Pulse-to-pulse Beam Modulation for KEKB and PF Injections and Energy Management at KEK 8GeV Linac

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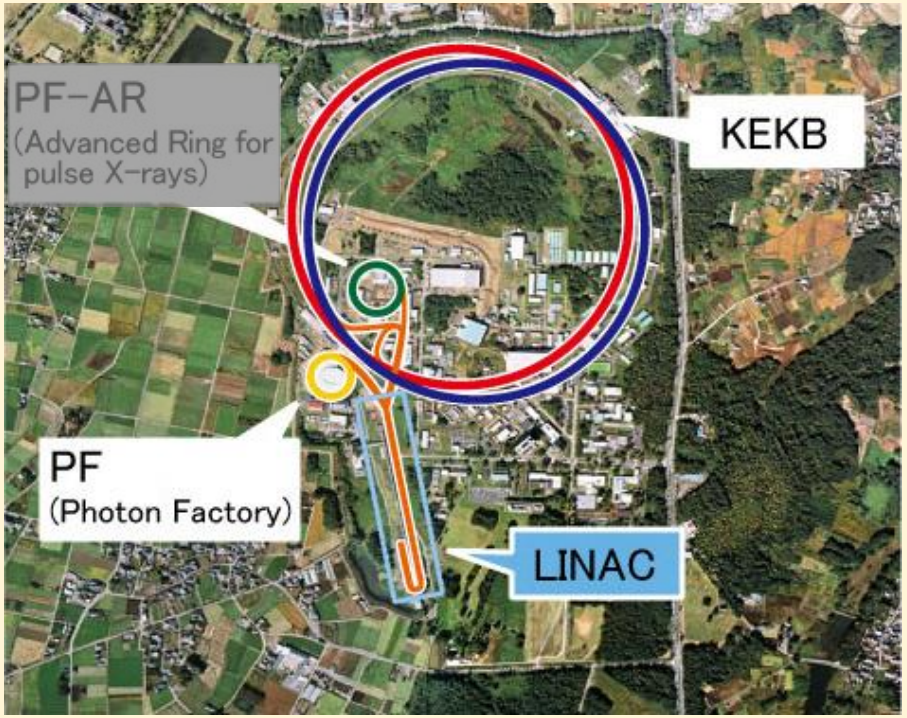
Electron Accelerator Complex

- **Linac clients**
  - **KEKB**
    - **8-GeV e– 1nC x2**
    - **3.5-GeV e+ 1nC x2**
    - **(with 10nC primary e–)**
  - **PF 2.5-GeV e– 0.1nC**
  - **PF-AR 3-GeV e– 0.2nC**

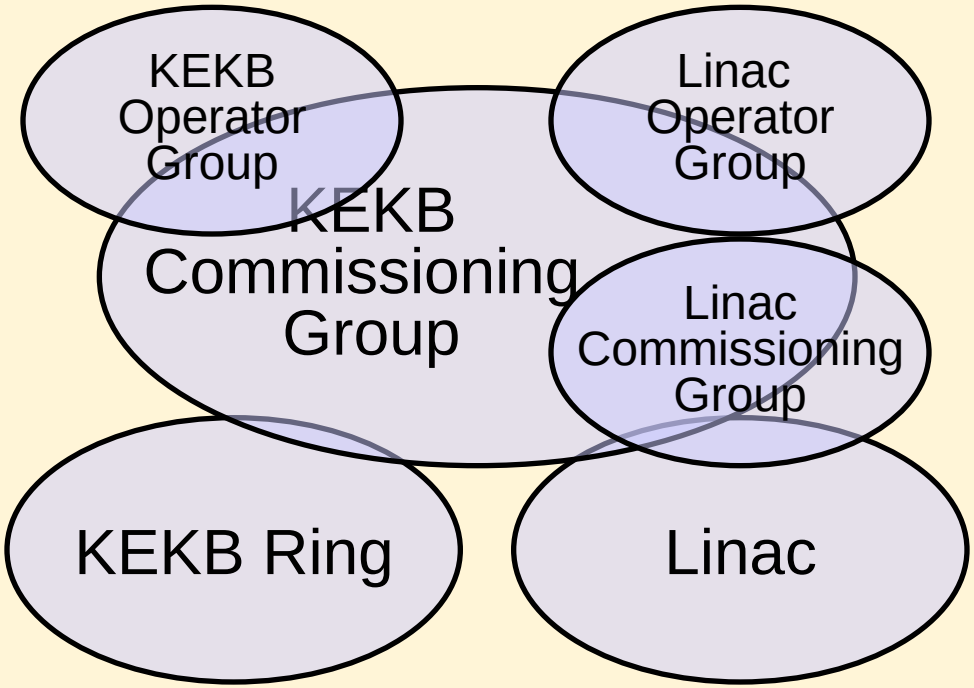


- **At first simultaneous top-up injections to three rings at KEKB and PF**
  - **Switching beams at 50Hz**
  - **For stable operation and higher quality exp. results**

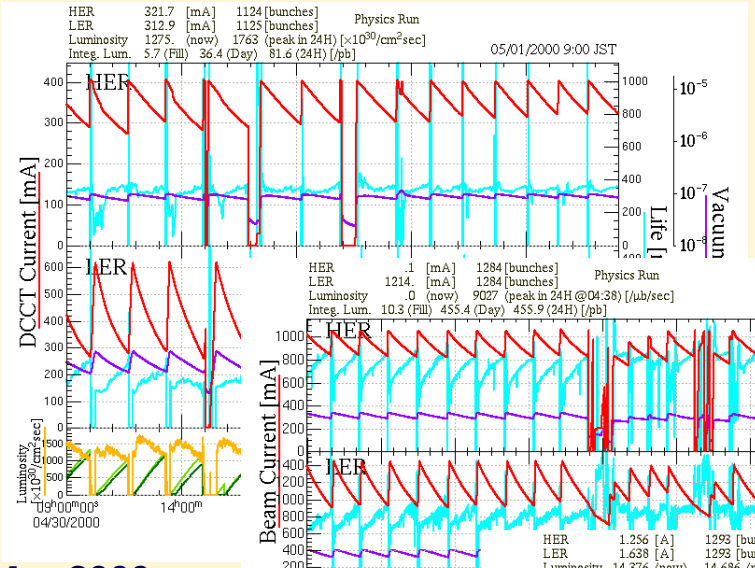
Operation

Operation groups at KEKB and linac

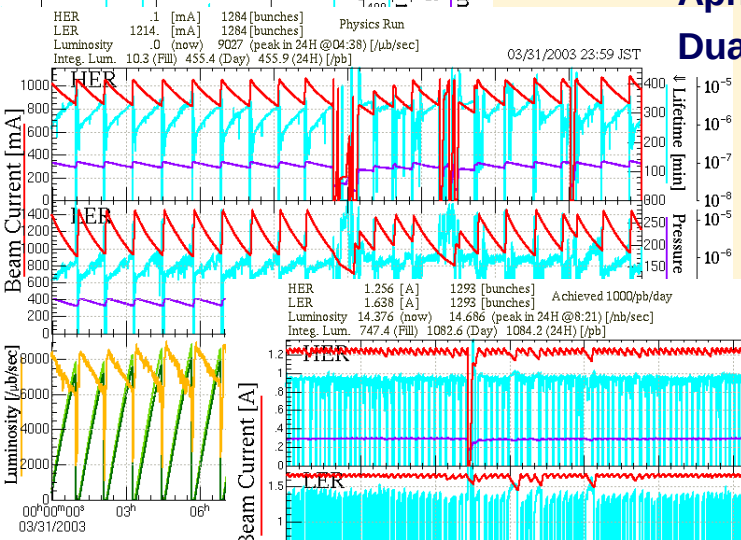
- Overlapped groups
- Many attend commissioning group from eq. groups
- Daily KCG meeting
- Weekly LCG meeting



KEKB Operation Improvement

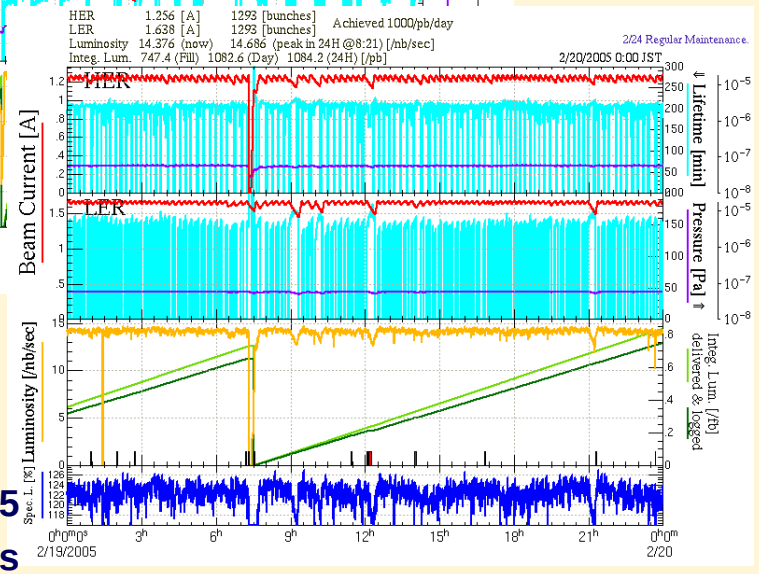


May.2000



Apr.2003

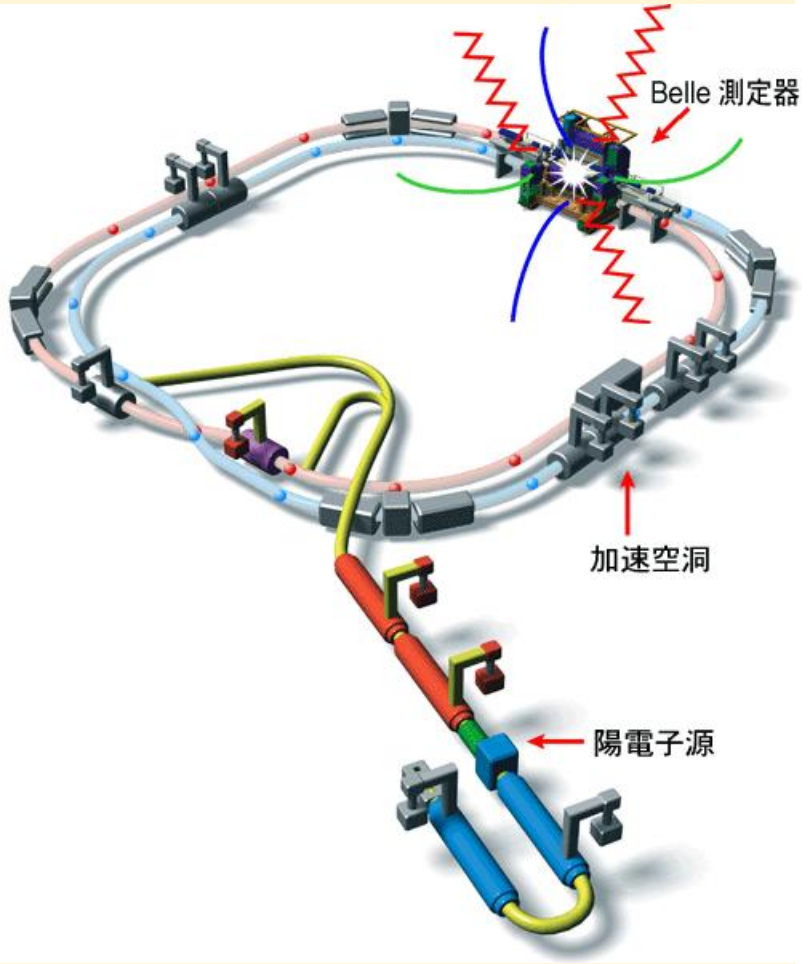
Dual Bunch e+



Feb.2005

Continuous

Injections



Fast beam switching or Simultaneous Injection

- **Luminosity degradation on beam studies at PF and PF/AR**
- **Future SuperKEKB injections with shorter lifetime**
- **Sensitive luminosity tuning with Crab cavities**
- **PF top-up injection 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**

