Induction Synchrotron Experiment in the KEK PS

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High Energy Accelerator Research Organization (KEK)

on behalf of
Super-bunch Group which consists of staffs
of KEK, TIT, NAT, and Nagaoka Tech. Univ.

25-29 June, 2007
Albuquerque, USA
2007 Particle Accelerator Conference

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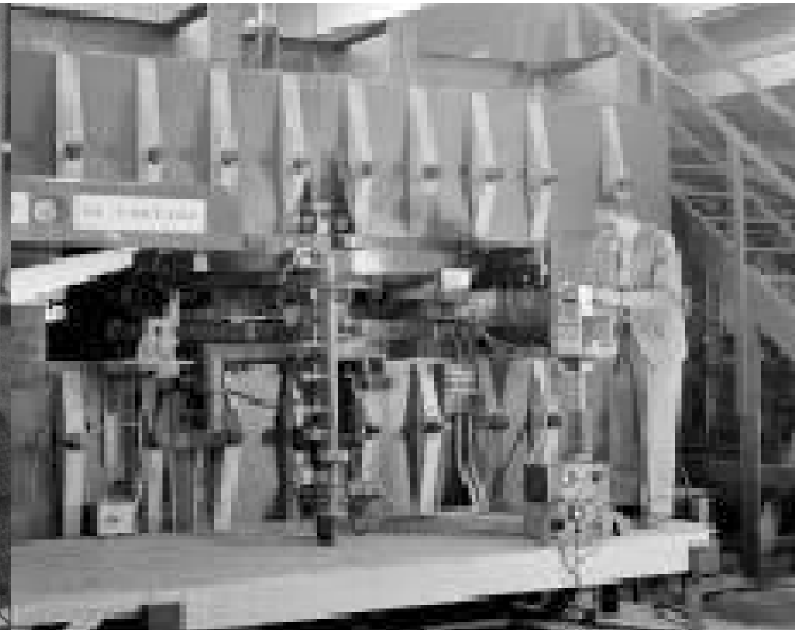
History of Induction Synchrotron Research at KEK

Year	Major topics & outputs	Events
1999	**Proposal of the Induction Synchrotron concept by K.Takayama and J.Kishiro**	νFACT'99
2000	R&D works on the 1MHz switching power supply started.	EPAC2000
2001	R&D works on the 2.5kV, 1MHz induction acceleration cell started. **Proposal of a Super-bunch Hadron Collider**	PAC2001 Snowmass2001
2002		ICFA-HB2002 EPAC2002,**RPIA2002**
2003	**5 years term Project using the KEK-PS officially started with a budget of 5M$.**	PAC2003 ICFA-HB2003
2004	●The first engineering model of the switching P.S. was established. 3 induction acceleration cells (2 kVx3=6 kV) were installed. (May) ●First experimental demonstration of induction acceleration in the KEK-PS (Oct. - Nov.) ●Barrier trapping at the injection energy of 500MeV and a 500 nsec-long bunch was achieved. (Dec.)	APAC2004 EPAC2004 ICFA-HB2004 CARE HHH2004
2005	**Proposal of All-ion Accelerators** Another 3 induction acceleration cells (2 kVx3=6kV) were installed (Sept). ●Quasi-adiabatic non-focusing transition crossing was demonstrated in the hybrid synchrotron (RF capture + induction acceleration), (Dec.)	PAC2005
2006	Another 4 induction acceleration cells (2 kVx4=8 kV) were installed.(Jan.) ●**Full demonstration of the IS concept (March)** ●**All-ion Accelerator was awarded a patent. (November)**	**RPIA2006,** HB2006 EPAC2006, HIF06

The first Synchrotron and newest one

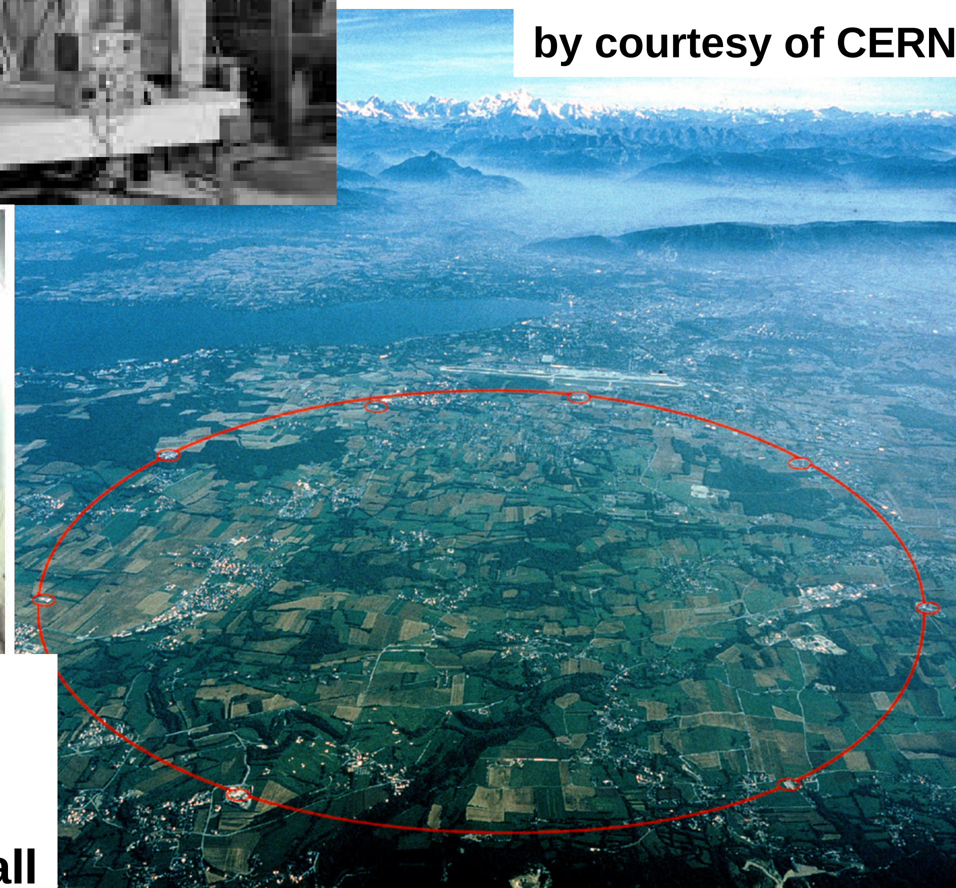


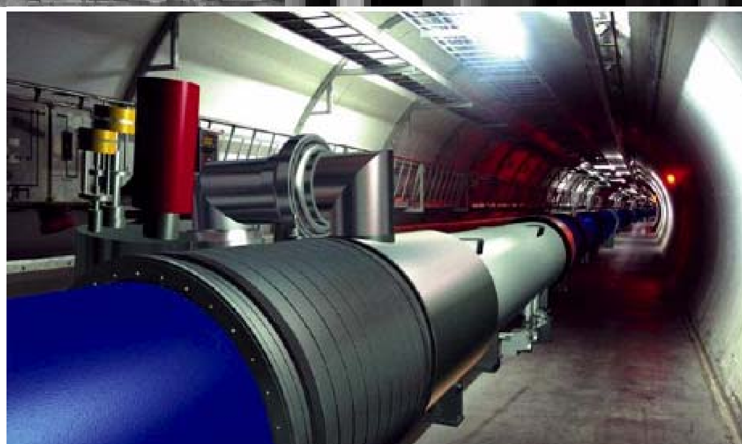
E=340MeV

Week focusing

by courtesy of LBNL

by courtesy of CERN





Large Hadron Collider

E=7 TeV

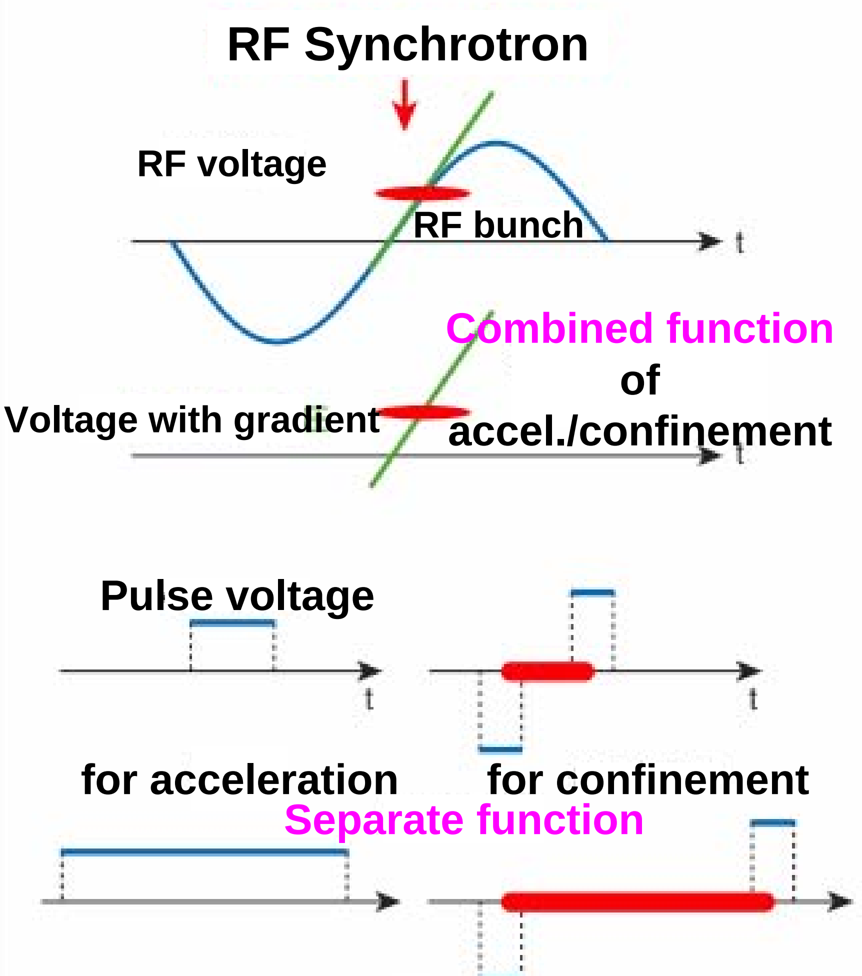
Circumference= 27km

Beam commissioning in 2007 fall

Concept of Induction Synchrotron

.Takayama and J.Kishiro, “Induction Synchrotron”, *Nucl. Inst. Meth.* A451, 304(2000)

