Present achievements of induction synchrotron and its possibility for super-bunch acceleration

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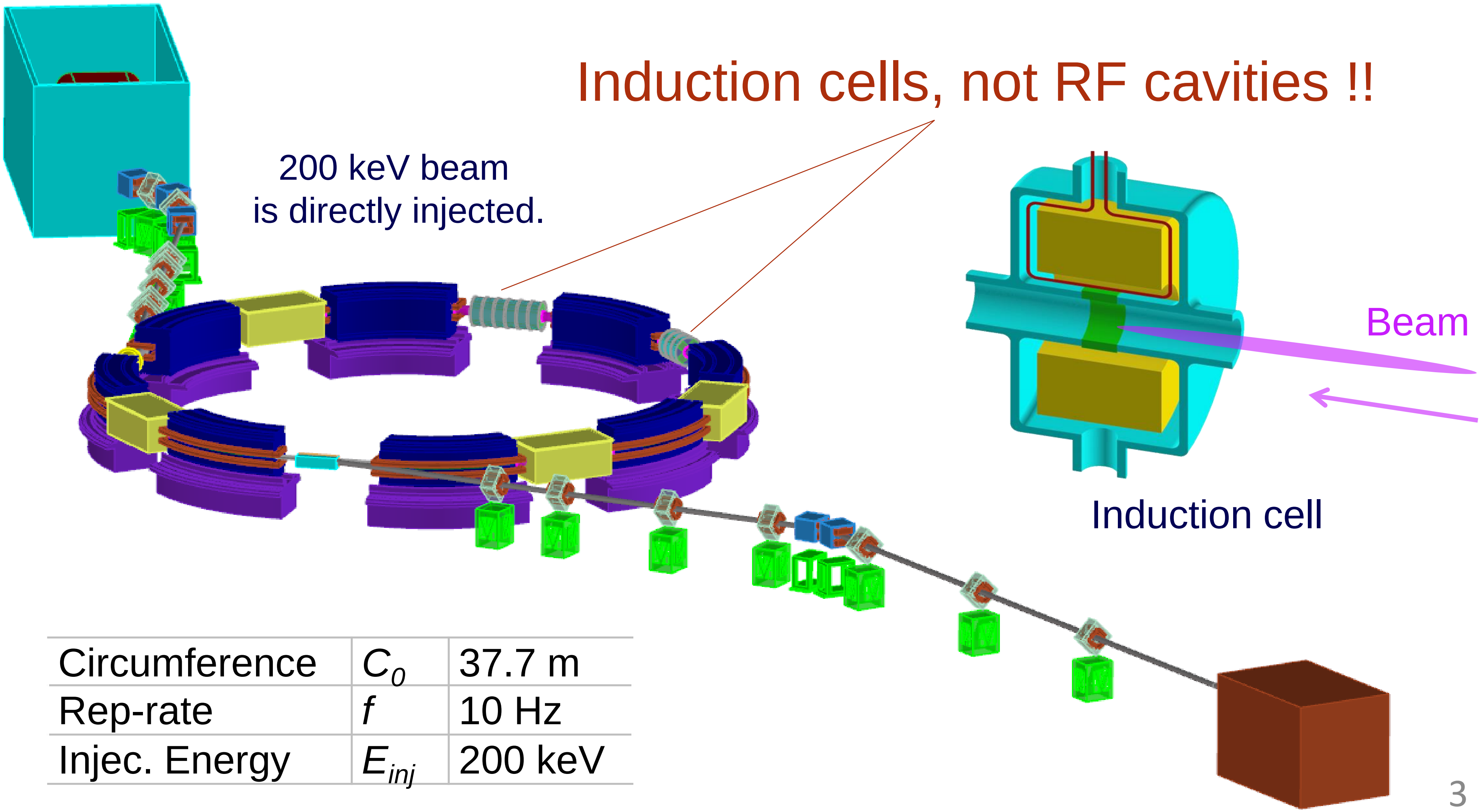
Contents

- What is induction synchrotron ?
- System of KEK digital accelerator
- Three induction acceleration technique
  - wide-band acceleration
  - novel beam handling
  - (super-bunch acceleration)
- Upgrade plan for super-bunch acceleration
- Problem of super-bunch acceleration

  in high intensity synchrotron
- Conclusion

What is Induction synchrotron ?

KEK digital accelerator (Wide-band fast cycling induction synchrotron)[1)]

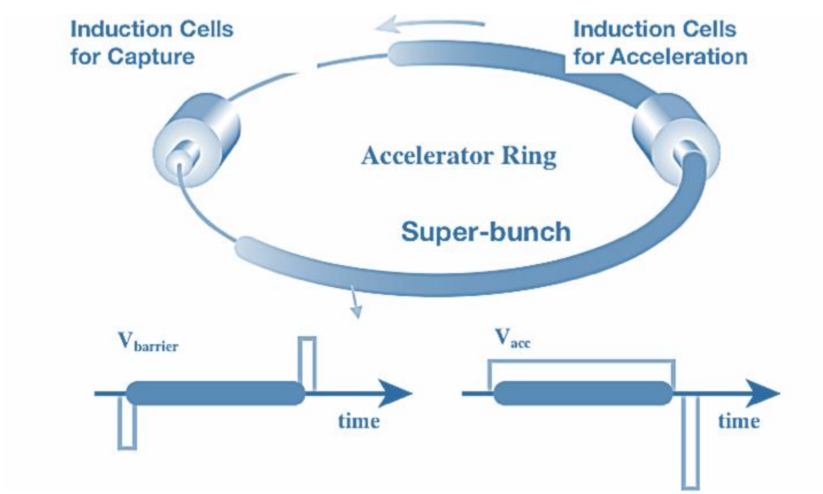


Circumference	C_0	37.7 m
Rep-rate	f	10 Hz
Injec. Energy	E_{inj}	200 keV

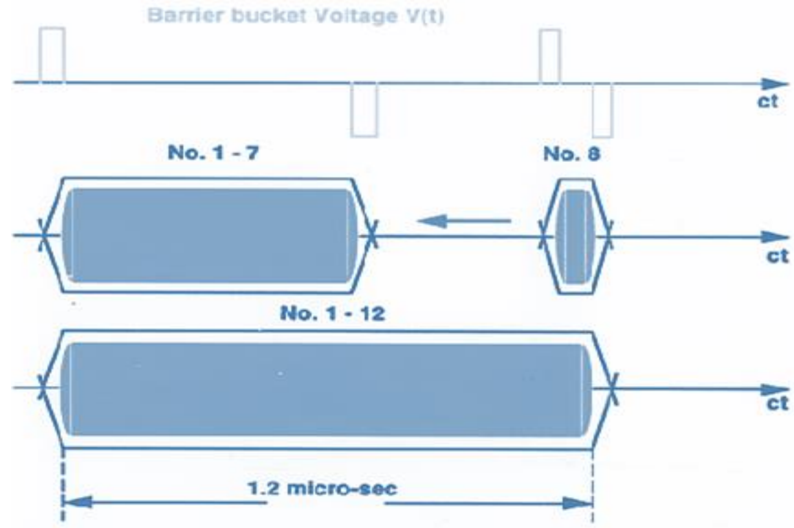
1) T. Iwashita, *et al.*, “KEK digital accelerator”, *Phys. Rev. ST-AB* 14, 071301(2011)
2) K. Takayama, *et al.* ,"Experimental Demonstration of the Induction Synchrotron" , *Phys. Rev. Lett.* 98, 054801 (2007)

Three distinguished features of Induction synchrotron

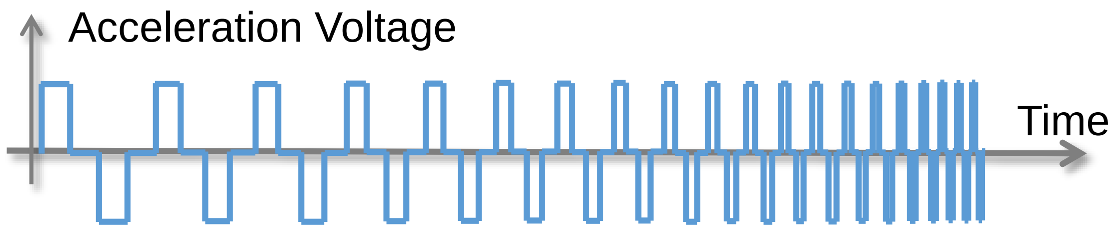
Super-bunch acceleration[1)]



Novel beam handling



Wide-band acceleration[2)]



Advantages

Rev. frequency: 0 ~ a few MHz

So many ion species can be provided in a broad energy range.

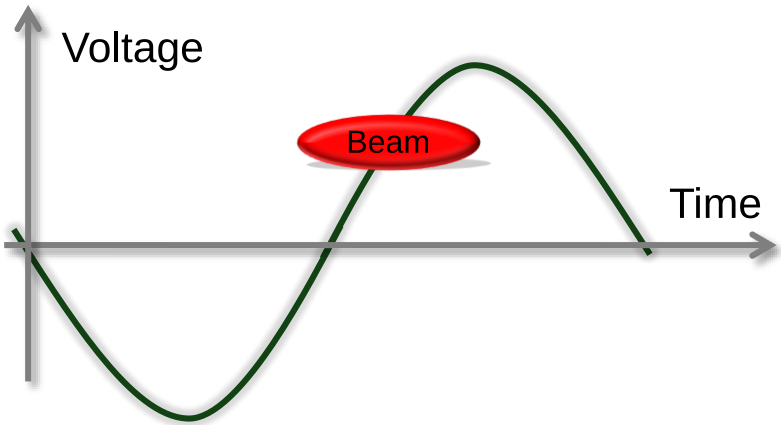
Disadvantages

- Space charge limit & residual gas interactions in low energy region
- In small ring (~100 m), max. rev. frequency is limited by semiconductor switching of acc. volt..

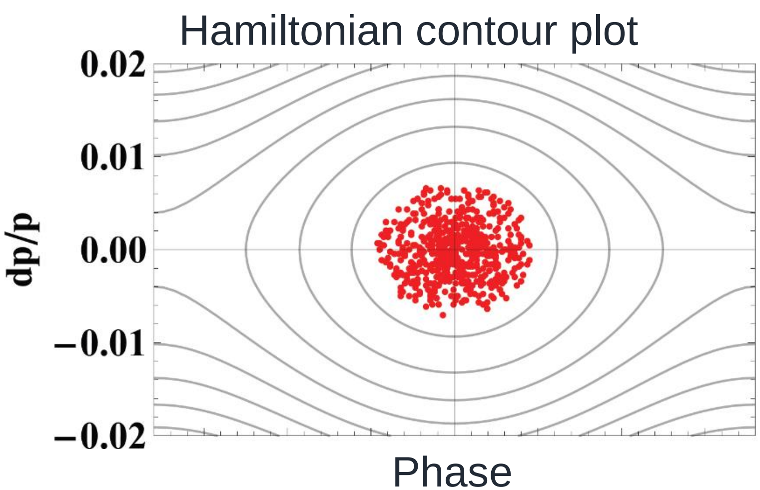
1) K.Takayama, *et al*, "Superbunch Hadron Colliders", *Phys. Rev. Lett.* 88, 144801 (2002)
2) K.Takayama, *et al*, "All-ion accelerators: An injector-free synchrotron", *Journal of Applied Physics* 101, 063304 (2007)

RF acceleration & Induction synchrotron

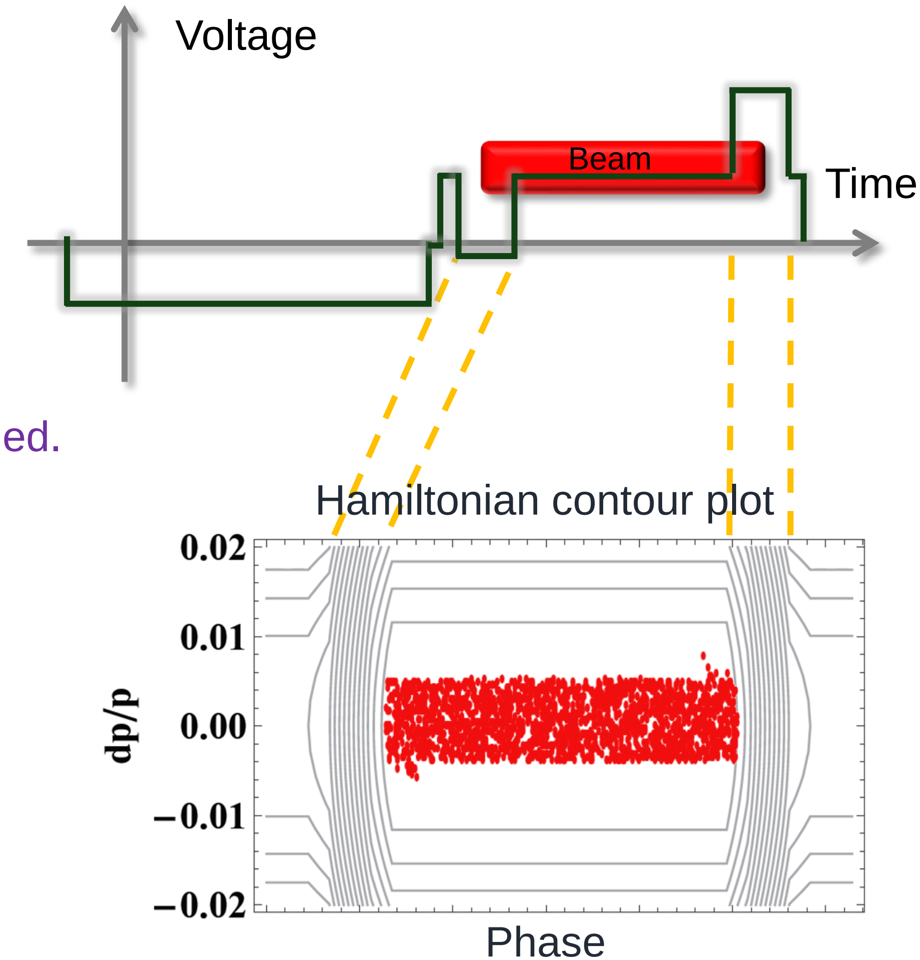
Conventional RF acceleration



Confinement & Acceleration function are combined.