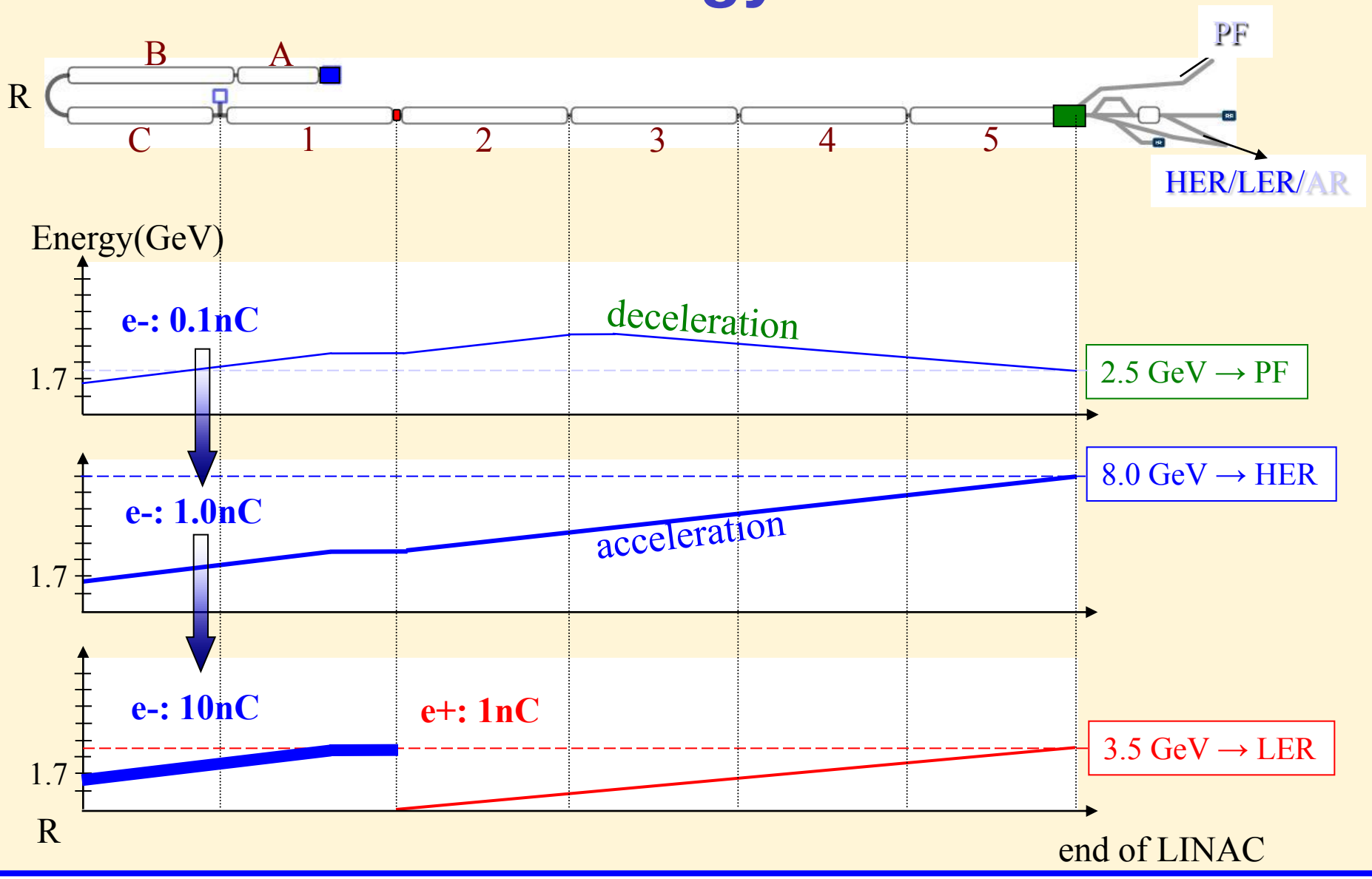
Requirements

- Maximum beam rate of 50Hz x 2bunches should be kept
- Most pulsed power supplies were designed to operate at constant rate (a restriction)
- 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

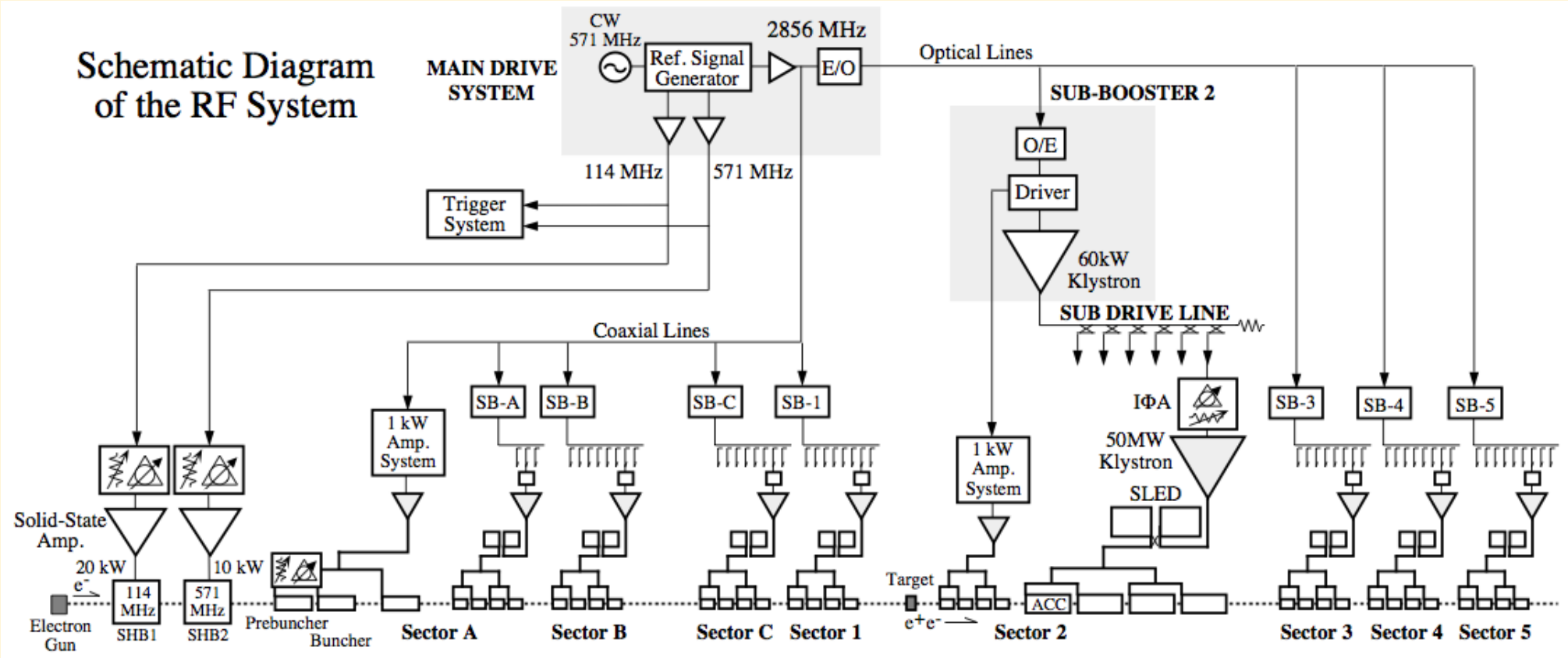
Hardware and Operation Improvements

- 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



Linac Energy Management



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)

Cavity and Klystron Database

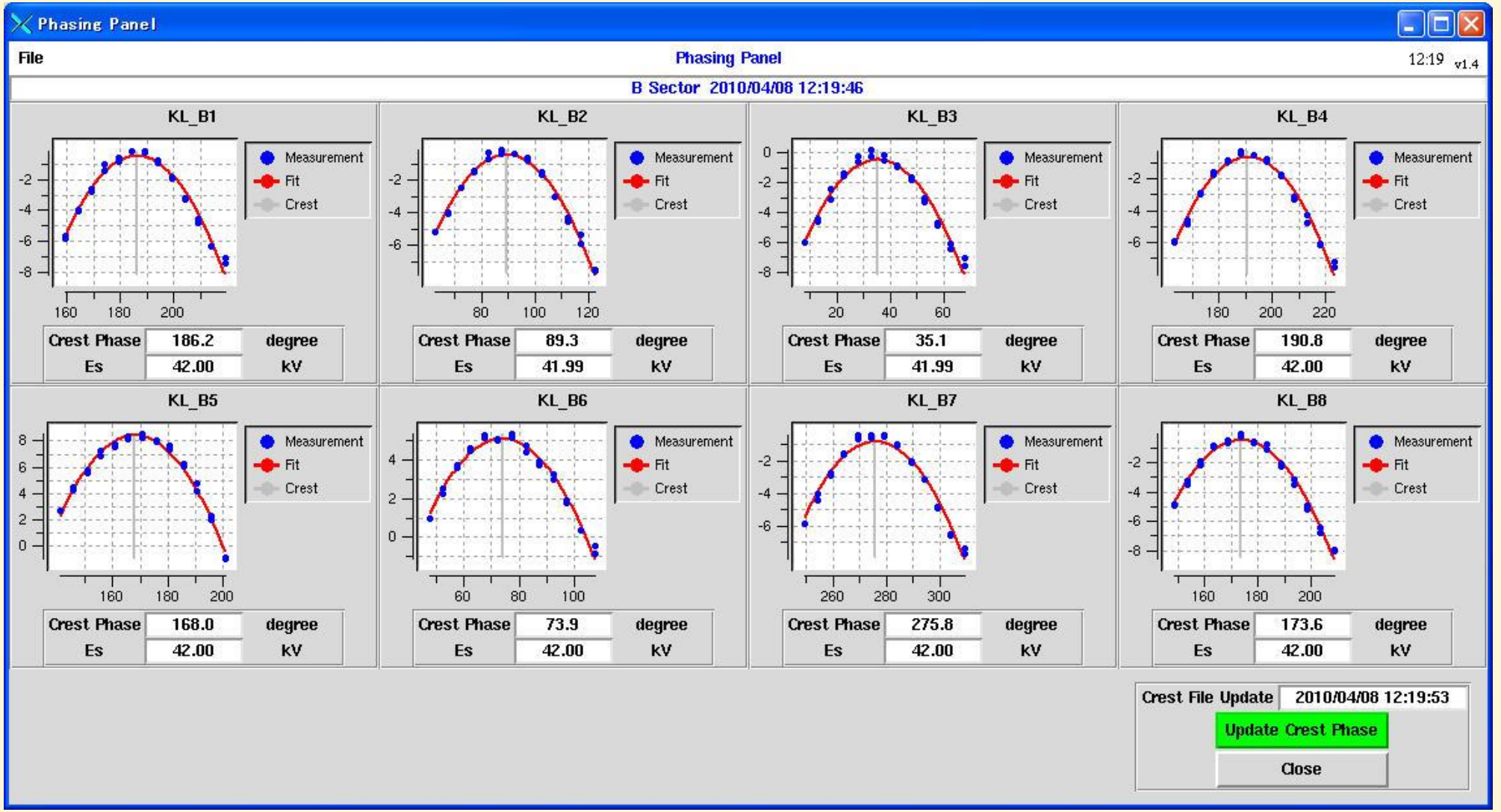
- **Updated on replacements of klystrons and cavities**
  - **Converted into control database**

