Injector Linac Experiences at KEKB / SuperKEKB

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SuperKEKB overview

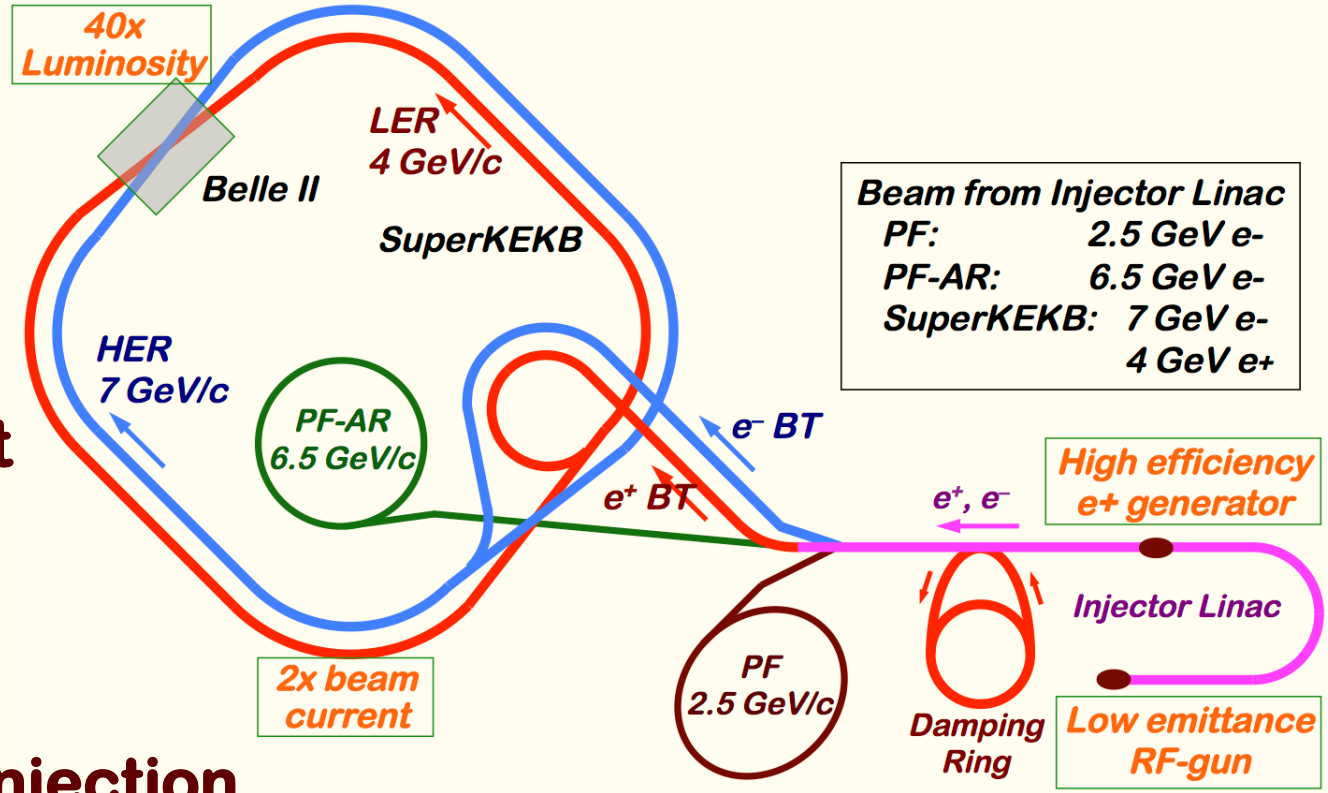
KEKB Injector Linac

SuperKEKB Injector Linac Progress

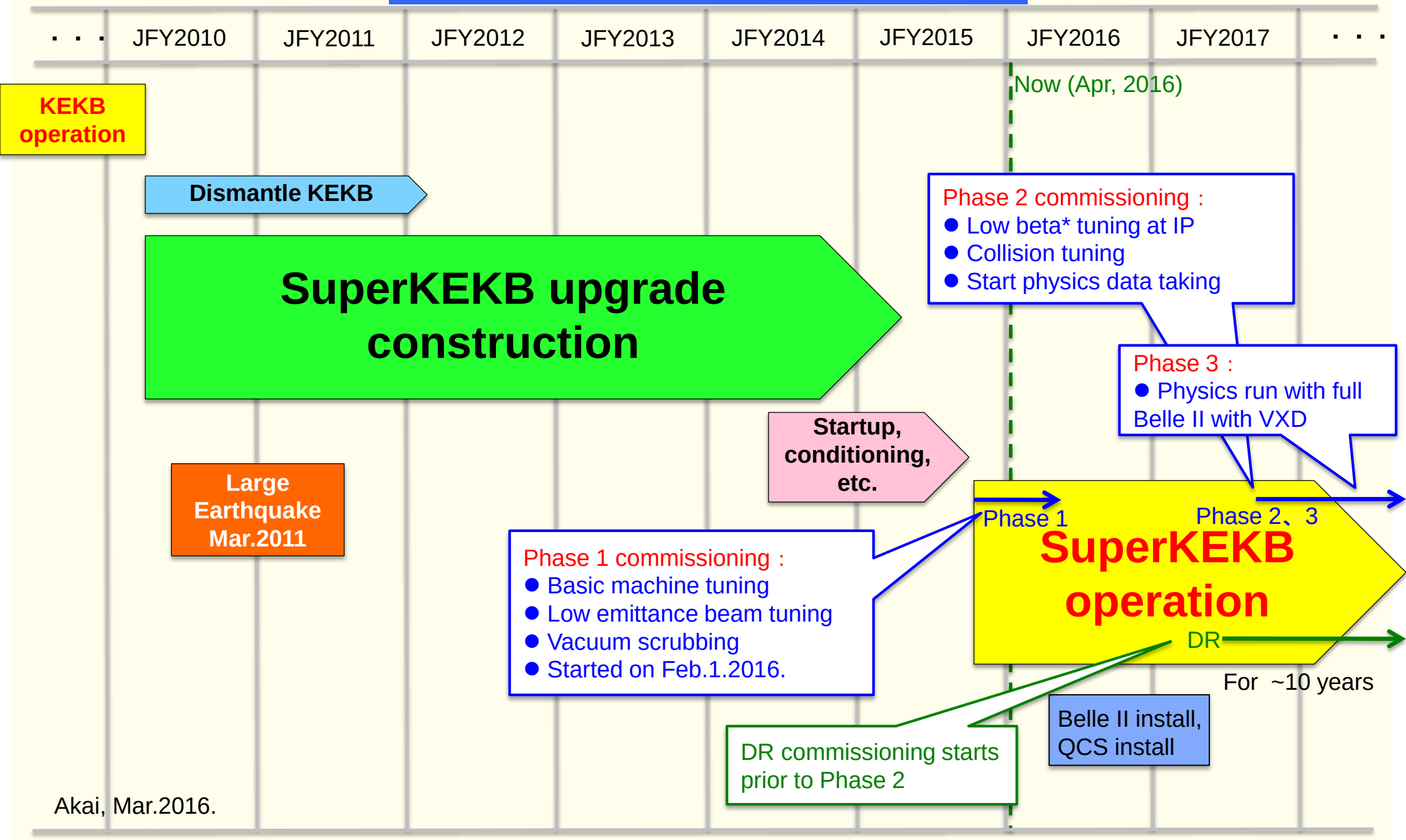
Operation

Mission of electron/positron Injector in SuperKEKB

- **40-times higher Luminosity**
  - 20-times higher collision rate with nano-beam scheme
    - → Low-emittance even at first turn → Low-emittance beam from Linac
    - → Shorter storage lifetime
  - Twice larger storage beam → Higher beam current from Linac
- **Linac challenges**
  - Low emittance e-
    - with high-charge RF-gun
  - Low emittance e+
    - with damping ring
  - Higher e+ beam current
    - with new capture section
  - Emittance preservation
    - with precise beam control
  - 4+1 ring simultaneous injection



SuperKEKB master schedule



Required injector beam parameters

Stage	KEKB (final)		Present Phase-I		SuperKEKB (final)	
Item	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
Bunch charge	Primary e- 10nC → 1 nC	1 nC	Primary e- 8nC → 0.4 nC	1 nC	Primary e-10nC → 4 nC	5 nC
Norm. Emittance ($\gamma\beta\varepsilon$) (μrad)	2100	200	2400	150	100/20 (Hor./Ver.)	50/20 (Hor./Ver.)
Energy spread	0.125%	0.125%	0.5%	0.5%	0.1%	0.1%
No. of Bunch / Pulse	2	2	2	2	2	2
Repetition rate	50 Hz		25 / 50 Hz		50 Hz	
Simultaneous top-up injection	3 rings (KEKB e–/e+, PF)		No top-up		4+1 rings (SuperKEKB e–/e+, DR, PF, PF-AR)	

SuperKEKB overview

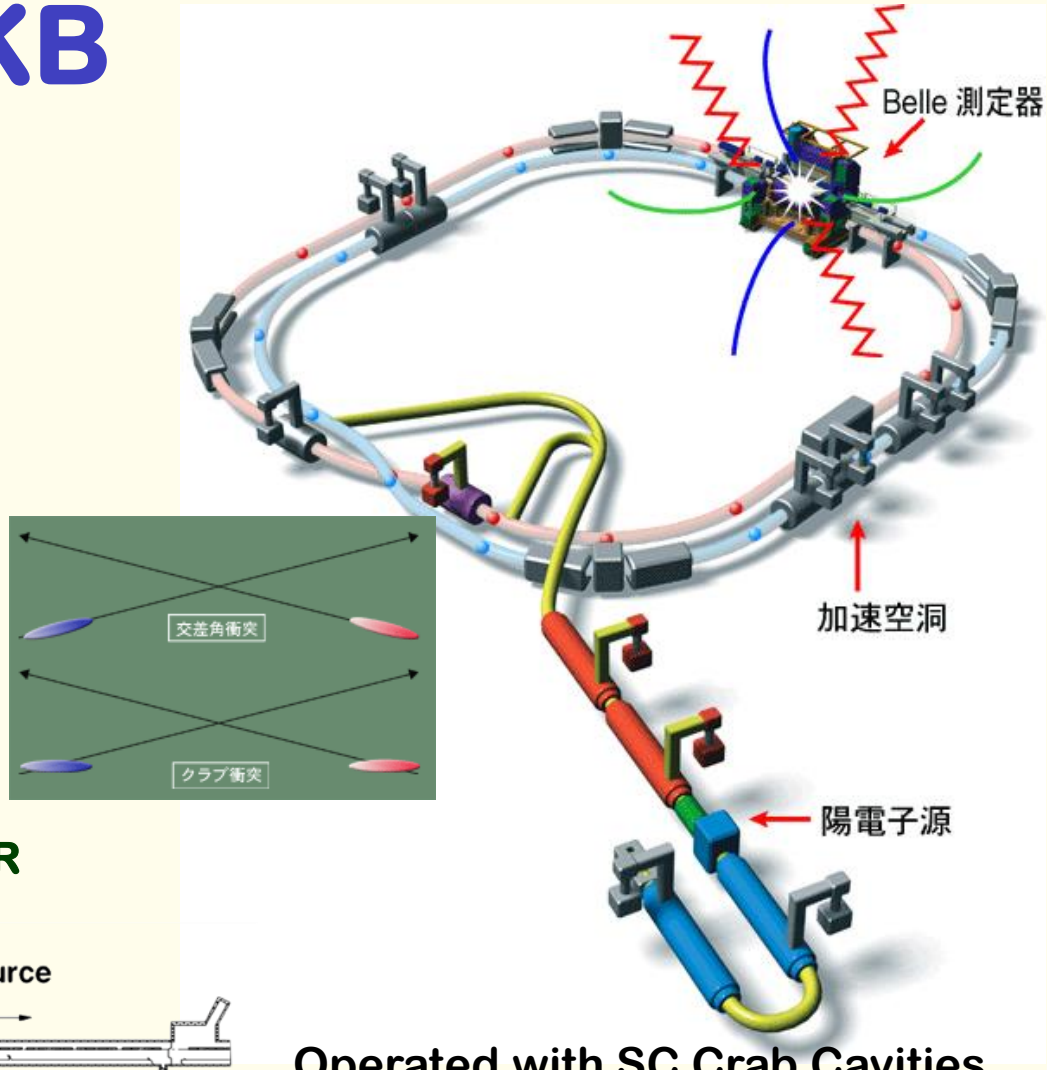
KEKB Injector Linac

SuperKEKB Injector Linac Progress

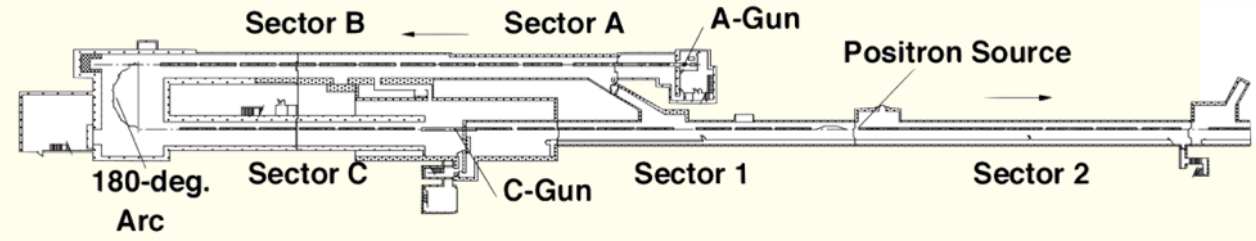
Operation

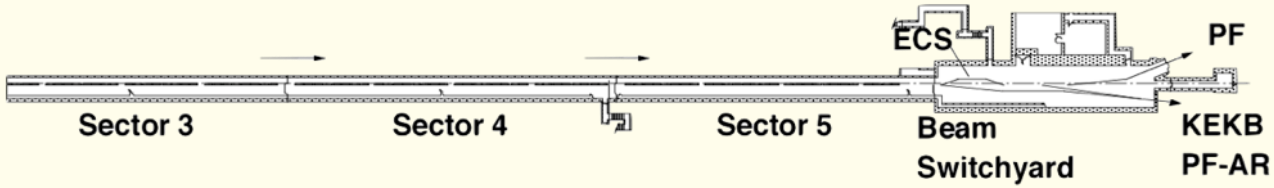
KEKB

- 1995-1999: Construction
- 1999-2010: Operation
- KEKB B-Factory
  - Electron-Positron Asymmetric Collider
  - Pursue study on CP-violation in B-meson system
  - ~3km dual ring:
    - Electron (8GeV - 1.4A)
    - Positron (3.5GeV - 1.8A)
    - Achieved world highest luminosity 2.1 x 10^{34}
    - Shared injection to light sources, PF and PF-AR



