# Experimental Results of the Induction Synchrotron and beyond That

**Ken Takayama**

***High Energy Accelerator Research Organization (KEK)***

**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**
**December 18-20, 2006**

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

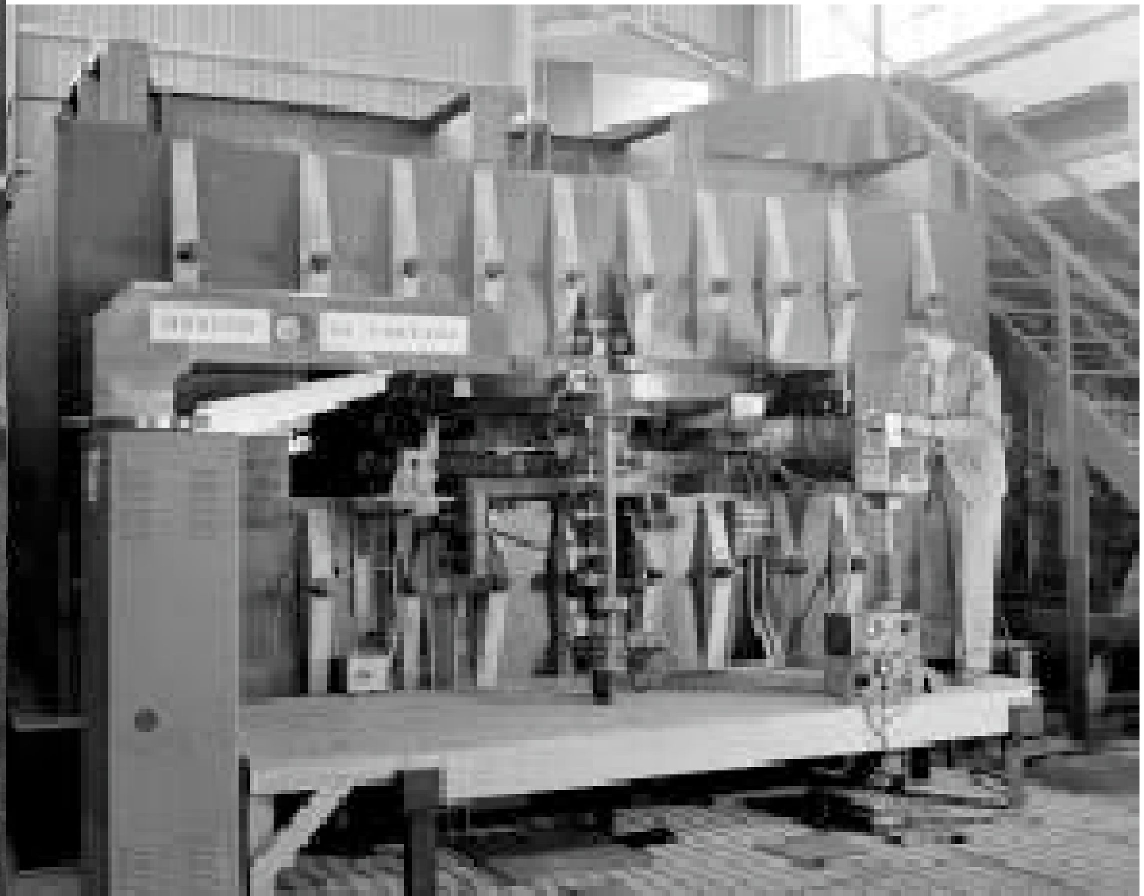
# History of Induction Synchrotron Research at KEK

| 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.<br>**Proposal of a Super-bunch Hadron Collider** | PAC2001<br>Snowmass2001 |
| 2002 | | ICFA-HB2002<br>EPAC2002,**RPIA2002** |
| 2003 | **5 years term Project using the KEK-PS officially started with a budget of 5M$.** | PAC2003<br>ICFA-HB2003 |
| 2004 | ●The first engineering model of the switching P.S. was established.<br>3 induction acceleration cells (2 kVx3=6 kV) were installed. (May)<br>●First experimental demonstration of induction acceleration in the KEK-PS (Oct. - Nov.)<br>●Barrier trapping at the injection energy of 500MeV and a 500 nsec-long bunch was achieved. (Dec.) | APAC2004<br>EPAC2004<br>ICFA-HB2004<br>CARE HHH2004 |
| 2005 | **Proposal of All-ion Accelerators**<br>Another 3 induction acceleration cells (2 kVx3=6kV) were installed (Sept).<br>●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.)<br>●**Full demonstration of the IS concept (March)**<br>●**All-ion Accelerator was awarded a patent. (November)** | **RPIA2006,** HB2006<br>EPAC2006, HIF06 |

