KEKB/SuperKEKB Linac

(and S-, C-, L-, X-bands developments)

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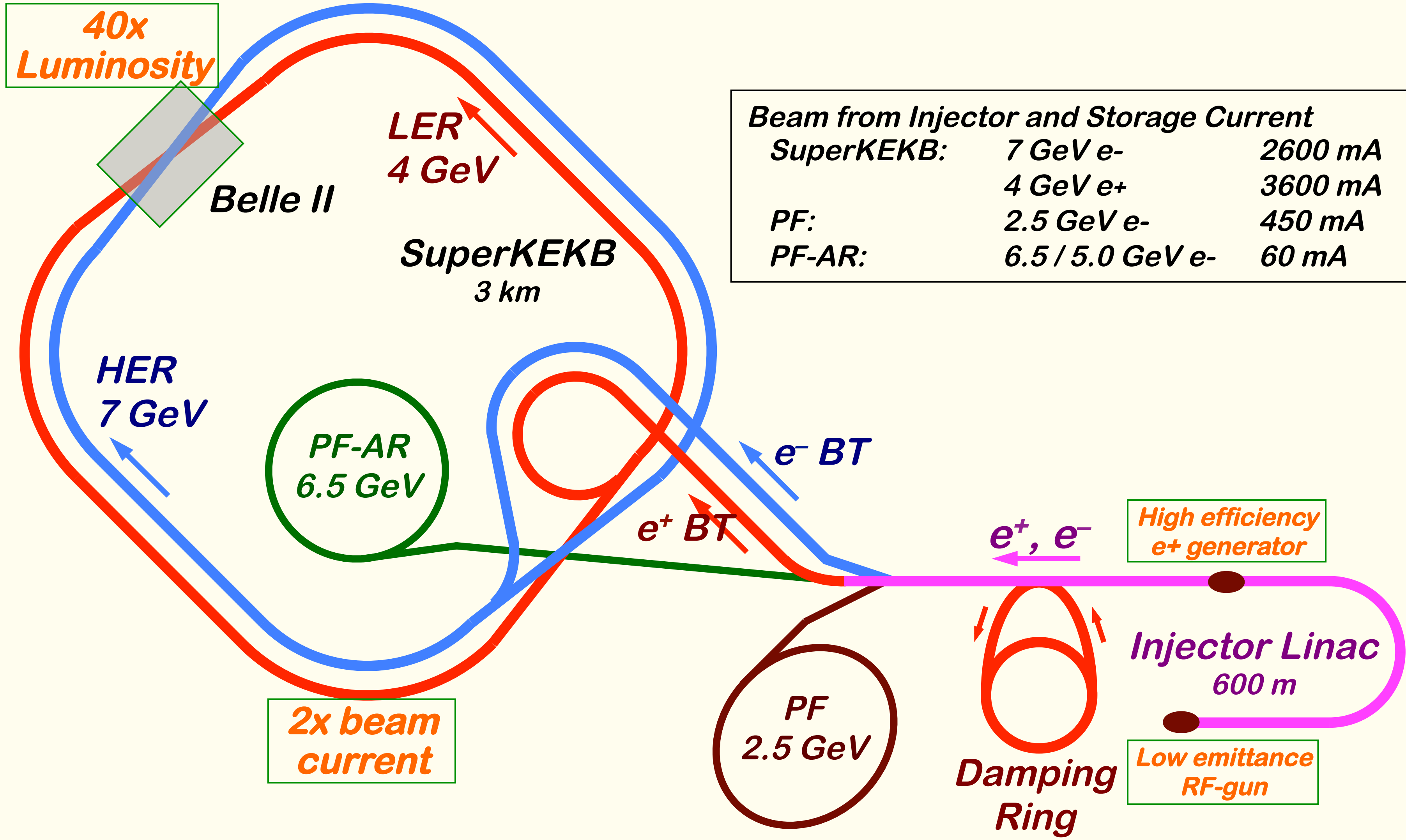
KEK Electron Accelerator Complex

◆ Present situation for SuperKEKB and light sources



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 / 5.0 GeV e-	60 mA

Advances in KEK Injector Linac

Machine Performance Improvement

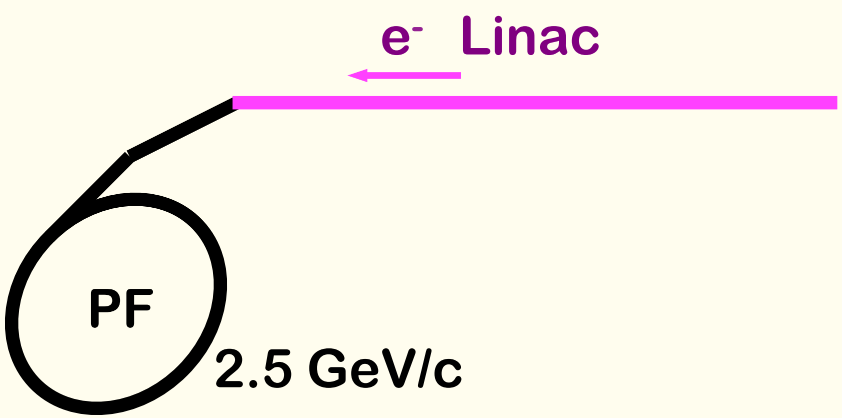
Challenges towards SuperKEKB

Upgraded Injector for SuperKEKB

Photon Factory Configuration (1982 –)

◆Electron injector to dedicated light source

Linac delivered:
for PF: 2.5 GeV e⁻

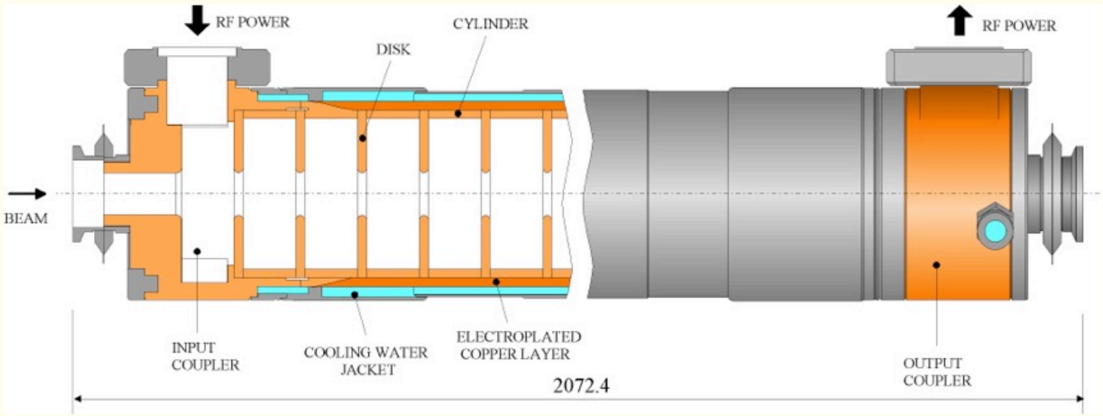


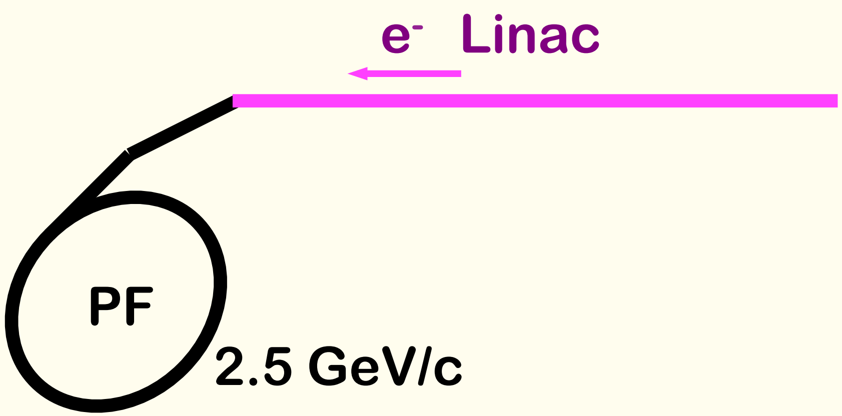
40 accelerator units were installed

Typical accelerator unit

2.5 GeV S-band Linac

- **Injector for dedicated light source, Photon Factory**
  - World-second dedicated (2nd generation) source after Daresbury
  - Construction: 1978 - 1982, Operation: 1982 - Now
- **Certain S-band experiences at universities in Japan**
  - ex. 300-MeV 300-Hz linac for nuclear physics
- **Foreseen collider project TRISTAN**
  - 2.5-GeV 400-m linac without booster
  - Quasi-constant gradient 2-m S-band structure





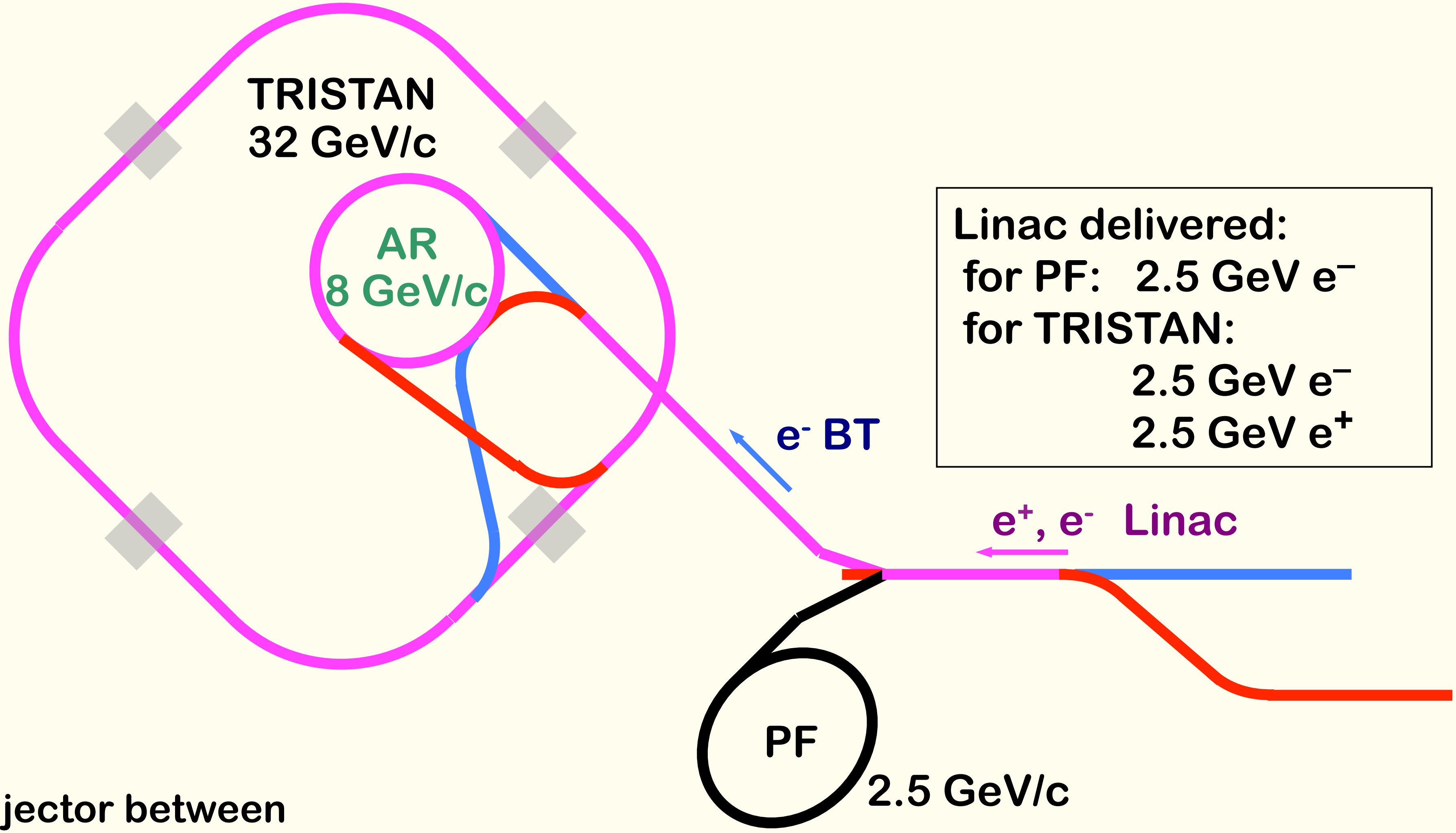
2.5 GeV S-band Structure

- **Quasi-constant gradient**
  - Disk 2a of 20 mm, 75 micron-step changing from entrance to exit
  - 5 sets of 2a to disperse transverse modes to avoid beam blow-up
- **Electroplating technique to fabricate**
  - No brazing, no need for tuning, and cost reduced
  - 160 structures 40 RF sources installed
- **Long-pulse injection**
  - up to 1 micro second, 8 MeV / m

- **Several different injection modes during 37 years**
  - Still serving 3000 users / year
  - Positron injection to cure ion instability under certain vacuum condition
  - Hybrid or shaft mode to serve single-bunch experiments as well
  - Simultaneous top-up injection to share the beams

TRISTAN Configuration (1986 – 1994)

◆Electron positron collider for Top quark



Linac delivered:
for PF: 2.5 GeV e^-
for TRISTAN:
2.5 GeV e^-
2.5 GeV e^+

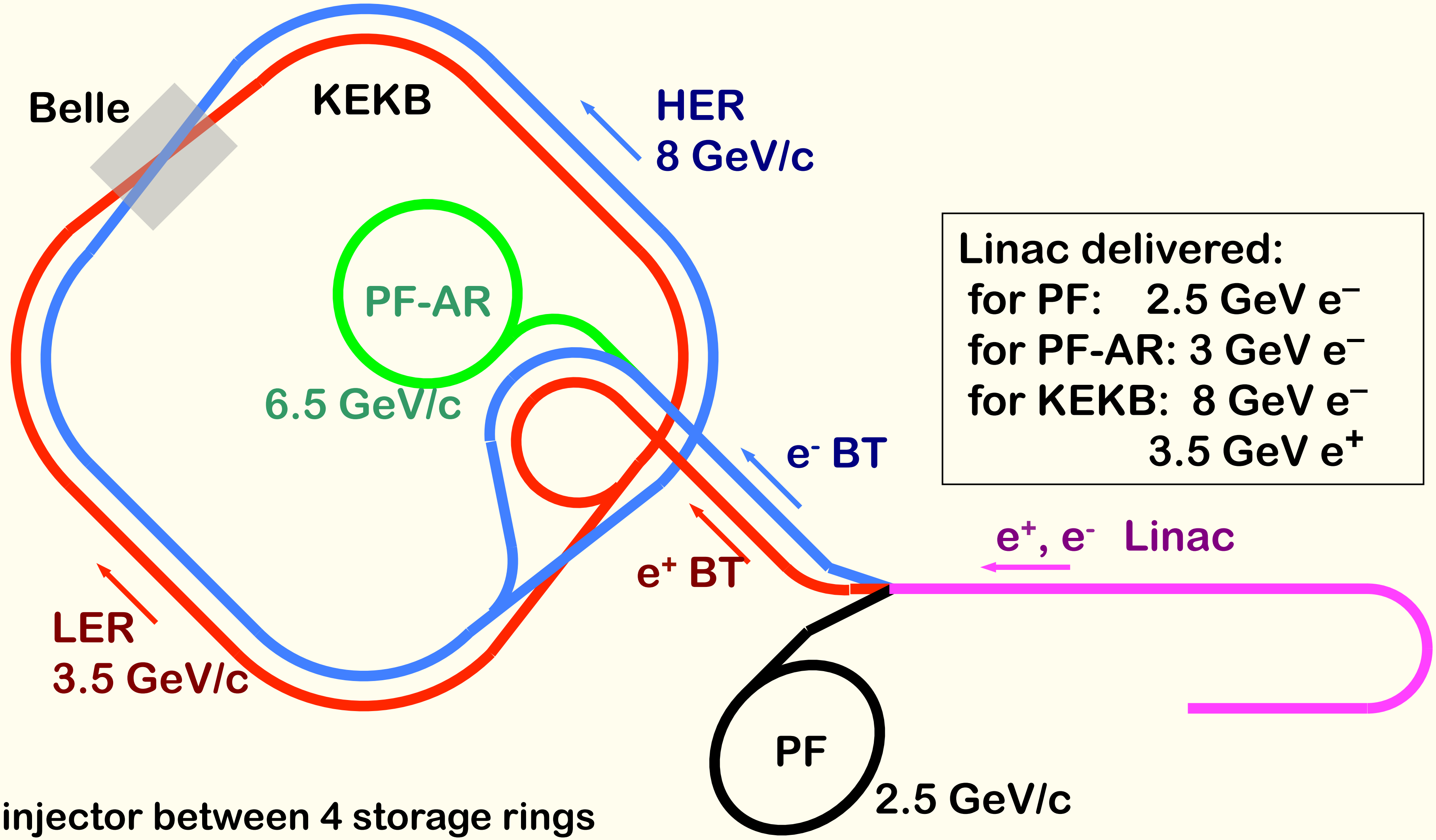
Shared single injector between
particle physics and photon experiments

