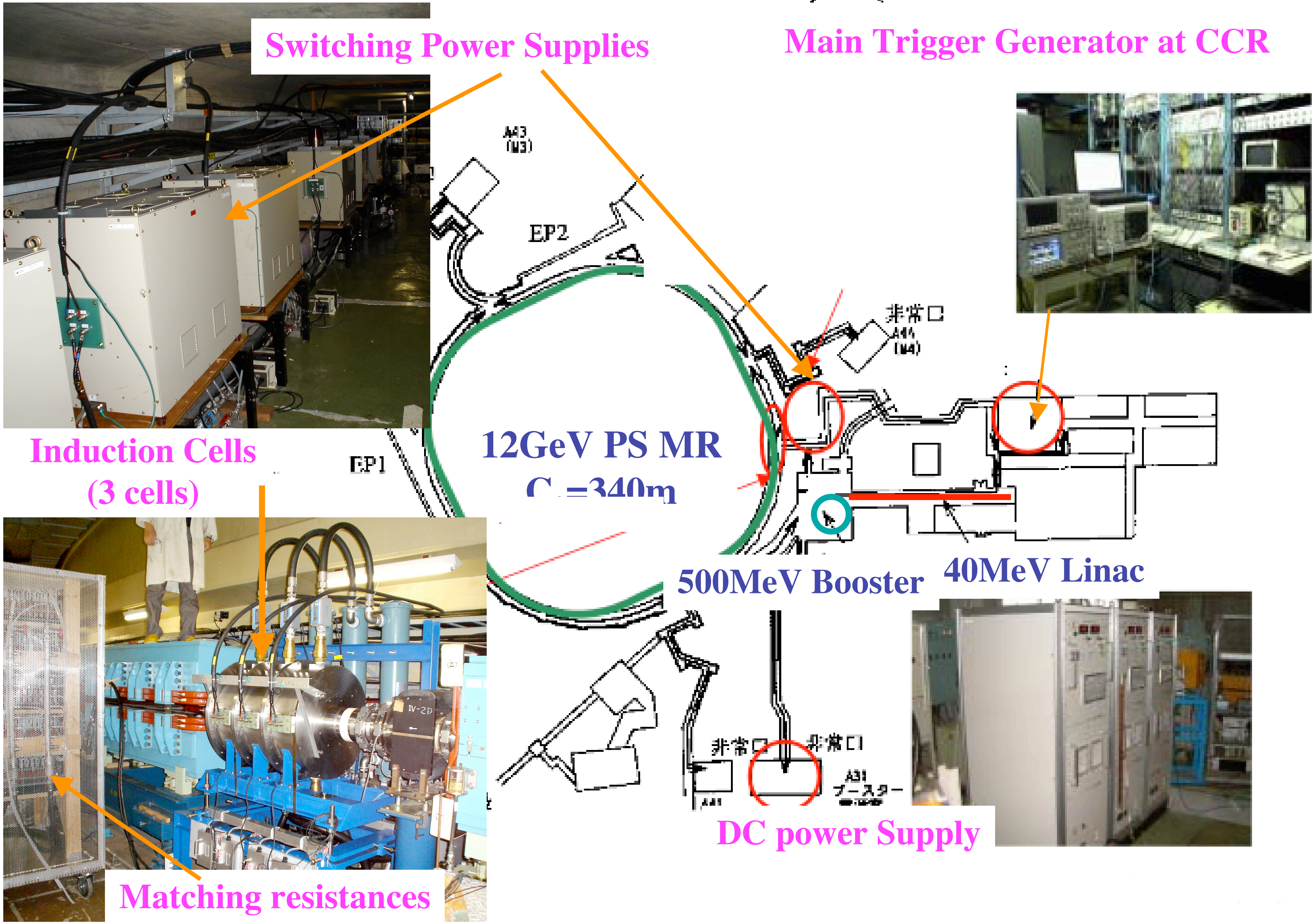
Step 3 Super-bunch Stacking
Acceleration (500MeV -> 8GeV)



9-12 times injection

Final goal is to modify the KEK PS (RF synchrotron) to an Induction Synchrotron at the last stage of its 30 years life.

KEK PS Accelerator Complex & Induction Accelerating System



Switching Power Supplies

Main Trigger Generator at CCR

Induction Cells
(3 cells)

12GeV PS MR
C =340m

500MeV Booster

40MeV Linac

DC power Supply

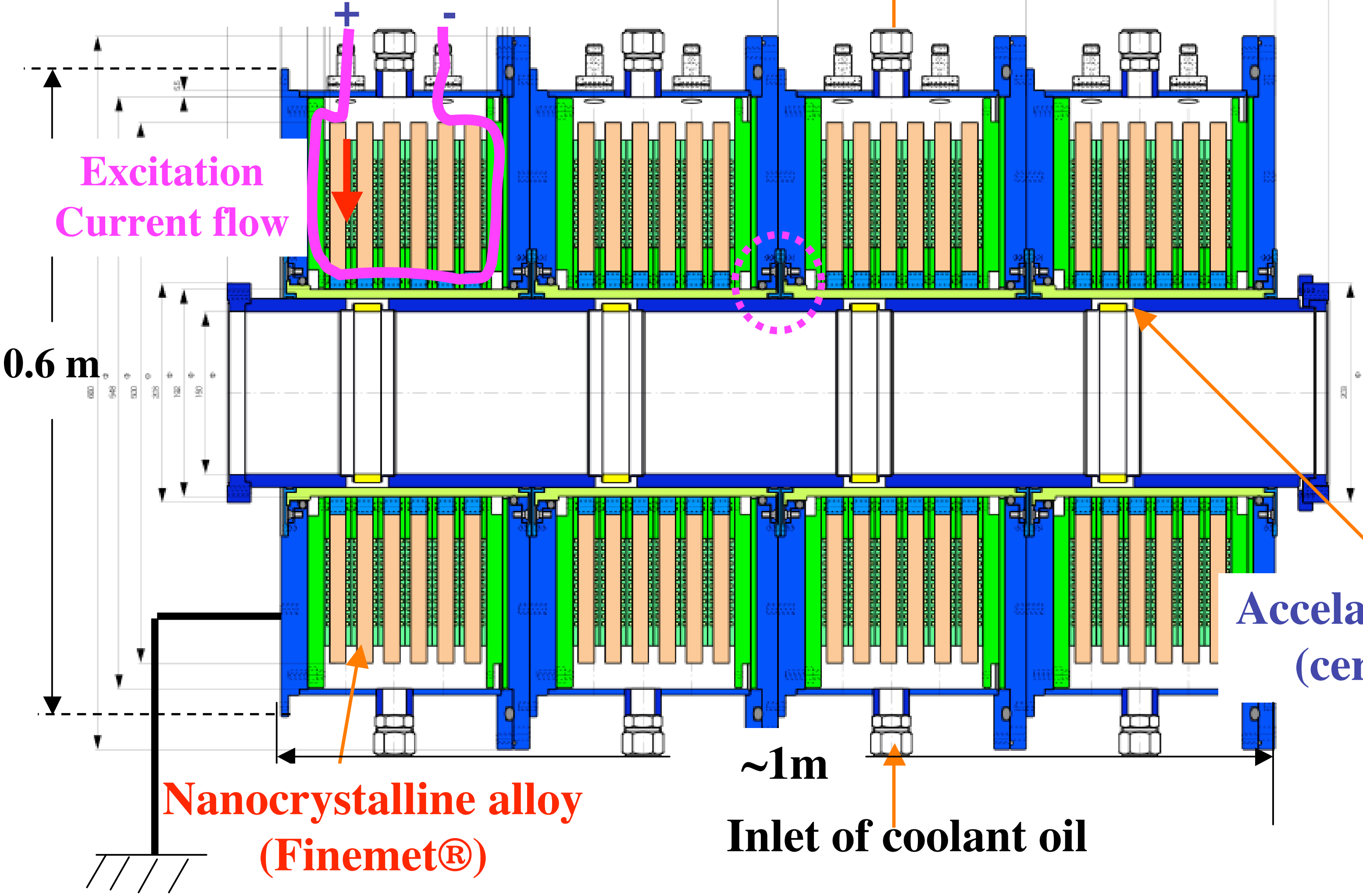
Matching resistances

Induction Acceleration Cavity consisted of 4 Cells(2kV/cell)

and a single inner chamber

L=110 μH
R=330 Ω
C=260 pF

Expedient parameters for cavity driving



Outlet of coolant oil

Excitation Current flow

0.6 m

Accelating Gap (ceramic)

~1m

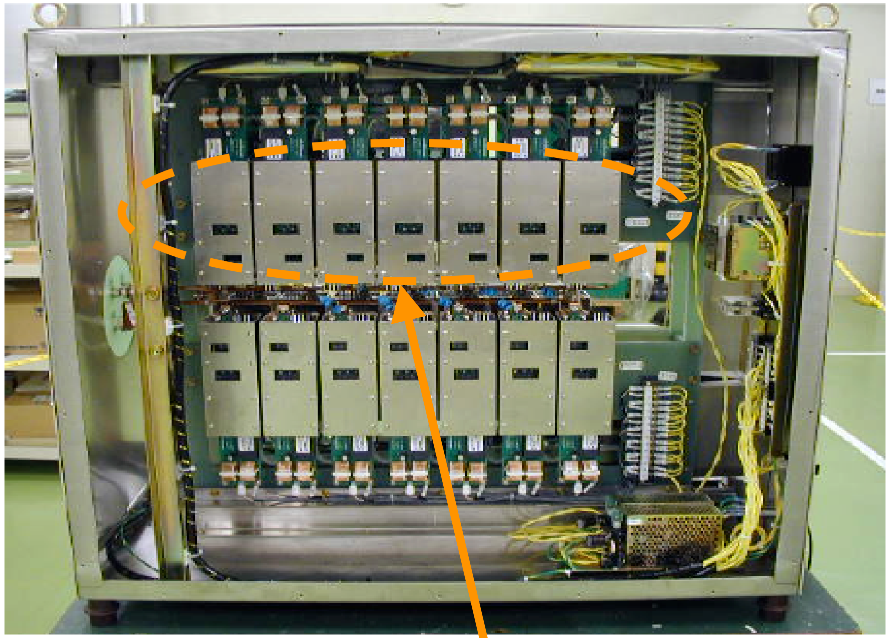
Nanocrystalline alloy (Finemet®)