Principle

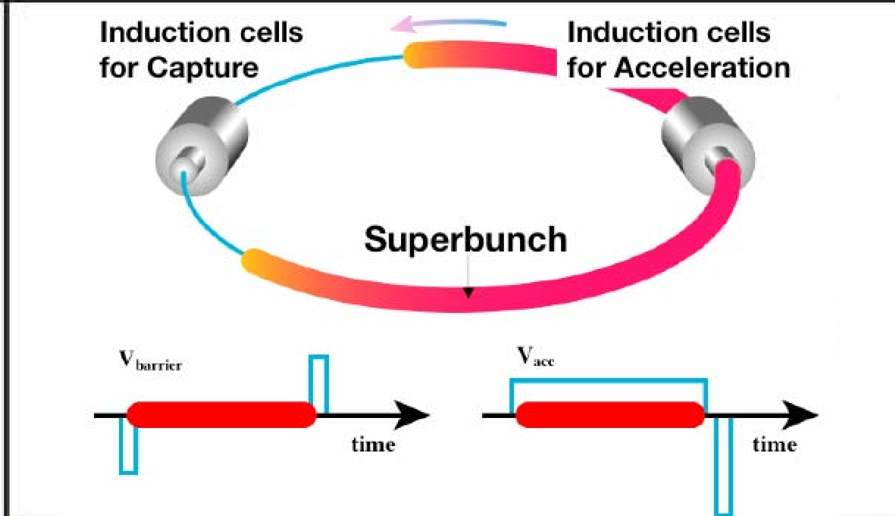


introducing a big freedom of beam handling

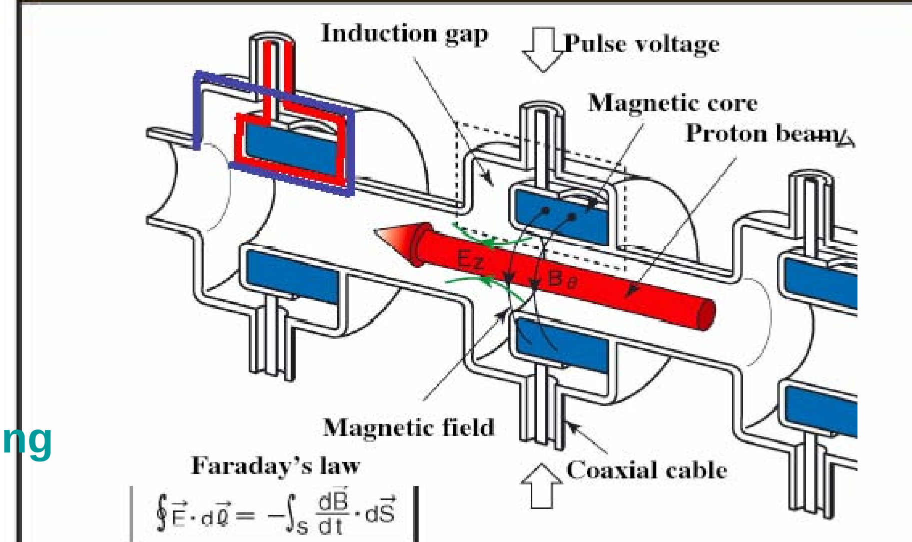
⬇

Induction Synchrotron

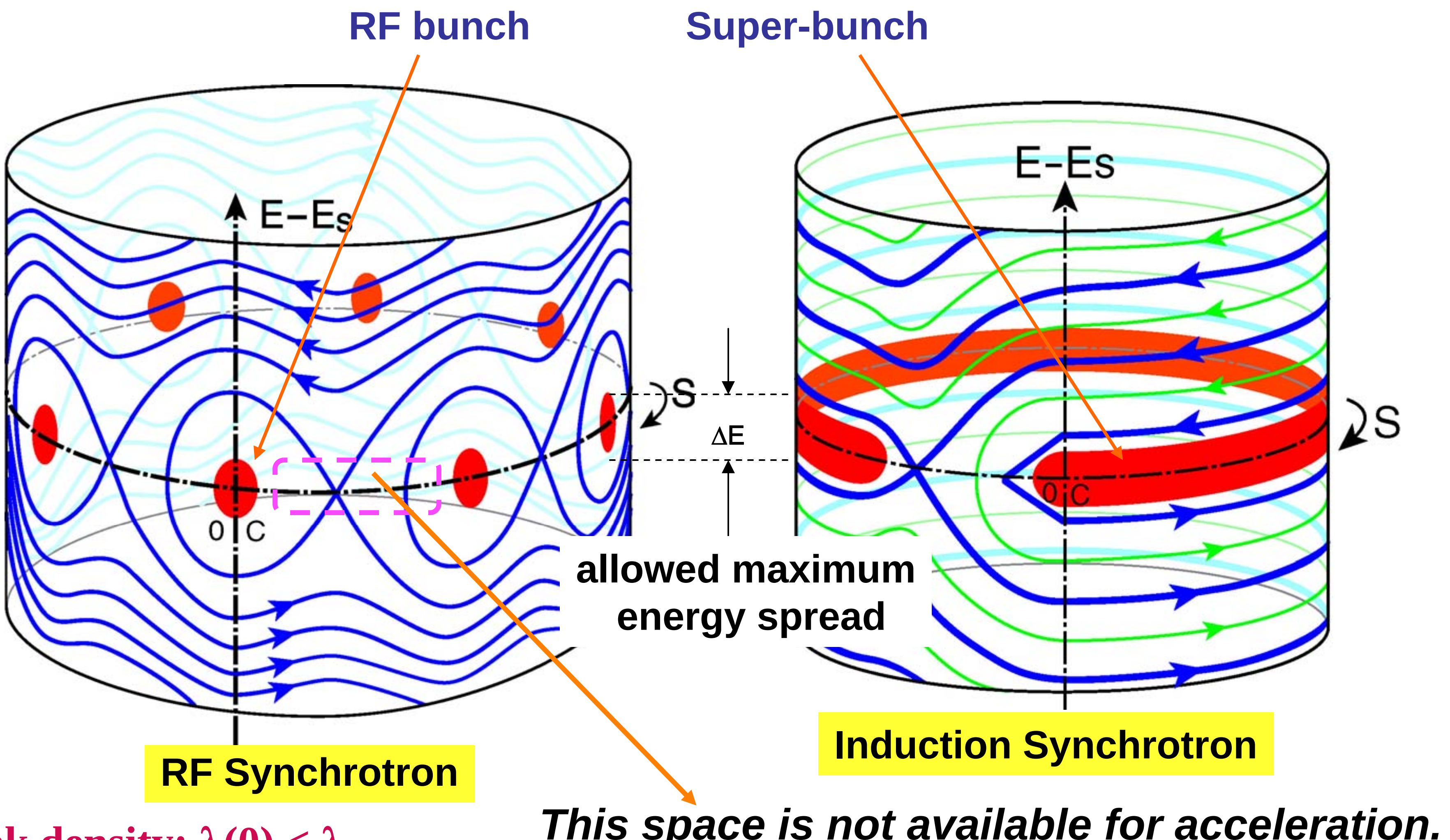
Image of Accelerator



Induction acceleration cells

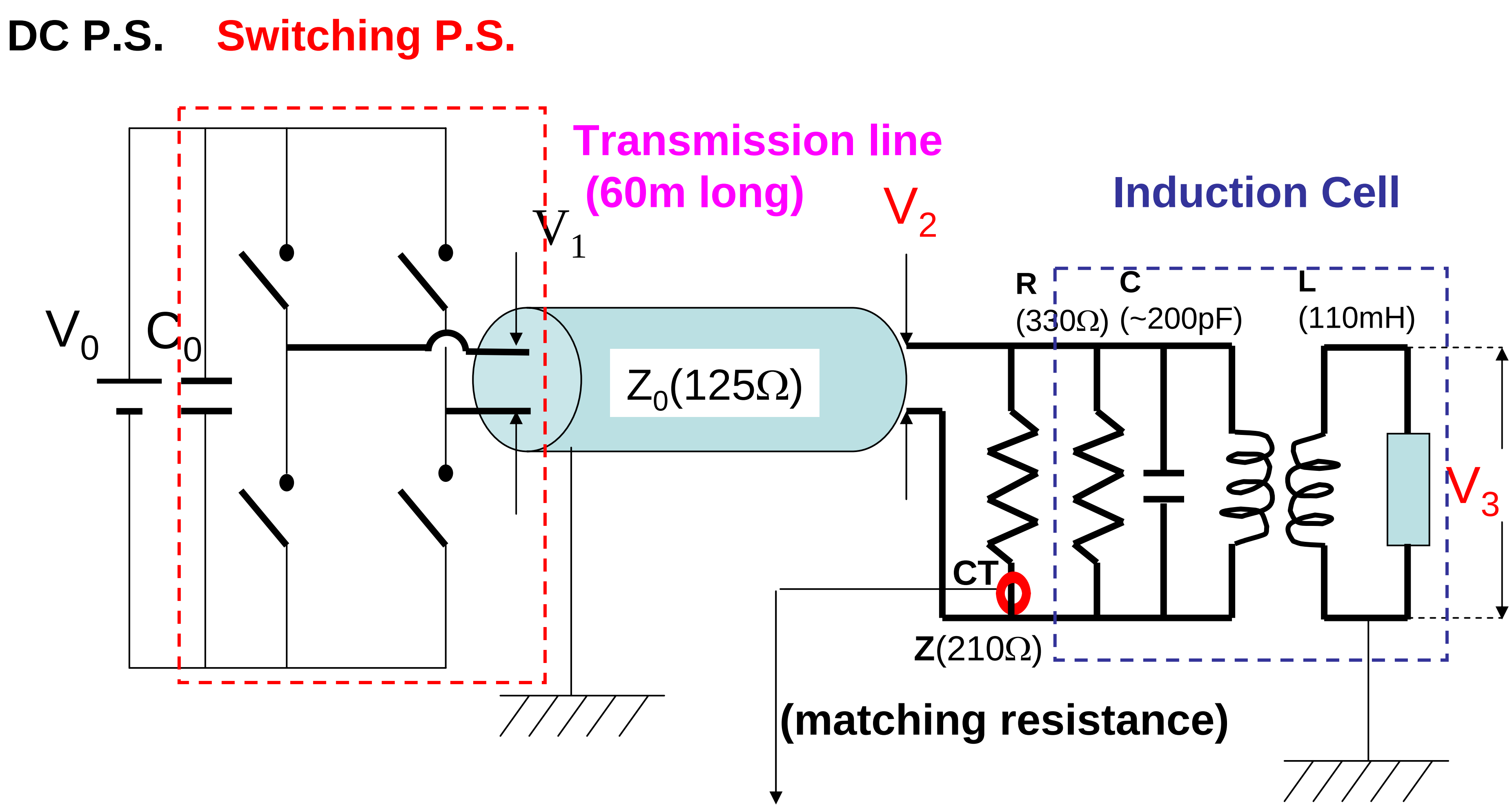


Difference between RF and Induction Synchrotron seen in Phase-space



peak density: $\lambda(0) < \lambda_{limit}$

Equivalent Circuit for 2.5kV Induction Accelerating System

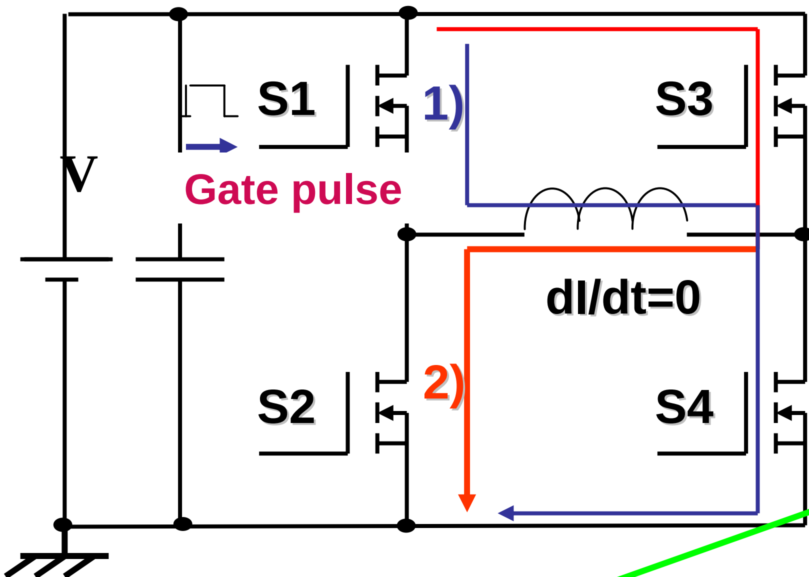


$V_0 \sim V_2 = V_3 \sim ZI_Z$ (calibrated)

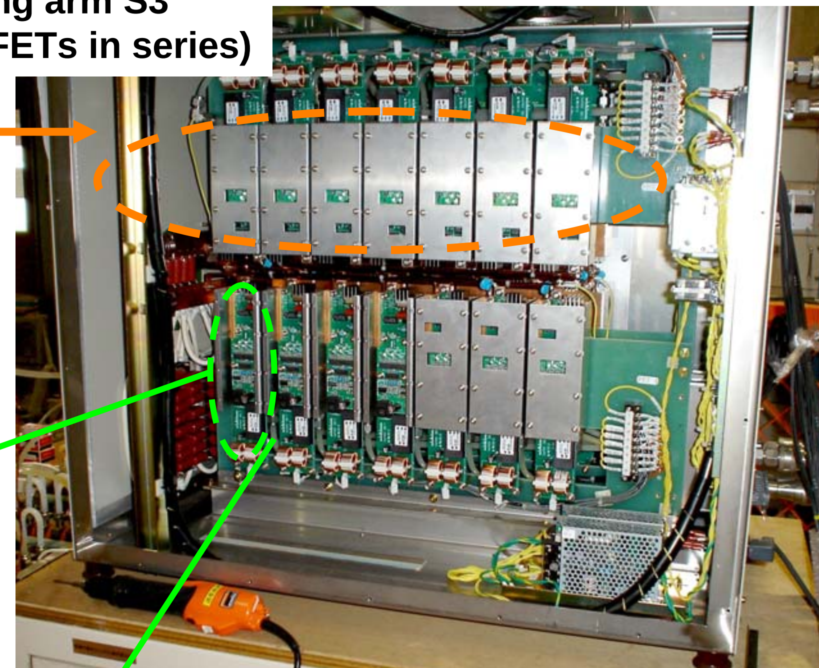
I_Z (always monitored)

