SuperKEKB damping ring timing system and event controls for simultaneous top-up injections for 4 storage rings

Kazuro Furukawa, Hitomi Ikeda, Hiroshi Kaji, Fusashi Miyahara, Tatsuro Nakamura, Itsuka Satake, Masanori Satoh, Hitoshi Sugimura, Makoto Tobiyama

KEK, Japan

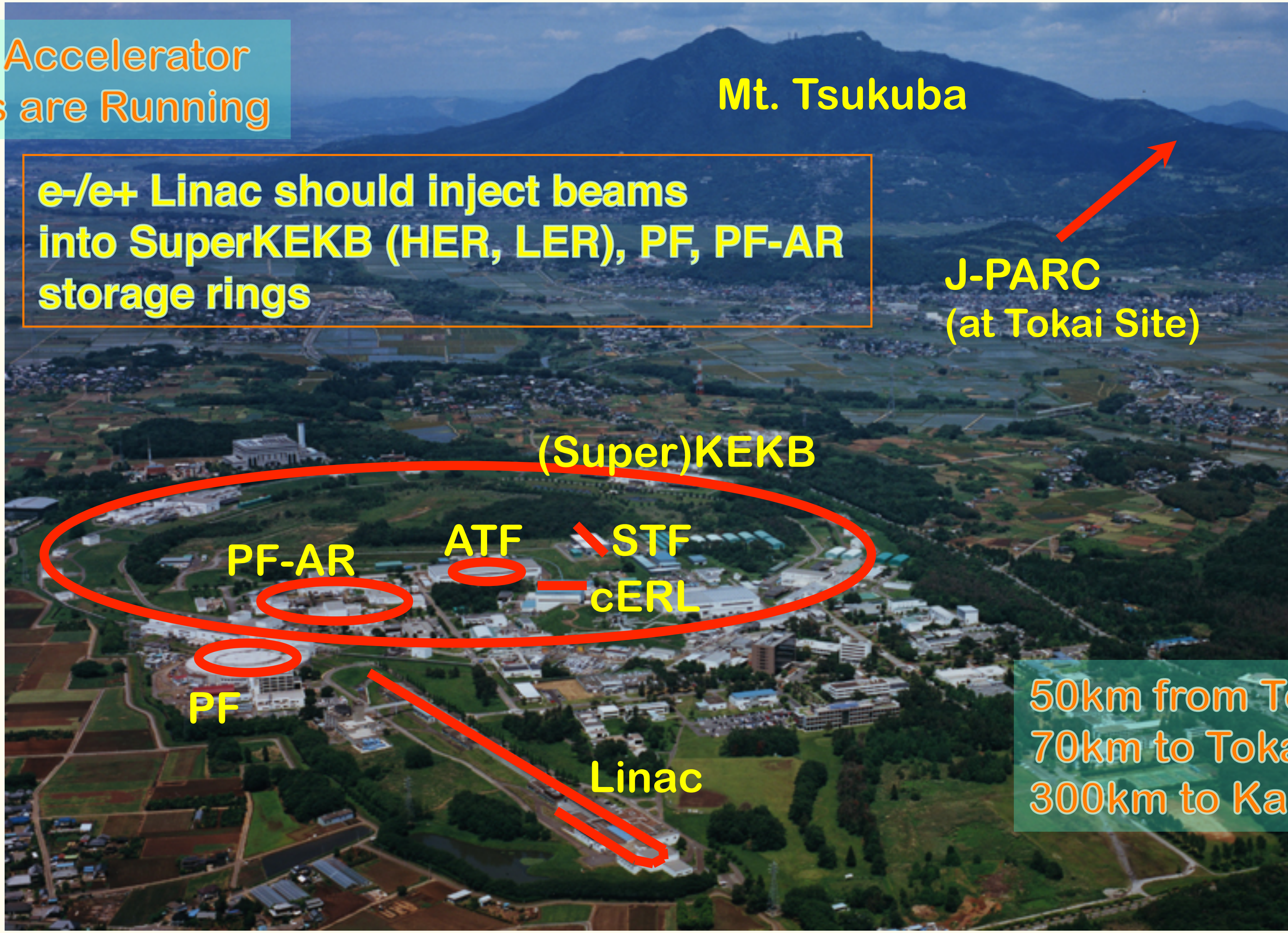
Contents

- Injector linac and damping ring
- Event based controls
- Synchronization between linac and rings
- Damping ring timing
- Conclusions

Particle accelerators at KEK

Several Accelerator Projects are Running

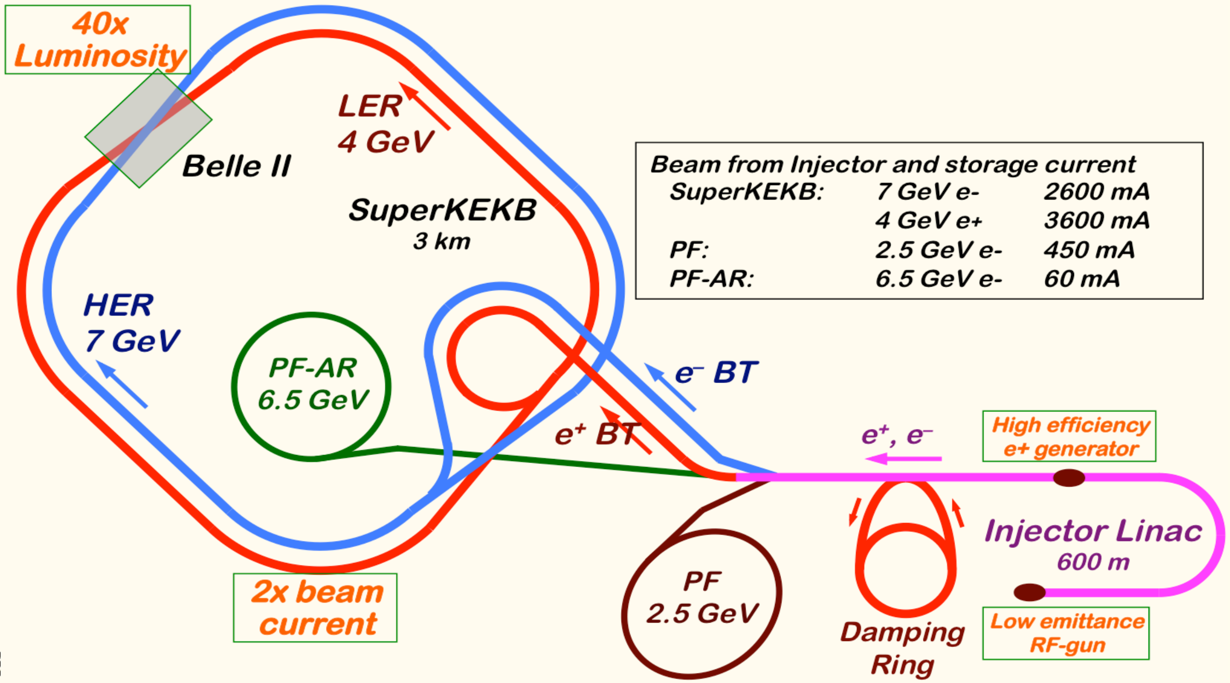
e-/e+ Linac should inject beams into SuperKEKB (HER, LER), PF, PF-AR storage rings



50km from Tokyo
70km to Tokai
300km to Kamioka

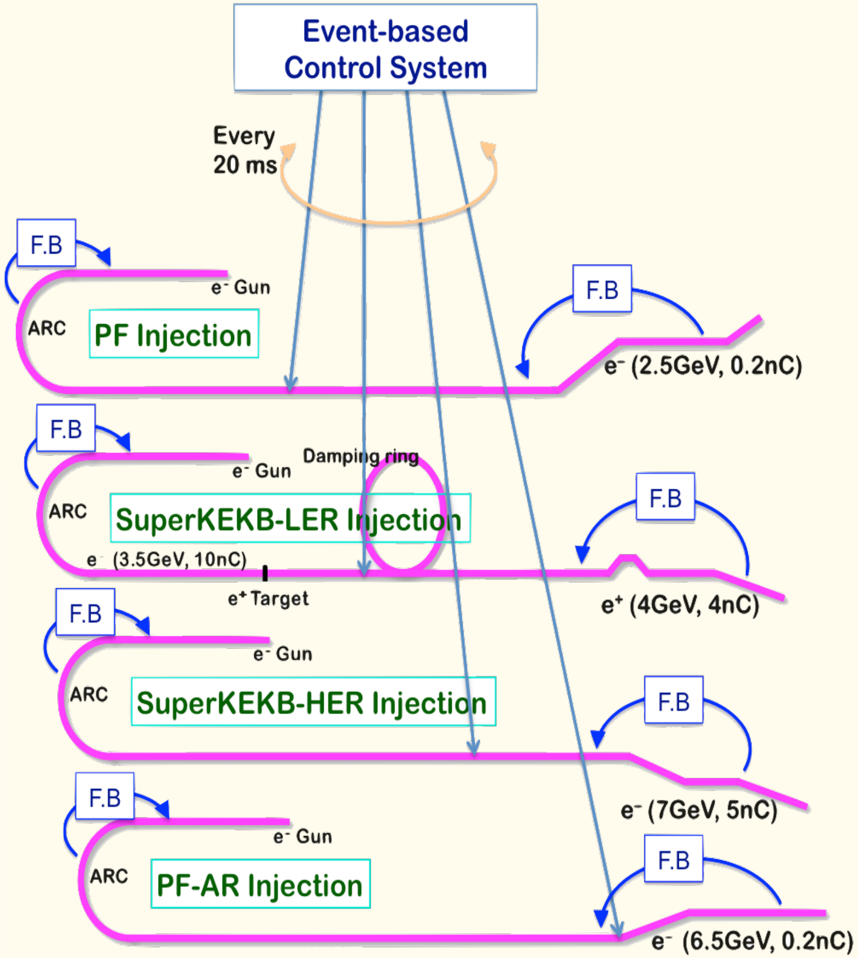
Mission of Electron/positron Injector in SuperKEKB

- For 40-times higher luminosity in SuperKEKB collider
- Low emittance & low energy spread injection beam with 4-5 times more beam current
  - New high-current photo-cathode RF gun
  - New positron capture section
  - Damping ring construction
  - Optimized beam optics and correction
  - Precise beam orbit control with long-baseline alignment
  - Simultaneous top-up injection to DR/HER/LER/PF/PFAR
- Balanced injection for the both photon science and elementary particle physics experiments



