

# Induction Acceleration in Synchrotrons and Cyclotrons

**K. Takayama**

*High Energy Accelerator Research Organization (KEK)  
Tokyo Institute of Technology*

**W. Jiang**

*Nagaoka University of Technology*

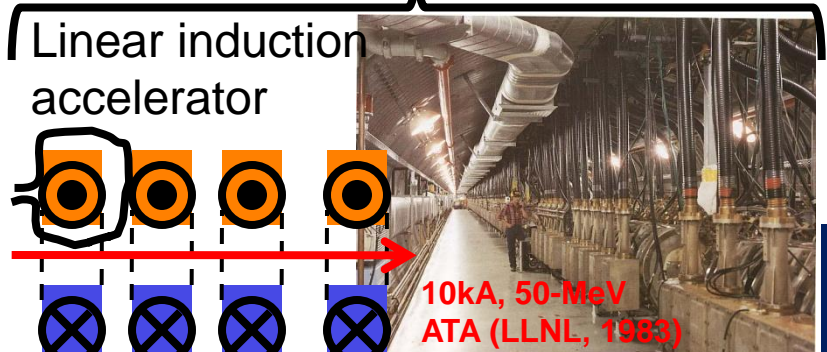
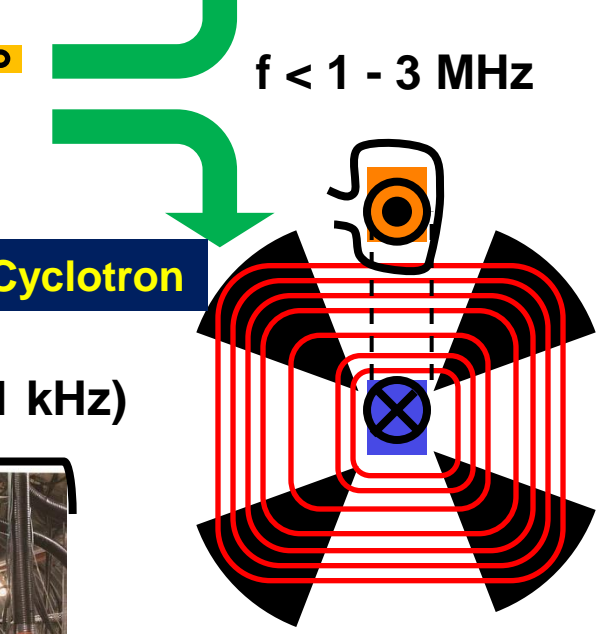
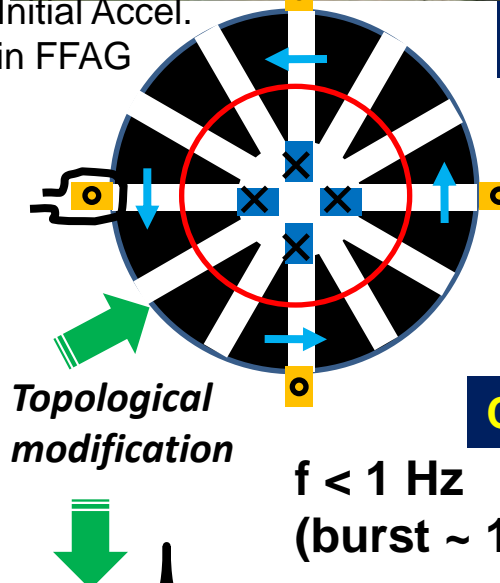
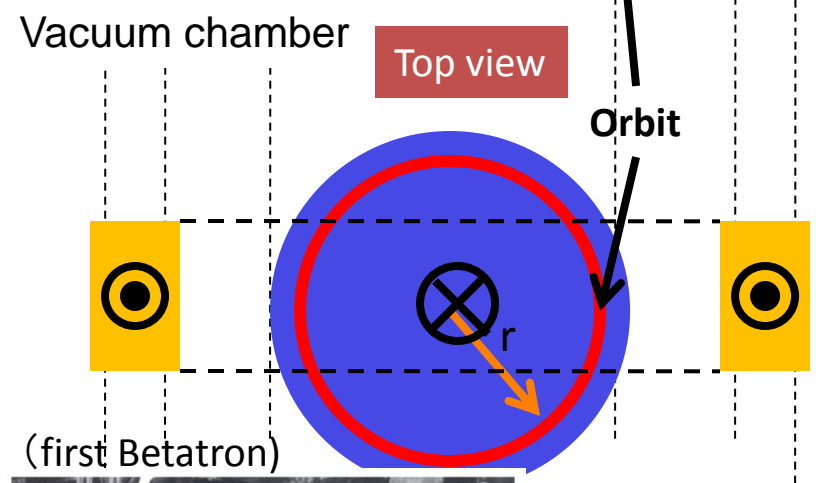
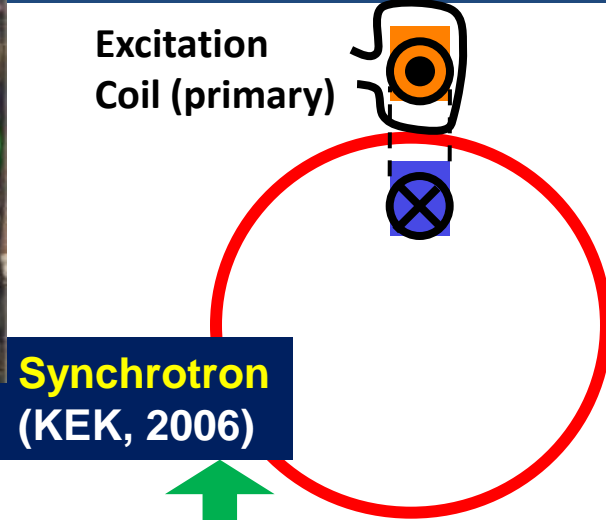
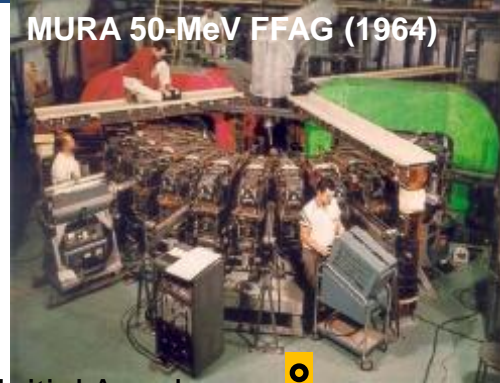
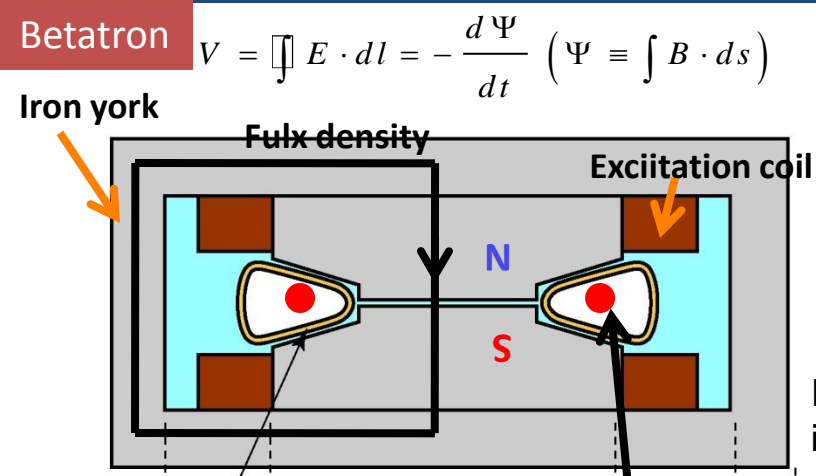
October 10-14, 2010 in Jeju

