The Einzel Lens Longitudinal Chopper

Ken Takayama[1,2,3], Leo K.W.[1,2], and Toshikazu Adachi[1,2]

[1]High Energy Accelerator Research Organization (KEK)
[2]The Graduate University for Advanced Studies
[3]Tokyo Institute of Technology

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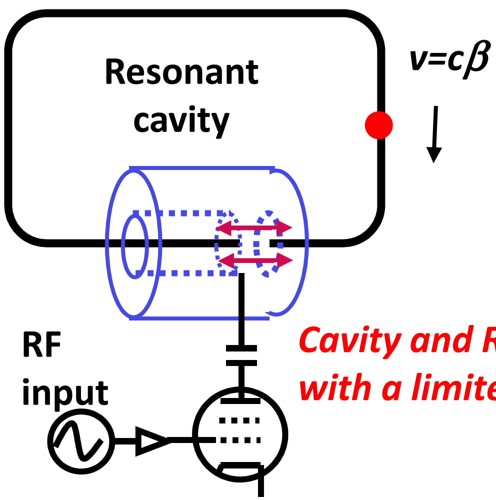
Reference:

[1] K.Takayama and R.Briggs (*Eds.*), "**Induction Accelerators**" (Springer, 2010)
[2] T. Iwashita *et al*., "**KEK Digital Accelerator**", *Phys. Rev. AB-ST* **14**, 071301 (2011).
[3] Leo K.W. *et al*., "**Permanent Magnet ECRIS for the KEK Digital Accelerator**", *ECRIS2010* ,TUPOT15 (2010)
[4] T. Adachi *et al*., "**A Solid-state Marx Generator driven Einzel lens Chopper**", *Rev. Sci. Inst.* **82**, 083305 (2011).
[5] Leo K.W. *et al*., "**Einzel Lens Chopper and Behavior of the Chopped Beam in the KEK Digital Accelerator**", *Phys. Rev. ST-AB* (2012), to be published.

Characteristics of Induction Synchrotron (Digital Accelerator)

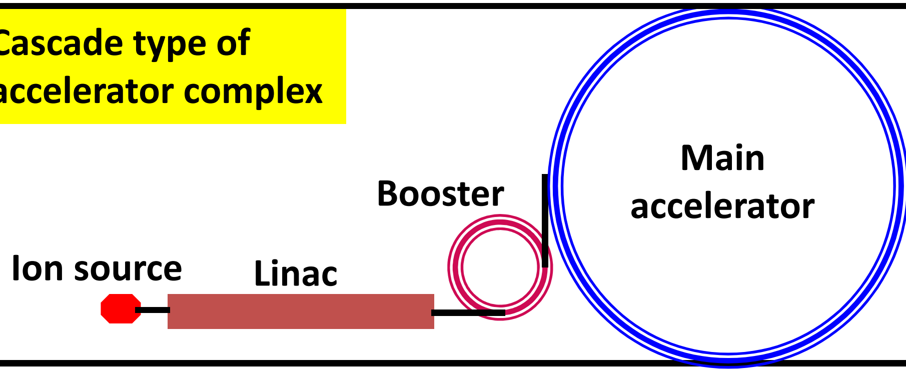
RF Synchrotron



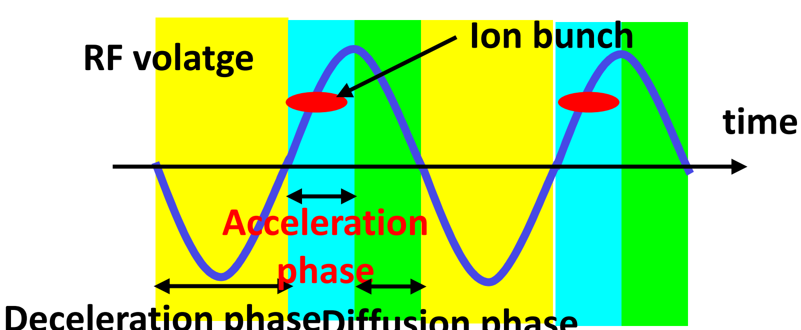
Cavity and RF amp. with a limited bandwidth

1945 E.M.McMillan, V.Veksler

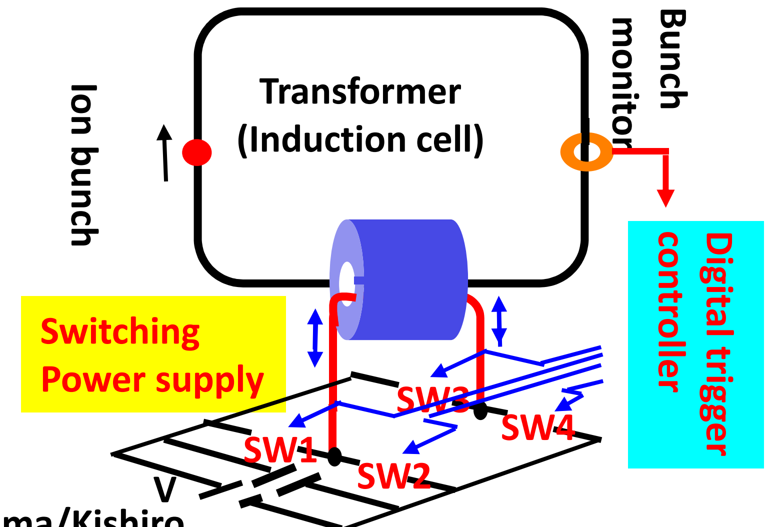
Cascade type of accelerator complex



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

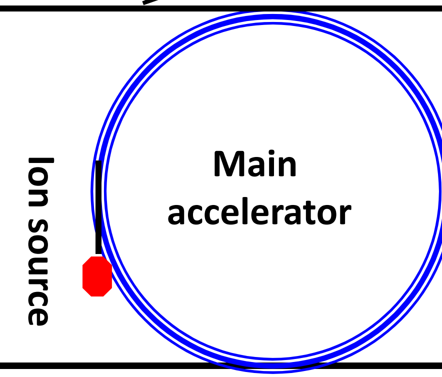


Induction Synchrotron

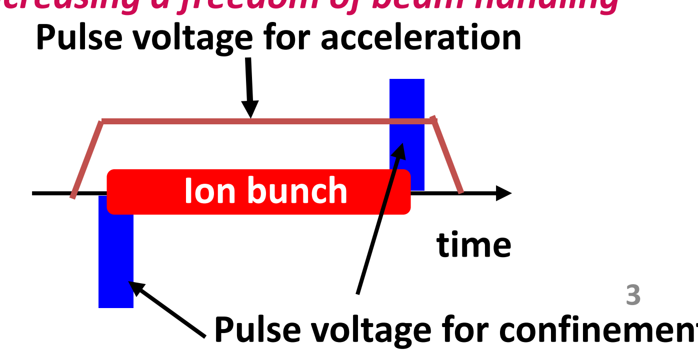


2000 Takayama/Kishiro

Single stage accelerator



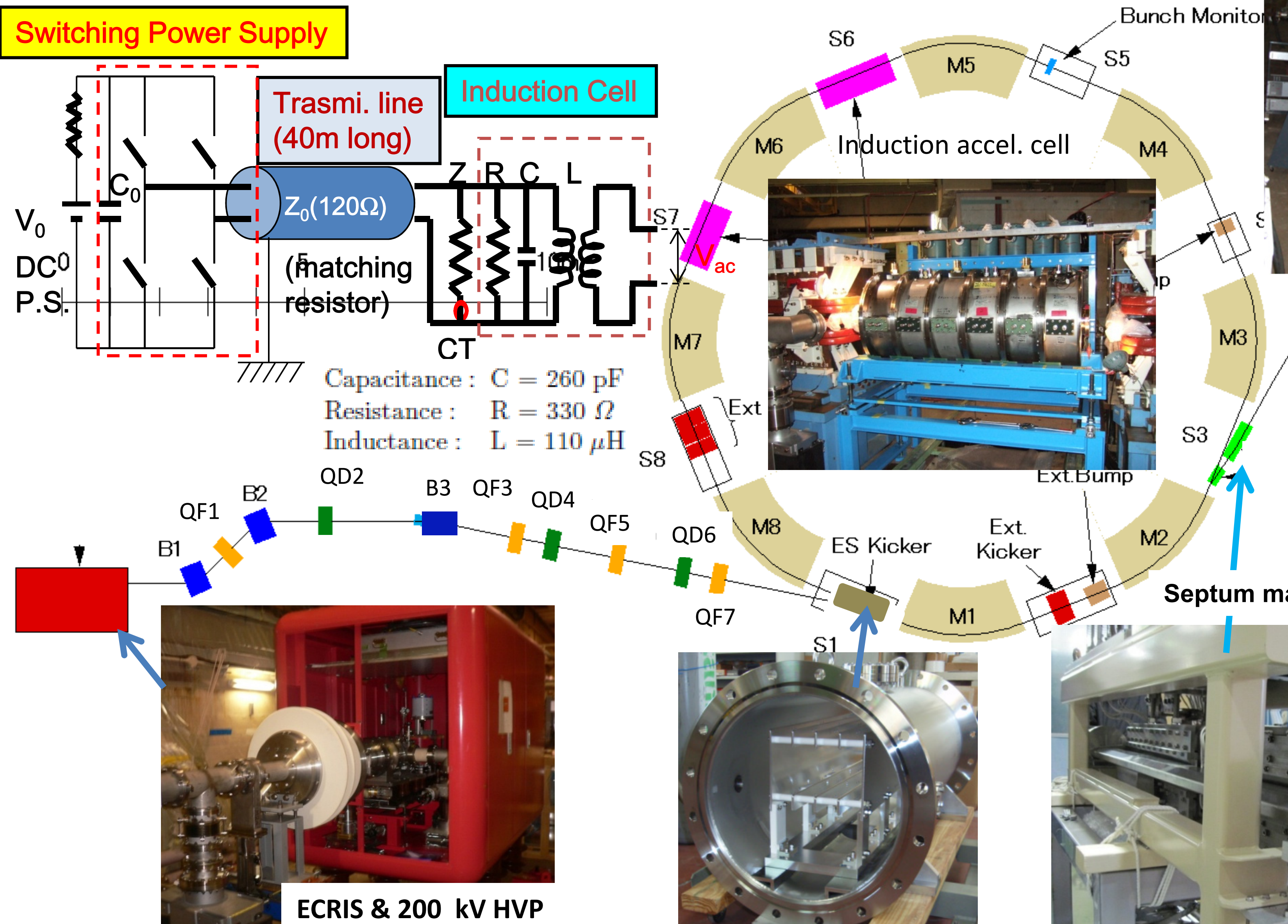
Functionally separated acceleration/confinement -> increasing a freedom of beam handling



