Timing system towards SuperKEKB controls

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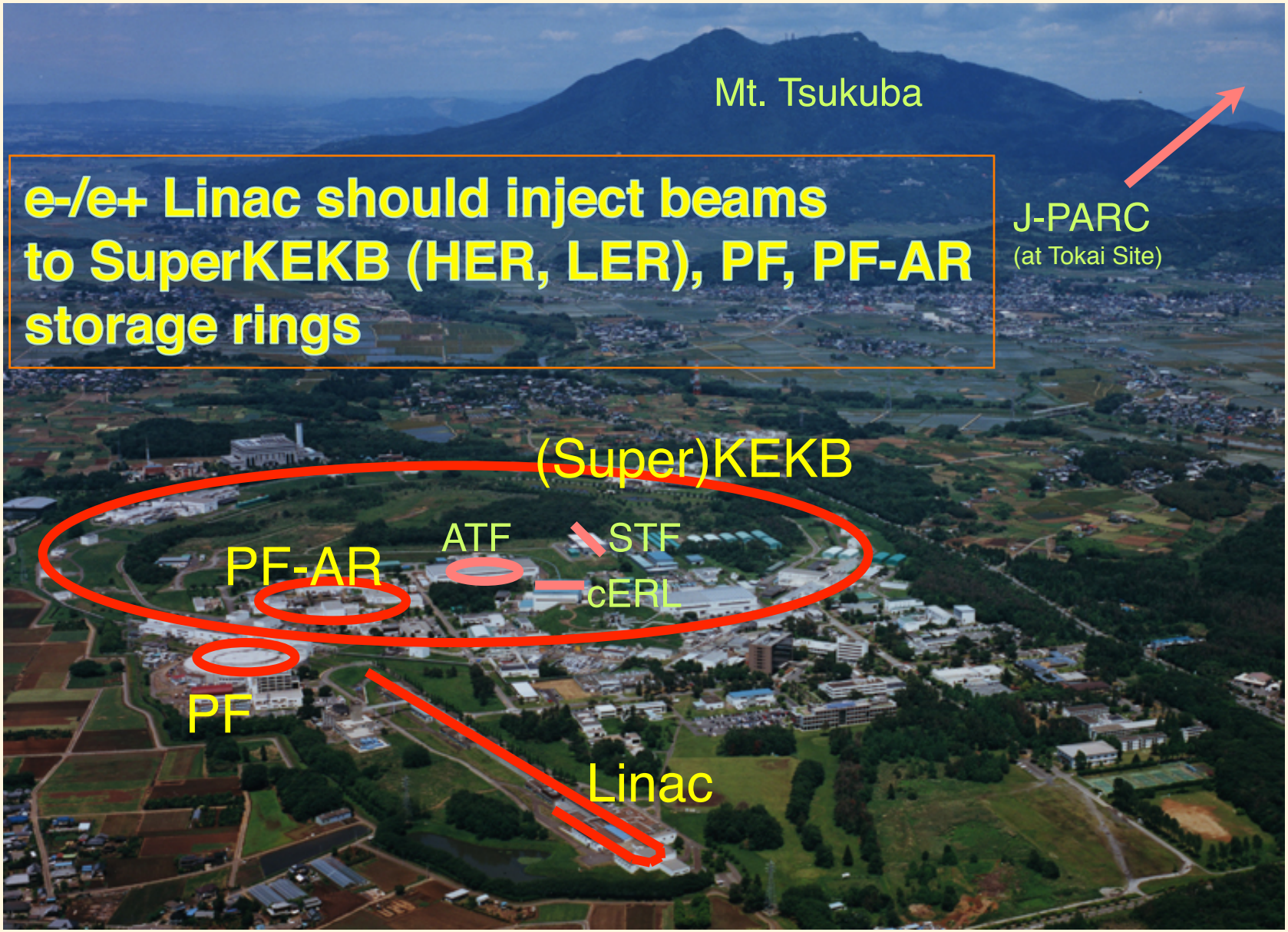
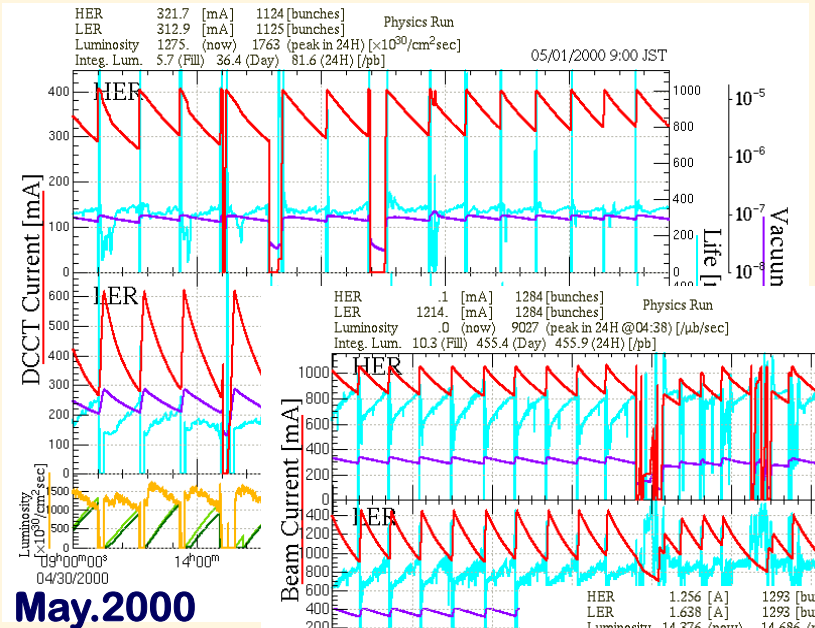
EPICS

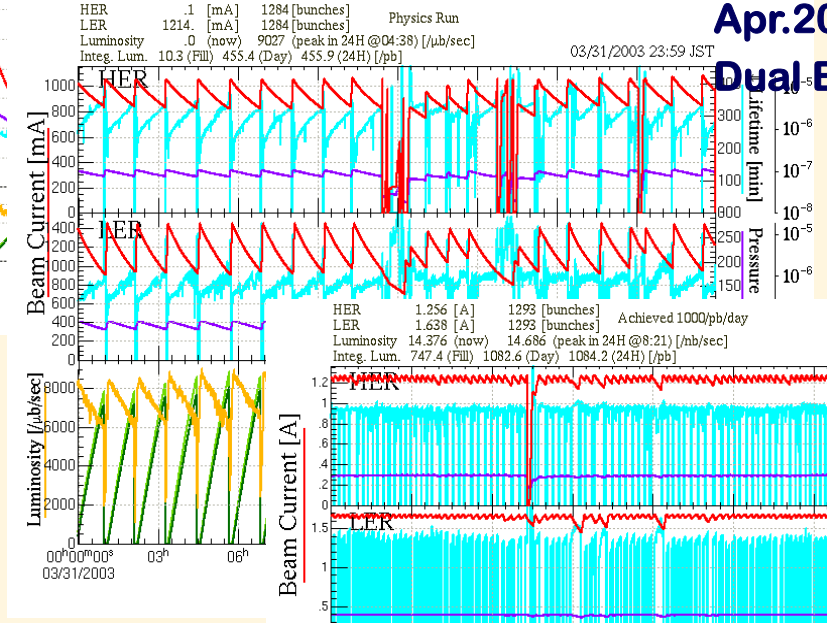
Accelerators at KEK



KEKB Operation Improvement up to 2007

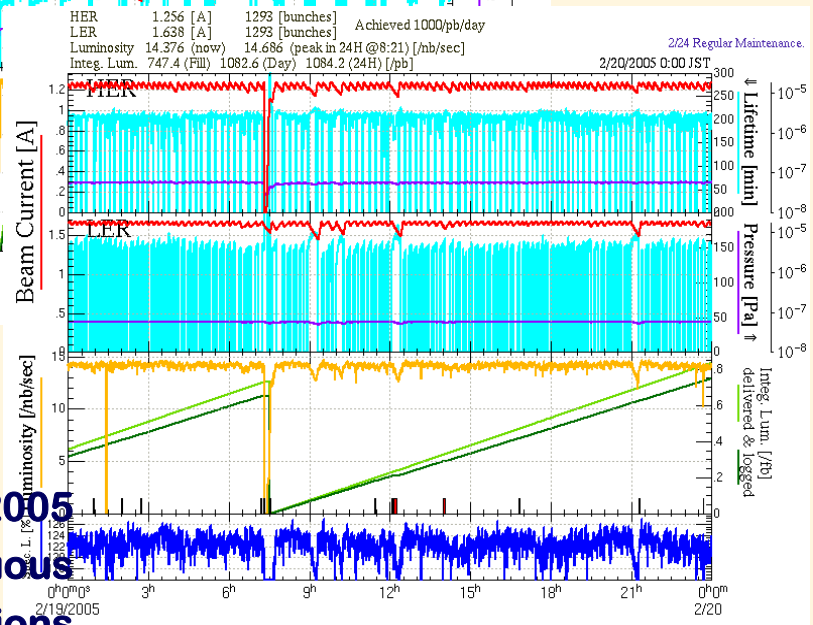


May.2000



Apr.2003

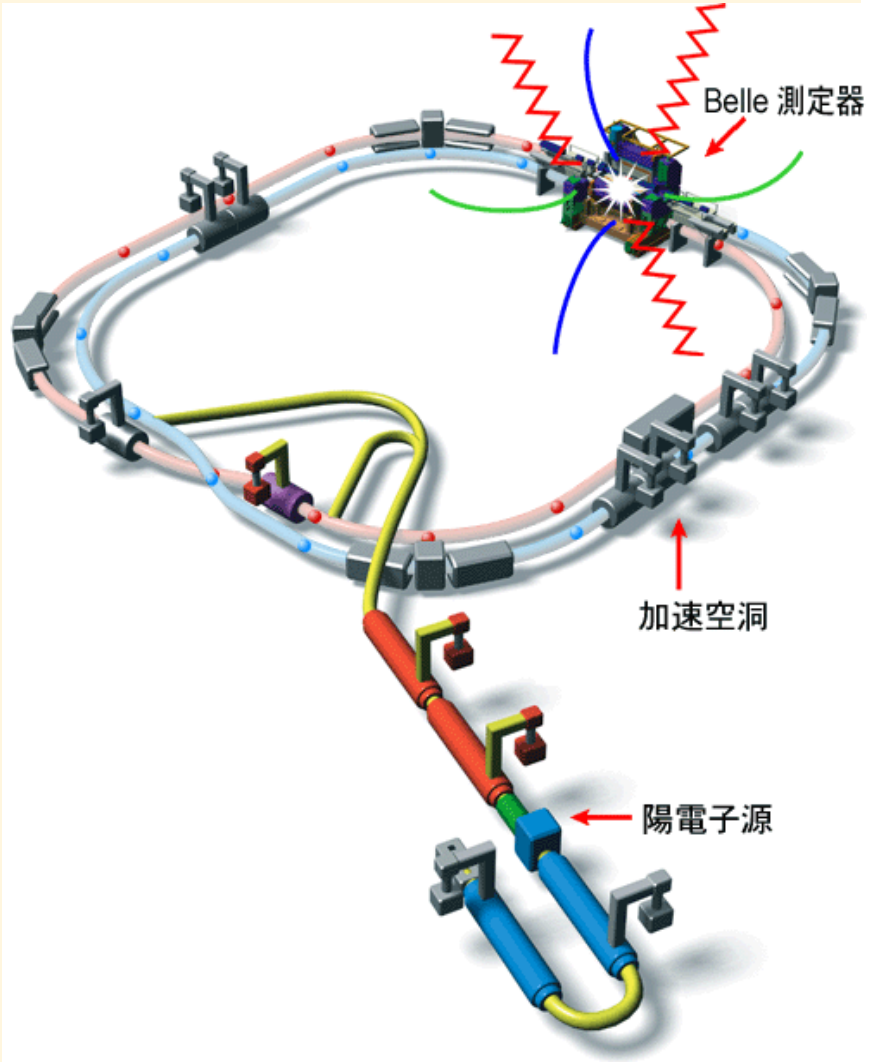
Dual Bunch e+



Feb.2005

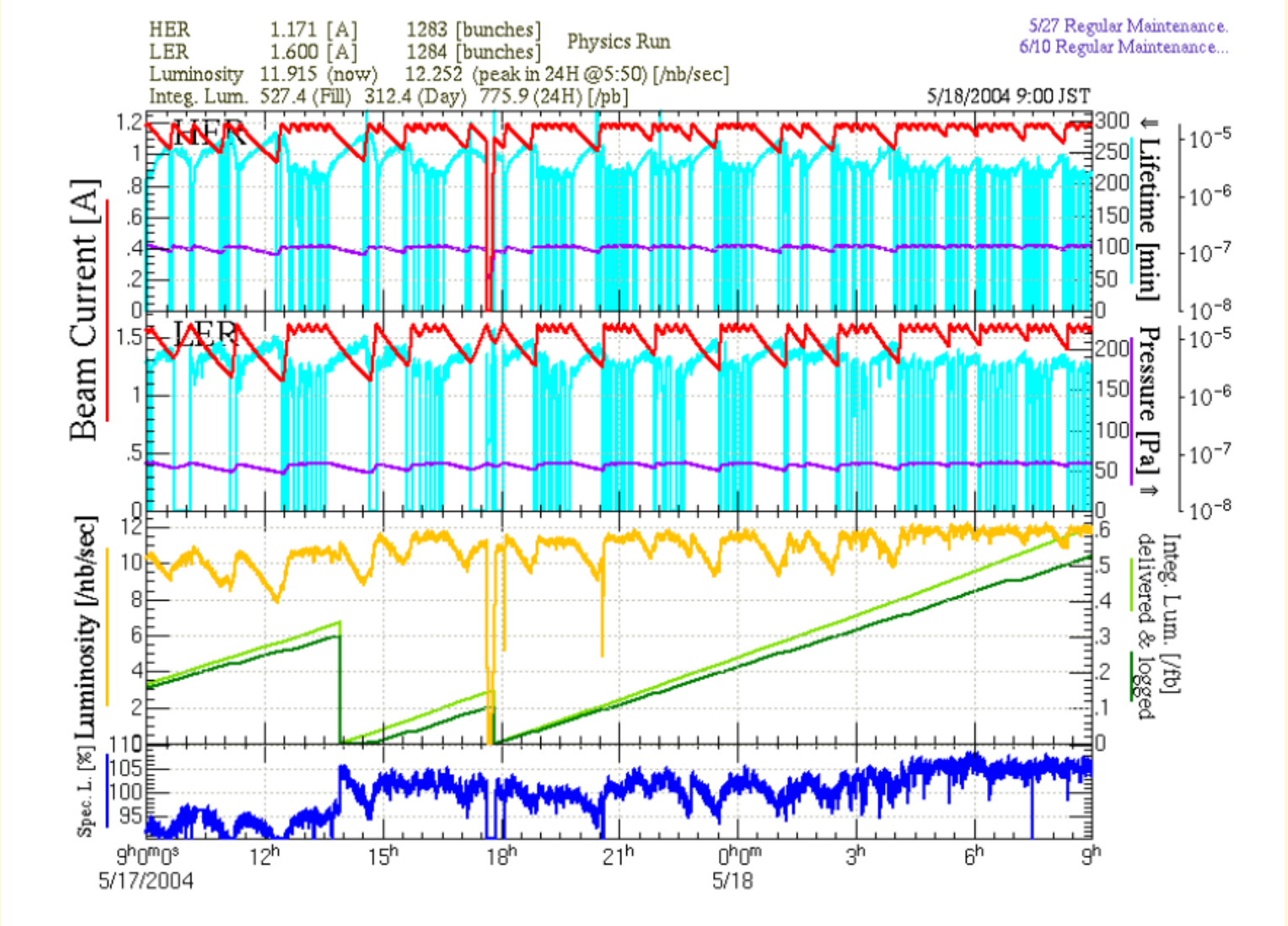
Continuous

Injections



EPICS

Sometimes injection needed simultaneously



EPICS

Fast beam switching or Simultaneous Injection

- KEKB Luminosity degradation on beam studies at PF and PF/AR
- Future SuperKEKB injections with shorter lifetime
- Sensitive luminosity tuning with Crab cavities
- PF (and PF-AR) top-up injections for higher quality experiments