**EAPPC 2010**

# Outline of Talk

1. A brief history of induction acceleration in circular rings
2. Example of Induction acceleration
  - KEK Induction Synchrotron/Digital Accelerator**
  - 2-1 Schematic features
  - 2-2 Key devices
3. Outline of Induction Sector Cyclotron (ISC)
  - 3-1 Acceleration and confinement
  - 3-2 Induction cell
4. Summary

# From Betatron to Induction Synchrotron / Cyclotron

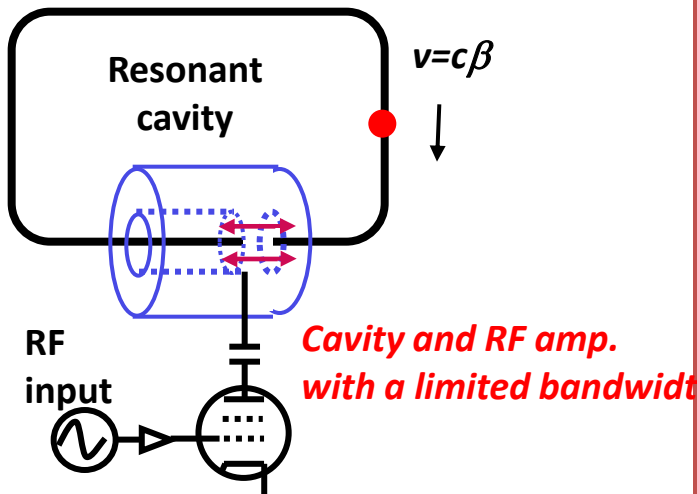


for more history

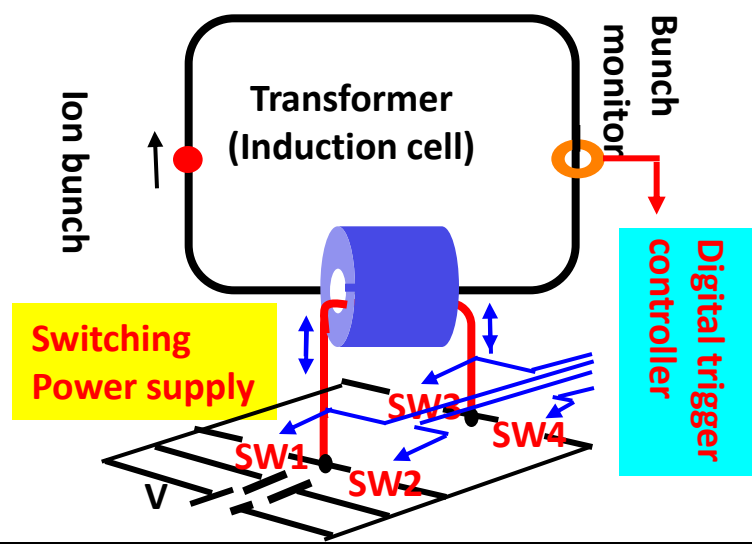
K.Takayama and R.Briggs (Eds.)  
"Induction Accelerators"  
(Springer, 2010 October)

# Characteristics of Circular Induction Accelerator (Synchrotron)

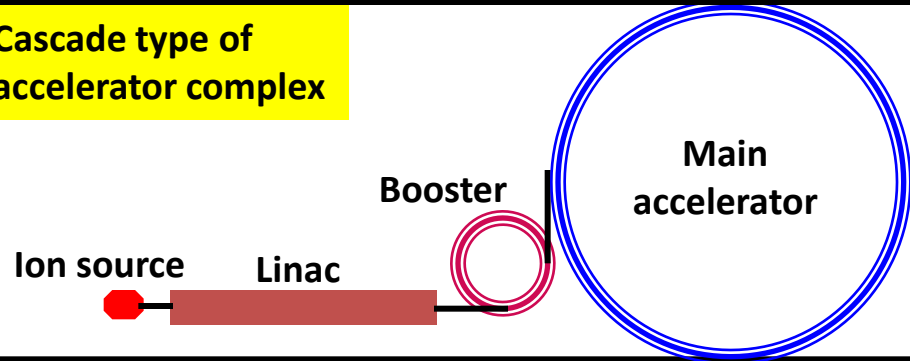
RF Synchrotron



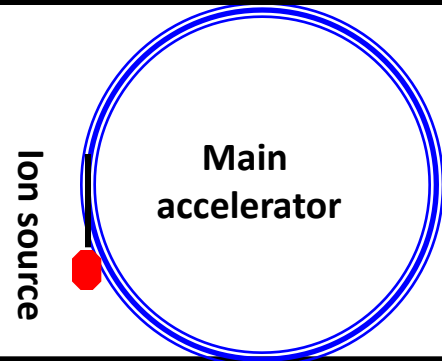
Induction Synchrotron



Cascade type of accelerator complex

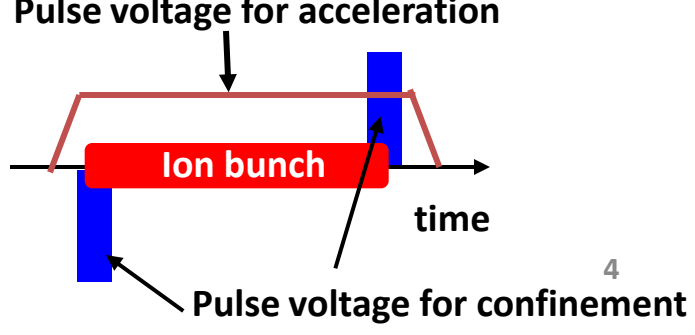
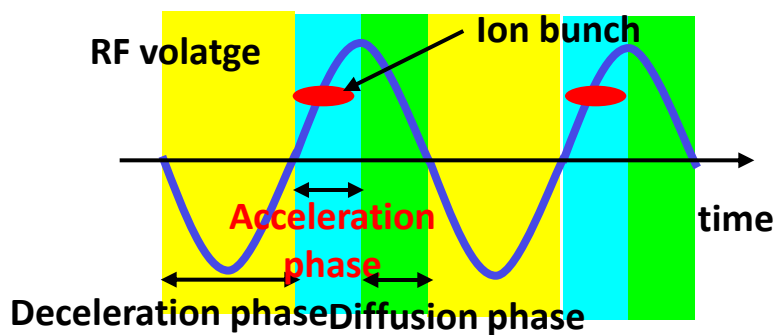


