KEK Digital Accelerator *and* Recent Beam Commissioning Result

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on behalf of KEK Digital Accelerator Group

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

Heavy Ion Accelerator Technology 2012

from 18h June to 22nd June 2012
Chicago

Contents

1. Concept of Induction Synchrotron(*)
2. Outline of KEK Digital Accelerator
   (A fast cycle induction synchrotron)
      Key components
3. Beam commissioning results
4. Summary

** References*

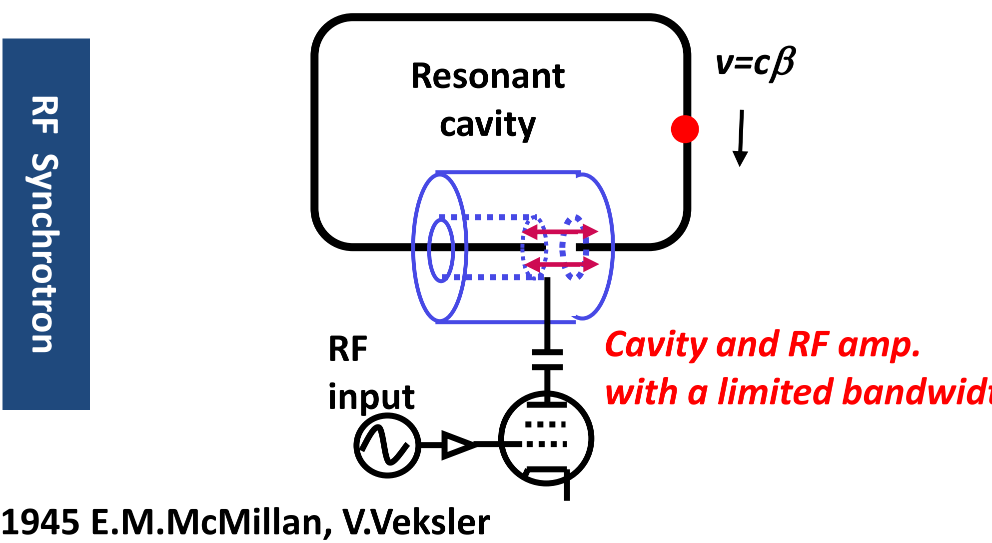
K.Takayama *et al*., "Experimental Demonstration of the Induction Synchrotron", *Phys. Rev. Lett*. **98**, 054801-4 (2007)

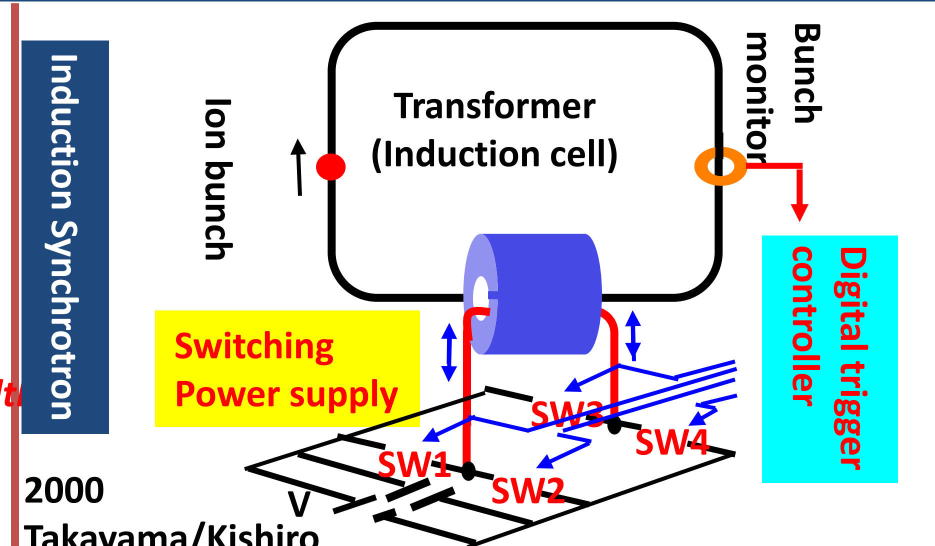
K.Takayama and R.J.Briggs, "Induction Accelerators", (Springer, 2010)

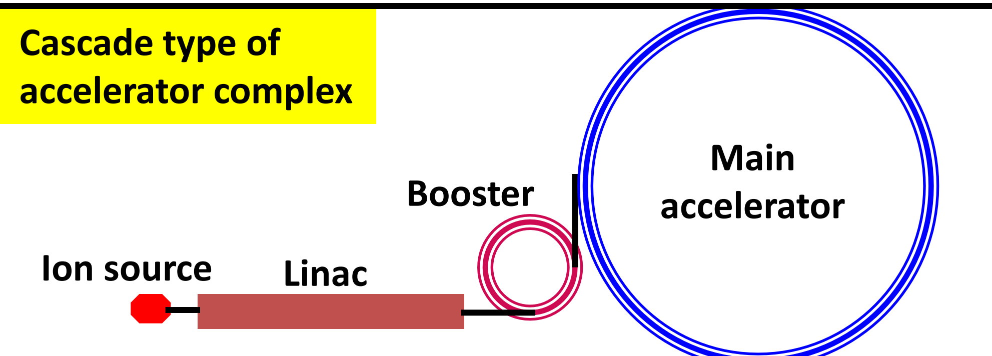
Companion paper (Poster Session of this afternoon, PO13):

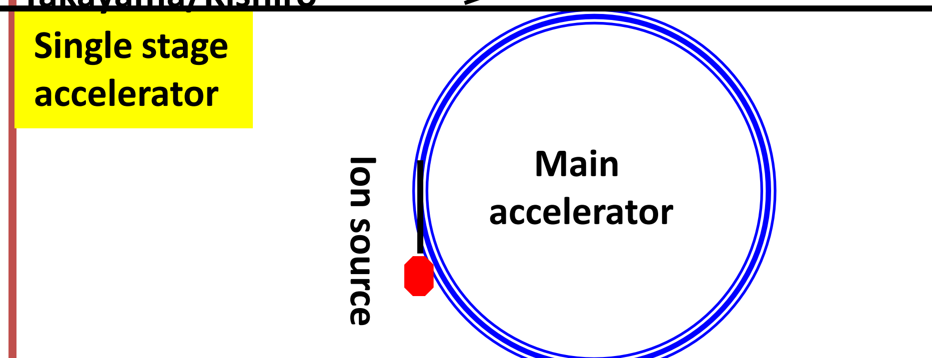
X. Liu *et al.,* "Longitudinal Beam Motion in the KEK Digital Accelerator: Tracking Simulation and Experimental Results"

Characteristics of Induction Synchrotron (Digital Accelerator)



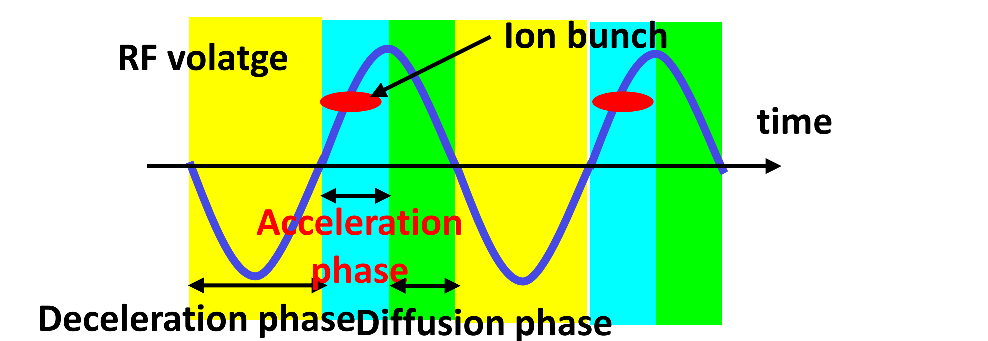


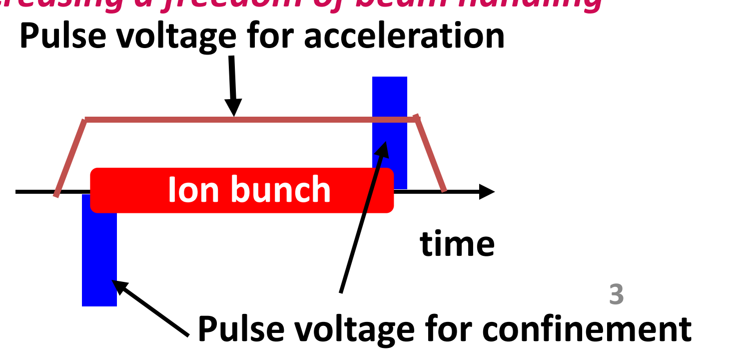




Functionally combined acceleration/confinement -> increase in the local density -> limit on a beam current