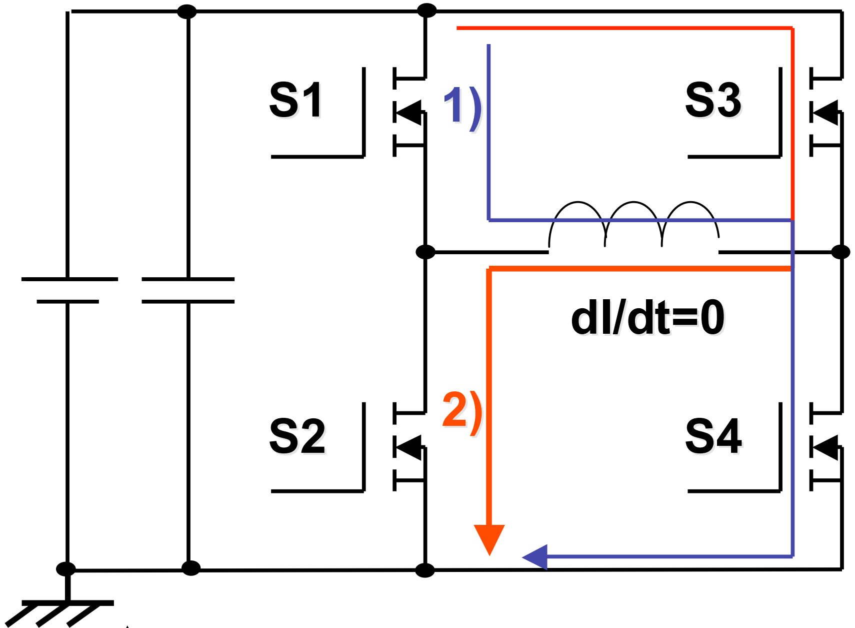
Inlet of coolant oil

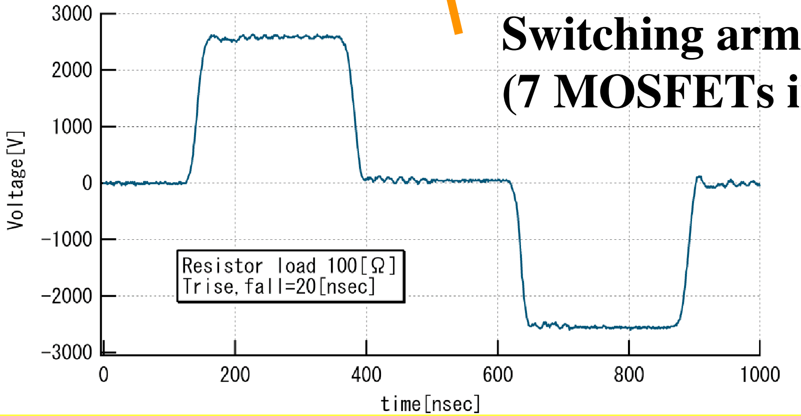
Switching Power Supply:switching sequence, output pulse

2.5kV, 20A, 1MHz, 500nsec

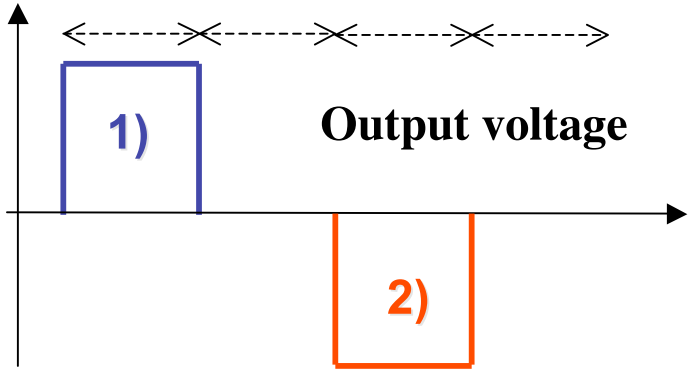
designed and measured by Koseki *et al.*(KEK)
assembled at Nichicon







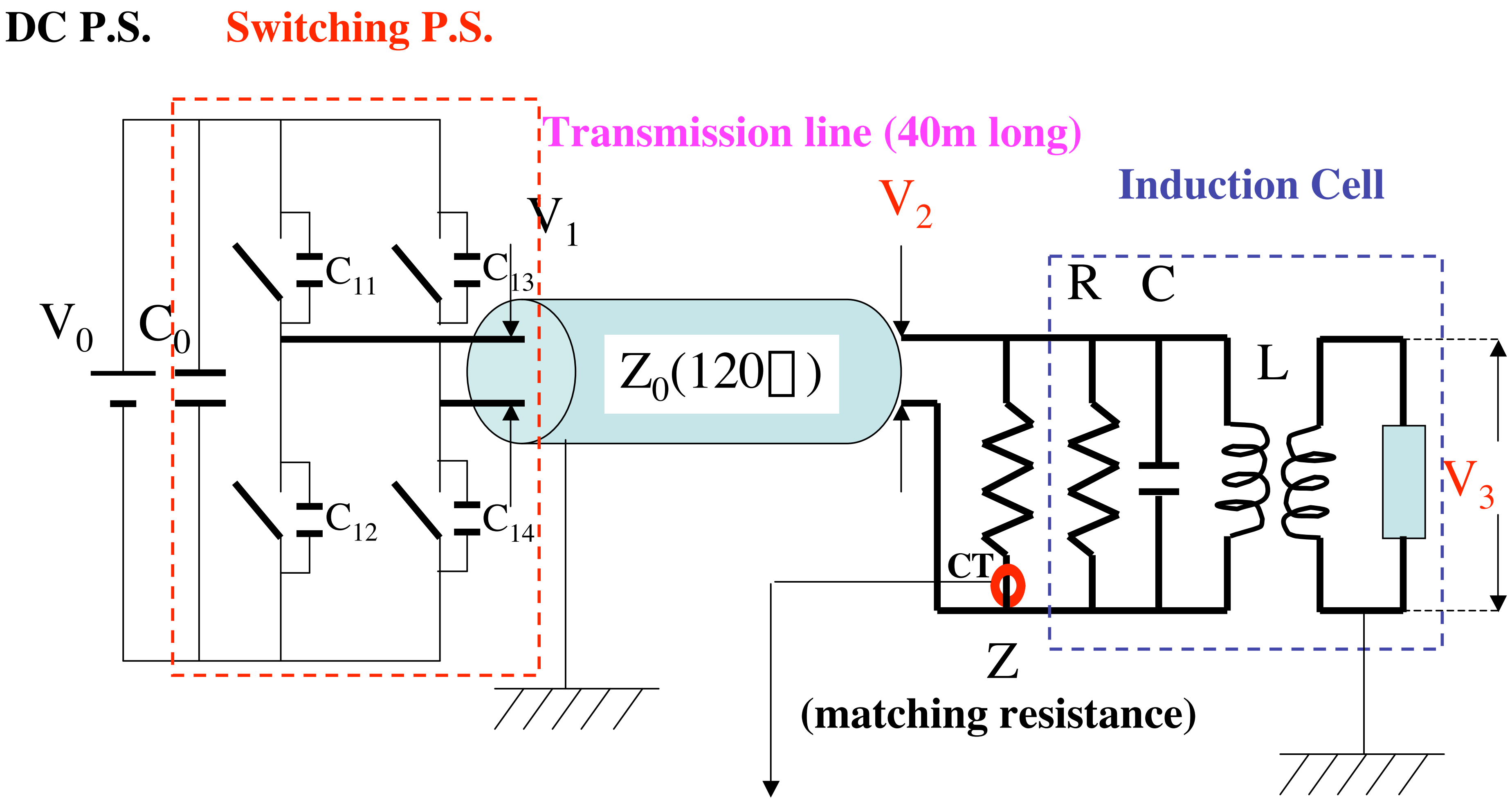
Switching arm S1
(7 MOSFETs in series)



Output voltage

Key point: pulse voltage can be generated at timing and with pulse duration that you want, by controlling a gate pulse of the MOSFETs.

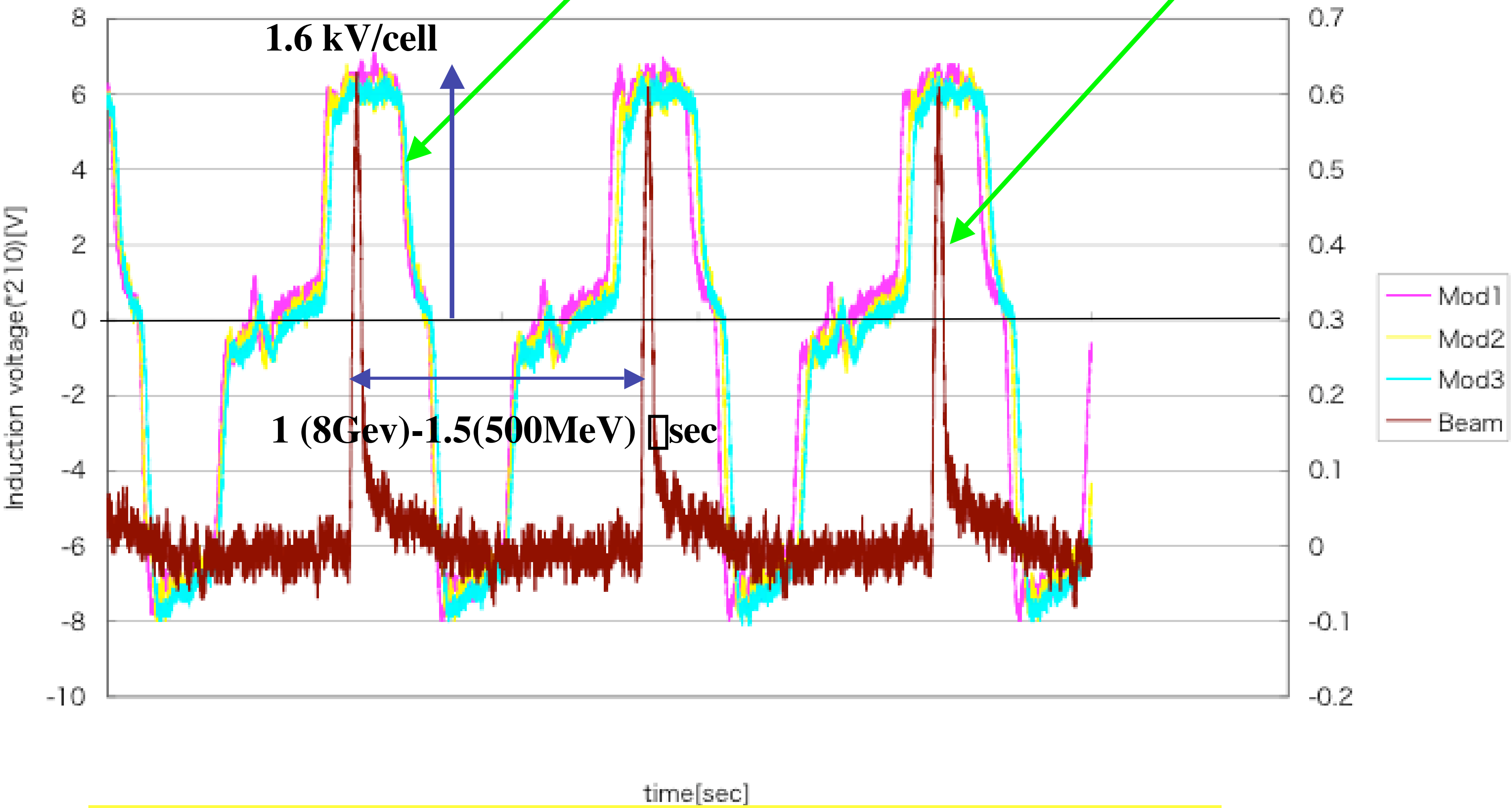
Equivalent Circuit for Induction Accelerating System