Single stage accelerator

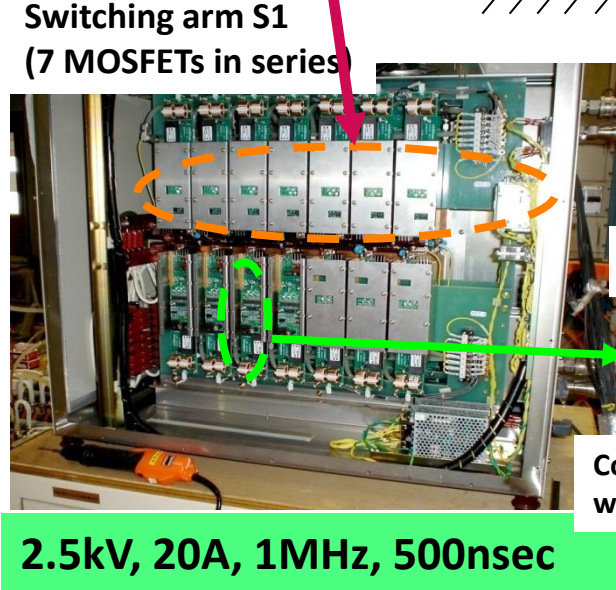
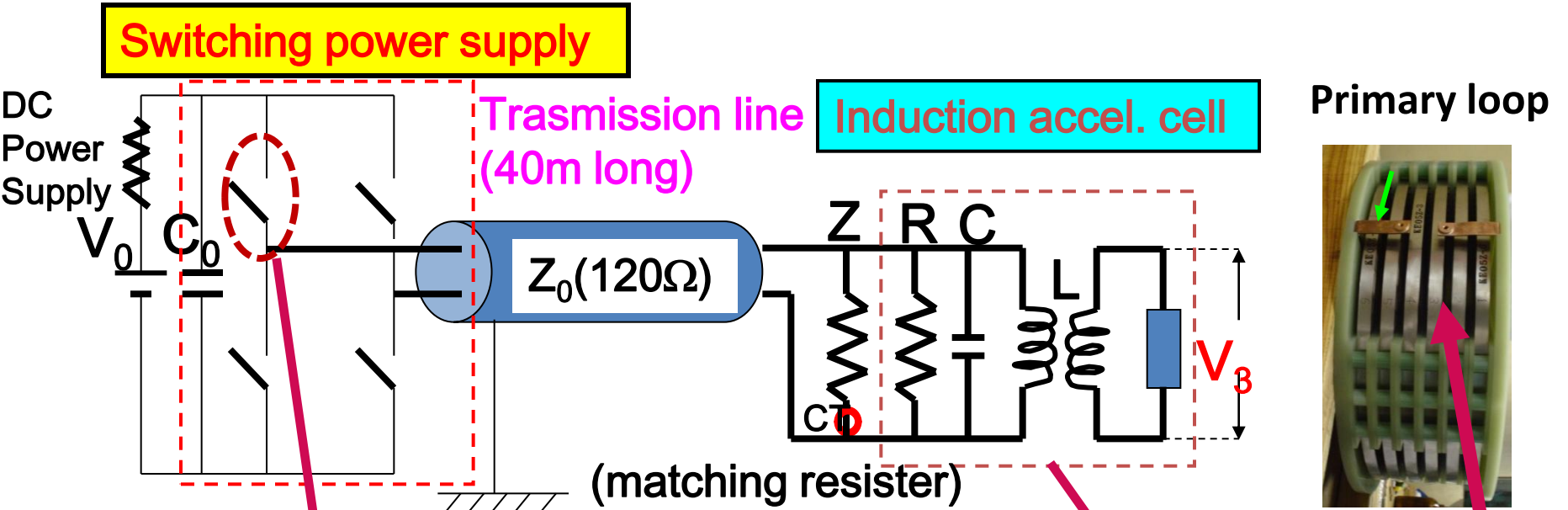


*Functionally combined acceleration/confinement -> increase in the local density -> limit on a beam current*

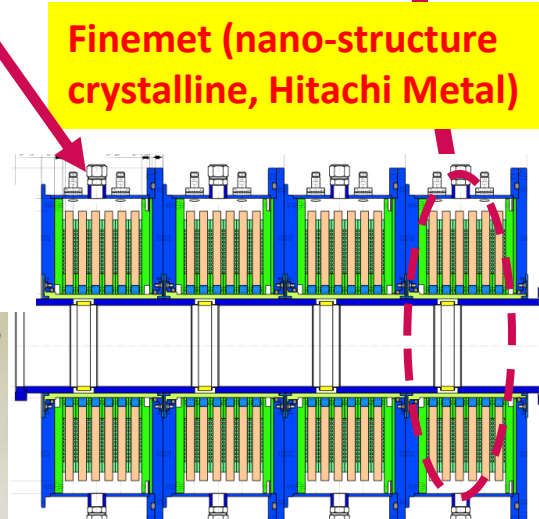
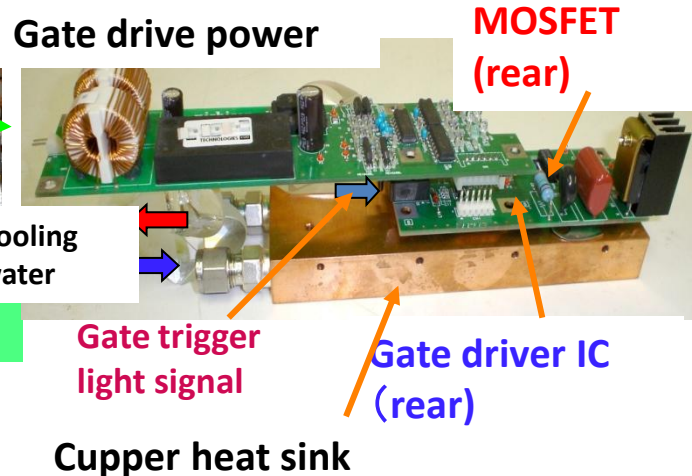
*Functionally separated acceleration/confinement -> increasing a freedom of beam handling*



# Equivalent Circuit of Induction Acceleration System and Individual Instruments



**MOSFET board**

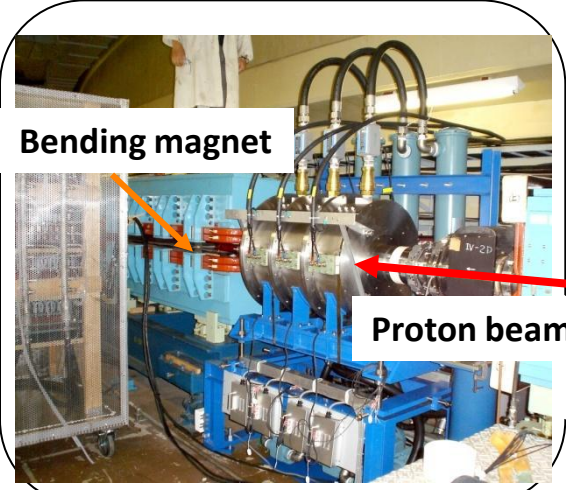
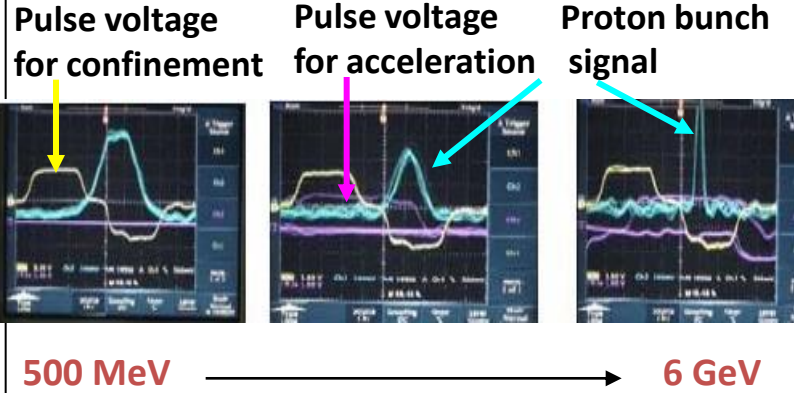