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

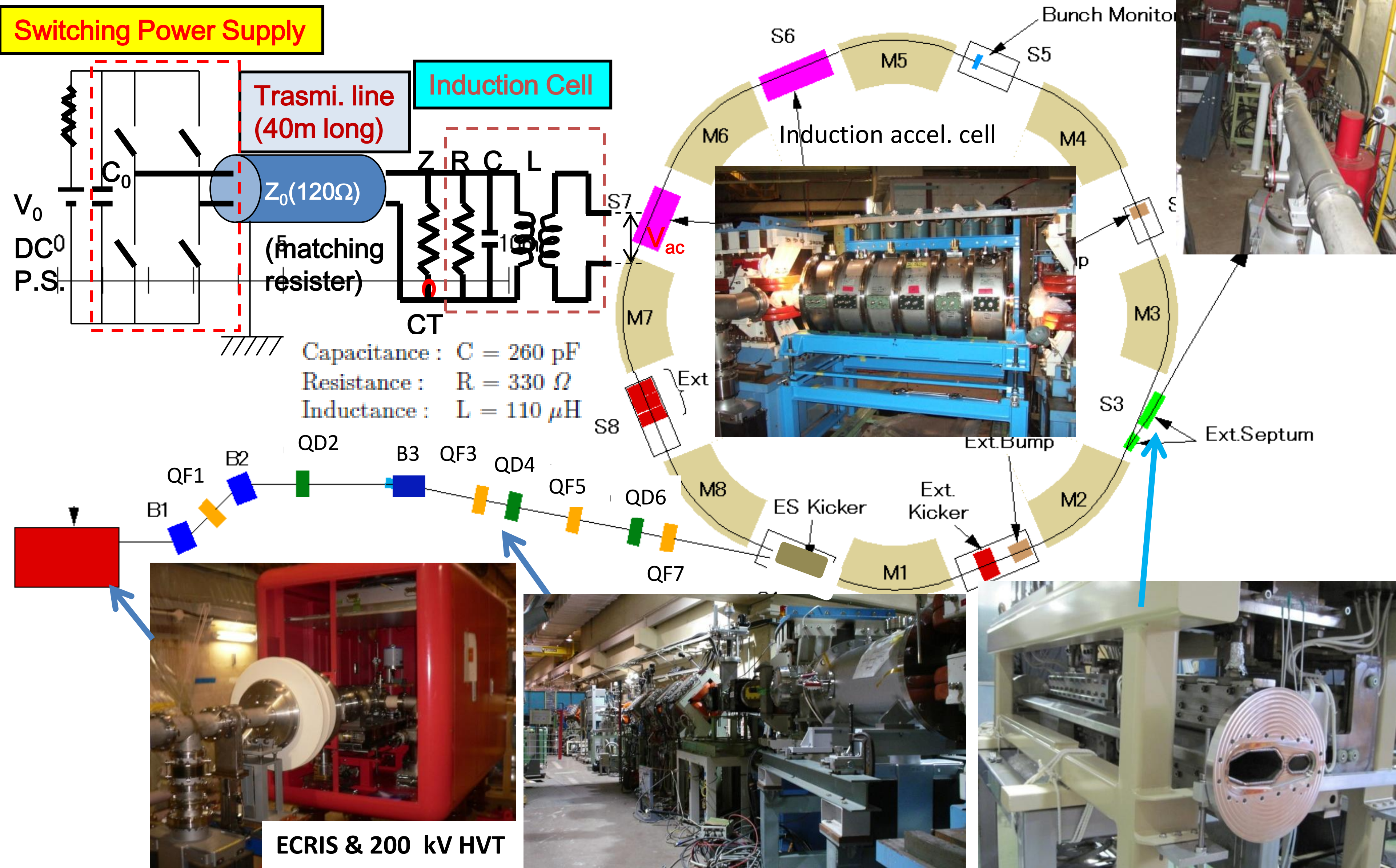




KEK Digital Accelerator (Rapid Cycle Induction Synchrotron)

T. Iwashita *et al.*, *"KEK Digital Accelerator"*, *Phys. Rev. ST-AB 14, 071301 (2011).*

Equivalent Circuit for Induction Acceleration System



Einzel Lens Longitudinal Chopper : Idea, Device, Performance

Why we need a Chopper?

1 turn injection < 10 μsec

A long pulse from ECRIS ~ 2 - 5 msec

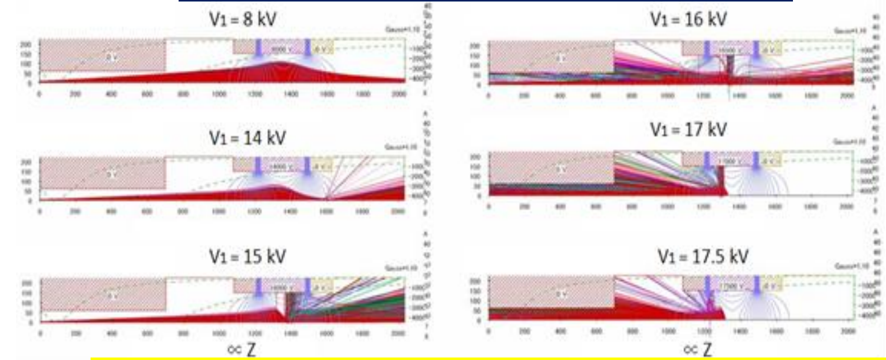
What type is desired?

Low energy operation
Low cost (~ $2,500)

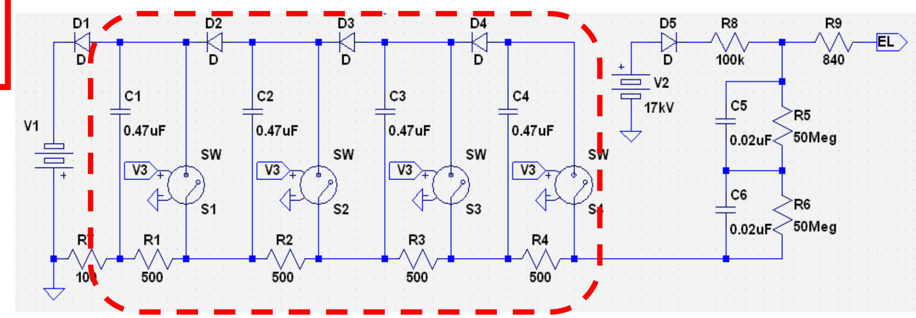
Low energy x-ray
Reduced out-gassing
Reduced secondary e⁻

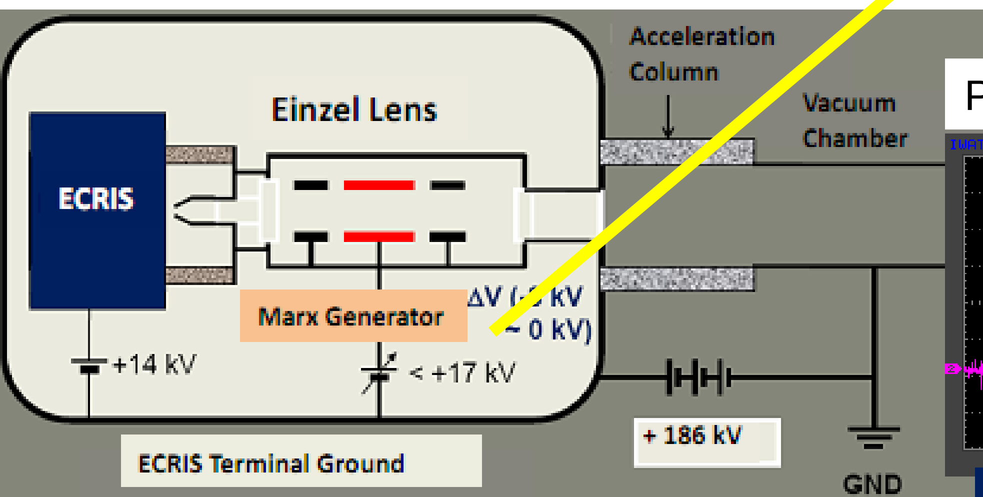
Einzel lens longitudinal chopper

Longitudinal gate study by IGUN

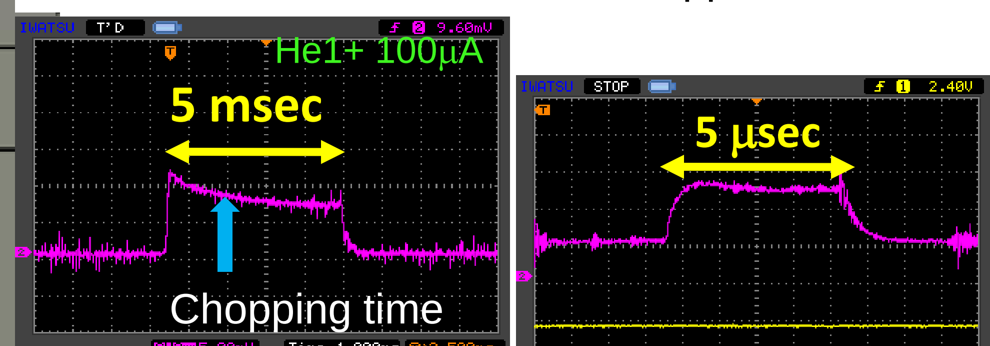


FET switch driven 4 stages Marx generator





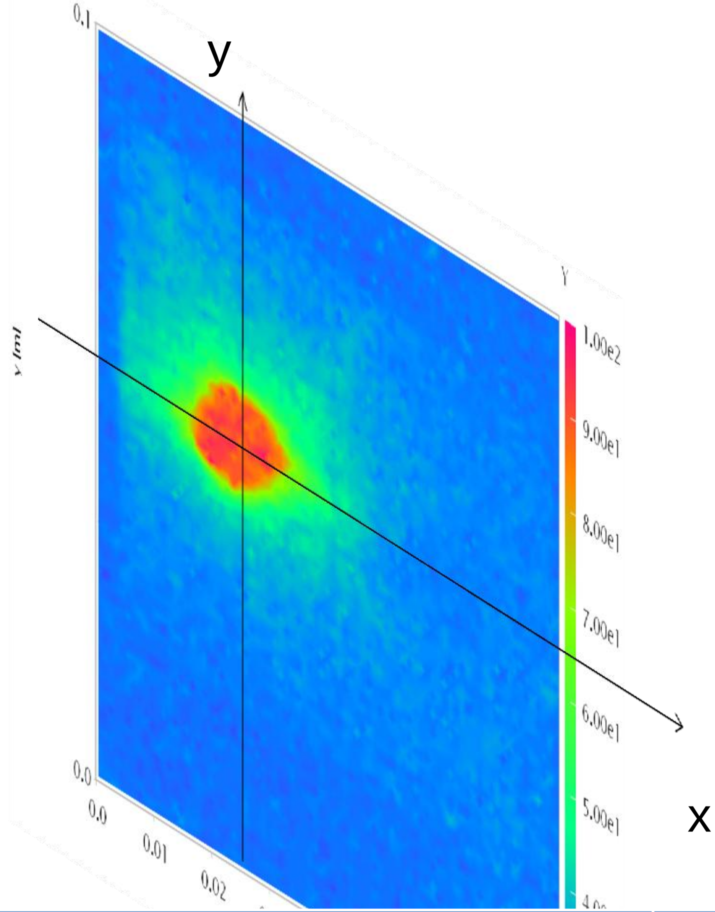
Pulsed beam from ECRIS | Chopped beam



T.Adachi, K.W.Leo *et al.*, *Rev. Sci. Inst.* 82, 083305 (2011)