  - CERN/PS switches beams every 1.2s (PPM)
  - SLAC/SLC switched beams at 180 Hz
  - KEK Linac had switched beams 360 times a day in 2008 (just before simultaneous injection)
  - 10~120seconds per switching

Requirements

- Maximum beam rate of 50Hz x 2bunches should be kept
- Most pulsed power supplies were designed to operate at constant rate (a restriction to beam mode pattern)
- Most linac magnets were not pulsed (except positron focusing coil)
  - Thus, it took much time for mag-field standardization
- Approx. 1000 devices in linac
  - 600 active devices (gun, RF, magnets, etc), 100 passive devices (BPM, WS, etc), and static devices
- 20ms beam switching became the solution

Timing system domain

- **Timing domain**
  - 20milli-second - Pulse-to-pulse, Beam mode flavors,
  - Micro-second - pulsed power supplies
  - Nano-second - Shape of pulses for pulsed microwave
  - Pico-second - Beam timing, instrumentation
  - < pico-second - Microwave phases
- **Hardware media / software**
  - Microwave – we always need this
    - Pulse shape, phase control
  - Event timing controls – intelligent timing
    - Pulse-by-pulse event manipulations

EPICS

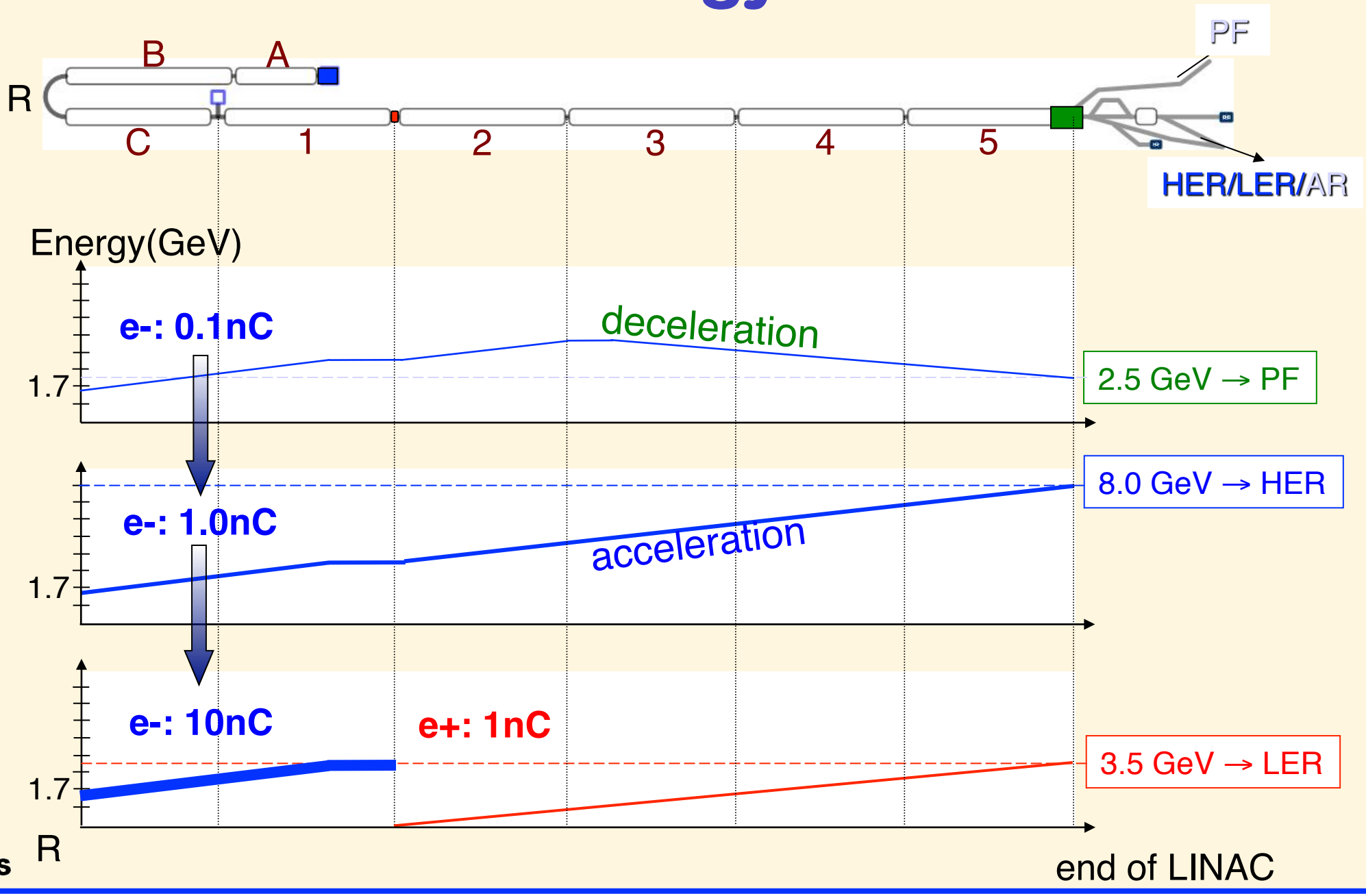
Detailed requirement at SuperKEKB

- Stable multiple frequencies (114, 571, 1298, 2856, 509MHz)
  - Beam bunching for large-current positron single-bunch generation
  - Need integer relations (common freq. 10.38MHz)
- Injection timing precision of 30 picoseconds
  - Integer relation to (Super)KEKB for aperture at IP
    - Accidental coincidence for PF and PF-AR with less severe condition
- Independent Circumference corrections at KEKB, PF, PF-AR
  - KEKB changes 4×10^{-7}, PF and PF-AR changes $4 \sim 20 \times 10^{-6}$
- 2bunches in a single pulse (50Hz)
  - Separated by 96ns (common freq. 10.38MHz)
- Simultaneous top-up injections to 4 rings SuperKEKB HER/ LER, PF and PF-AR
  - Common beam transport to KEKB and PF-AR will be upgraded

Hardware and Operation Improvements

- Separate BT for PF (2005)
- Pulsed bending magnet for PF (2007)
- PF beam from common gun (A1) (2007)
- Beam charge safety interlock (2007)
- Event-based fast control system (2008)
- Pulsed steering magnets (2008)
- Electron bypass hole at positron target (2008)
- Interface between ring-linac RF (2008)
- Multi-energy linac optics (2008)
- Simultaneous injections (Apr.2009)

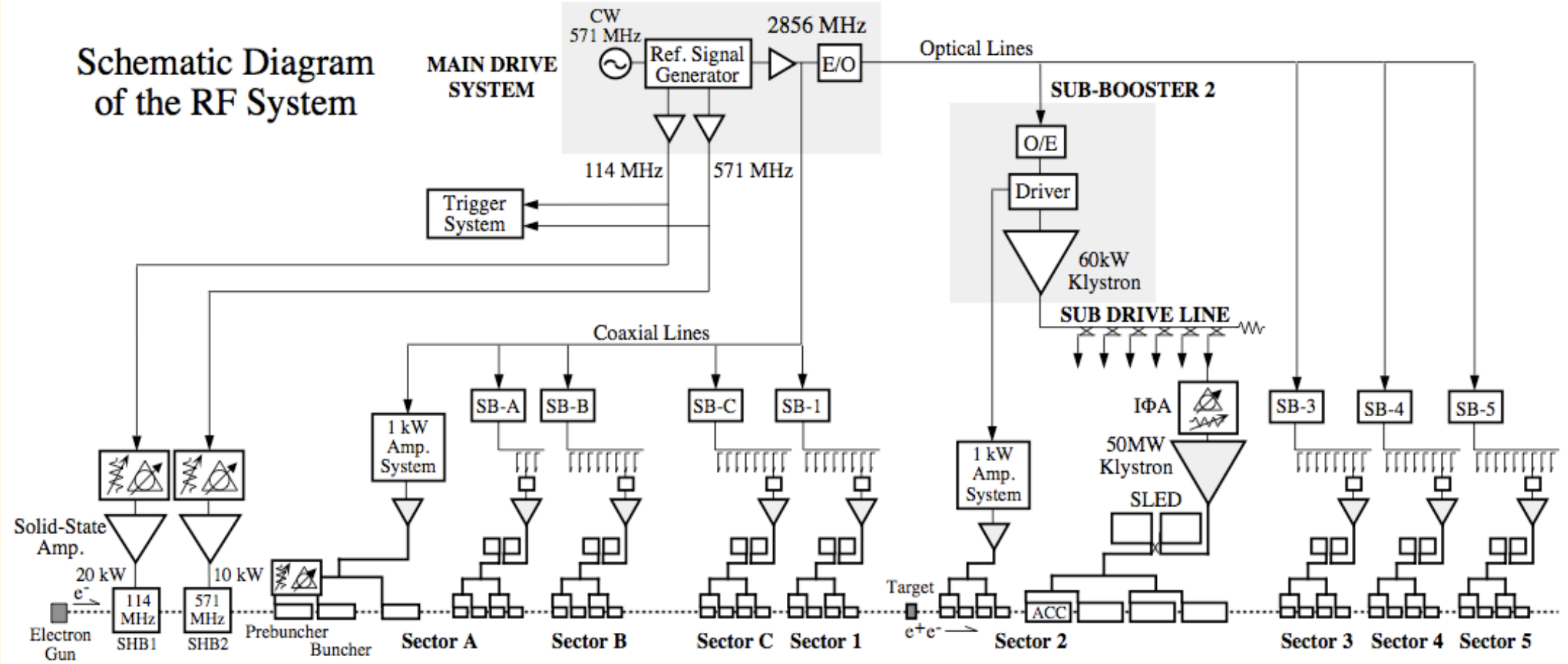
Linac Energy Profile



Power Management

- Power management at each power source
  - of 60 50-MW power sources
  - In order to maximize the power
  - But not to increase the trip rate
    - Interlock at a reflection level VSWR of 1.4
    - If a trip rate is higher, the voltage is lowered
    - Surveyed statistically every week
- Some sources will be stand-by state
  - As backups, if the energy is enough
    - KEKB e+ has several stand-by, KEKB e– has typically one
- Energy conversion
  - Energy gain = constant x sqrt(power)