sector	unit	No	新/旧	typ	d(WG) m	α	M	Es-Power データ更新	c2	c1	c0	Es kV	Power MW	Gain MeV	Gain MeV	Eave MV/m	stand by	Total MeV
A	1	0	旧	—	—	—	1.00	04.08.30	-0.04728	6.58617	-138.81662	40.0	49.0	19.0	19	—	1	19
		1	新	A	14.33	0.94400	1.00	04.08.30	-0.04728	6.58617	-138.81662	40.0	49.0	24.0	48	12.7	"	43
		2	新	A	14.33	0.94400	"	"	"	"	"	"	"	24.0	"	12.7	"	67
	8	1	旧	D	13.28	0.93868	1.85	98.10.01	0.00000	1.93650	-38.76900	41.5	41.6	43.5	171	23.0	1	3004
		2	旧	D	13.35	0.93834	"	"	0.00000	"	"	"	"	43.5	"	23.0	"	3047
		3	旧	D	13.28	0.93868	"	"	0.00000	"	"	"	"	43.5	"	23.0	"	3091
		4	旧	A	13.35	0.93834	"	"	0.00000	"	"	"	"	40.8	"	21.6	"	3131
1	1	1	旧	E	13.28	0.93868	1.85	—	0.00000	2.07020	-46.72400	43.0	42.3	44.8	179	23.7	1	3176
		2	旧	E	13.35	0.93834	"	"	0.00000	"	"	"	"	44.8	"	23.7	"	3221
		3	旧	E	13.28	0.93868	"	"	0.00000	"	"	"	"	44.8	"	23.7	"	3266
		4	旧	E	13.35	0.93834	"	"	0.00000	"	"	"	"	44.8	"	23.7	"	3310
	2	1	旧	C	13.28	0.93868	1.85	03.09.16	0	2.47830	-65.41700	41.5	37.4	40.4	162	21.4	1	3351
		2	旧	C	13.35	0.93834	"	"	0.00000	"	"	"	"	40.4	"	21.4	"	3391
		3	旧	C	13.28	0.93868	"	"	0.00000	"	"	"	"	40.4	"	21.4	"	3432
		4	旧	C	13.35	0.93834	"	"	0.00000	"	"	"	"	40.4	"	21.4	"	3472
	3	1	旧	D	13.28	0.93868	1.85	98.11.15	0.00000	2.32860	-55.54400	42.5	43.4	44.4	178	23.5	1	3516
		2	旧	D	13.35	0.93834	"	"	0.00000	"	"	"	"	44.4	"	23.5	"	3561
		3	旧	D	13.28	0.93868	"	"	0.00000	"	"	"	"	44.4	"	23.5	"	3605
		4	旧	D	13.35	0.93834	"	"	0.00000	"	"	"	"	44.4	"	23.5	"	3650
	4	1	旧	C	13.28	0.93868	1.85	06.08.30	-0.12241	12.00654	-248.55271	43.5	42.1	42.8	171	22.7	1	3693
		2	旧	C	13.35	0.93834	"	"	0.00000	"	"	"	"	42.8	"	22.7	"	3735
		3	旧	C	13.28	0.93868	"	"	0.00000	"	"	"	"	42.8	"	22.7	"	3778
		4	旧	C	13.35	0.93834	"	"	0.00000	"	"	"	"	42.8	"	22.7	"	3821
	5	1	旧	E	13.28	0.93868	1.85	01.04.22	0	2.33330	-53.62000	44.0	49.0	48.2	191	25.5	1	3869
		2	旧	E	13.35	0.93834	"	"	0.00000	"	"	"	"	48.2	"	25.5	"	3918

Crest Phase Calibration

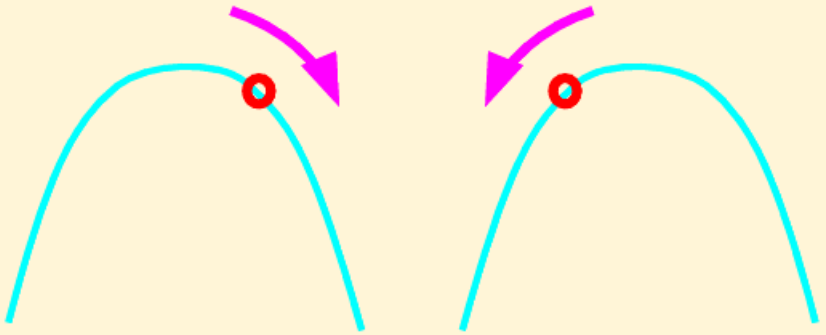
- **Each power source with slow phase shifter**
  - **Energy measurement scanning the phase shifter**
    - **Primitive but reliable, while there were several methods**
    - **Chicken and egg issue exists on bootstrap**
      - **If no beam at the end, no measurement possible**
  - **Every several month 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