500-MeV Positron for TRISTAN

- **Injection part**
  - High current thermionic gun
  - 119 MHz sub-harmonic buncher for single bunch operation
- **The same electroplating structure**
  - But combined 4-m structure for higher gradient
- **Certain end-point experiments in-between injections**
  - Axion search
  - Slow positron experiments for material science and particle physics
  - Detector developments

KEKB Configuration (1999 – 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 re-use 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**

Advances in KEK Injector Linac

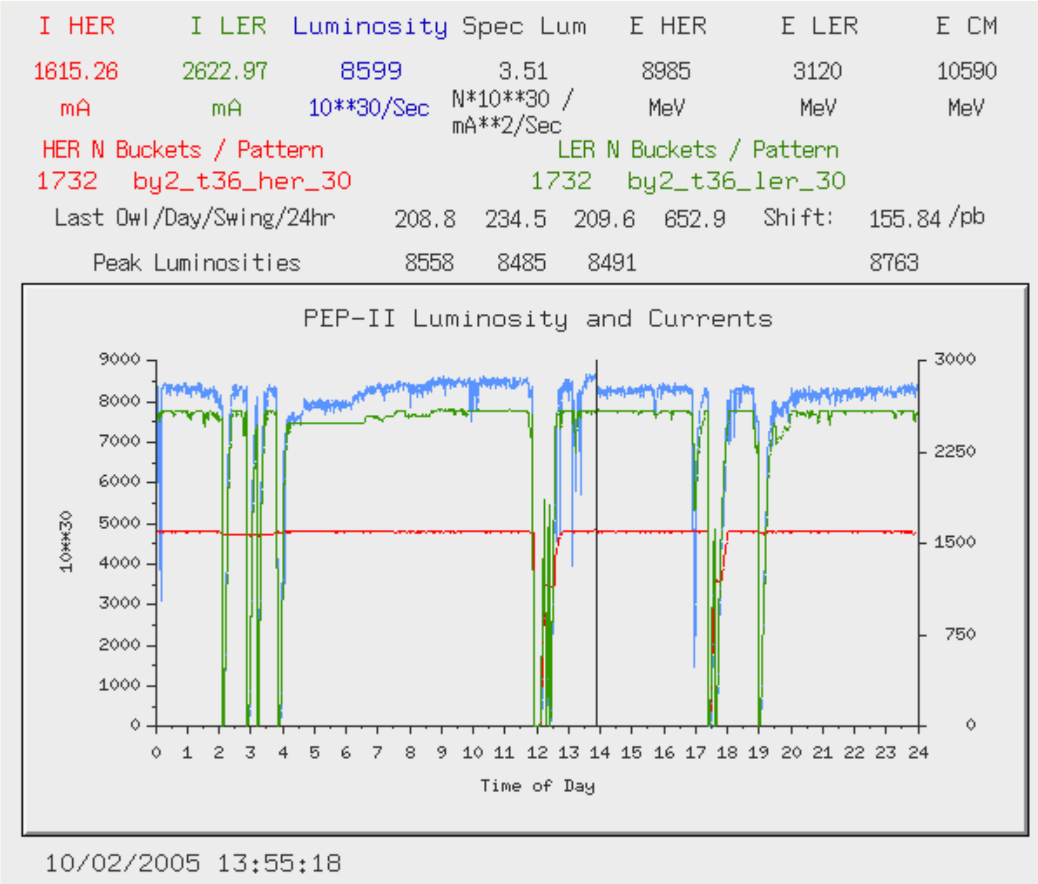
Machine Performance Improvement

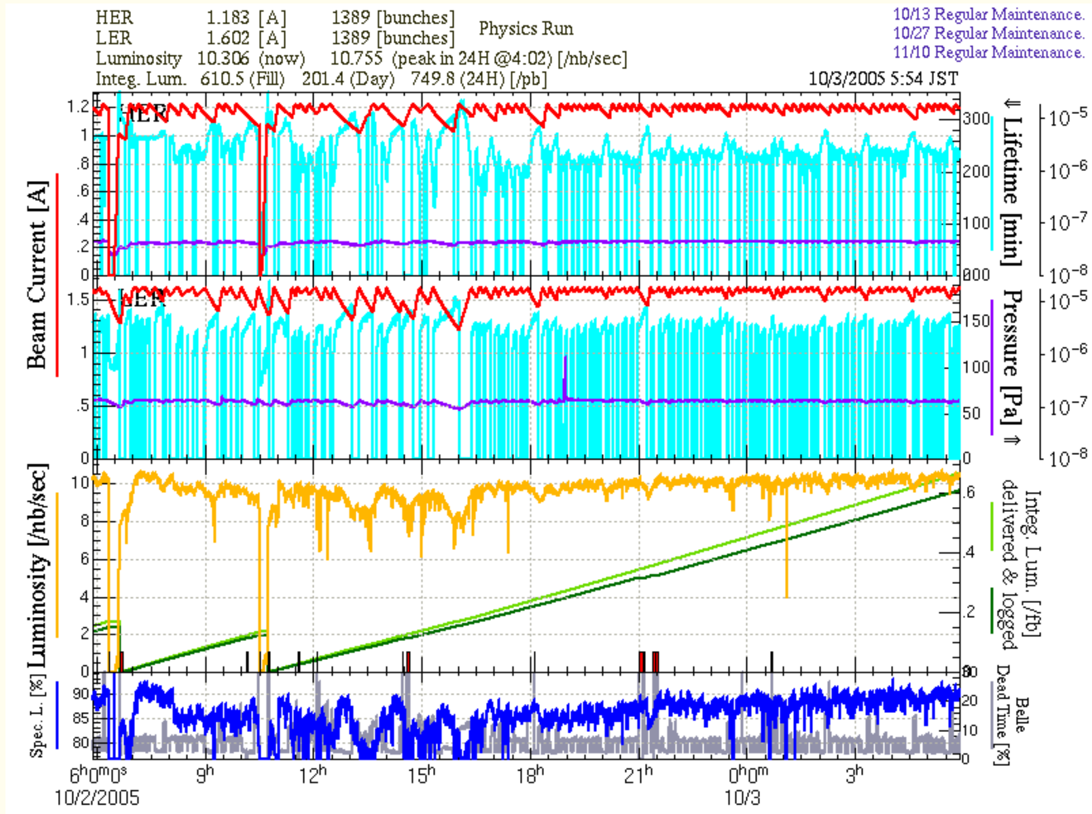
Challenges towards SuperKEKB

Upgraded Injector for SuperKEKB

PEP-II/SLAC and KEKB

◆ **We shared ideas/experiences between PEP-II and KEKB control rooms**





¤ **Friendly competition** **(above plots were on the same day in Oct.2005)**

Performance improvements at KEKB

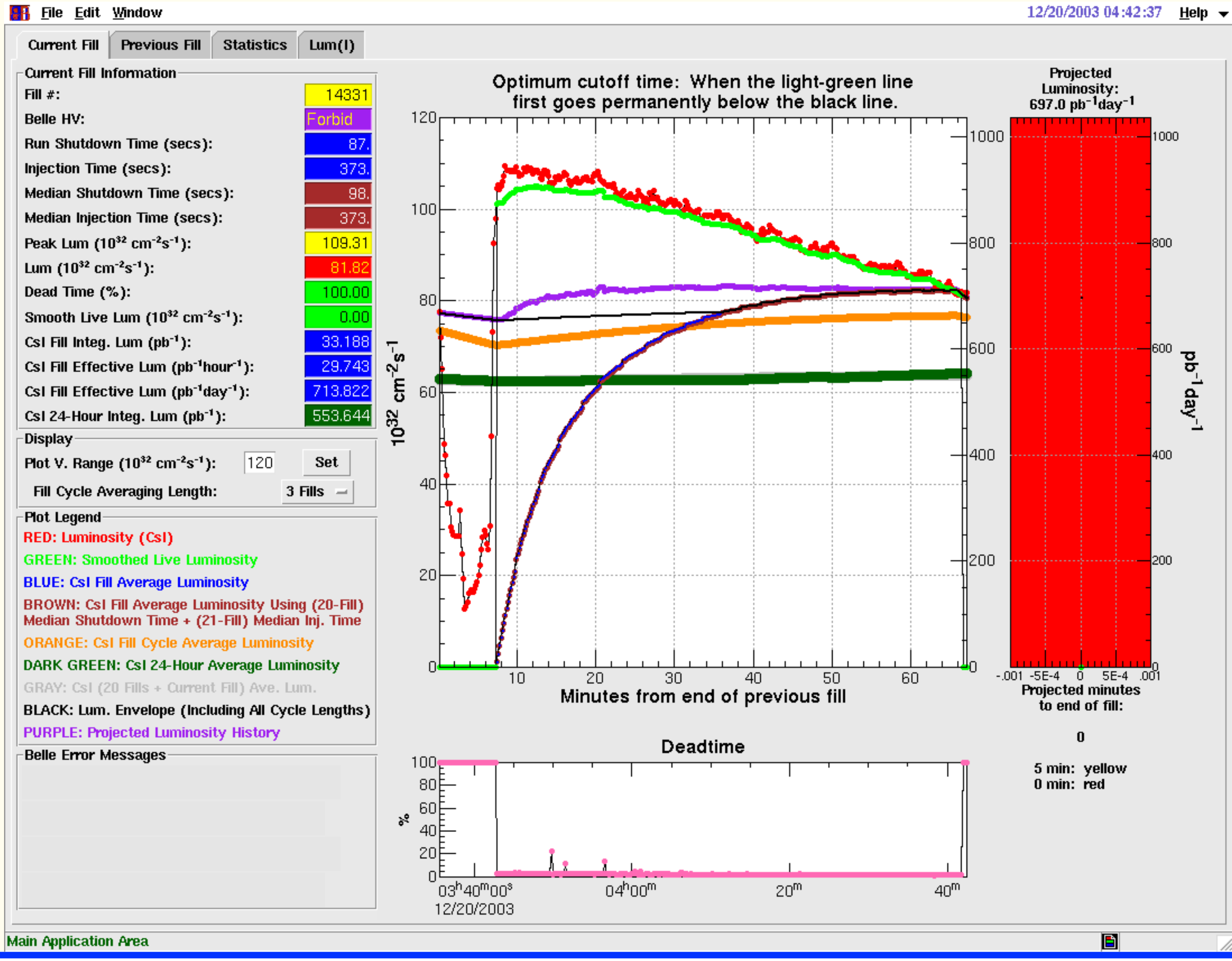
- **Competition with SLAC PEP-II**
  - One of worries was the injector capability
    - Injection beam quality
    - Beam stability
    - Beam current, especially positron
    - Injection time to fill the both storage rings
    - And, integrated luminosity

- **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

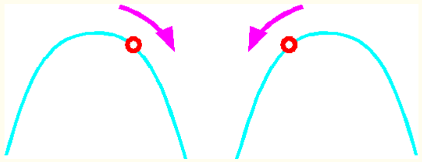
◆For example, run-length optimization

❖One of 100 automations

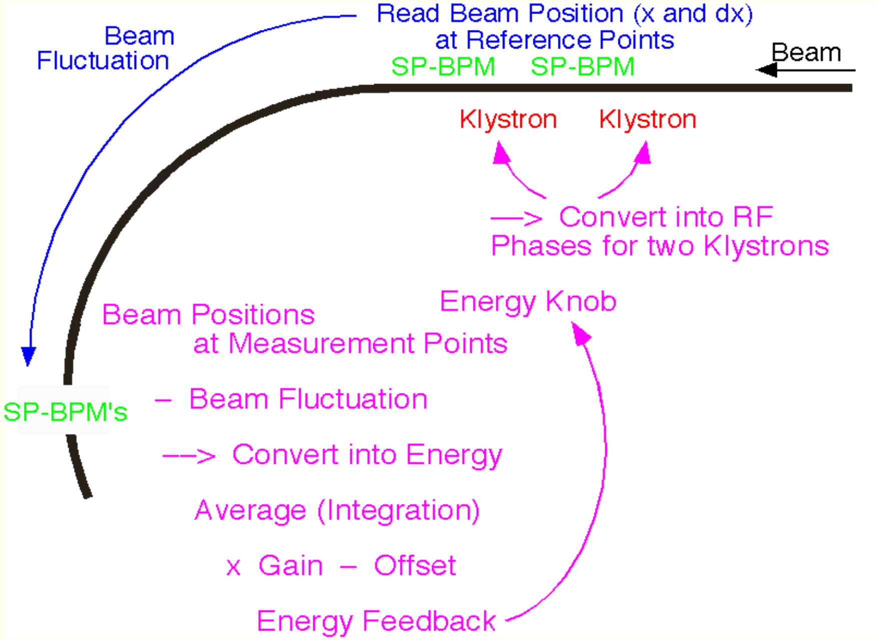


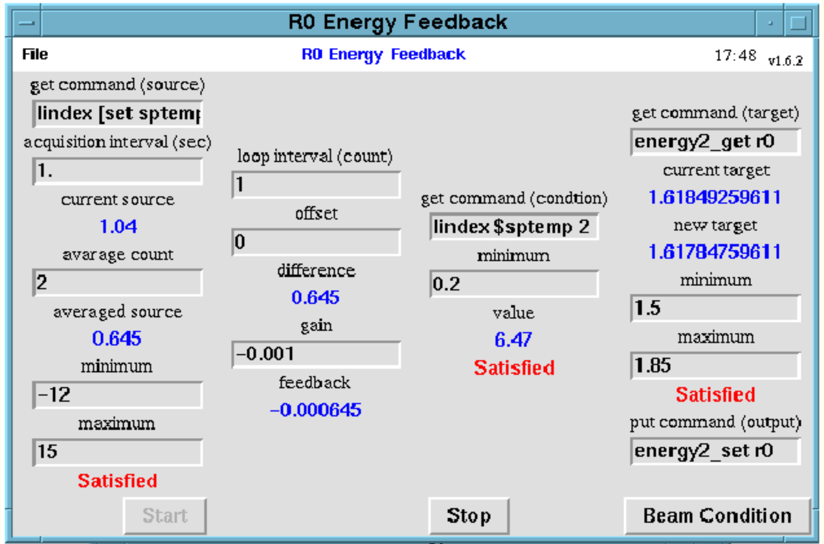
Energy Stabilization Loops

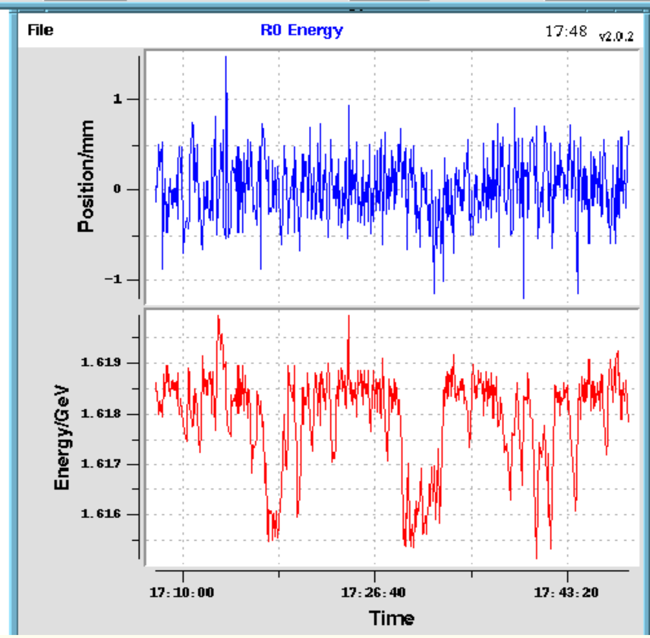
- **BPMs - Energy knob**
  - **Energy knob without energy spread**