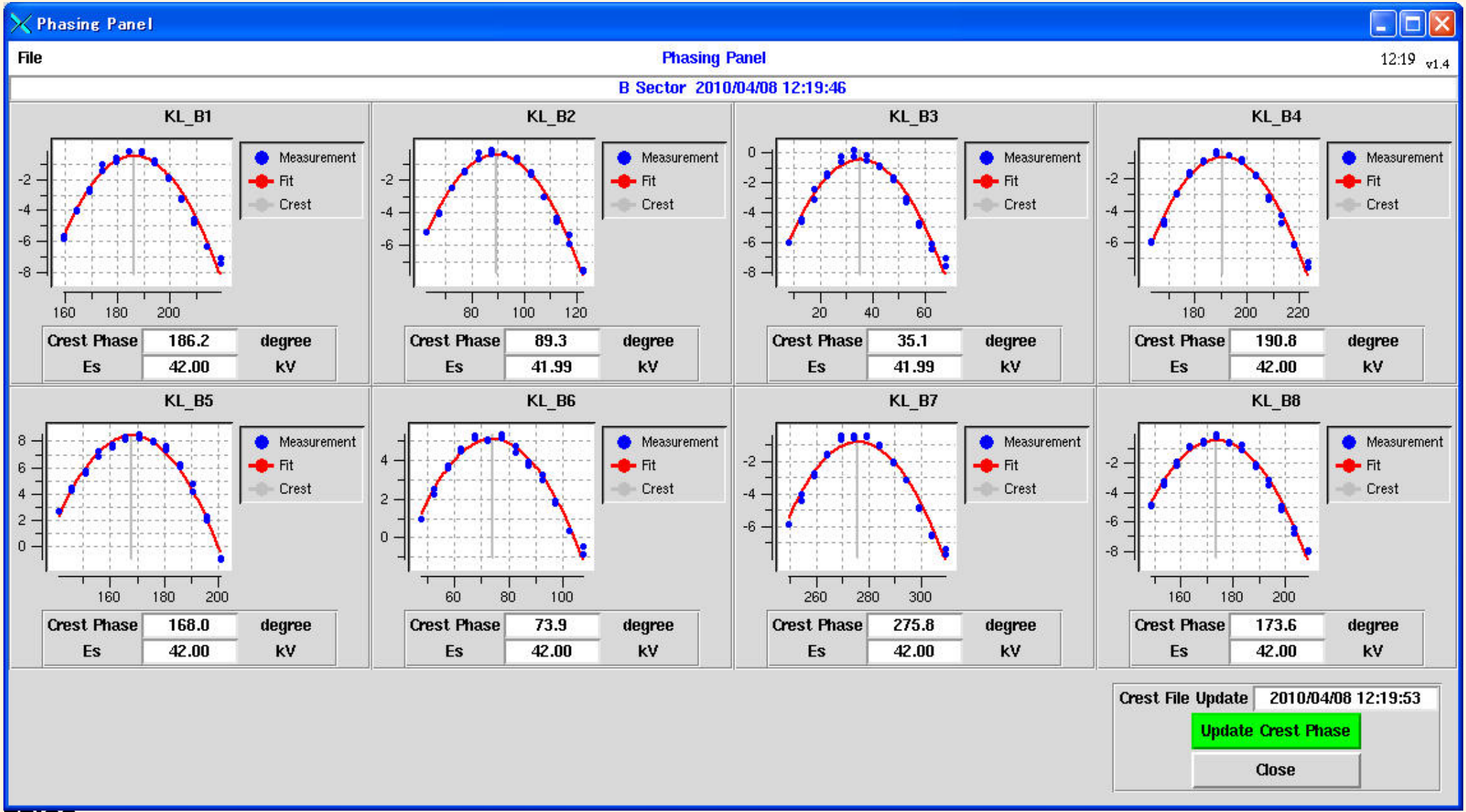
Linac Energy Management



Crest Phase Calibration

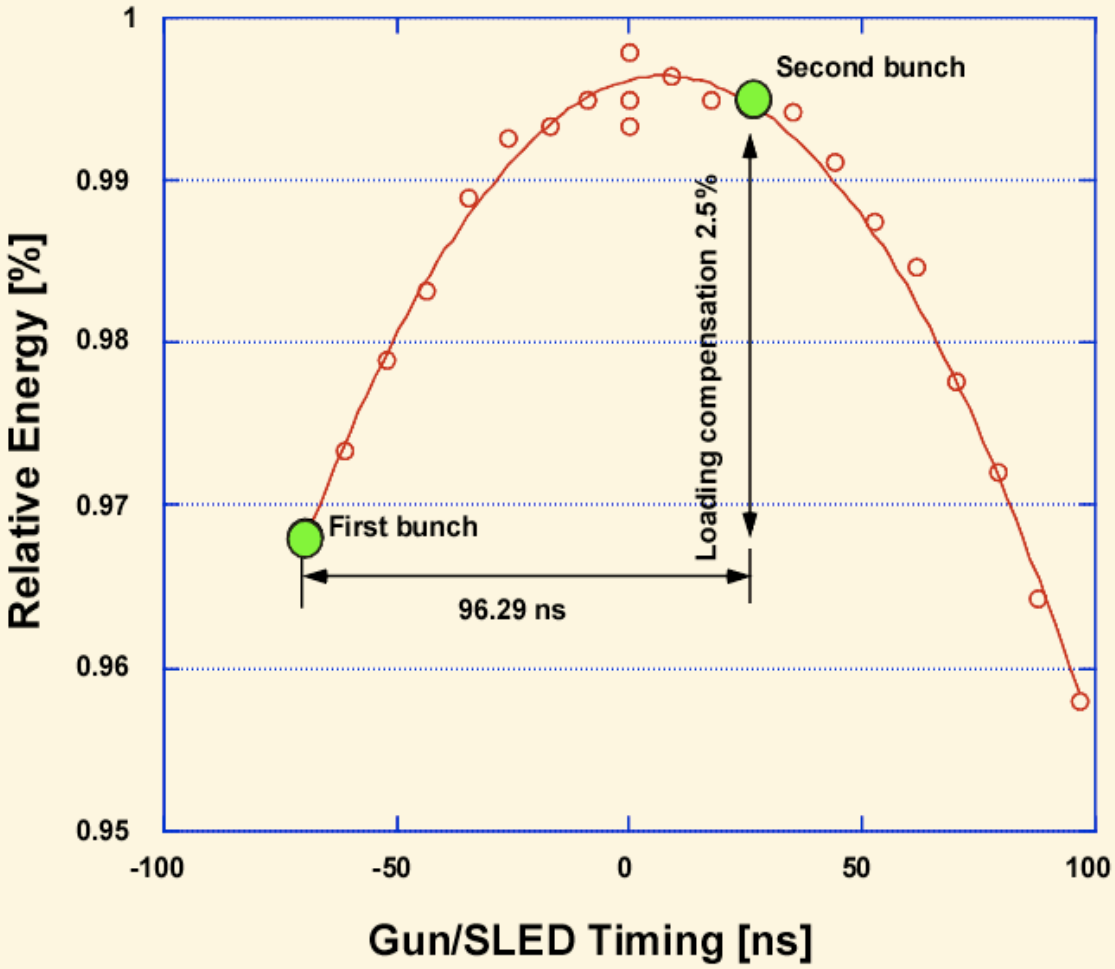
- Each power source with slow phase shifter
  - Energy measurement scanning the phase shifter
    - Primitive but reliable, while there were several methods
    - Chicken and egg issue exists on bootstrap
      - If no beam at the end, no measurement possible
  - Every several month at least after the long shutdown
    - Automated measurement takes ~2hours for 60 sources
  - Result is saved as a reference to other software
    - If the voltage was changed, nominal crest change is applied (1kV => ~8degree) (to be measured later)

Typical Automated Phase Calibration



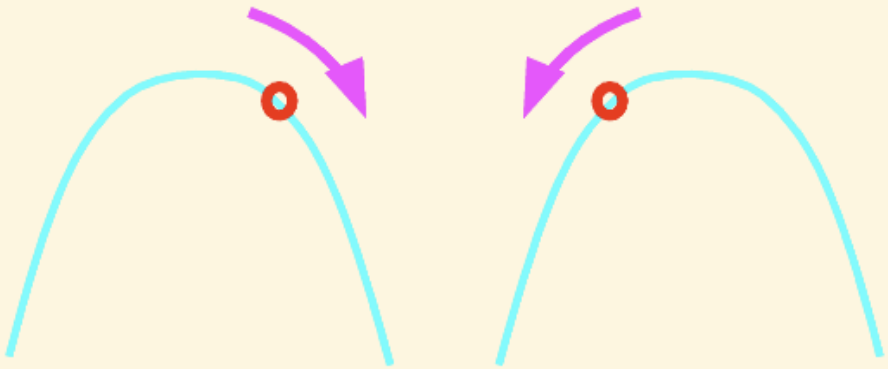
Two-bunch Energy Equalization

- **Two bunch in a pulse**
  - **Energy compensation**
    - Depending on beam charge
- **Fast timing adjustment**
  - **Automated measurement**
  - **Same procedure**
    - As crest phase measurement
    - With ns timing as a variable



Energy Profile

- 8 driver klystrons with fast phase shifters
  - Each manage ~8 high power klystrons
  - Define the overall energy profile
  - With Small phase angle (from the crest)
    - Energy spread compensation depending on beam charge
- 4 klystrons with fast phase shifters
  - Forming two energy-knobs to adjust the energies
    - Before the arc and at the end of the linac
  - Not to enlarge the energy spread
    - Two klystrons are grouped

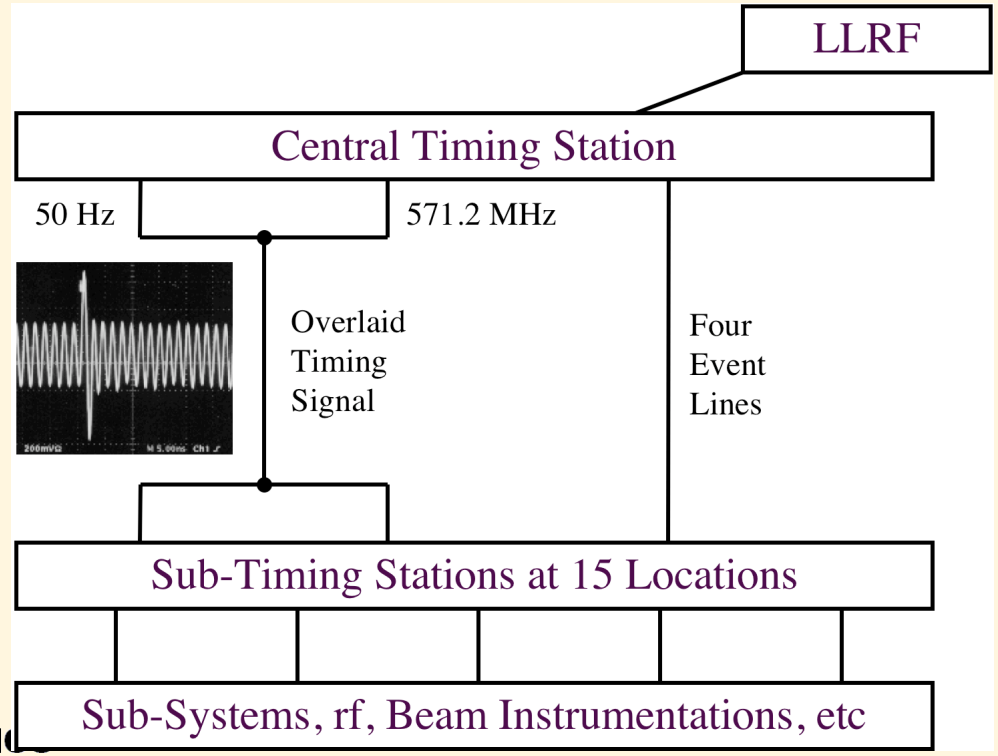


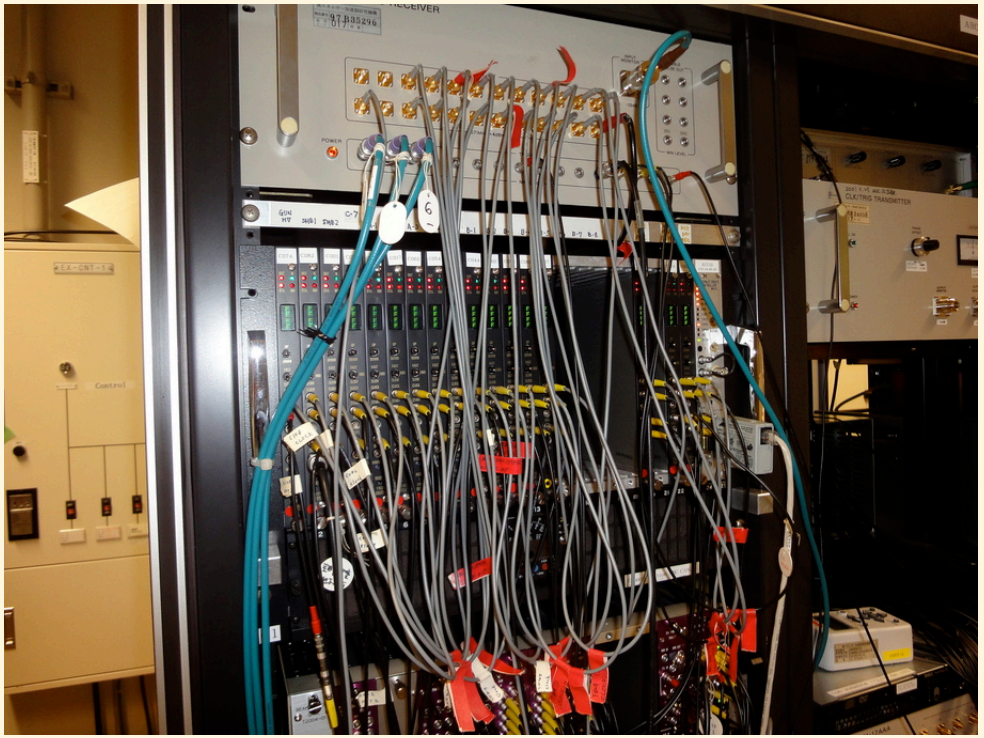
Fast Controls

- ~150 parameter switching within 20ms
  - Keep most of magnet fields with compatible optics
  - Control llrf to change energy
- Pulsed magnet triggers and delays
  - Delays to keep the constant rate for certain power-supplies
- LLRF phases and delays
- Gun voltage and fine delay
- Interface to bucket selection, etc
- (Ethernet-based controls are not reliable enough?)
- FPGA and fiber-optic RocketIO might be the way ?

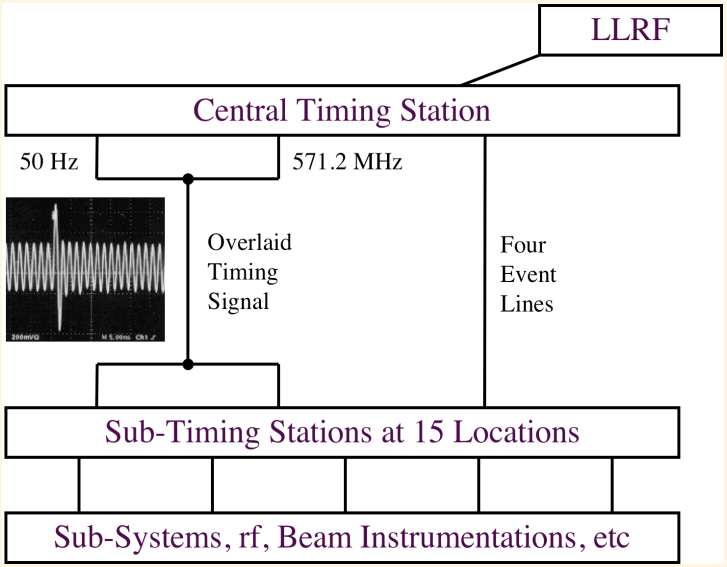
Old timing system

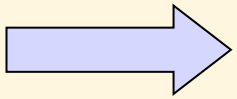
- Distribution of RF and trigger fiducial
- Many delay modules (~200)
- Did not need fast controls
- KEKB ring has additional slow (μs) events (8bits)