$V_0 \sim V_2 = V_3 \sim ZI_Z$ (calibrated)

I_Z (always monitored at CCR)

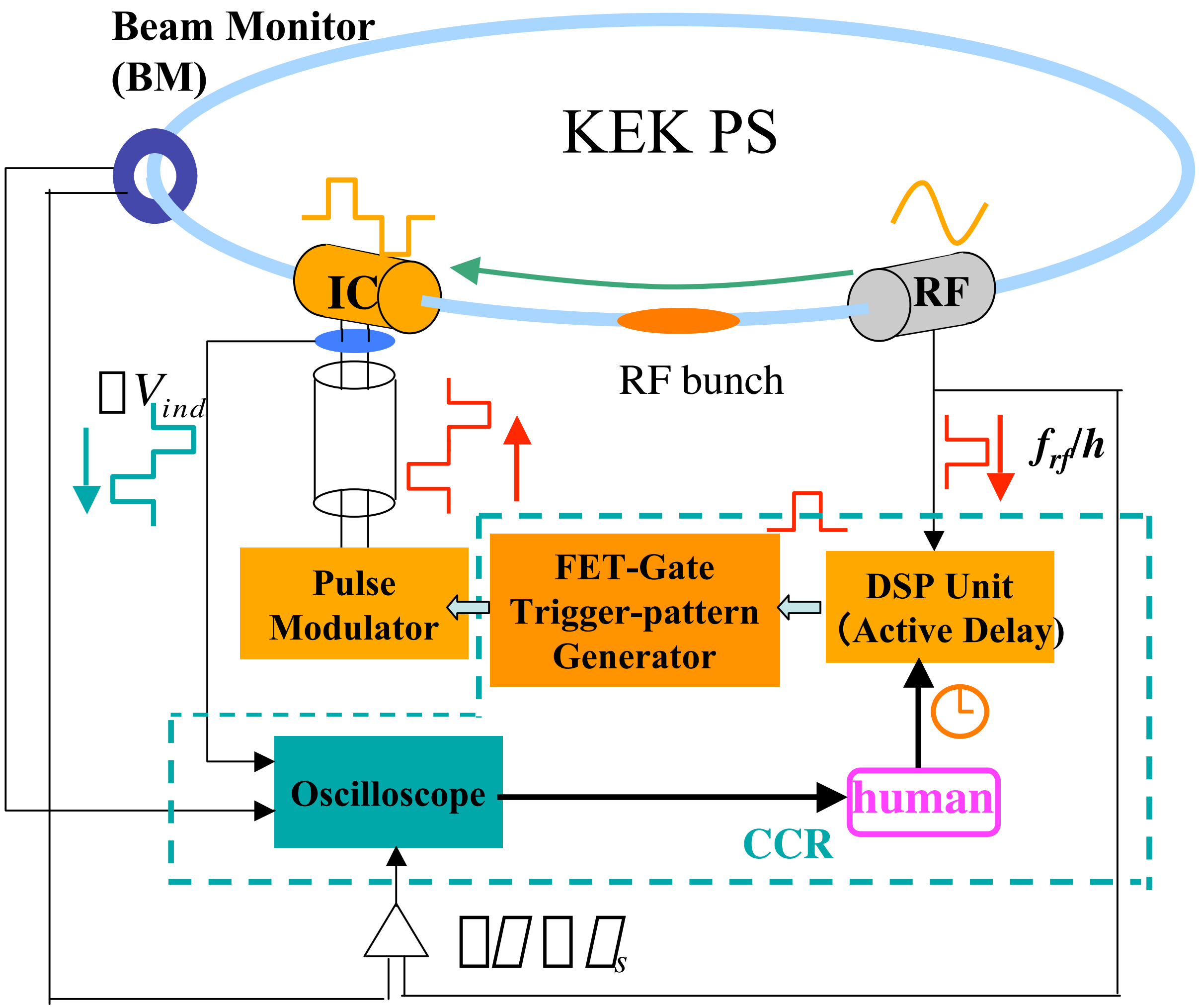
Monitored signals of induction voltage and an RF bunch signal

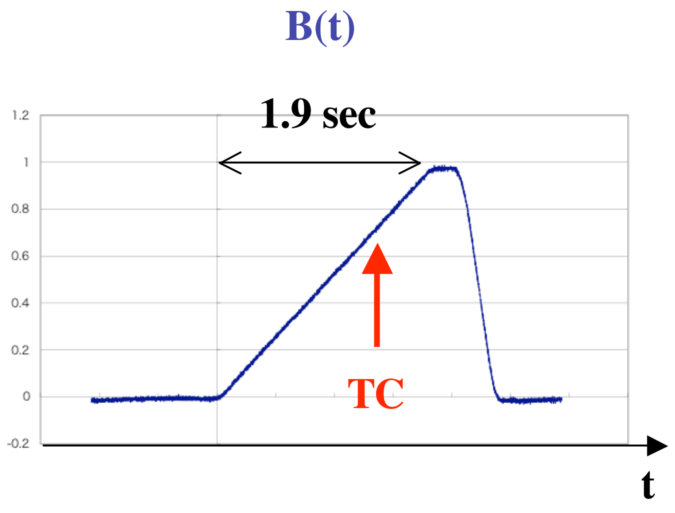


- Beam bunch signal was monitored at the 4th acceleration gap.
- Synchronization between two signals has been confirmed through an entire acceleration.

Machine Parameters and Control/Monitoring System

Circumference	**339m**
Trans. energy $\square_t$	**6.68**
Inj./ext. energy	**500MeV/8GeV**
Rev. frequency	**667-880 kHz**
Ramping time	**1.9sec**
RF voltage	**48 kV**
Harmonic numb.	**9**
Induction voltage	**4.8 kV**





Theoretical background to confirm induction acceleration

Force balance in the radial direction:

$$m\gamma \cdot \frac{(c\beta)^2}{\rho} = ec\beta \cdot B(t)$$

Acceleration equation:

$$mc^2 \cdot \dot{\gamma} = \frac{ec\beta}{C_0} \cdot V_{acc}(t)$$

given by ramping pattern of bending field

$$V_{acc}(t) = \rho \cdot C_0 \cdot \boxed{dB/dt}$$

Voltage received by bunch center:

$$\boxed{V(t) = V_{rf} \sin\phi_s + V_{ind}}$$

Desired acceleration condition

$$V(t) = V_{acc}(t)$$

$V_{acc}(t) = V_0$ (constant for linear ramp: dB/dt = constant)

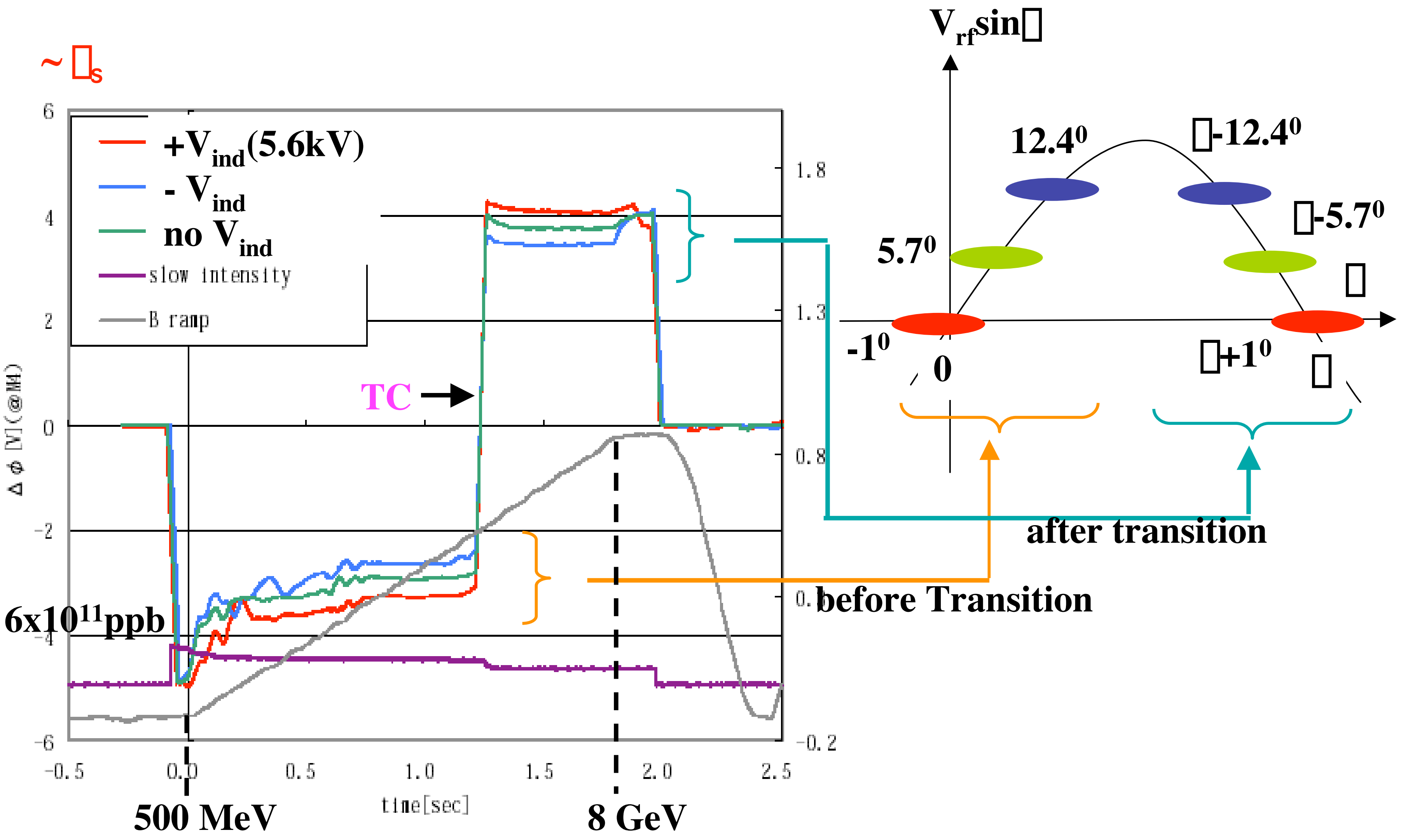
a) $V_{ind} = V_0$ (acceleration) $\qquad \phi_s \approx 0$