**Stacked induction cells (output: 2 kV/cell)**

**Development by KEK · Nichicon**

# Demonstration of the Induction Synchrotron Concept (2006, March)

ion:  $H^+$   
 500 MeV  $\rightarrow$  6 GeV  
 $N=2.5 \times 10^{11}$



Switching Power Supply  
 (40kW, Max  $f_{rep}=1\text{MHz}$ )

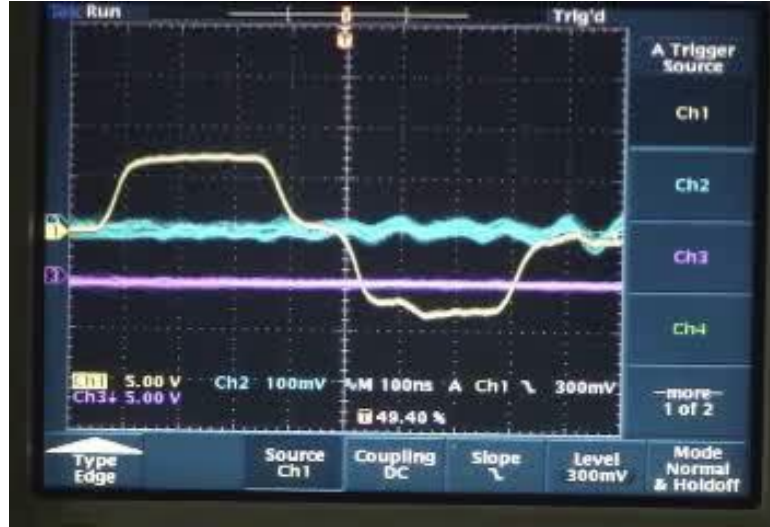
Induction cell  
 10 cells  
 $V_{out}=2\text{kV/cell}$