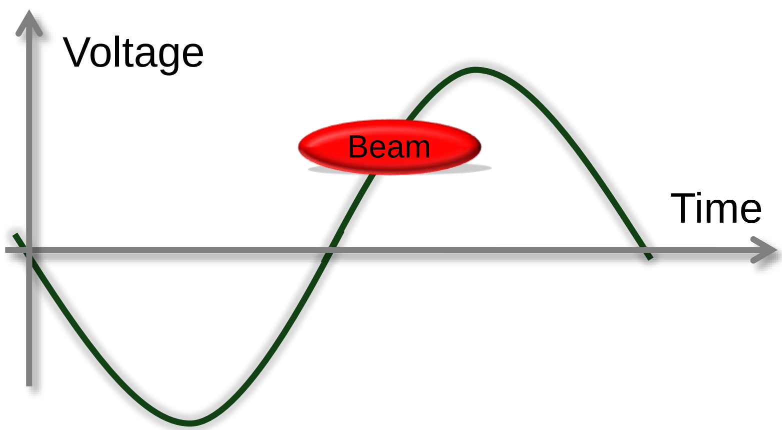


Induction acceleration

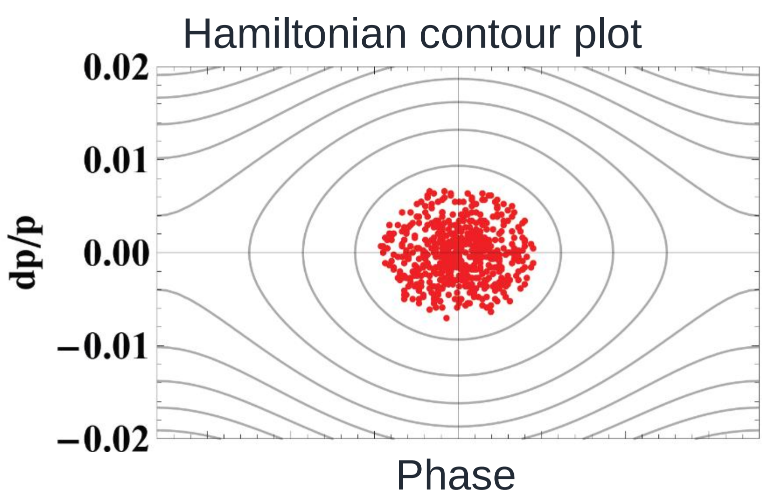


RF acceleration & Induction synchrotron

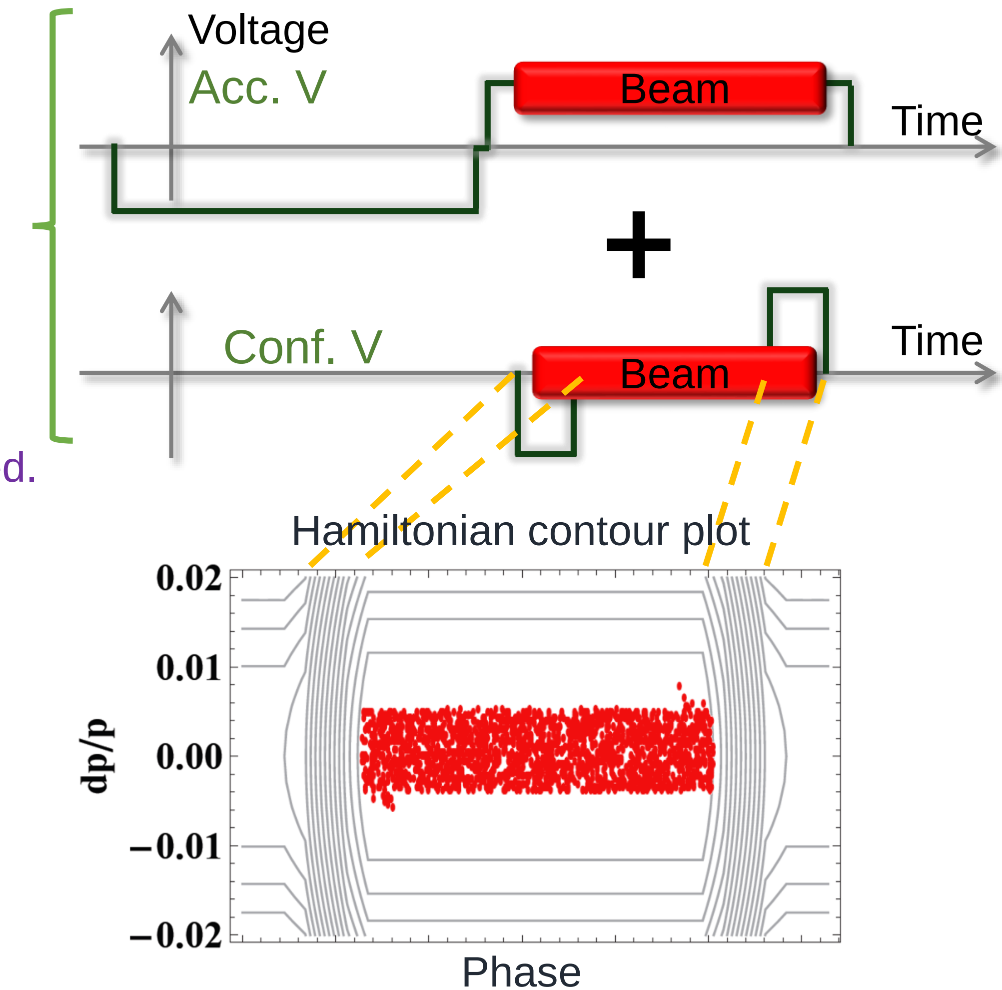
Conventional RF acceleration



Confinement & Acceleration function are combined.

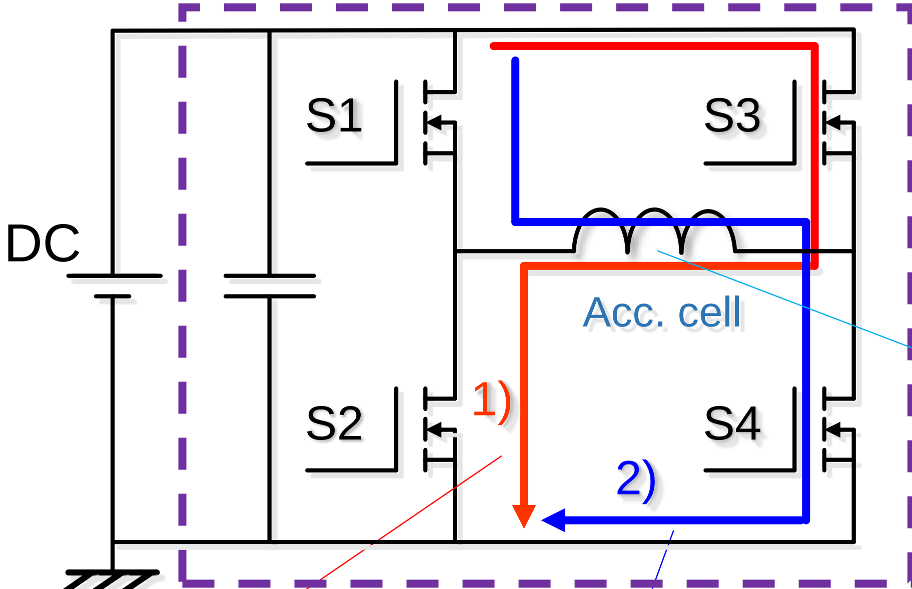


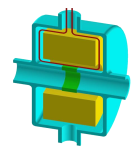
Induction acceleration

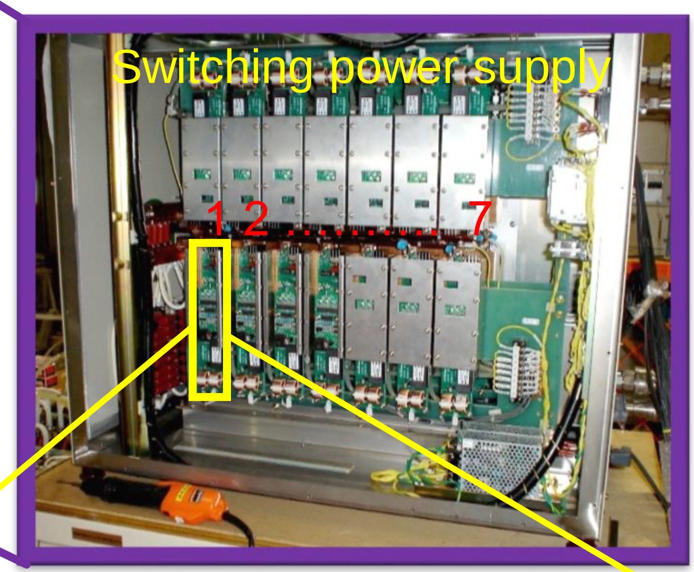


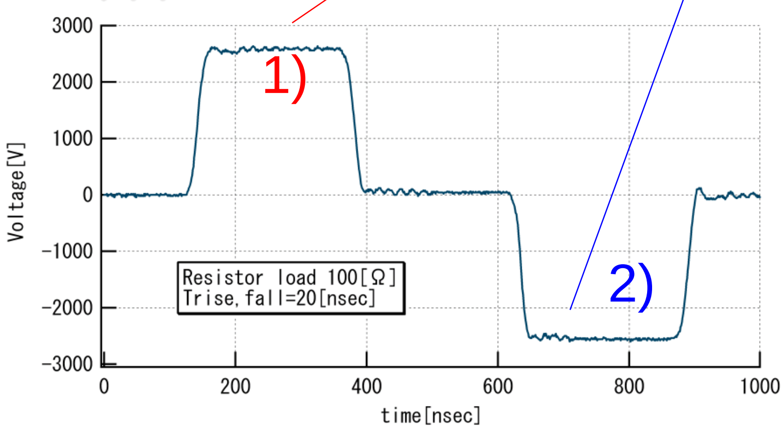
Separate function can creates a longer bucket ⇒Diminishing space charge effect.