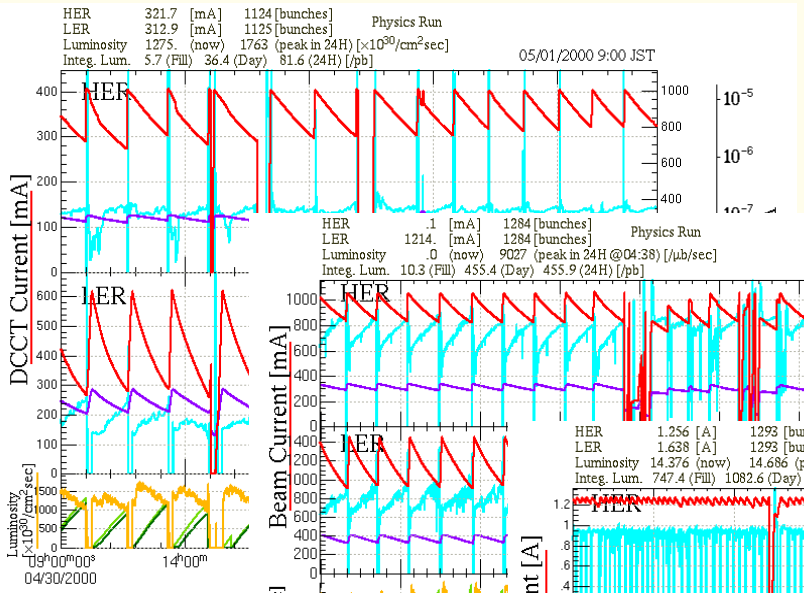
Operated with SC Crab Cavities



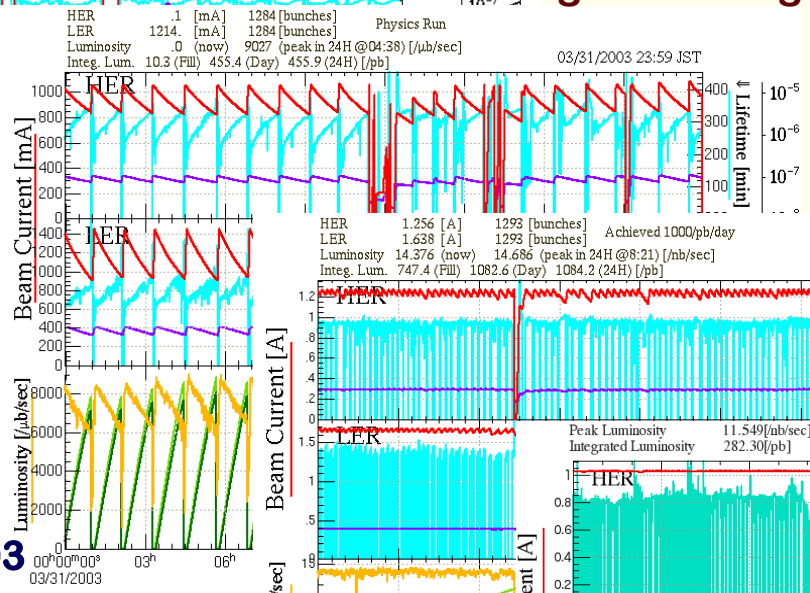


KEKB Operation Improvement (base of SuperKEKB)

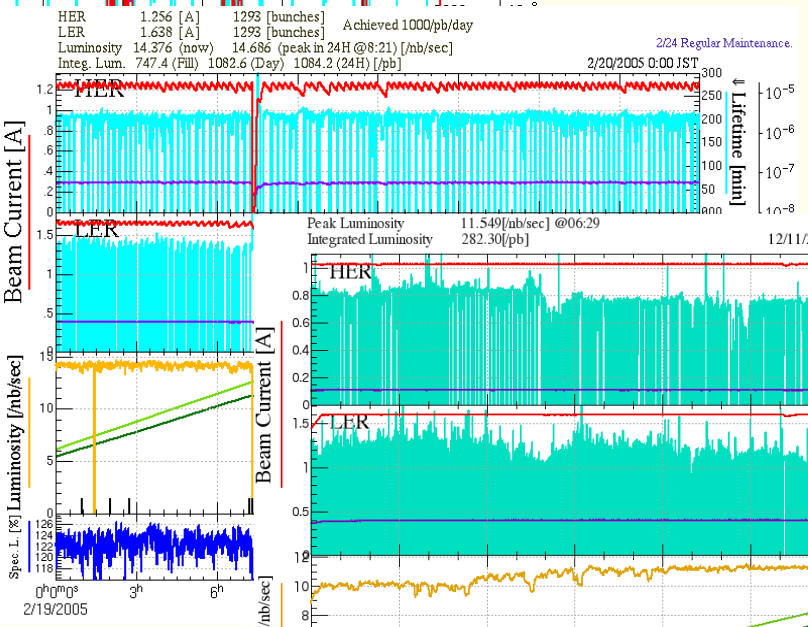
red: beam current (e-, e+)
purple: vacuum (e-, e+)
yellow: luminosity
green: integrated luminosity



May.2000

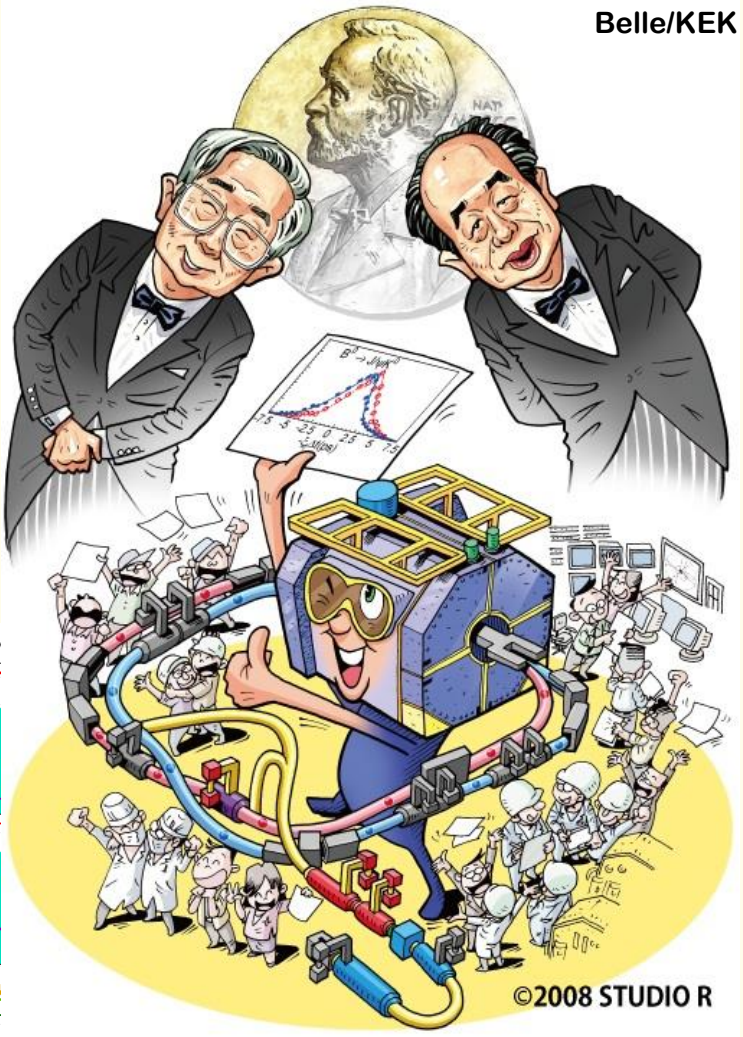


Apr.2003
Dual Bunch e+



Feb.2005
Continuous
Injections

Dec.2008
Crab Cavities and
Simultaneous Injection



Keeps world
luminosity record

Operation Improvements (1)

- **Many slow closed feedback loops for beam**
  - Beam orbit, energy, and often device
  - Until related hardware was stabilized
  - Also useful when studying beams
- **Tolerance study to understand fluctuations**
  - For example, single-parameter tolerance to keep 90% of beam transmission
  - Good reference to consider the beam stability
- **Fight against discharges in structures**
  - Especially at 1st cavities after gun and positron target
  - Solenoids, beam loss, etc.
  - Optimization for rf power and shorter rf pulse

Operation Improvements (2)

- **Dual bunches in a pulse for higher beam charge**
  - 50 Hz x 2 bunches doubled the injection beam
  - Especially for positron
- **Faster beam switching, continuous injection**
  - Between electron / positron and for light sources
  - Magnet hysteresis consideration
- **Even faster simultaneous injections**
  - Pulse-to-pulse modulation at 50 Hz (20 ms)
  - ~150 parameters were switched in KEKB for 3 beams
    - ~250 parameters in SuperKEKB for 4 beams

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

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.

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

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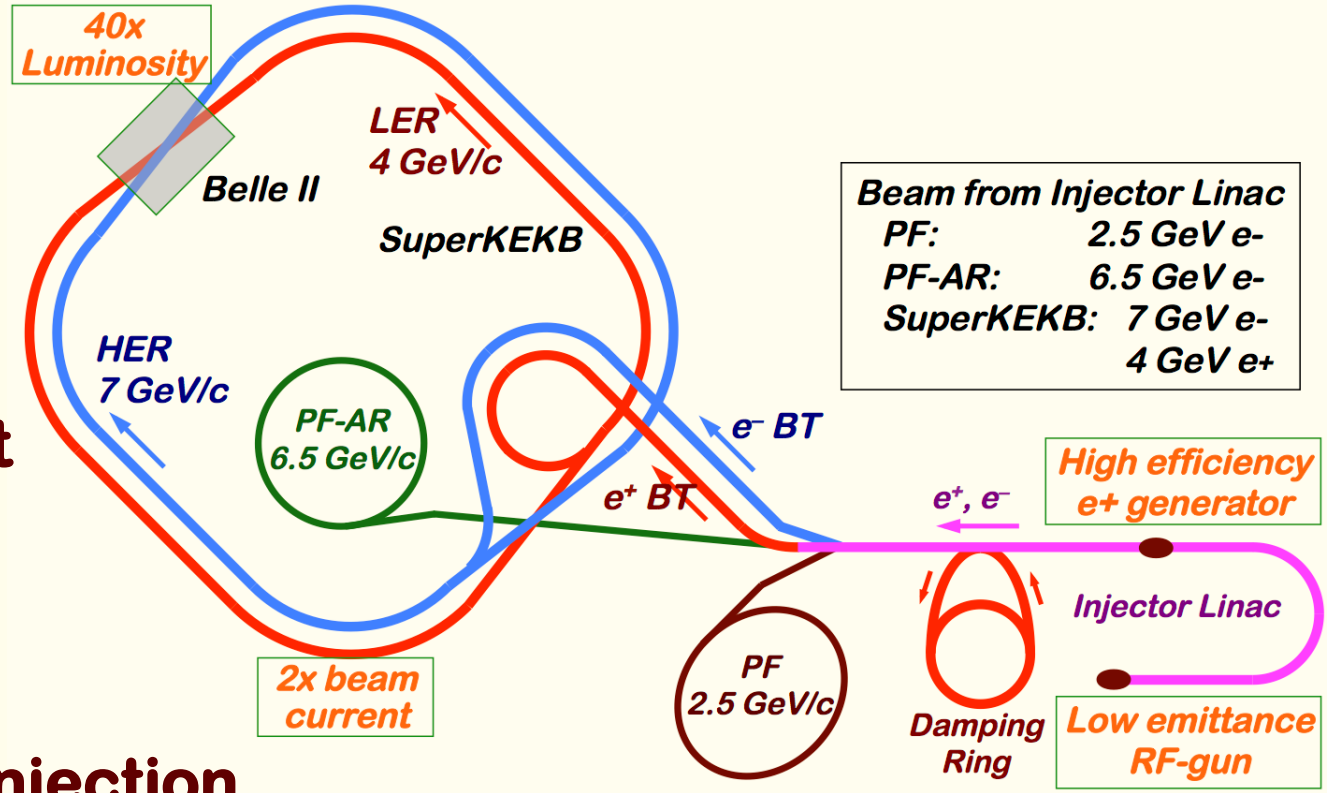


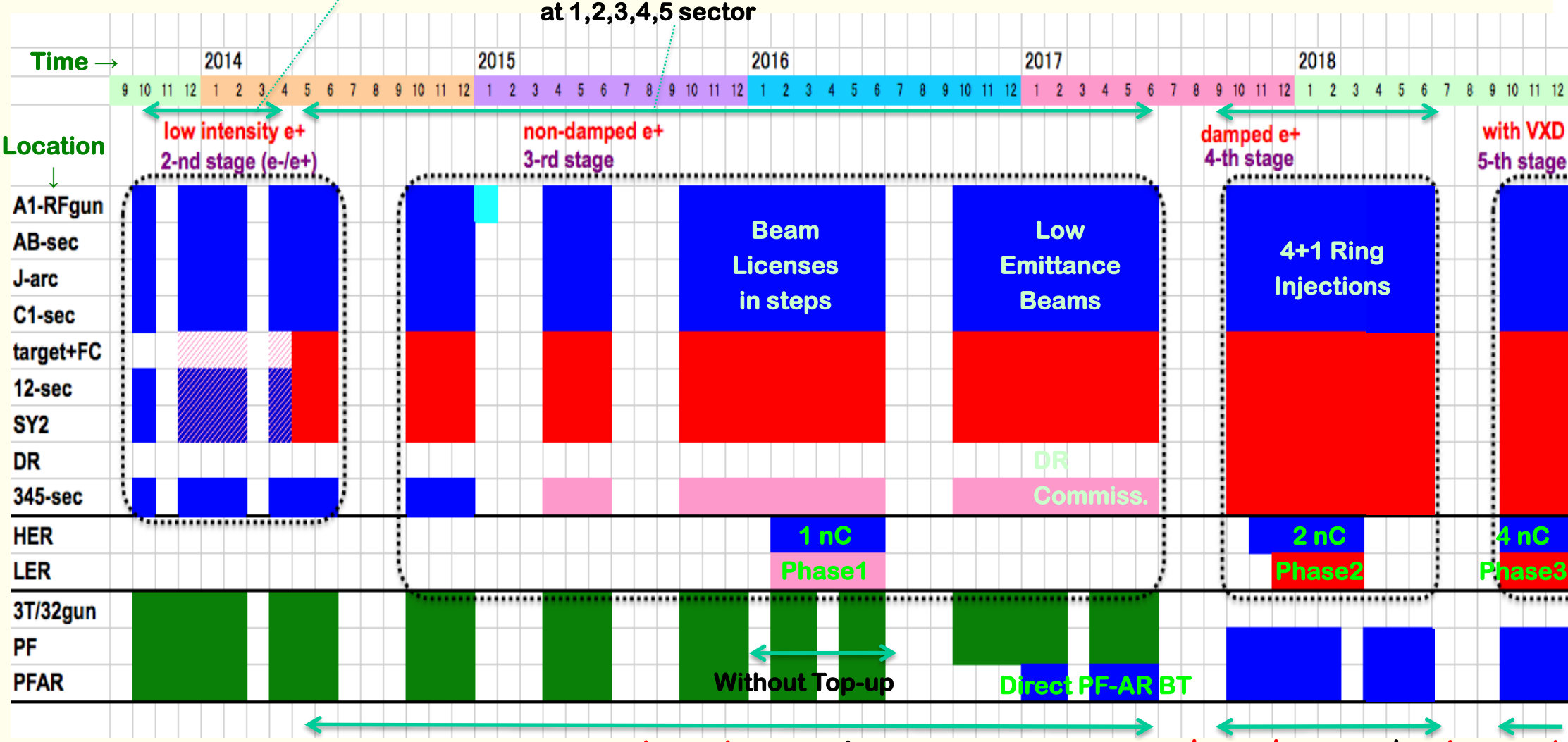
Linac Schedule Overview

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

e- commiss. at A,B,J,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- = 1~5nC

