Experimental Results of the Induction Synchrotron and beyond That

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

9th US -Japan Workshop
on
Heavy Ion Fusion and High Energy Density Physics
at LBNL
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Contents

■ Brief history of the *Induction Synchrotron* R&D at KEK

■ Outline of the *Induction Synchrotron* (IS)

■ Experimental results using the KEK 12GeV PS

■ A modification plan of the KEK 500MeV Booster to an All-ion Accelerator (Injector-free IS) as a driver of medium energy heavy ions

■ Summary

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

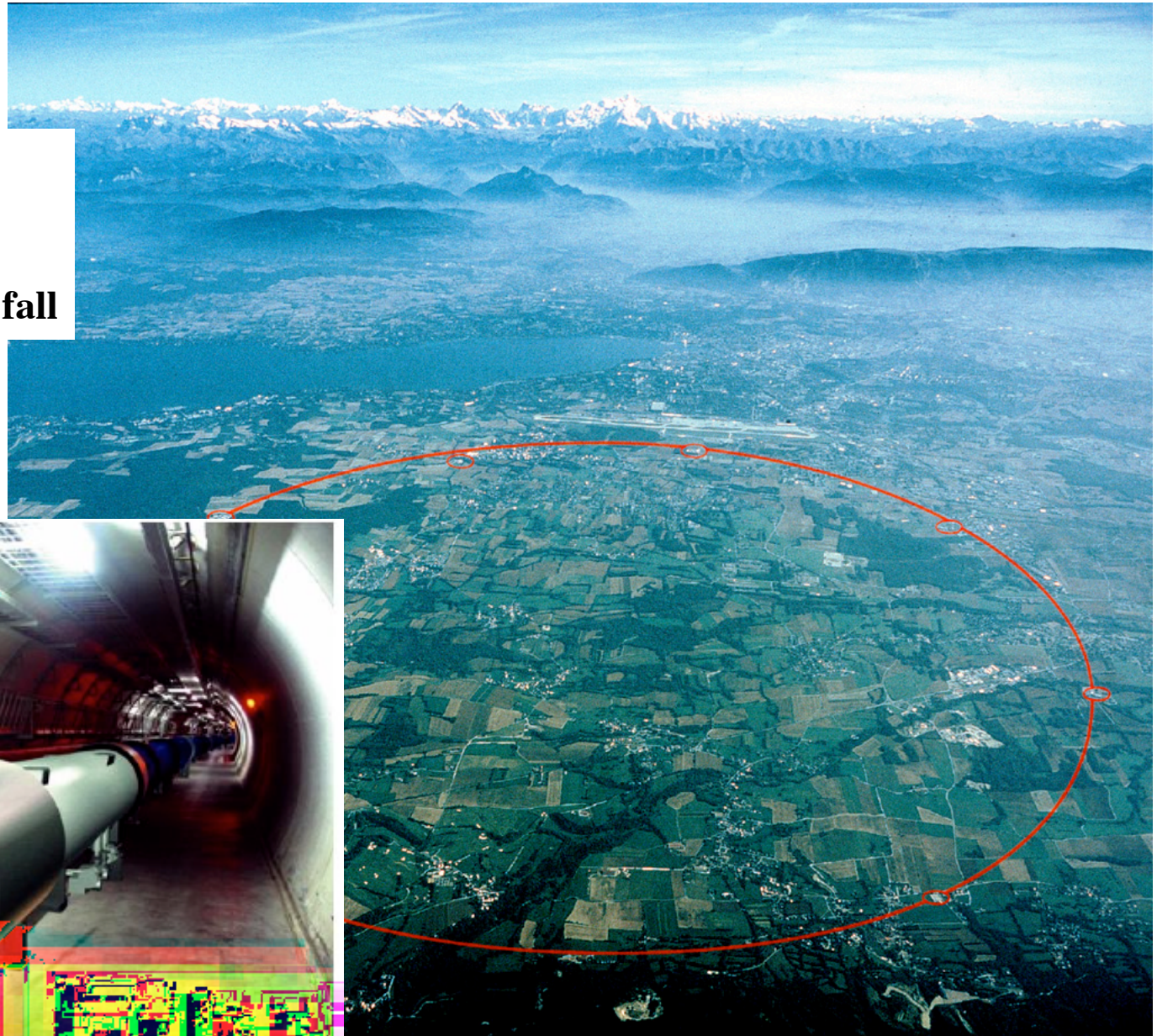# E.M.McMillan & the first Synchrotron@LBL (1945)
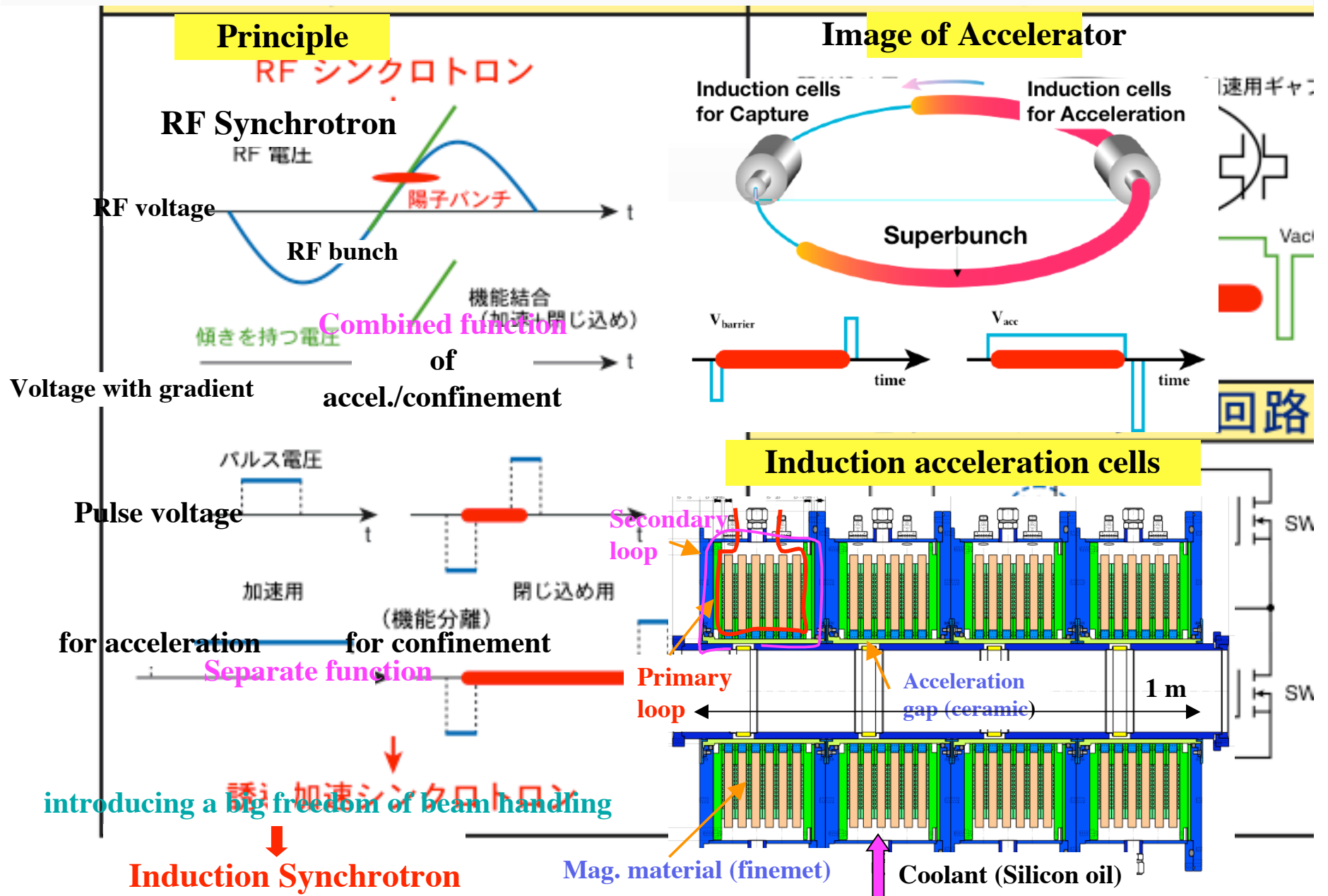
E=340MeV
Week focusing
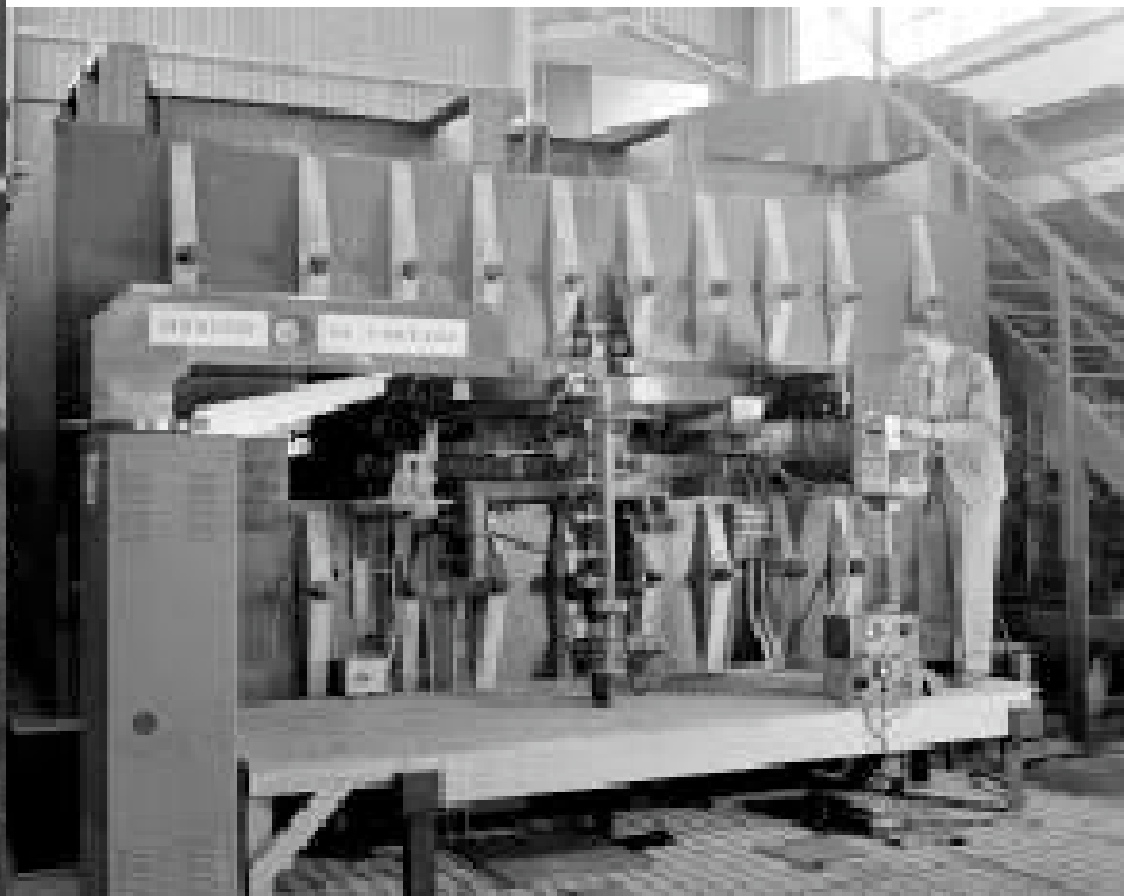
by courtesy of LBNL

CERN

Large Hadron Collider
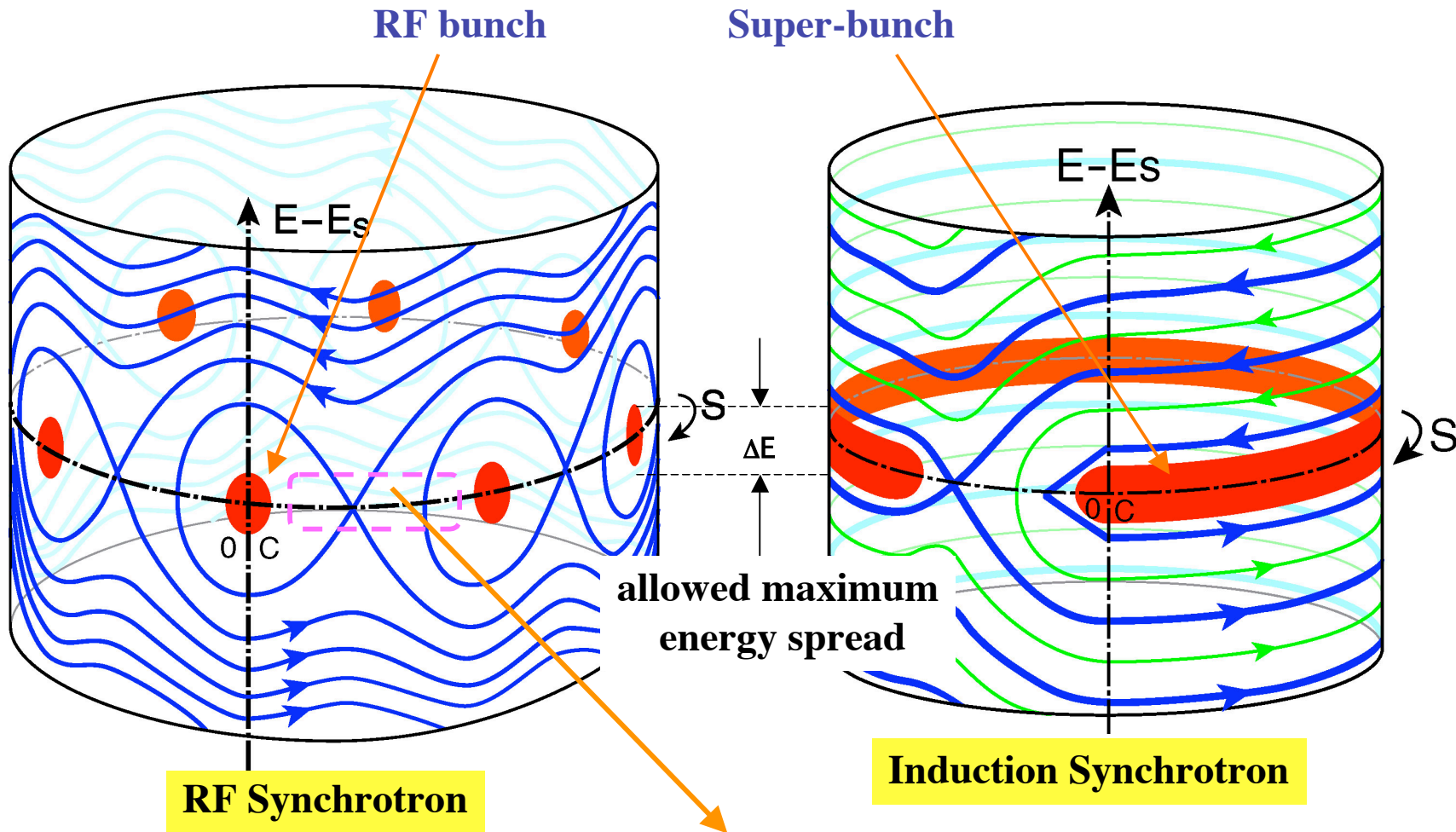E=7 TeV
Circumference= 27km
Beam comission in 2007 fall