# E.M.McMillan & the first Synchrotron@LBL (1945)

E=340MeV

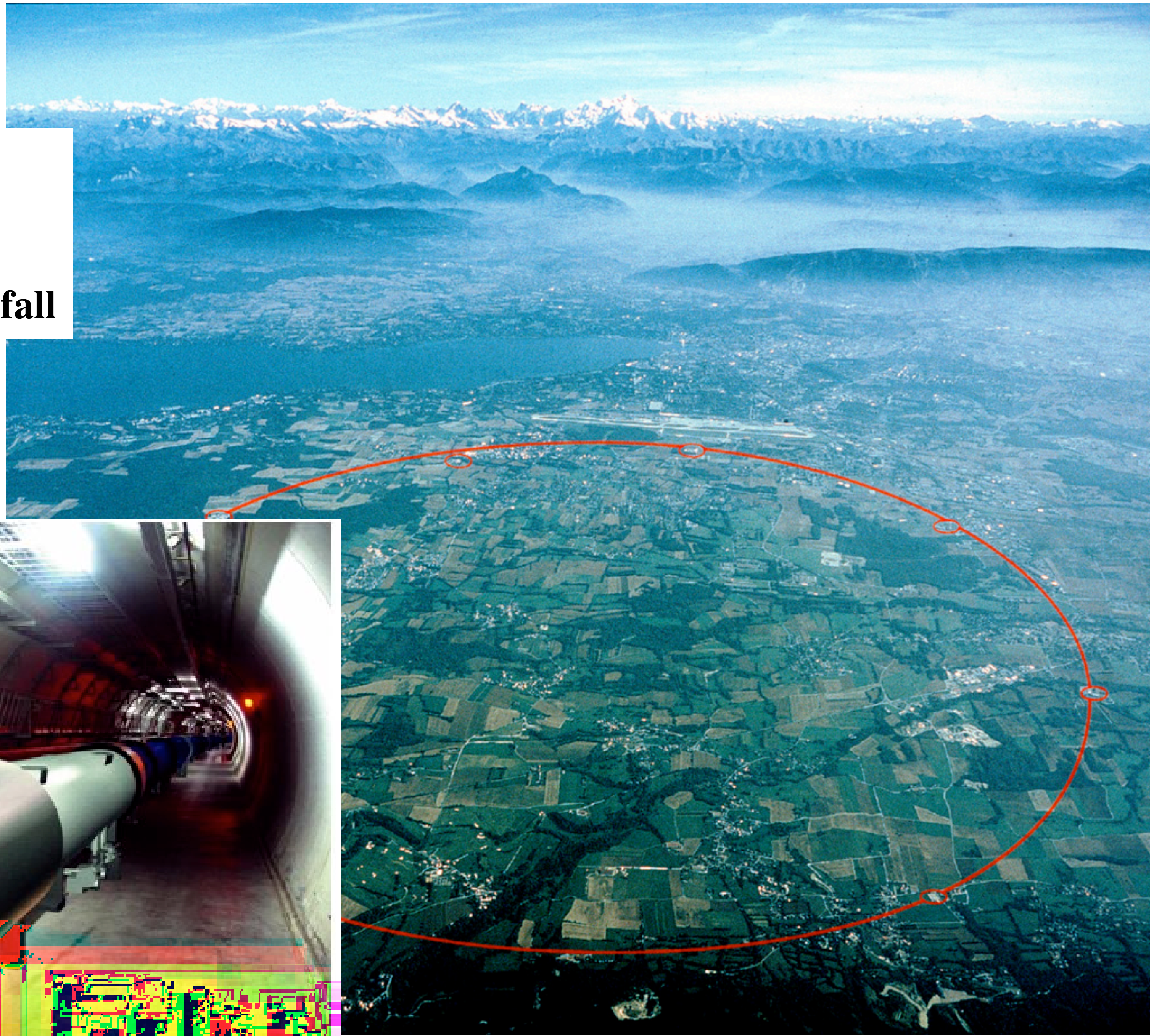
**Week focusing**

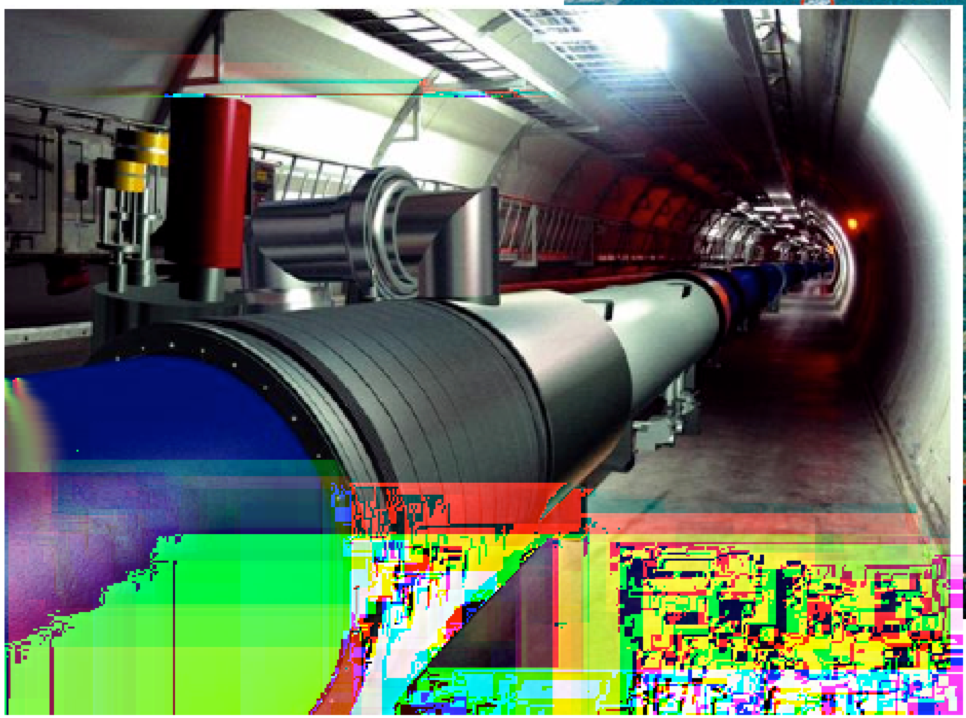


**by courtesy of LBNL**

CERN

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

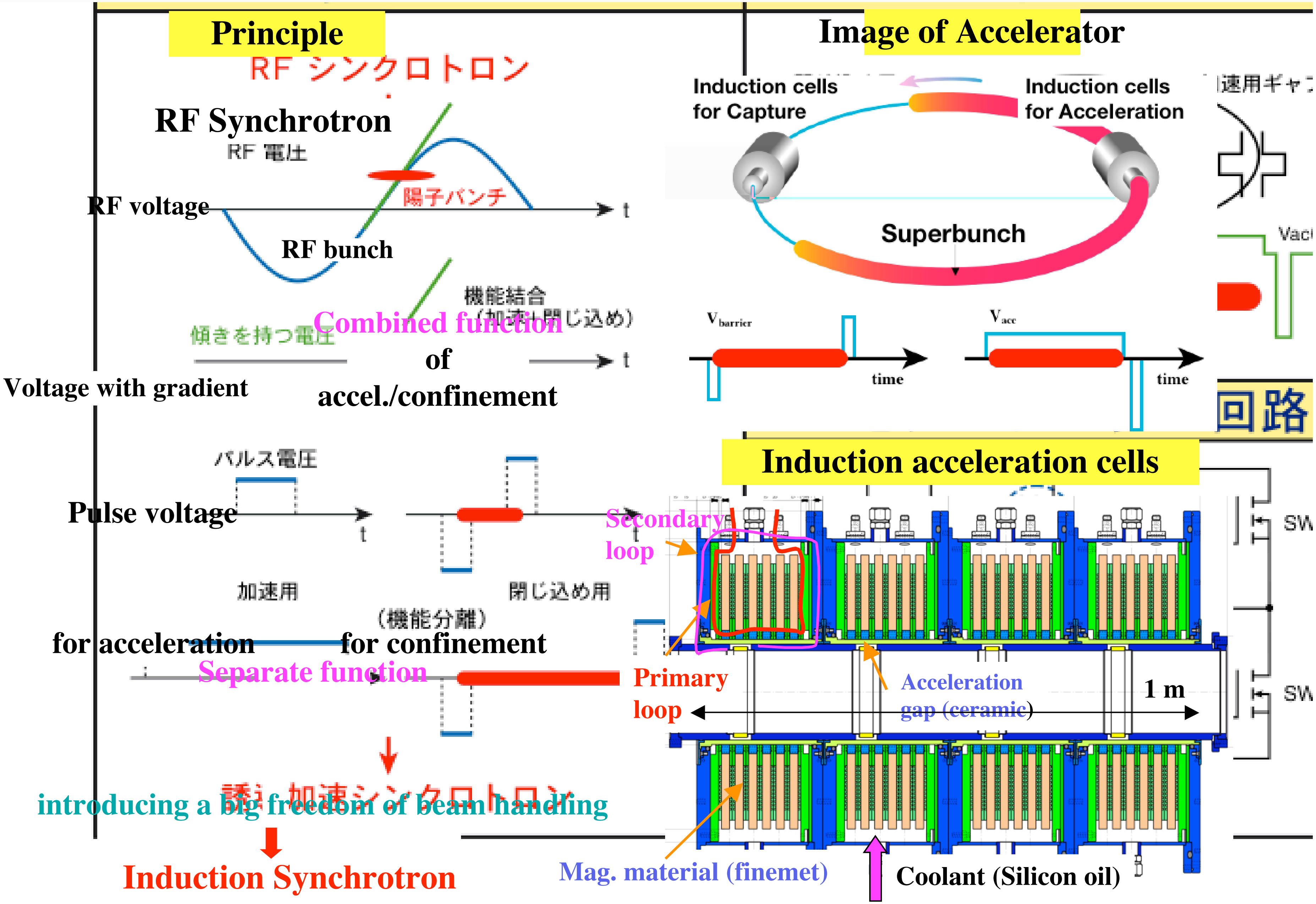




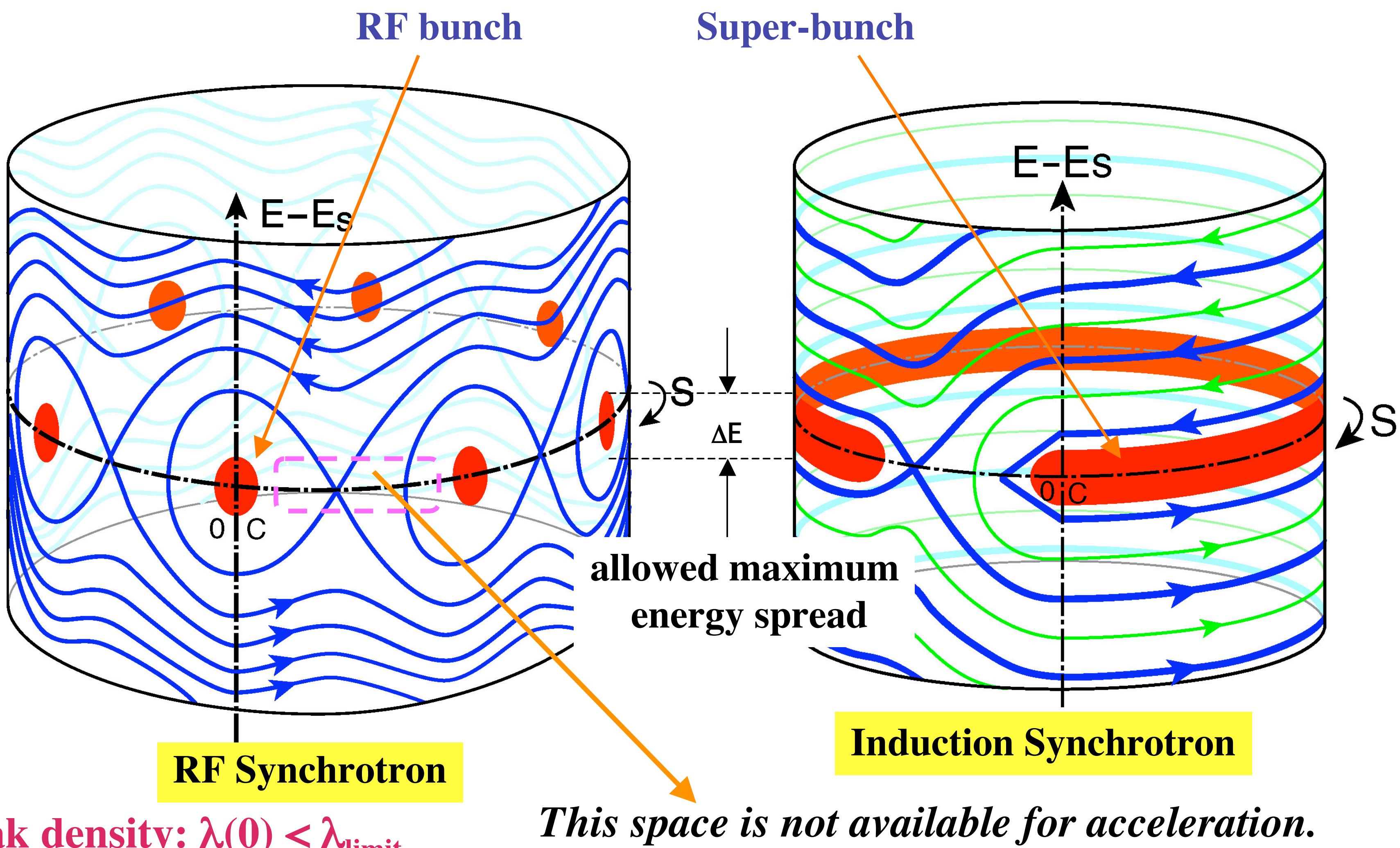
**by courtesy of CERN**

# Concept of Induction Synchrotron 概念

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

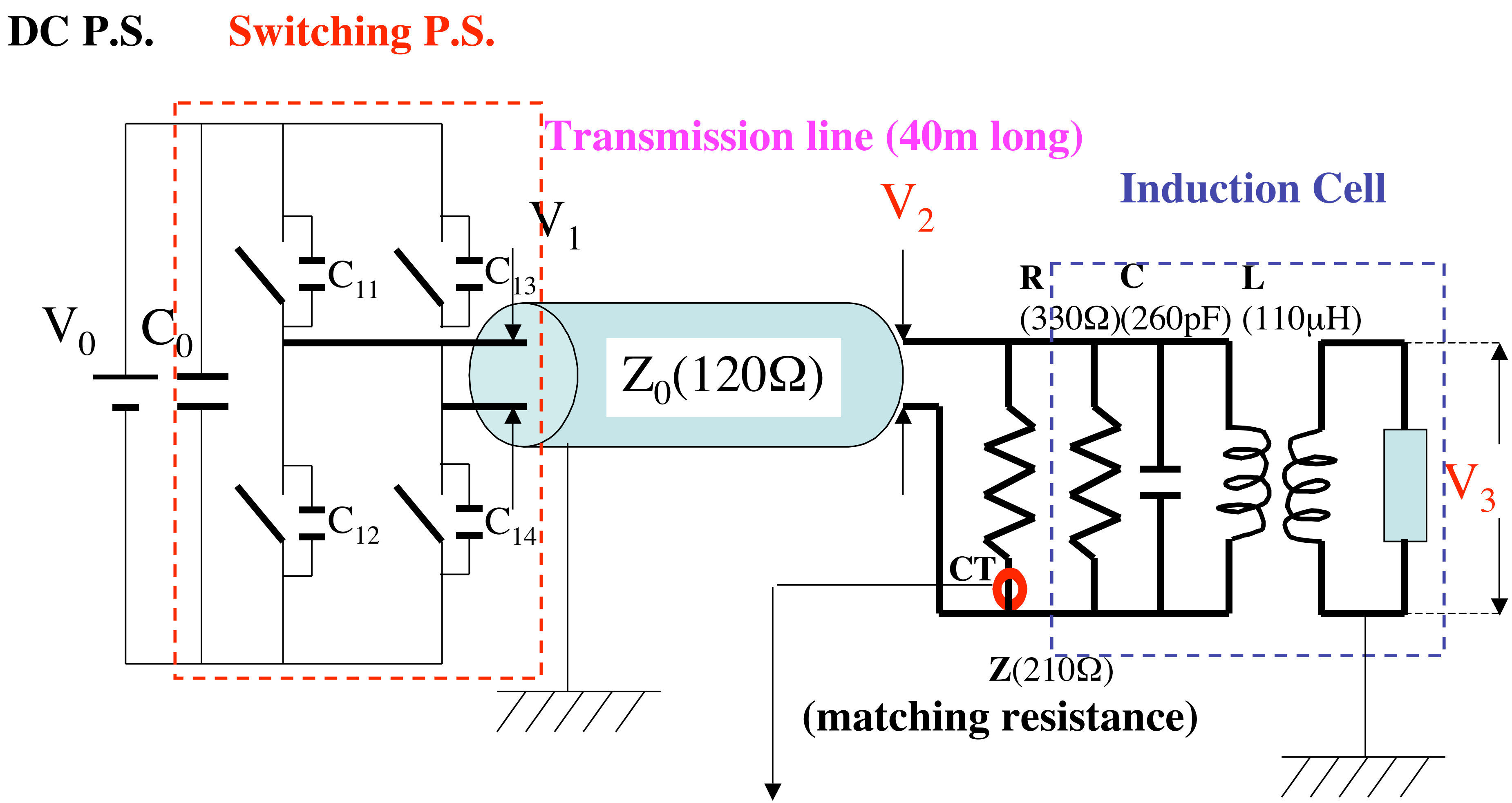


# Difference between RF and Induction Synchrotron seen in Phase-space




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

# Equivalent Circuit for 2.5kV Induction Accelerating System

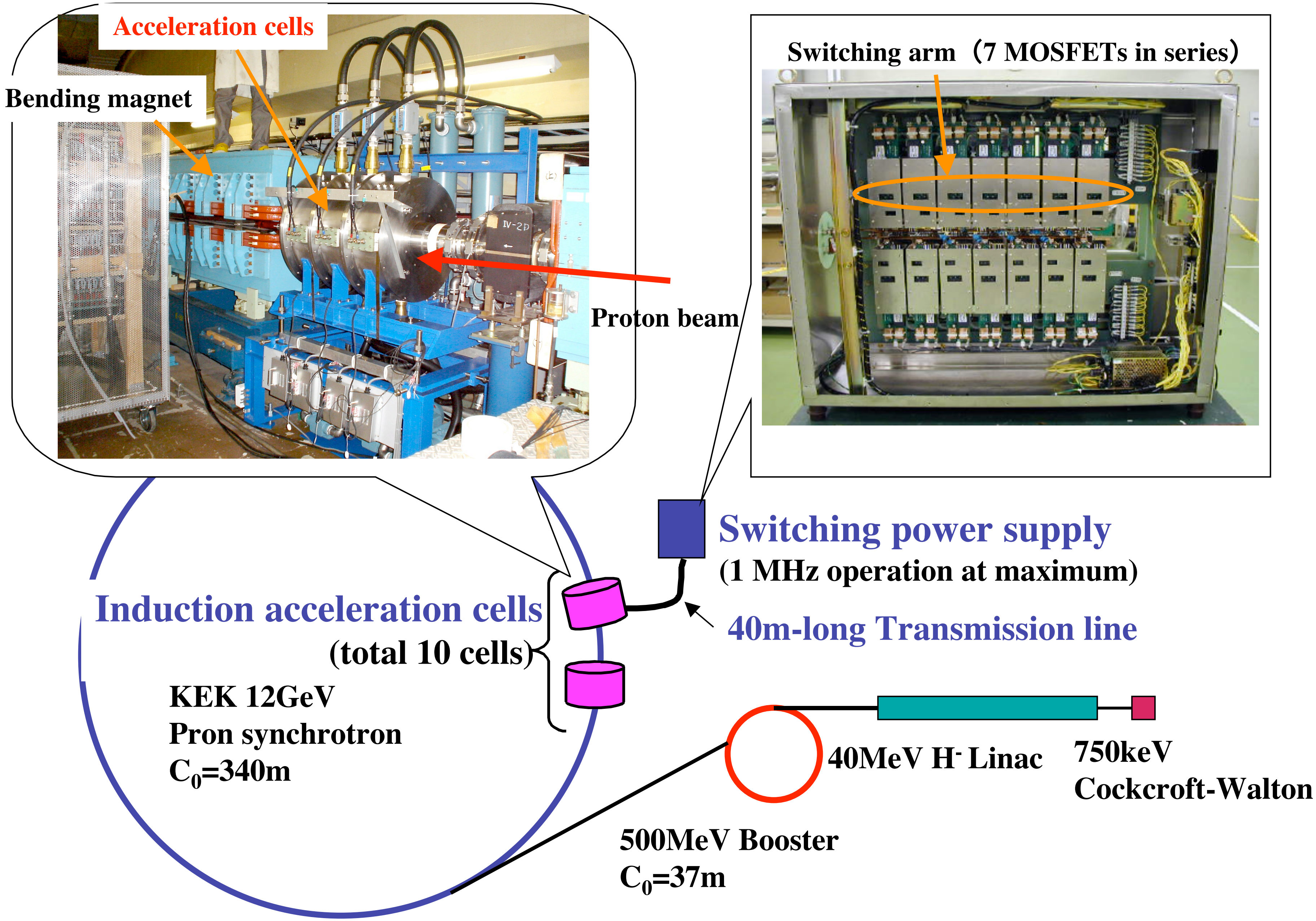



$V_0 \sim V_2 = V_3 \sim ZI_Z$ (calibrated)