Beam Profile on the Screen Monitor placed upstream in LEBT

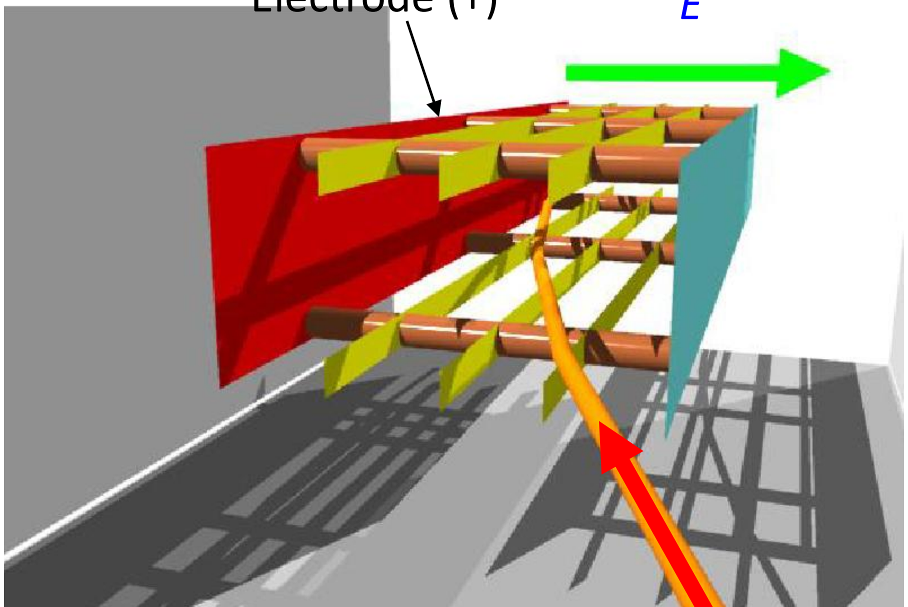
Beam profile plotted from by the result from “Screen Monitor

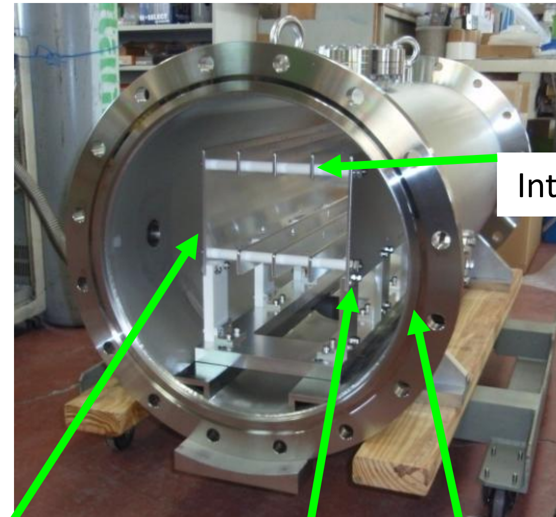


200 keV
H1+
100 μA

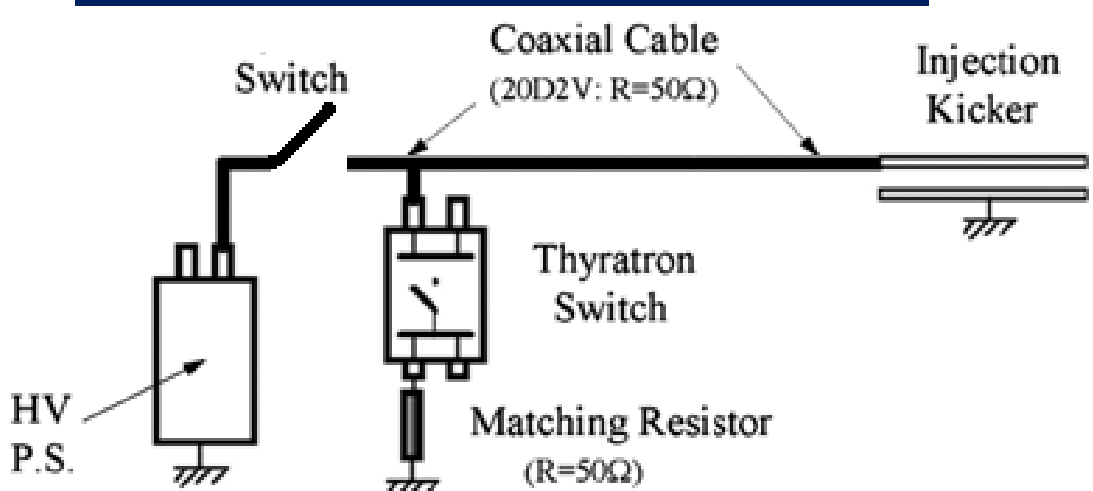
	Horizontal rms emittance ε_x[μmrad]	Vertical rms emittance, ε_y[μmrad]
Measuremenr by Pepper pot device	~100	~75

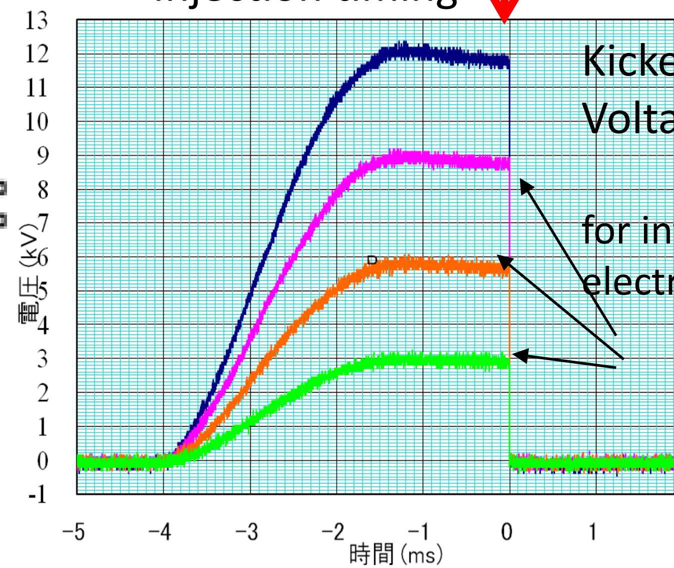
Electrostatic Injection Kicker





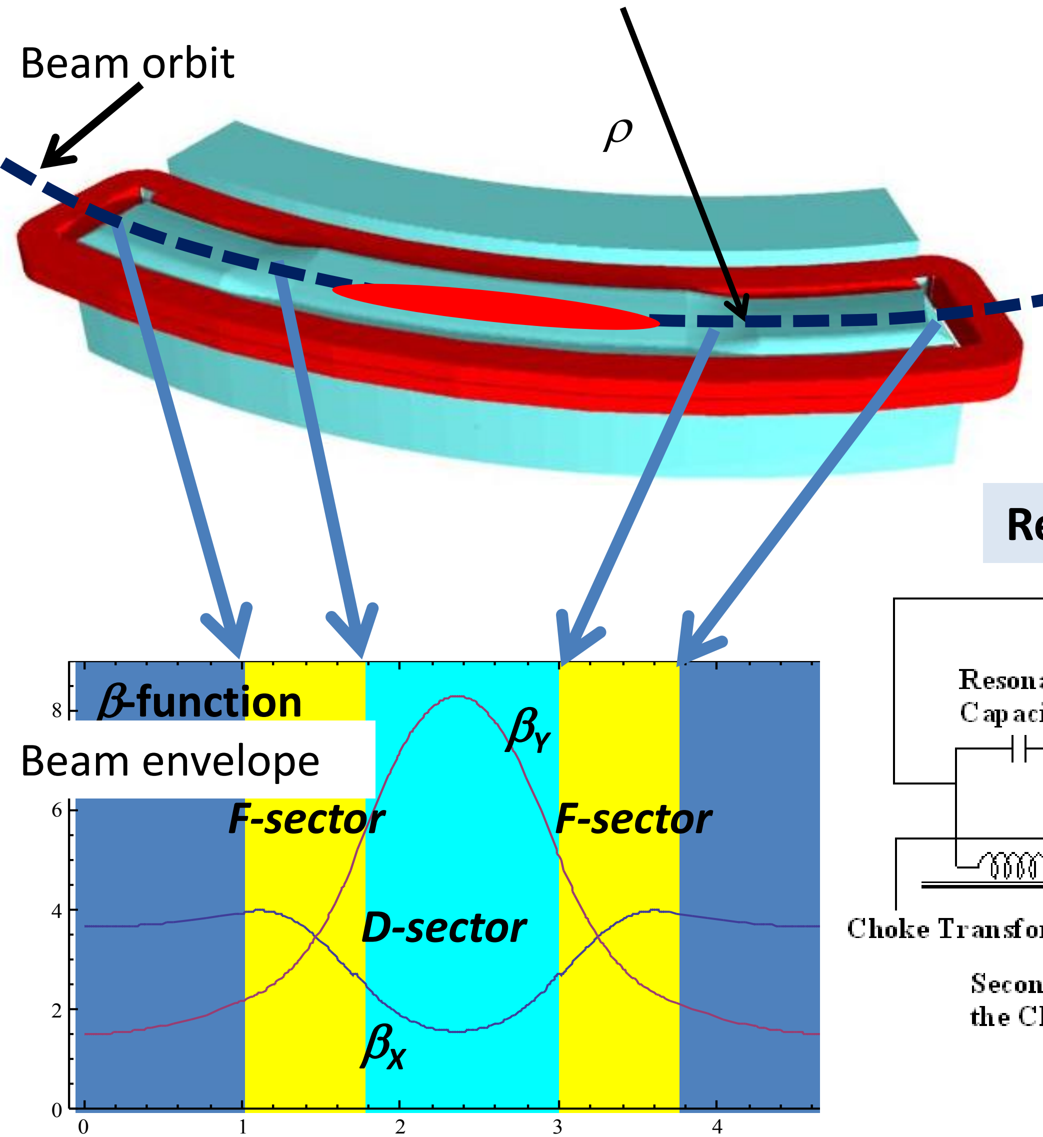
Driving circuit of the injection ES kicker