Improved RF gun

Required injector beam parameters

Stage	KEKB (final)		Present Phase-I		SuperKEKB (final)	
Beam	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
Stored current	1.6 A	1.1 A	1 A	1 A	3.6 A	2.6 A
Life time	150 min.	200 min.	100 min.	100 min.	6 min.	6 min.
Bunch charge	Primary e-10nC → 1 nC	1 nC	Primary e- 8nC → 0.4 nC	1 nC	Primary e-10nC → 4 nC	5 nC
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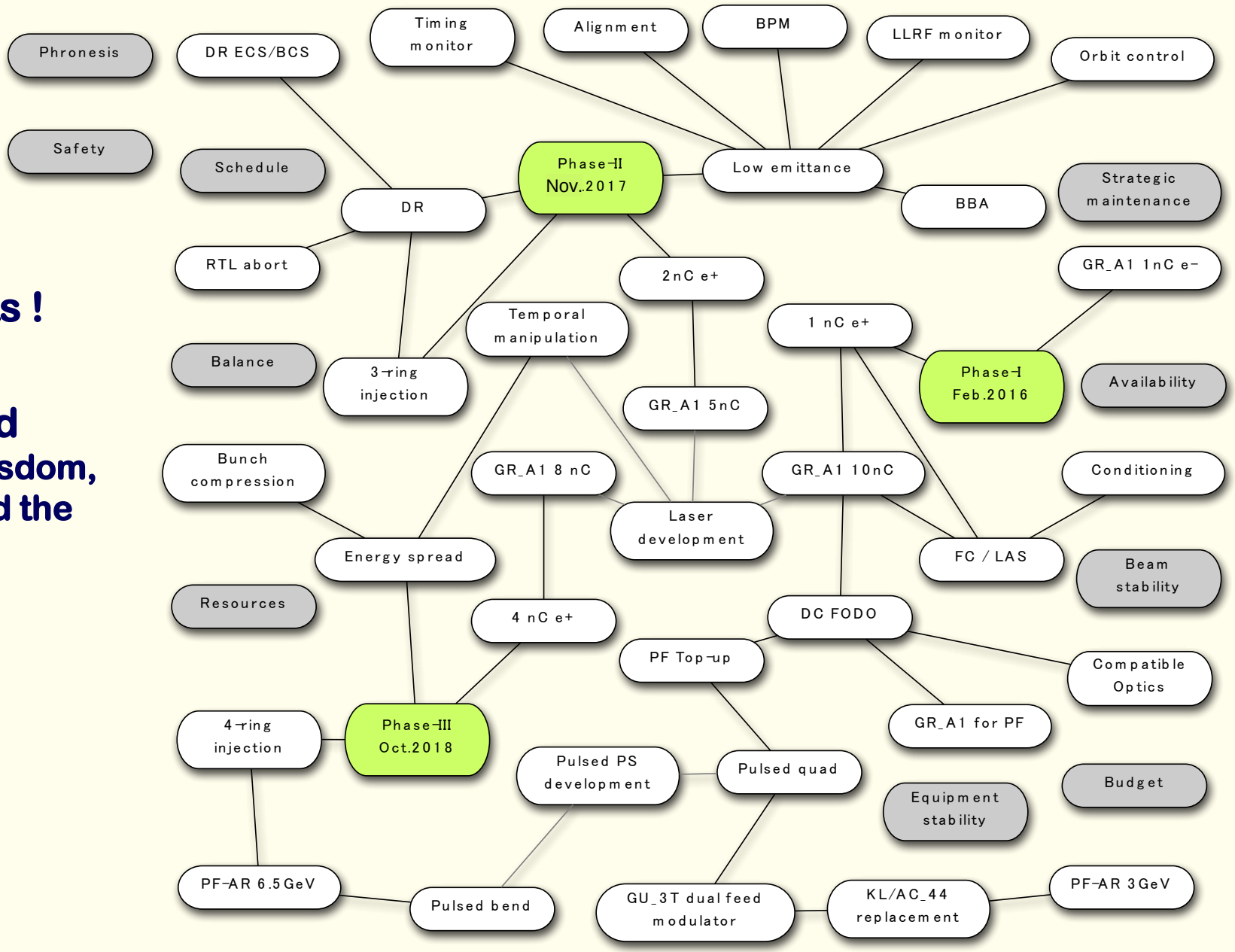
Simultaneous top-up injection (PPM)	3 rings (KEKB e–/e+, PF)		No top-up		4+1 rings (SuperKEKB e–/e+, DR, PF, PF-AR)	

Subjects to Consider

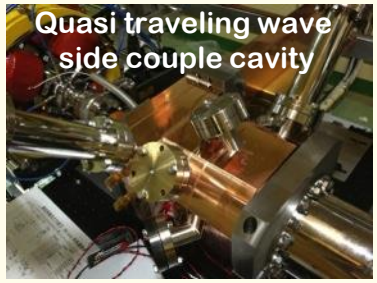
- **Have to consider too many subjects !**
- **Phronesis needed**
  (Greek: Practical wisdom, Ability to understand the Universal Truth)



Linac Upgrade Progress towards SuperKEKB (1)

High-charge low-emittance RF gun development

- QTWSC cavity and Ir5Ce photo cathode developments
- Laser development is underway

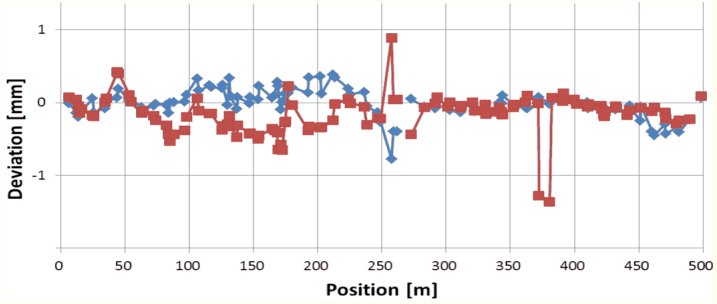


Positron generator commissioning

- Good agreement with the simulation results
- Will solve discharge issues

Precise alignment for emittance preservation

- Recovering after large earthquake in 2011
- Reaching specification of 0.1~0.3mm
- Longer term stability will be solved

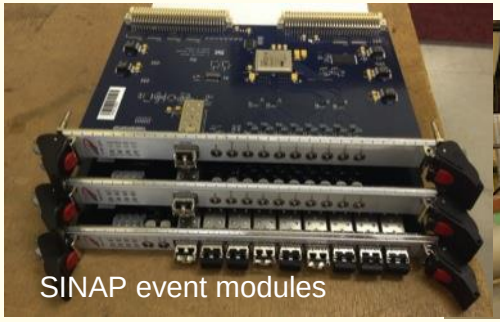


Utility upgrade during FY2014

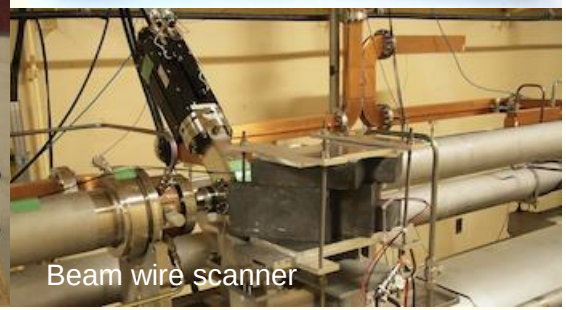
- for electricity (+1.5MW) and cooling water (+1400L/min)

Linac Upgrade Progress towards SuperKEKB (2)

- **High-power microwave modulator upgrades**
- **Low-level RF controls/monitor upgrades**
  - Pulse-to-pulse modulation (PPM) between 4+1 rings
  - More spaces for increased number of devices
- **Beam instrumentation**
  - Large/small aperture beam position monitors (BPM)
  - Precise/fast and synchronized BPM readout system
  - Wire scanners and beam loss monitors
  - Streak cameras
  - (Deflectors, etc.)
- **Event-based control and timing system upgrades**
  - Combination of MRF & SINAP modules
  - Essential for PPM operation
  - Precise timing & synchronized controls
  - Bucket selection at DR and MR

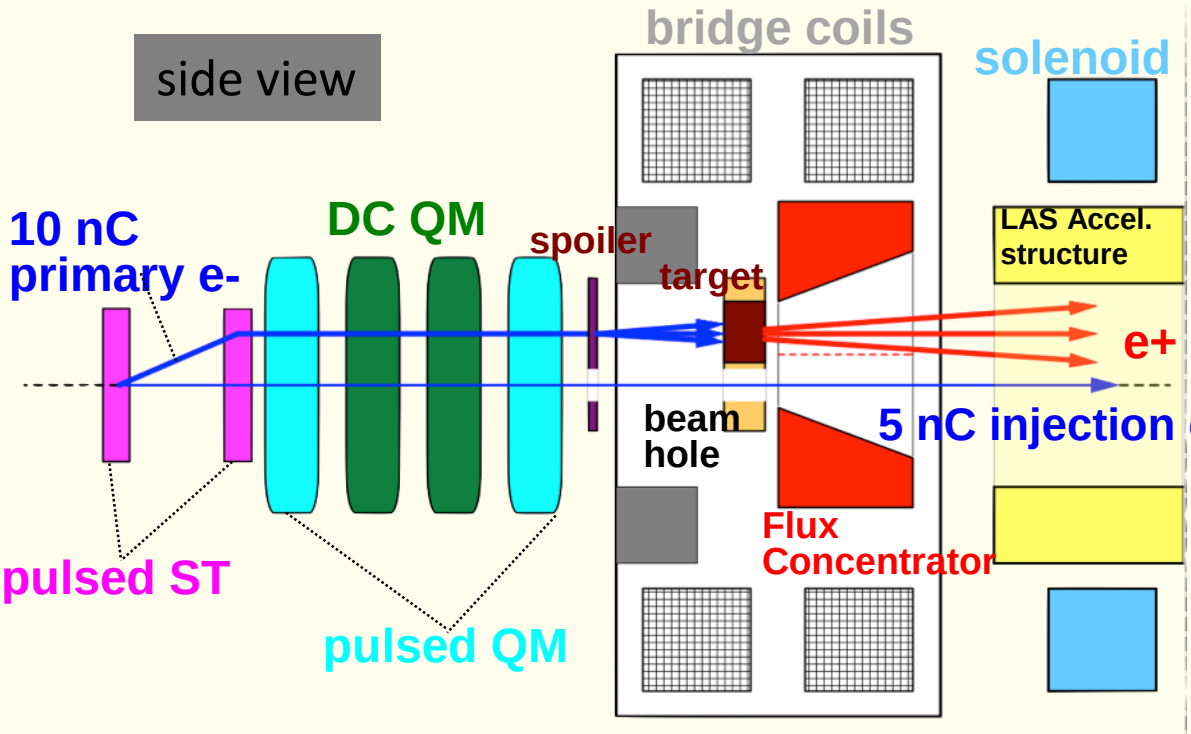


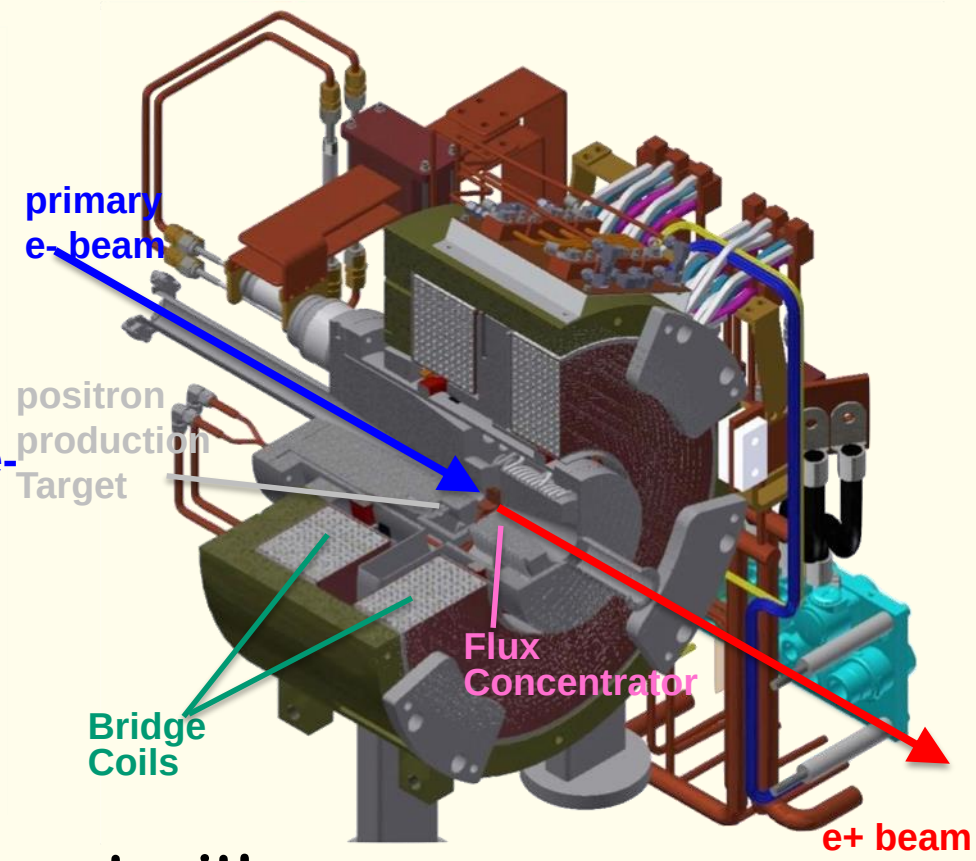
SINAP event modules



Beam wire scanner

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

RF-Gun development strategy for SuperKEKB

- **Cavity : Strong electric field focusing structure**
  - Disk And Washer (DAW) => 3-2, A-1(test)
  - Quasi Traveling Wave Side Couple (QTWSC) => A-1