$I_Z$ (always monitored)

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

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



# Scenario of the POP Experiment

*The scenario has been divided into three steps.*

**1 st Step:**

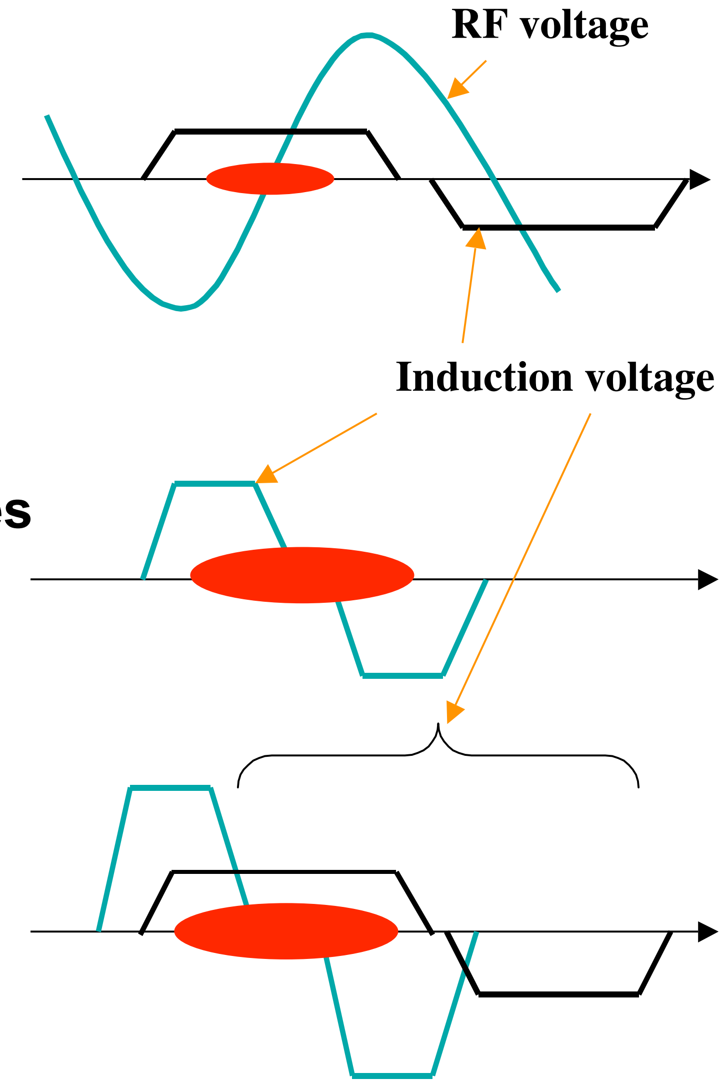
RF trapping + induction accel.
(Hybrid Synchrotron)
500 MeV -> 8 GeV for $6 \times 10^{11}$ppb
2004/10-2005/3

**2nd Step:**

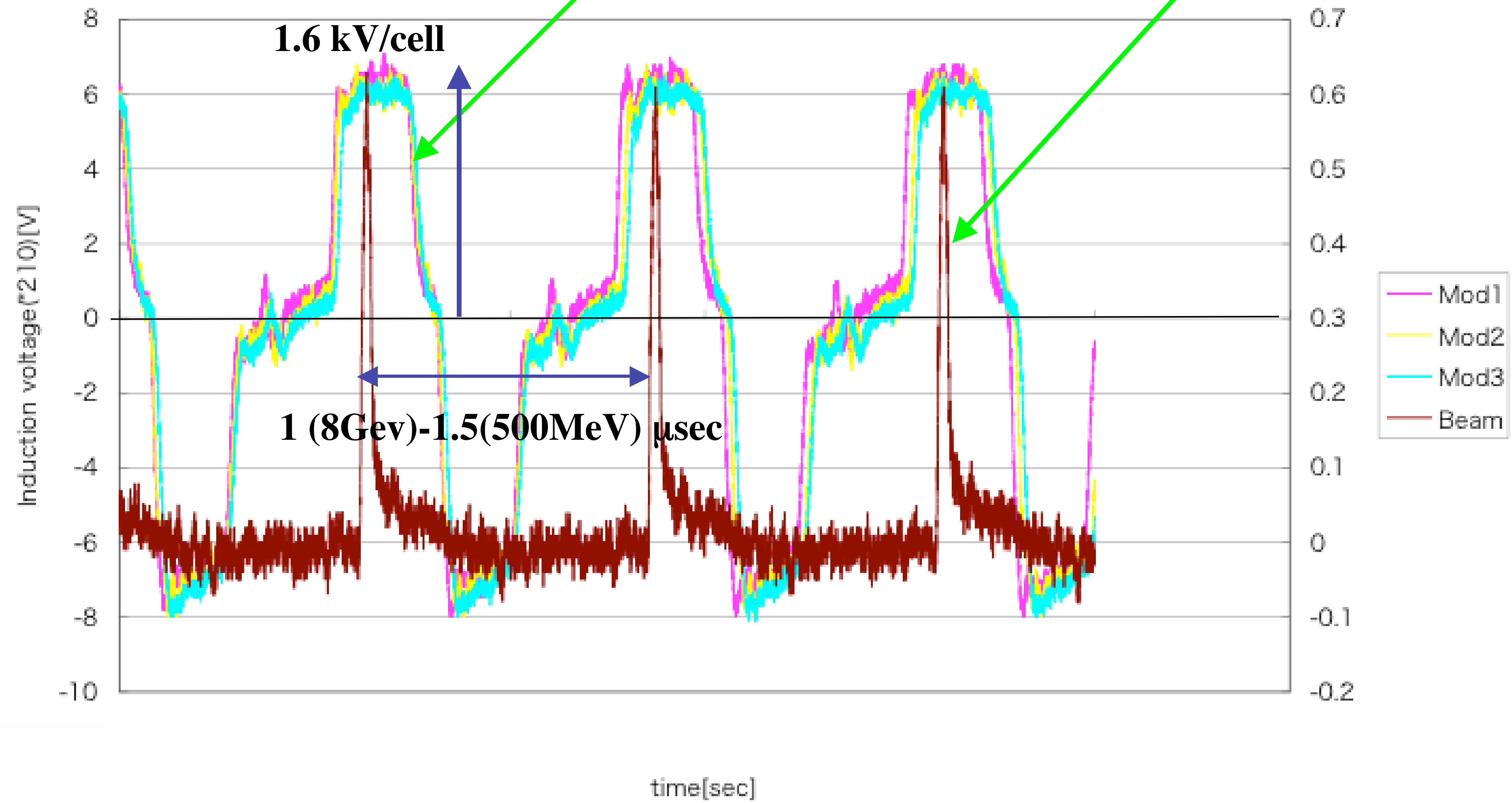
Barrier trapping by induction step-voltages
at 500 MeV
through 2005

**3rd Step:**

Barrier trapping + induction accel.
(Induction Synchrotron)
500 MeV -> 6 GeV for $2\text{-}3 \times 10^{11}$ppb
2006/1-3



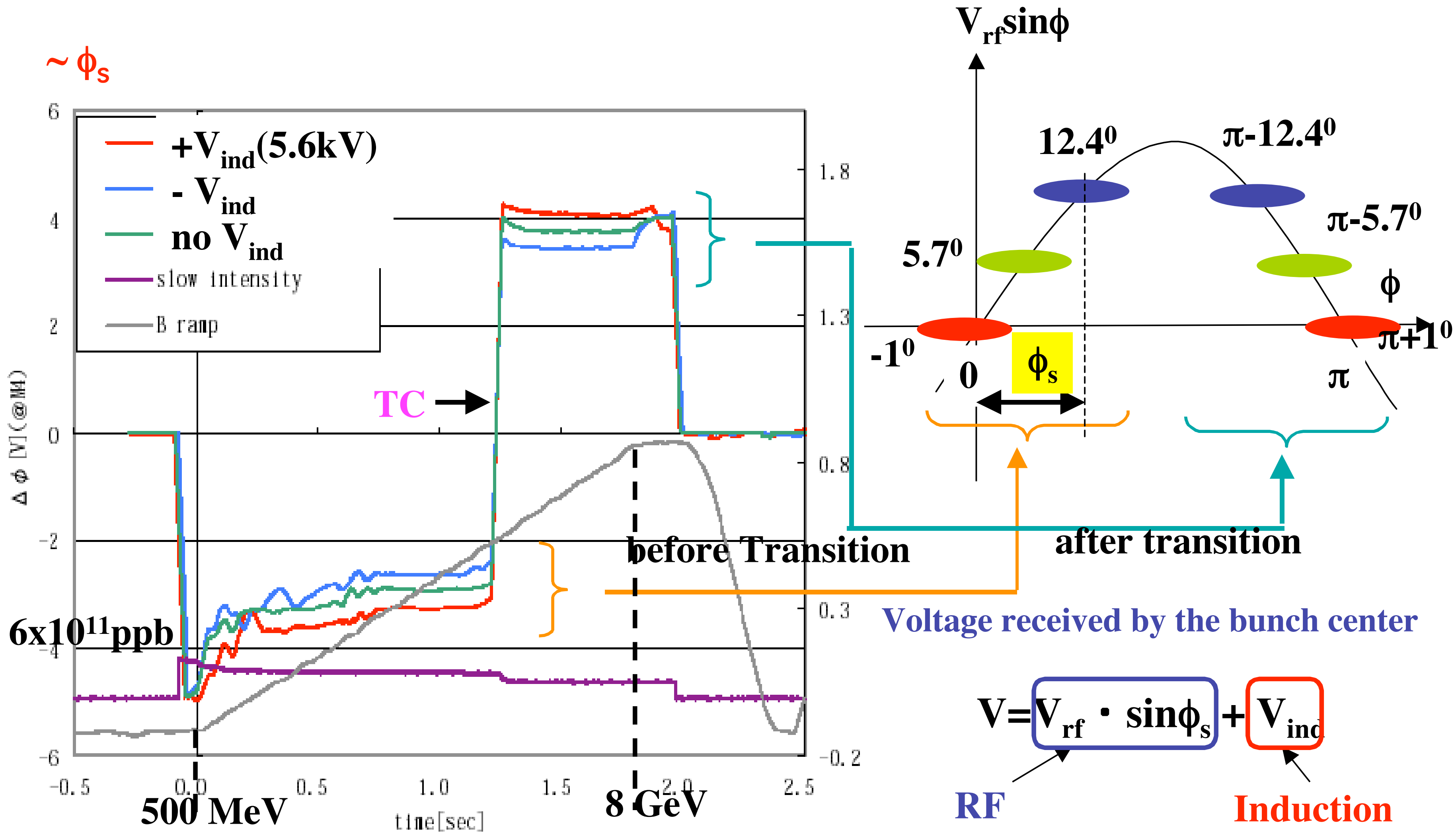
# Monitored signals of induction voltage and an RF bunch signal in the step 1 experiment




- 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



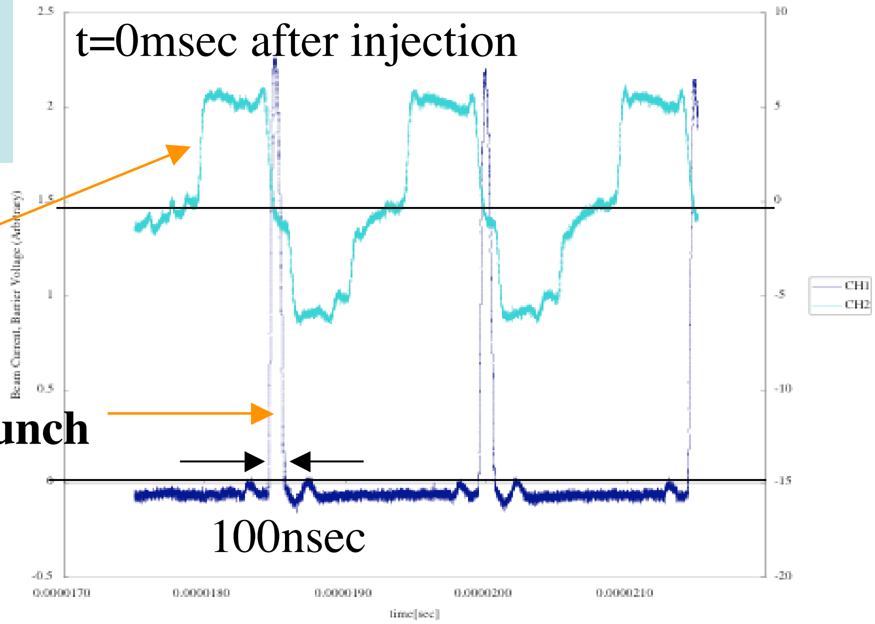

K.Takayama *et al.*, *Phys. Rev. Lett.* 94, 144801 (2005).