by courtesy of CERN

Concept of Induction Synchrotron 概忌

Principle

RF シンクロトロン

RF Synchrotron

RF 電圧

RF voltage

陽子バンチ

RF bunch

Combined function of accel./confinement

機能結合
（加速・閉じ込め）

傾きを持つ電圧

Voltage with gradient

パルス電圧

Pulse voltage

加速用   閉じ込め用

（機能分離）

for acceleration   for confinement

Separate function

introducing a big freedom of beam handling

誘導加速シンクロトロン

Induction Synchrotron

Image of Accelerator

Induction cells for Capture

Induction cells for Acceleration

加速用ギャ

Superbunch

$V_{barrier}$

time

V_{acc}

time

Vac

回路

Induction acceleration cells

Secondary loop

Primary loop

Acceleration gap (ceramic)

1 m

SW

SW

Mag. material (finemet)   **Coolant (Silicon oil)**

Difference between RF and Induction Synchrotron seen in Phase-space

RF bunch

Super-bunch

$E-E_s$

$E-E_s$

S

ΔE

0 C

0 C

S

allowed maximum energy spread
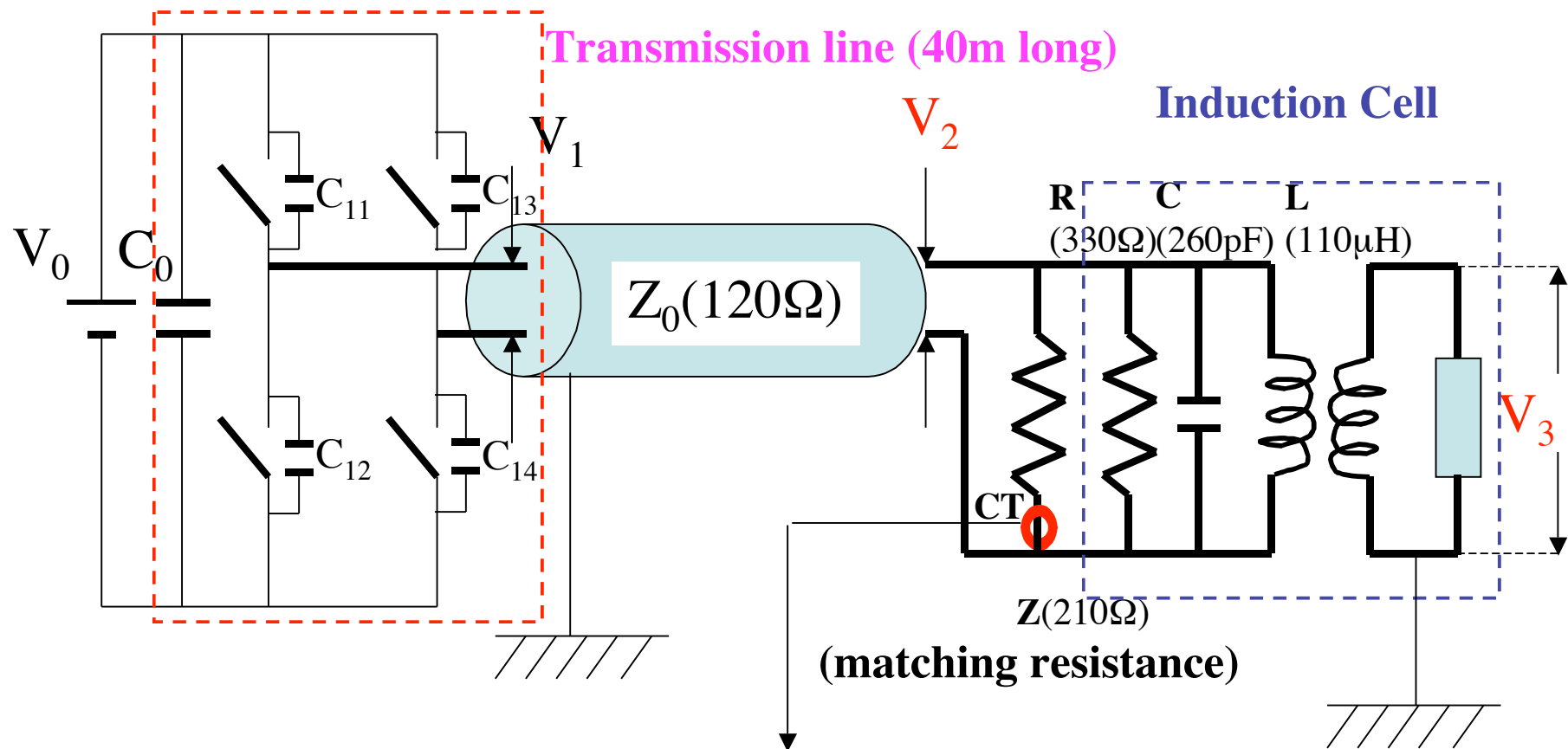
RF Synchrotron

Induction Synchrotron

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

This space is not available for acceleration.

Equivalent Circuit for 2.5kV Induction Accelerating System
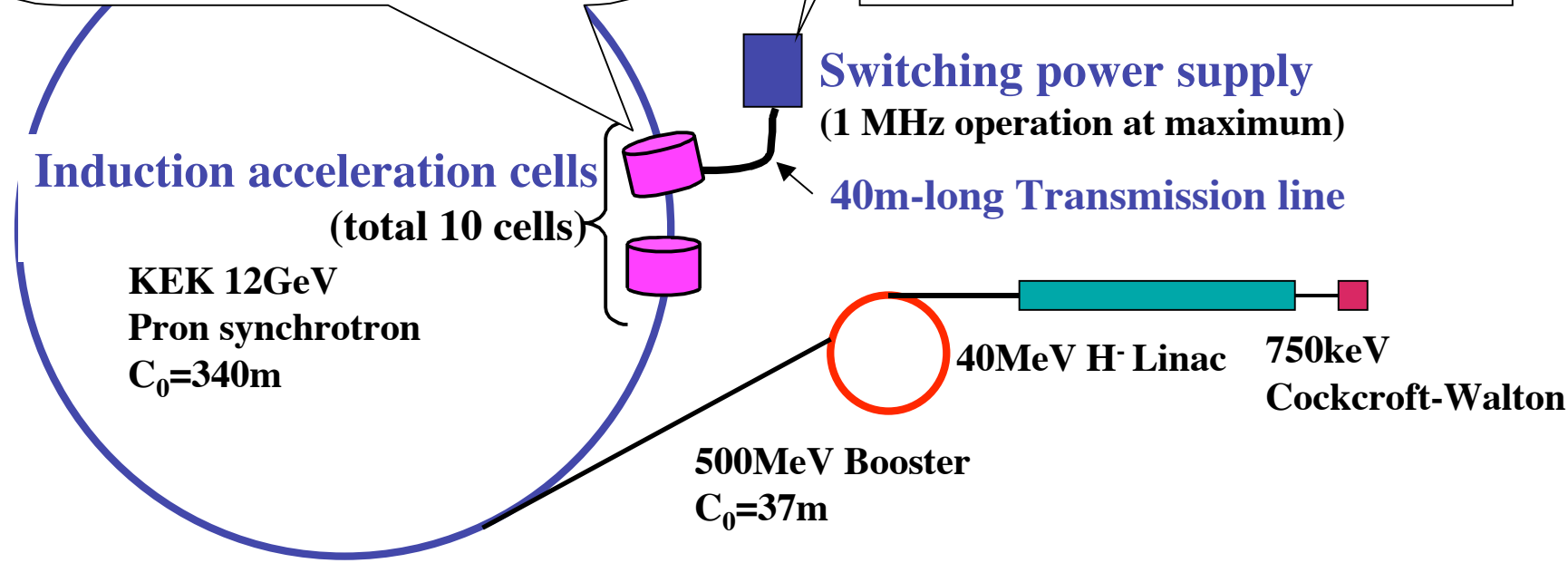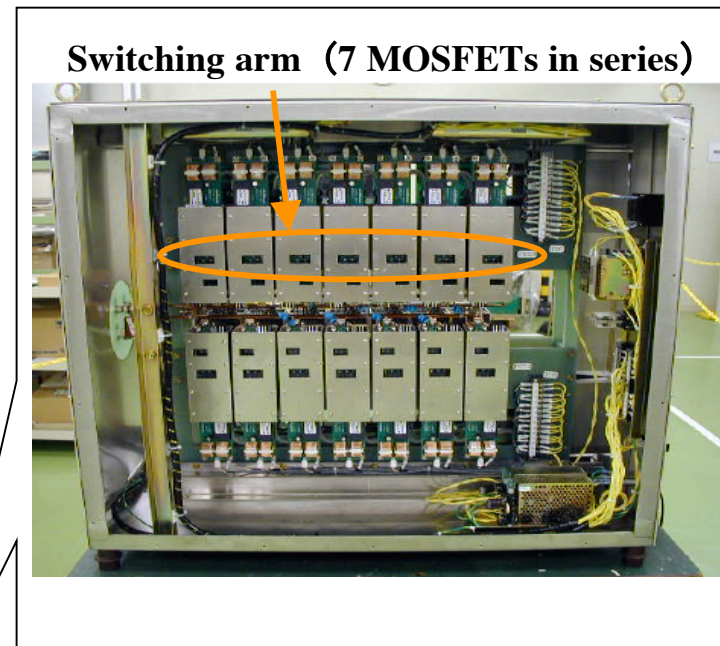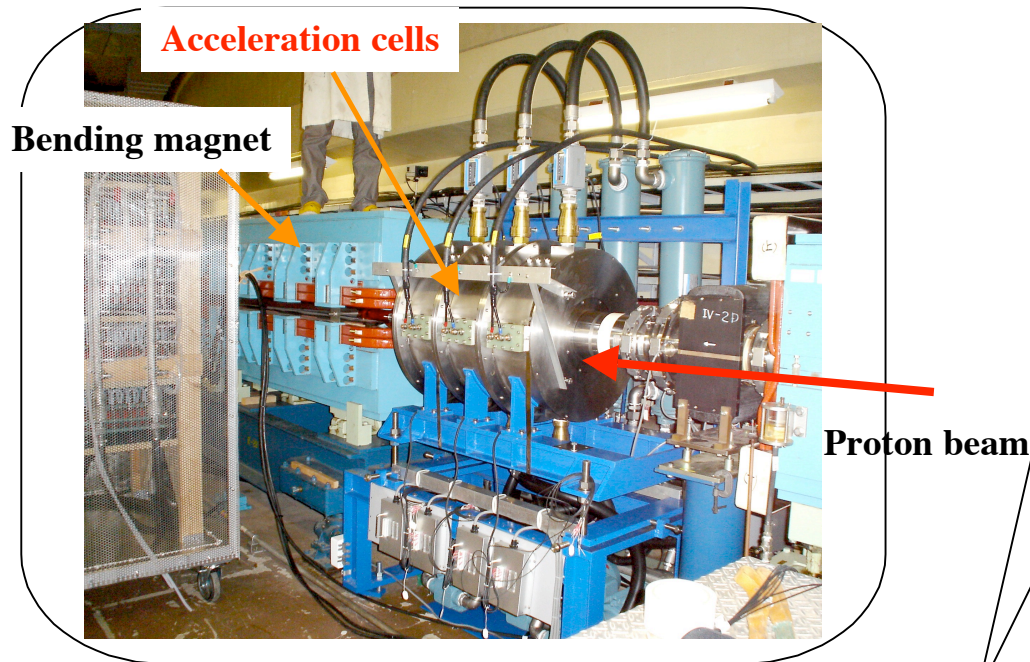
DC P.S. **Switching P.S.**

Transmission line (40m long)

