KEKB Injection Developments

(as a base of SuperKEKB)

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KEKB Injector overview

Dual bunches in a pulse

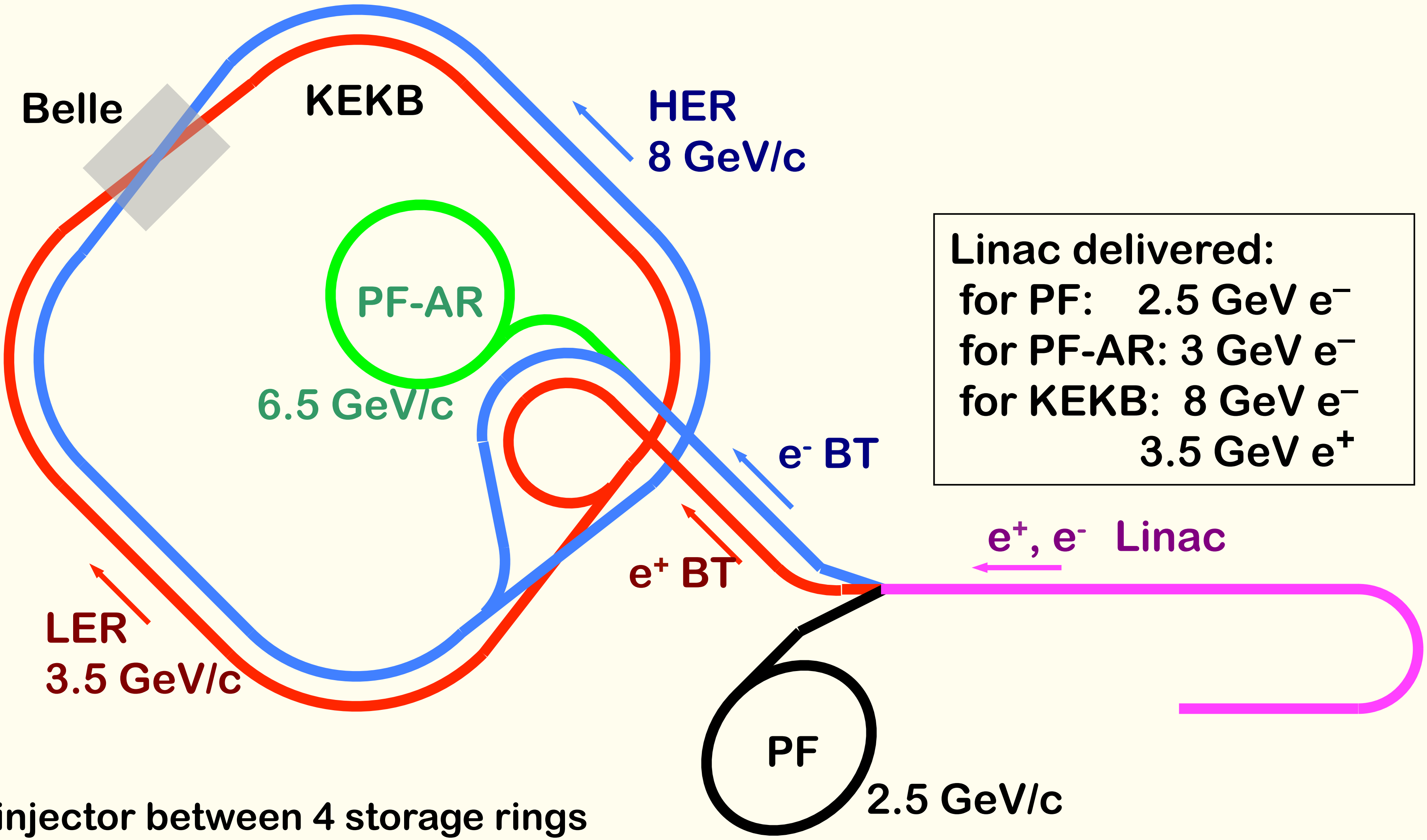
Continuous injection

Simultaneous top-up injection

Upgrade towards SuperKEKB

KEKB Configuration (– 2010)

◆Electron Positron Accelerator Complex at KEK



Linac delivered:
for PF: 2.5 GeV e^-
for PF-AR: 3 GeV e^-
for KEKB: 8 GeV e^-
3.5 GeV e^+

Shared single injector between 4 storage rings
Shared beam transport line between HER & PF-AR

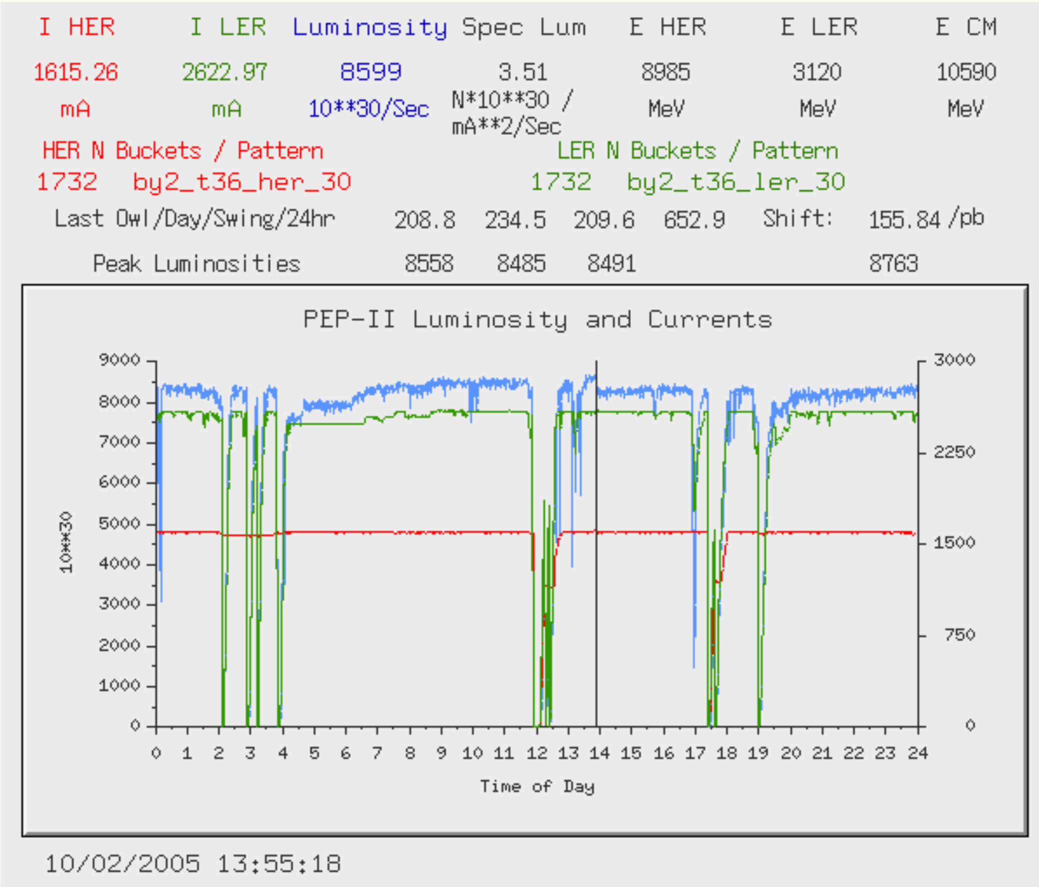
KEKB Design

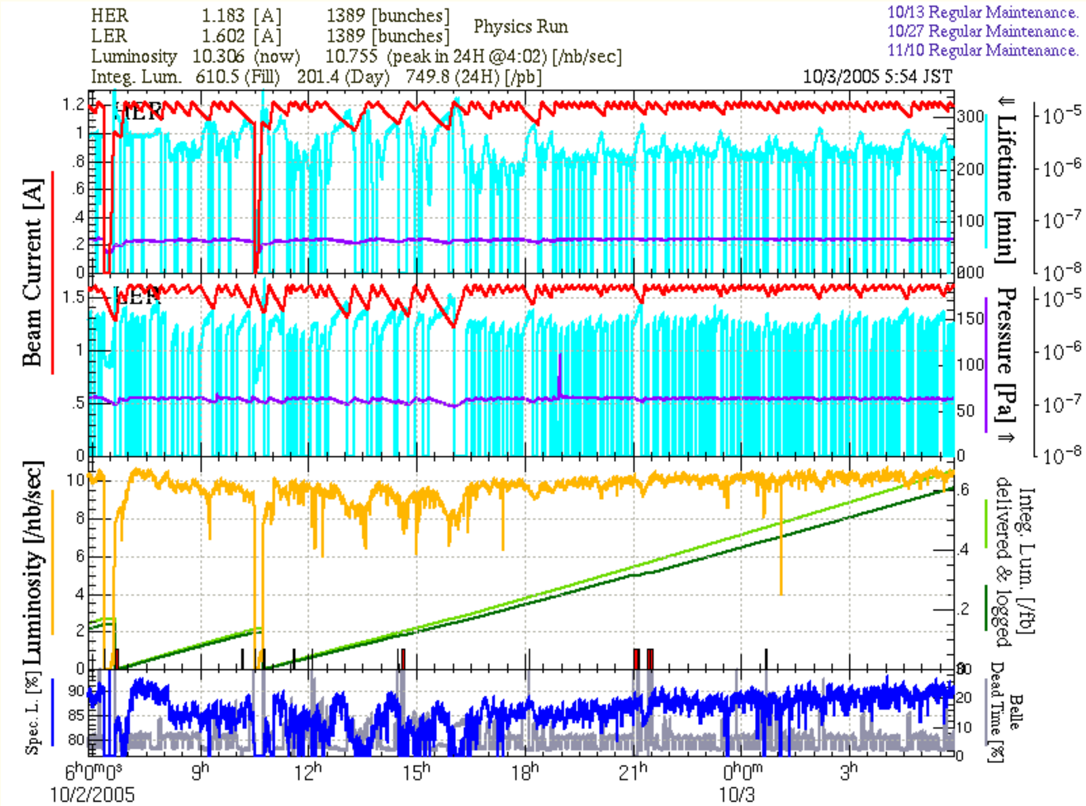
- **Maximum reuse of TRISTAN inheritance**
- **However, still many improvements applied, ex.**
  - **Many bunch collisions with dual ring collider**
    - **Energy asymmetry for the boost of center of mass of Bs**
  - **Full energy injection**
    - **Energy upgrade with SLED RF pulse compressor**
      - **from 2.5 GeV (400 m) → 8 GeV (600 m)**
  - **Injection aperture of 30 ps**
    - **Slight RF frequency modification to have an integer relation**
      - **Linac 2856 MHz : 10.386 MHz x 275**
      - **Ring (508.5 MHz →) 508.9 MHz : 10.386 MHz x 49**
  - **And so on**

PEP-II/SLAC and KEKB

◆We exchanged ideas between PEP-II and KEKB

❖Viewed each other from control rooms





¤ **Friendly competition**

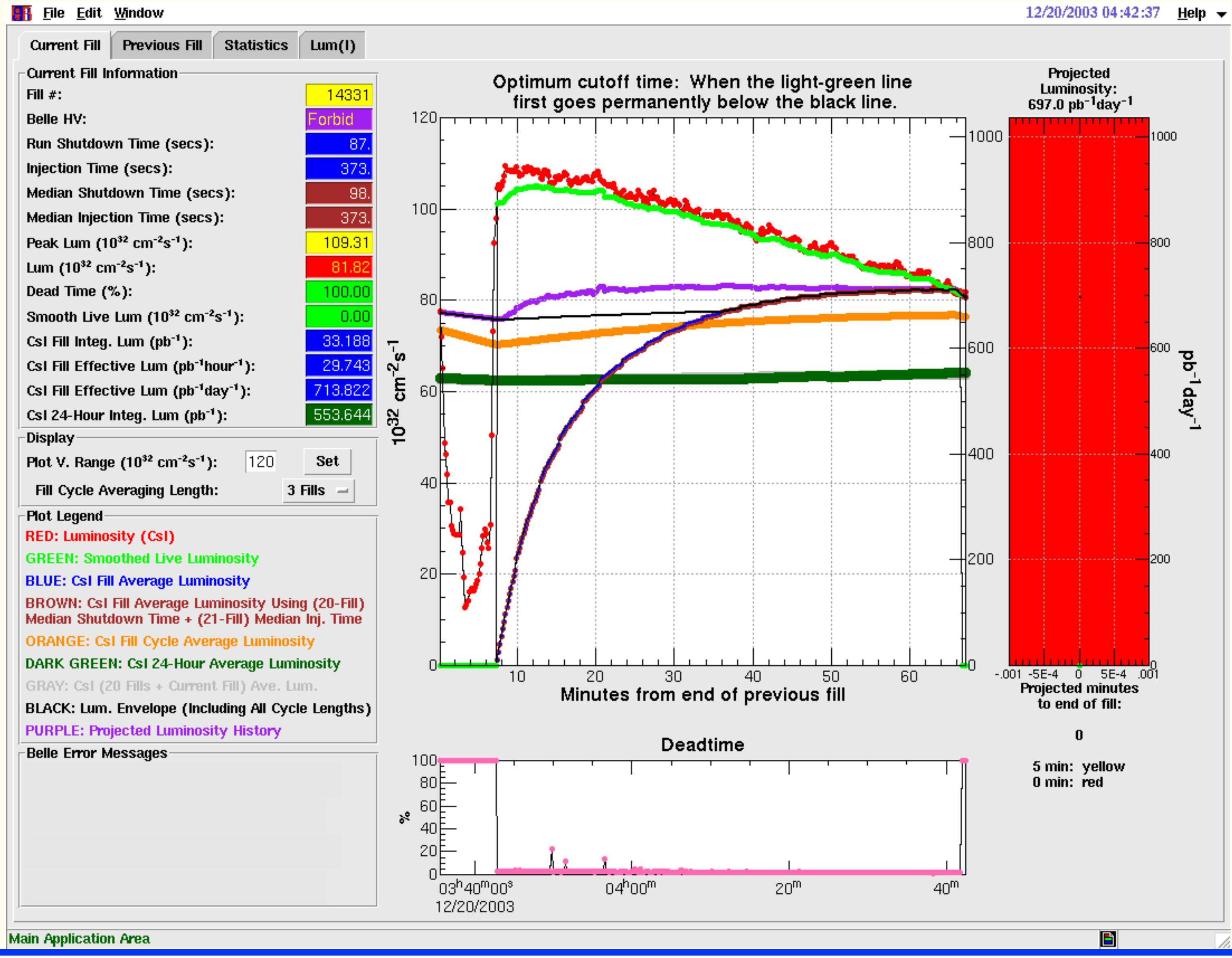
Performance improvements at KEKB

- **Competition with SLAC PEP-II**
  - One of worries was the injector capability
  - Injection beam quality
  - Beam stability
  - Beam current, especially positron
  - Injection time to fill the both storage rings
  - And, integrated luminosity

