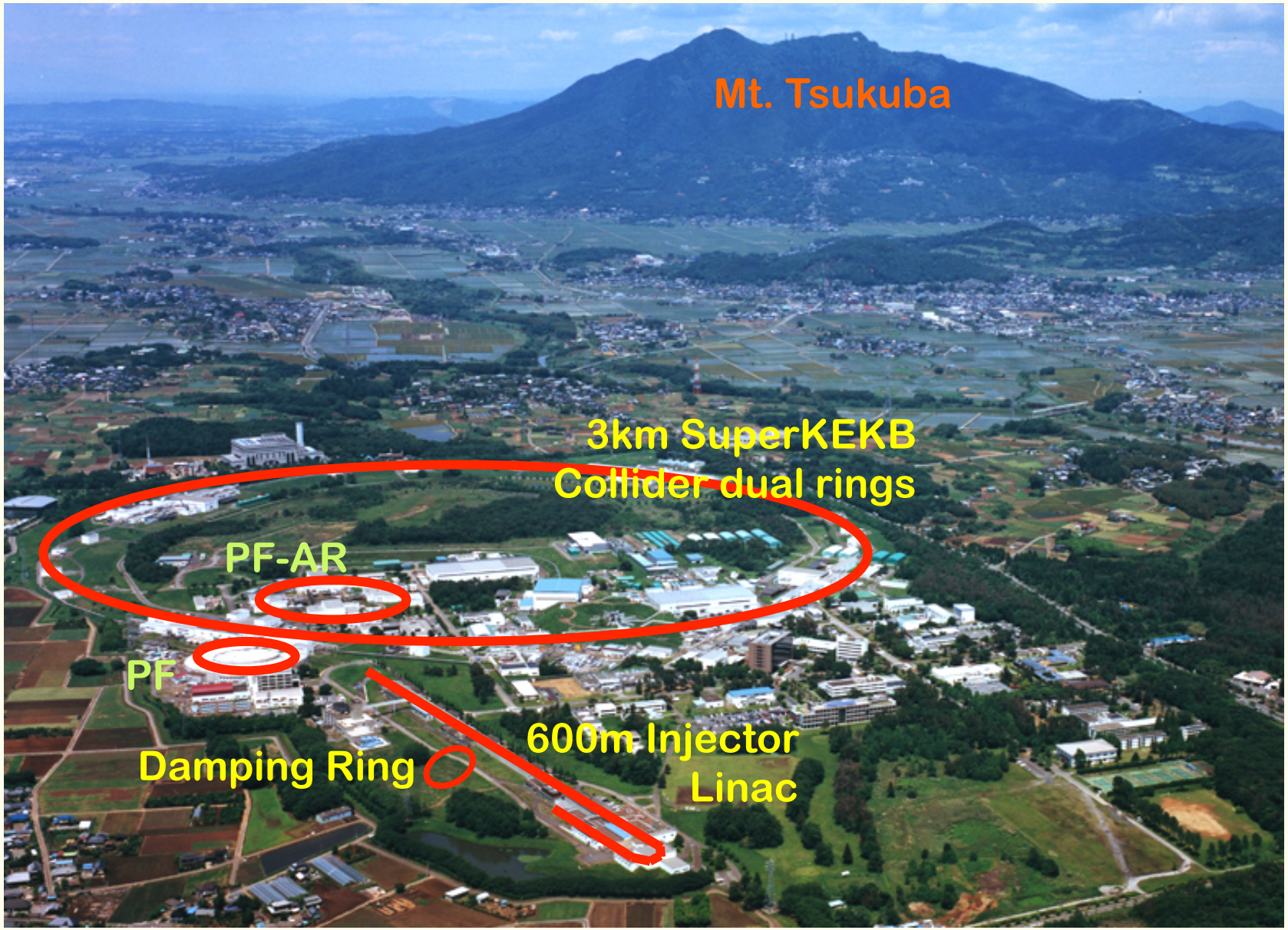
Injector and Collider Rings of SuperKEKB B factory

– with some emphasis on the injector –

Kazuro Furukawa

for SuperKEKB Injector and Rings, KEK

<kazuro.furukawa@kek.jp>


Mt. Tsukuba
3km SuperKEKB
Collider dual rings
PF-AR
PF
600m Injector
Linac
Damping Ring

KEKB and SuperKEKB overview

Daily performance improvements

Dual bunches in a pulse

Continuous injection

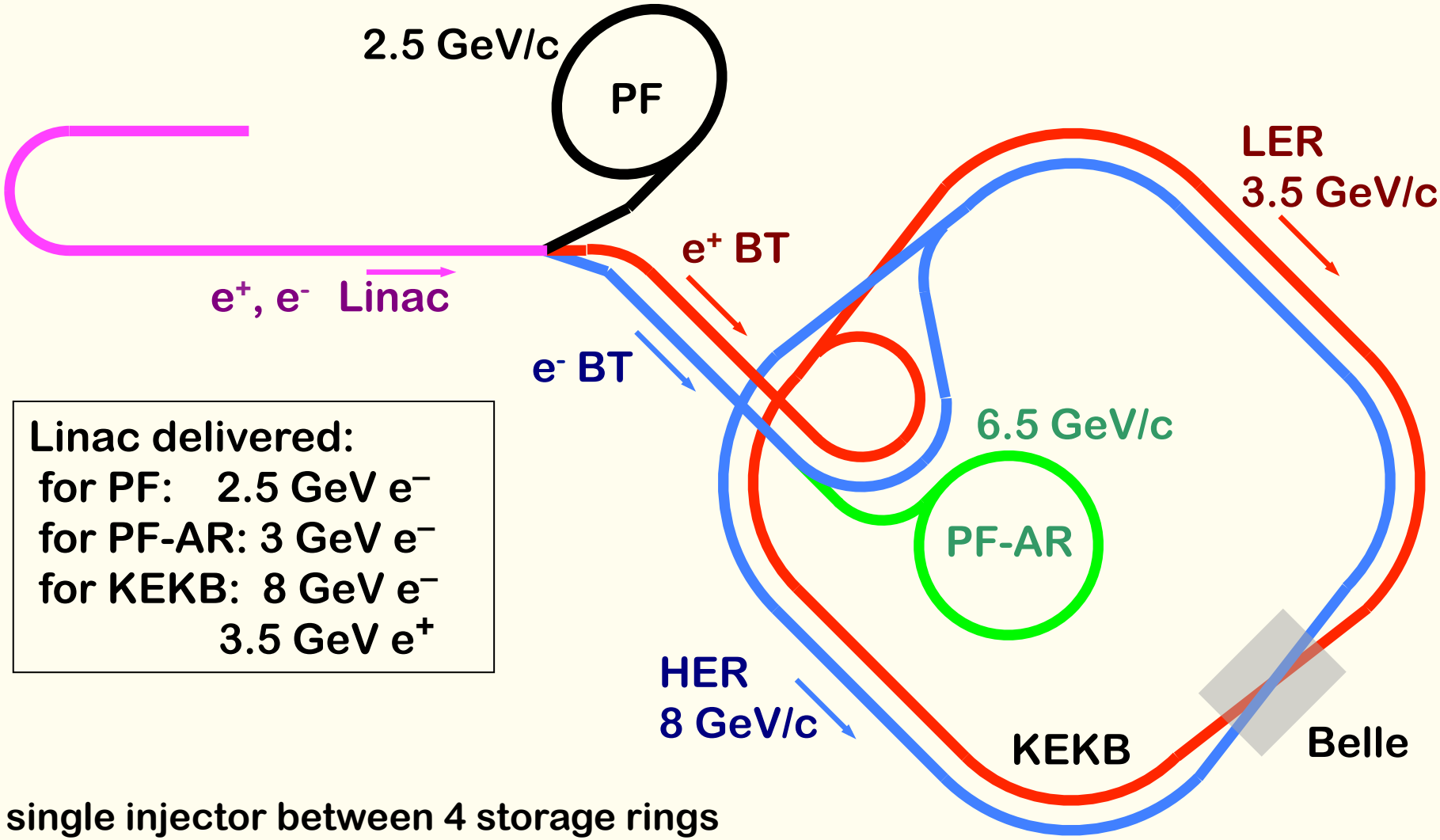
Simultaneous top-up injection

Upgrade towards SuperKEKB

Summary

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^+

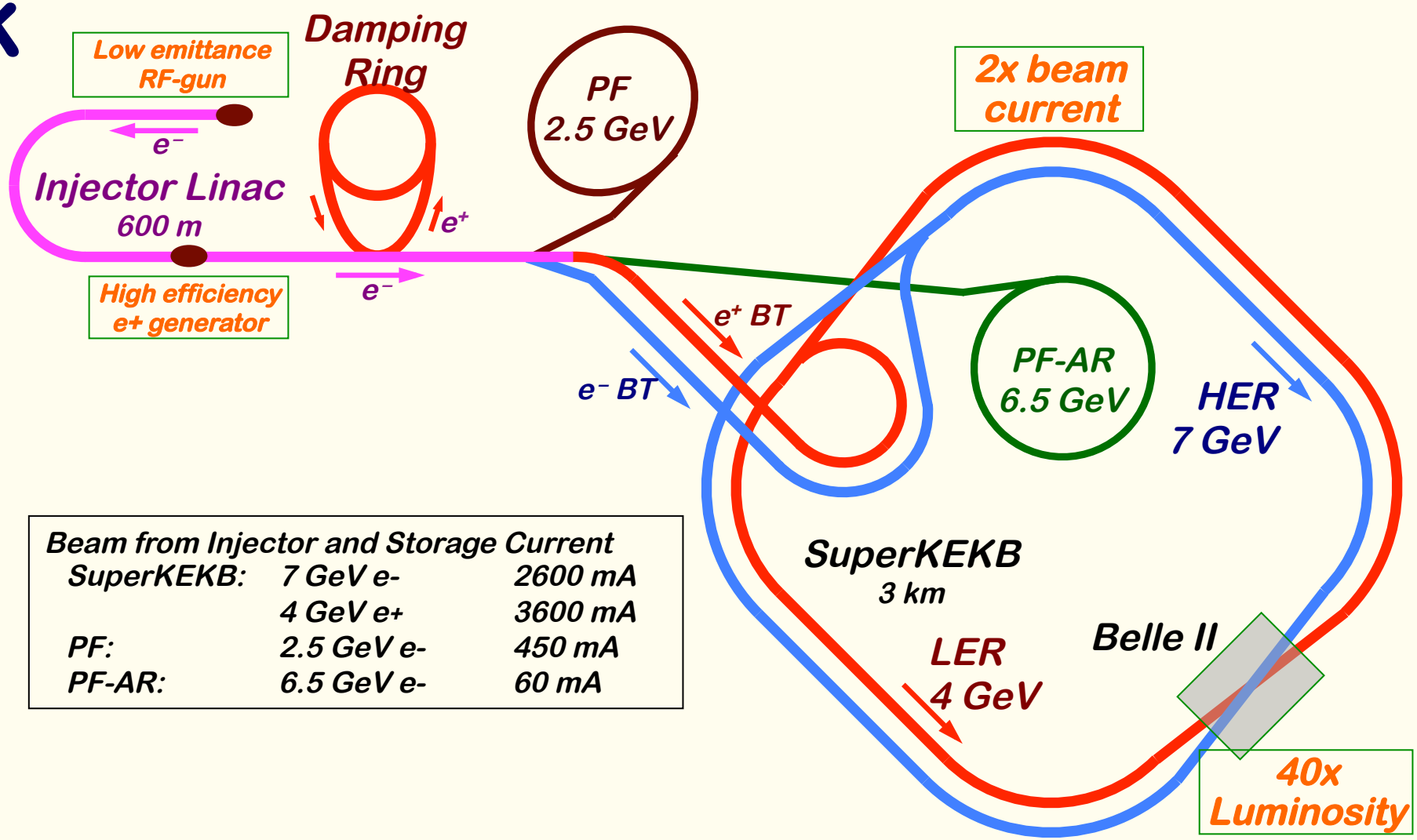
Shared single injector between 4 storage rings
Shared beam transport line between HER & PF-AR

KEKB Design

- Maximum 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

SuperKEKB Configuration (2018 –)

Newer Electron Positron Accelerator Complex at KEK



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

SuperKEKB Design

- Maximum reuse of KEKB inheritance
- However, still many improvements applied, ex.
  - Nanobeam collision scheme (with beam sizes of 50nm)
    - For 40-fold higher luminosity avoiding hourglass effect
  - Precise superconducting focusing magnets
    - With many corrector coils
  - RF system additions for twice higher beam current
  - Many magnet additions/replacements for low emittance
  - Damping ring construction
  - PF-AR direct beam transport line construction
  - Many improvements to inject even under nanobeam
    - At injector linac