Induction Cell

V_1

V_2

V_0 C_0

C_{11} C_{13}

C_{12} C_{14}

$Z_0(120\Omega)$

R **C** **L**
(330Ω)(260pF) (110μH)

V_3

CT

Z(210Ω)

(matching resistance)

I_Z (always monitored)

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

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

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

Acceleration cells

Bending magnet

Switching arm （7 MOSFETs in series）

Proton beam

Switching power supply
(1 MHz operation at maximum)

Induction acceleration cells
(total 10 cells)

40m-long Transmission line

KEK 12GeV
Pron synchrotron
C_0=340m

40MeV H⁻ Linac

750keV
Cockcroft-Walton

500MeV Booster
C_0=37m

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 6×10^{11}ppb
2004/10-2005/3
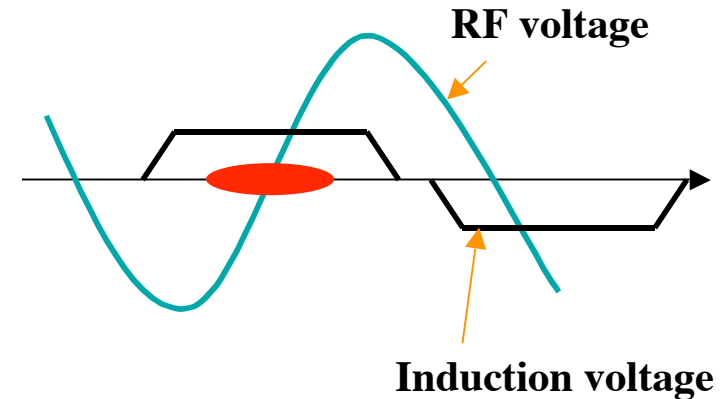
2nd Step:
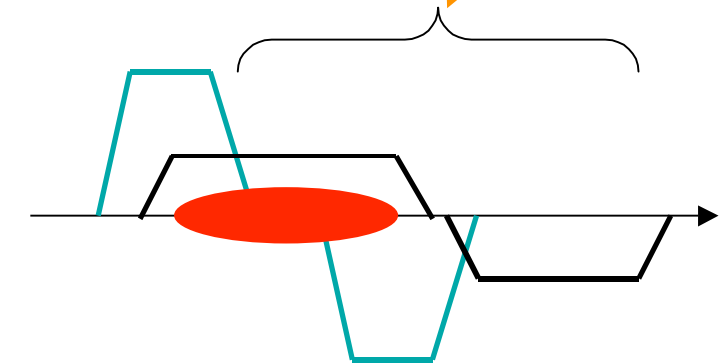   Barrier trapping by induction step-voltages
at 500 MeV
through 2005
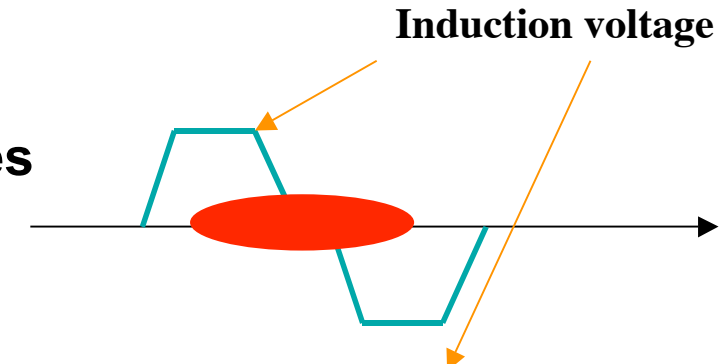
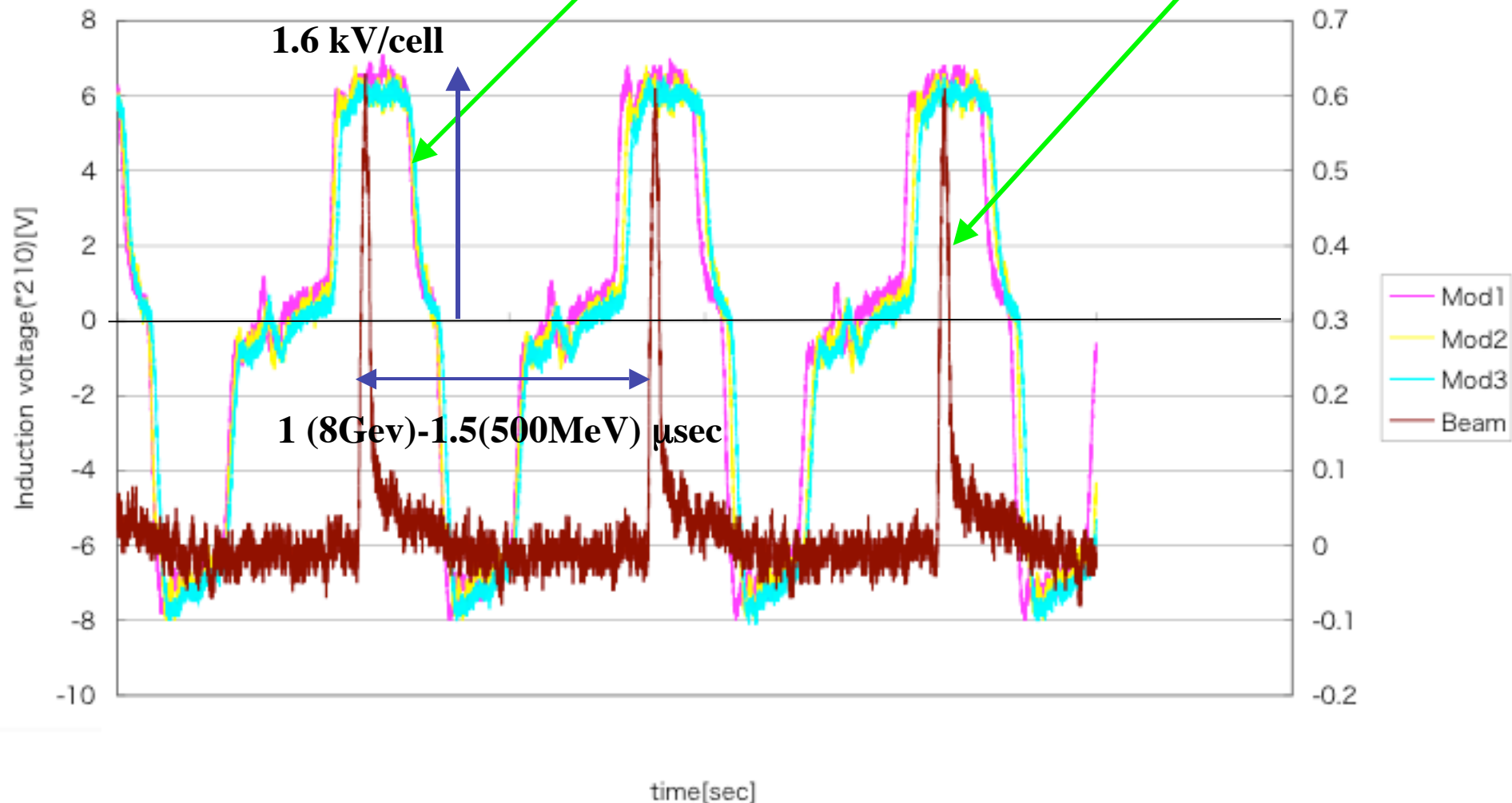**3rd Step:**
   Barrier trapping + induction accel.
(Induction Synchrotron)
500 MeV -> 6 GeV for $2\text{-}3 \times 10^{11}$ppb
2006/1-3
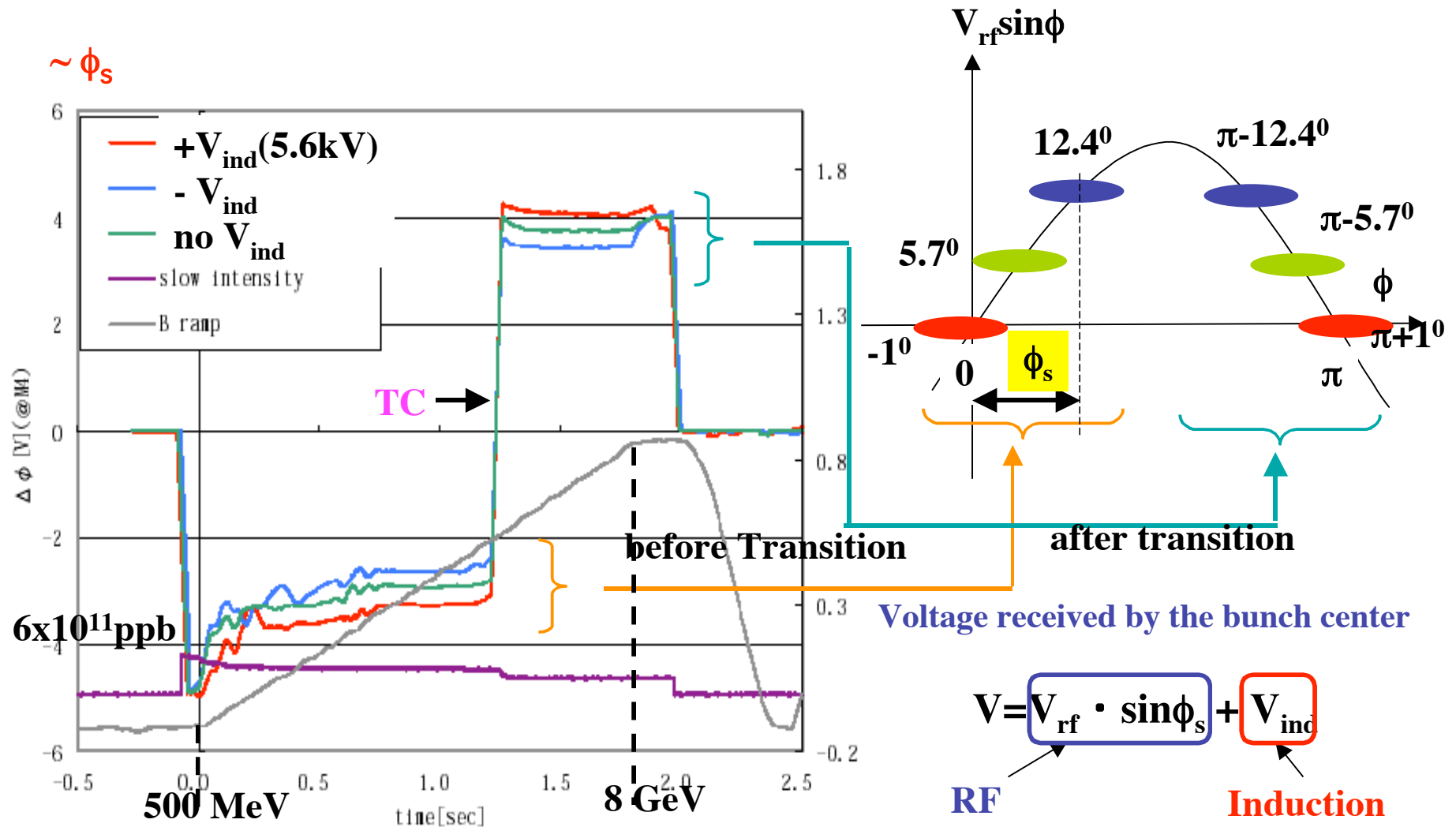
RF voltage