Switching Power Supply for Induction cells



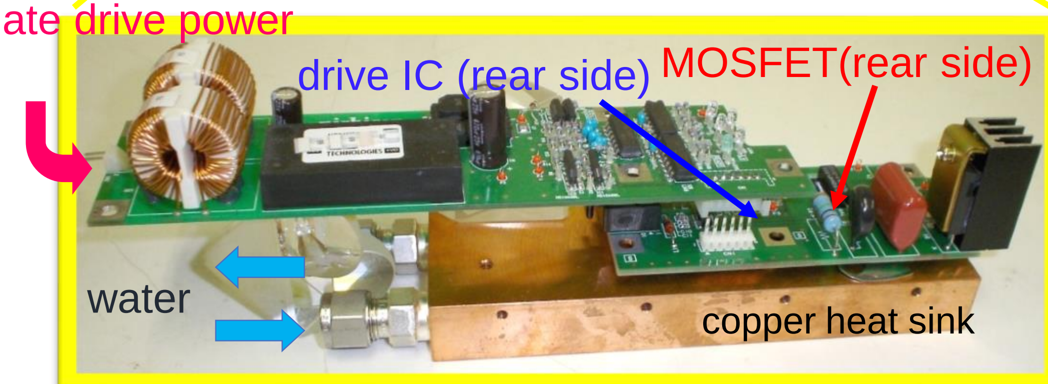






Waveform generated by switching power supply
(2.5kV, 20A, 1MHz)

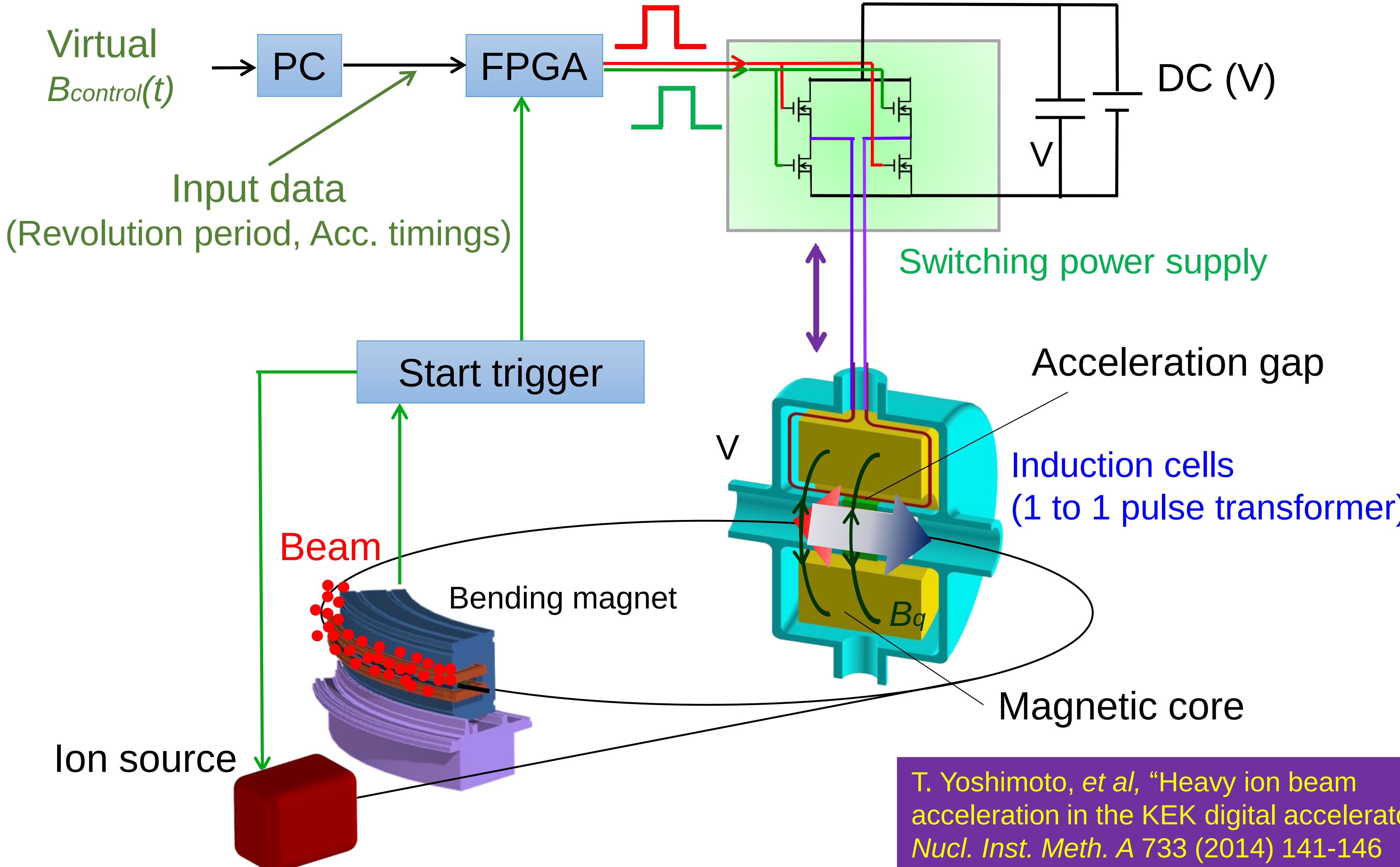
One arm consists of 7-series MOSFETs.



Next generation of SPS: K.Okamura, *et al*, MOPME068 in IPAC'14
"SiC-JFET Switching Power Supply toward for Induction Ring Accelerators"

Fully programmed control of KEK digital accelerator

In advance, all information for acceleration timings is load to FPGA.
Virtual *B(t)* decides ideal revolution period and acc. timings.



T. Yoshimoto, *et al*, "Heavy ion beam acceleration in the KEK digital accelerator: ~", *Nucl. Inst. Meth. A* 733 (2014) 141-146

How to generate confinement voltages

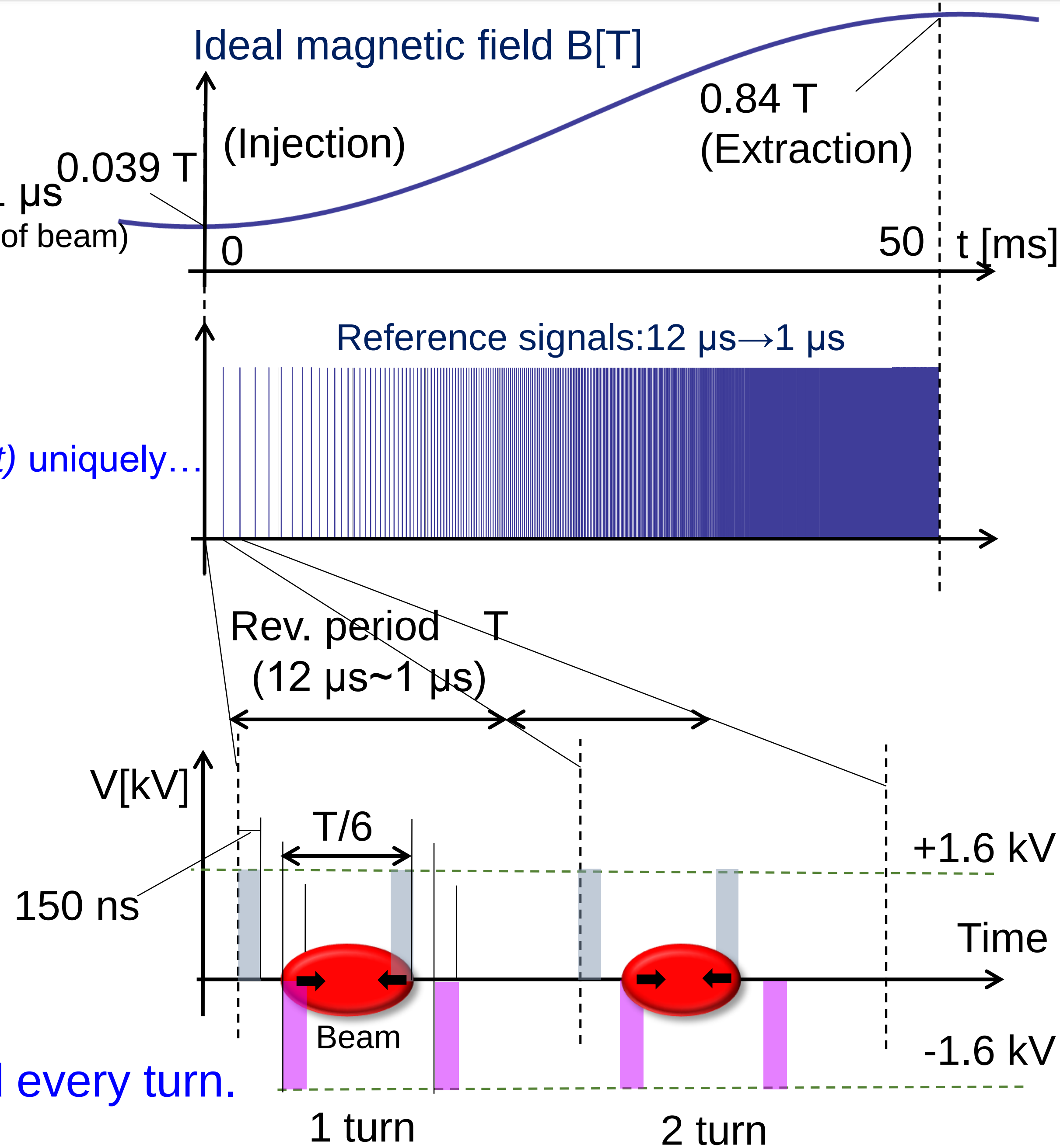
Reference signals:12 μs→1 μs
(which generate every ideal rev. period of beam)

$$T(t) = \frac{C_0}{c}\sqrt{\frac{1+D}{D}}$$

B(t) determines *T(t)* uniquely…

$$D = \left\{\left(\frac{Q}{A}\right)\left(\frac{e\rho}{m_0 c}\right)\right\}^2 B^2$$

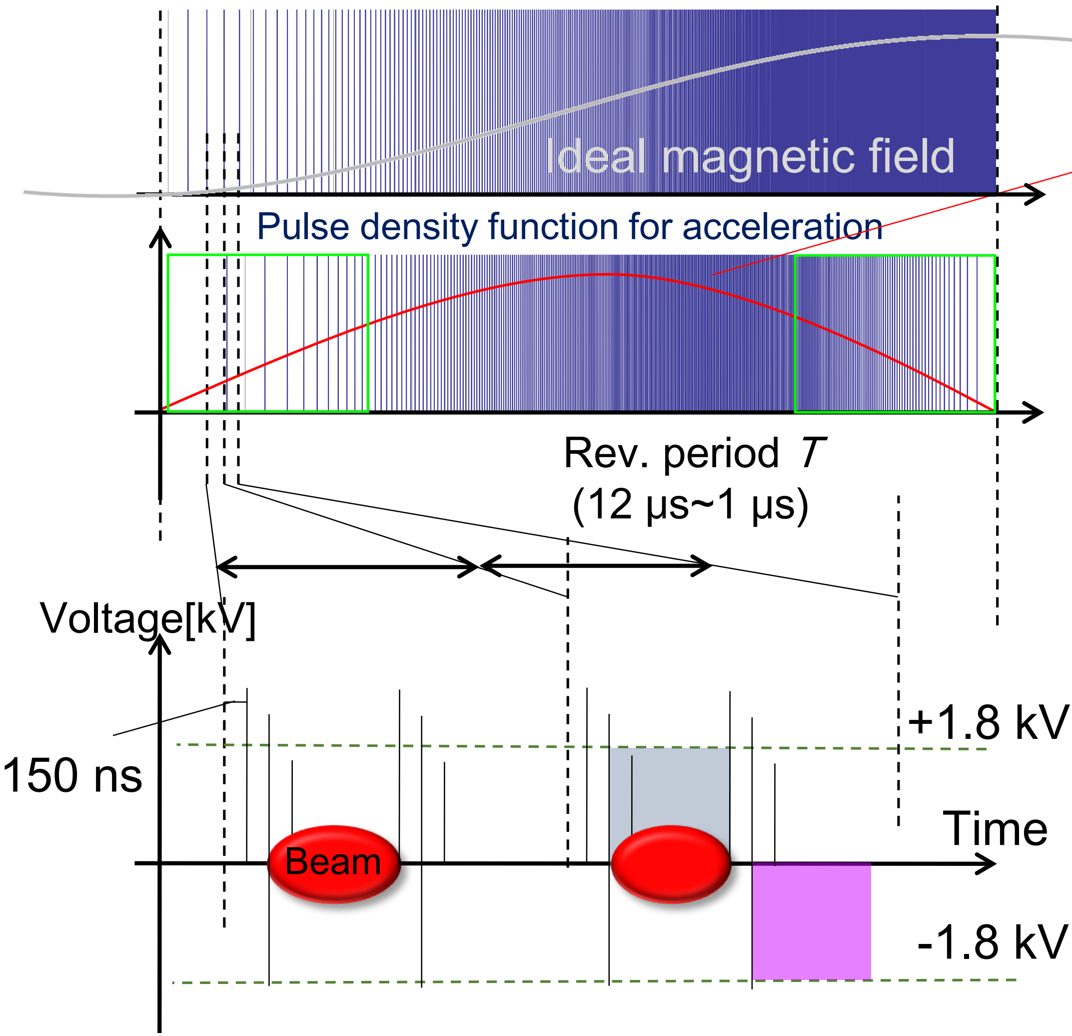
Here,
ratio of charge to mass : *Q/A*
charge element : *e*
bending radius: *r*
unit mass: m_0
ideal magnetic field : *B(t)*



Conf. voltages are generated every turn.