b) $V_{ind} = 0 \qquad \phi_s \approx \sin^{-1}\left(\frac{V_0}{V_{rf}}\right) \approx \frac{V_0}{V_{rf}}$

c) $V_{ind} = -V_0$ (deceleration) $\qquad \phi_s \approx \sin^{-1}\left(\frac{2V_0}{V_{rf}}\right) \approx \frac{2V_0}{V_{rf}}$

observable as a relative position of an RF bunch to RF phase

Experimental Facts: Change in □$_s$, Beam Intensity, and B



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

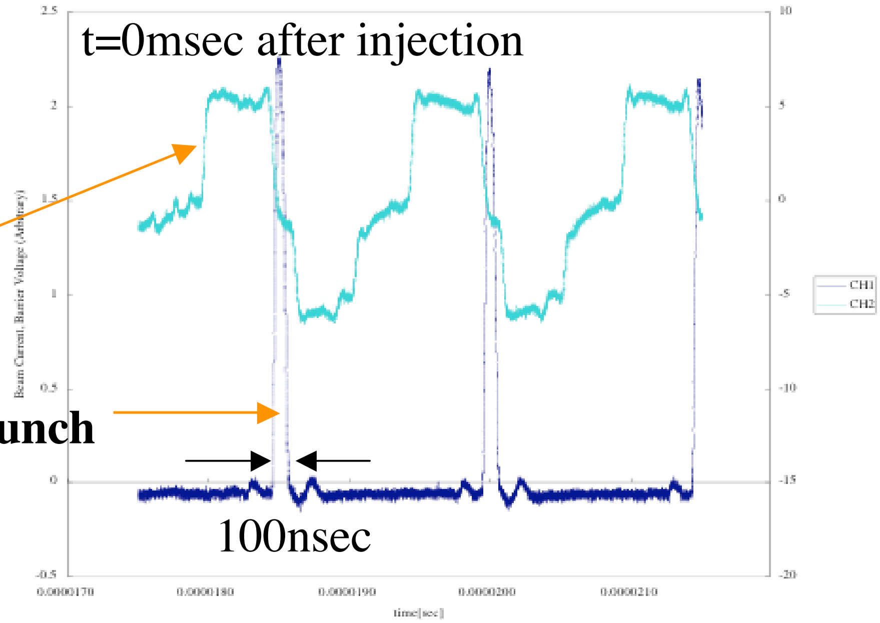

Aトリガ
ソース
Ch1
Ch2
Ch3
Ch4
1.00 V
Ch2 5.00 V
M 200ns
A Ch1
740mV
Ch3 500mV
Ch4 1.00 V
16.40 %
ソース
Ch1
結合
DC
スロープ
レベル
740mV
モードと
ホールドオフ
エッジ