Beam from Injector and storage current

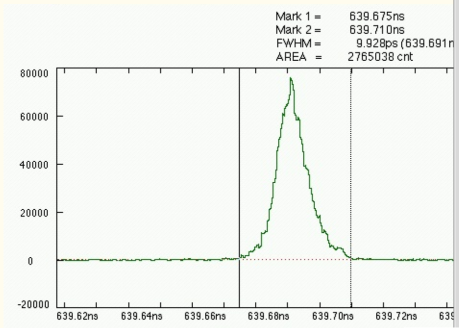
SuperKEKB:	7 GeV e-	2600 mA
	4 GeV e+	3600 mA
PF:	2.5 GeV e-	450 mA
PF-AR:	6.5 GeV e-	60 mA



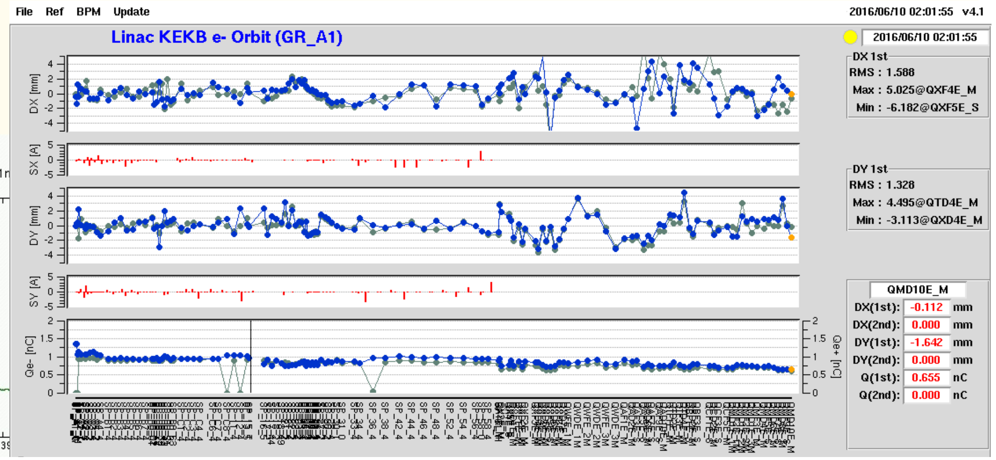
The single injector would behave as multiple injectors to multiple storage rings by the concept of virtual accelerator

Development of Photo-cathode RF Gun

- **Succeeded in injection during SuperKEKB Phase 1 commissioning for 11 days**
- **Employs Yb-doped-fiber and Nd/Yb:YAG laser, Ir5Ce/Ir2Ce cathode, QTWSC or cutdisk structures**
- **Stability improving**
- **Beam instrumentation improvements and comparison with simulation codes underway**

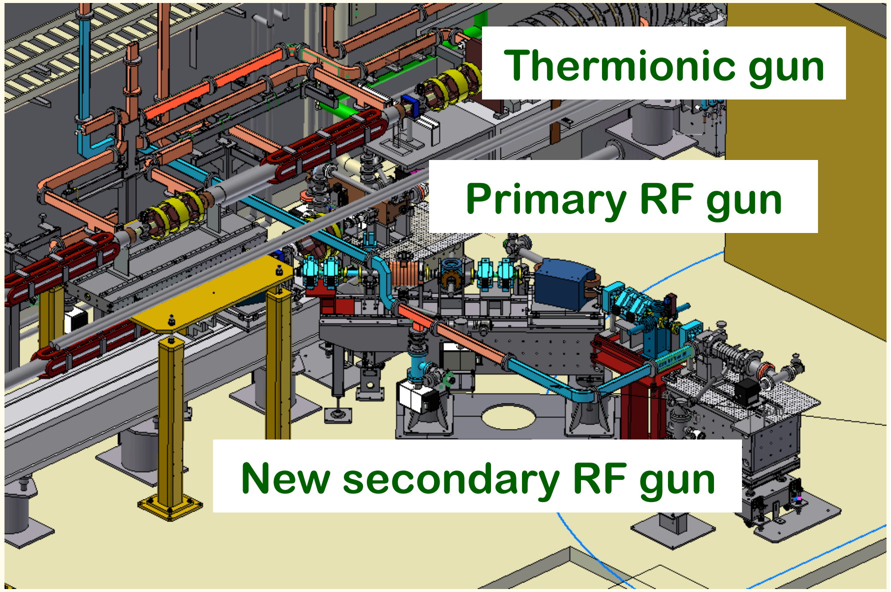


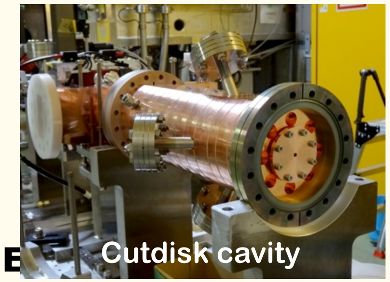
Bunch width

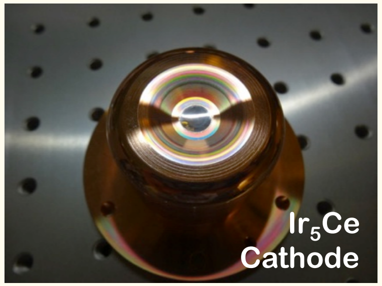


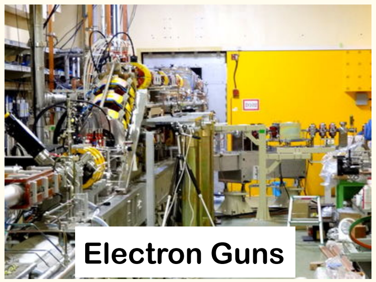
Beam orbit measurement

- **Secondary RF gun is being constructed as a backup**
- **Incorporate suggestions by review committee for availability and so on**

