Injector Linac Experiences at KEKB / SuperKEKB

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SuperKEKB overview

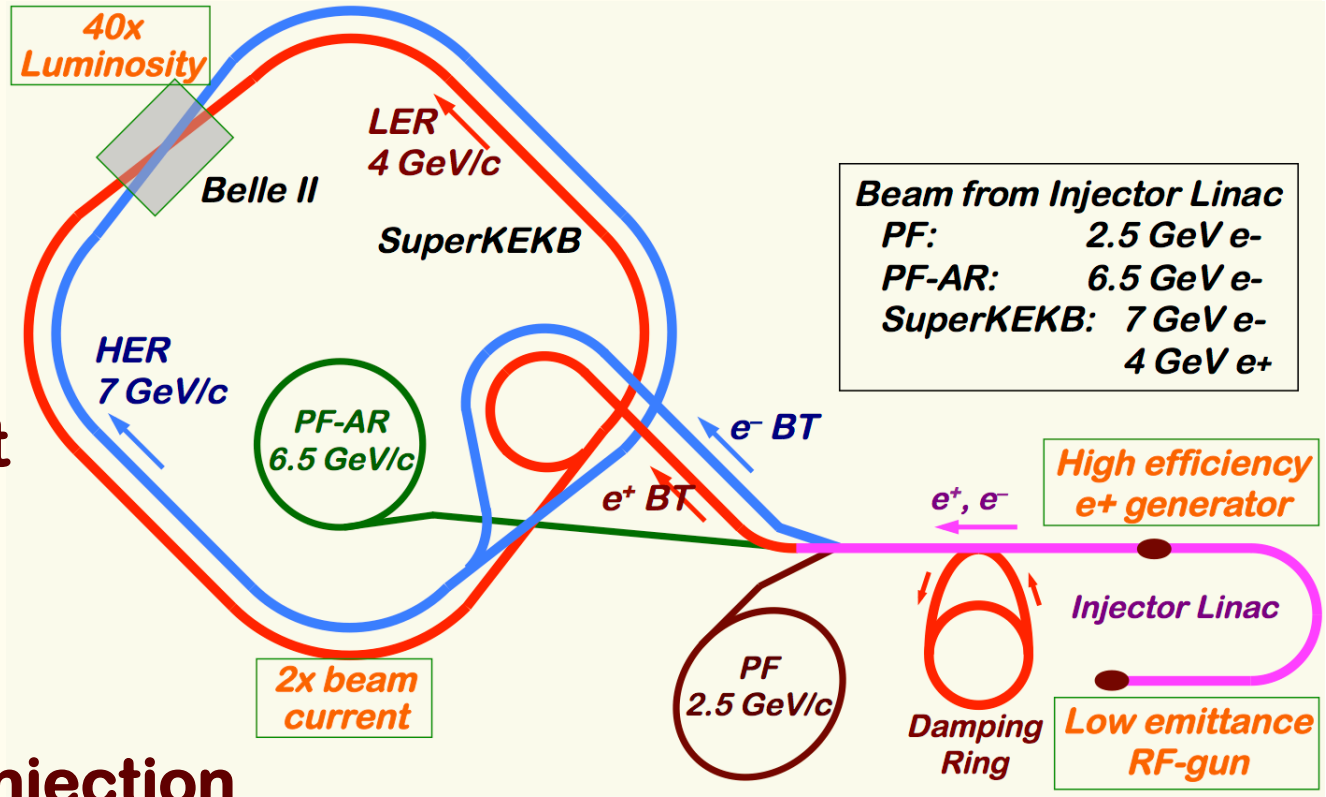
KEKB Injector Linac

SuperKEKB Injector Linac Progress

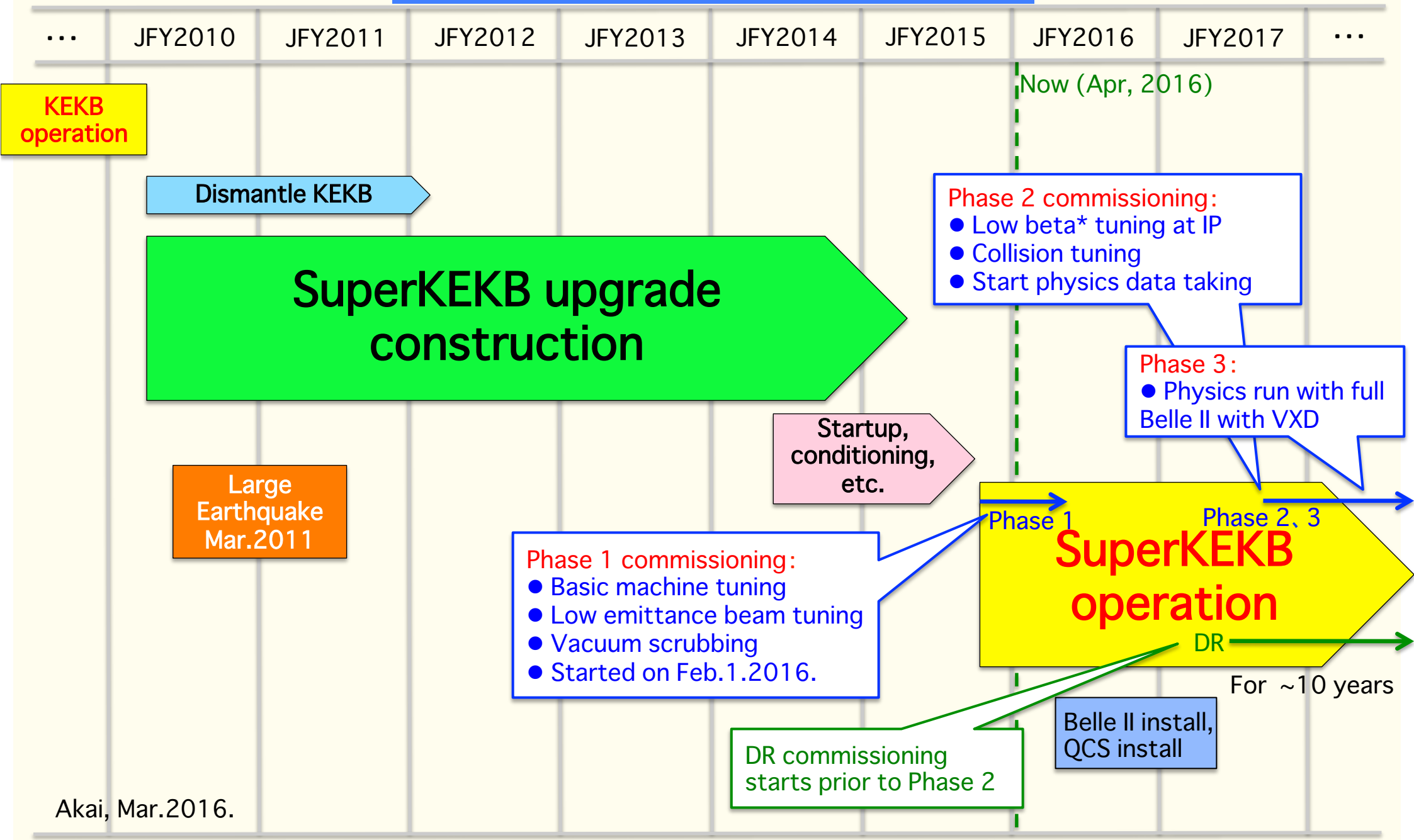
Operation

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

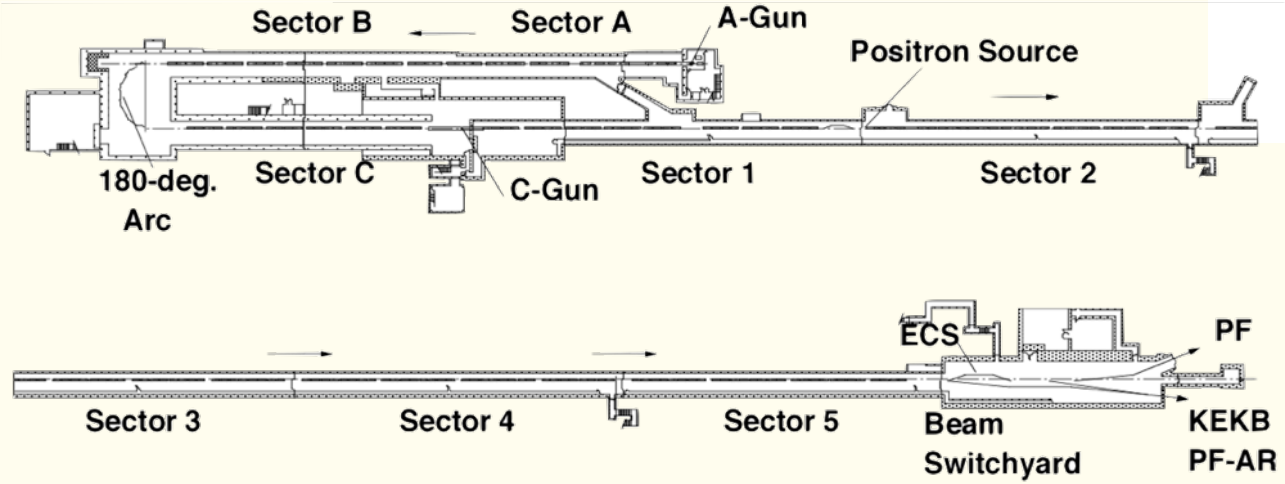
KEKB Injector Linac

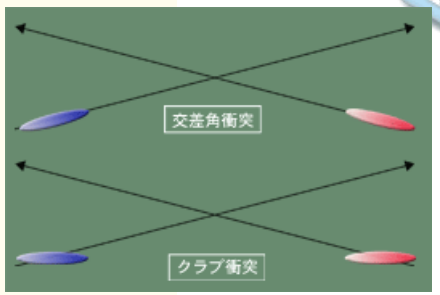
SuperKEKB Injector Linac Progress

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

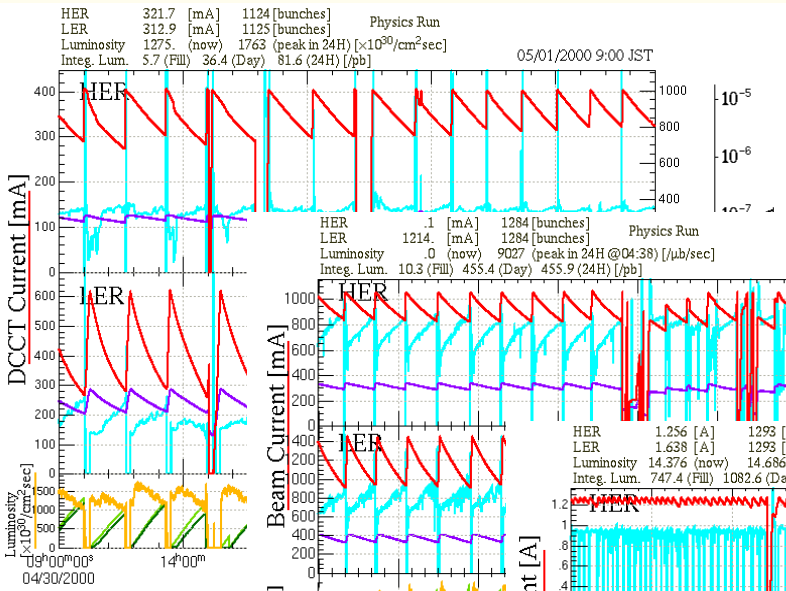




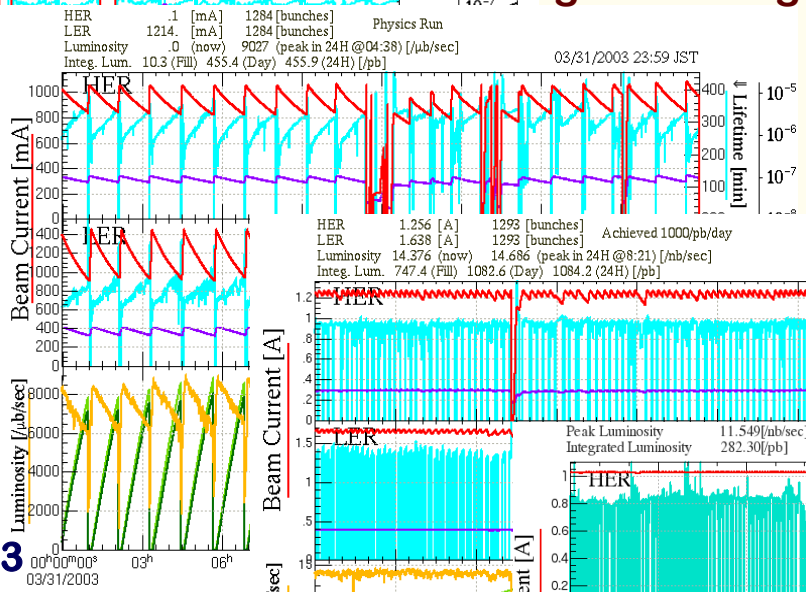
Operated with SC Crab Cavities

KEKB Operation Improvement (base of SuperKEKB)

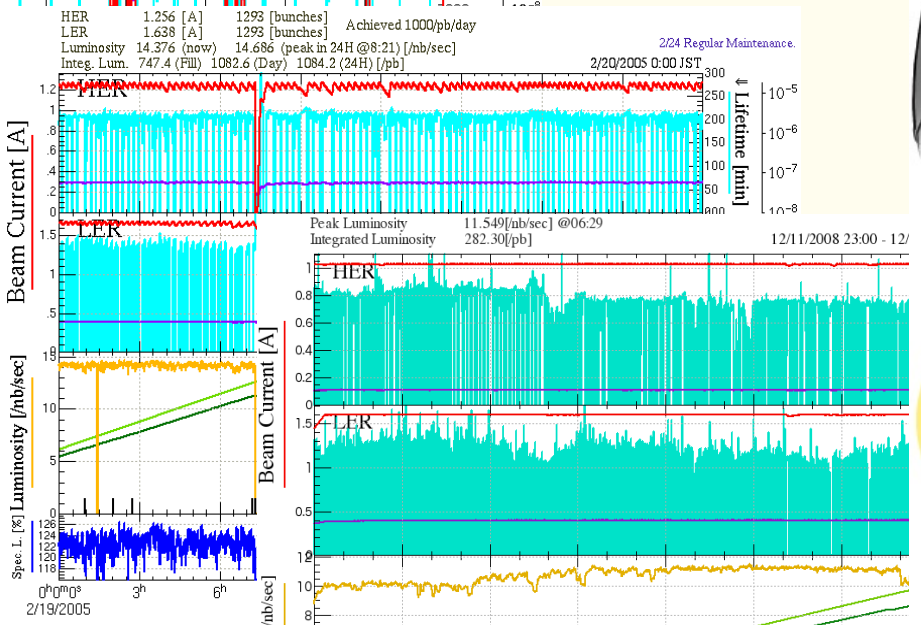
red: beam current (e-, e+)
purple: vacuum (e-, e+)
yellow: luminosity
green: integrated luminosity