How to generate acceleration voltage

Reference signals (signals of ideal rev. period) :12 μs→1 μs



Required acc. voltage per turn *V(t)*:

$$V(t)=\rho C_0 \frac{dB(t)}{dt}$$

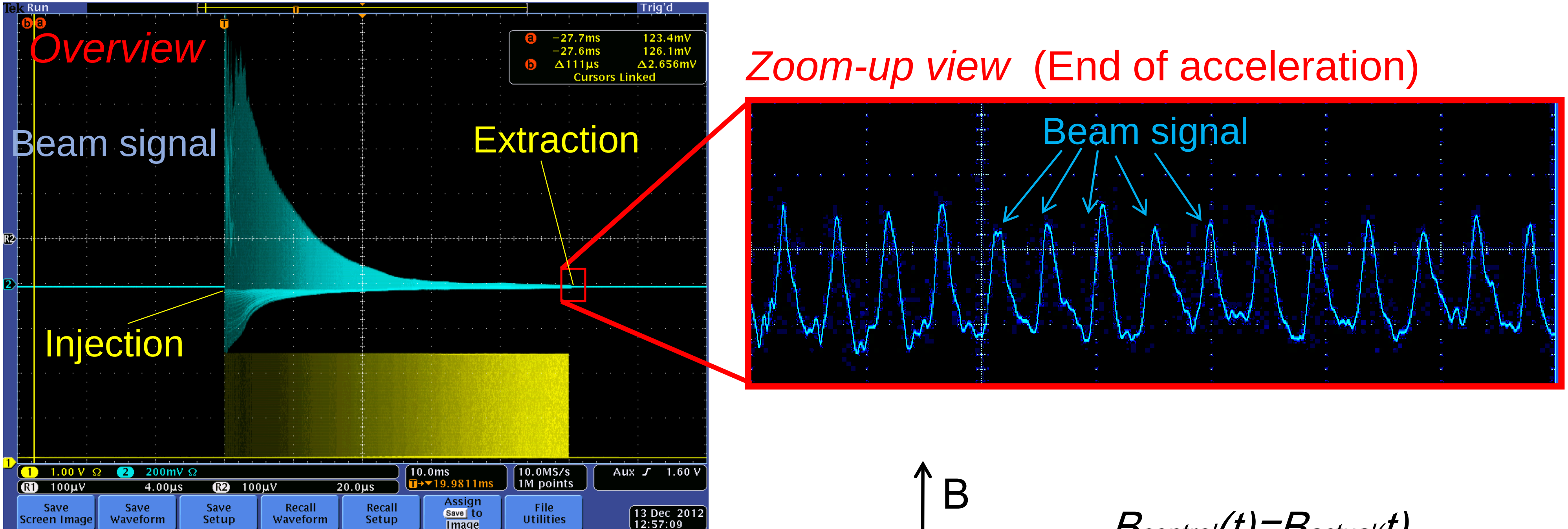
ρ : bending radius
C₀ : circumference
B(t): ideal magnetic field

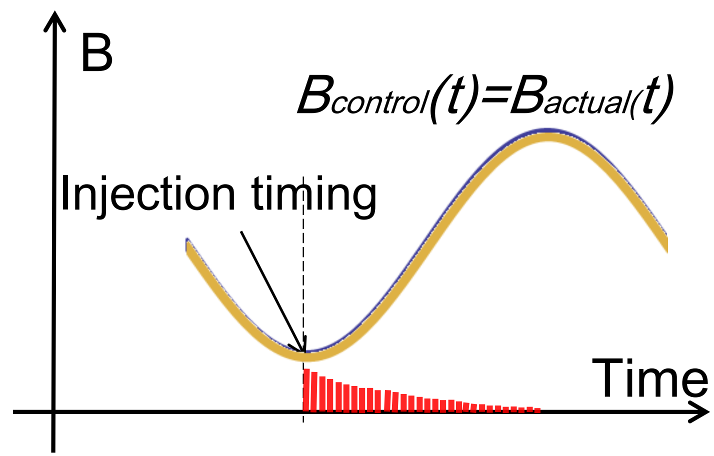
$$\delta(N+1)=\begin{cases} 1 & \cdots\left(\sum_{n=1}^{N+1} V(n)-V_0\sum_{n=1}^{N}\delta(n)>V_0\right) \\ 0 & \cdots\left(\sum_{n=1}^{N+1} V(n)-V_0\sum_{n=1}^{N}\delta(n)<V_0\right) \end{cases}$$

V_0: constant induction acc. voltage
$\delta(n)$: acc. density table
N: turn number

Induction acc. voltages are generated discretely in order to give required acc. voltage spuriously. ➡ Pulse density control

Result of beam acceleration





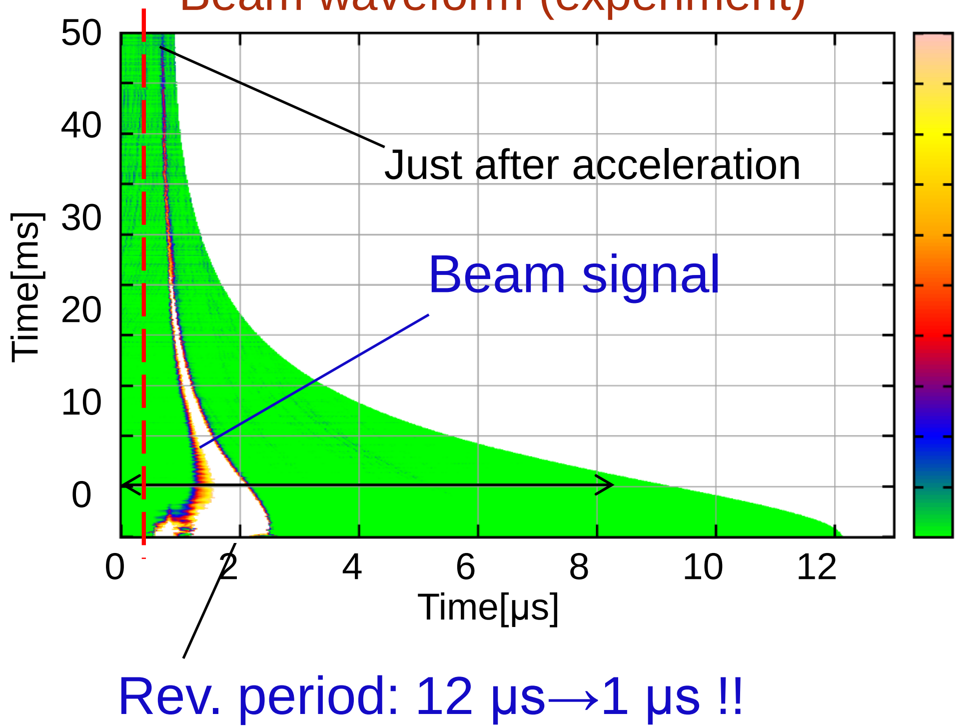
Experimental conditions:

Bending magnetic flux density	0.039 → 0.51 [T]
Mass to charge ratio A/Q	4/1
Energy	0.05→8 [MeV/u]
Injection current	~100 μA

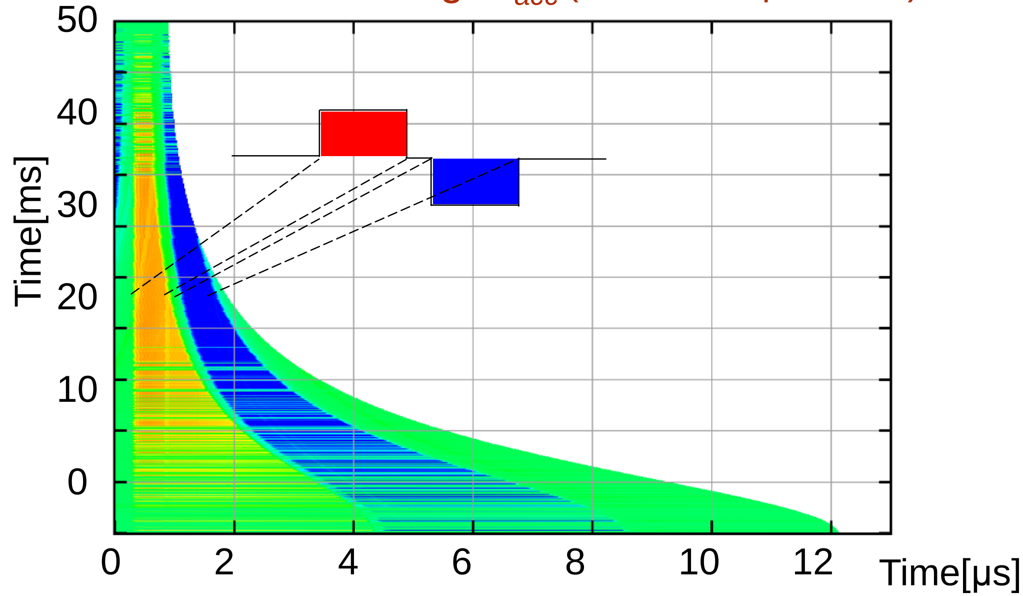
*K.Takayama, T.Yoshimoto, *et al* ,“Induction acceleration of heavy ions in the KEK digital accelerator”, *Phys. Rev. ST-AB* 17, 010101(2014)

Wide-band acceleration (experiment)

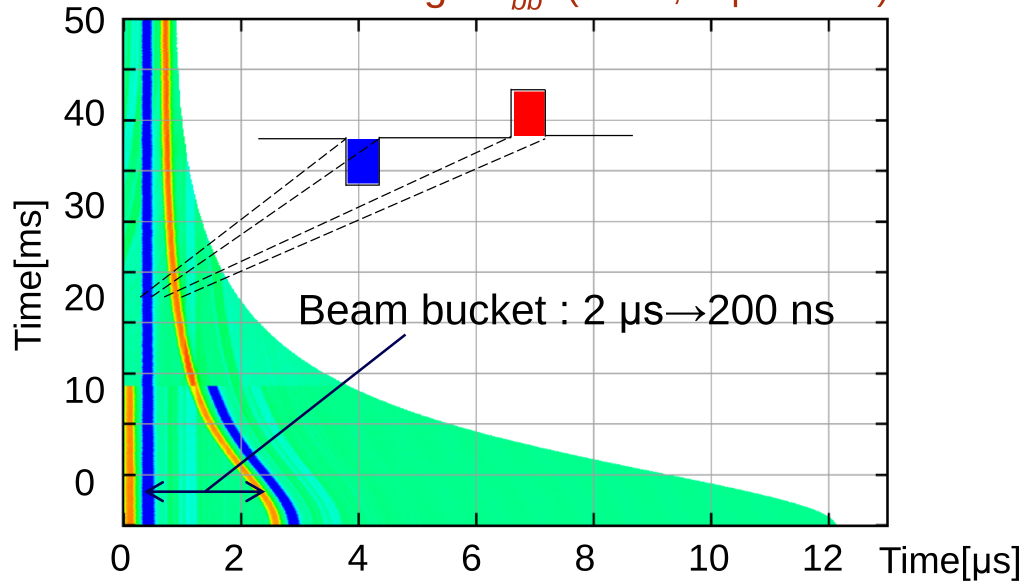
Beam waveform (experiment)



Acceleration voltage V_{acc} (±1.6 kV, experiment)



Cofinement voltage V_{bb} (±2 kV, experiment)



Beam survival & discussion

Beam survival: ~ 10%

Reasons

- Vacuum (~ 10^{-6} Pa)

Strong interaction with residual gas in low energy (200 keV ~)

- Non-zero dispersion optics (D = 1.4 m at Induction cell region)

Unfortunately, present optics was designed for the PS booster ring 40 years ago.