Induction voltage

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:
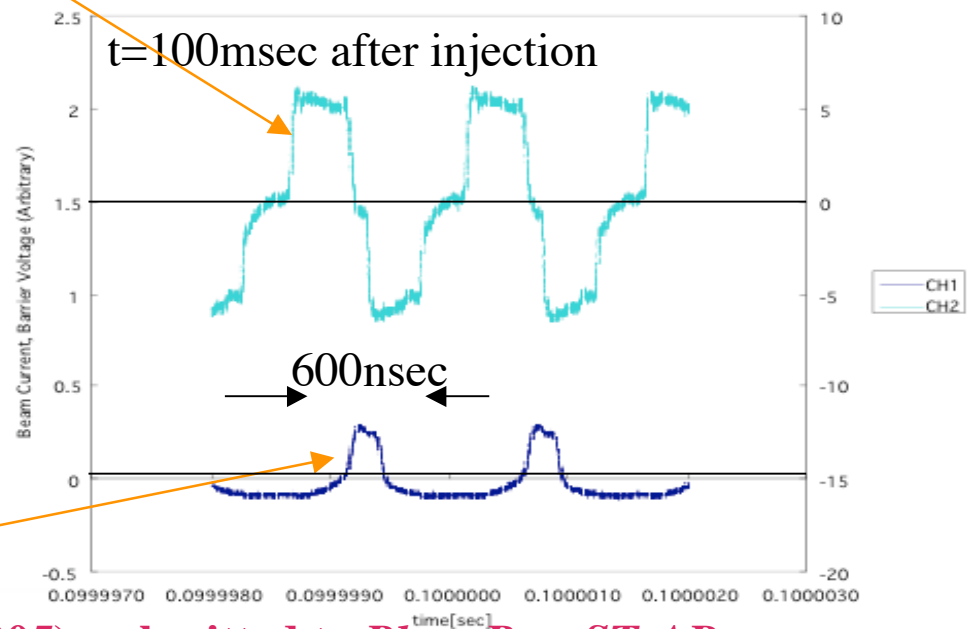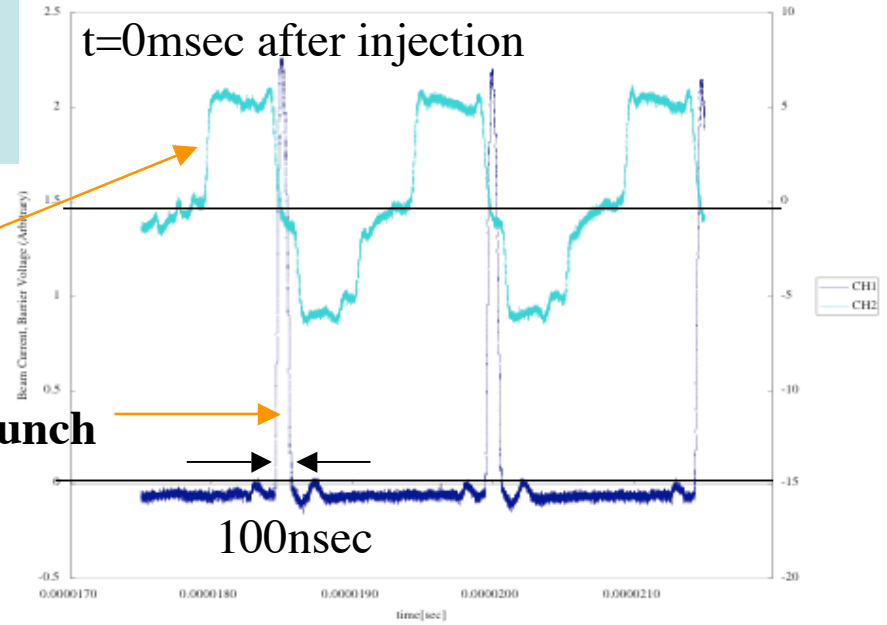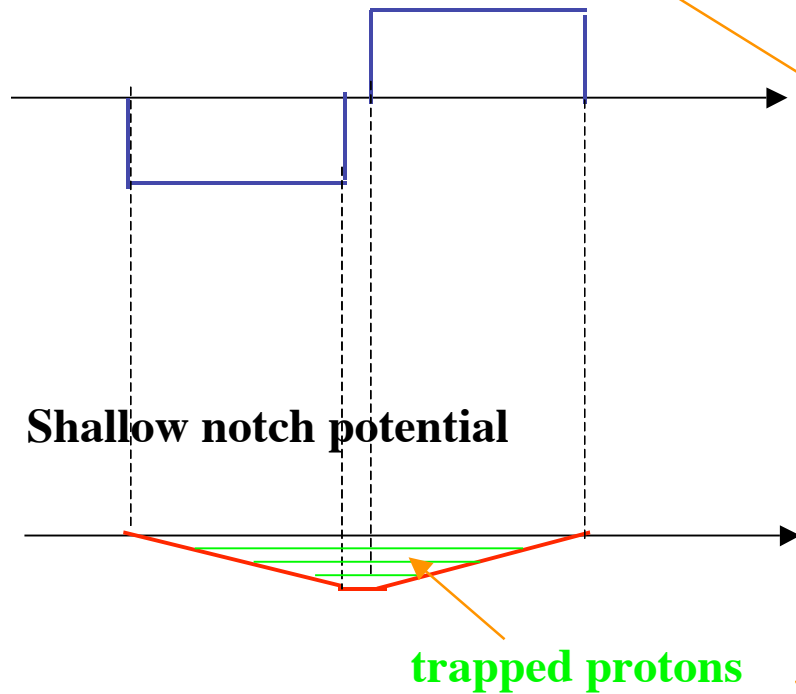## Position of the bunch centroid in the RF phase

$\sim \phi_s$

+V_{ind}(5.6kV)
- V_{ind}
no V_{ind}
slow intensity
B ramp

TC

$\Delta \phi$ [V] (@M4)

6×10^{11}ppb

500 MeV

8 GeV

before Transition

after transition

$V_{rf}\sin\phi$

12.4^0 $\pi-12.4^0$

$\pi-5.7^0$

5.7^0

-1^0 0 ϕ_s π $\pi+1^0$

ϕ

Voltage received by the bunch center

$$V = \boxed{V_{rf} \cdot \sin\phi_s} + \boxed{V_{ind}}$$

RF   Induction

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

Step 1
Hybrid Synchrotron

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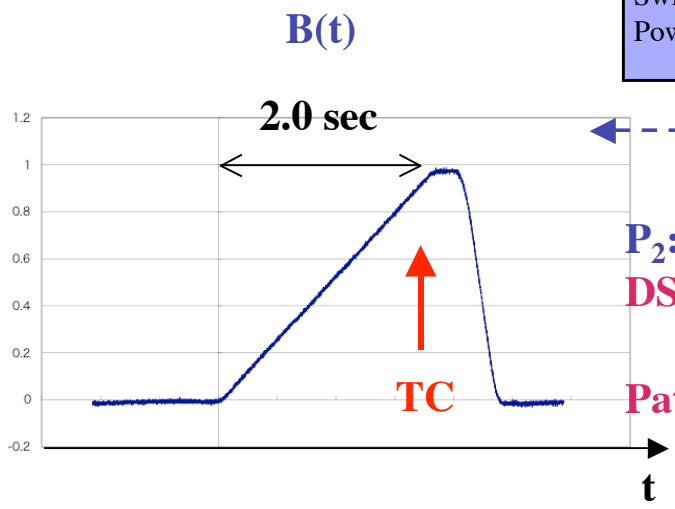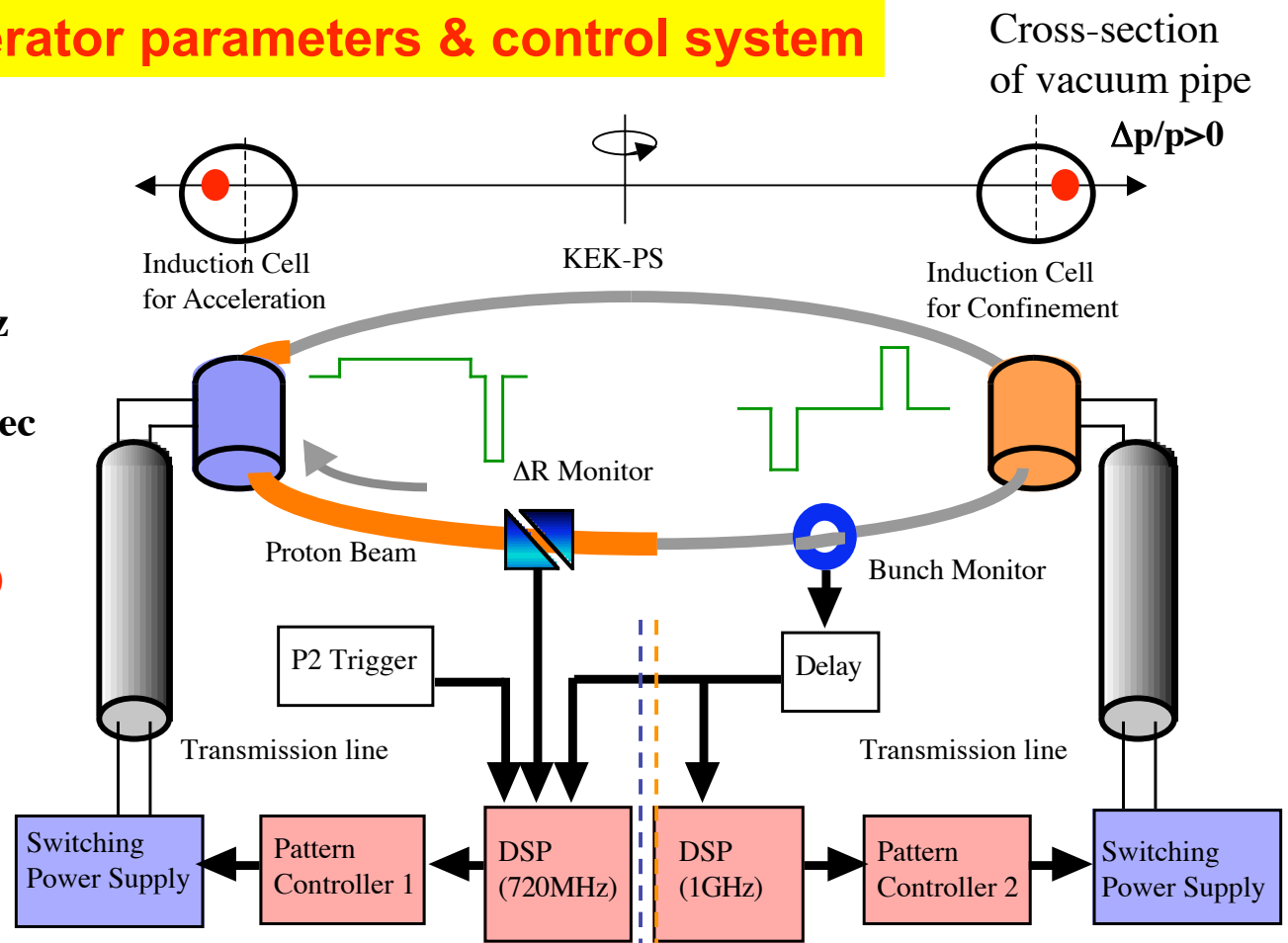**Formation of a 600nsec-long bunch**

t=0msec after injection

6kV barrier-voltage

injected proton bunch

100nsec

Shallow notch potential

t=100msec after injection

600nsec

trapped protons

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

Accelerator parameters & control system

Cross-section of vacuum pipe

Δp/p>0

C₀ ..... 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 Tesla/sec**
Induction acceleration voltage:
   acceleration ..... **6.4 kV (4 sets)**
   confinemet ..... **10.8 kV (6 sets)**

Induction Cell for Acceleration

KEK-PS

Induction Cell for Confinement

ΔR Monitor

Proton Beam

Bunch Monitor

P2 Trigger

Delay

Transmission line

Transmission line

| Switching Power Supply | Pattern Controller 1 | DSP (720MHz) | DSP (1GHz) | Pattern Controller 2 | Switching Power Supply |

B(t)
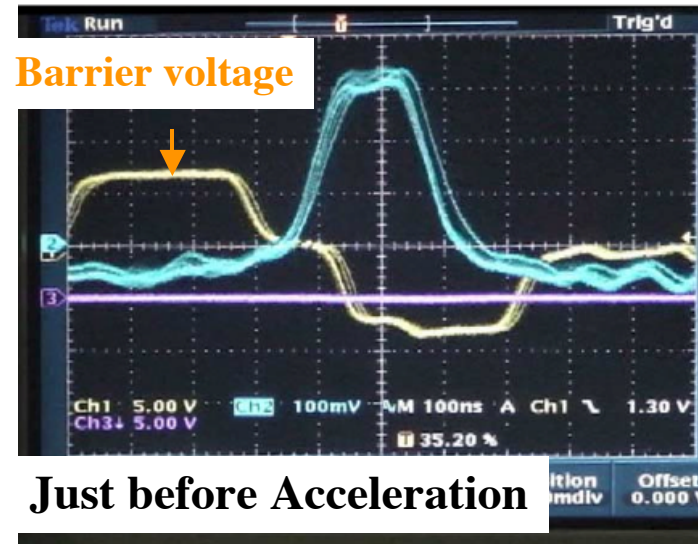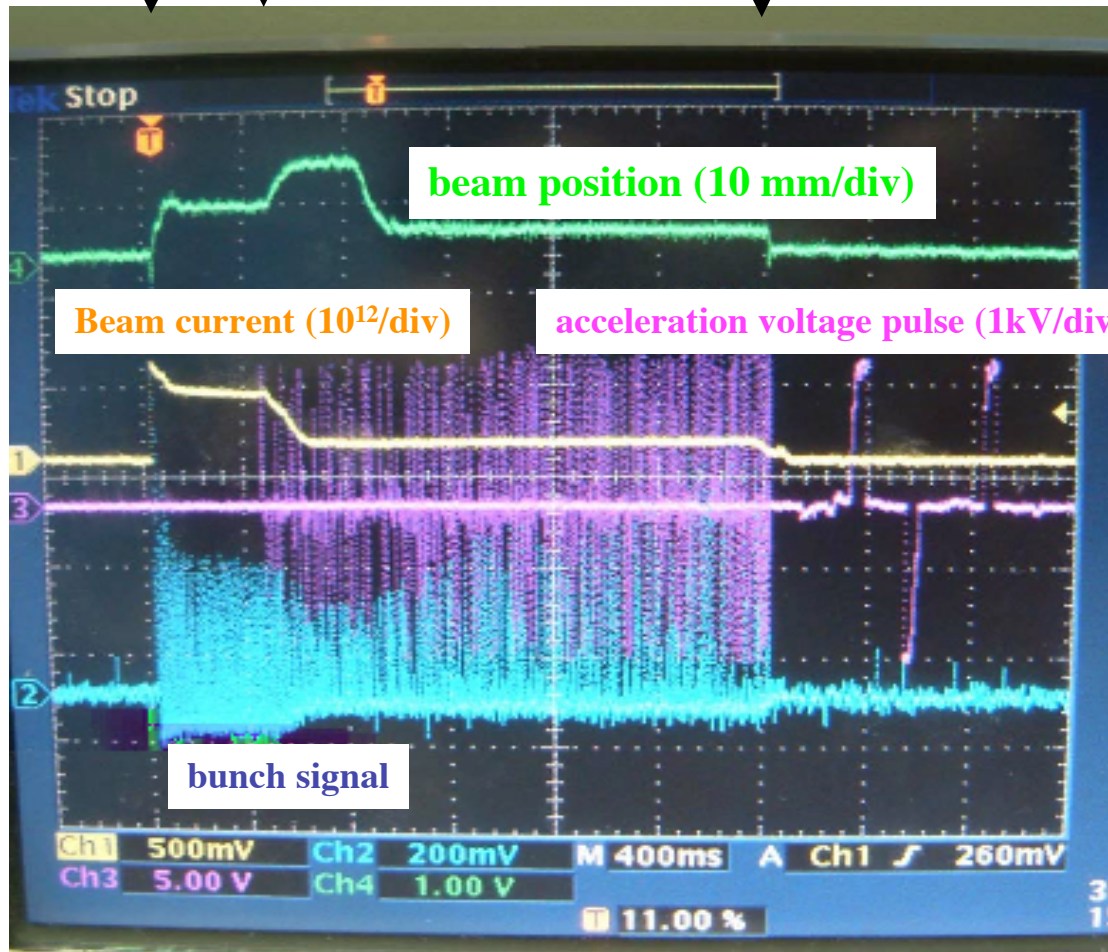
2.0 sec