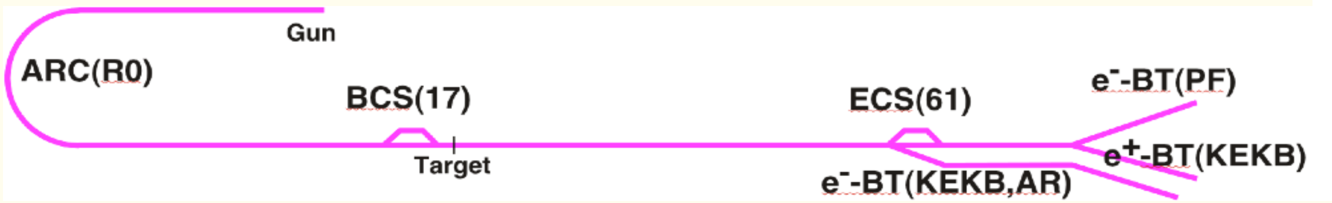
  - **Simple P.I. Loop**







6 feedback loops along the linac depending on the modes



Feedback Stabilizer 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

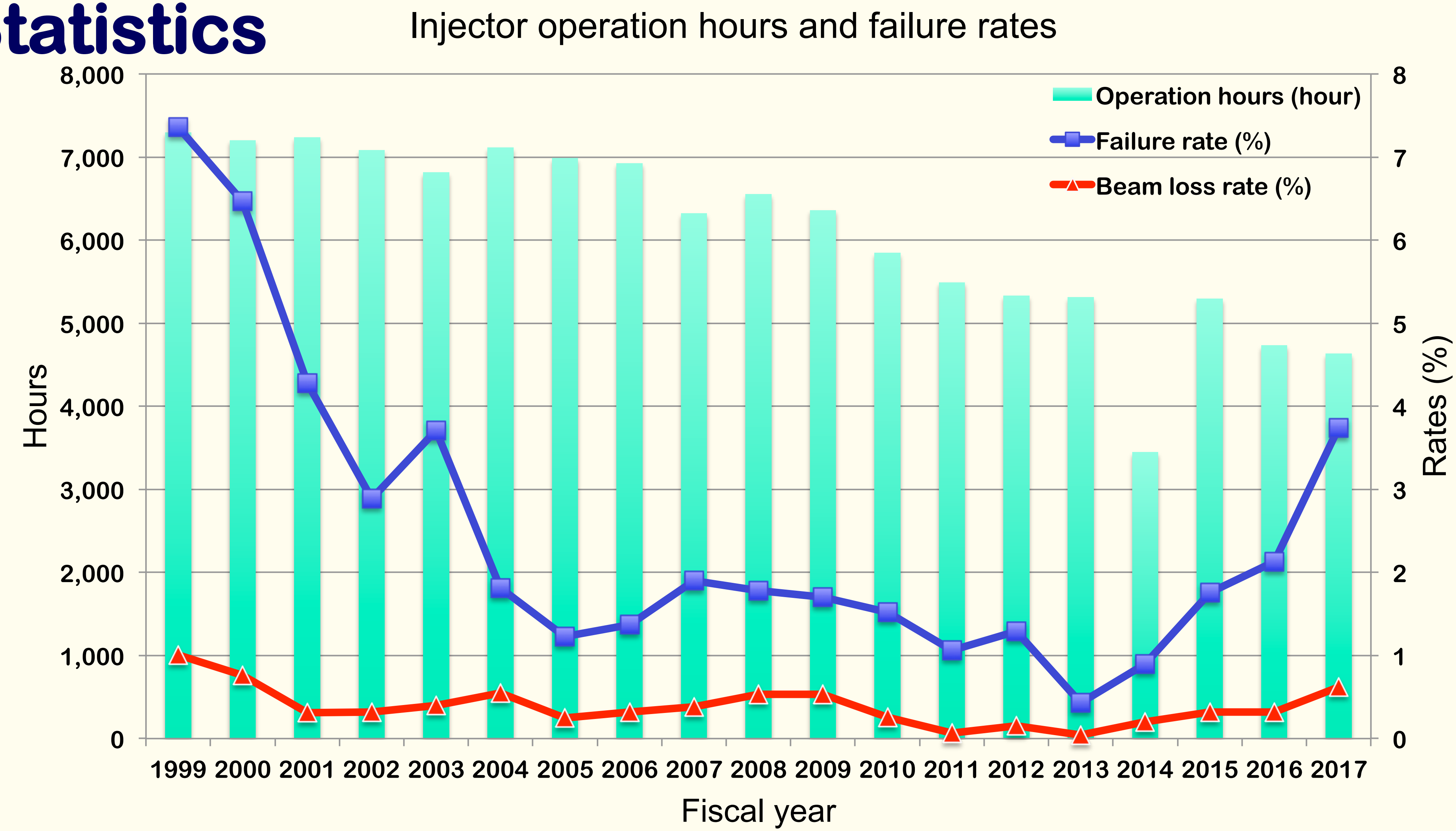
summay — Thu Jan 31 18:29:34 2002

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**

Two bunches in a pulse

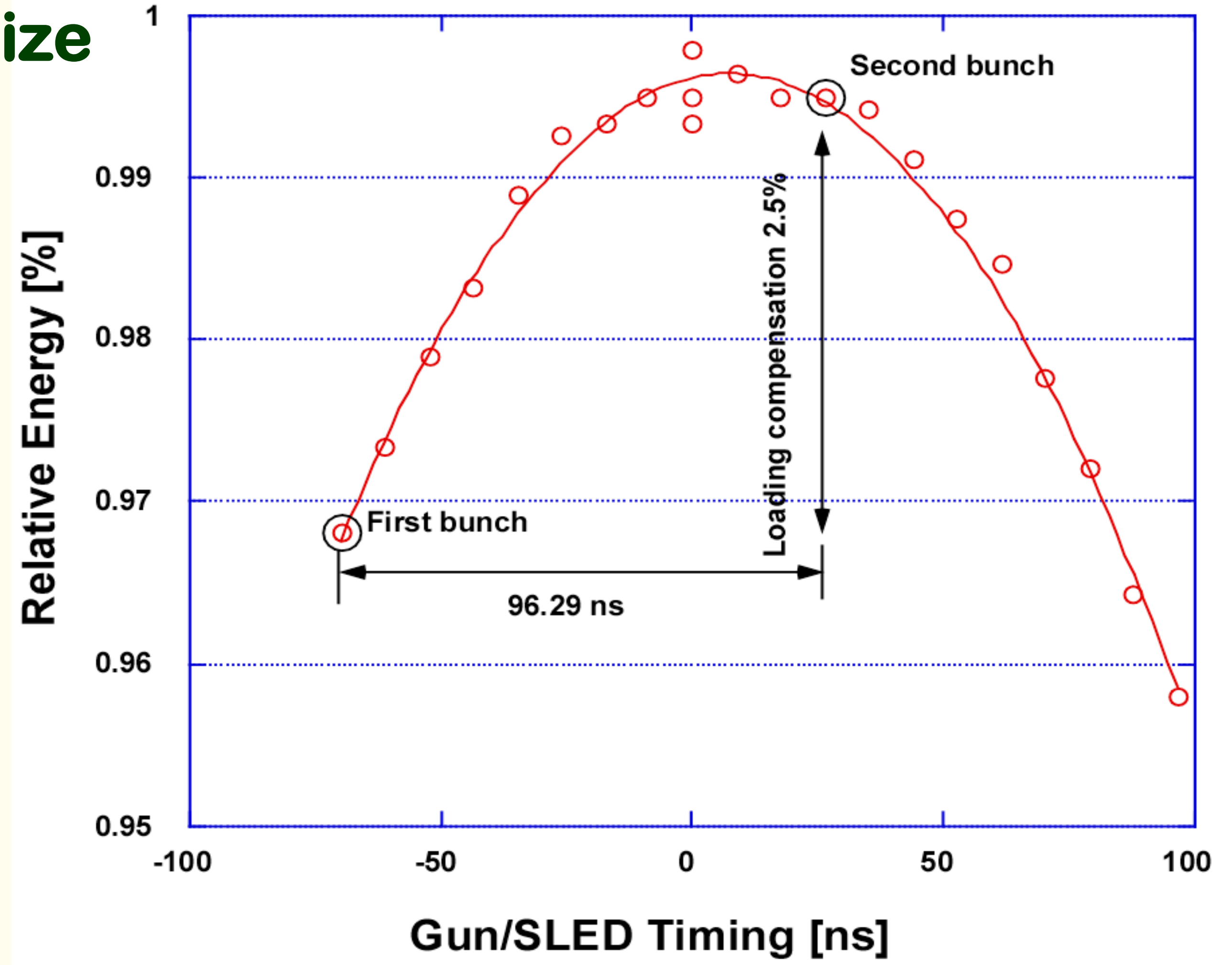
- As the stored beam current in MR increases, much more injection beam current was required
- Especially for the positron injection rate

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

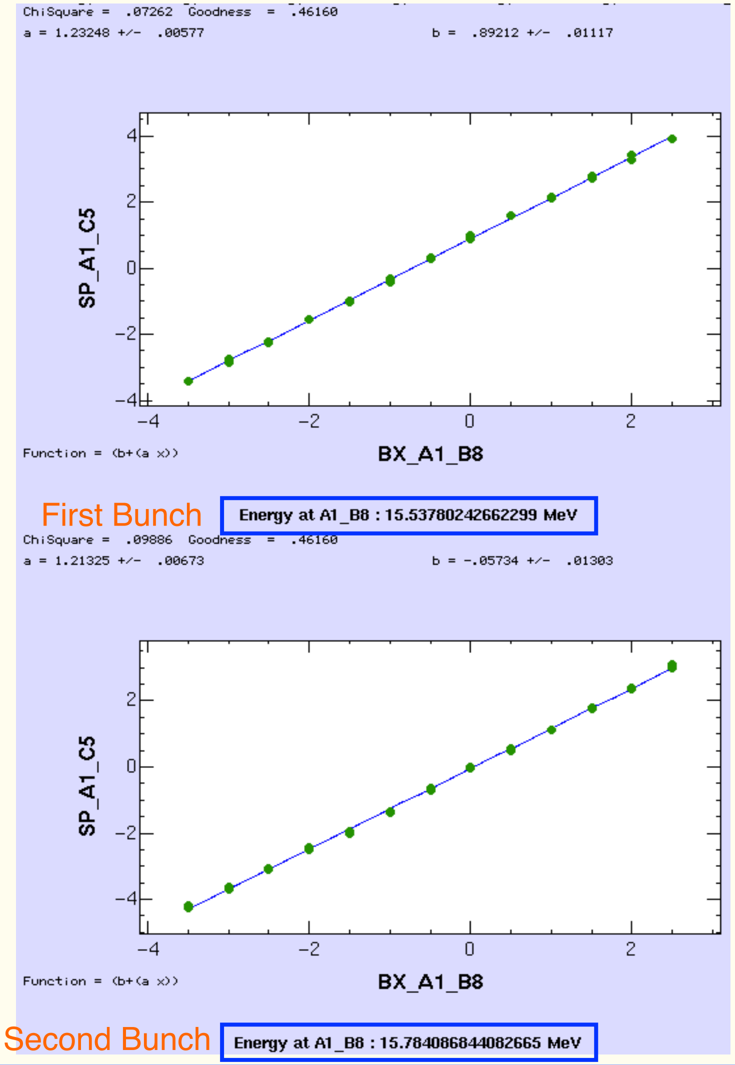
- **Beam loading compensation**
  - **For bunch separation of 96 ns**
    - **Or we sometimes utilize energy difference in order to equalize the beam orbits**

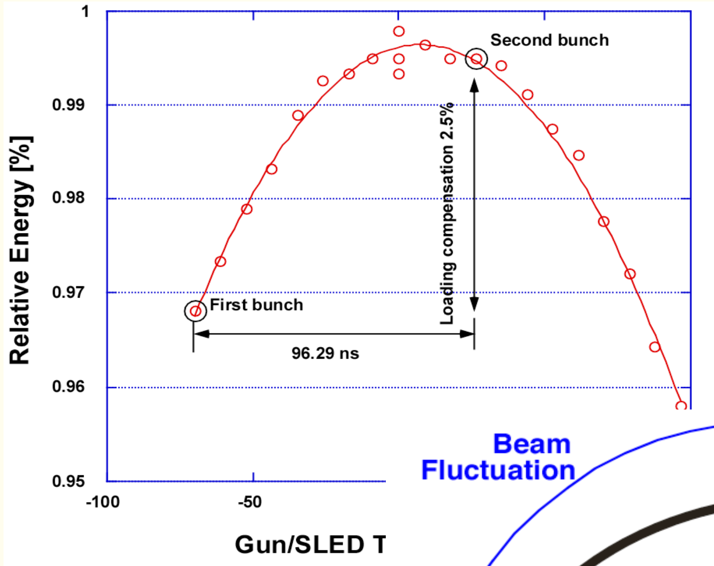


Dual-bunch Energy Equalization, and Feedback

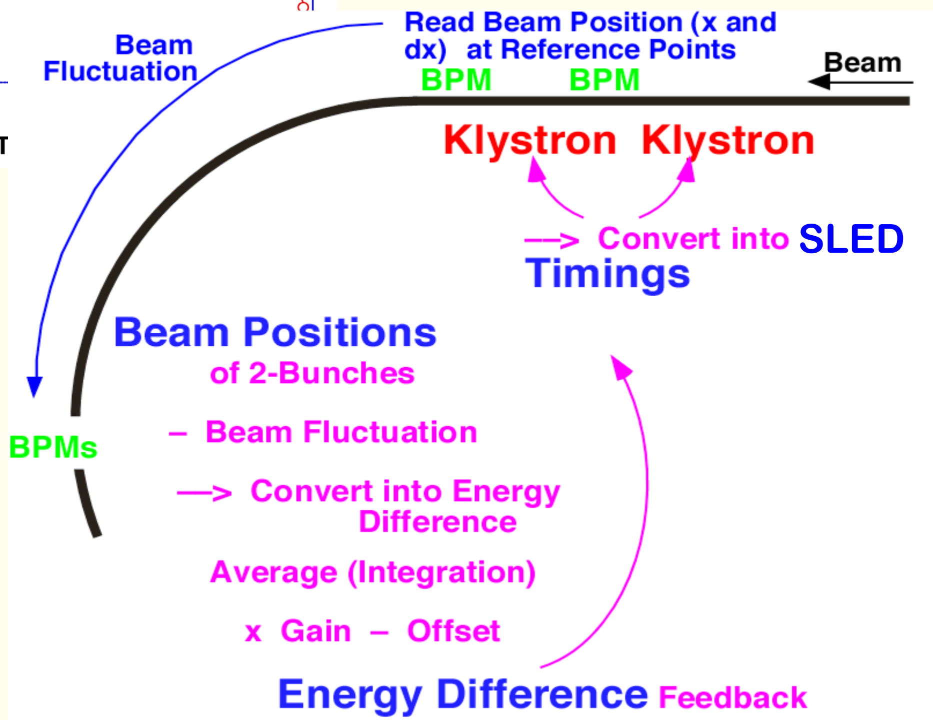
◆ Energy equalization is important for stable operation