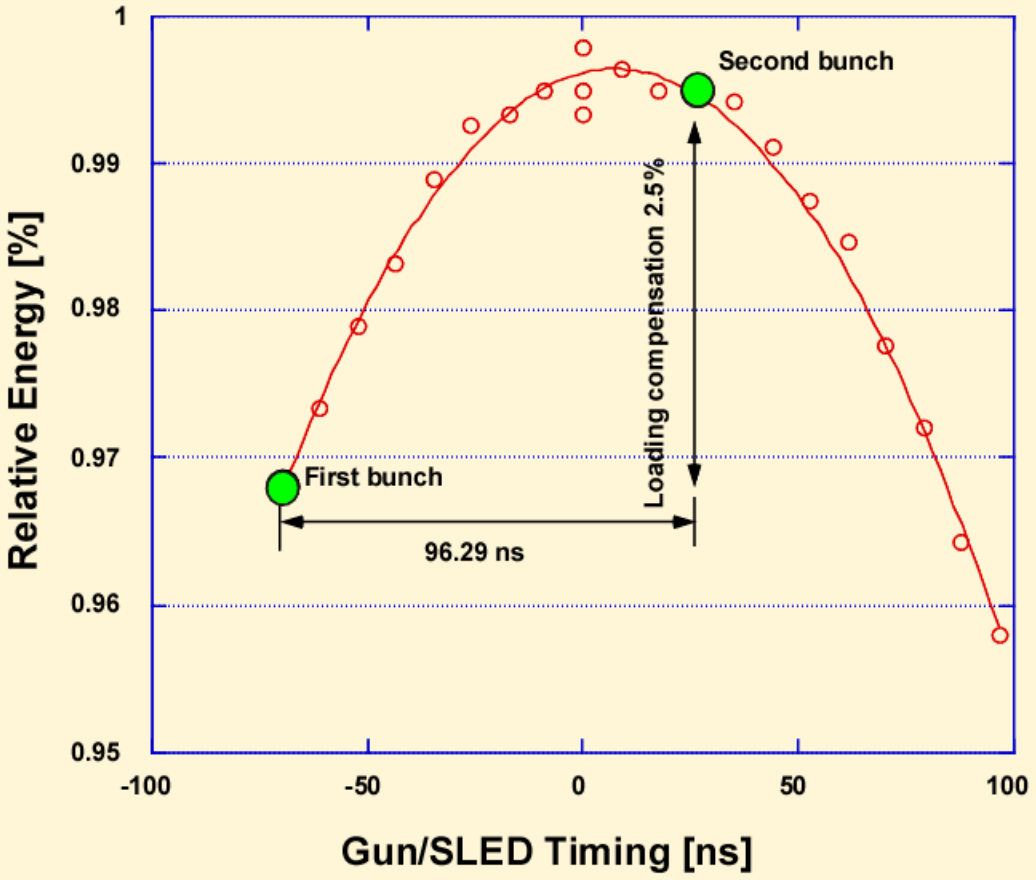
Energy Profile

- **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

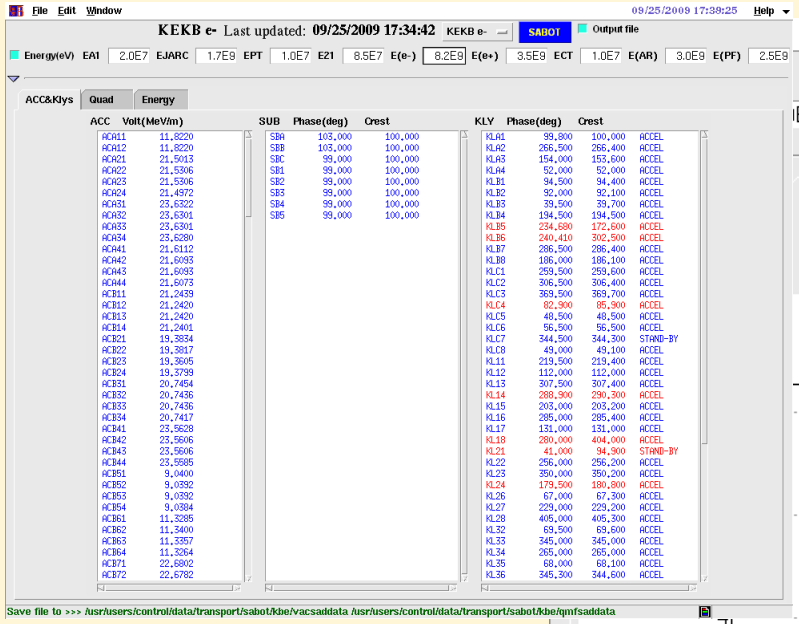


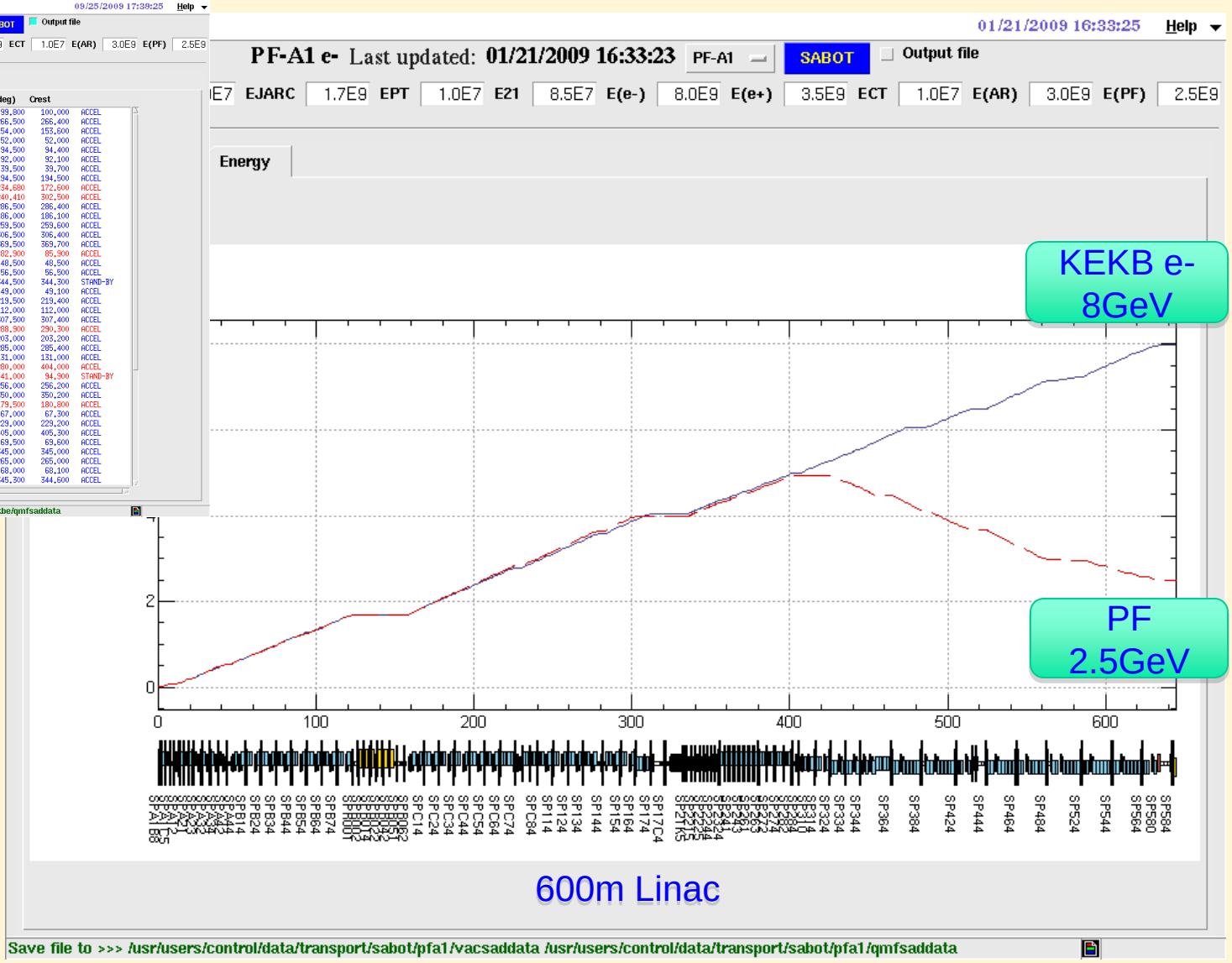
Two-bunch Energy Equalization

- **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**



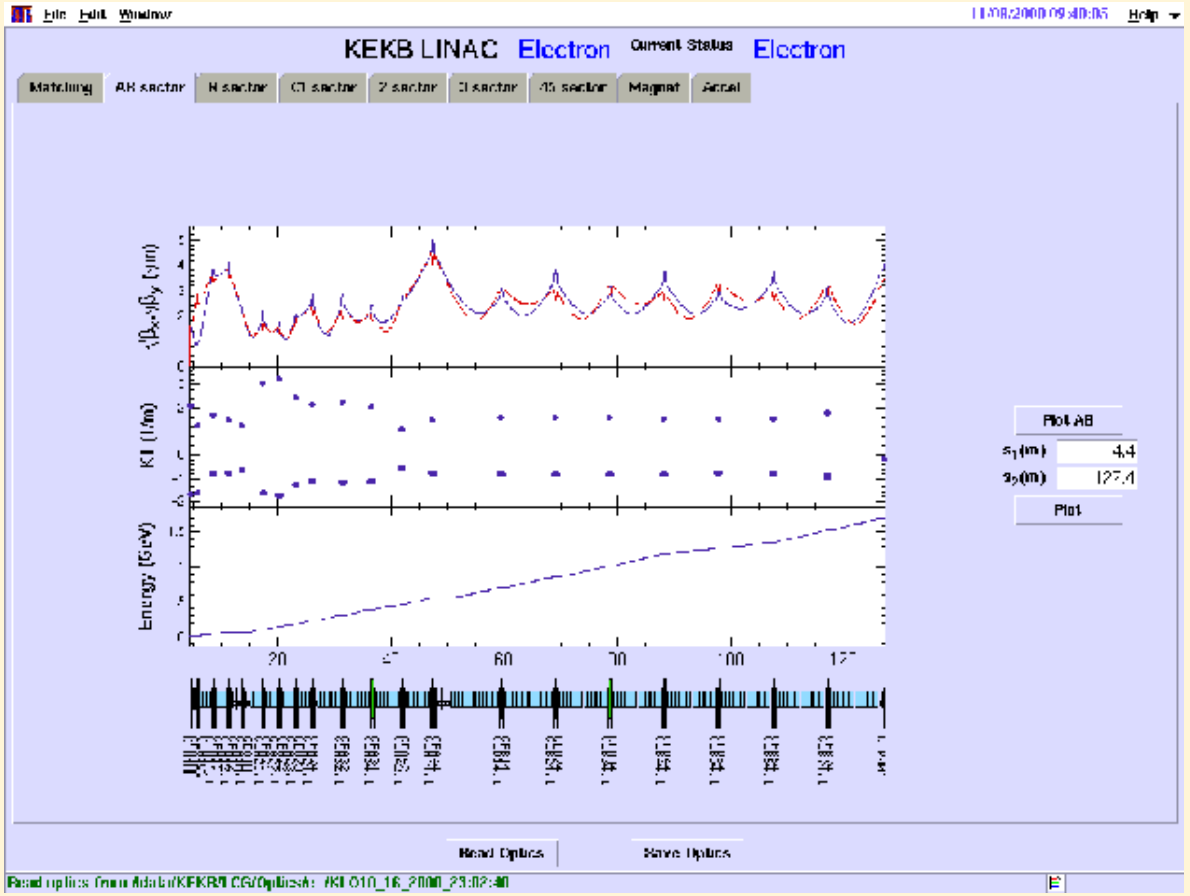
Energy Profile Calculation





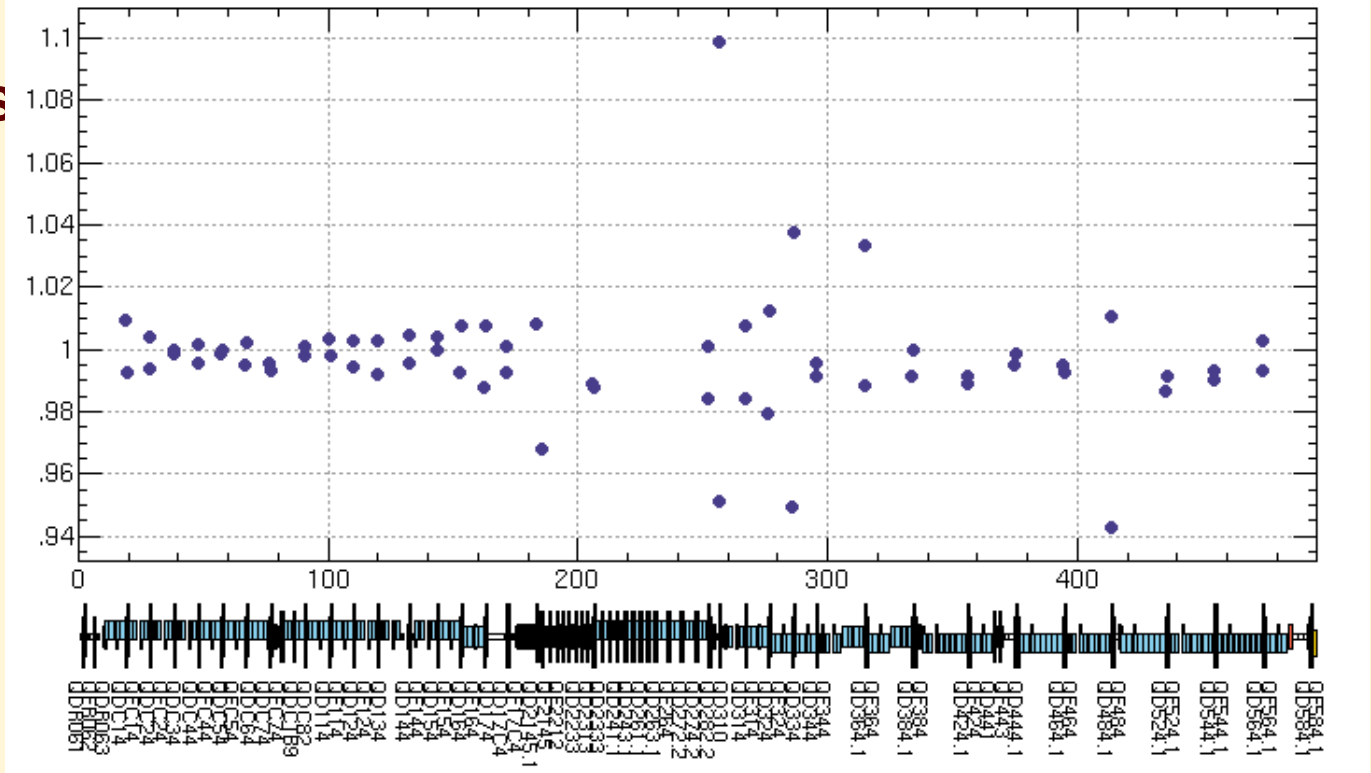
Beam Optics Matching

- **Based on energy profile, fudge factors, etc.**
  - **Wire scanner measurements**
  - **Every several days**
  - **Somewhat affected by background noise**
  - **Matching by a push button**



Quad Fudge Factor

- **Twiss parameter measurement with wire scanners**
- **Fudge factor determination, last done in 2008**
  - **Orbit Observation with Single kicks**
  - **Several iterations**
    - **One wiring error was found**

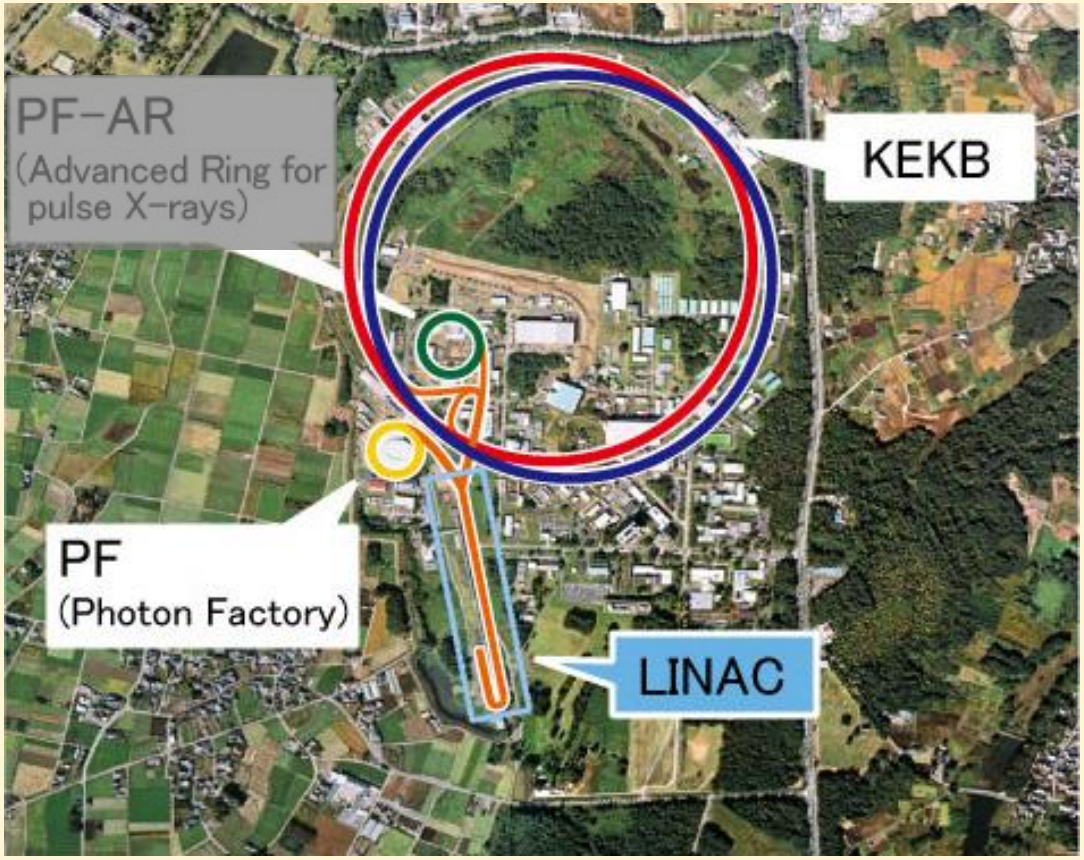


Fast Controls for Three Energy Profiles

- 8 driver klystrons with fast phase shifters
  - for overall energy profile and energy spread comp.
- Acceleration/stand-by for 60 klystrons
  - for rough energy adjustment, for back-up
- 4 energy knob klystrons
  - for final energy adjustment
- SLED timing of LLRF at 8 driver klystrons
  - for two-bunch in a pulse energy equalization

