# Injector Commissioning

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The 20th KEKB Accelerator Review Committee, Feb. 23-25, 2015

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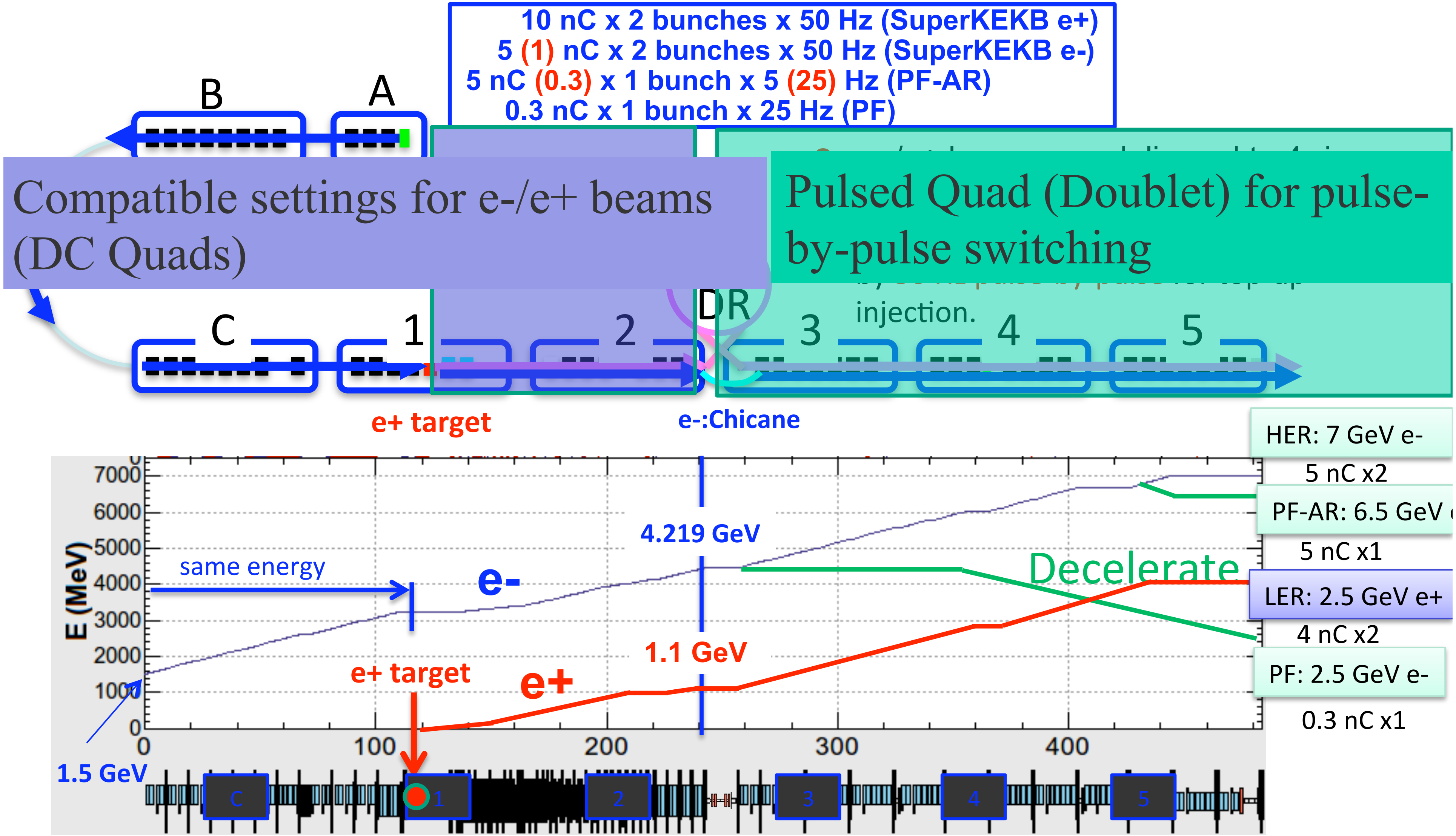
# Injector upgrade overview

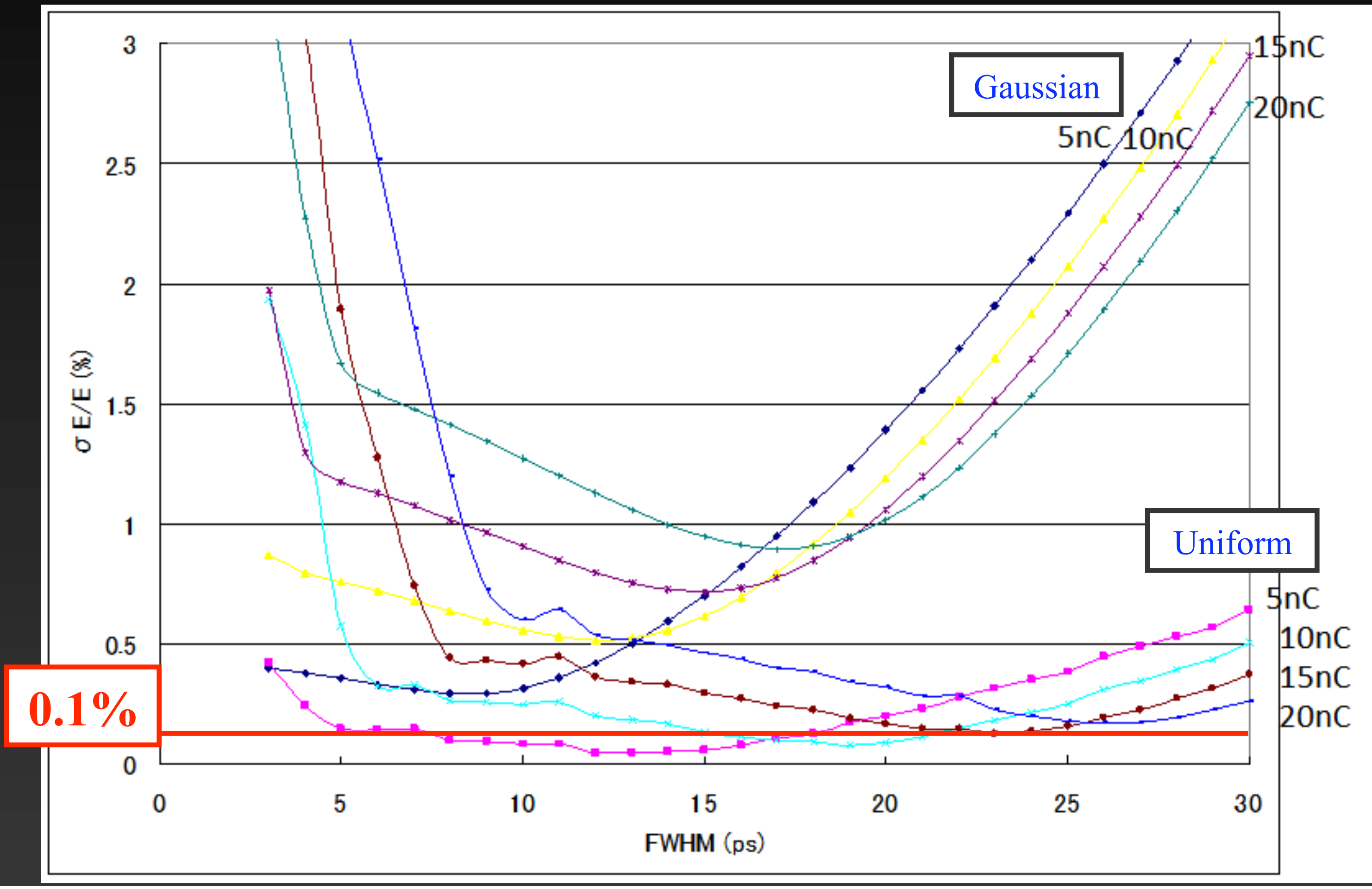
- Low emittance photo-cathode rf gun
  - e-:  1 nC, 100 mm·mrad (KEKB) => 5 nC, 20(H)/50(V) mm·mrad (SuperKEKB)
  - e+: 1 nC, 2100 mm·mrad (KEKB)=> 4 nC, 20(H)/100(V) mm·mrad (SuperKEKB)
  - Component alignment and fine beam control for low emittance preservation
- New positron capture system (Flux concentrator, Large aperture S-band structure), and damping ring
- New timing system (bucket selection for DR/MR)
- Fast RF monitor, high precision BPM readout and other new subsystems
- Simultaneous top-up injection
- Main ring commissioning Phase-I: Jan. of 2016
  - e-/e+ 1nC w/o low emittance