Measurement at bunching section
after energy equalization
with RF pulse timing





Stabilization at bending section
with SLED timing



Continuous Injection

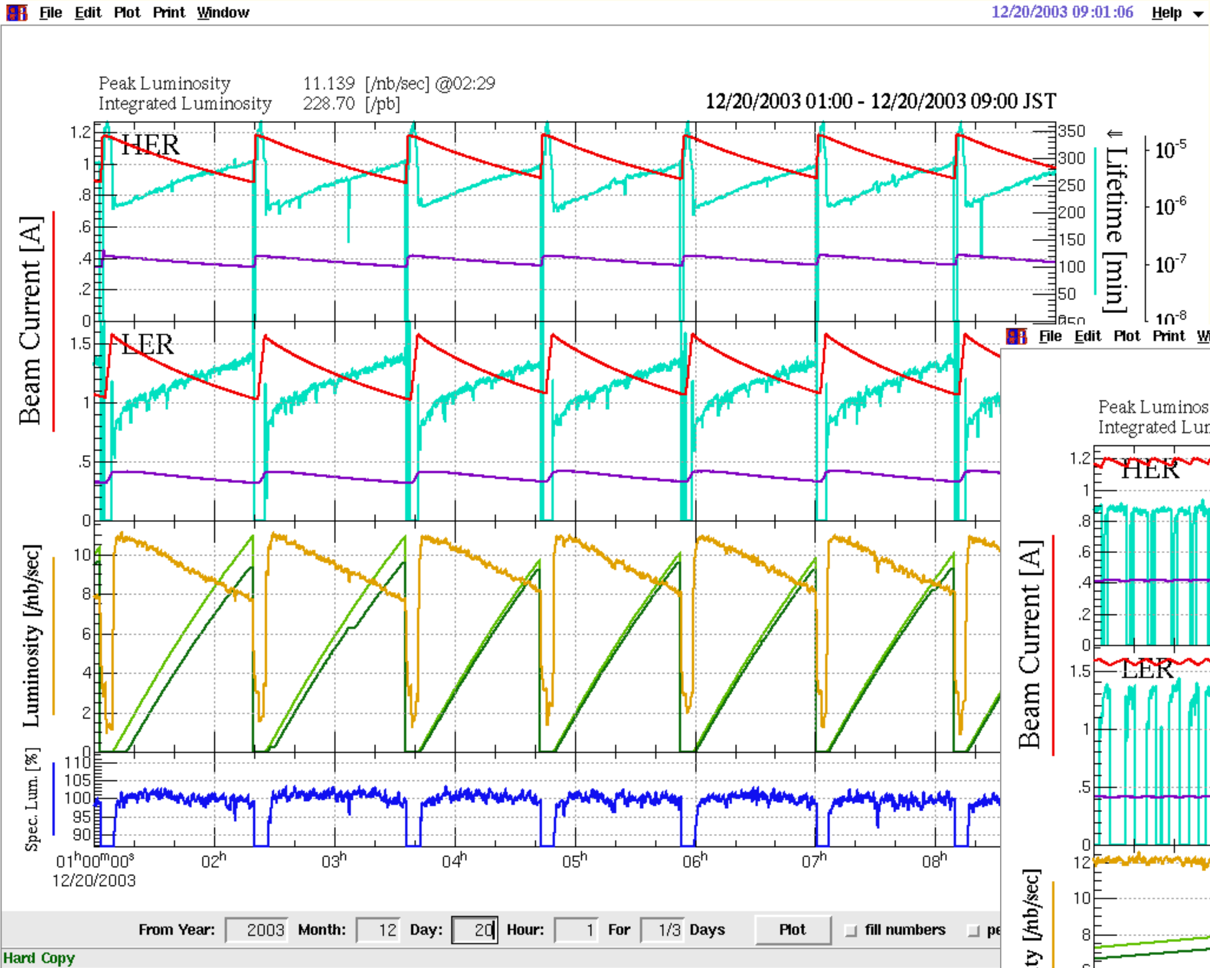
- Detector data acquisition stopped during the injection and the detector high voltage (HV) preparation
- Especially for the positron injection rate

Continuous Injection with detector HV applied was another major step forward

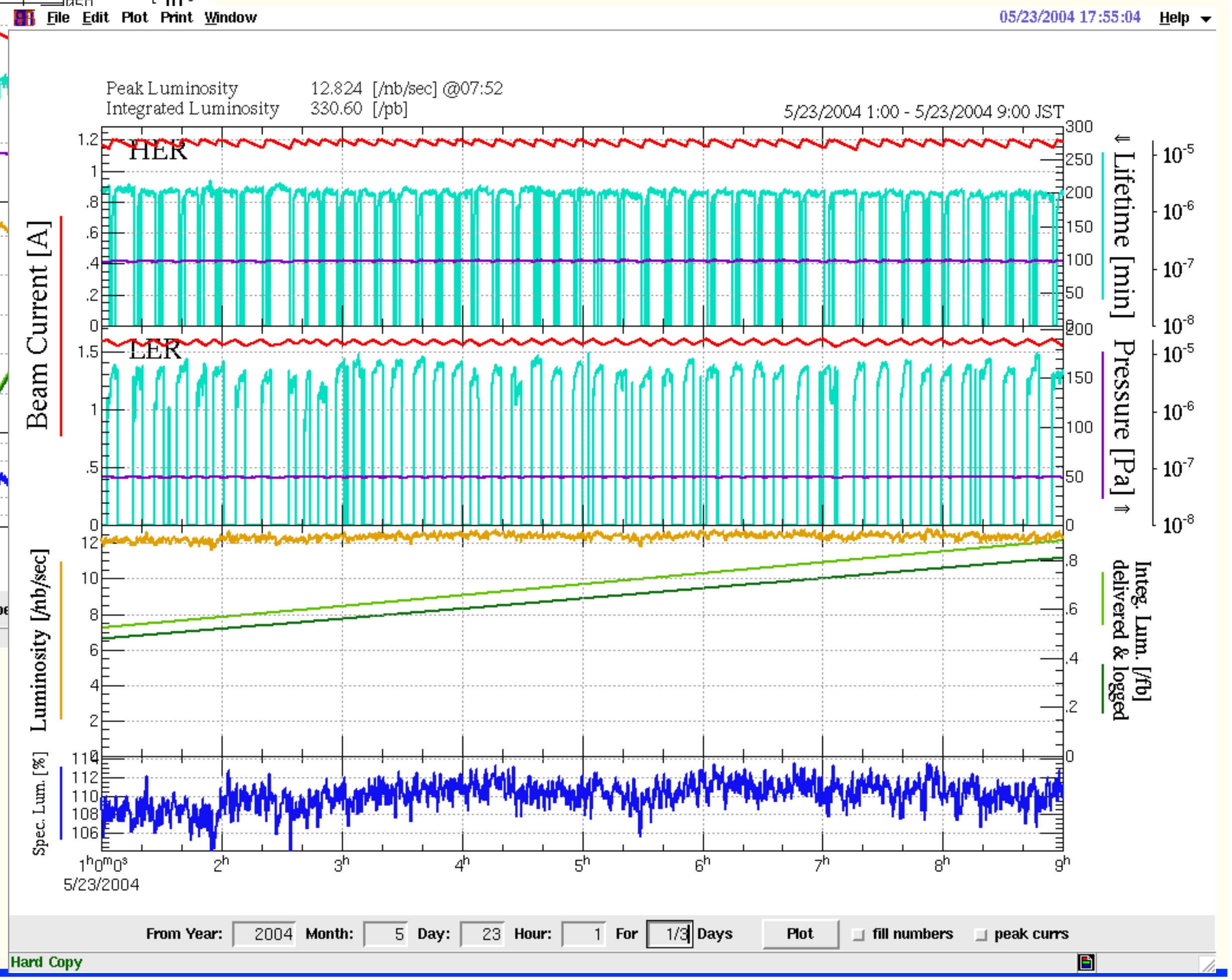
- For higher integrated luminosity
- by detector improvements, esp. CDC, TOF, DAQ
- with certain benefit from collision with crossing angle
  - without bending magnet at IP, for lower background
- Then, approximately 26% gain achieved

Continuous injection

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

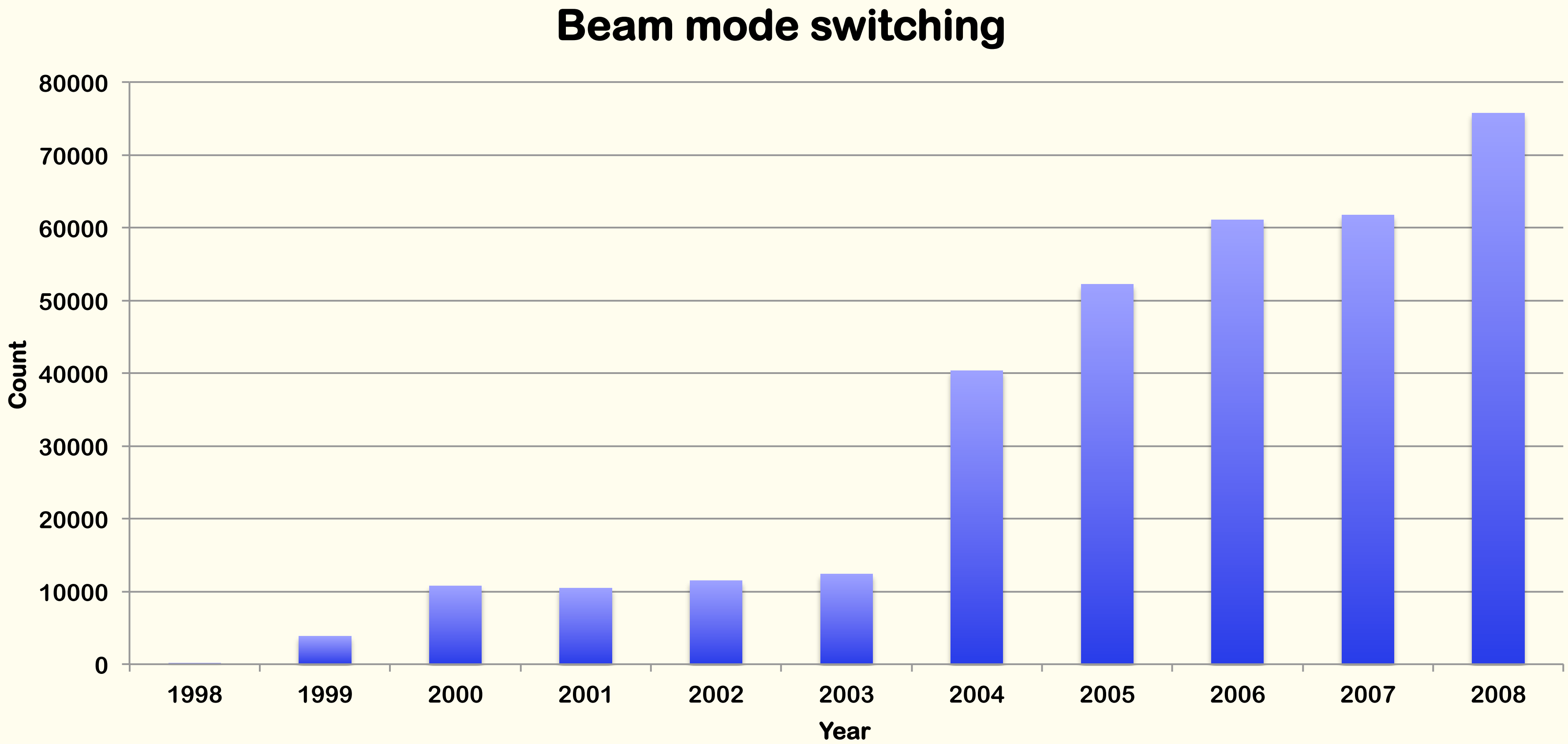


2003, before continuous injection was applied
Data acquisition stopped during injection
(8-hour history of beam current, luminosity, etc.)



Beam mode switching improvements

- ◆ Continuous injection was applied in 2004



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

Simultaneous Top-up Injections

- Even faster beam mode switches

- **Pulse-to-pulse modulation (PPM) at 50 Hz**
  - PPM was first applied at PS/CERN (1977) at 1.2 second
  - ~150 parameters were switched every 20 ms for 3 beams

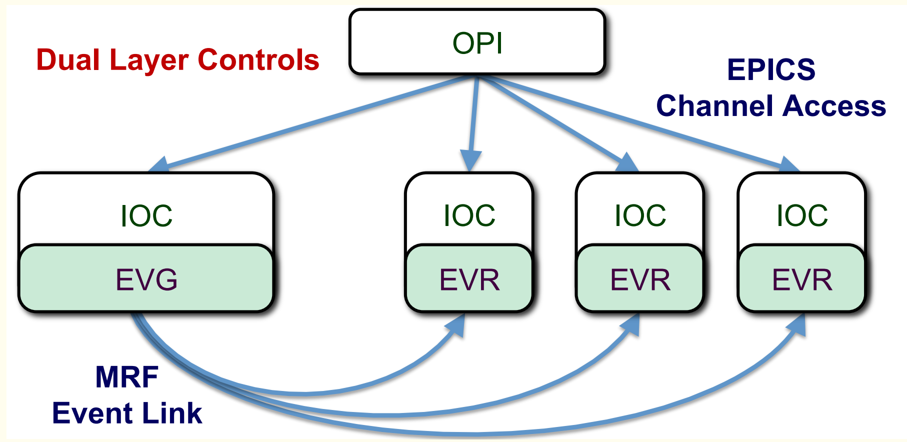
- **Many Hardware improvements as well as controls**
  - PF top-up injection for higher quality experiments
  - Sensitive luminosity tuning with Crab cavities

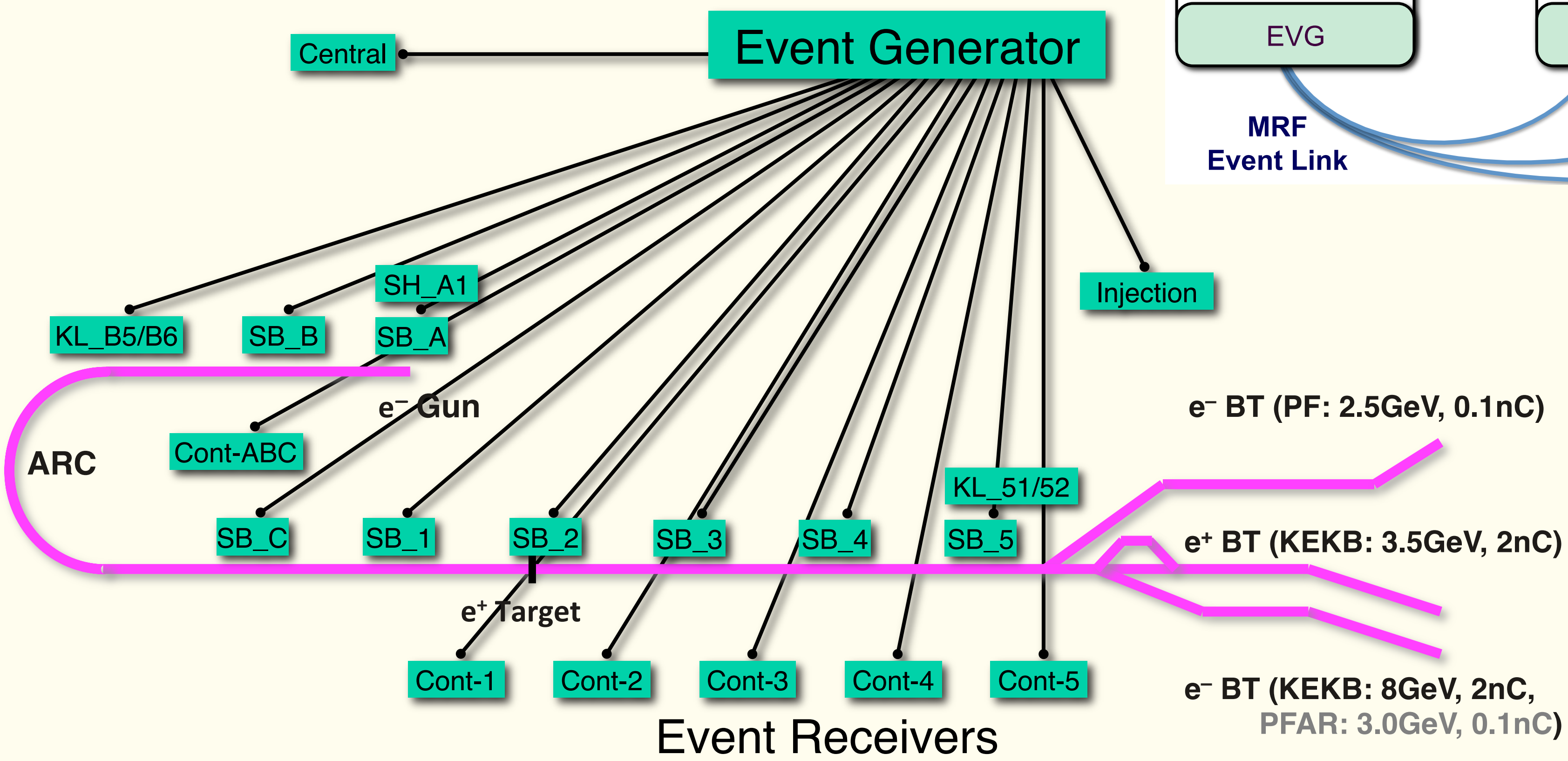
  - Many more parameters in SuperKEKB for 4 beams