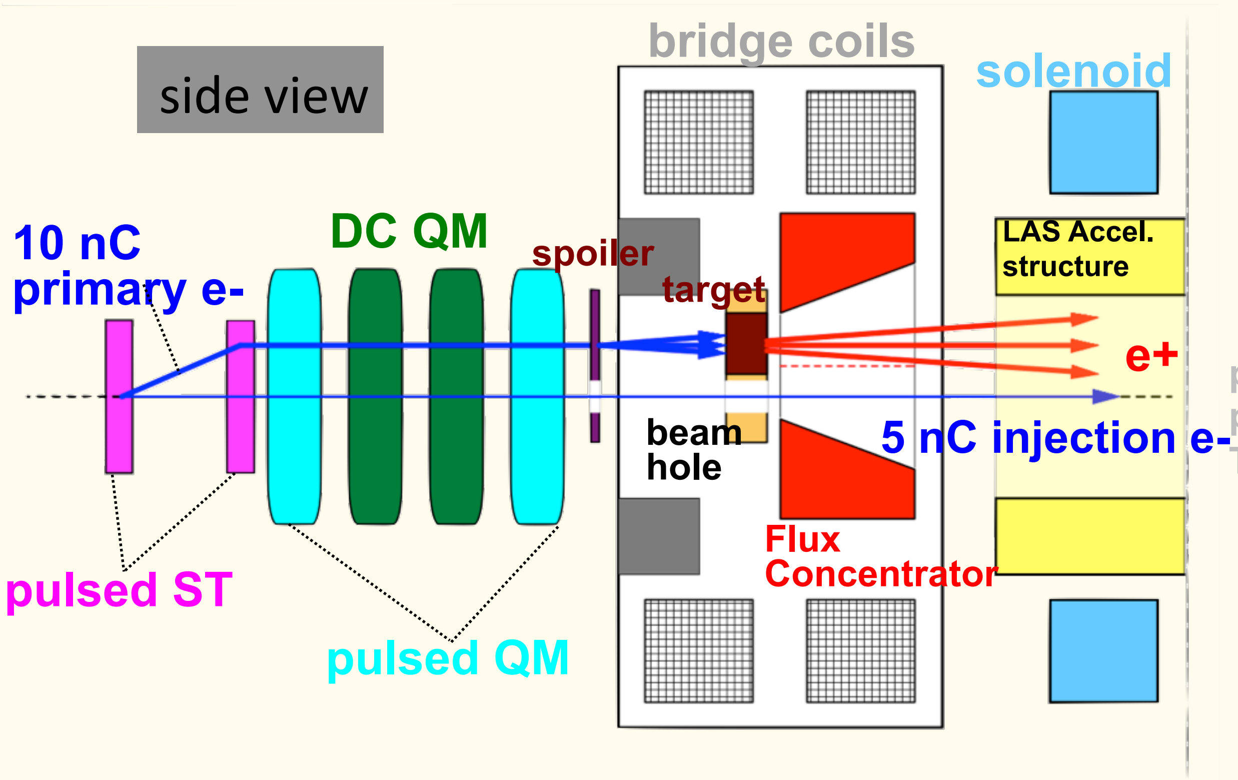




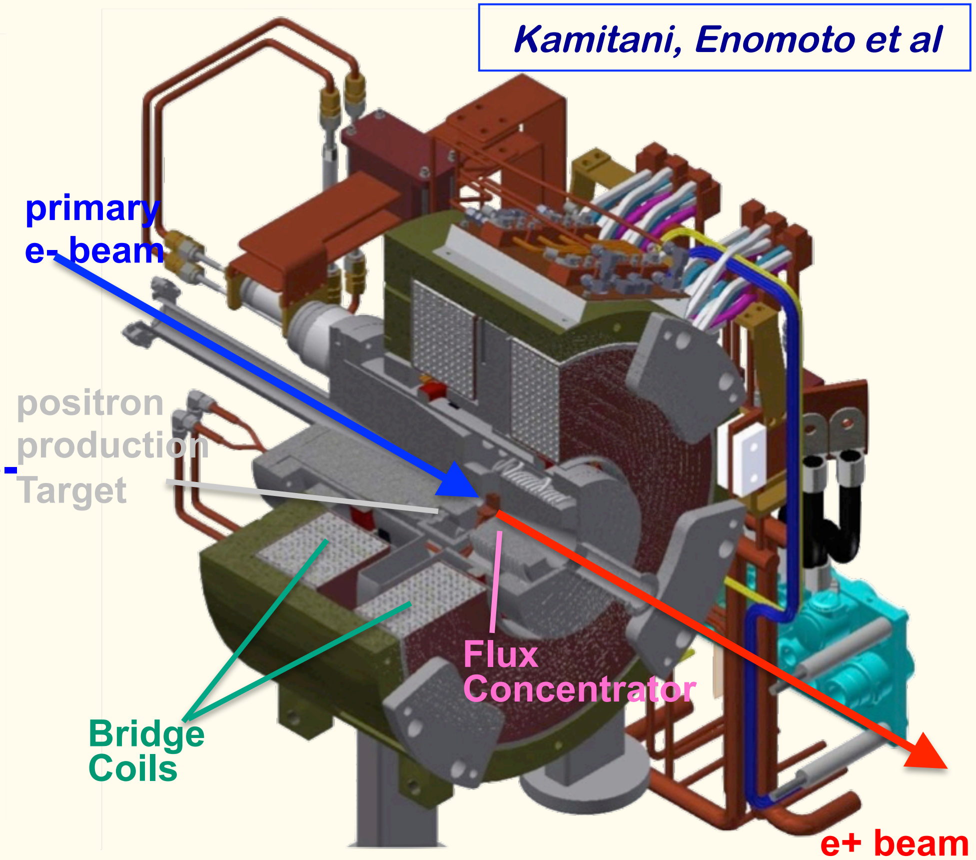




Positron generation for SuperKEKB



Kamitani, Enomoto et al

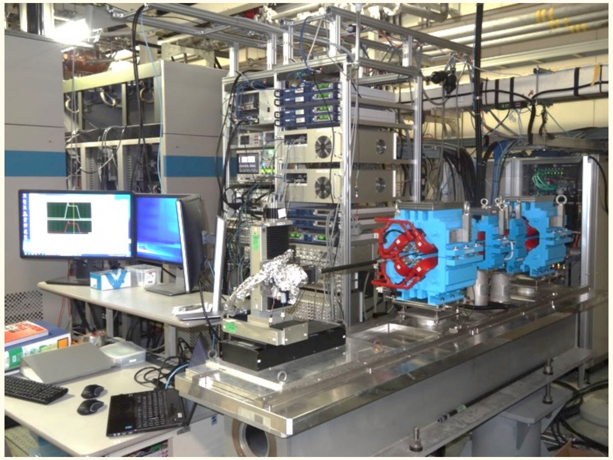


New positron capture section after target with
Flux concentrator (FC) and large-aperture S-band structure (LAS)
Satellite bunch (beam loss) elimination with velocity bunching
Pinhole (2mm) for passing electrons beside target (3.5mm)
Replacement mechanism even under higher radiation
Resolving recent discharge difficulties at maximum field

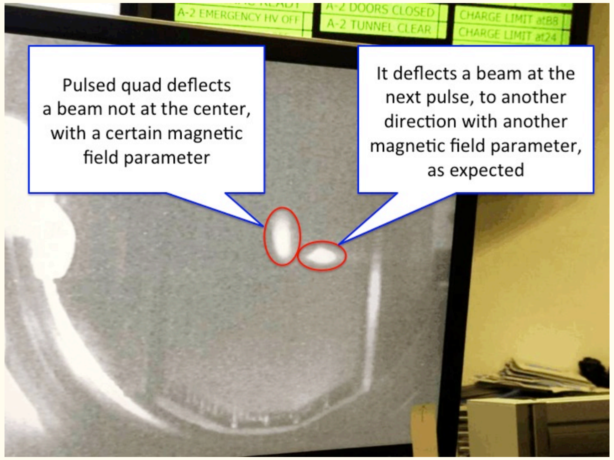
Development and installation of pulsed magnets

- Pulsed magnets and power supplies will be installed in 2017 for resource optimization
- 30 quads, 36 steerings, 2 bends, 13 girders are being fabricated and installed
- Quads with advanced design at 1 mH, 330 A, 340 V, 1 ms with energy recovery up to 75%
- Small form factor of 19 inch width and 3U height each
- Steering power supplies were also developed in-house
- Essential for SuperKEKB low emittance injection and simultaneous top-up injections
- 4+1 ring injections with virtual accelerator concept

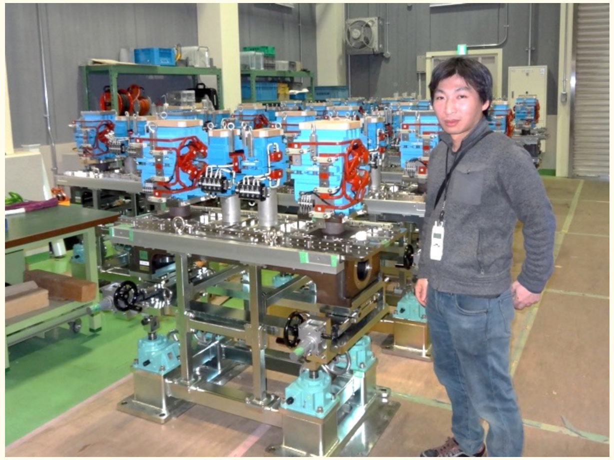
Enomoto, Natsui et al



- Long term tests at a stand
- Satisfies specifications
- Control synchronization



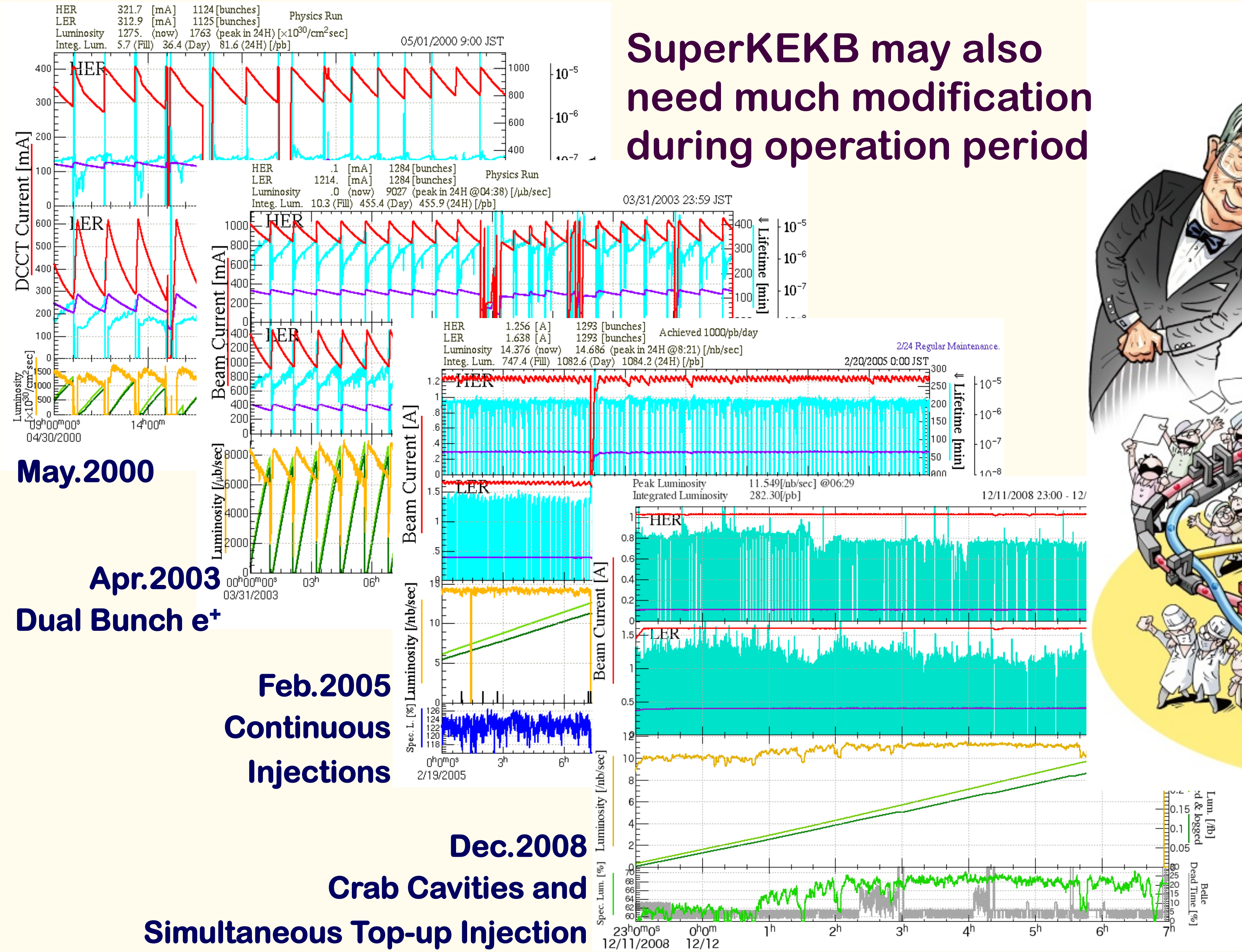
- Beam test with two quads
- Successful fast beam switches
- Switching features are comfirmed



- Girders are tested as well
- In-house drawings to save rsc.
- 0.1mm alignment precision
- Ready for Phase-3 upgrade

KEKB Operation Improvement (base of SuperKEKB)

SuperKEKB may also need much modification during operation period

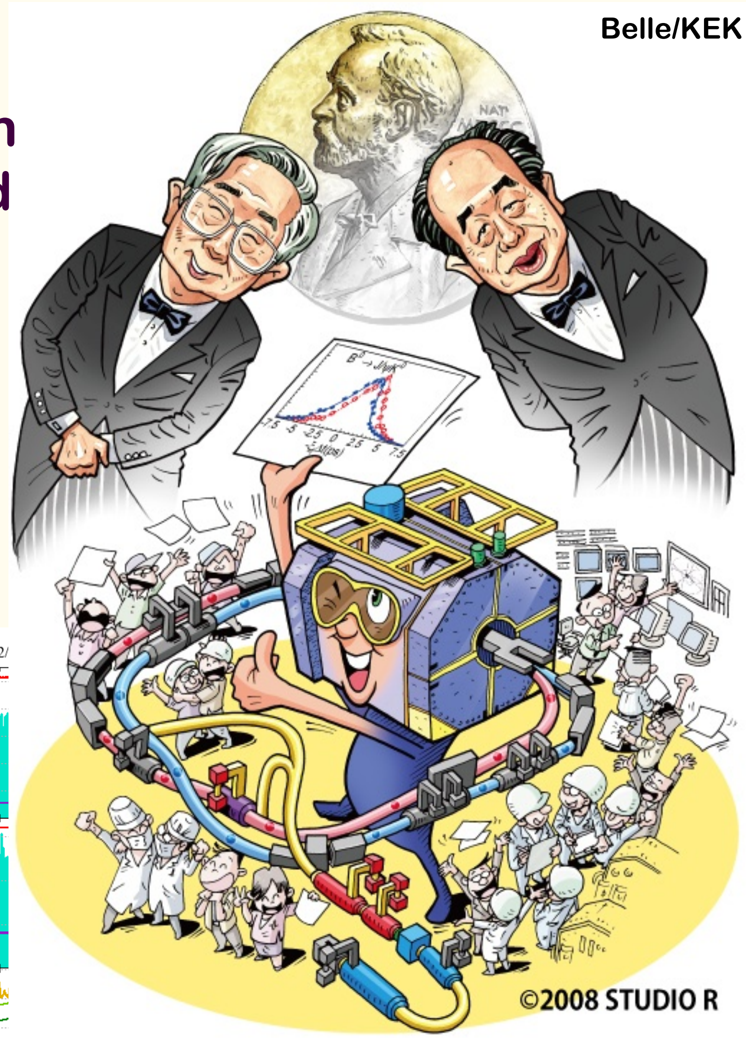


May.2000

Apr.2003
Dual Bunch e⁺

Feb.2005
Continuous Injections

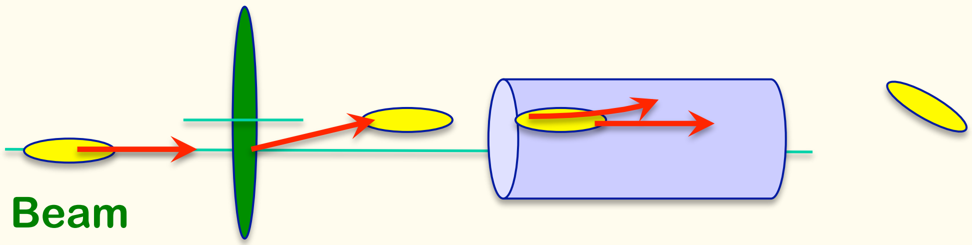
Dec.2008
Crab Cavities and Simultaneous Top-up Injection