More information on key devices: http://conference.kek.jp/rpia2006/

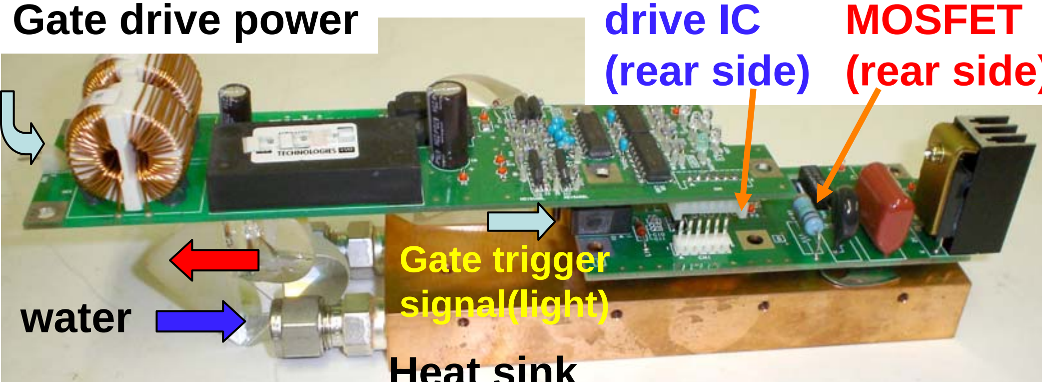
Switching Power Supply: switching sequence, output pulse



Switching arm S3
(7 MOSFETs in series)

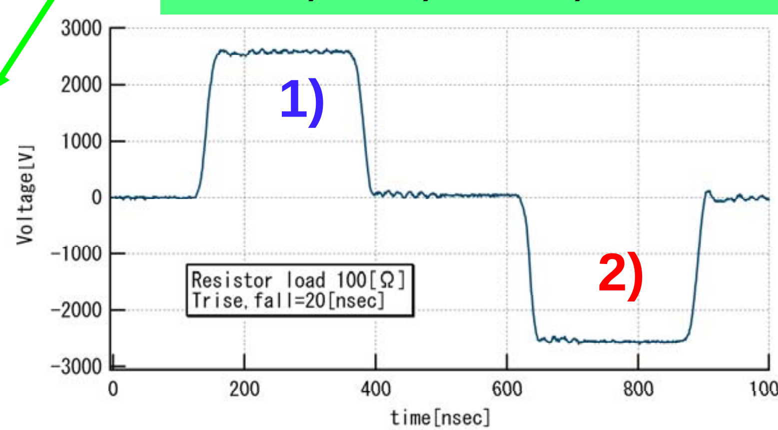


MOSFET board



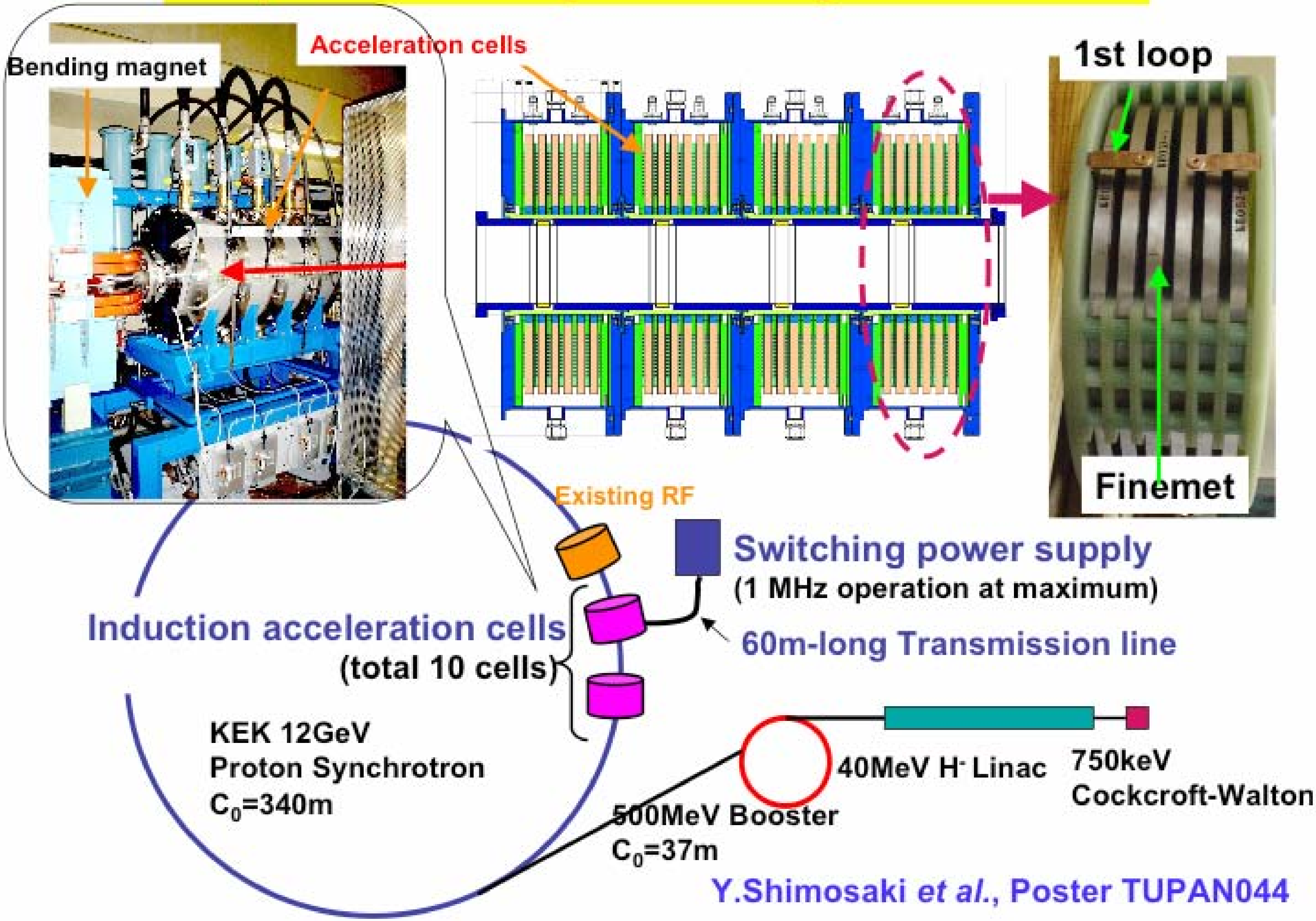
Heat sink
for MOSFET & drive IC

2.5kV, 20A, 1MHz, 500nsec



M.Wake *et al.* MOPAN042

Set-up of the induction synchrotron using the KEK 12GeV PS



Y.Shimosaki *et al.*, Poster TUPAN044

Scenario of the POP Experiment

The scenario has been divided into three steps.

1 st Step:

RF trapping + induction accel.

(Hybrid Synchrotron)

500 MeV -> 8 GeV for 6x10^{11}ppb

2004/10-2005/3

2nd Step:

Barrier trapping by induction step-voltages

at 500 MeV

through 2005

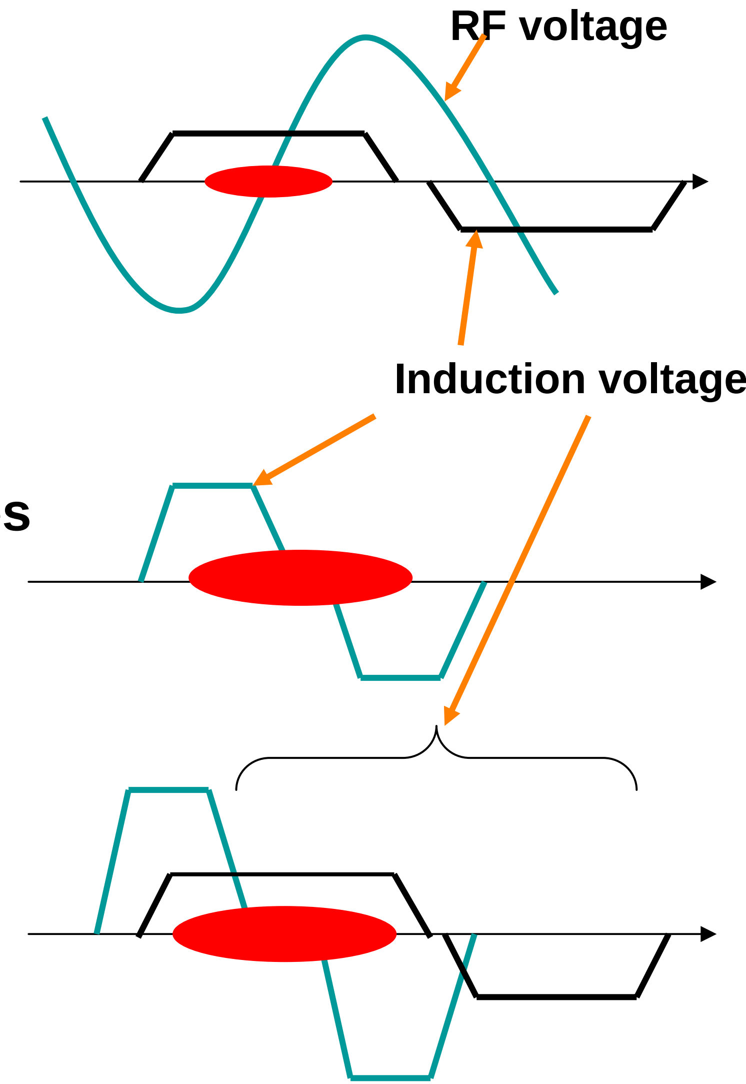
3rd Step:

Barrier trapping + induction accel.

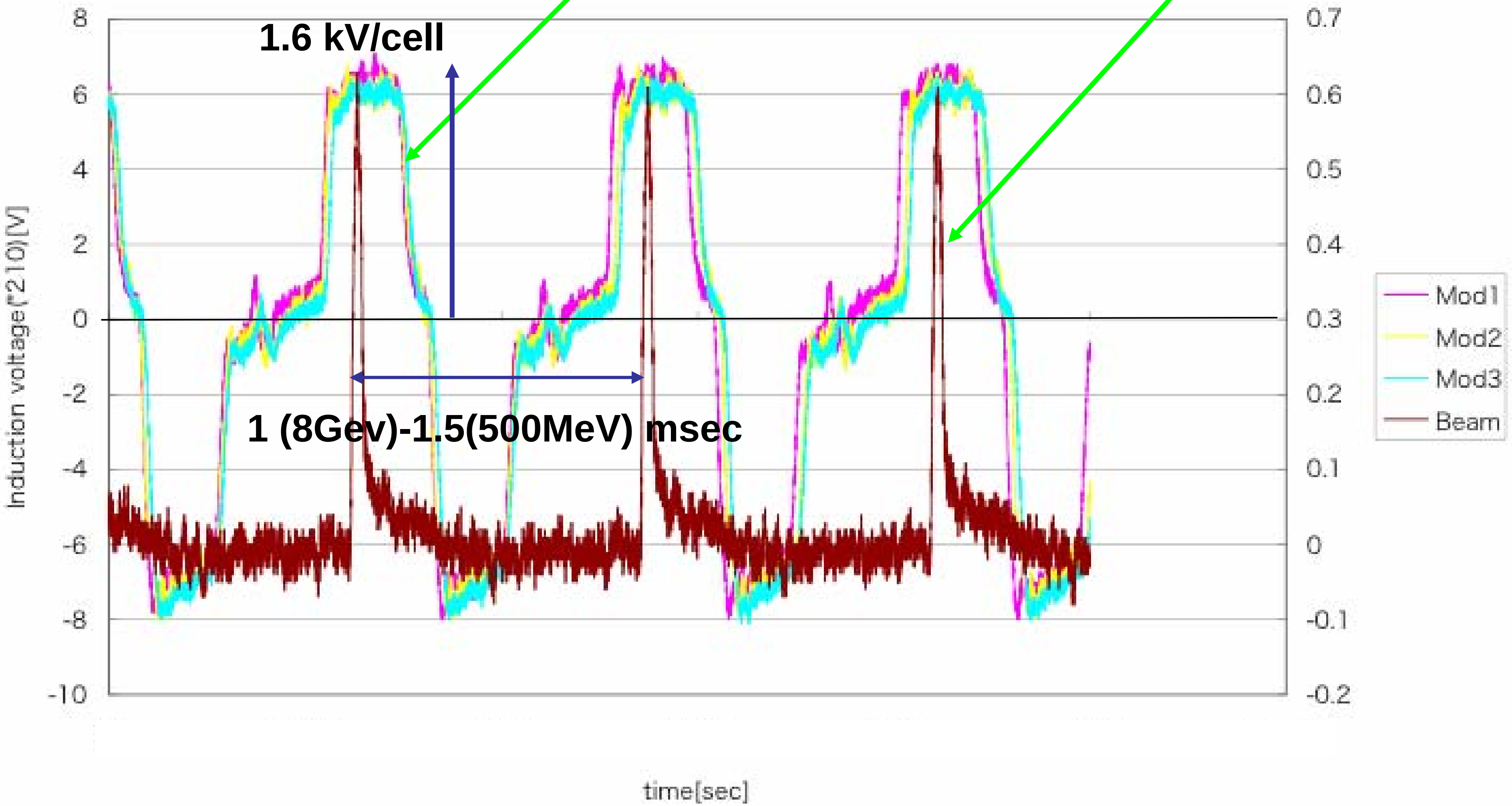
(Induction Synchrotron)