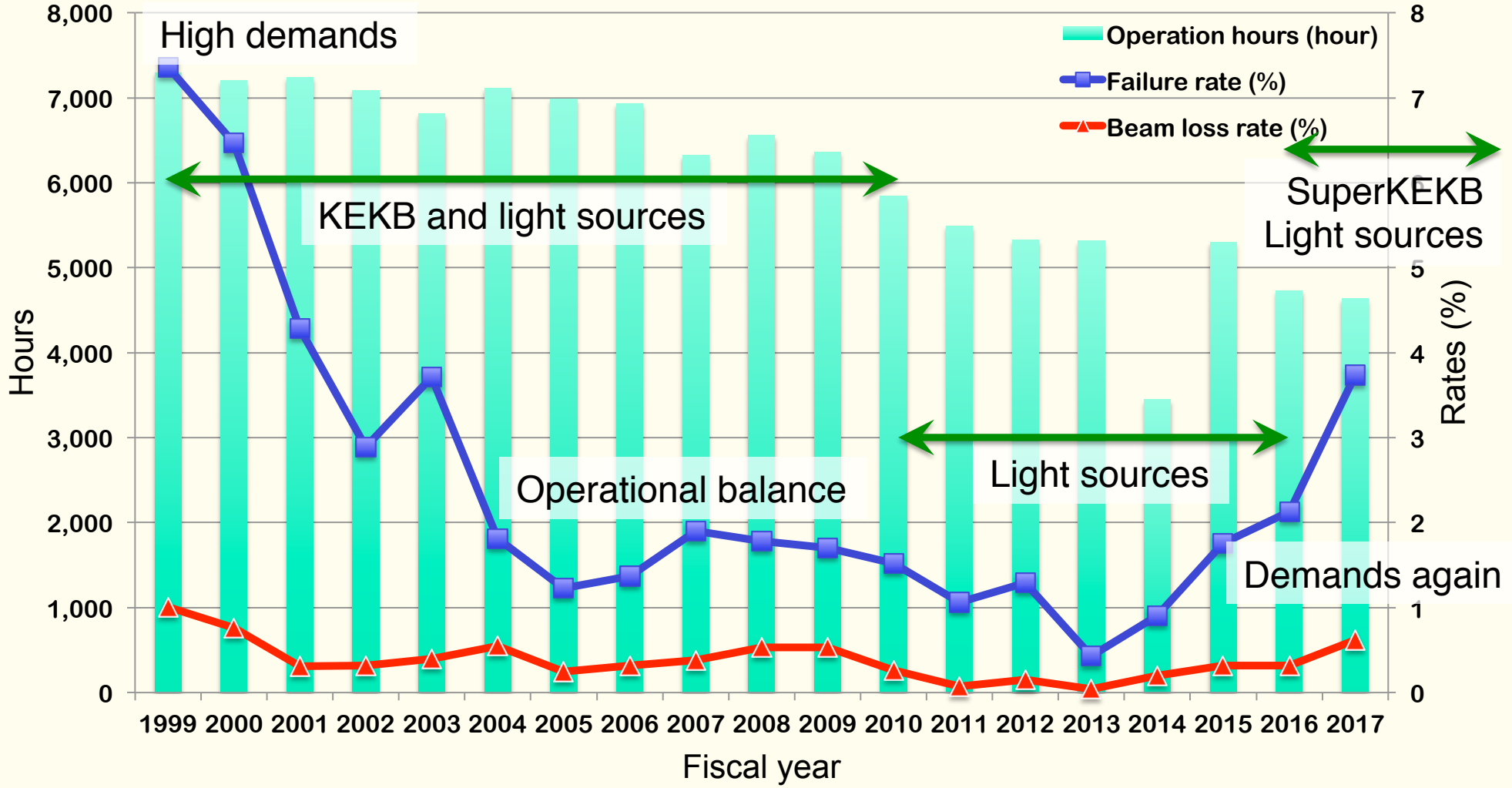
Operator Shifts

- **Operators for every 8-hour**
  - KEKB control room for SuperKEKB, PF-AR, Linac (Beam)
    - 3/2/2 Operators for SuperKEKB, PF-AR [A]
    - 1/1/1 Operators for Linac [B]
    - 1.5/1.5/1 Commissioning shifts for SuperKEKB and Linac [C]
    - 0.5/0.5/1 Safety shifts for SuperKEKB [D]
  - Linac control room
    - 1/1/1 Operators for Linac (Hardware) [B]
    - 1/1/1 Safety shifts for Linac [E]
  - Cryogenic control room
  - PF control room
- **Members**
  - Outsourcing: [A] x12, [B] x12
  - SuperKEKB Staff: x55, Linac Staff: x30 (basically all staff)
  - Staff: [C] x50, [D] x48, [E] x27 (overlapping)

Injector Operation Statistics

Statistics

Injector operation hours and failure rates



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

KEKB and SuperKEKB overview

Daily performance improvements

Dual bunches in a pulse

Continuous injection

Simultaneous top-up injection

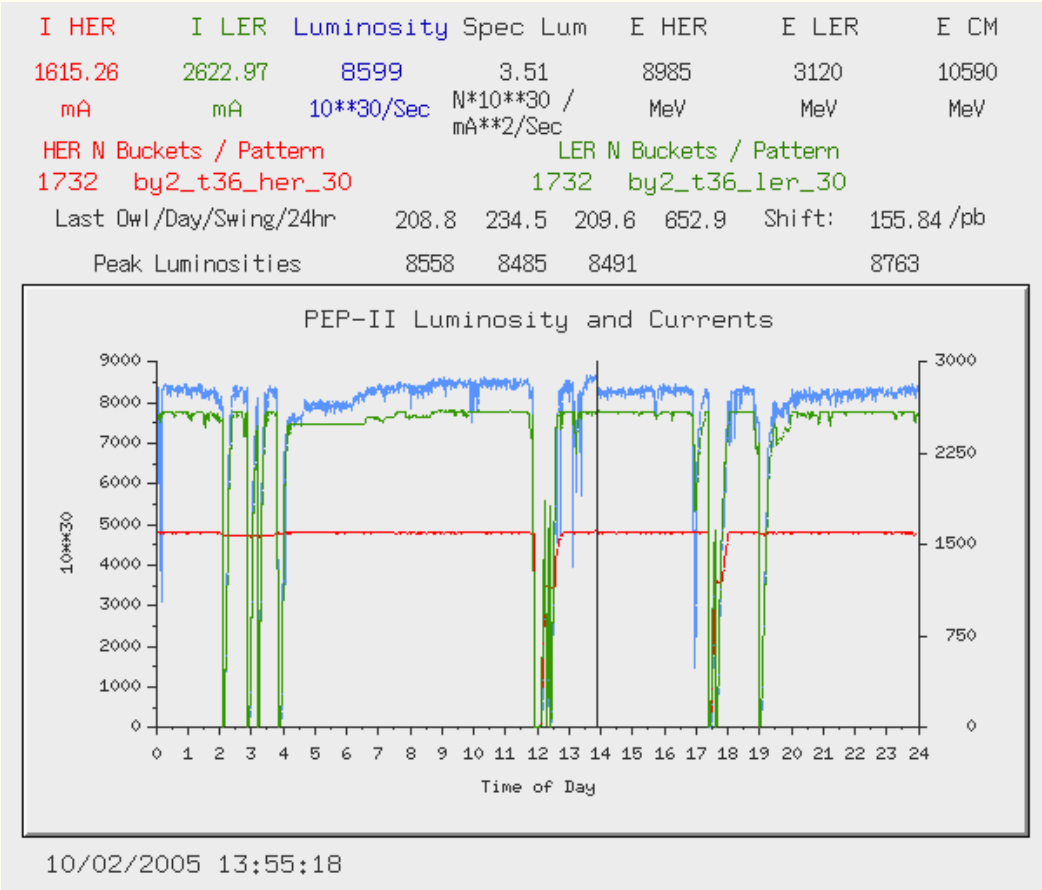
Upgrade towards SuperKEKB

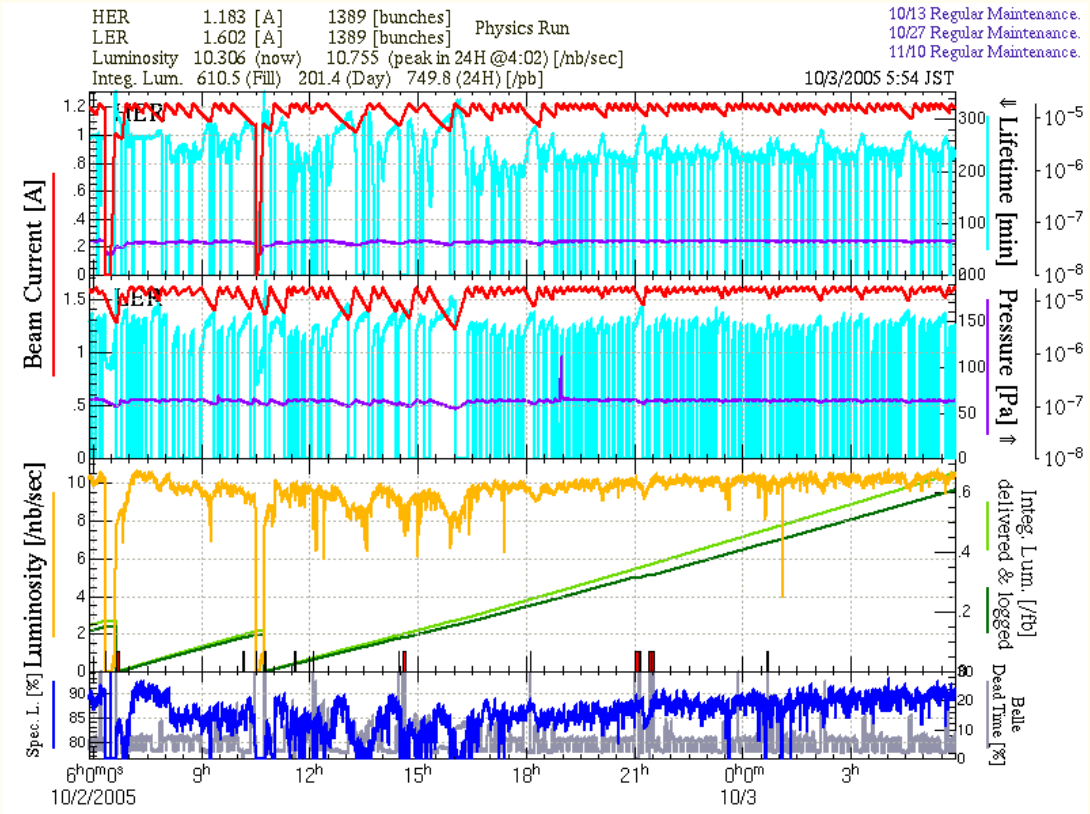
Summary

PEP-II/SLAC and KEKB

We exchanged ideas between PEP-II and KEKB

Viewed each other from control rooms





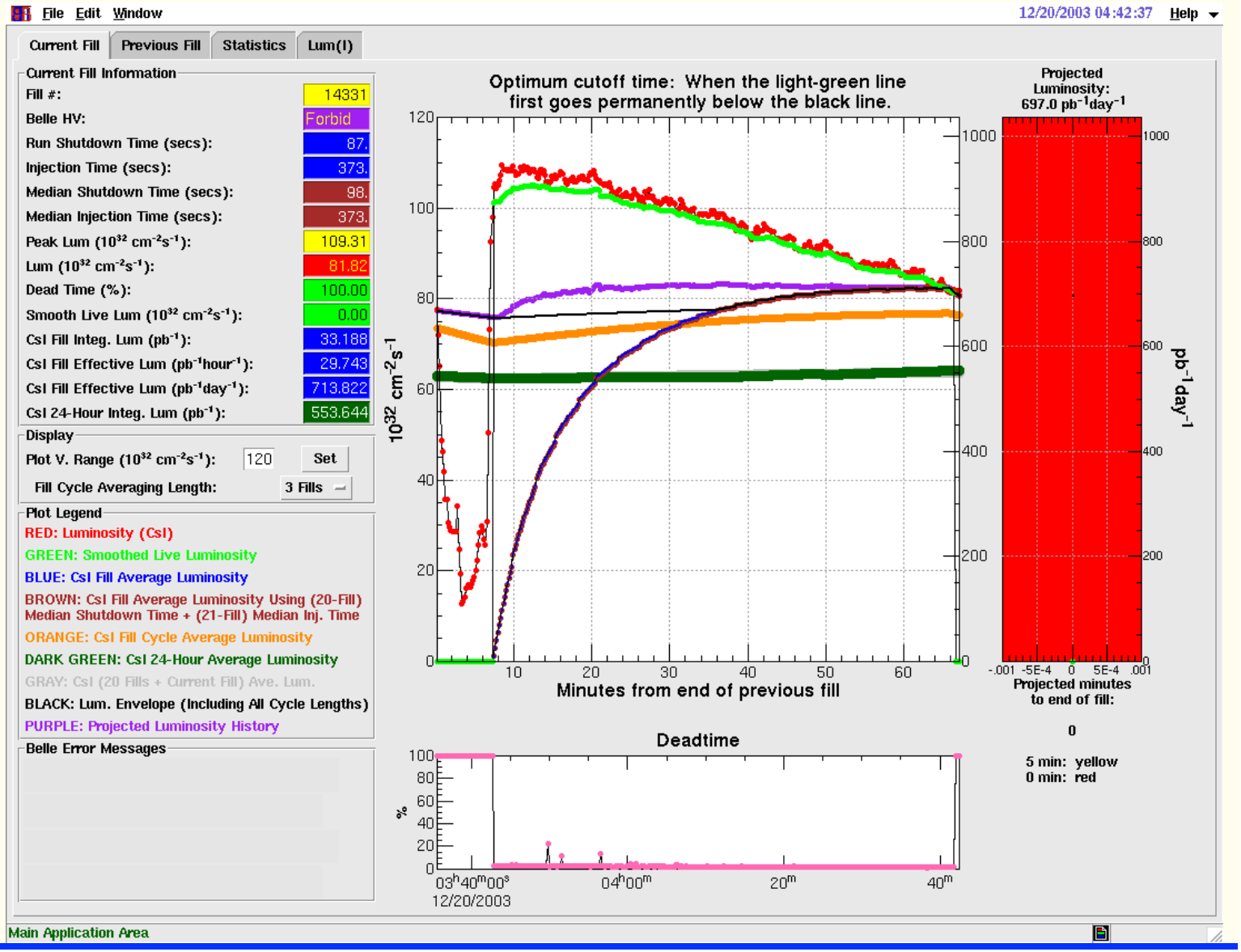
Friendly competition

Daily Morning Meeting

- Every morning on weekdays and weekend from 9 a.m.
- **Very often novel ideas are proposed for performance improvement of beams, devices and operation**
  - Bright new idea in the morning meeting could make the operation much advanced in the evening
    - Only some ideas are effective, so rapid prototyping is important
  - EPICS control framework and Scripting languages
    - Especially, SADscript as a bridge btw. Accelerator simulation, Numeric manipulation, Graphic interface and EPICS controls