- Parameter change every 20ms is necessary

Simultaneous Injection and Fast Controls

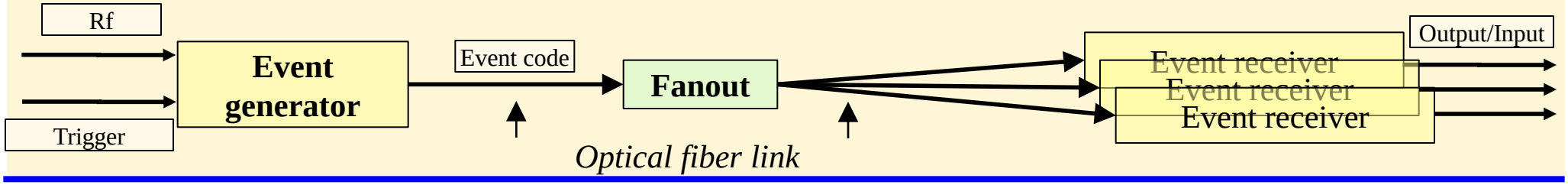


Fast Controls

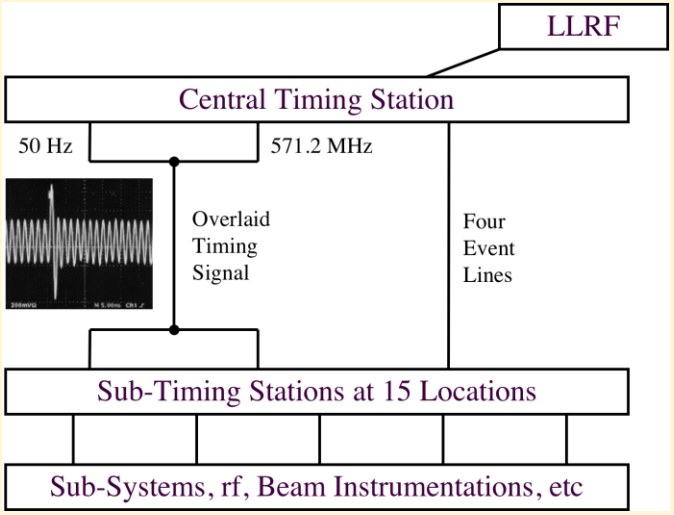
- ~100 parameter switching within 20ms
  - Keep most of magnet fields with compatible optics
  - Control llrf to change energy
- Pulsed magnet triggers and delays
  - Delays to keep the constant rate for certain power-supplies
- LLRF phases and delays
- Gun voltage and fine delay
- Interface to bucket selection, etc
- Ethernet-based controls are not reliable enough
- FPGA and fiber-optic RocketIO might be the way ?

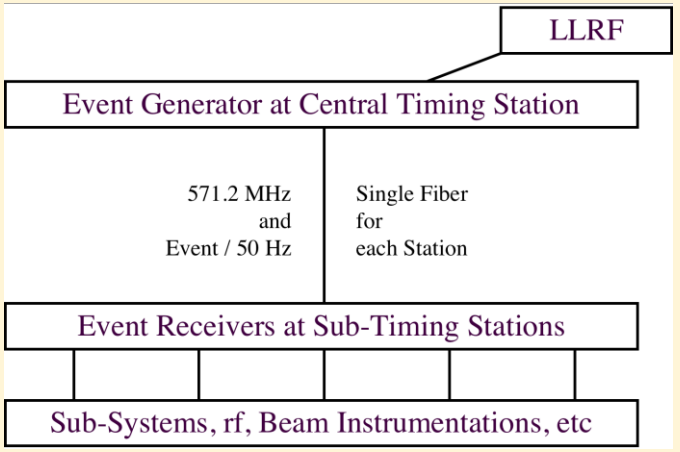
Event System

- **Many accelerator system require timing signals and accompanying information (event)**
  - **Several primitive facilities are combined and used at KEKB and Linac**
    - **Fast Timing signals are provided with delay module TD4/TD4V**
      - **Need timing trigger and rf clock**
    - **(Slow) Events are provided in another facility**
      - **Combining Hardware and Software**
  - **Event/Timing Systems which distribute the both timing and event are developed at Argonne/SLS/Diamond, and are employed at many institutes (Event Generator/Receiver)**
    - **Fast Timing, rf clock, Hardware event, Software Interrupt, can be handled in one combined system with a single fiber cable**
    - **Especially in EPICS, event can be connected EPICS Event directly, so record/database programming is possible**

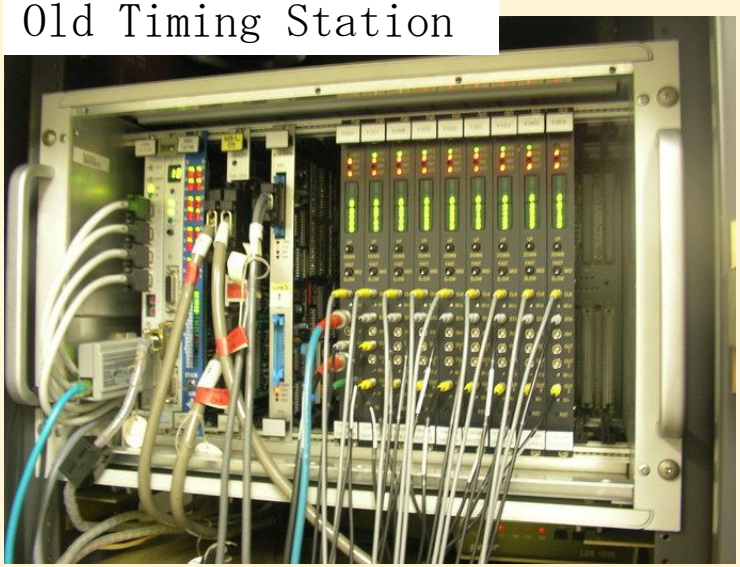


Timing System





Old Timing Station



New Event Receiver Station with 16 outputs

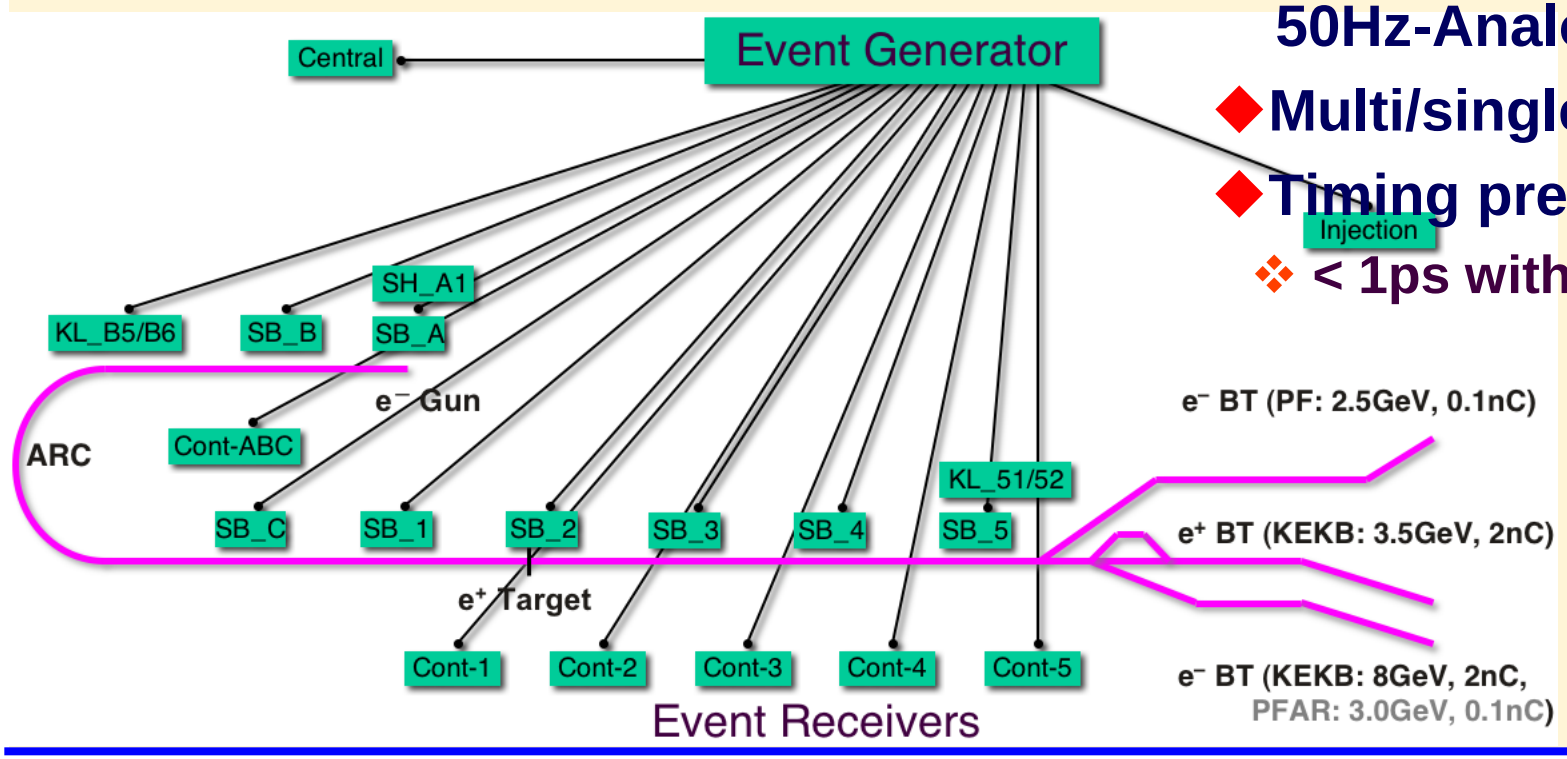
Event System

- **Simultaneous Injection**
  - to KEKB-HER, KEKB-LER, and PF
  - 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 Configuration

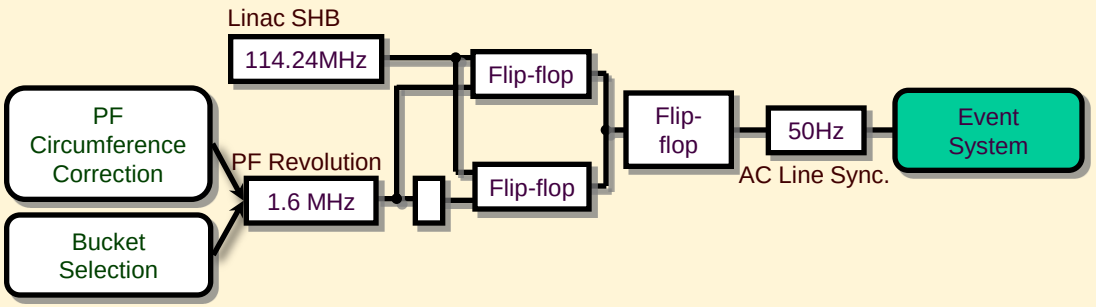
- MRF's series-230 Event Generator / Receivers
- VME64x and VxWorks v5.5.1
- EPICS R3.14.9 with DevSup v2.4.1
- 17 event receivers up to now

- 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.