Confinement by Induction Step-barriers

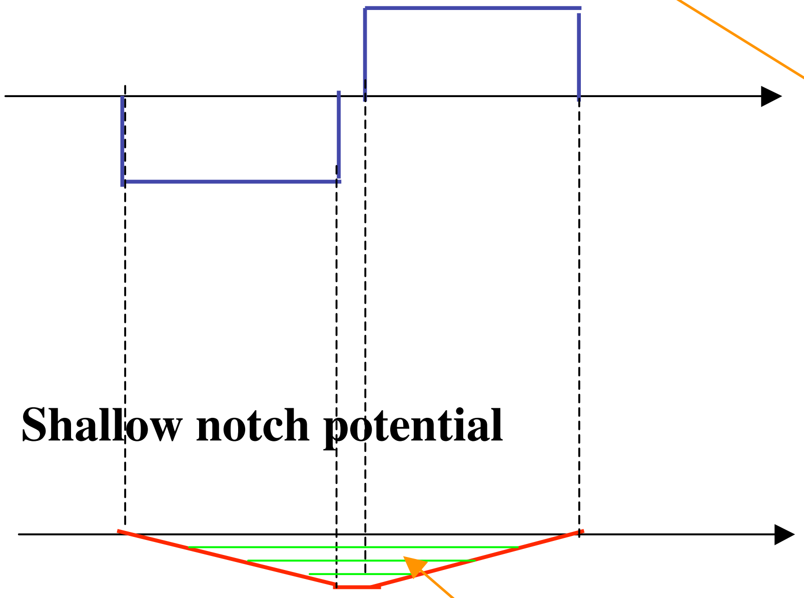
Formation of a 600nsec-long bunch

6kV barrier-voltage

injected proton bunch

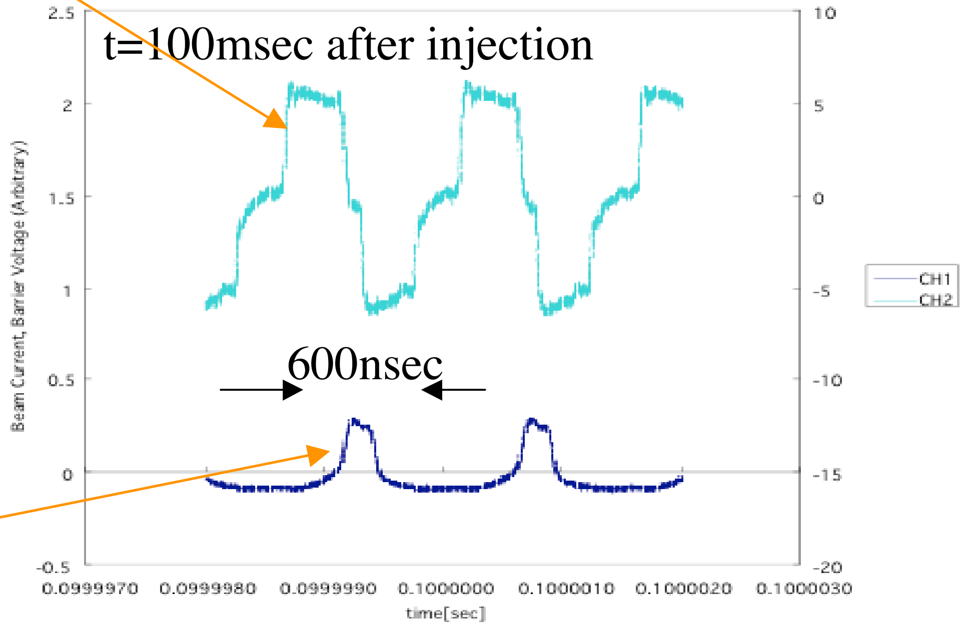

t=0msec after injection

100nsec



Shallow notch potential

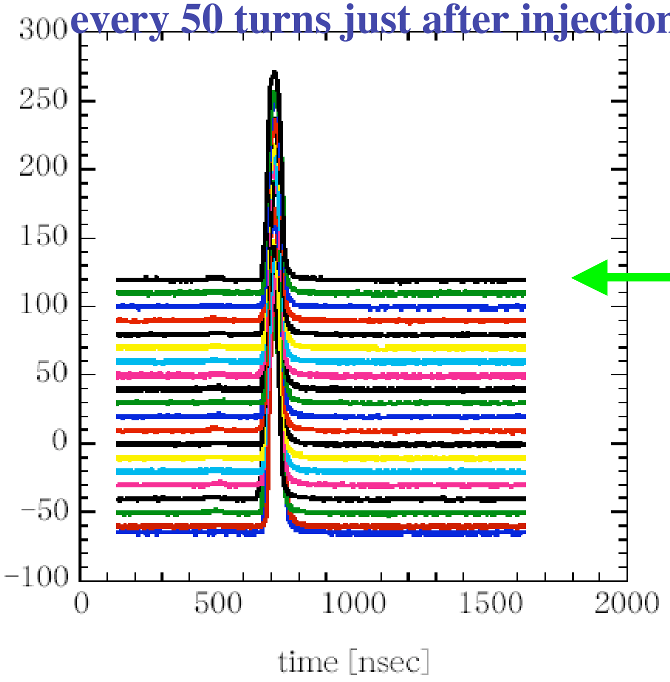
trapped protons


t=100msec after injection

600nsec

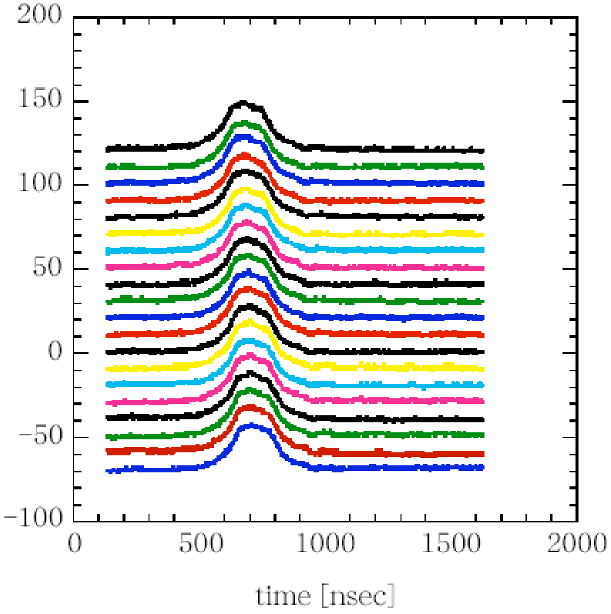
Mountain View

RF On
every 50 turns just after injection

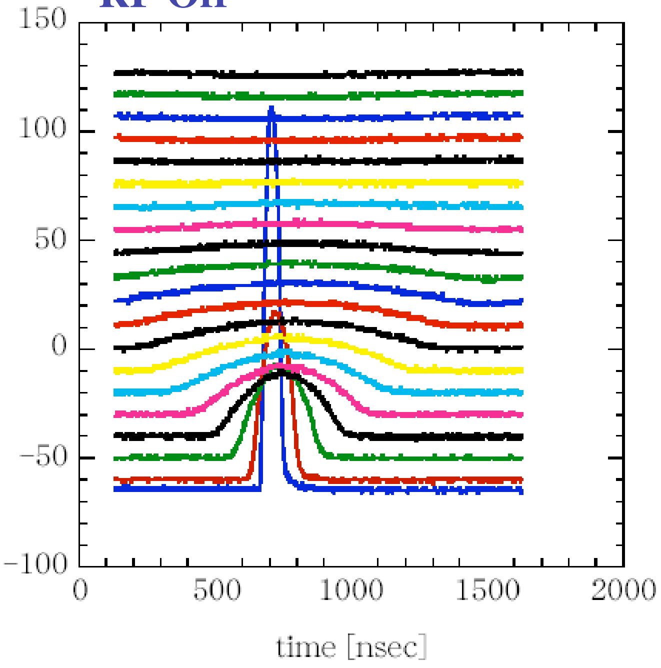


RF bucket Trapping

150msec after injection
every 1 turn

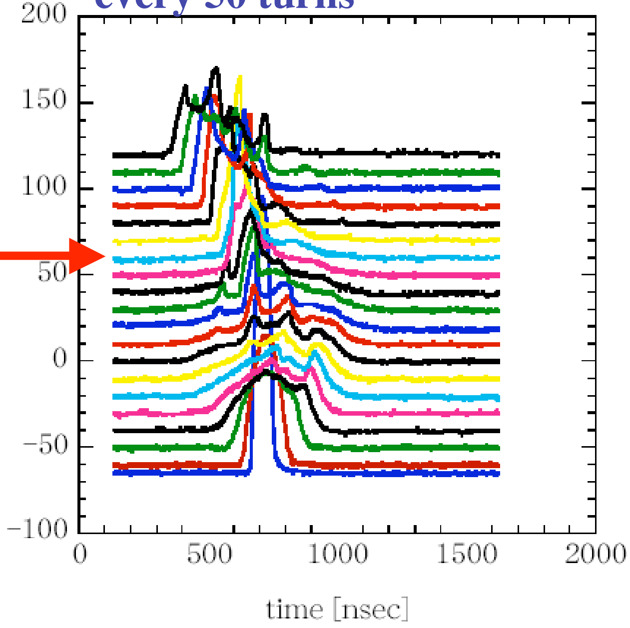


RF Off



Notch Potential Trapping

just after injection
every 50 turns



Schedule of this and next year

task	‘04	‘05	‘06	‘08	‘09
Induction acceleration of 1 RF bunch from 500MeV to 8GeV with 3 induction acceleration cells	↔	↔			
Confinement with induction step-barrier voltages at 500MeV with 3 cells		↔			
Induction acceleration of 1 barrier trapped bunch to 6 or 8GeV with 6 cells (2 for accel. and 4 for confinement)		↔			
Induction acceleration of a barrier trapped super-bunch to 8GeV with 10 cells (4 for accel. and 6 for confinement)			↔		

We are here now.

Possible Applications of Induction Synchrotron Concept

energy region	Application	Property	
		separated function	arbitrary switching frequency
high energy E > TeV	Super-bunch Hadron Collider K.Takayama et al., *PRL* 88, 1448(2002), Snowmass 2001	super-bunch	MHz
medium energy 10 GeV< E < 1 TeV	Proton Driver K.Takayama and J.Kishiro *N.I.M.* A451, 304 (2000)	super-bunch	MHz
low energy 1MeV< E <10GeV	All-ion Accelerator from p to U	bunch combining	kHz -> MHz operation

Motivation for All-ion Accelerators (AIA)

from the experimental demonstration of induction acceleration in the KEK-PS

- Stable performance of the switching power supply from ~0Hz to 1MHz
- Master trigger signal for the switching P.S. can be generated from a circulating beam signal

Allow to accelerate even quite slow particles

Betatron motion doesn't depend on ion mass and charge state, once the magnetic guide fields are fixed.

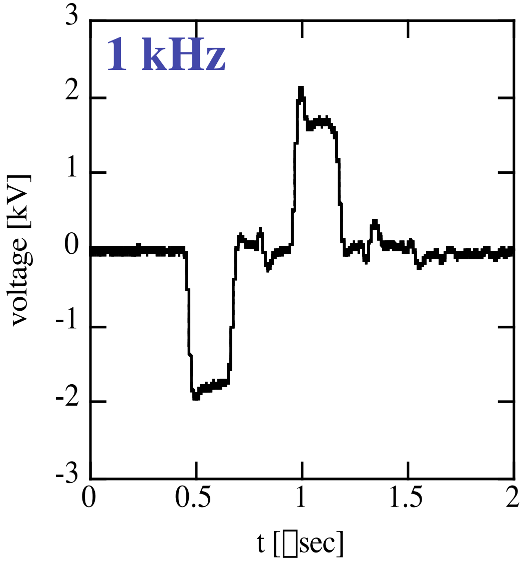
A single circular strong-focusing machine can accelerate from proton to uranium.

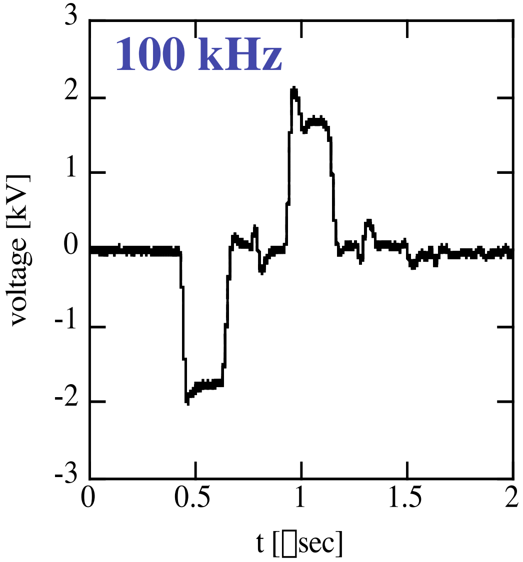
Concept of an all-ion accelerator

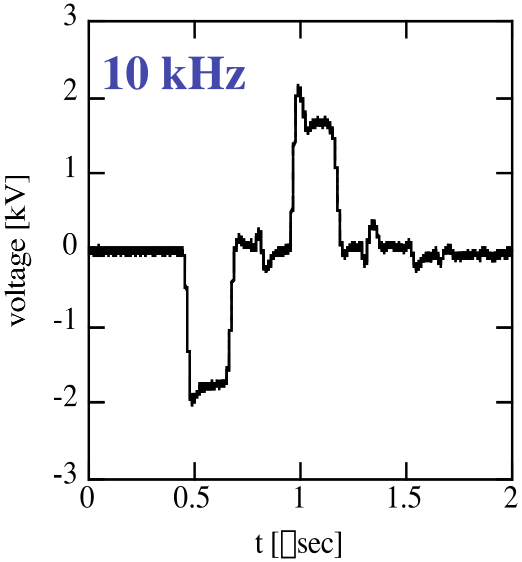
almost injector-free for a low intensity

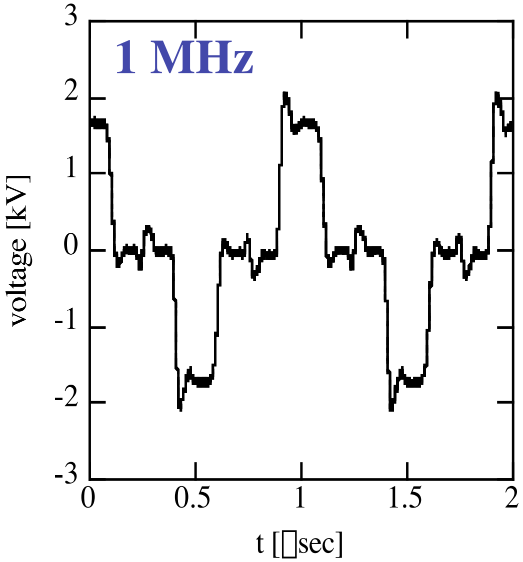
K.Takayama, K.Torikai, Y.Shimosaki, and Y.Arakida, "All Ion Accelerators", submitted for publication (2005) and applying for a patent