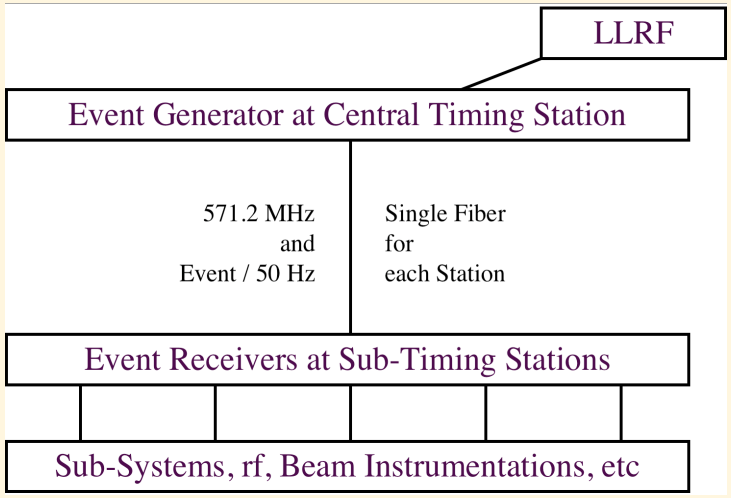




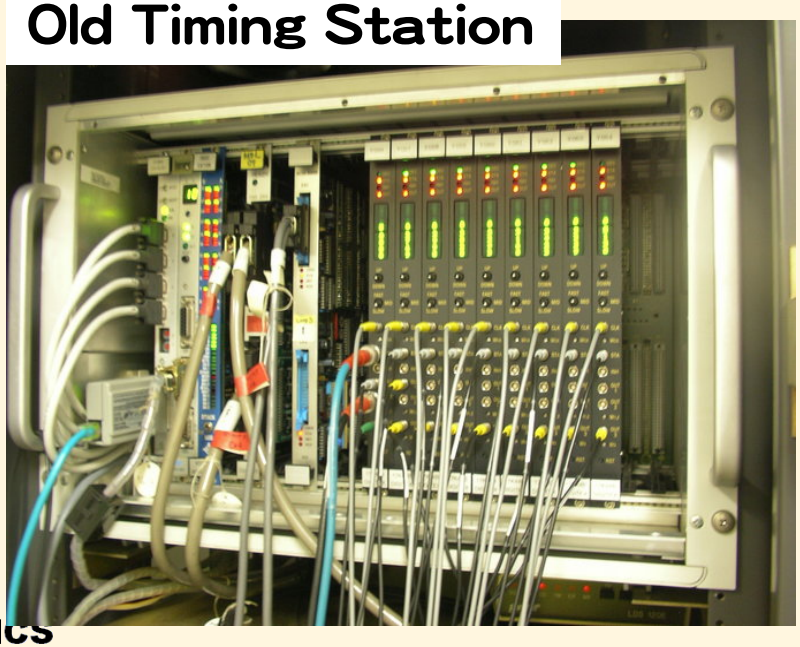
Timing System







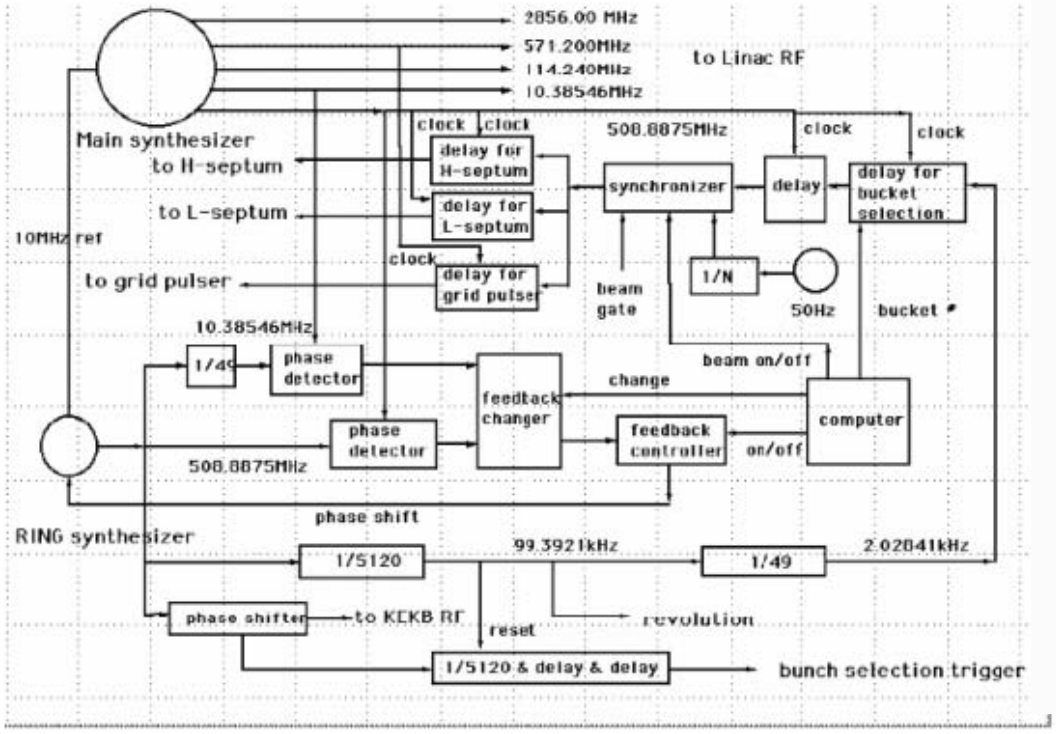
Old Timing Station

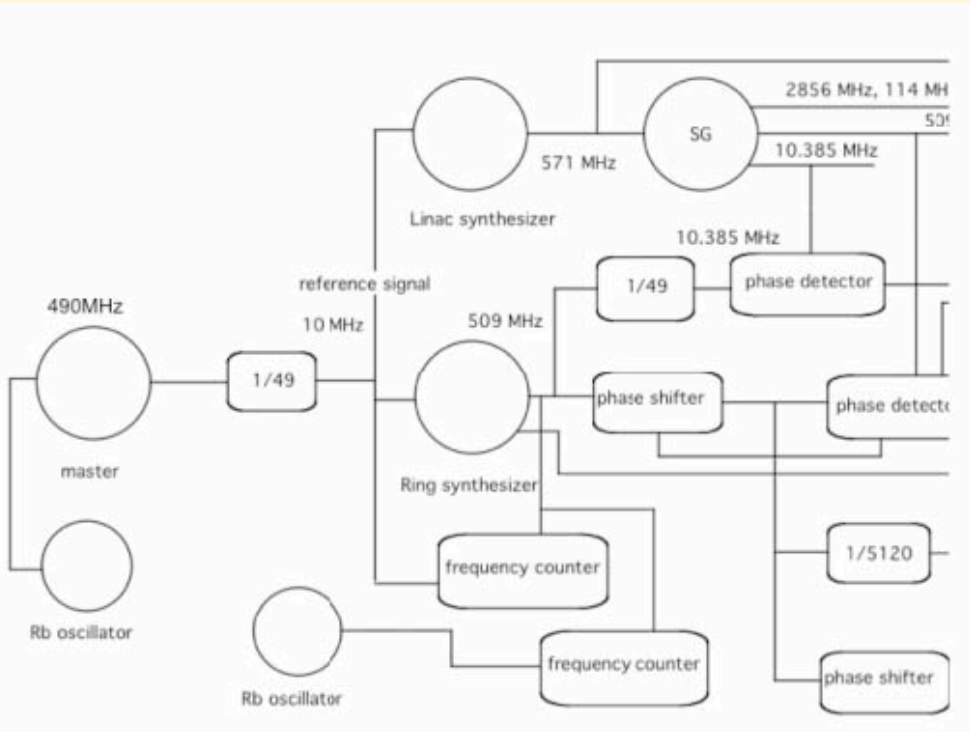


New Event Receiver Station with 14 outputs

Ring - Linac

- **Separate oscillators**
  - Dispersion measurement at ring
  - Phase lock / release at high (rf) / low (revolution) frequencies
- **Precision < 30ps**
  - Small aperture at the collision point





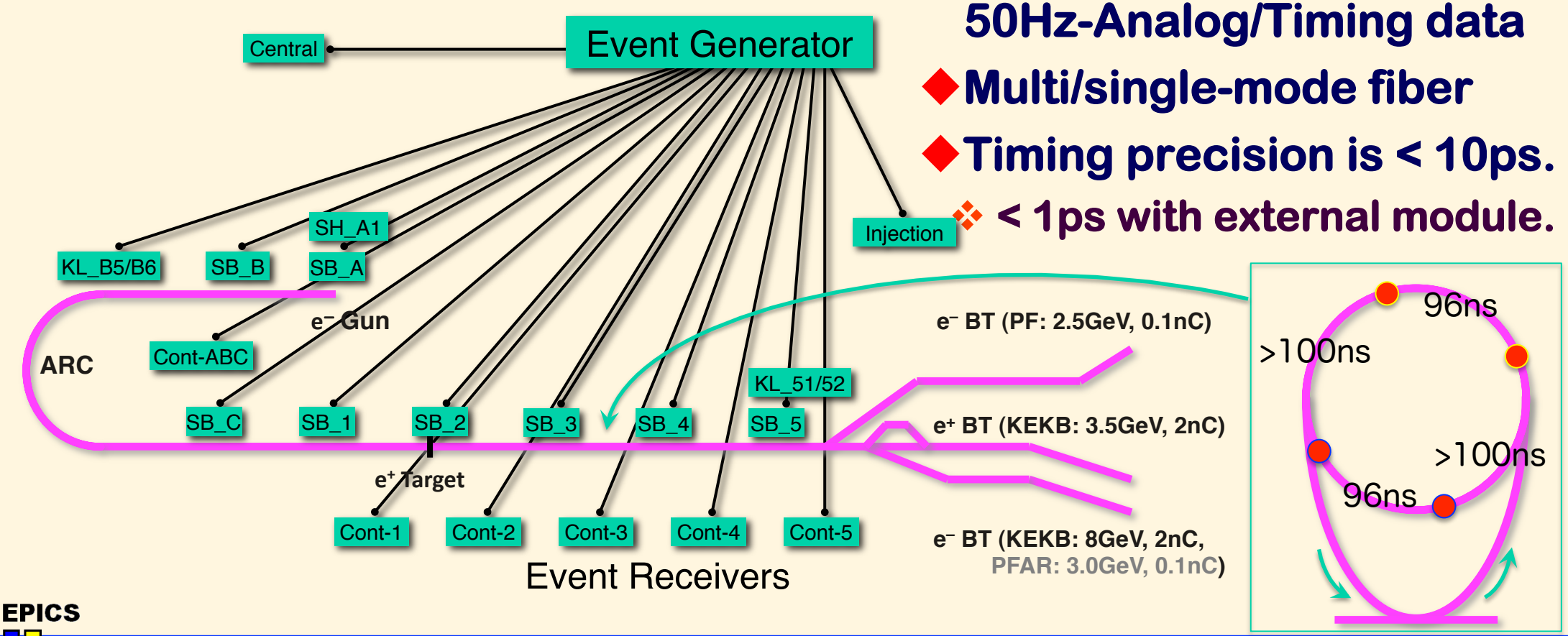
Event System

- **Simultaneous Injection**
  - to KEKB-HER, KEKB-LER, and PF, PF-AR
  - 2.5GeV to 8GeV, 0.1nC to 10nC
- **Stable stored beam current at three rings**
  - Should improve collision tuning with Crab cavities
  - Should improve the quality of experimental data at PF
- **Fast switching of many device parameters**
  - In 20ms / 50Hz
  - Should be reliable because beam power is much different
- **MRF Series 230 Event Generator / Receiver**
  - VxWorks 5.5.1, MVME5500 (Originally with RTEMS but…)
  - Timing precision less than 10ps is sufficient (TD4 provides 3ps)
  - Multi-mode fiber, and single-mode fiber for longer distance

Event System for Simultaneous Injection

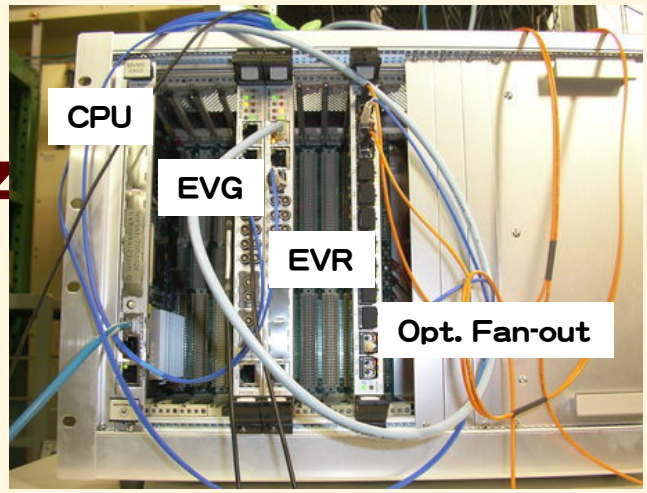
- MRF's series-230 Event Generator / Receivers
- VME64x and VxWorks v5.5.1
- EPICS R3.14.9 with DevSup v2.4.1
- 17 event receivers up to now

- 114.24MHz event rate, 50Hz fiducials
- More than hundred 50Hz-Analog/Timing data
- Multi/single-mode fiber
- Timing precision is < 10ps.
  - < 1ps with external module.



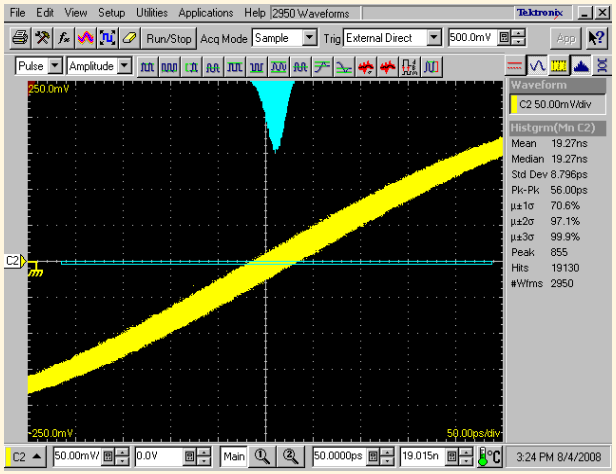
Linac Event System

- **Satisfies the requirements**
  - Event rate : 114.24MHz (bit rate : ~2.3GHz)
  - Fiducial rate : 50Hz
  - Timing jitter (Short term) : ~8ps
  - No. of defined events : ~50
  - No. of receiver stations : 17
  - No. of Fast parameters : ~130



EVR & LLRF

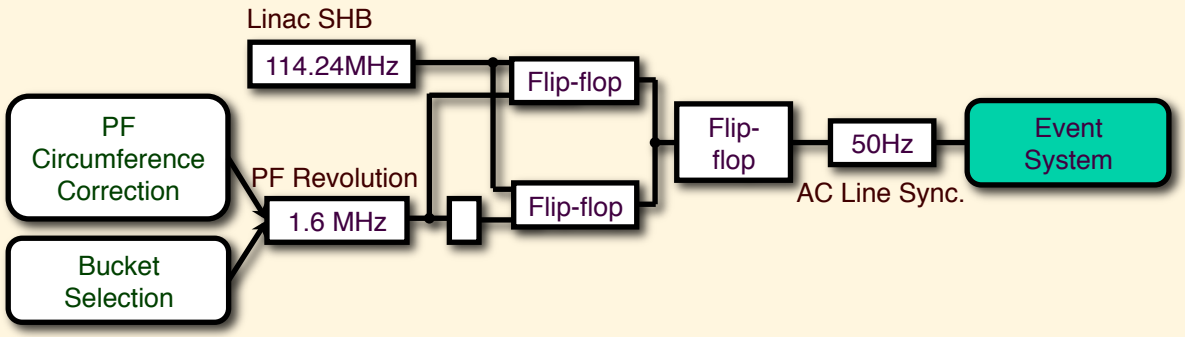
- CPU stopped 4 times since Sep.2008 for 18 stations



