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

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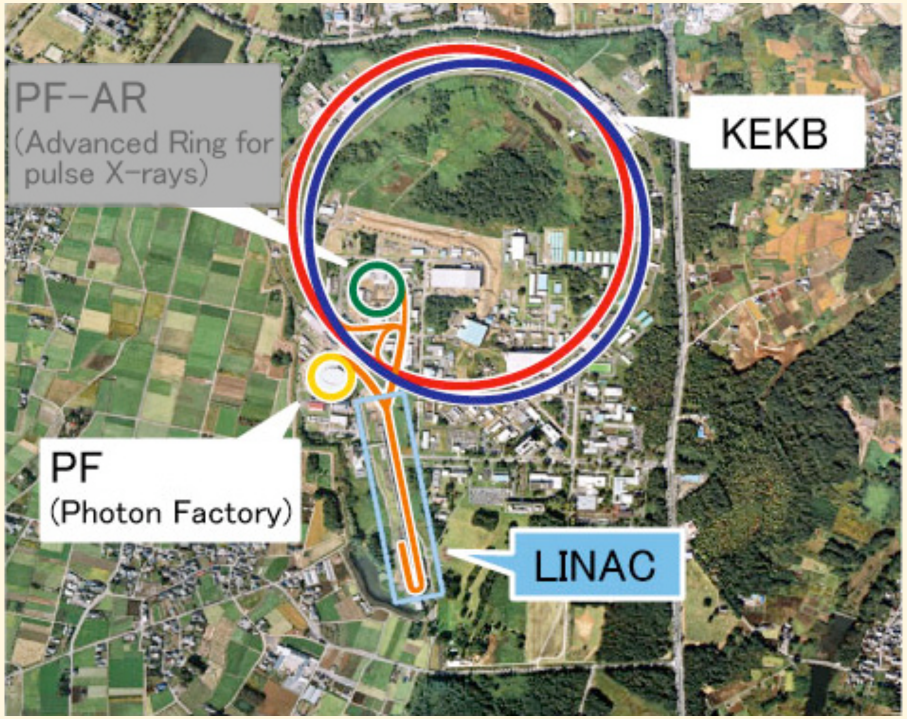
Electron Accelerator Complex

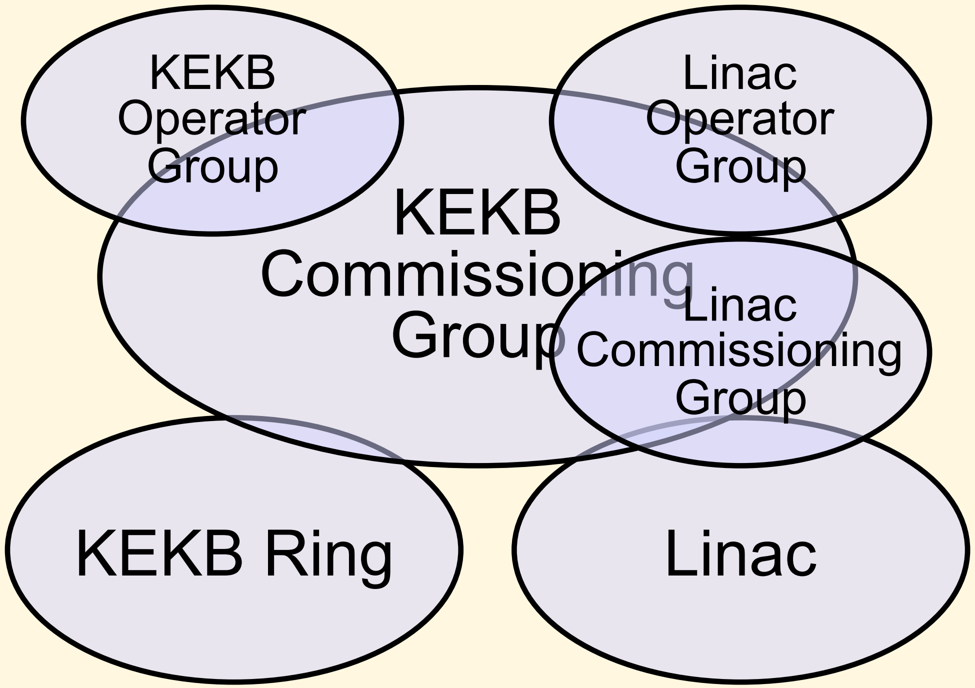
- **Linac clients**
  - **KEKB**
    - 8-GeV e– 1nC x2
    - 3.5-GeV e+ 1nC x2
    - (with 10nC primary e–)
  - **PF 2.5-GeV e– 0.1nC**
  - **PF-AR 3-GeV e– 0.2nC**



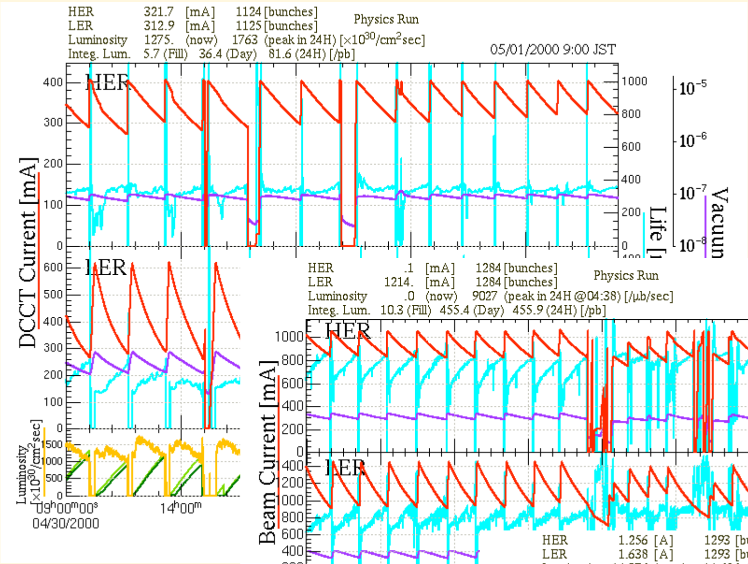
- **At first simultaneous top-up injections to three rings at KEKB and PF**
  - **Switching beams at 50Hz**
  - **For stable operation and higher quality exp. results**

Operation

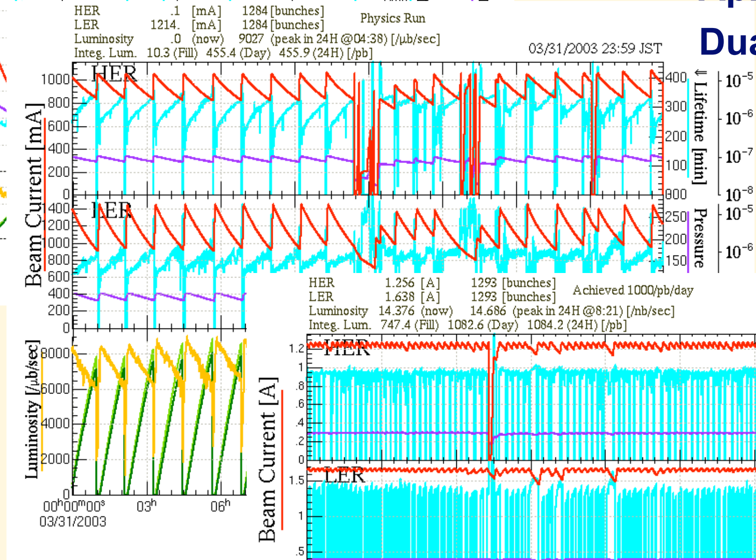
- **Operation groups at KEK B and linac**
  - **Overlapped groups**
  - **Many attend commissioning group from eq. groups**
  - **Daily KCG meeting**
  - **Weekly LCG meeting**