Fast Global Synchronous Controls

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

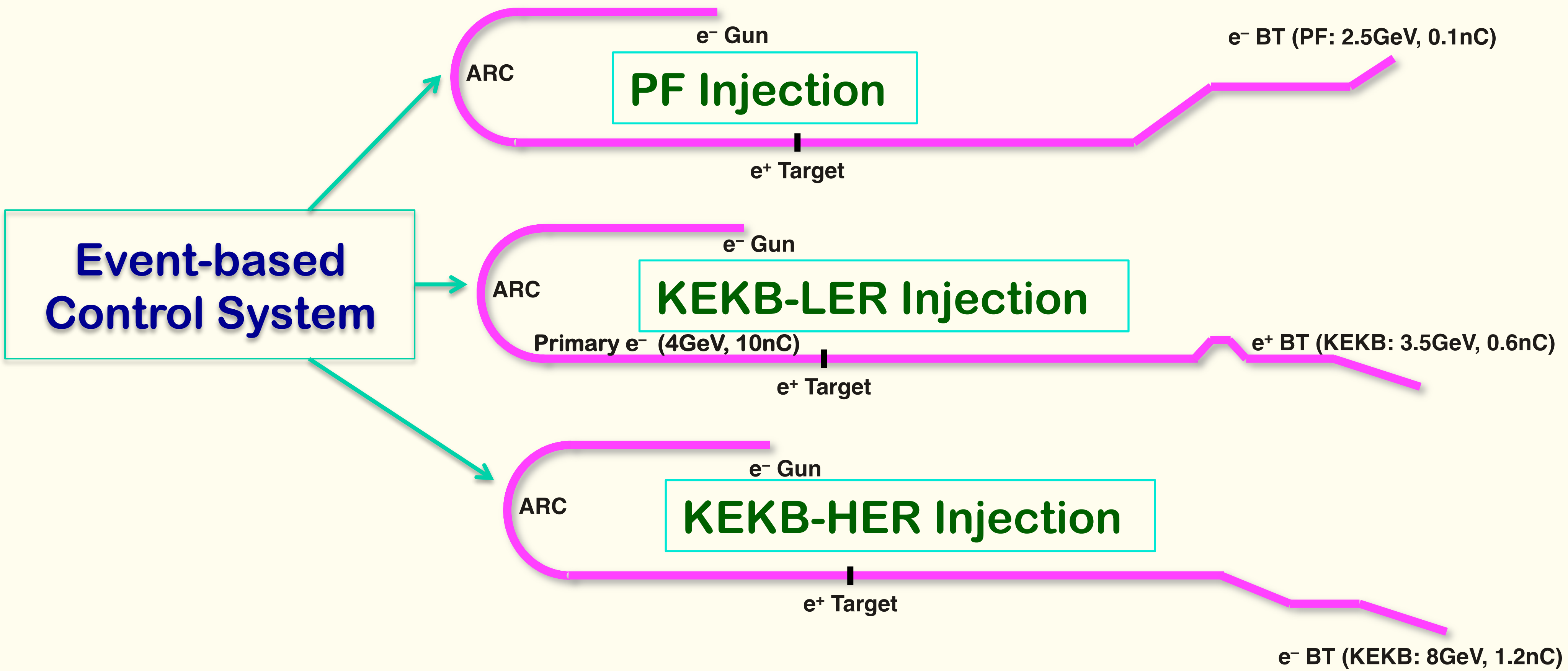
Dual layer control concept





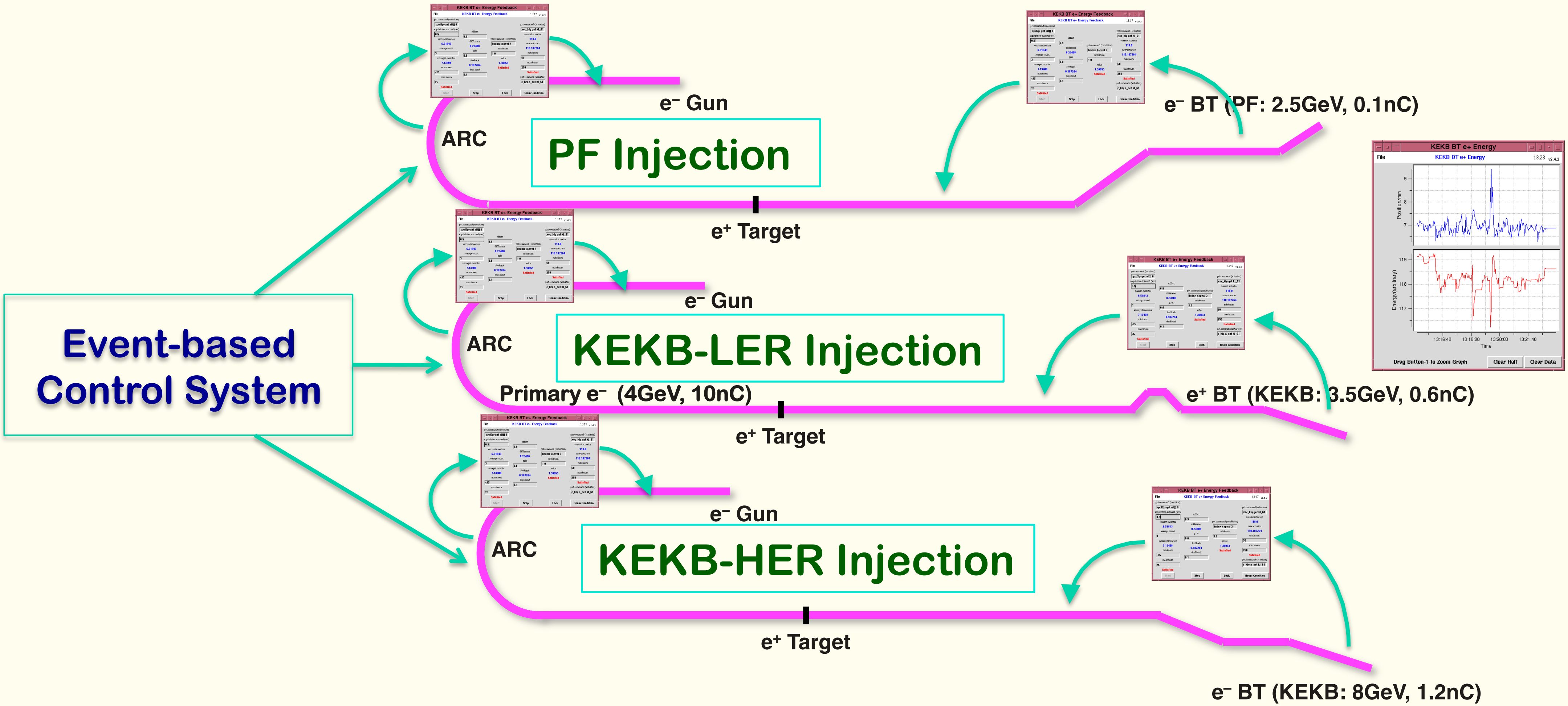
One Machine, Multiple Virtual Accelerators (VAs)

- **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



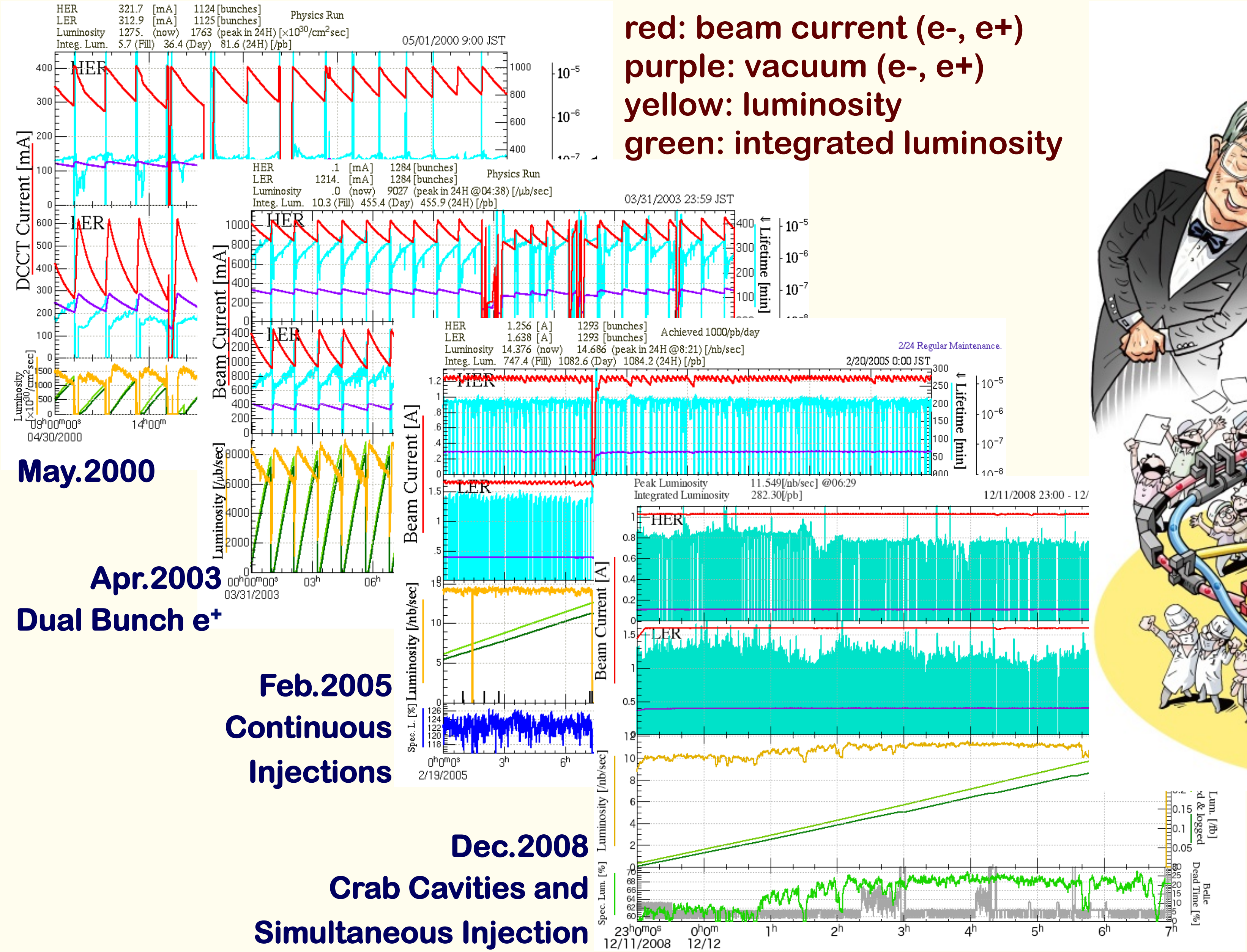
Multiple Closed Loop Controls Overlapped

- 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



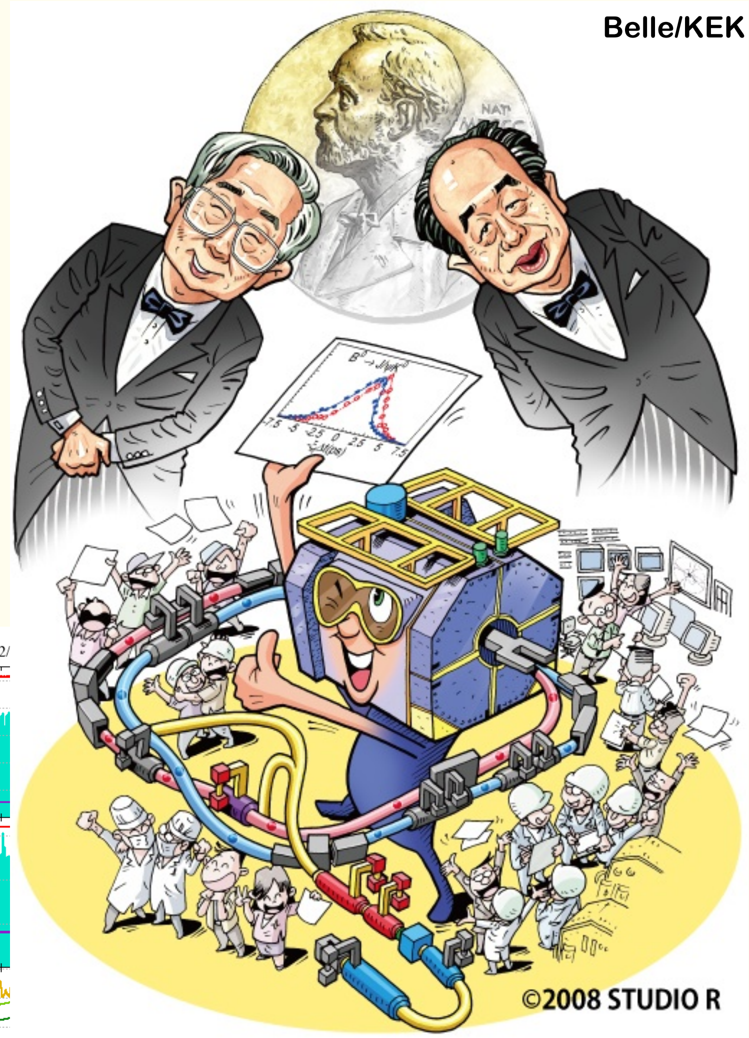
May.2000

Apr.2003
Dual Bunch e+

Feb.2005
Continuous
Injections

Dec.2008
Crab Cavities and
Simultaneous Injection

Belle/KEK



Keeps world
luminosity record

Advances in KEK Injector Linac

Machine Performance Improvement

Challenges towards SuperKEKB

Upgraded Injector for 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

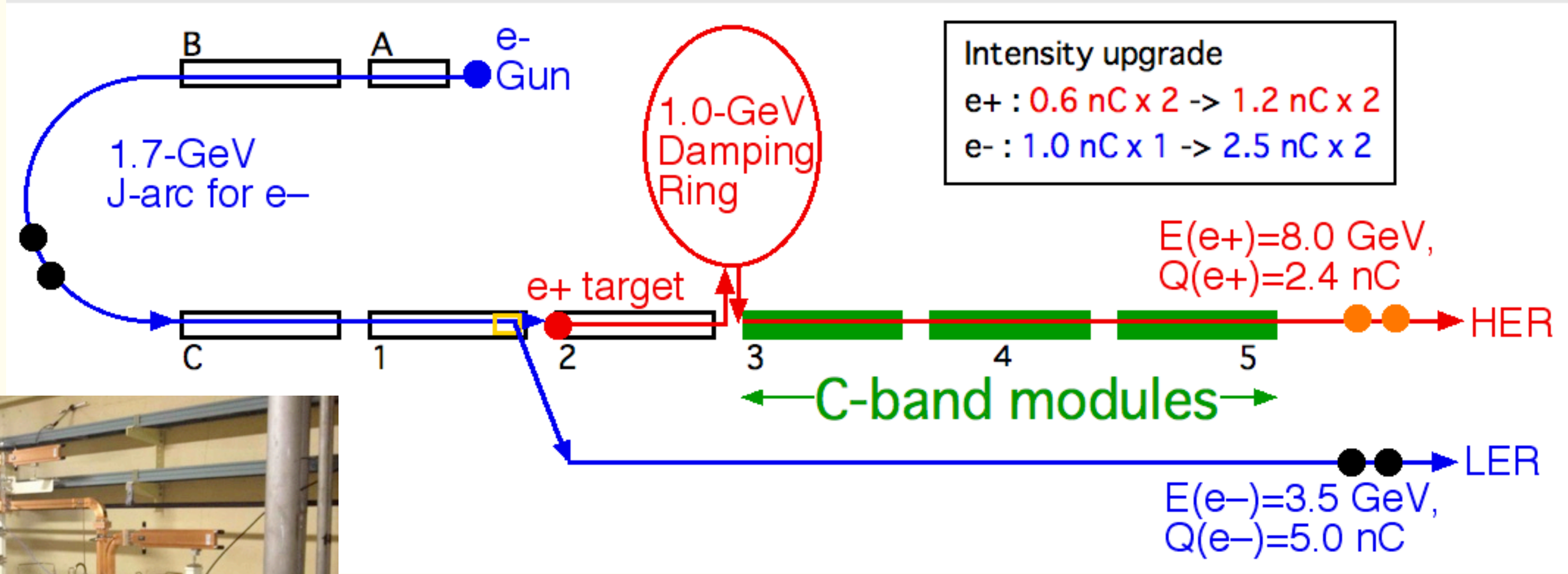
  (3) is the Major Challenge, as well as (2)

  Two Schemes are Considered
  - (a) Higher Gradient with C-band Structures
  - (b) Recirculation of Positron

K.Furukawa, Linac2002, Aug.2002.