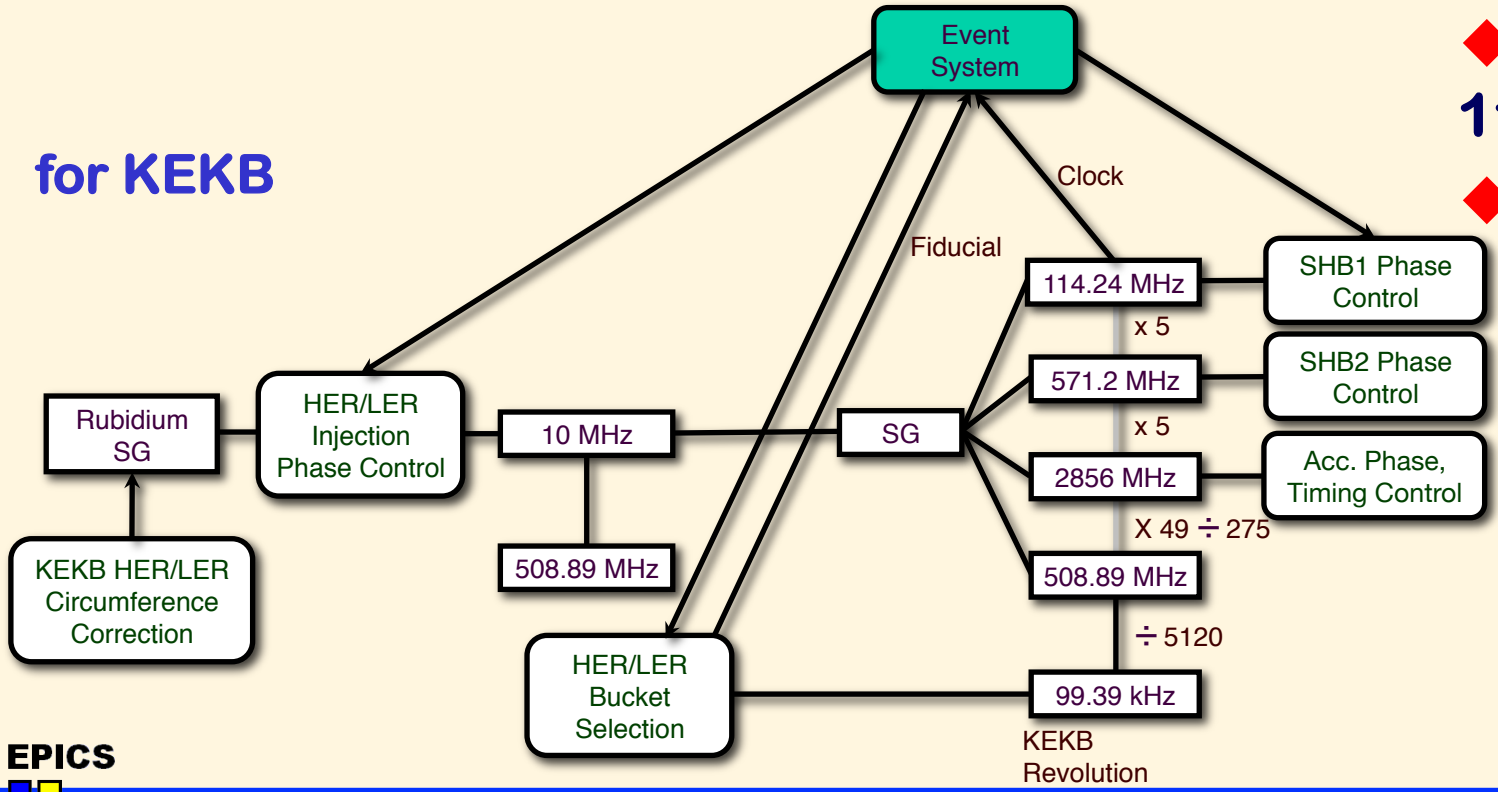
EPICS

Synchronization Scheme

for PF



for KEKB



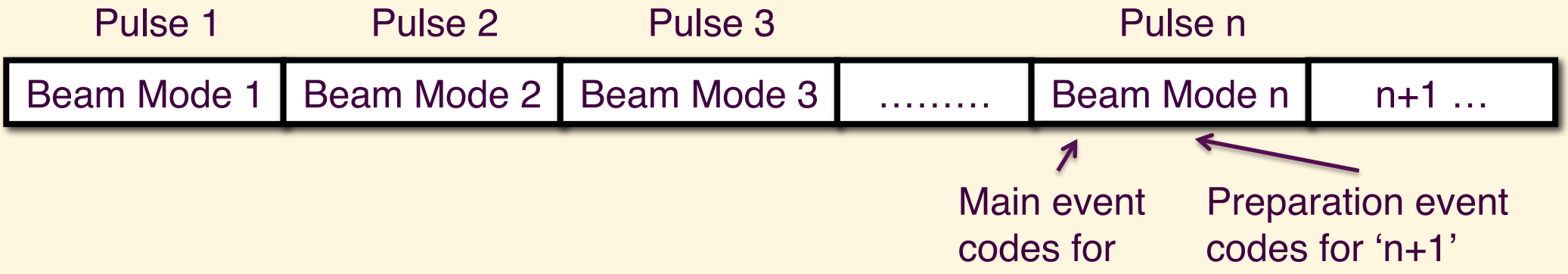
- **Synchronization Req.**
  - **KEKB : < 30ps**
  - **PF : < 300~700ps**
- **Linac rf is Synchronized to KEKB rf**
- **Event Clock is 114.24MHz**
- **We have to manage**
  - **Circumference compensation**
  - **Bucket selection**
  - **Injection phase controls**

EPICS

Beam bucket selection at KEKB

- Beam pattern restrictions for beam intervals
- Select bucket where the stored current is low, partially independent on the fast timing
  - KEKB has 5120 buckets at 509MHz
  - Common frequency between Linac – Ring, 10.38MHz corresponds to 49 buckets (96ns)
  - We can select any buckets if we wait maximum of 5120 x 96ns = ~500μs

Beam Mode Pattern Generation



- Every pulse (every 20ms) corresponds to a beam mode
- 10 different beam modes are defined (for KEKB e+, etc)
- One beam pulse may contain several event codes
  - At least one main code and a preparation code for the next pulse
- About 50 event codes are defined
  - Some events correspond to many functions, and others to specific devices
- Beam pattern buffer length (n) can be 2 to 500 (20ms x 500 = 10 seconds)
- A new pattern can be loaded at the end of the previous pattern
  - Otherwise, the pattern repeats forever.
- Main events and preparation events in sequence
  - Main events trigger timing signals
  - Preparation events trigger software to exchange analog and delay parameters

Event Manipulation

Human Operator

Injection Programs

Arbitrate and Generate Beam Mode Pattern (in PythonTk)
- considering priorities of the rings
- equalizing pulsed power supply interval
- in 4 arrays (waveforms) of length 2 (40ms) to 500 (10s)
- each element corresponds to a 20-ms time slot and a beam mode

Generate Events for the Next 20-ms Time Slot (in Event Generator)
- reading two consecutive elements from the beam mode pattern
- generate several events for the next pulse
- generate preparation events for the next after next

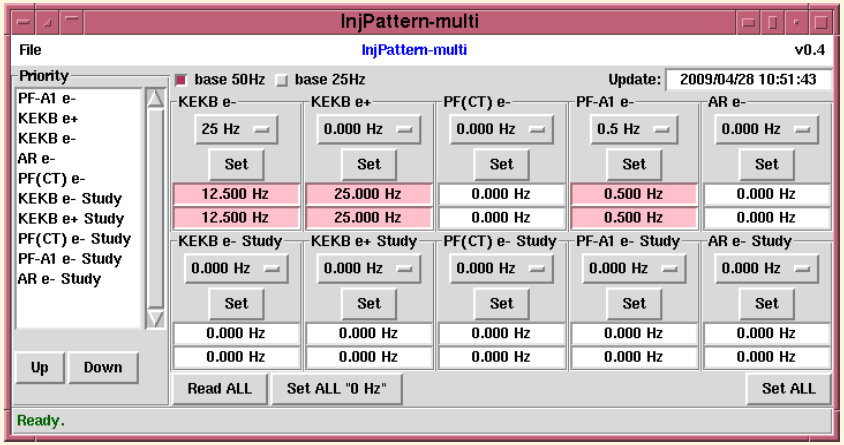
Generate Signals based on Received Events (in Event Receiver)
- generate pulsed signals as prepared in the previous time slot
- program the signals (enable/disable, delays, etc) for the next
- start to generate analog signals for the next

EPICS

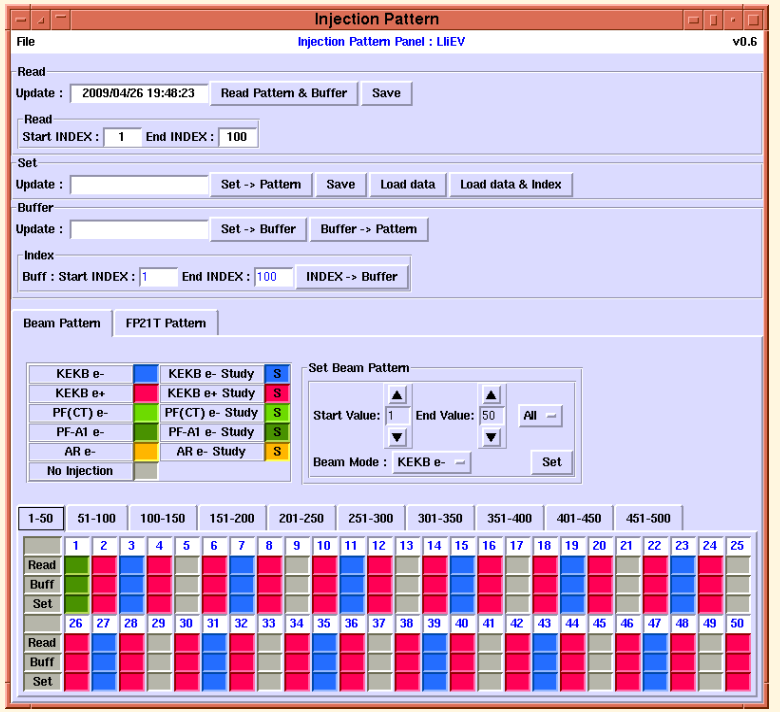
Beam Mode Pattern Generators

- **Pattern panel arbitrates requests**
  - From downstream rings with priorities, or human operators
  - There are several pattern rules due to pulse device features and limitations
  - Pattern arbitrator software was written in scripting languages to meet daily changes during the commissioning stage

Remote controlled automatic pattern arbitrator



Manual pattern generator



- Typical operation in 2009.
  - ~25Hz for KEKB LER
  - ~12.5Hz for KEKB HER
  - ~0.5Hz for PF

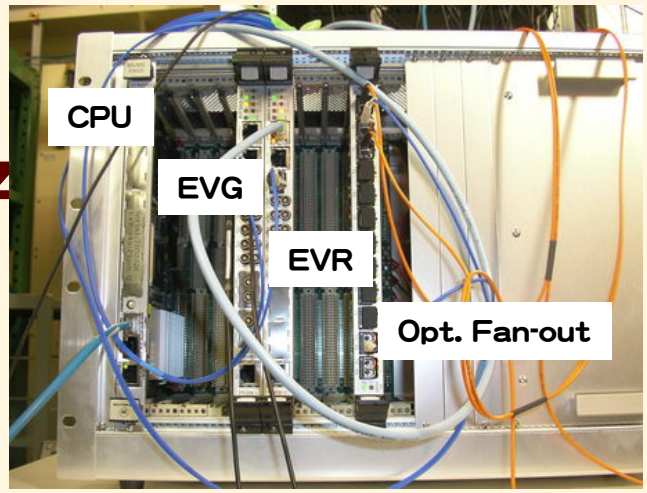
EPICS

Parameters

- Parameters switching via Event system
  - LLRF phase/timing : 14x4
  - HP RF timing : ~60
  - Gun voltages, picosecond delay : 4
  - Pulsed magnets/solenoid : 14
  - Injection phase : 2
  - Bucket selection : 2
  - BPM : ~100x3
- Basically sufficient for fast beam mode switching
- More parameters coming
- Integrity monitors
- Improved slow beam feedback, fast feedback, etc.

Linac Event System

- **Satisfies the requirements**
  - Event rate : 114.24MHz (bit rate : ~2.3GHz)
  - Fiducial rate : 50Hz
  - Timing jitter (Short term) : ~8ps
  - No. of defined events : ~50
  - No. of receiver stations : 17
  - No. of Fast parameters : ~130



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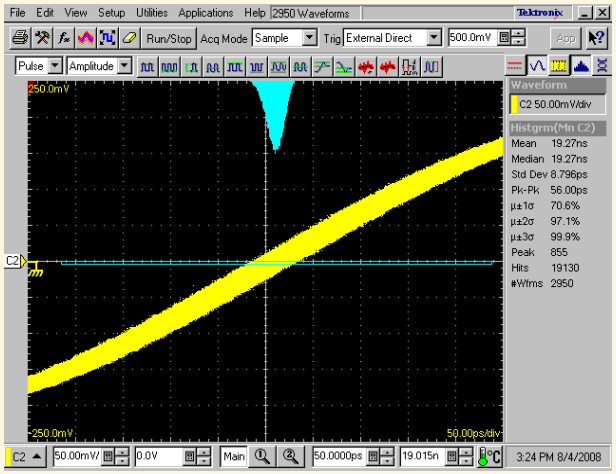
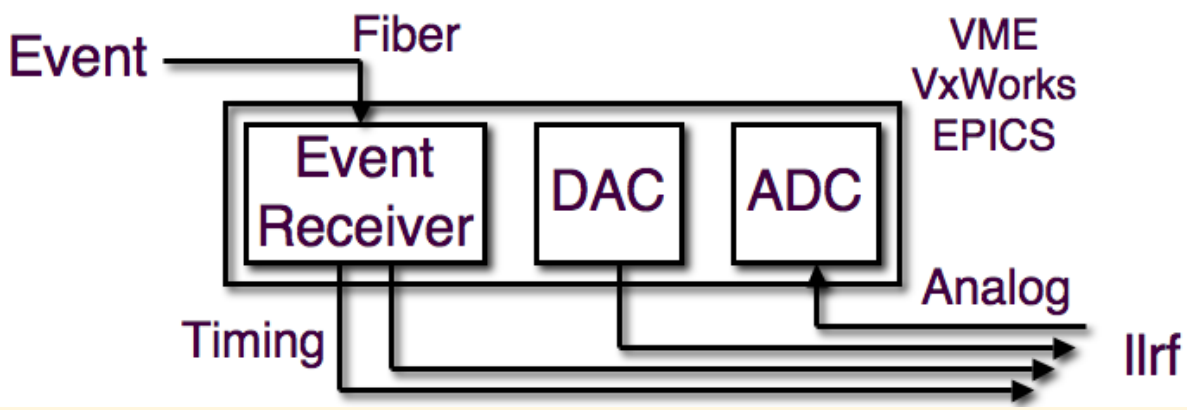
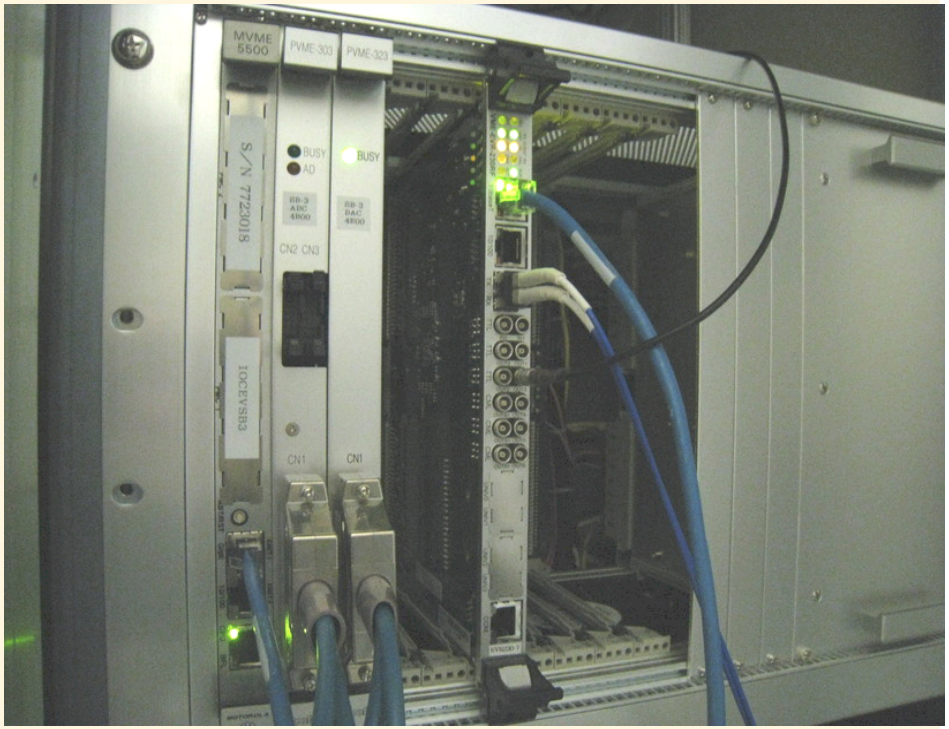