KEKB Operation Improvement

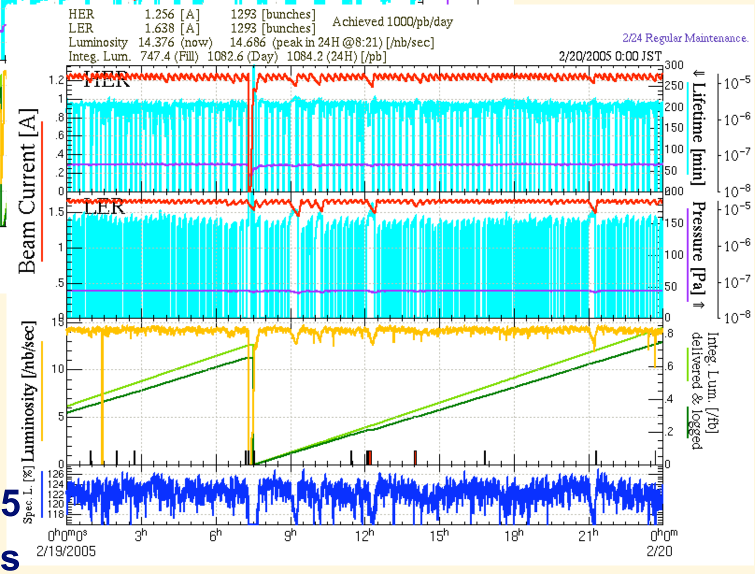


May.2000



Apr.2003

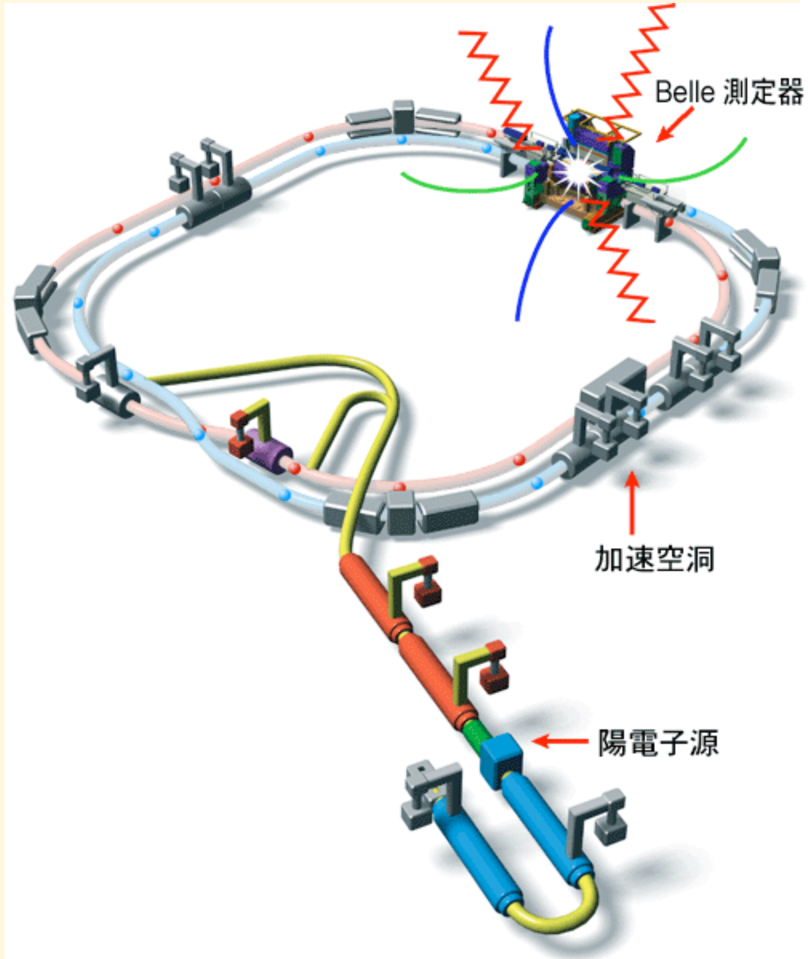
Dual Bunch e+



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

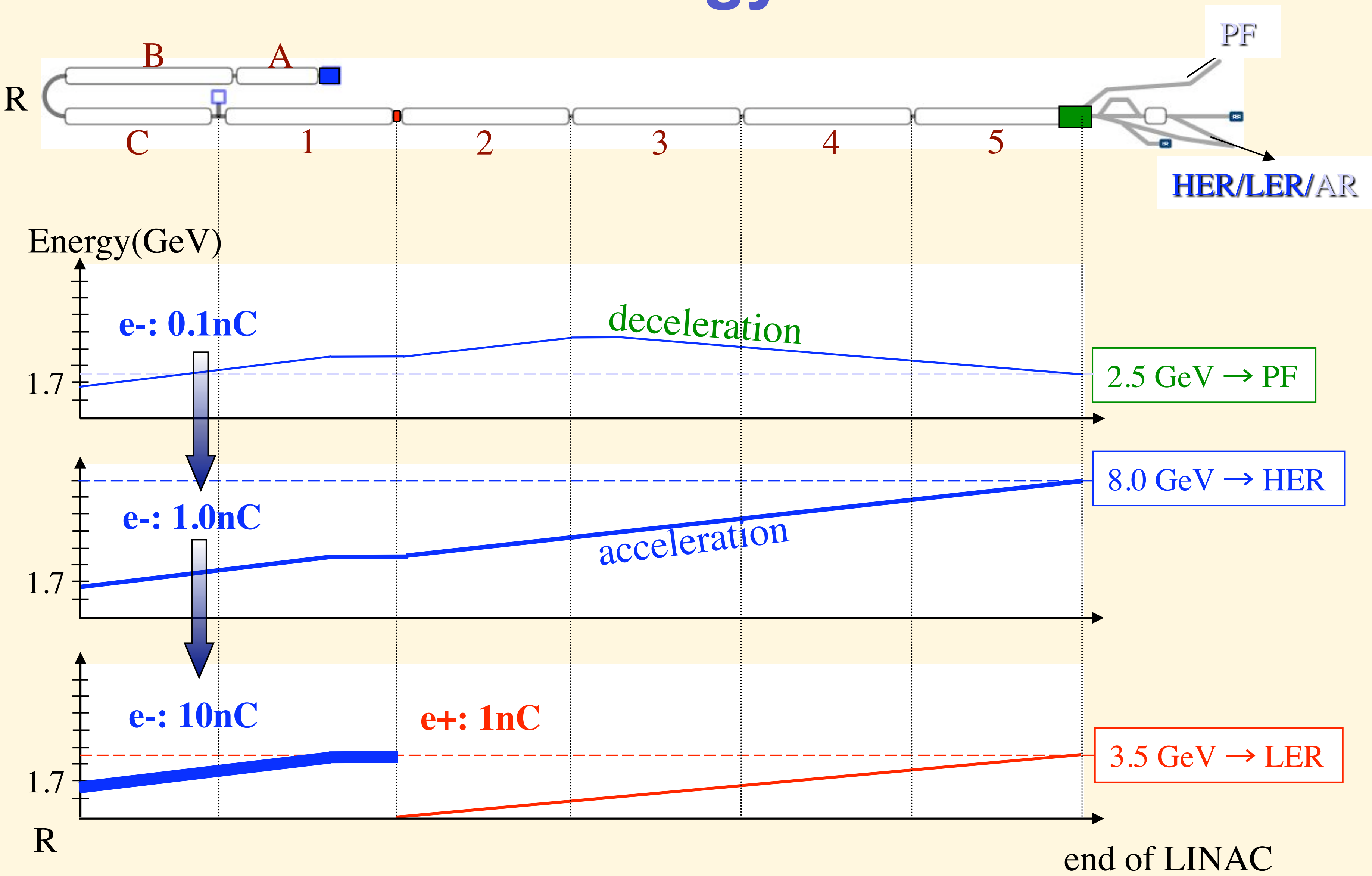
Requirements

- 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

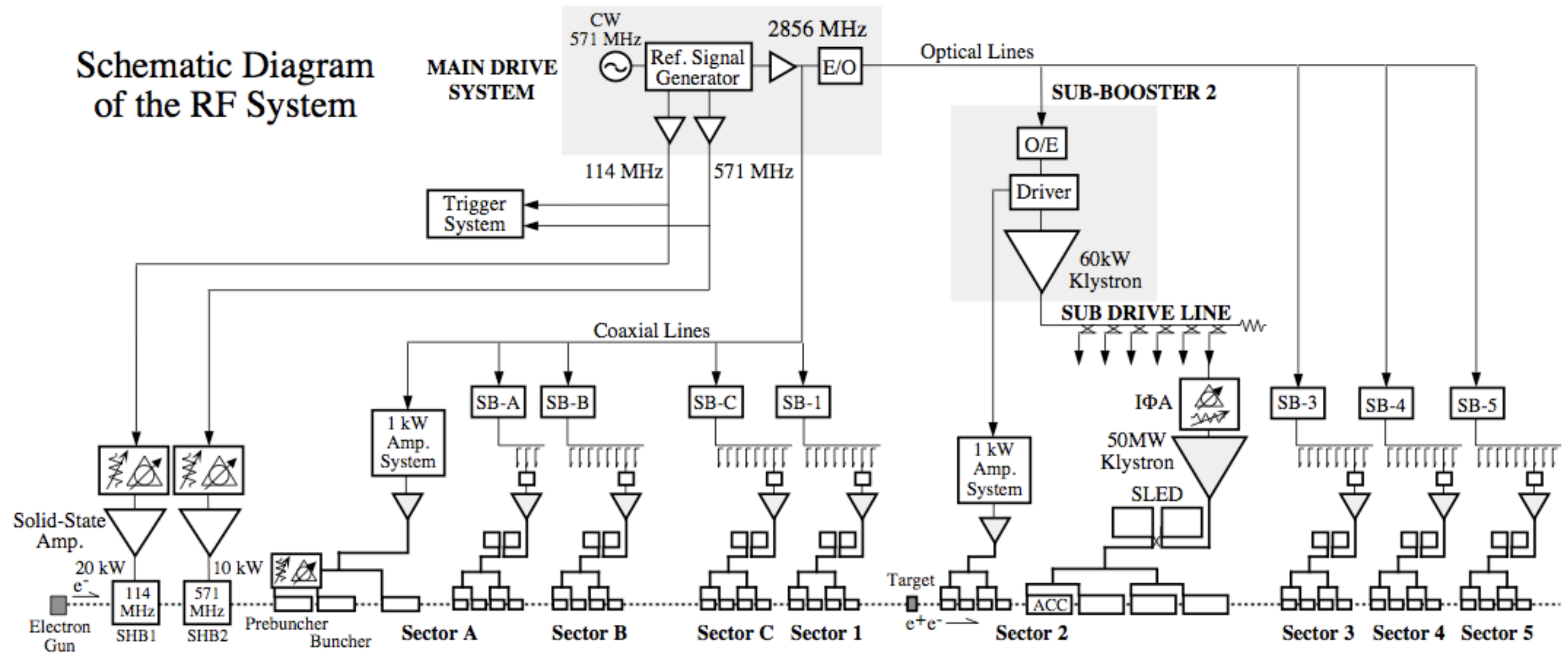
Hardware and Operation Improvements

- 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

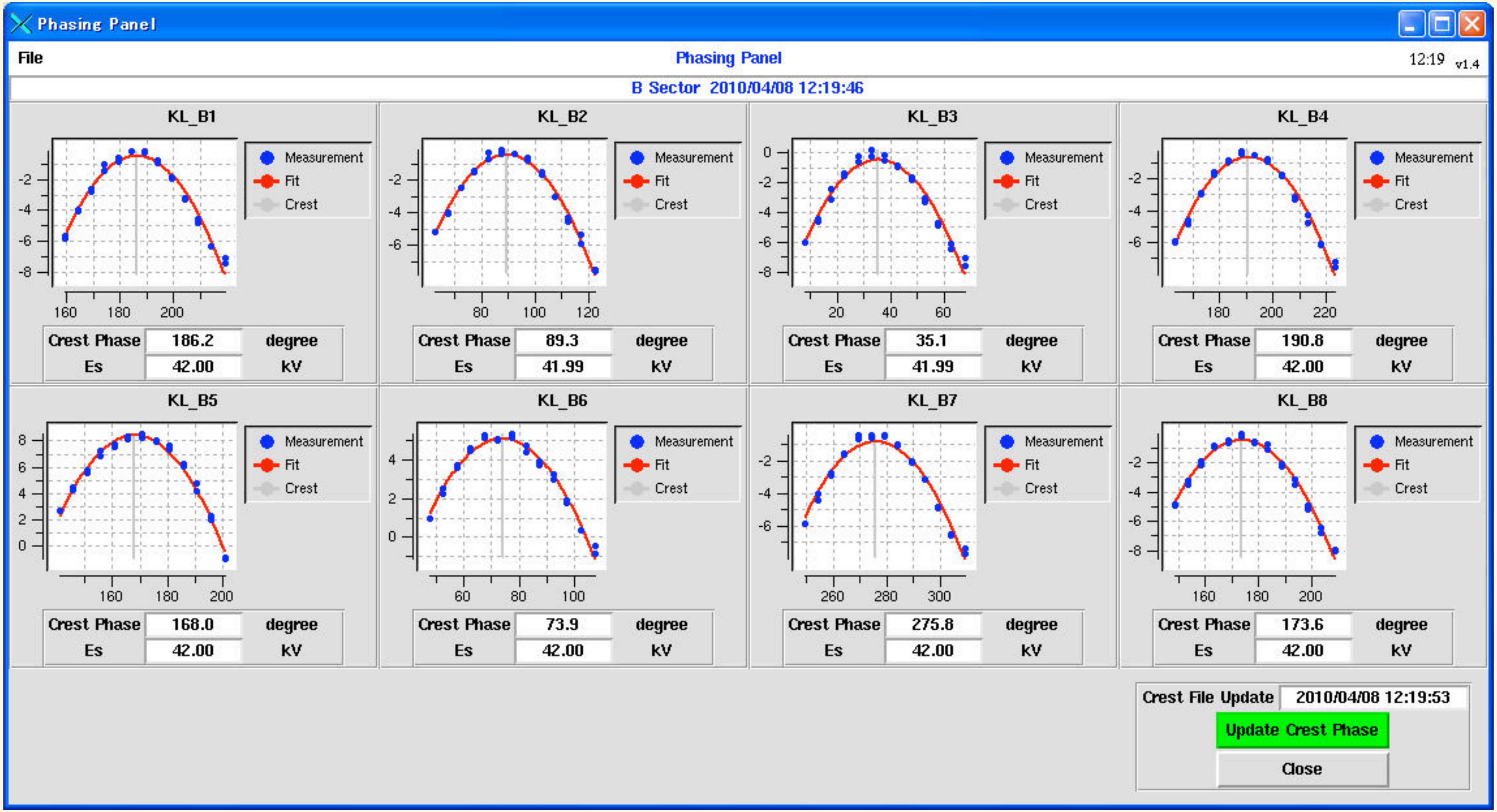
❖ Converted into control database