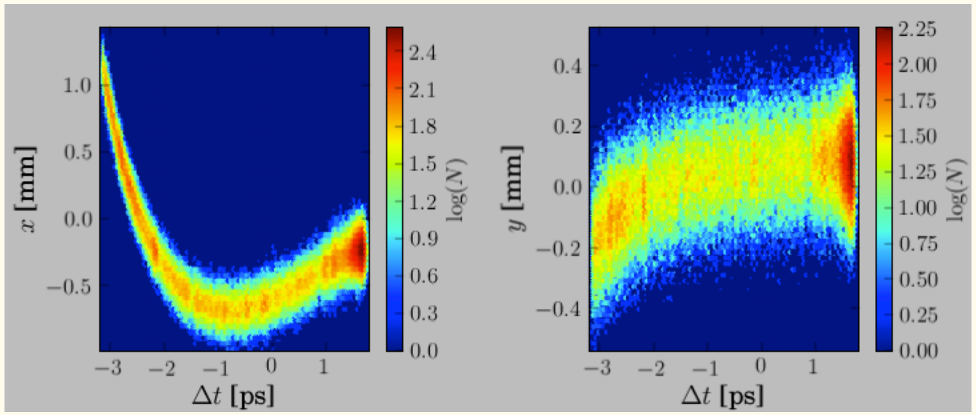
EPICS

Emittance Preservation

- **If Device is off center of the beam**
  - **Focusing magnet (quad) kicks the beam bunch**
  - **Accelerating structure (cavity) excites wakefield, to bend the tail**
- **Distorted bunch in banana shape**
  - **Emittance dilution or blow-up**
  - **Depending on the beam optics and the beam charge**
- **Orbit correction and alignment management are crucial to preserve the emittance along linac**



Sugimoto et al.



Transverse distribution in time direction

Main features of controls at KEKB

- **EPICS as Main control Software Toolkit**
  - Provided a robust basis of equipment controls
  - Reduced software design efforts much

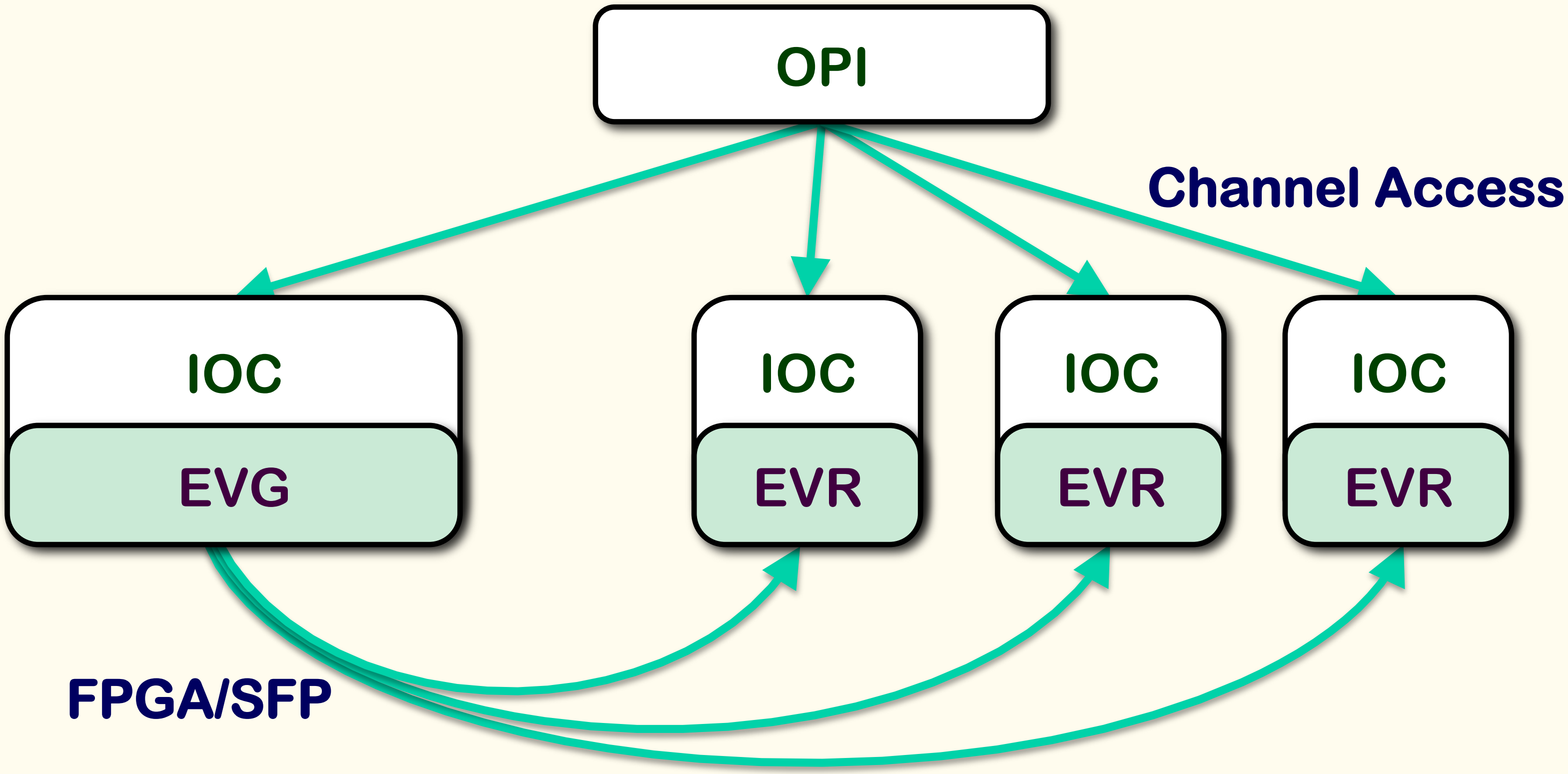
- **Scripting Languages for Operational Software**
  - SADscript/Tk, Python/Tk, Tcl/Tk used much
    - Especially, SADscript as a bridge btw. Accelerator simulation, Numeric manipulation, Graphic interface and EPICS controls
  - Bright new idea in the morning meeting could make the operation much advanced in the evening
    - Great tool to optimize the operation

SuperKEKB Controls

- **Inherit Good part of KEKB Controls**
  - EPICS
  - Scripting languages
- **EPICS Channel Access (CA) Everywhere**
  - Embed EPICS control software (IOC) everywhere possible
  - Reduce efforts on protocol design, testing, etc
- **Dual Tier: Another layer in addition to EPICS/CA**
  - Event system helps EPICS with another channel/layer
  - Additional functionality, synchronization and speed

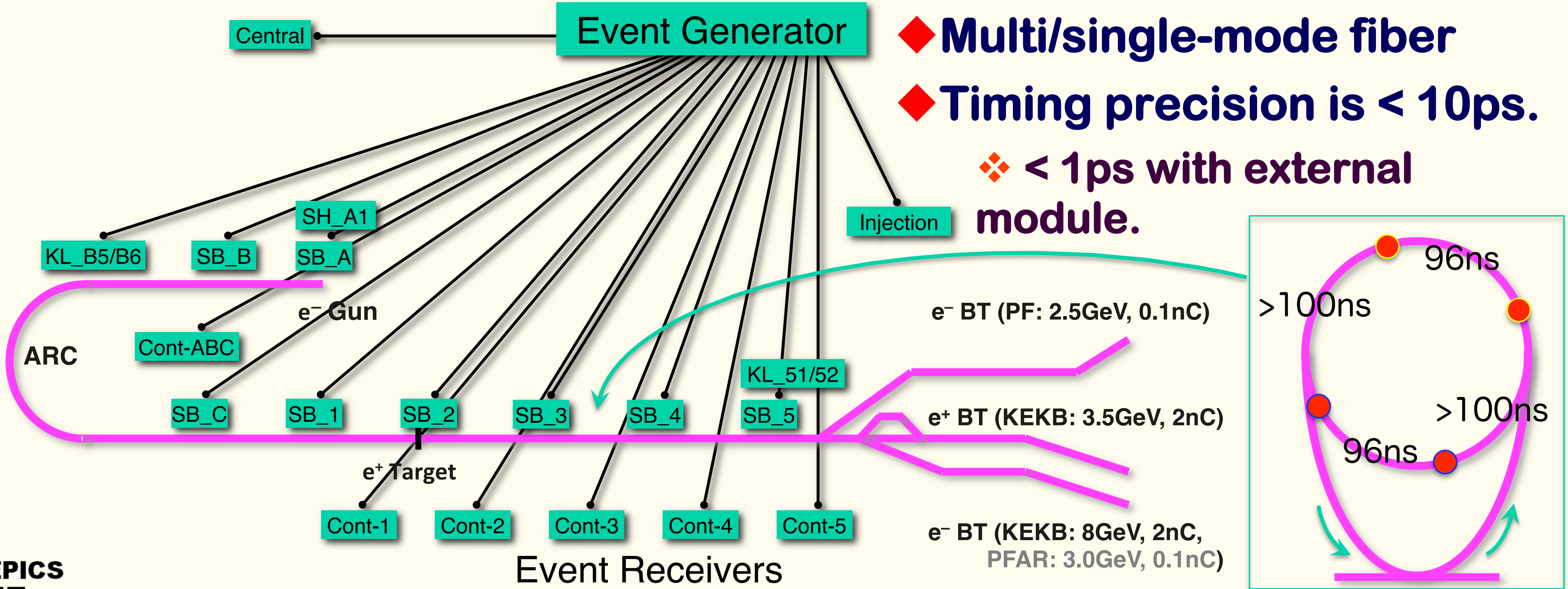
Dual-tier Controls

- **IOC controls via Conventional EPICS CA**
  - Above 1ms, ordered controls
- **Fast FPGA controls via SFP/Fiber (MRF)**
  - 10ps ~ 100ms, 114MHz synchronous controls