- **Many improvements required, however**
  - Two serious damages in accelerator structure in 2001
    - after the performance was pushed too hard
    - We found our way with optimized performance

Operational Optimizations

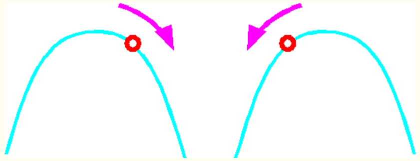
◆For example, run-length optimization



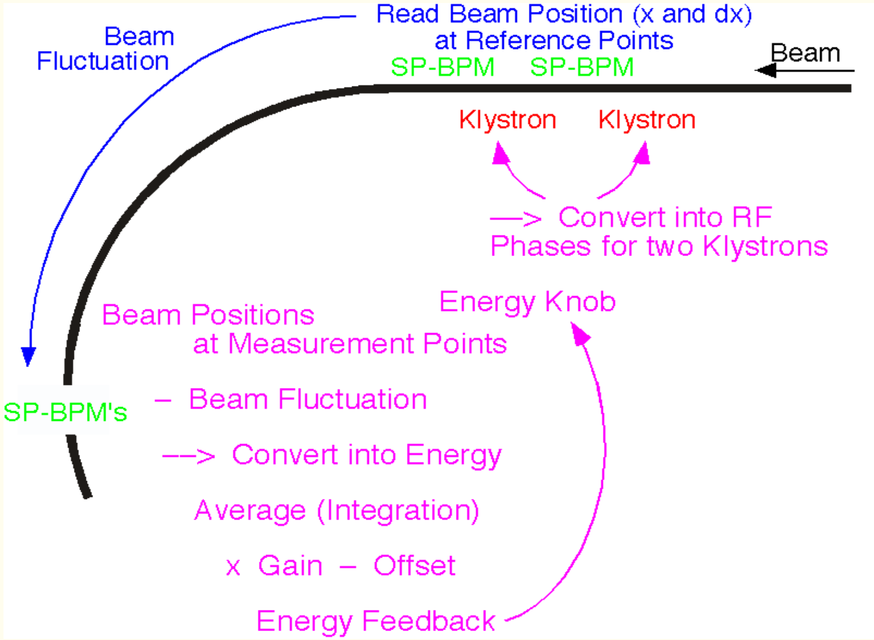
Energy Stabilization Loops

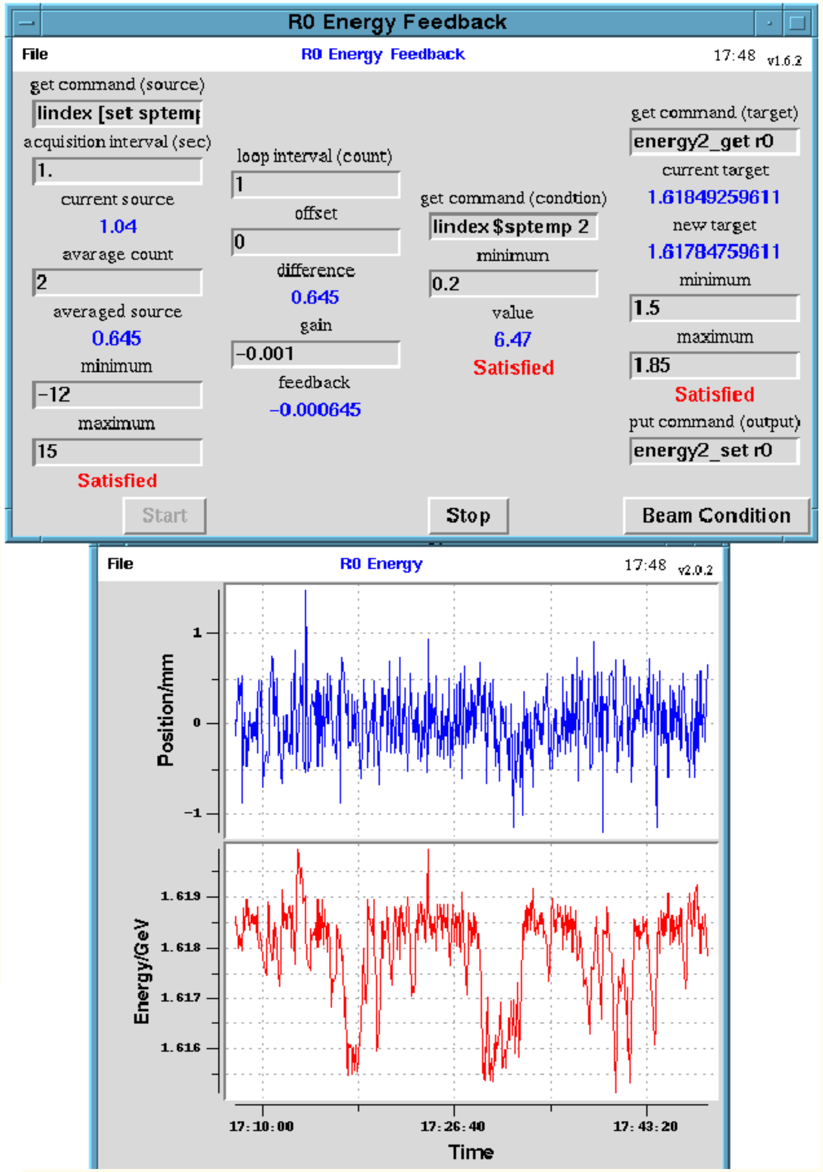
◆ BPMs - Energy knob

❖ **Energy knob without energy spread**



❖ **Simple P.I. Loop**

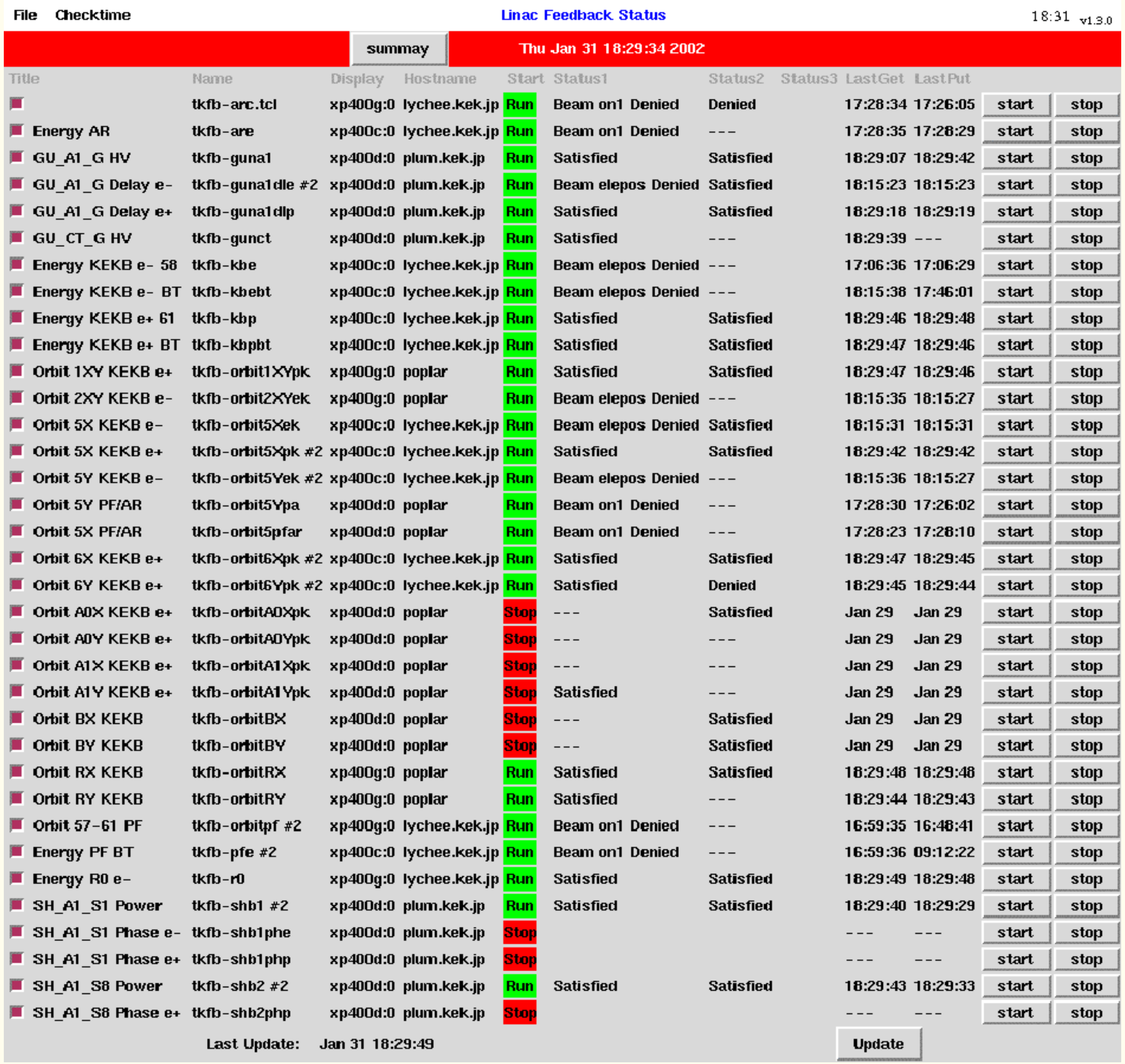




6 feedback loops along the linac depending on the modes

Feedback loop monitor

- **Robust operation is essential**
  - Remote monitoring in summary panel
  - Several conditions, limits in loop variables
  - Beam-mode dependent operation
  - Status and variable logging, and their viewers