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

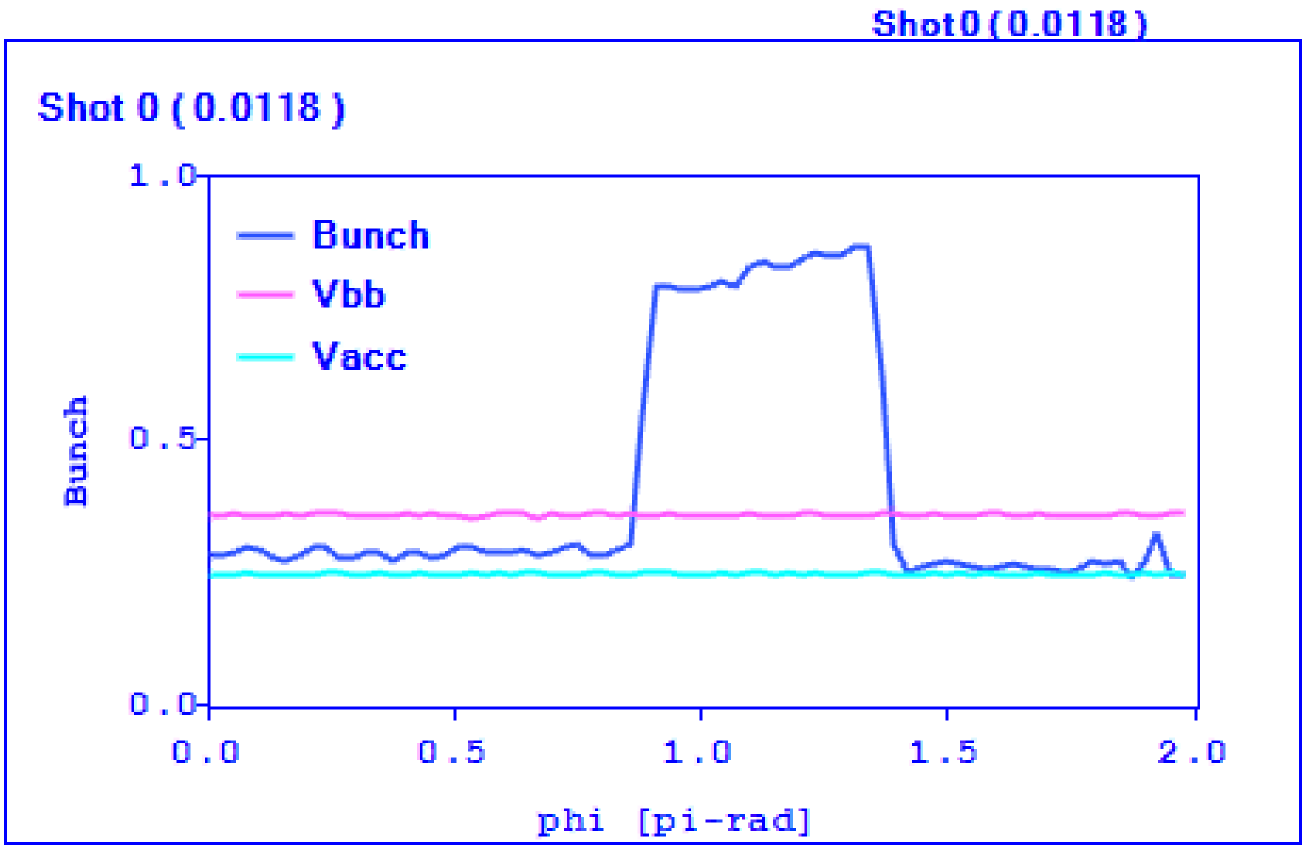


Machine parameters

C_0	37.7 m
B_{max}	0.84 T
f	10 Hz

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

Turn No   Time after injection



He ion bunch signal

Barrier voltage pulse

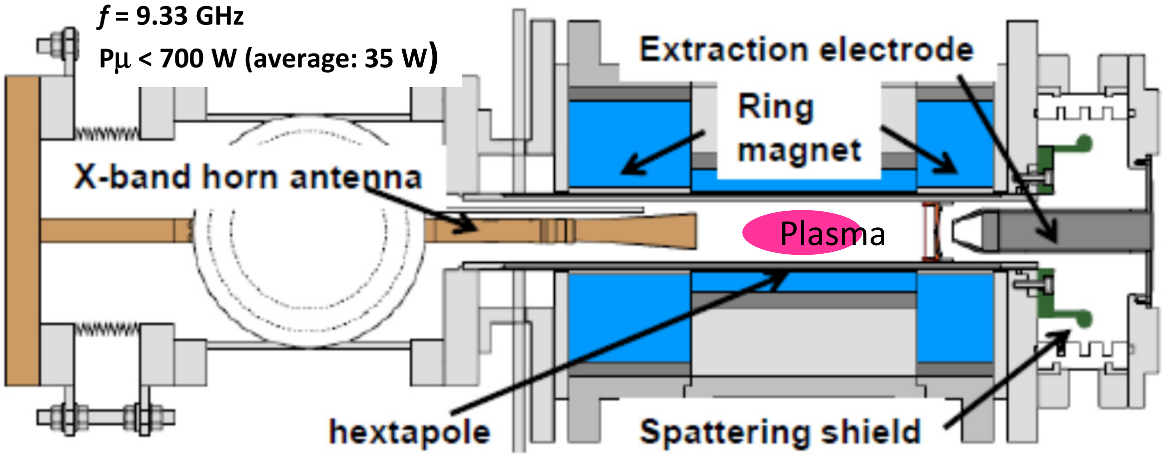
Acceleration voltage pulse

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	$< 10^{9}$

TABLE I. Parameters of KEK-DA ECRIS

ECR Ion Source : Schematic and Output

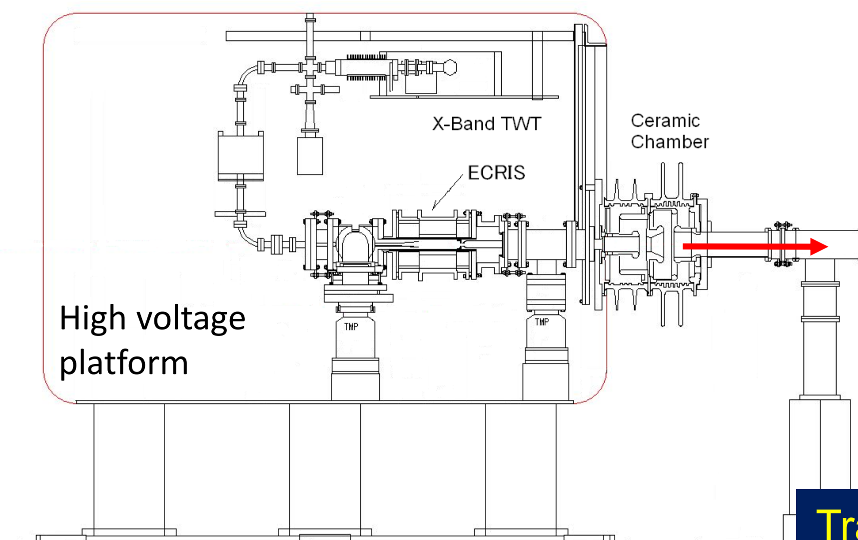


Properties:
Permanent magnets
10 Hz pulse mode operation

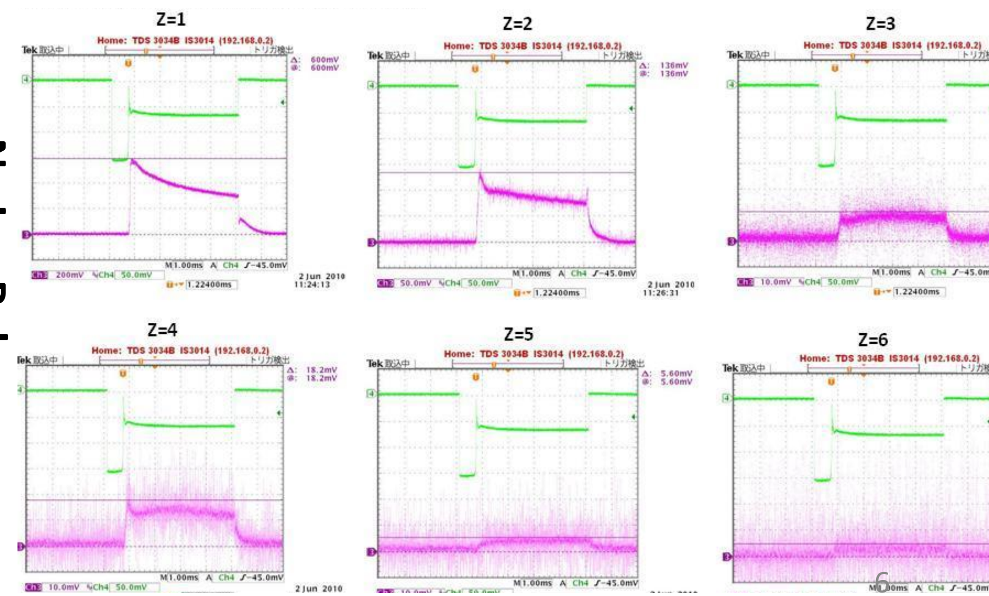
No power for guiding magnets
No cooling water