Repetition dependence of the induced voltage

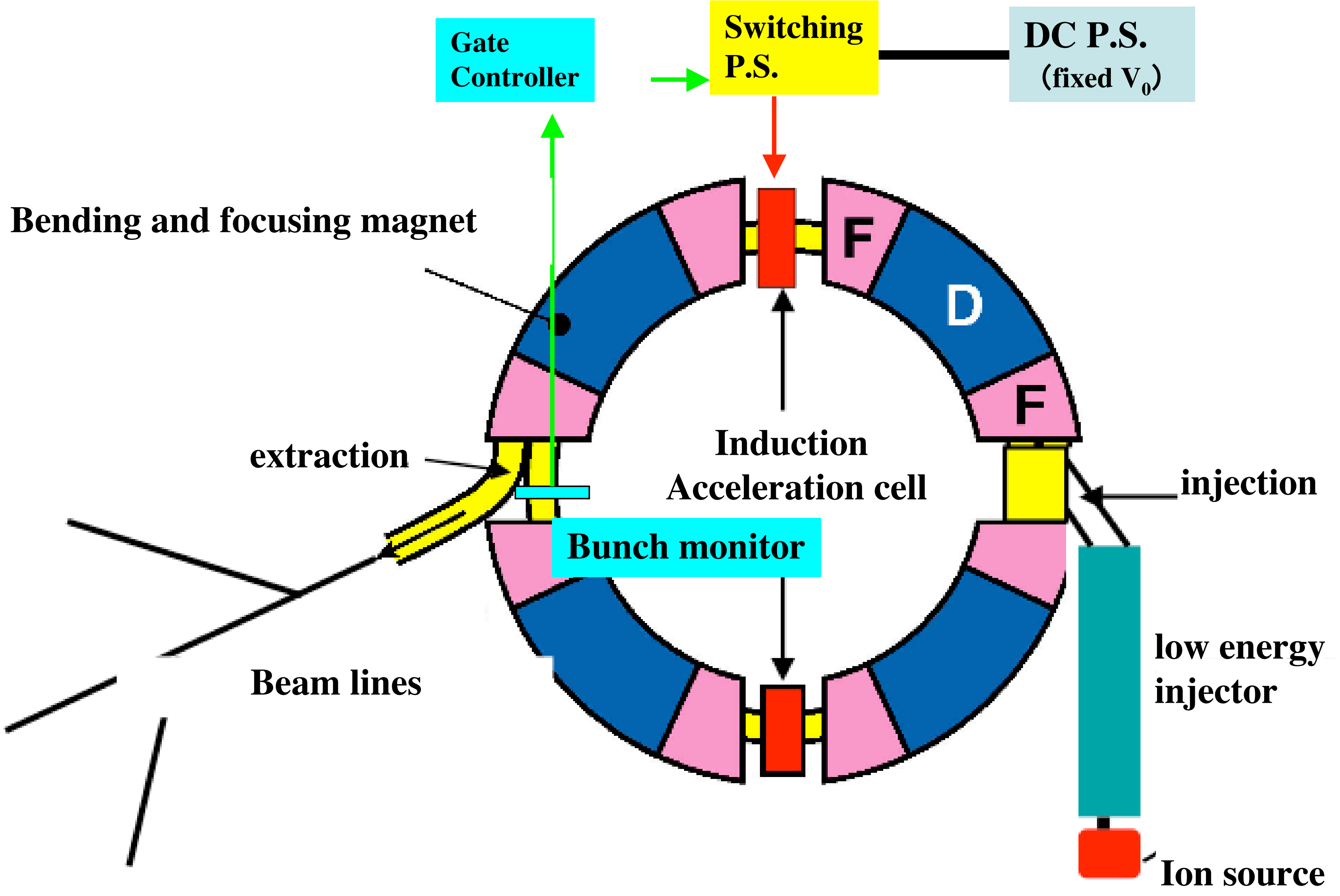








Schematic View of AIA



Gate Controller

Switching P.S.

DC P.S. (fixed V_0)

Bending and focusing magnet

extraction

Induction Acceleration cell

injection

Bunch monitor

low energy injector

Beam lines

Ion source

Acceleration in the AIA (1)

Ion: ***M=Am, Q=Ze*** **(*A:mass number, Z: charge state*)**

Force balance:

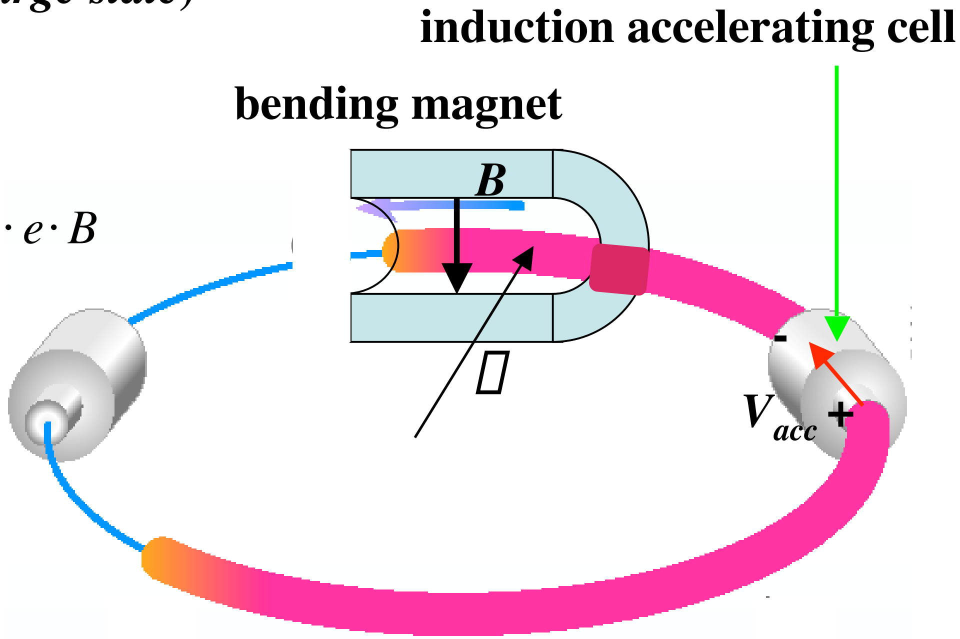
$$M\gamma\frac{(c\beta)^2}{\rho}=Q\cdot(c\beta)\cdot B \quad \Rightarrow \quad A\cdot m\cdot\gamma\frac{c\beta}{\rho}=Z\cdot e\cdot B$$

Local acceleration -> averaged acceleration:

$$A\cdot mc^2\cdot\dot{\gamma}=\frac{Z\cdot ec\beta}{C_0}\cdot V_{acc}(t)$$

$$\downarrow$$

$$\boxed{V_{acc}(t)=\rho\cdot C_0\cdot\frac{dB}{dt}}$$



C_0: circumference of the accelerator ring
B : magnetic flux density of the bend. mag.
ρ: bending radius
(always fixed through the acceleration)

Required accelerating voltage V_{acc} is uniquely determined by dB/dt.

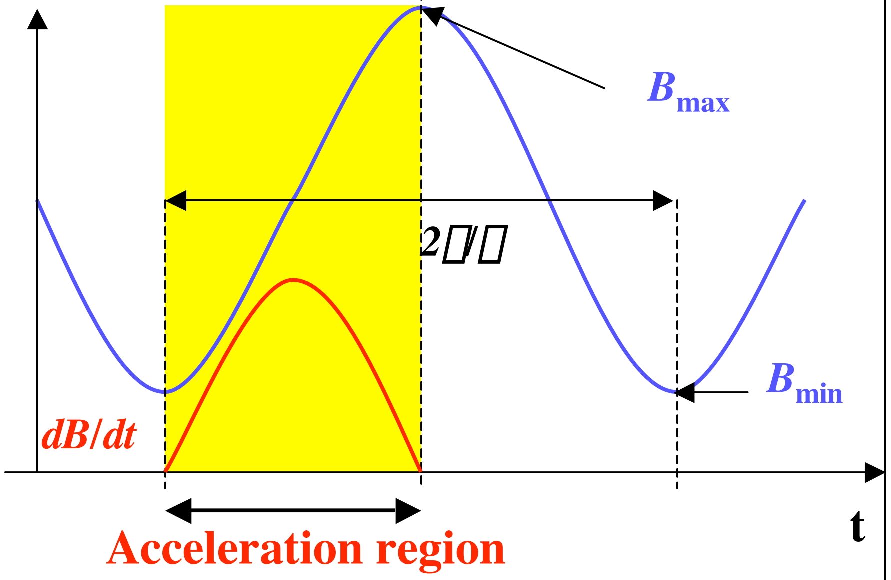
Acceleration in the AIA (2)

Change in an effective acceleration voltage
by control of the gate-pulse density (Patent)

Rapid cycle synchrotron

Resonant circuit power supply

$$B(t) = \frac{1}{2}\left[\left(B_{\max} + B_{\min}\right) - \left(B_{\max} - B_{\min}\right)\cos(\omega \cdot t)\right]$$

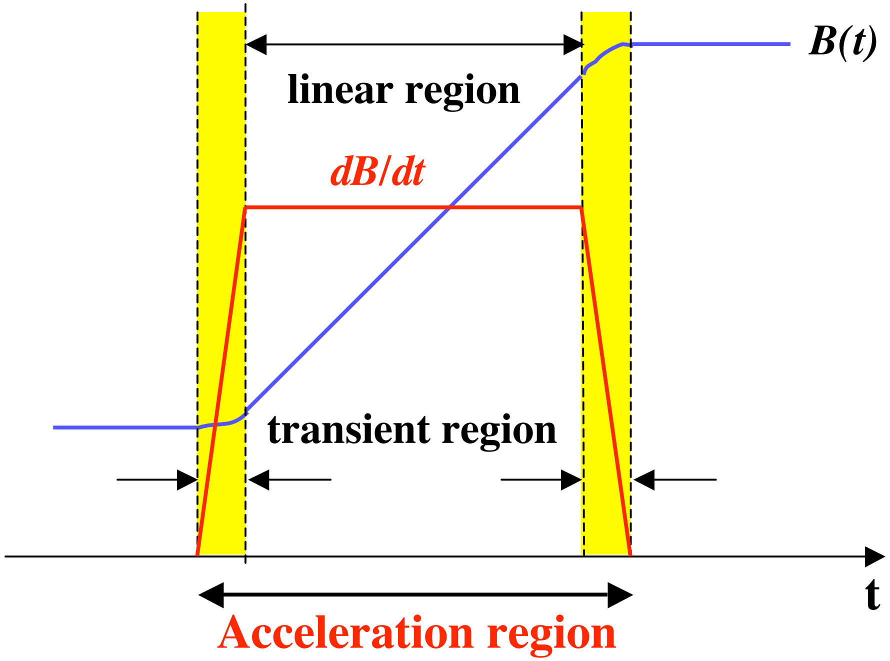


$$\left(dB/dt\right)_{\max} = \frac{\omega}{2}\cdot\left(B_{\max} - B_{\min}\right)$$

$(V_{acc})_{\max} = \rho C_0 \omega (B_{\max} - B_{\min})/2$

Slow cycle synchrotron

Patterned power supply



Required accelerating voltage is almost constant except the transient regions.
This was demonstrated in the KEK-PS

Revolution frequency and Switching frequency

revolution frequency:

$$f = c\beta / C_0$$

$$f = \frac{c}{C_0}\sqrt{\frac{D}{1+D}}$$

$$D \equiv (\beta\gamma)^2 = \left[\left(\frac{Z}{A}\right)\left(\frac{e\rho}{mc}\right)\right]^2 B^2(t)$$

$$\beta\gamma = \left(\frac{Z}{A}\right)\left(\frac{e\rho}{mc}\right) B$$

kinetic energy as a function of the revolution frequency:

$$T = Mc^2(\gamma - 1) = A\cdot mc^2\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right) = A\cdot mc^2\left(\frac{1}{\sqrt{1-\left(\frac{f\cdot C_0}{c}\right)^2}} - 1\right)$$

Defect of the induction acceleration driven by the switching power supply:

Induction step voltage can't follow $V_{acc}(t)$.
It must be constant, V_0, from a technical reason that it is difficult to change an output voltage of the DC power supply within tens of mseconds.