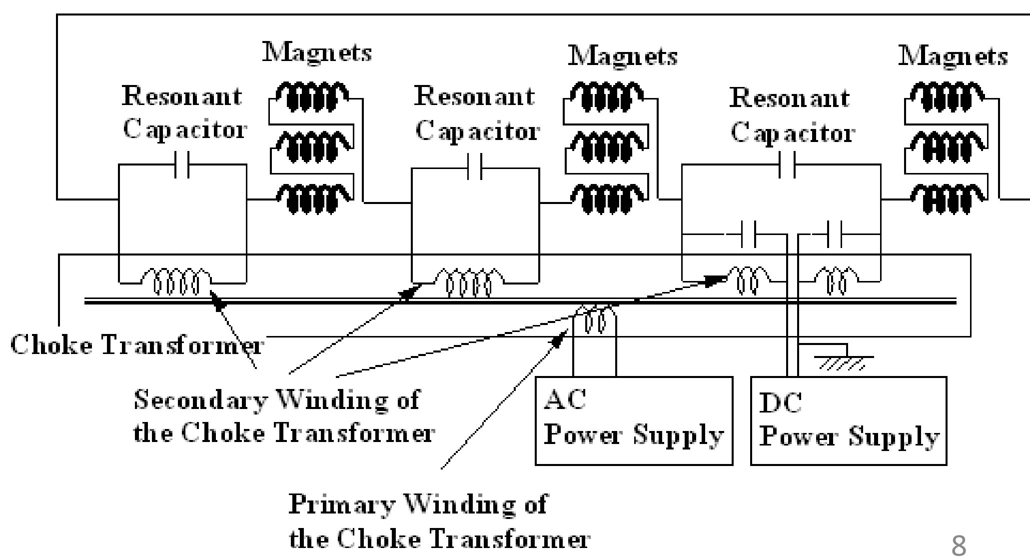
DA Ring Machine & Beam Parameters

Combined-function type magnet (lower half)

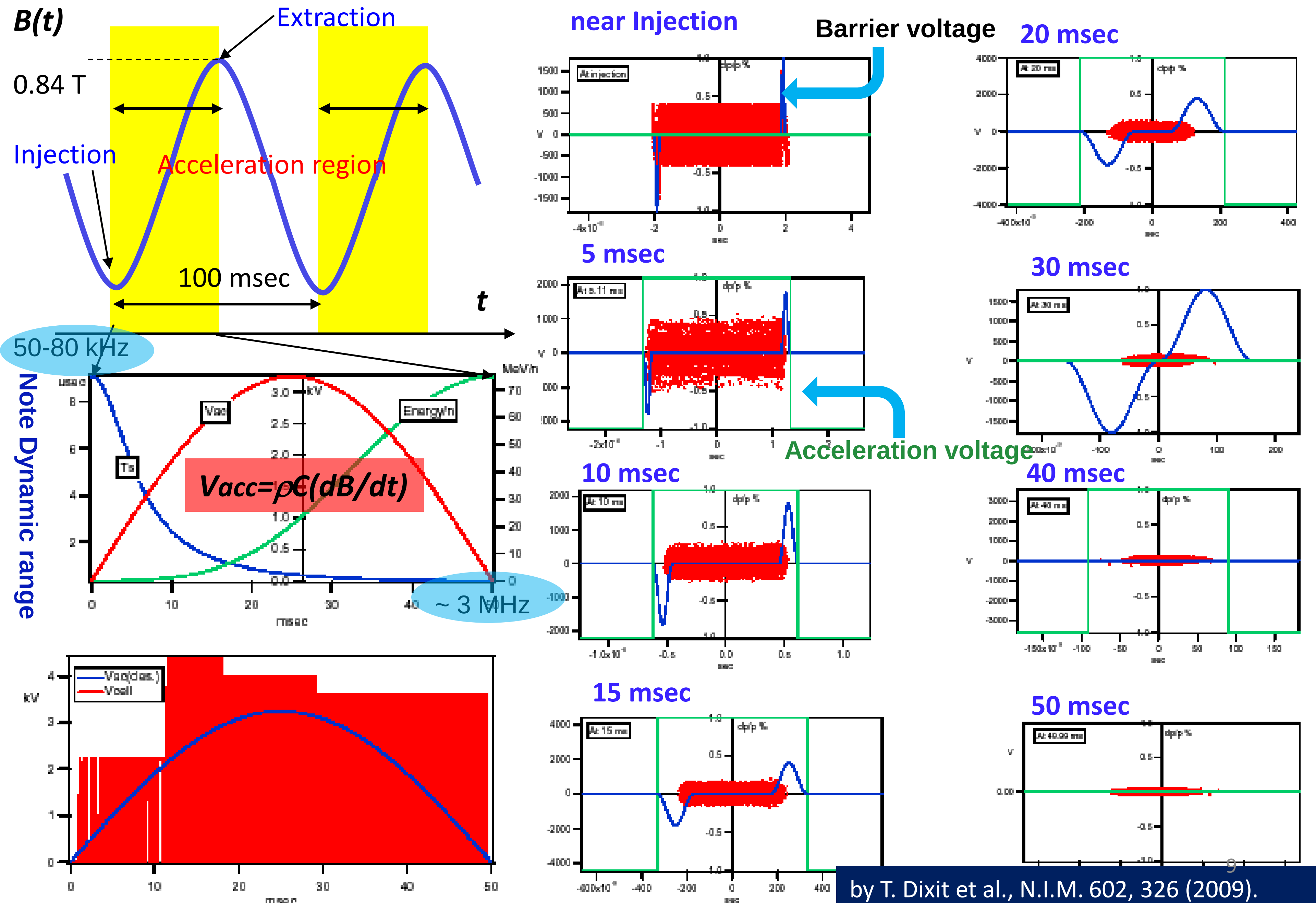


Bending radius	ρ	3.3 m
Ring circumference	C_0	37.7 m
Maximum flux density	B_{max}	0.84 T (1.1 T)
Accel. voltage/turn	V	3.24 kV
Repetition rate	f	10 Hz
Betatron tune	ν_x/ν_y	2.17/2.3

Resonant LCR Circuit Power Supply



Scenario of induction acceleration/capture of He2+ and C6+



by T. Dixit et al., N.I.M. 602, 326 (2009).

Induction Acceleration Scenario

Technical Limitation of Induction Acceleration Cell

Fixed output voltage V_{out}= ~ 1 - 2 kV/cell

Primary voltage is not easily changed.

Maximum pulse length ~ 0.5 - 2 μsec/pulse

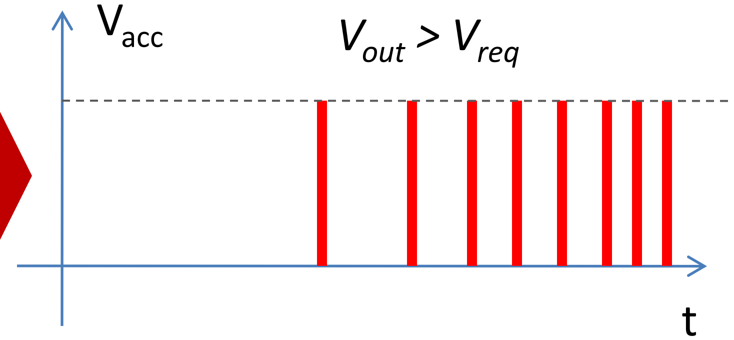
Voltage pulse length is determined by droop.

Maximum rep-rate ~ 1 MHz

Heat deposit is serious beyond 1 MHz.

(If magnet ramping is slow)

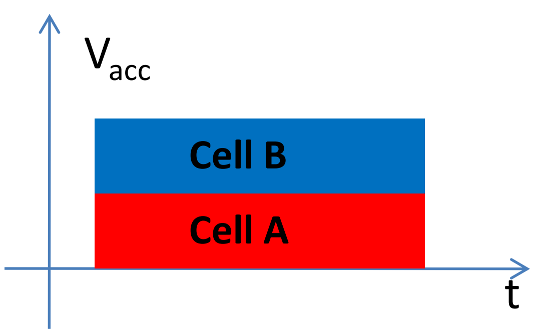
1) Pulse density control



When requirement exceeds its capability of rep-rate and puse-width,

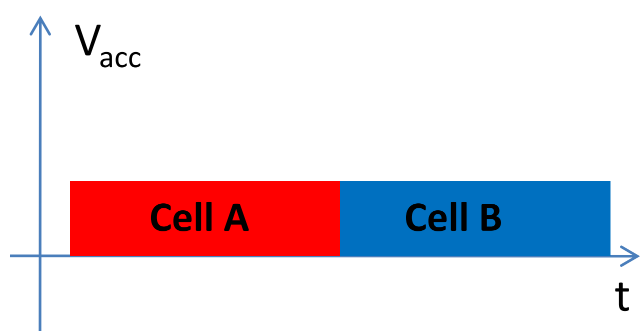
(If larger acceleration voltage is required)

2) Superimpose of pulses in time



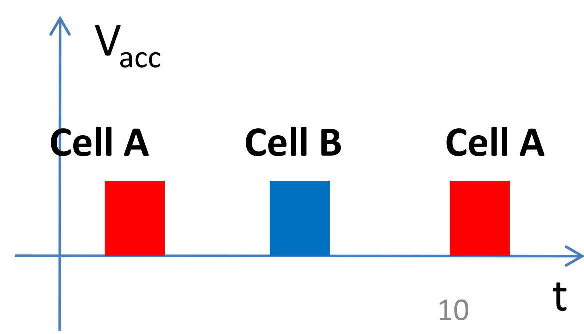
(If longer pulse width is required)

3) Sequential trigger in time



(If higher rep-rate is required)