  => Reduce beam divergence and projected emittance dilution
- **Cathode : Long term stable cathode**
  - Middle QE (QE=10^{-4}～10^{-3} @266nm)
  - Solid material (no thin film) => Metal composite cathode

    => Started with LaB_6 (short life time)

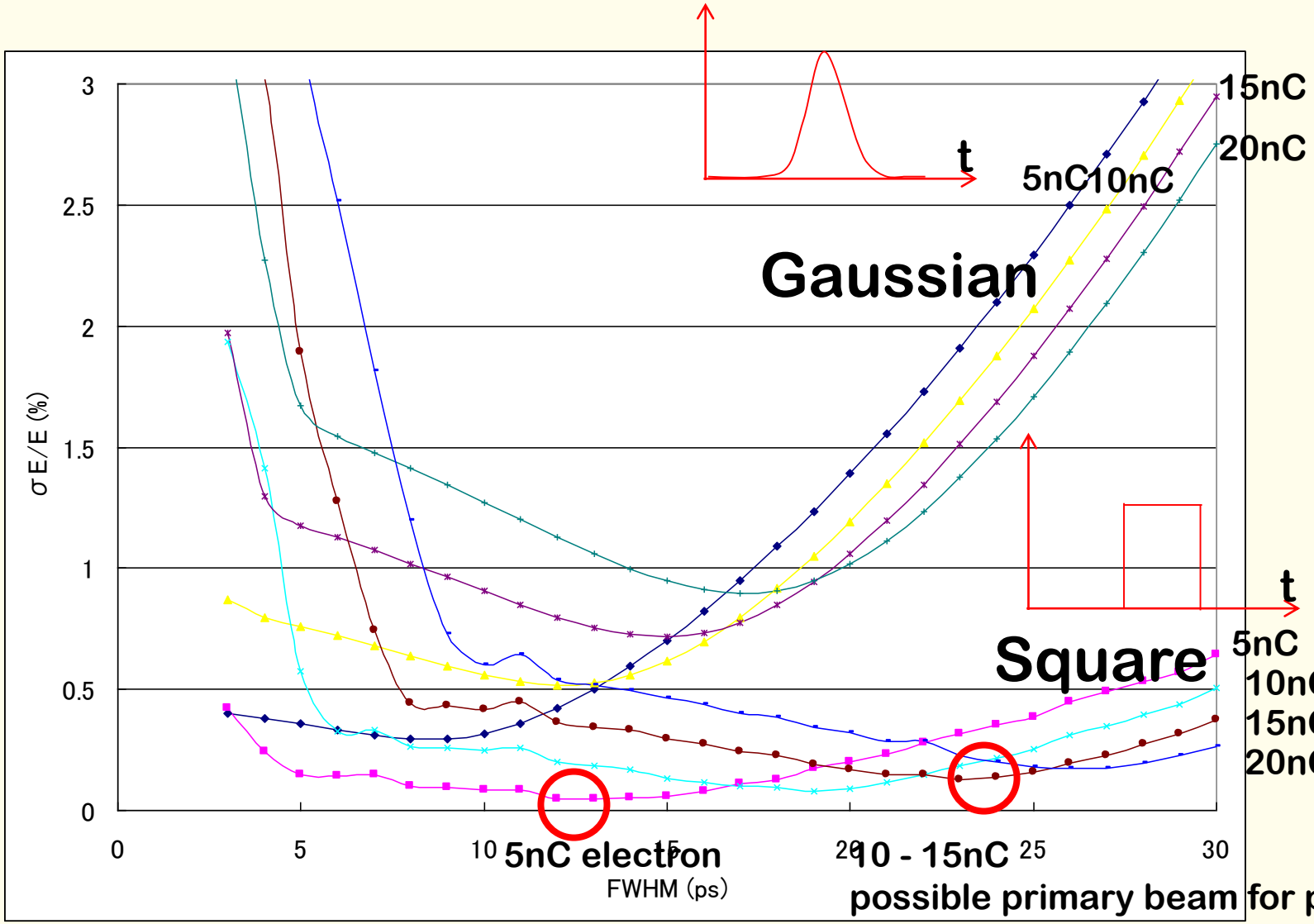
    => Ir_5Ce has very long life time and QE>10^{-4} @266nm
- **Laser : Stable laser with temporal manipulation**
  - Fiber laser oscillator / amplifier = Yb doped
  - LD pumped laser medium => Nd / Yb doped
  - Temporal manipulation => Yb doped

    => Minimum energy spread

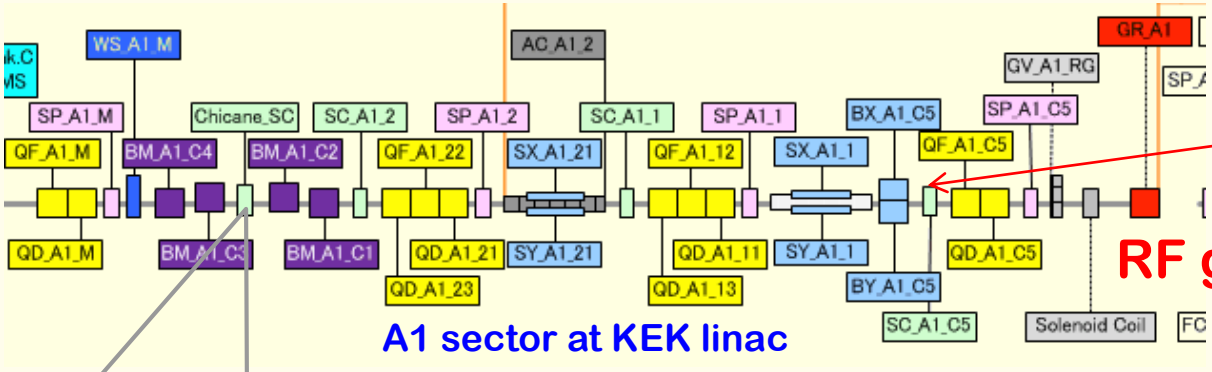
Energy spread reduction using temporal manipulation

M. Yoshida

Energy spread of 0.1% is required for SuperKEKB synchrotron injection.

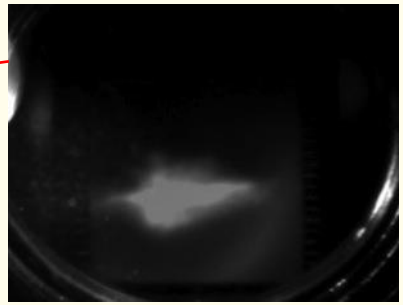


RF Gun Result Example

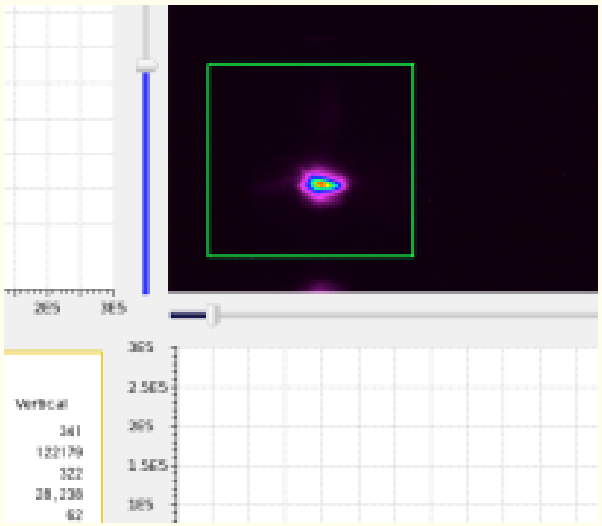


A1 sector at KEK linac

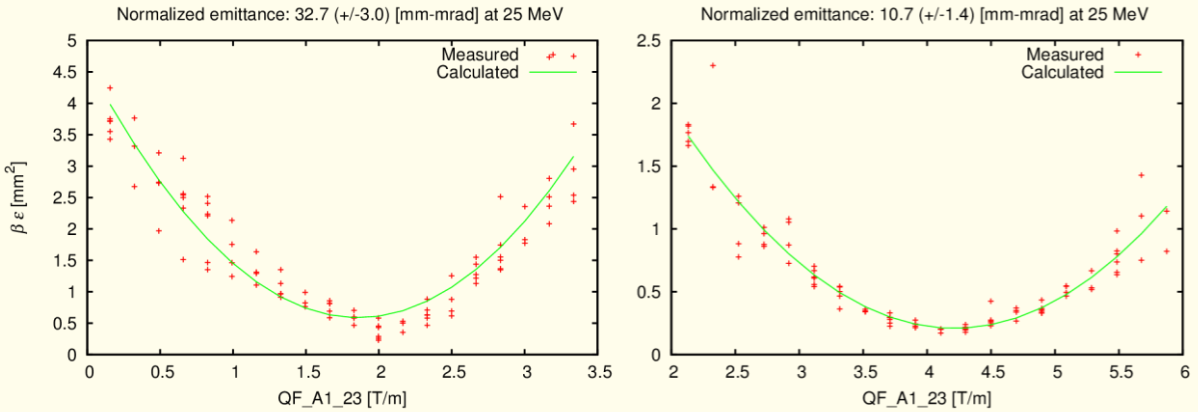
5.6 nC bunch charge was observed.



RF gun



beam size measurement for Q-scan



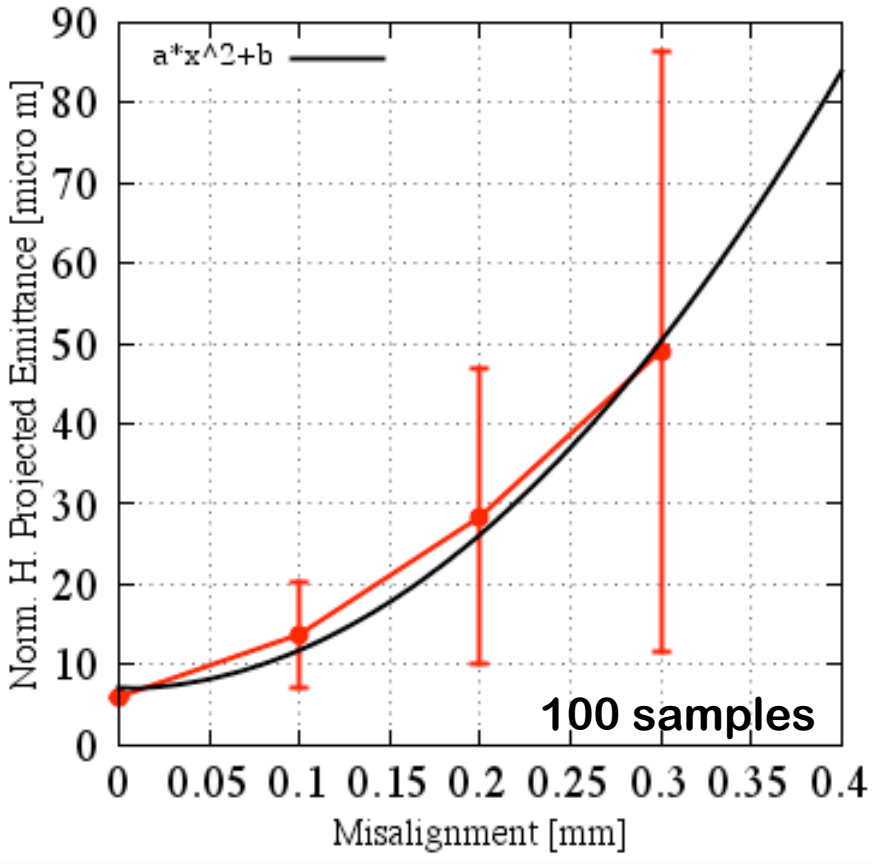
Q-scan emittance measurement

x	y
32.7 ±3.1 mm-mrad	10.7 ±1.4 mm-mrad

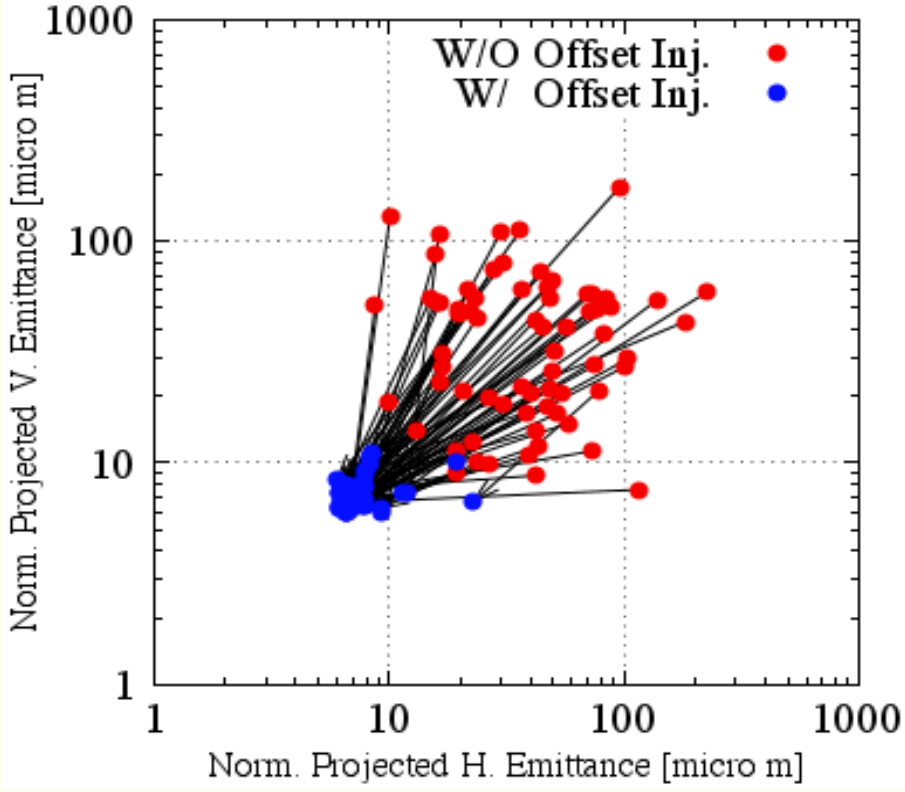
Emittance Preservation

- Offset injection may solve the issue
- Orbit have to be maintained precisely
- Mis-alignment should be <0.1mm locally, <0.3mm globally

Mis-alignment leads to Emittance blow-up



Orbit manipulation compensates it



Sugimoto et al.