File Checktime — Linac Feedback Status — 18:31 v1.3.0

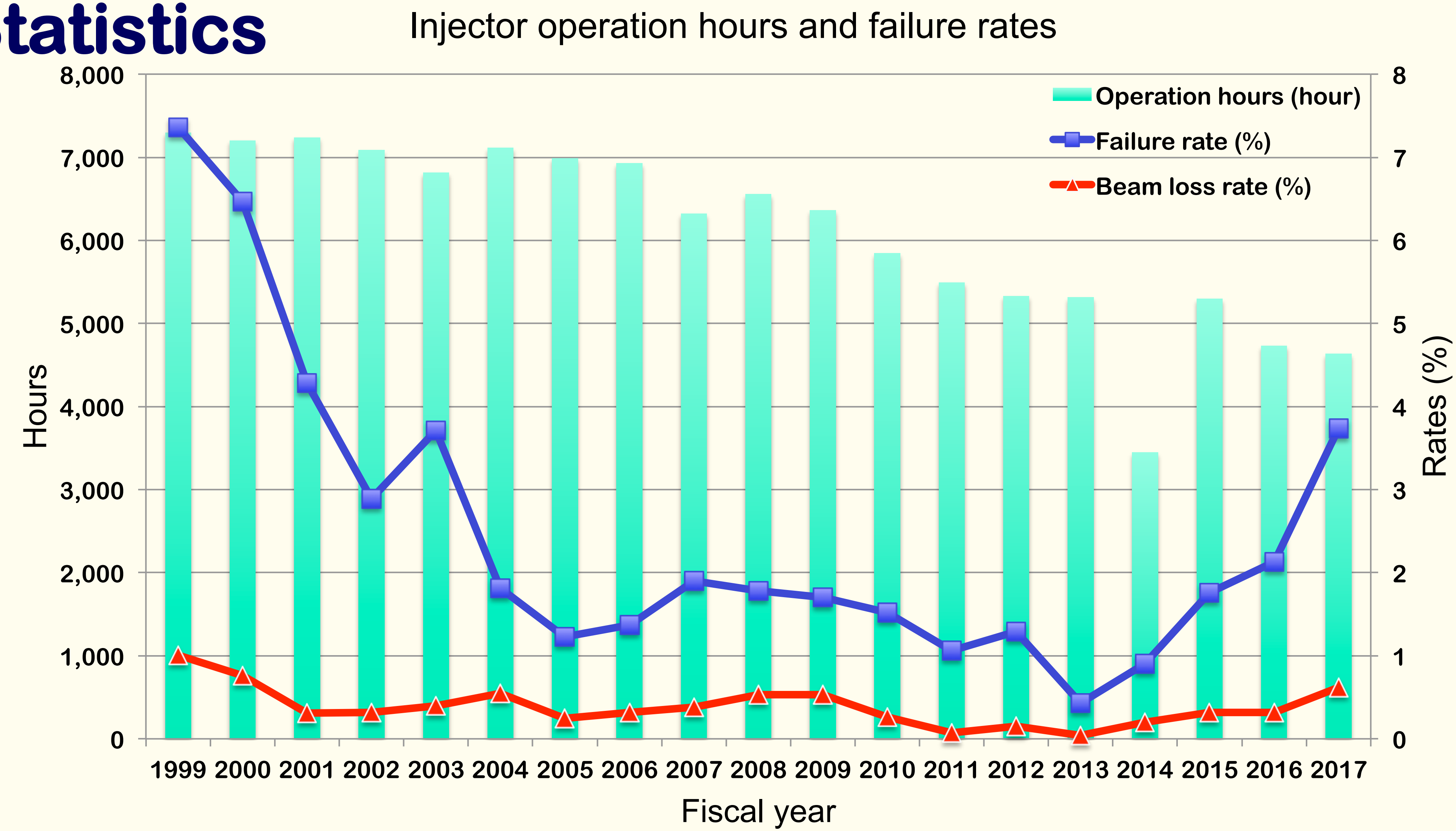
summay — Thu Jan 31 18:29:34 2002

Title	Name	Display	Hostname	Start	Status1	Status2	Status3	LastGet	LastPut		
	tkfb-arc.tcl	xp400g:0	lychee.kek.jp	Run	Beam on1 Denied	Denied		17:28:34	17:26:05	start	stop
Energy AR	tkfb-are	xp400c:0	lychee.kek.jp	Run	Beam on1 Denied	---		17:28:35	17:28:29	start	stop
GU_A1_G HV	tkfb-guna1	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:07	18:29:42	start	stop
GU_A1_G Delay e-	tkfb-guna1dle #2	xp400d:0	plum.kek.jp	Run	Beam elepos Denied	Satisfied		18:15:23	18:15:23	start	stop
GU_A1_G Delay e+	tkfb-guna1dlp	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:18	18:29:19	start	stop
GU_CT_G HV	tkfb-gunct	xp400d:0	plum.kek.jp	Run	Satisfied	---		18:29:39	---	start	stop
Energy KEKB e- 58	tkfb-kbe	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	---		17:06:36	17:06:29	start	stop
Energy KEKB e- BT	tkfb-kbebt	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	---		18:15:38	17:46:01	start	stop
Energy KEKB e+ 61	tkfb-kbp	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:46	18:29:48	start	stop
Energy KEKB e+ BT	tkfb-kbpbt	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:47	18:29:46	start	stop
Orbit 1XY KEKB e+	tkfb-orbit1XYpk	xp400g:0	poplar	Run	Satisfied	Satisfied		18:29:47	18:29:46	start	stop
Orbit 2XY KEKB e-	tkfb-orbit2XYek	xp400g:0	poplar	Run	Beam elepos Denied	---		18:15:35	18:15:27	start	stop
Orbit 5X KEKB e-	tkfb-orbit5Xek	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	Satisfied		18:15:31	18:15:31	start	stop
Orbit 5X KEKB e+	tkfb-orbit5Xpk #2	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:42	18:29:42	start	stop
Orbit 5Y KEKB e-	tkfb-orbit5Yek #2	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	---		18:15:36	18:15:27	start	stop
Orbit 5Y PF/AR	tkfb-orbit5Ypa	xp400d:0	poplar	Run	Beam on1 Denied	---		17:28:30	17:26:02	start	stop
Orbit 5X PF/AR	tkfb-orbit5pfar	xp400d:0	poplar	Run	Beam on1 Denied	---		17:28:23	17:28:10	start	stop
Orbit 6X KEKB e+	tkfb-orbit6Xpk #2	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:47	18:29:45	start	stop
Orbit 6Y KEKB e+	tkfb-orbit6Ypk #2	xp400c:0	lychee.kek.jp	Run	Satisfied	Denied		18:29:45	18:29:44	start	stop
Orbit A0X KEKB e+	tkfb-orbitA0Xpk	xp400d:0	poplar	Stop	---	Satisfied		Jan 29	Jan 29	start	stop
Orbit A0Y KEKB e+	tkfb-orbitA0Ypk	xp400d:0	poplar	Stop	---	---		Jan 29	Jan 29	start	stop
Orbit A1X KEKB e+	tkfb-orbitA1Xpk	xp400d:0	poplar	Stop	---	---		Jan 29	Jan 29	start	stop
Orbit A1Y KEKB e+	tkfb-orbitA1Ypk	xp400d:0	poplar	Stop	Satisfied	---		Jan 29	Jan 29	start	stop
Orbit BX KEKB	tkfb-orbitBX	xp400d:0	poplar	Stop	---	Satisfied		Jan 29	Jan 29	start	stop
Orbit BY KEKB	tkfb-orbitBY	xp400d:0	poplar	Stop	---	Satisfied		Jan 29	Jan 29	start	stop
Orbit RX KEKB	tkfb-orbitRX	xp400g:0	poplar	Run	Satisfied	Satisfied		18:29:48	18:29:48	start	stop
Orbit RY KEKB	tkfb-orbitRY	xp400g:0	poplar	Run	Satisfied	---		18:29:44	18:29:43	start	stop
Orbit 57-61 PF	tkfb-orbitpf #2	xp400g:0	lychee.kek.jp	Run	Beam on1 Denied	---		16:59:35	16:48:41	start	stop
Energy PF BT	tkfb-pfe #2	xp400c:0	lychee.kek.jp	Run	Beam on1 Denied	---		16:59:36	09:12:22	start	stop
Energy R0 e-	tkfb-r0	xp400g:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:49	18:29:48	start	stop
SH_A1_S1 Power	tkfb-shb1 #2	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:40	18:29:29	start	stop
SH_A1_S1 Phase e-	tkfb-shb1phe	xp400d:0	plum.kek.jp	Stop				---	---	start	stop
SH_A1_S1 Phase e+	tkfb-shb1php	xp400d:0	plum.kek.jp	Stop				---	---	start	stop
SH_A1_S8 Power	tkfb-shb2 #2	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:43	18:29:33	start	stop
SH_A1_S8 Phase e+	tkfb-shb2php	xp400d:0	plum.kek.jp	Stop				---	---	start	stop

Last Update: Jan 31 18:29:49 — Update

Operation statistics and improvements

◆ Statistics



- **Failure: device failures that prevent optimum performance**
- **Beam loss: time when beam injection was really impossible**

KEKB Injector overview

Dual bunches in a pulse

Continuous injection

Simultaneous top-up injection

Upgrade towards SuperKEKB

Two bunches in a pulse

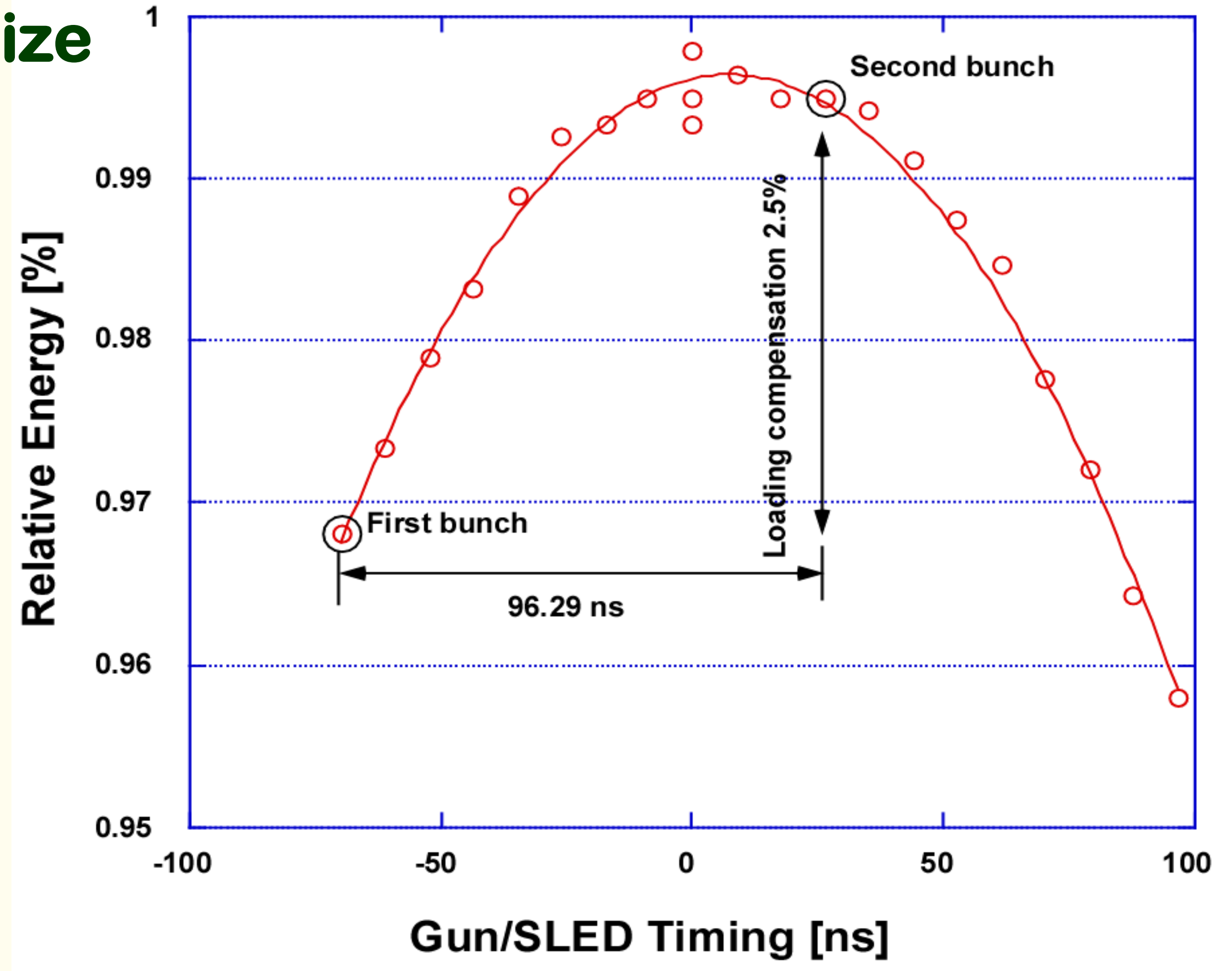
- As the stored beam current in MR increases, much more injection beam current was required
- Especially for the positron injection rate

Two bunches in a pulse acceleration in order to to double the positron beam current planned

- Minimum bunch separation of 96 ns (10.386 MHz)
- Parallel dual grid pulsers for a single cathode
- Beam instrumentation with 96 ns separation
- Timing manipulation and bucket selection
- Energy equalization

Energy Equalization

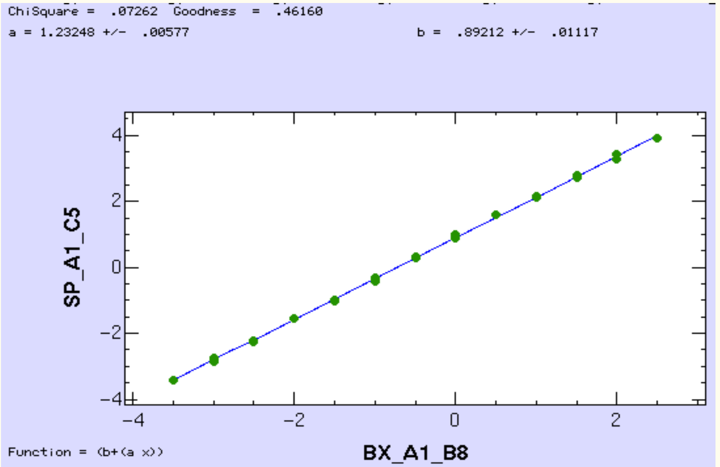
- **Beam loading compensation**
  - **For bunch separation of 96 ns**
    - **Or we sometimes utilize energy difference in order to equalize the beam orbits**



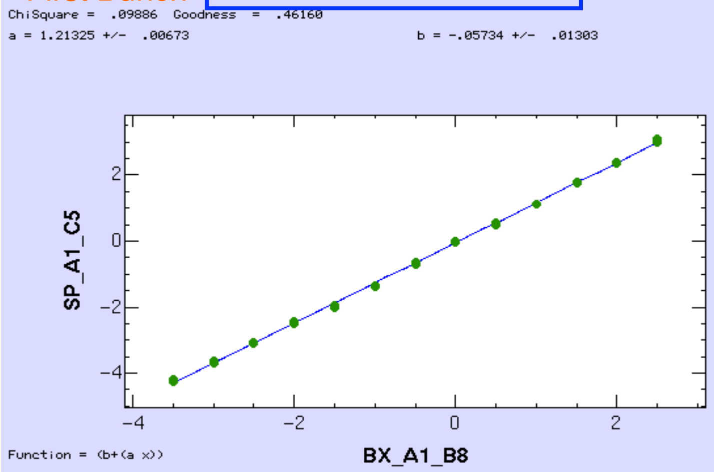
Dual-bunch Energy Equalization, and Feedback

- **Energy equalization is important for stable operation**

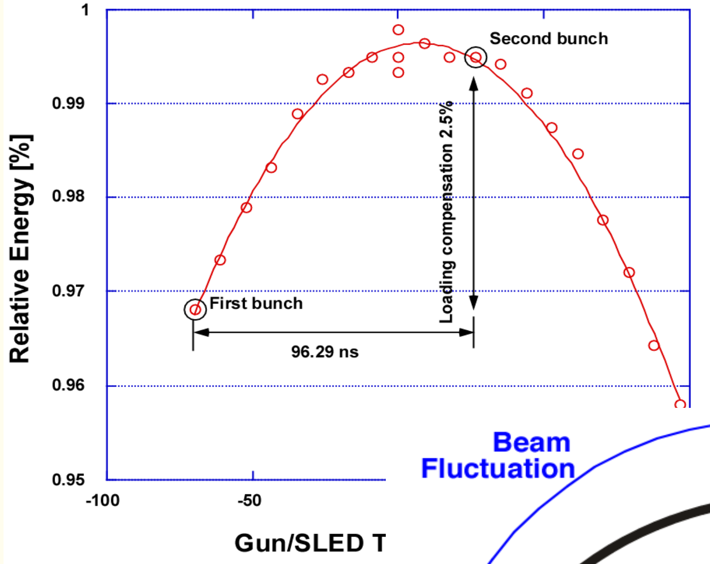
Measurement at bunching section
after energy equalization
with RF pulse timing



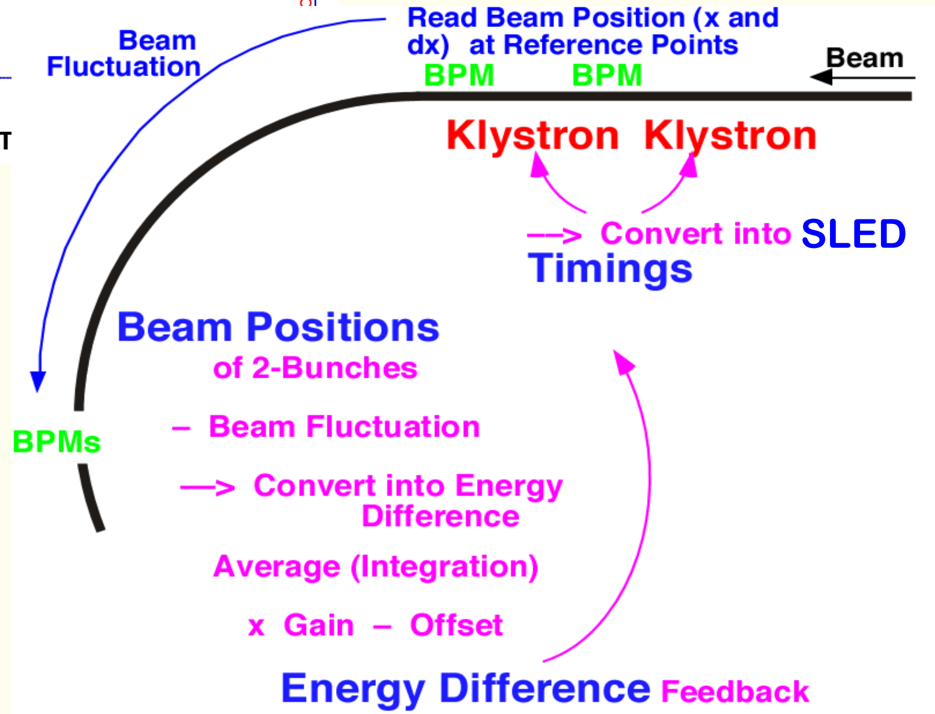
First Bunch **Energy at A1_B8 : 15.53780242662299 MeV**