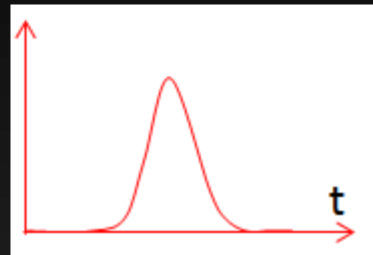
# Energy profiles and beam properties

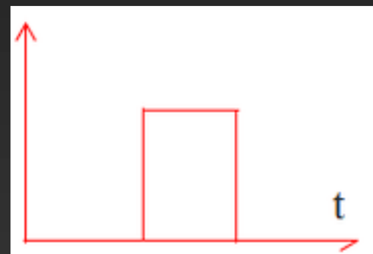


# Energy spread requirement

- Energy spread should be less than 0.1%.
- Uniform beam distribution is necessary for mitigation longitudinal wakefield and reduce energy spread.
- Temporal manipulation of laser system

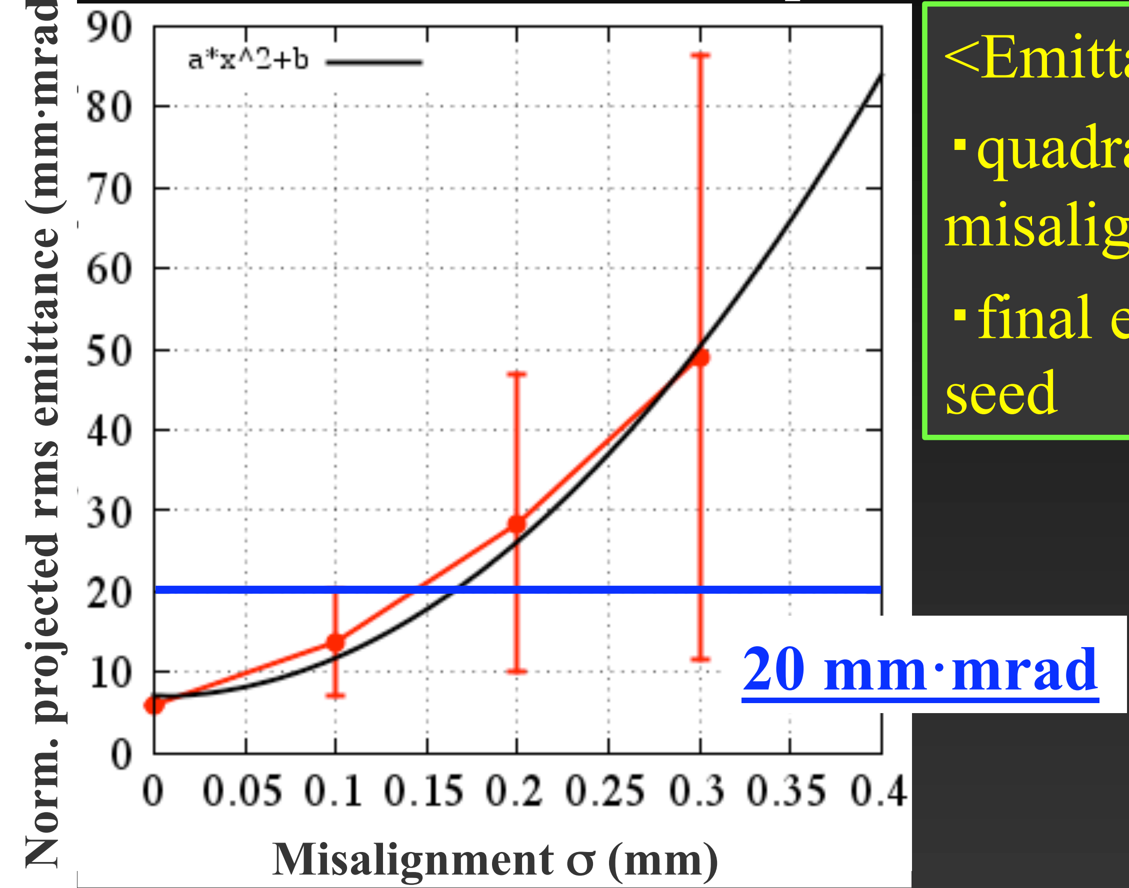


# Emittance growth due to component misalignment

- Simulation results from 100 different seeds.
- Misalignment of Quadrupole magnets and Accelerating structure:
  - $\sigma$ < 0.1 mm: $\beta\gamma\varepsilon$ 20 mm·mrad is almost satisfied.
  - $\sigma$ > 0.1 mm: emittance preservation is required by some methods.