- Discrete acceleration

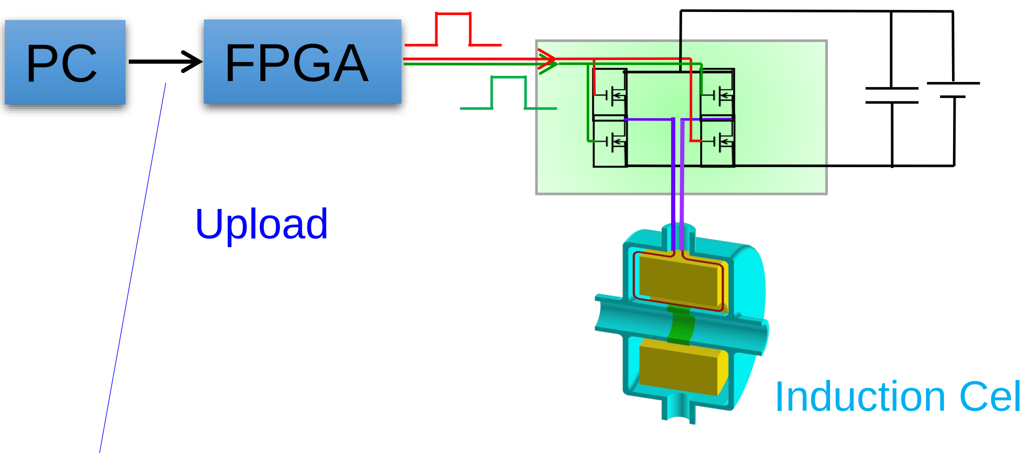
In our case, acc. voltages are constant because of DC power supply.
Therefore we do not generate acc. voltage every turn.

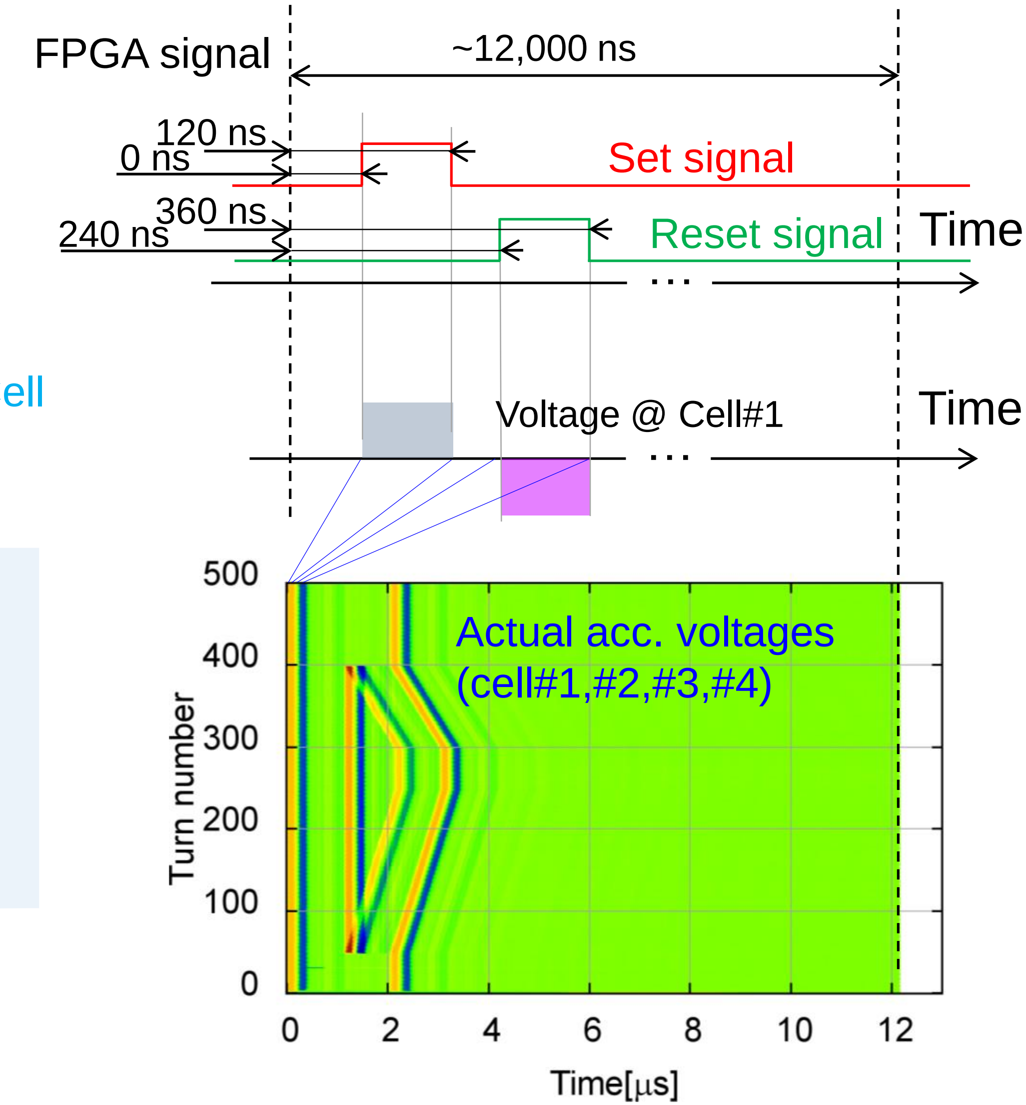
Solution:

Time varying DC power supply to meet required voltage demand may be ideal,

especially for super-bunch acceleration.

Development of FPGA code for novel beam handling





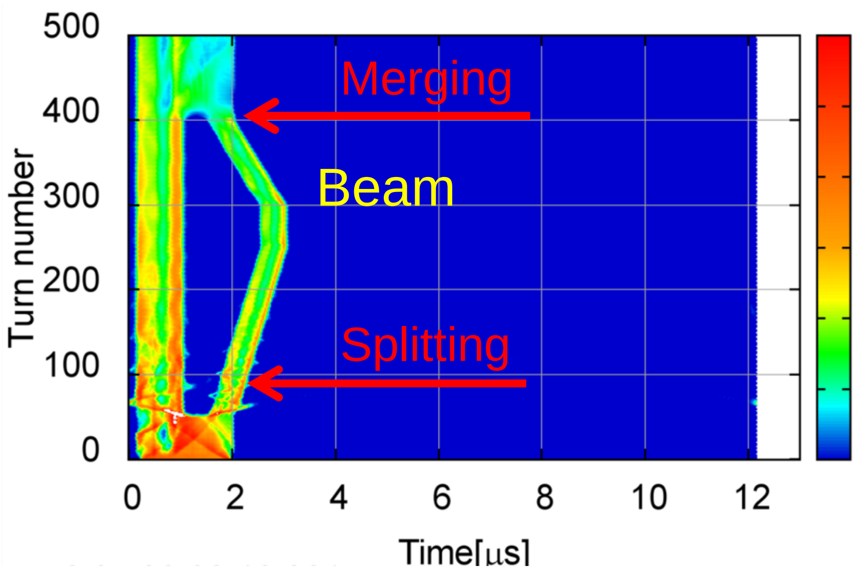
Calculated clock table (1 clock = 5 ns @200MHz)

Turn	Period	cell#1	cell#2…
1	2400	0,24,48,72	400,412,424,436,…
2	2399	0,24,48,72	400,412,424,436
⋮	⋮	⋮	⋮

This FPGA code can generate arbitral pulse timings at each cell (Max.5) in each turn (Max.5000). Therefore everyone can program each arbitral pulse easily and flexibly.

Comparison of IS and RF beam handling

IS splitting & merging (experiment) @ KEK



RF splitting (experiment)[1]@ CERN

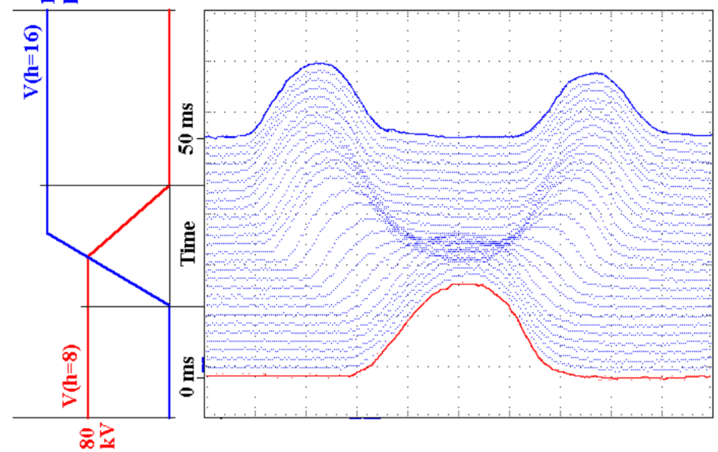
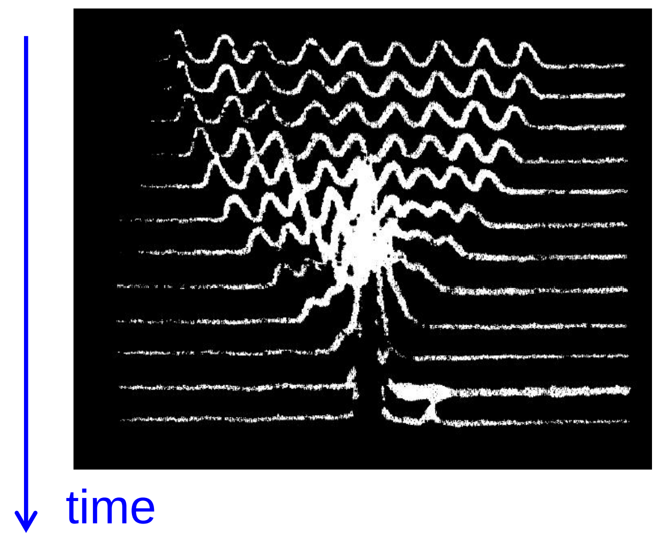


Figure 1: Beam pick-up signal and RF voltages during splitting at 3.57 GeV/c in the PS.

RF merging (experiment)[2]@ FERMI



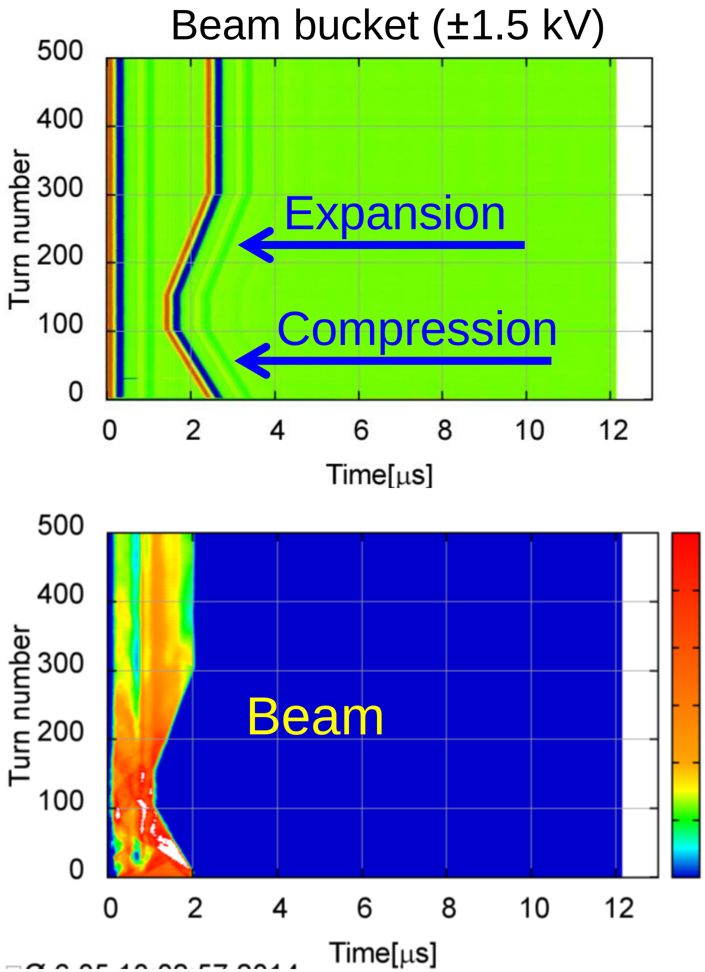
IS and RF beam handlings are qualitatively different.