Second Bunch **Energy at A1_B8 : 15.784086844082665 MeV**



Stabilization at bending section
with SLED timing



KEKB Injector overview

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Upgrade towards SuperKEKB

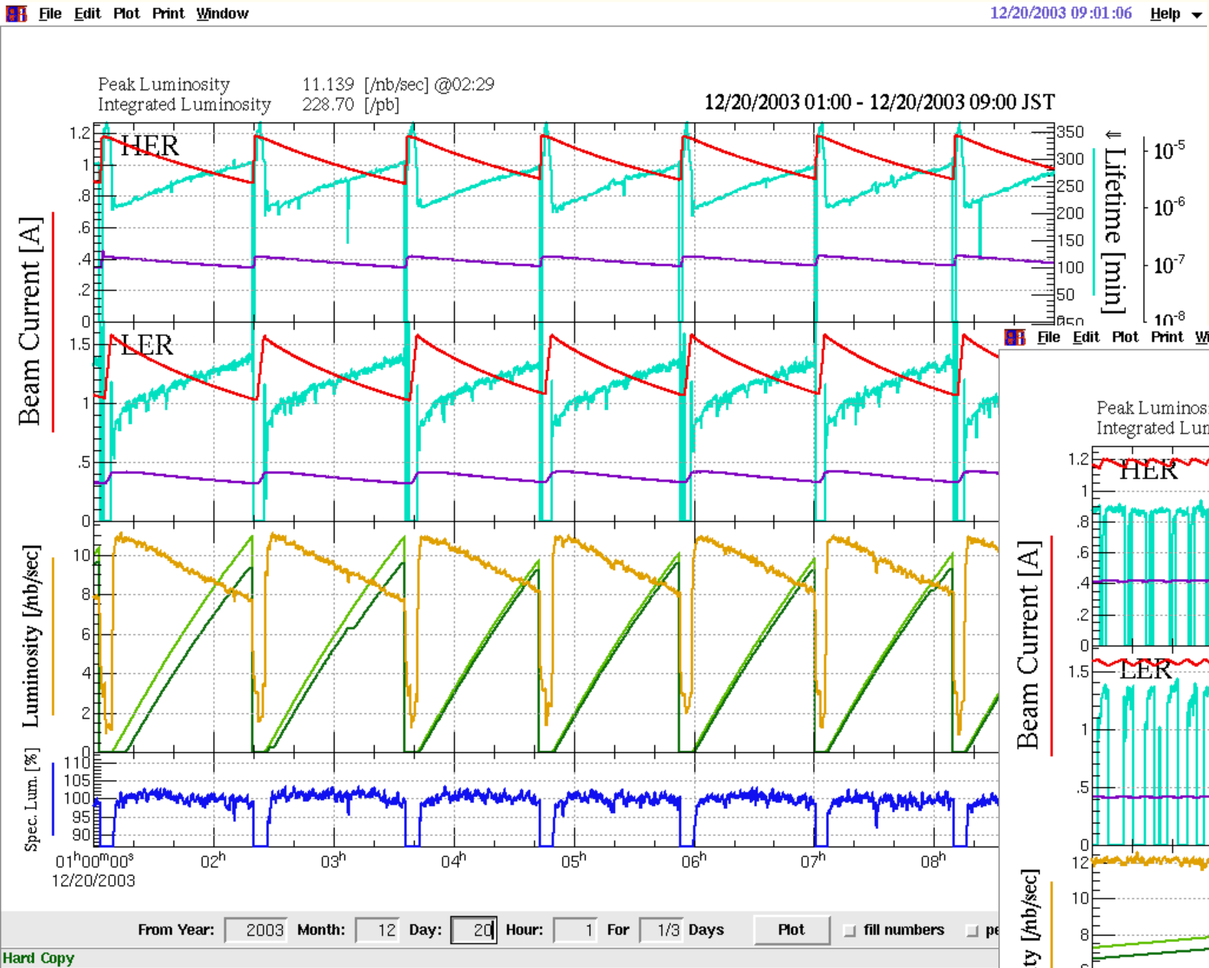
Continuous Injection

- Detector data acquisition stopped during the injection and the detector high voltage (HV) preparation
- Especially for the positron injection rate

Continuous Injection with detector HV applied was another major step forward

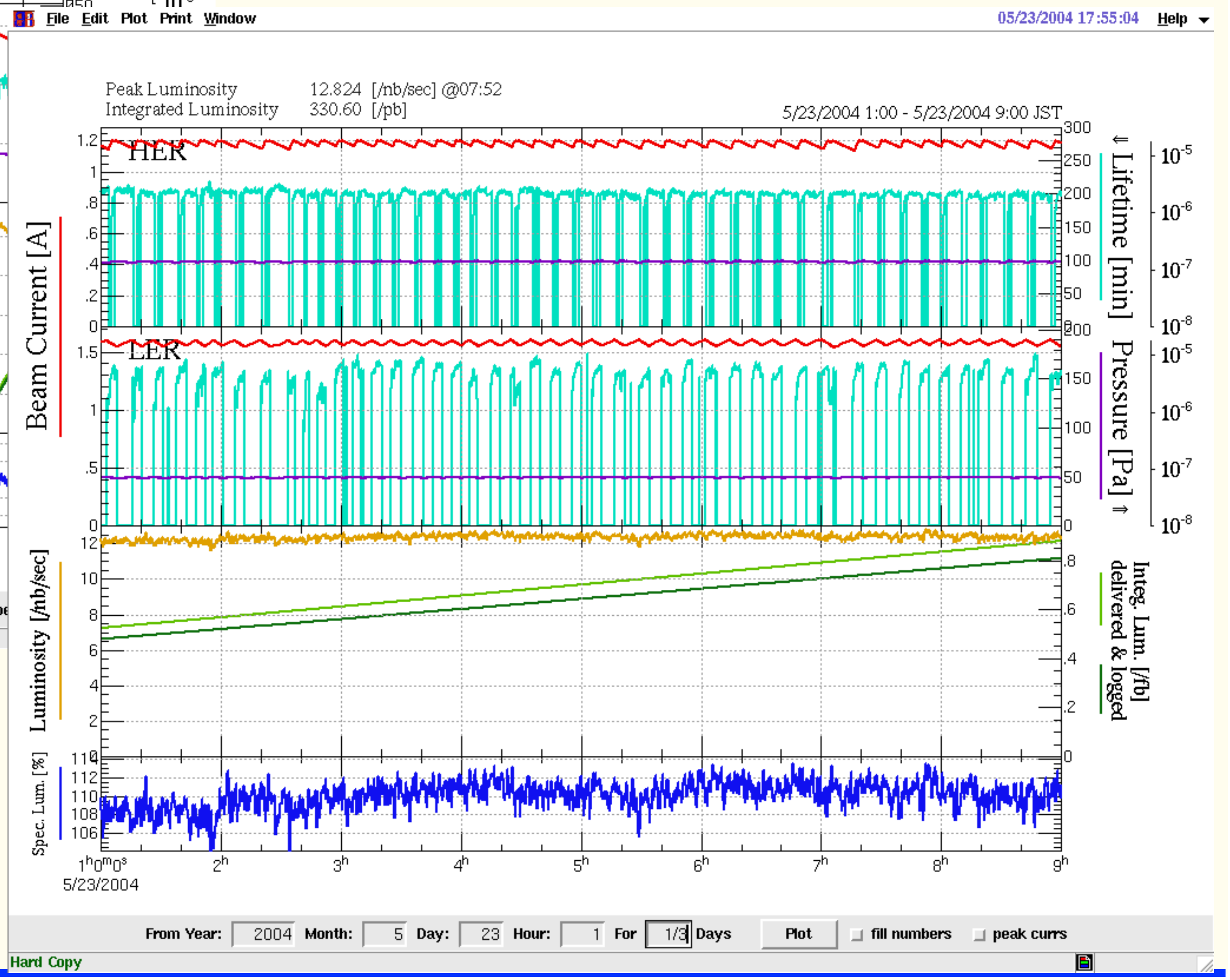
- For higher integrated luminosity
- by detector improvements, esp. CDC, TOF, DAQ
- with certain benefit from collision with crossing angle
  - without bending magnet at IP, for lower background
- Then, approximately 26% gain achieved

Continuous injection



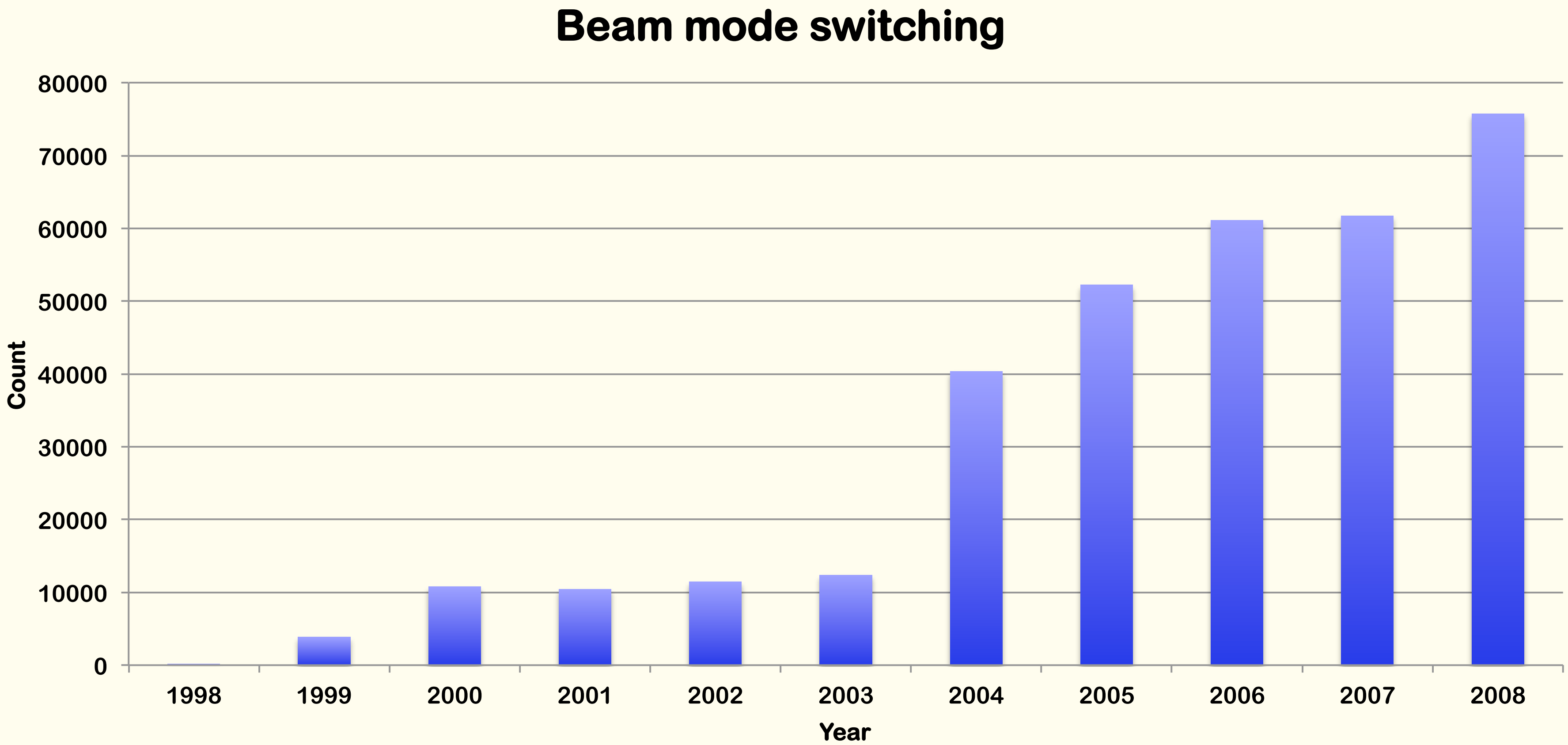
2003, before continuous injection was applied
Data acquisition stopped during injection
(8-hour history of beam current, luminosity, etc.)

2004, after continuous injection was applied
Data acquisition continued during injection
(8-hour history of beam current, luminosity, etc.)