Operational Optimizations

- For example, run-length optimization
  - Hundreds of tools were developed
  - with graphical user interface for operators
  - often automated
  - Past examples follow from the next slide



KEKB and SuperKEKB overview

Daily performance improvements

Dual bunches in a pulse

Continuous injection

Simultaneous top-up injection

Upgrade towards SuperKEKB

Summary

Two bunches in a pulse

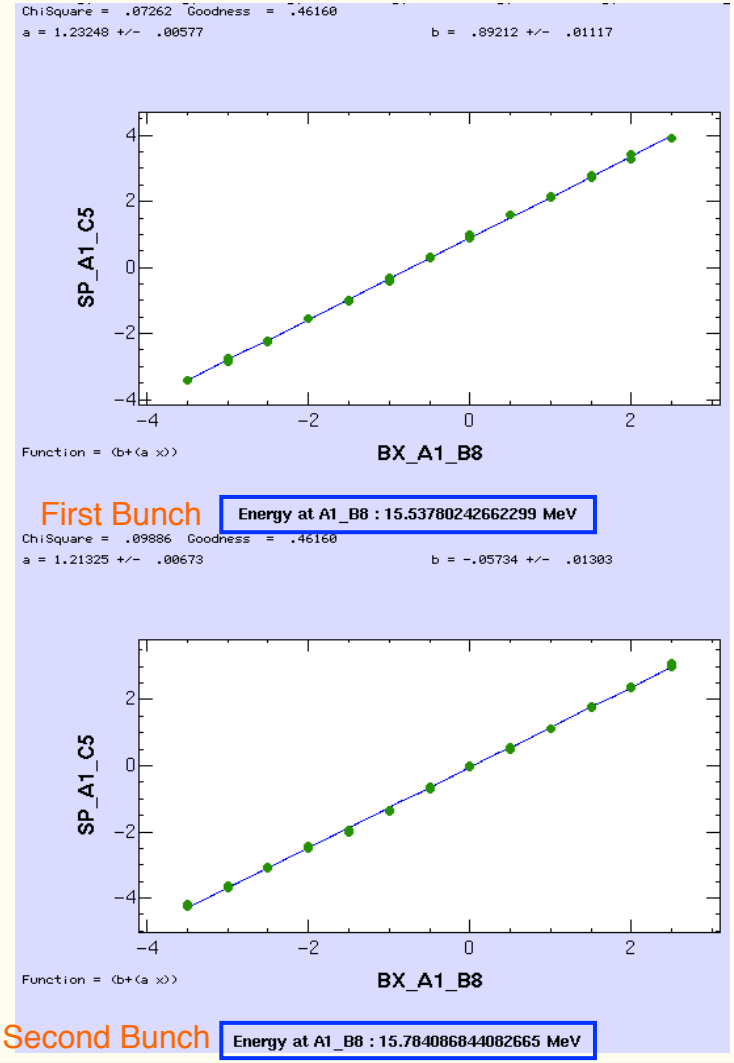
- As the stored beam current in MR increases, much more injection beam current was required
- Especially for the positron injection rate

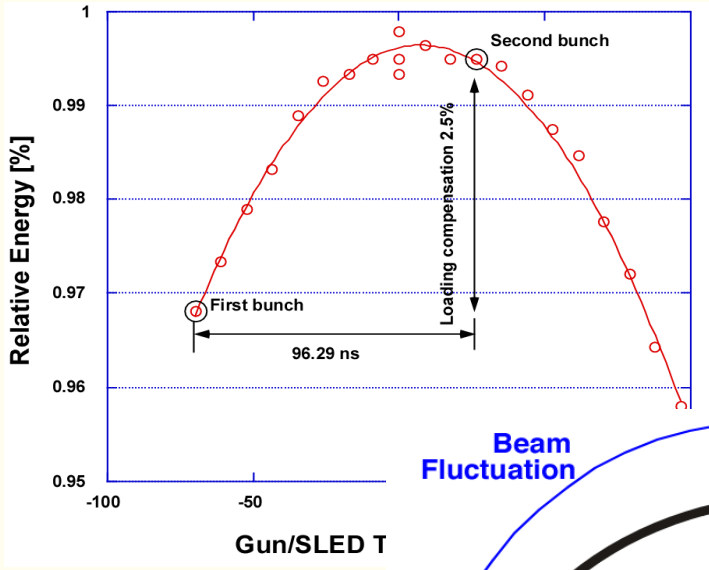
- **Two bunches in a pulse acceleration in order to to double the positron beam current planned**
  - Minimum bunch separation of 96 ns (10.386 MHz)
  - Parallel dual grid pulsers for a single cathode
  - Beam instrumentation with 96 ns separation
  - Timing manipulation and bucket selection
  - Energy equalization

Dual-bunch Energy Equalization, and Feedback

Energy equalization is important for stable operation

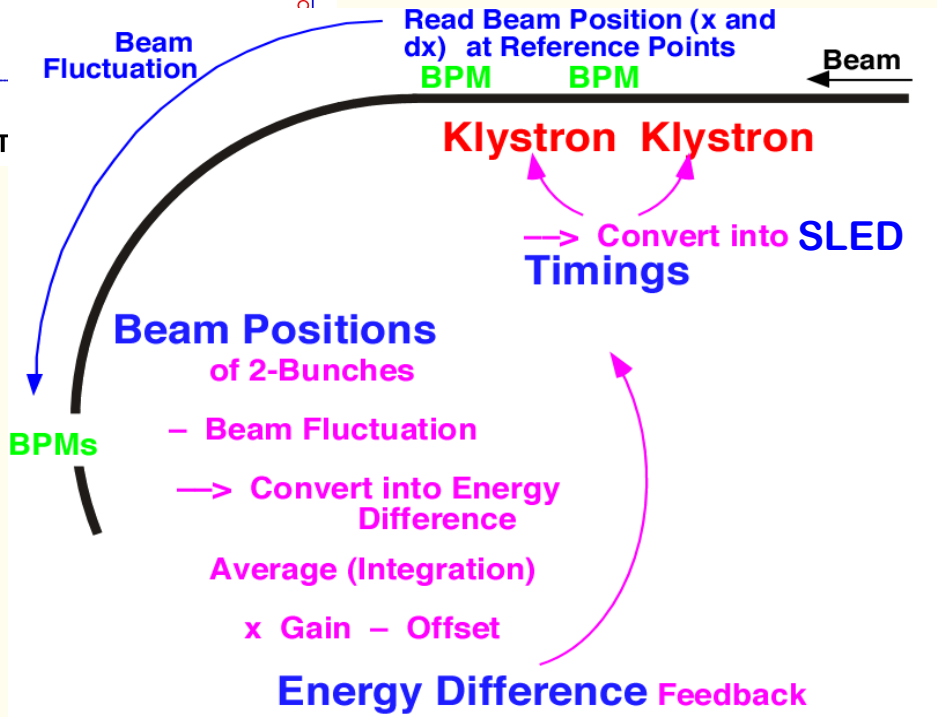
Measurement at bunching section
after energy equalization
with RF pulse timing