1. It is easy to decide each beam length and quantity.
2. Timing control of acc. voltages is so simple.

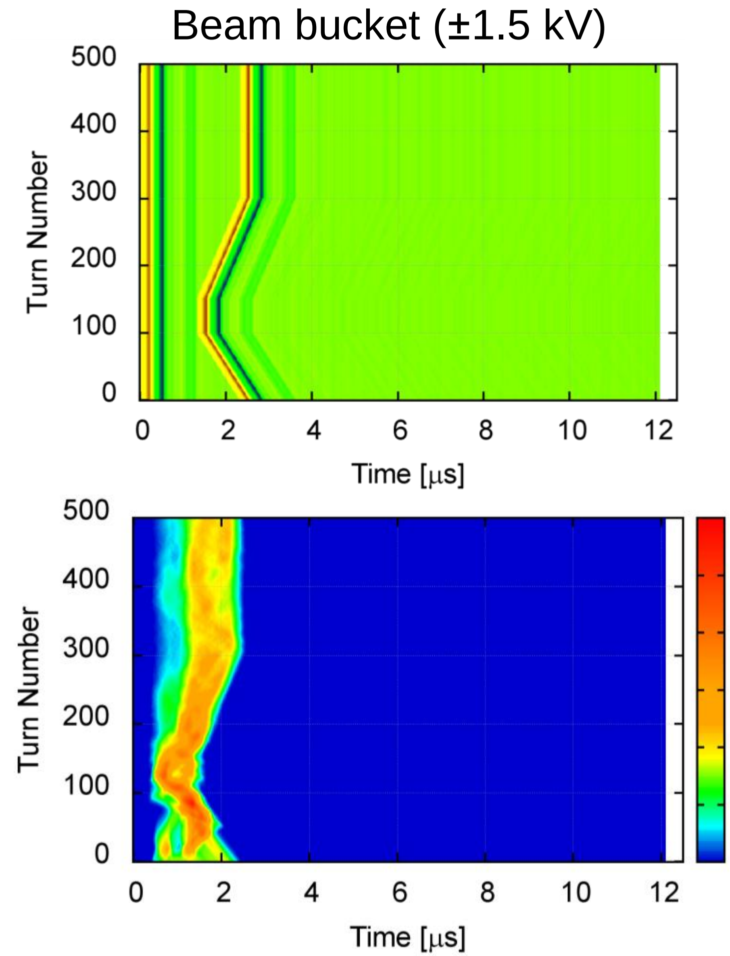
1. R.Garoby: STATUS OF THE NOMINAL PROTON BEAM FOR LHC IN THE PS,CERN/PS 99-013 (RF)
2. Philip S. Martin and David W. Wildman: BUNCH COALESCING AND BUNCH ROTATION IN TBE FERNILAB MAIN RING: OPERATIONAL EXPERIENCE AND COMPARISON WITH SMJLATIONS, Proc. EPAC88, *Rome*, *Italy*, 1988 (IOP, 1989) p.785

Simulation of novel beam handling

Experiment



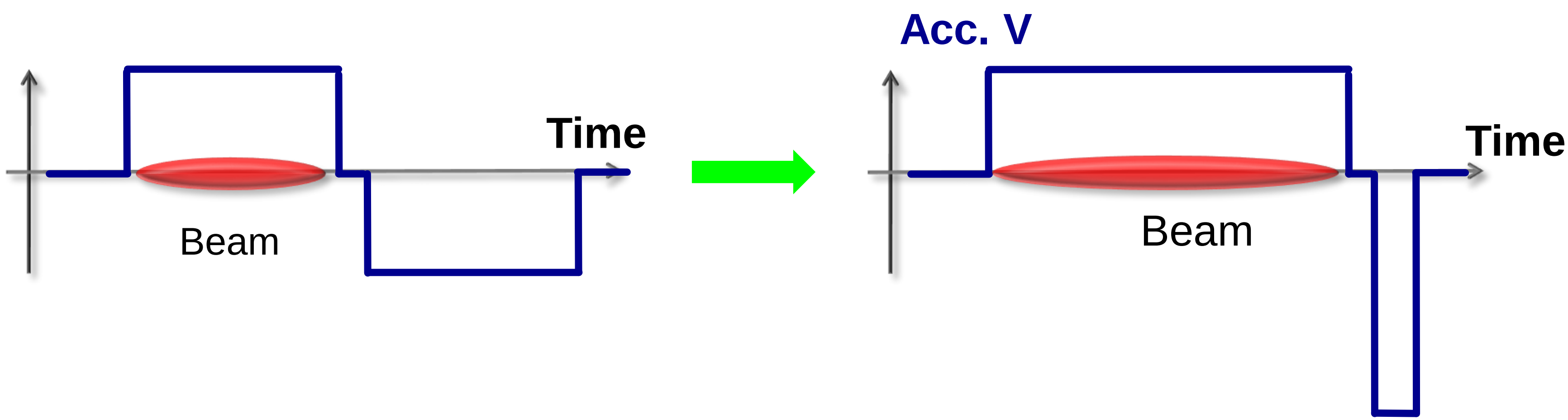
Simulation



The beam motion of the experiment is reproduced in the simulation macroscopically. Therefore it is easy to design the beam length and quantity.

How to realize super-bunch acceleration in the KEK digital accelerator ?

1. Asymmetric pulse for super bunch acceleration

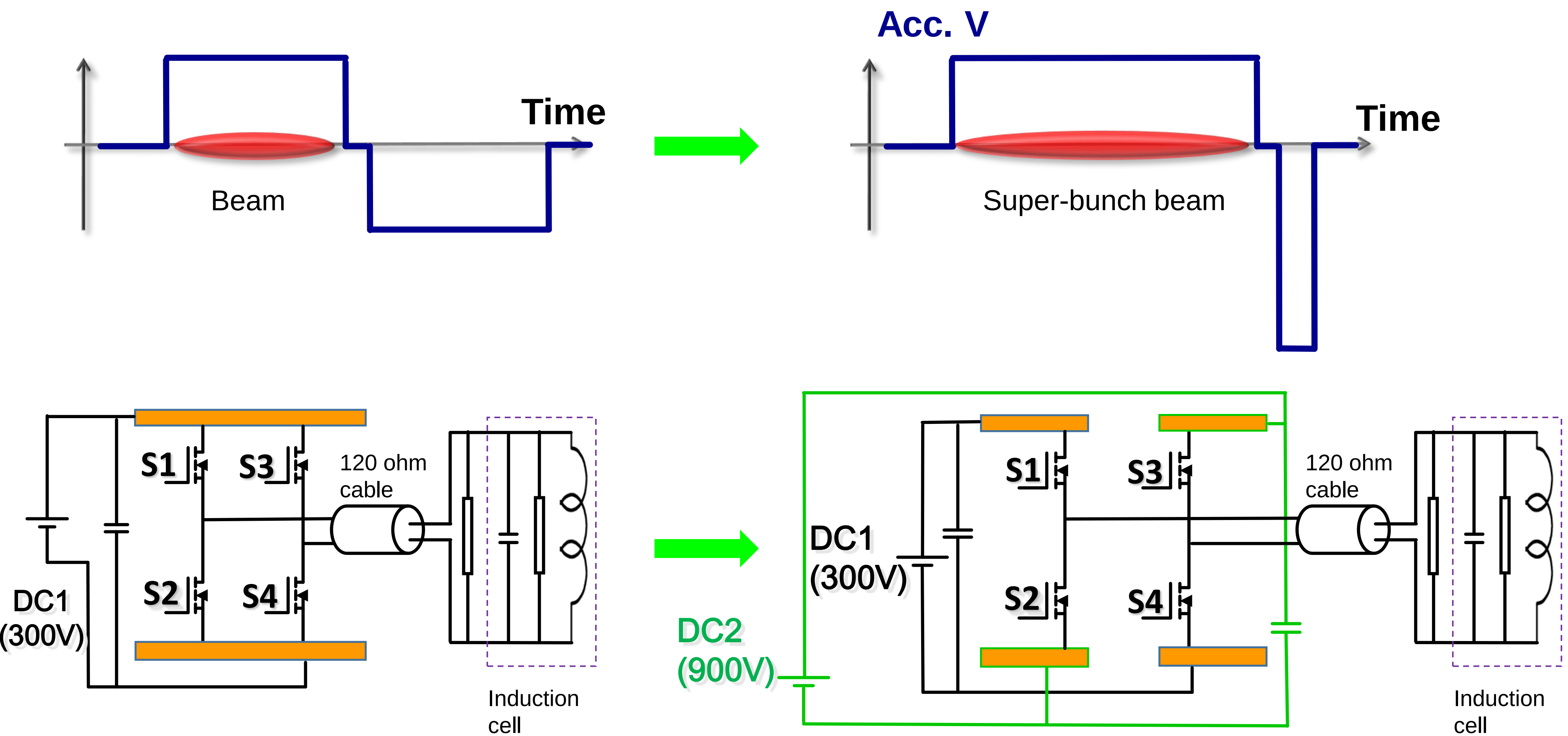


2. Time varying DC power supply

Discrete acceleration

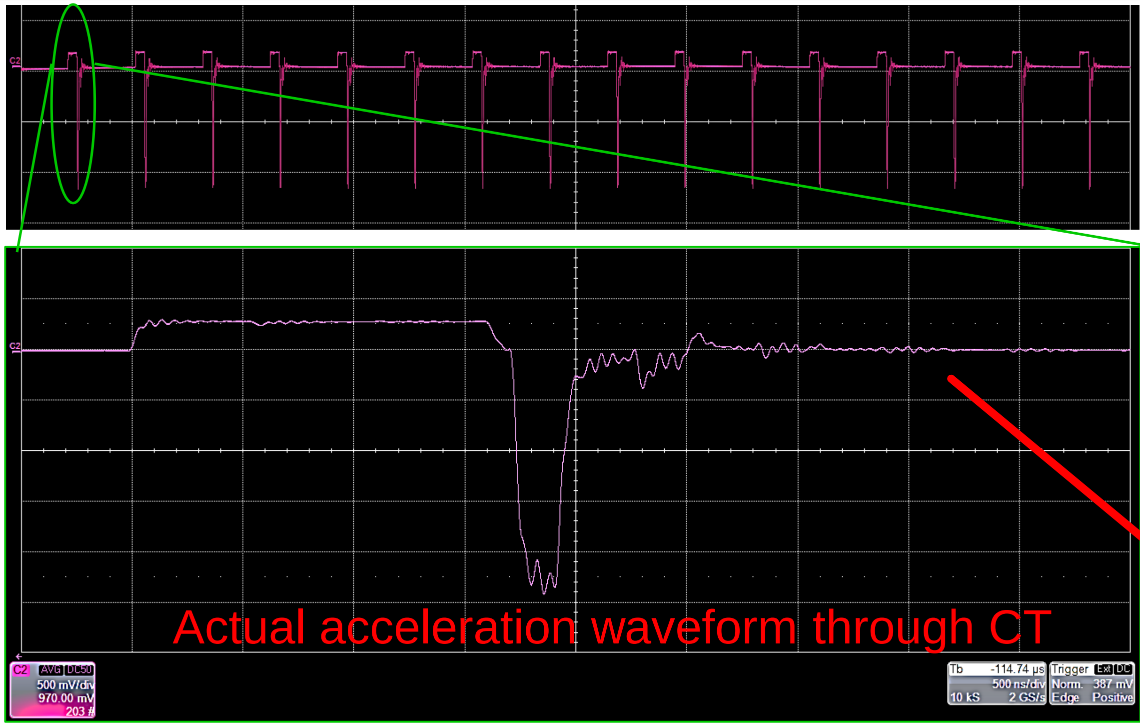
➡ Continuous acceleration at every turn

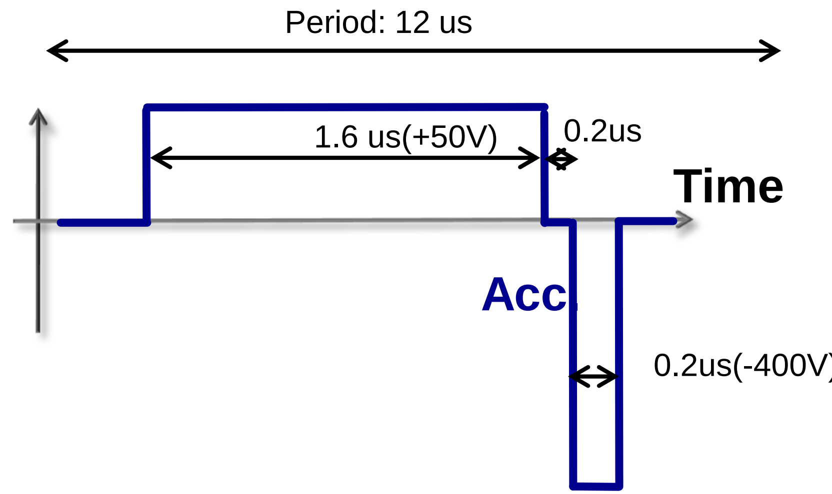
1. Asymmetric pulse for super bunch acceleration

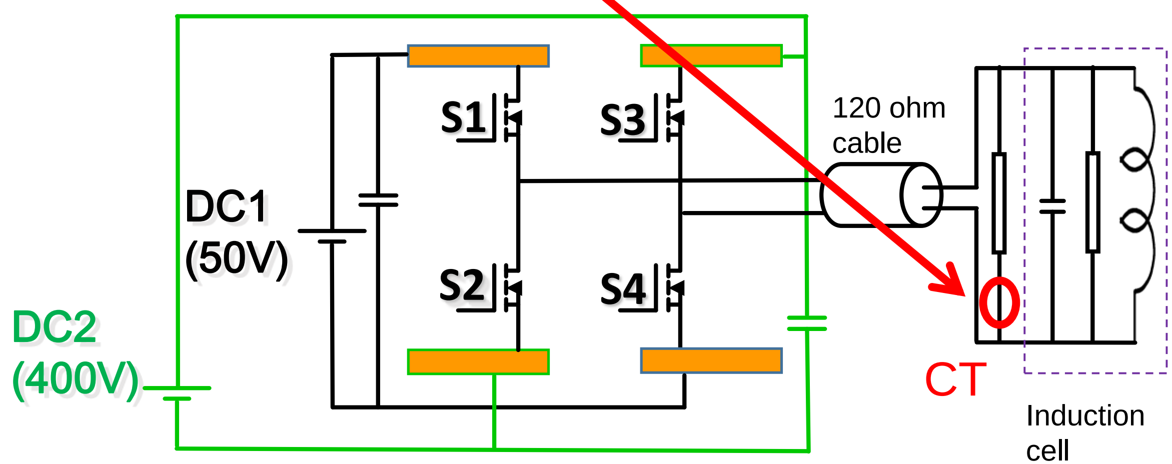


Different voltages are applied to positive and negative pulses.