Beam mode switching improvements

- Continuous injection was applied in 2004



- Switched 360 times / day in 2008
- Simultaneous top-up injection was applied in 2009

KEKB Injector overview

Dual bunches in a pulse

Continuous injection

Simultaneous top-up injection

Upgrade towards SuperKEKB

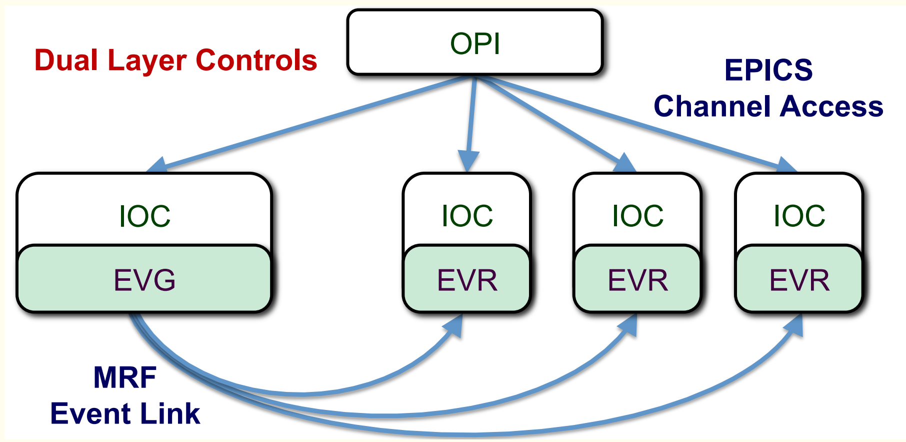
Simultaneous Top-up Injections

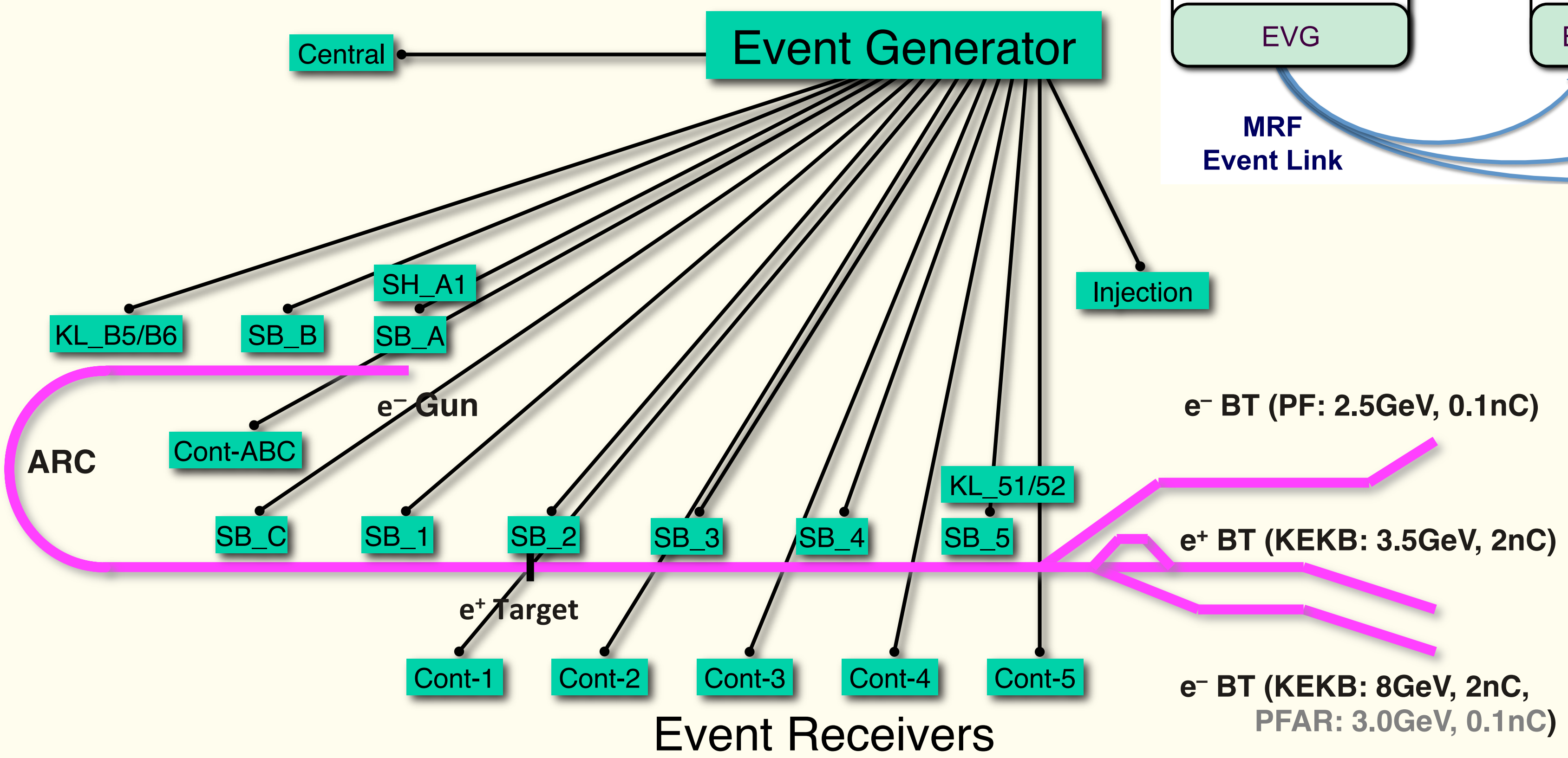
- Even faster beam mode switches
- **Pulse-to-pulse modulation (PPM) at 50 Hz**
  - PPM was applied at PS/CERN (1977?) at 1.2 s
  - ~150 parameters were switched every 20 ms for 3 beams
- **Many Hardware improvements as well as controls**
  - PF top-up injection for higher quality experiments
  - Sensitive luminosity tuning with Crab cavities
  - Many more parameters in SuperKEKB for 4 beams

Fast Global Synchronous Controls

- **Event-based controls (MRF)**
- **114.24MHz event rate, 50Hz fiducials**
- **Timing precision < 10ps**

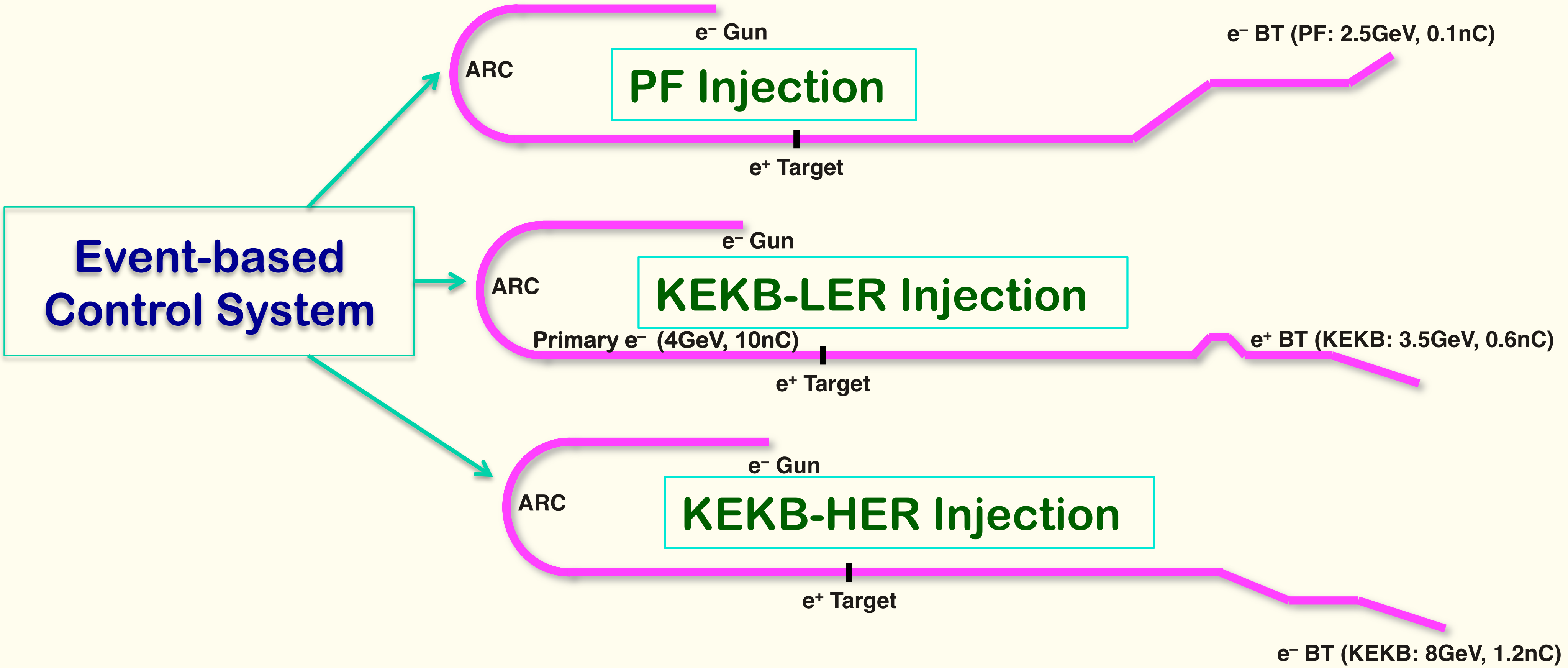
Dual layer control concept





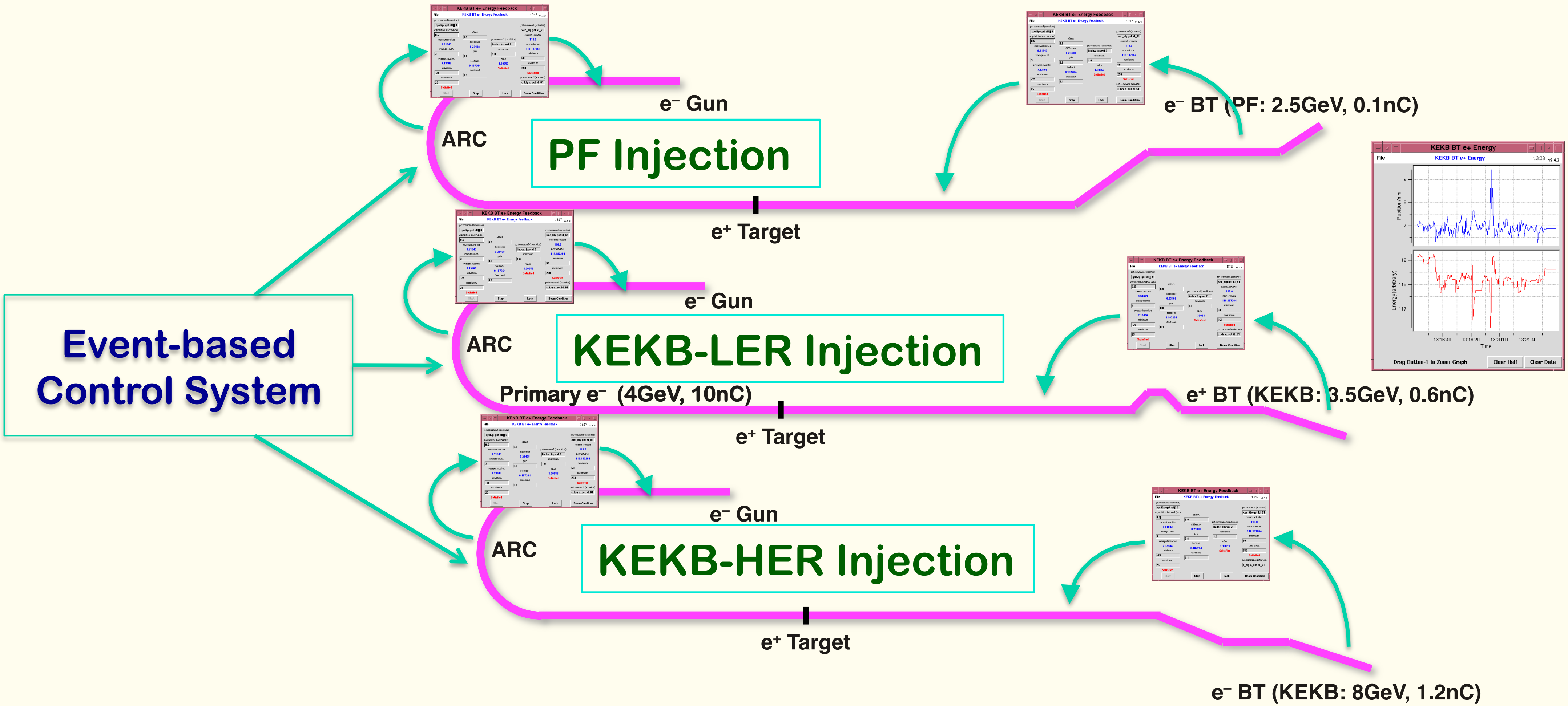
One Machine, Multiple Virtual Accelerators (VAs)

- **Control/Monitor are carried dependent on a VA**
  - **Mostly independent between VAs**
- **Independent parameter set for each VA, one of the VAs is controlled at a time**
  - **VAs for Injections (HER (e-), LER (e+), PF, PF-AR) and Linac-only in SuperKEKB project**



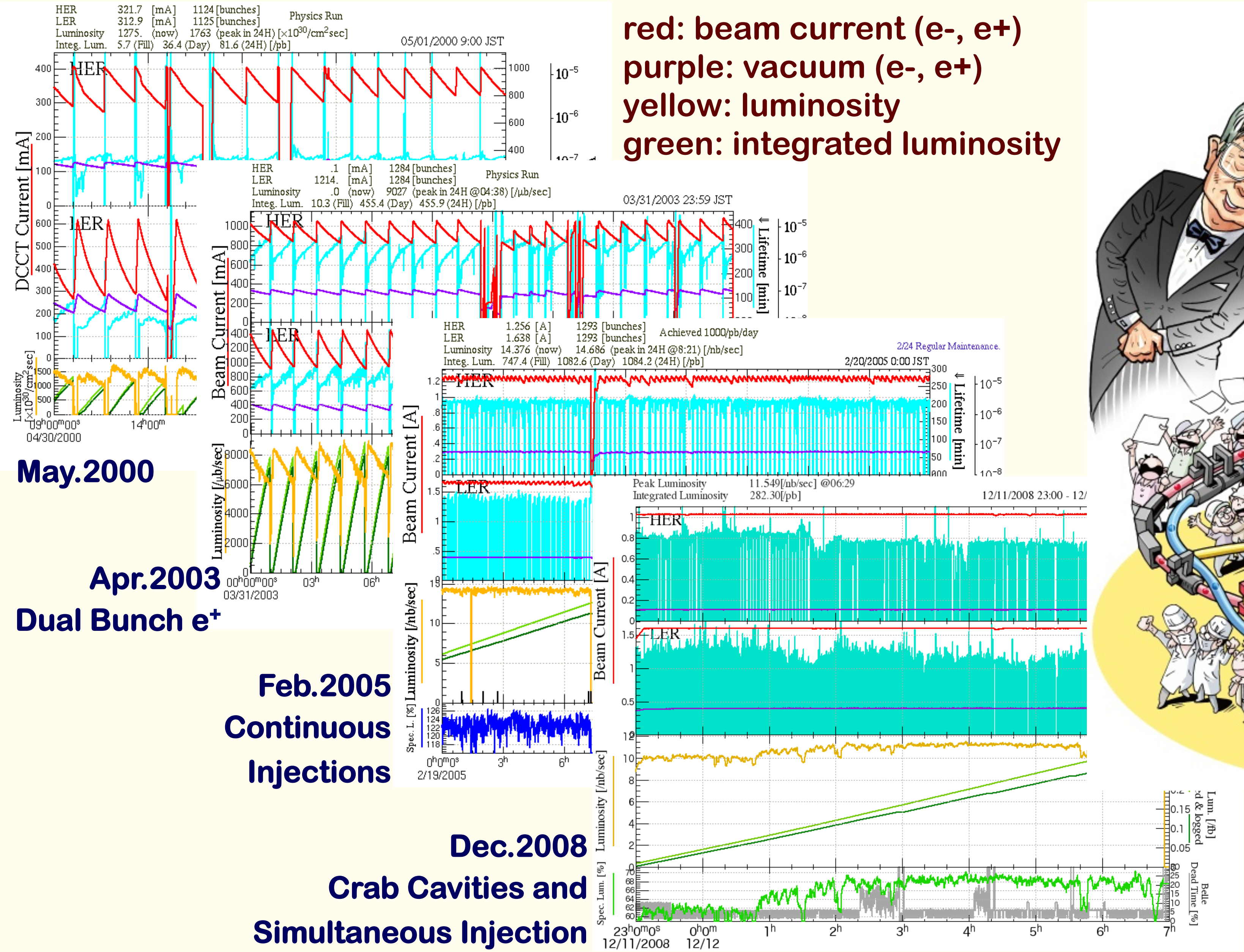
Multiple Closed Loop Controls Overlapped