Beam loading compensation

Stabilization at bending section
with SLED timing



KEKB and SuperKEKB overview

Daily performance improvements

Dual bunches in a pulse

Continuous injection

Simultaneous top-up injection

Upgrade towards SuperKEKB

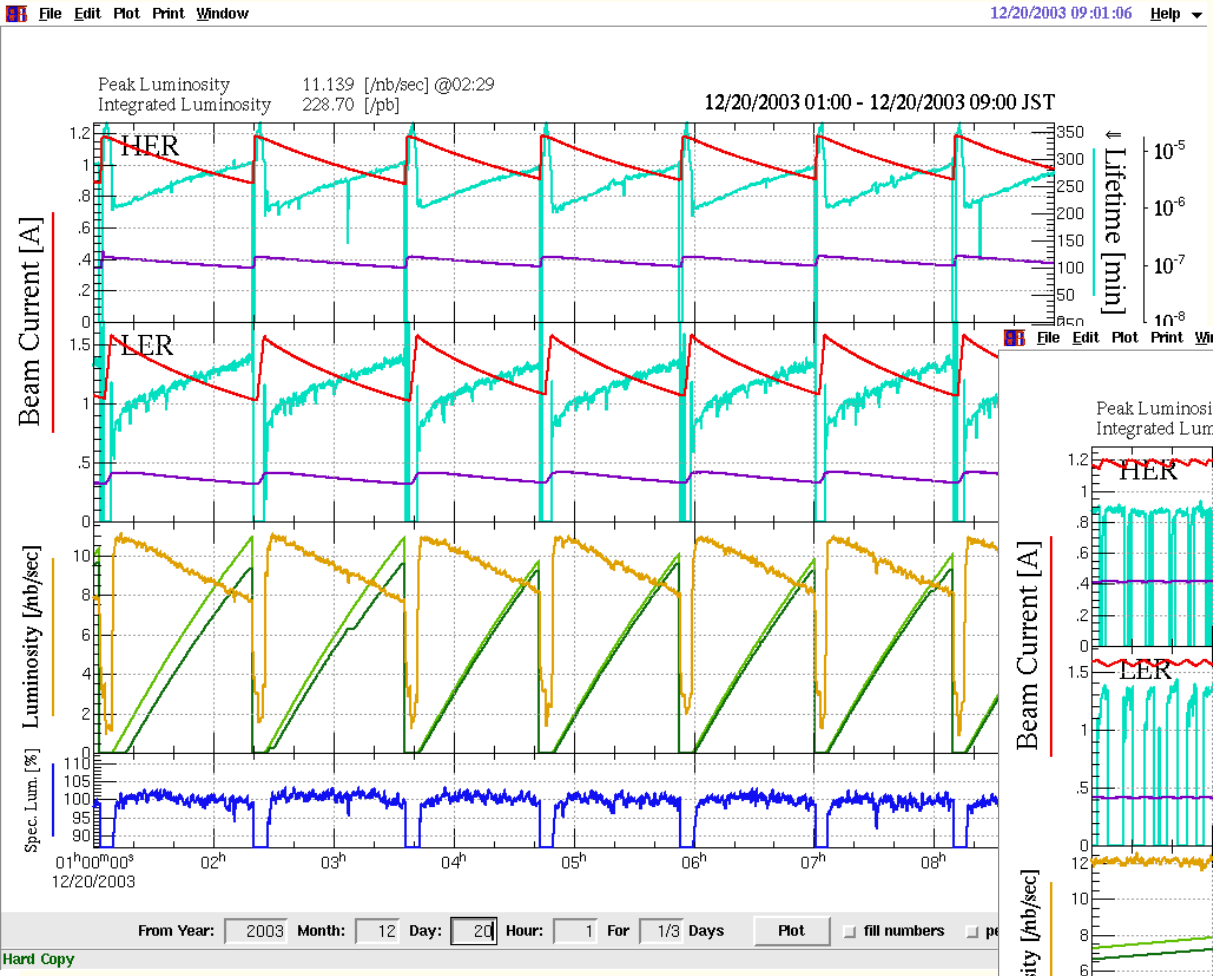
Summary

Continuous Injection

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

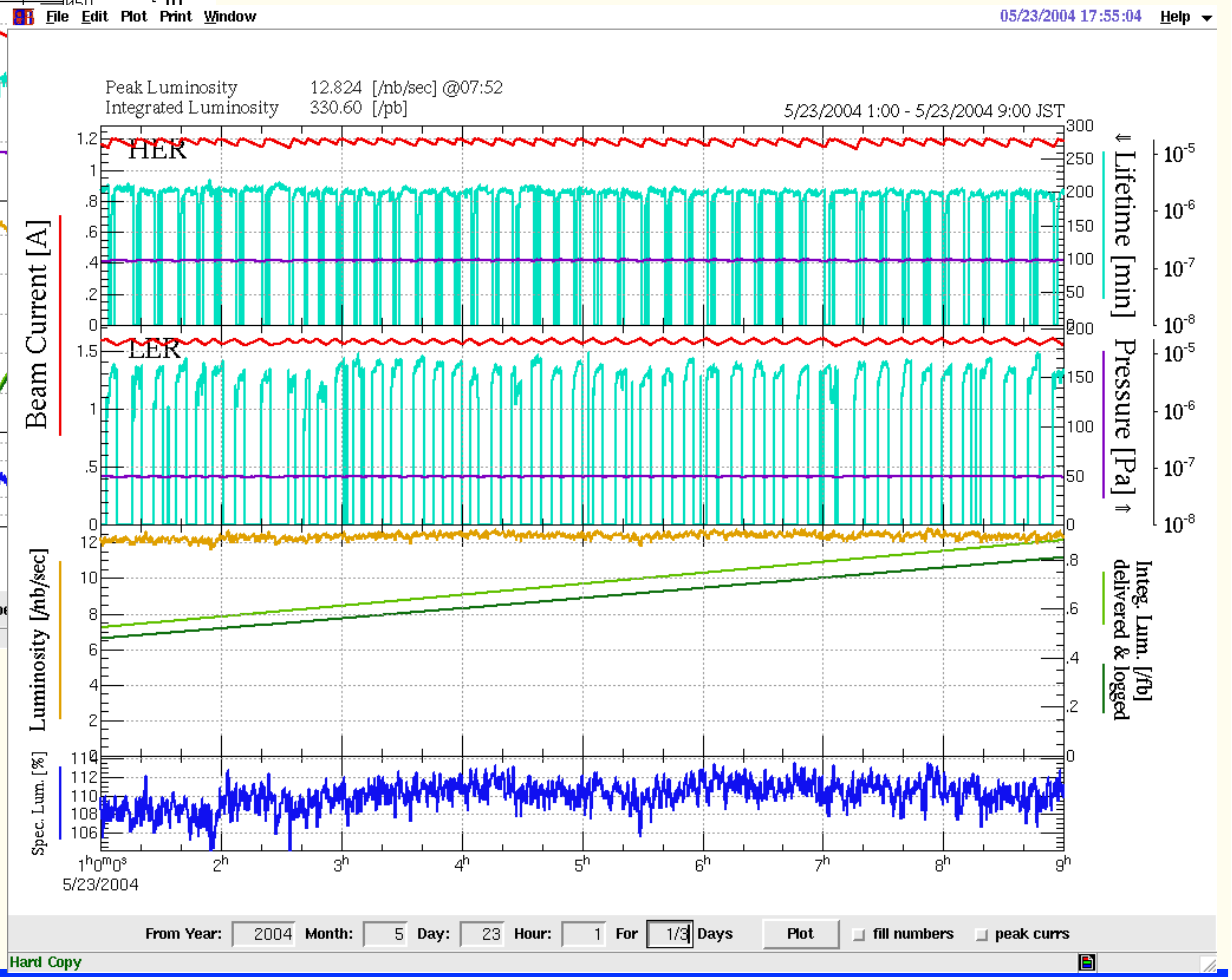
- **Continuous Injection with detector HV applied was another major step forward**
  - For higher integrated luminosity
  - by detector improvements, esp. CDC, TOF, DAQ
  - with certain benefit from collision with crossing angle
    - without bending magnet at IP, for lower background
  - Then, approximately 26% gain achieved

Continuous injection



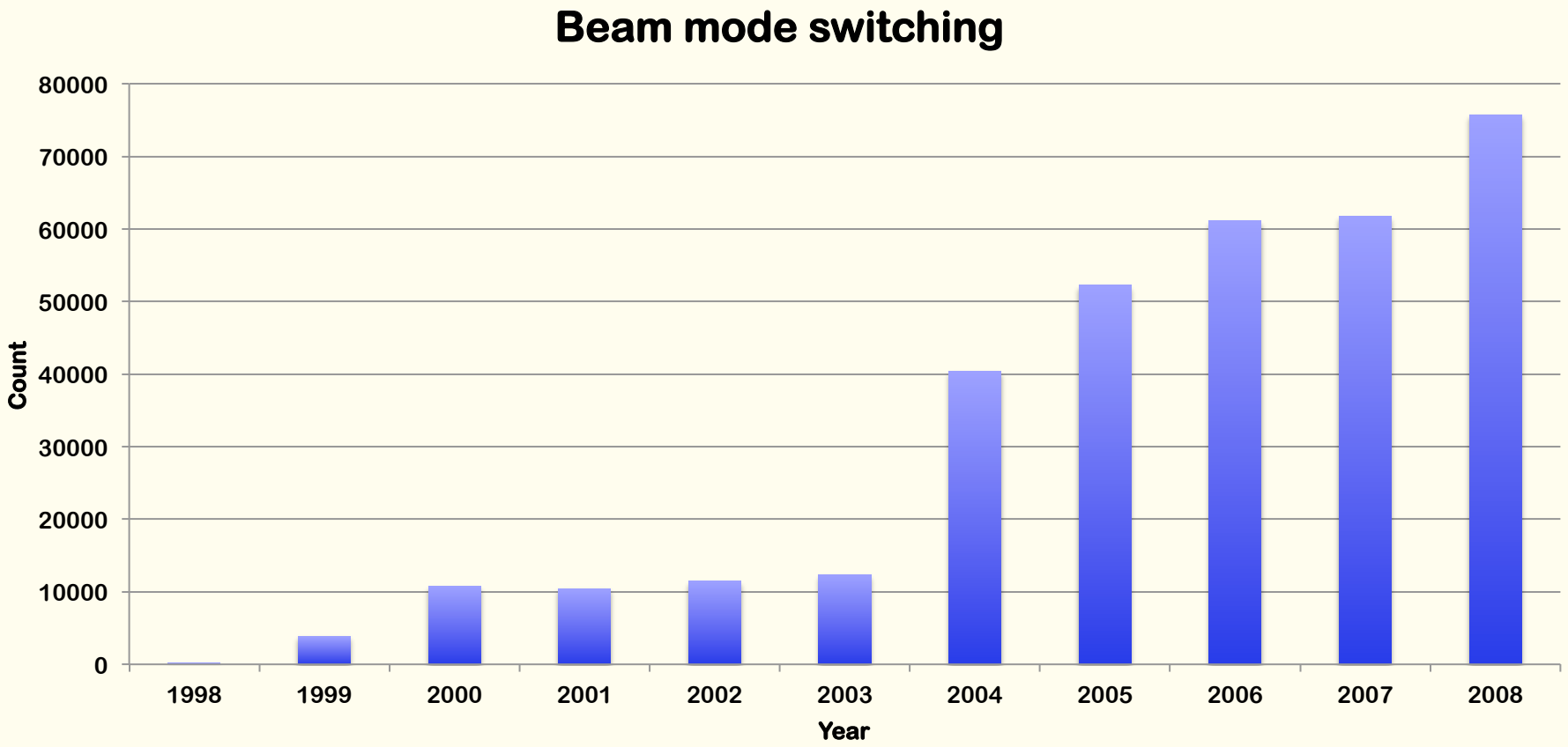
2003, before continuous injection was applied
Data acquisition stopped during injection
(8-hour history of beam current, luminosity, etc.)

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
  - to enable switching every 20 ms (4 million times / day)

KEKB and SuperKEKB overview

Daily performance improvements

Dual bunches in a pulse

Continuous injection

Simultaneous top-up injection

Upgrade towards SuperKEKB

Summary

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

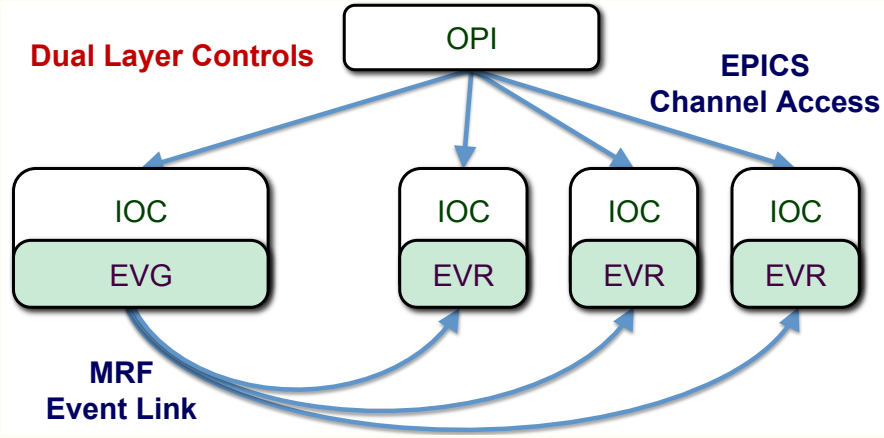
- PF top-up injection for higher quality experiments
- Sensitive luminosity tuning with Crab cavities

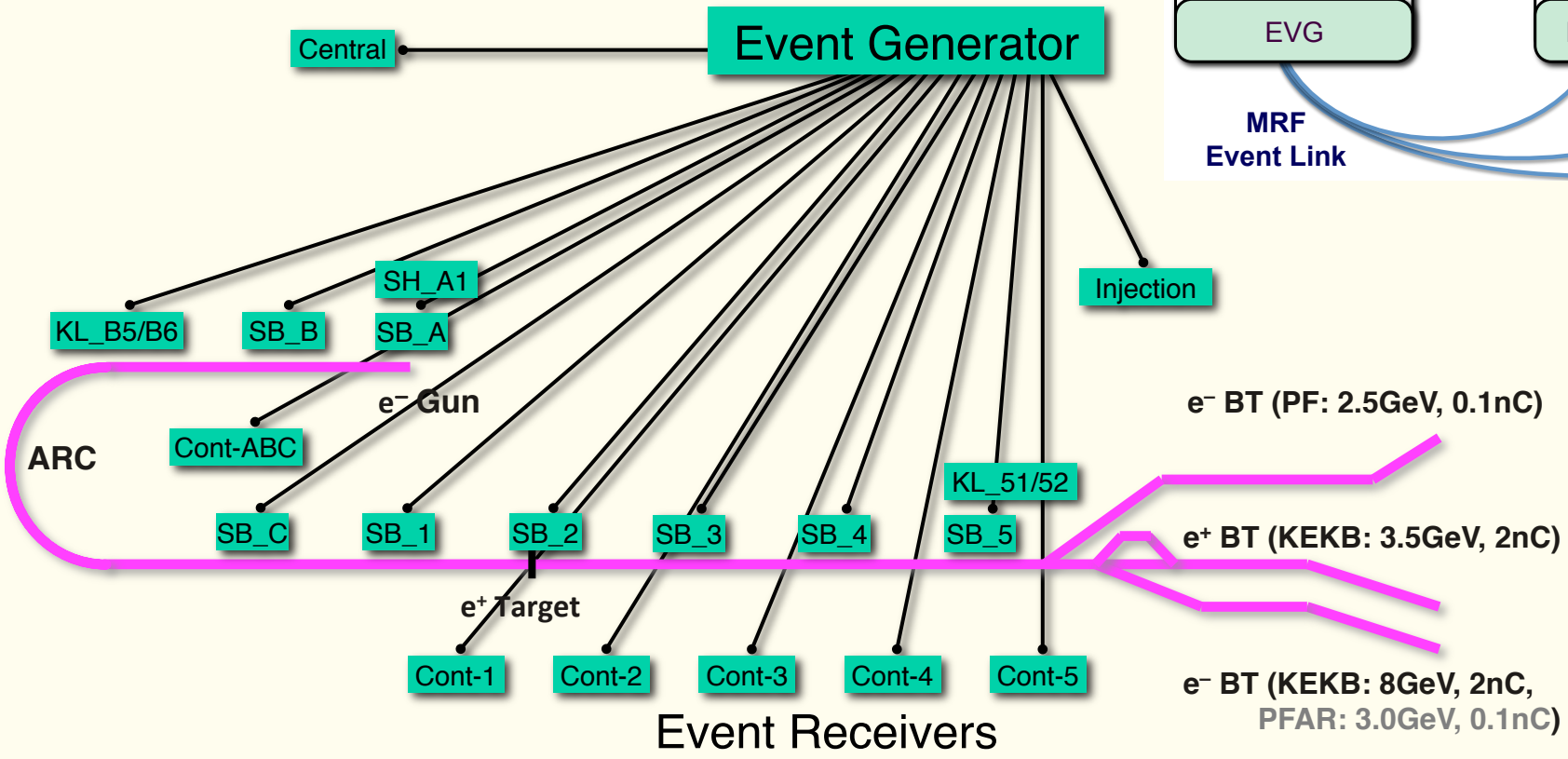
- Many more parameters in SuperKEKB for 4 beams

Fast Global Synchronous Controls

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

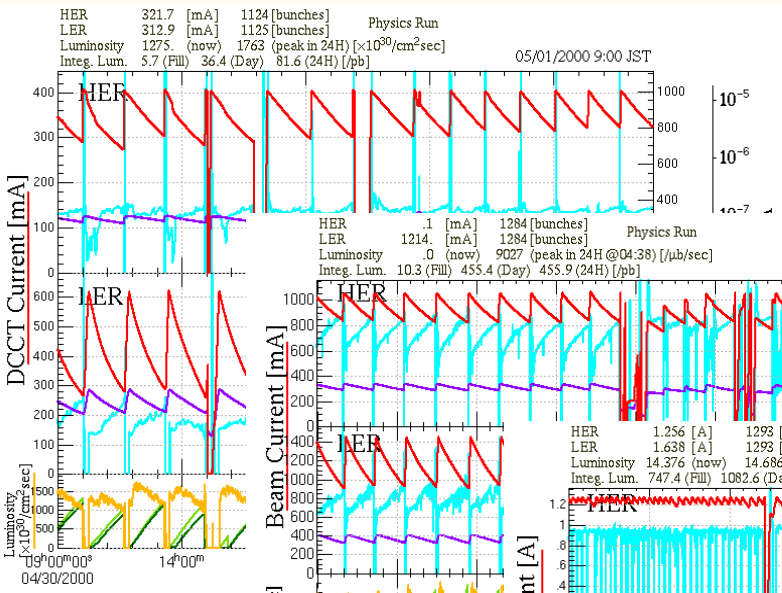
Dual layer control concept



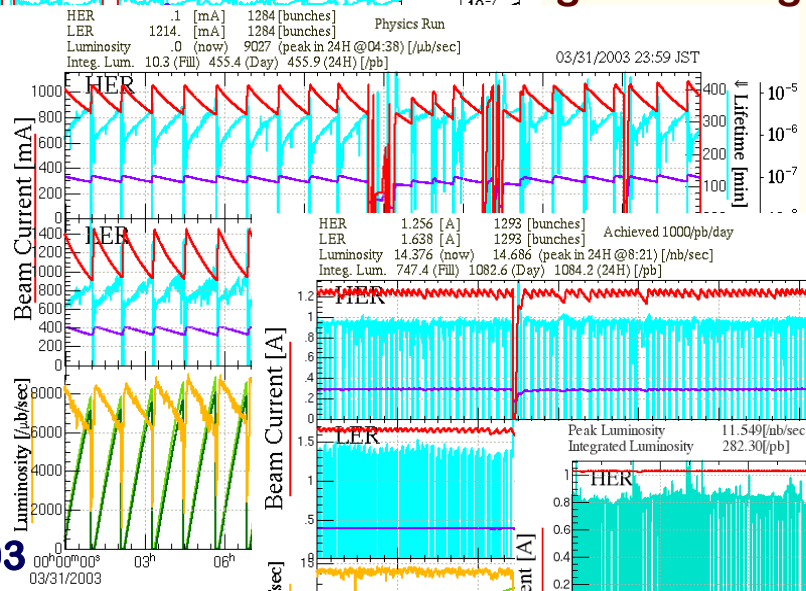


KEKB Operation Improvement (base of SuperKEKB)