sector	unit	No	新/旧	typ	d(WG)	α	M	Es-Power	c2	c1	c0	Es	Power	Gain	Gain	Eave	stand	Total
					m			データ更新				kV	MW	MeV	MeV	MV/m	by	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

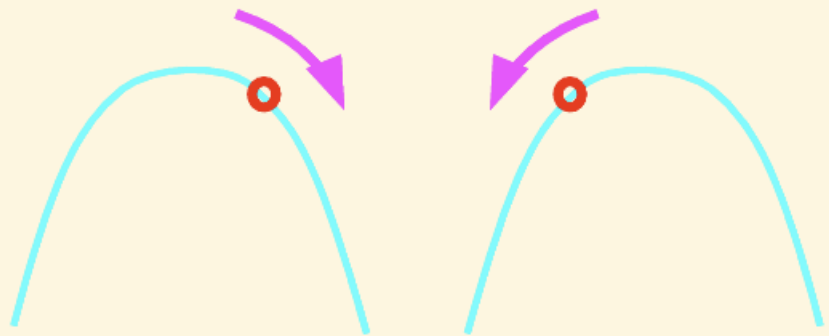
- Each power source with slow phase shifter
  - Energy measurement scanning the phase shifter
    - Primitive but reliable, while there were several methods
    - Chicken and egg issue exists on bootstrap
      - If no beam at the end, no measurement possible
  - Every several month at least after the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