4) Intermittent operation



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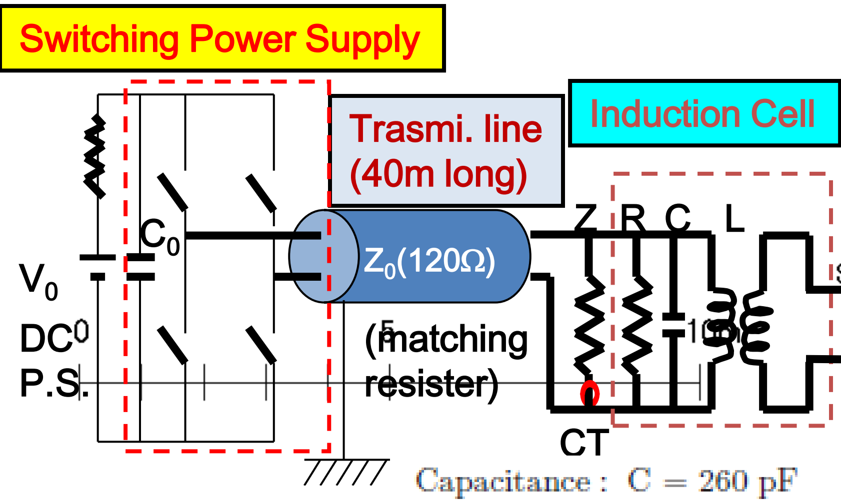
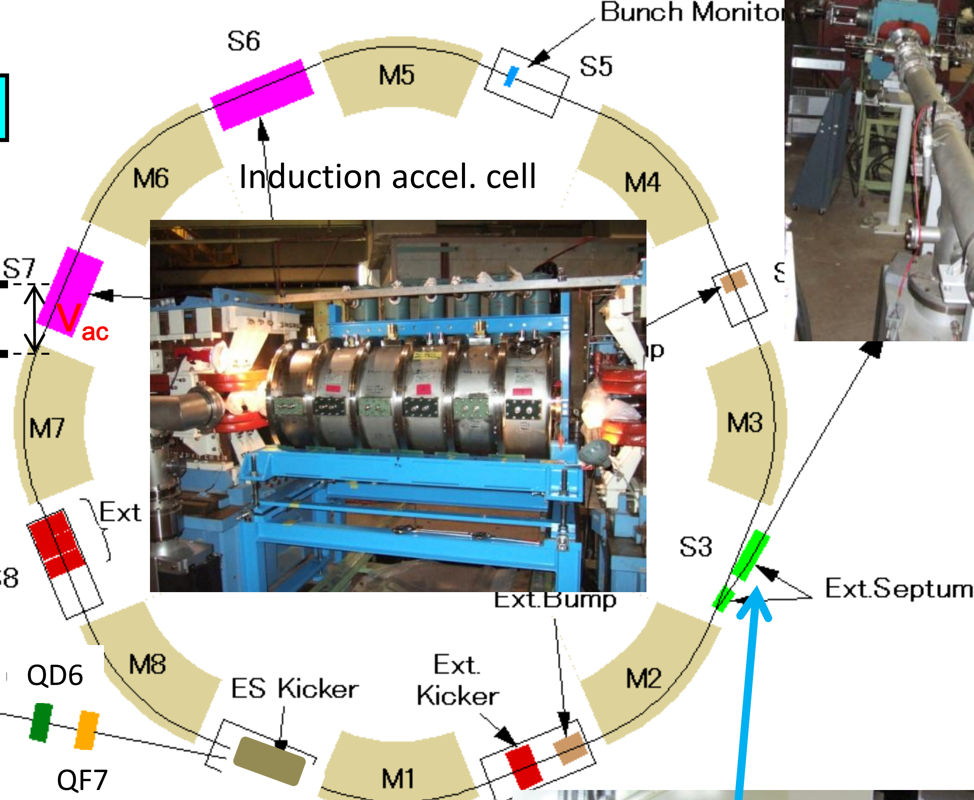
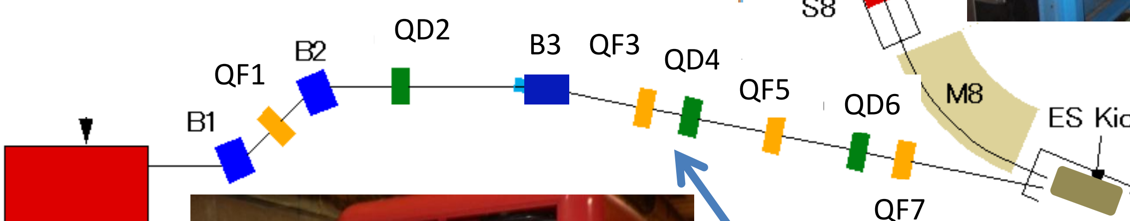
Equivalent Circuit for Induction Acceleration System

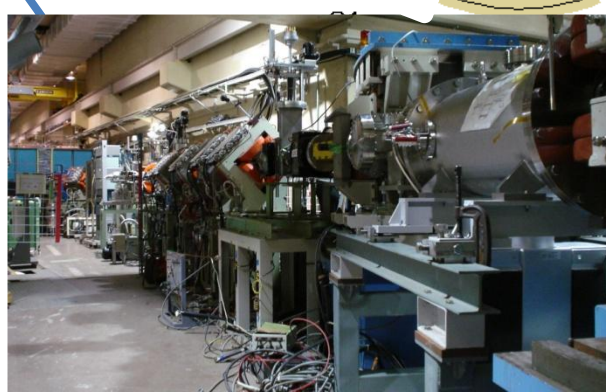


Capacitance : C = 260 pF
Resistance : R = 330 Ω
Inductance : L = 110 μH

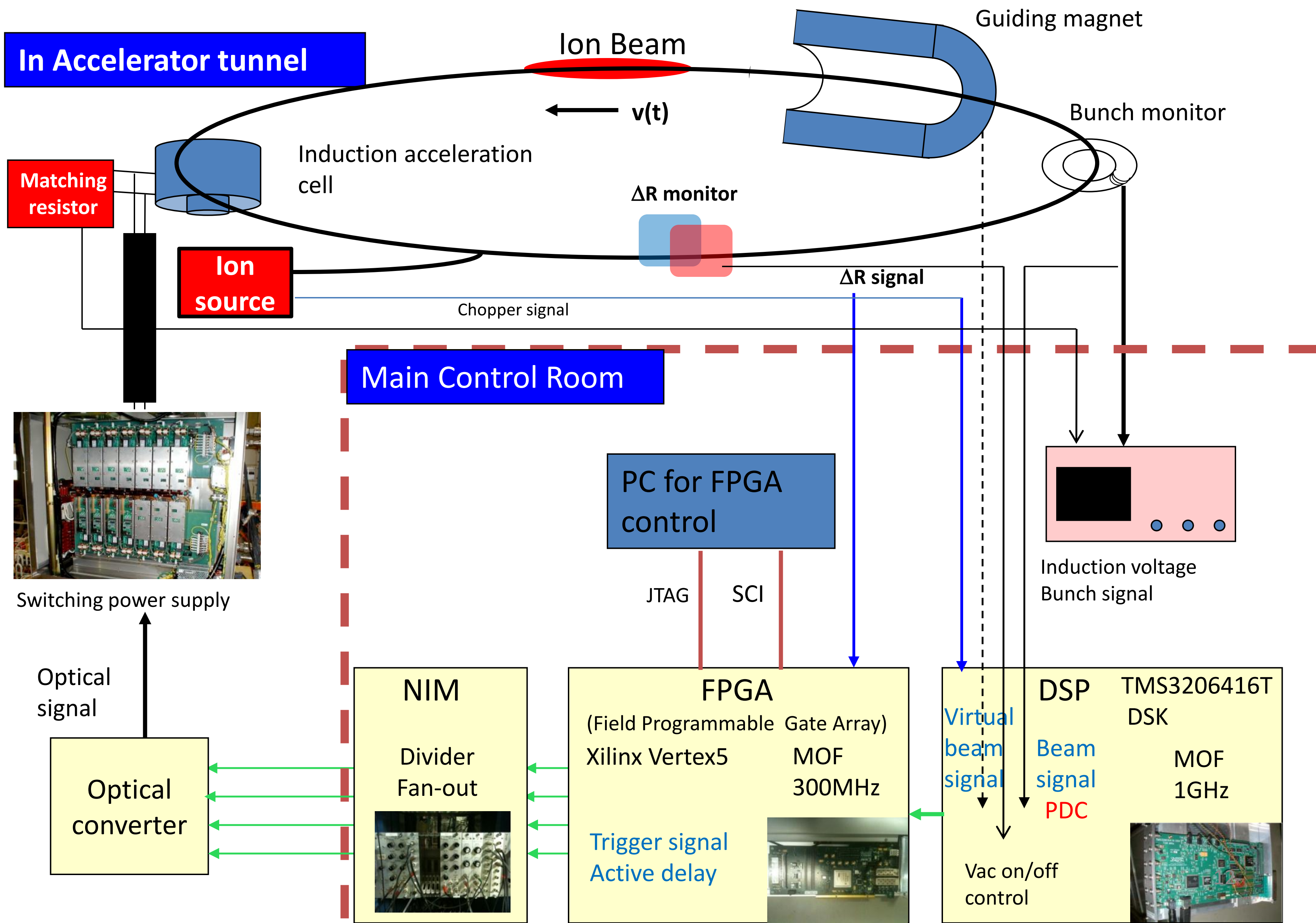




ECRIS & 200 kV HVT



Induction Acceleration Control System using FPGA/DSP



Closed Orbit Distortion

originated from residual flux density in the main magnets

$5\ \text{Gauss} < B_{remnant} < 10\ \text{Gauss}$

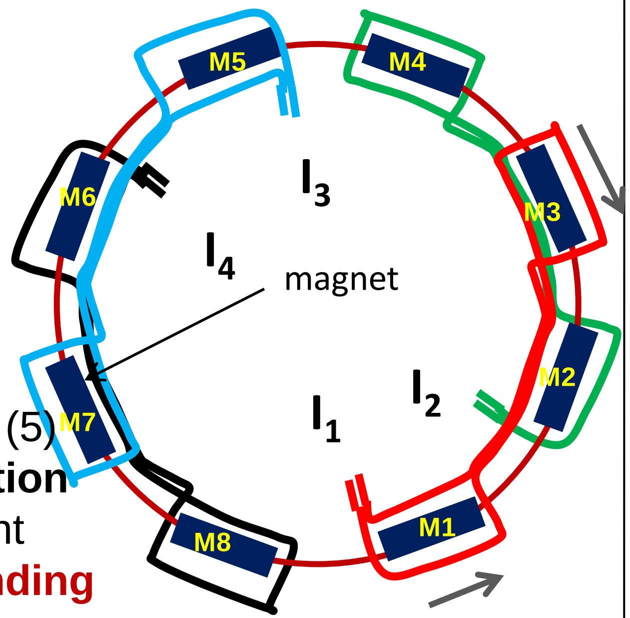
$B_{inj} \cong 200 - 400\ \text{Gauss}$

It is significant at the injection energy.