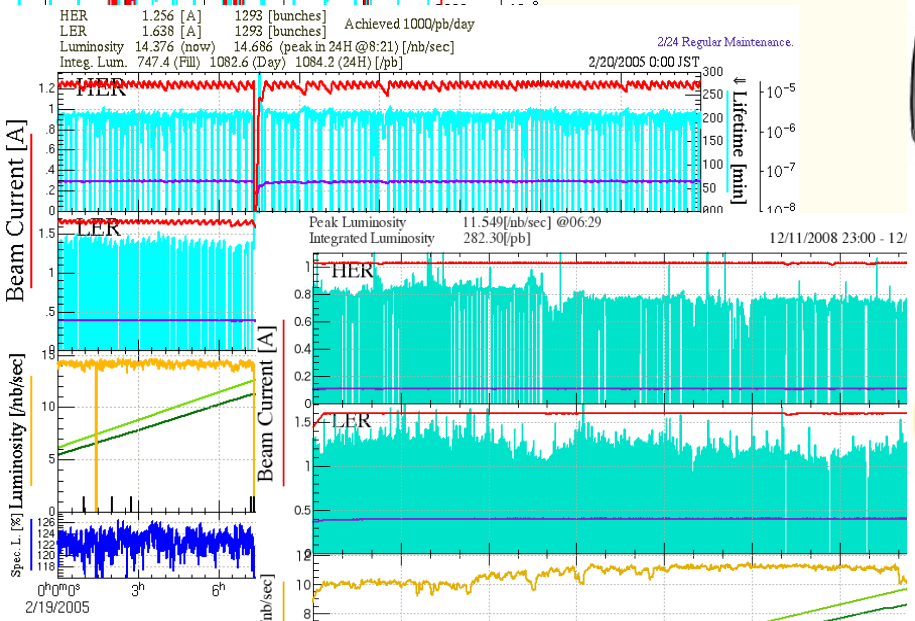
red: beam current (e-, e+)
purple: vacuum (e-, e+)
yellow: luminosity
green: integrated luminosity



May.2000

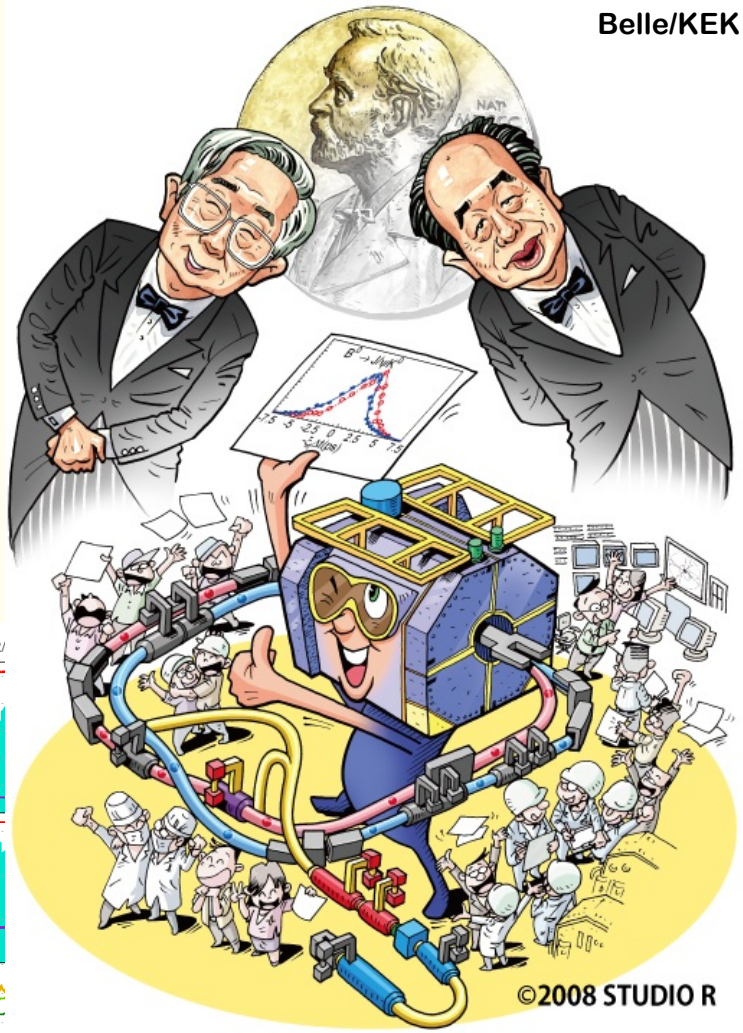


Apr.2003
Dual Bunch e+



Feb.2005
Continuous
Injections

Dec.2008
Crab Cavities and
Simultaneous Injection



Keeps world luminosity record

KEKB and SuperKEKB overview

Daily performance improvements

Dual bunches in a pulse

Continuous injection

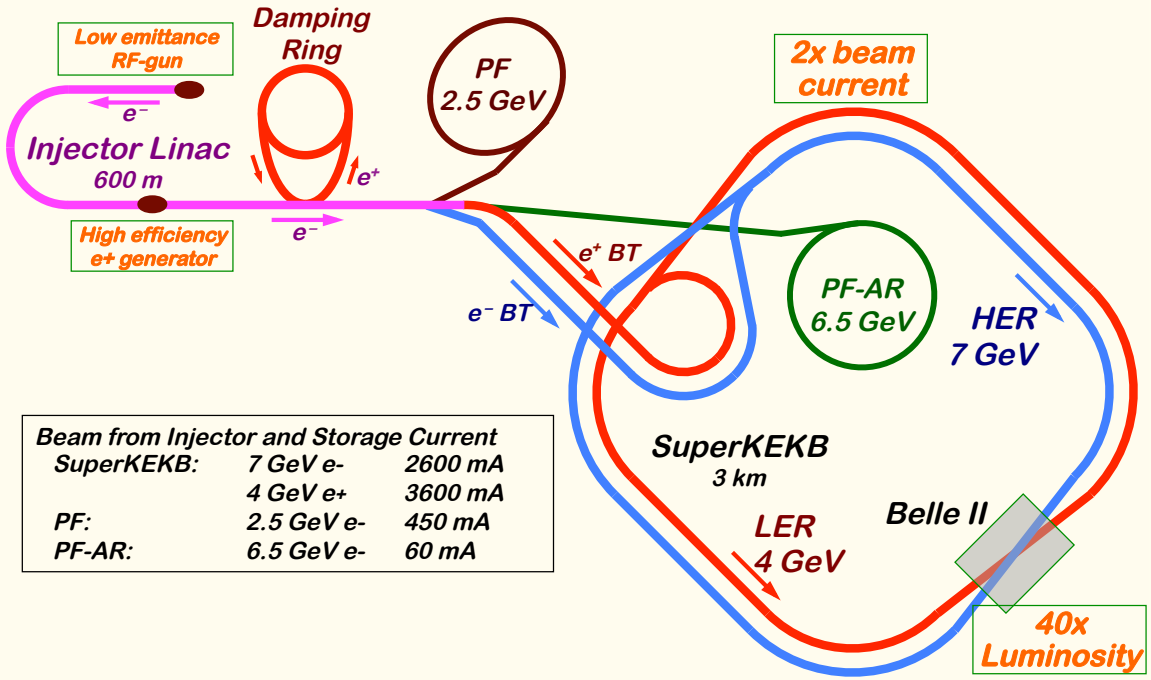
Simultaneous top-up injection

Upgrade towards SuperKEKB

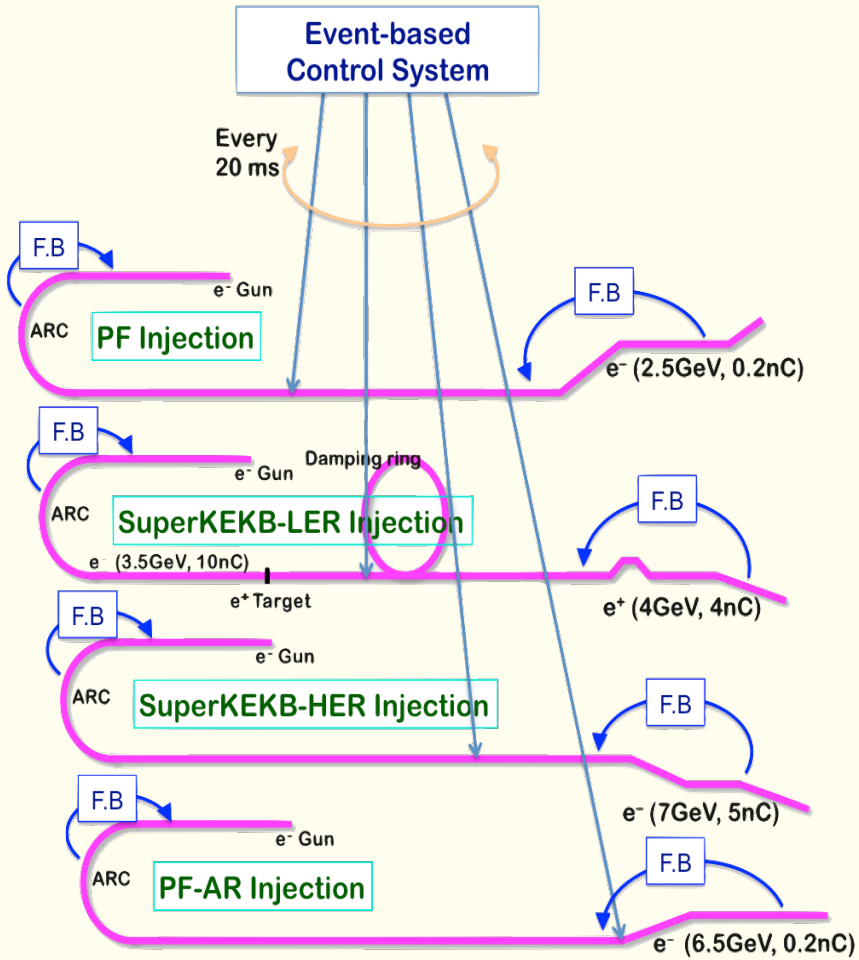
Summary

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



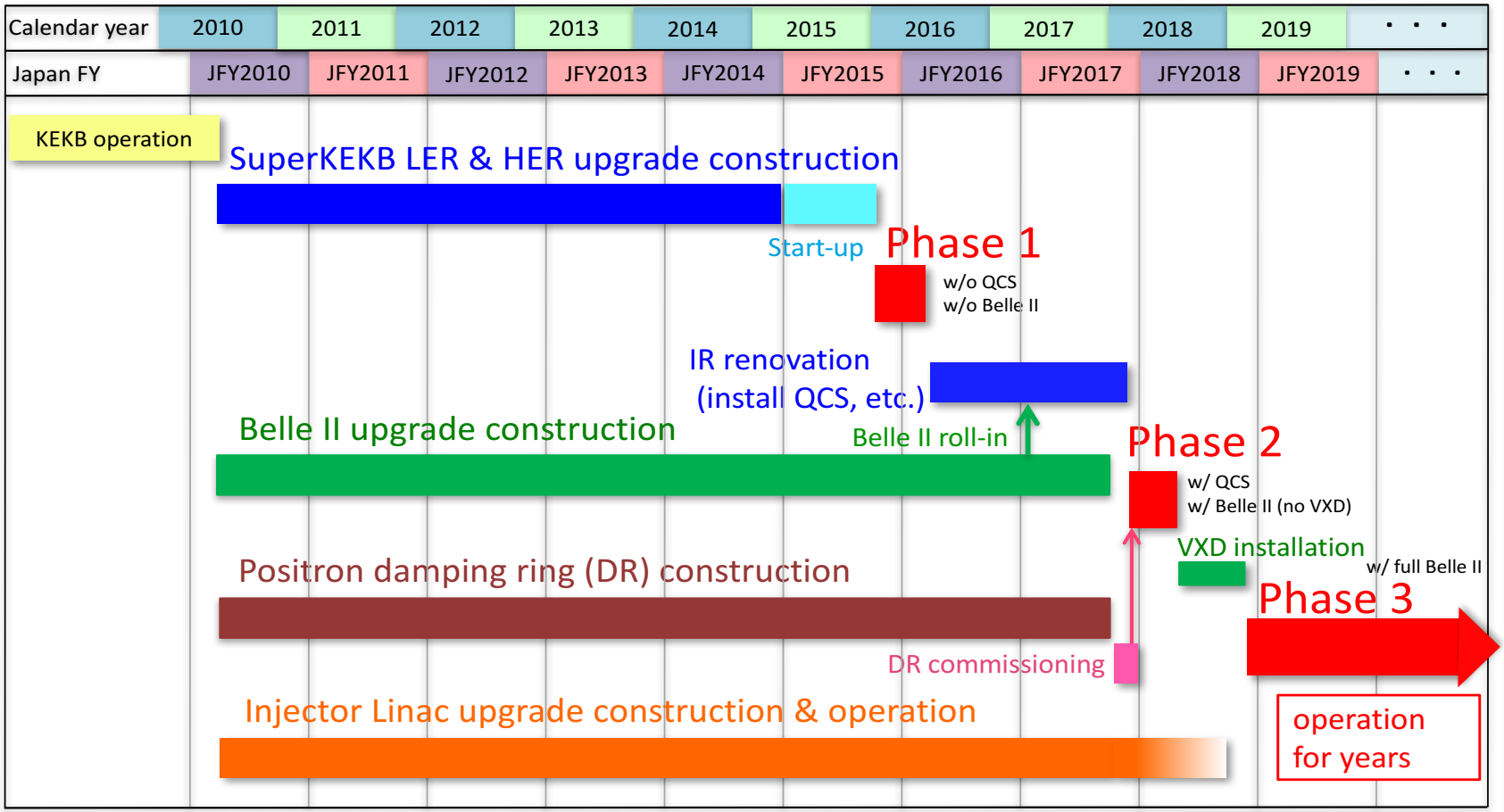
Beam from Injector and Storage Current		
SuperKEKB:	7 GeV e-	2600 mA
	4 GeV e+	3600 mA
PF:	2.5 GeV e-	450 mA
PF-AR:	6.5 GeV e-	60 mA