C-band Developments for Energy Exchange

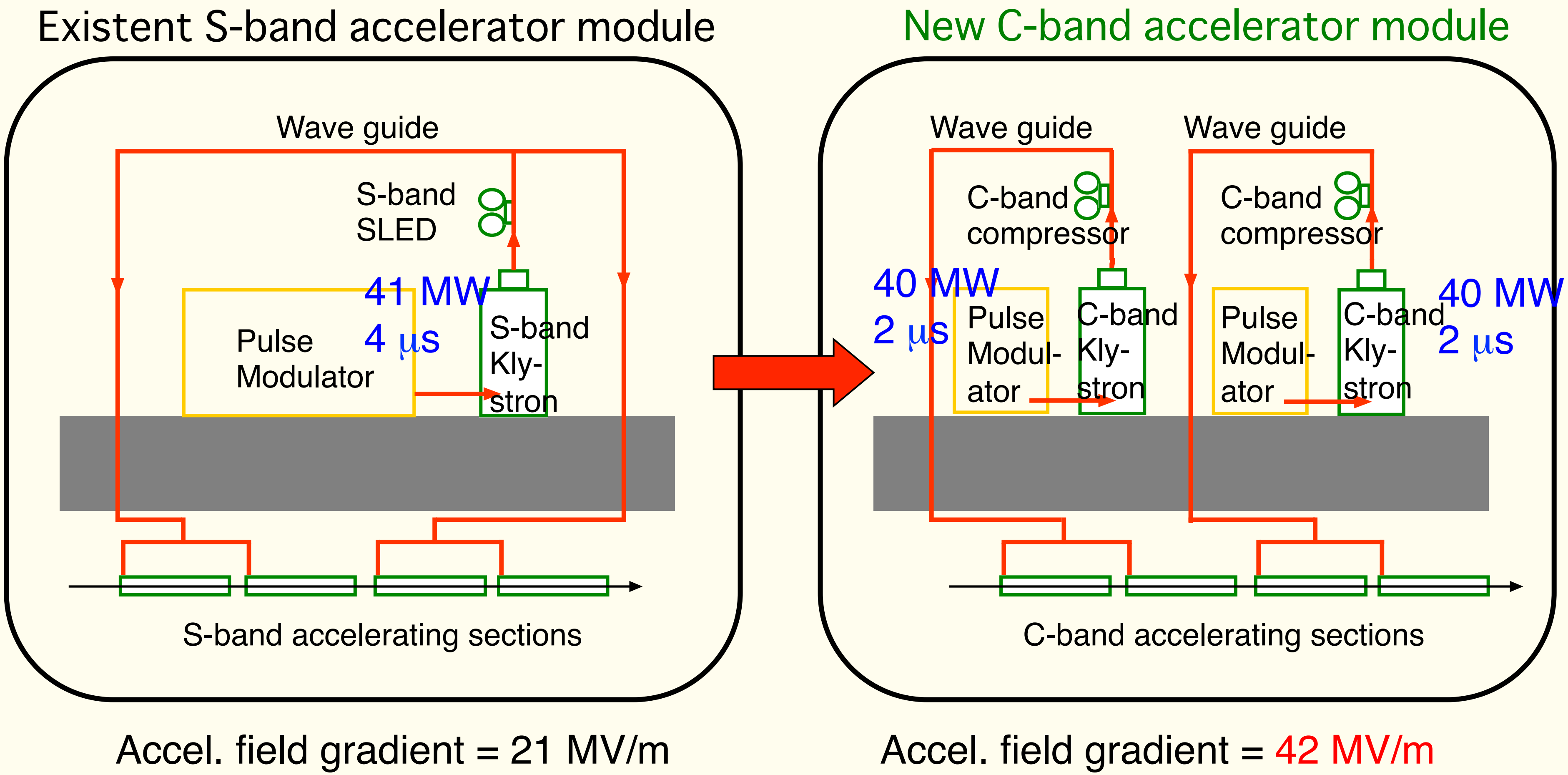
- **Electron cloud instability in the positron ring could be partially cured with higher energy in SuperKEKB**



- **The same electroplating technique was applied for the 1-m structures, and succeeded doubling the gradient**

Converting S-band unit into C-band units

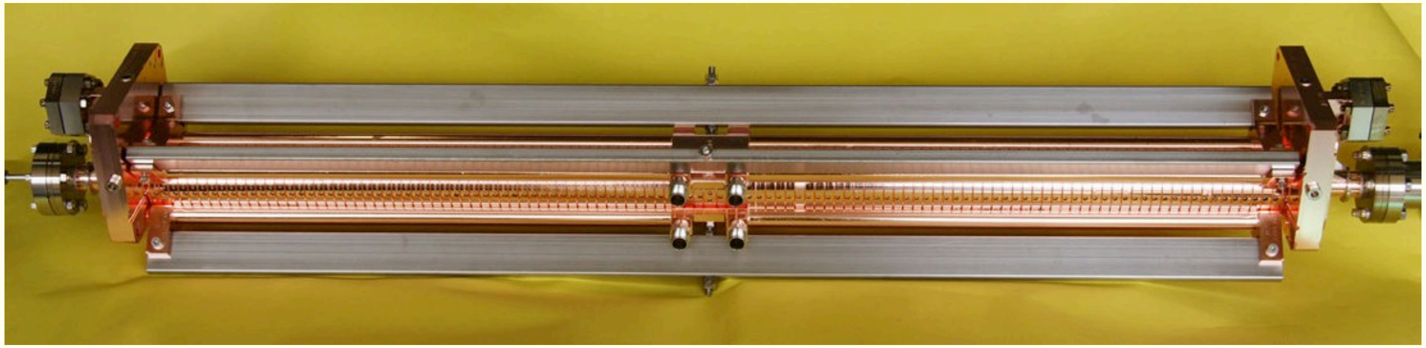
- **2 units were actually installed and operated for injections during the KEKB project**



- **However, later scheme did not allow small apertures to avoid emittance growth, and removed for SuperKEKB**

X-band Developments

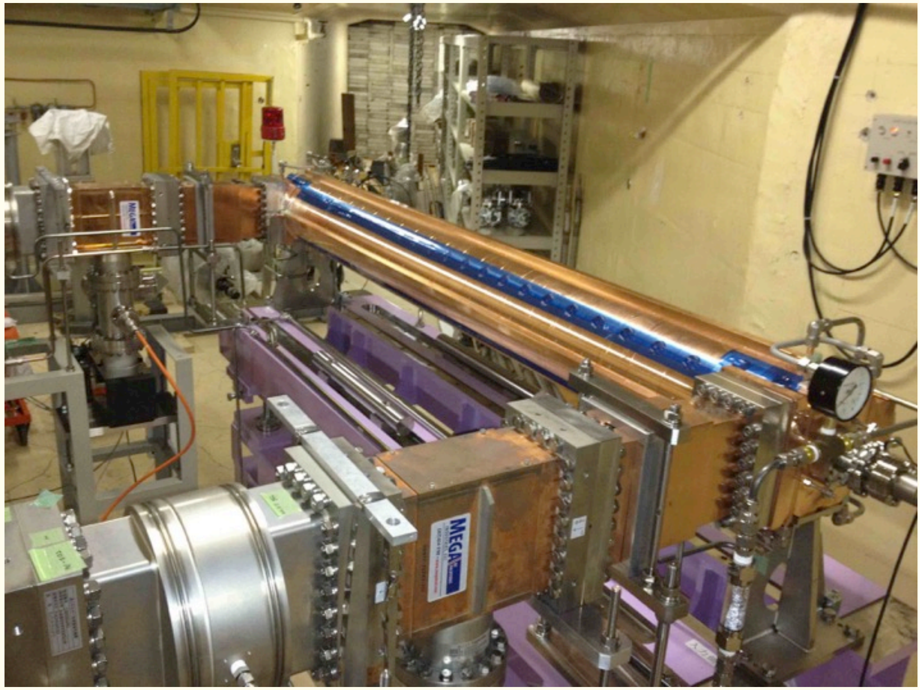
- **X-band deflector was developed**
  - For single-shot emittance measurement
  - In collaboration with SLAC
  - Medium power klystron and power modulators were developed
  - Installation delayed for beamline design



- **General purpose high-gradient acceleration study**
  - In collaboration with CERN, SLAC, Beijing, Shanghai, ···
  - Especially CLIC collaboration and CLIC prototype structure tests

L-band Developments for Positron Yield

- L-band structure was developed to enhance the positron yield
  - After the positron target for large-aperture capturing
  - After the damping ring for bunching
- Kantal coaxial RF load to fit inside of solenoids
- Synergy expected with 1.3 GHz RF ILC development
  - 2856 x 5 ÷ 11
    - "11" is needed anyway for the ring synchronization
  - S-band satellite bunches can be filtered with this frequency
- Klystron was developed as well
  - High power test succeeded
- Now this is a backup plan



Large Aperture S-band Development

- L-band system may consume large resources
- Beam simulation suggests S-band may suffice
  - With velocity bunching
  - For capturing, bunching, and satellite elimination
- Larger aperture S-band structure was designed
  - 20 mm → 30 mm aperture, double feed, fitting into solenoids
  - Electroplating → brazing because of small productions

Advances in KEK Injector Linac

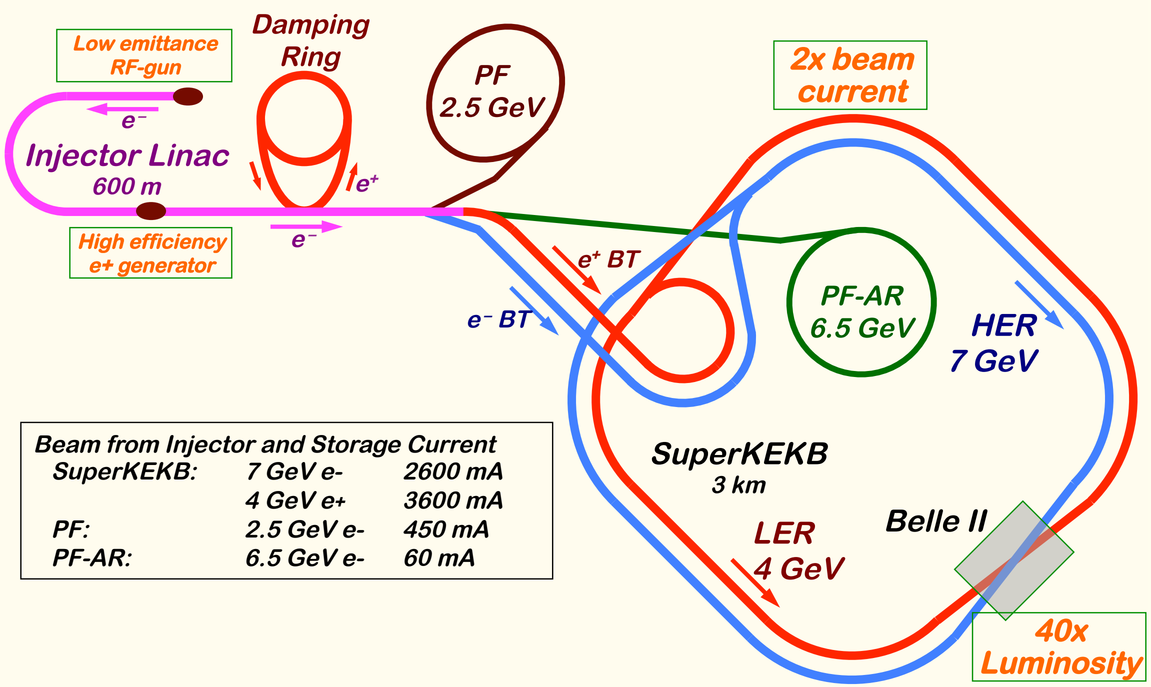
Machine Performance Improvement

Challenges towards SuperKEKB

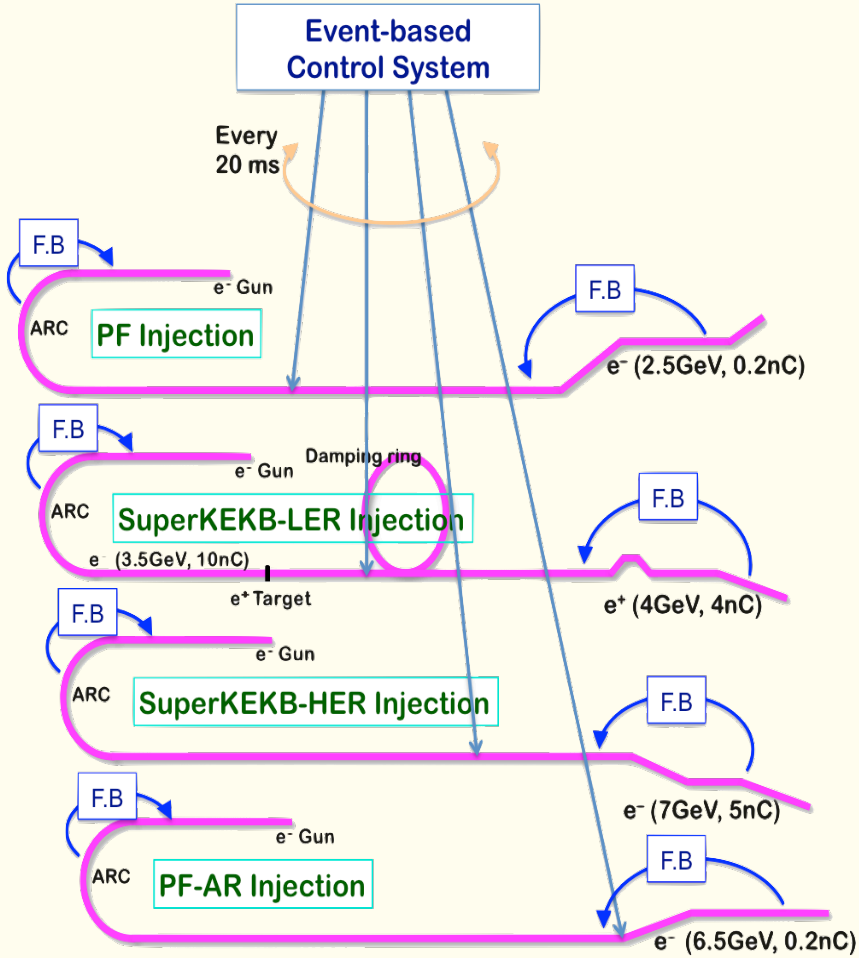
Upgraded Injector for SuperKEKB

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**

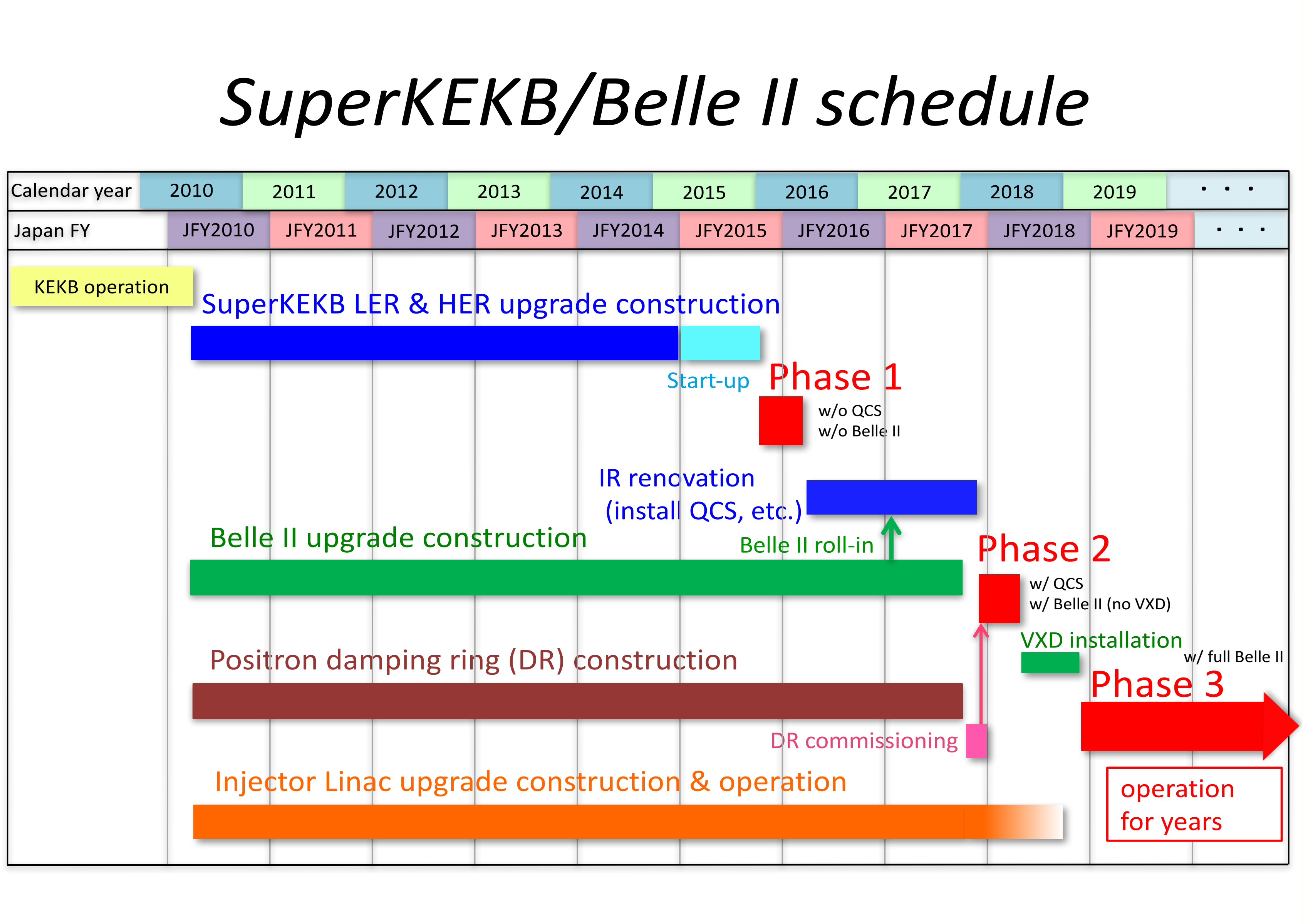


Beam from Injector and Storage Current		
SuperKEKB:	7 GeV e-	2600 mA
	4 GeV e+	3600 mA
PF:	2.5 GeV e-	450 mA
PF-AR:	6.5 GeV e-	60 mA