Plasma chamber diameter	30 mm
Hexapole length	148 mm
B_{res}	0.334 T
B_{max}	0.710 T
B_{max}	0.565 T
B_{min}	0.178 T
B_{rad}	0.597 T

He^{2+}, N^{x+}, O^{5+}, Ne^{5+}, Ar^{5+} at this moment



Ne Ion Pulse



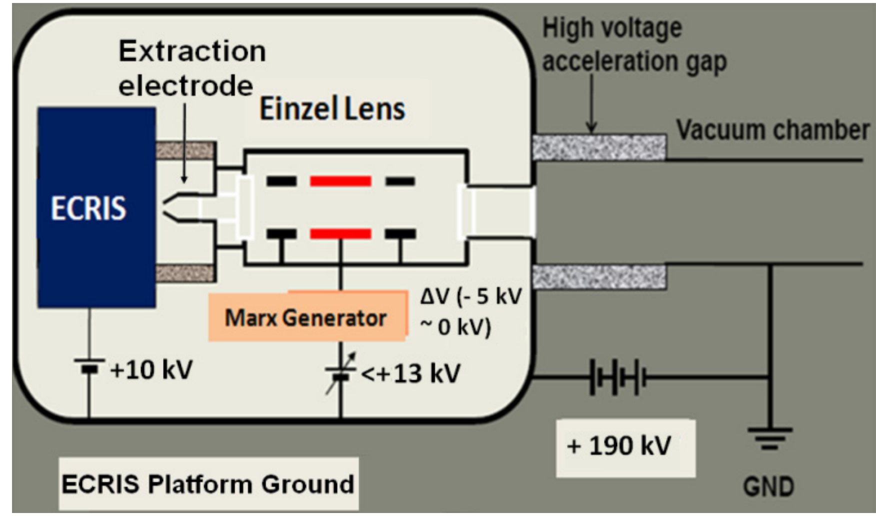
TrapCAD was helpful to understand some physics there.

Necessity of Chopper and Possible Schemes

Why we need a Chopper?

1 turn injection < 10 μsec
A long pulse from ECRIS ~ 2 - 5 msec

What type is desired?



High energy operation

- *High energy x-ray*
- *Out-gassing*
- *Secondary e^-*
- *Higher cost*

Low energy operation

- *Low energy x-ray*
- *Reduced out-gassing*
- *Reduced secondary e^-*
- *Lower cost*

Transverse chopper

- *Extra head*
- *Extra space*

Longitudinal chopper

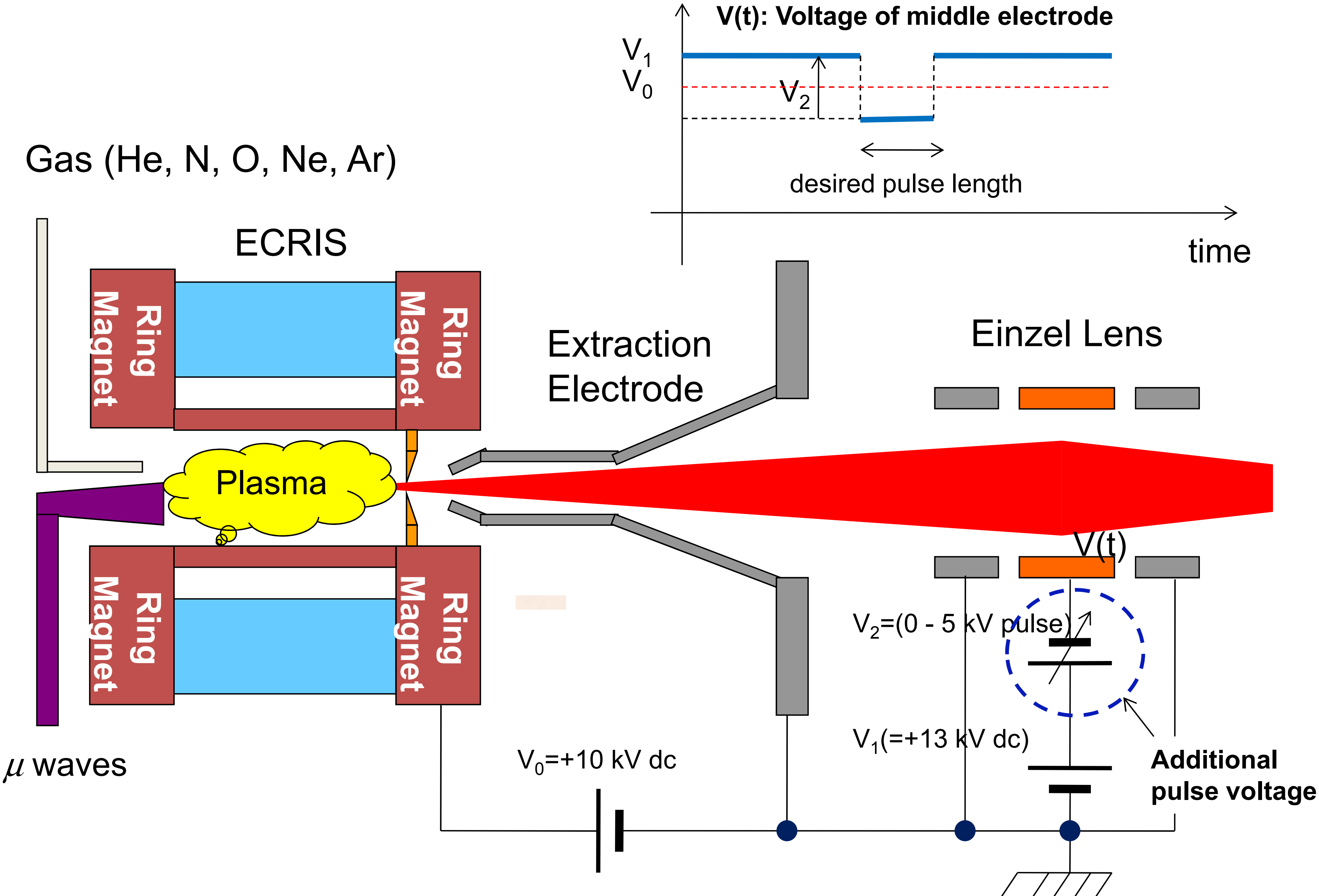
Einzel lens chopper

- *Existing EL electrode is available as chopper head*
- *No extra space*

Modulation of ECRIS extraction voltage

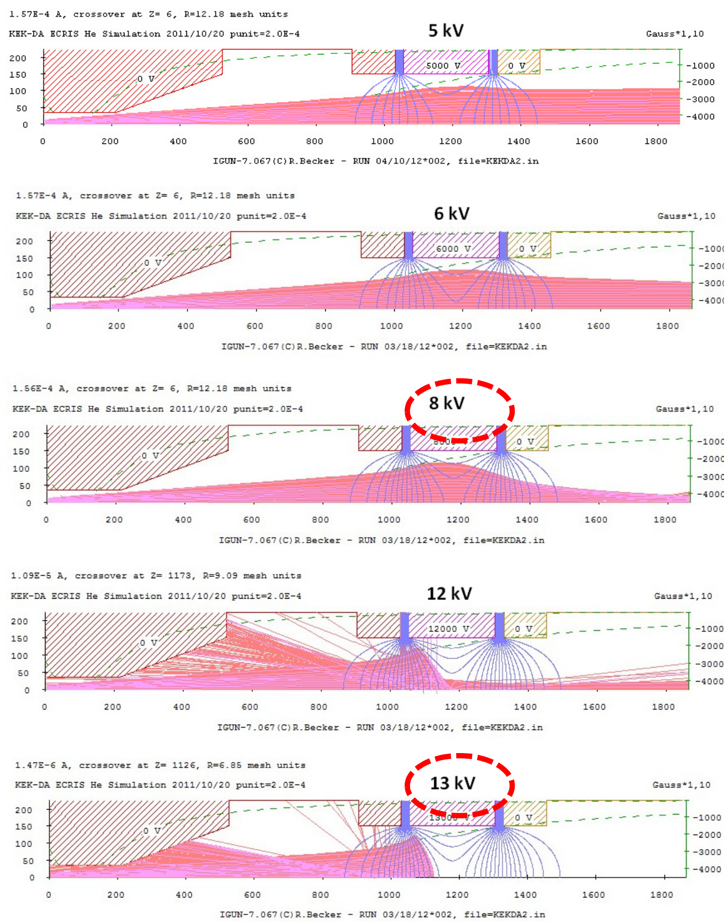
- *Large stray capacitance -> sharp pulse isn't expected*