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

SuperKEKB Schedule

SuperKEKB/Belle II schedule

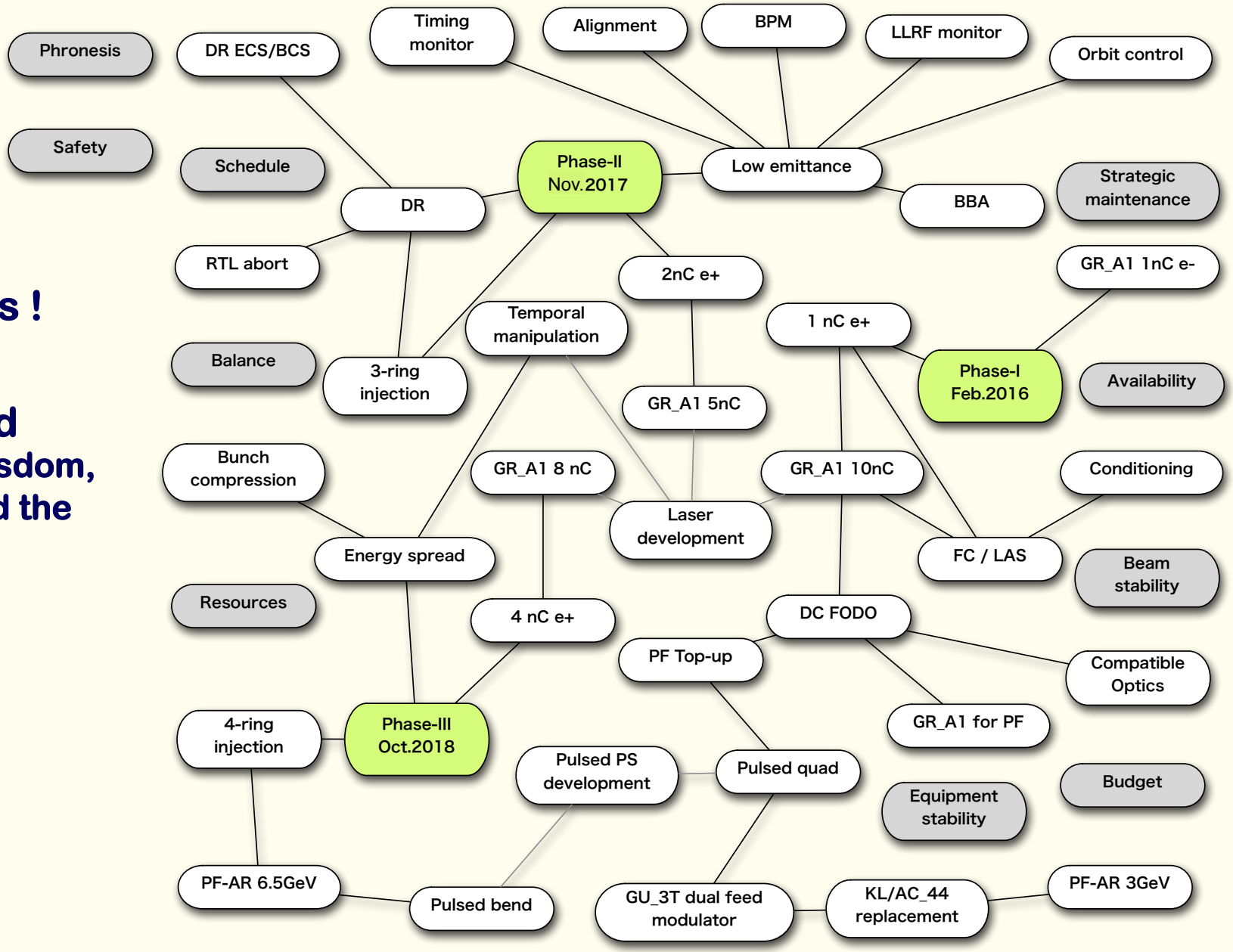


Required injector beam parameters

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 ($\gamma\beta\varepsilon$) (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)	

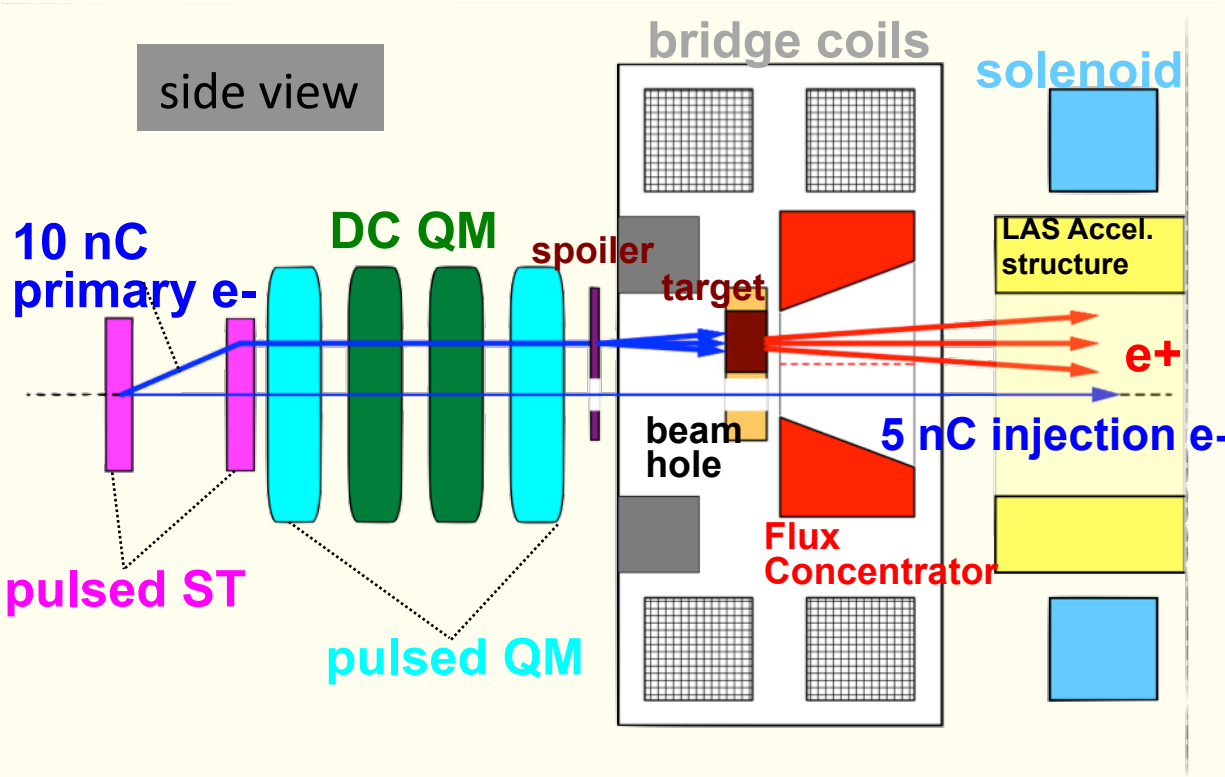
Subjects to Consider at Injector

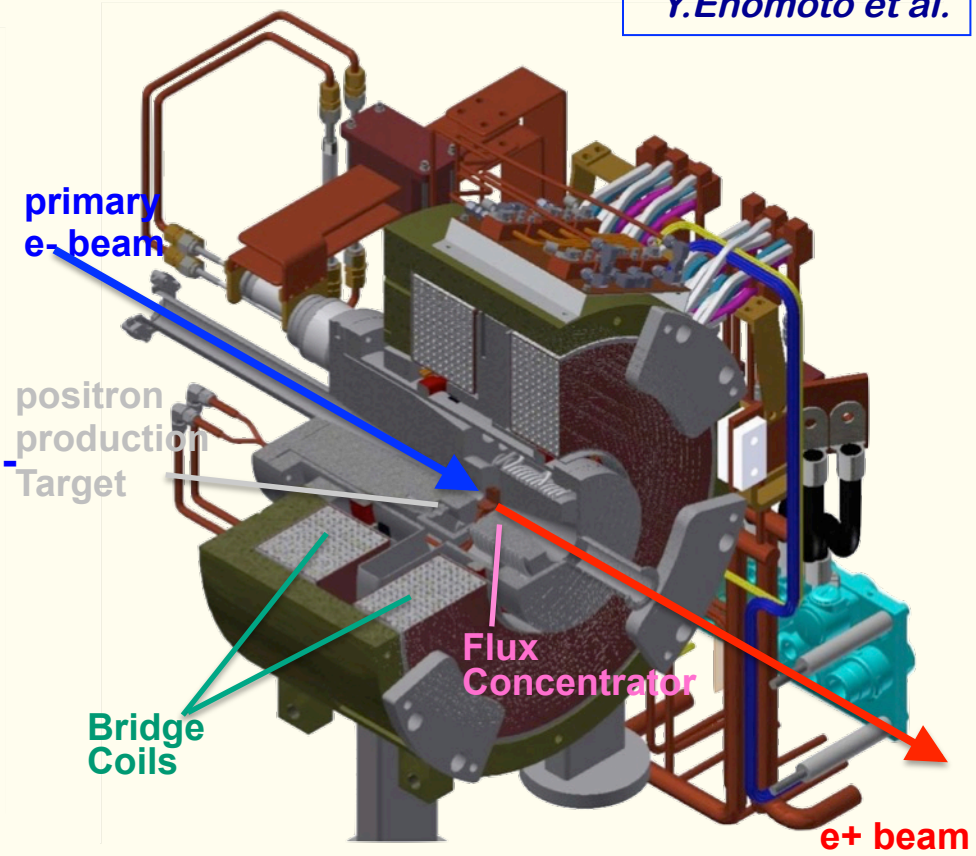
- (As of 2014)
- Have to consider too many subjects !
- Phronesis needed
  (Greek: Practical wisdom, Ability to understand the Universal Truth)



Positron generation for SuperKEKB

Y.Enomoto et al.