COD correction method:

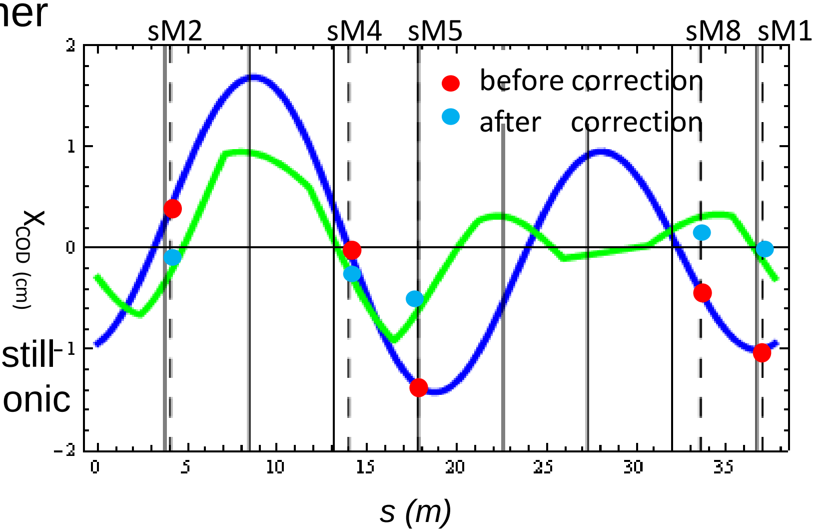
Limitation: limited number of position monitor (5)

- ■ 1st and 2nd **harmonic correction**
  Q_x =2.17 → N=1, 2 dominant
- ■ **8 figure correction coil winding** between every other magnets to avoid induced voltage on P.S.



Results:

- ➢ Practically its size is acceptable.
- ➢ Current correction is still not enough; 3rd harmonic seems to appear in residual COD.



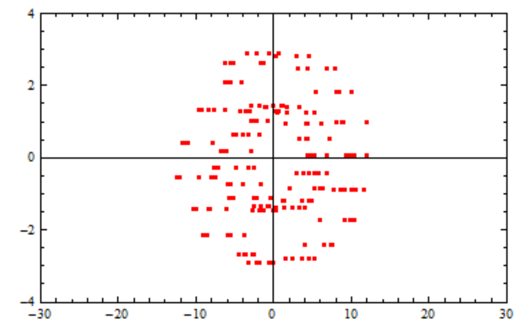
Emittance blow-up

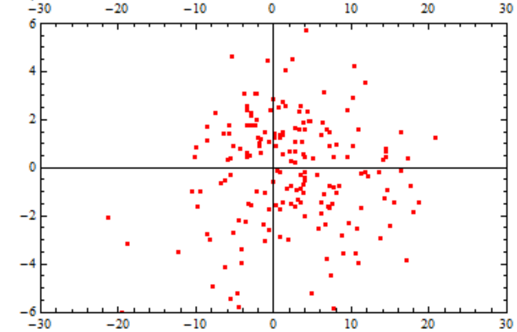
originated from

Synchro-beta Coupling

No dispersion-free lattice

$$\begin{pmatrix} x_i(n+1) \\ \dot{x}_i(n+1) \end{pmatrix} = \begin{pmatrix} \cos(2\pi Q_i(n)) & \beta_x \cdot \sin(2\pi Q_i(n)) \\ -\dfrac{1}{\beta_x} \cdot \sin(2\pi Q_i(n)) & \cos(2\pi Q_i(n)) \end{pmatrix} \times \begin{pmatrix} x_i(n) - D\left(\dfrac{\Delta p}{p}\right)_T \\ \dot{x}_i(n) \end{pmatrix}$$



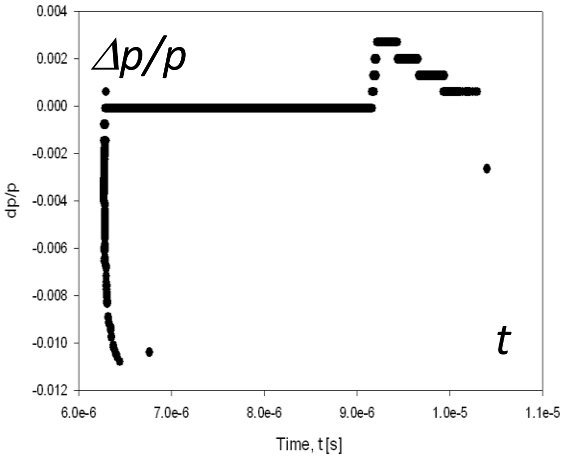


Introduction of a combination of low/high voltage pulses

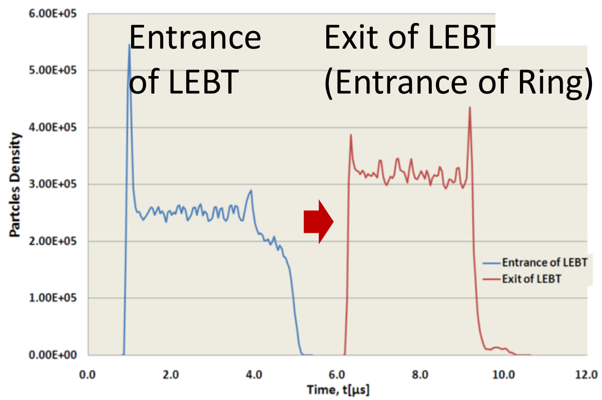
Beam Commissioning (1): Free Circulation at E_{inj} under B_{min}

Notable facts in LEBT:

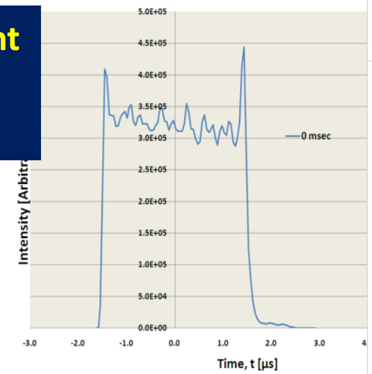
- Modulation in the momentum space caused by the transient fields of the chopper
- Drift compression



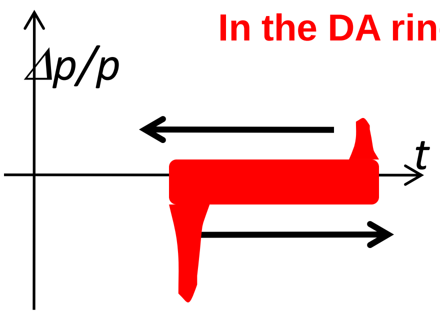
simulation



Measurement at 1 turn in the ring



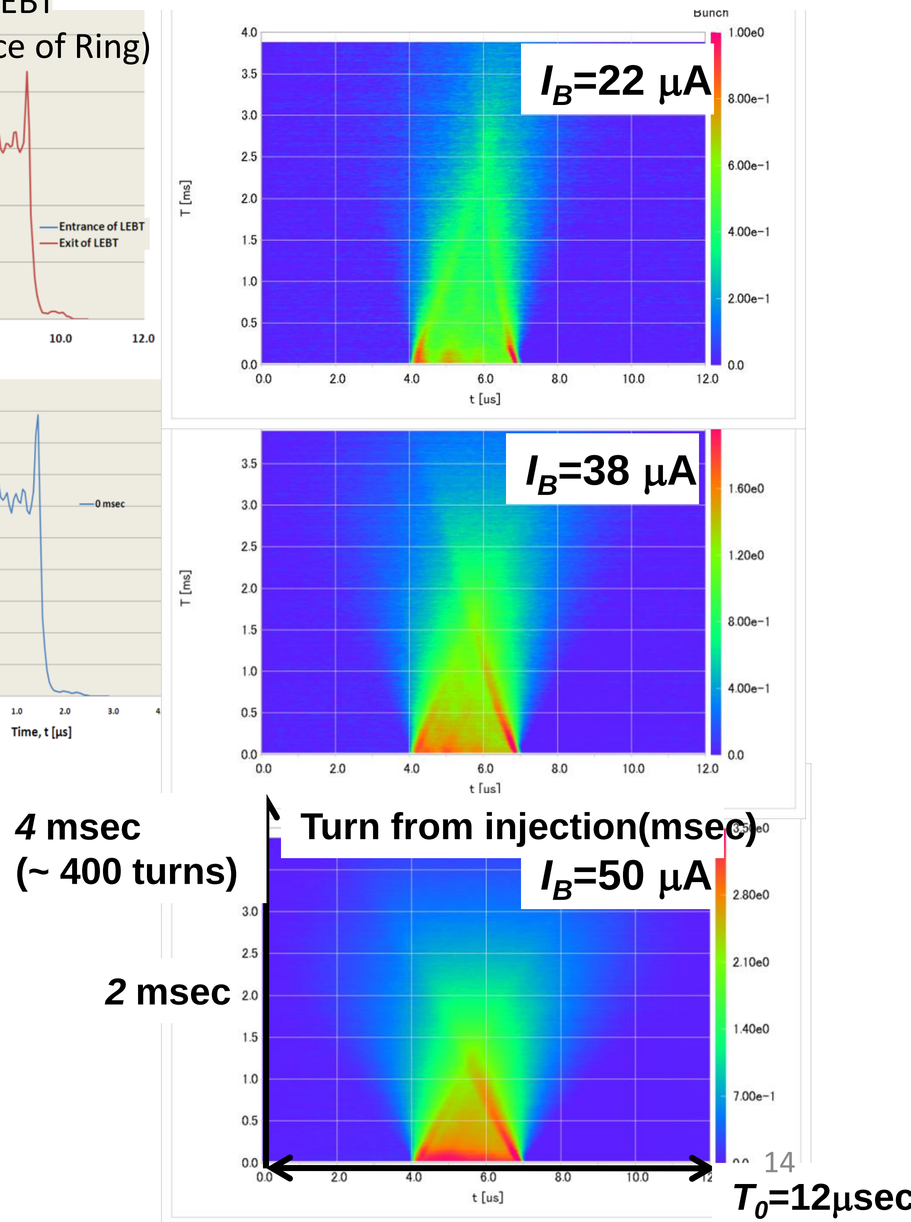
In the DA ring



Slippage factor: $\eta = \frac{1}{\gamma_T^2} - \frac{1}{\gamma^2} \prec 0$

$$\Delta t \propto \eta \cdot \frac{\Delta p}{p}$$

Projection of Bunch Signal Mountain view (3D) In Ring

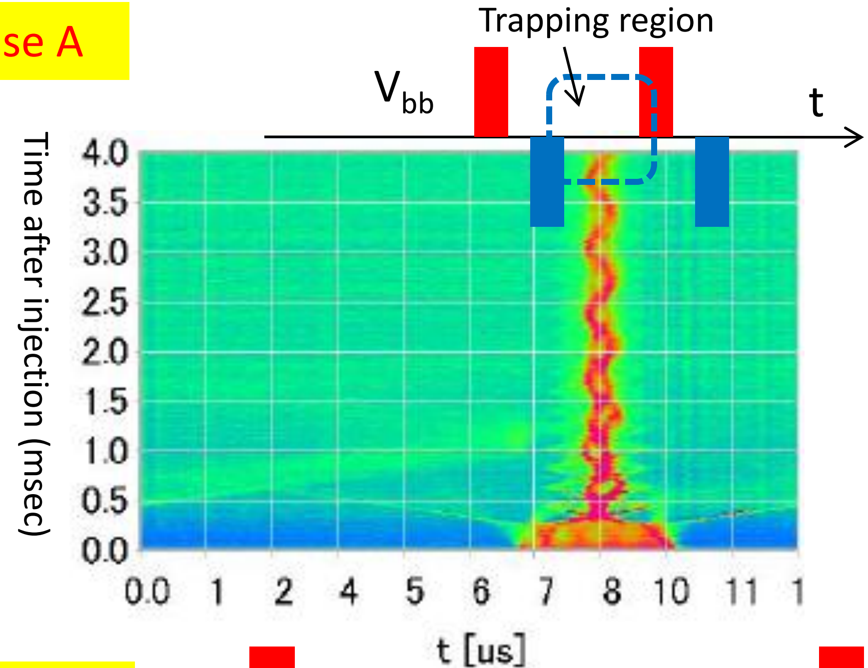


Notable facts:

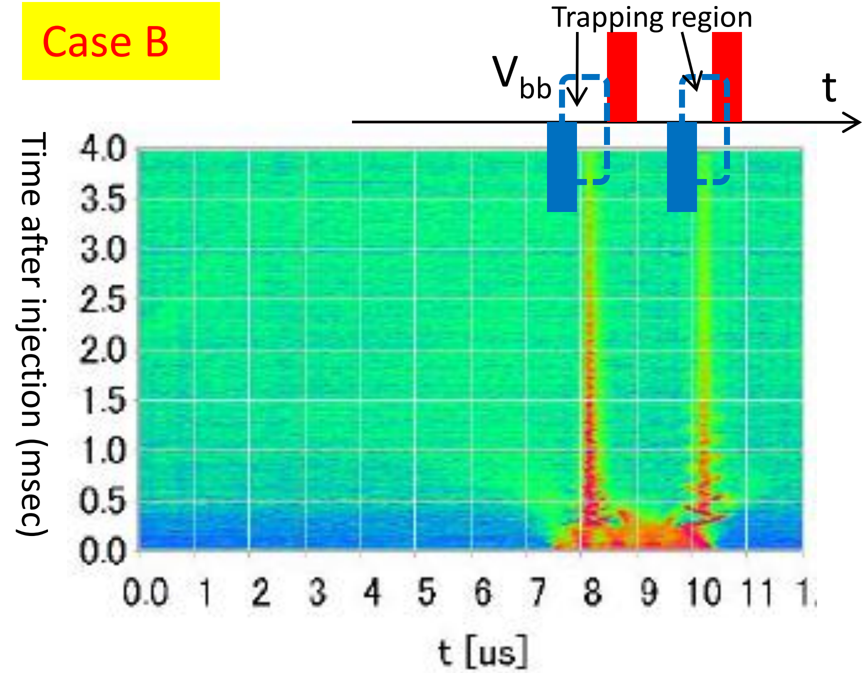
- Some spread in the momentum space
- Diffusion and further compression depends on beam intensity

Beam Commissioning (2): Barrier Volt. Confinement at E_{inj} under B_{min}

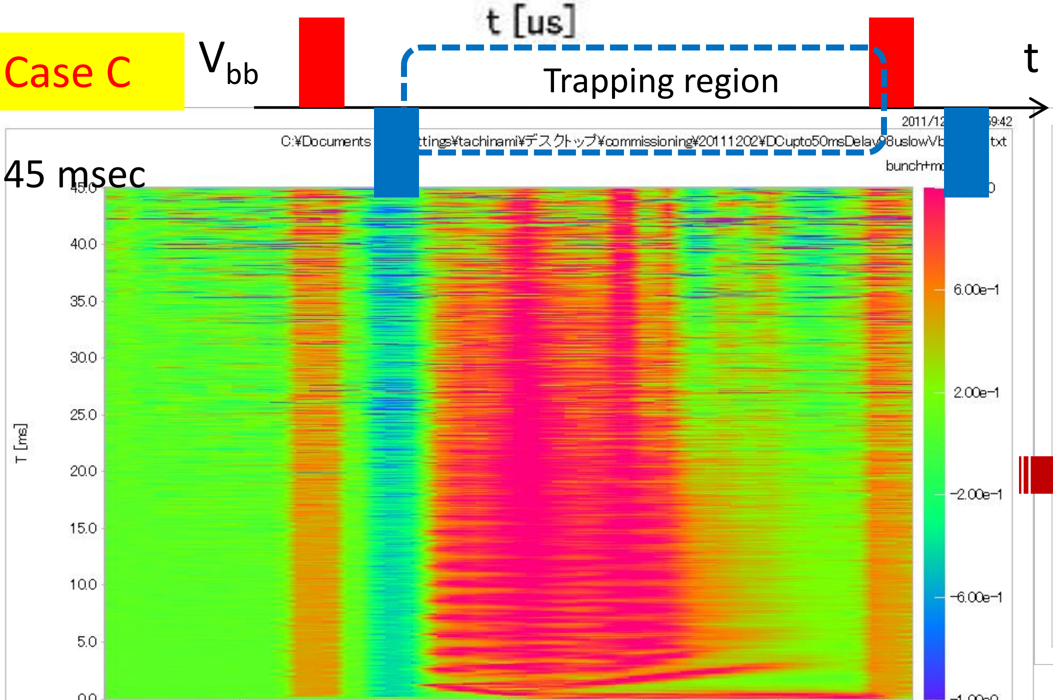
Case A



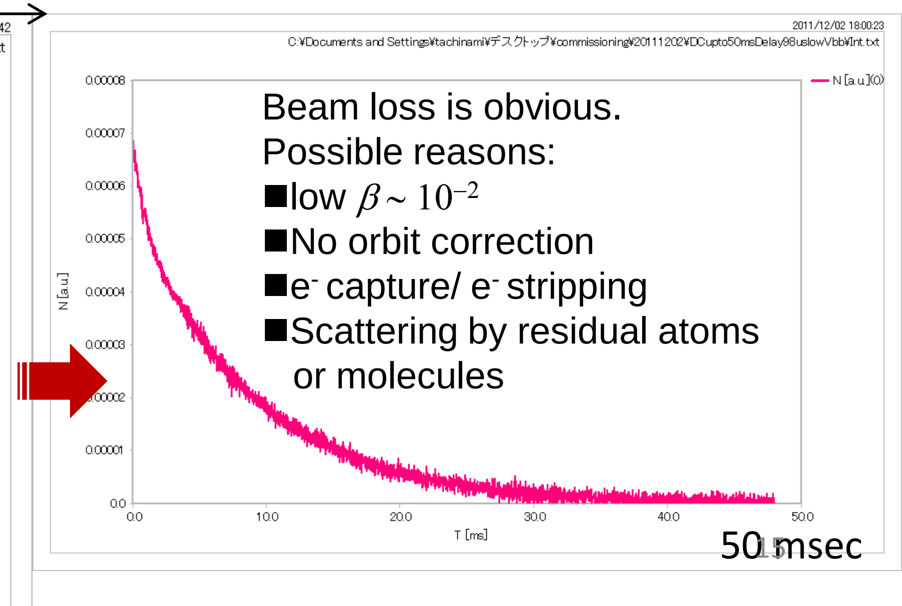
Case B



Case C

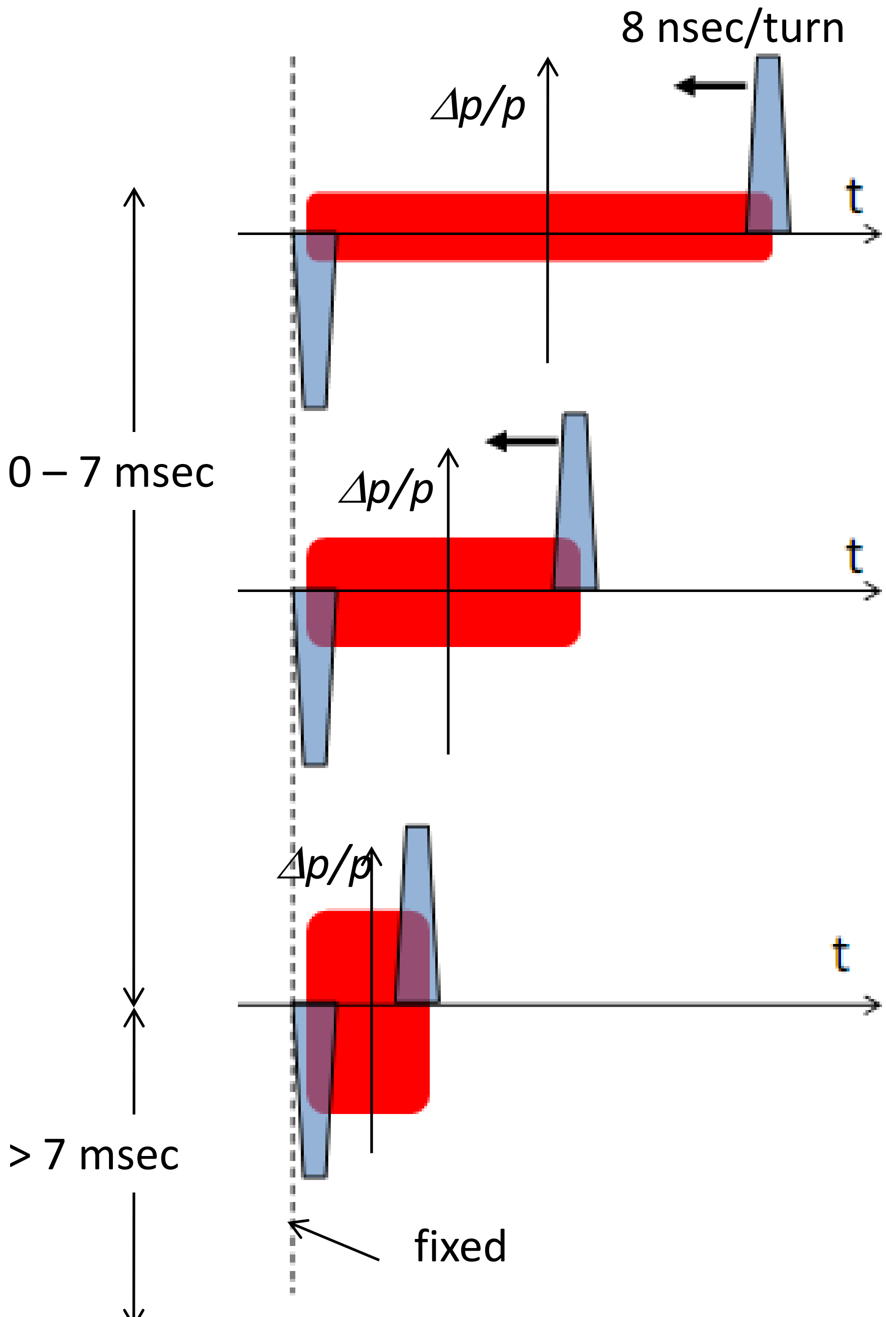


Beam survival



Beam loss is obvious.
Possible reasons:
- ■low $\beta \sim 10^{-2}$
- ■No orbit correction
- ■e^- capture/ e^- stripping
- ■Scattering by residual atoms or molecules