500 MeV -> 6 GeV for 2-3x10^{11}ppb

2006/1-3



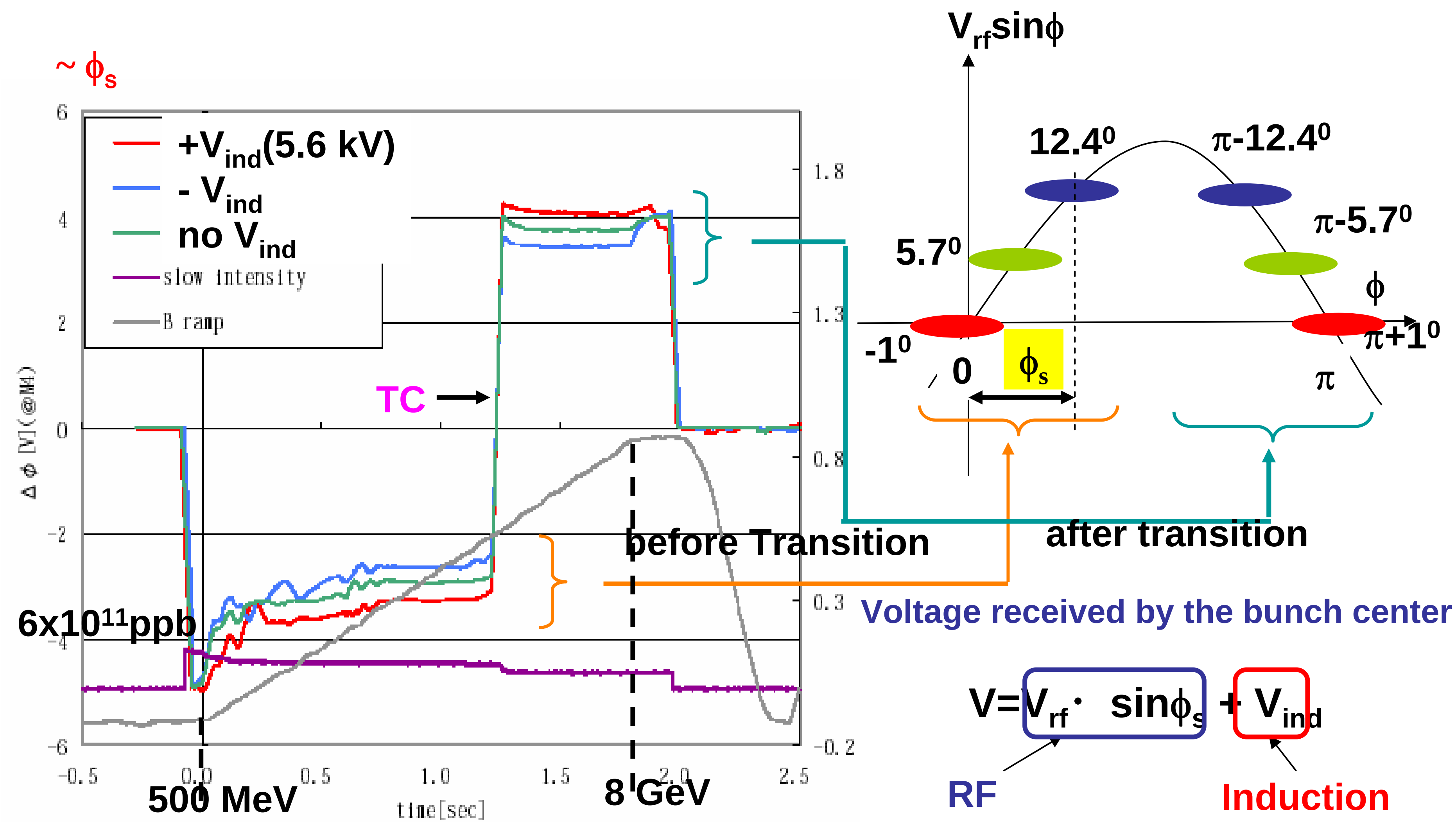
Monitored signals of induction voltage and an RF bunch signal in the step 1 experiment



- **Synchronization between two signals has been confirmed through an entire acceleration.**

Step 1
Hybrid Synchrotron

Proof of the induction acceleration in the Hybrid Synchrotron:
Position of the bunch centroid in the RF phase



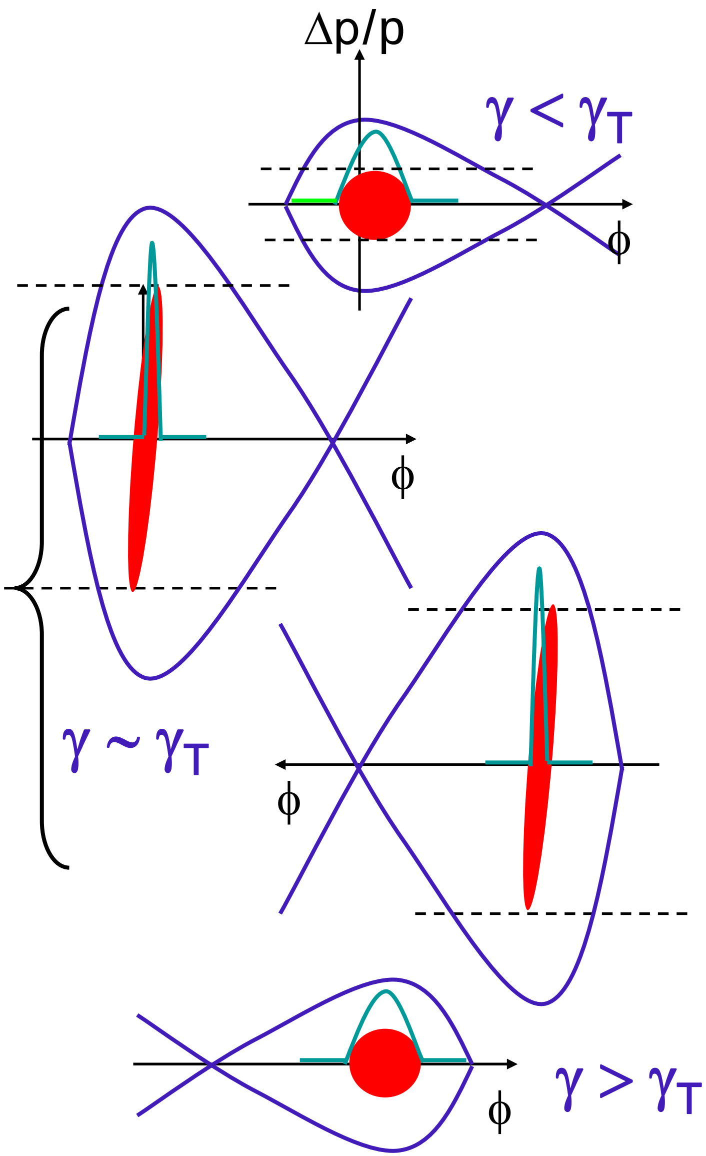
K.Takayama *et al.*, *Phys. Rev. Lett.* 94, 144801 (2005).

Step 1
Hybrid Synchrotron

Focusing-free Transition Crossing (FFTC) in the Hybrid Synchrotron

RF Synchrotron

- RF voltage: always on around γ_T



Hybrid Synchrotron

- RF voltage: off around Transition energy.
- Induction voltage: continuously triggered for acceleration.

Specific features in TC:

- Non-adiabatic motion
- Sync. motion frozen

↓

stretched in Δp/p
compressed in phase

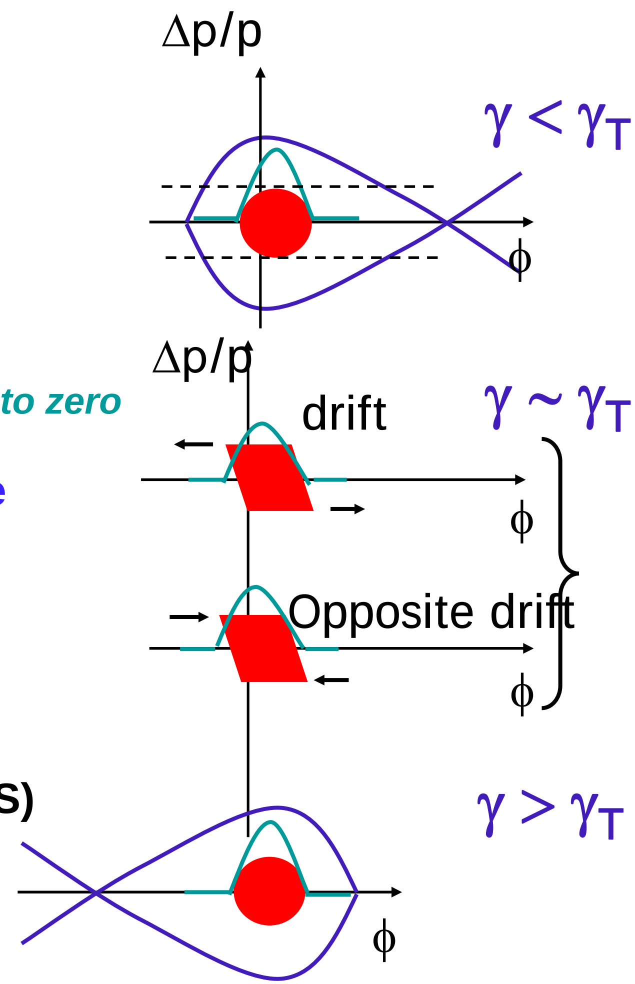
↓

reach momentum aperture
Jonsen effects: serious

$$\phi_{n+1}=\phi_n+2\pi\eta(\Delta p/p)_{n+1} + k\,(\Delta p/p)^2_{n+1}$$

goes to zero

Instabilities:
Microwave instability @ (KEK-PS)
e-p instability (RHIC)