KEK 12GeV  
 Proton Synchrotron  
 $C_0=340\text{m}$

500MeV Booster  
 $C_0=37\text{m}$

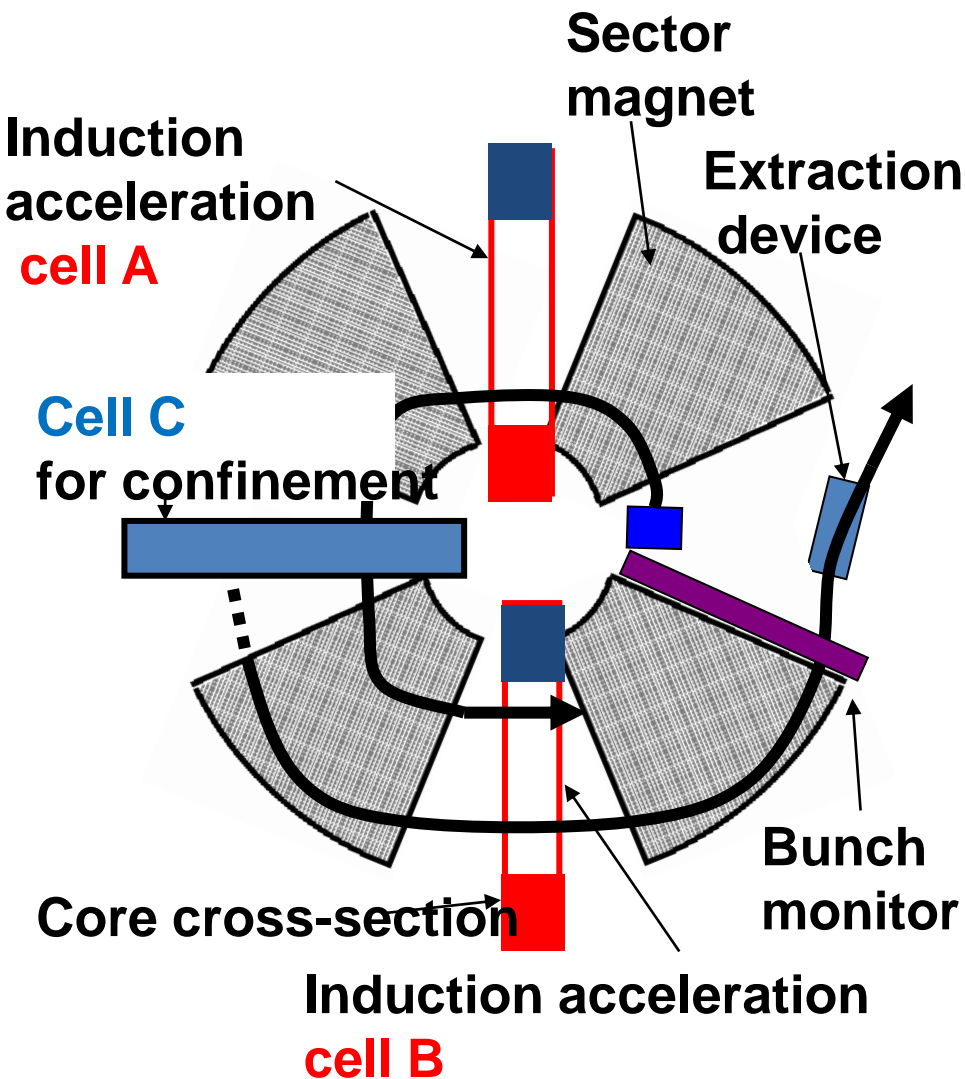
40MeV H-Linac

750keV  
 Cockloft

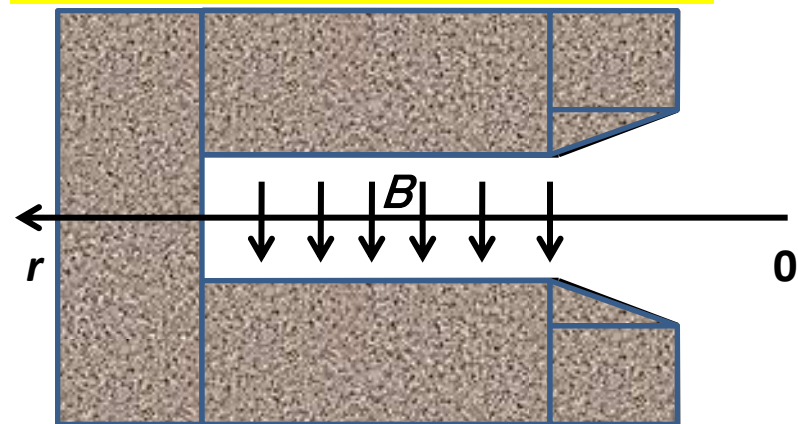




# Layout of Induction Sector Cyclotron

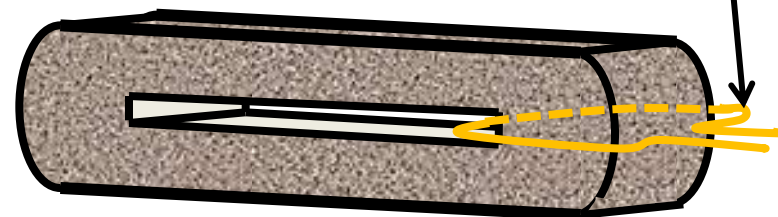


## Sector magnet cross-section



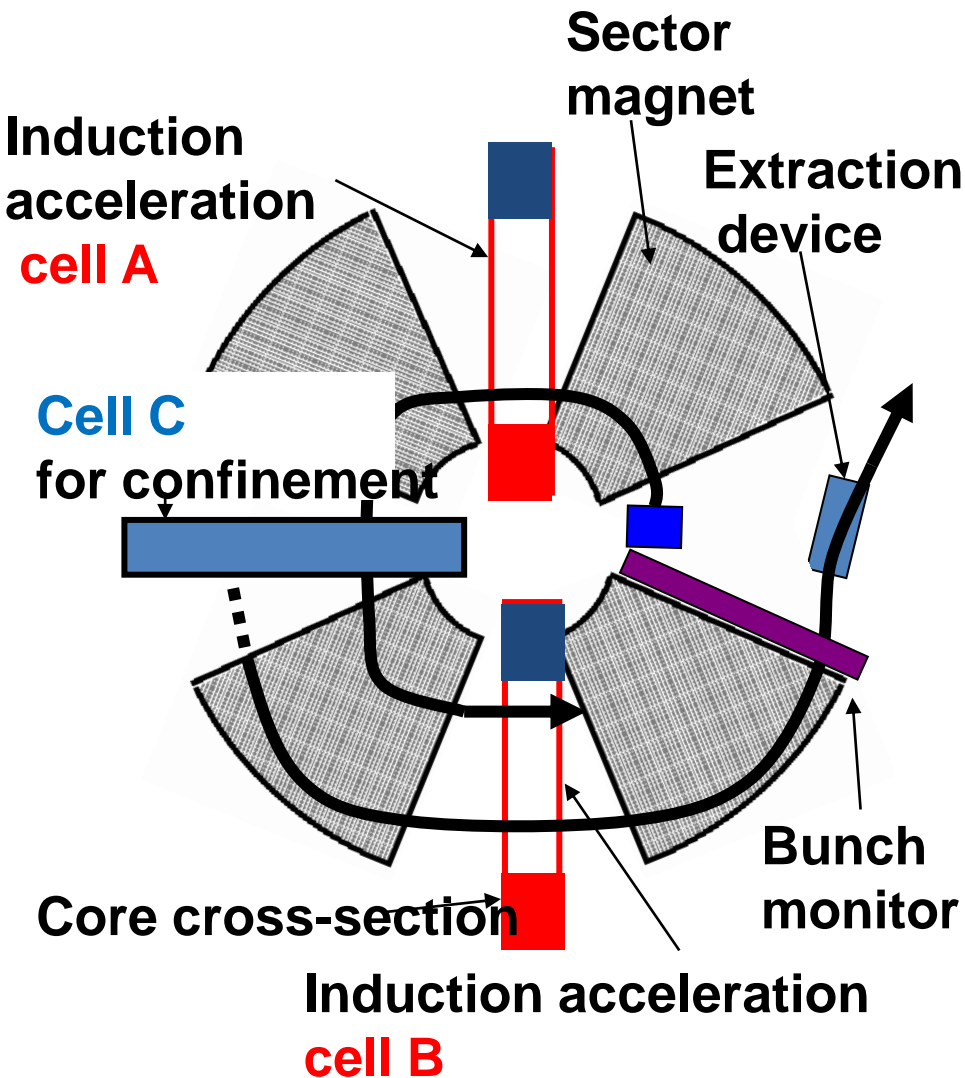
## Induction core

Excitation coil

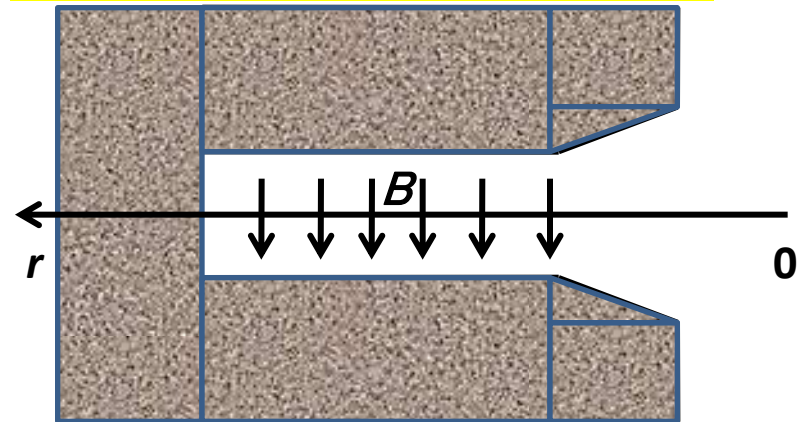


- Induction cells are located between adjacent sector magnets. Two type cells will be used.  
**Cell A/B for acceleration**  
**Cell C for confinement**
- Horizontally wide aperture induction cells are required. In order to realize this shape, a nanocrystalline thin tape as a magnetic material will be wound in a race-track shape.