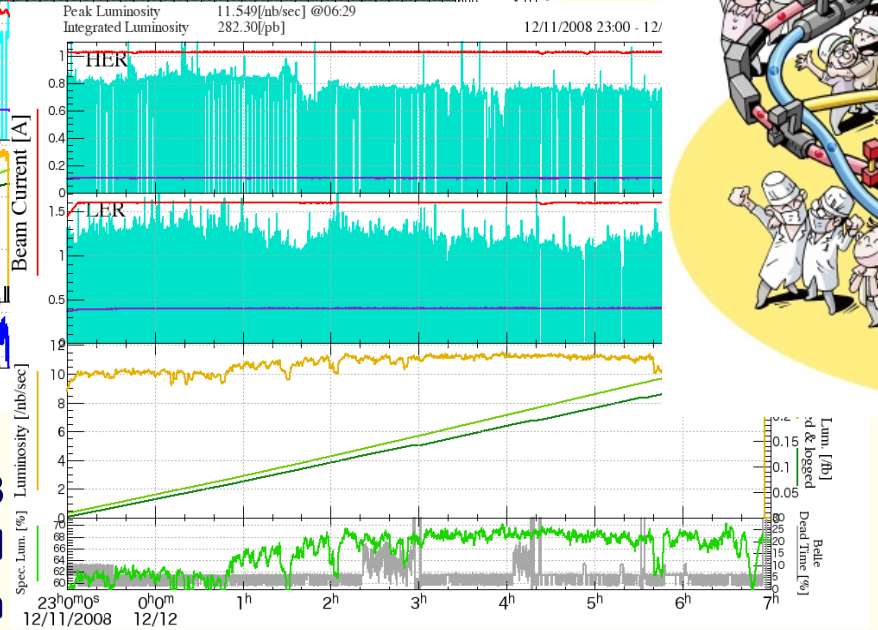
May.2000



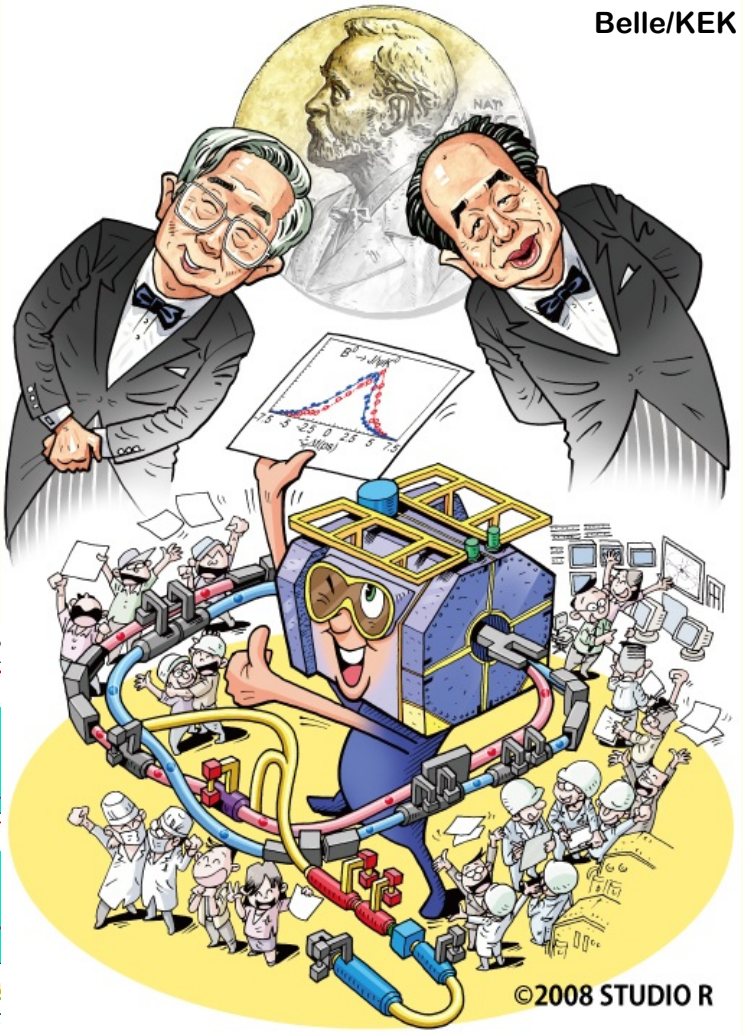
Apr.2003
Dual Bunch e+



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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  - Emittance preservation
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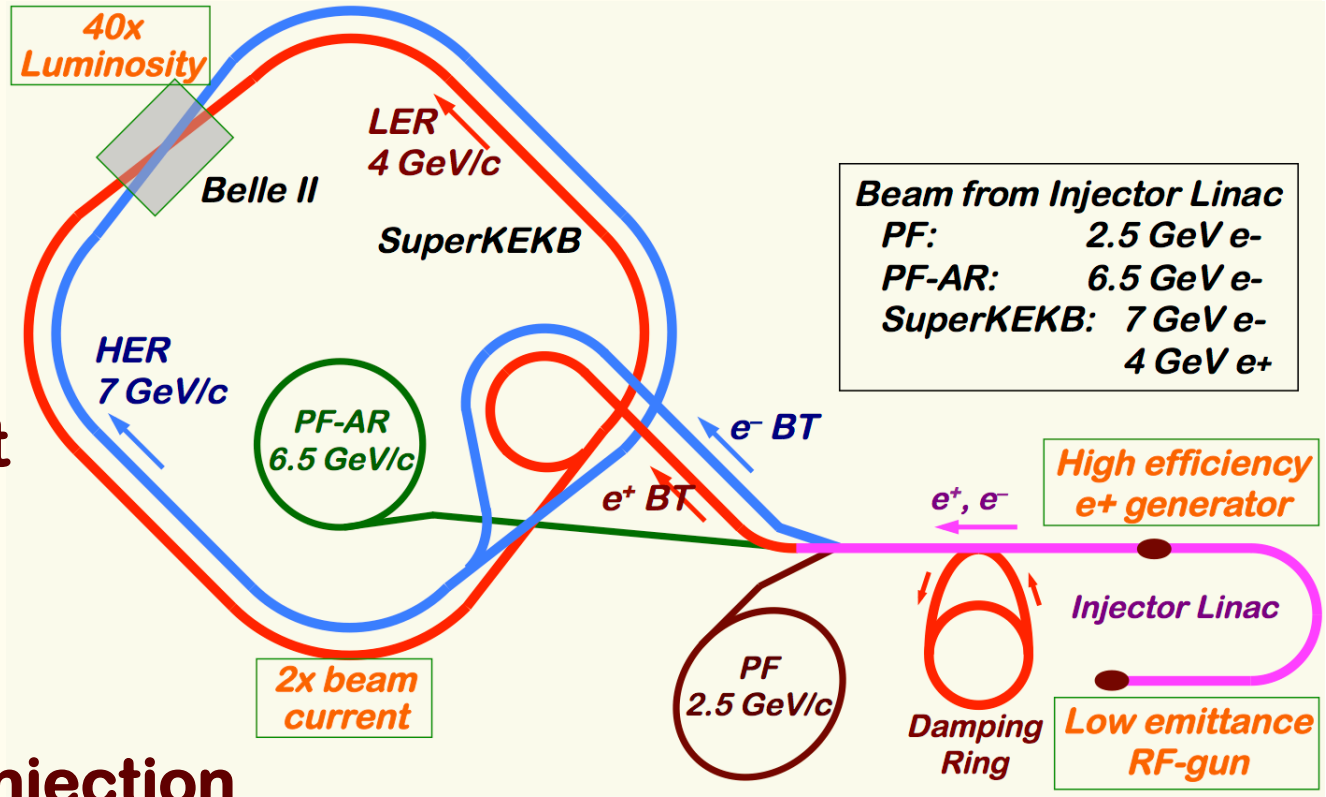