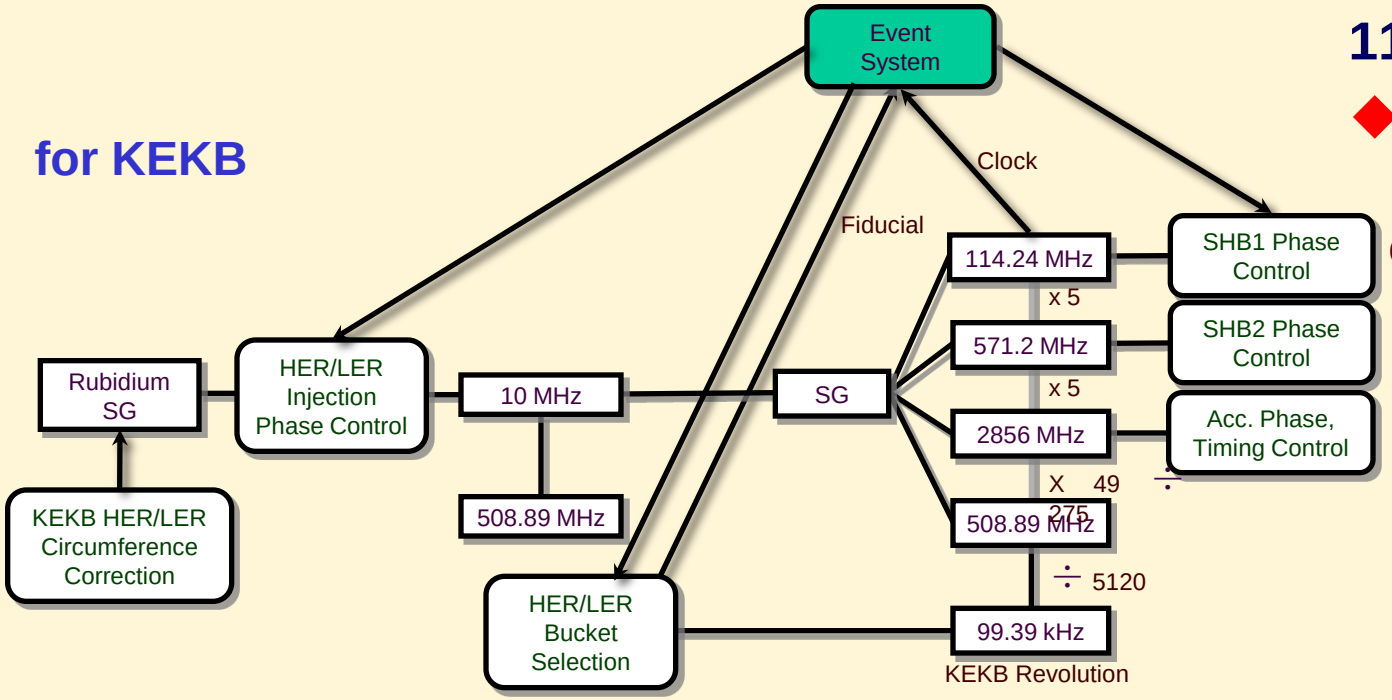


Synchronization Scheme

for PF

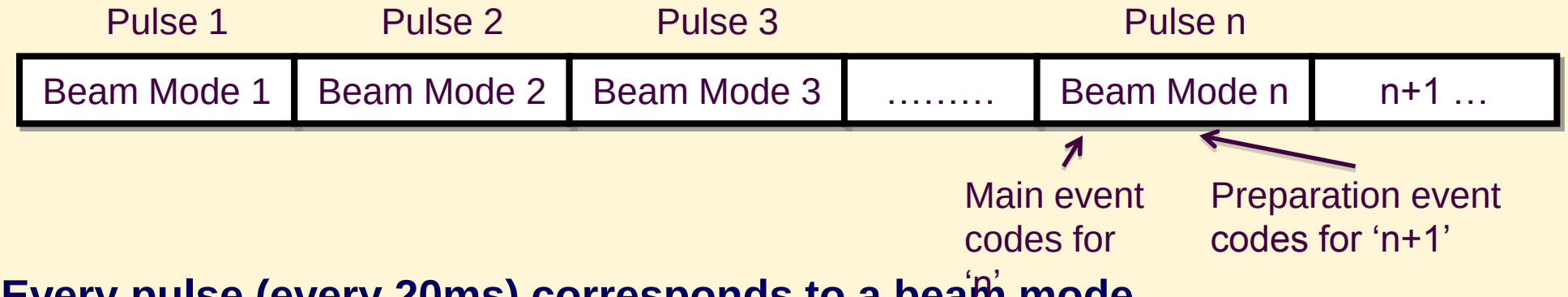


for KEKB



- **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**

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 mode 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

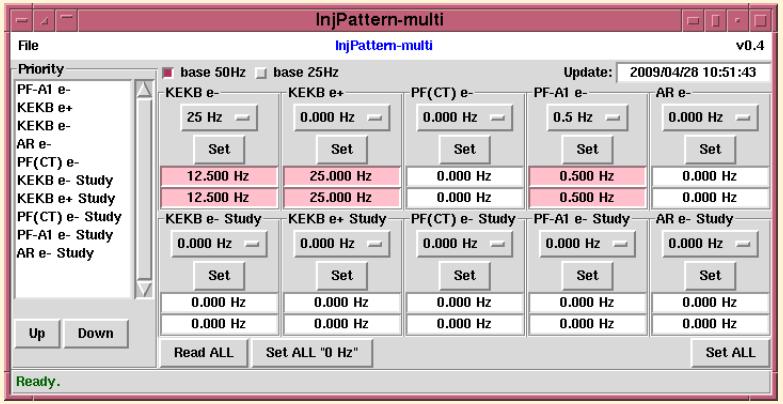
Generate Events for the Next 20-ms Time Slot (in Event Generator)
- reading two consecutive elements from the beam mode pattern
- generate several events for the next pulse
- generate preparation events for the next after next

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

Beam Mode Pattern Generators

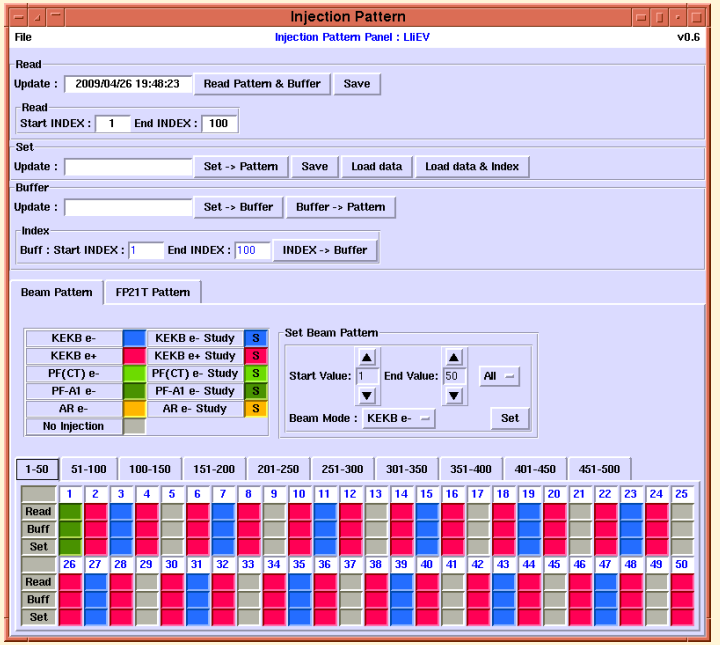
- **Pattern panel arbitrates requests**
  - From downstream rings with priorities, or human operators
  - There are several pattern rules due to pulse device features and limitations
  - Pattern arbitrator software was written in scripting languages to meet daily changes during the commissioning stage

Remote controlled automatic pattern arbitrator



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

Manual pattern generator

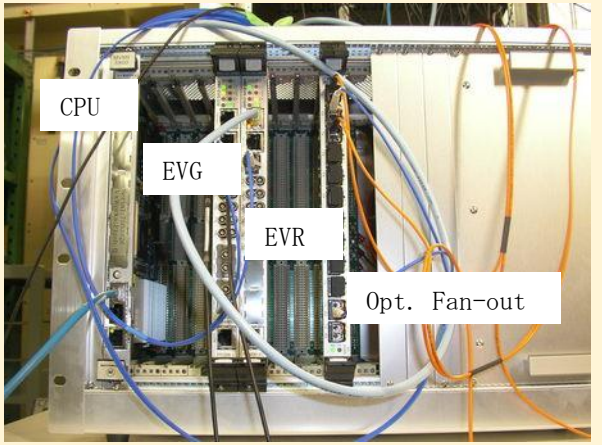


Parameters

- **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 comming**
- **Integrity monitors**
- **Improved slow beam feedback, fast feedback, etc.**