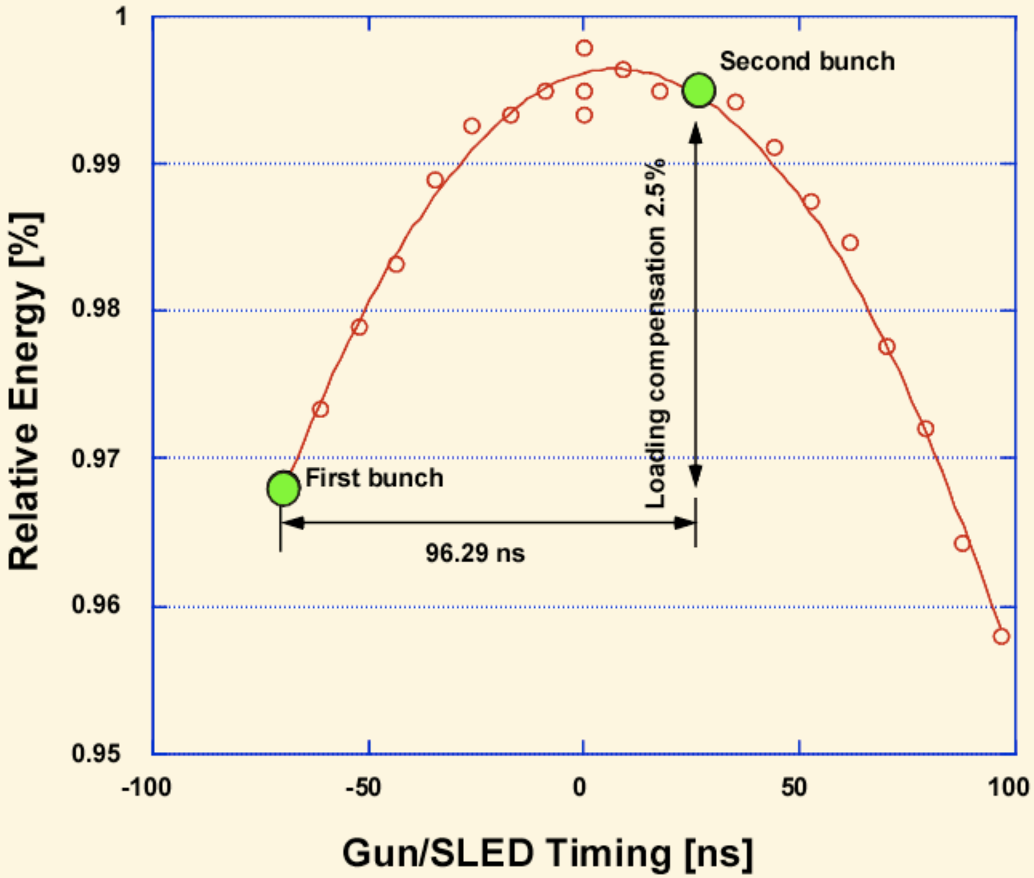
Energy Profile

- **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**

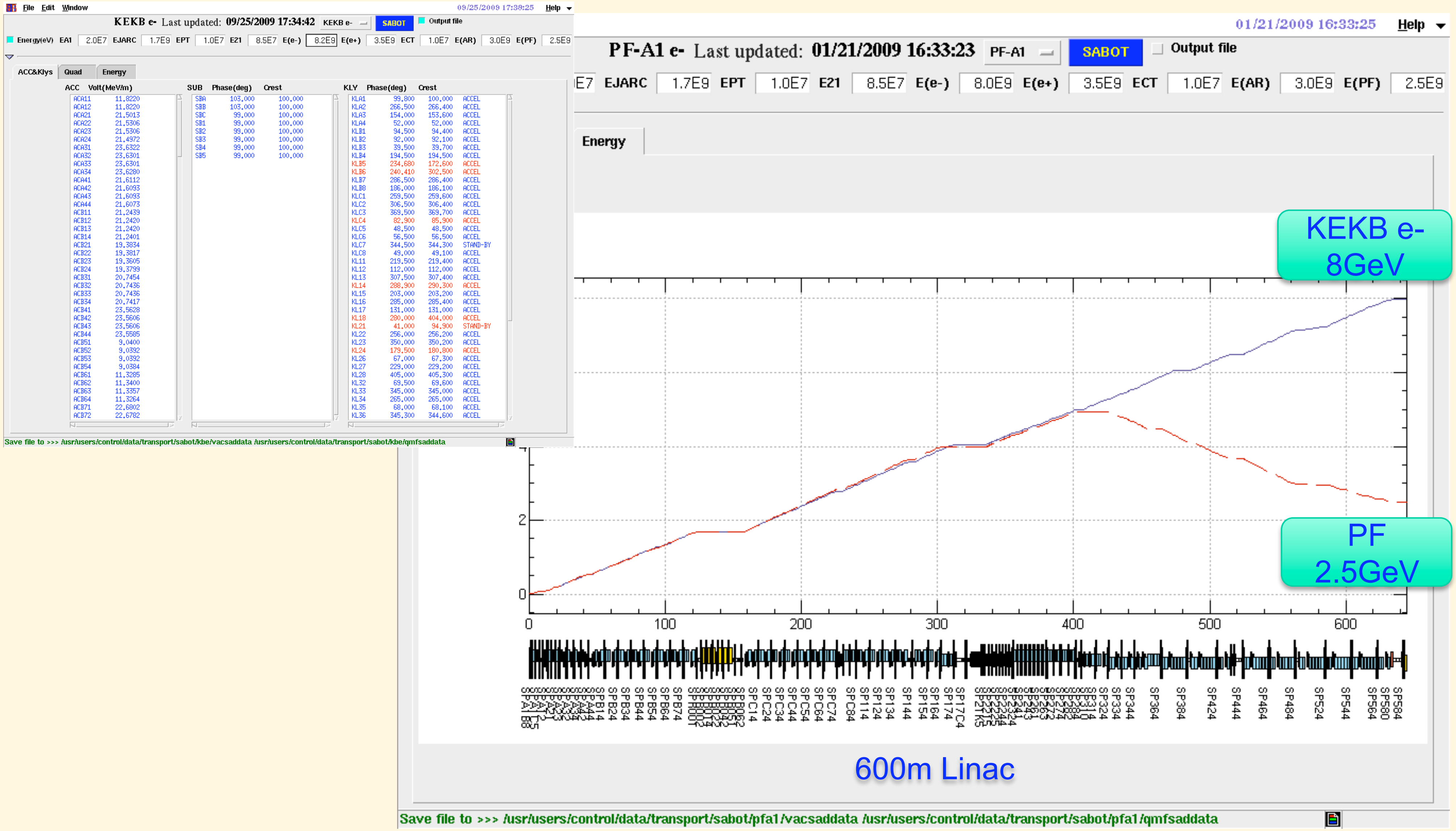


Two-bunch Energy Equalization

- **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**

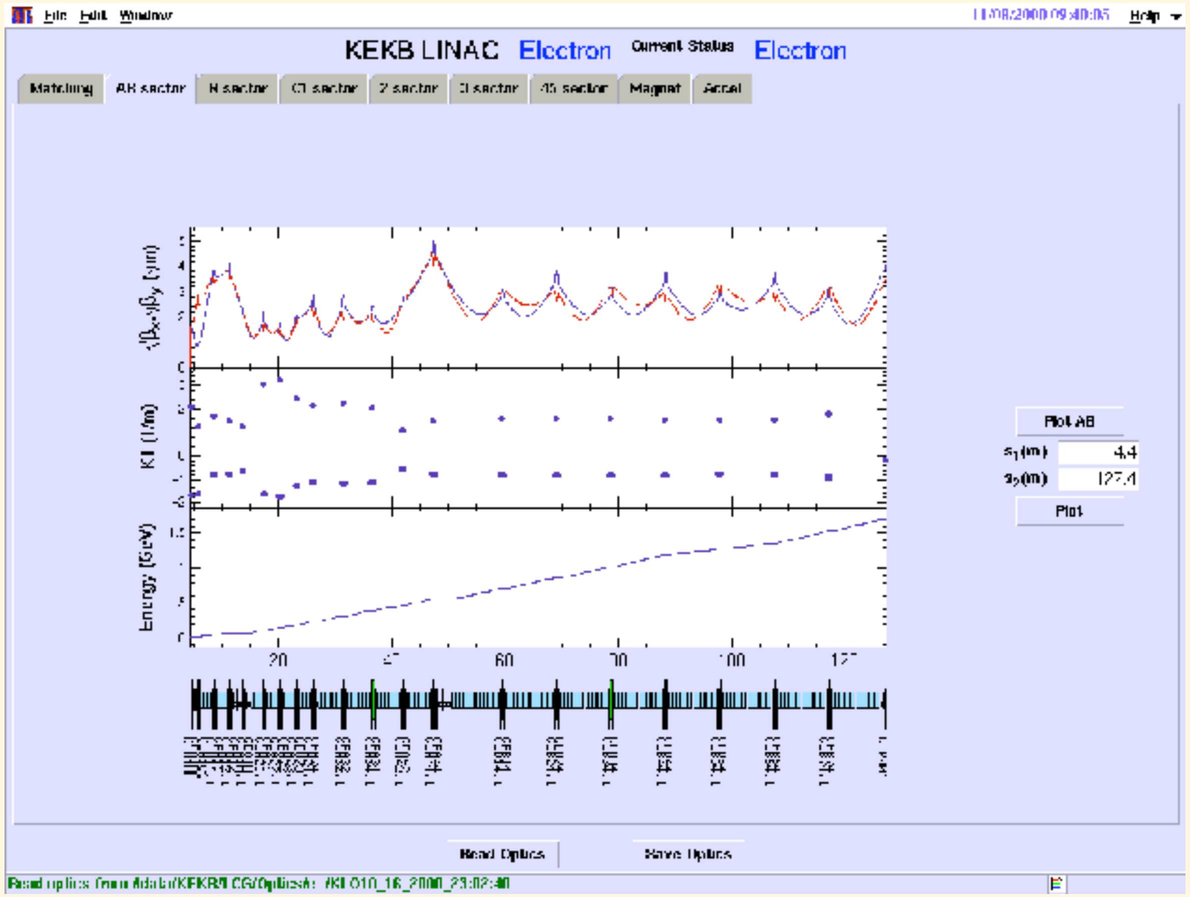


Energy Profile Calculation



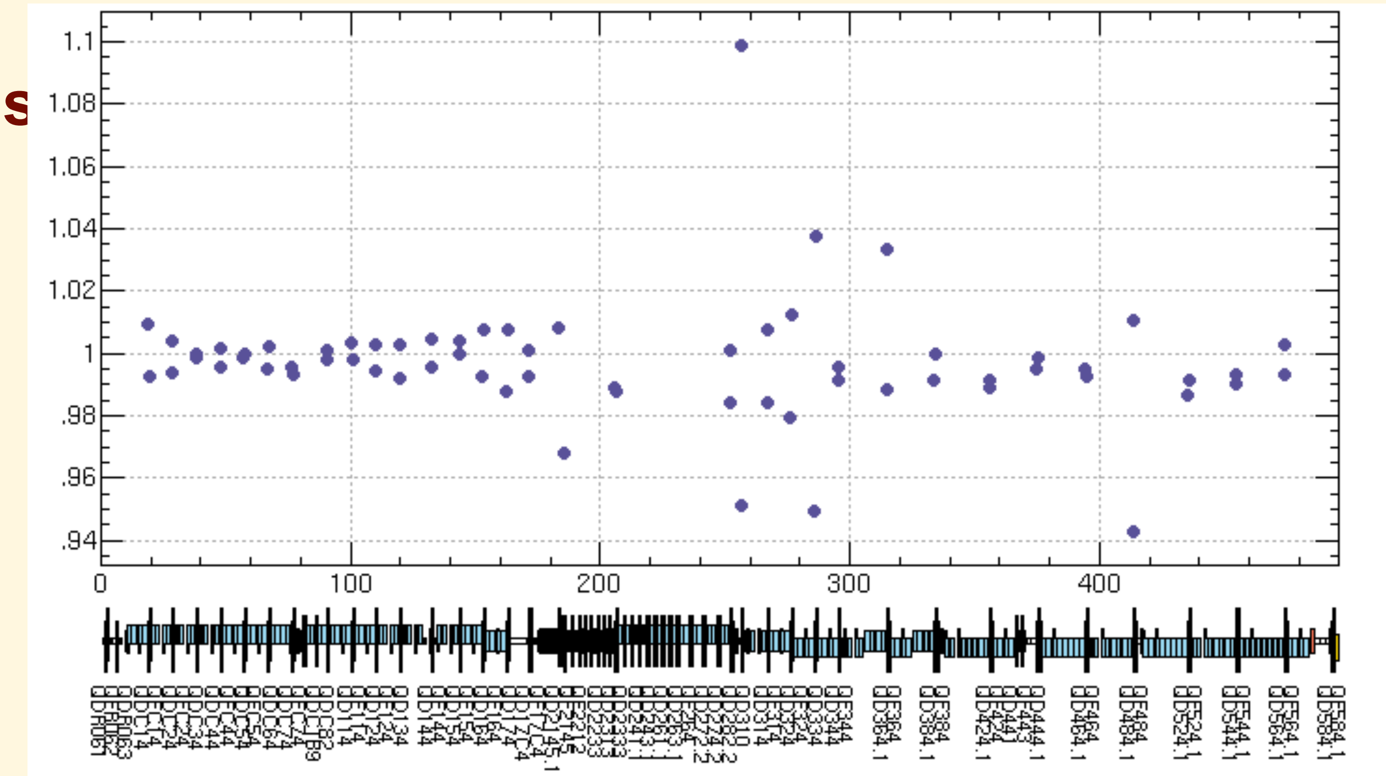
Beam Optics Matching

- **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**

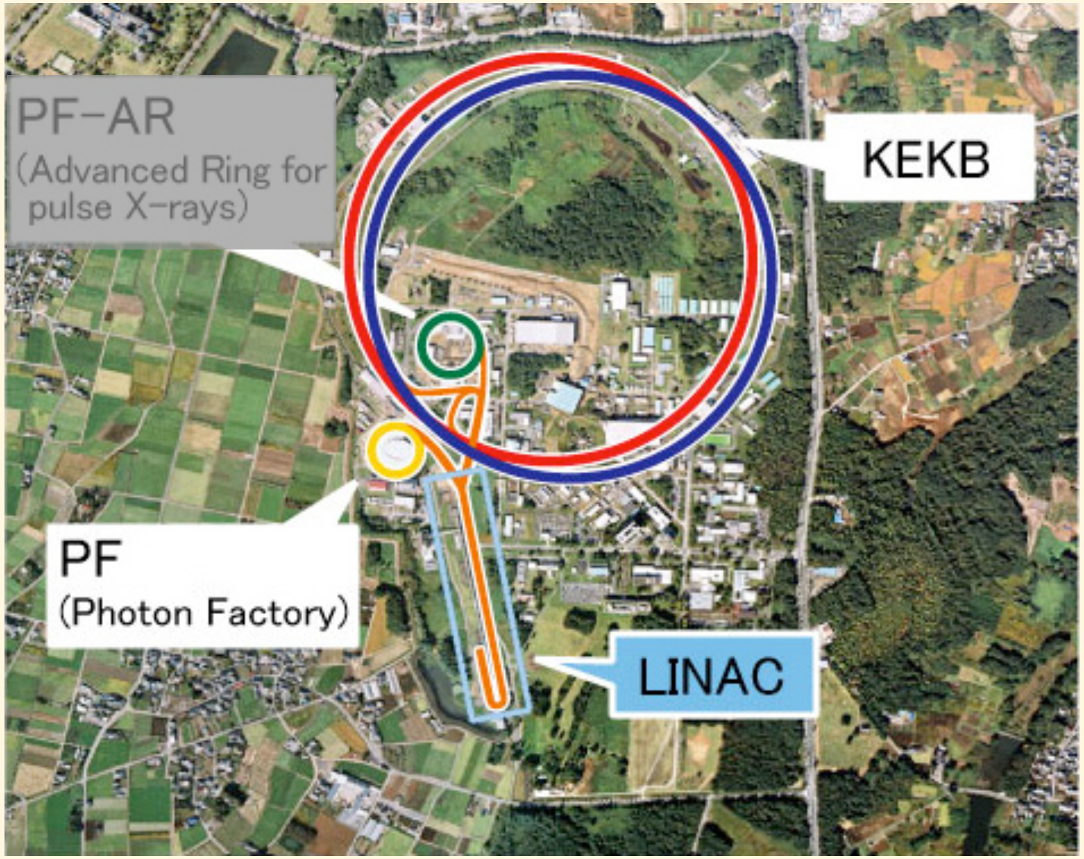


Fast Controls for Three Energy Profiles