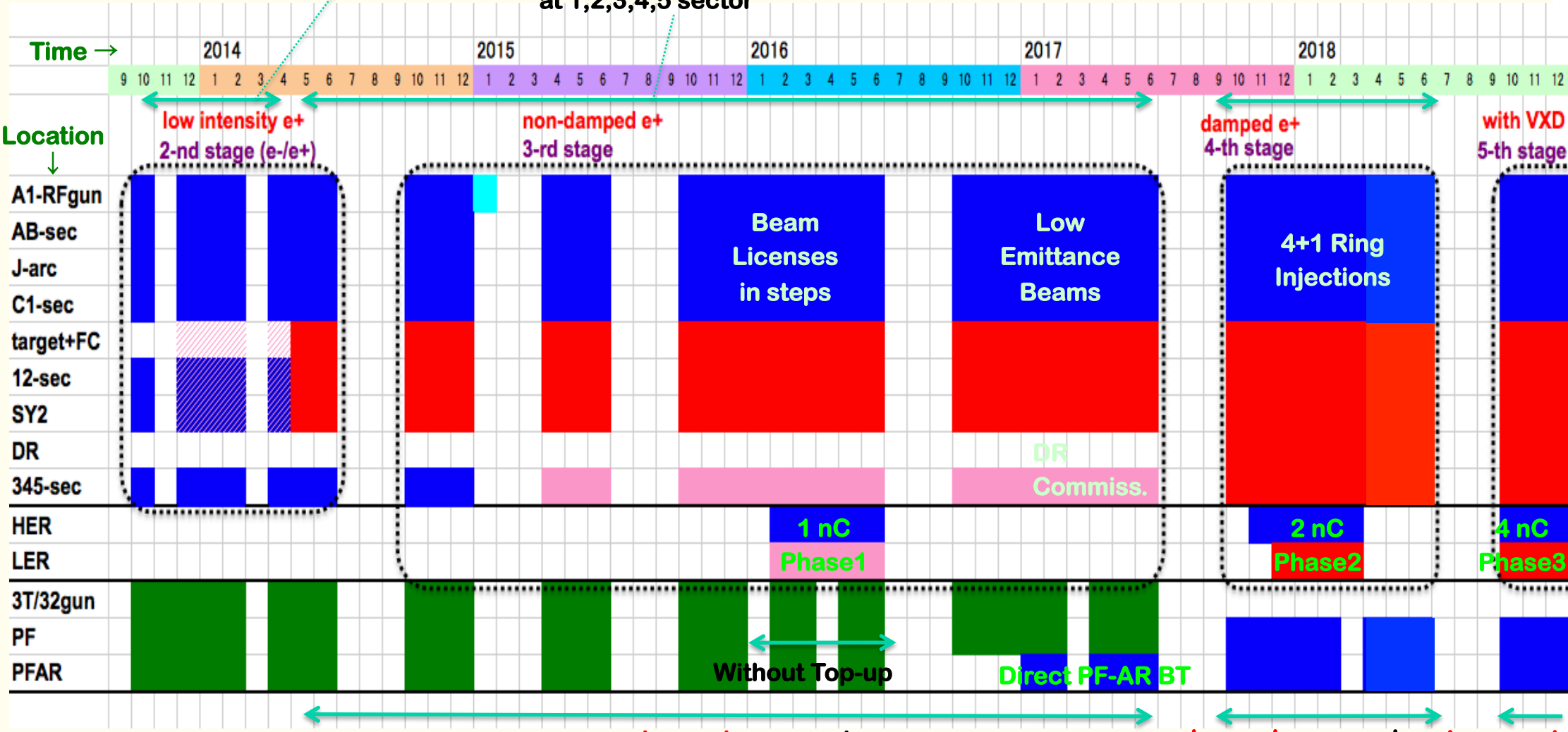
Linac Schedule Overview

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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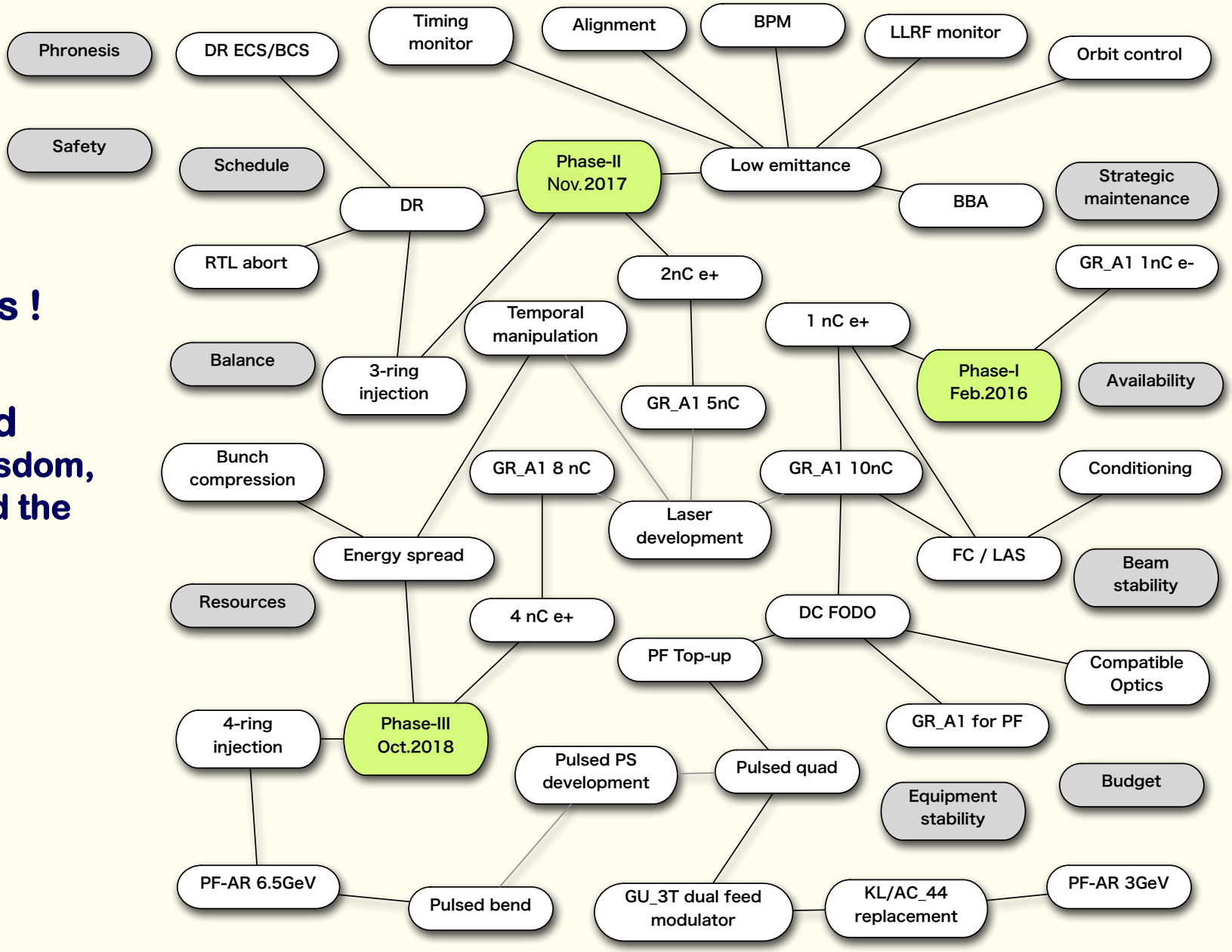
Repetition rate	50 Hz		25 / 50 Hz		50 Hz	
Simultaneous top-up injection (PPM)	3 rings (KEKB e–/e+, PF)		No top-up		4+1 rings (SuperKEKB e–/e+, DR, PF, PF-AR)	

Subjects to Consider

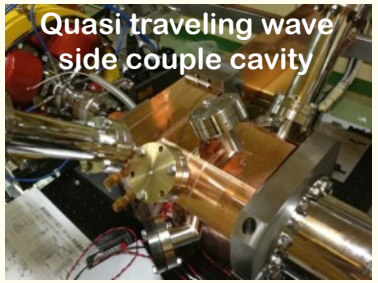
- **Have to consider too many subjects !**
- **Phronesis needed**
  (Greek: Practical wisdom, Ability to understand the Universal Truth)

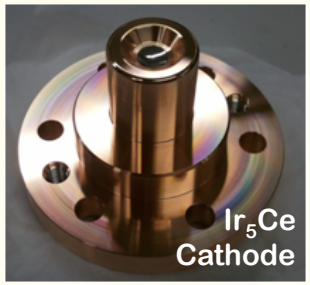


Linac Upgrade Progress towards SuperKEKB (1)

High-charge low-emittance RF gun development

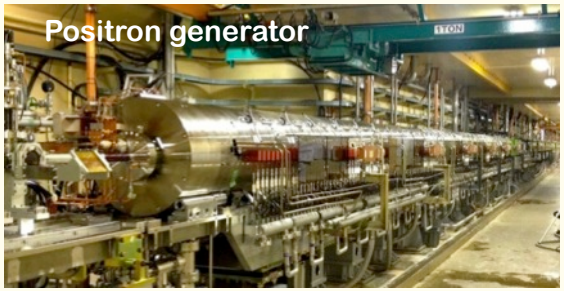
- QTWSC cavity and Ir5Ce photo cathode developments
- Laser development is underway





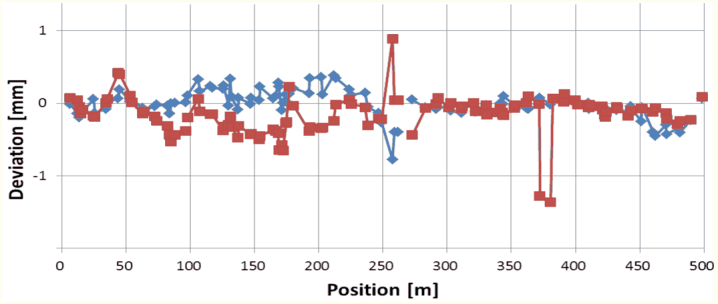
Positron generator commissioning

- 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

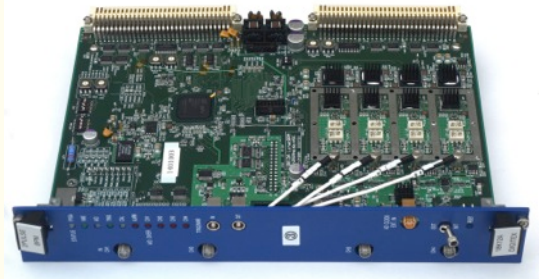


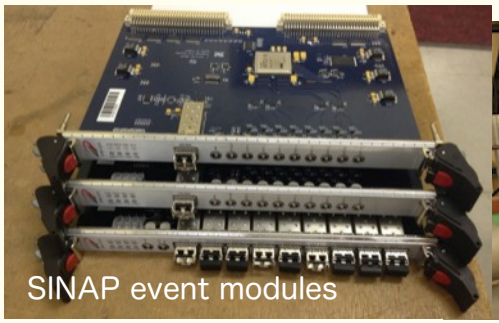
Utility upgrade during FY2014

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

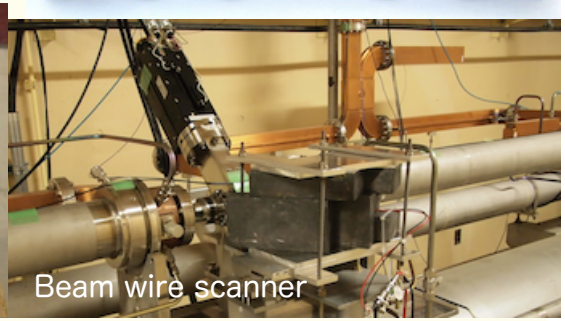
Linac Upgrade Progress towards SuperKEKB (2)

- **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



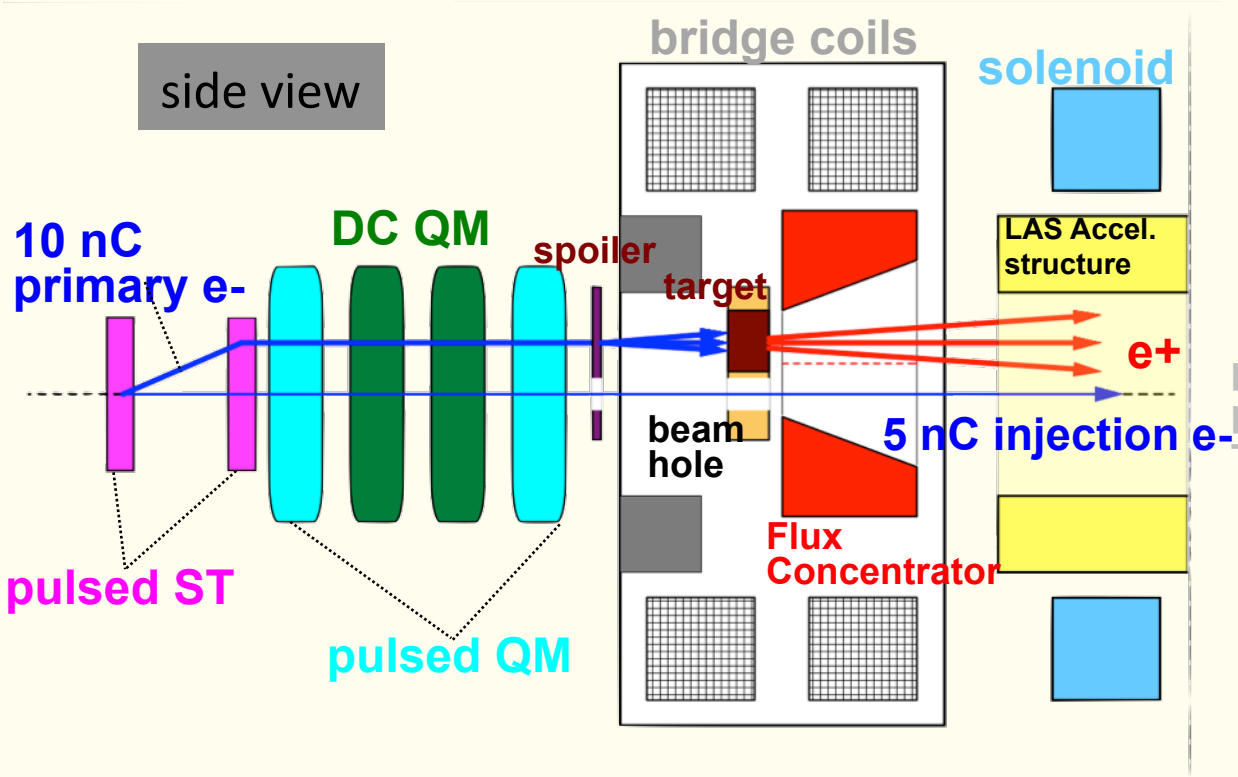


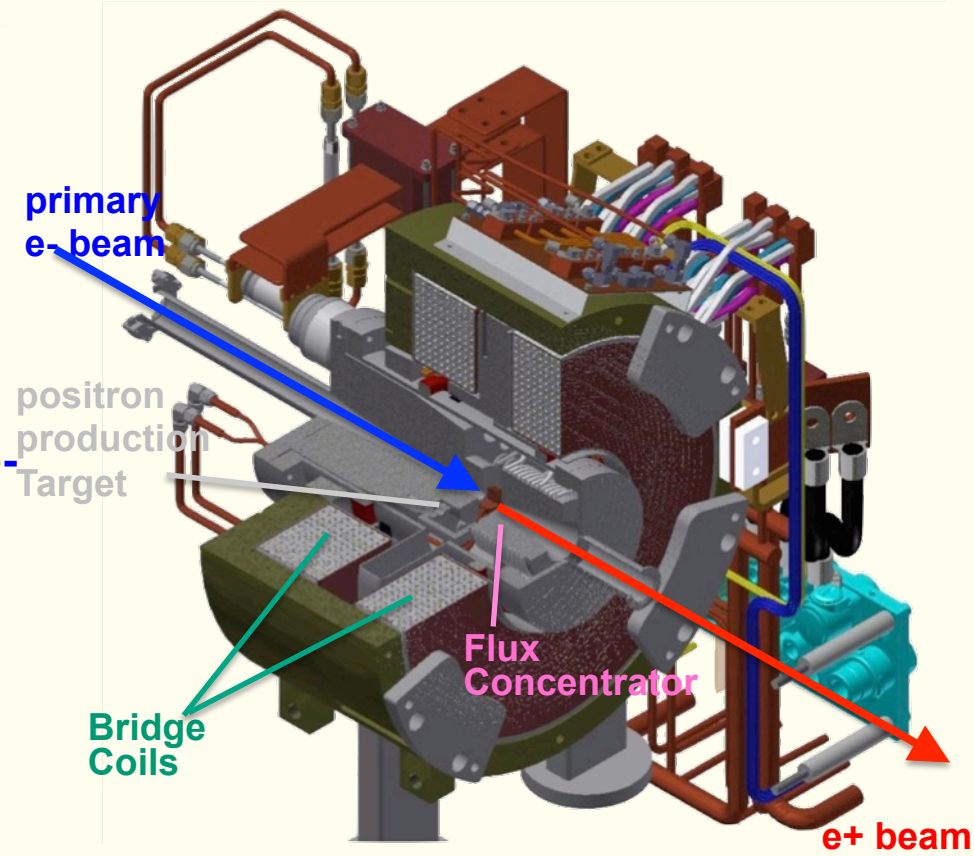
SINAP event modules



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

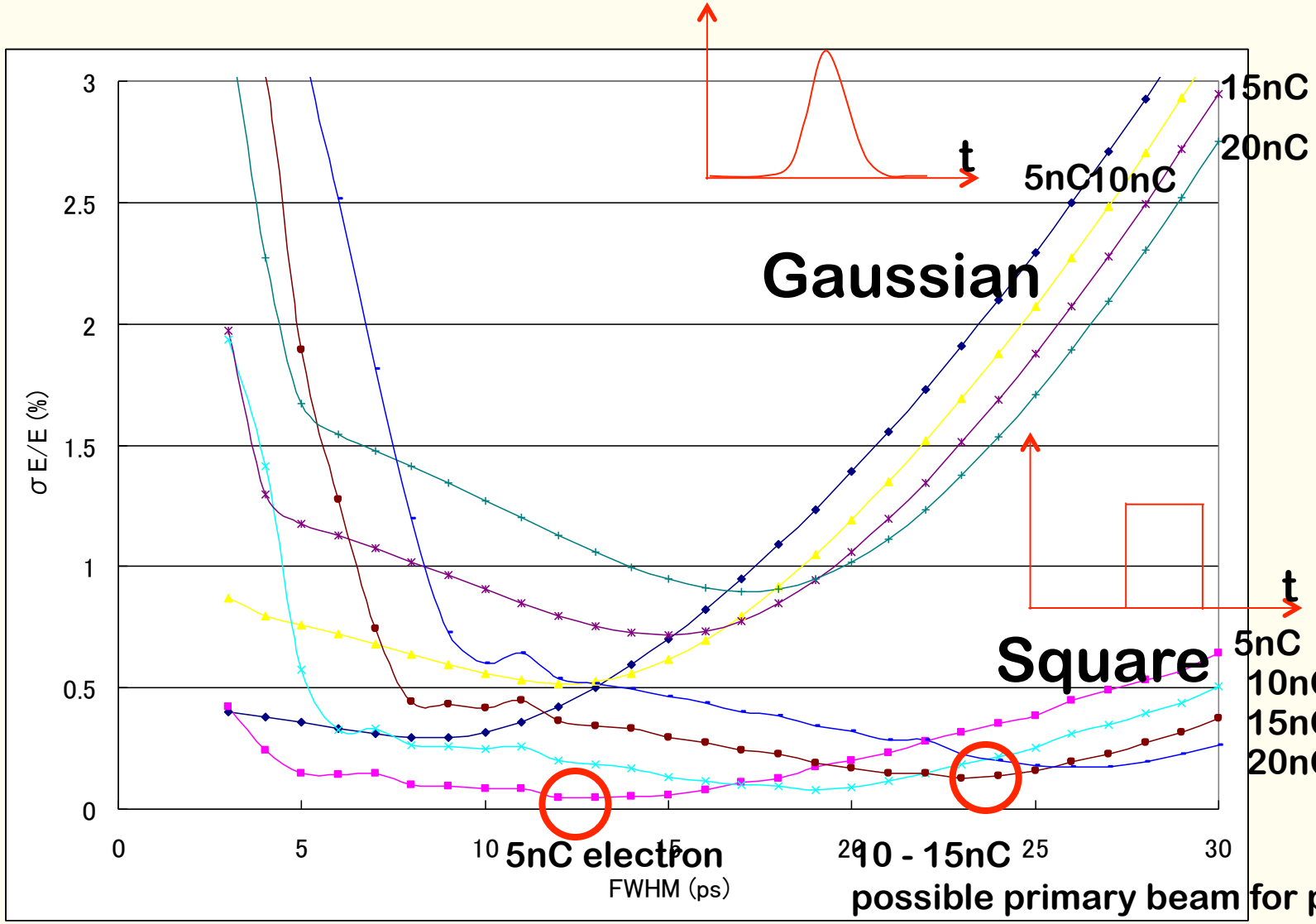
RF-Gun development strategy for SuperKEKB