Principle of Einzel Lens Longitudinal Chopper

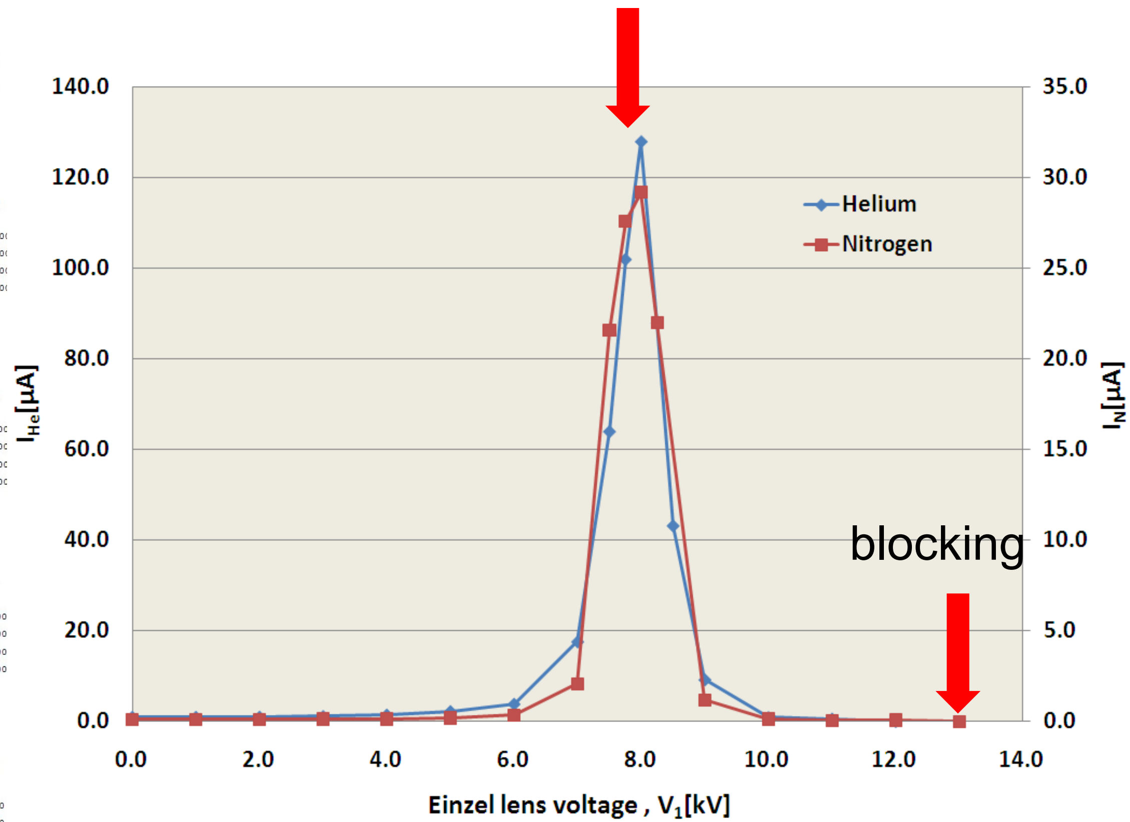


Verification of the Idea by Simulation and Experiment (static)

Inside extraction electrode   Einzel lens region

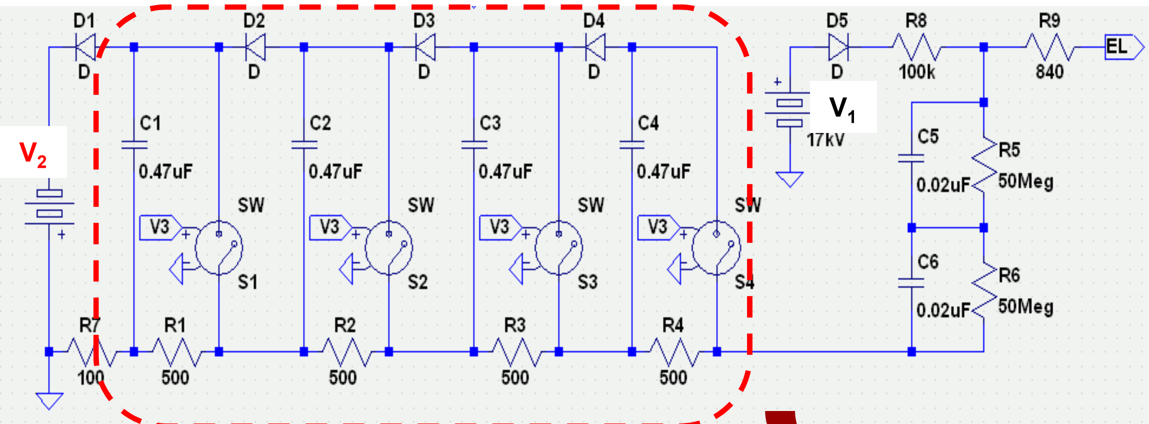


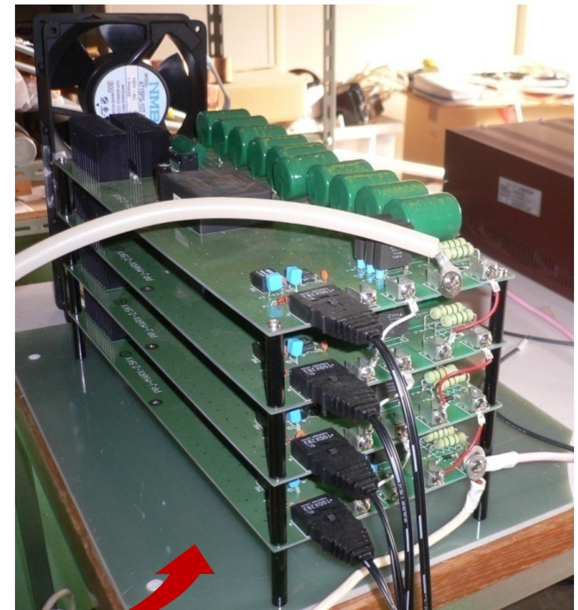
Matching for beam transport

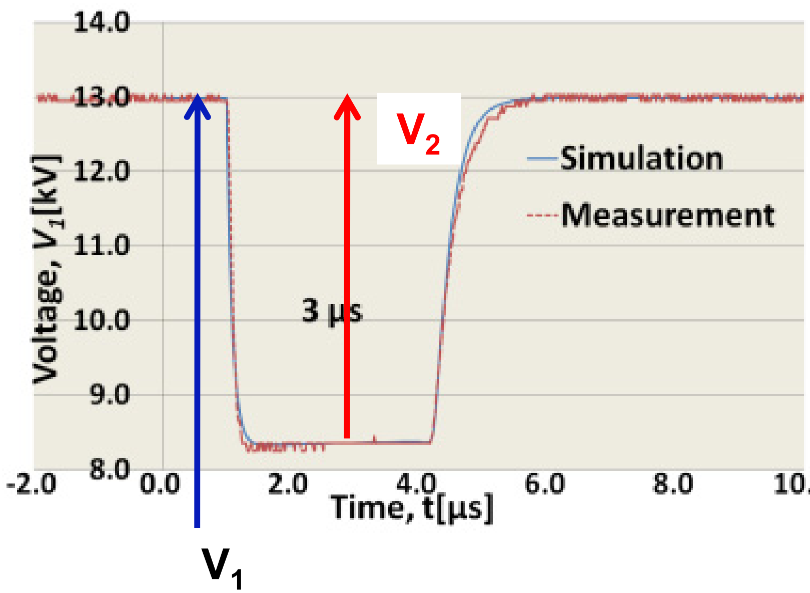


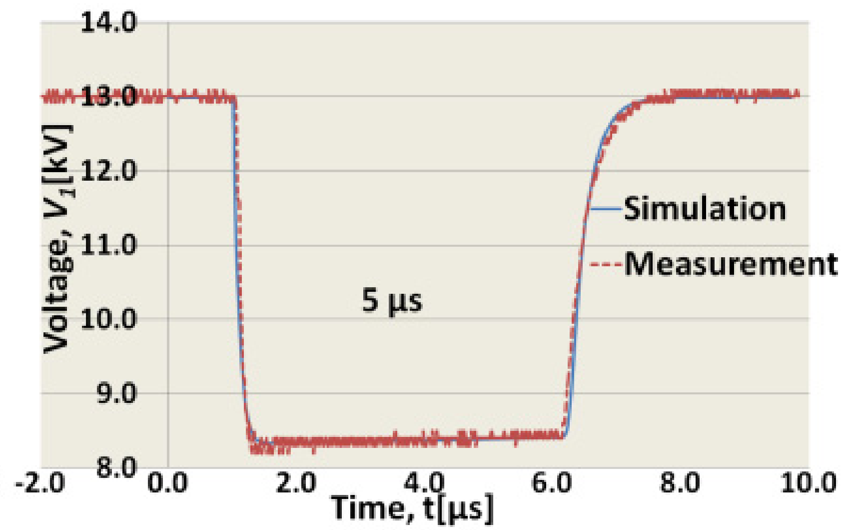
Solid-state Marx Generator as a Pulse Power Supply for the Chopper