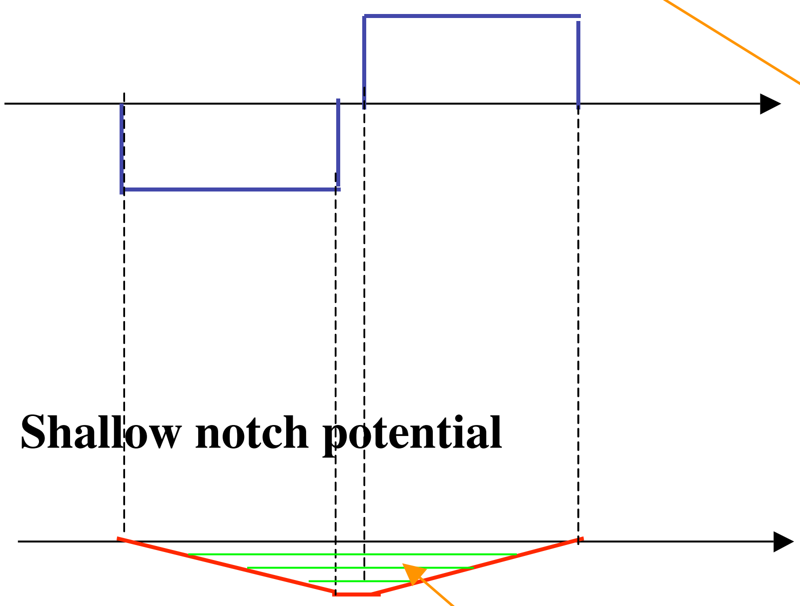
Step 1
Hybrid Synchrotron

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

**6kV barrier-voltage**

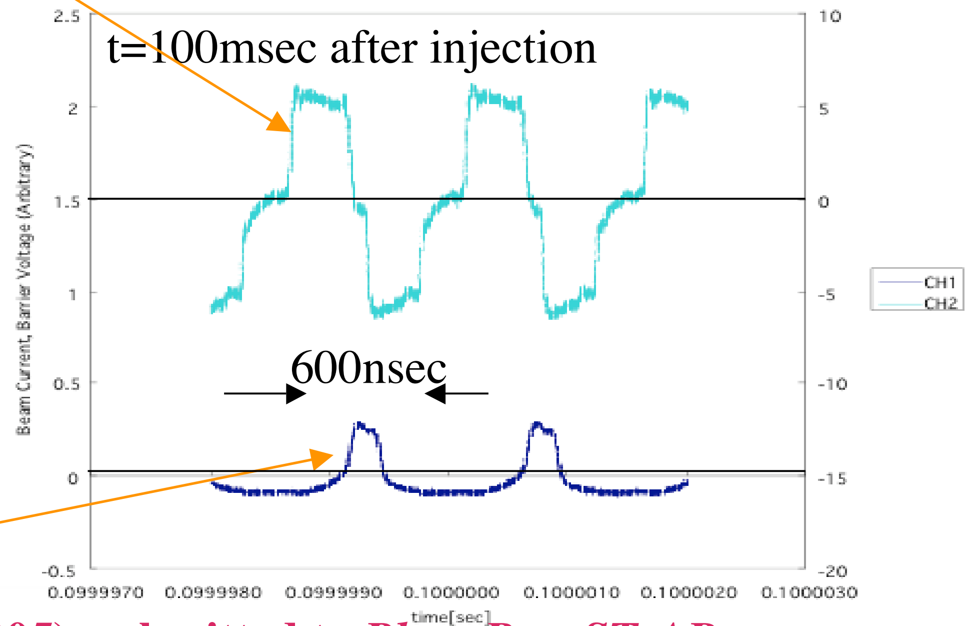
**injected proton bunch**



**Shallow notch potential**

**trapped protons**



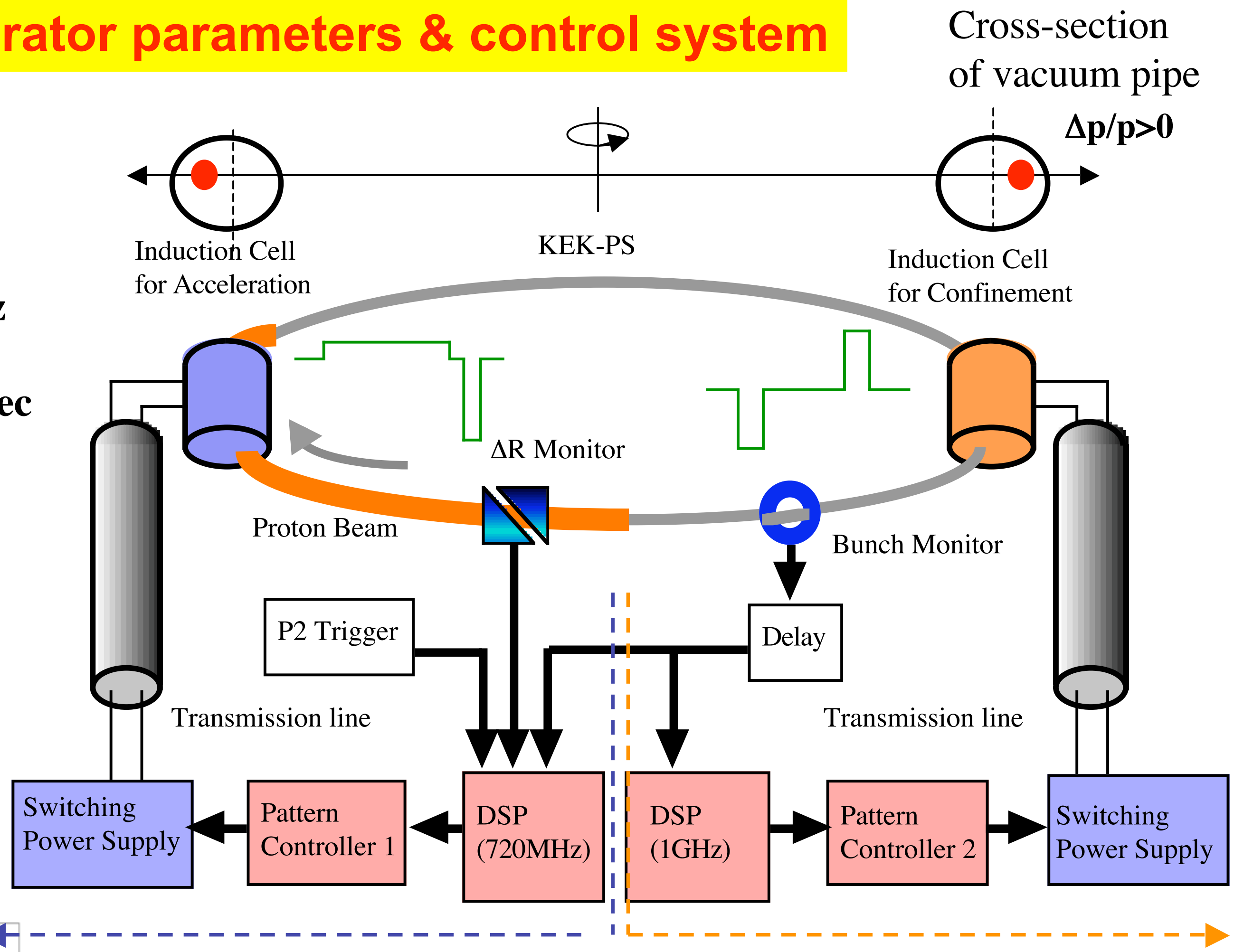

K.Torikai et al., KEK Preprint 2005-80 (2005), submitted to *Phys. Rev. ST-AB*

# Accelerator parameters & control system

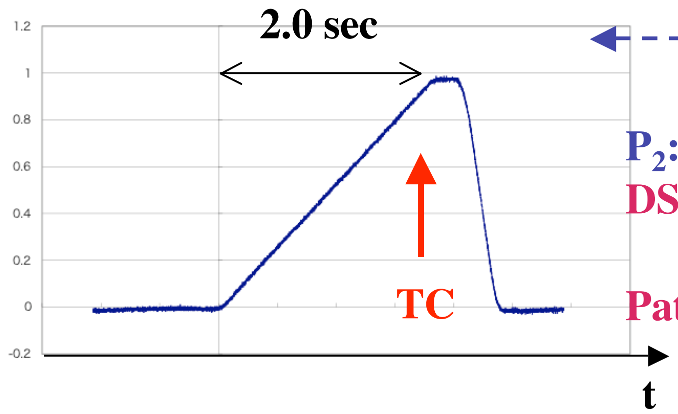
| | |
|---|---|
| $C_0$ | 339 m |
| Inj/Ext Energy | 0.5/6 GeV |
| Revolu fre. | 667- 876 kHz |
| Accel. time period | 2.0 sec |
| dB/dt | 0.377 Tesla/sec |

**Induction acceleration voltage:**

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




B(t)




**$P_2$: acceleration start**

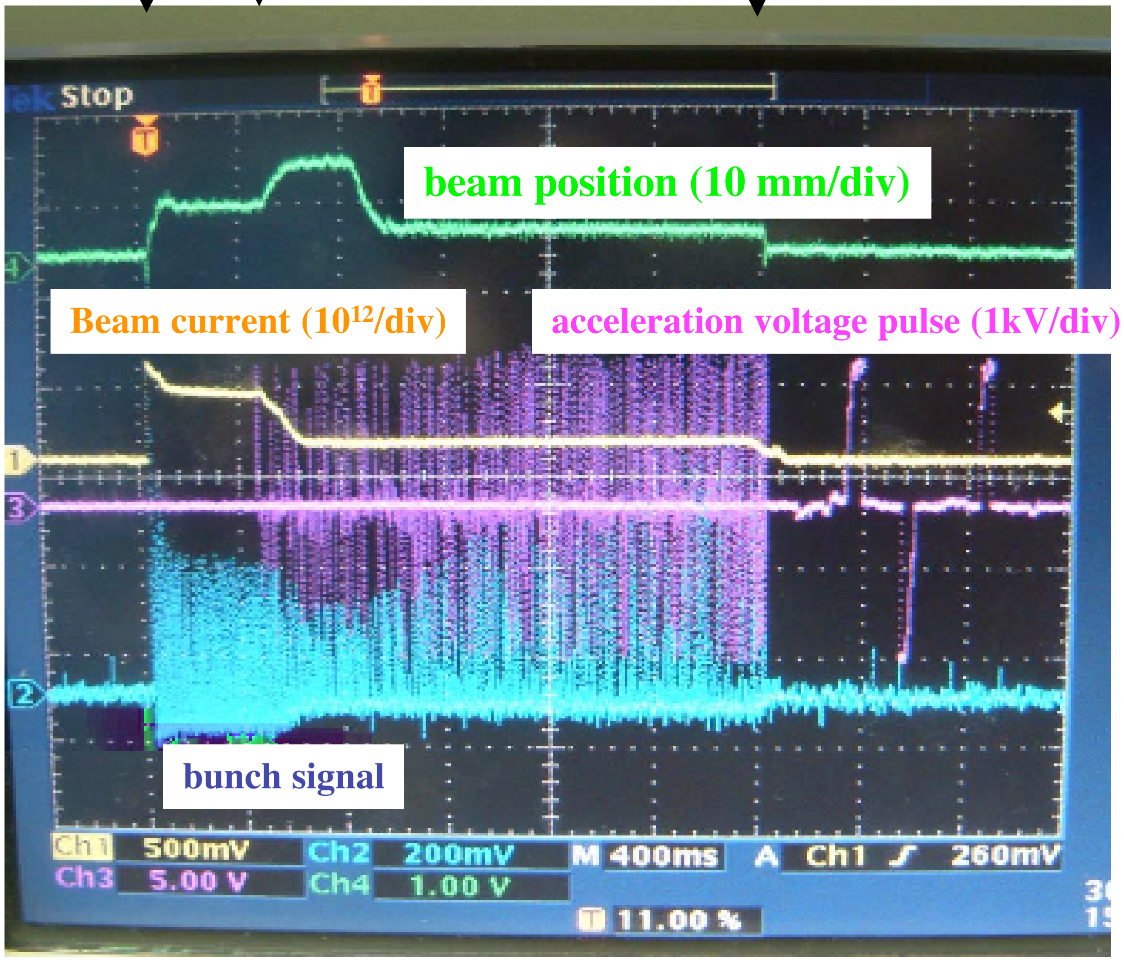
**DSP (digital signal processor): logical processing of the input signals (delay in master signal, on/off decision)**