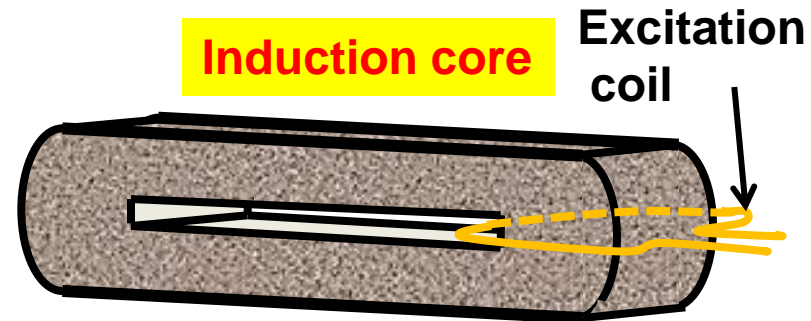
# Layout of Induction Sector Cyclotron



## Sector magnet cross-section

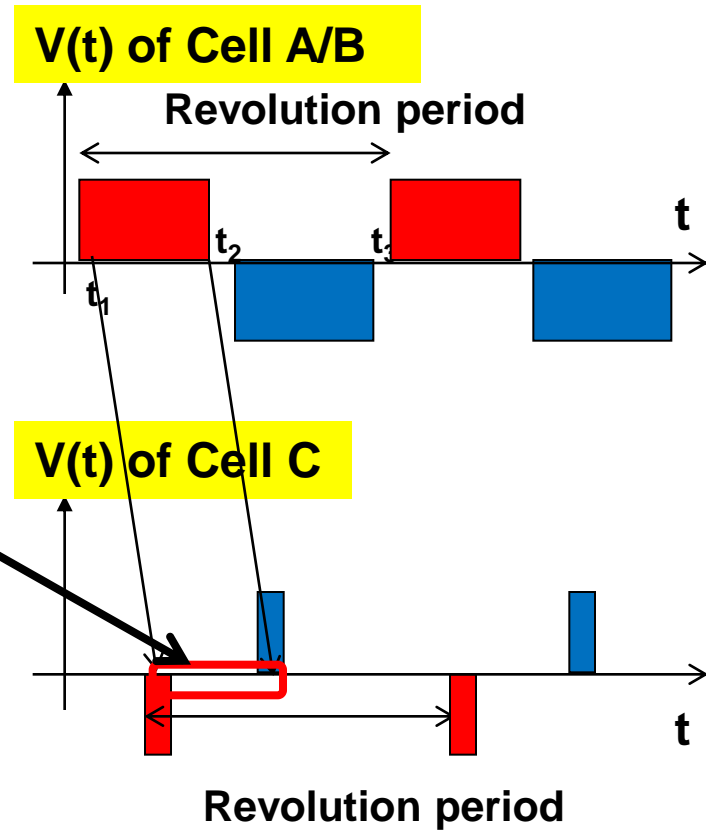
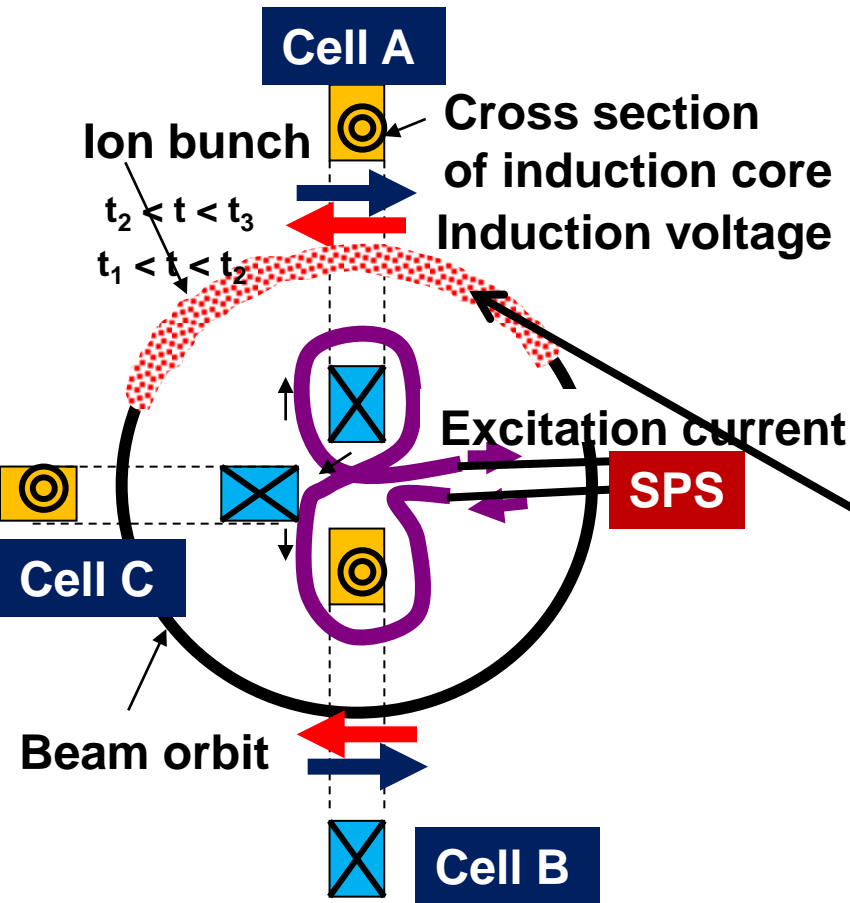


## Induction core



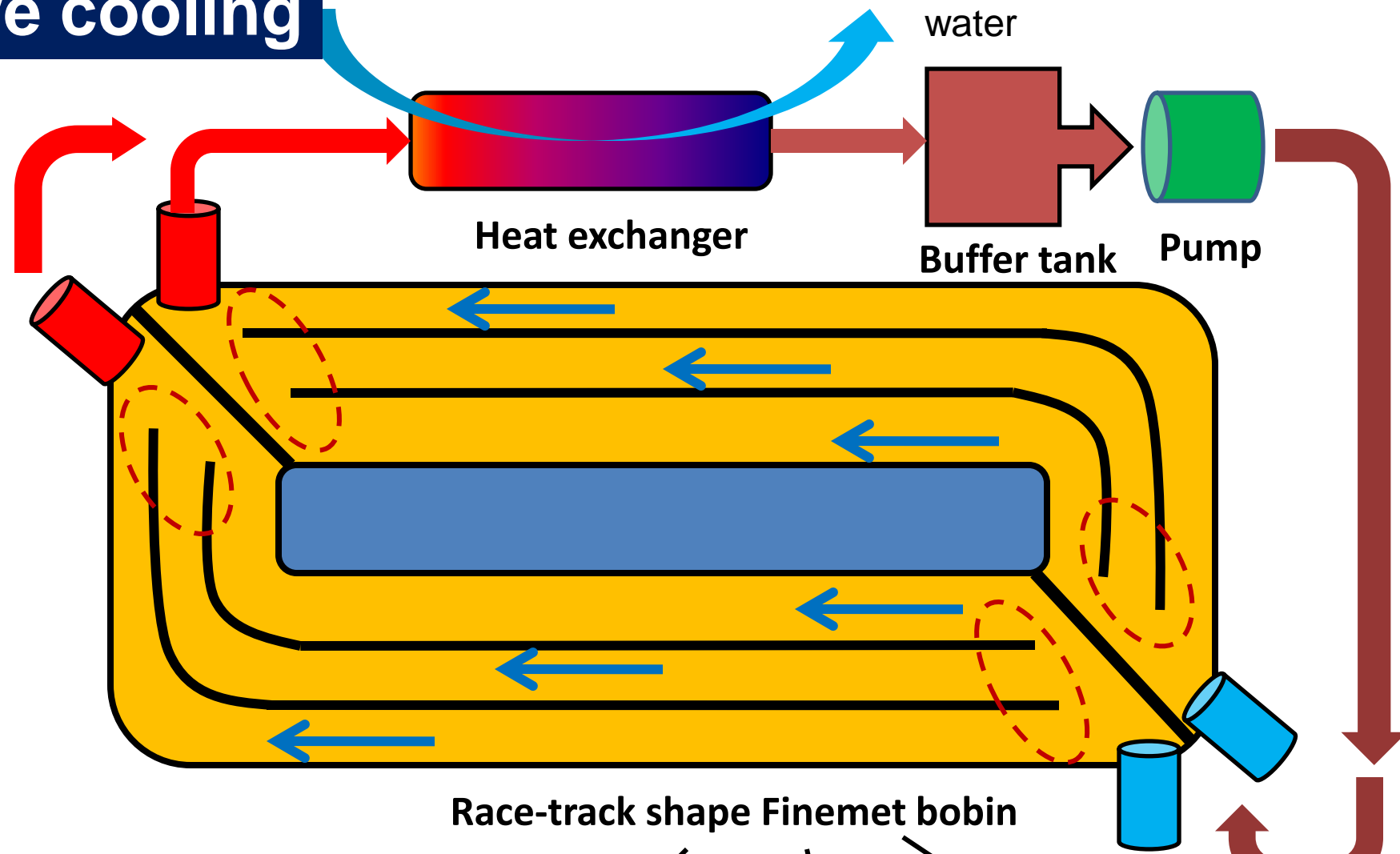
- Induction cells are located between adjacent sector magnets.  
Two type cells will be used.  
**Cell A/B for acceleration**  
**Cell C for confinement**
- Horizontally wide aperture induction cells are required.  
In order to realize this shape, a nanocrystalline thin tape as a magnetic material will be wound in a race-track shape.