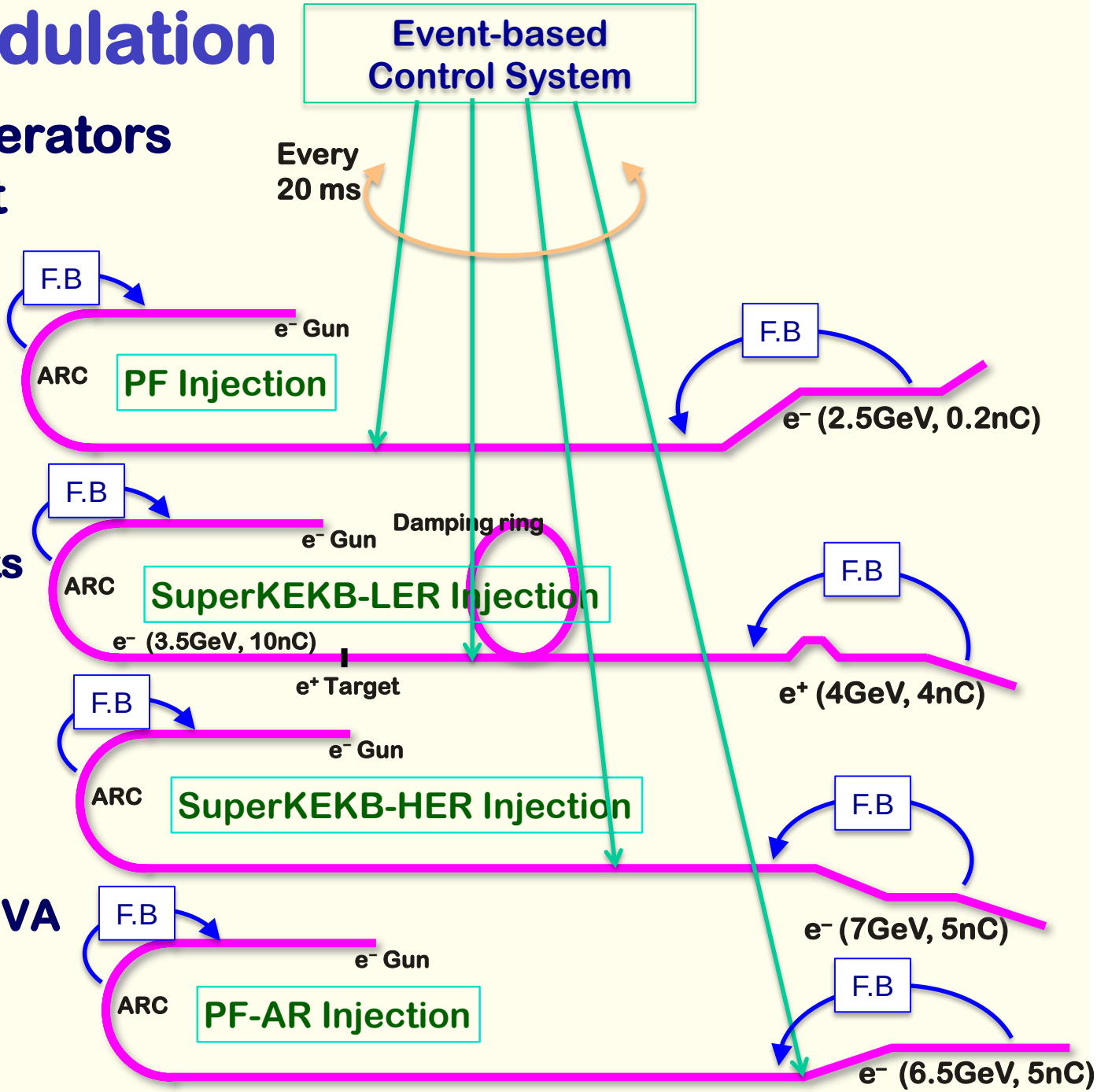
Pulse-to-pulse modulation

- **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



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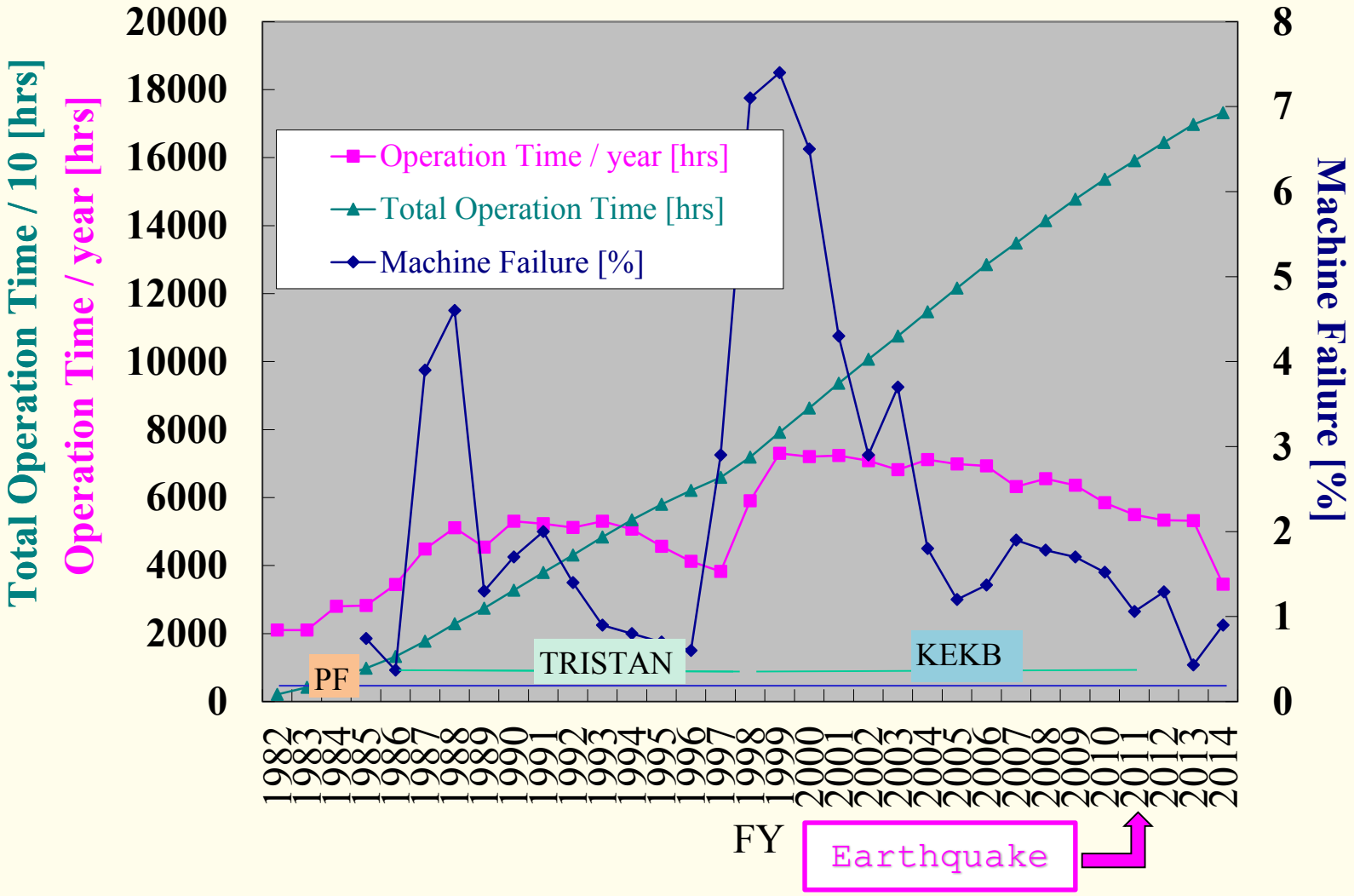
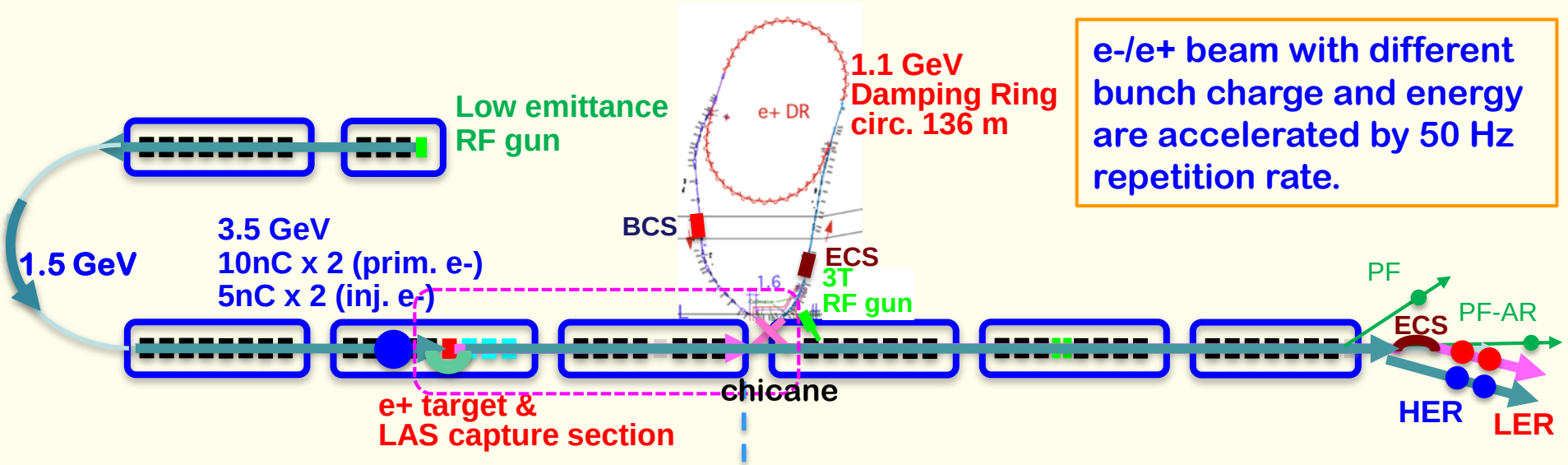
Injector Linac Operation History

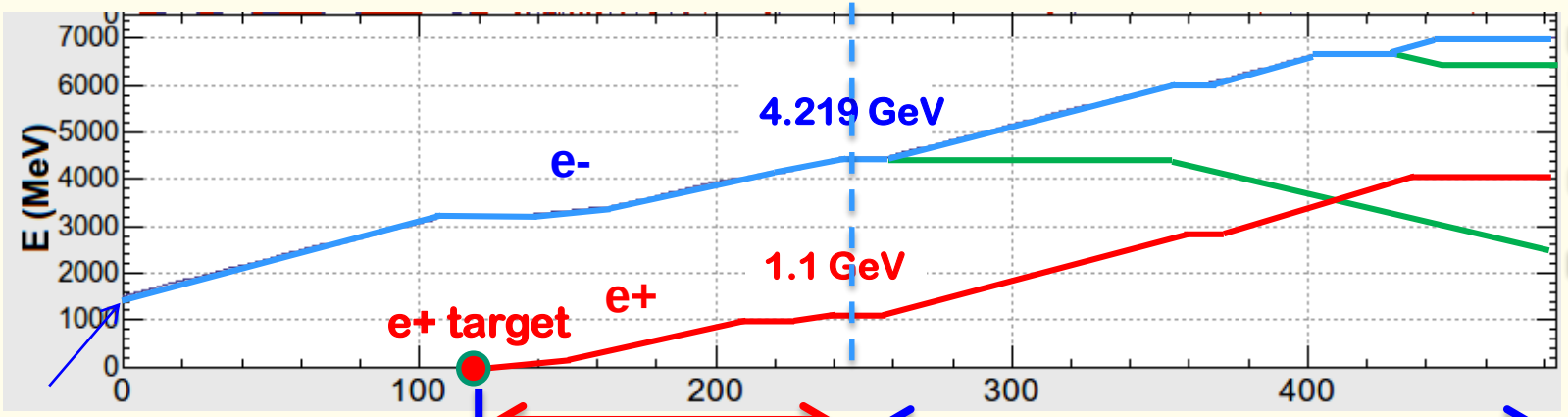


Routine maintenance was important to improve the reliability (Failure rate includes rf trips)

Injector Linac Energy Management



e-/e+ beam with different bunch charge and energy are accelerated by 50 Hz repetition rate.