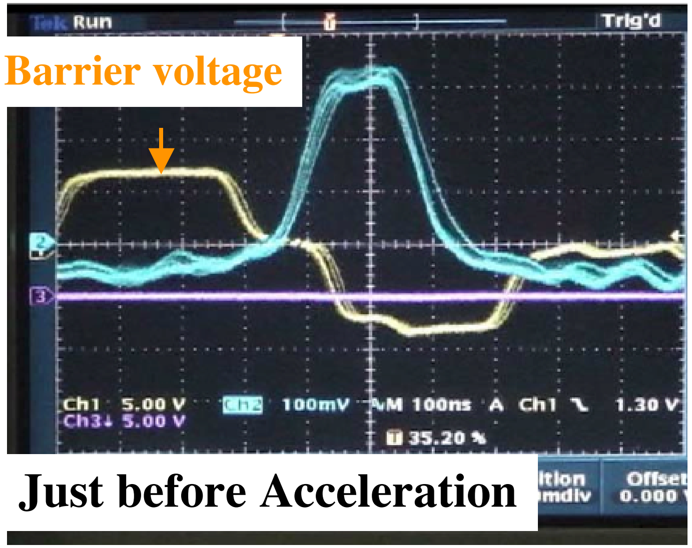
**Pattern Controller: generation of the gate trigger pattern**

**Step 3**
**Induction**

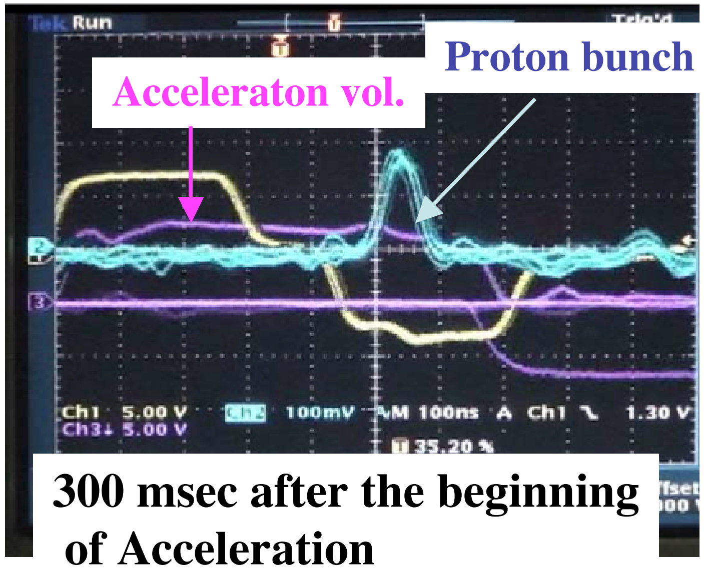
# Step 3
# Induction Synchrotron

Injection(500MeV) Start of acceleration End of acceleration (6GeV)




Just before Acceleration



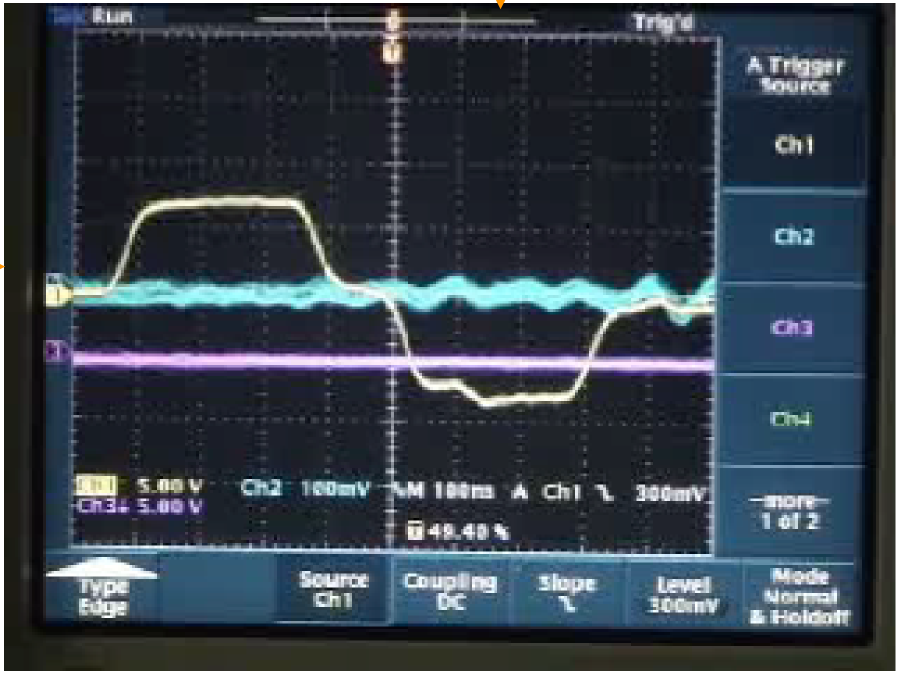

300 msec after the beginning of Acceleration

Step 3
Induction Synchrotron

# Movie show of the full demonstration

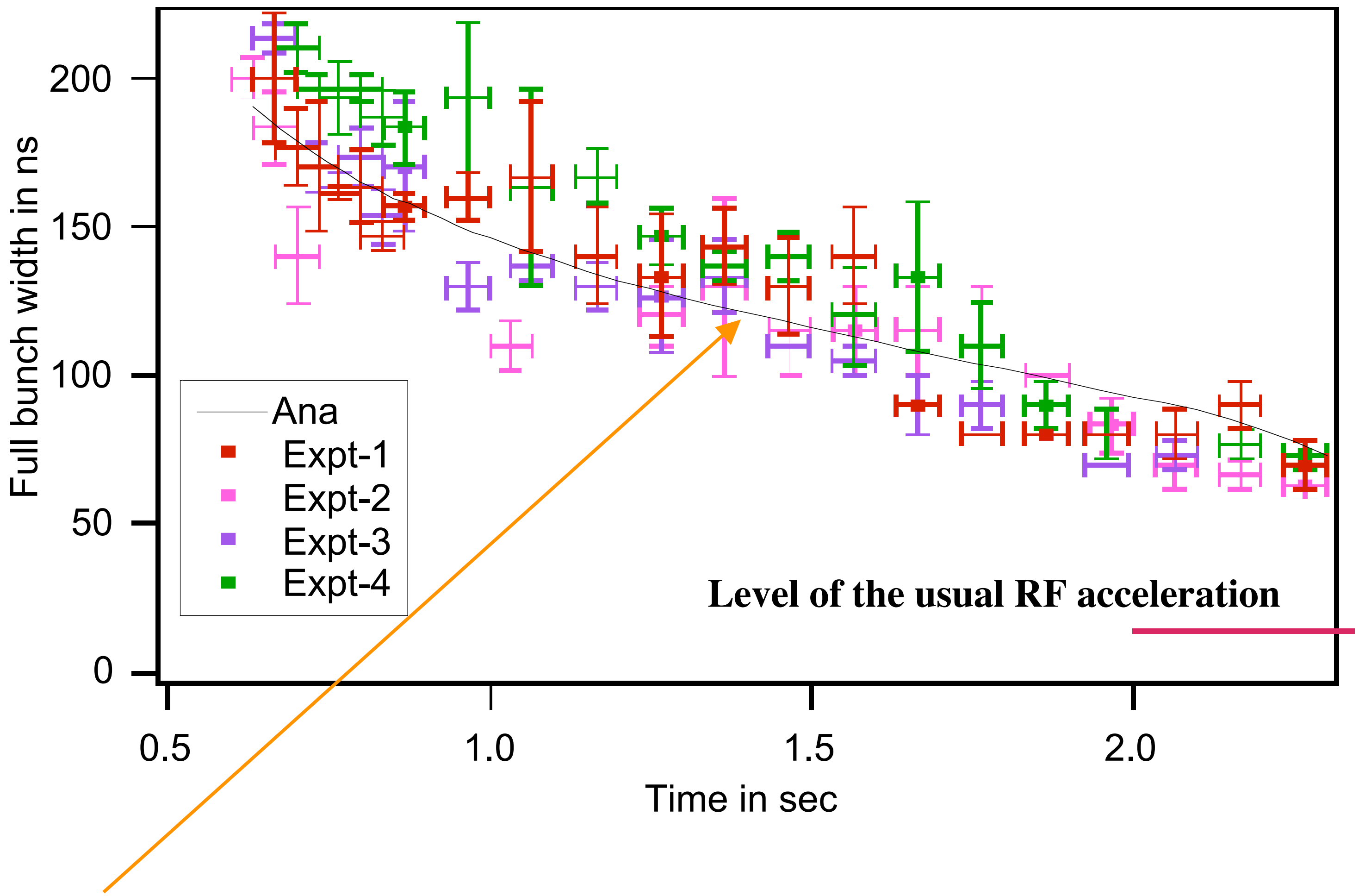
Bunch signal
(sky blue)

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.