TC

P₂: **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**

Step 3
Induction

Step 3
Induction Synchrotron

Injection(500MeV)

Start of acceleration

End of acceleration (6GeV)

beam position (10 mm/div)

Beam current (10^{12}/div)

acceleration voltage pulse (1kV/div)

bunch signal

Ch1 500mV Ch2 200mV M 400ms A Ch1 ∫ 260mV
Ch3 5.00 V Ch4 1.00 V
T 11.00 %

Barrier voltage

Just before Acceleration

Proton bunch

Acceleraton vol.
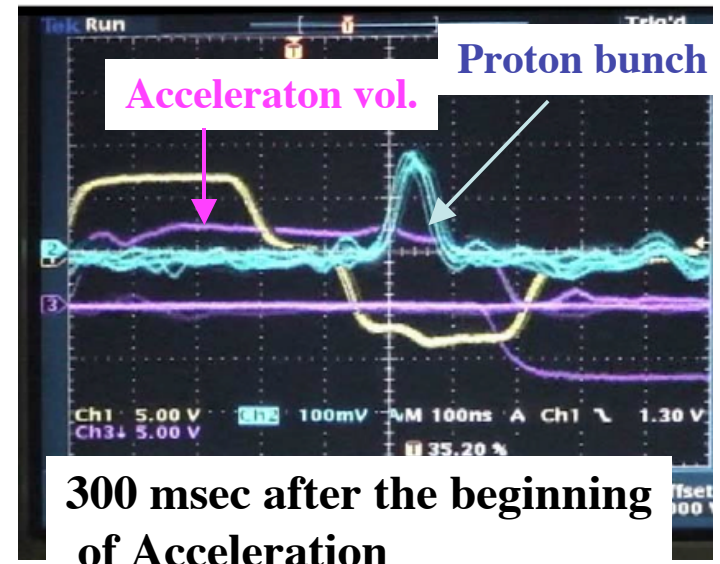
300 msec after the beginning
 of Acceleration

Movie show of the full demonstration

Bunch signal
(**sky blue**)

Barrier voltage
(**yellow**)
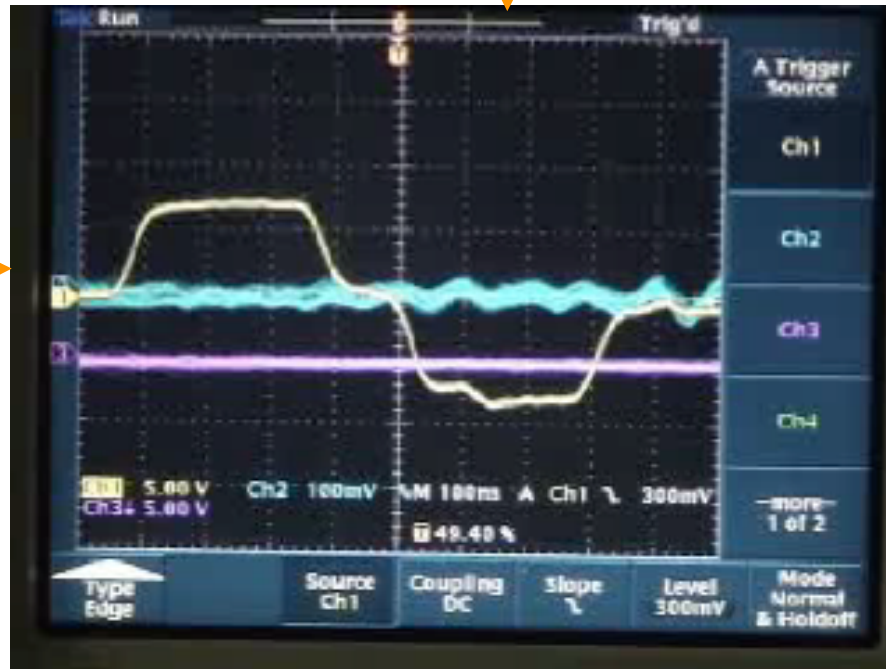
Induction accel. vol.
(**purple**)

Temporal Evolution of the Bunch Length: Adiabatic dumping in the Induction Synchrotron
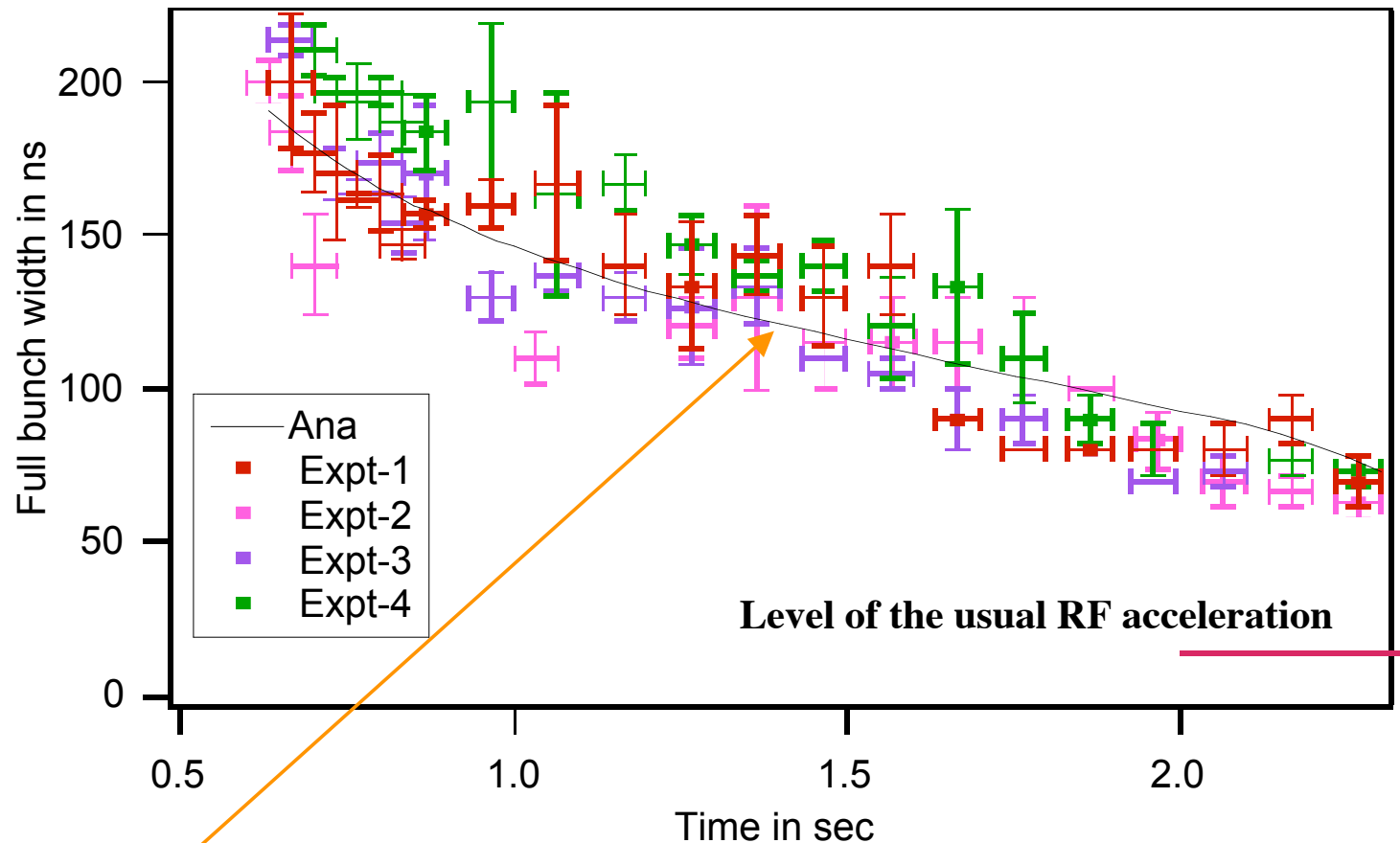
Theory: A WKB-like solution of the amplitude-dependent oscillation system (synchrotron oscillation in the barrier bucket)

T. Dixit et al., "Adiabatic Dumping of the Bunch-length in the Induction Synchrotron", submitted for publication (2006).

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

K.Takayama, K.Torikai, Y.Shimosaki, and Y.Arakida, "All Ion Accelerators", (Patent PCT/JP2006/308502)

500 MeV KEK-Booster

Existing RF

Combined fuction magnet

Extraction kicker
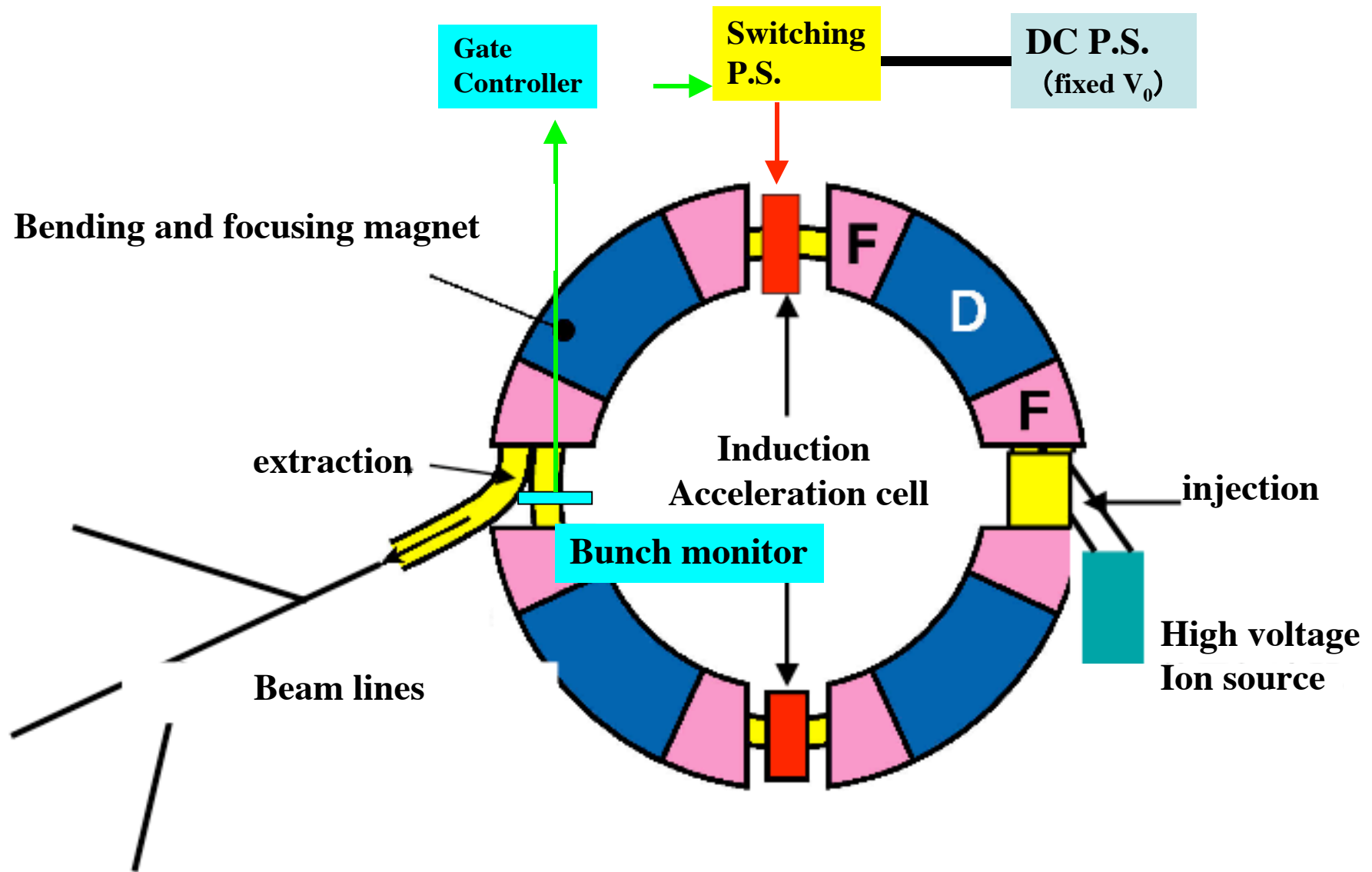
Injection line
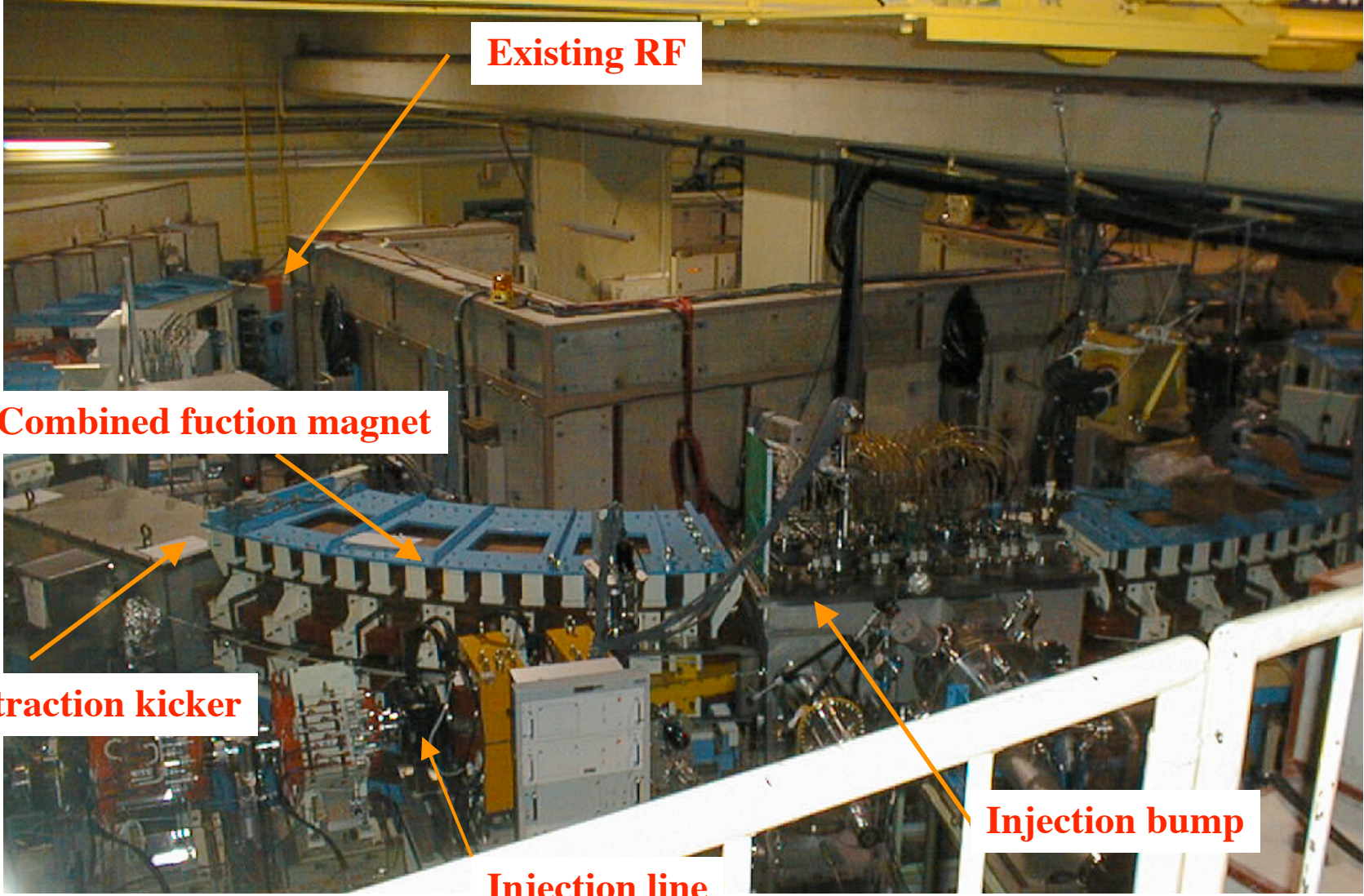
Injection bump