Counter measure: intermittent switching
instantaneously averaged switching frequency $g(t)$

ΔE: energy gain per short time-period Δt
$g(t)=(V_{acc}(t)/V_0)f(t)$

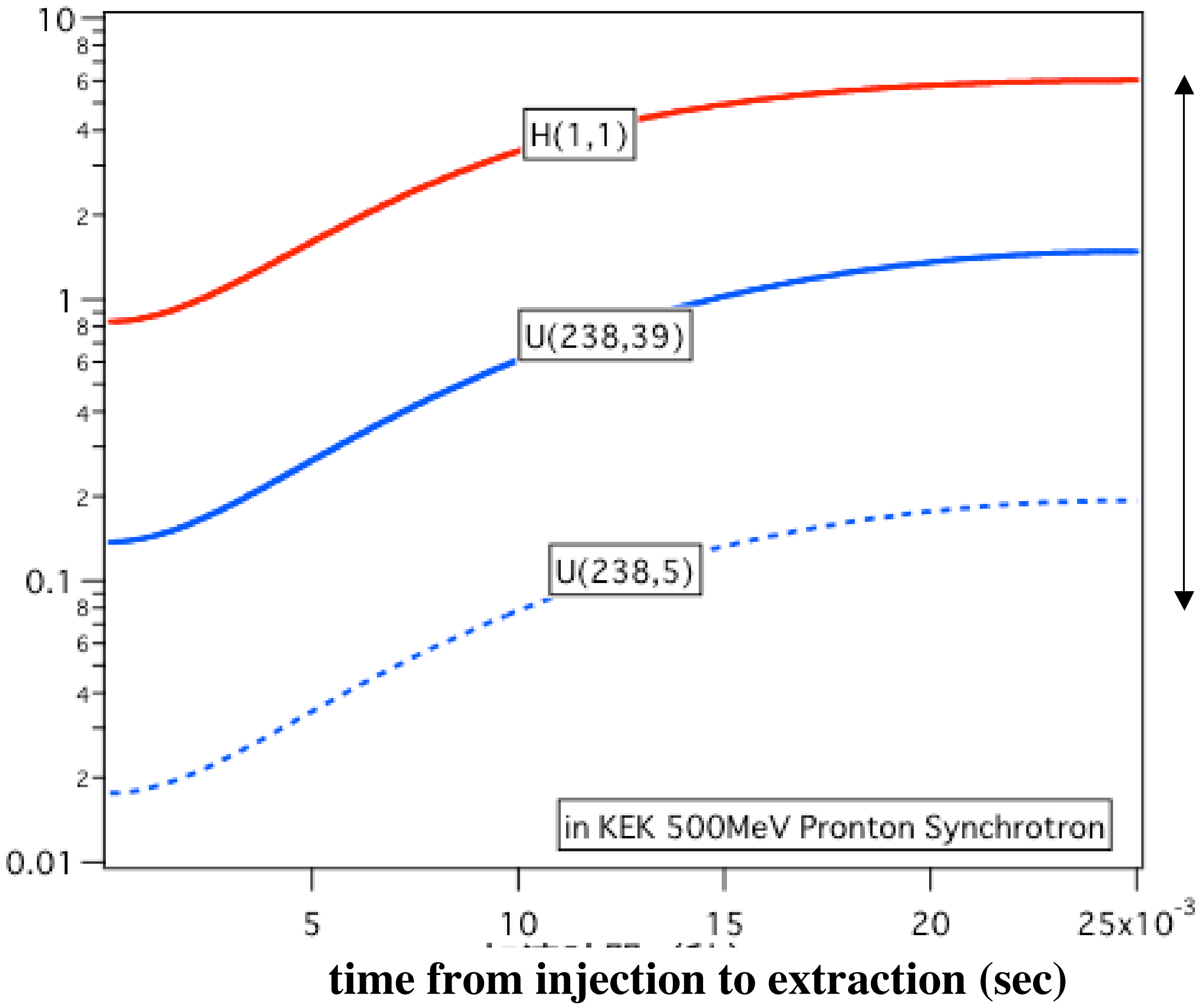
$$\Delta E = \int_t^{t+\Delta t} eV_{acc}(t')f(t')dt'$$

$$= eV_0 \int_t^{t+\Delta t} g(t')dt'$$

KEK 500MeV Booster & 12GeV PS

item	symbol	KEK 500MeV booster synchrotron		C: KEK 12GeV PS linear ramping
		A: excitation by resonant circuit	B: linear ramping	
circumference (m)	C_0	340/9	340/9	340
curvature (m)	▯	3.3	3.3	24.6
minimum field (T)	B_{min}	0.2	0.1	0.146
maximum field (T)	B_{max}	1.1	1.7	1.7
ramping time (sec)	▯	0.05	0.8	0.8
acceleration voltage (kV) from (3)	V_{acc}	7.05 (max)	0.25	16.3

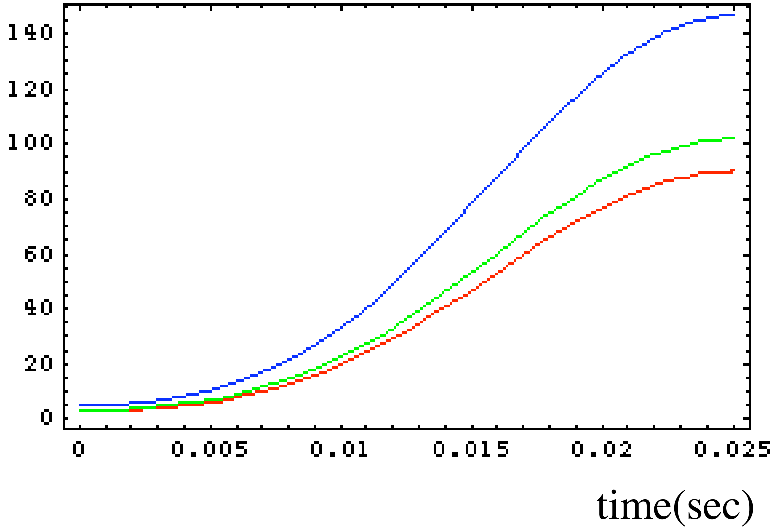
Revolution frequency (MHz)



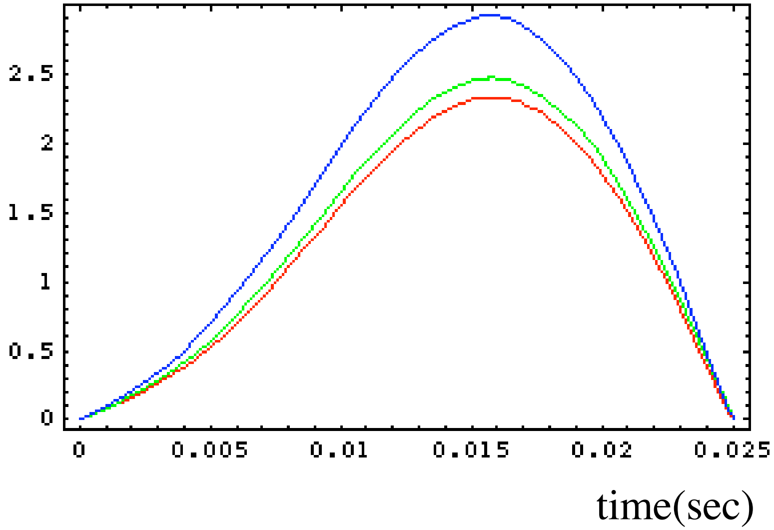
existing
ions

Case A: sinusoidal ramp in Booster

***E*(t) (MeV)/nucleon**

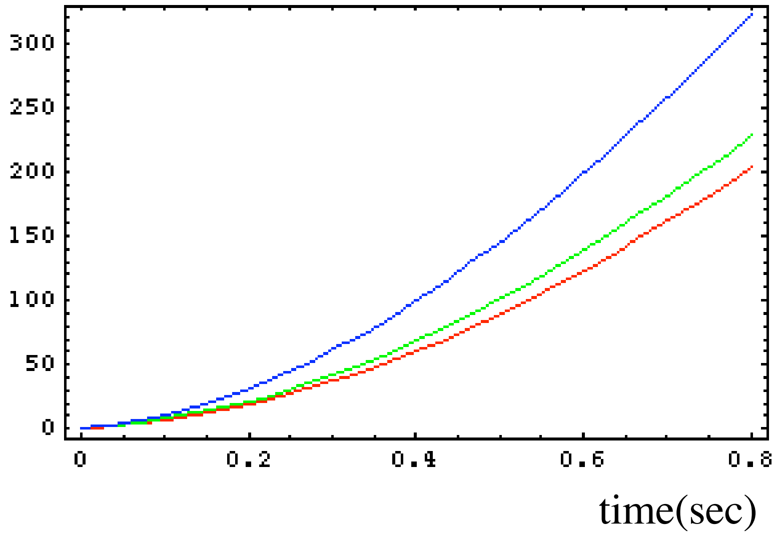


Switching frequency(MHz) *g*(t)

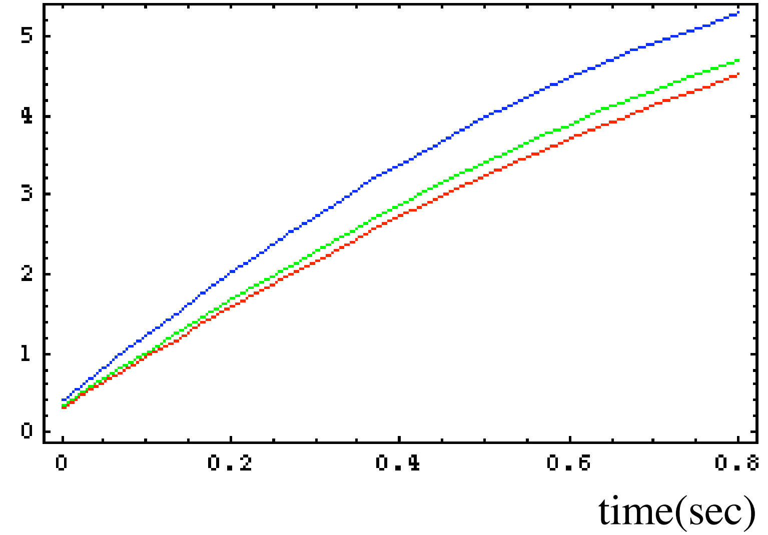


Case B: linear ramp in Booster

***E*(t) (MeV)/nucleon**



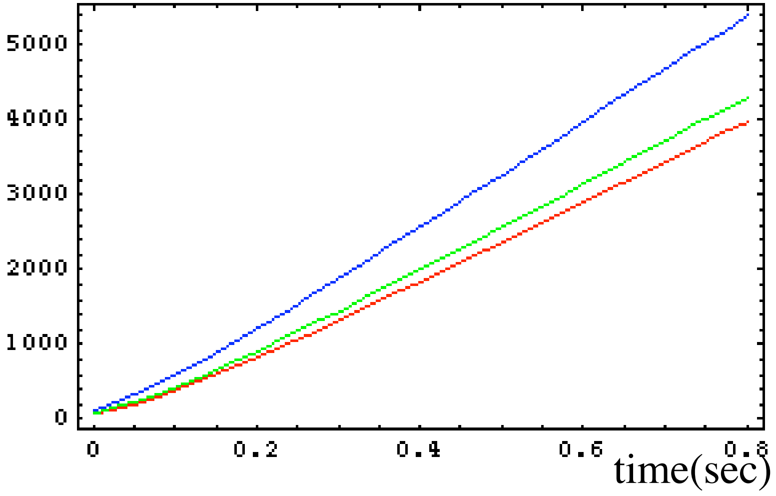
Switching frequency (MHz) *g*(t)(=*f*(t))