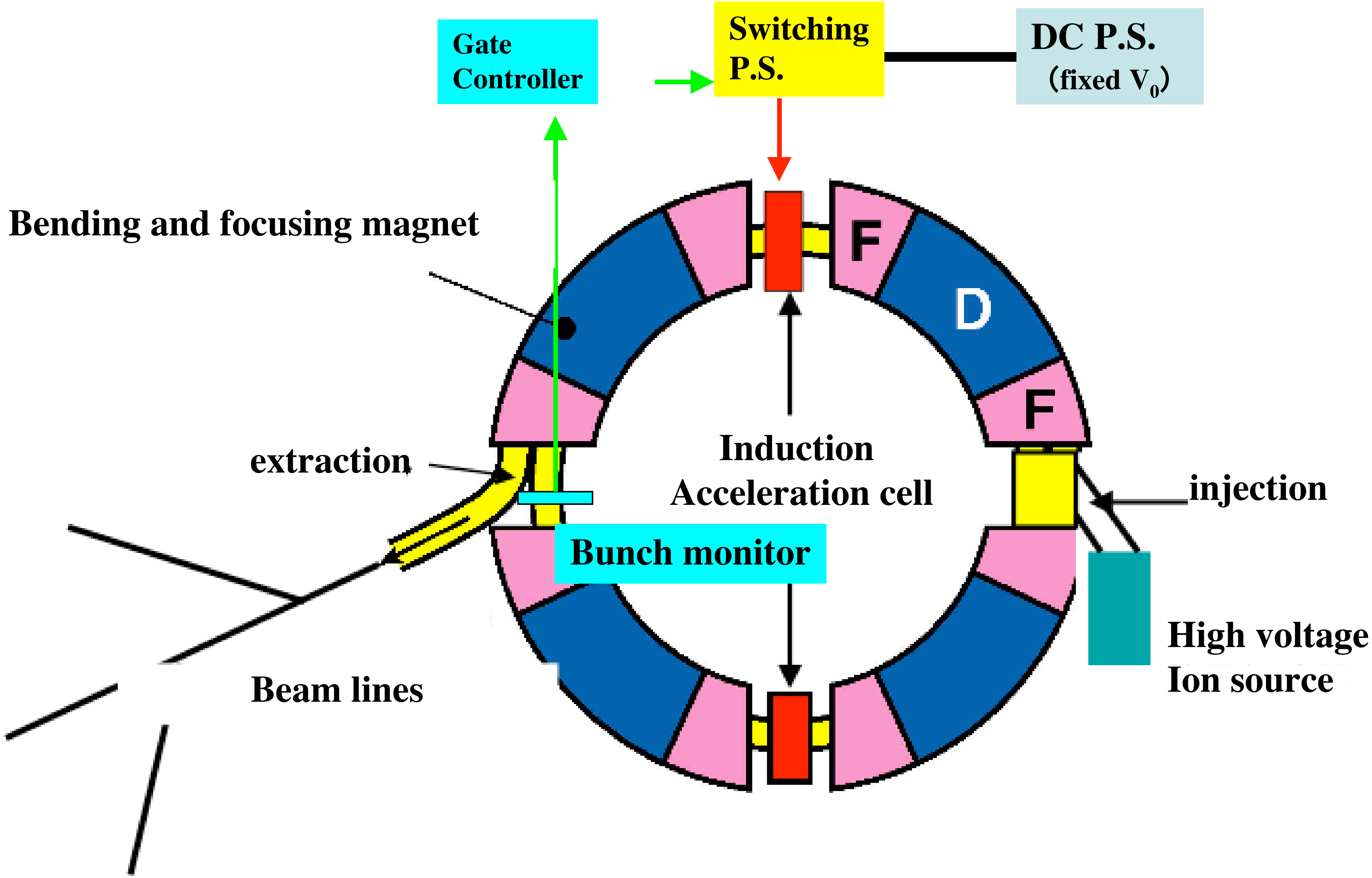
↓

**Concept of an all-ion accelerator**

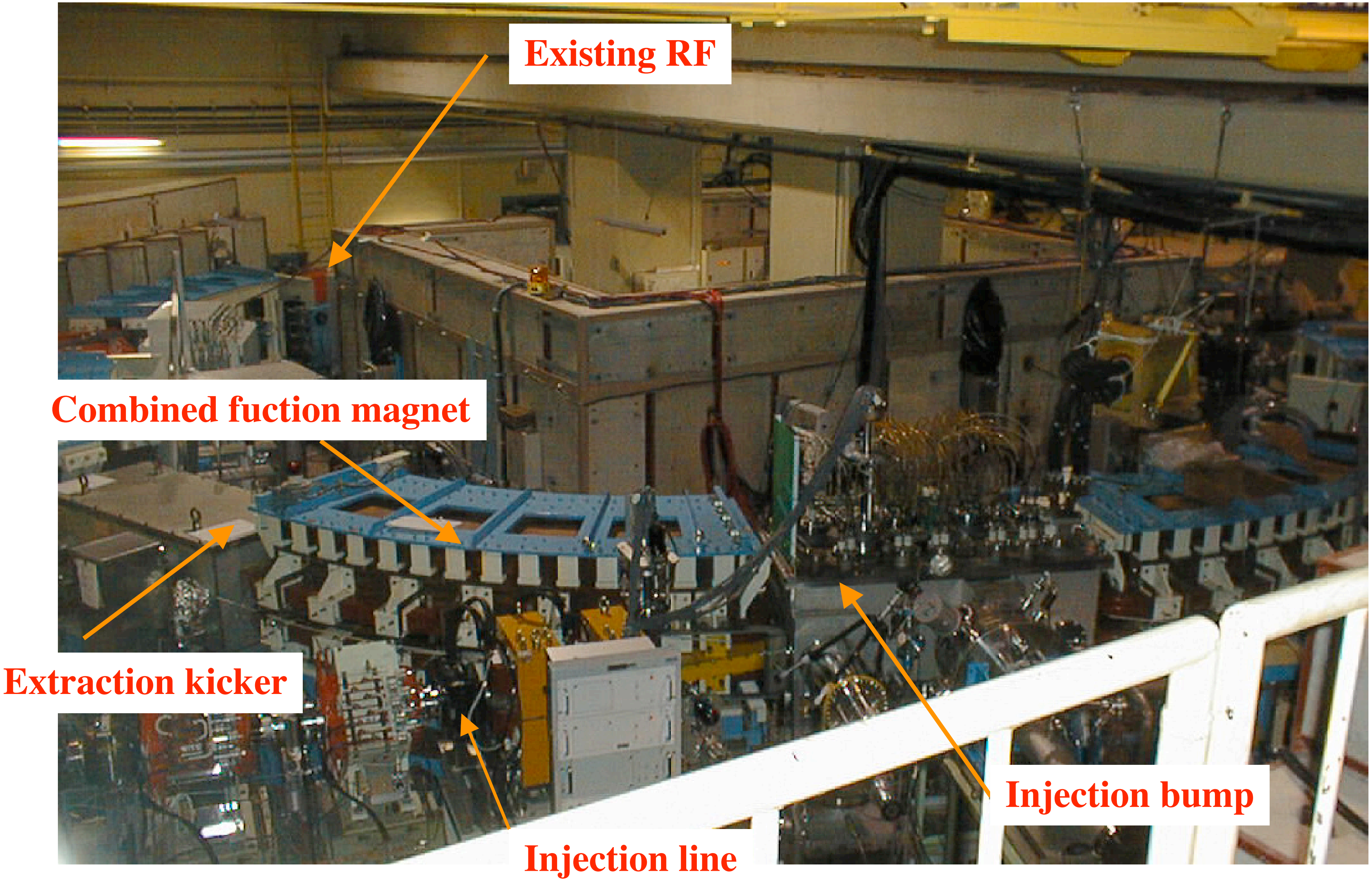
**almost injector-free**
**for a low intensity beam**