- **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

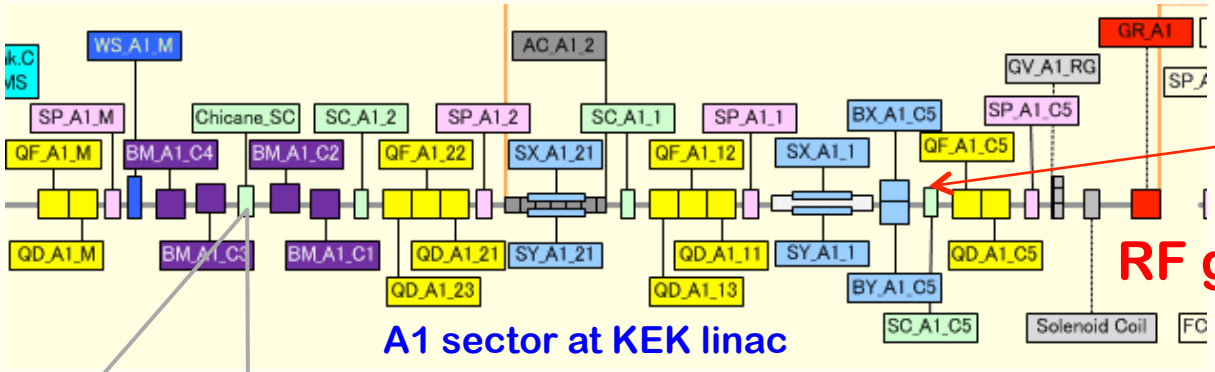
Energy spread reduction using temporal manipulation

M. Yoshida

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

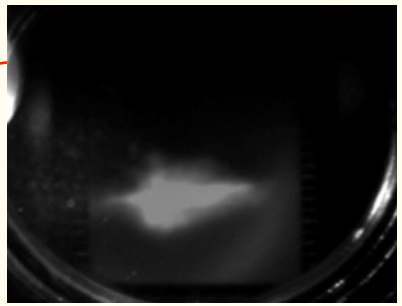


RF Gun Result Example

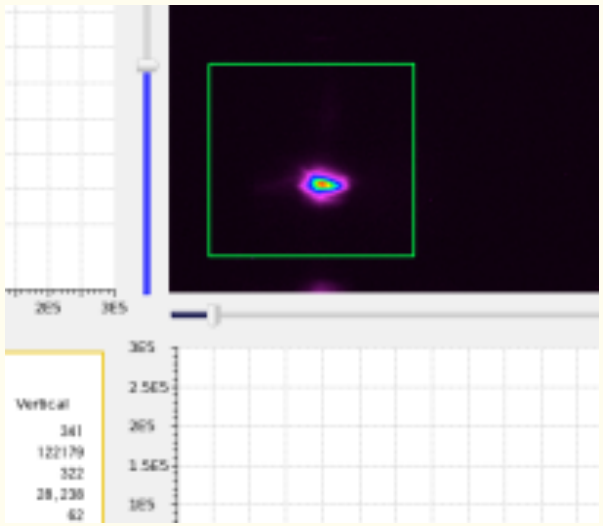


A1 sector at KEK linac

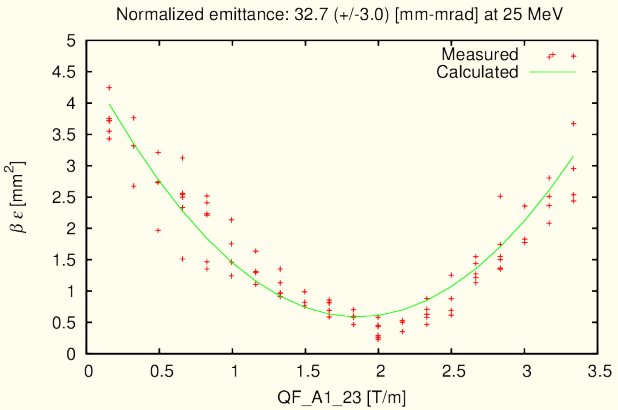
5.6 nC bunch charge was observed.

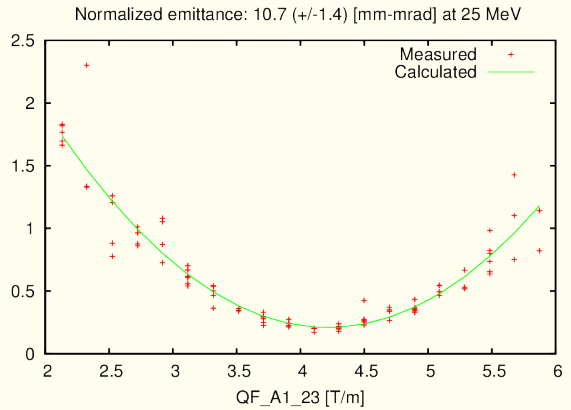


RF gun



beam size measurement for Q-scan





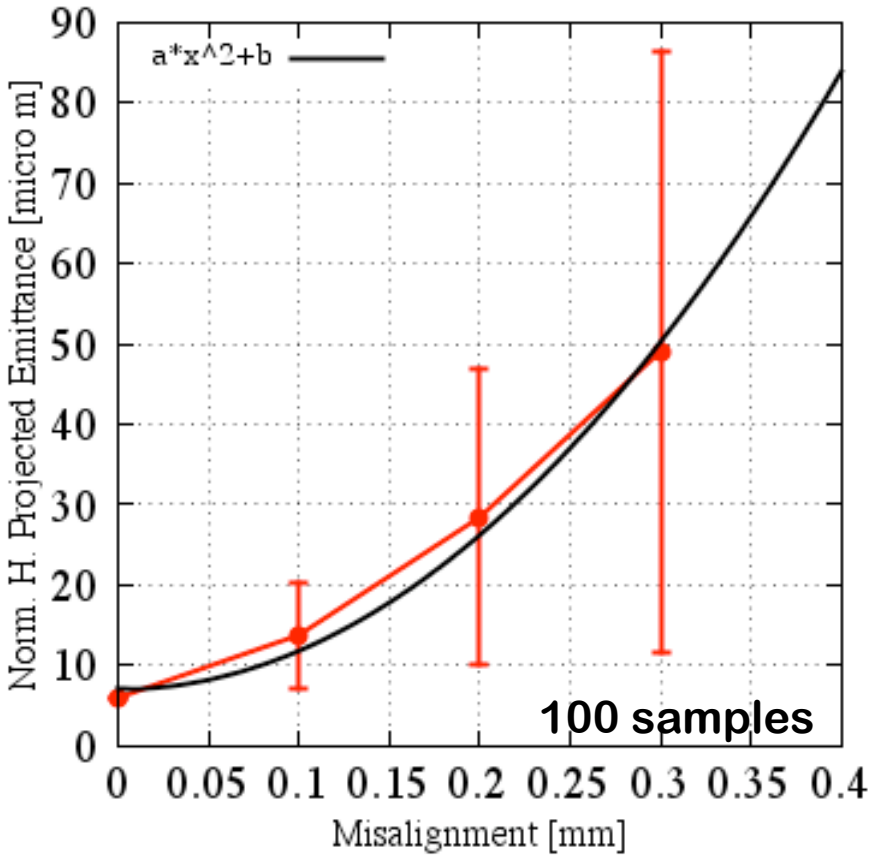
Q-scan emittance measurement

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

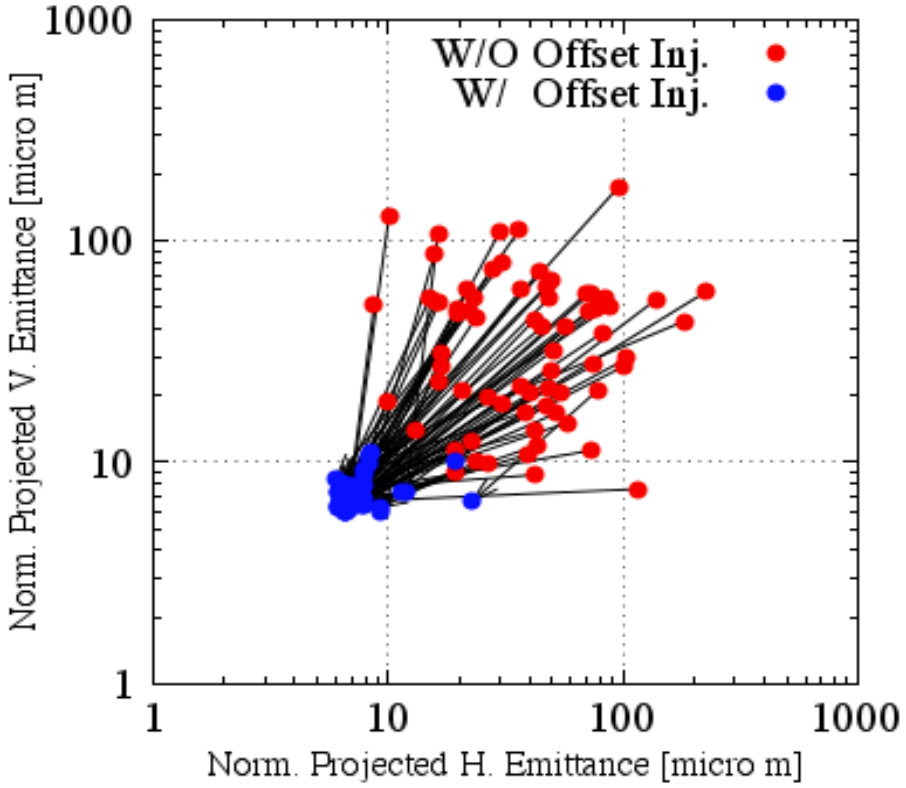
Emittance Preservation

- 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.