EPICS

LLRF

- LLRF Timing/analog signals are essential for absolute energy, energy spread, and dual-bunch energy equalization
- Signals are switched pulse-by-pulse
- Value changes are triggered by a preparation event
- Driver klystrons (SB), energy tuner klystron (KL), and sub-harmonic bunchers (SH) are managed by the event system



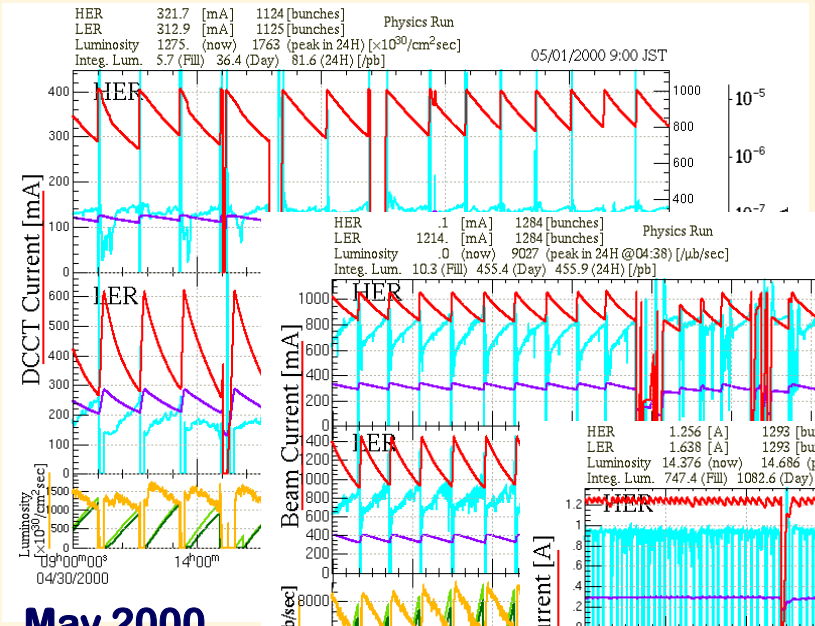


EPICS

More Measurement Technique

- **Switching between Four Rings**
  - Challenging to improve beams during operation
- **Event-based Controls may Help More**
  - No-destructive measurements with four beams
  - Stealth (used beam-pulse) measurements
    - With beam deflector
  - Dithering pulse-by-pulse
    - If very good resolution was achieved

KEKB Operation Improvement (base of SuperKEKB)



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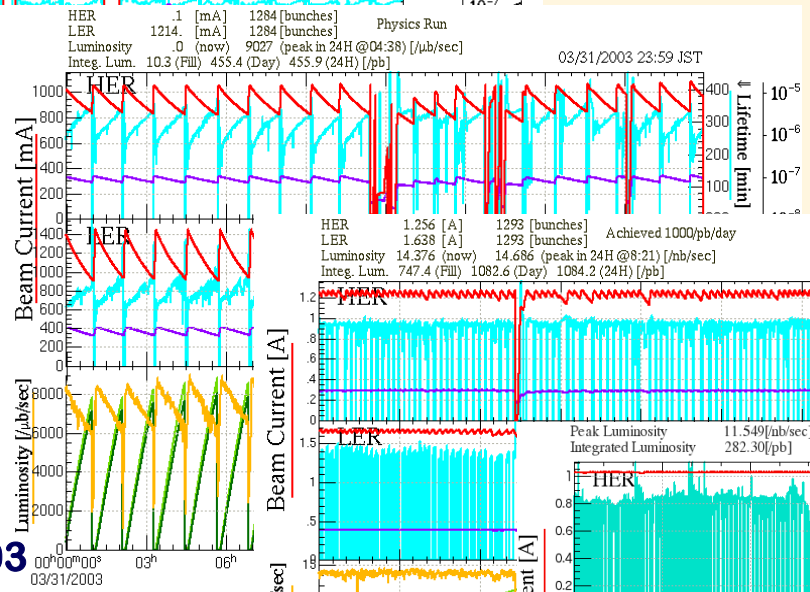
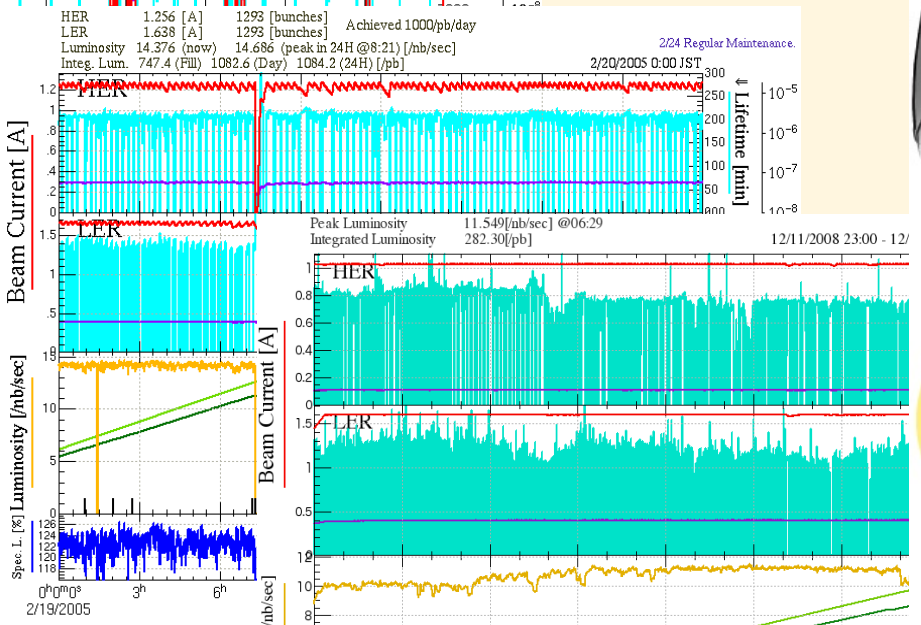


Apr.2003

Dual Bunch e+



Feb.2005

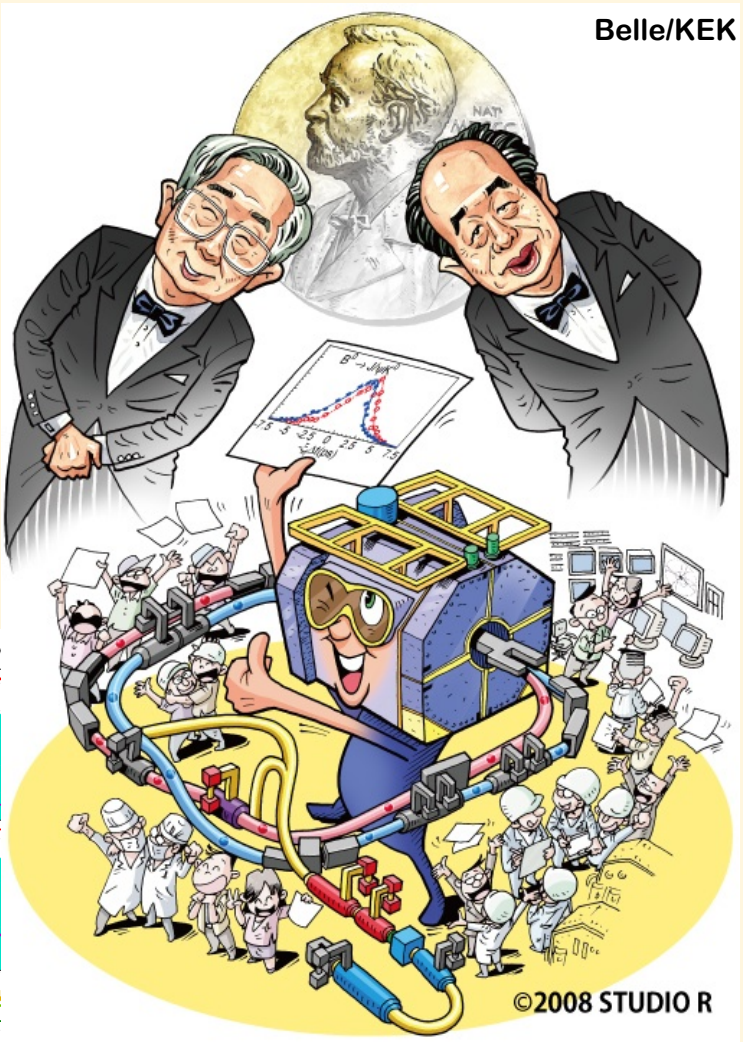
Continuous

Injections

Dec.2008

Crab Cavities and

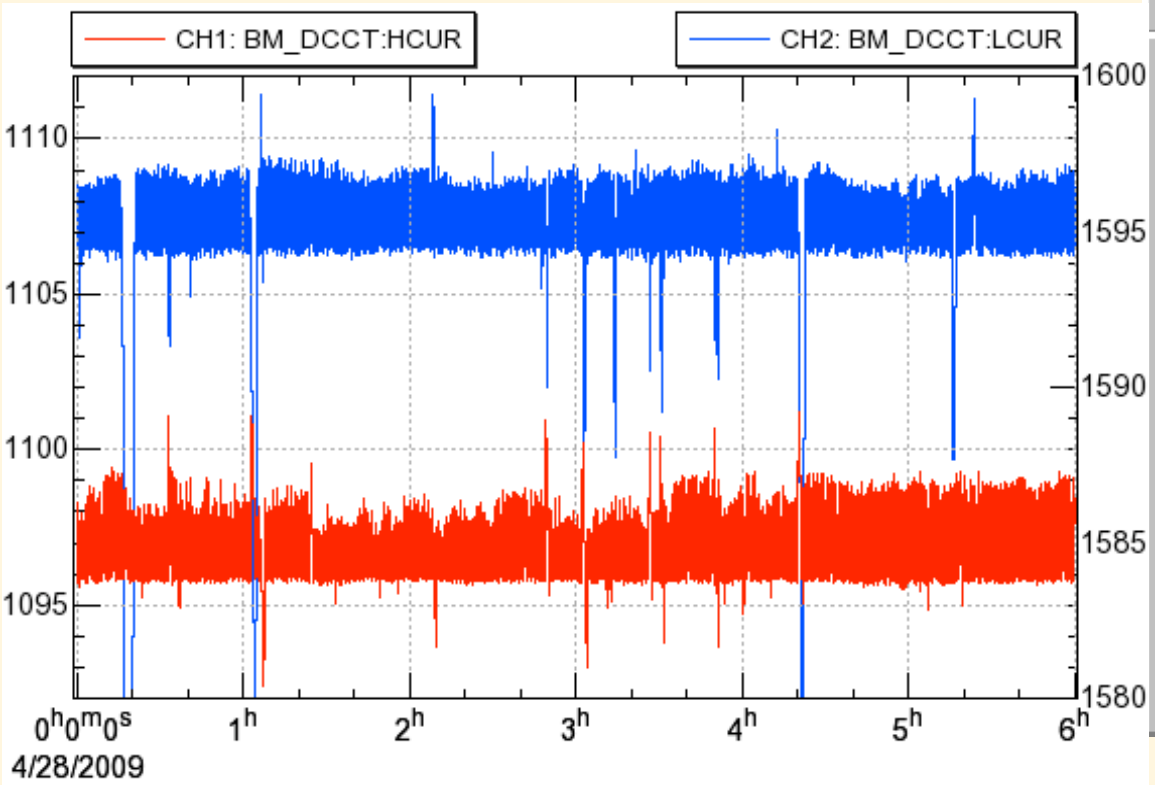
Simultaneous Injection

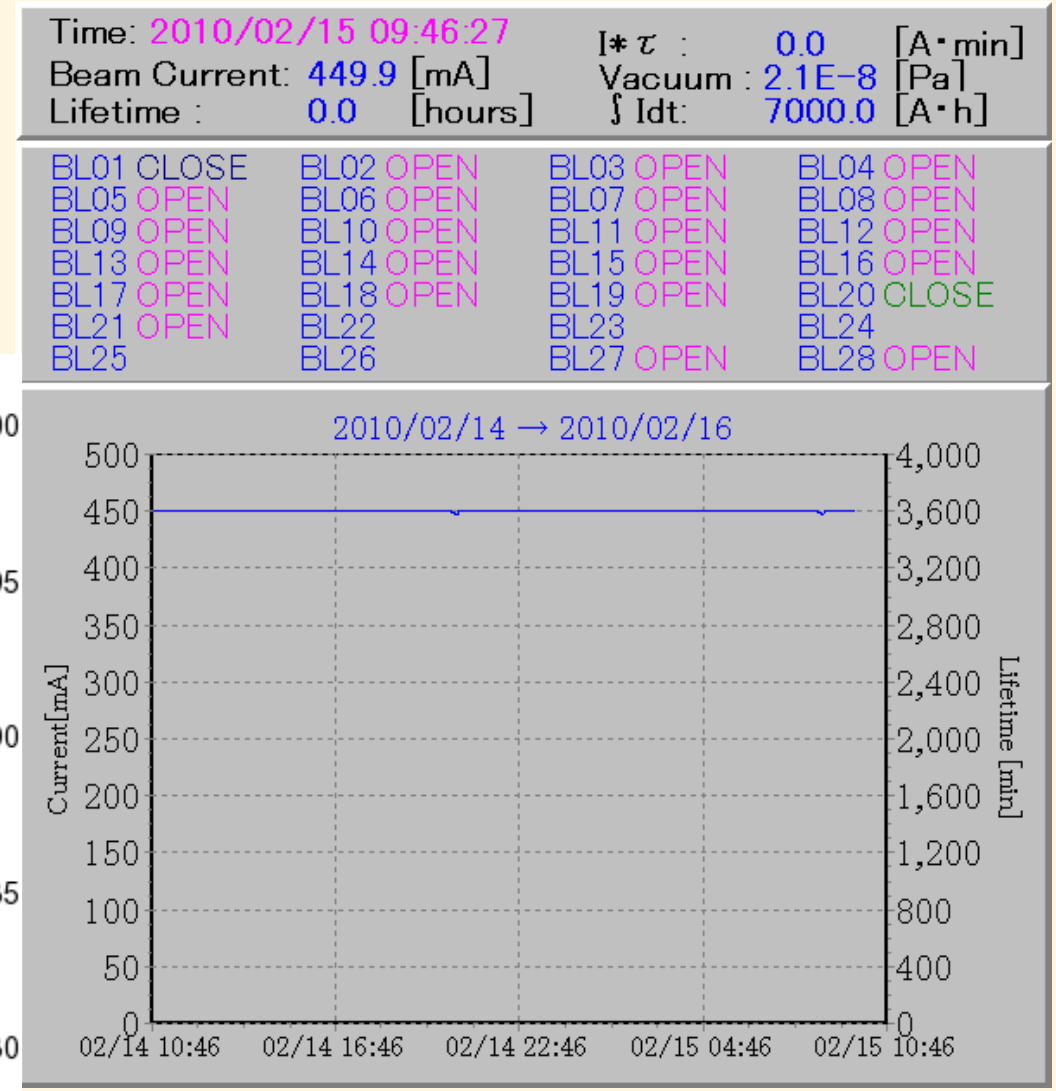


EPICS

Top-up Beam Currents at Storage Rings

- **Beam currents were kept**
  - **KEKB 1mA (~0.05%)**
  - **PF 0.05mA (~0.01%)**