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

# Schematic View of AIA

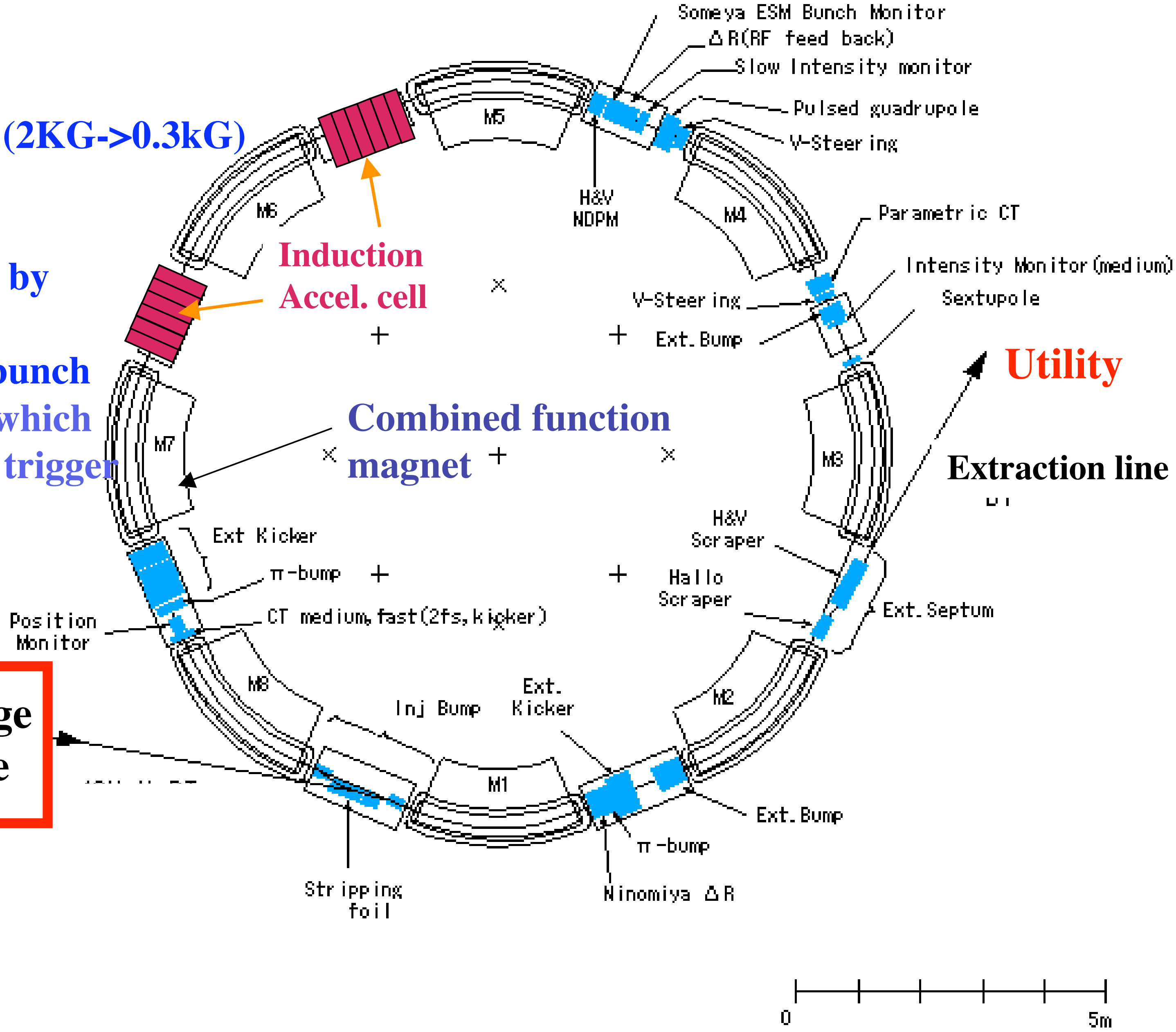


# 500 MeV KEK-Booster



# 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**



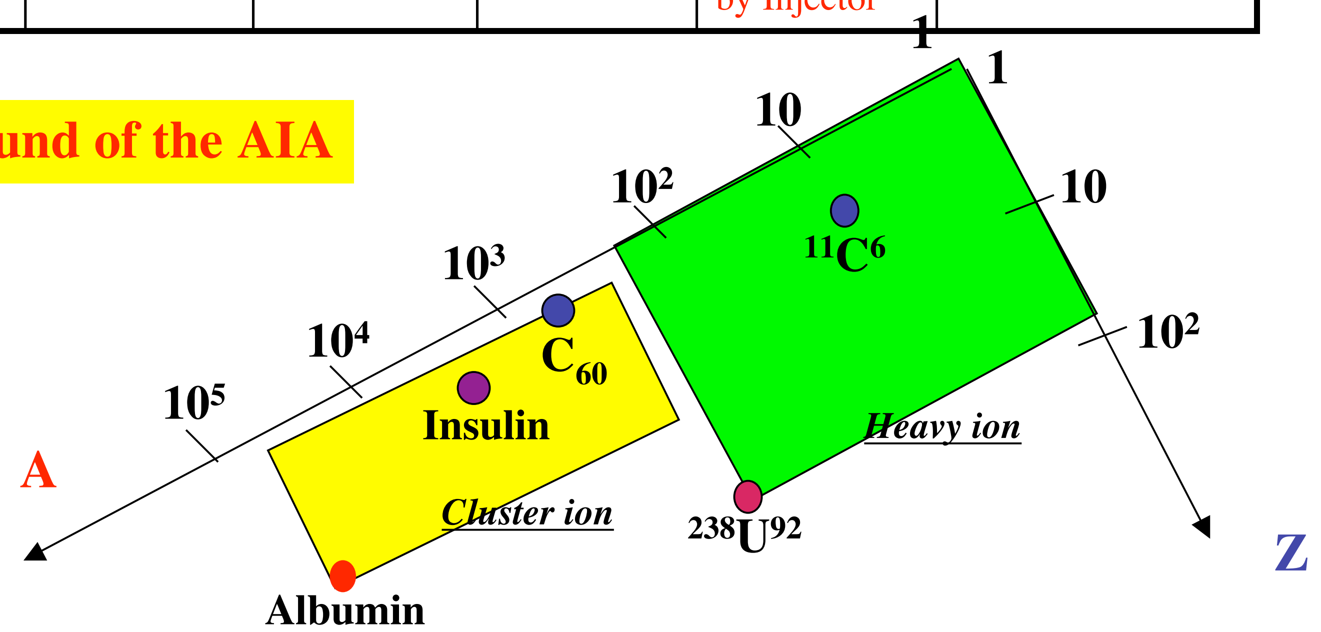

**High Voltage Ion Source**

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

# 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 |

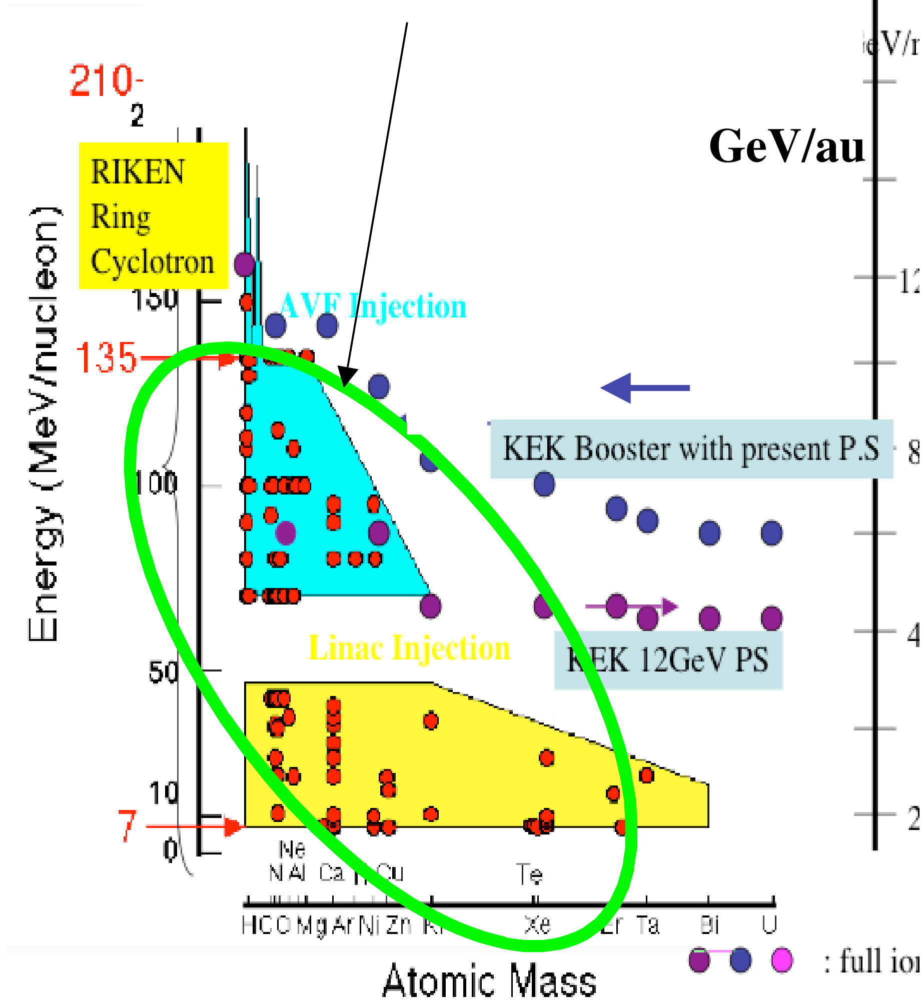
**Play ground of the AIA**




*if an extremely good vacuum is available*

# Comparison of the AIA with other existing medium energy ion drivers

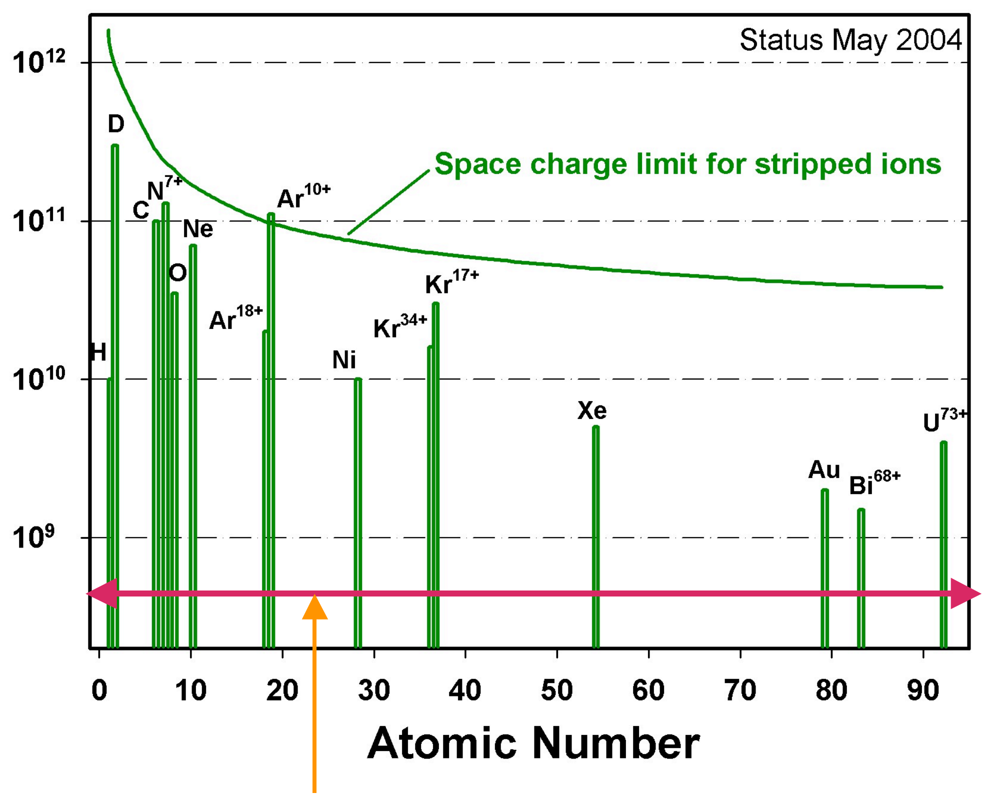
Ring Cyclotron@RIKEN




**SIS-18@GSI**

$C_0 = 216$ m
$f_0 = 214$ kHz
$f = 1$ Hz

## Particle Numbers per Cycle(1sec)




*The AIA will try to cover all region.*

# 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

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

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

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

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**

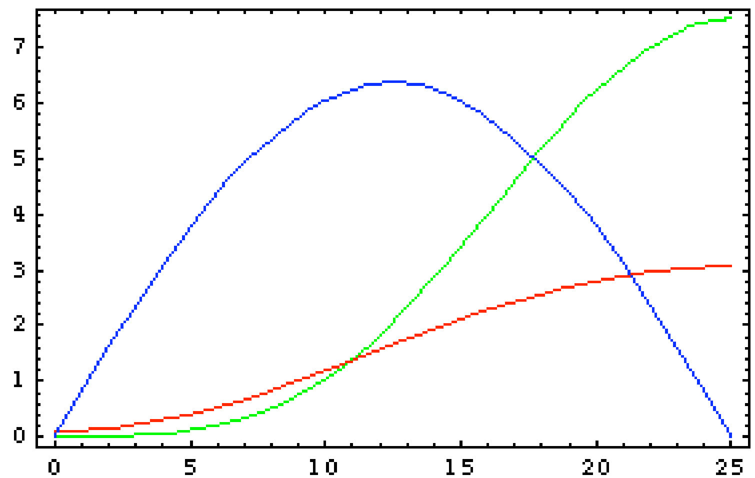
**$B_f$=0.7, $f$=10Hz**

**We will try at first.**

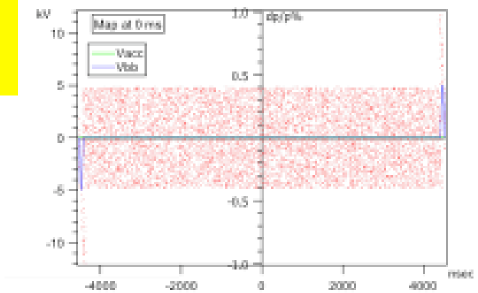
| | $^{12}C^{+6}$ | $^{40}Ar^{+18}$ | $^{197}Au^{+79}$ |
|---|---|---|---|
| *A/Z* | 12/6 | 40/18 | 197/79 |
| $N_{limit}(=N_i)$ | 1.3x10$^{11}$ | 4.7x10$^{10}$ | 1.1x10$^{10}$ |
| *N/sec* | 1.3x10$^{12}$ | 4.7x10$^{11}$ | 1.1x10$^{11}$ |
| extract. E (MeV/au) | | 75 | |
| depo.energy (J/cc) | | 2.3x10$^{3}$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

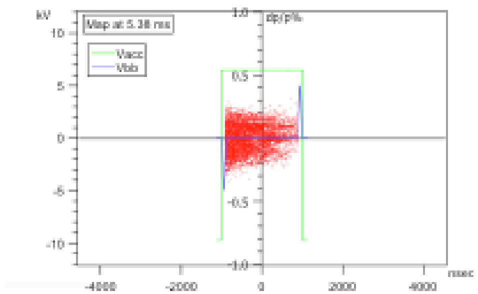
# Example of $Ar^{+18}$ Acceleration

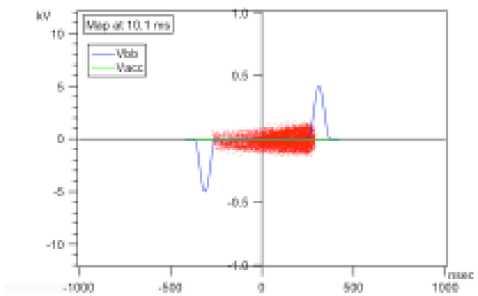
*E(t)/10* (MeV/au), $V_{acc}(t)$ (kV), *f(t)* (MHz)

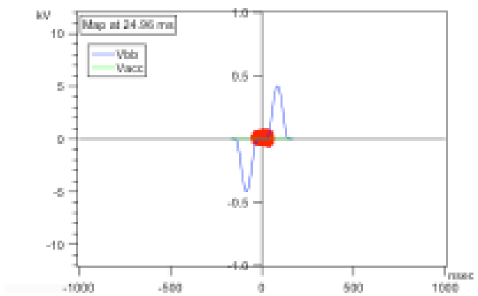


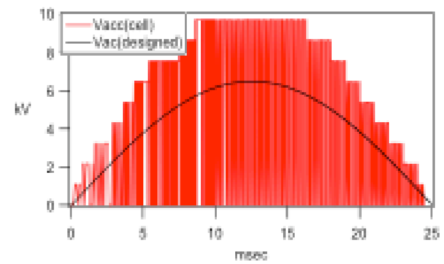
**t (msec)**



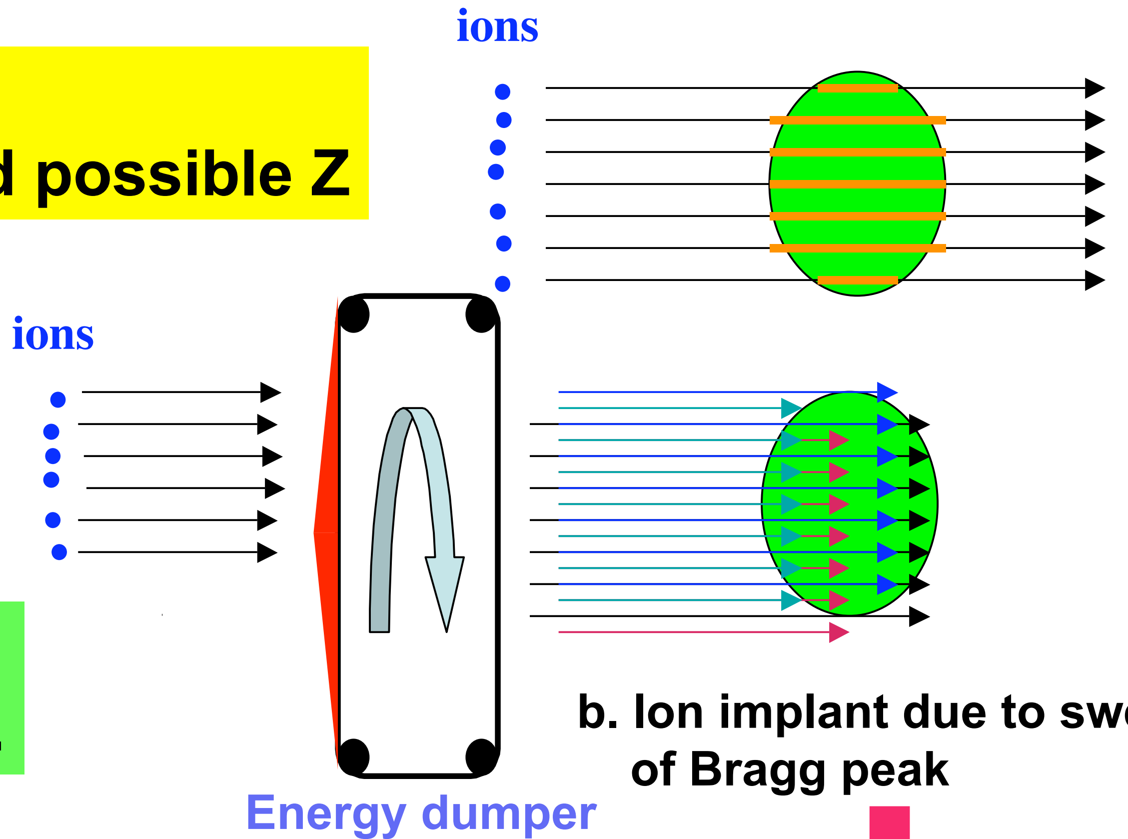
# B. Bulk Material Science

irradiate

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

**a. Energy deposit due to electro-excitation**

**Ions**
**with arbitray A and possible Z**




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

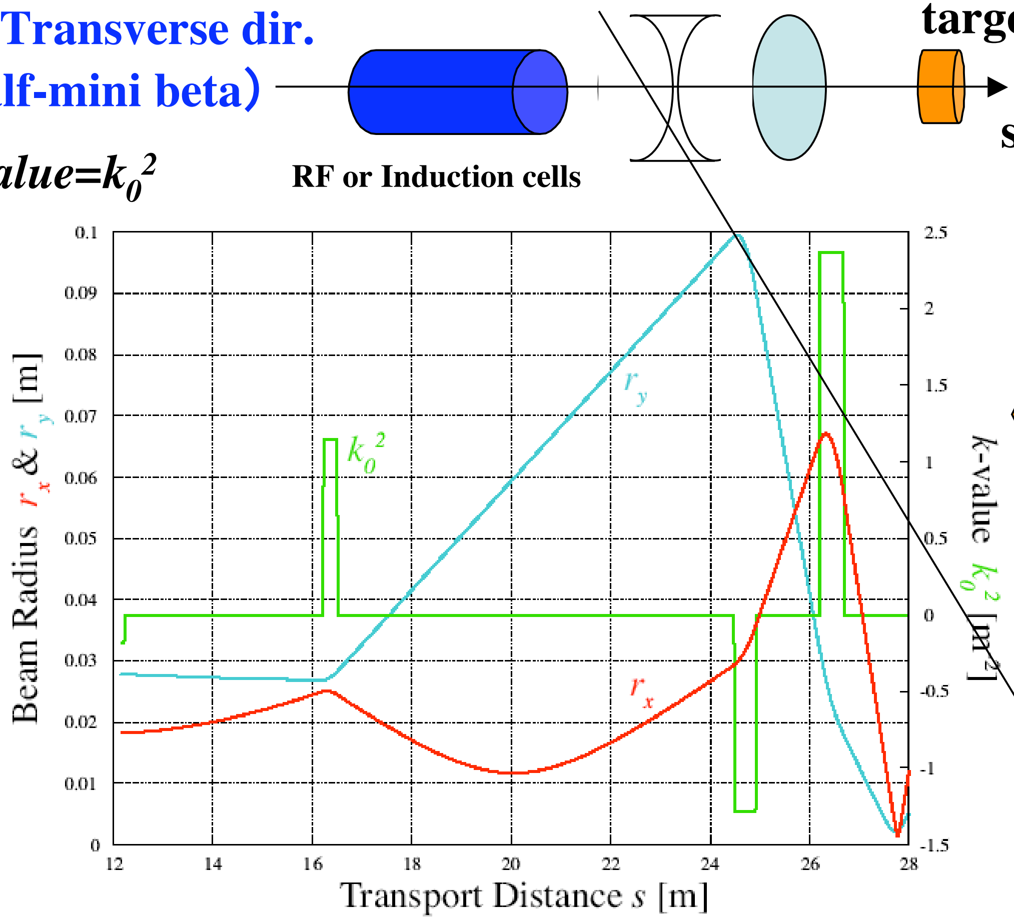
**b. Ion implant due to sweeping of Bragg peak**