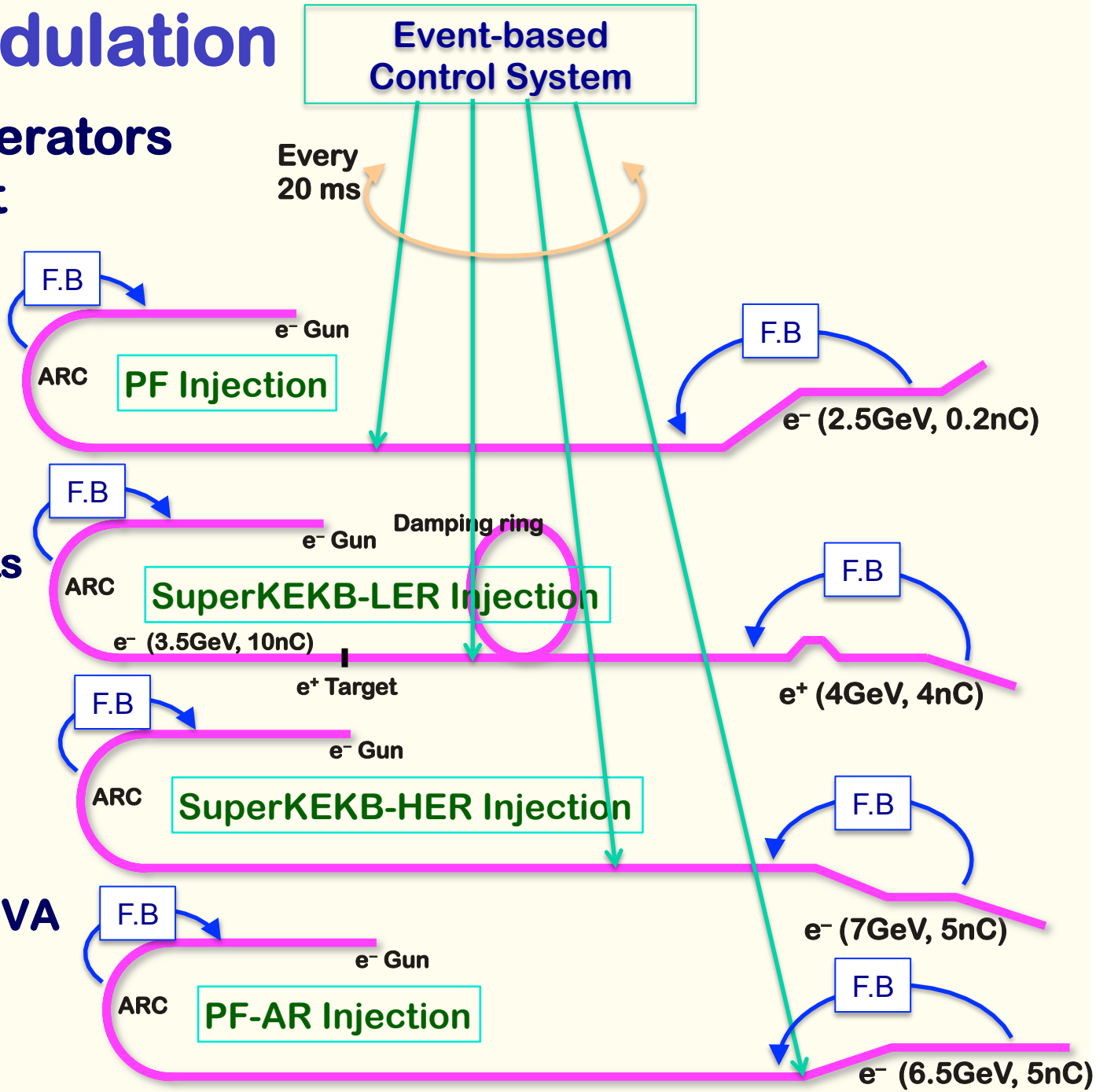
Pulse-to-pulse modulation

- **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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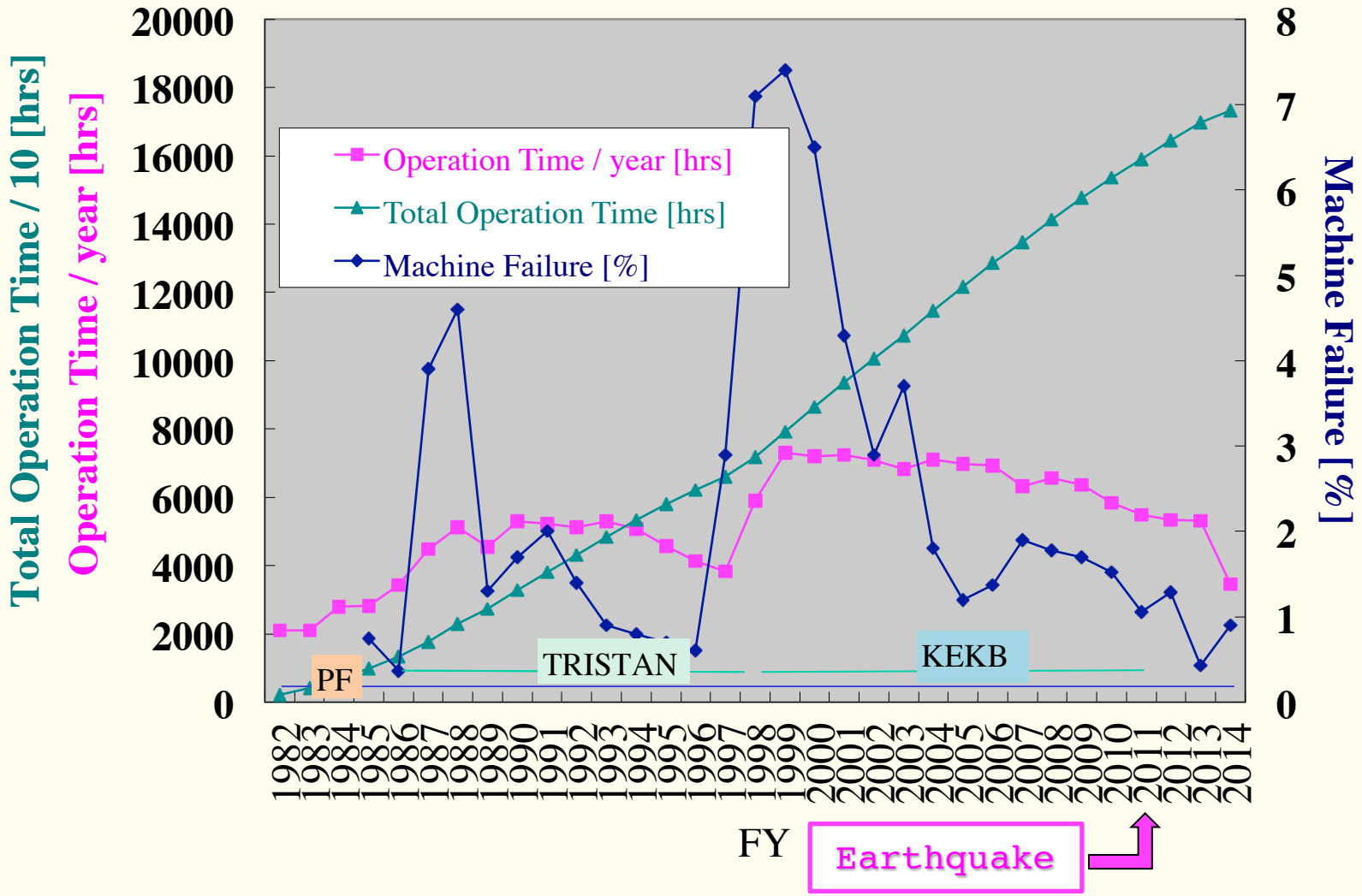
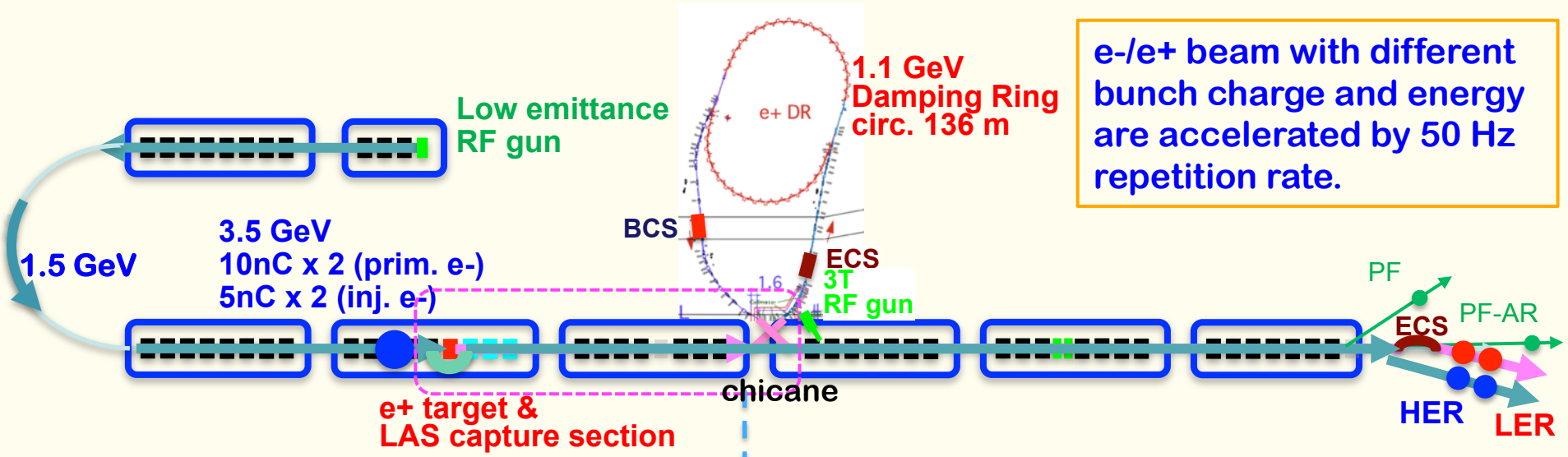
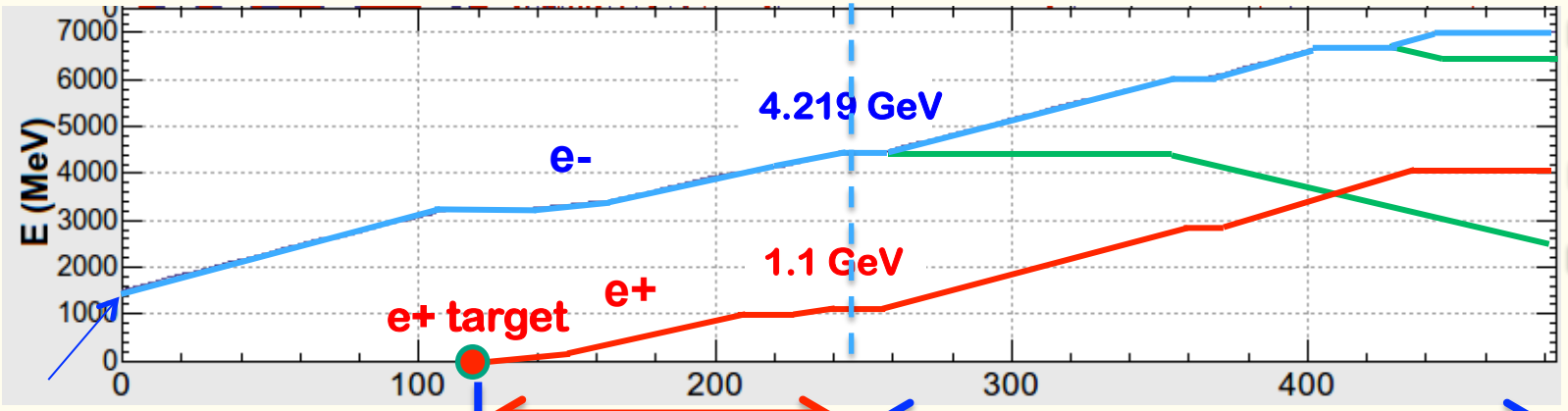


Routine maintenance was important to improve the reliability (Failure rate includes rf trips)

Injector Linac Energy Management



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

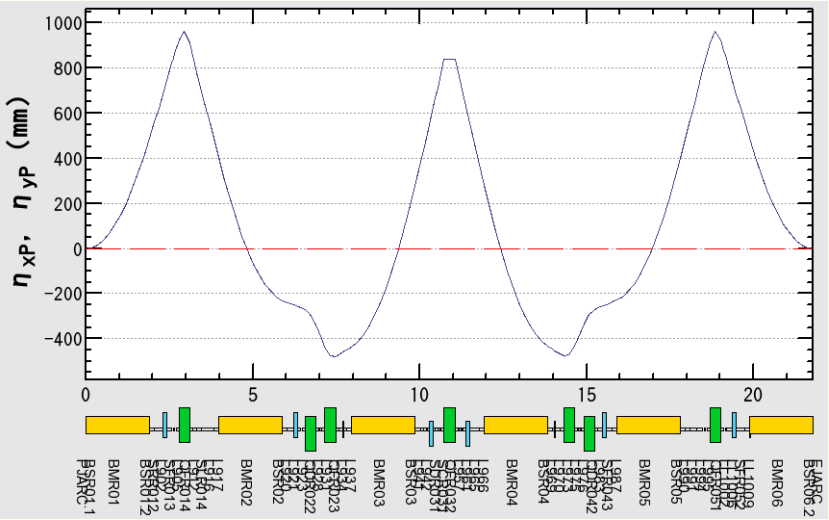


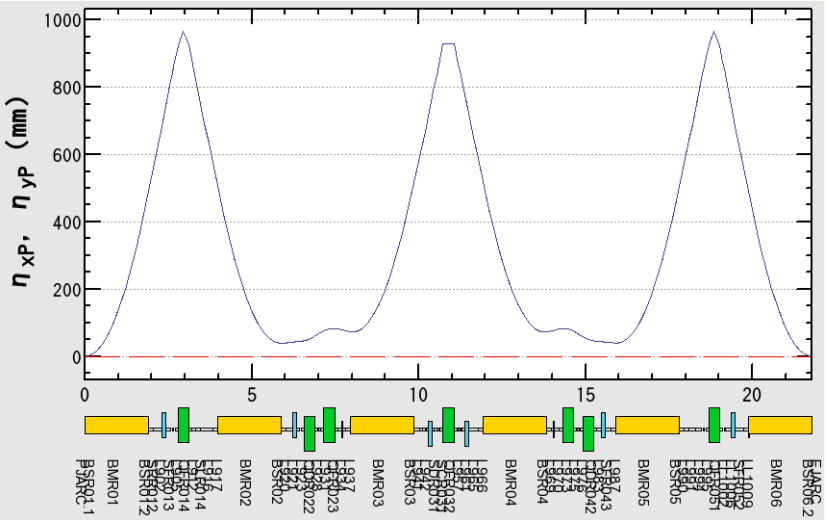
5 nC x2
HER: 7GeV e-
PF-AR: 6.5GeV e-
5nCx1
LER: 4GeV e+
4 nCx2
PF: 2.5 GeV e-
0.1nCx1