<Emittance growth>

･quadratic curve as a function of misalignment

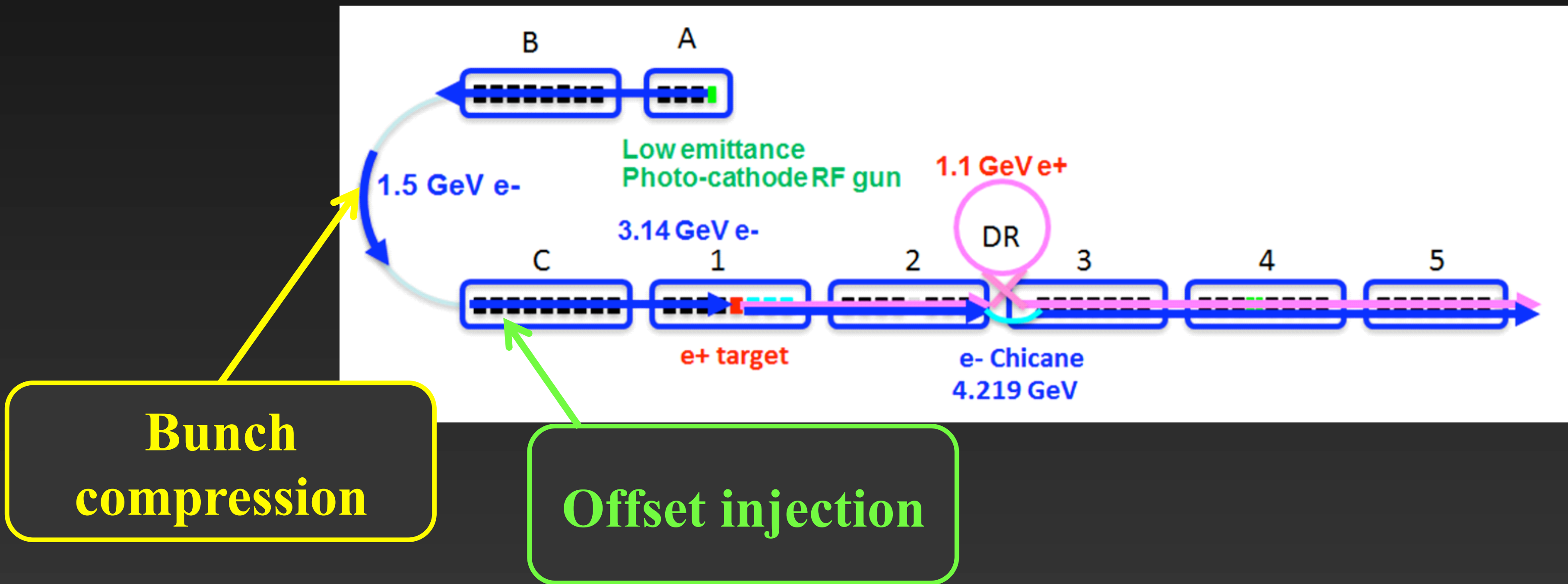
･final emittance depends on error seed

**Simulation**

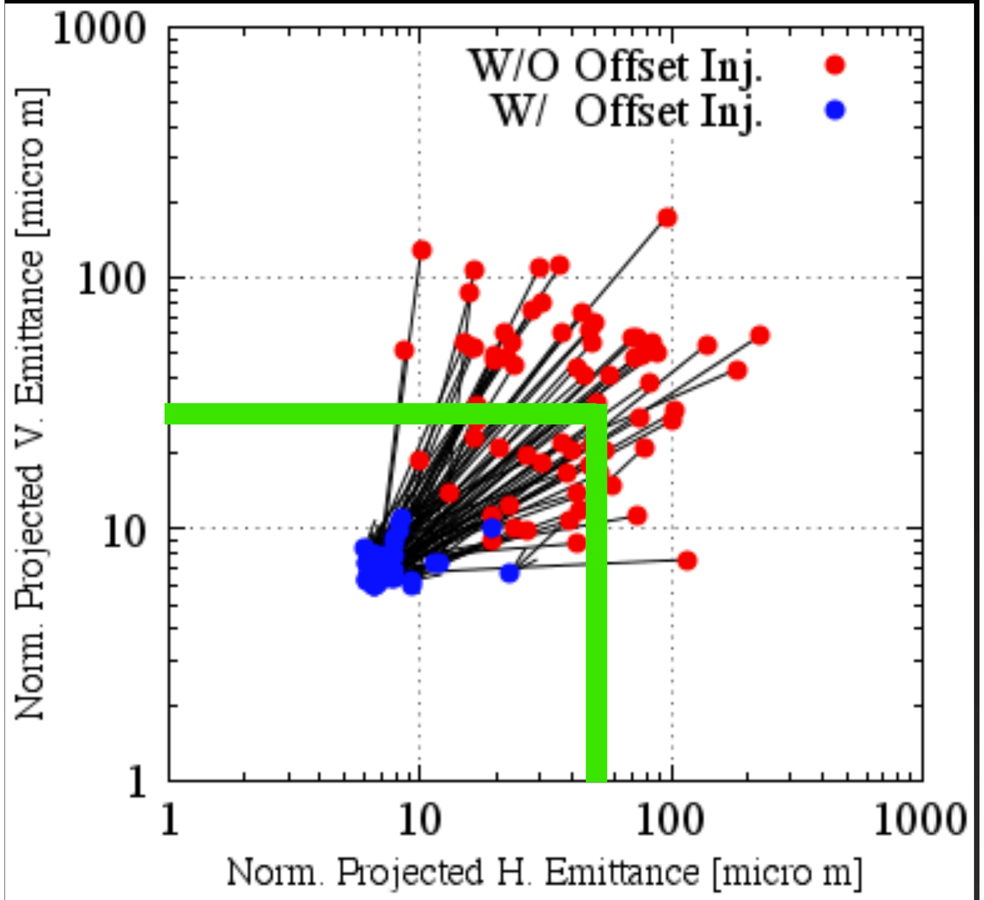
SAD code, Elegant
Initial bunch charge: 5 nC
Initial emittance: 6 mm·mrad
Initial bunch length: 10 ps (FWHM)
Initial energy spread : 0.4%
Initial beam energy: 20 MeV
Uniform longitudinal beam distribution

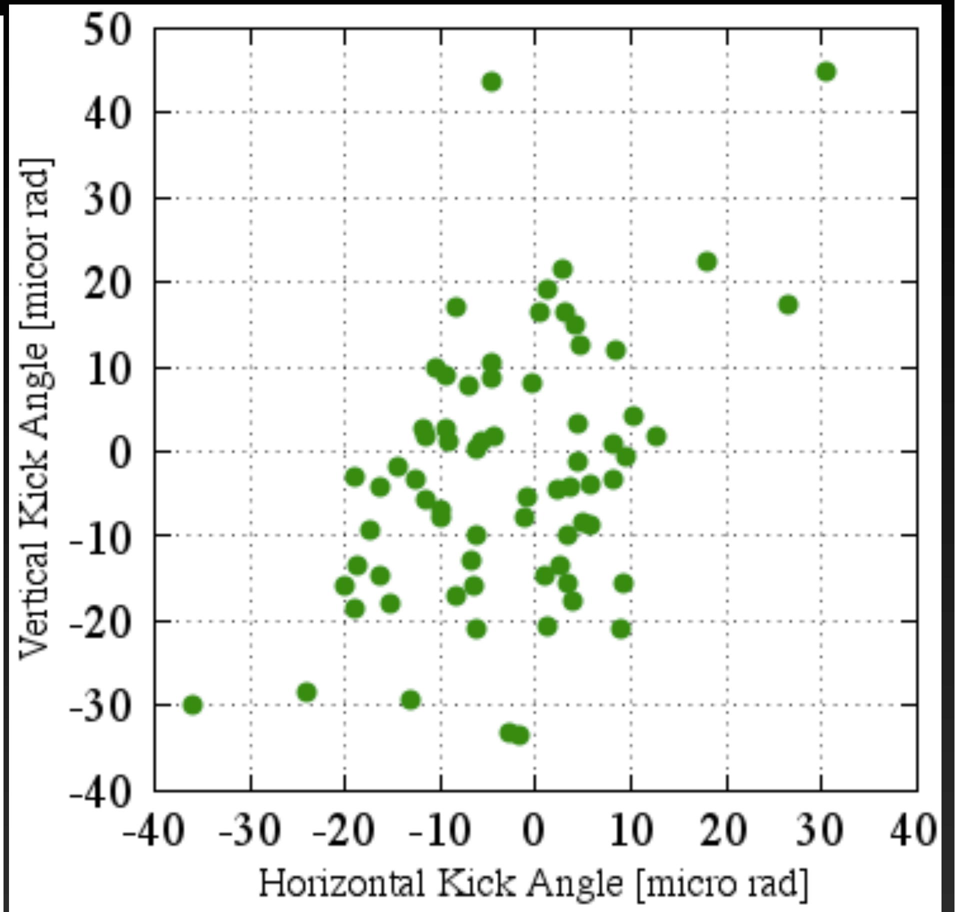
# Offset injection for emittance preservation

- Low emittance e- beam transport w/o damping ring
- Emittance preservation is key issue for e- beam.
- Offset injection: intentional change of misalignment seed.
- Control the steering magnet at the beginning of Sector C