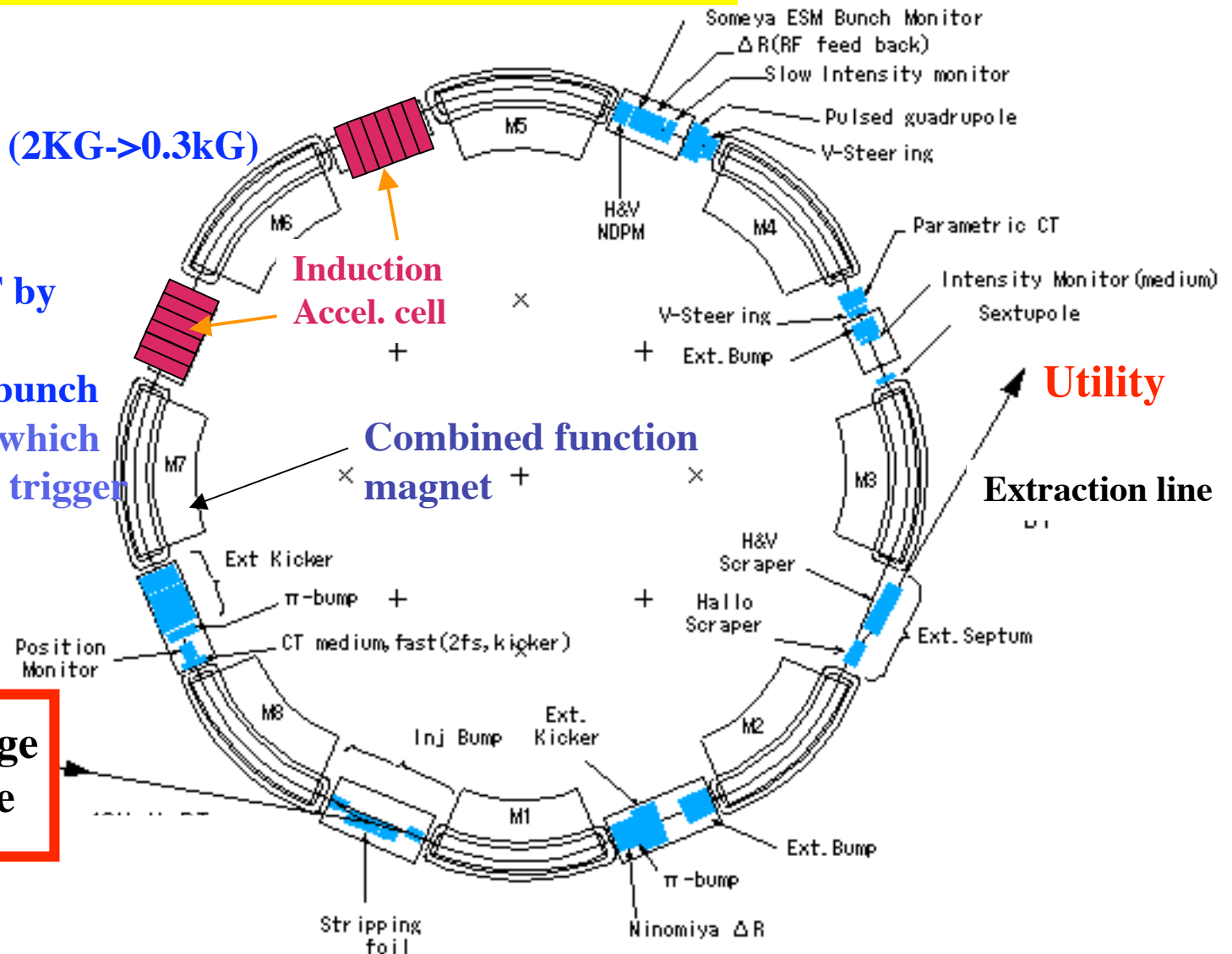**Modification of the 500MeV Booster to the AIA**

- **200kV Ion-source**
- **Low-field injection (2KG->0.3kG)**
  COD correction
  tune adjustment
- **Replacement of RF by induction cells**
- **Improvement of a bunch monitoring system which is integrated in the trigger control system**

Induction Accel. cell

Combined function magnet

Utility

Extraction line

High Voltage Ion Source

Combined-type
$C_o = 37$ m
$f = 10$ Hz

Someya ESM Bunch Monitor
ΔR(RF feed back)
Slow Intensity monitor
Pulsed quadrupole
V-Steering
Parametric CT
Intensity Monitor (medium)
Sextupole
Ext.Bump
V-Steering
H&V NDPM
M4
M5
M6
M7
M8
M1
M2
M3
Ext Kicker
π-bump
CT medium, fast (2fs, kicker)
Position Monitor
H&V Scraper
Hallo Scraper
Ext.Septum
Ext. Kicker
Inj Bump
Ext.Bump
π-bump
Ninomiya ΔR
Stripping foil

0   5m

Principal property of the existing accelerators

Energy E/au	Static Accelerator	RFQ+DTL	Induction Linac	Cyclotron	RF Synchrotron	All-ion accelerator (Ind. Synchrotron)
Low < MeV	No limit	Limited Z/A	No limit	limited Z/A charge state	limited Z/A	No limit
Medium < GeV	NA	Limited Z/A (expensive)	No limit (expensive)	limited Z/A charge state	limited Z/A	No limit
High >> GeV	NA	Limited Z/A (expensive)	No limit (expensive)	NA	No limit but limited by Injector	No limit

Play ground of the AIA
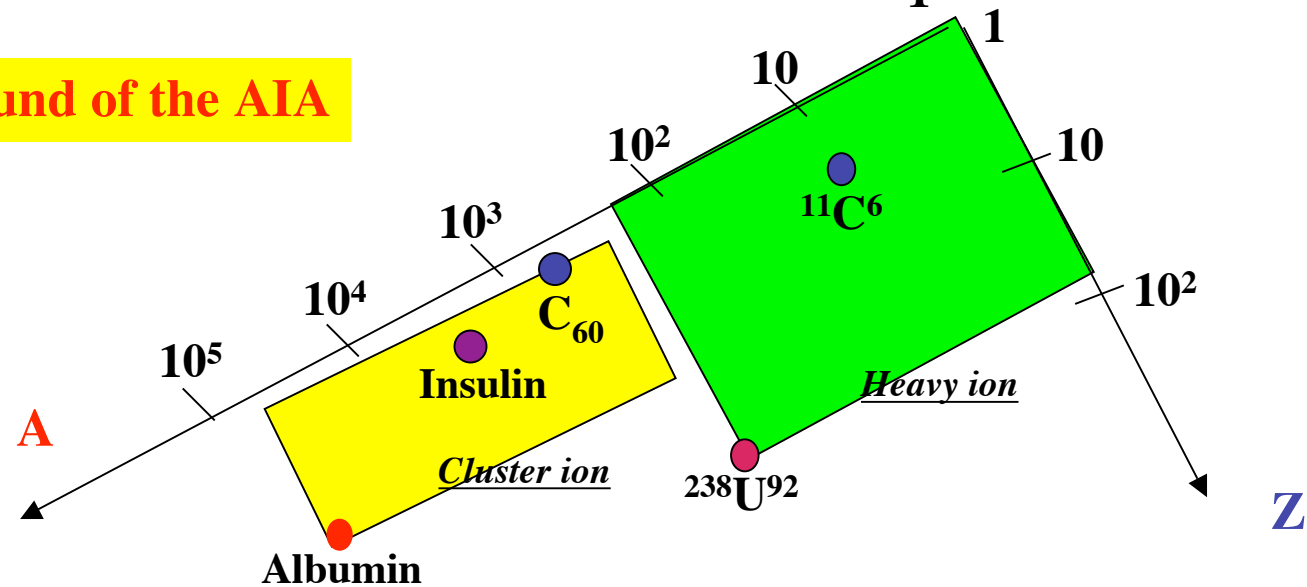
if an extremely good vacuum is available