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

Beam Manipulation Study

At 180-deg arc

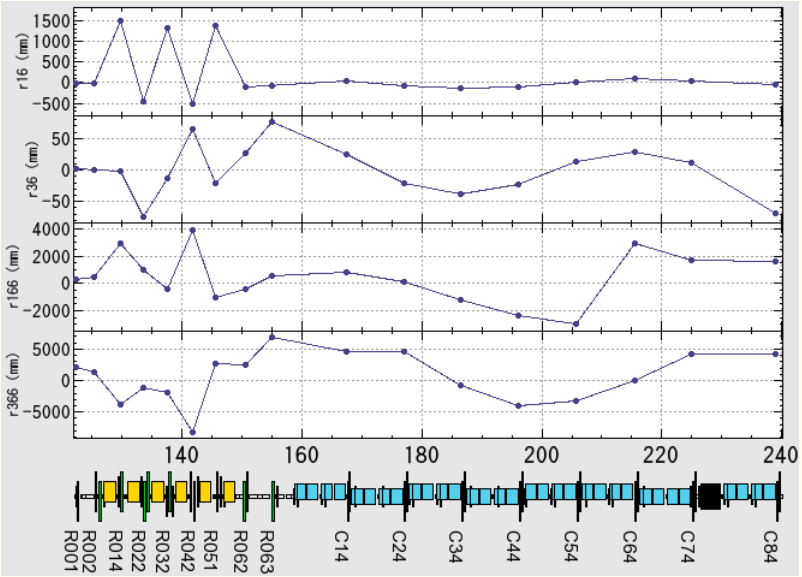


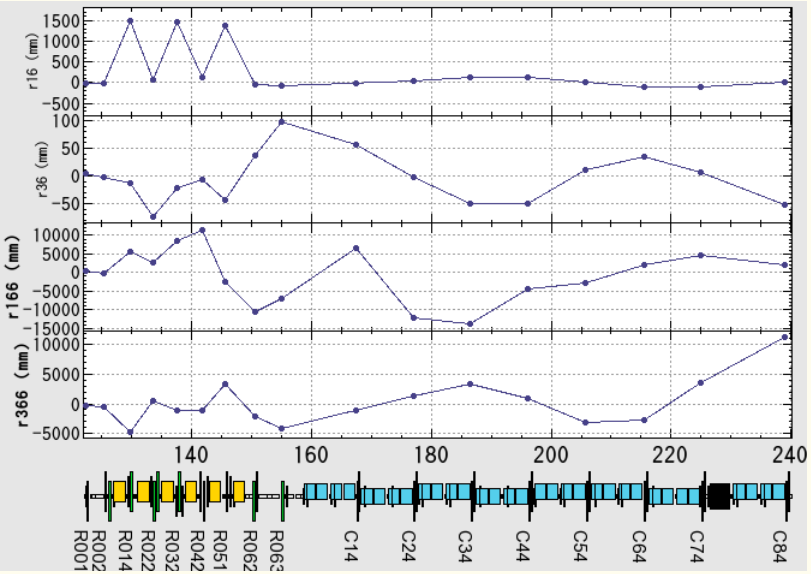


Optics design with R56 = 0 and -0.6 for bunch compression

BPM will be replaced with 5-times better resolution

Streak camera should follow

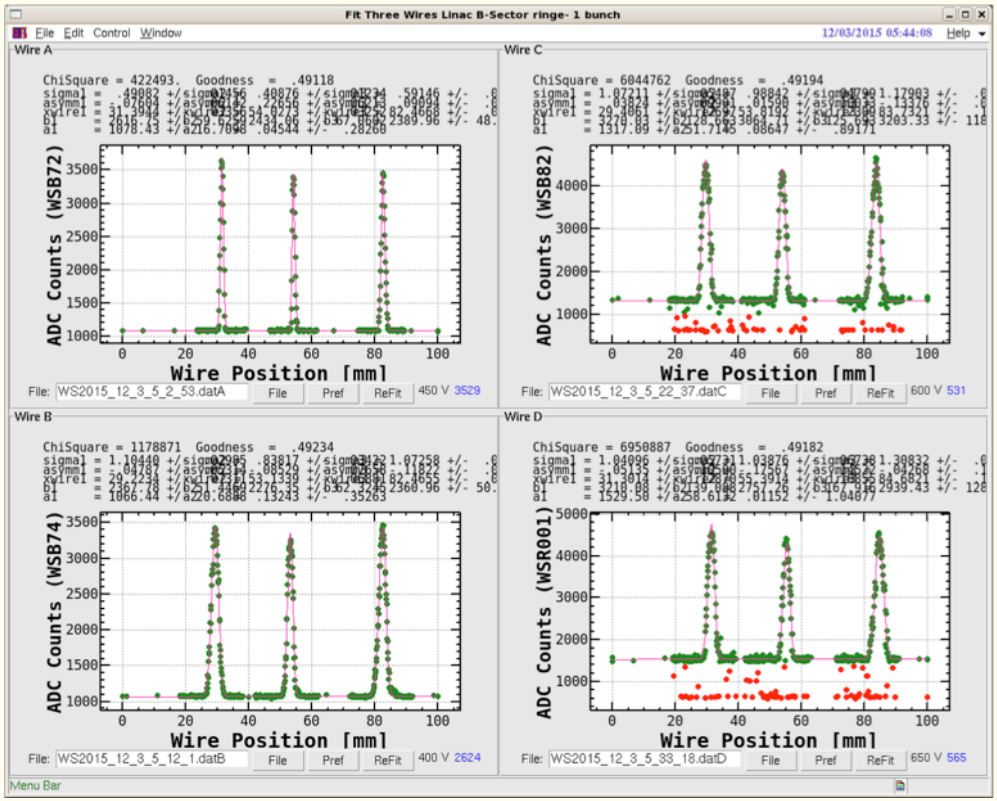


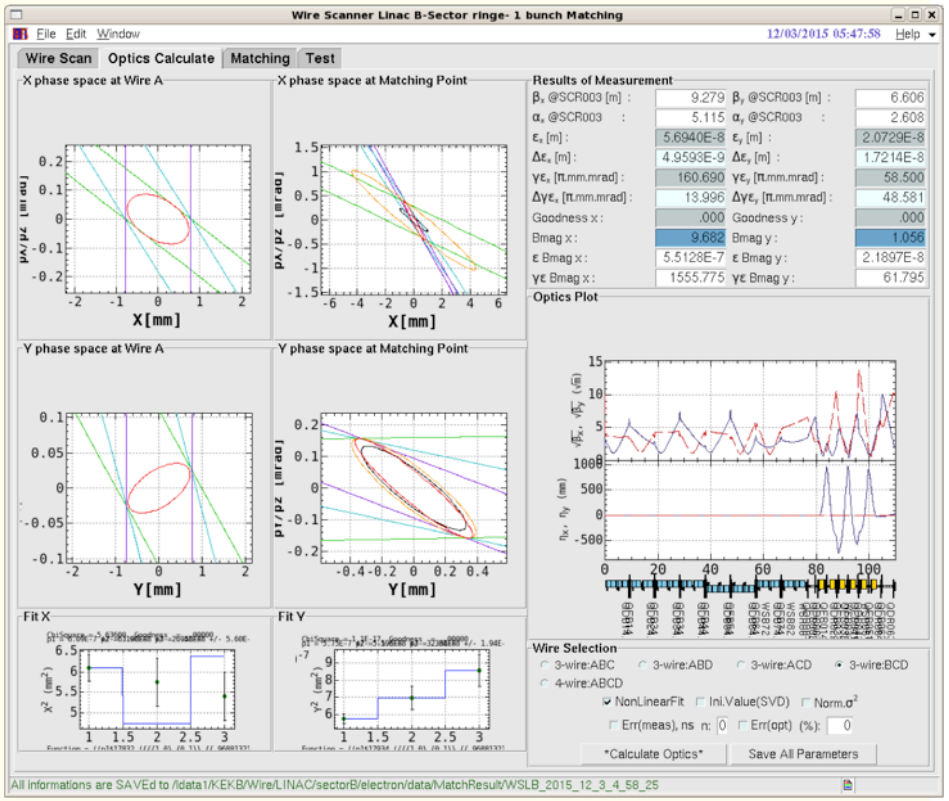


Measurement of dispersion functions for R56 = 0 and -0.6
Soon with timing measurement by streak camera

Linac Optics Measurement / Management

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

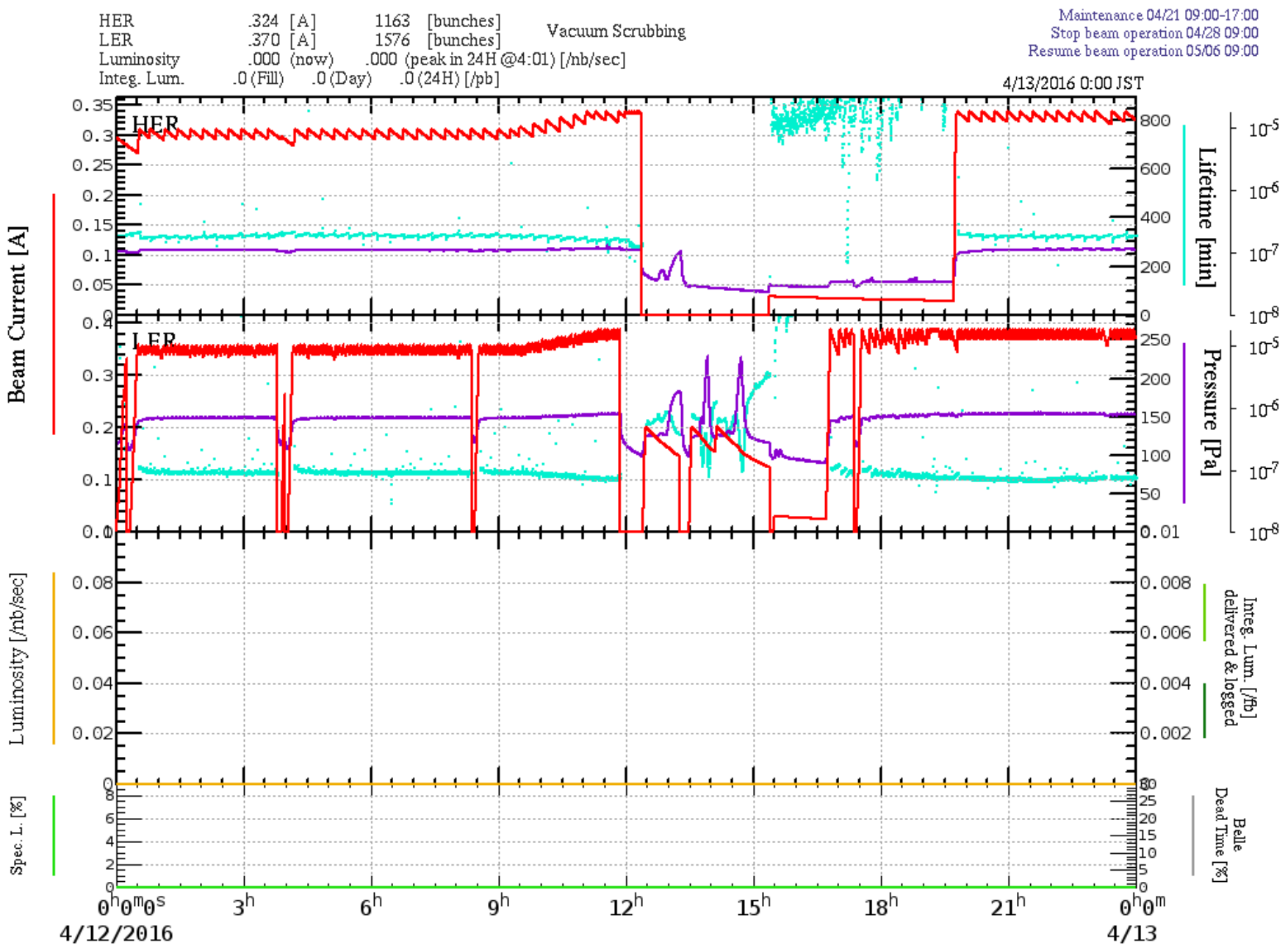




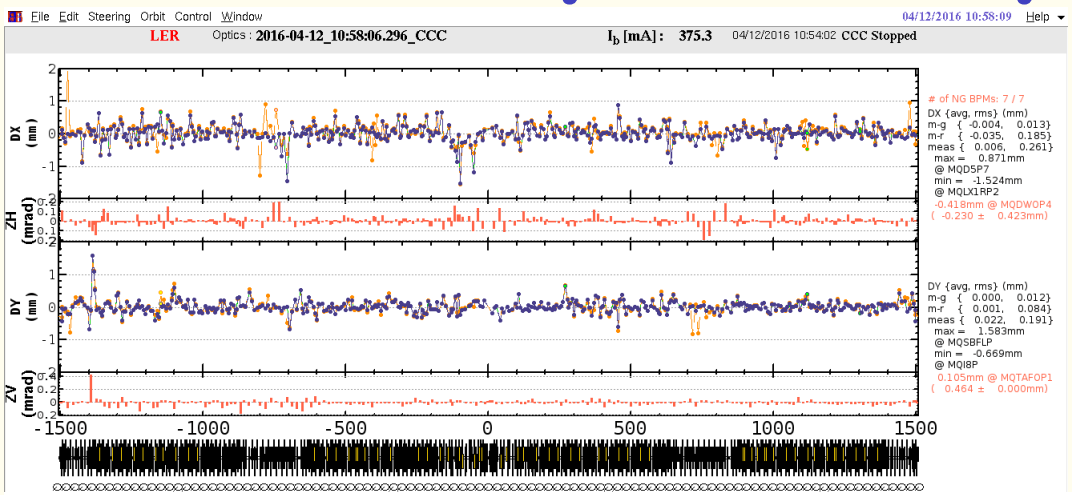
- Wire scanner measurements performed everyday
- If necessary (if Bmag is large), re-matching is performed by operator
- For pulse-to-pulse vertical measurement, X-band deflector will be installed