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

SuperKEKB Schedule

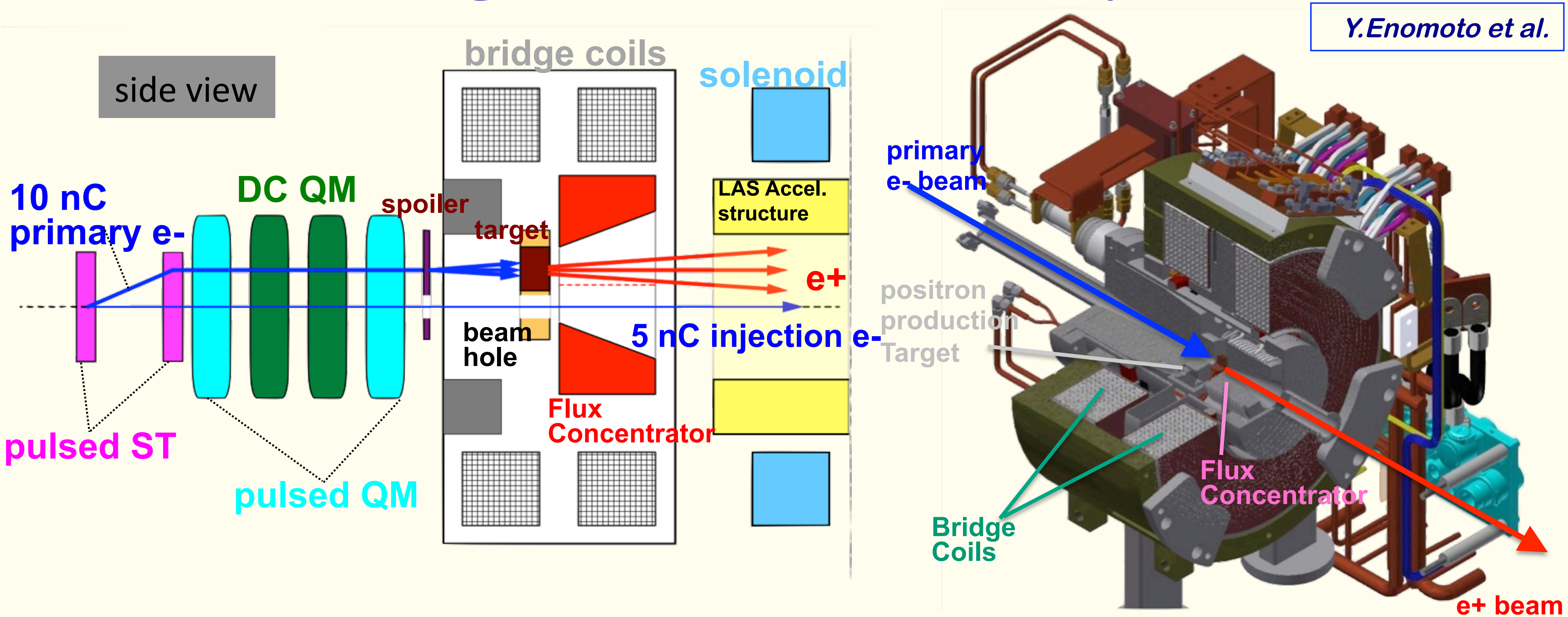


Required injector beam parameters

Injector Linac Parameters

Stage	KEKB Achievements		Phase-I Achievements		Phase-II Requirements		Pre- Phase-II Achievements		Phase-III 1st Year Plan		Phase-III Final Requirements	
Beam	e+	e–	e+	e–	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	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	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	1.4	2.5	primary e- 10 1 - 3	1 - 3	primary e- 10 → 4	4
Norm. Emittance (γβε) (μrad)	1400	310	1000	130	200/40 (Hor/Ver)	150	200/5 (Hor/Ver)	20 @ SectorB	100/15 (Hor/Ver)	40/20 (Hor/Ver)	100/15 (Hor/Ver)	40/20 (Hor/Ver)
Energy spread	0.13%	0.13%	0.50%	0.50%	0.16%	0.10%	?	?	0.16%	0.07%	0.16%	0.07%
Bunch / Pulse	2	2	2	2	2	2	2	2	2	2	2	2
Repetition rate	50 Hz		25 Hz		25 Hz		25 Hz		50 Hz		50 Hz	
Simultaneous top-up injection (PPM)	3 rings (LER, HER, PF)		No top-up		Eventually		Only for LER, PF, PF-AR		4+1 rings (LER, HER, DR, PF, PF-AR)		4+1 rings (LER, HER, DR, PF, PF-AR)	

Positron generation for SuperKEKB



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

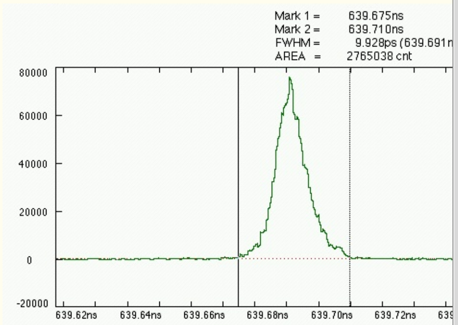
Pinhole (2mm) for passing electrons beside target (3.5mm)

Recently, facing discharge difficulties at maximum field

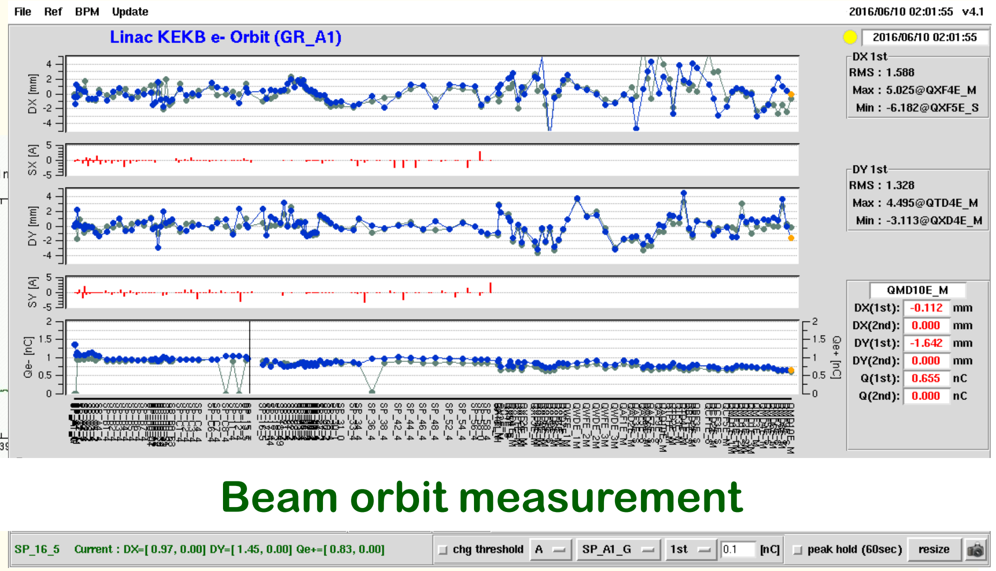
Development of Photo-cathode RF Gun

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**

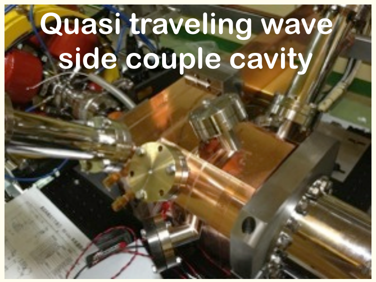


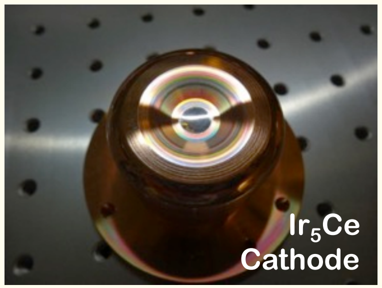
Bunch width

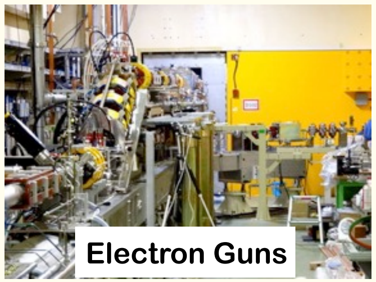


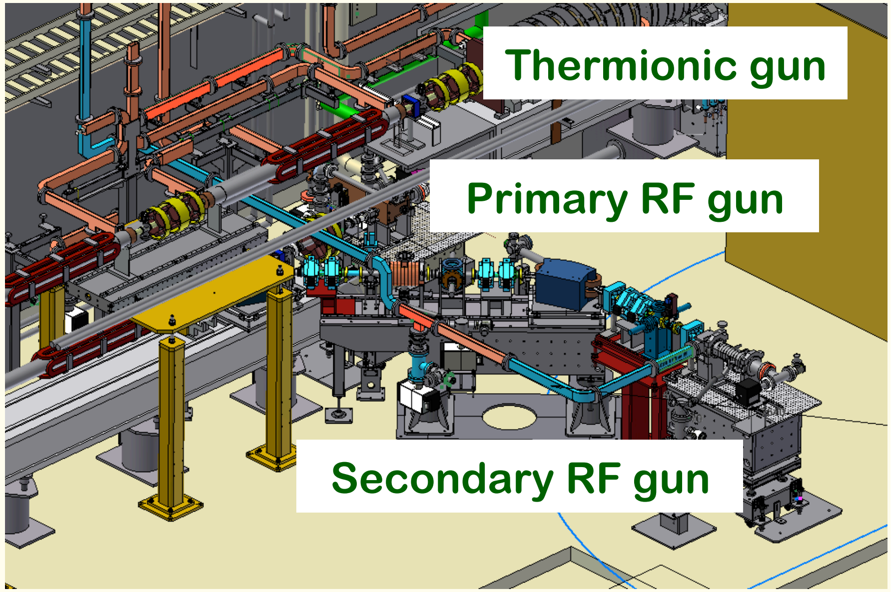
Beam orbit measurement

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





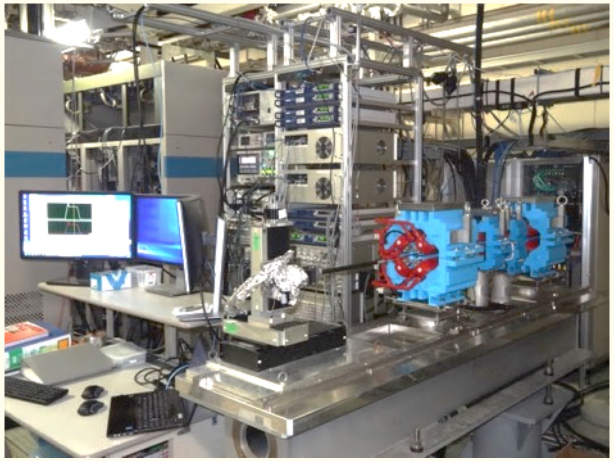




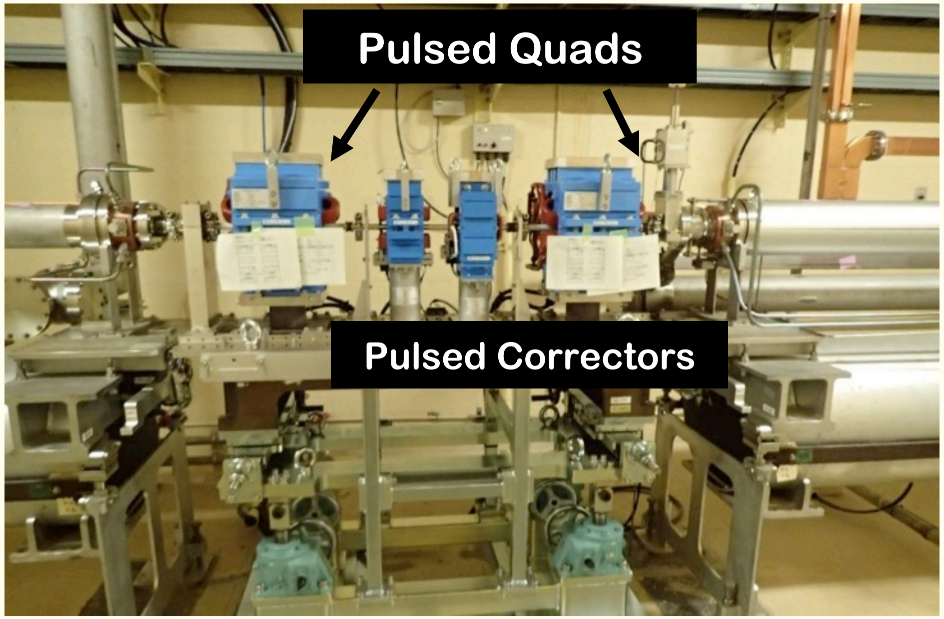
Development and installation of pulsed magnets

- Pulsed magnets and power supplies were installed in 2017
- >30 quads, >40 steerings, 2 bends, 14 girders are operational
- 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



- Successful fast beam switches
- 0.01% reproducibility and stability
- Girders with In-house drawings to save resources
- 0.1mm alignment precision