# Offset injection (simulation)

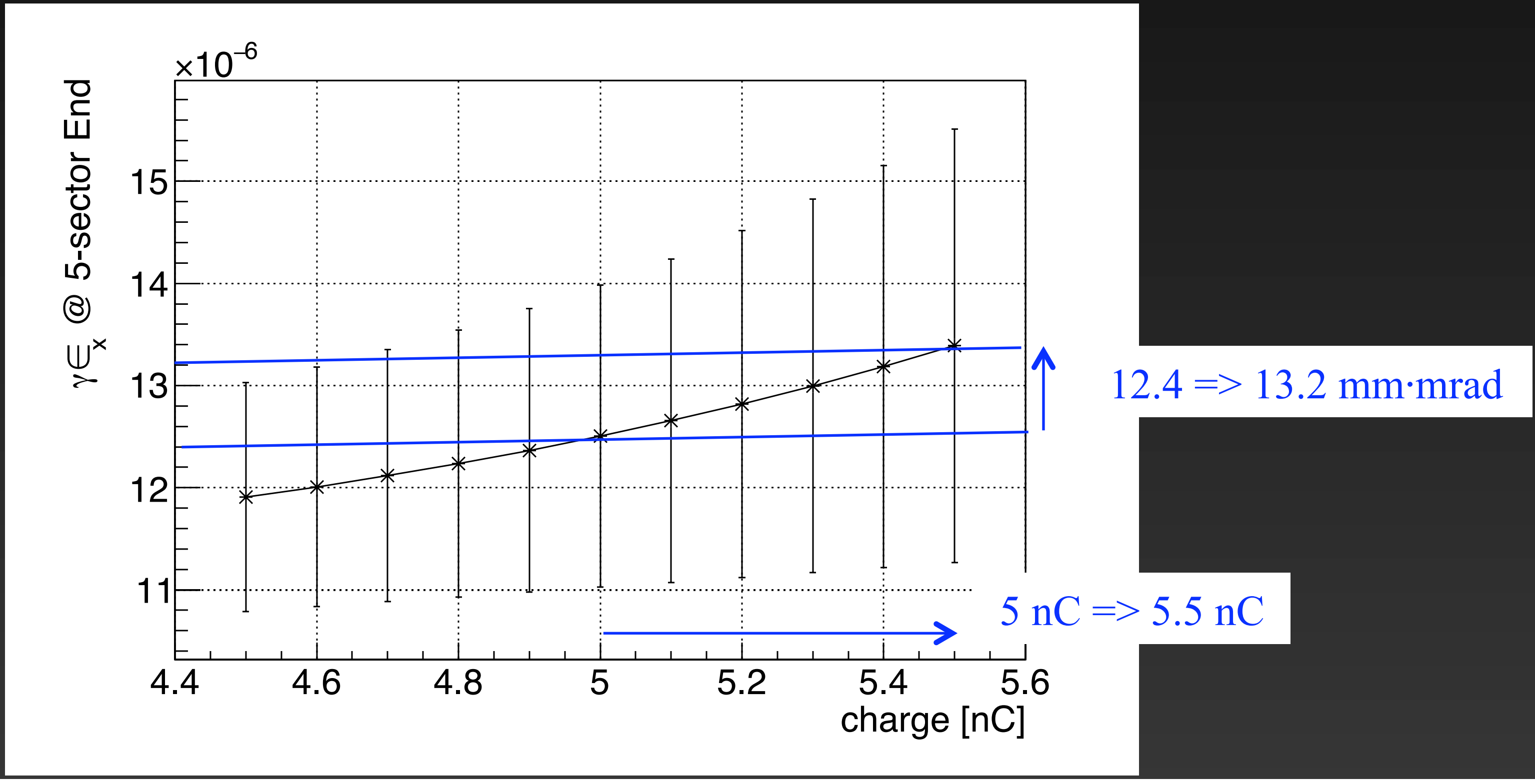


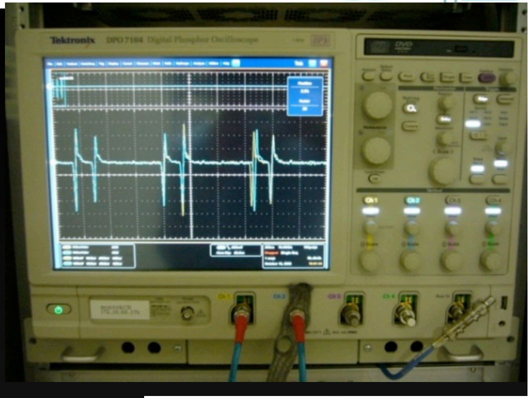

- Kick angle is relatively small.
- Need a high-precision and stable orbit control.

# Emittance w/ bunch charge fluctuation

- Emittance simulation w/ 10 misalignment seeds (accelerating structure).
- SectorC to Sector5 (Linac end)
- Assuming 5 nC, initial emittance of 10 mm·mrad (SectorC)
- When bunch charge increases by 10%, emittance increases by 6.5%.
- Try simulations w/ measured component misalignment, dynamic beam line movement, energy jitter.

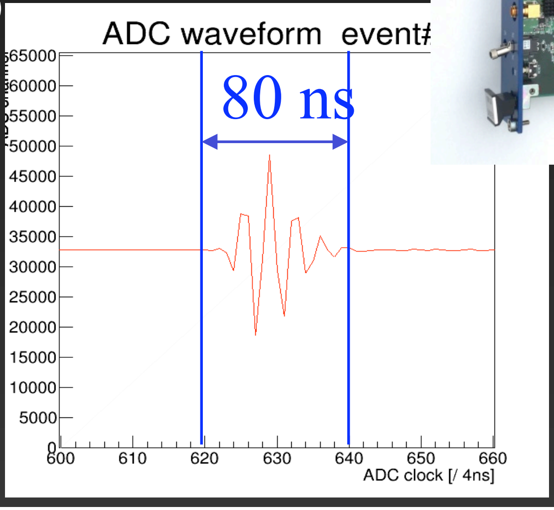


# BPM readout system



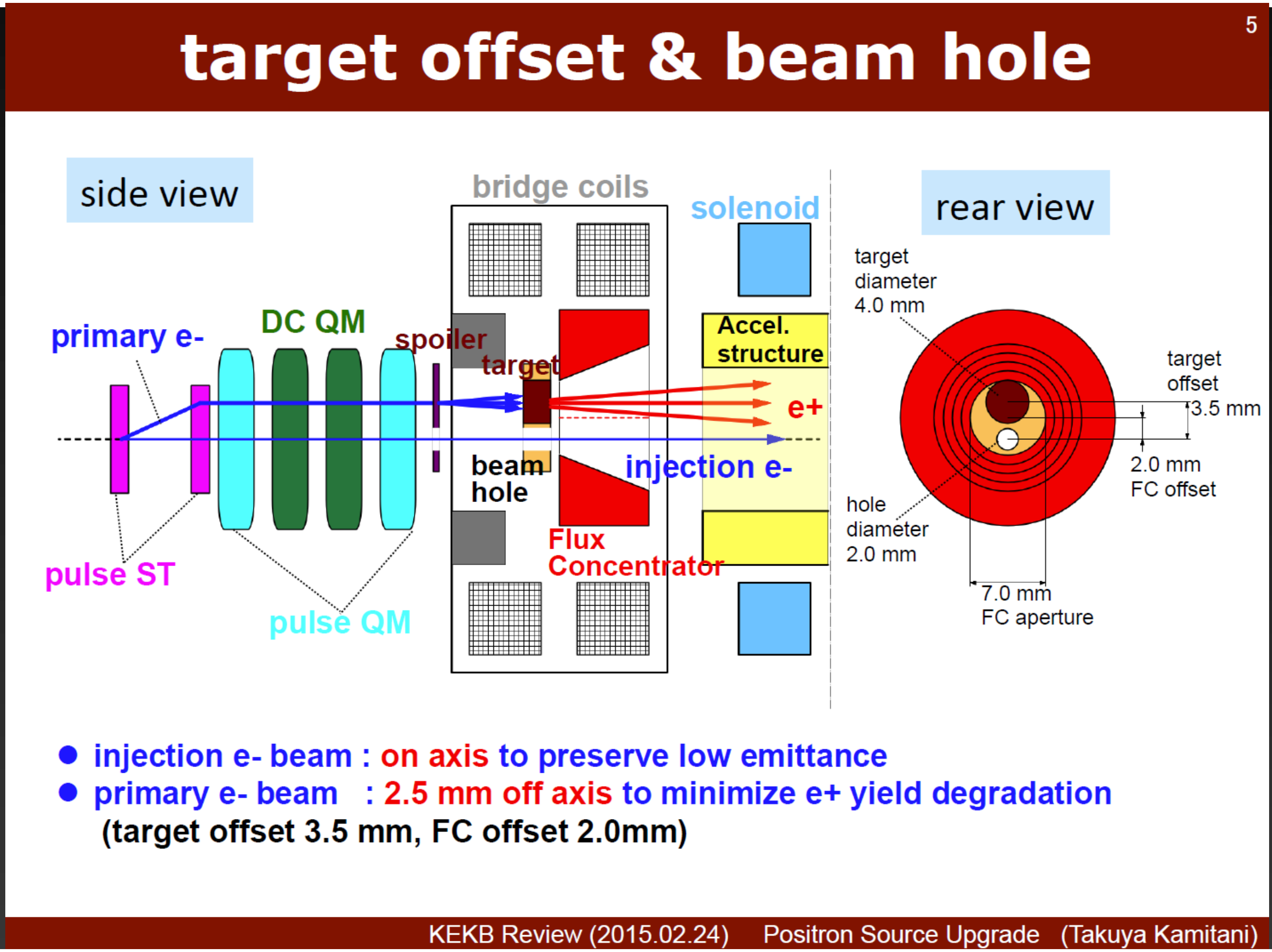
- Current system:
  - Windows-based digital oscilloscope
    - 10 GSa/s, 8 bit, 1 GHz bandwidth, 4 channels
    - Twenty four systems process: 90 BPMs
    - Position measurement precision: 25～50 μm (3-BPM)
- New system:
  - VME module w/ band-pass sampling scheme
    - 250 MSa/s, 16 bit ADC,
    - BPF (fc: 180 MHz, BW: 60 MHz, 22 MHz)
    - Signal can be well damped within 80 ns
  - Meas. precision: 3 μm