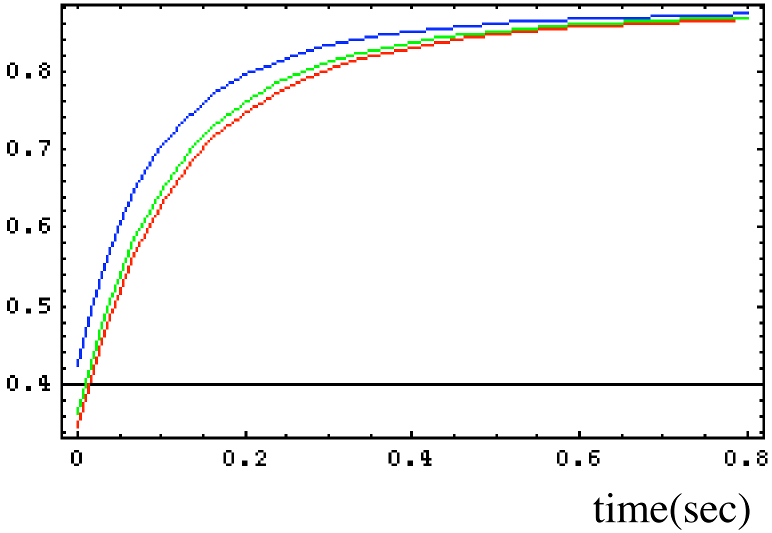
— **O(16,8)**　— **Xe(131,54)**　— **U(238,92)**

Case C: linear ramp in 12GeV PS

E(t) (MeV)/nucleon



Switching frequency (MHz) *g*(t)(=*f*(t))



O(16,8) **Xe(131,54)** **U(238,92)**

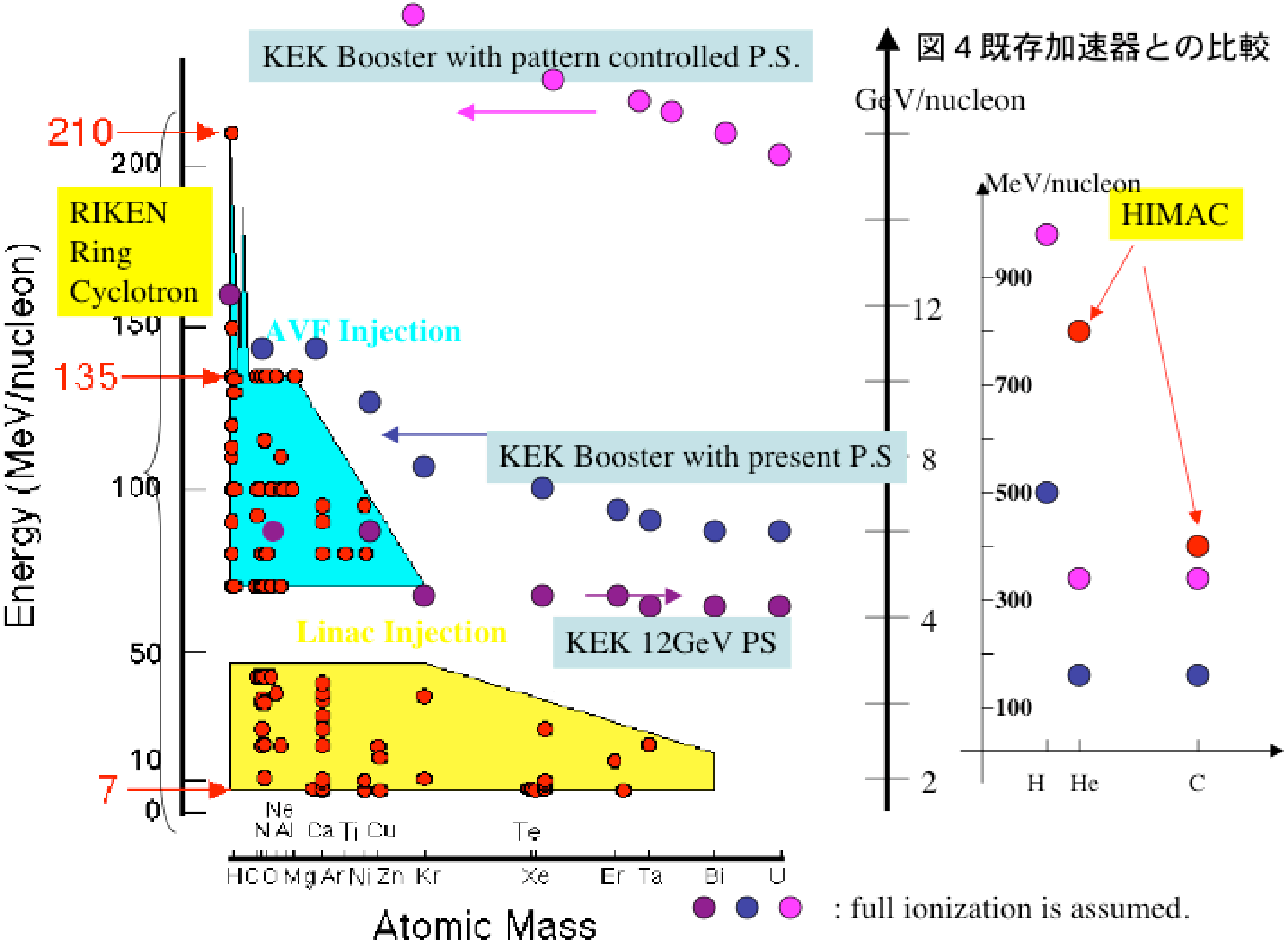


図４既存加速器との比較

Transverse Focusing in the AIA

Equation of motion in the transverse direction:

$$A\cdot m\cdot\frac{d}{dt}\left(\square\cdot v_{\square}\right)=Z\cdot e\cdot v_{\parallel}\cdot B\square x$$

with $$B\square\equiv\frac{\partial B_y}{\partial x}$$

$$\square\cdot c\square_{\parallel}\cdot\frac{d}{ds}\square\frac{dx}{ds}\square=\frac{Z}{A}\square\frac{e}{m}\square\cdot B\square x\quad\square\quad\frac{d^2x}{ds^2}+K(s)x=0$$

$$K(s)=\square\frac{Z}{A}\square\cdot\frac{(e/m)}{c\square\square}\cdot\frac{\partial B_y}{\partial x}$$

$$K(s)=\frac{\partial B_y/\partial x}{B\square}$$

Betatron frequency doesn't depend on ion.

Easy accelerator tuning for any ions

common

COD

Betatron tune

Injection/extraction orbit

gate timing is determined from the circulating bunch signal.

Interesting option

Simultaneous acceleration of different ion species with different (*Z*/*A*) in the same ring

gate triggers are generated every ion species.

Current and future items for R&D on Induction accelerating system

item	necessity	measures
Droop compensation (2005)	•Droop gives additional focusing (above □$_t$) and defocusing (below □$_t$) •indispensable for acceleration of a super-bunch	introduce an additional compensation cell
□R-feedback system (2005)	•The beam centroid must be hold on the design orbit. •There is no phase-feedback system as found in RF-synchrotrons. •to relax a precise control of the induction voltage	apply for a patent (presented at PAC2005)
Low impedance system (2005-2006)	•have to stand up to significant beam loading caused by super-bunches •currently limited due to the arm current of the pulse modulator (deposited heat)	•increase the arm current by a change in the circuit architecture •Otherwise employ other power switching elements •replace with transmission cable and matching resistance of low impedance

Summary

- **A reliable full module for the induction accelerating system consisting of 50kW DC P.S., Pulse Modulator, Transmission Cable, Matching Resistance, Induction Cell, which is capable of operating at 1 MHz, has been confirmed to run over 24 hours without any troubles.**
- **The *induction acceleration* of protons(6x10^{11}ppb) in a circular accelerator ring has been observed, where a single RF bunch was accelerated from 500MeV to 8GeV (flat-top) with an energy gain of 4.8 kV/turn.**
- **A *600nsec-long proton bunch* trapped in a shallow notch potential, which is generated with induction step-voltages, has been demonstrated.**
- **These results are crucial milestones to realize *Induction Synchrotrons* and *Super-bunch Hadron Colliders*.**
- **The acceleration in circular rings has entered into a new era with induction devices driven by a switching driver.**

One of possible and unique applications in a low energy region may be All-ion Accelerator.

Appendix

RPIA2006

2nd International Workshop on Recent Progress in Induction Accelerators

March 7-10, 2006

KEK, Tsukuba, Japan

Organized by
High Energy Accelerator Research Organization
Tokyo Institute of Technology

URL http://conference.kek.jp/RPIA2006/

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traditional trawling boats in Lake Kasumi (photo by K.Kuroda)

We will discuss

- Induction devices for LINAC and Circular Ring
  (Induction cell, Modulator, Switching elements, System architecture)

- Hybrid system combining RF and Induction acceleration

- Beam dynamics in extremely high intensity accelerators

- Super-bunch beam dynamics, barrier-bucket beam dynamics

- Applications
  - Heavy Ion Fusion Driver
  - Induction Synchrotron
  - Super-bunch Hadron Collider, Super-bunch FFAG
  - Novel Ion Accelerator
  - Chopper, High-rep rate Kicker
  - others

Contributions from Proton driver, Neutrino Factory, Hadron Collider,
Inertial Fusion, Pulsed-power technology, Linear Collider Societies
quite welcome