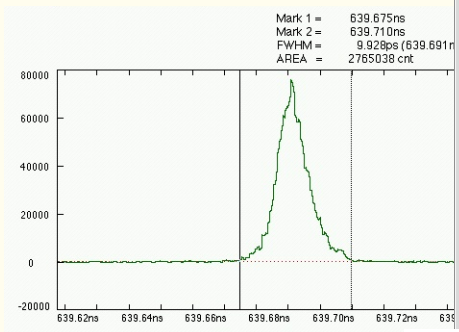


New positron capture section after target with
Flux concentrator (FC) and large-aperture S-band structure (LAS)
Satellite bunch (beam loss) elimination with velocity bunching
Pinhole (2mm) for passing electrons beside target (3.5mm)
Recently, facing discharge difficulties at maximum field

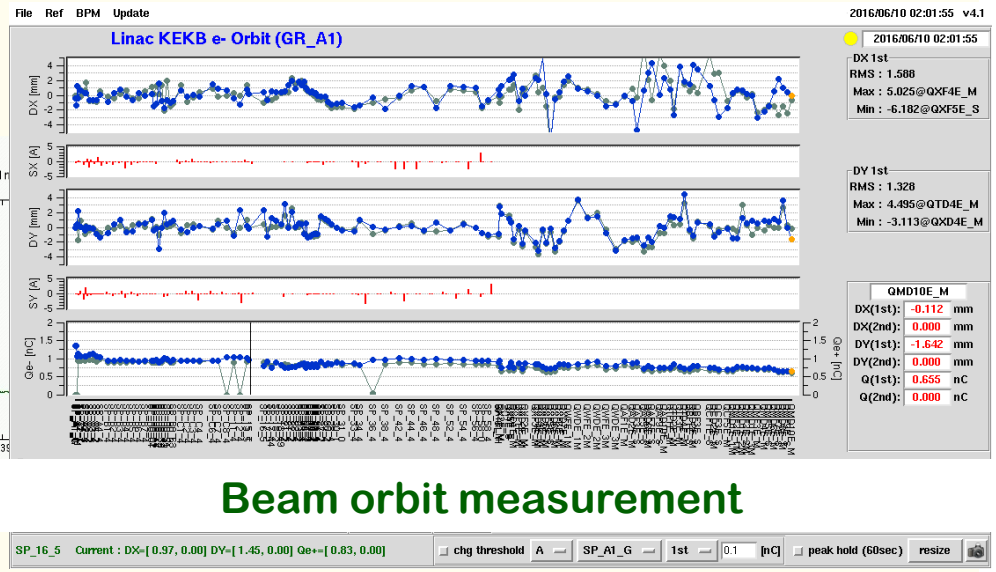
Development of Photo-cathode RF Gun

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

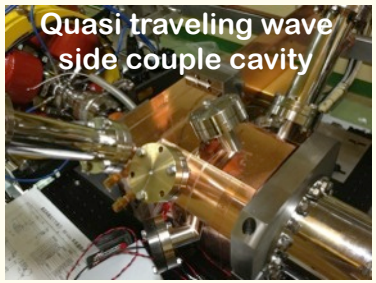


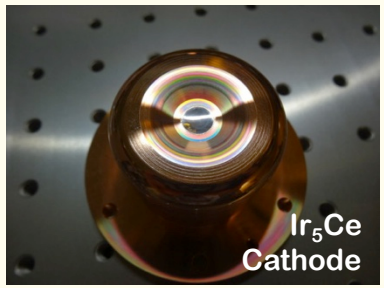
Bunch width

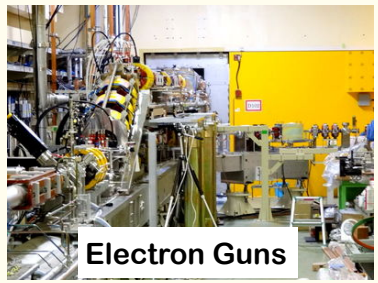


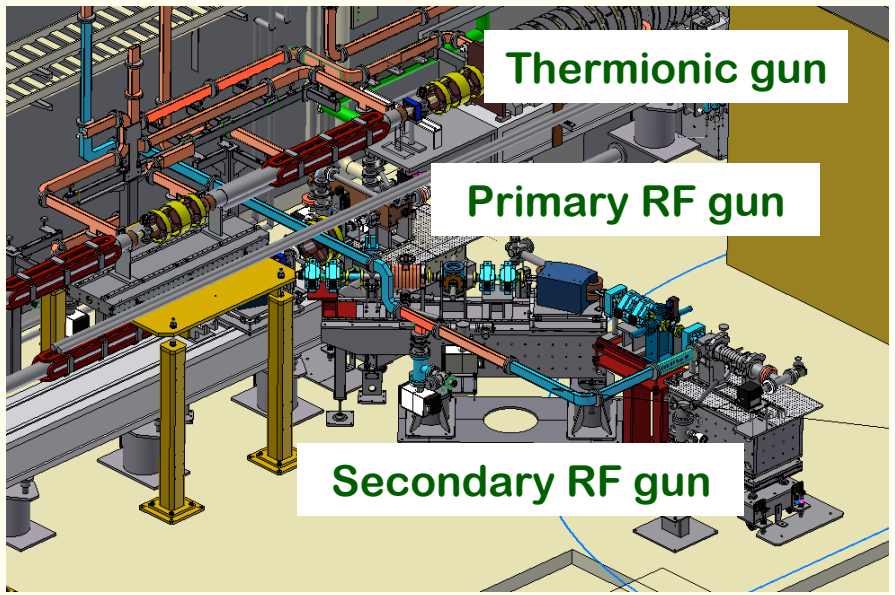
Beam orbit measurement

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





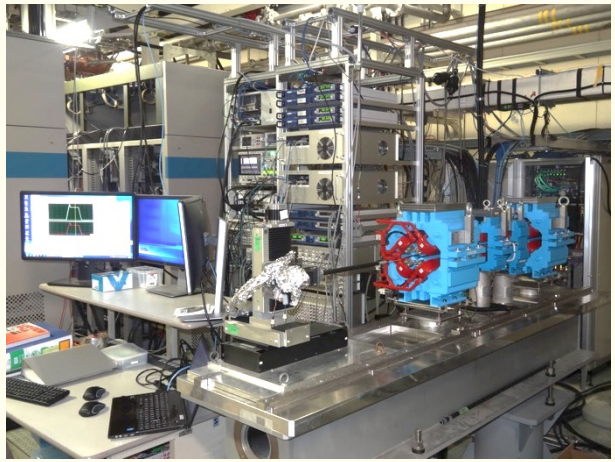




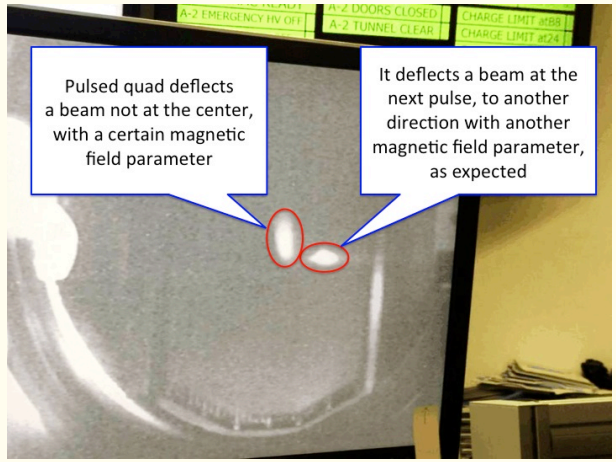
Development and installation of pulsed magnets

- 100 Pulsed magnets and power supplies are installed in 2017 - 2019
- 30 quads, 36 steerings, 2 bends, 13 girders were fabricated and installed in 2017
- Quads with advanced design in-house for 1 mH, 330 A, 340 V, 1 ms
- Small form factor of 19 inch width and 3U height each, with energy recovery up to 75%
- 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

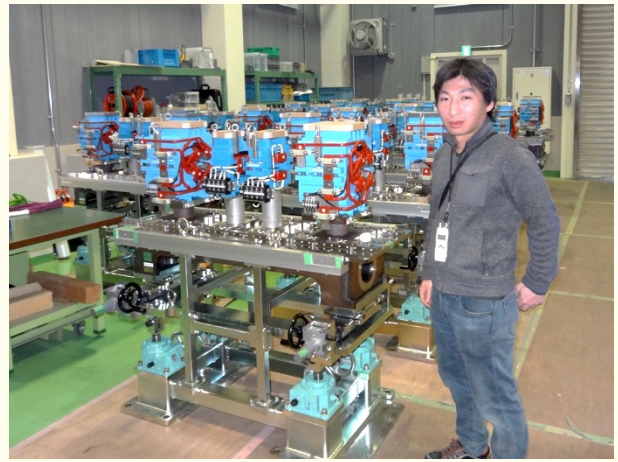
Enomoto, Natsui et al



- Long term tests at a stand
- Satisfies specification, 0.01%
- Control synchronization



- Beam test with two quads
- Successful fast beam switches
- Switching features are confirmed
- Now all in operation



- Girders are tested as well
- In-house drawings to save rsc.
- 1μm alignment precision
- Ready for Phase-3 upgrade

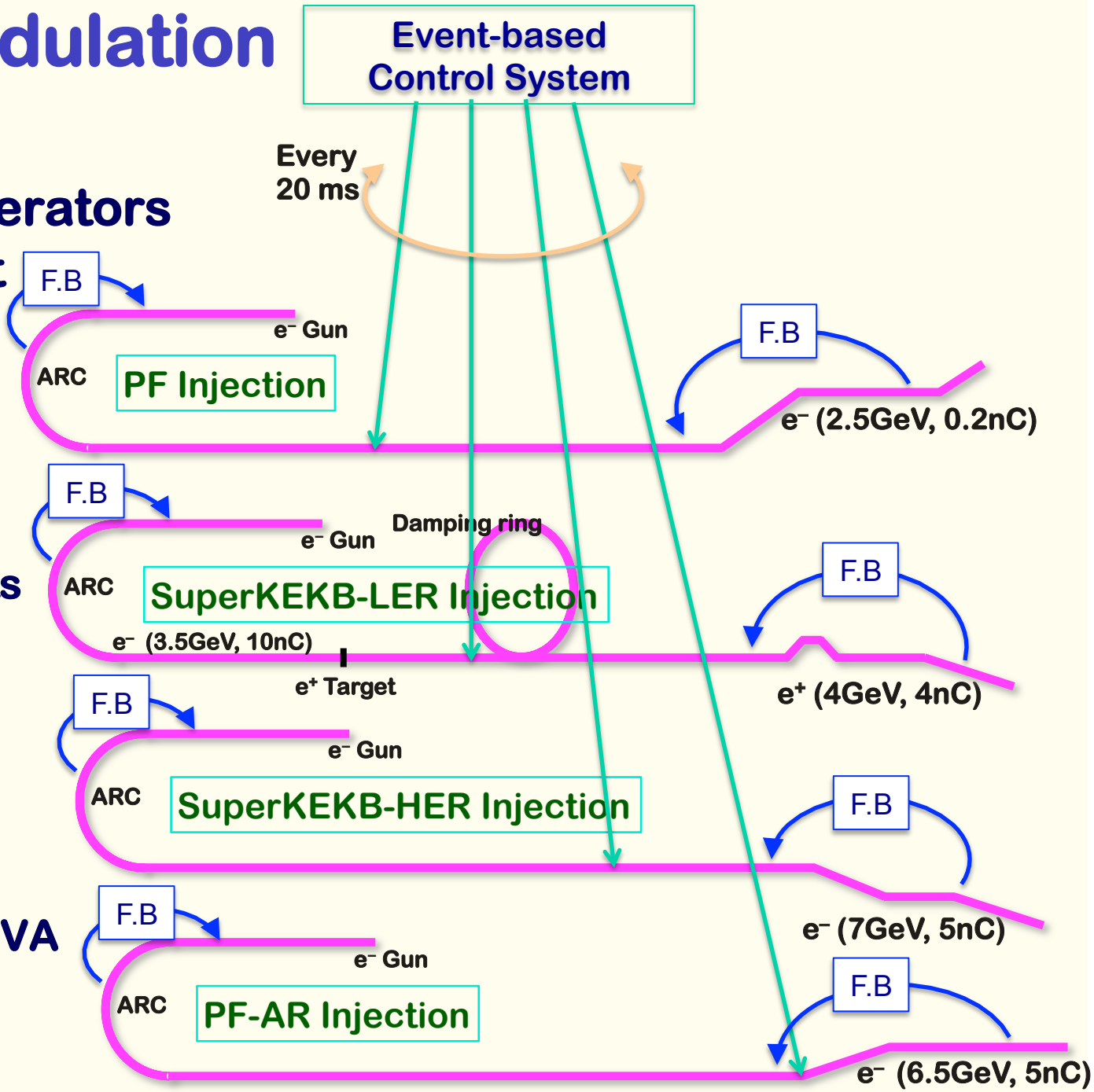
Pulse-to-pulse modulation

- Simultaneous injection
- Four PPM virtual accelerators for SuperKEKB project

Based on
Dual-tier controls with
EPICS and event-system

Independent parameter sets
for each VA (20ms)
>250 parameters
for equipment controls
many more
for beam controls