**Creation of novel bulk materials**

**Beam-line for the WDM Science**

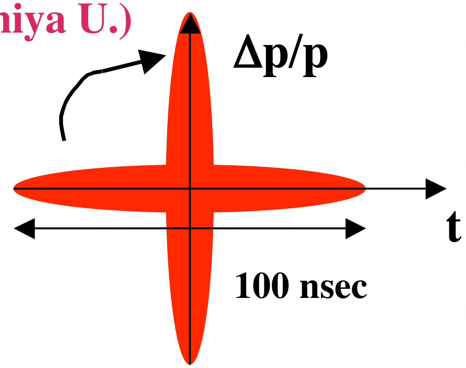
**a. Transverse dir. (half-mini beta)**

***K-value=$k_0^2$***

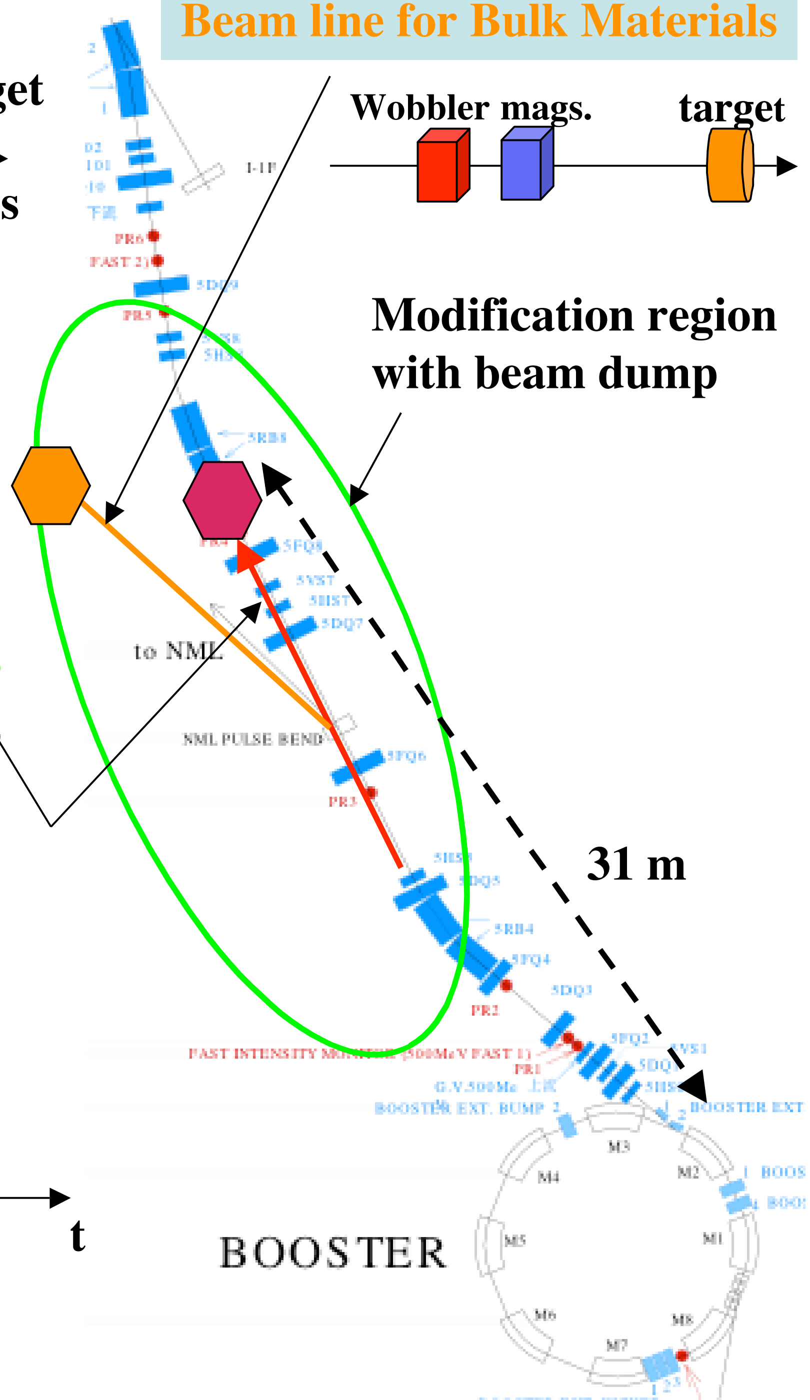



**Calculation by Kikuchi (Utsunomiya U.)**

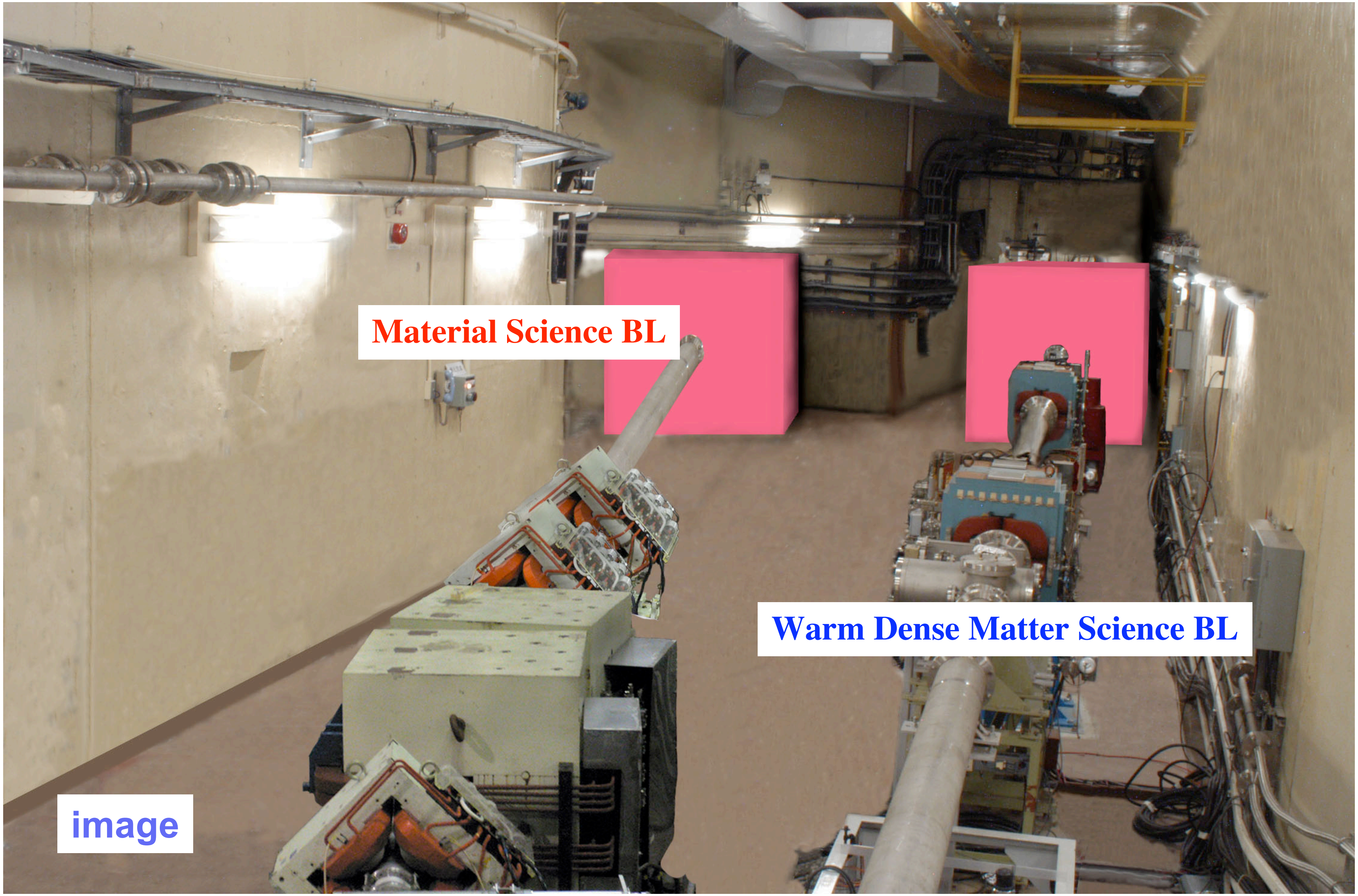
**b. Compression in the longitudinal direction (Phase-rotation)**



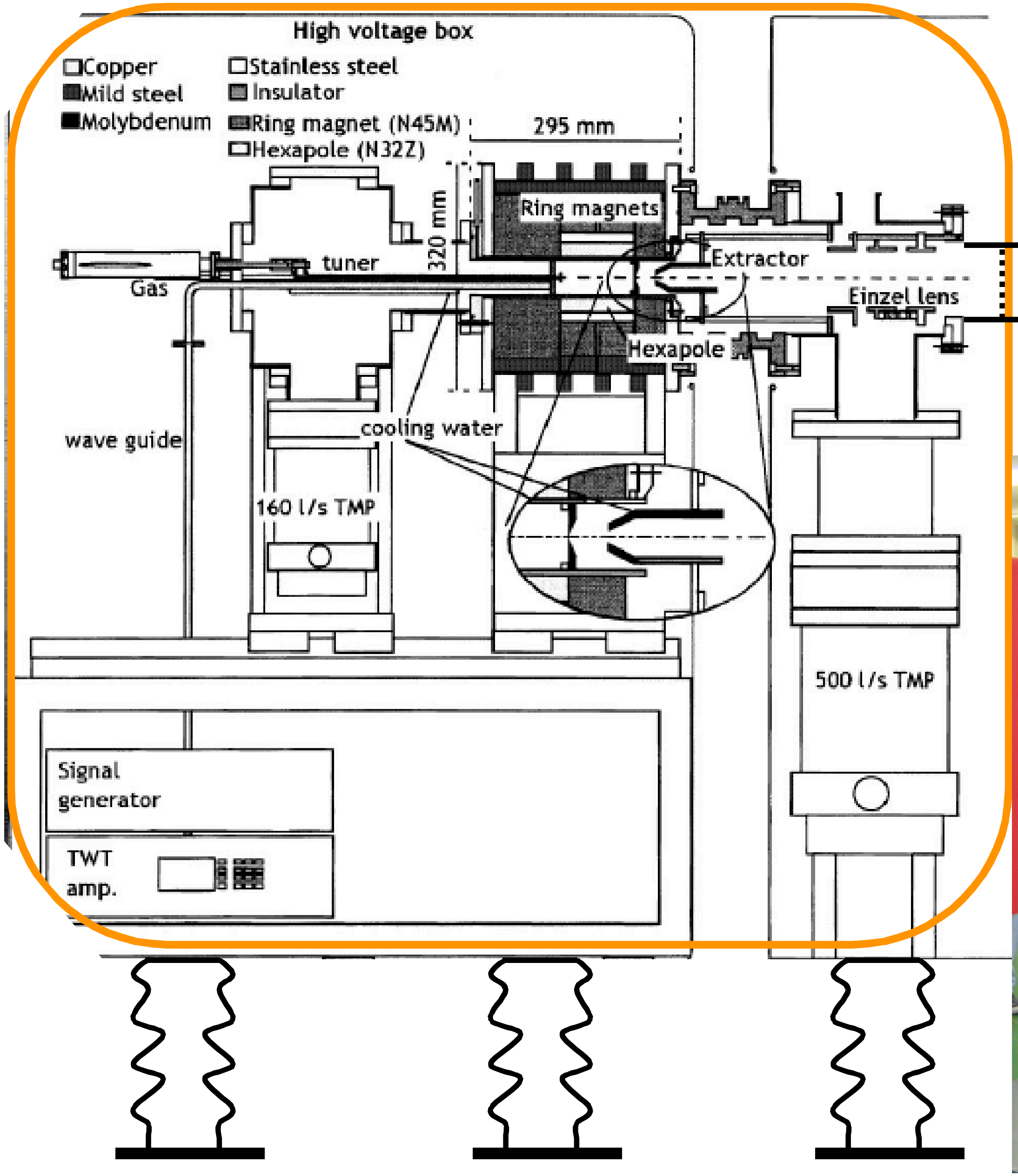

**Beam line for Bulk Materials**



# Modified Beam-lines

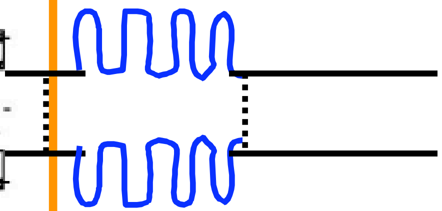


# 200KV Ion-Source




9.4 GHz permanent-mag. ECR

200kV acceleration tube



# 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.