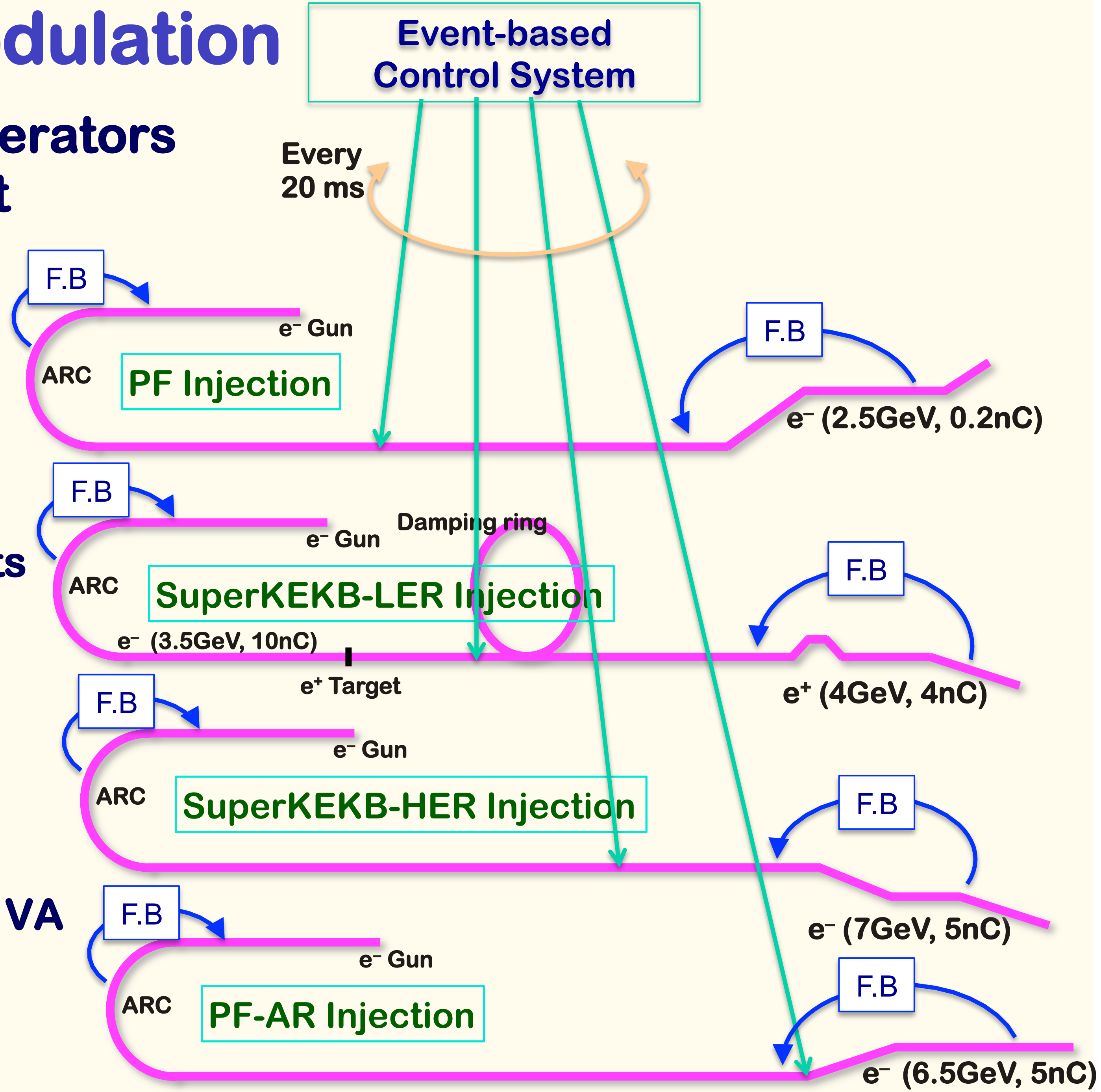
Event System for Simultaneous Top-up Injection

- Fast, global and synchronous controls
- MRF's series-230 Event Generator / Receivers
- VME64x and VxWorks v6.8
- EPICS R3.14.12 with mrfioc2 devsup
- ~50 event timing receivers
- ~30 FPGA-based event receivers
- 114.24MHz event rate, 50Hz fiducials
- More than 200 dynamic 50Hz Analog/Timing param.
- Multi/single-mode fiber
- Timing precision is < 10ps.
  - < 1ps with external module.



Pulse-to-pulse modulation

- **Four PPM virtual accelerators for SuperKEKB project**



Based on
Dual-tier controls with
EPICS and event-system

Independent parameter sets
for each VA (20ms)
>200 parameters
for equipment controls
many more
for beam controls

maybe with additional PPM VA
of stealth beam
for measurement

Possible Configuration for SuperKEKB

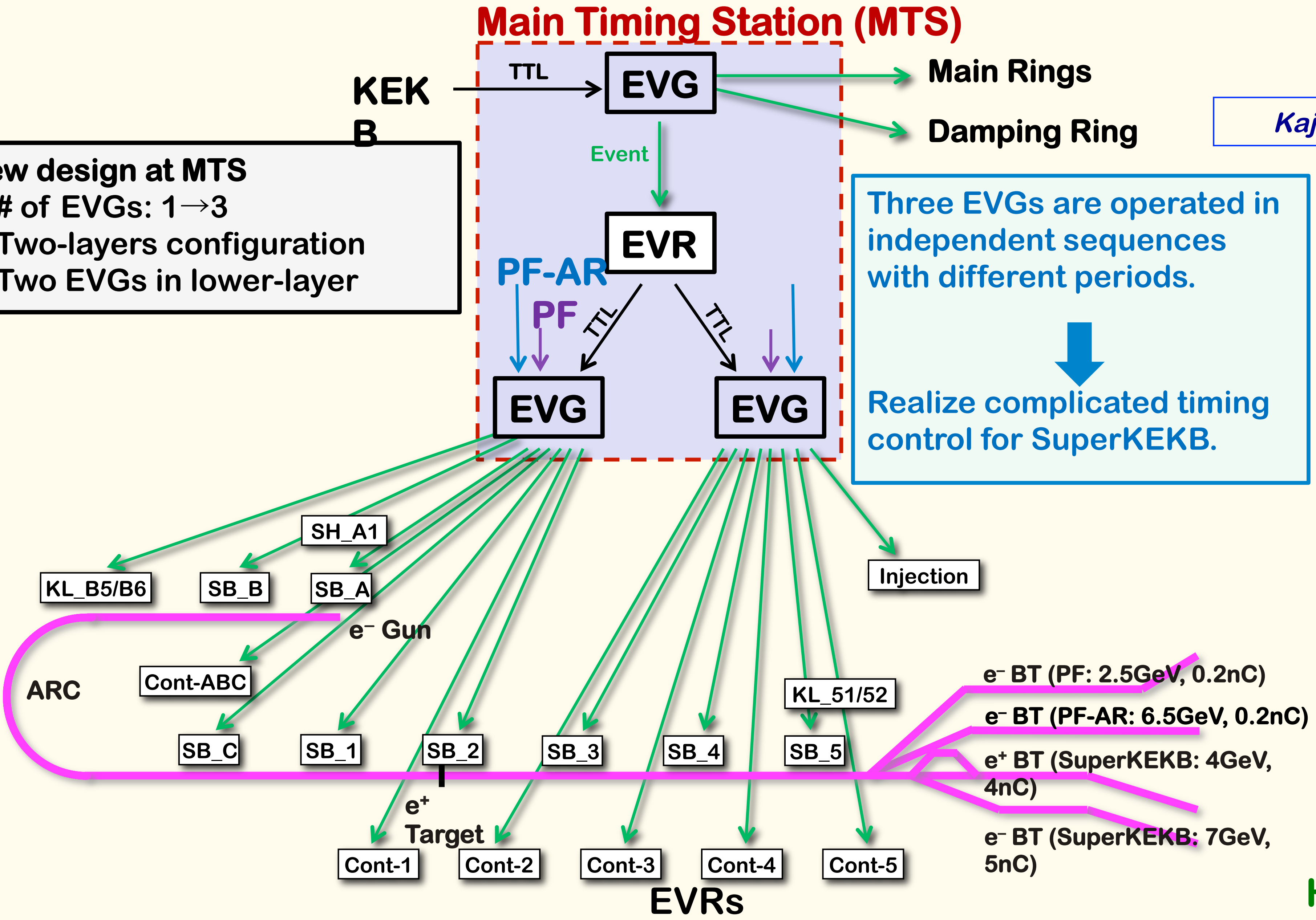
New design at MTS
- # of EVGs: 1→3
- Two-layers configuration
- Two EVGs in lower-layer

Kaji et al

Three EVGs are operated in independent sequences with different periods.

⬇

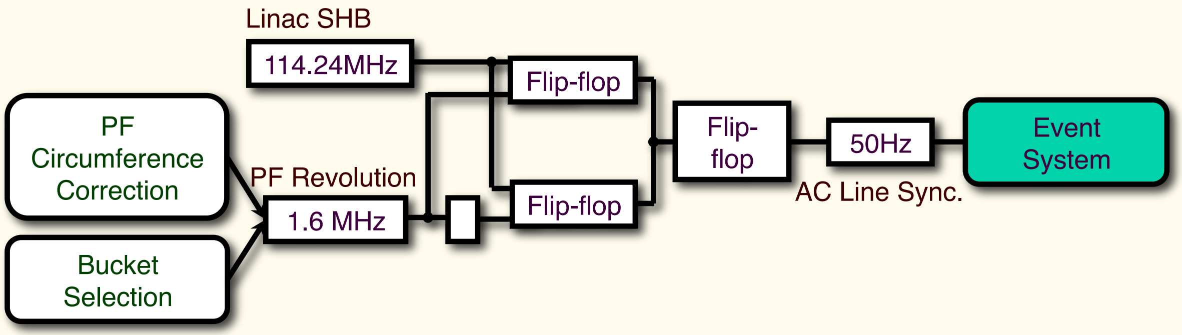
Realize complicated timing control for SuperKEKB.