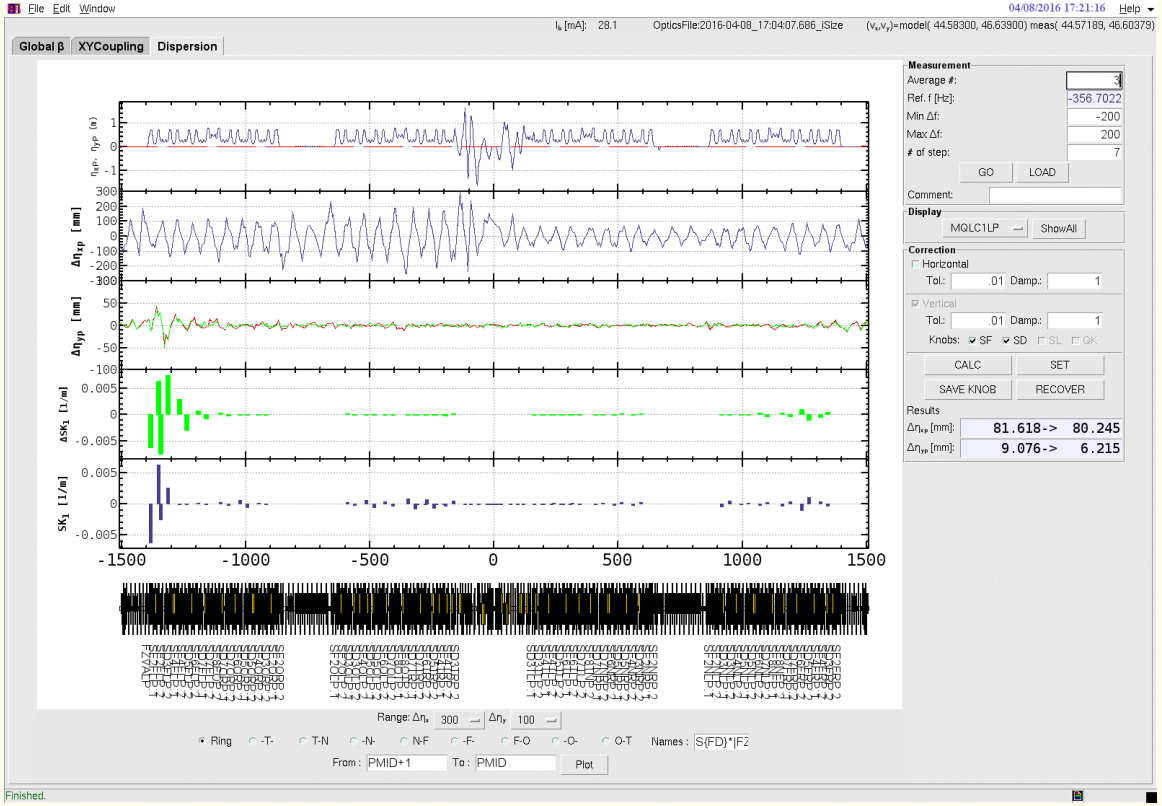
Typical Phase-1 Daily Operation

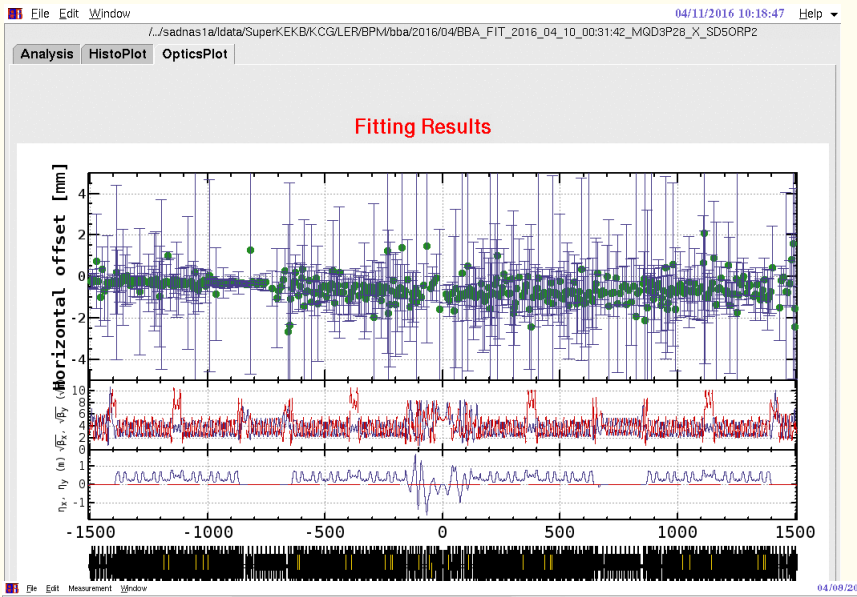
- More than 300mA stored this week in the both e-/e+ rings
- In daytime increases beam current, and performs optics studies
- In night time continue vacuum scrubbing
- No collision yet
- Collision expected at the end of 2017

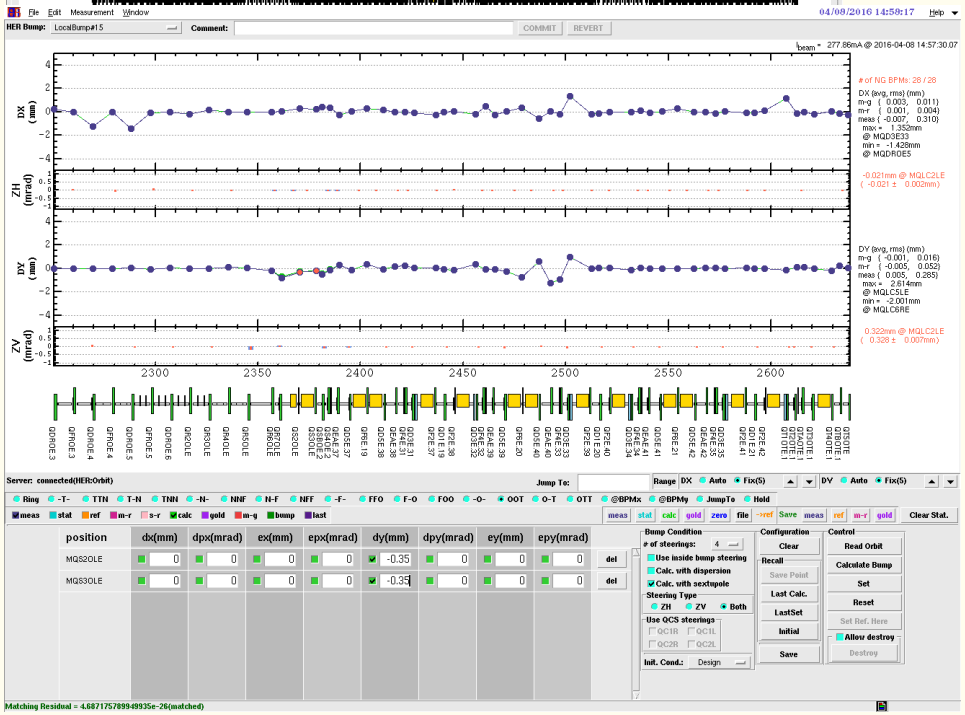


Examples of Operational Panels







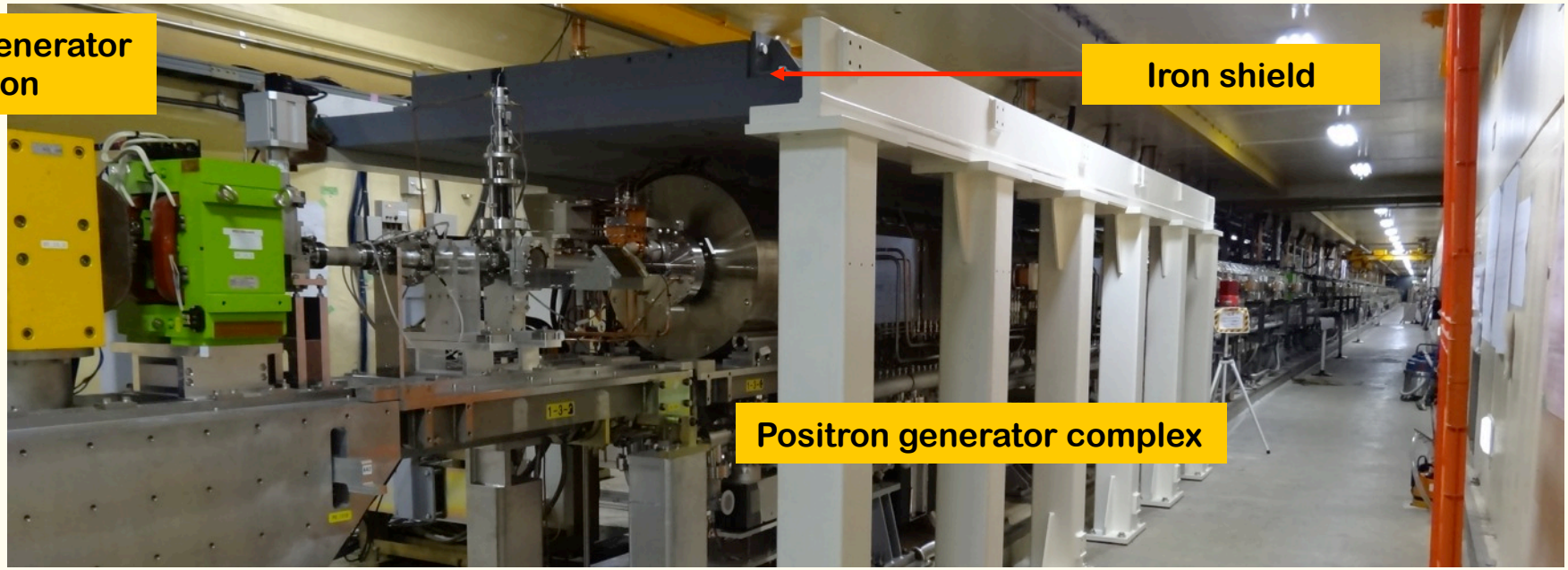


Radiation control licenses

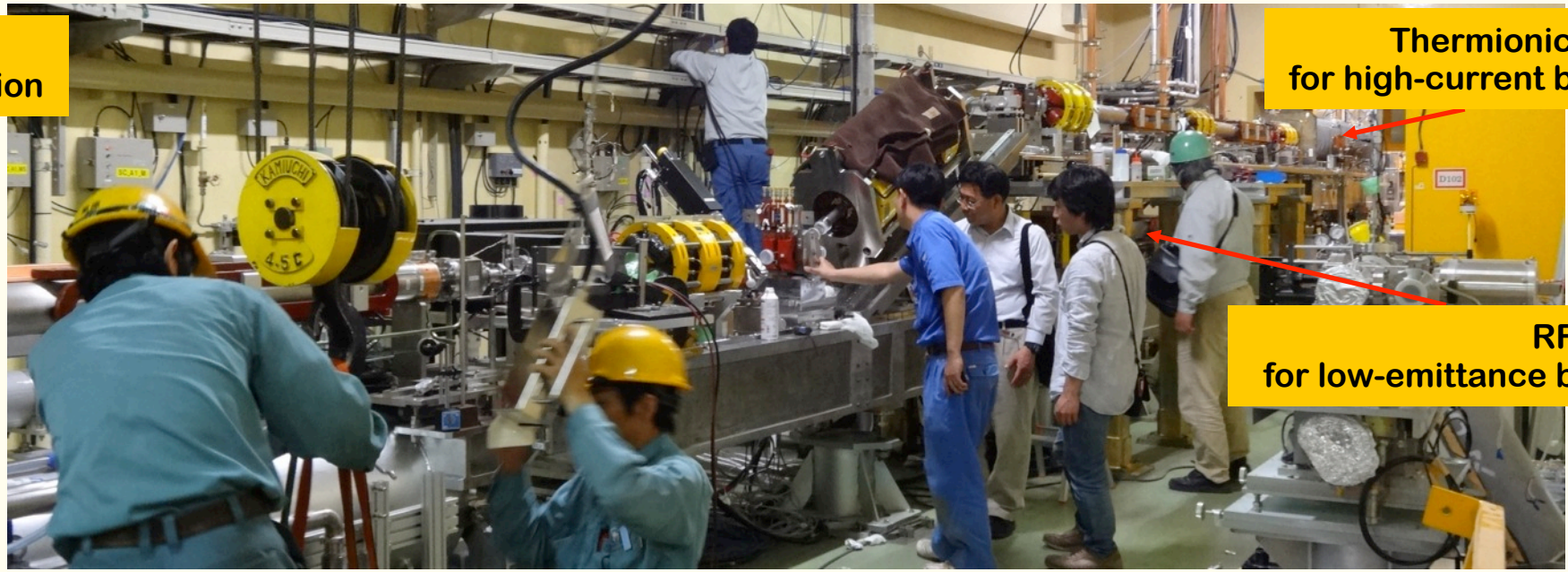
- Step-by-step upgrade of beam limits
- Final goal in linac is 1250/625 nA before/after target
- License applications
  - Fall.2013. 10 nA at #28 dump, 1250 nA at #A2 dump
  - Spring 2014. New utility rooms, 50 nA at #61 straight dump
  - Jun.2015. 200 nA at #15 target
  - Early 2016. 800 nA at #15 target, 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