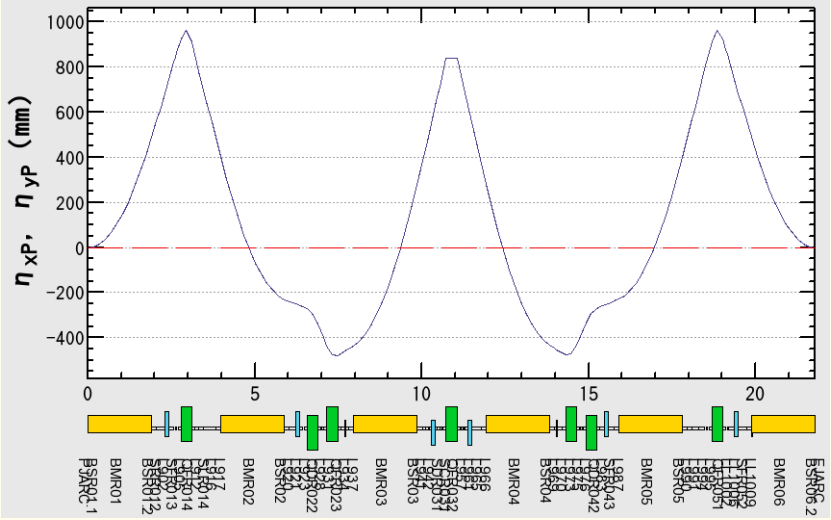
5 nC x2
HER: 7GeV e-
PF-AR: 6.5GeV e-
5nCx1
LER: 4GeV e+
4 nCx2
PF: 2.5 GeV e-
0.1nCx1

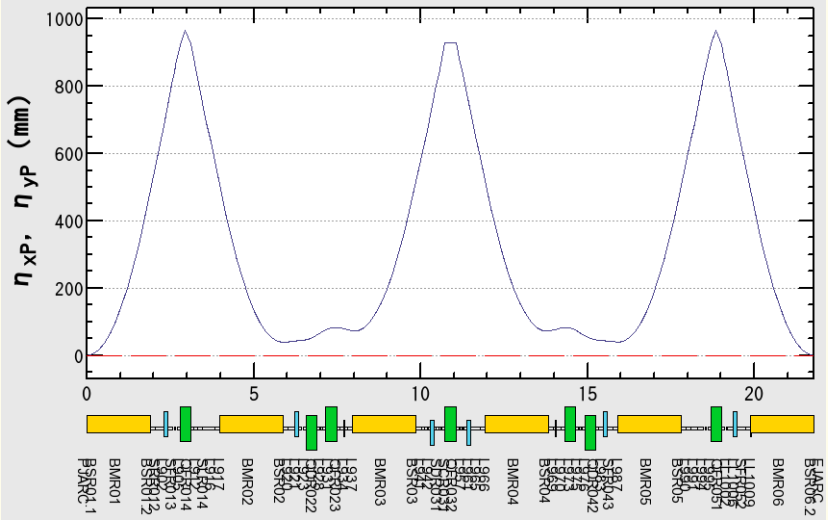
e-/e+ compatible optics

Optics is changed for each pulse by using pulsed quads (Doublet) & steering magnets

Beam Manipulation Study

At 180-deg arc

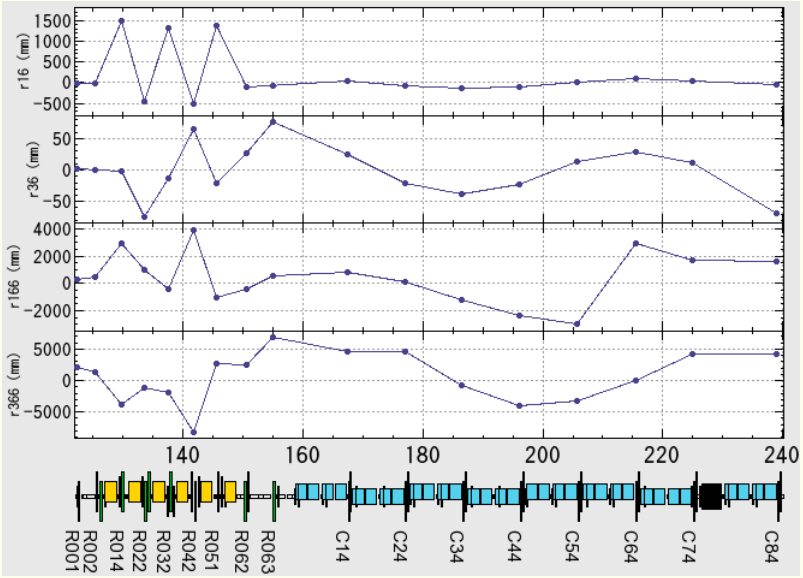


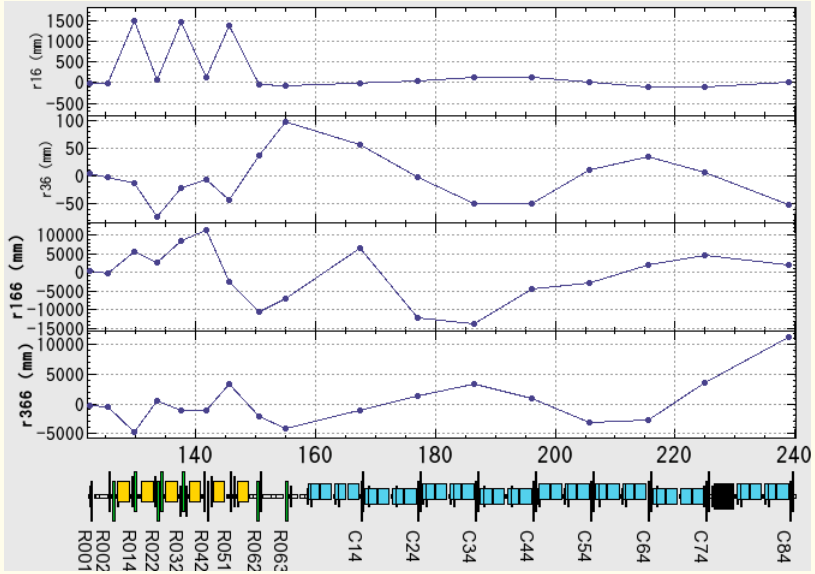


Optics design with R56 = 0 and -0.6 for bunch compression

BPM will be replaced with 5-times better resolution

Streak camera should follow



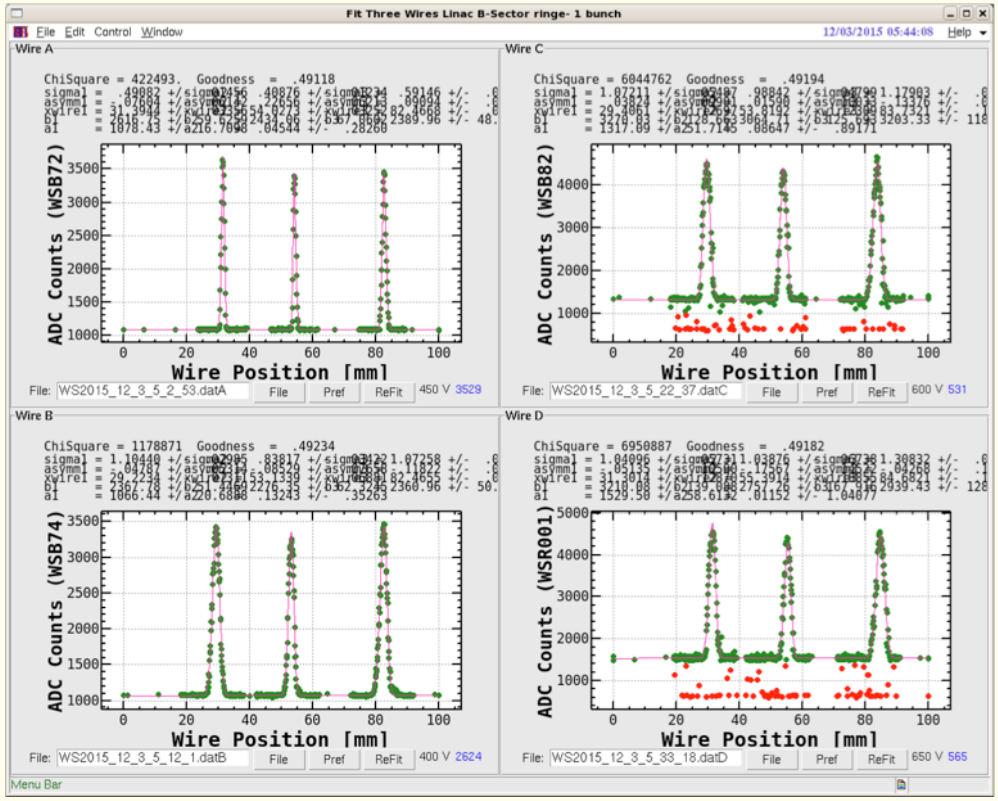


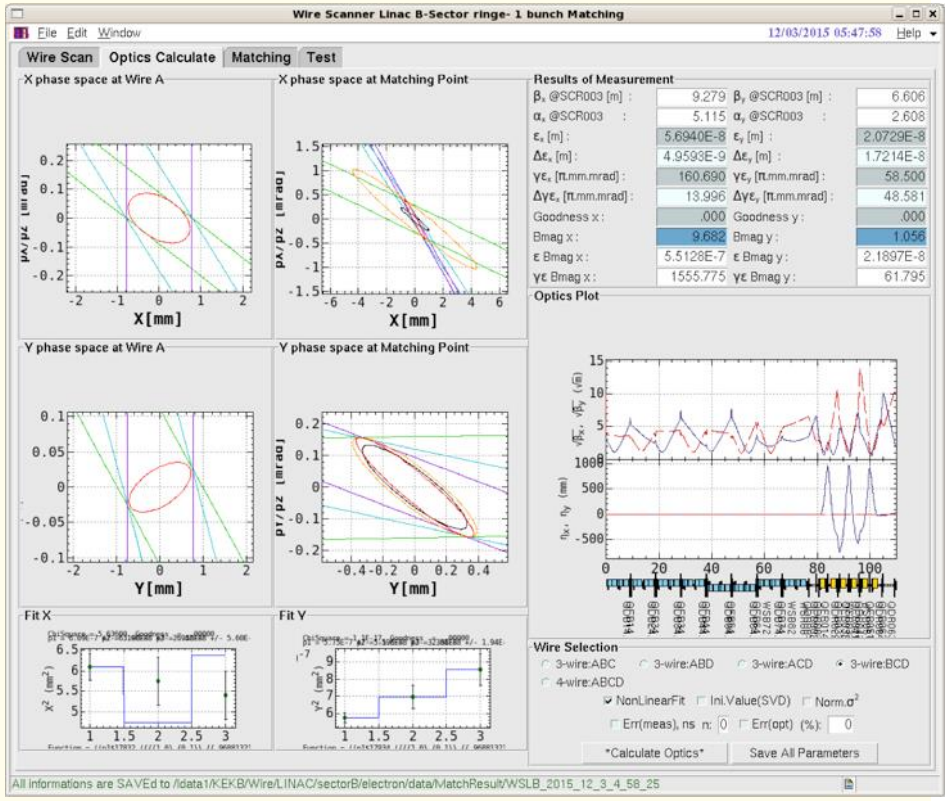
Measurement of dispersion functions for R56 = 0 and -0.6

Soon with timing measurement by streak camera

Linac Optics Measurement / Management

- Wire scanner is used to manage twiss parameters along linac
- ~6 sets of wire scanners will be installed





- Wire scanner measurements performed everyday
- If necessary (if Bmag is large), re-matching is performed by operator
- For pulse-to-pulse vertical measurement, X-band deflector will be installed

Typical Phase-1 Daily Operation

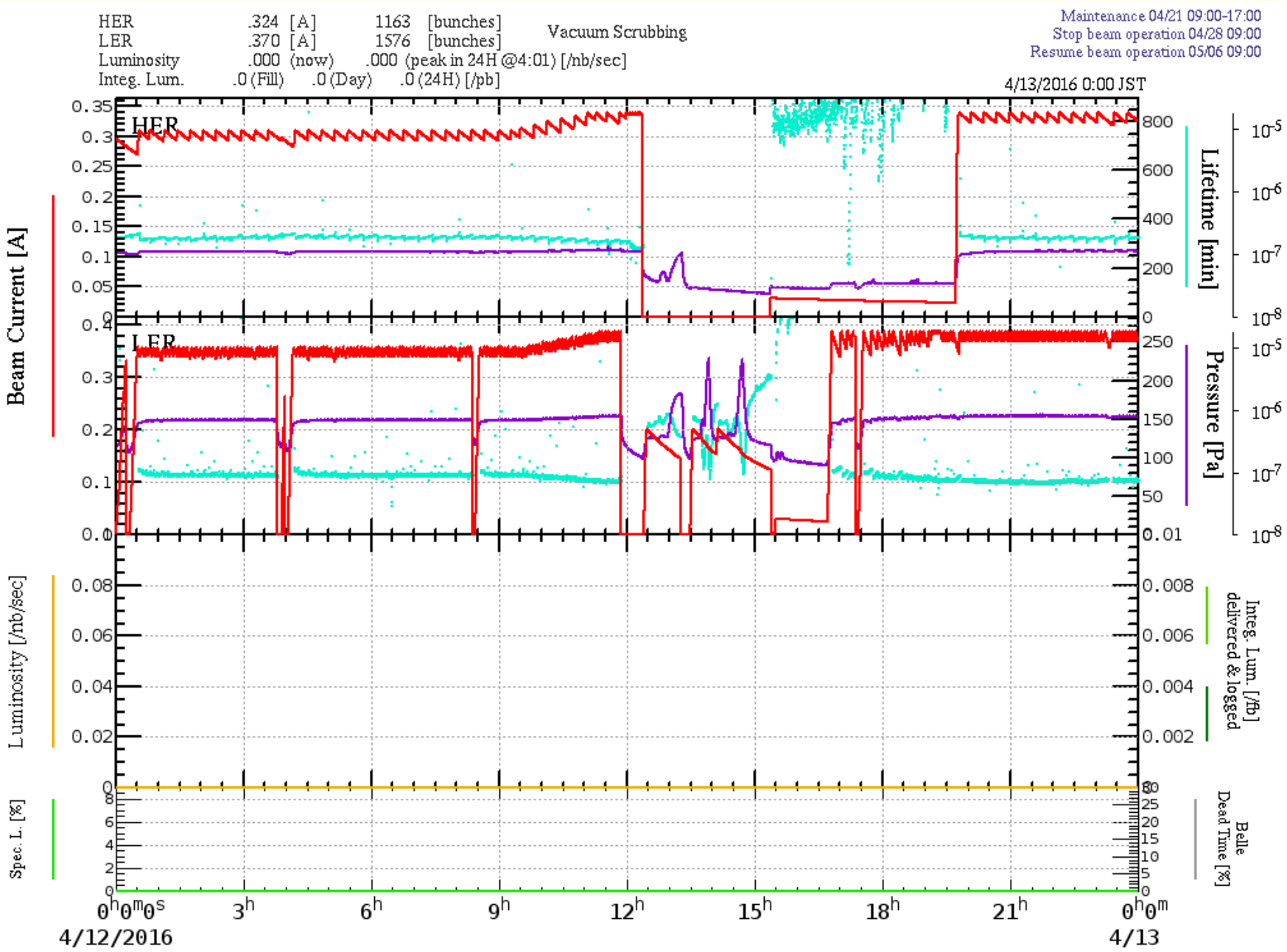
More than 300mA stored this week in the both e-/e+ rings