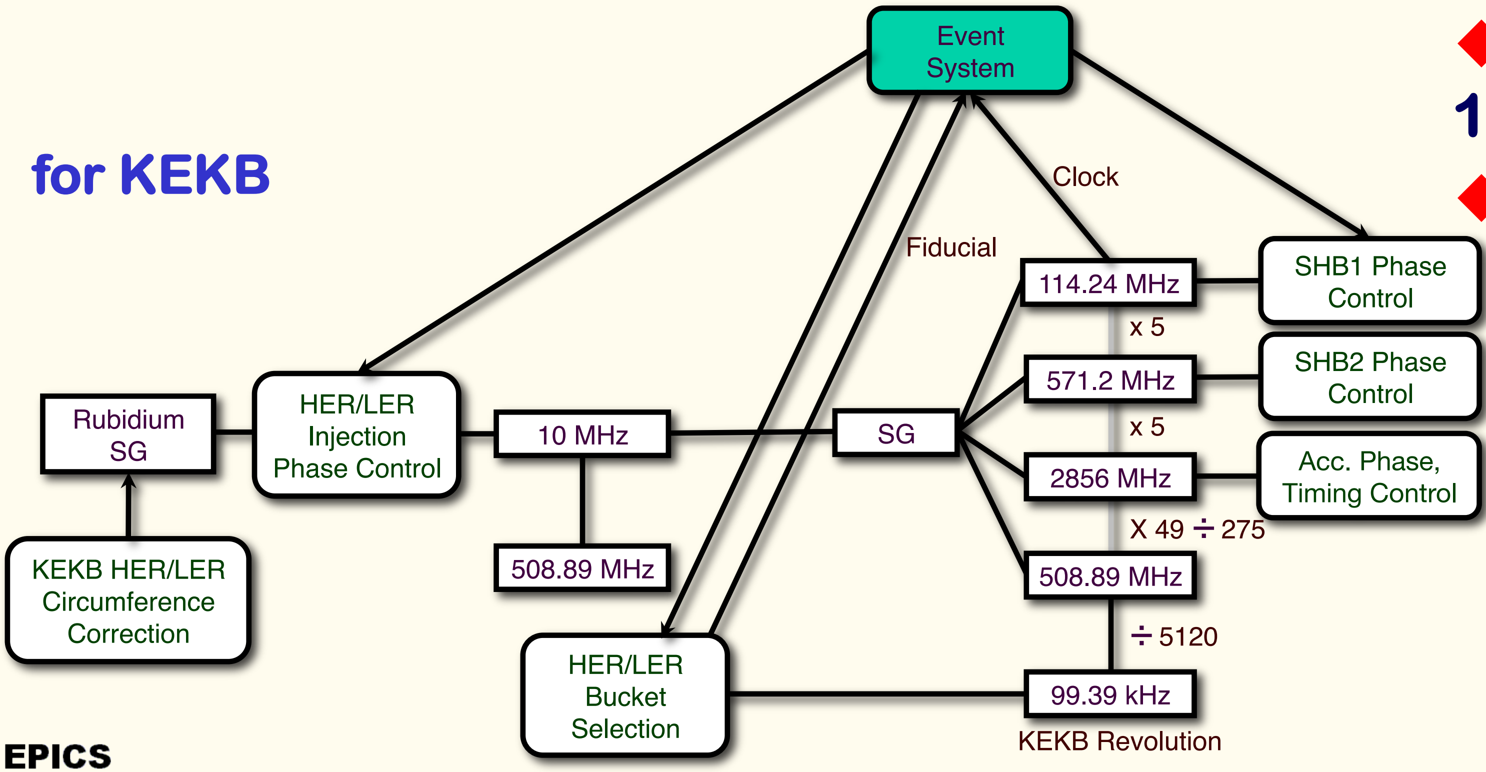
H. Kaji

KEKB (old) Synchronization Scheme

for PF



for KEKB



- **Synchronization Req.**
  - **KEKB : < 30ps**
  - **PF : < 300~700ps**
- **Linac rf is Synchronized to KEKB rf**
- **Event Clock is 114.24MHz**
- **We have to manage**
  - **Circumference compensation**
  - **Bucket selection**
  - **Injection phase controls**

RF Clock Relation

- **2856MHz: Injector linac main RF - following SLAC convention**
- **571.2, 114.24MHz: Subharmonic bunchers**
  - Bunching high-charge primary electron beam for positron generation
- **508.9MHz: SuperKEKB ring RF (deep tunnel)**
  - Integer relations
    - common freq. 10.385 == 114.24 / 11 == 571.2 / (11x5) == 2856 / (11x5x5)
    - common freq. 10.385 == 508.9 / 49
  - Continuous circumference compensation (CCC) changes RF clock
    - based on closed orbit measurement
    - CCC ~ 10^{-6} / year, ~ 10^{-7} / day
  - Injection timing jitter is only allowed up to 30 ps
- **508.5MHz: PF-AR RF (shallower tunnel)**
    - CCC ~ 4 x 10^{-6} / year, ~ 10^{-7} / day
- **500MHz: PF ring RF (even shallower)**
    - CCC ~ 2 x 10^{-5} / year, ~ 4 x 10^{-6} / day
  - Injection timing jitter is allowed up to ~ 700 ps
- **Clock synchronization**
  - Linac and SuperKEKB share the common rubidium clock source
  - PF ring or PF-AR is injected based on accidental RF phase coincidence within 700 ps

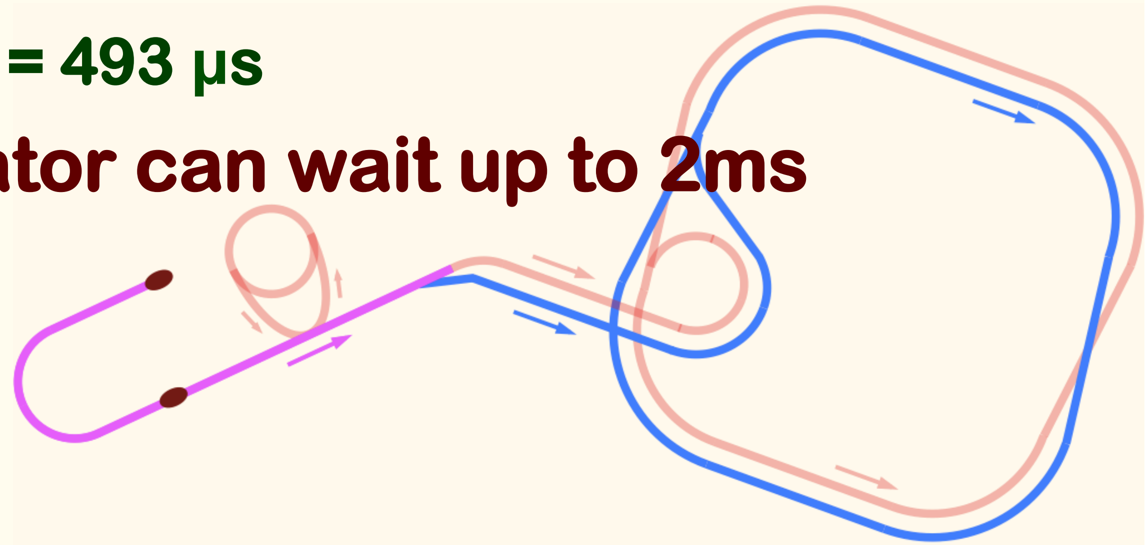
Large delay for asynchronous rings

- Pulsed magnets need ~3 ms pre-trigger
- If EVG programmed carefully, SuperKEKB injections should be OK as linac and rings are synchronized
- For PF and PF-AR injections, realization of both accidental coincidence and large delay may introduce timing jitter, as the clocks has ~10^{-6} drifts because of continuous circumference compensation
- Needs careful prediction of timings (and RF phase)
  - Succeeded in the beam tests

Electron Injection into SuperKEKB

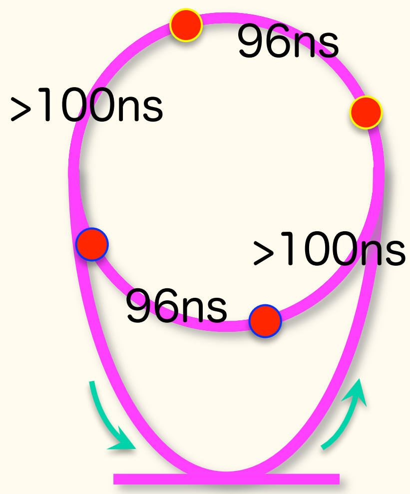
How much time we wait for injection

- Need to fill a bucket which has smaller bunch charge
- There are 5120 buckets (508.9 MHz) in SuperKEKB HER
- Linac can inject a beam bunch every 49 bucket (10.385 MHz)
- 5120 and 49 are coprime / disjoint
- An arbitrary bucket can be filled within
  - 96.3 ns (10.385 MHz) x 5120 = 493 μs
- High-power 50Hz modulator can wait up to 2ms



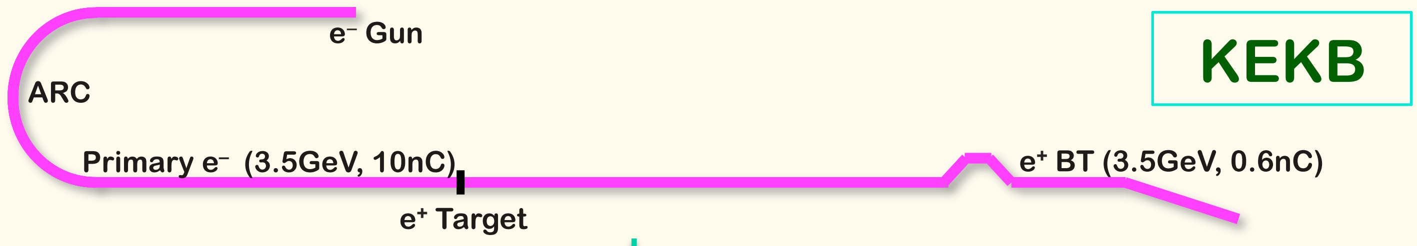
Positron Injection into SuperKEKB

- **Damping ring in the middle**
  - 40 ms damping while linac operate at 50 Hz
  - Can accommodate 2 bunches x 2 pulses
  - 2 bunches in a pulse are separated by 96.3 ns (10.385 MHz)
  - Injection/extraction kickers rise/fall times are ~100 ns
  - Harmonic number of 230 was chosen
    - to maximize the freedom, to make the size of the ring smaller
  - An arbitrary bucket in MR can be filled within
    - 96.3 ns (10.385 MHz) x 5120 x 23 = 11.3 ms
  - Even though the bucket in DR carefully chosen, 4-bunch arrangement in DR limit the possibilities
  - High-power 50Hz modulator can wait only up to 2ms