1. Asymmetric pulse (Result in low voltage experiment)



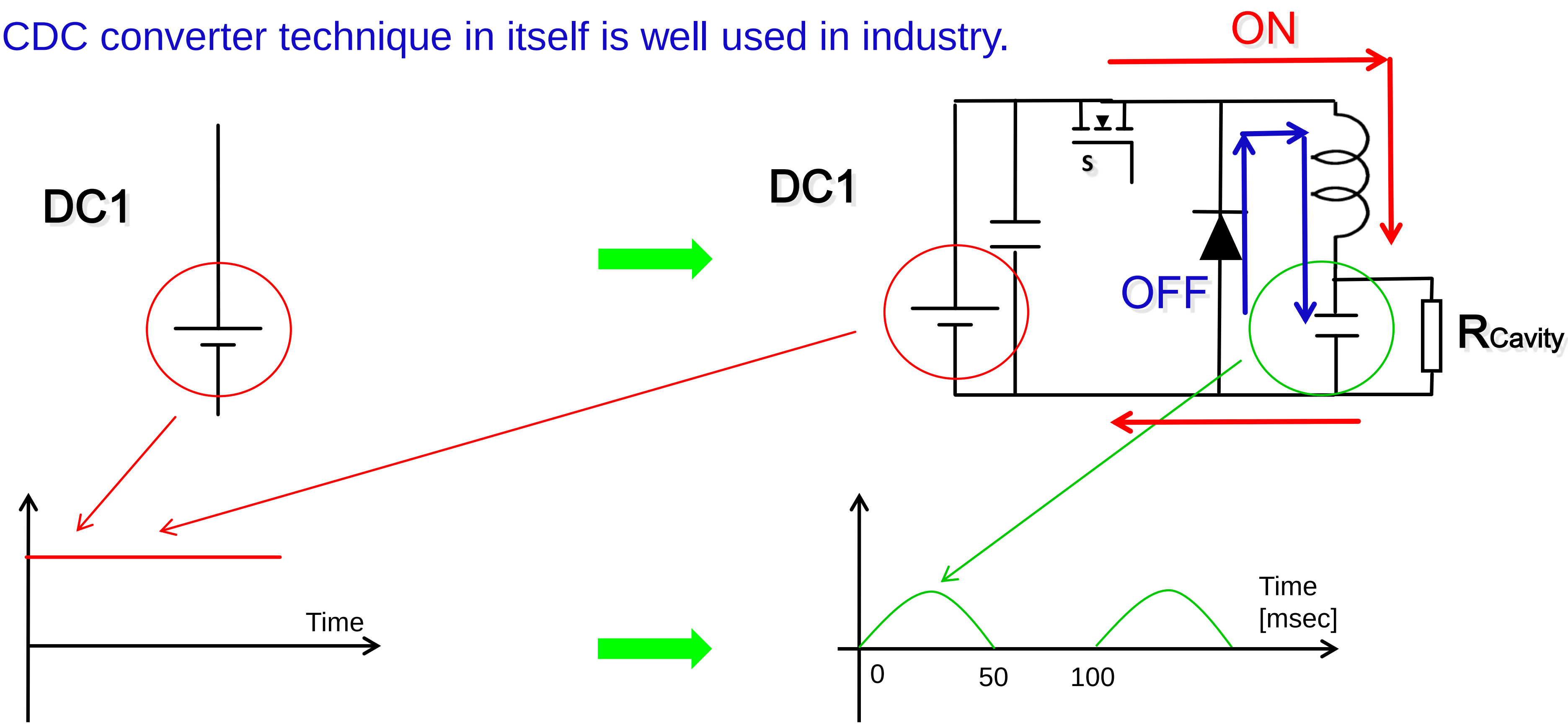




Asymmetric pulses can be generated with bridge circuits easily.

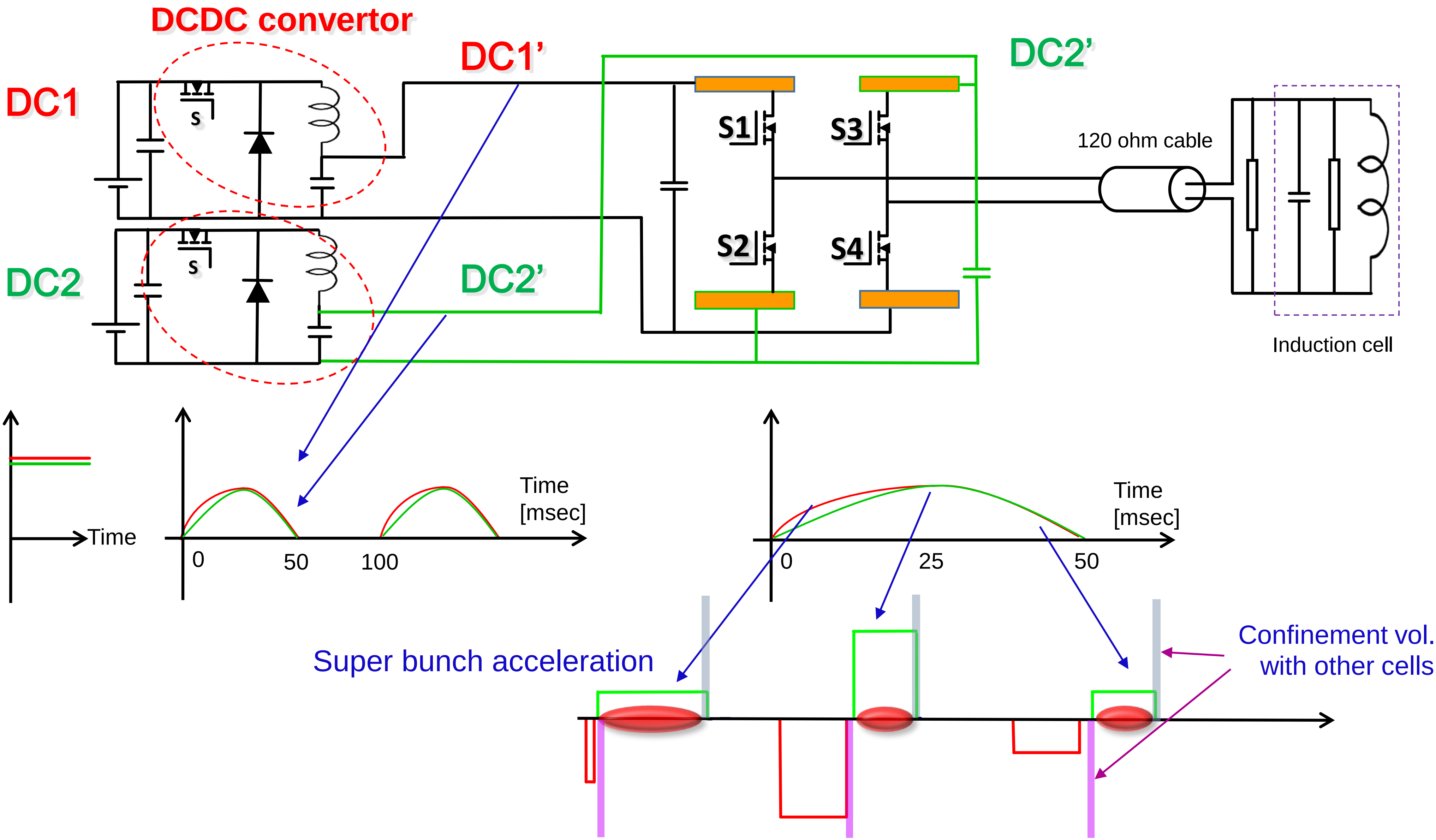
2. Time varying DC power supply

DCDC converter technique in itself is well used in industry.



- msec-control is not so difficult.
- Output voltage should be the same of actual needed acceleration voltage.

Asymmetric pulse & Time varying DC power supply



- Super bunch acceleration is needed at injection because of space charge limit.
- Maximum voltage should be reduced because of difficulty of high-voltage and MHz switching.

Can super-bunch acceleration be applied to high-intensity machine such as RCS(300m~) @ J-PARC ?

1. Difference of RF (MA cavity) and Induction cells
2. High acceleration voltage
3. Beam loading effect

What is the difference between MA cavity and Induction cell ?

MA cavity @ JPARC-RCS

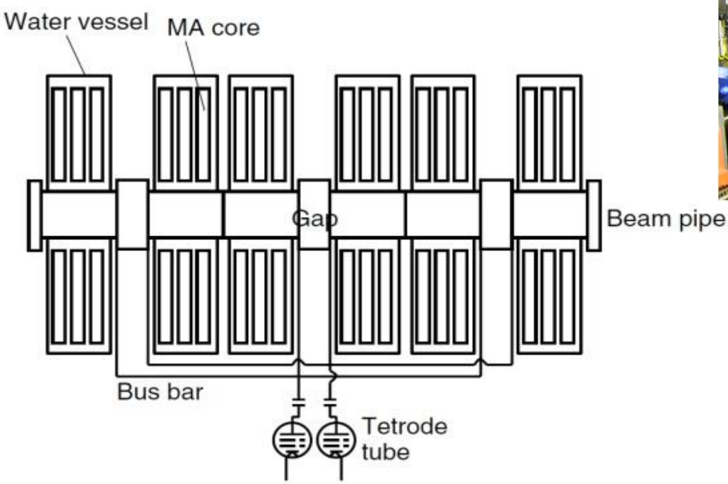
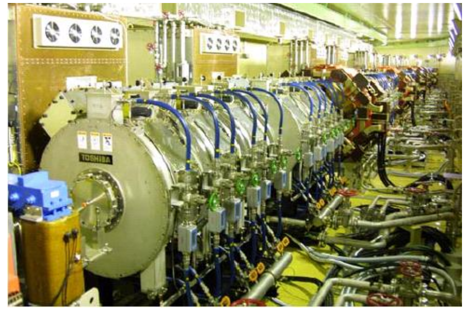


Figure 1: The MA cavity for the RCS.