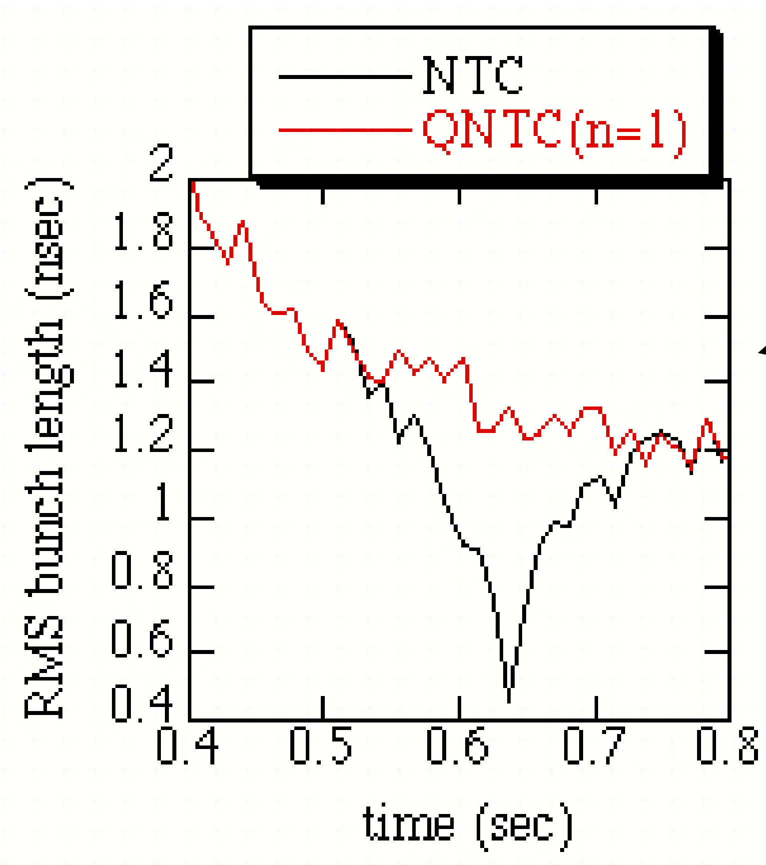


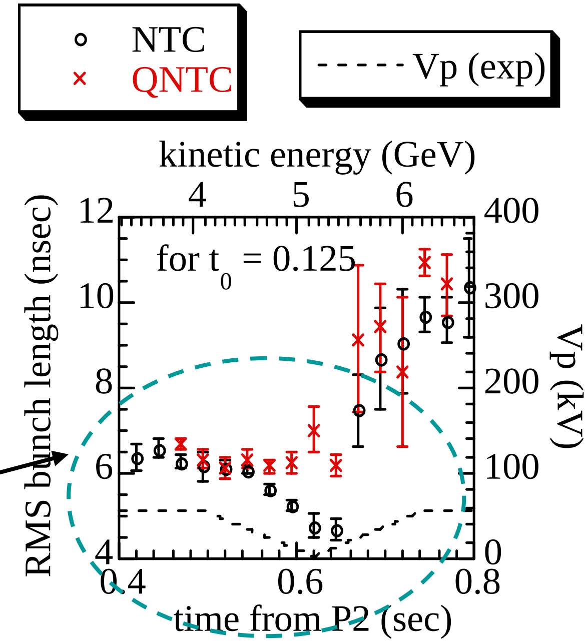
Simulation Results

Experimental Results for QNTC

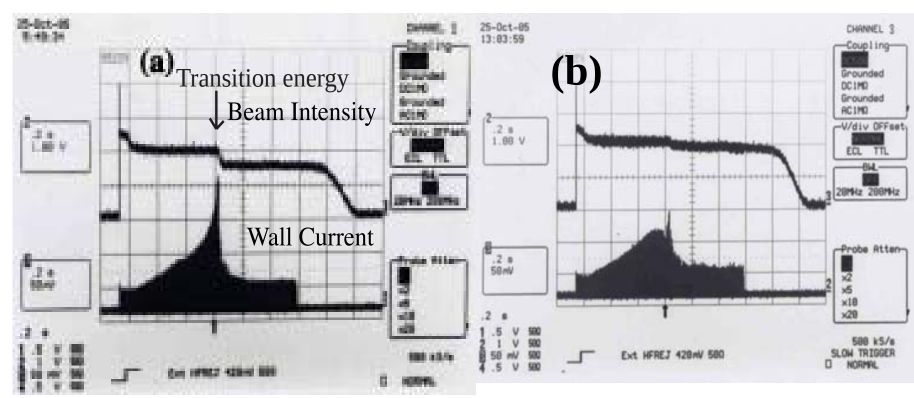
Polynomial reduction

$$V_{rf}(t) = a|t|^n \sin\left[\omega_{rf} t\right]$$





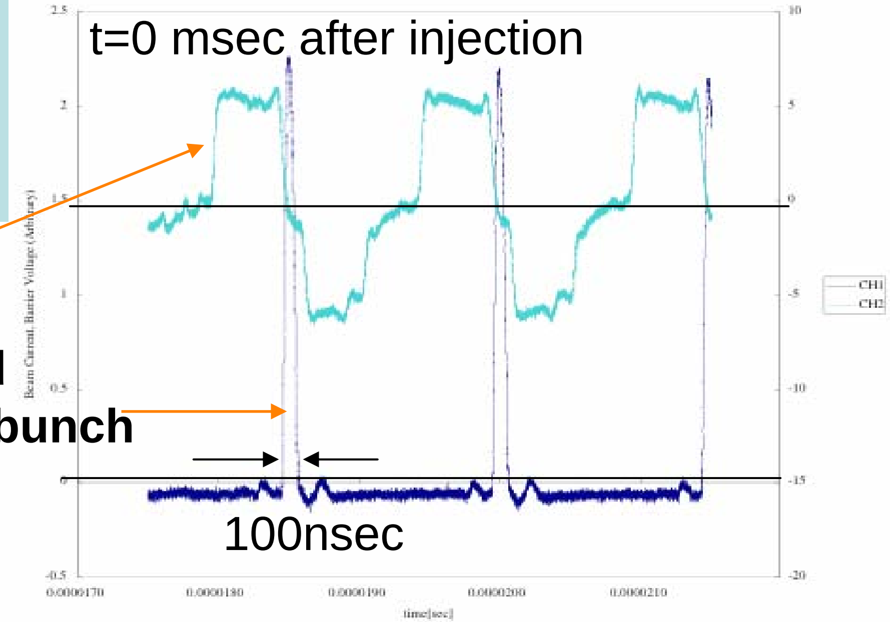
Bunch length measured by Wall Current Monitor.



Y.Shimosaki, K.Takayama, and K.Torikai, *Phys. Rev. Lett.* 96, 134801 (2006).

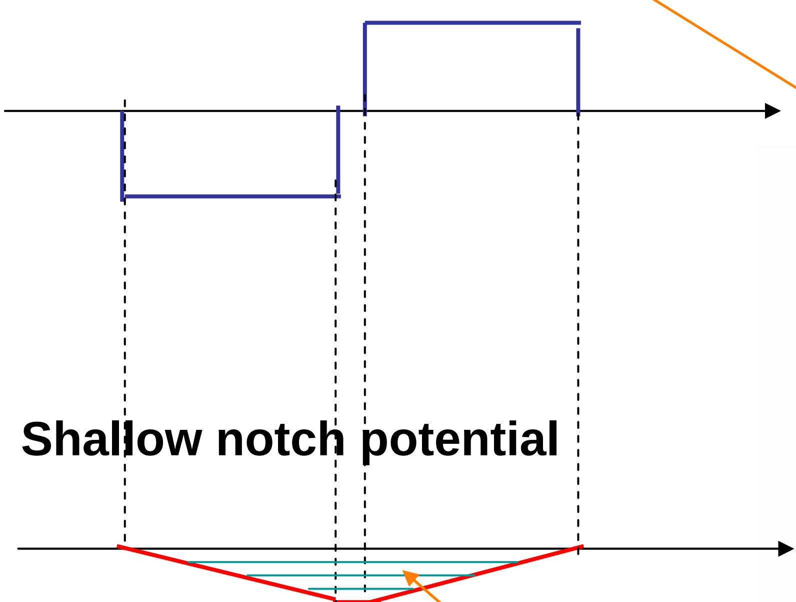
Beam Intensity measured by Slow Intensity Monitor (2×10^{11}ppb/div) and Wall current measured by Wall Current Monitor(a) NTC and (b) QNTC.

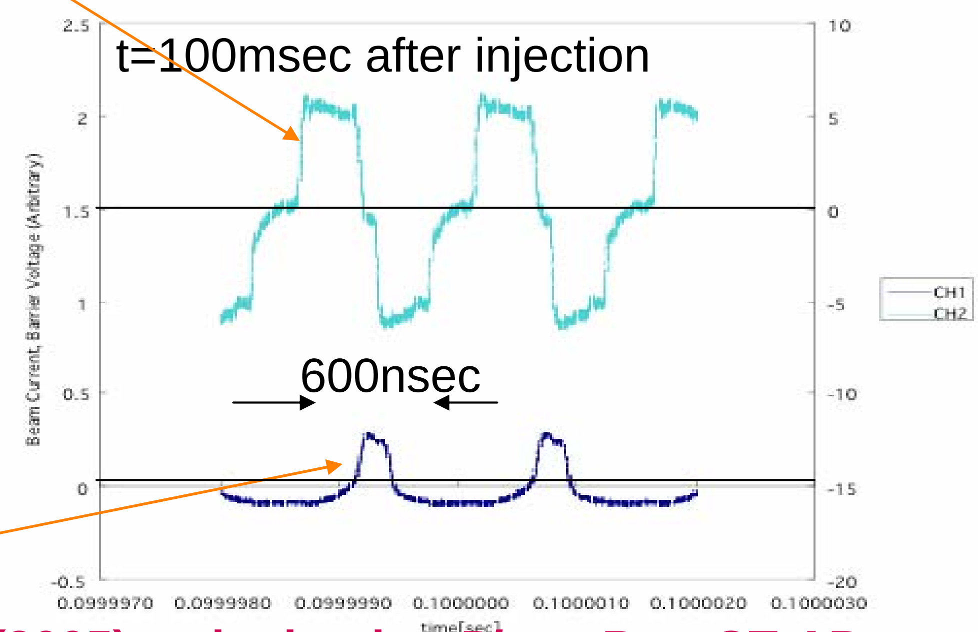
Step 2:
Confinement by Induction Step-barriers
Formation of a 600nsec-long bunch



6 kV barrier-voltage

injected proton bunch



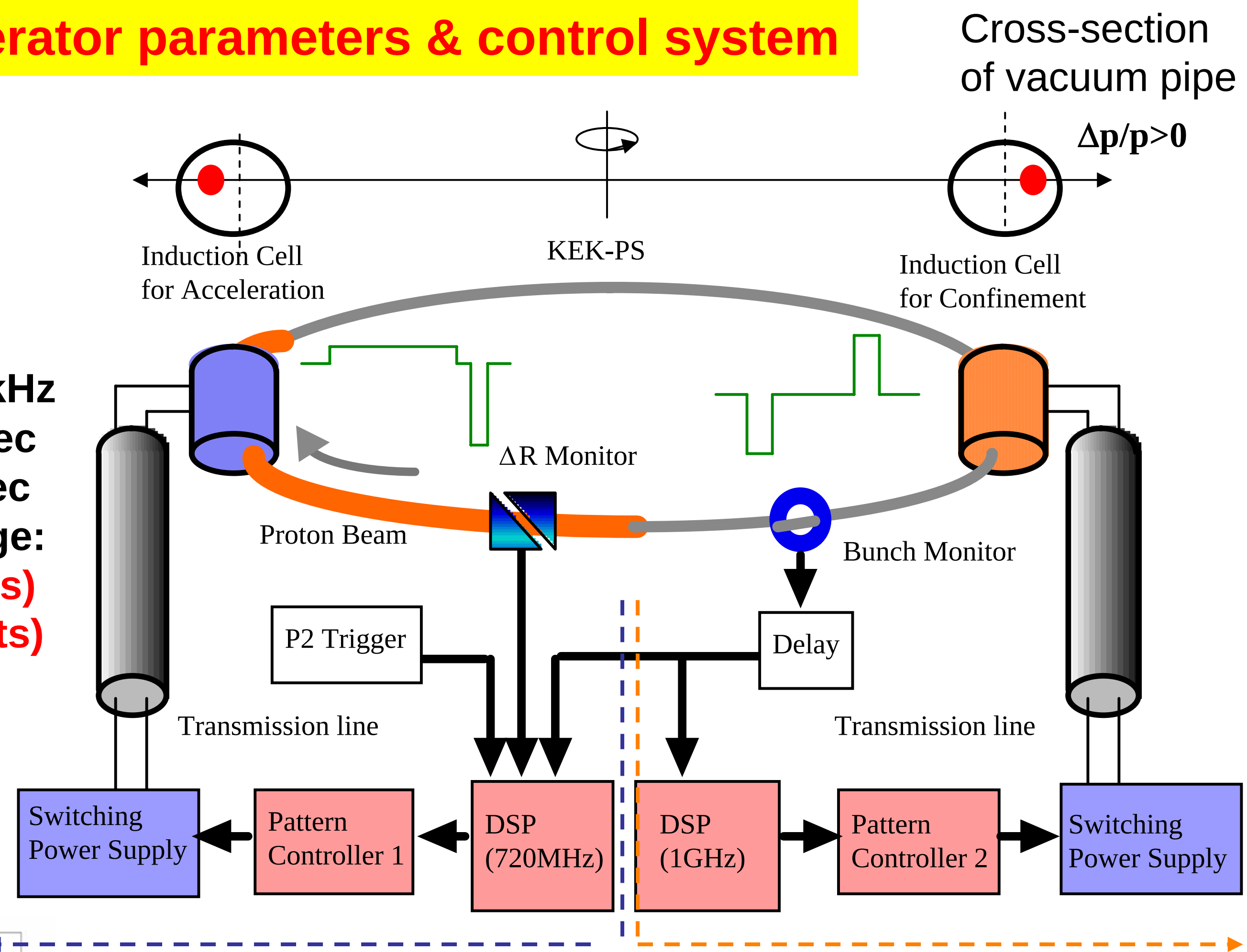


trapped protons

K.Torikai et al., KEK Preprint 2005-80 (2005), submitted to *Phys. Rev. ST-AB*

Step 3-1 Induction Synchrotron

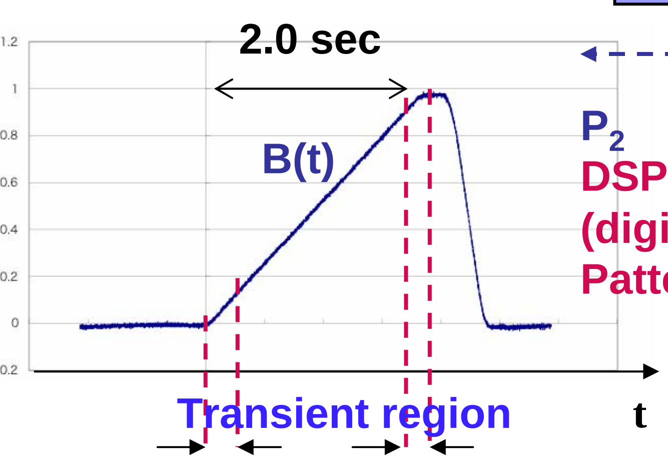
Accelerator parameters & control system



C_0	339 m
Inj/Ext Energy	0.5/6 GeV
Revolu fre.	667- 876 kHz
Accel. time period	2.0 sec
dB/dt	0.377 T/sec

Induction acceleration voltage:

acceleration	6.4 kV (4 sets)
confinemet	10.8 kV (6 sets)



P_2 : timing of acceleration start

DSP (digital signal processor) : logical processing of the input signals (delay in master signal, on/off decision)

Pattern Controller : generation of the gate trigger pattern

T.Iwashita *et al.*, TUPAN044 in this PAC

Step 3-2 Induction Synchrotron

P2 (just start of accel.)