Towards SuperKEKB

Nano-beam scheme at SuperKEKB

- Requires low-emittance large current beams
  - Photo cathode RF gun for e- 7GeV, 5nC
  - New capture section and new damping ring for e+ 4GeV, 4nC
  - 40 times more luminosity
- Design of damping ring
  - Selection of RF
  - Selection of harmonic number
- Injection to PF-AR
  - Common BT to KEKB
    - PF-AR Injection needs 5-10 minutes
    - Shorter life time of 10min at SuperKEKB

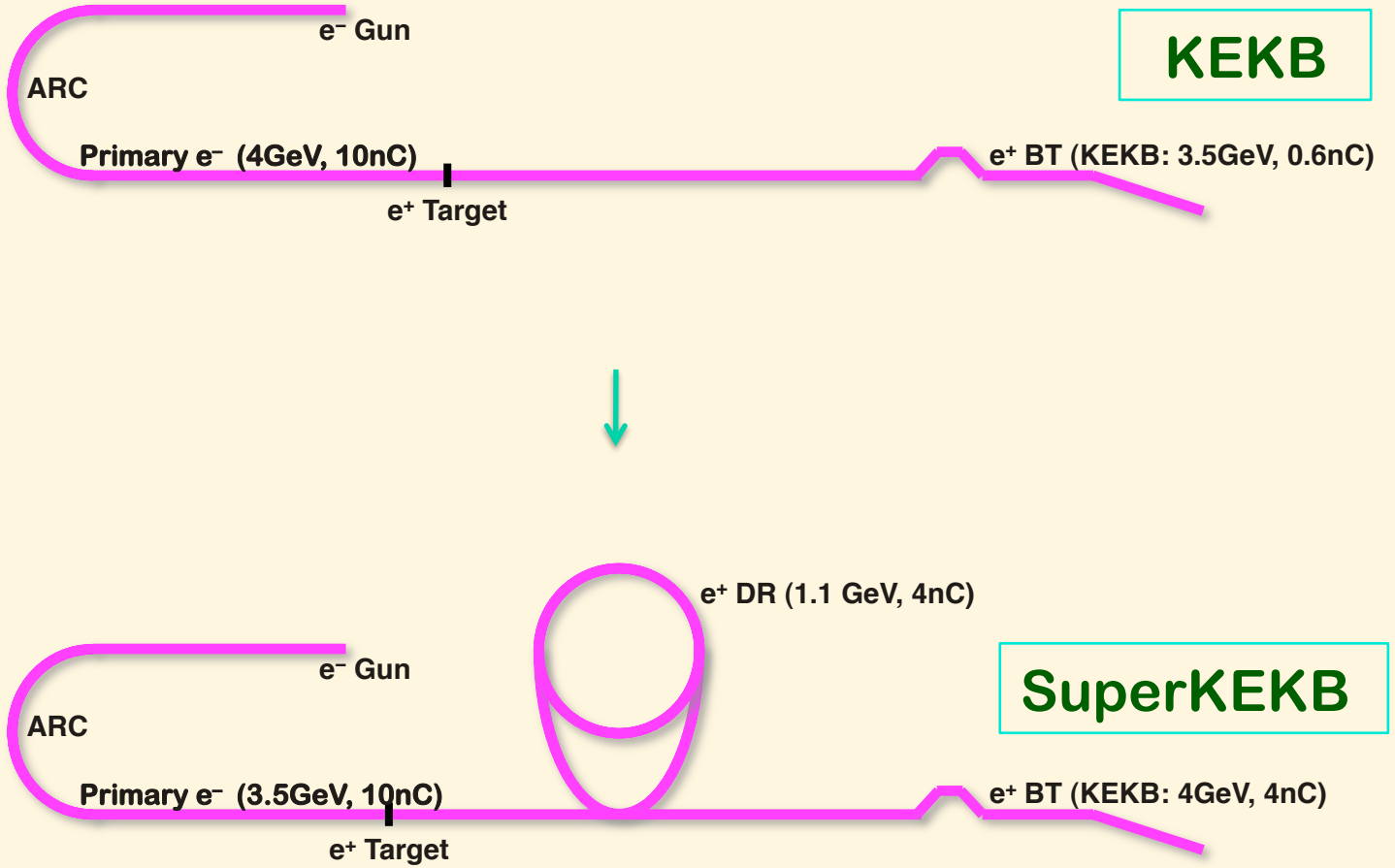
KEKB		SuperKEKB	
e–	e+	e–	e+
8GeV	3.5GeV	7GeV	4GeV
1nC	1nC	5nC	4nC
100μm	2000μm	20μm	10μm
2bunch	2bunch	2bunch	2bunch

Damping ring injection for SuperKEKB

- **Accommodate 2 bunches 2 pulses**

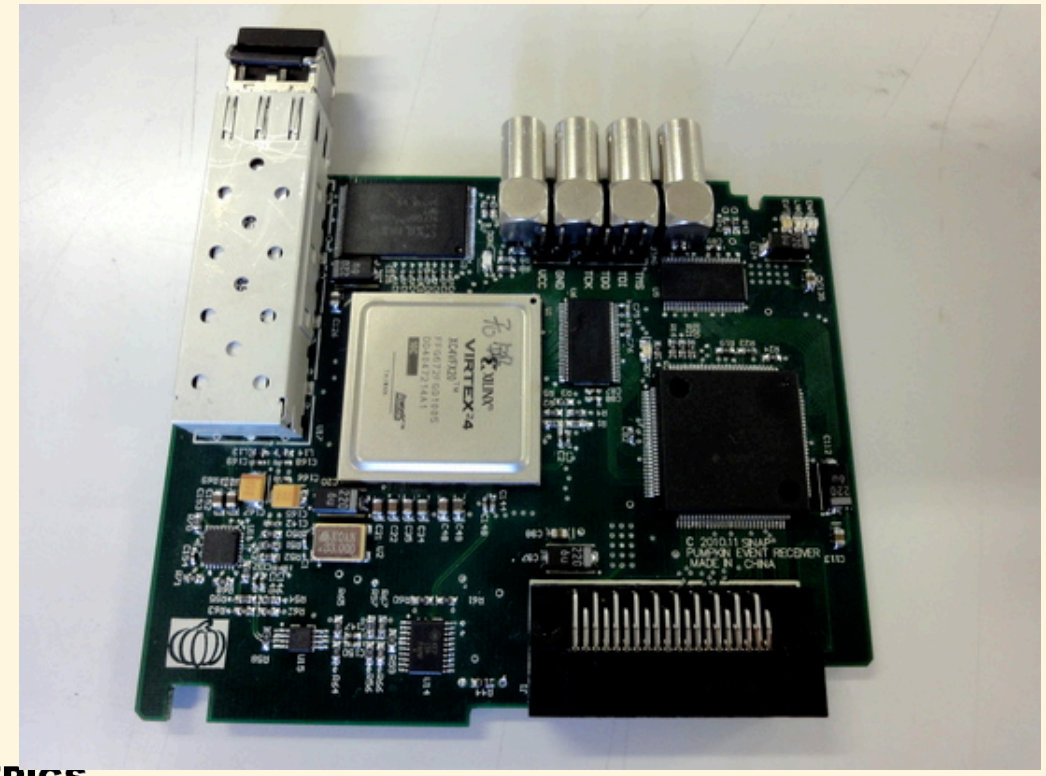
For e+ 25Hz e– 25Hz

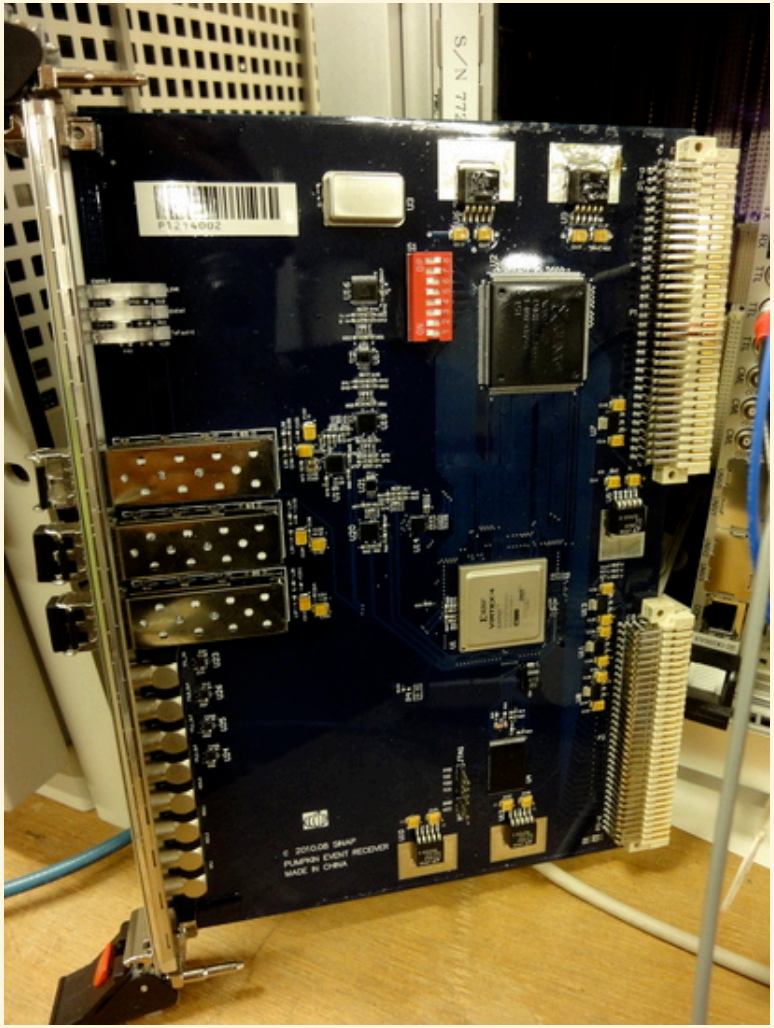
Inj.	D.R.	Ext.
e+ 1	e+ 1	
e– 2	e+ 1	e– 2
e+ 3	e+ 3,1	e+ 1
e– 4	e+ 3	e– 4
e+ 5	e+ 5,3	e+ 3
e– 6	e+ 5	e– 6



Development of EVR/PLC at SSRF

- For Yokogawa FAM3 PLC with F3RP61 linux CPU
- Prototype in 2010
- Production version at Oct.2011
- Will simplify the additional stations





SuperKEKB timing software upgrade

- Basically the same configuration as KEKB
  - Intelligent panels – pulse-by-pulse EVG Sequences – EVR PV databases
- Need to upgrade to newer device driver/support with new register mapping
  - Under evaluation with newer firmware/EPICS support
- Need more coordinated beam pattern generation
  - Need dependencies between pulses
  - Need to decide whether to change phases at DR
- Need synchronization to laser rf gun
  - Laser based on local oscillator, need PLL and stabilization strategy
- Possible more addition of event receivers to BT and Rings
- Possible upward links for bucket selection data (SSRF or MRF)
- Linux-based device support for EVR/PLC from SSRF on F3RP61
  - Should be simple (?) based on standard FAM3 bus access

Summary

- Simultaneous injections to three rings (KEKB HER/LER and PF) achieved
- Challenging for four rings (incl. PF-AR) with a damping ring
- Event-based controls : another layer of controls bellow EPICS slow controls
- <http://www-linac.kek.jp/cont/epics/event/>
- There should be much room to establish further controls utilizing beam monitors, rf monitors, and more
  - With Phronesis (Ability to understand the universal truth, Greek word) we can enjoy our accelerator more

Thank You

谢谢您

Thank you

Backup

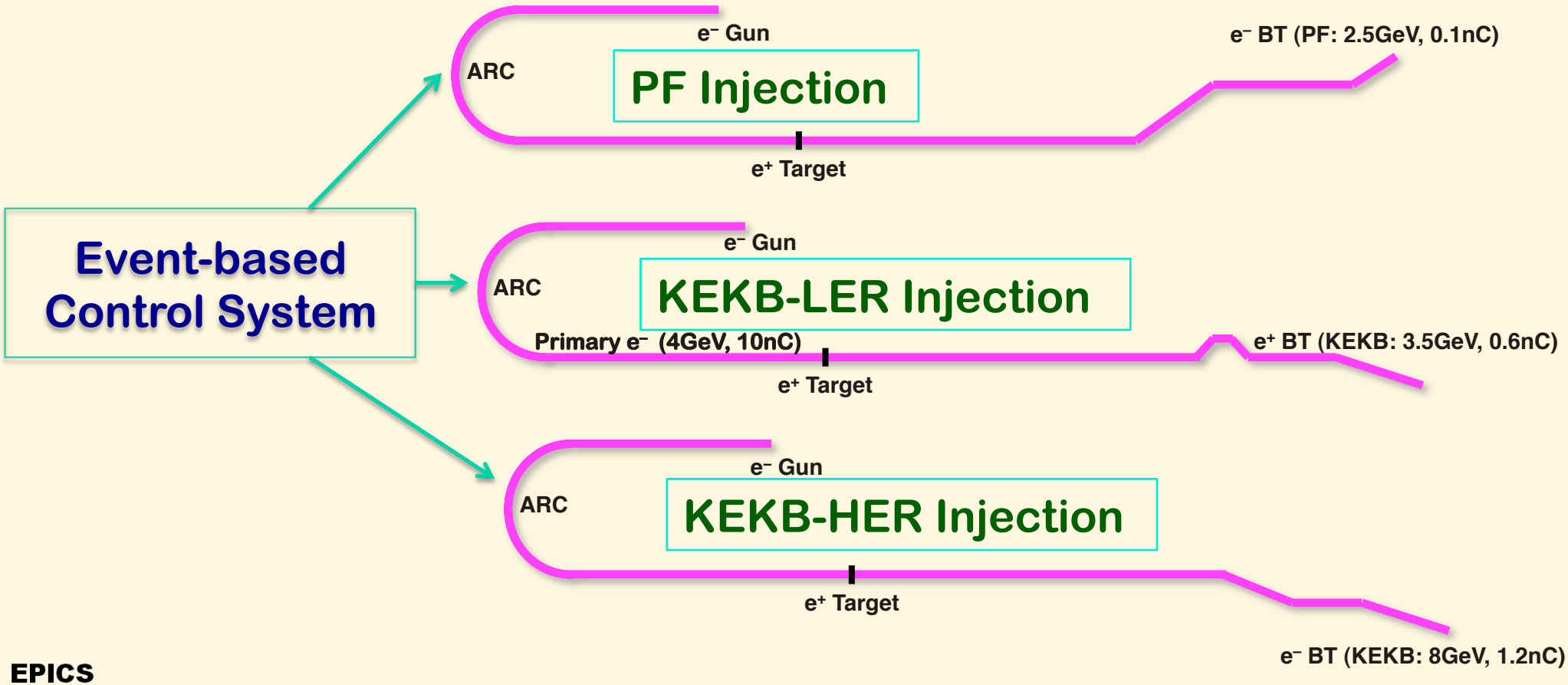
Parameters

- **Parameters switched via event system**
  - LLRF phase/timing : 14x4
    - Overall energy profile, dual-bunch energy equalization, final energy adjustment
  - HP RF timing : ~60
    - Energy profile and backup management
  - Gun voltages, picosecond delay : 4
    - Beam charge selection, dual bunch selection, bunching
  - Pulsed magnets/solenoid : 14
    - Beam transport selection, orbit controls, positron focusing
  - Injection phase interface : 2
  - Bucket selection interface : 2
  - BPM : ~100x3
- **Sufficient for fast beam mode switching**
- **Integrity monitors soon**