Beam Commissioning (3): Bunch Squeezing Experiment

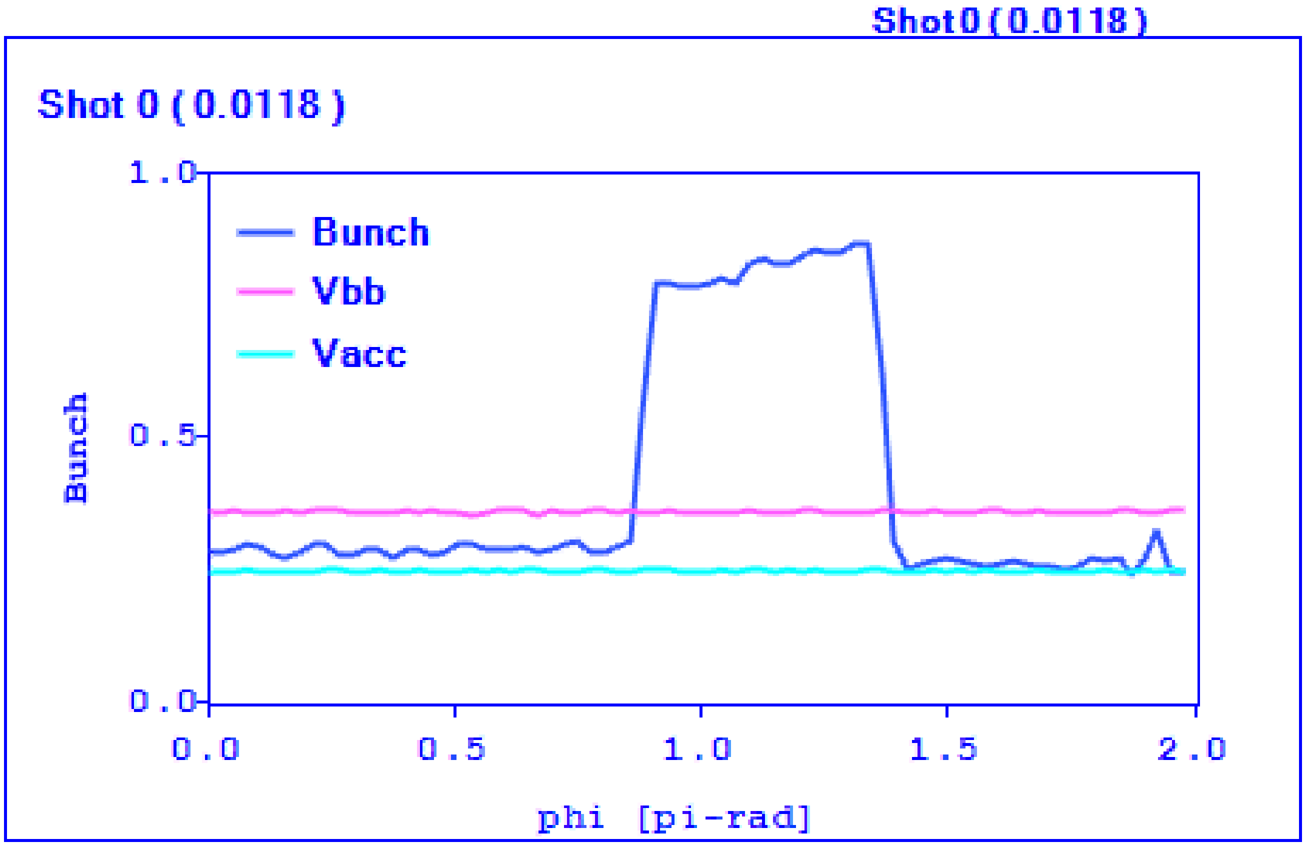


Bunch signal

Note: Polarity of barrier voltage signal is opposite.

Beam Commissioning (4): Demonstration of He1+ Acceleration (Preliminary)

Turn No Time after injection



He ion bunch signal

Barrier voltage pulse

Acceleration voltage pulse

Provided ion species and parameters at KEK Digital Accelerator

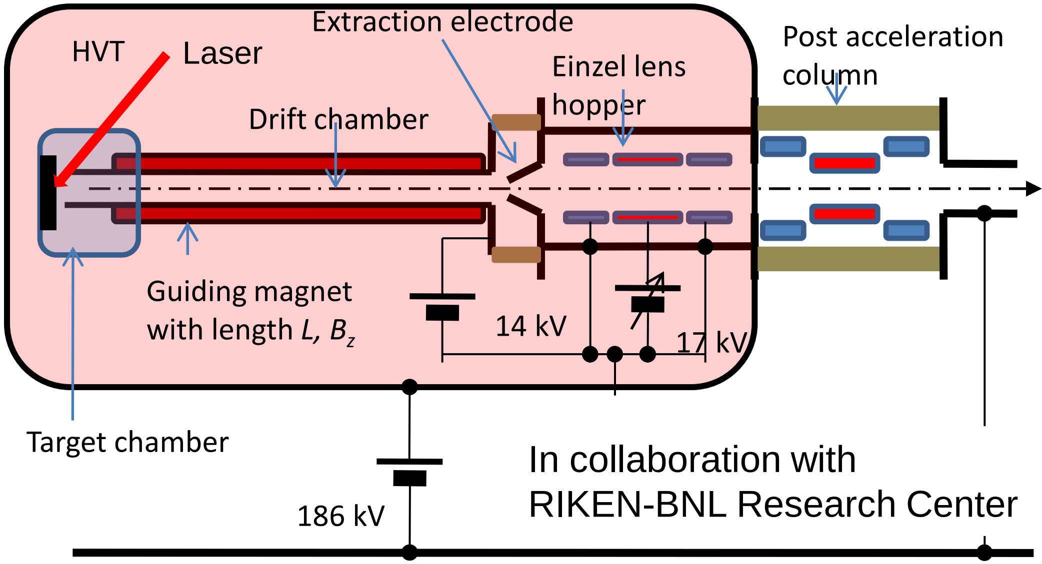
Ion source	ion	energy	Particle number/sec
ECR Ion Source	H, He, C, N, O, Ne, Ar	< 140 MeV/au, 200MeV	$<10^{10}$
Laser Ablation Ion Source	Xe, Fe, Cu, Ag, Au	< 70 MeV/au	$< 10^{9}$

Coming half year and Future Plans

Confirmation of Induction Acceleration toward the last stage in the KEK-DA

1. by Completely programmed control based on B-clock trigger
2. by Beam feedback control

Introduction of LAIS for Metal ions (Fe, Cu, Ag, Au)



In collaboration with RIKEN-BNL Research Center

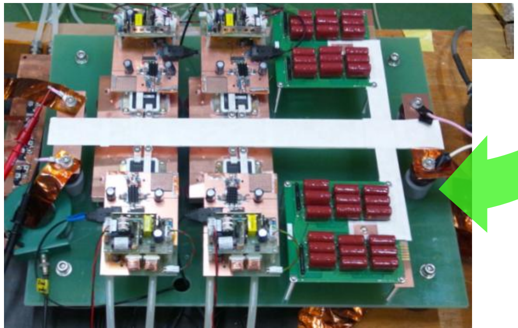
Deliver of p, He, C, N, Ar to applications

Laboratory Space Science experiment using virtual cosmic rays

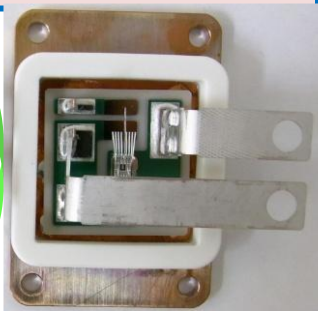
In collaboration with JAXA-ISAS/NAO/Yokohama Nat. Univ.

Replacement by S.P.S. employing SiC-JFETs

Present S.P.S.(7 MOSFETs in series)



1.2/2.4 kV SiC-JFET Package devloped by KEK/SunA



In collaboration with SunA and JPPL

Summary

- Noble device such as Einzel lens longitudinal chopper has been developed. Its capability is excellent.

- Beam Commissioning of KEK Digital Accelerator
  - Induction acceleration was confirmed (but not complete yet).
  - Beam handling using barrier voltage pulses was demonstrated with increasing freedom of beam handling in the longitudinal direction.

Consequently,

- it turned out that Induction Synchrotron Concept can work both as
  Slow Cycle Synchrotron (2 sec, KEK 12 GeV PS, 2006)
  Rapid Cycle Synchrotron (50 msec, KEK-DA, 2011)
- Plan/possibility of applications utilizing heavy ions (virtual cosmic-rays)
  - *Laboratory Space Science:* Systematic development of electric circuits to work in space (single ion phenomena), confirmation of "*origin of life*" (authorized)
  - *Industrial use:* Deep implantation of RI particle into materials
    Use of high energy ion track through materials
  - *Medical use:* The next generation of hadron cancer therapy with option of *C-11 cancer therapy*