P2+400 msec

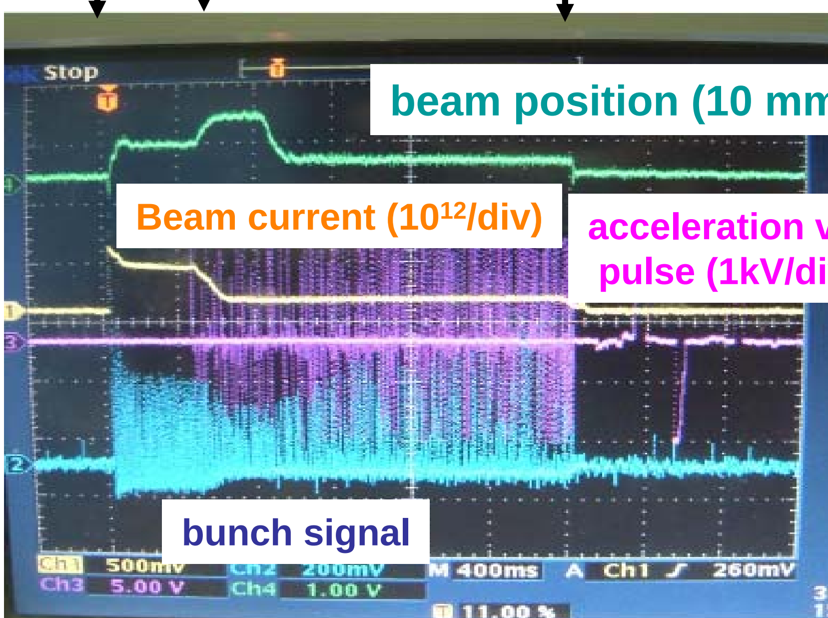
near end of accel. (6GeV)

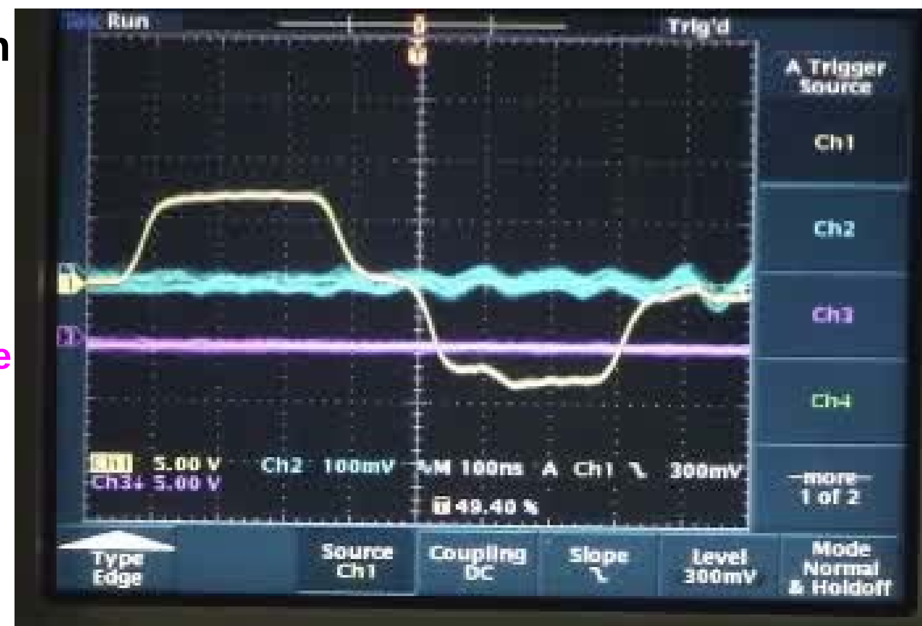
Movie show of the full demonstration

Injection (500MeV)

Start of acceleration

End of acceleration (6GeV)

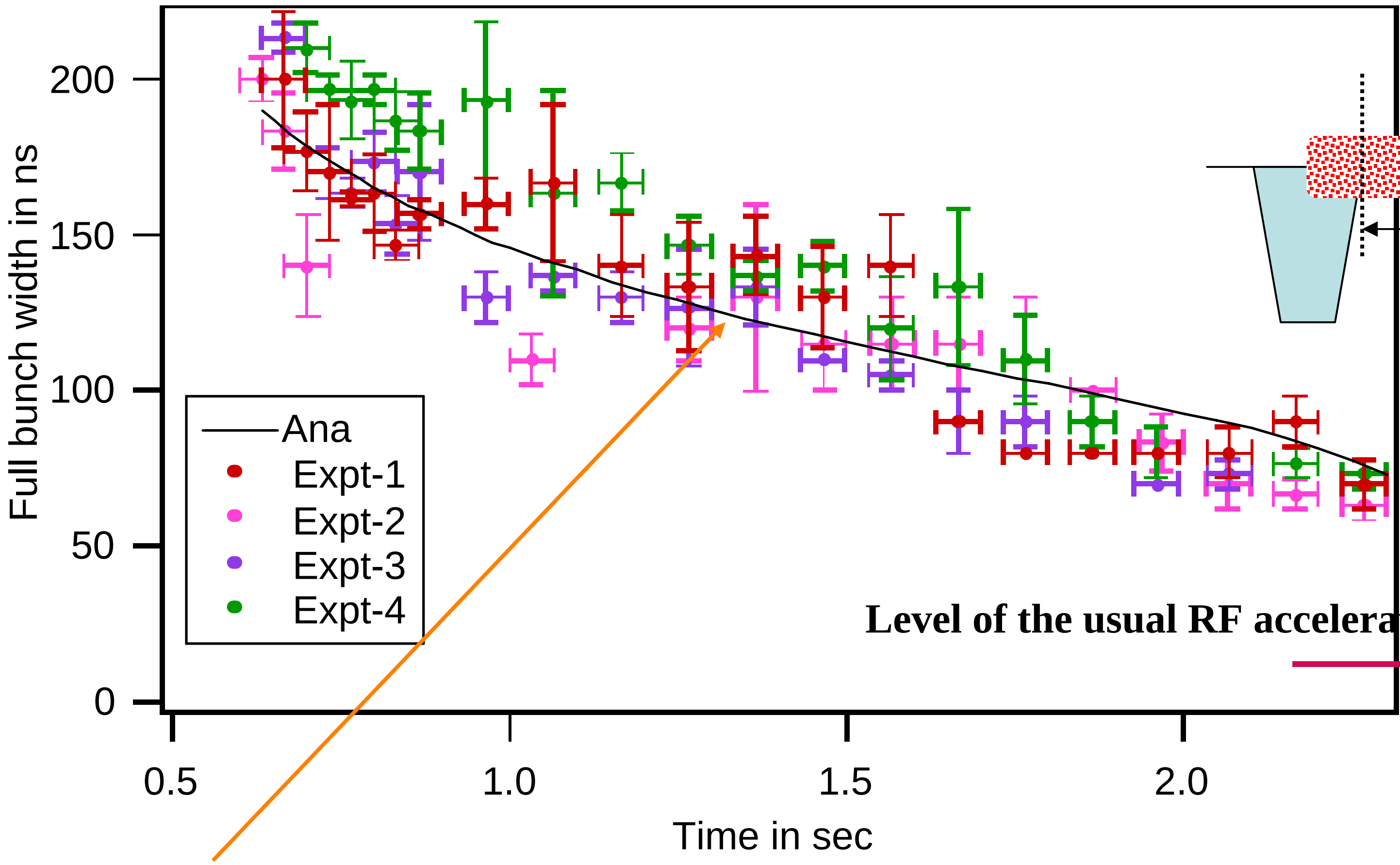


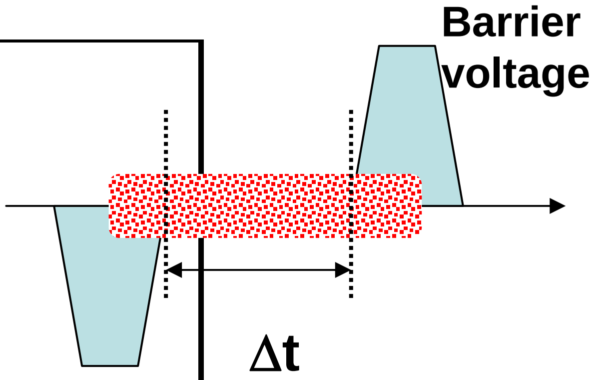


K.Takayama et al., "Experimental Demonstration of the *Induction Synchrotron*", *Phys. Rev. Lett.* 98, 054801 (2007)

Step 3-3 Induction Synchrotron

Temporal Evolution of the Bunch Length: Adiabatic dumping in the Induction Synchrotron





Theory: A WKB-like solution of the amplitude-dependent oscillation system (synchrotron oscillation in the barrier bucket)

T. Dixit et al., "Adiabatic Dumping of the Bunch-length in the Induction Synchrotron", published in N.I.M. (2007). **Poster FRPMN033 in this conference**

Technical Issues and further R&D Works

Noise Problems (TUPAN050)

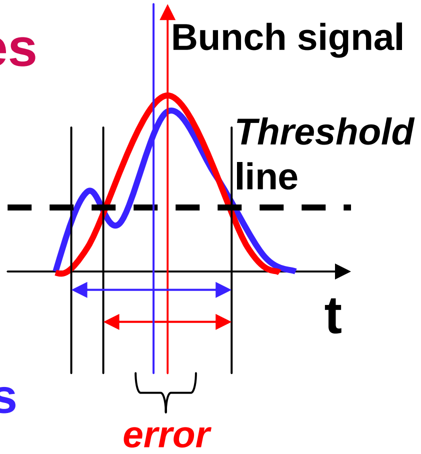
Essentially pulse devices with reflection

-> potential noise sources

-> pulse leak currents through the earth or EM waves propagate in air

-> shielding or protection by optimized cabling

Importance of Trigger Control and Beam Physics Issues



How to get the macroscopic center of bunch correctly

-> incorrect gate timing

- -> acceleration or deceleration by the barrier voltage
- Over-focusing and defocusing due to the droop voltage
- Chaotic diffusion caused by the discrete barrier voltages
- beam loss due to adiabatic motion of barrier voltage-pulses

Next Generation of Switching Power Supply (MOPAN042)

Requirement of high intensity beam acceleration

-> beam loading effects

-> low impedance acceleration cell at 1 MHz

-> high driving current keeping the same accelerating voltage

-> large switching arm current

-> novel solid-state switching elements, such as SIThy or SiC

from the Induction Synchrotron to All-ion Accelerators

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.