～ 100 modules under pre-delivery inspection



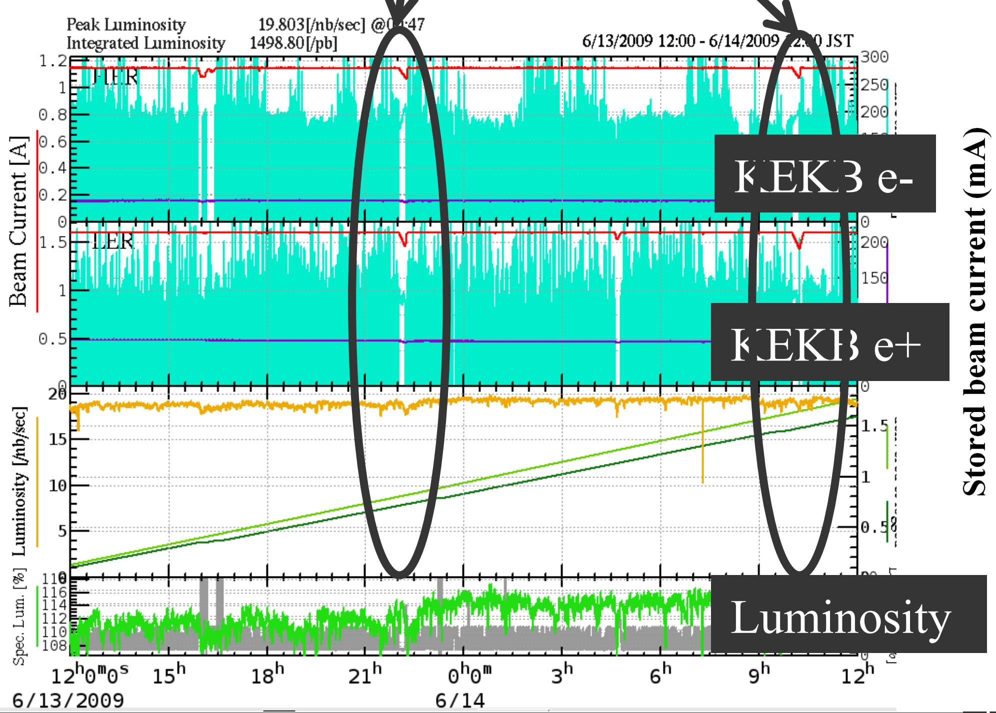
# e-/e+ beam fast switching (SuperKEKB)

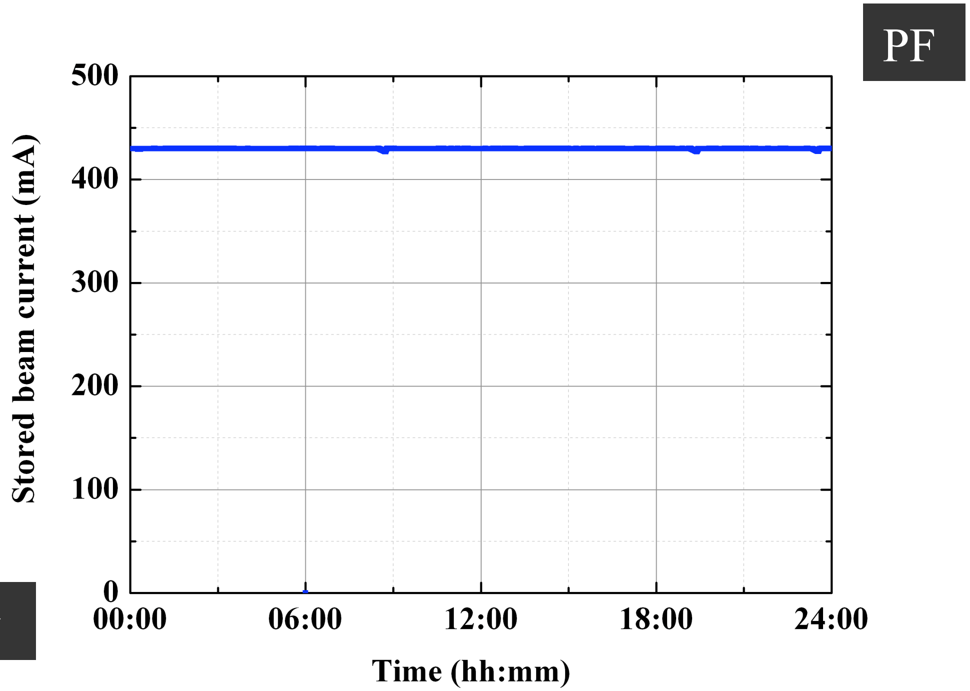
- Positron production target with a hole (e- beam pass through inside a hole)
- A hole is at the center of beam line for low emittance e- beam.
- Same scheme was successful in KEKB operation.



# Simultaneous top-up injection for three rings

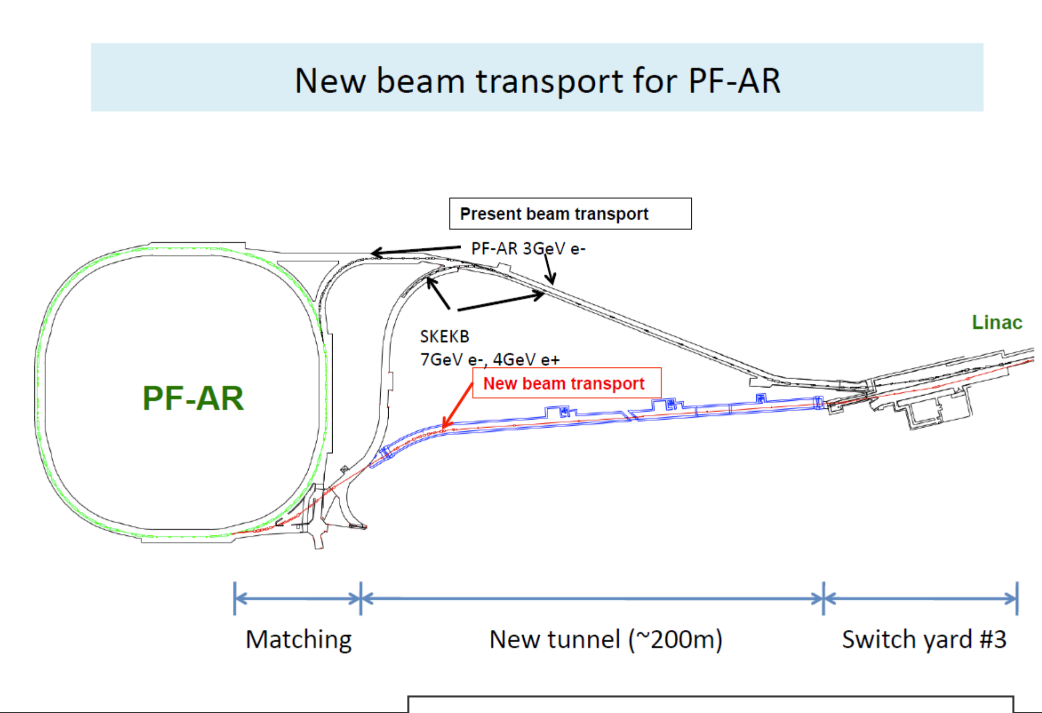
- PF-AR injection (twice daily) interrupt KEKB injection.
- Big issue for SuperKEKB operation.
- Beam lifetime ~ 6 min.