Comparison of the AIA with other existing medium energy ion drivers
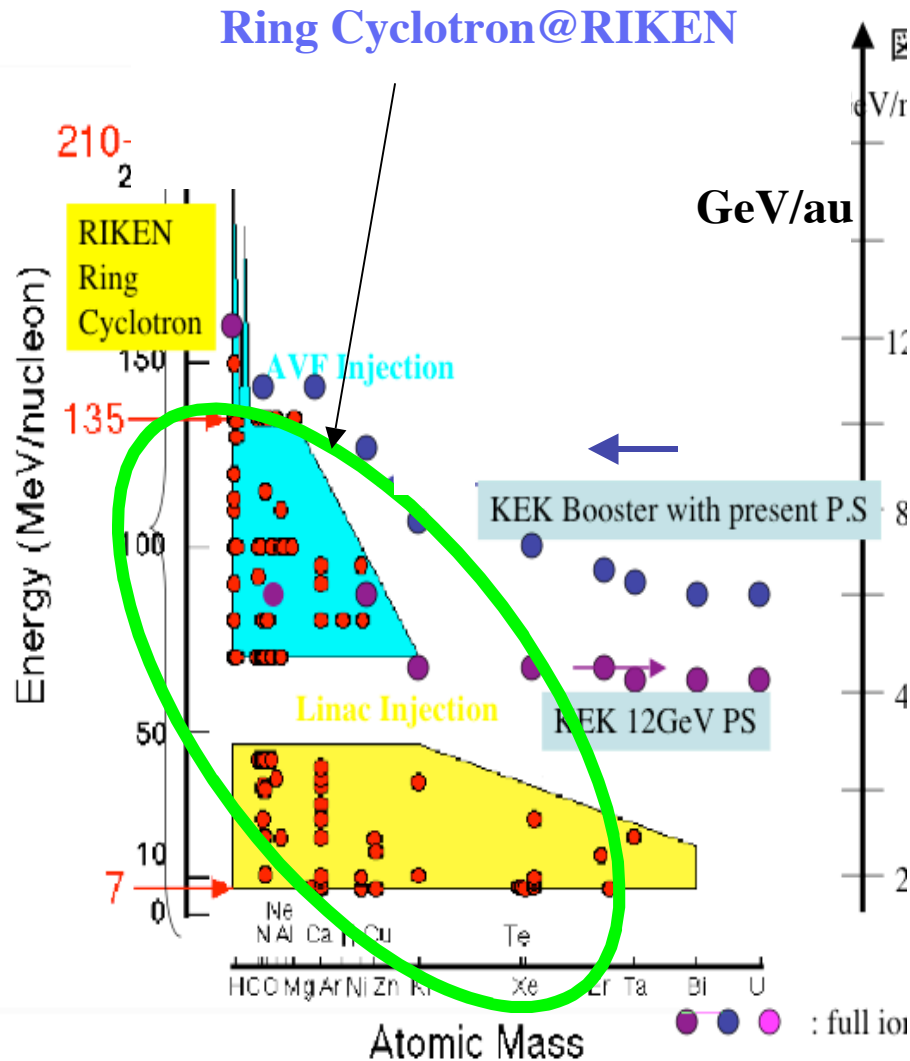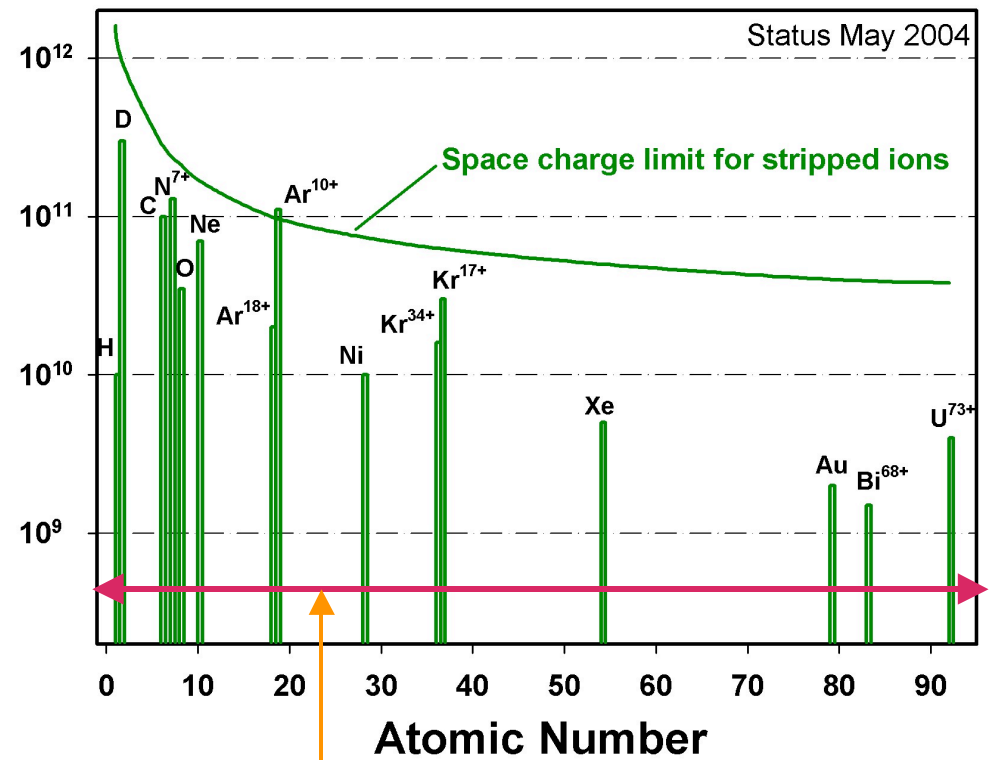
Low energy injection and space-charge limited current

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	

Example of Ar^{+18} Acceleration

$E(t)/10$ (MeV/au), $V_{acc}(t)$ (kV), $f(t)$ (MHz)
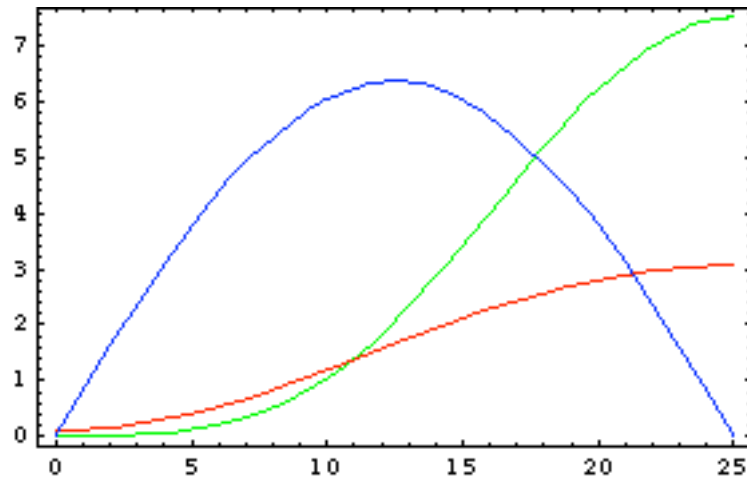
t (msec)
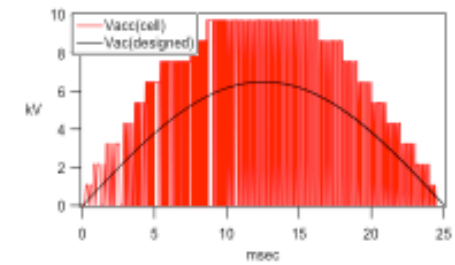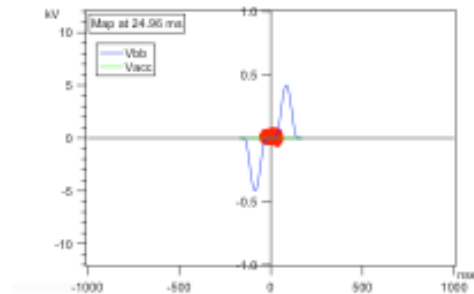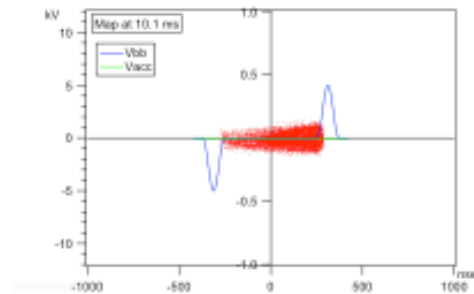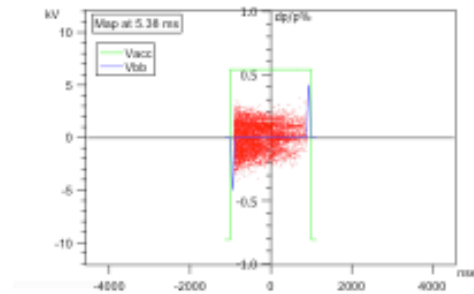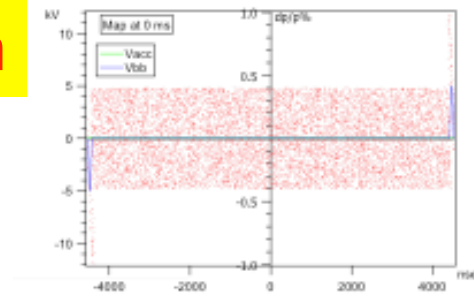
B. Bulk Material Science

irradiate

Bulk materials:
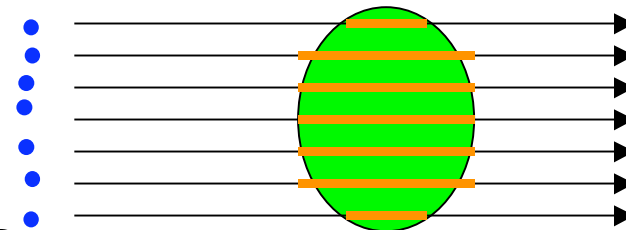metal, ceramic, semi-condutor
magnetic material, polymer

a. Energy deposit due to electro-excitation

ions

**Ions
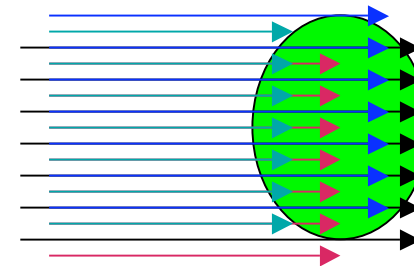with arbitray A and possible Z**

ions

**AIA
Injector-free I.S.**
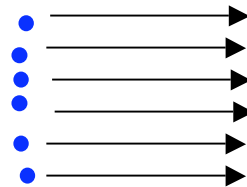
Energy dumper

b. Ion implant due to sweeping
of Bragg peak

Creation of novel bulk materials
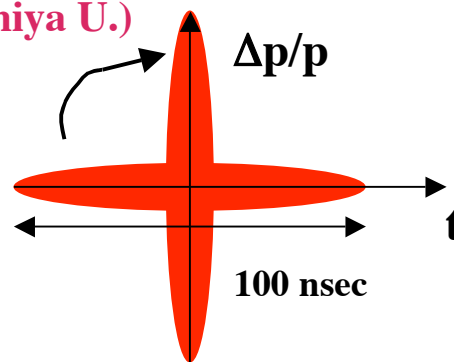
Beam-line for the WDM Science

Beam line for Bulk Materials

a. Transverse dir.
（half-mini beta）

D   F

target

K-value$=k_0^2$

RF or Induction cells

s

Wobbler mags.   target

Modification region with beam dump

r_y

k_0^2

r_x

Beam Radius r_x & r_y [m]

k-value k_0^2 [m^{-2}]

Transport Distance s [m]

to NML

NML PULSE BEND

31 m

Calculation by Kikuchi (Utsunomiya U.)