- **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

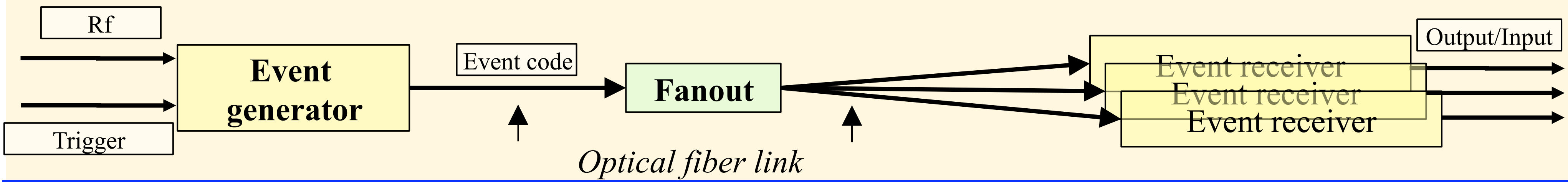


Fast Controls

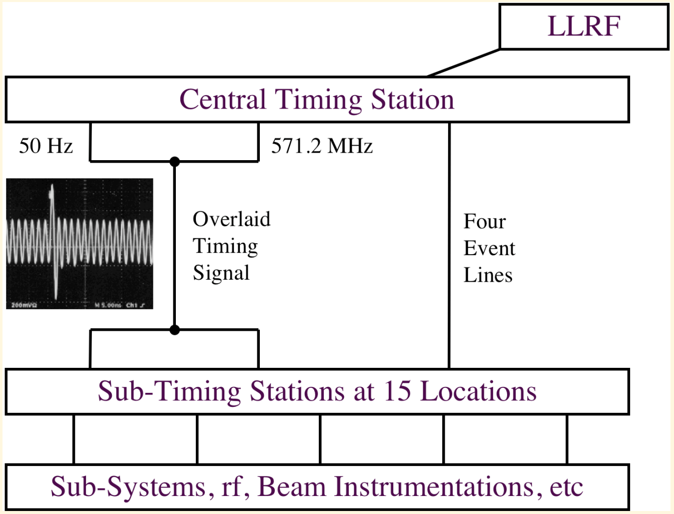
- ~100 parameter switching within 20ms
  - Keep most of magnet fields with compatible optics
  - Control llrf to change energy
- Pulsed magnet triggers and delays
  - Delays to keep the constant rate for certain power-supplies
- LLRF phases and delays
- Gun voltage and fine delay
- Interface to bucket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