# Simultaneous top-up including PF-AR injection

- PF-AR and KEKB share the long part of beam transport line.
- Existing tunnel space is very tight.
- New tunnel has been constructed in Mar. of 2014.
- Pulsed bend will be installed at #3 switch yard of Linac.
- New BT will be available in Jan. of 2017.



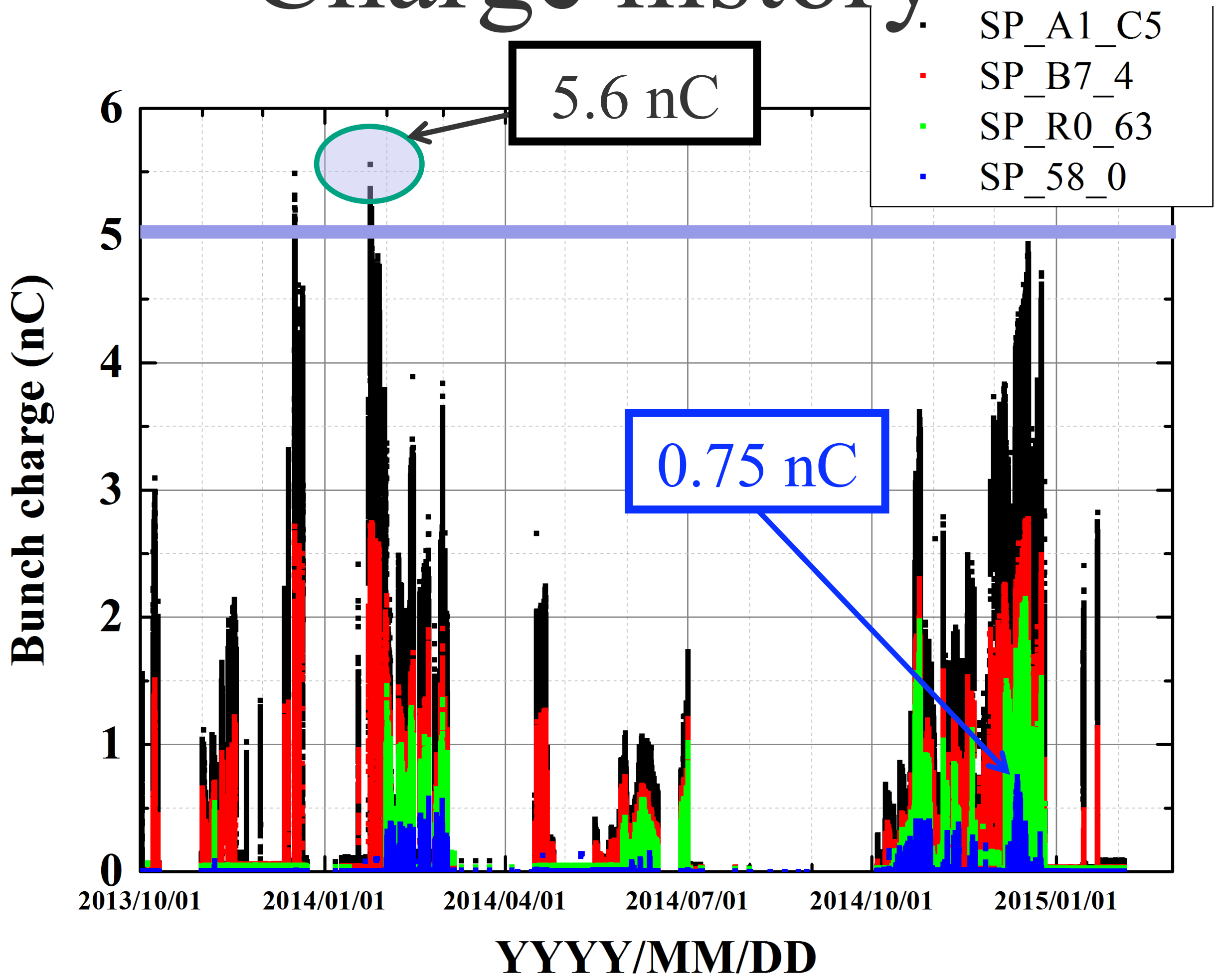

H. Takaki (KEKB review 2013)

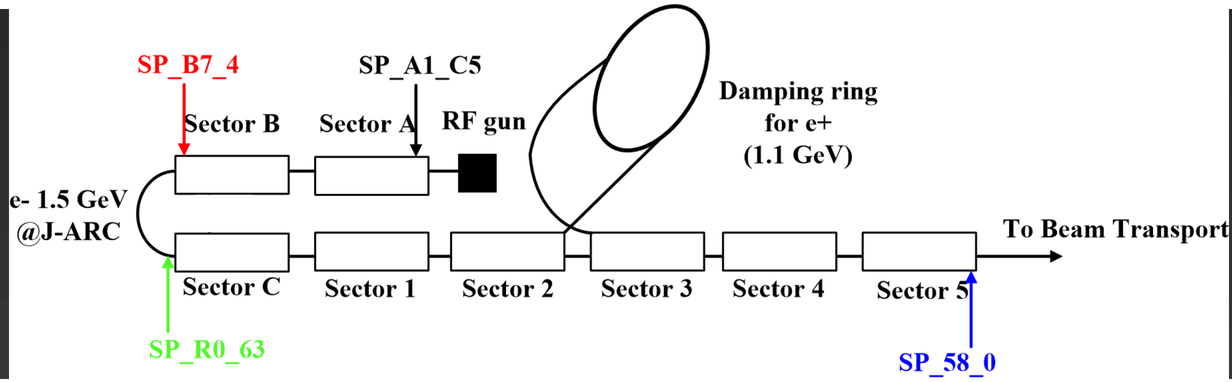
# Injector commissioning

- Injector commissioning has been started in Oct. of 2013.
  - Oct. and Dec. of 2013 (e+ beam line construction in Nov.)
  - Apr. ~ Jun. of 2014
  - Oct. ~ Dec. of 2014
  - Commissioning (Jan.-Mar. of 2015) was canceled. (operation budget)