- Closed loops were installed on each VA independently

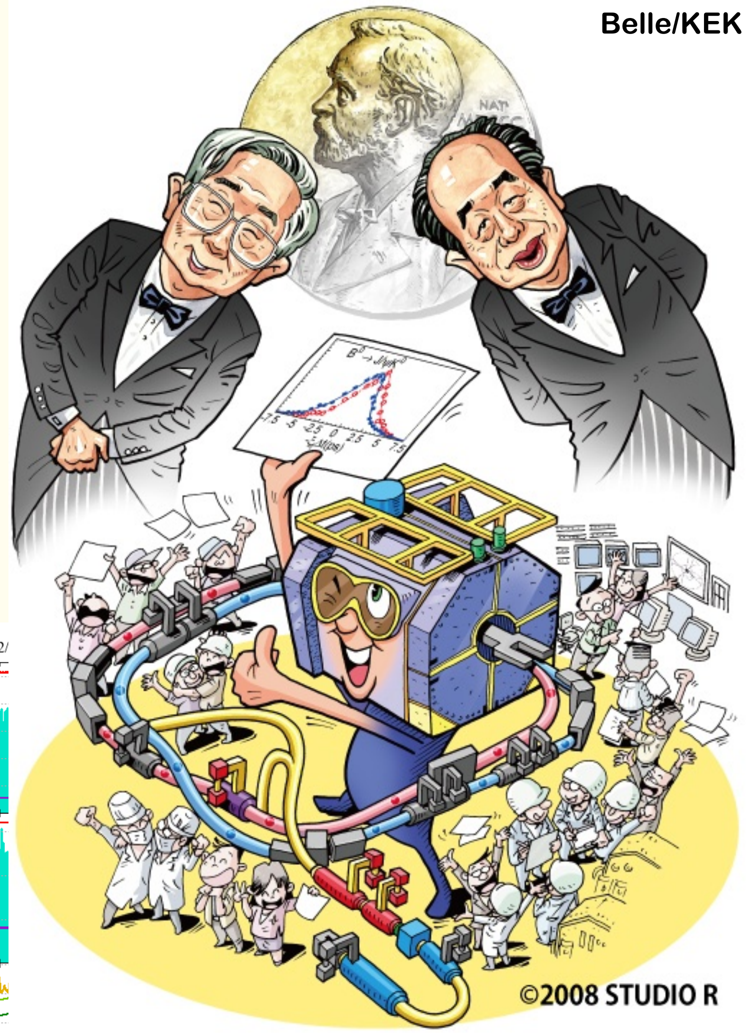


KEKB Operation Improvement (base of SuperKEKB)

red: beam current (e-, e+)
purple: vacuum (e-, e+)
yellow: luminosity
green: integrated luminosity



Belle/KEK



Keeps world luminosity record

KEKB Injector overview

Dual bunches in a pulse

Continuous injection

Simultaneous top-up injection

Upgrade towards SuperKEKB

SuperKEKB at 2002

- **Some consideration on upgrade for SuperKEKB was presented already in 2002**
- **Much different from present form, but this shows a project needs a long lead time**

  - **Later,**
  - **Energy exchange was rejected**
  - **Nano-beam scheme was employed**

Present Status and Future Upgrade of KEK e^- Linac

Linac / Ring Upgrade for SuperKEKB

- for Precise Measurement of *B*-meson System Parameters and Search for New Physics (ex. SUSY)

  SuperKEKB : Luminosity of 10^{35} cm^{-2} s^{-1}

  with Major Upgrade of Linac and Ring

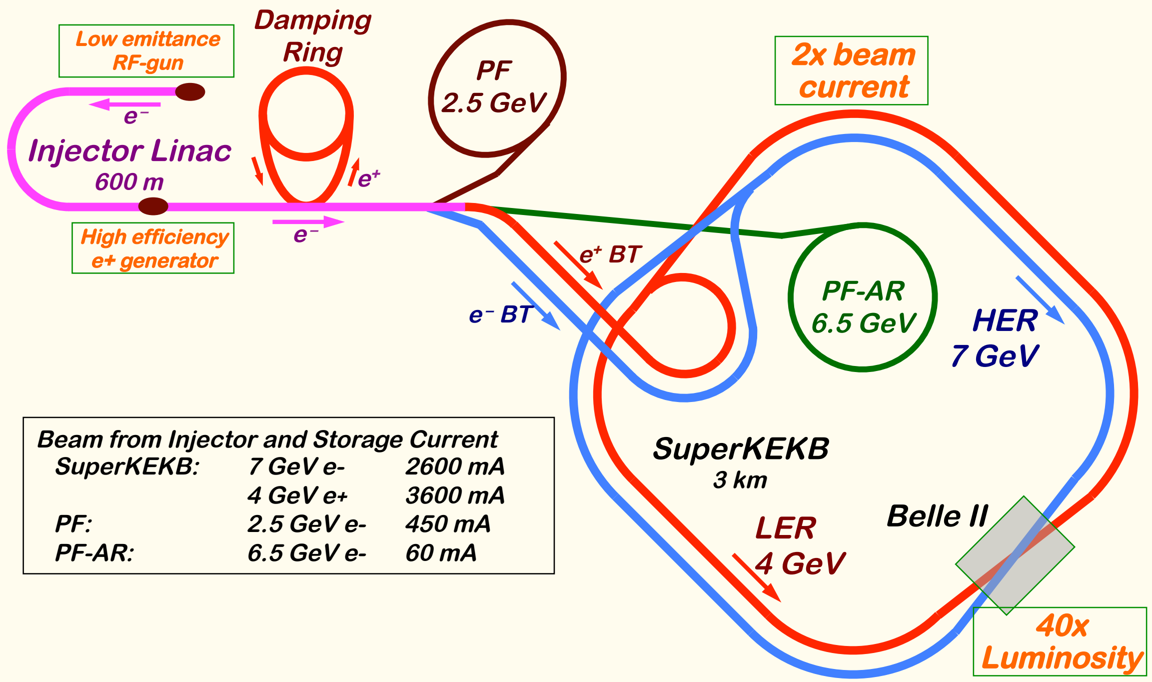
- Luminosity Increase
  - (1) Squeezing Beta at Interaction Region (by factor of 3.3)
  - (2) Increasing e^- and e^+ Beam Current (by factor of 3.3)
  - (3) Exchanging Energies of e^- and e^+ (to cure e^- cloud issues)

- for Linac
  - (3) is the Major Challenge, as well as (2)
  - Two Schemes are Considered
    - (a) Higher Gradient with C-band Structures
    - (b) Recirculation of Positron

K.Furukawa, Linac2002, Aug.2002.

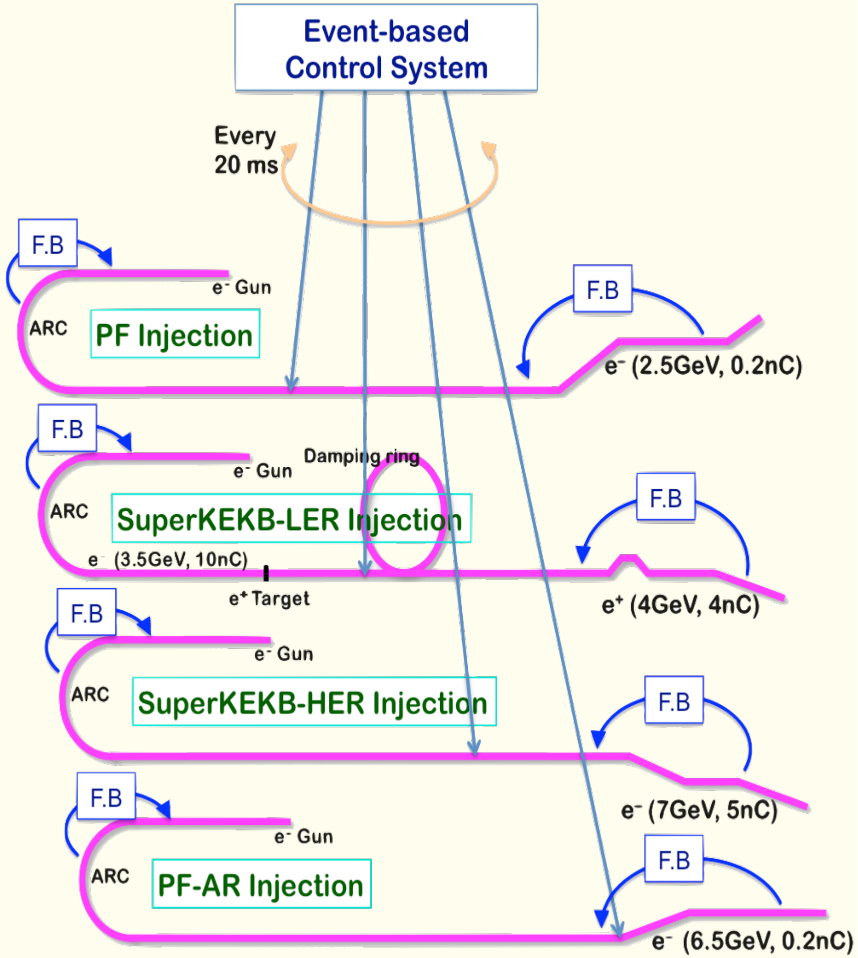
Mission of Electron/positron Injector in SuperKEKB

- **For 40-times higher luminosity in SuperKEKB collider**
- **Low emittance & low energy spread injection beams with 4 times higher beam current**
  - **New high-current photo-cathode RF gun**
  - **New positron capture section**
  - **Positron damping ring injection/extraction**
  - **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**