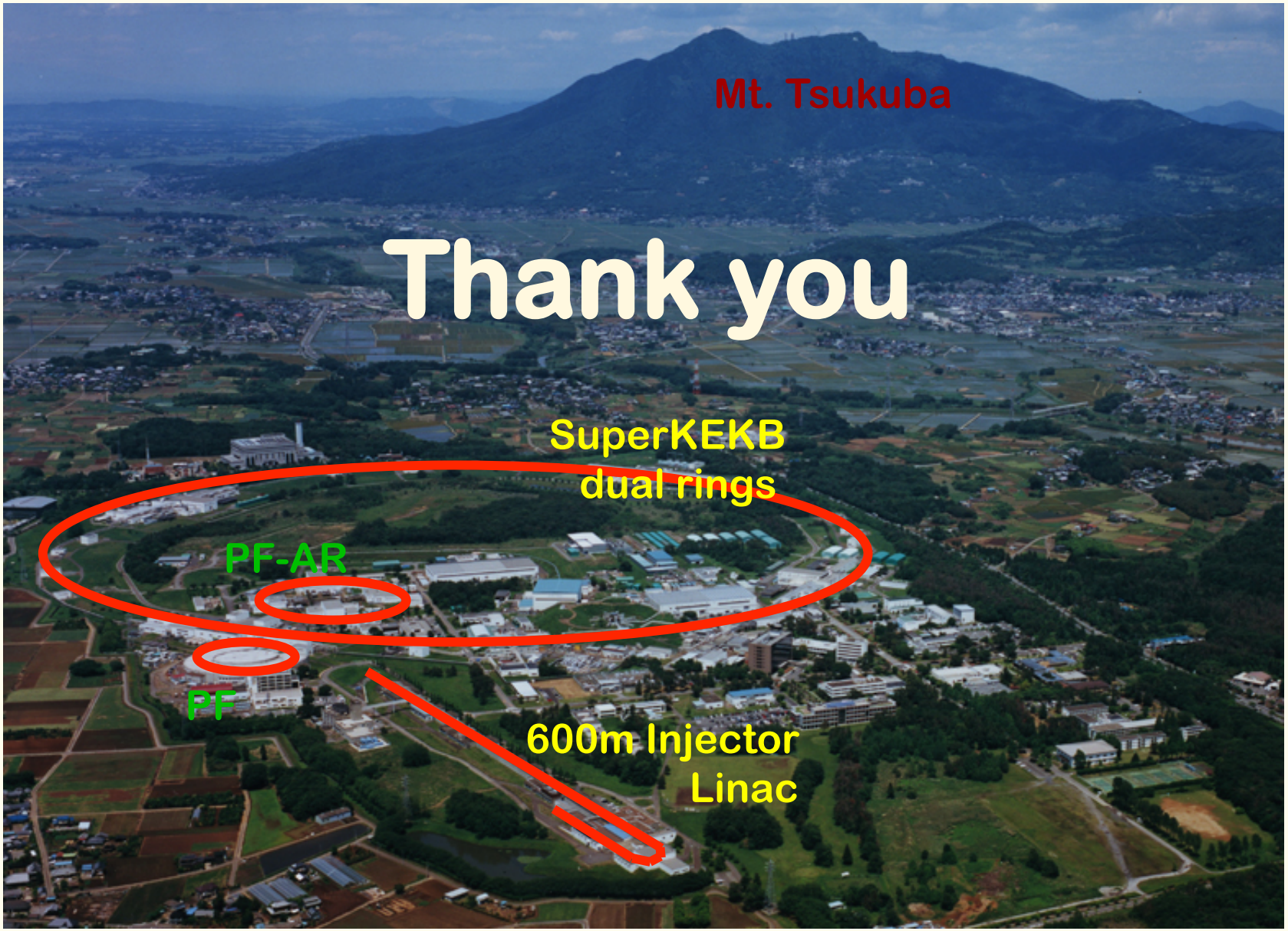


Guns at #A1 region



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

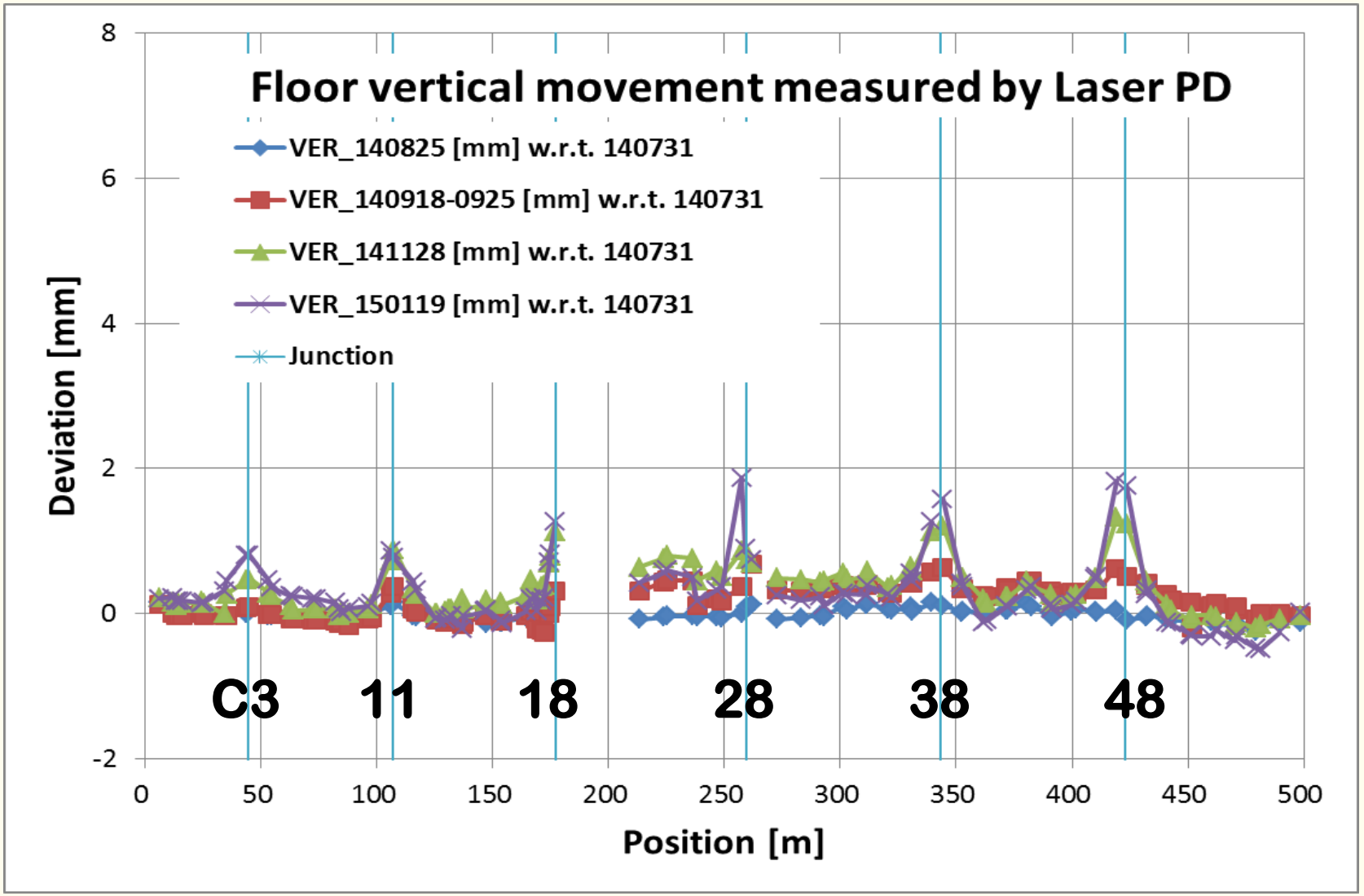


Conference papers at <http://www-linac.kek.jp/linac/>

Floor vertical movement

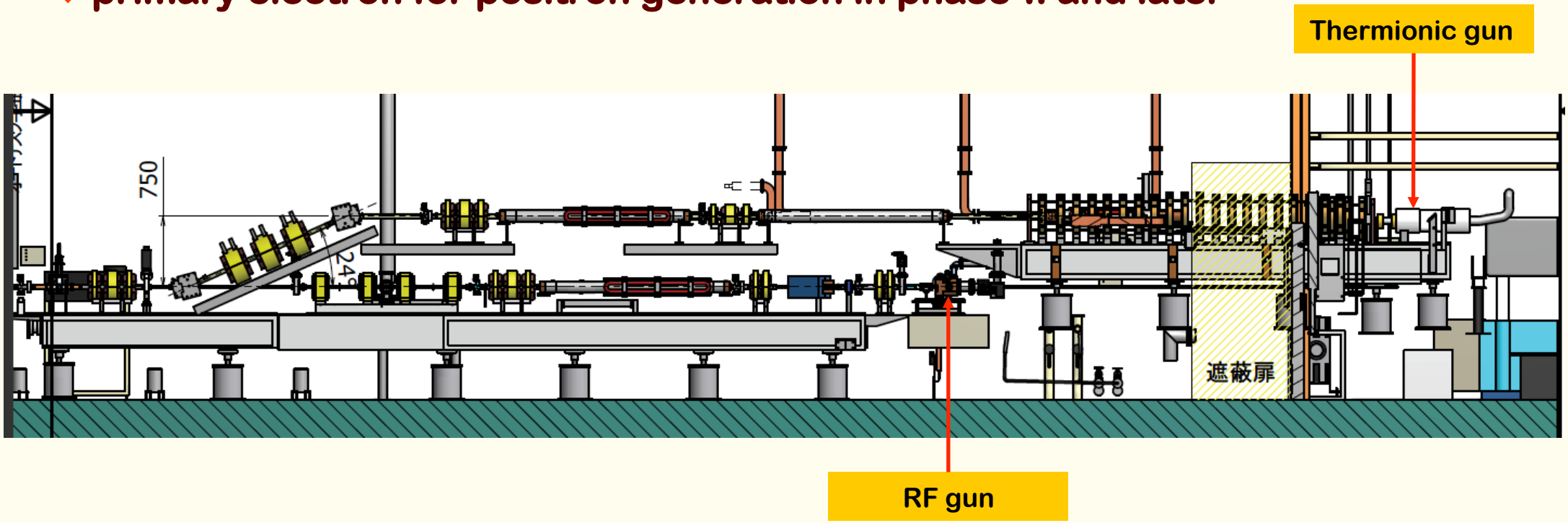
in a half year from summer to winter

Higo et al.



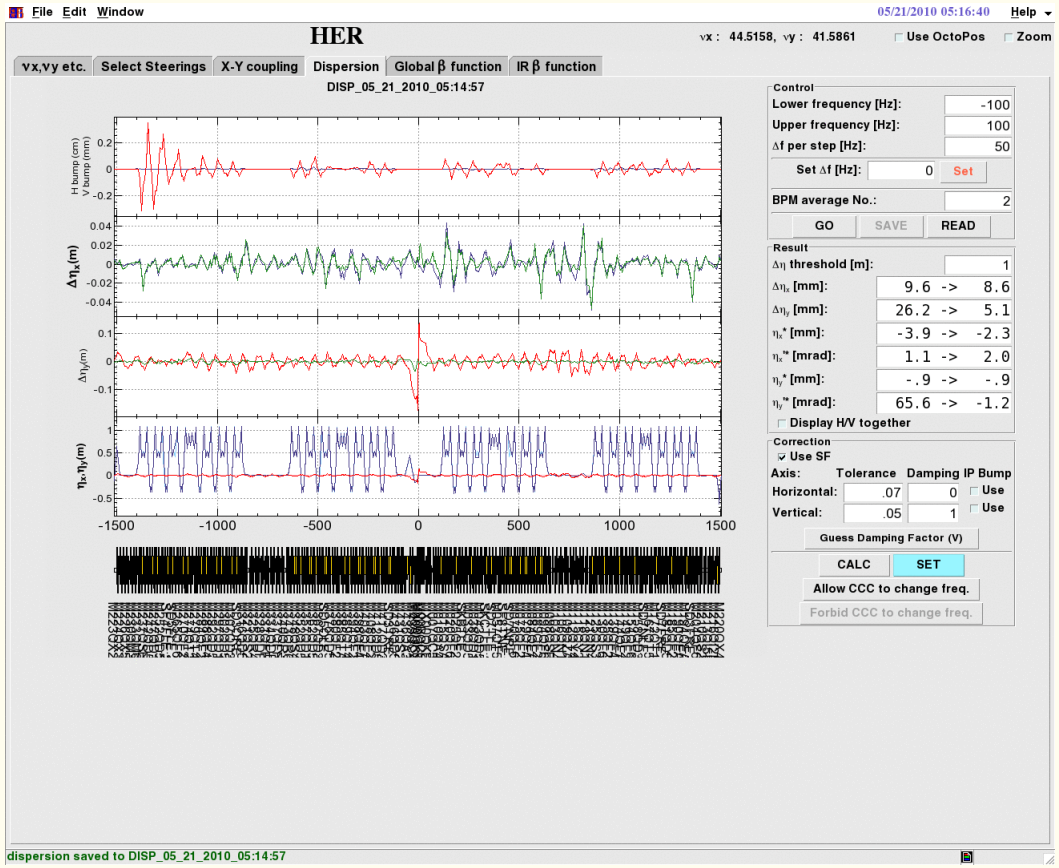
Preparation of Thermionic Gun

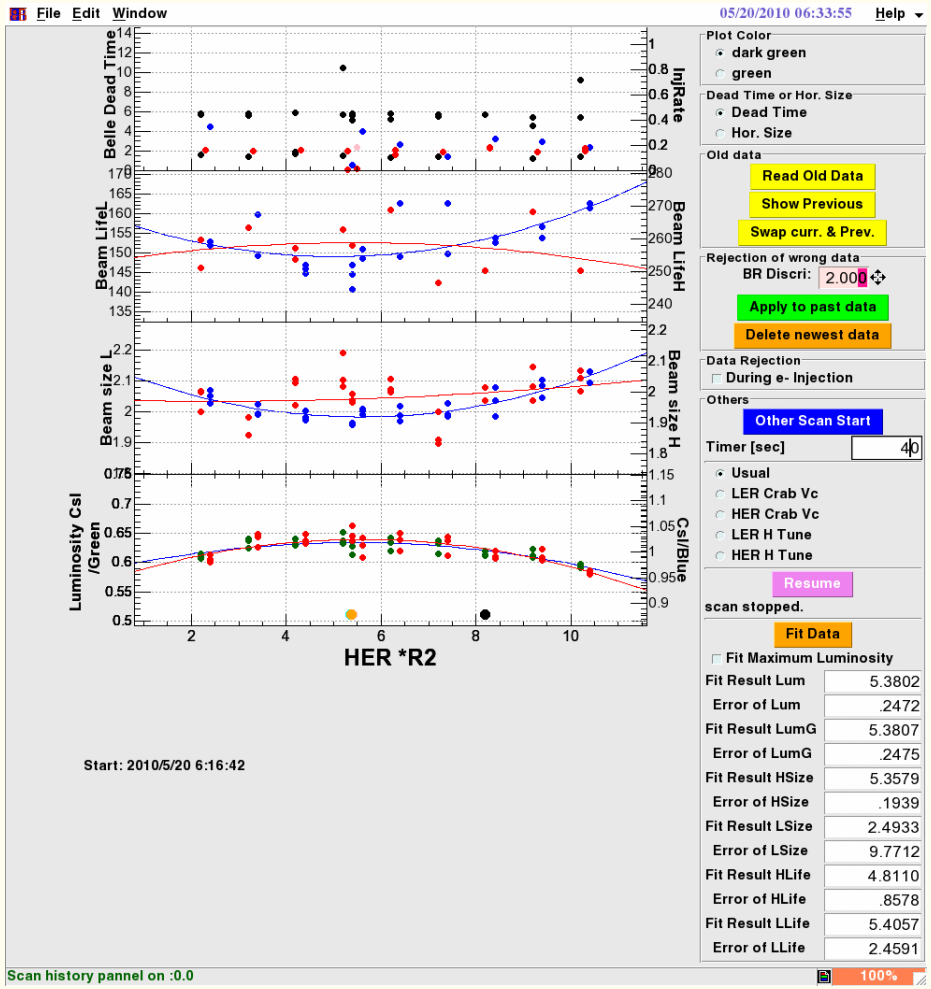
- **Refurbished and recommissioned**
  - Raise by 75cm not to conflict with straight RF-gun
    - As well as angled RF-gun
  - ~ Jun.2015.
- **Beside RF gun, thermionic gun may serve**
  - electrons in phase-I
  - primary electron for positron generation in phase-II and later



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