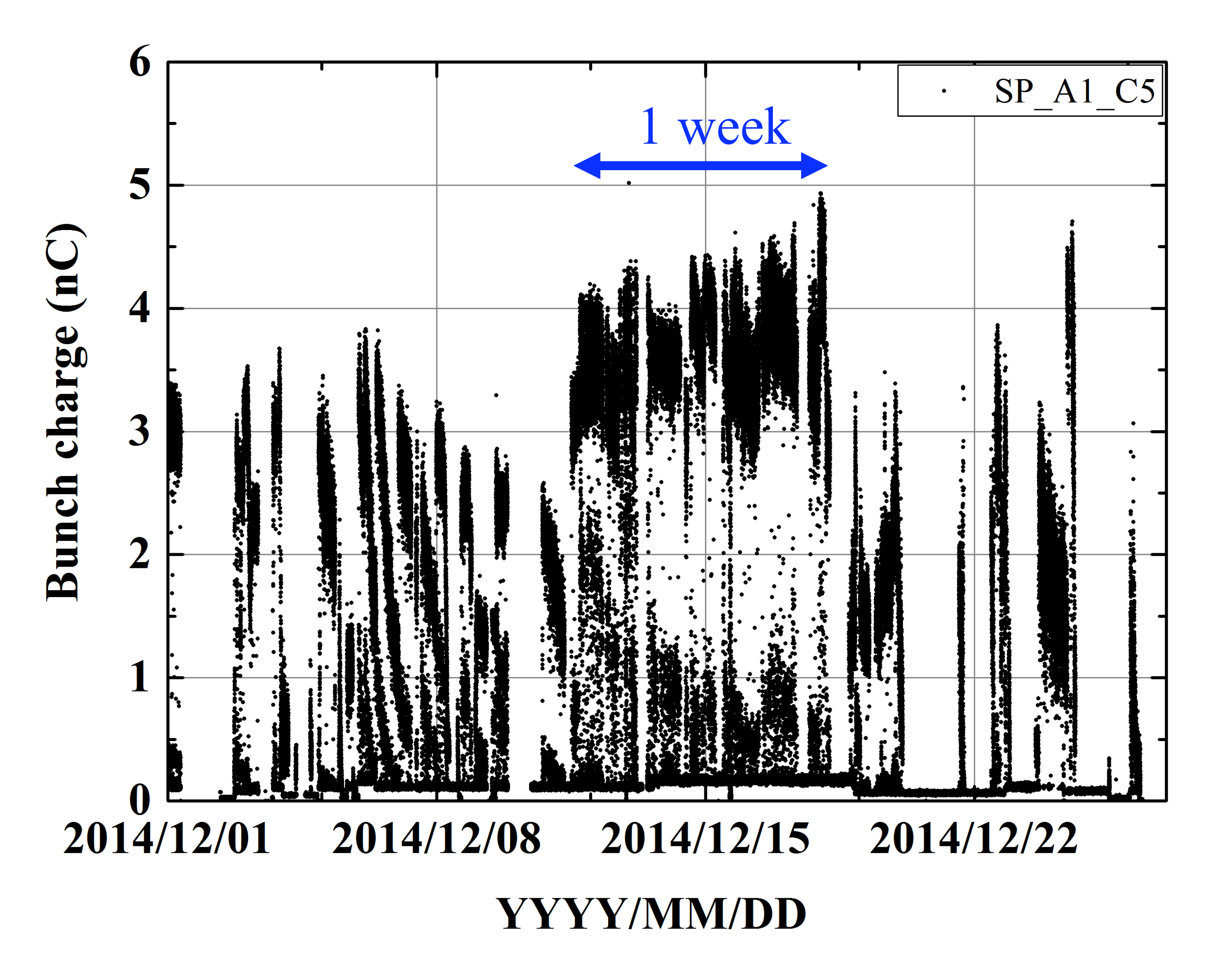
  - Day shift: beam line construction, laser tuning
  - Evening shift: beam study
  - Early morning shift: beam study, rf conditioning