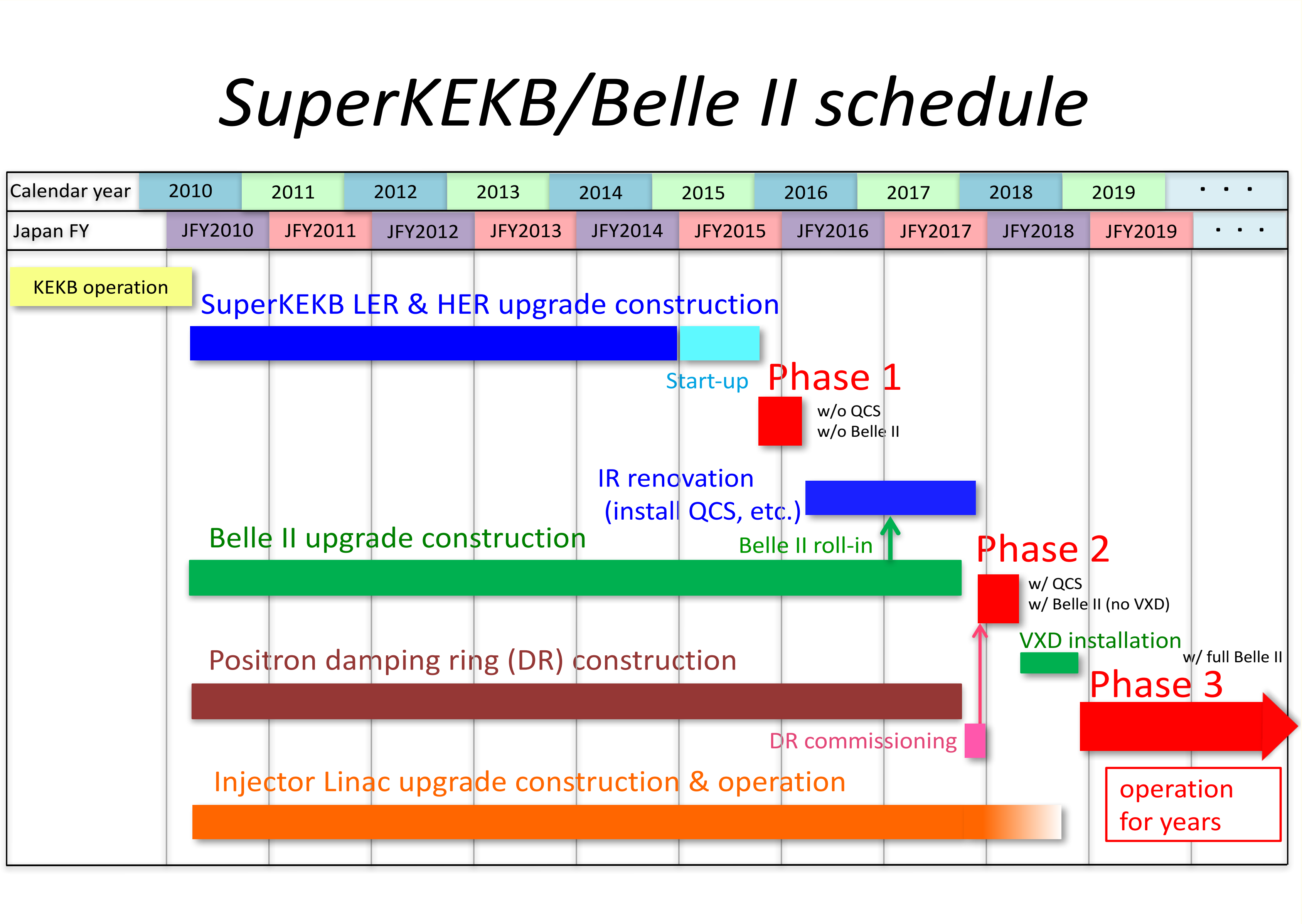
Beam from Injector and Storage Current

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

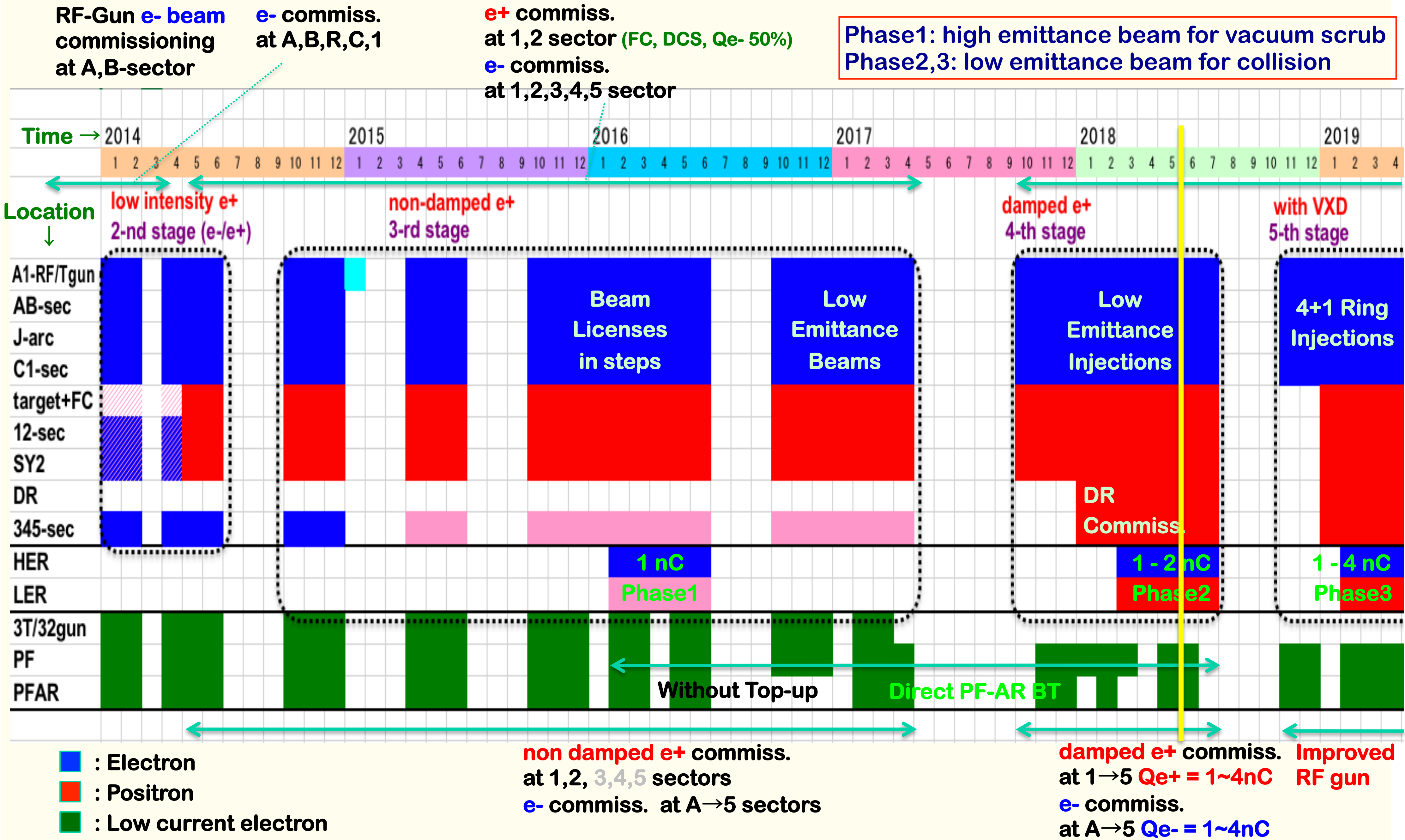


The single injector would behave as multiple injectors to multiple storage rings by the concept of virtual accelerator

SuperKEKB Schedule



Linac Schedule Overview 2018

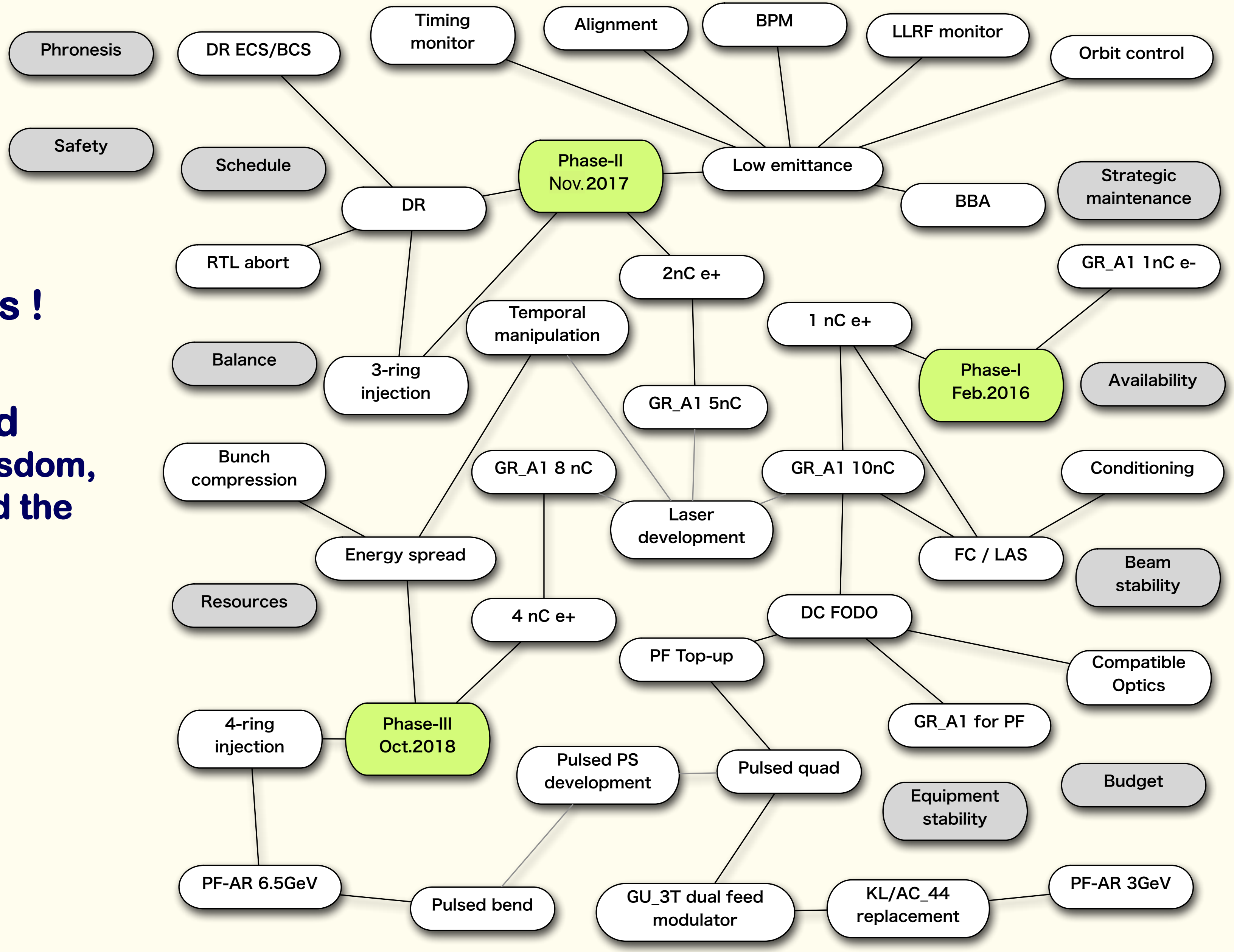


Required injector beam parameters

Stage	KEKB (final)		Phase-I		Phase-II		SuperKEKB (final)	
Beam	e+	e–	e+	e–	e+	e–	e+	e–
Energy	3.5 GeV	8.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV
Stored current	1.6 A	1.1 A	1 A	1 A	1.8 A	1.3 A	3.6 A	2.6 A
Life time (min.)	150	200	100	100	–	–	6	6
Bunch charge (nC)	primary e- 10 → 1	1	primary e- 8 → 0.4	1	0.5	1	primary e- 10 → 4	4
Norm. Emittance (γβε) (μrad)	1400	310	1000	130	200/40 (Hor./ Ver.)	150	100/15 (Hor./Ver.)	40/20 (Hor./ Ver.)
Energy spread	0.125%	0.125%	0.5%	0.5%	0.16%	0.1%	0.16%	0.07%
Bunch / Pulse	2	2	2	2	2	2	2	2
Repetition rate	50 Hz		25 Hz		25 Hz		50 Hz	
Simultaneous top-up injection (PPM)	3 rings (LER, HER, PF)		No top-up		Eventually		4+1 rings (LER, HER, DR, PF, PF-AR)	

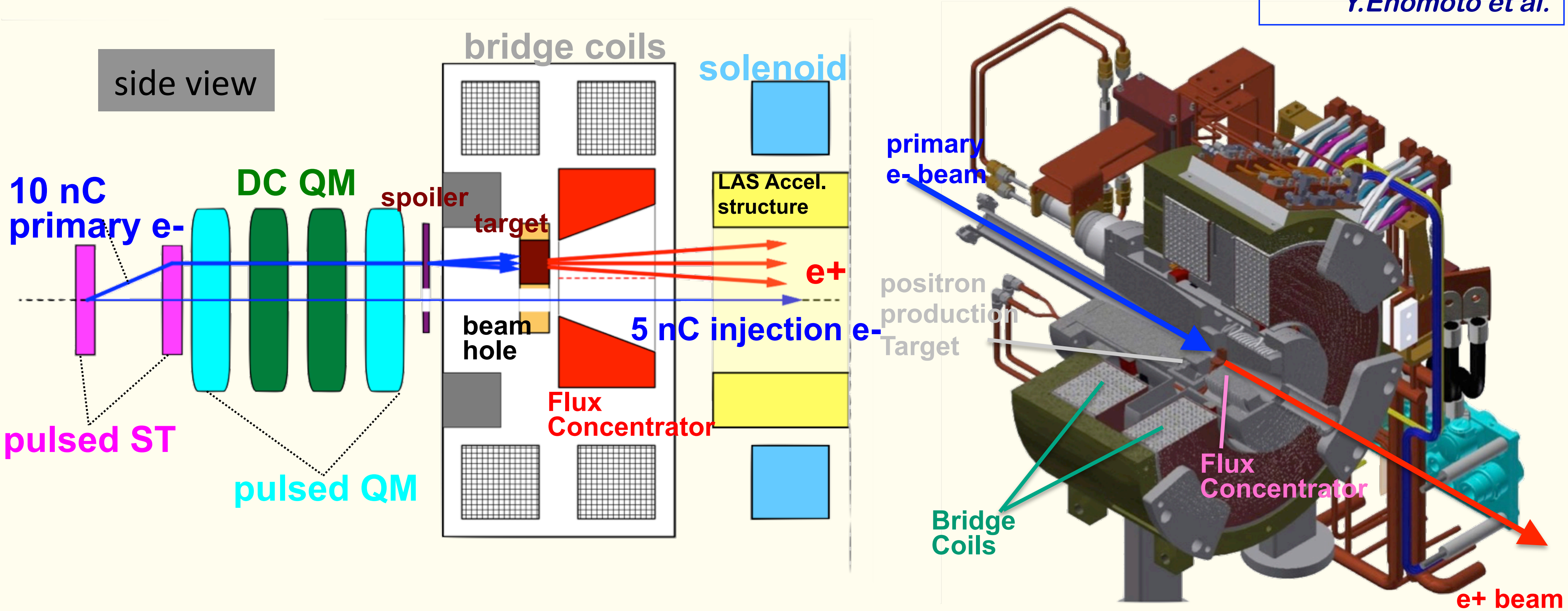
Subjects to Consider at Injector

- **(As of 2014)**
- **Have to consider too many subjects !**
- **Phronesis needed**
  (Greek: Practical wisdom, Ability to understand the Universal Truth)



Positron generation for SuperKEKB

Y.Enomoto et al.

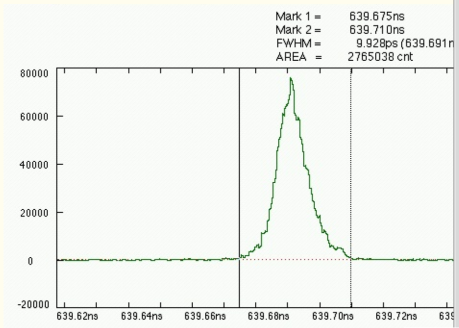


New positron capture section after target with
Flux concentrator (FC) and large-aperture S-band structure (LAS)
Satellite bunch (beam loss) elimination with velocity bunching
Pinhole (2mm) for passing electrons beside target (3.5mm)
Recently, facing discharge difficulties at maximum field

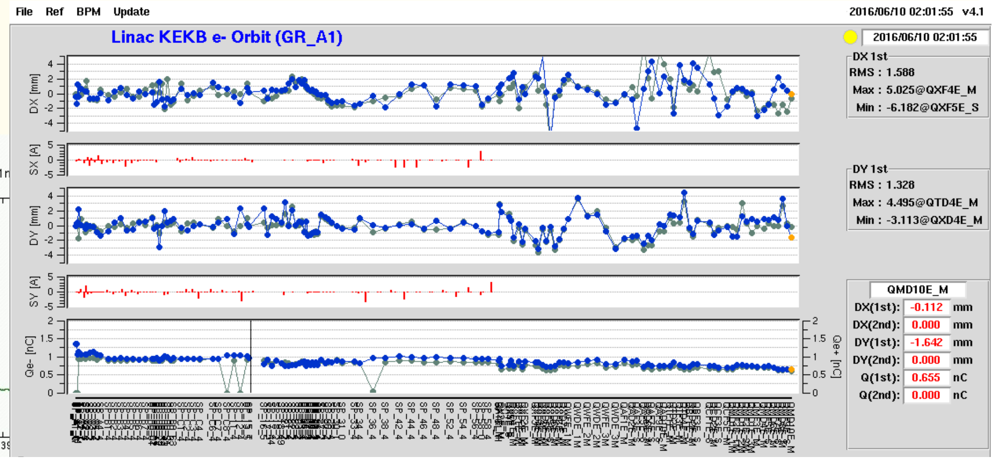
Development of Photo-cathode RF Gun

M.Yoshida et al.