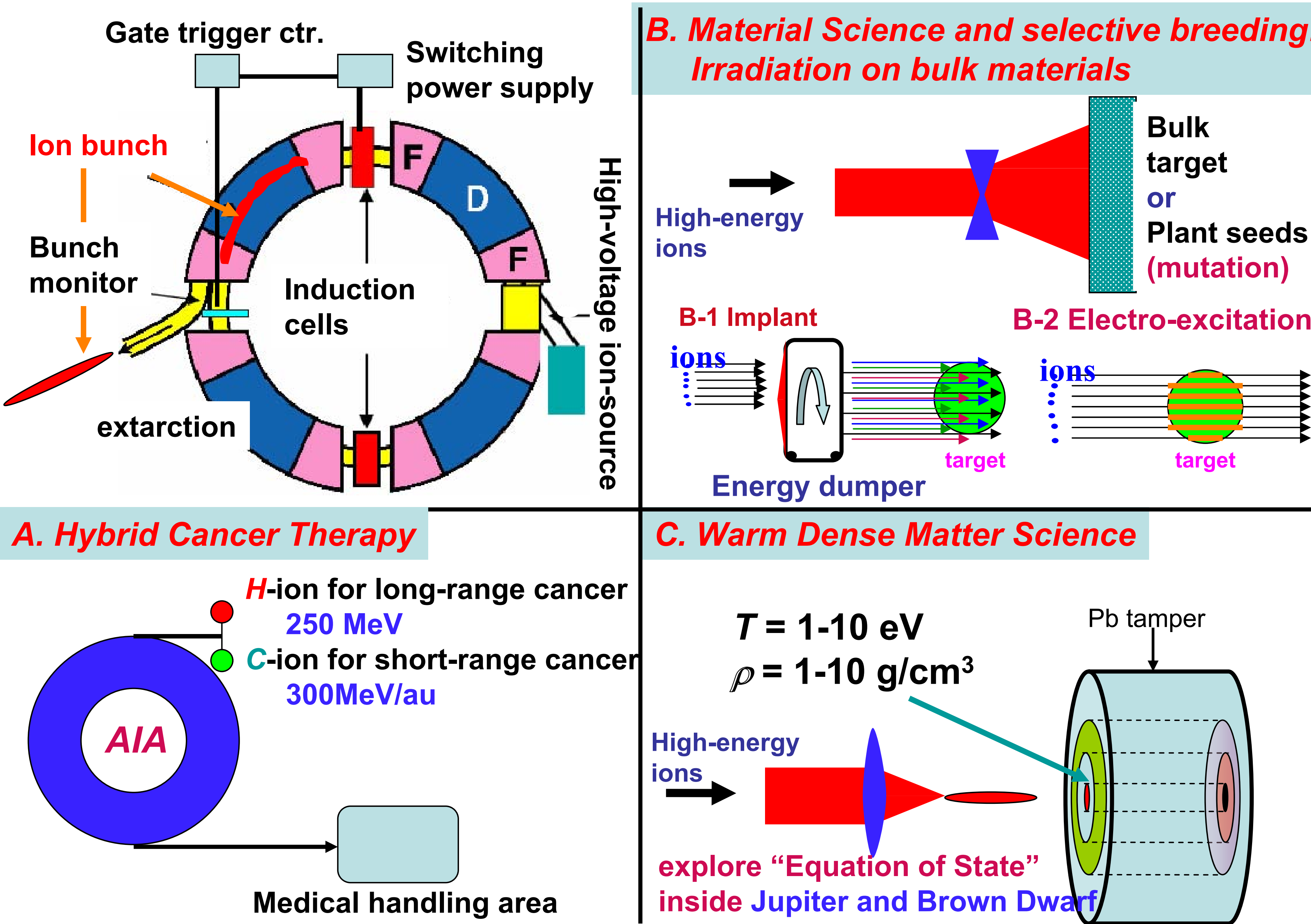
↓

All-ion accelerators

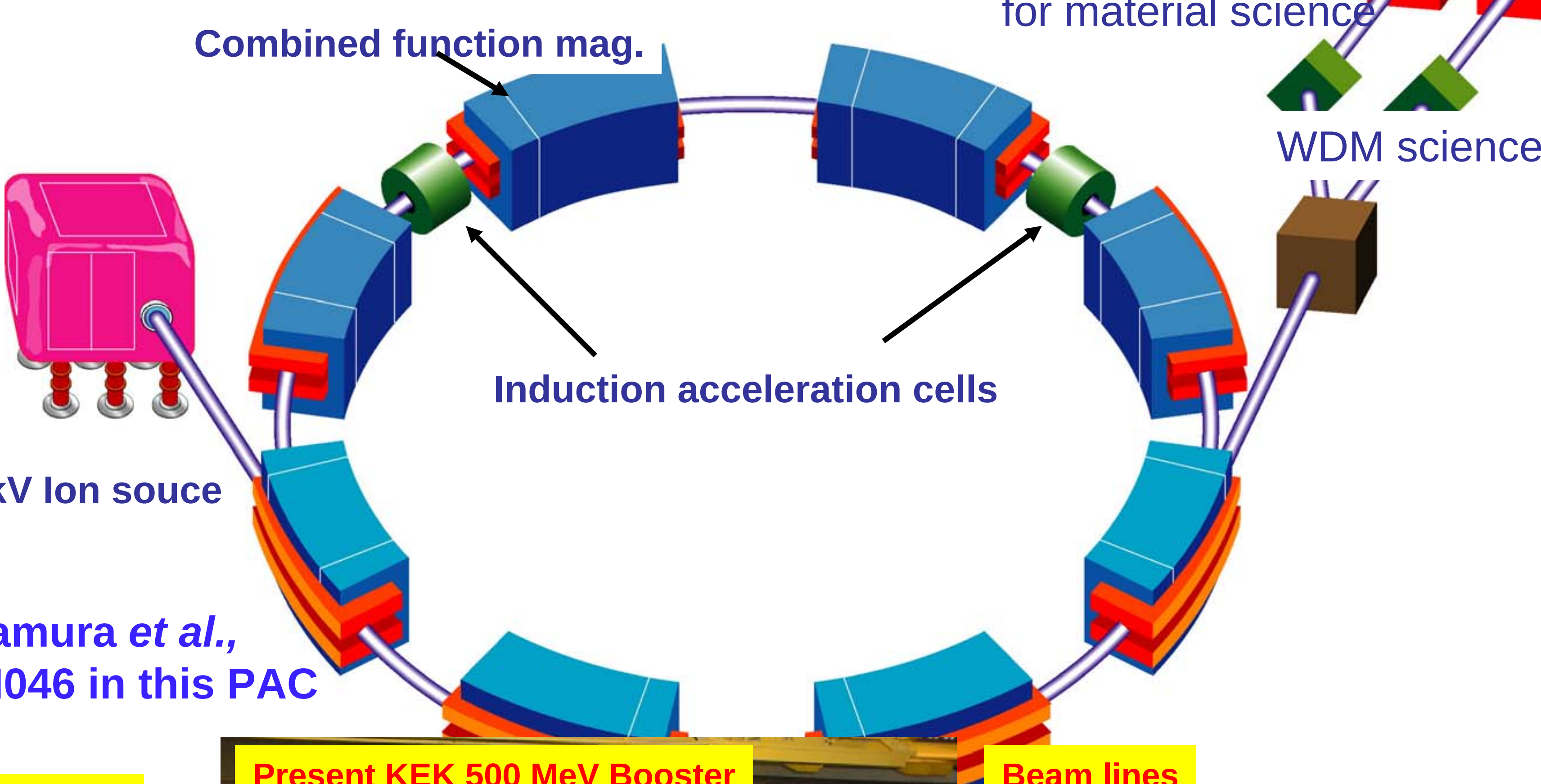
almost <u>injector-free</u>
for a low intensity beam

K.Takayama, K.Torikai, Y.Shimosaki, and Y.Arakida, "All Ion Accelerators", (Patent 3896420, PCT/JP2006/308502), and *J. of Appl. Phys.* 101, 063304 (2007)

All-ion Accelerator (Injector-free synchrotron) & its Applications



Outline of the KEK All-ion Accelerator

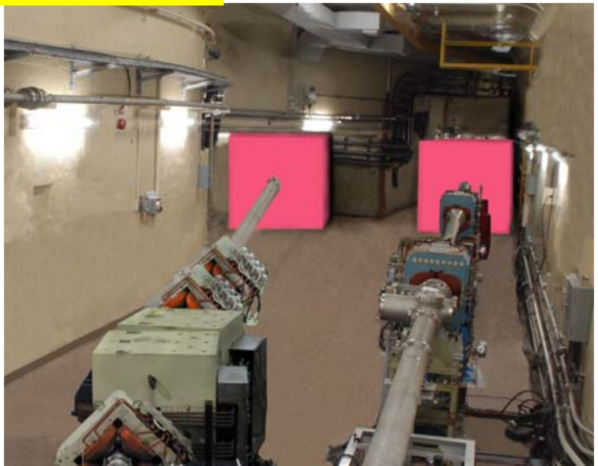


E. Nakamura *et al.*,
TUPAN046 in this PAC

High vol. terminal

Present KEK 500 MeV Booster

Beam lines



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 100 hours without fatal troubles.
- The digital gate control system with a function of beam feed-back has been developed.
- A 400 nsec-long proton bunch captured in the barrier bucket was accelerated up to 6 GeV with the induction acceleration voltage.

This is a full demonstration of the Induction Synchrotron Concept.

- Novel beam handling (Qusi-adiabatic non-focusing TC method) in the hybrid synchrotron (functionally separated synchrotron) has been demonstrated.

One of possible and unique applications of IS in a low/medium energy region may be

an *All-ion Accelerator (AIA): the injector-free induction synchrotron*.

- A modification plan of the KEK Booster Ring to the AIA was briefly introduced. Hopefully, available heavy ion beams will be provided for WDM Science, bulk material science, and cancer therapy.

Idea of Quasi-adiabatic Non-focusing Transition Crossing

$$\begin{cases} \Delta E_{m+1} = \Delta E_m + eV_{rf}(\Delta t_m) \\ \Delta t_{m+1} = \Delta t_m + \eta_{m+1} T \dfrac{\Delta E_{m+1}}{\beta^2 (E_s)_{m+1}} \end{cases}$$

Polynomial reduction

$$V_{rf}(t) = a|t|^n \sin[\omega_{rf} t]$$

Shimosaki's idea:

Linear change in RF amplitude n=1

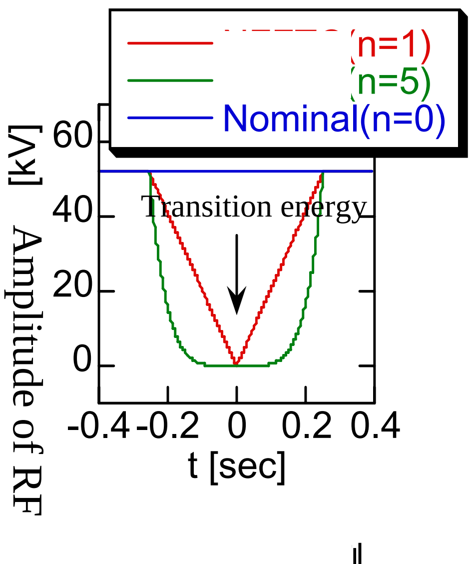
$$\begin{cases} J_{1/2}\left(\dfrac{b}{2}\cdot t^2\right) = \dfrac{2}{t\sqrt{\pi b}} \sin\left(\dfrac{b}{2}\cdot t^2\right), \\ N_{1/2}\left(\dfrac{b}{2}\cdot t^2\right) = -J_{-1/2}\left(\dfrac{b}{2}\cdot t^2\right) = -\dfrac{2}{t\sqrt{\pi b}} \cos\left(\dfrac{b}{2}\cdot t^2\right) \end{cases}$$

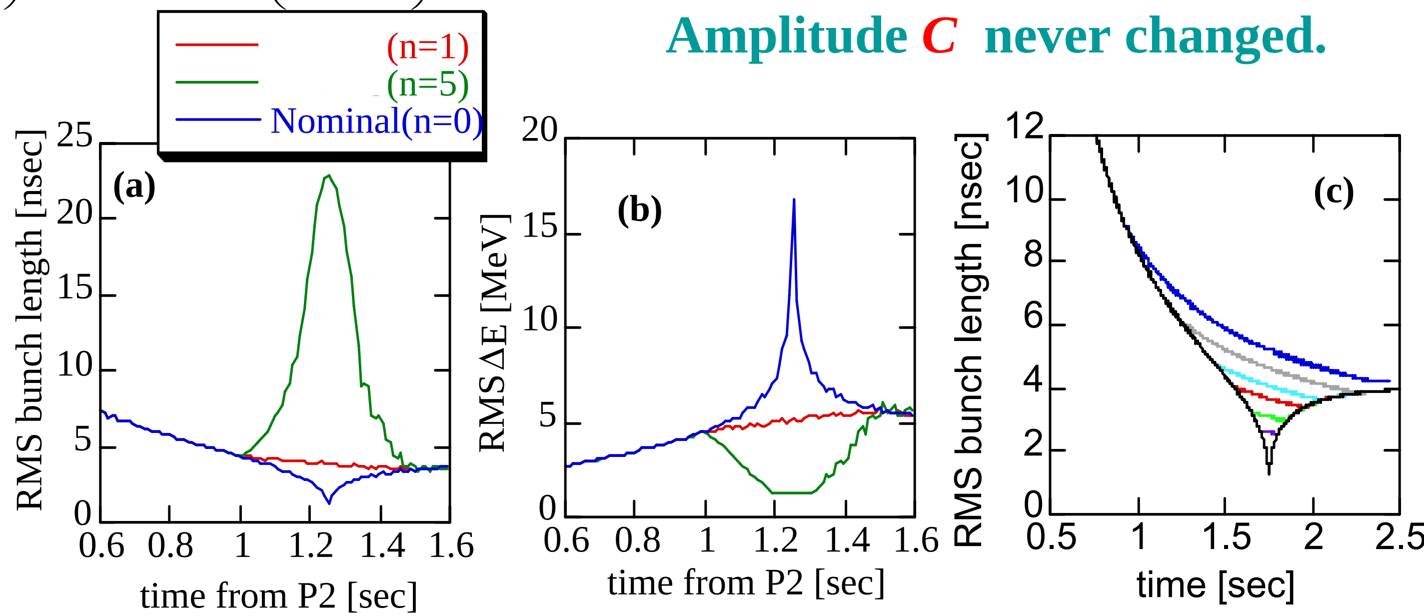
Exact solution for small amplitude oscillation near TC

$$\Delta t(t) = A \cdot t \cdot J_{\frac{2}{n+3}}\left(\frac{2bt^{\frac{n+3}{2}}}{n+3}\right) + B \cdot t \cdot N_{\frac{2}{n+3}}\left(\frac{2bt^{\frac{n+3}{2}}}{n+3}\right)$$

$$\Delta t(t) = C \cdot \sin\left(\frac{b}{2}\cdot t^2 + \delta\right)$$

Amplitude *C* never changed.