Bucket selection in Phase-2 with DR

- **Without DR, simply wait up to 5120 x 96 ns ~ 493 μs**
  - **96 ns : highest common frequency between linac – ring**

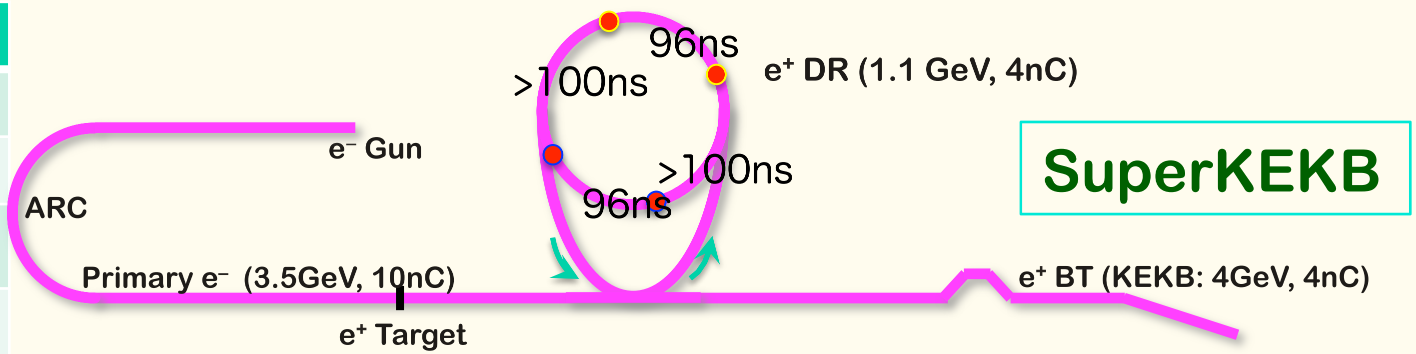


Kaji et al

- **With DR, in order to select arbitrary bucket in MR, have to wait up to ~4.5 ms, even if a bucket in DR was carefully selected**
  - **Power supply can wait only 2 ms, one of only 2798 buckets in 5120 buckets can be selected, may have to change LLRF condition at latter half of linac every pulse**

For
e+ 25Hz
e– 25Hz

Inj.	D.R.	Ext.
e+ 1	e+ 1	
e– 2	e+ 1	e– 2
e+ 3	e+ 3,1	e+ 1
e– 4	e+ 3	e– 4
e+ 5	e+ 5,3	e+ 3
e– 6	e+ 5	e– 6



Can be a big challenge in LLRF precision

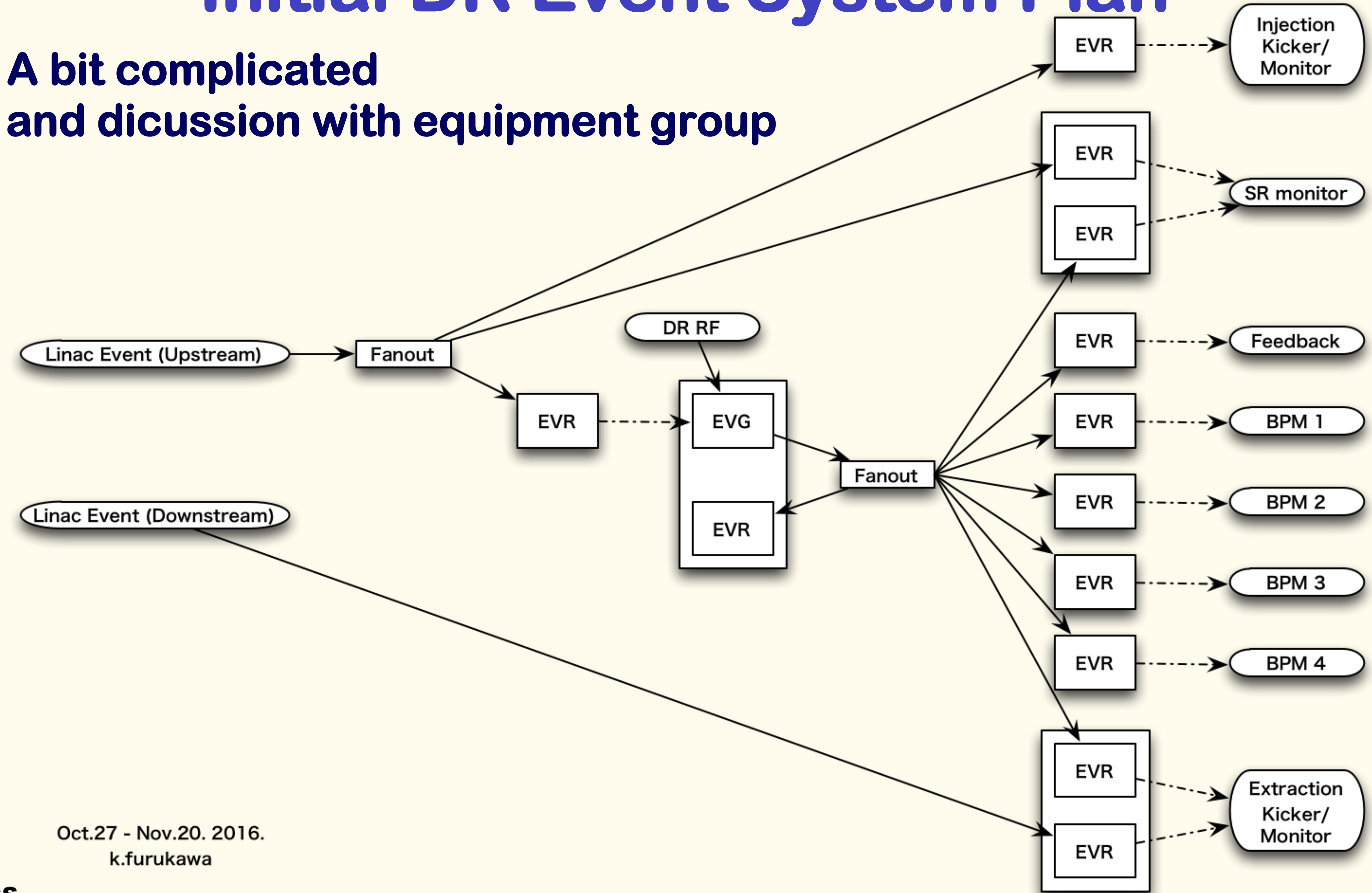
EPICS

Damping Ring Timing Requirement

- Need to change main 508.9 MHz clock ± 50 kHz
  - for beam dispersion function analysis
  - should be disconnected from other clocks
- Injection / extraction kicker need charging trigger ~15 ms before firing
  - for extraction beam stability not to blow up in linac
- Pulse trains should be provided for BPM
  - at revolution frequency (508.9MHz / 230)
  - synchronized to one of the beam bunches in DR
- Several other timing signals for
  - BT BPM, SOR light monitor, Bunch feedback, etc.