- **Succeeded in injection** during SuperKEKB Phase 1 and 2 commissioning
- Employs **Yb-doped-fiber and Nd/Yb:YAG laser**, **Ir5Ce cathode**, **QTWSC or cut disk cavities**
- Stability improving
- Beam instrumentation improvements and comparison with simulation codes underway

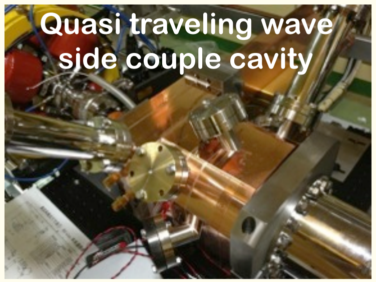


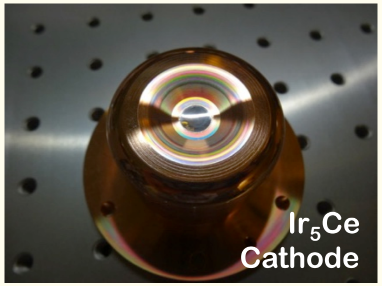
Bunch width

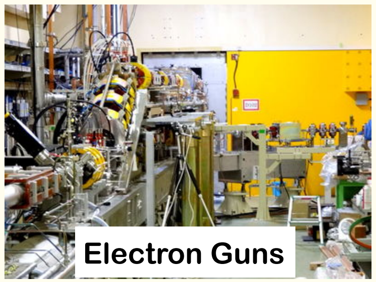


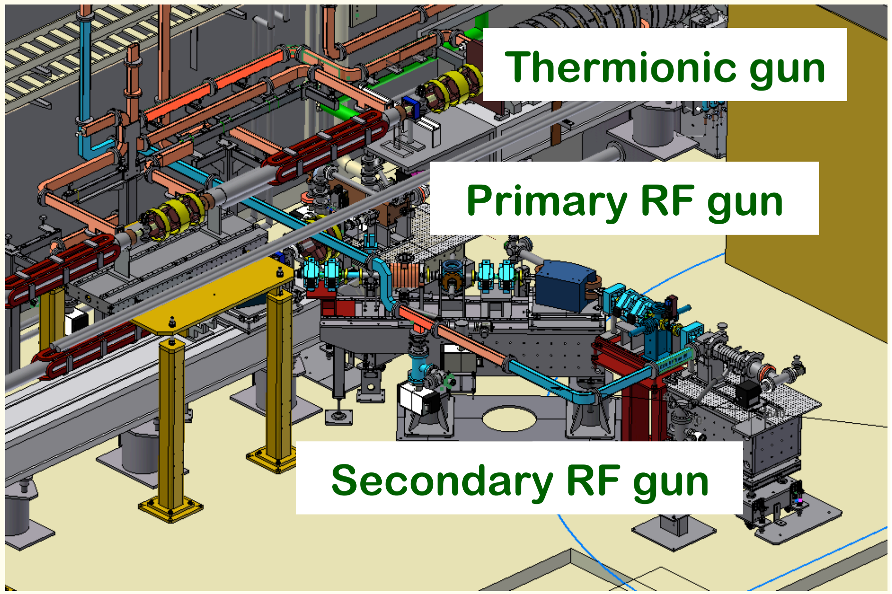
Beam orbit measurement

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





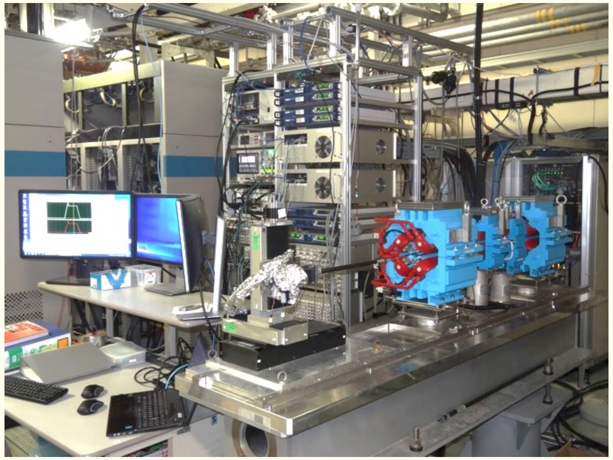




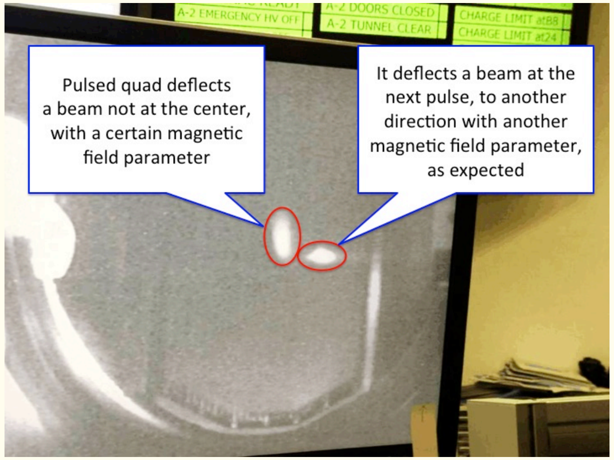
Development and installation of pulsed magnets

- 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 for simultaneous injection
- 4+1 ring simultaneous injections with virtual accelerator concept

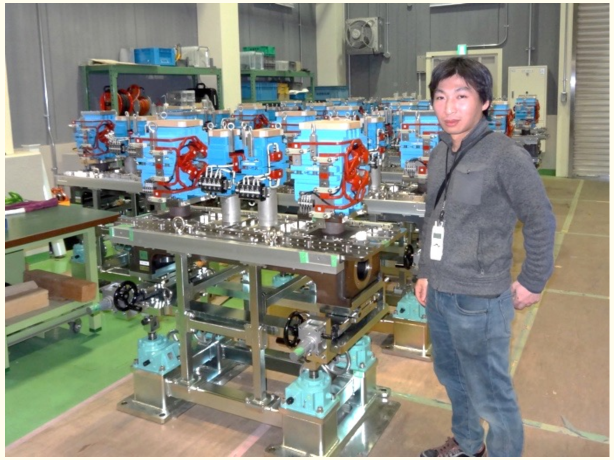
Enomoto, Natsui et al



- 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

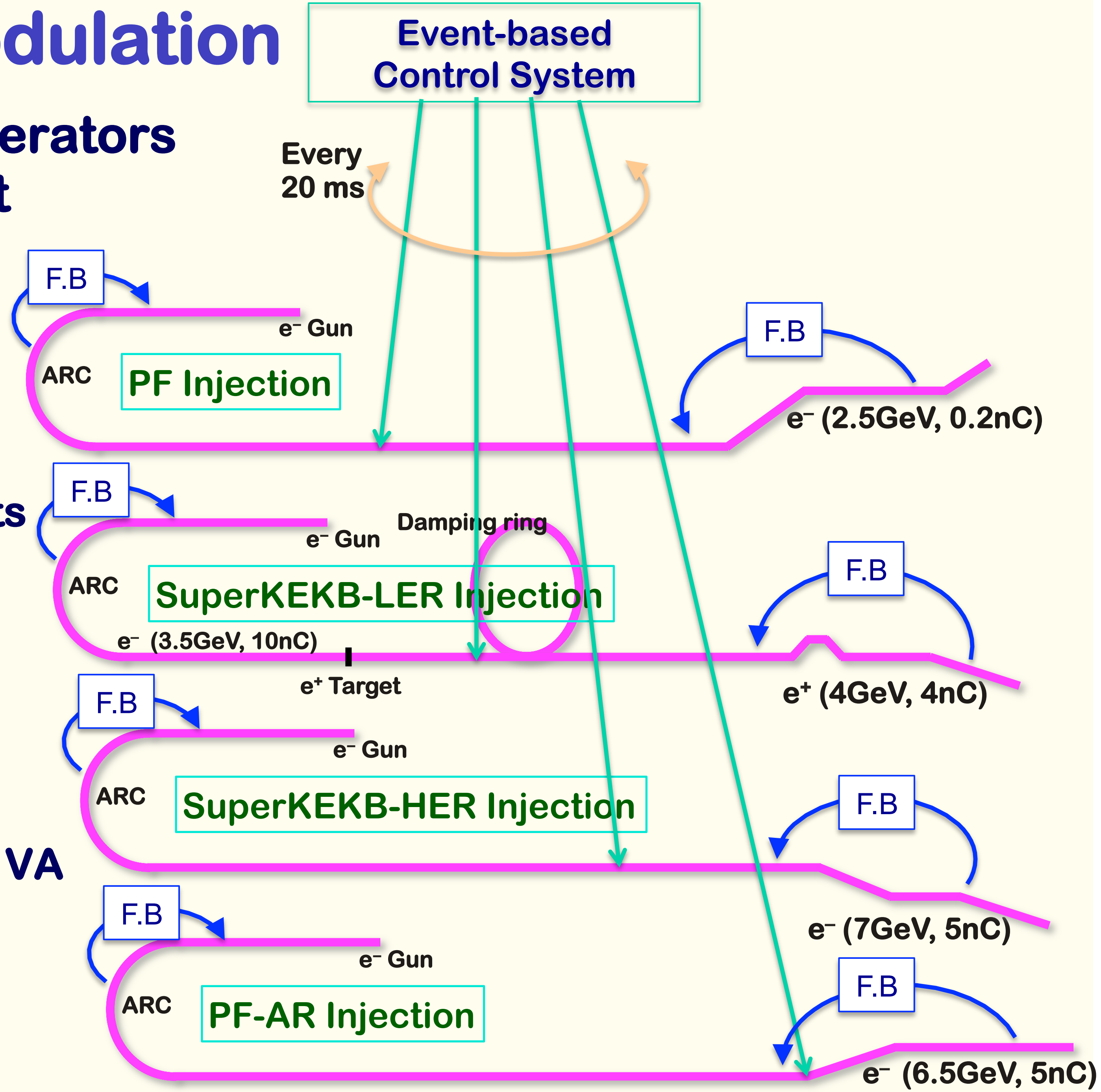
Pulse-to-pulse modulation

- **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

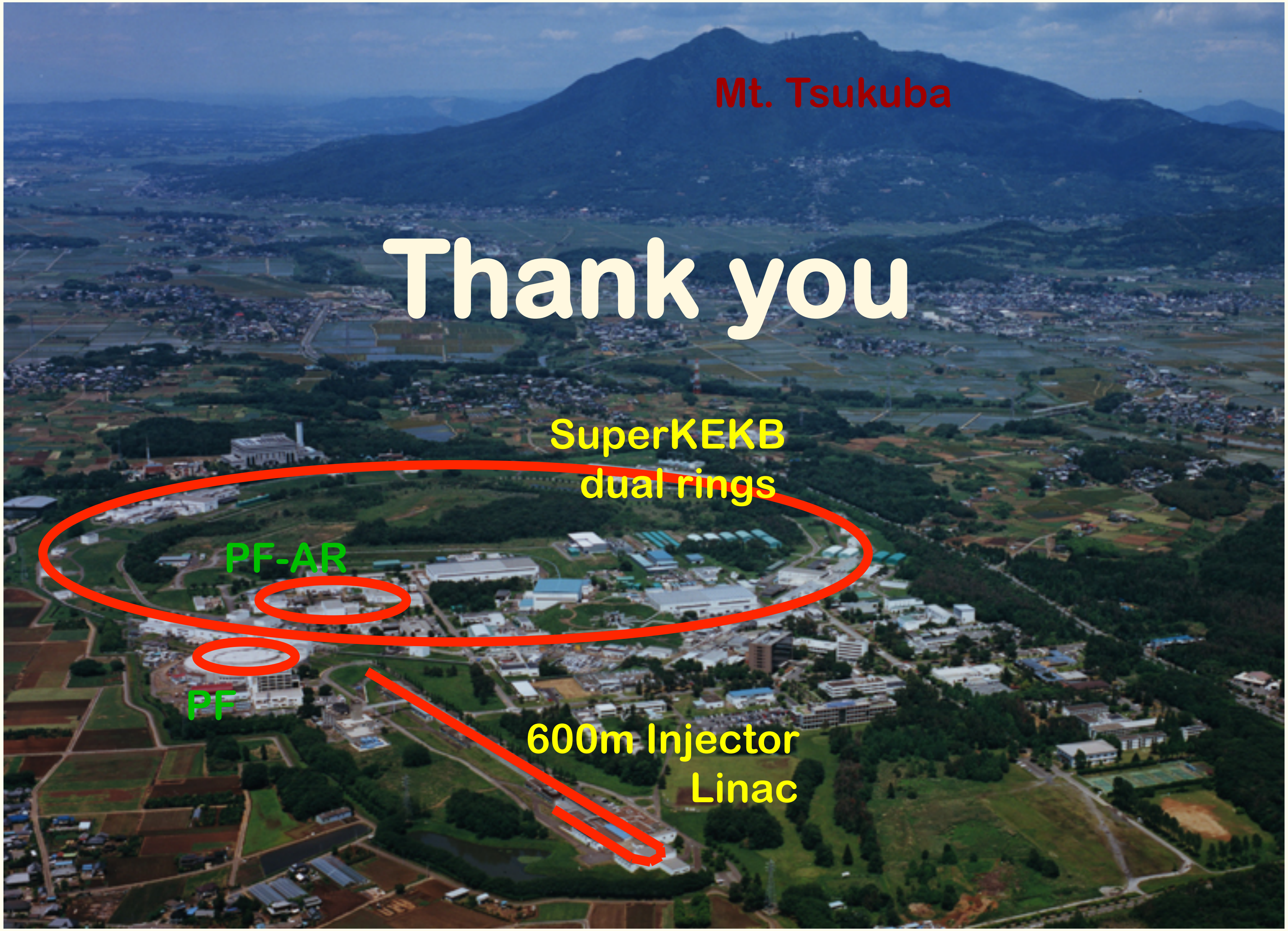
maybe with additional PPM VA
of stealth beam
for measurement



Summary

Summary

- We learned a lot during KEKB injection operation
- It contributed to achieve the world highest luminosity
- Injection into SuperKEKB is another challenge with higher beam charge and lower transverse/longitudinal emittance
- Steady progress towards designed injection beam in steps
- Then, we may need to improve the injection further
  - ex. stealth beam measurement / optimizer, etc
- With some Phronesis we may enjoy beam commissioning



Conference papers at <http://www-linac.kek.jp/linac/>