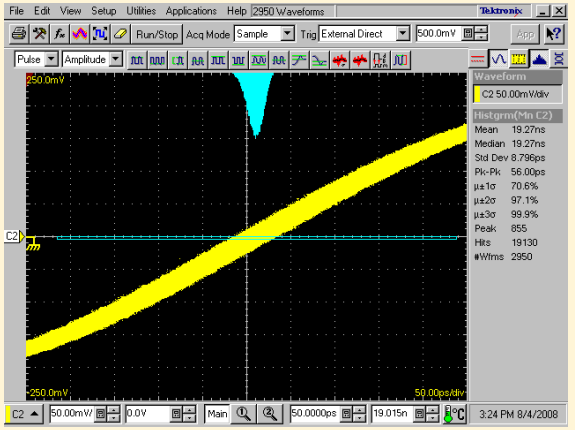
Linac Event System

- **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



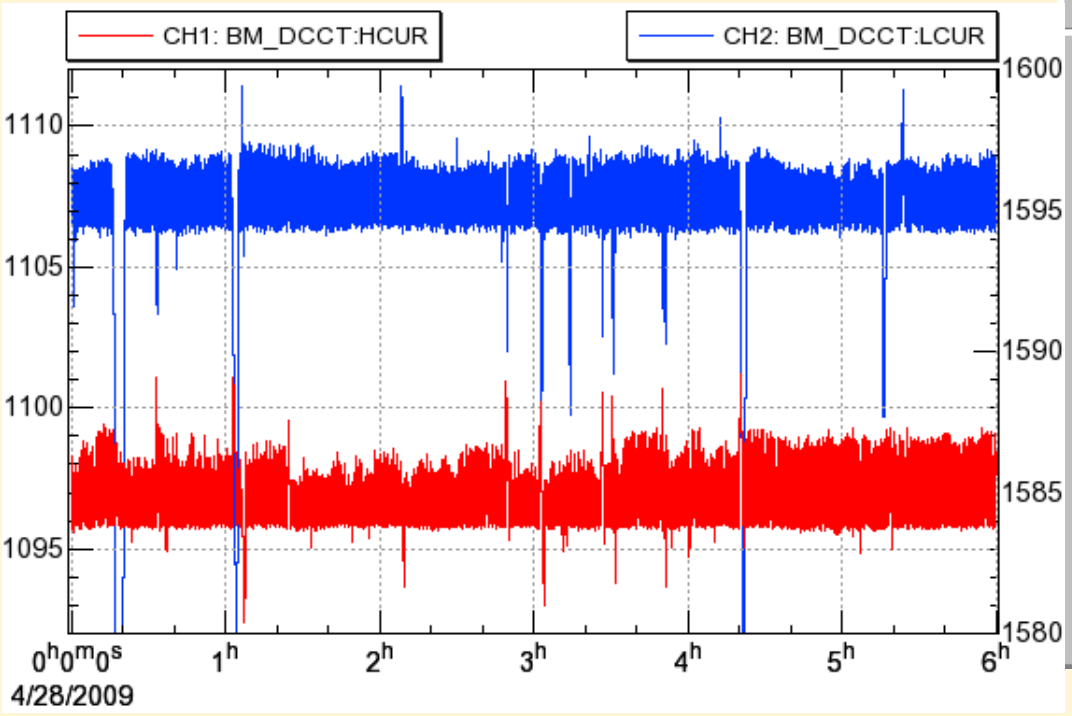
EVR & LLRF

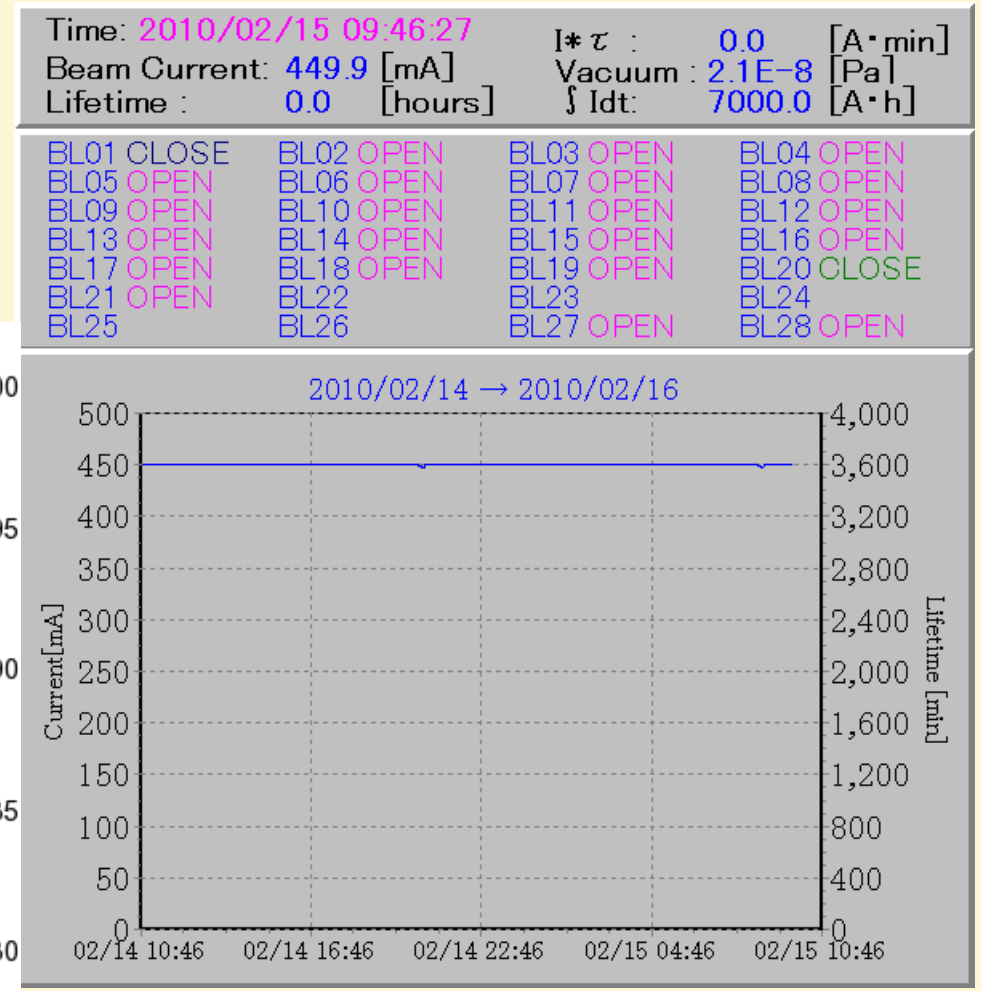
- CPU stopped 4 times since Sep.2008 for 18 stations