FET switch driven 4 stages Marx generator



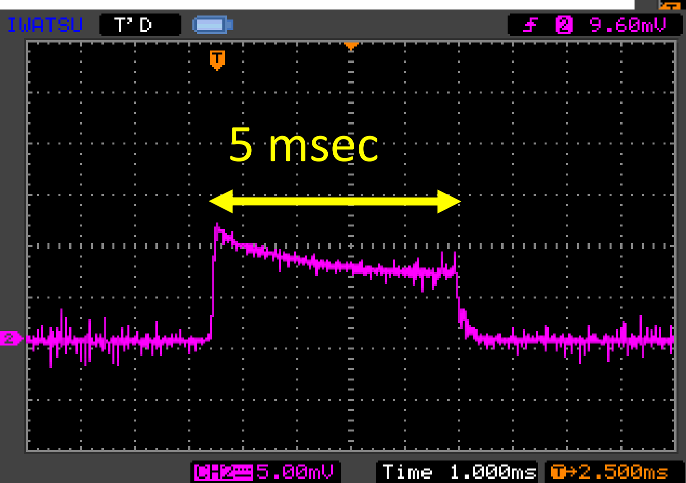


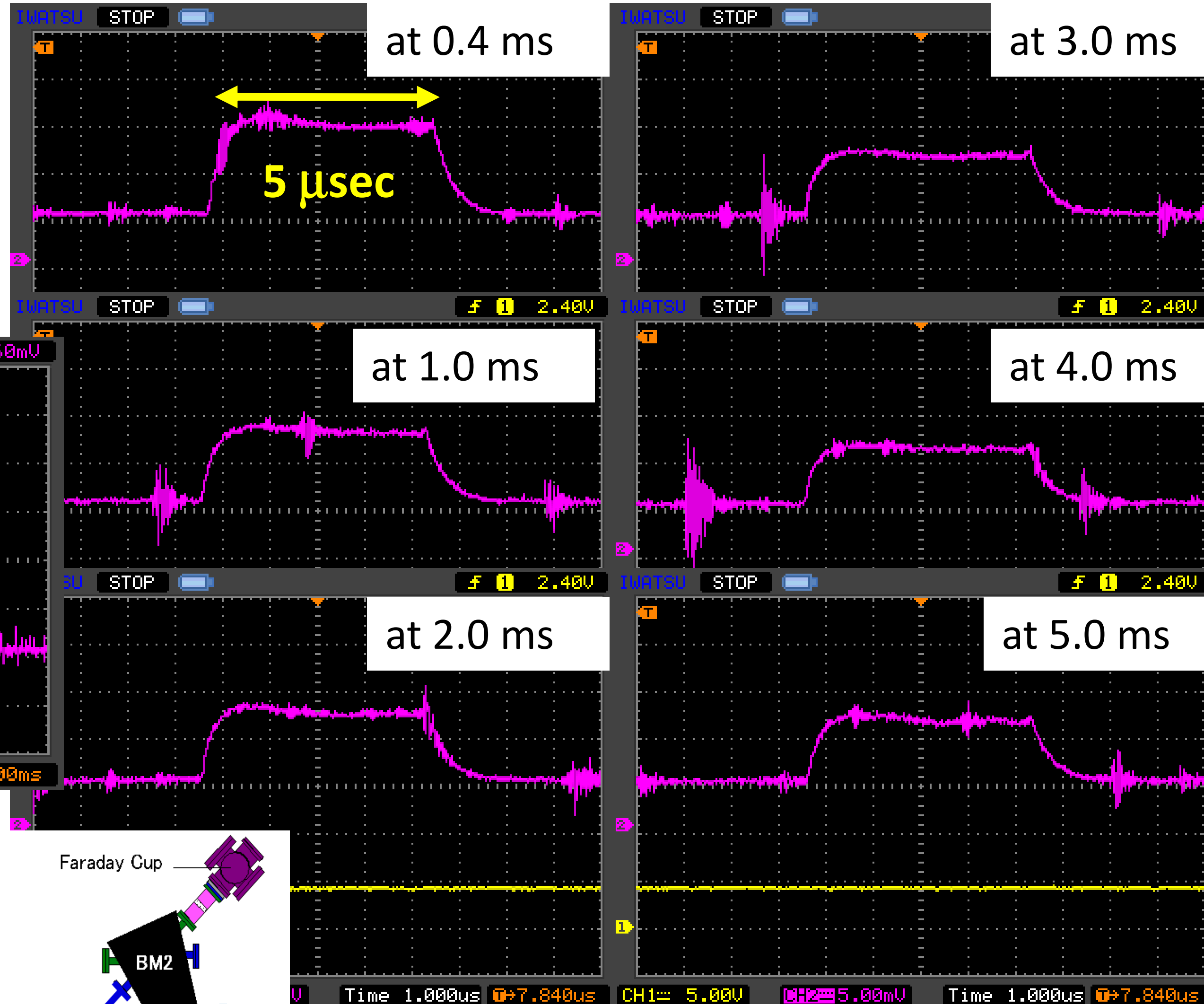




Chopping Experiments

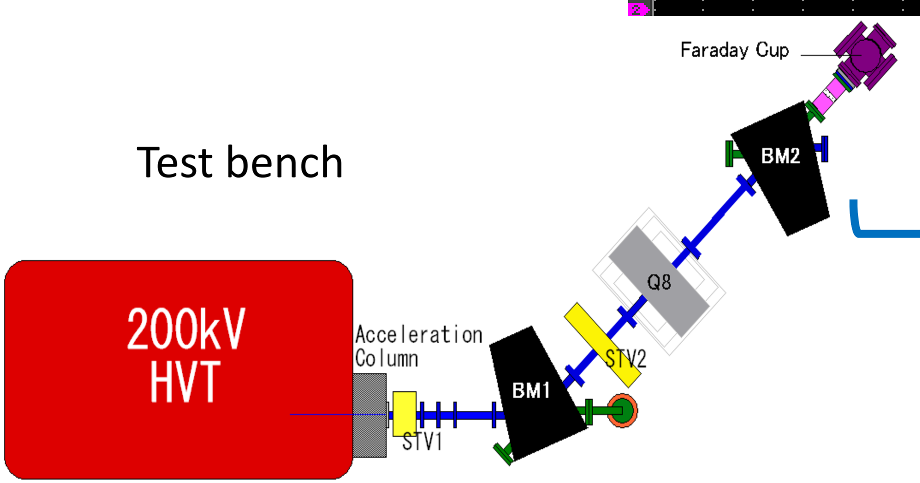
He1+ beam from ECRIS





He1+ pulses chopped at different timing

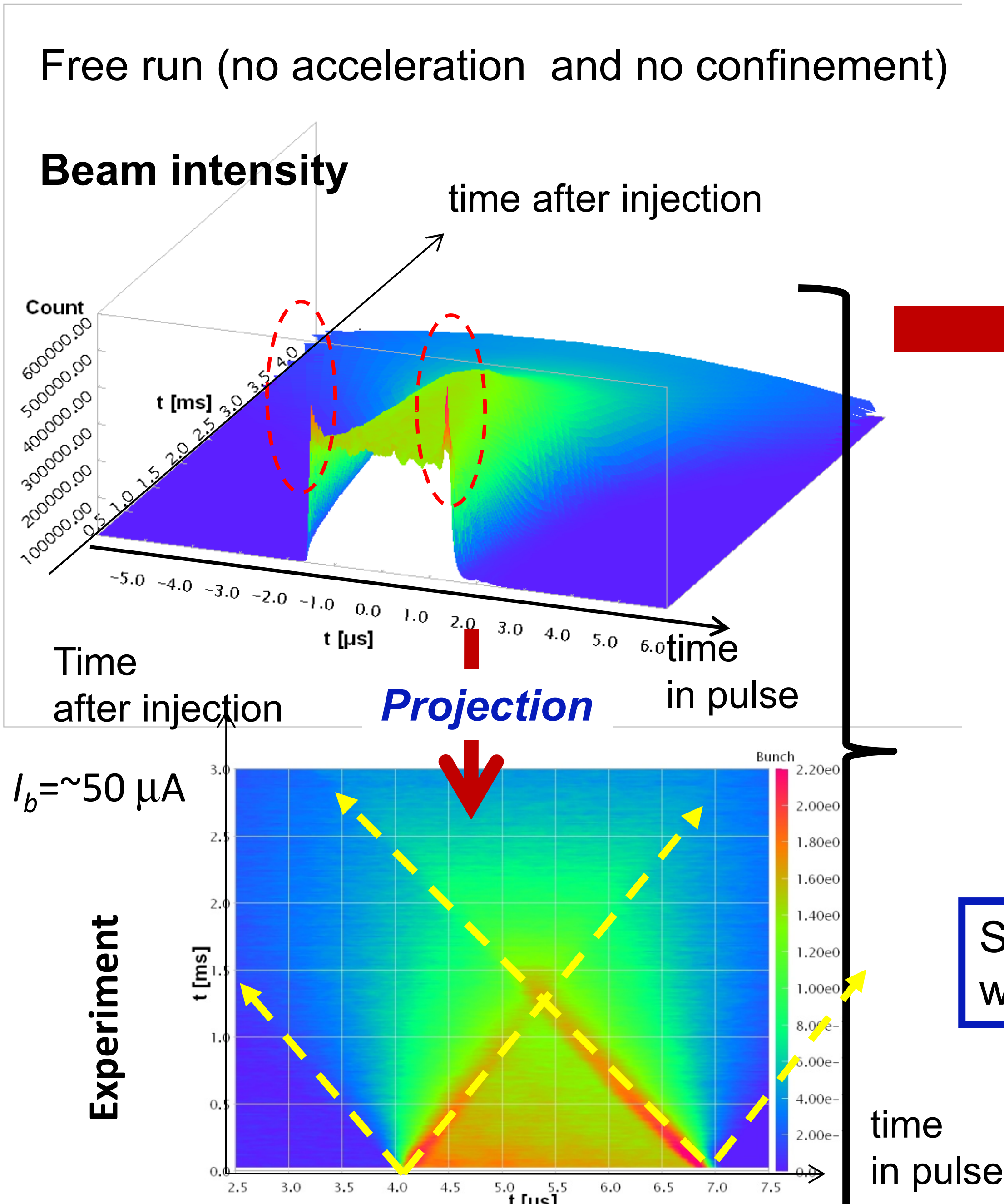
Test bench



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

Behavior of a Chopped Beam Pulse in the Ring and its Characteristics

Free run (no acceleration and no confinement)