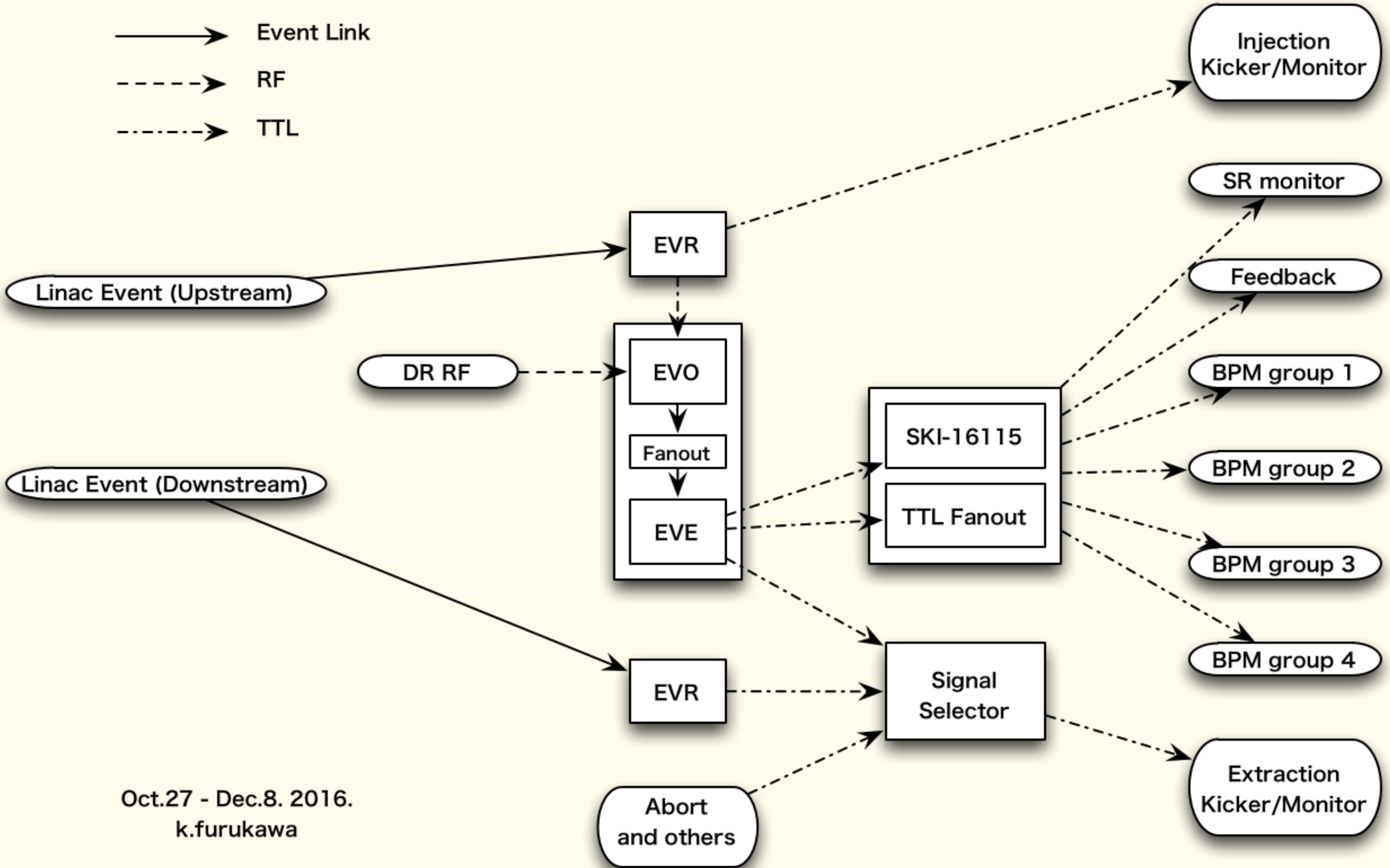
Initial DR Event System Plan

- **A bit complicated and dicussion with equipment group**



DR Event Timing System

- **Simplified timing configuration with MRF and SINAP modules**

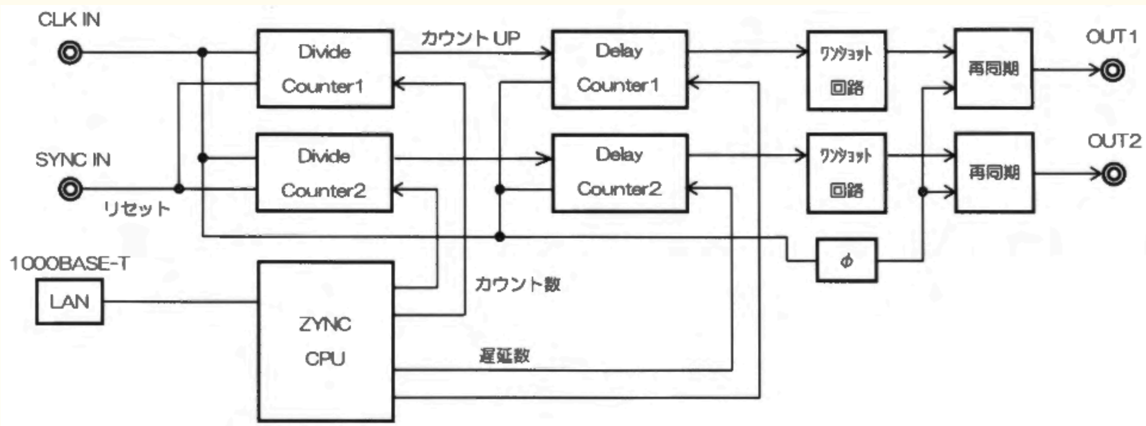


Pulse Train Generator for BPM

- **SKI-16115 arbitrary delay repetition pulse generator**

Tobiyama, Ikeda et al

  - **Meet the specifications from BPM hardware**
  - **EVR/MRF or EVE/SINAP can generate those pulse trains but this dedicated module may play better role**



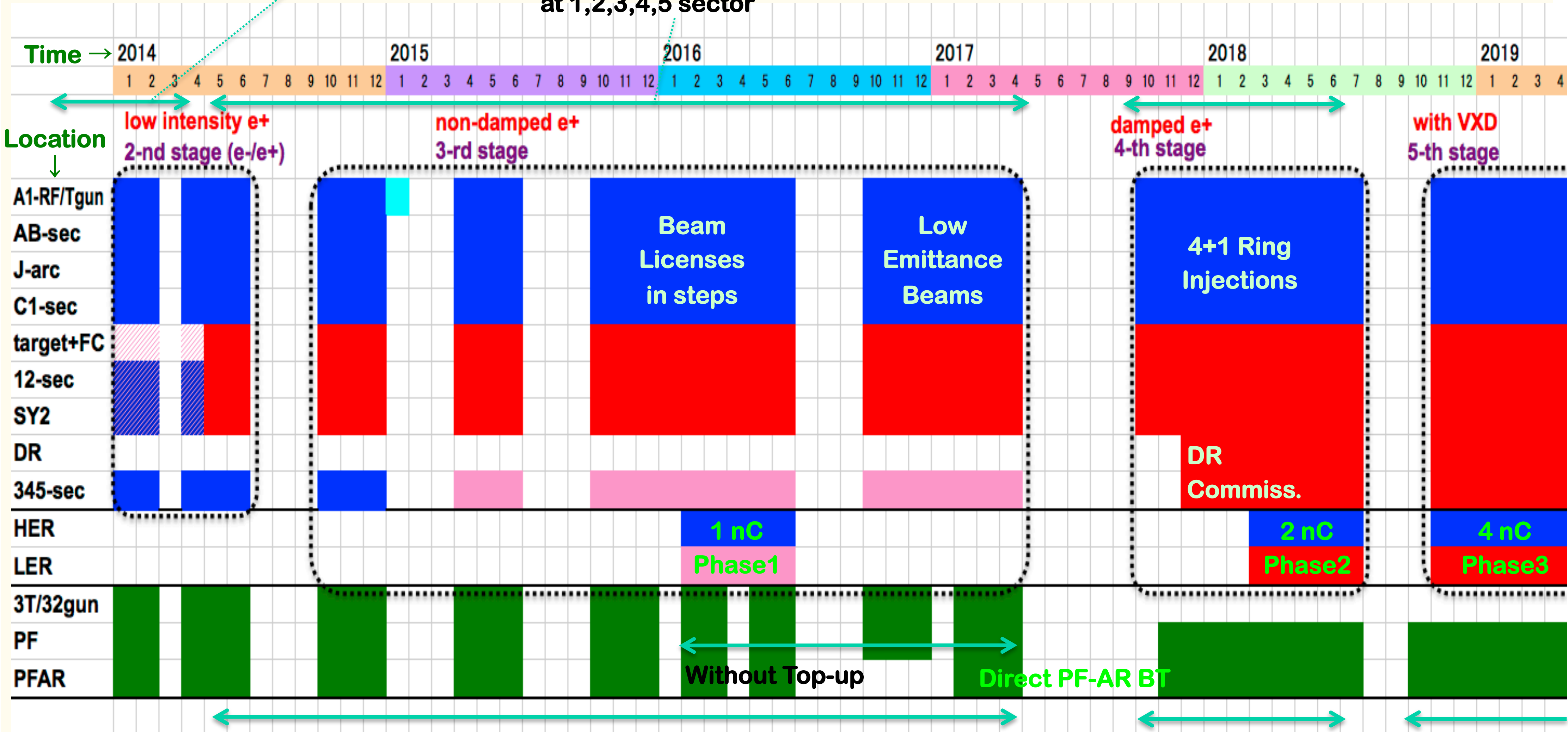
Linac Schedule Overview at May.2017

RF-Gun e- beam commissioning at A,B-sector

e- commiss. at A,B,J,C,1

e+ commiss. at 1,2 sector (FC, DCS, Qe- 50%)
e- commiss. at 1,2,3,4,5 sector

Phase1: high emittance beam for vacuum scrub
Phase2,3: low emittance beam for collision



- : Electron
- : Positron
- : Low current electron

non damped e+ commiss. at 1,2, 3,4,5 sectors
e- commiss. at A→5 sectors

damped e+ commiss. at 1→5 Qe+ = 1~4nC
e- commiss. at A→5 Qe- = 1~5nC

Improved RF gun

Labview and PXI (off topic)

- **Pulsed magnet controls, and several others**
  - **Labview local controls**
    - On PXI (cPCI) and Windows as well as cRIO, ~15 systems
    - Stable ! and runs at 50Hz more than several months
    - With remote EPICS/CA viewer, and local archiver
    - Managed by an equipment group
  - **This system will be used at least for the initial stage**
    - Whether the control group take care as is … ?
  - **Hope to exchange experiences between users**

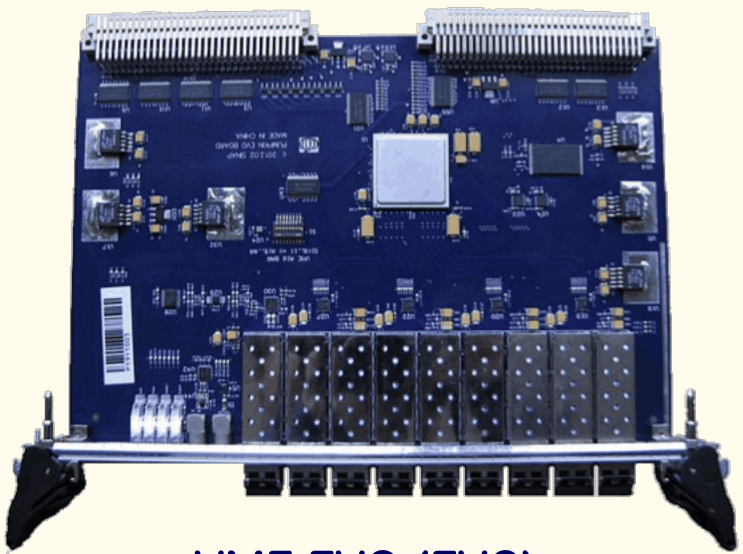
  - **Another discussion is PXI or µTCA to solve performance issues ?**

Conclusion

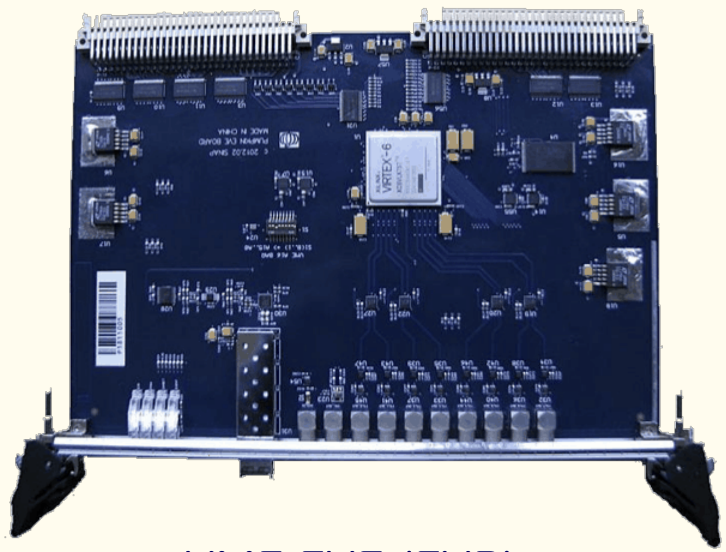
- Injector linac, damping ring, EPICS control system, event-based synchronous system are being constructed
- Partially confirmed in phase-I commissioning in 2016
- Phase-II commissioning is just around the corner

Compatible MRF-Event Hardware

- **RF monitor system**
  - **Embedded EVR for event sync. with Vertex-6 and SFP**
- **LLRF system for damping ring**
  - **MicroTCA LLRF module with Vertex-5 and SFP**
- **Detector interface**
  - **Possible embedded EVR in fast detector-veto system**
- **SINAP VME and PLC modules for damping ring**



VME EVO (EVG)



VME EVE (EVR)

PLC EVR