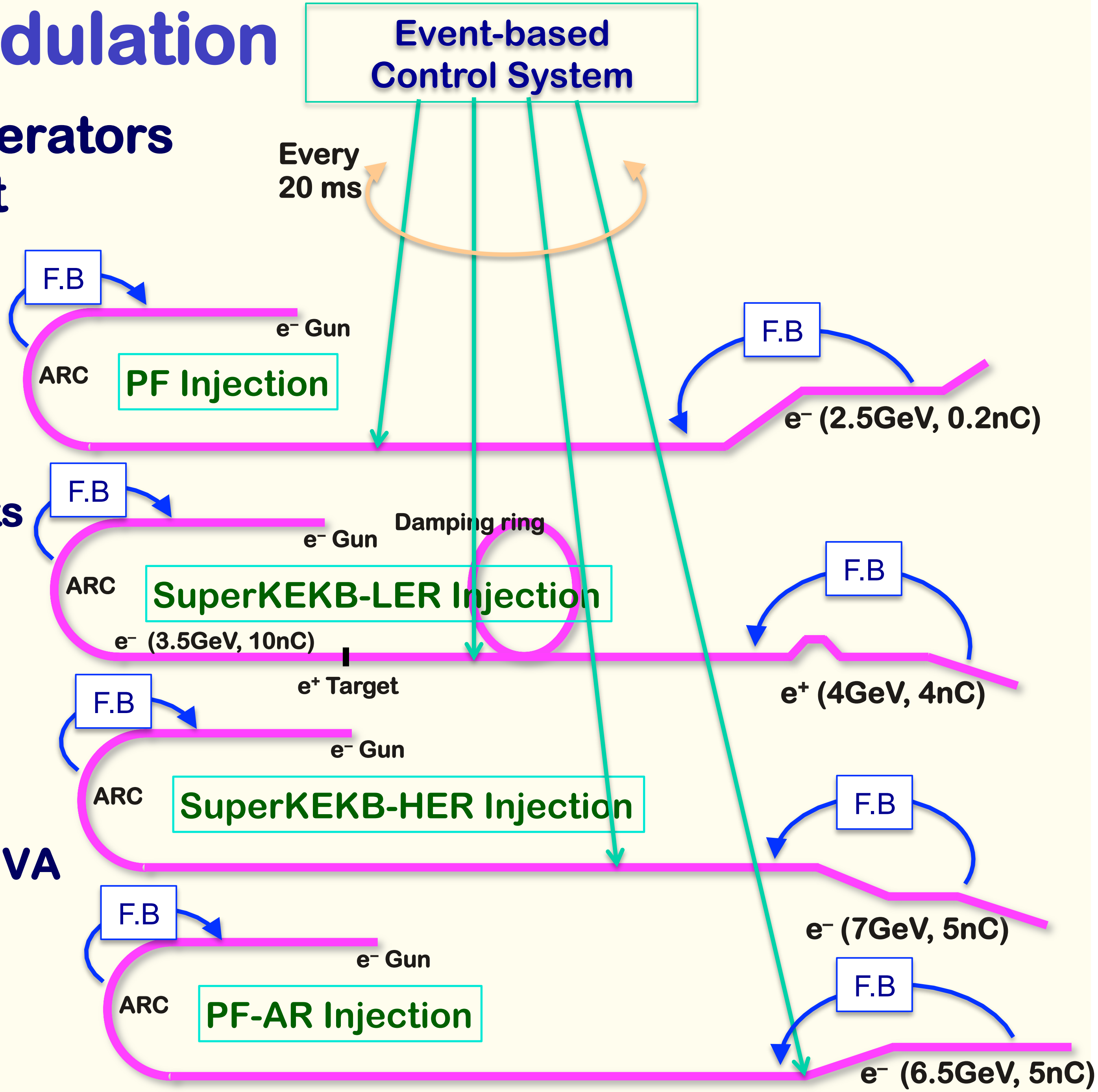
Pulse-to-pulse modulation

- **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

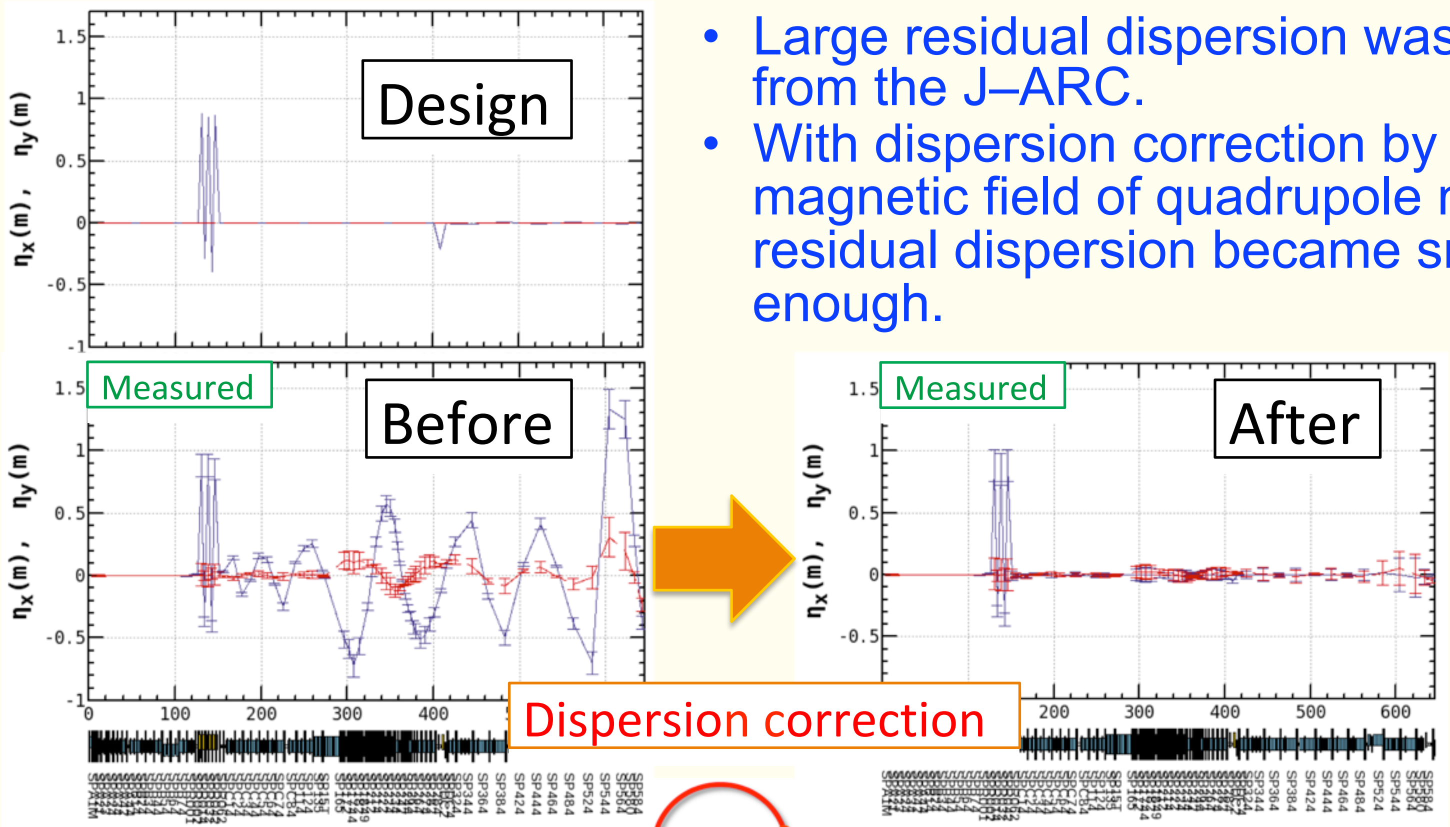
maybe with additional PPM VA of stealth beam for measurement

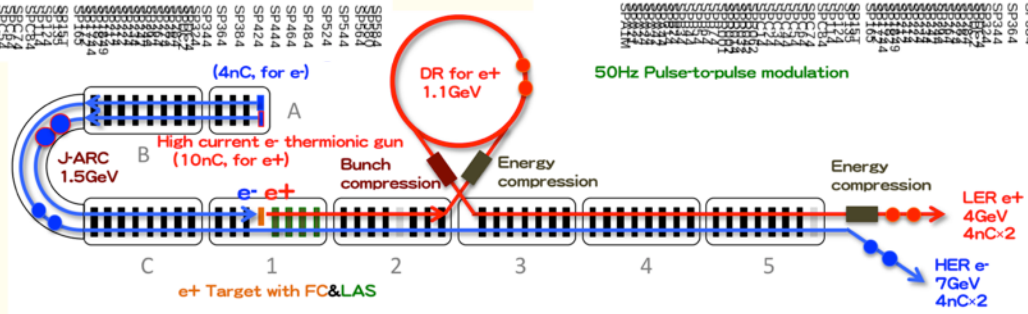


Residual Dispersion Function in Linac

Y. Seimiya et al.

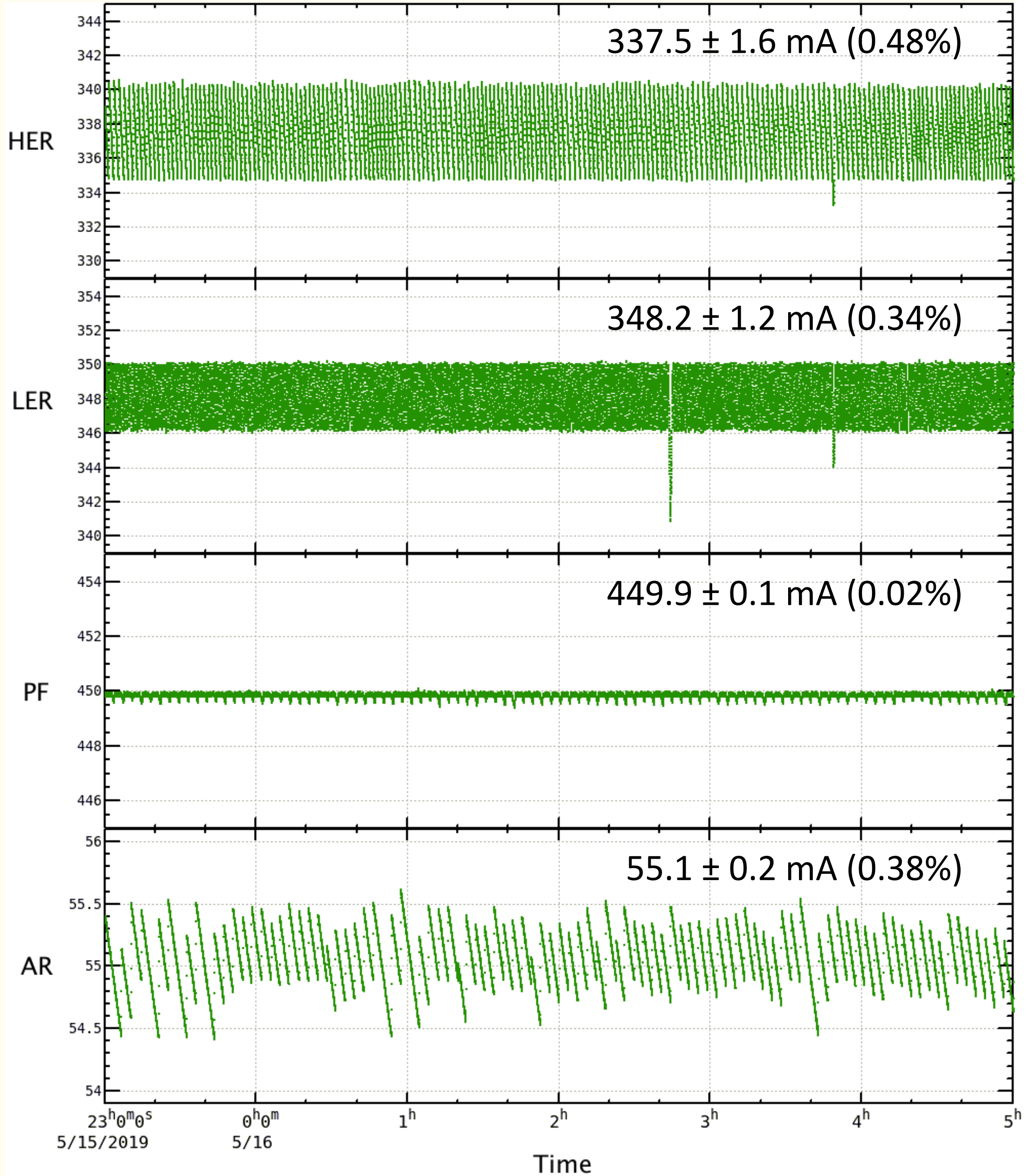
- Large residual dispersion was generated from the J–ARC.
- With dispersion correction by tuning the magnetic field of quadrupole magnets, residual dispersion became small enough.





Simultaneous 4 + 1 Ring Top-up Injection

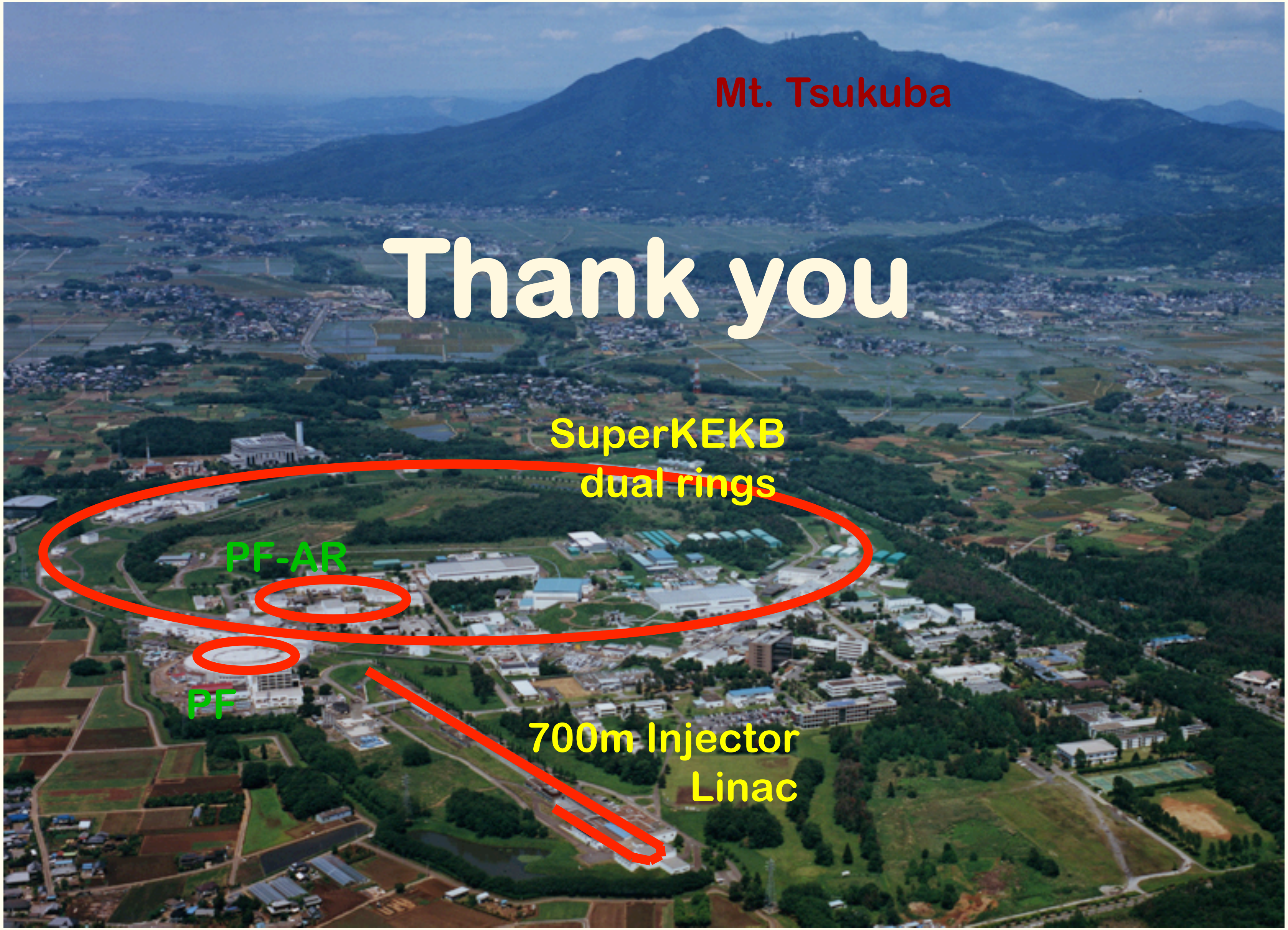
- **Realized for the first time**
  - SuperKEKB HER 7 GeV e–
  - SuperKEKB LER 4 GeV e+
  - Photon Factory 2.5 GeV e–
  - PF-AR 5.0 / 6.5 GeV e–
- 4 beams are modulated at 20 ms PPM
- More than 200 pulsed devices were constructed for SuperKEKB, as well as beam and RF monitors
- Injection noise (background) were well studied and routinely adopted from the 3rd week of May (after a severe fire)



Summary

Summary

- We learned a lot during injector development and operation for 4 decades
- It contributed to achieve the world highest luminosity
- Injection into SuperKEKB is another challenge with higher beam charge and lower transverse/longitudinal emittance
- Trial and error for a new accelerator may be necessary depending on many parameters along the accelerator chain
- With some Phronesis we can enjoy accelerators
  - Phronesis [Greek]: Practical wisdom, Ability to understand the Universal Truth



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