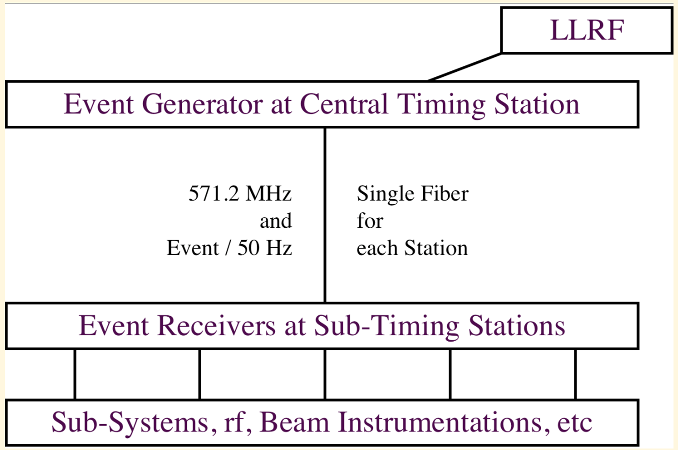
Event System

- **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**

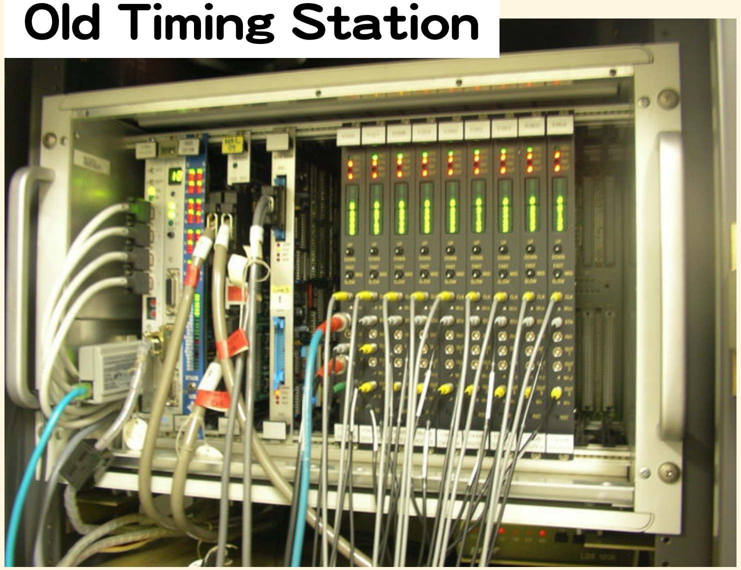


Timing System





Old Timing Station



New Event Receiver Station with 16 outputs

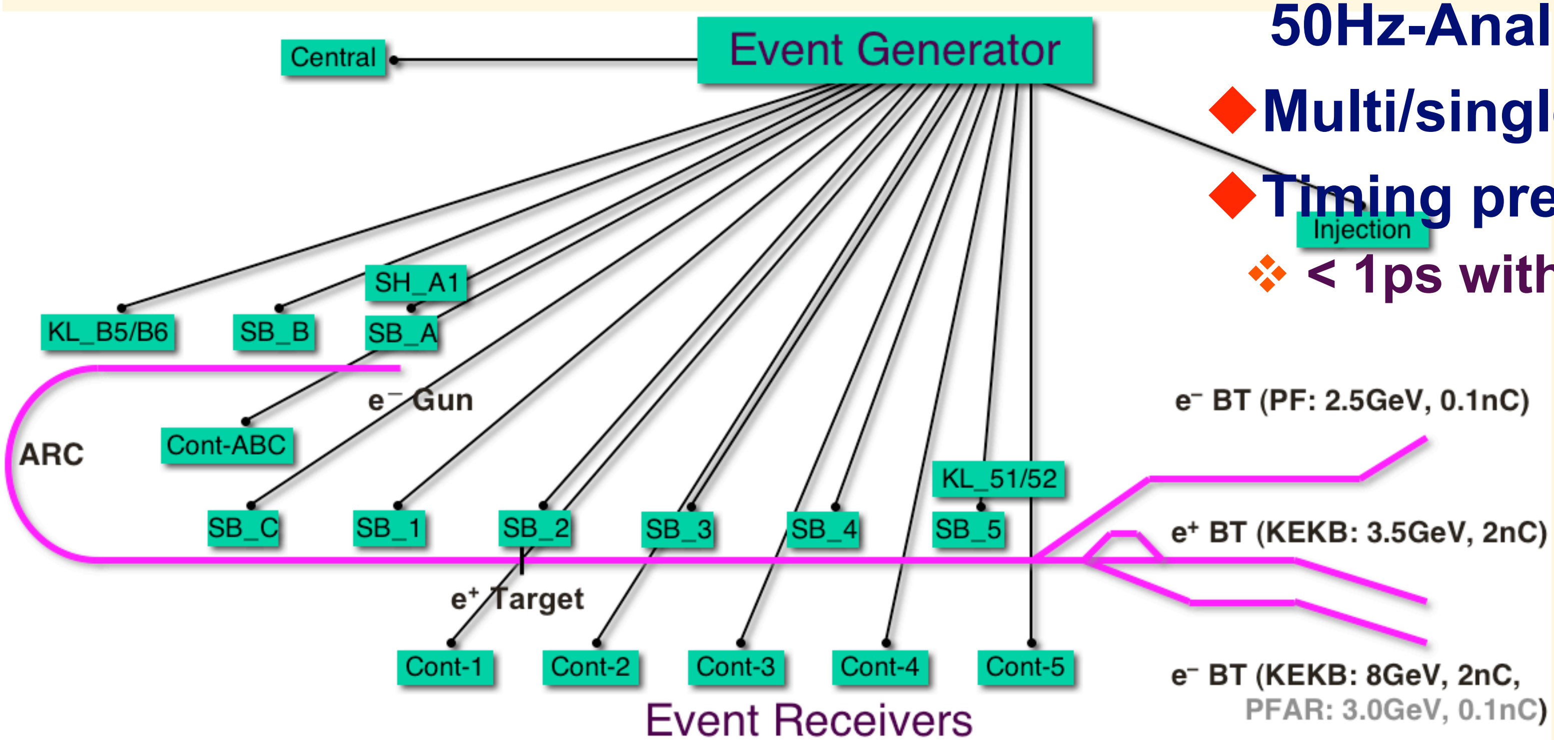
Event System

- **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

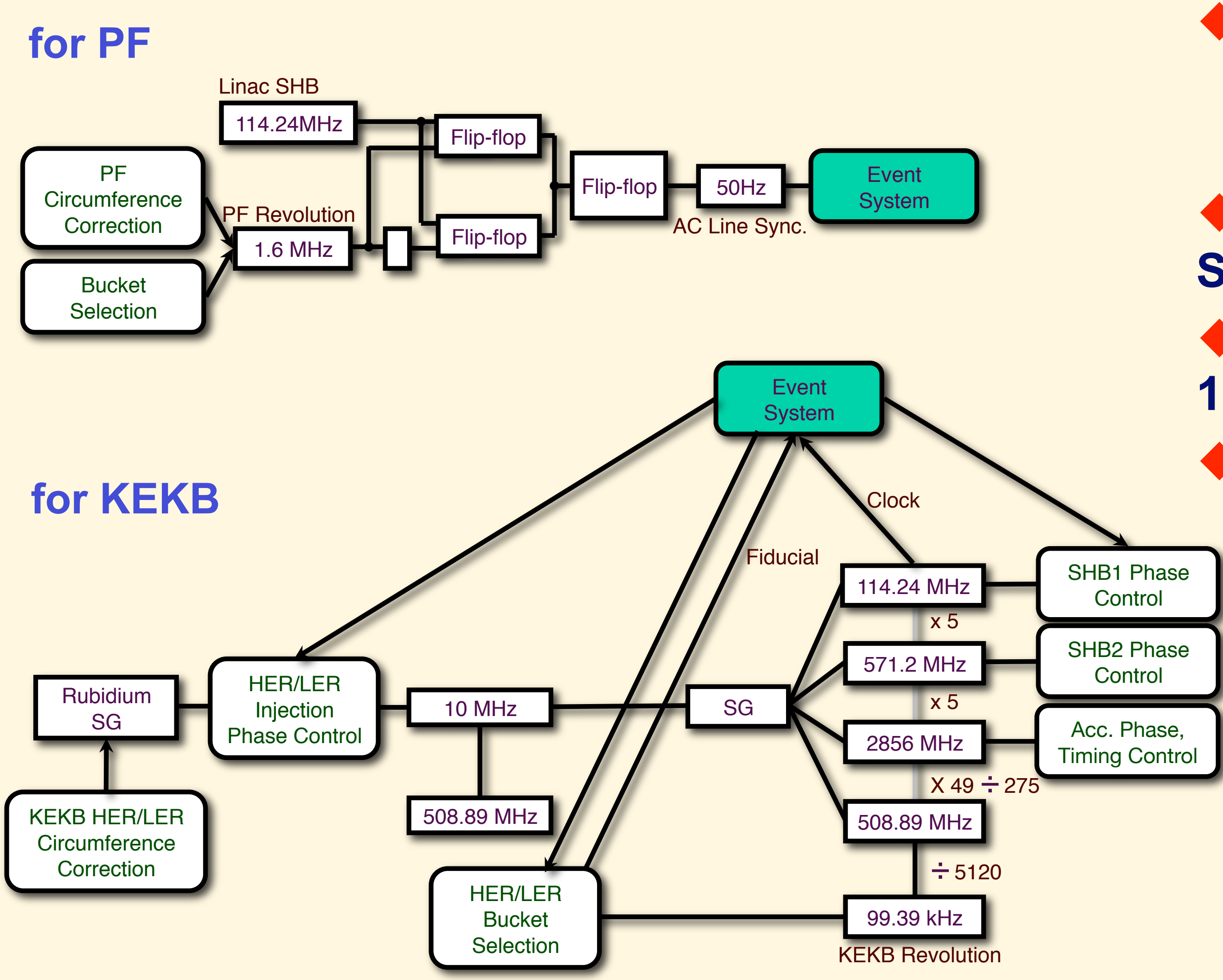
Event System Configuration

- 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



- **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

Pulse 1	Pulse 2	Pulse 3		Pulse n	
Beam Mode 1	Beam Mode 2	Beam Mode 3	………	Beam Mode n	n+1 …

Main event codes for ‘n’

Preparation event codes for ‘n+1’