In daytime increases beam current, and performs optics studies

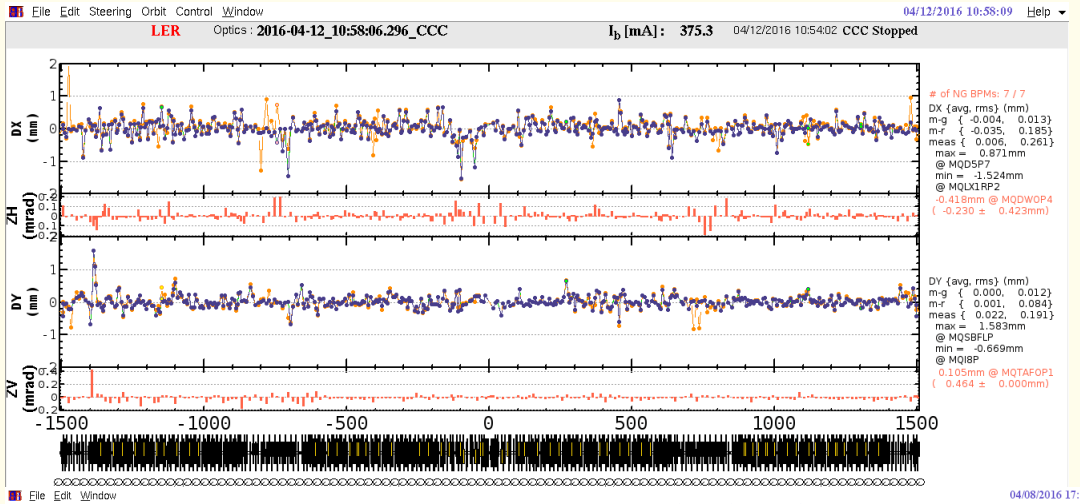
In night time continue vacuum scrubbing

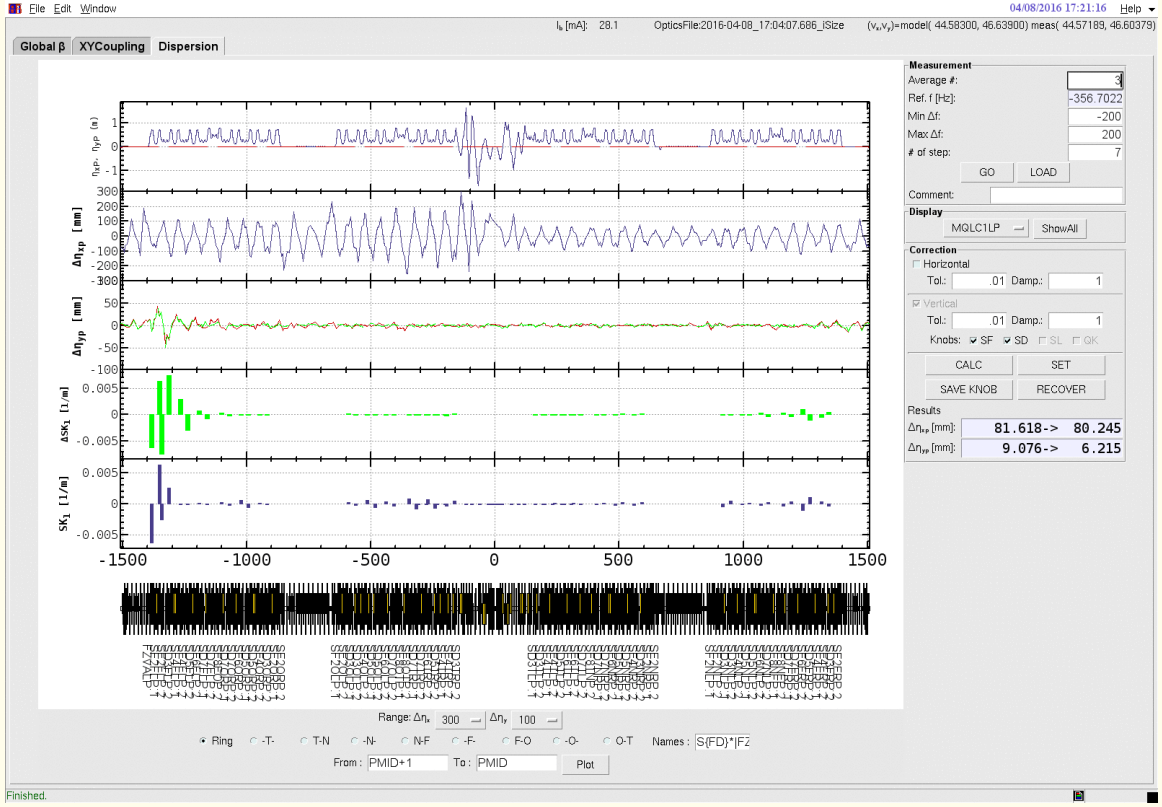
No collision yet

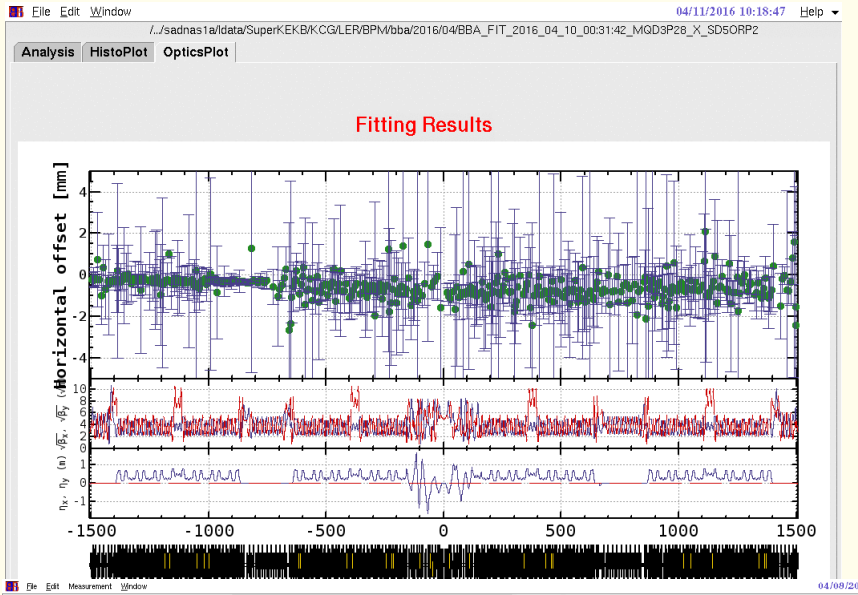
Collision expected at the end of 2017

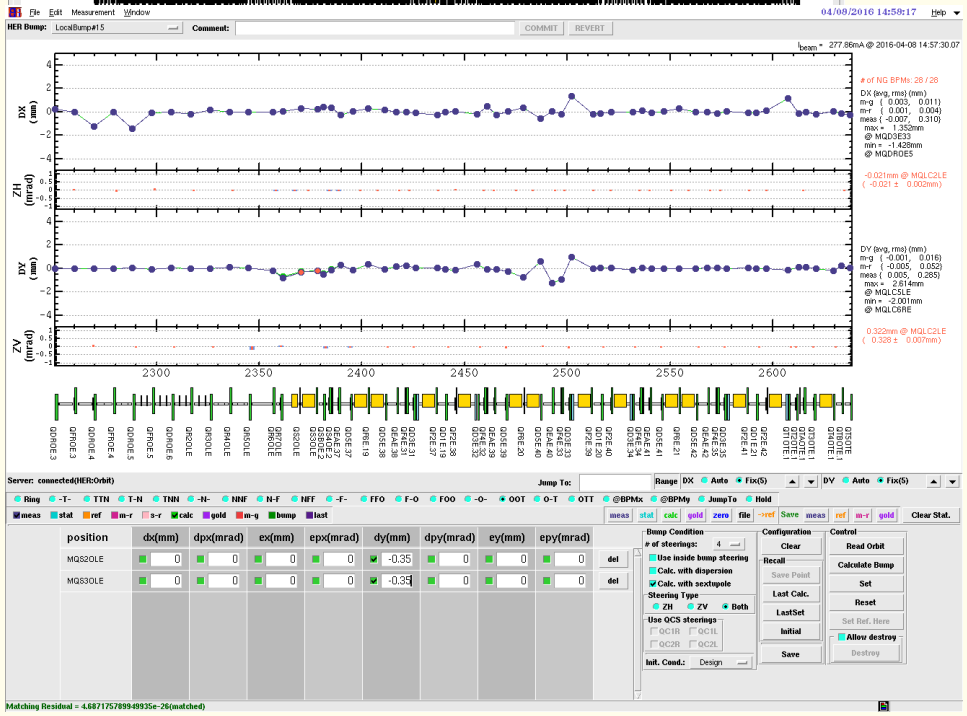


Examples of Operational Panels







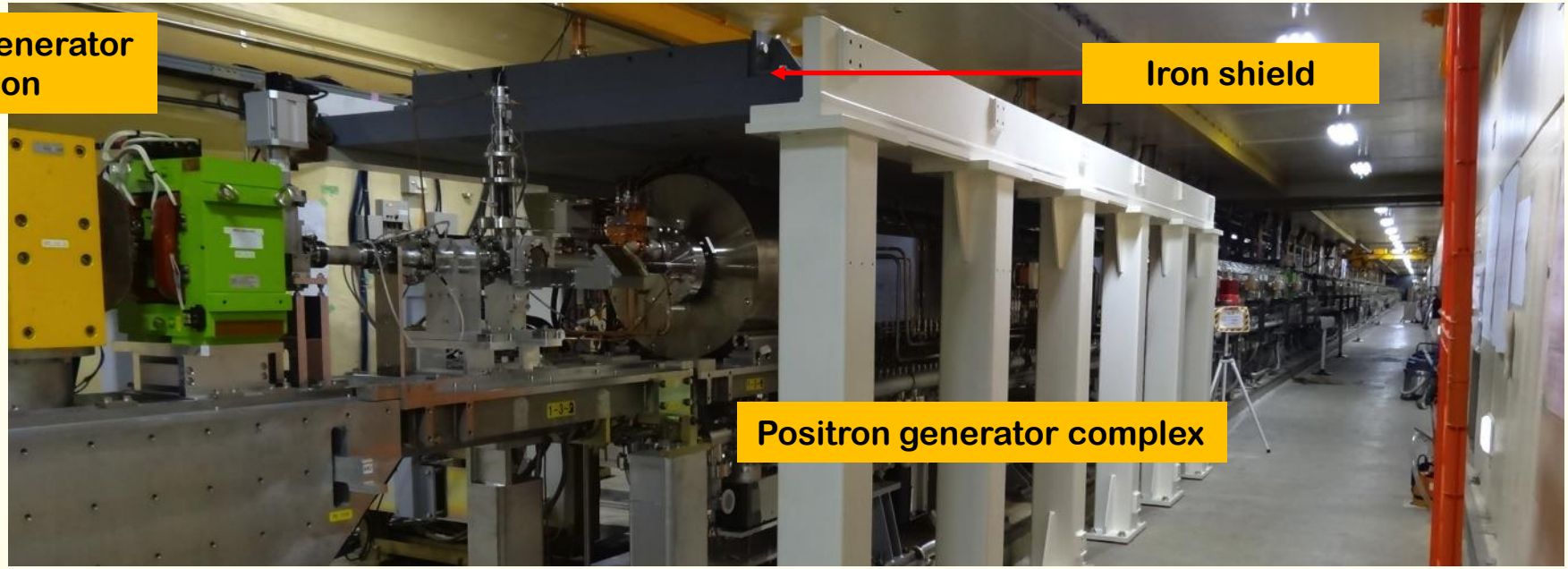


Radiation control licenses

- Step-by-step upgrade of beam limits
- Final goal in linac is 1250/625 nA before/after target
- License applications
  - Fall.2013. 10 nA at #28 dump, 1250 nA at #A2 dump
  - Spring 2014. New utility rooms, 50 nA at #61 straight dump
  - Jun.2015. 200 nA at #15 target
  - Early 2016. 800 nA at #15 target, 625 nA at #61
  - Sometime 2017.(?) 1250 nA at #15 target
- Shield, shield, shield, shield …
  - Gun, 180deg-arc, Target, Electron stopper, Collimator, etc.

Recent Works

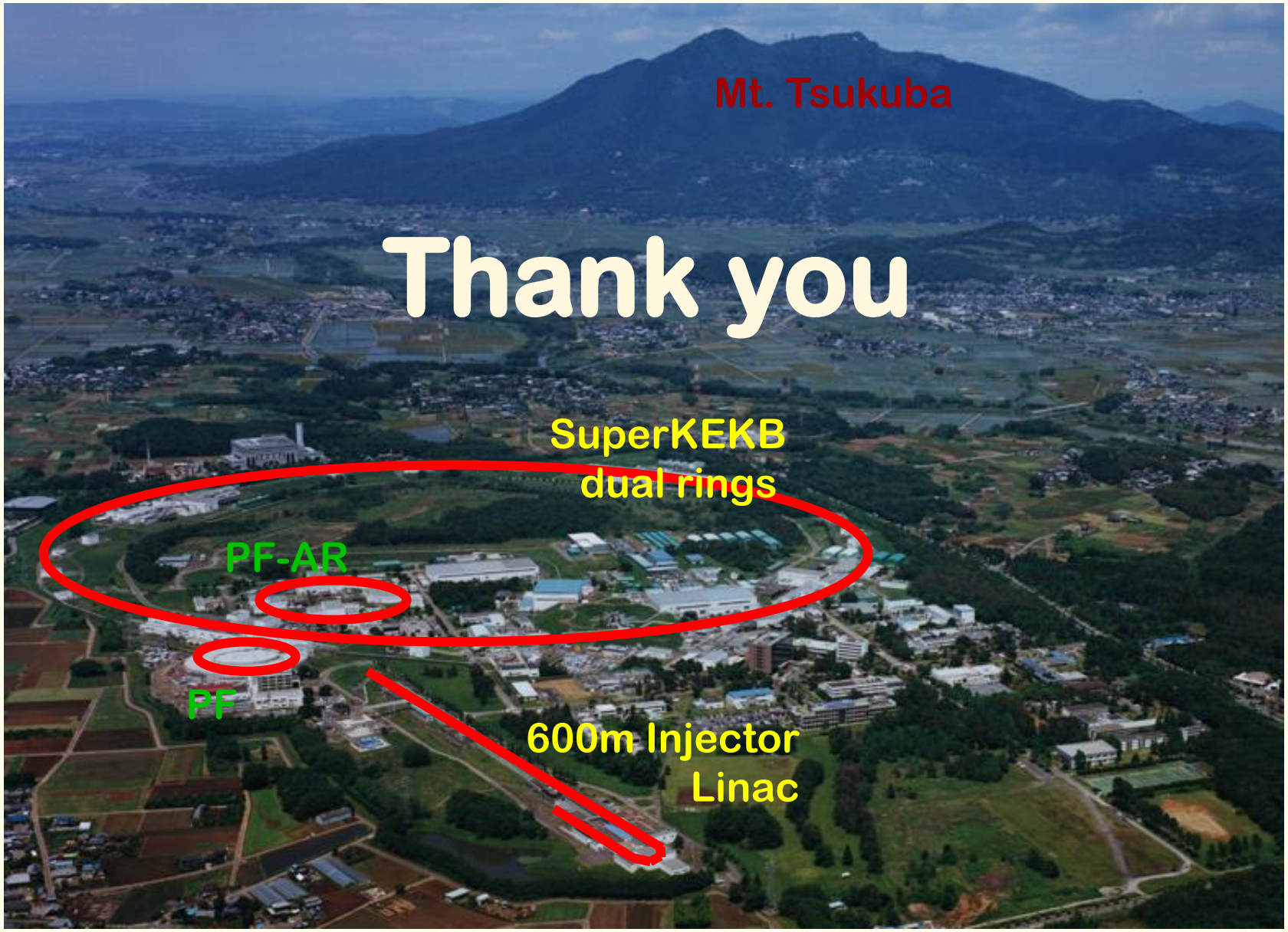
Positron generator at #15 region



Guns at #A1 region

Summary

- We learned a lot during KEKB construction and operation
- It contributed to achieve the world highent luminosity
- Injection into SuperKEKB is another challenge with higher beam charge and lower emittance
- Steady progress towards designed injection beam in steps
  - Alignment: almost confident on the required precision (0.1-mm local, 0.3-mm global), need to maintain for longer term
  - Positron generator: another license test, need discharge analysis
  - Thermionic gun: re-commissioned, working
  - RF gun: following recommendations at review meetings
  - Need much more radiation shield
- Will balance between final beam quality and progressive operation
- Will select optimized route depending on available resources
- With some Phronesis we may enjoy beam commissioning