maybe with additional PPM VA
of stealth beam
for measurement
and optimization



KEKB and SuperKEKB overview

Daily performance improvements

Dual bunches in a pulse

Continuous injection

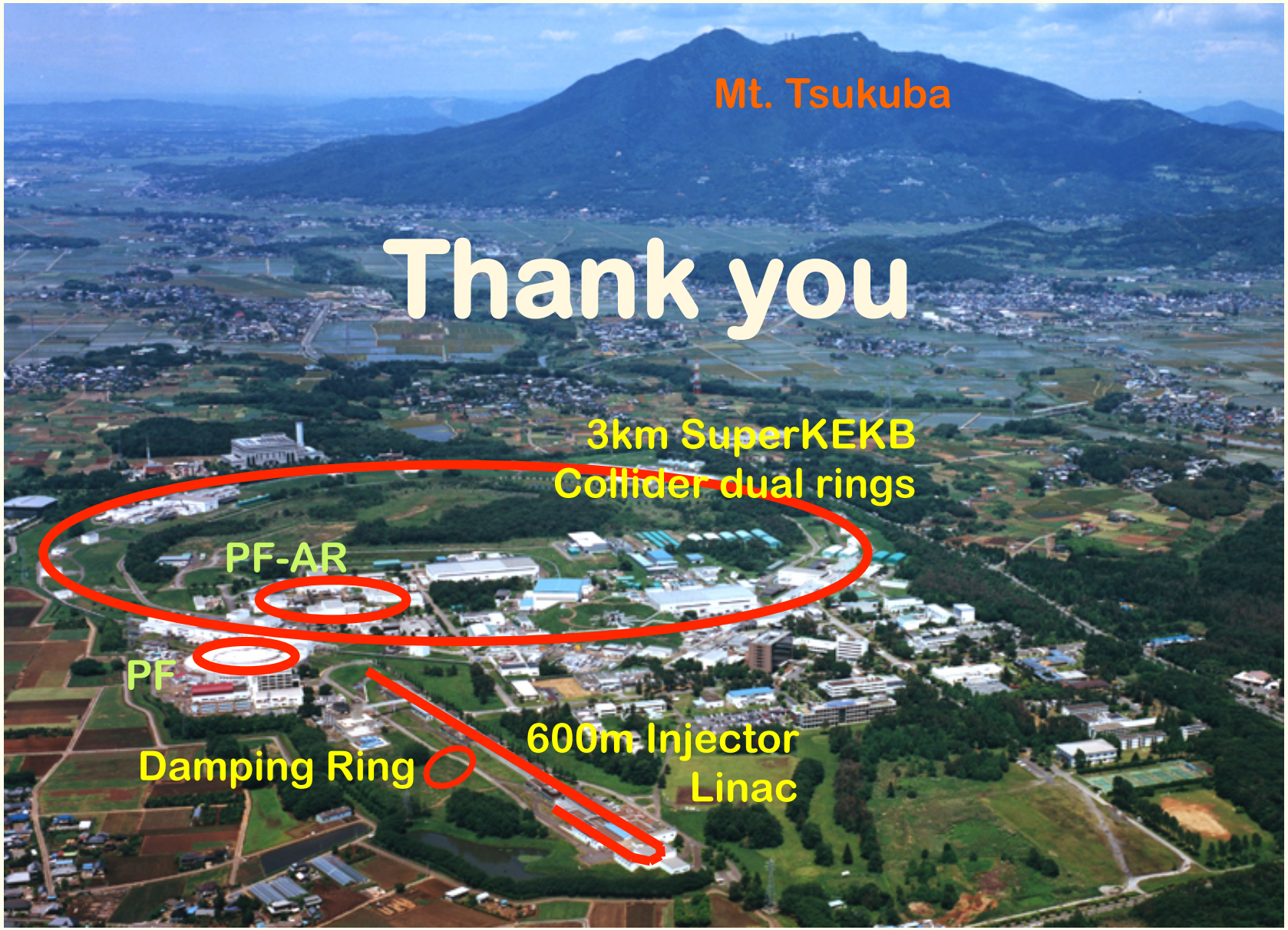
Simultaneous top-up injection

Upgrade towards SuperKEKB

Summary

Summary

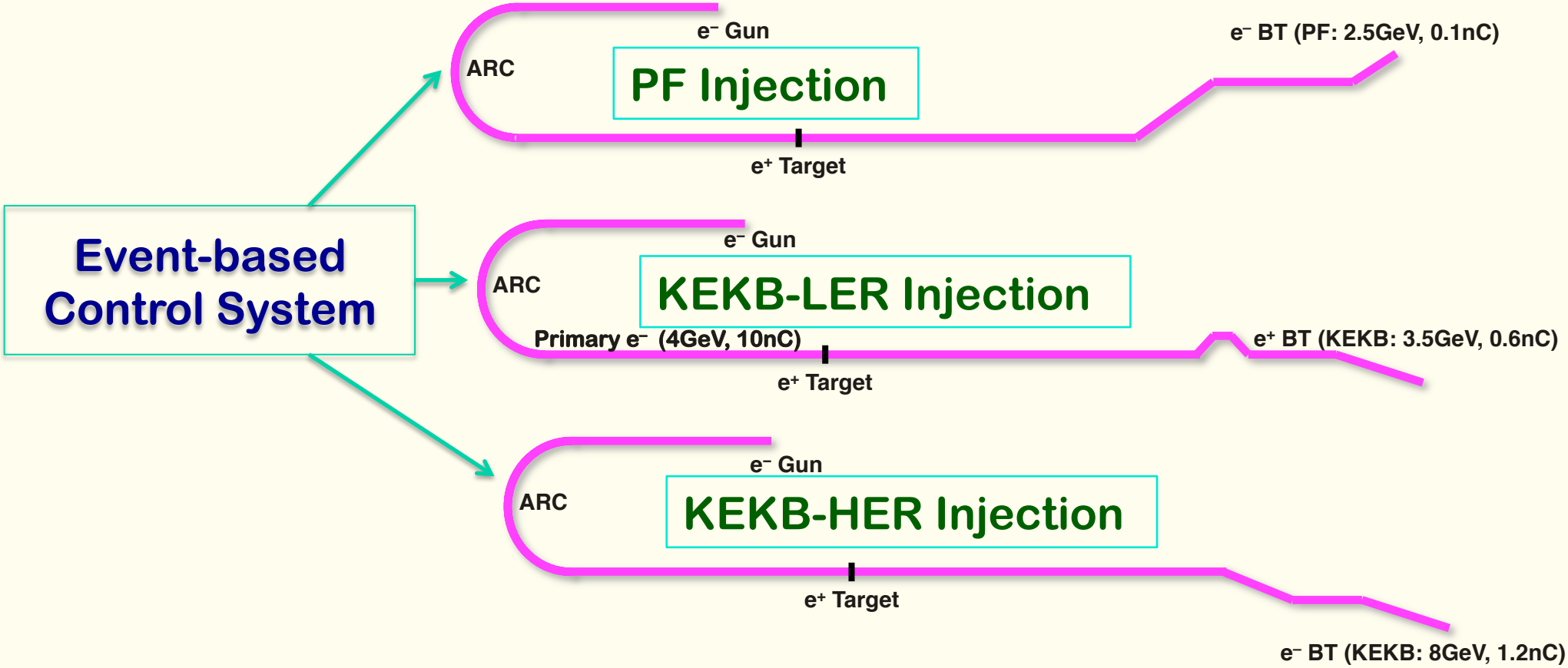
- We learned a lot during KEKB operation
- It contributed to achieve the world highest luminosity
- SuperKEKB is another challenge with higher beam charge and lower transverse/longitudinal emittance
- Steady progress is made towards designed beam in steps
- We may need to improve the injection further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



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

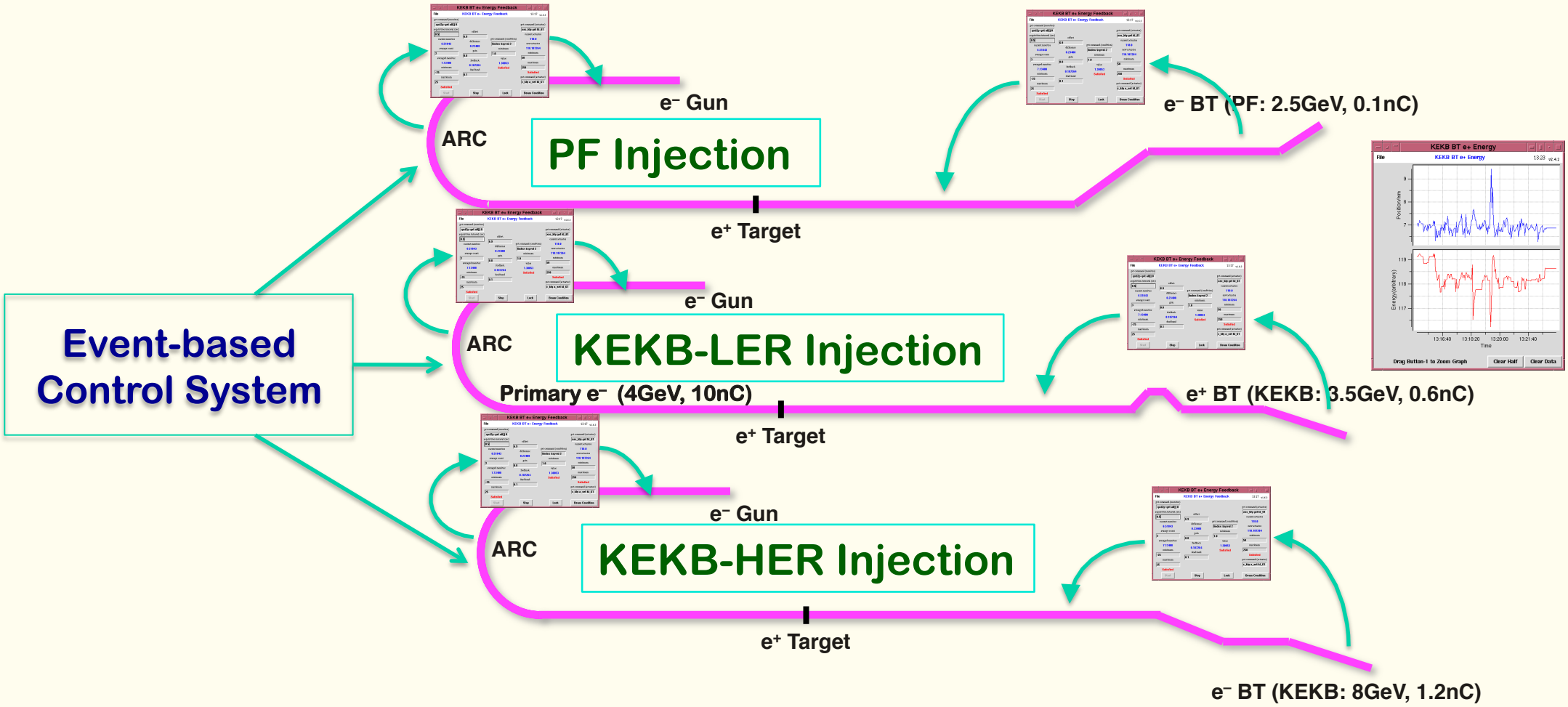
One Machine, Multiple Virtual Accelerators (VAs)

- **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



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.

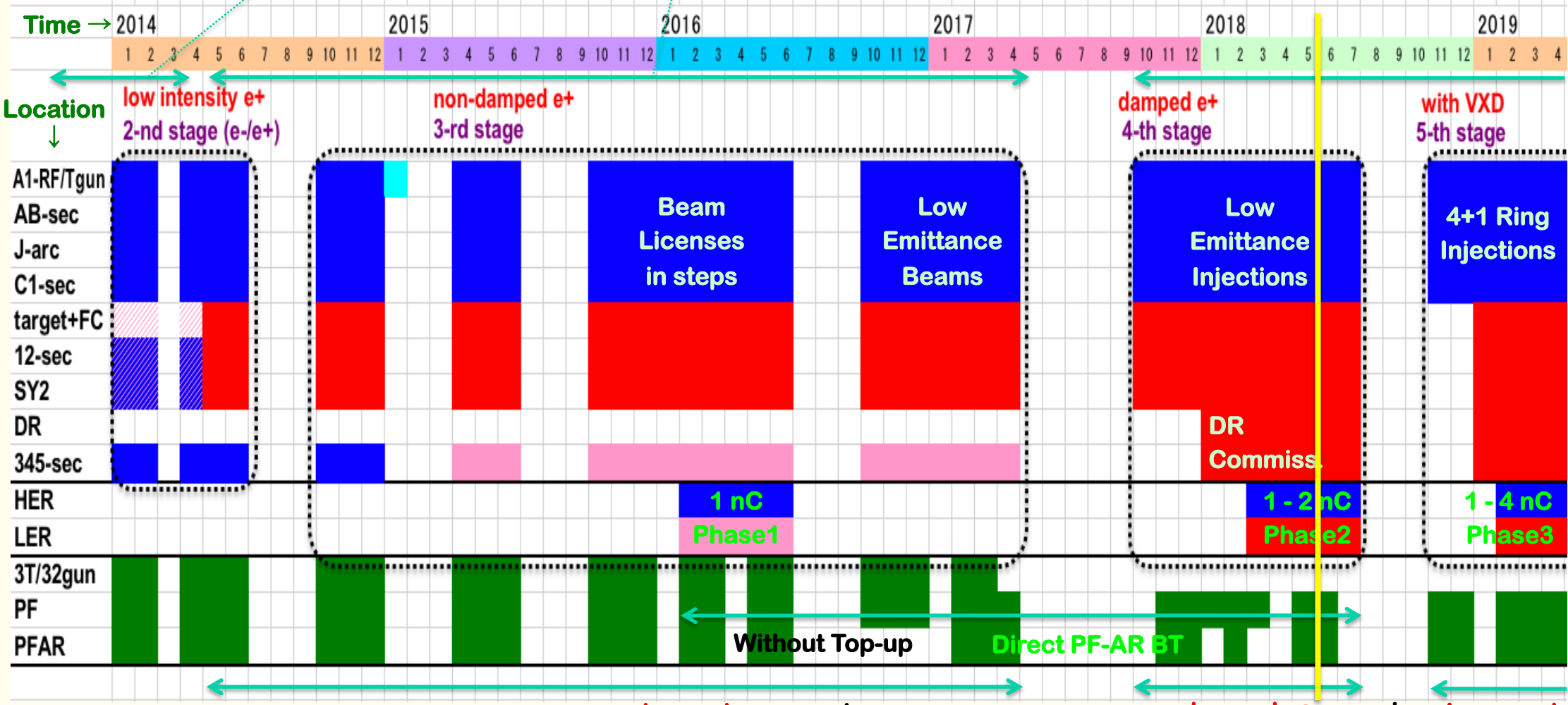
Linac Schedule Overview 2018

RF-Gun e- beam commissioning at A,B-sector

e- commiss. at A,B,R,C,1

e+ commiss. at 1,2 sector (FC, DCS, Qe- 50%)
e- commiss. at 1,2,3,4,5 sector

Phase1: high emittance beam for vacuum scrub
Phase2,3: low emittance beam for collision



: Electron
: Positron
: Low current electron

non damped e+ commiss. at 1,2, 3,4,5 sectors
e- commiss. at A→5 sectors

damped e+ commiss. at 1→5 Qe+ = 1~4nC
e- commiss. at A→5 Qe- = 1~4nC

Improved RF gun