- **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

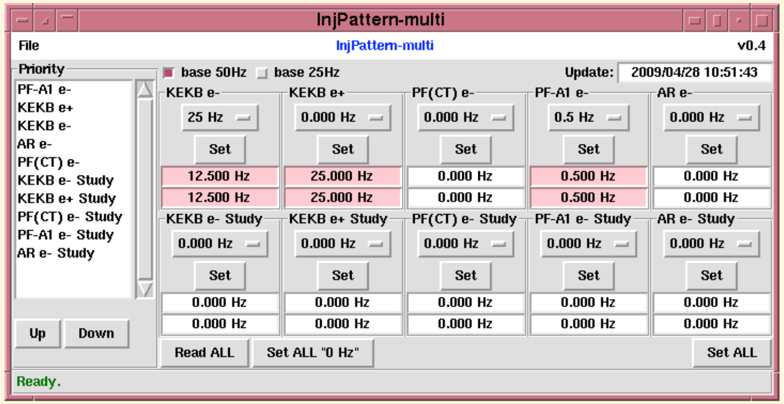
Generate Events for the Next 20-ms Time Slot (in Event Generator)
- reading two consecutive elements from the beam mode pattern
- generate several events for the next pulse
- generate preparation events for the next after next

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

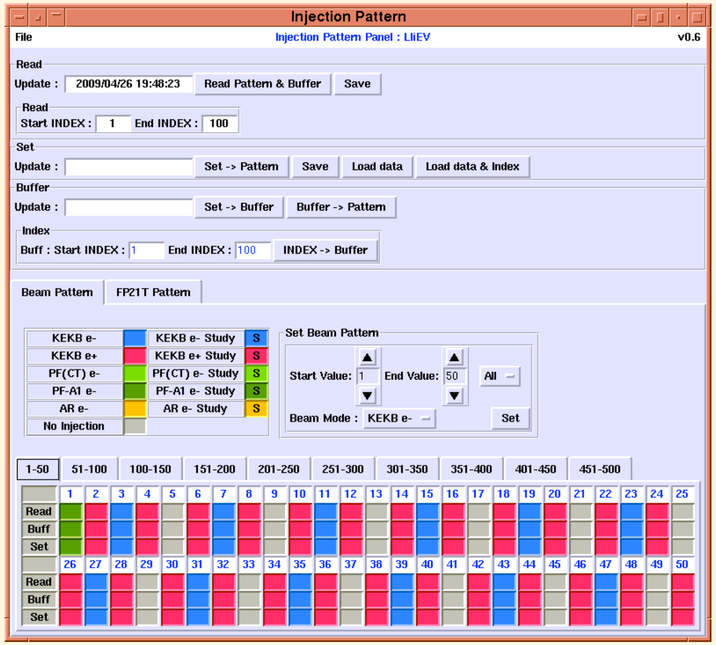
Beam Mode Pattern Generators

- **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



Manual pattern generator

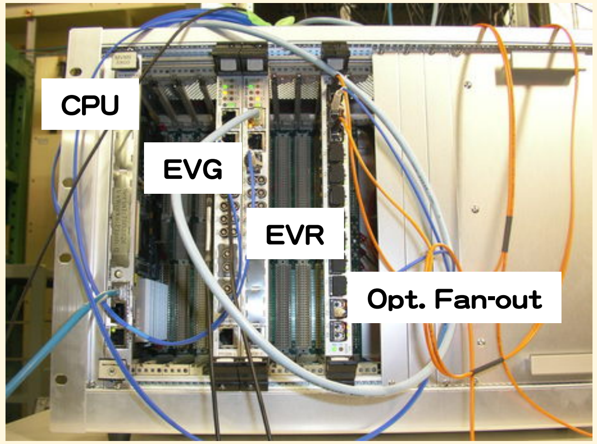


- **Typical operation in 2009.**
  - **~25Hz for KEKB LER**
  - **~12.5Hz for KEKB HER**
  - **~0.5Hz for PF**