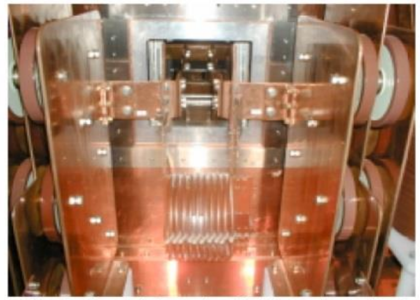


Fig. 6: 10 turn inductor installed for testing inside the push-pull RCS tube amplifier

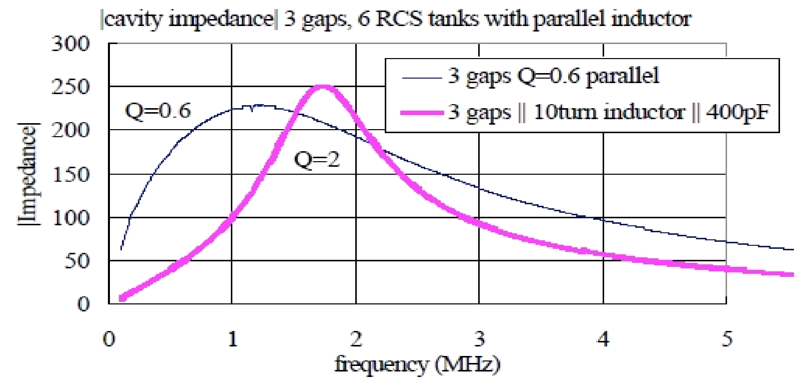
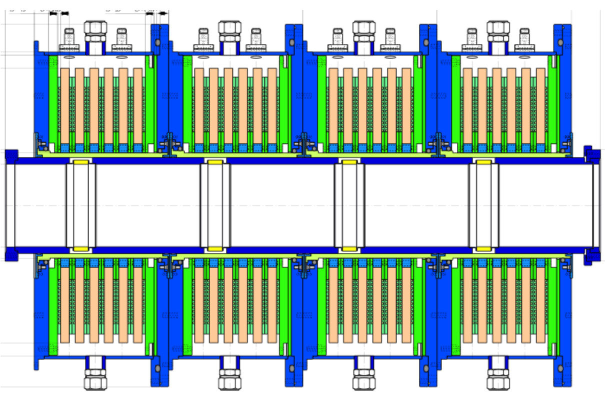
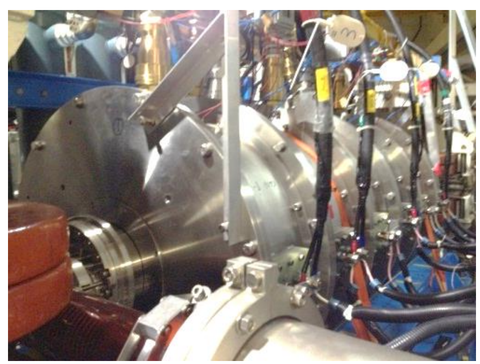
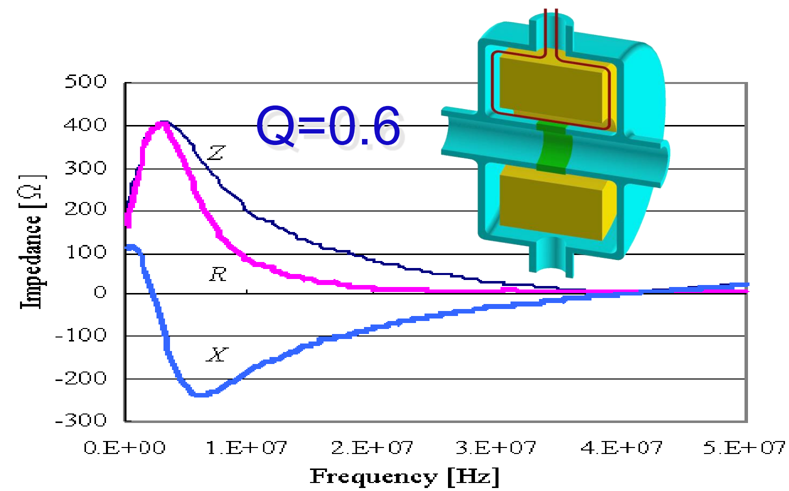


Fig. 5: Q_x=2 at 1.7MHz with parallel inductor

Induction cell @ KEK digital accelerator







MA cavity with low Q is the same of induction cavity.

Demand of acceleration voltage height

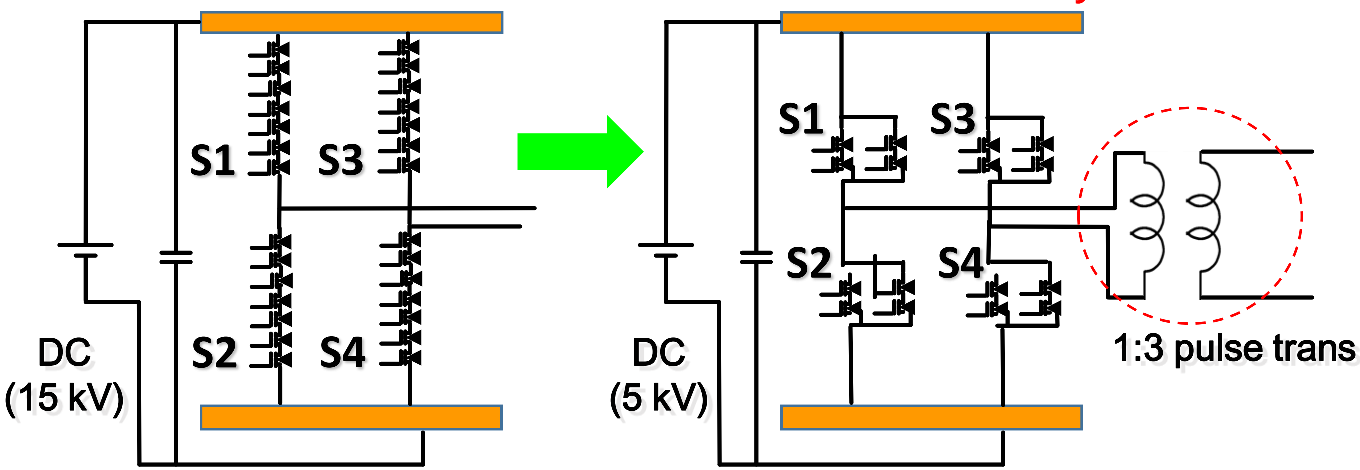
parameter	RCS	MR
circumference [m]	348.3	1567.5
bending radius [m]	11.65	89.381
energy [GeV]	0.181–3	3–30
max voltage [kV]	450 (400)	280 (160)
period [s]	40×10^{-3}	3.52
No. of cavities	12 (11)	7+3 (5+0)
Q-value of cavity	2	26

$$400\,kV \times \sin(\frac{\pi}{2}) = 280\,kV$$

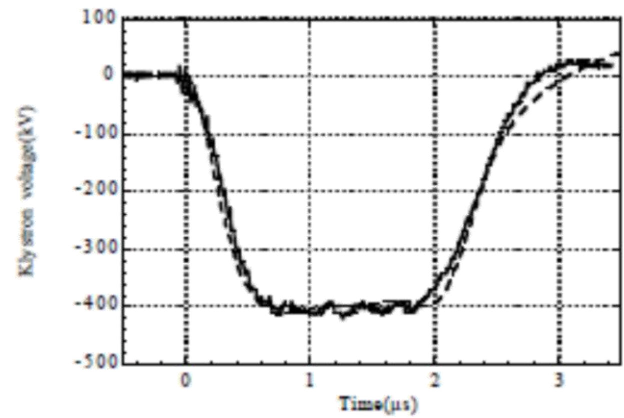
Needed acc. voltage: 280 kV (Max.)
Therefore,
Max. V = 280 kV/10 cavity(9)/3 gaps
= **9.3(10.4) kV**

Series is difficult !!

Parallel is easy !!



Pulse transformer
(Primary :5kA, 33kV
Turn ratio:1:14)

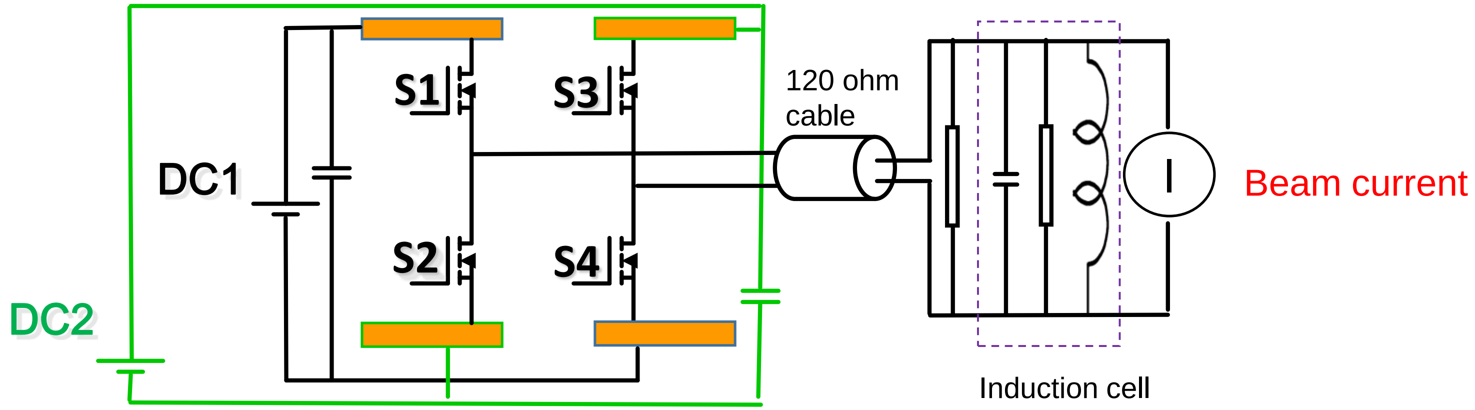


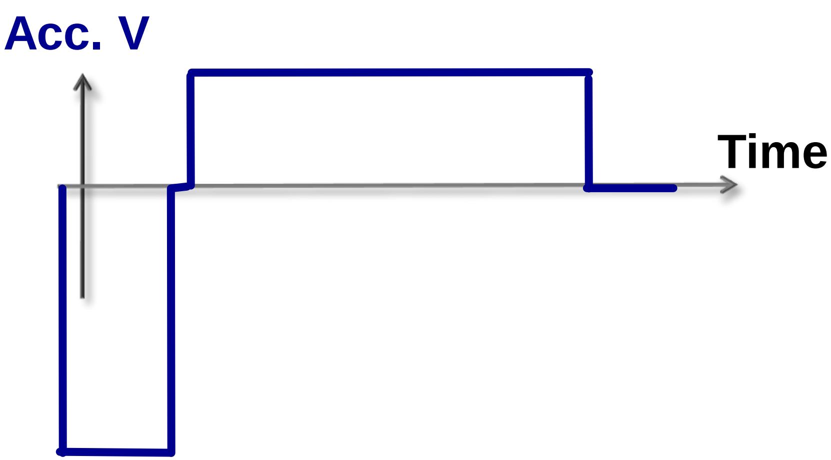
In many series of MOSFET switch, each voltage are imbalance.

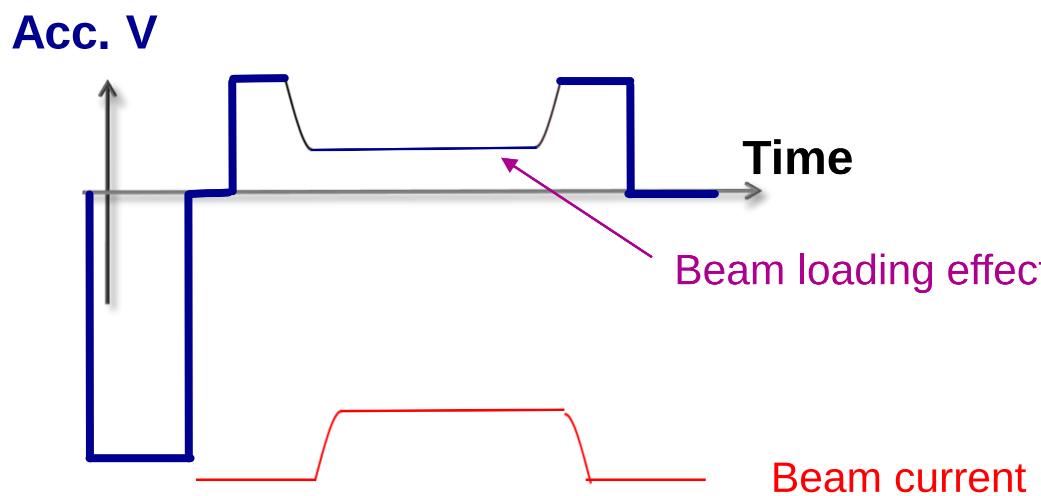
Figure 6. Output pulse waveform at the kly

M. Akemoto *et al*, "PULSE TRANSFORMER R&D FOR NLC KLYSTRON PULSE MODULATOR",SLAC–PUB–7583

Beam loading problem







Without beam

With beam

- Beam distribution and acceleration waveform are interacted with each other.
- The inequality in area of positive and negative pulse generates inductance saturation.
- Low impedance system reduce beam loading effect but increase electric power loss.

Conclusion

- We demonstrated Wide-band acceleration and Novel beam handling.

- Asymmetric pulse generation and time varying DC power supply
  are concretely designed for super-bunch acceleration scheme .

- Problems in high-intensity super-bunch acceleration are clarified.

Especially, beam loading effect is key problem.

Thank you for attention !!