# Acceleration Principle and Pulse Profiles



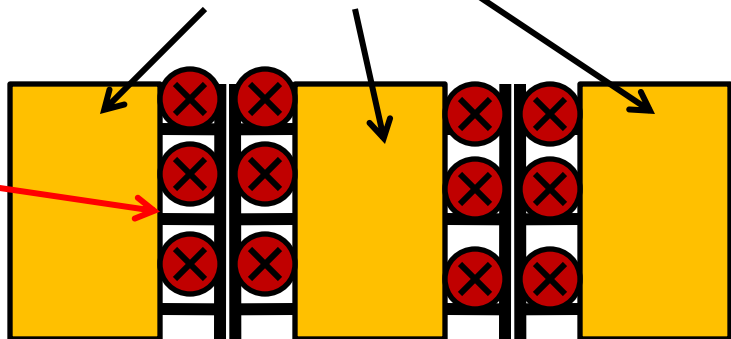
- An ion beam is bunched by barrier voltages generated in Cell C. The beam pulse occupies less than half of the orbit length.
- Cell A/B are set and reset every turn of the ion bunch to avoid saturation of the core material.
- The primary coil of Cell A/B is connected in series with 8-figure, being driven by a common PS.  
**Set-voltage in Cell A and reset voltage in Cell B contribute to the induction acceleration.**
- This series connection is helpful to duplicate the core inductance, resulting in mitigation of the droop voltage.