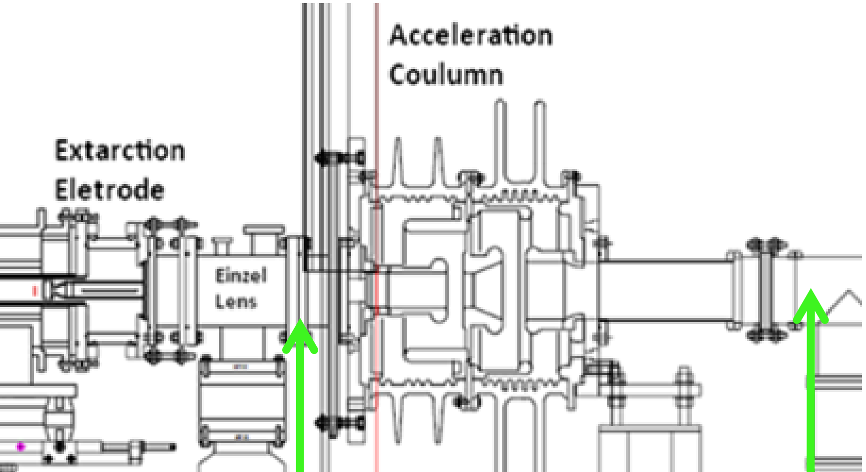
- ■Sharp peak at head/tail of pulse
- ■Different components in Momentum spread

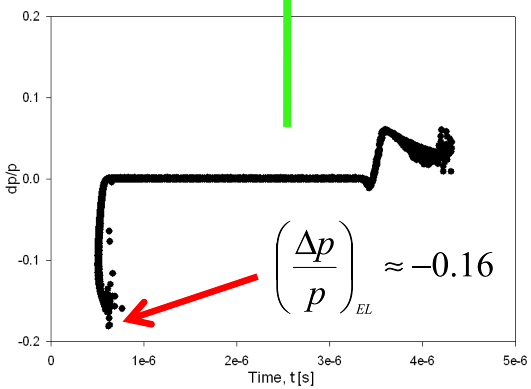
motivated

Simulation works to confirm what happens in the chopper region

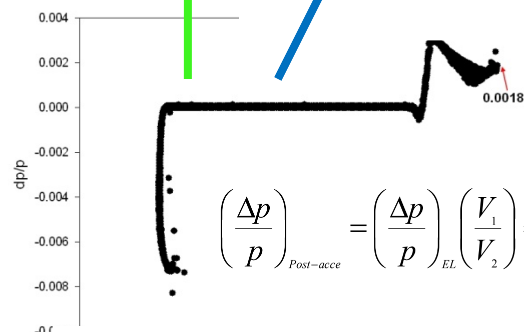
Work by K.W. Leo

Simulation Results

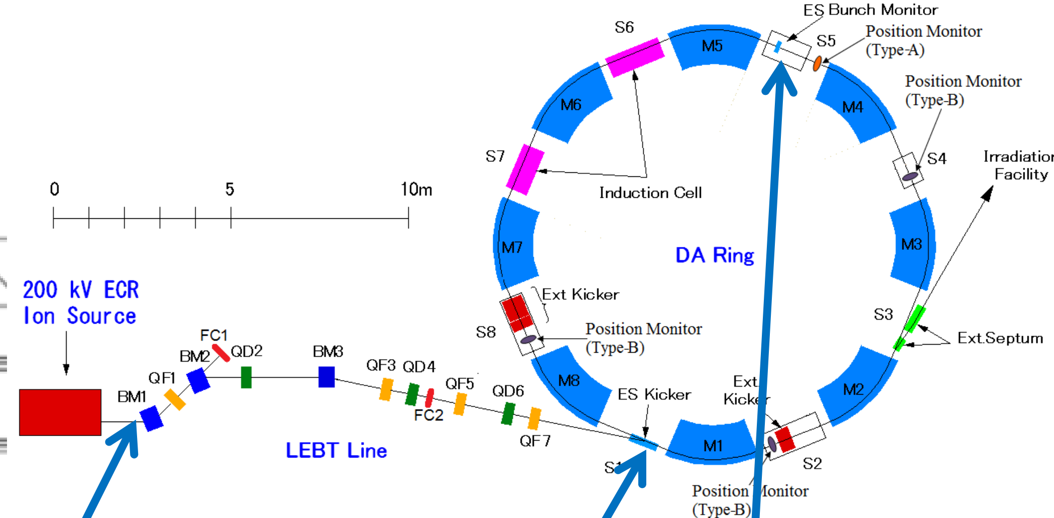


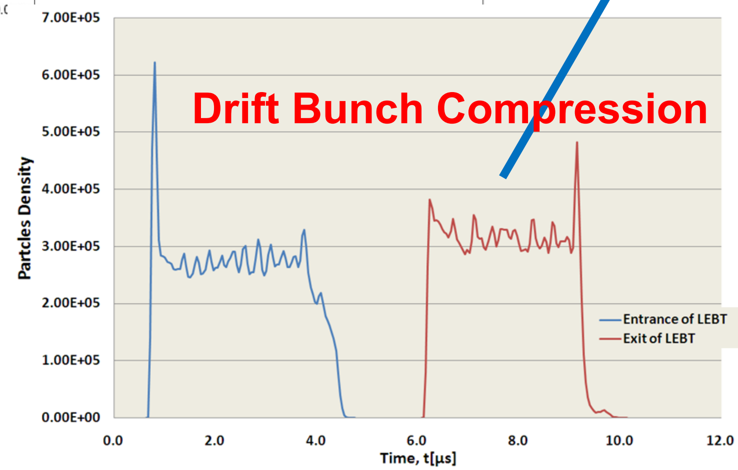


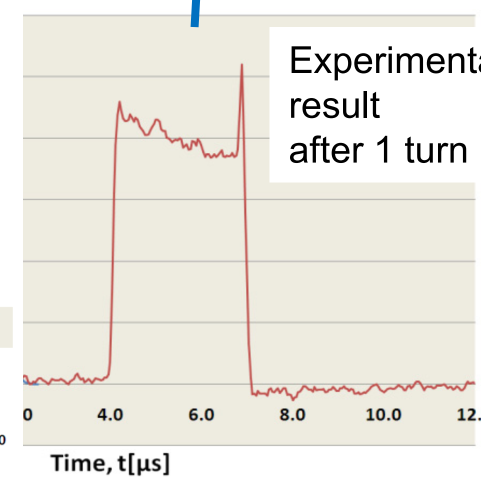
$$\left(\frac{\Delta p}{p}\right)_{EL} \approx -0.16$$



$$\left(\frac{\Delta p}{p}\right)_{Post-acce} = \left(\frac{\Delta p}{p}\right)_{EL}\left(\frac{V_1}{V_2}\right) \approx (-0.16)\left(\frac{10k}{200k}\right) \approx -0.008$$





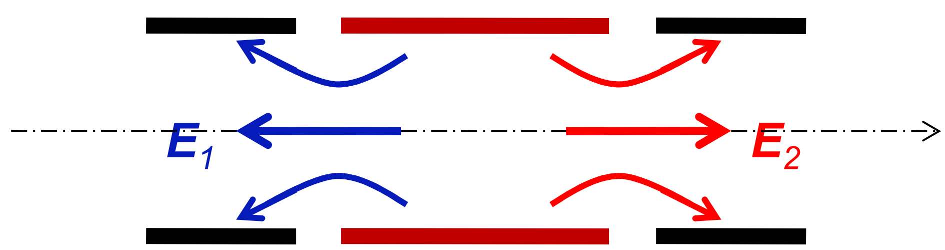


Notable characteristics:

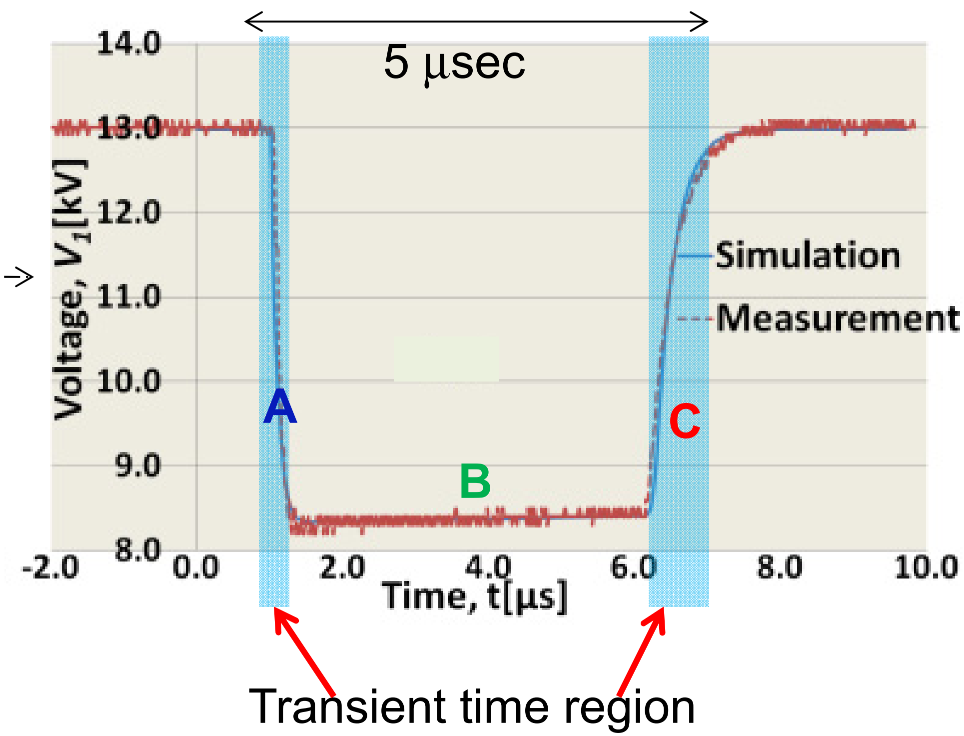
Large momentum deviation
at pulse head/tail

Momentum Deviation and Temporal Change in Chopper Pulse Voltage

Middle electrode of EL



Chopper pulse voltage



Let consider three particles of **A, B**, and **C**.