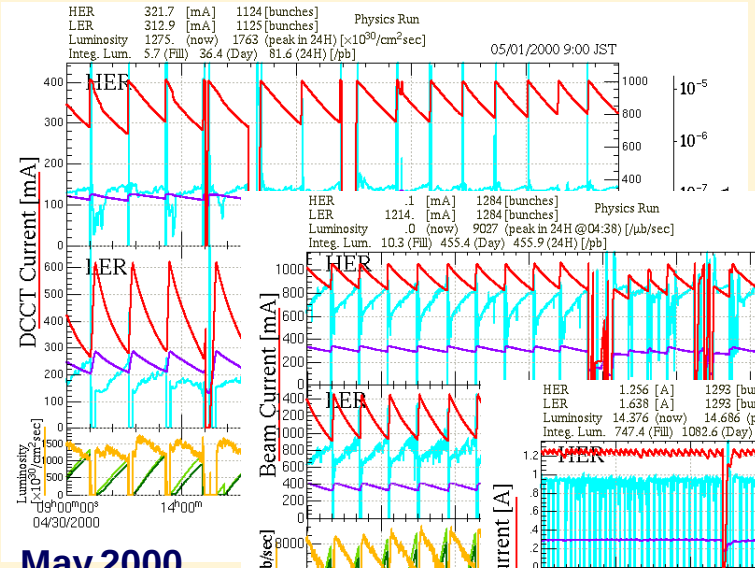
Beam Current

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

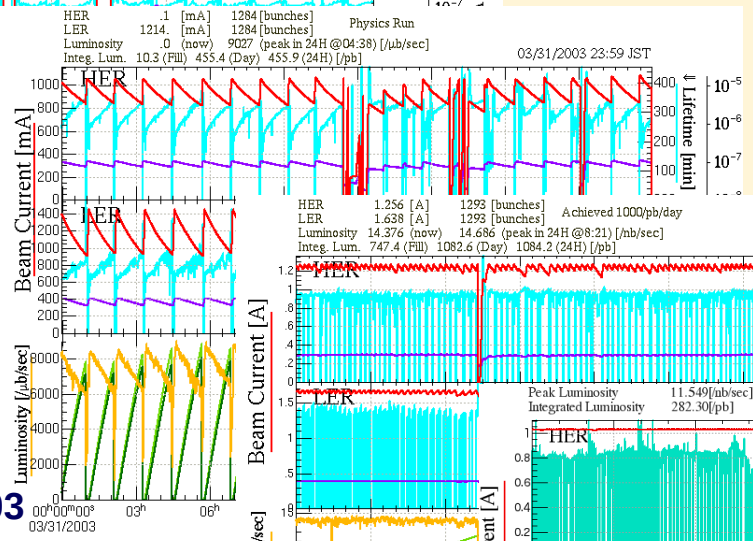




KEKB Operation Improvement

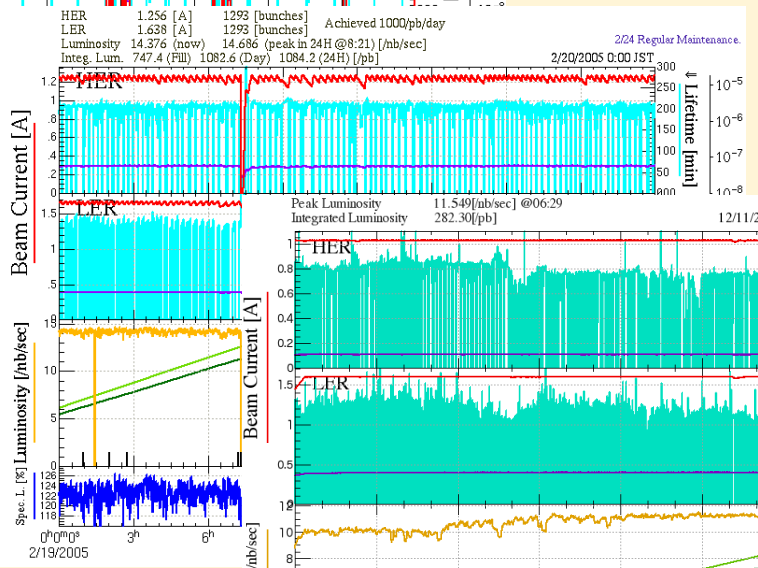


May.2000



Apr.2003

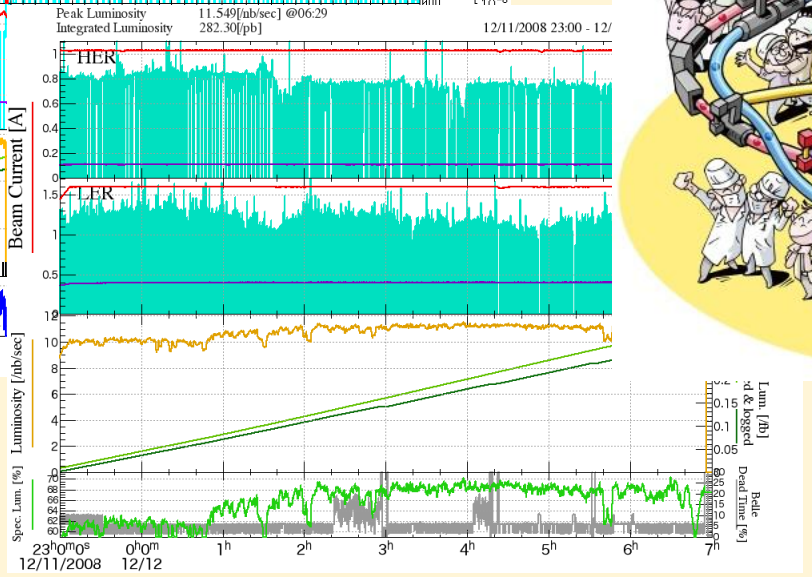
Dual Bunch e⁺



Feb.2005

Continuous

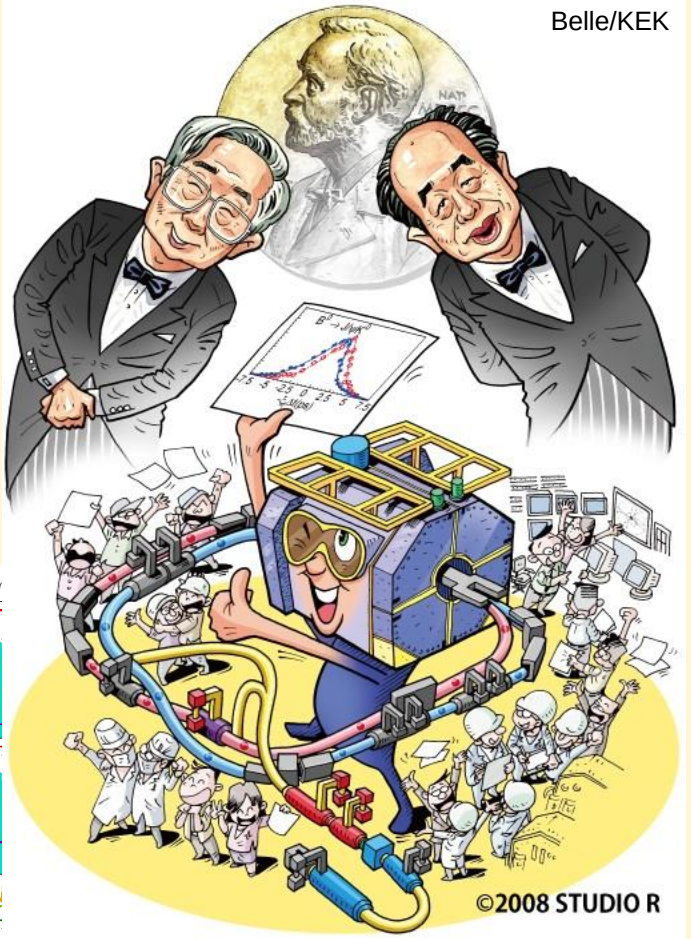
Injections



Dec.2008

Crab Cavities and

Simultaneous Injection



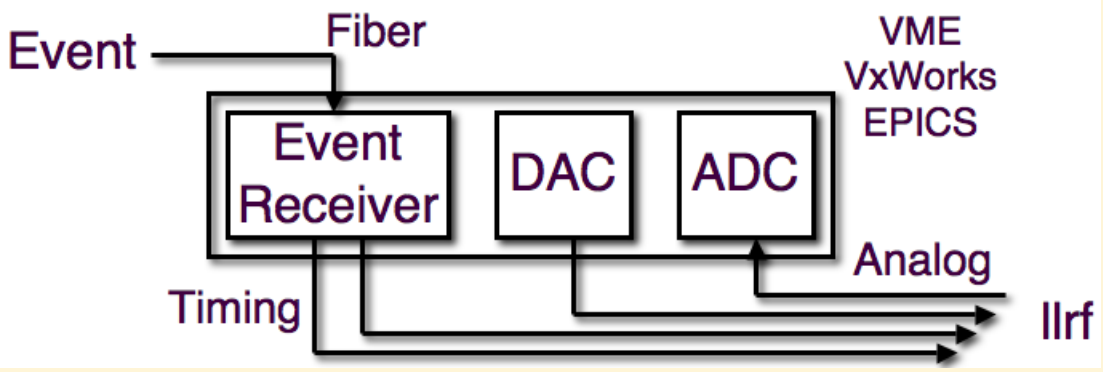
Summary

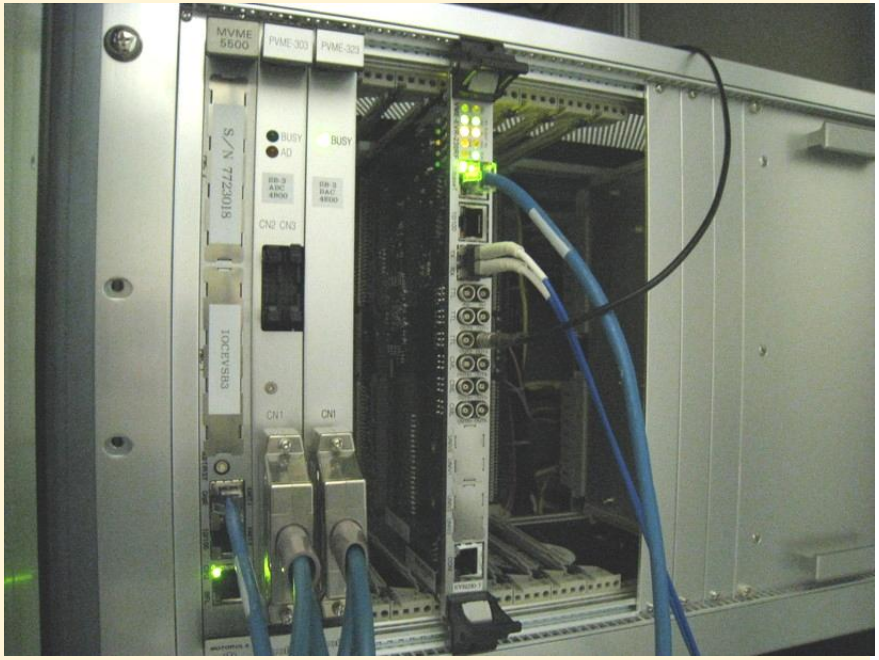
- **Energy management of KEKB linac was successfully applied to simultaneous injection**
  - **Covers 2.5GeV – 8GeV, 0.1nC – 10nC**
  - **Beam optics diagnosis down to ~1%**
- **Simultaneous injection to HER/LER/PF was successful**
  - **Development and installation for various kind of hardware**
  - **Another layer of controls based on a fast event system**
    - **Pulse-to-pulse reprogramming of event system**
- **Simultaneous injection will be the base for SuperKEKB as well**

Thank you

LLRF

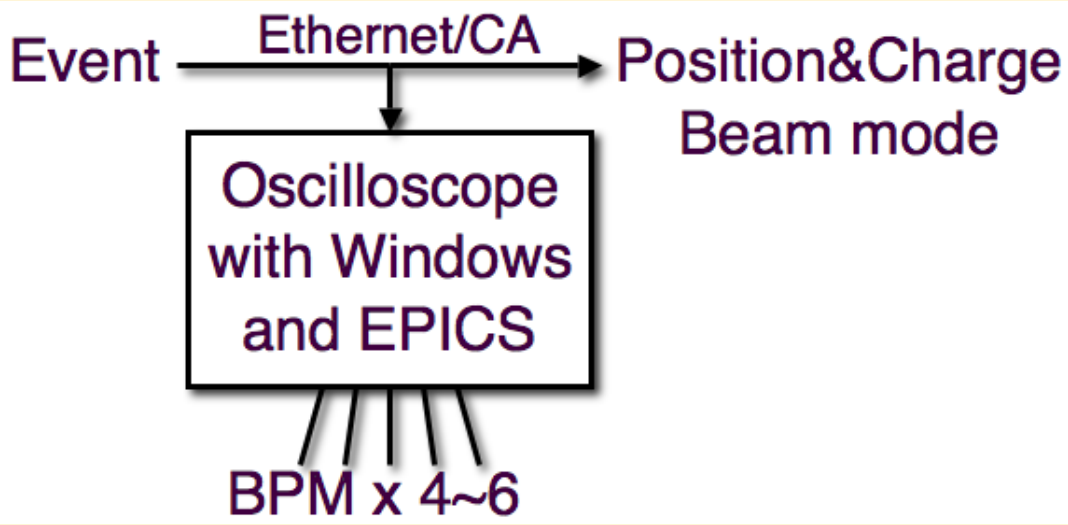
- LLRF Timing/analog signals are essential for absolute energy, energy spread, and dual-bunch energy equalization
- Signals are switched pulse-by-pulse
- Value changes are triggered by a preparation event
- Driver klystrons (SB), energy tuner klystron (KL), and sub-harmonic bunchers (SH) are managed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

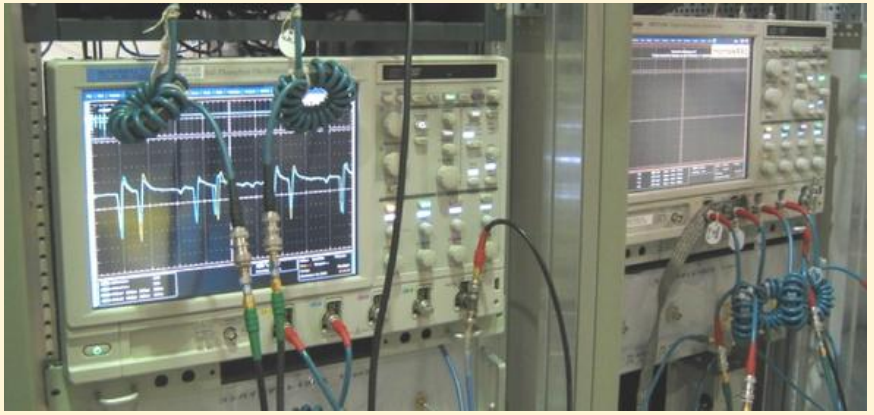




BPM

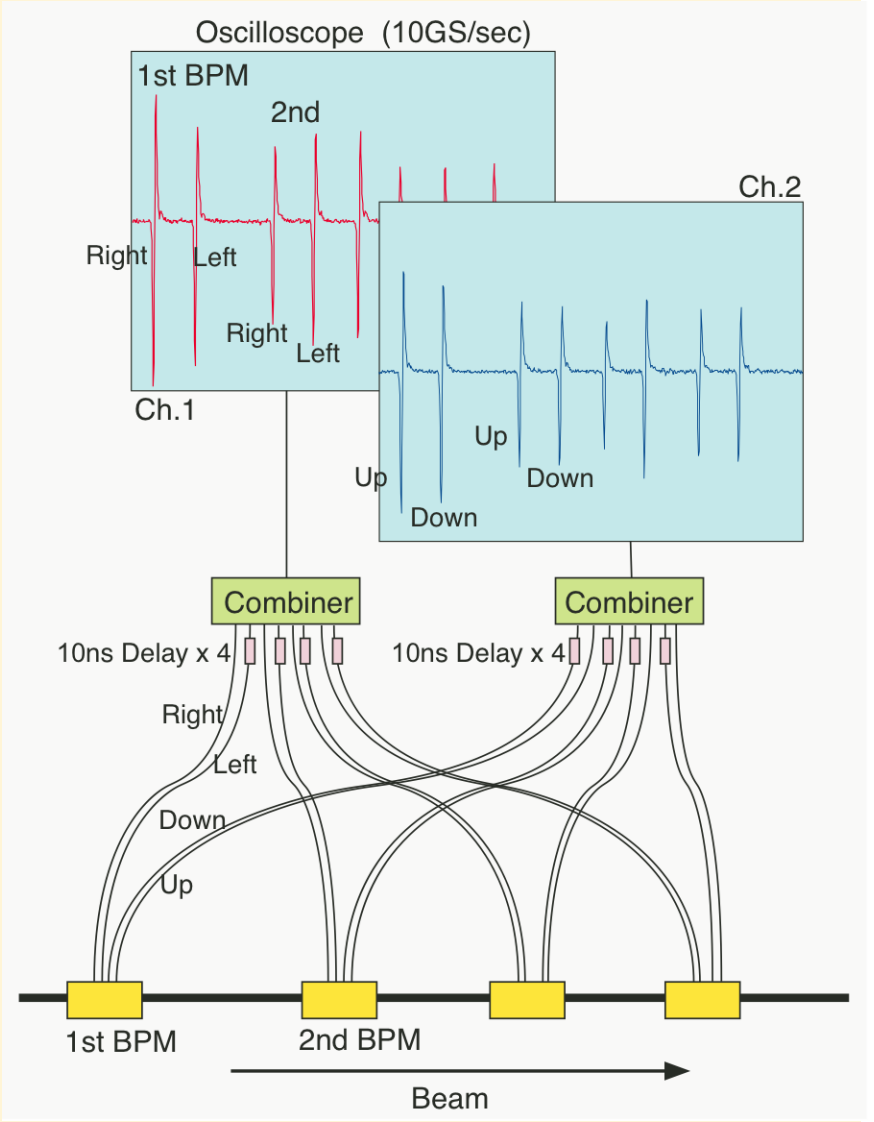
- Tektronix DPO7104 can acquire data at >50Hz.
  - With embedded EPICS
- Beam modes are recognized by events through CA network.
- Clients can monitor data of an interested beam mode.
- 26 oscilloscopes are installed.
- 100 BPMs are synchronized. (100 BPMs at BT as well soon)





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**



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**

KEKB Injections during Beam Studies at PF and PF/AR