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

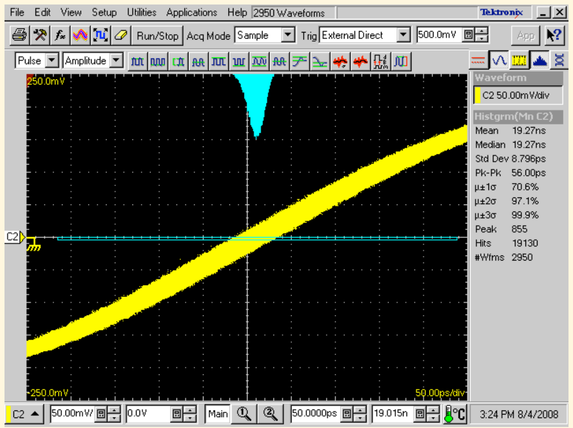


◆Satisfies the requirements

- ❖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

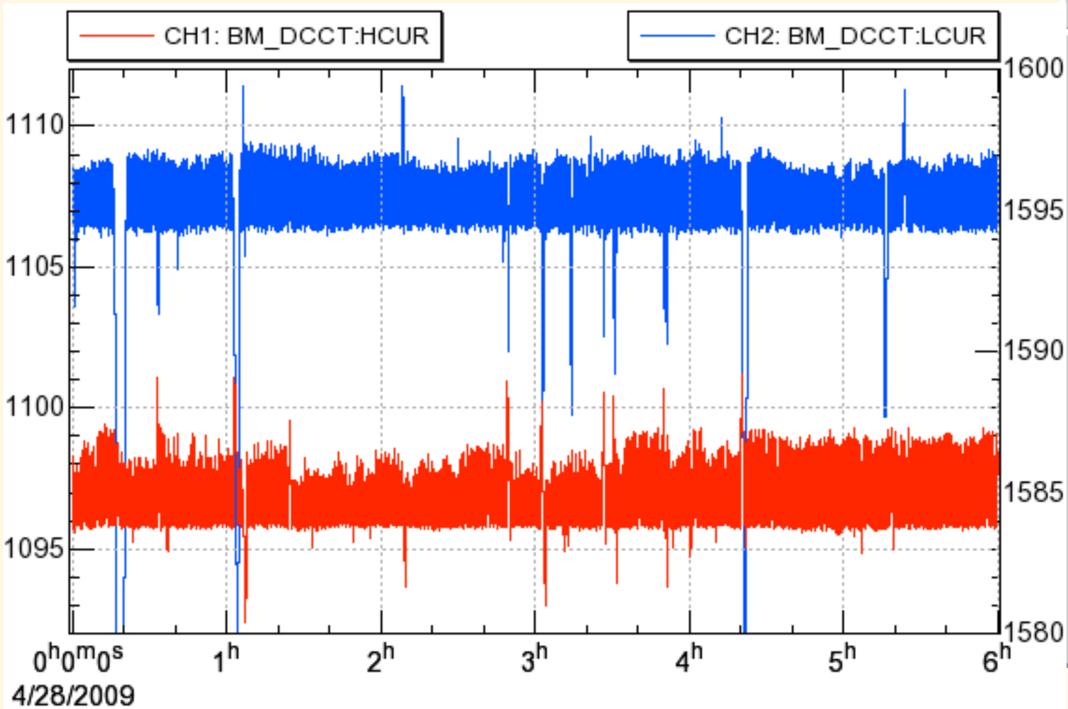
EVR & LLRF

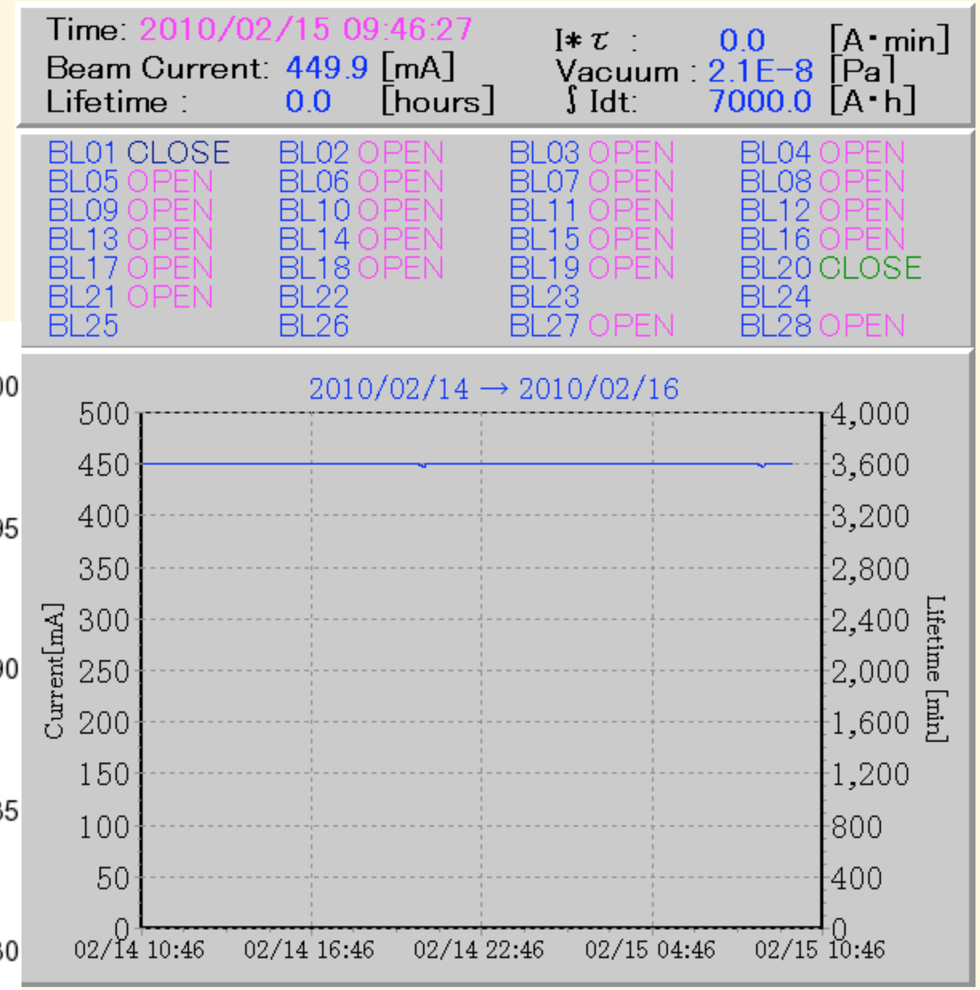
- ❖CPU stopped 4 times
  since Sep.2008
  for 18 stations



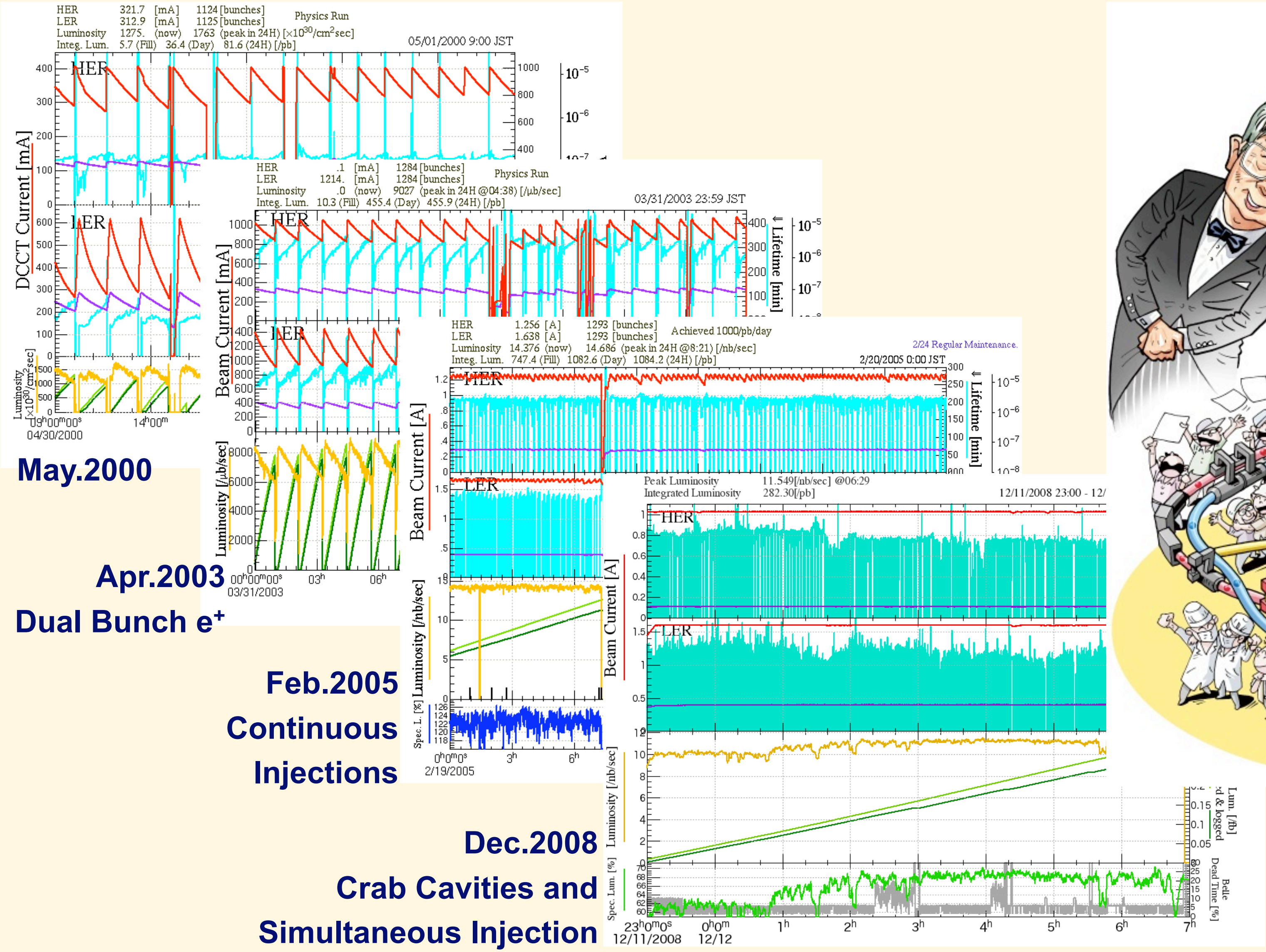
Beam Current

- **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

Belle/KEK

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