E_1 and E_2 are electric fields exerting on specific particle **A**, **B** and **C** at the gaps.

Particle **A**: pass through the EL region during time region A, where $|E_1| > |E_2|$ -> $\Delta p/p < 0$

Particle **B**: pass through the EL region during time region B, where $|E_1| = |E_2|$ -> $\Delta p/p = 0$

Particle **C**: pass through the EL region during time region C, where $|E_1| < |E_2|$ -> $\Delta p/p > 0$

Momentum deviation in the chopped pulse

Intrinsic feature of the longitudinal chopper

Further Evolution and Application of the Einzel Lens Chopper are expected ?

Possible evolution:

■Longer pulse chopper

Droop in pulse voltage leads to degradation in current uniformity of a chopped beam.

Limit on pulse length

Measure → introducing Droop compensation circuit

■Fast rising/falling chopper with small momentum deviation

Transient time period of On/Off is determined

by (1) Switching time of solid-state switching element (~ 5-10 nsec)

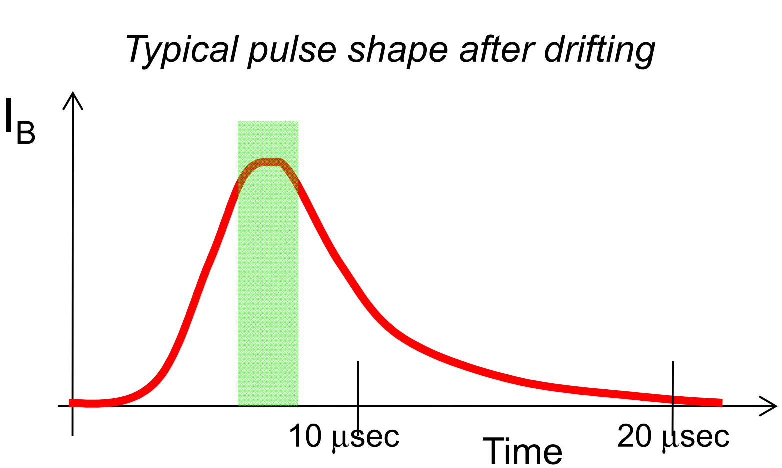
(2) Stray capacitance (100 pF) of chopper head (~ a few hundred nsec)

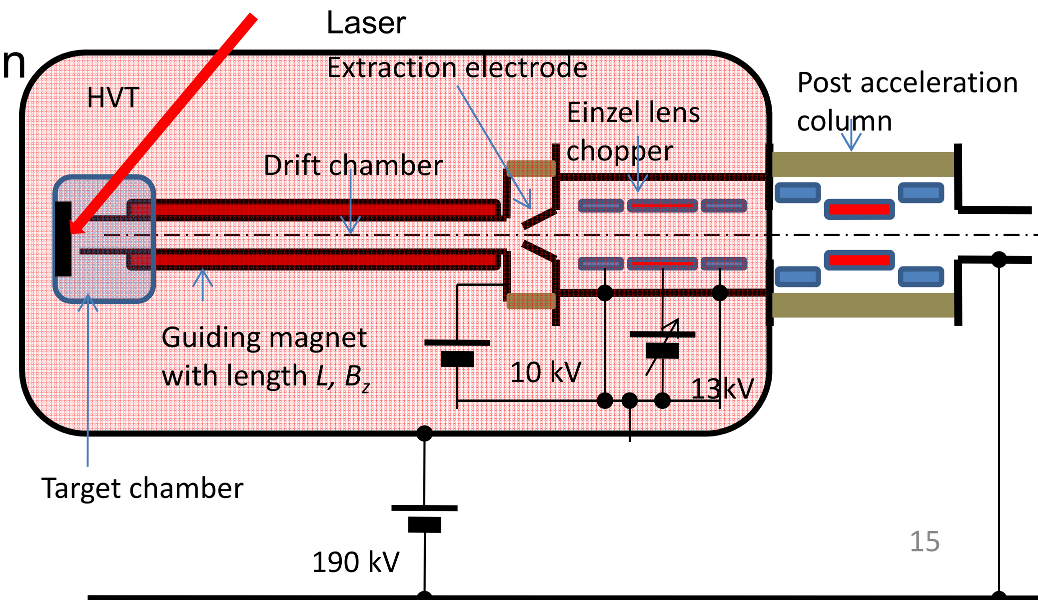
Measure → reduce the stray capacitance (practical limit from its geometry)

Applications: combination with other ion sources

■Laser ablation ion source

chopping of an uniform beam fraction



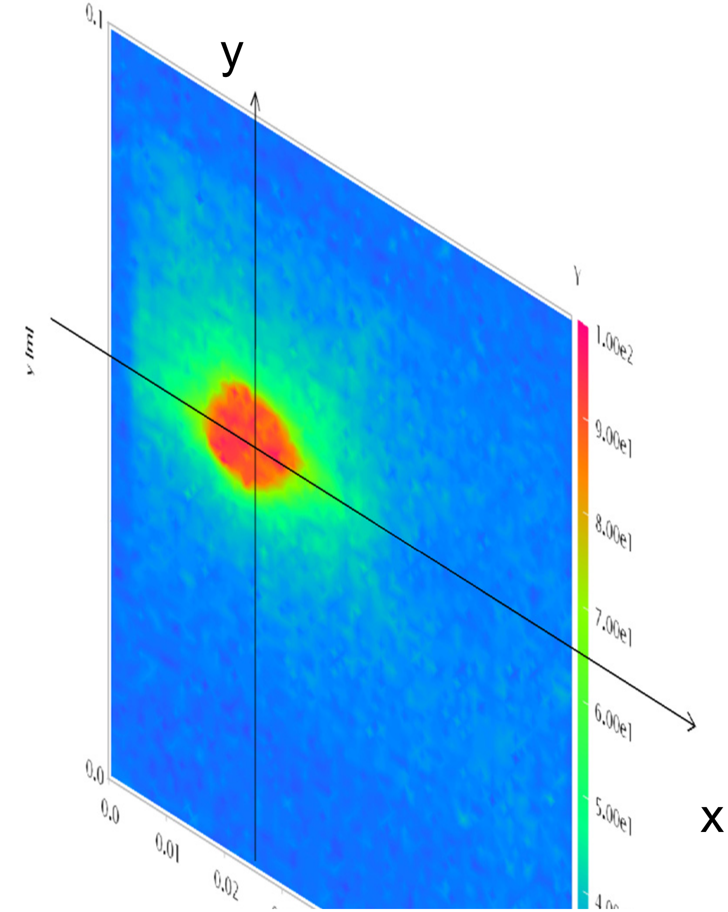


Summary

- **Performance of the Einzel Lens Longitudinal Beam Chopper has been confirmed.**
  - **Droop (< 2%) for 5 msec pulse** with acceptable rising/falling time.
  - **Momentum modulation at pulse head/tail** caused by a chopper voltage pulse with a finite time of rising/falling
    (still acceptable but this feature is generic in the ECL)
  - Work without any trouble over one year for the KEK Digital Accelerator
  - Following figure of merits are emphasized
    low voltage control, no specific chopper head, no extra space, no degradation of vacuum, low X-ray energy/dose, low secondary electrons, low cost ($2.5K)
- **Further Improvements and for future Ion Source**
  - Additional correction circuit parameters for improvement of the droop.
  - Minimize **stray capacitance** to get a more sharp chopper pulse
  - Integration with Laser Ablation Ion Source (under test)