# Core cooling



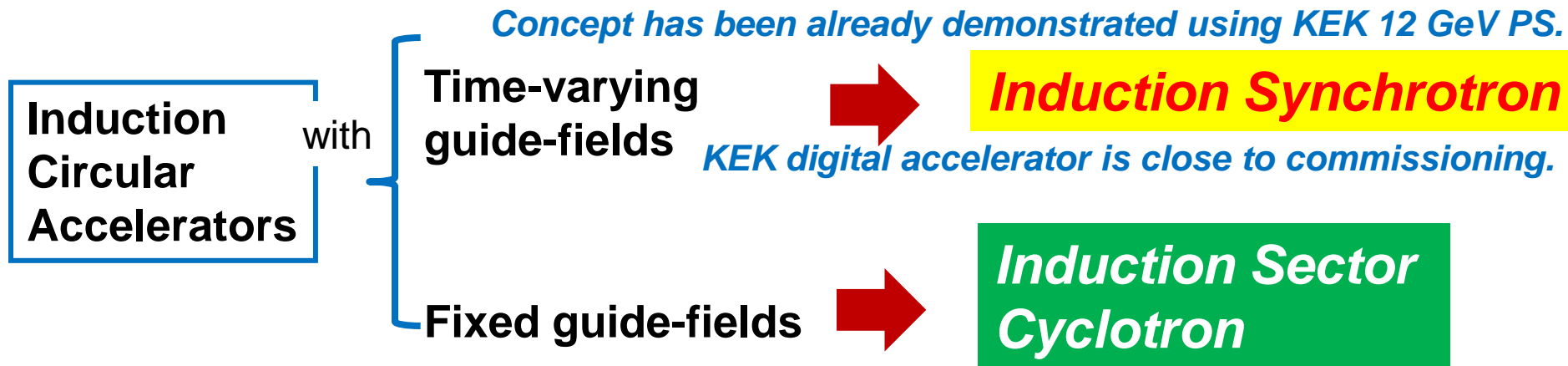
Race-track shape Finemet bobin

Spacer with cooling channel



Insulating silicon oil

# Summary



## Properties:

**Turn-by turn acceleration**

Functionally separated **acceleration** and **confinement**

## Key devices:

Extremely high rep-rate switching power supply



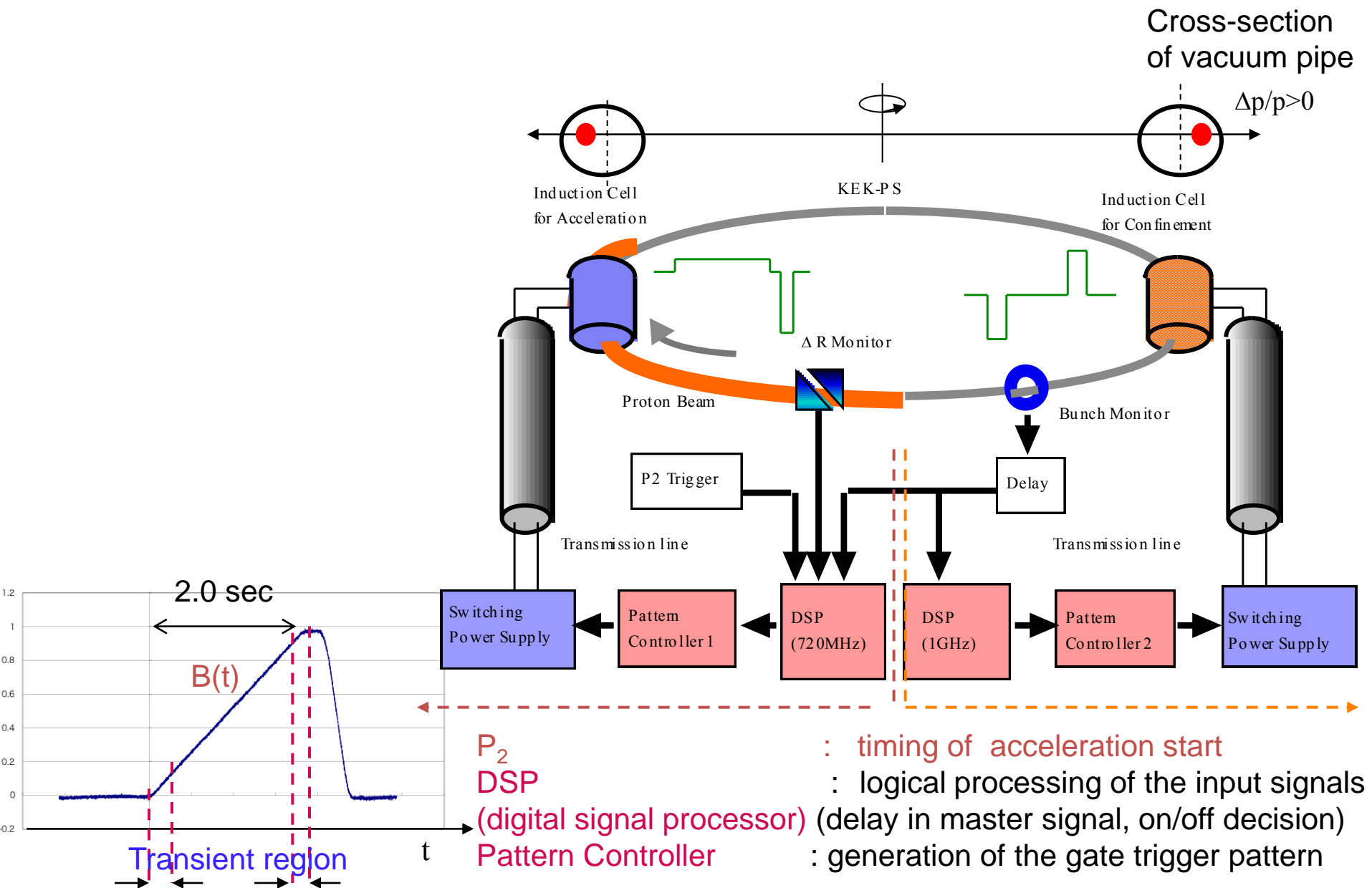
Solid-state switching element/module

with voltage resistance of **2-3 kV** and carrying current of **50 A**

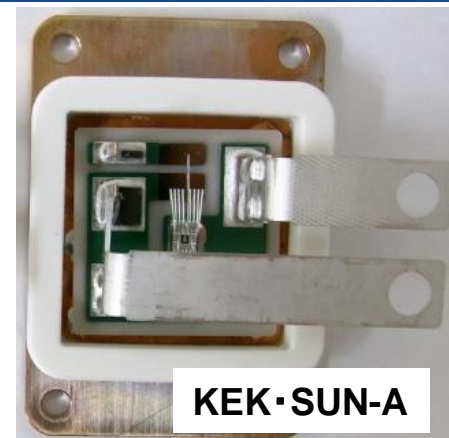
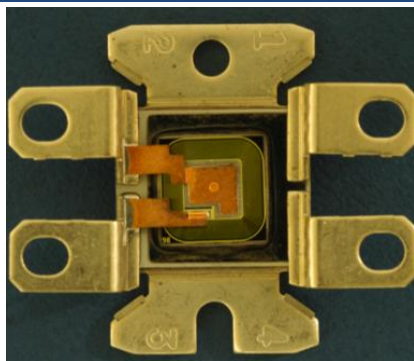
rising/falling time < **100 nsec**

capable of operating at **1 MHz rep-rate**

# Control of Acceleration



# Development of Switching Module and Switching Power Supply at KEK



## Chip provider

SiC-JFET (SICED)  
SIThy (秋田新電元・NGK)  
others

## Virtual R&D Center

### Development of module

- Chip coating
- circuit design
- dye bonding
- wire/ribbon bonding
- thermal design
- overall package design

### Development of S.P.S.

- design of circuit architecture
- prototype
- operation

## Heat transfer material provider

KEK  
Nagaoka Tech  
Iwate U.  
TIT  
JPPL

## Packaging

SUN-A  
KYOCERA  
Hitachi-Haranomachi  
NEC-Network/Sensor

## Manufacturer

Nichicon-Kusatsu  
NEC  
Sawafuji Elec. Co.  
JPPL  
others

> 50 kVA, < 3 MHz, long life  
■ Solid-state Marx Generator  
■ Solid-state modulator

KEK·other institutes

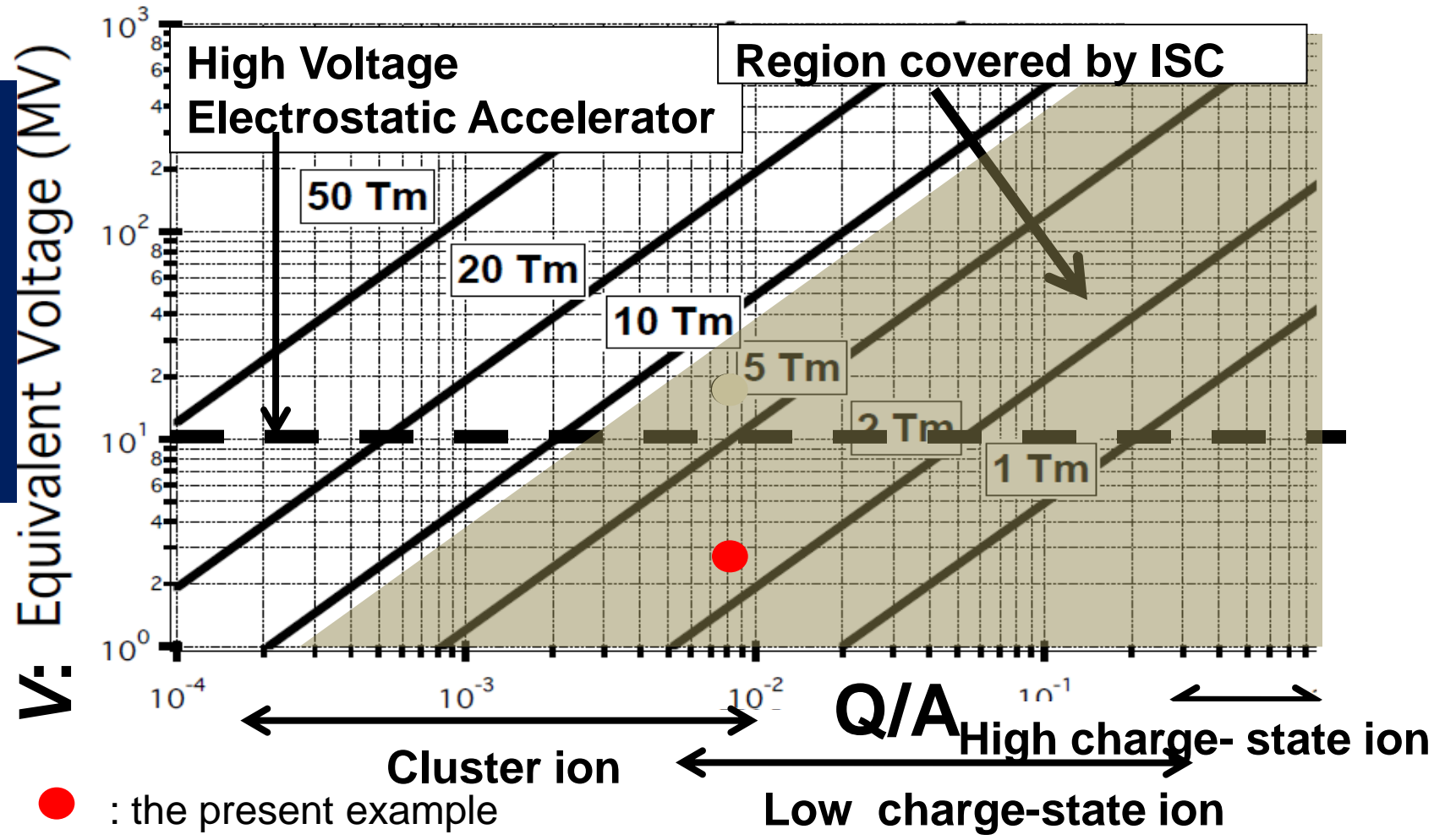
*Request (fast rising/fall high rep-rate):*

Kicker, Septum magnet  
Chopper, Air core mag.  
Induction cell  
Other pulse devices

feedback

# Achievable Energy vs. Magnetic Rigidity of ISC

$E = QV \text{ (MeV)}$



- Achievable energy is simply dependent of the **magnetic rigidity** of sector magnet as well as in other cyclotrons.
- Equivalent voltage, which can be easily compared with the acceleration voltage of electro-static accelerator, is shown as a function of the **ratio of charge state "Q" to mass number "A"**.

# Motivation

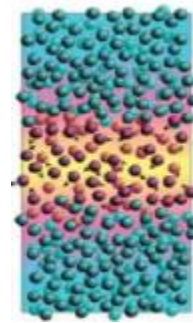
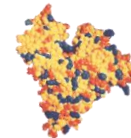
Acceleration of cluster ions,  $Q/A$  of which is extremely small ( $< 1/10-100$ ).  
Its acceleration frequency falls out of that of RF.  
So far a unique solution has been an electrostatic accelerator.  
A single-end electrostatic accelerator has a limitation of achievable charge-state.

## Why

$A=720$



$A \sim 10^4$



Energy density of swift cluster ions is extremely high in space.



Deep damage on a target material is unpredictable because of nonlinear effects.



- Unique driver for development of functionally noble materials
- Unique driver for studying Material Science or Warm Dense Matter Science