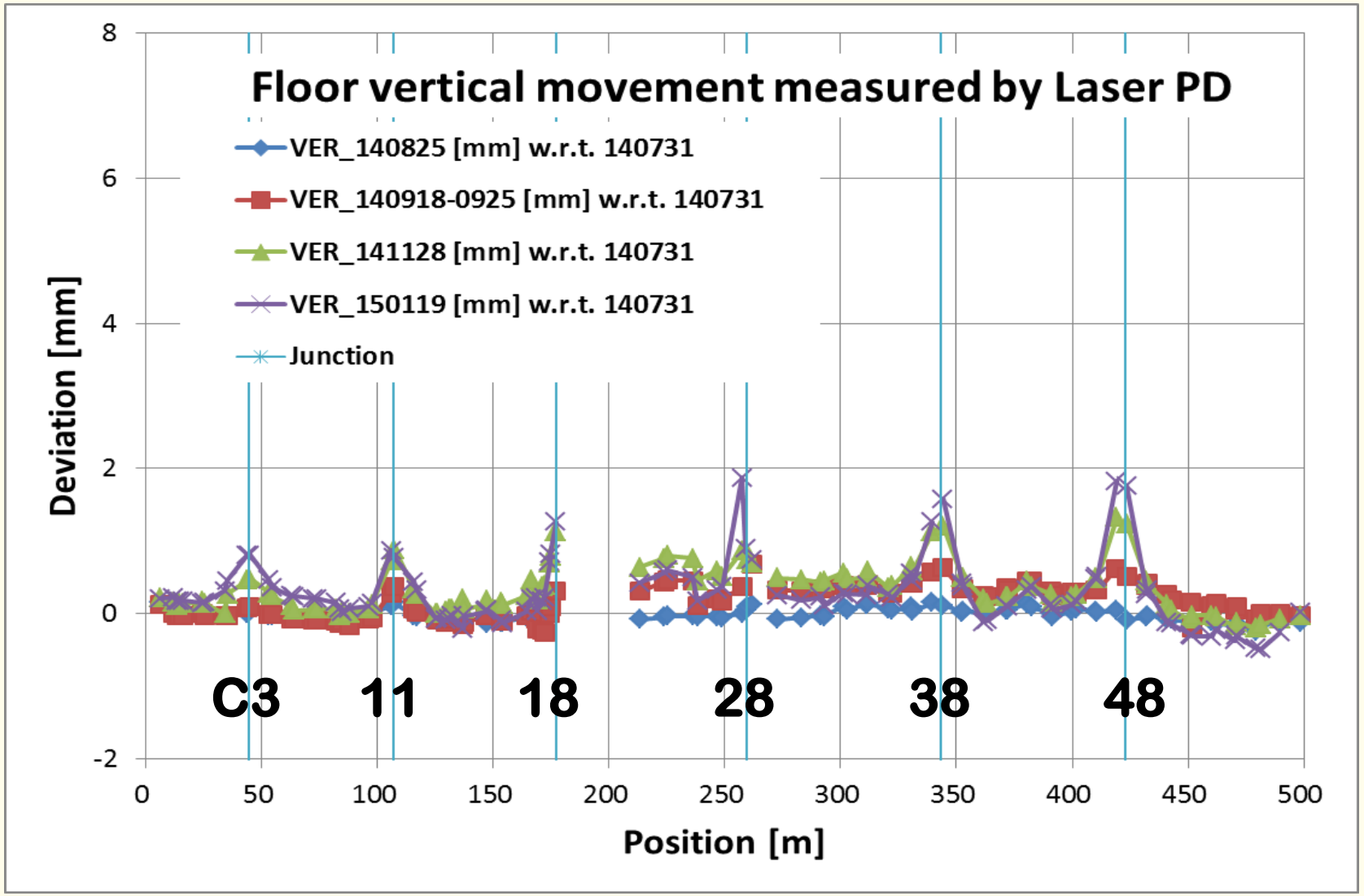


Conference papers at <http://www-linac.kek.jp/linac/>

Floor vertical movement

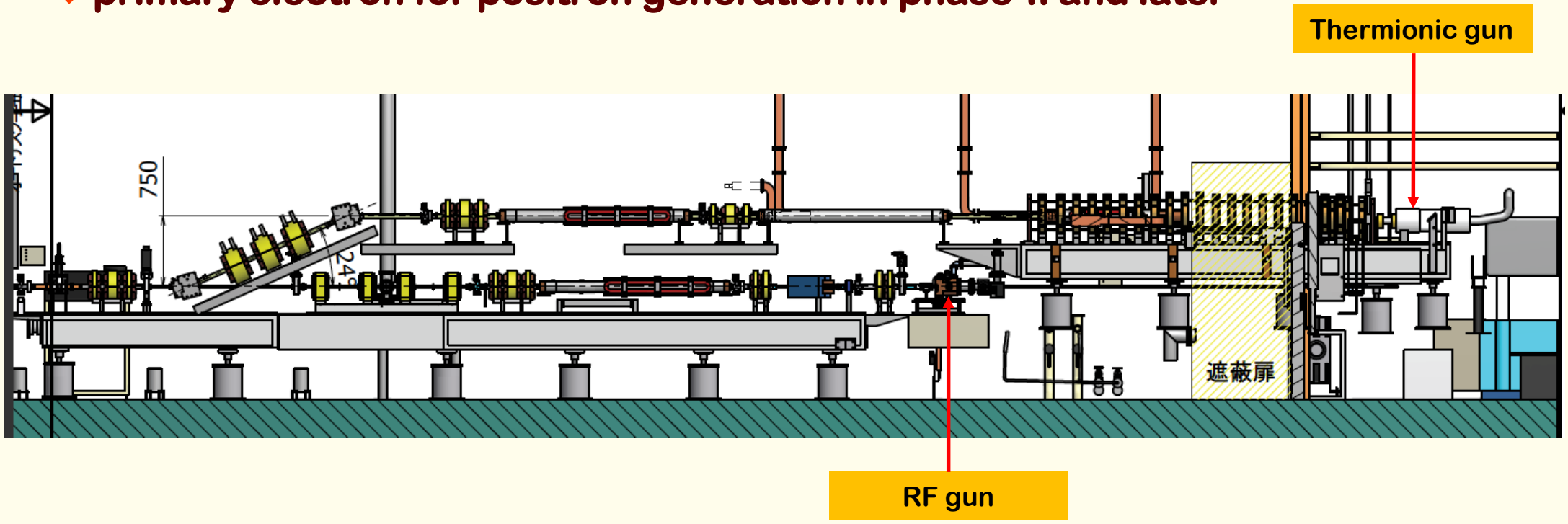
in a half year from summer to winter

Higo et al.



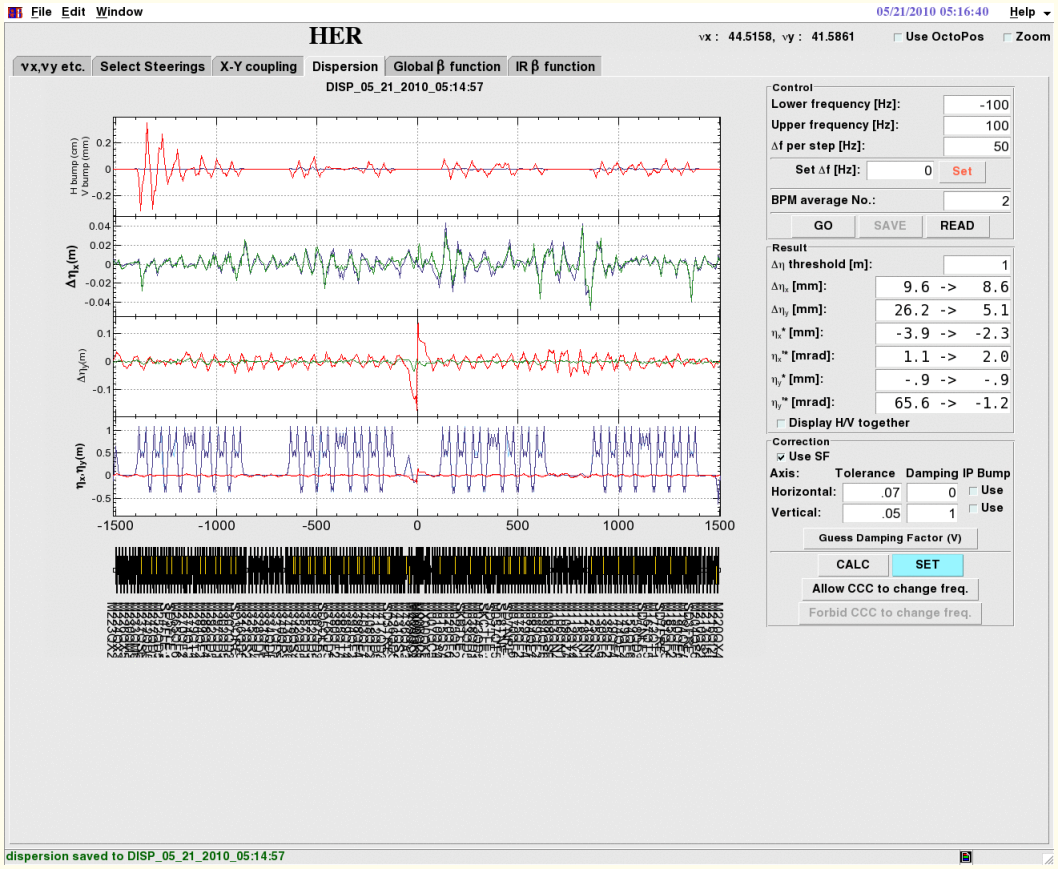
Preparation of Thermionic Gun

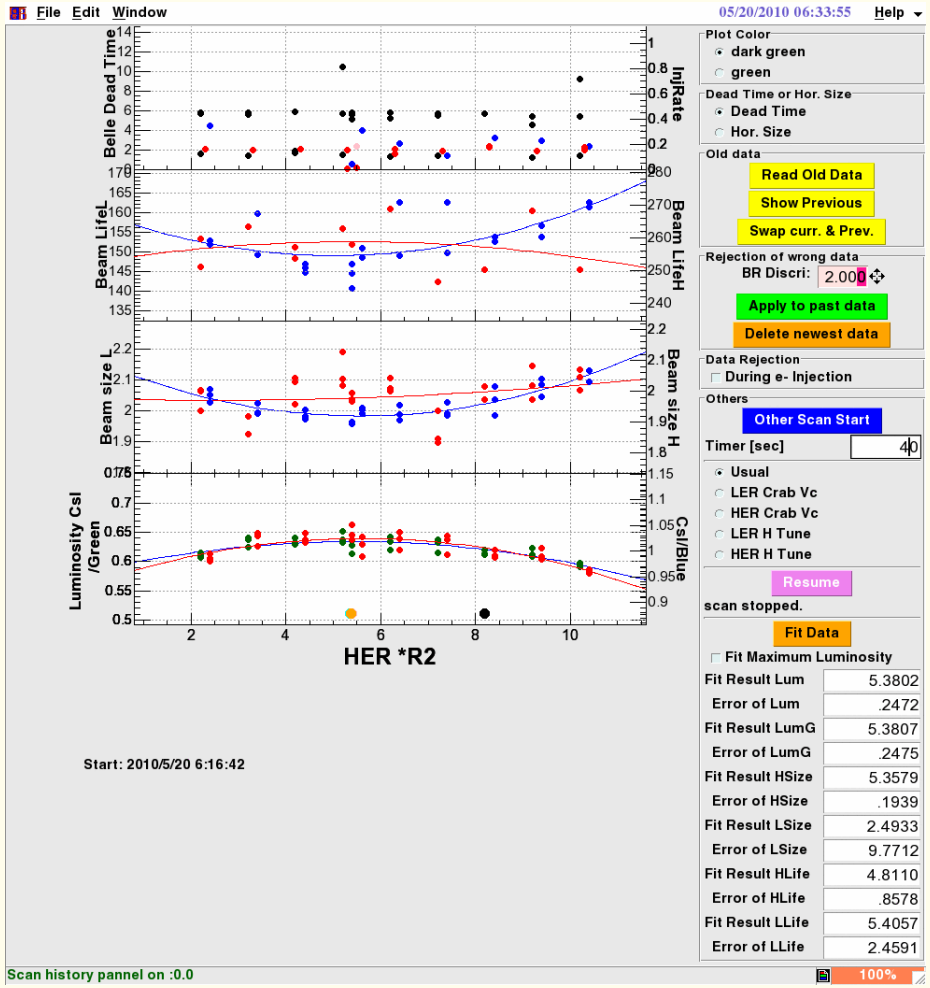
- **Refurbished and recommissioned**
  - Raise by 75cm not to conflict with straight RF-gun
    - As well as angled RF-gun
  - ~ Jun.2015.
- **Beside RF gun, thermionic gun may serve**
  - electrons in phase-I
  - primary electron for positron generation in phase-II and later



SADscripts

- **Many machine diagnostic and correction/feedback tools**





SADScript

- **Mathematica-like Language**
  - Not Real Symbolic Manipulation (Fast)
  - EPICS CA (Synchronous and Asynchronous)
    - CaRead/CaWrite[ ], CaMonitor[ ], etc.
  - (SQL Database)
  - Tk Widget
  - Canvas Draw and Plot (Mathematica-like Plot)
    - High quality plots to be used in publications
  - KBFrame on top of Tk
  - Data Processing (Fit, Modeling, FFT, Optimization, …)
  - Inter-Process Communication (Exec, Pipe, etc)
    - System[ ], OpenRead/Write[ ], BidirectionalPipe[ ], etc.
  - Greek Letter
  - Full Accelerator Modeling Capability (this the main part, of course)
  - Also Used for non-Accelerator Applications
  - Other institutes depend on MAD, XAL, but very different architecture