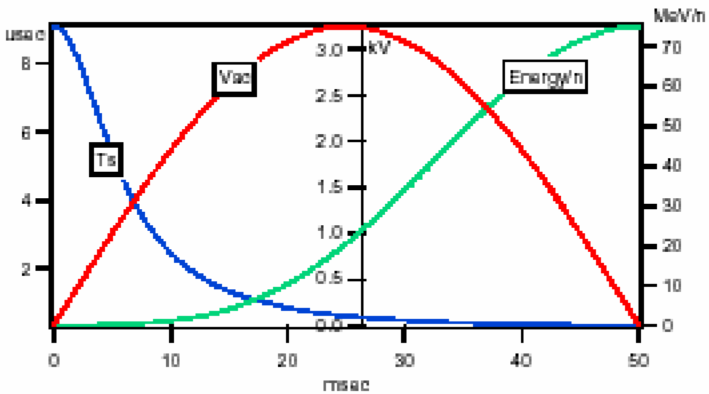


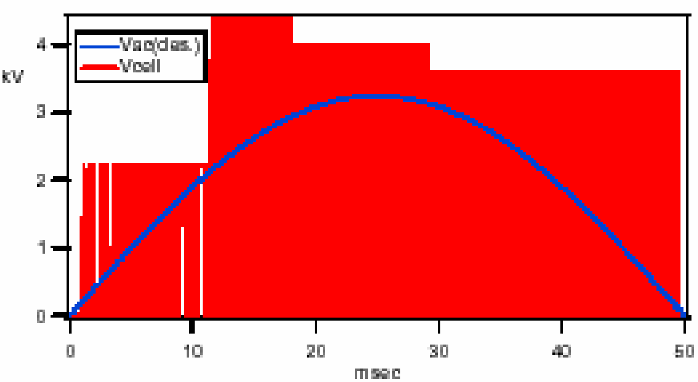


(a) Δt and (b) ΔE size depend on n. (c) Bunch length control by QNTC(n=1). (sim)

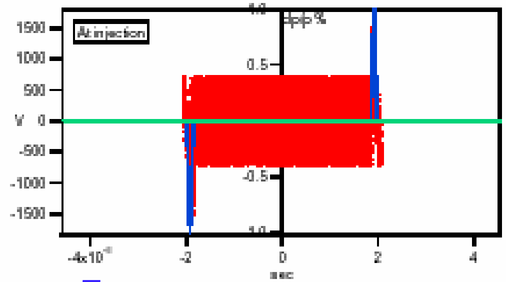
Example of Ar^{+18} Acceleration Simulation

10 Hz operation

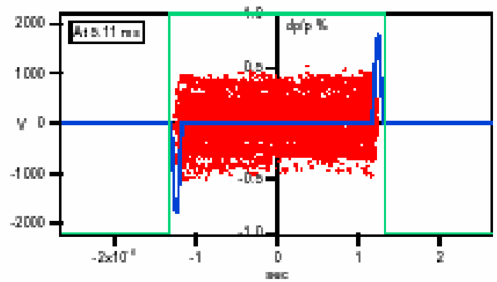




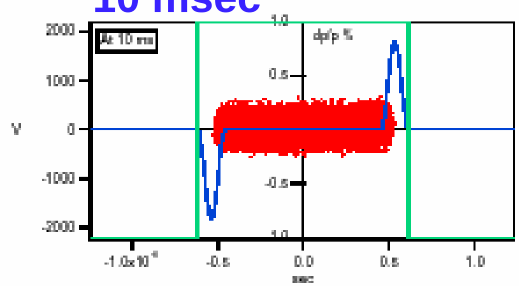
near Injection



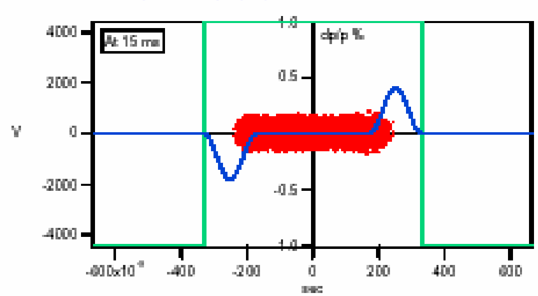
5 msec



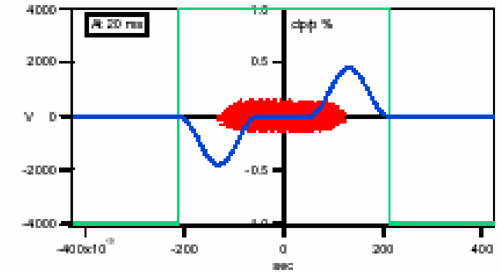
10 msec



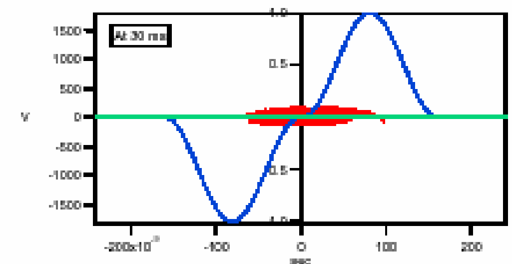
15 msec



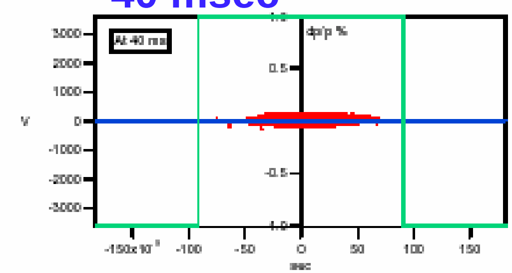
20 msec



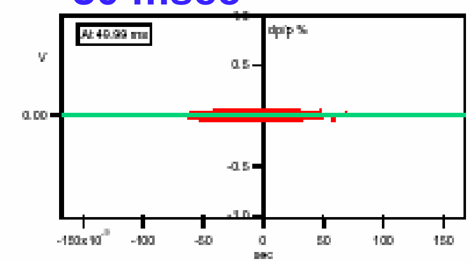
30 msec



40 msec



50 msec



D. Iwashita, T.Dixit *et al.*,
Poster TUPAN044

Low energy injection and space-charge limited current

Low energy injection -> low Space-charge limit -> restrict high intensity operation

***V*: extraction voltage from the ion source**
***v*: injection velocity into the all-ion accelerator**

$$\frac{1}{2} A \cdot m v^2 = e \cdot Z \cdot V$$

$$v = \sqrt{\left(\frac{Z}{A}\right) \cdot \frac{2e}{m} \cdot V}$$

$$\beta \propto \sqrt{\left(\frac{Z}{A}\right) \cdot V}$$

Laslett tune-shift: ΔQ

$$0.25 \geq \Delta Q \propto \frac{Z^2 \cdot N}{A \cdot B_f \cdot \beta \cdot \gamma^2} \propto \frac{Z^2 \cdot N}{A} \sqrt{\frac{A}{Z \cdot V}} = N \cdot \sqrt{\frac{Z^3}{A \cdot V}}$$

Space-charge limit particle number:

$$\frac{N_i}{N_p} = \left(\frac{A}{Z^2}\right)\left(\frac{\beta_i \cdot \gamma_i^2}{\beta_p \cdot \gamma_p^2}\right)\frac{(B_f)_{AIA}}{(B_f)_{RF}} \cong \sqrt{\frac{A}{Z^3}} \cdot \sqrt{\frac{V_i}{V_p}} \cdot \frac{(B_f)_{AIA}}{(B_f)_{RF}}$$

Scaled from the data for Proton

our experience:

in the 500MeV Booster

N_{limit} =3x10^{12} /bunch, V_p= 40 MV

B_f =0.3, *f*=20Hz

Other assumptions in AIA:

same transverse emittance

V_i=200 kV

B_f =0.7, *f*=10Hz

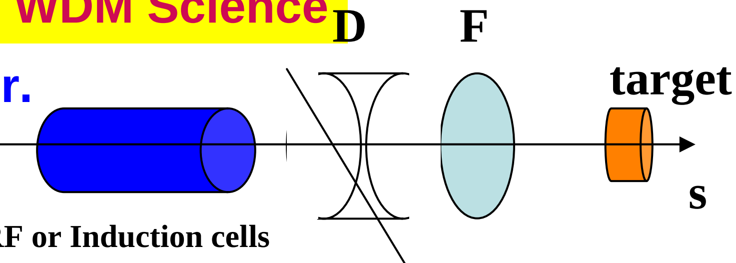
We will try at first. ↓

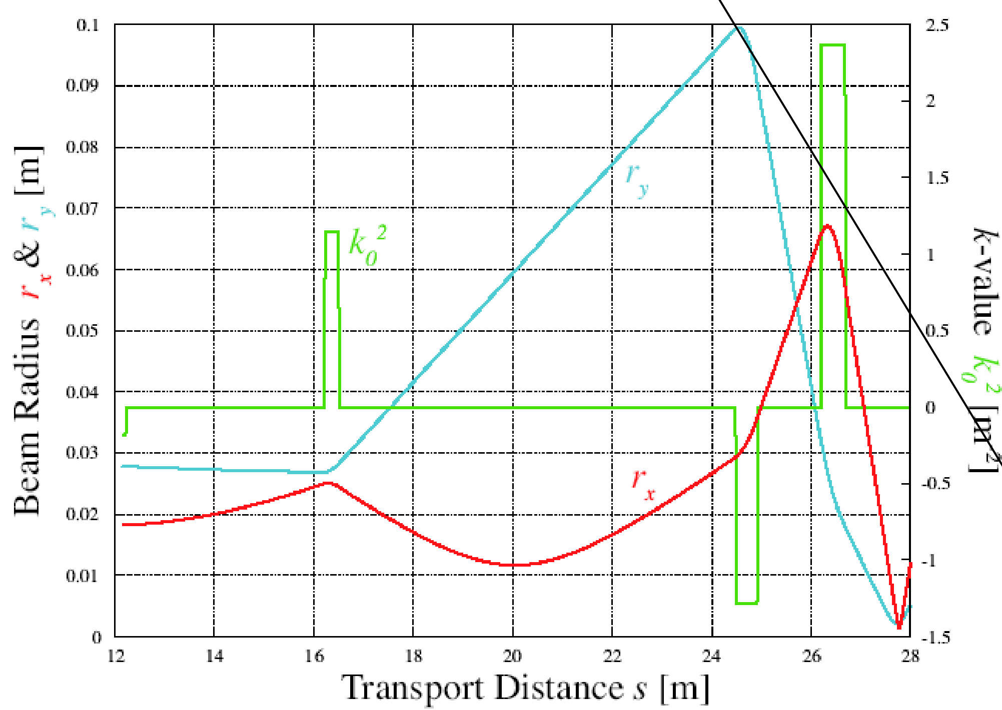
	$^{12}C^{+6}$	$^{40}Ar^{+18}$	$^{197}Au^{+79}$
A/Z	12/6	40/18	197/79
$N_{limit}(=N_i)$	1.3x10^{11}	4.7x10^{10}	1.1x10^{10}
N/sec	1.3x10^{12}	4.7x10^{11}	1.1x10^{11}
extract. E (MeV/au)		75	
depo.energy (J/cc)		2.3x10^{3}	

Beam-line for the WDM Science

a. Transverse dir. (half-mini beta)

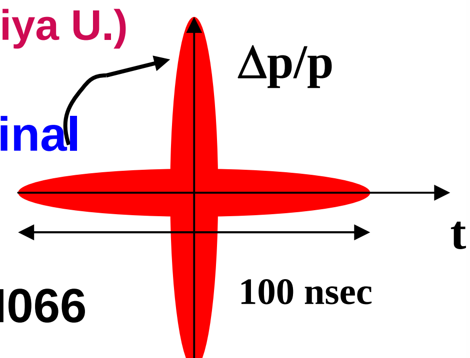
K-value=k_0^2





Calculation by Kikuchi (Utsunomiya U.)

b. Compression in the longitudinal direction (Phase-rotation)



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Beam line for Bulk Materials