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

$\Delta p/p$

t

100 nsec

BOOSTER
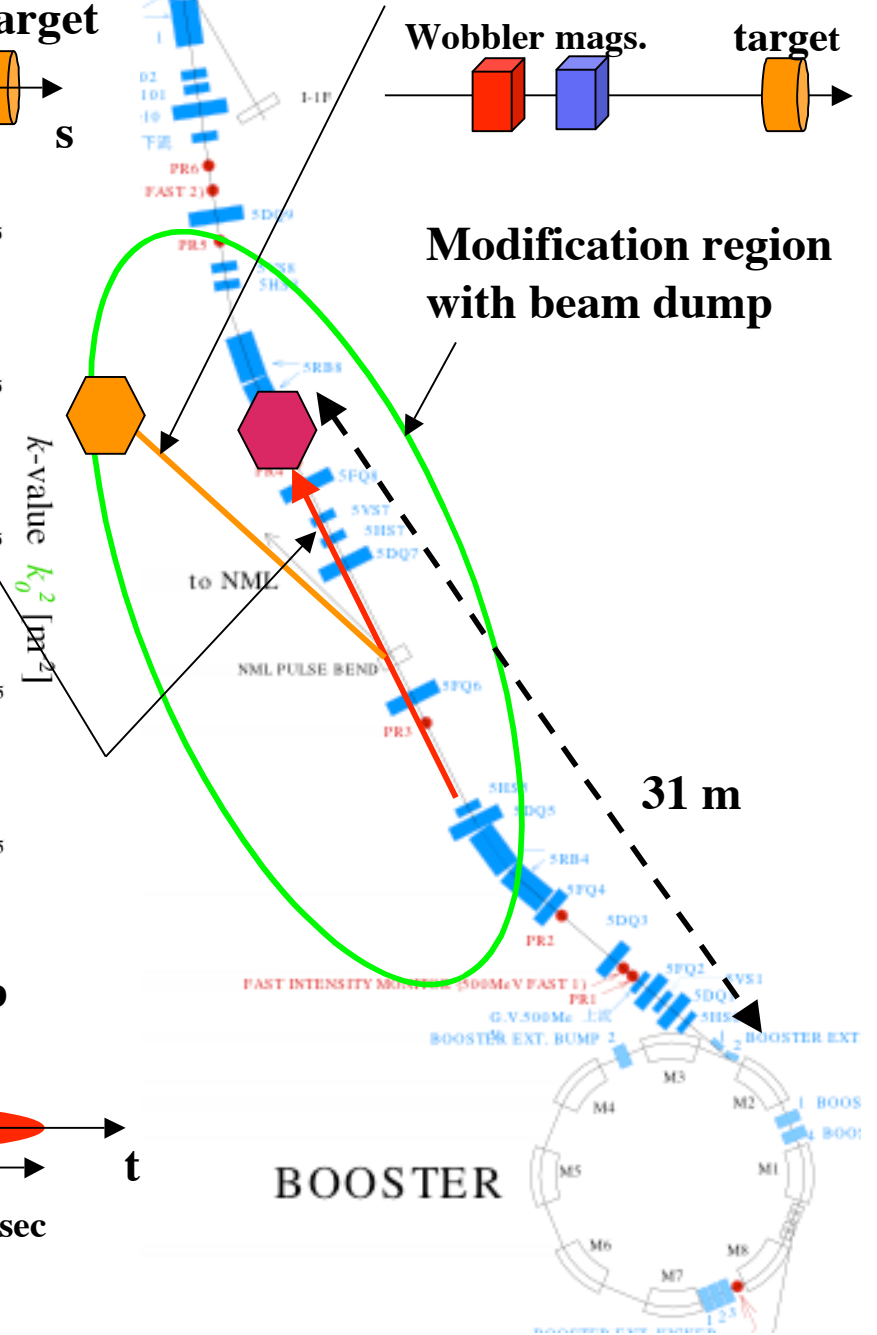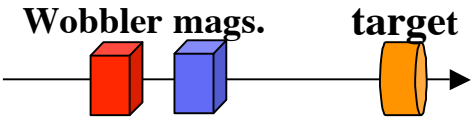
Modified Beam-lines
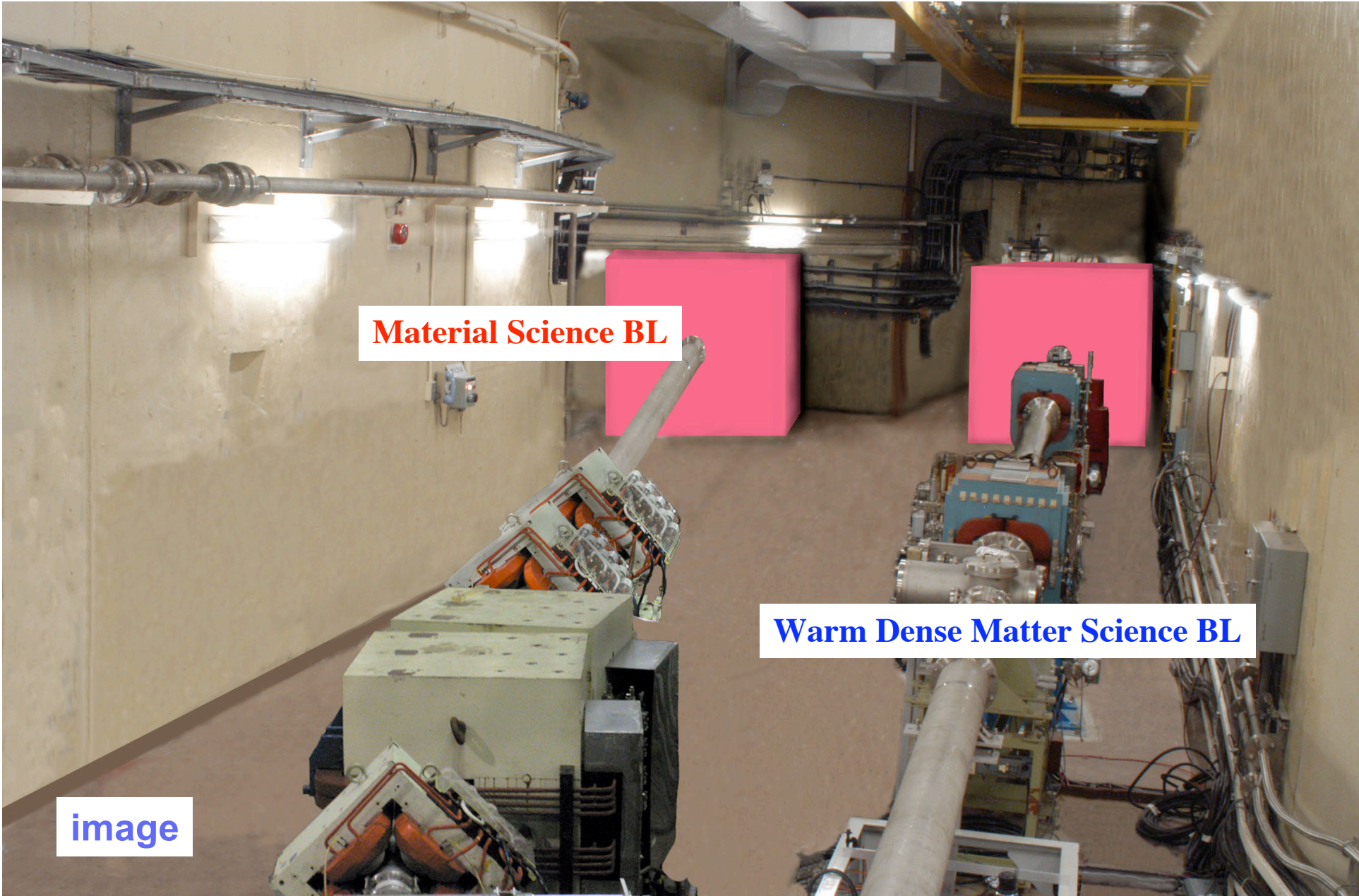
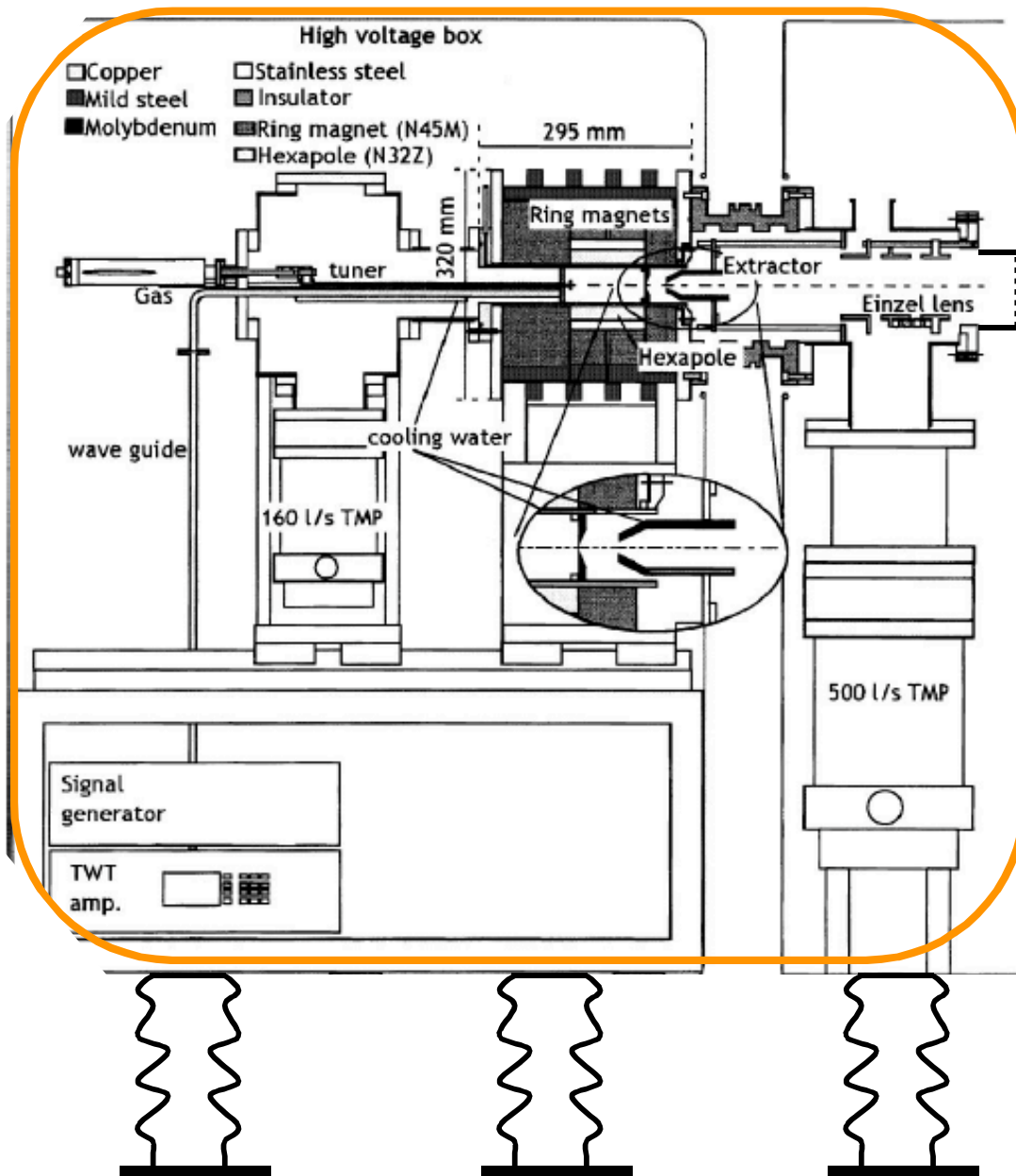Material Science BL

Warm Dense Matter Science BL

image

200KV Ion-Source

9.4 GHz permanent-mag. ECR

200kV acceleration tube

High voltage box

Copper   Stainless steel
Mild steel   Insulator
Molybdenum   Ring magnet (N45M)
Hexapole (N32Z)

295 mm

320 mm

Ring magnets

tuner

Gas

Extractor

Einzel lens

Hexapole

wave guide

cooling water

160 l/s TMP

500 l/s TMP

Signal generator

TWT amp.
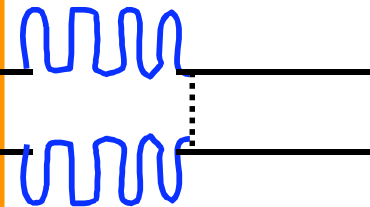
Expected Heavy Ion Beam Facility Organization (All Japan)

Program Leader

Ion-beam Driver

Accelerator Lab., KEK
Nat. Inst. for Fusion Sci.
Nagaoka Tech.&Sci. Univ.

Applications

WDM Science

Tokyo Inst. of Tech.
Utsunomiya Univ.

Bulk Material Science

Nat. Inst. for Mat. Sci.
Inst. for Mat. Struct. Sci., KEK
JAEA
Ibaraki Univ.
Hyogo Prefectural Univ.
Aichi Education Univ.
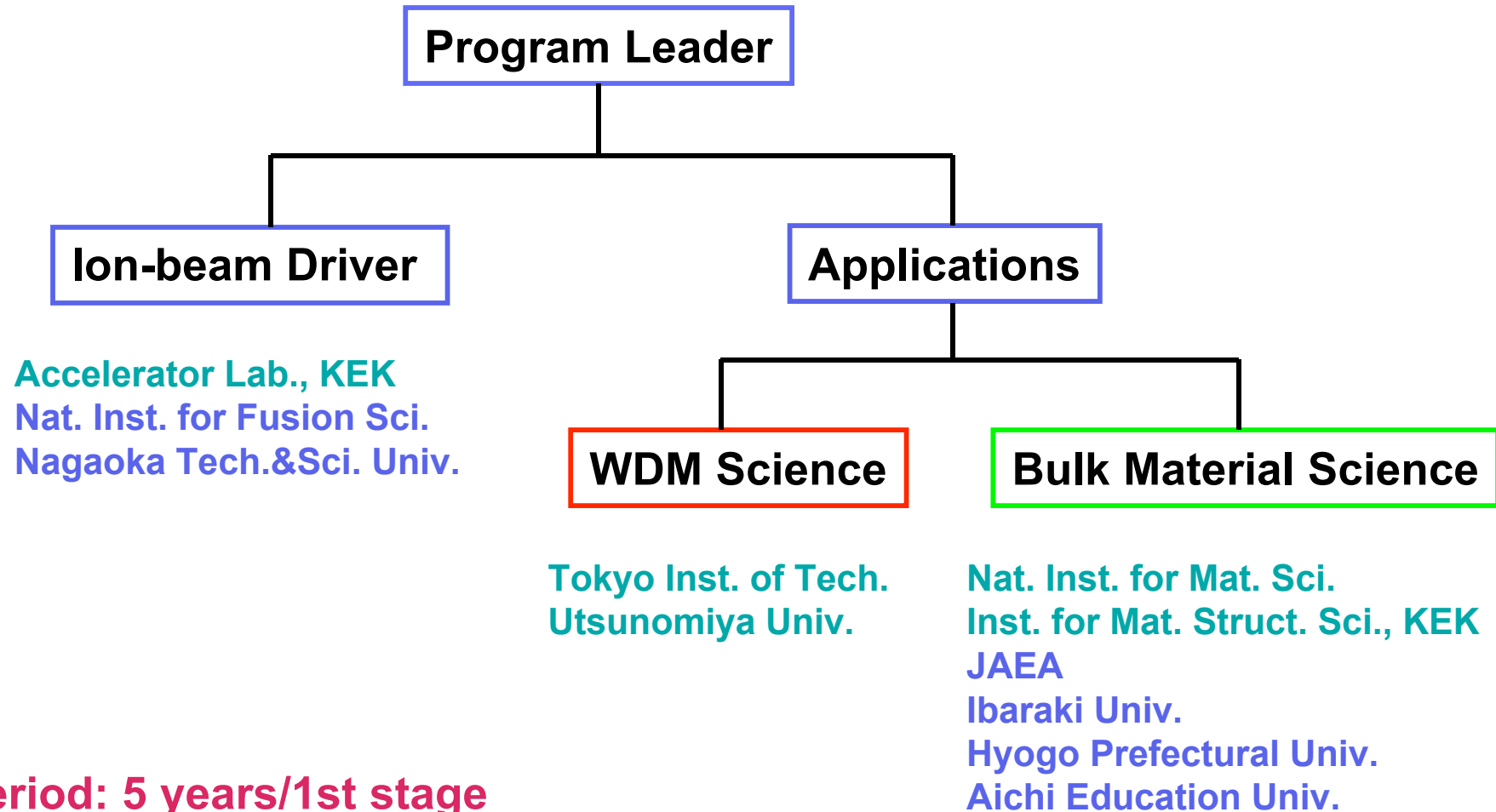
Period: 5 years/1st stage
Cost: ~ 7 M$
now on reviewing by the financial agency

Road Map

A: Warm Dense Material Science, B:Modification of Bulk Materials

		'07	'08	'09	'10	'11	remarks
Accelerator & Beam test	Modification of the Booster to the AIA						
	Beam commissioning						
Beam Line & Target Area	Beam lines						
	Preparation of irrad. Bench for A						
	Preparation of irrad. Bench for B						
Experiment	Planning/Experiment for A						
	Planning/Experiment for B						
	Theory and Simulation works						
	R&D toward future						

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 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.

One of its possible and uniqueapplications in a 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 described. Hopefully, available heavy ion beams will be provided for WDM Science and bulk material science.