Beam Profile on the Screen Monitor placed upstream in LEBT

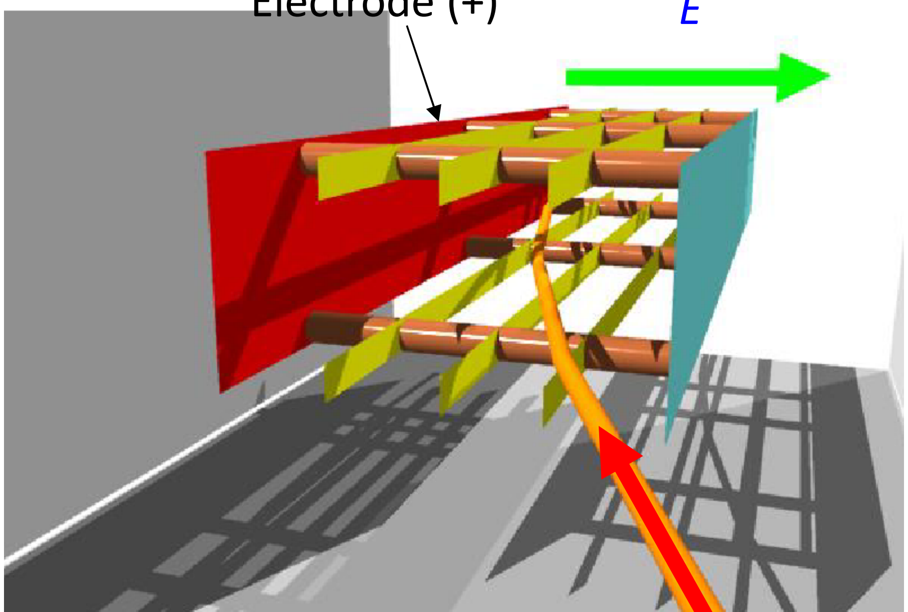
Beam profile plotted by the result from “Screen Monitor”

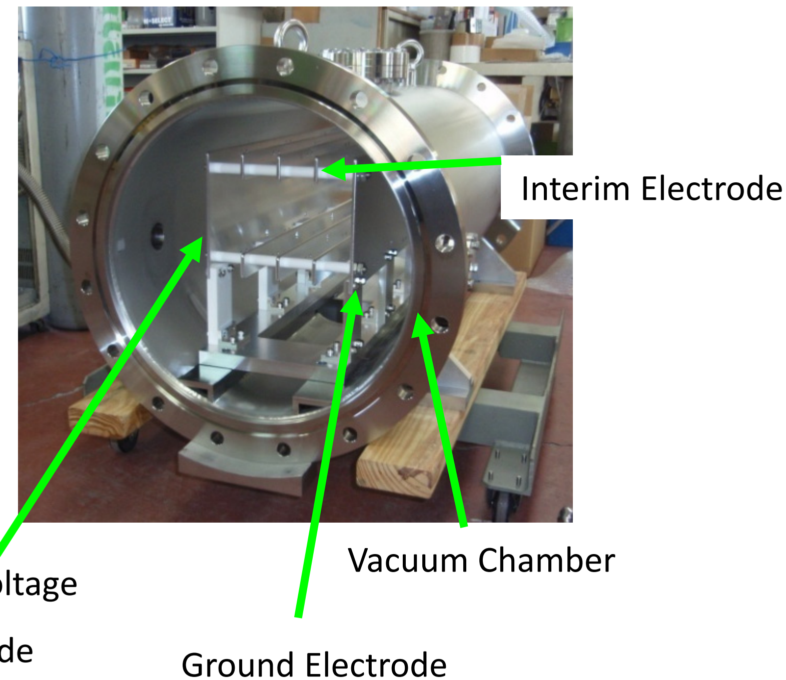


200 keV
He1+
100 μA

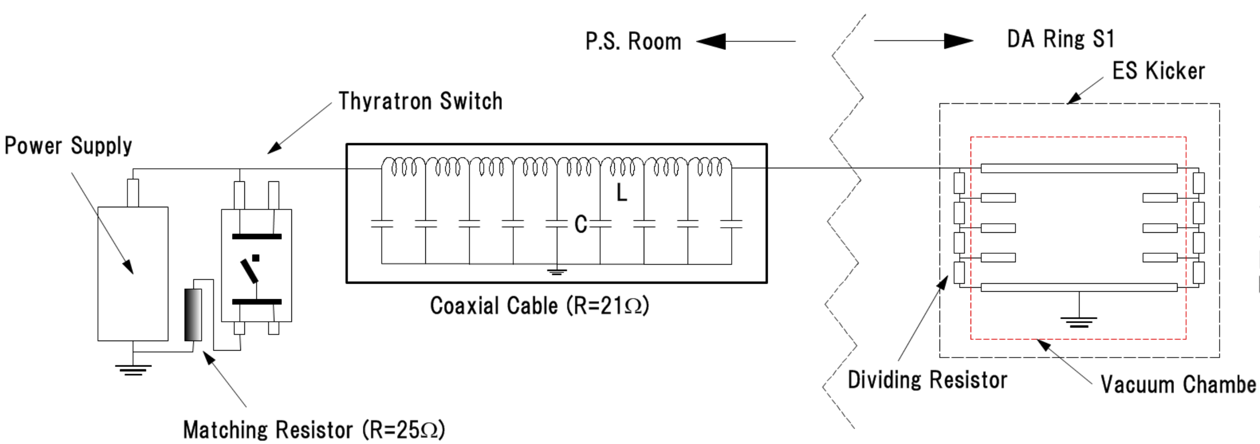
	Horizontal rms emittance ε_x[μmrad]	Vertical rms emittance, ε_y[μmrad]
Measurement by Pepper pot device	~100	~75

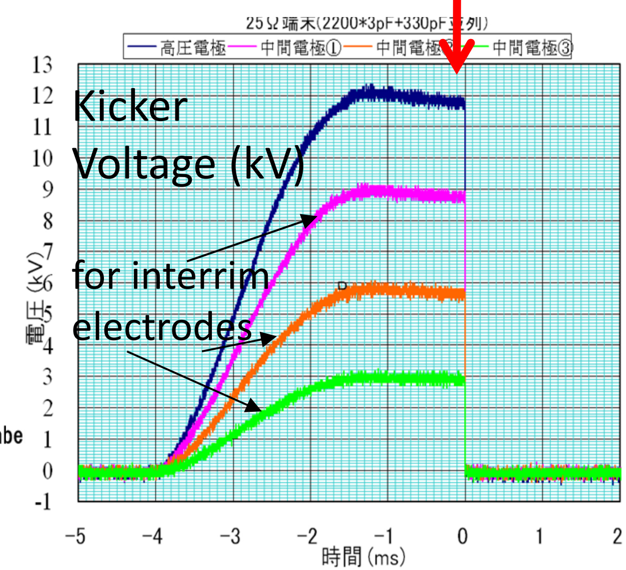
Electrostatic Injection Kicker





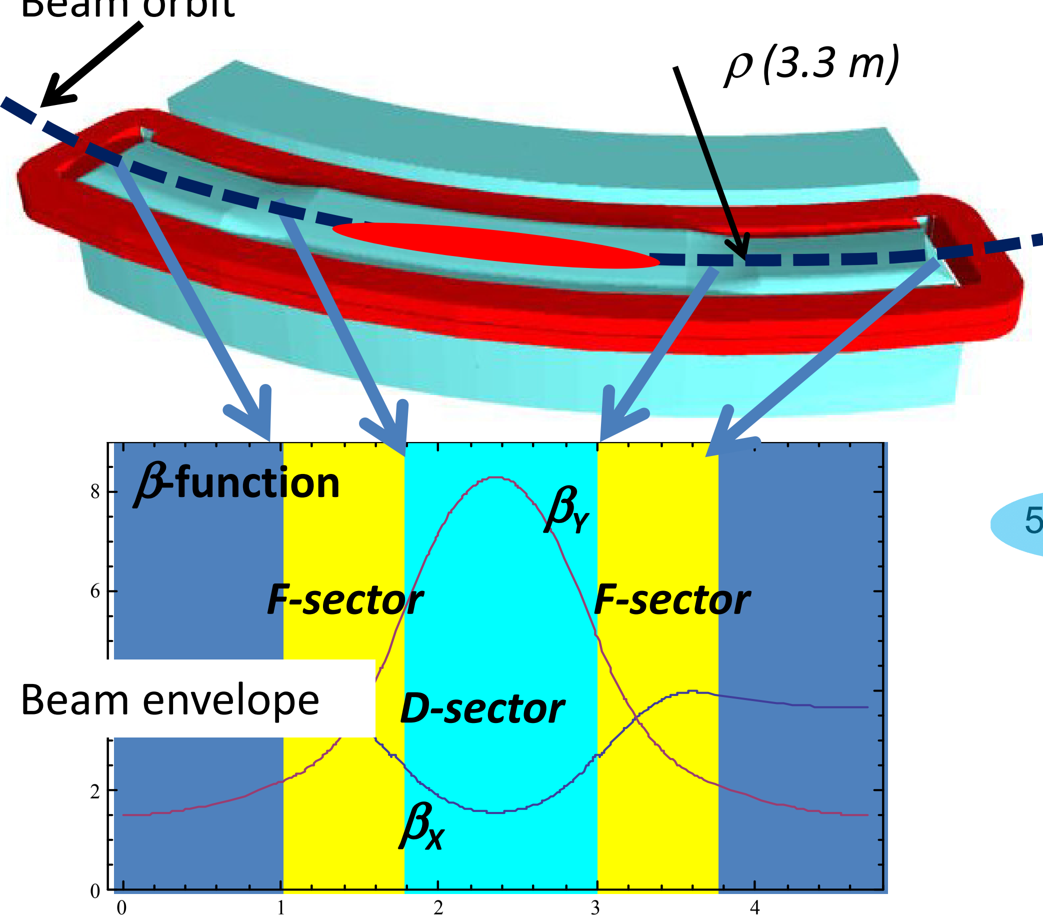
Driving circuit of the injection ES kicker





DA Ring Machine & Beam Parameters

Combined-function type magnet (lower half)



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

Field ramping and acceleration