EPICS

Three Virtual Accelerators

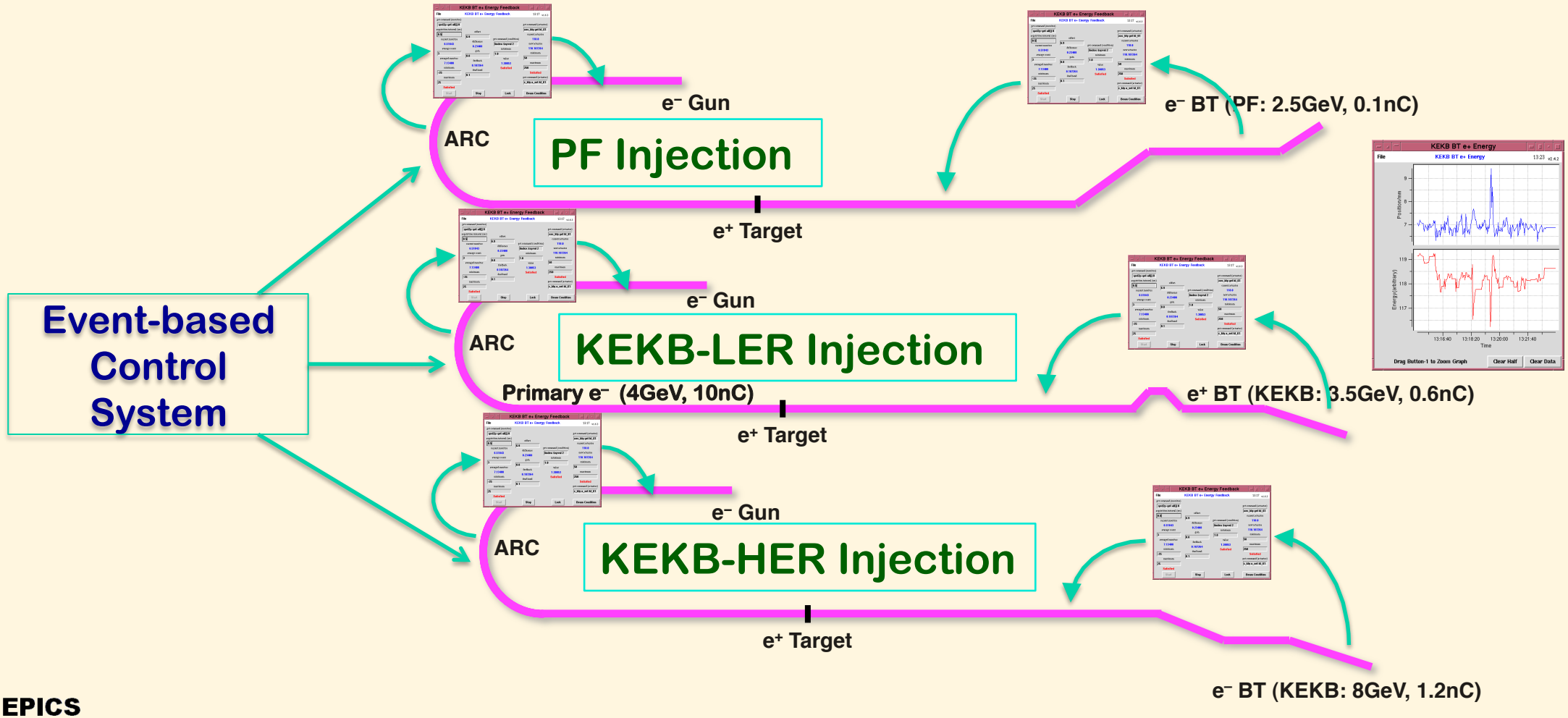
- Controls and instrumentations are essentially mode-dependent, and mutually independent
- Selecting a real machine out of three virtual machines
  - Managing three parameter sets (four under SuperKEKB environment)



EPICS

Three-fold Independent Closed Loops

- **Feedback loop software act on one of three virtual machines**
  - **Managing independent parameter sets**



For SuperKEKB Complex

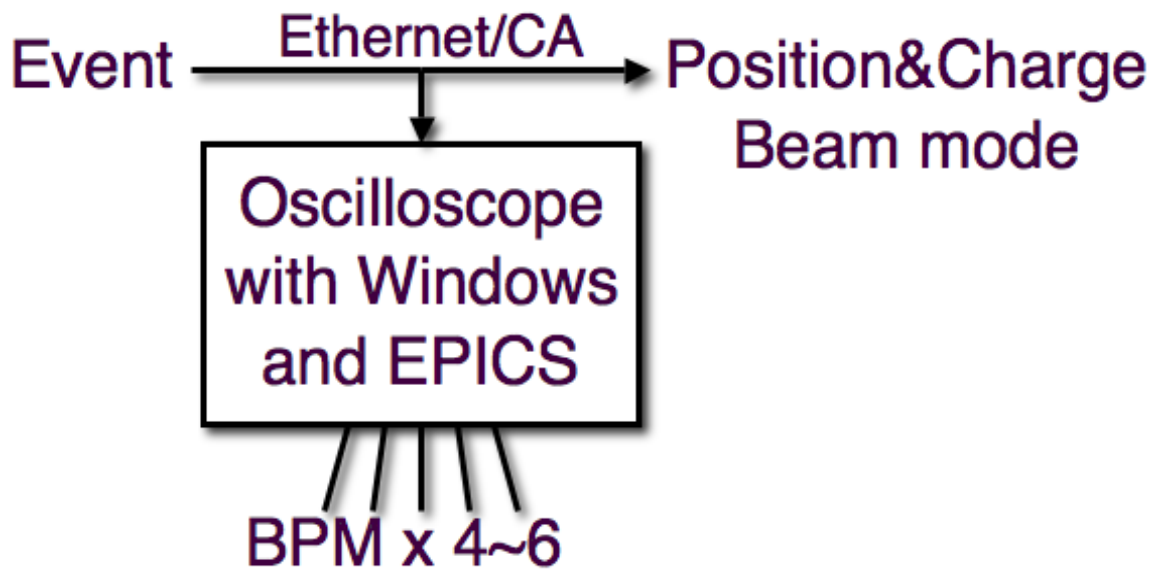
- **Slightly More Complicated Conditions with DR**
  - Harmonic number of SuperKEKB-MR (509MHz) is 5120
  - Common frequency between Linac-MR is 10.38MHz (49 buckets, 96ns)
  - DR should have common frequency, RF chosen to be 509MHz
  - 2x2 bunches, bunch separation of 49-bucket , kicker rise/fall time of 100ns
  - Jitter (wait-time) of HP modulator (50Hz) must be <~2ms
  - Harmonic number of DR was chosen to be 230
- **In order to Select All the Buckets in SuperKEKB MR**
  - Active (Pulse-to-pulse) LLRF controls necessary at linac
    - Better LLRF monitor is required
  - Dependency between pulses increases
- **For PFAR Injection**
  - Positron have to be used to share the beam-transport
  - Independent circumference controls will interfere
    - PF can use 2.5GeV electron with accidental synchronization (<~300ps)
    - More investigation underway

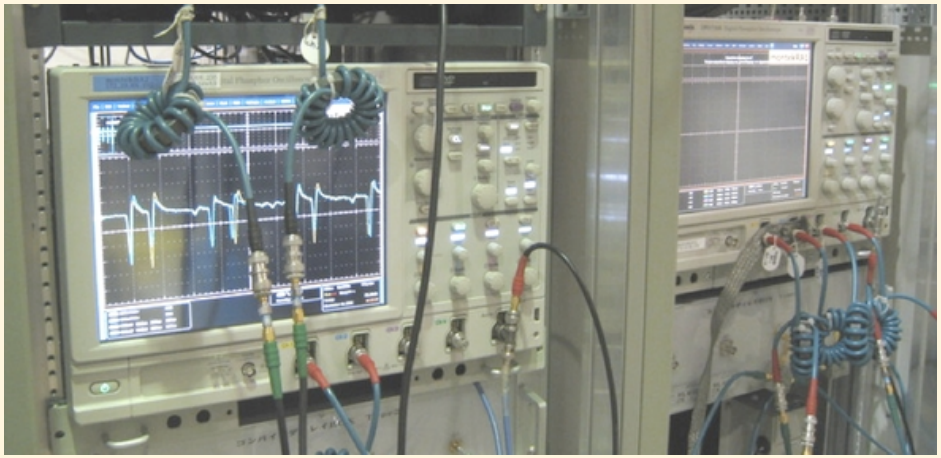
Event System Consideration for SuperKEKB

- **Possibly Cascaded Event Systems**
  - For damping ring, main ring and other sub-systems
- **New firmware with new register map**
  - For newer device support software in EPICS community
    - Several local modification already, want to synchronize with other institutes
  - Several institutes in Asia may use CompactPCI as well
    - Whether PLC version can use the same environment??
- **Several fast control projects for SuperKEKB**
  - Several embedded systems with PLC EVRs for RF stations
  - Bucket selection to cover both damping and main rings
    - In KEKB, separate system was used and selection signal was used as AC to EVG
  - Fast feedbacks in Linac and in main ring
- **Several others**

BPM

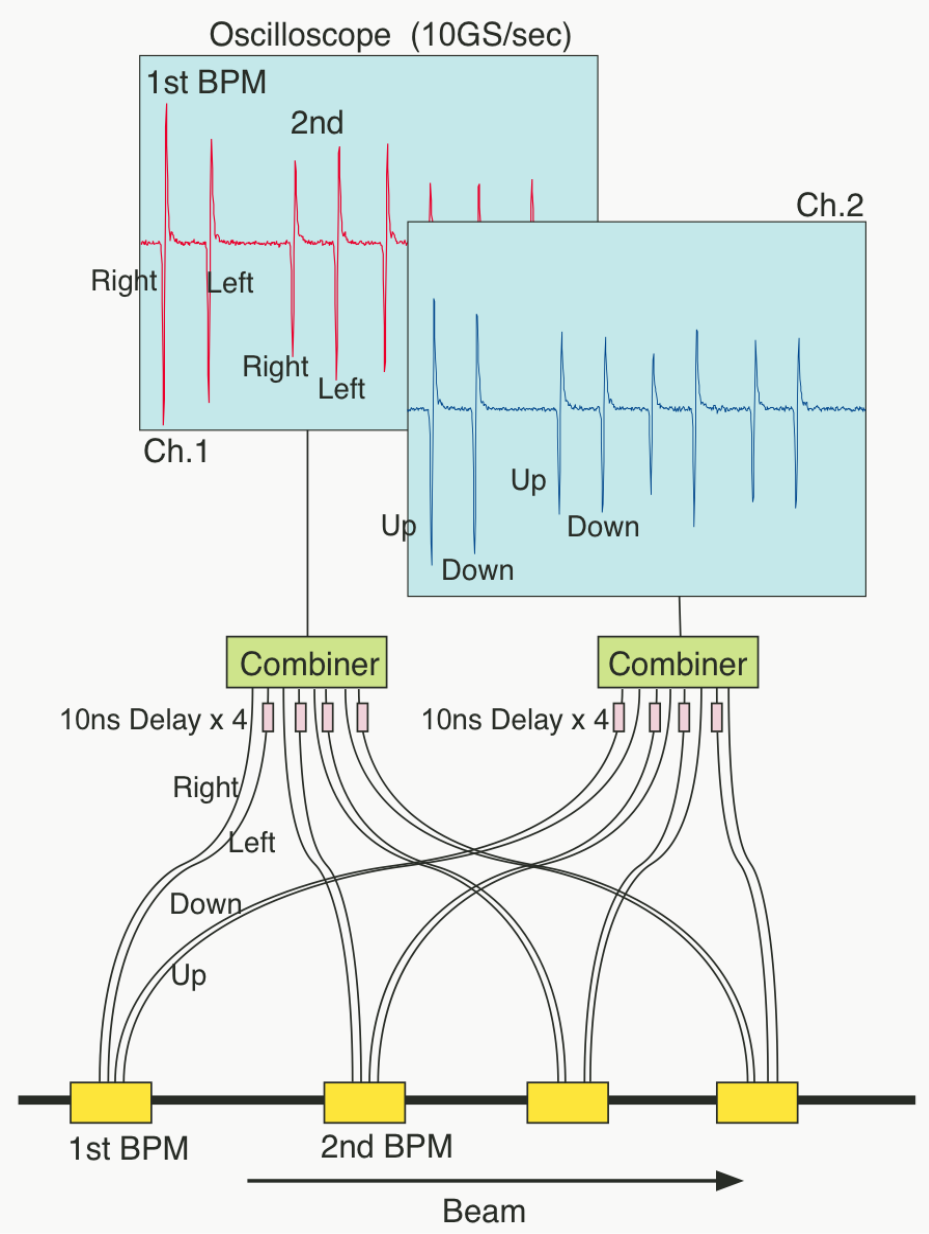
- Tektronix DPO7104 can acquire data at >50Hz.
  - With embedded EPICS
- Beam modes are recognized by events through CA network.
- Clients can monitor data of an interested beam mode.
- 26 oscilloscopes are installed.
- 100 BPMs are synchronized. (100 BPMs at BT as well soon)





Measurement and Data Acquisition

- **Originally much efforts to develop detectors, shaping amplifiers**
  - No budget for all BPMs
- **Switched to direct waveform acquisition**
  - Minimized active components, then minimized calibration tasks, maintenance
  - Equal-length cables
  - One oscilloscope covers about 5 BPMs, or combined 20 (or 40) waveforms
  - 5 - 10Gs/s (with additional interpolation)
  - Possible to measure dual bunches
  - Solved many issues at once!
  - Extract each signal, apply calibration factors, send to upper layer at 50Hz



EPICS

Embedded IOC on Oscilloscope

- DPO7104, 10Gs/s, 4ch, 8bit
  - Windows-XP
  - Cygwin software development environment
  - Microsoft Visual C++ 2008
    - http://www-linac.kek.jp/cont/epics/win32/
  - EPICS 3.14.8.2
  - Fast data-acquisition at ~150Hz was tricky, but was possible
  - Event triggers the data acquisition
  - Beam positions and charges are calculated based on ~30 coefficients, and tagged with beam modes
  - 50Hz processing is stable at Linac
  - Very efficient for us

EPICS