# Charge history



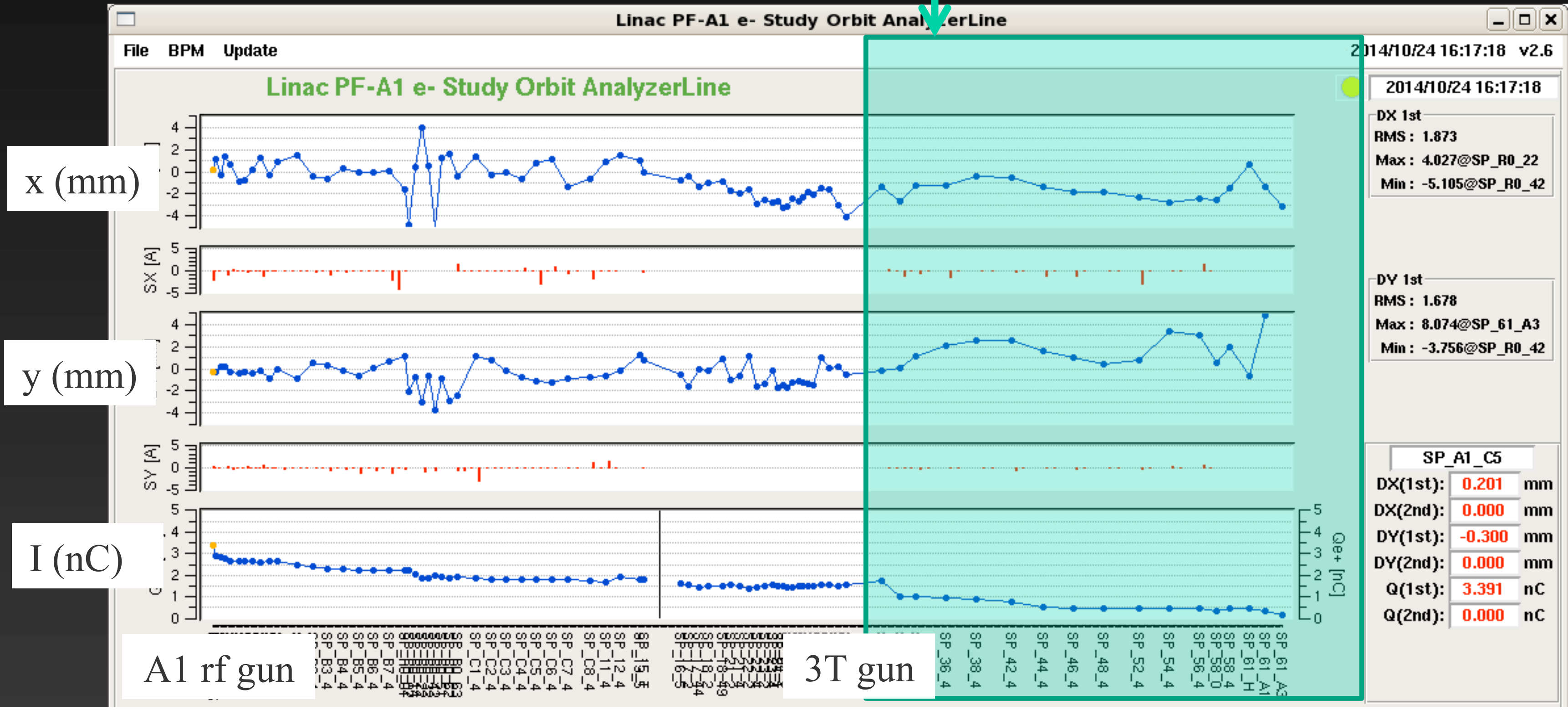



# Bunch charge from rf gun in last Dec.

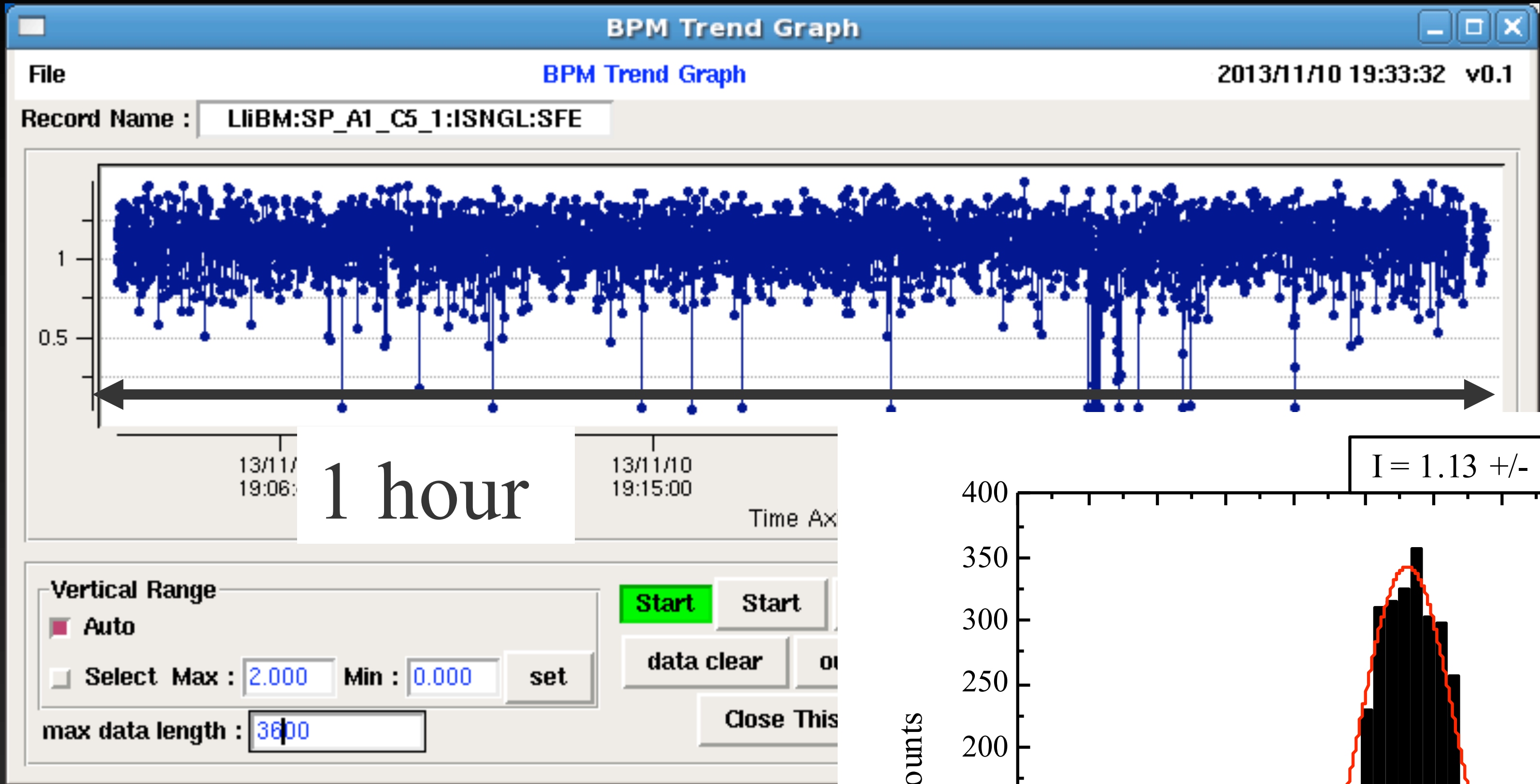


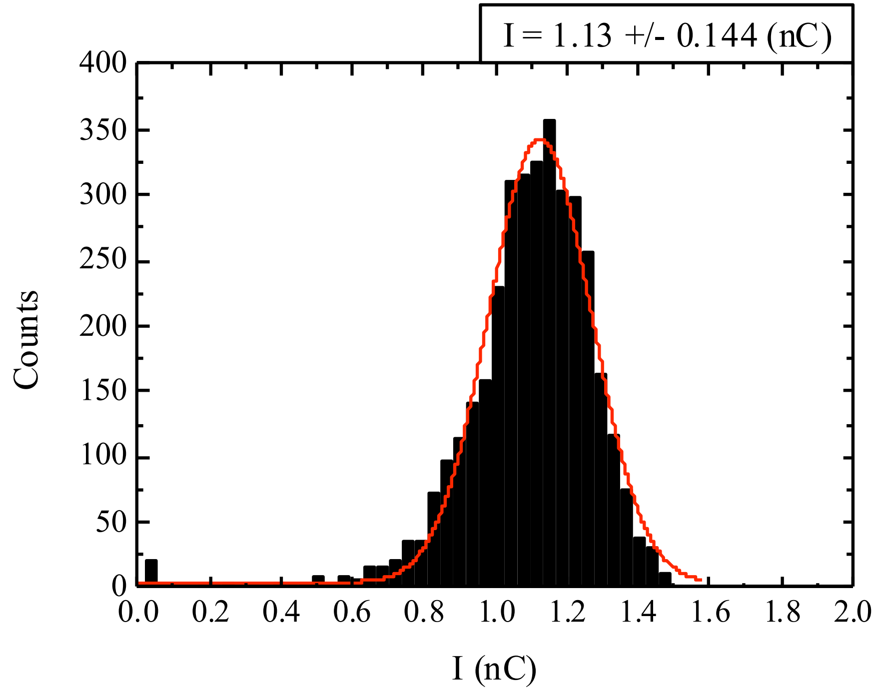
# Beam orbit example

- During commissioning, 3T gun continuously provides e- beam for PF ring (top-up).
- Full Linac study can be conducted in Wednesday.
- PF dedicated magnet settings are used in Sector3 - Sector5
- RF Φ can switched in pulse-by-pulse (LLRF Φ control)



# Typical beam charge stability



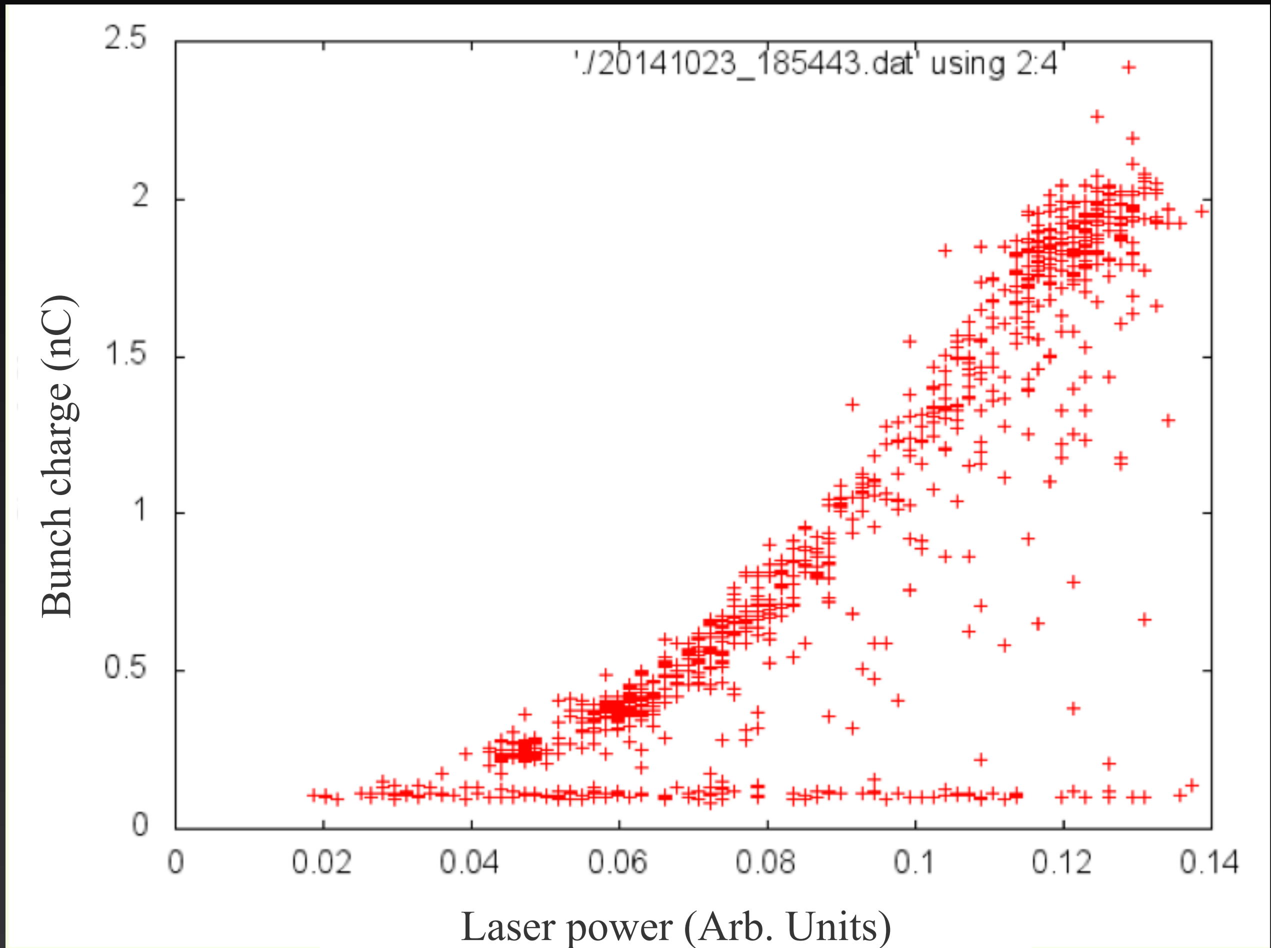




$\sigma_I$: 10% ~ 20%

~ 2.5% (KEKB operation)

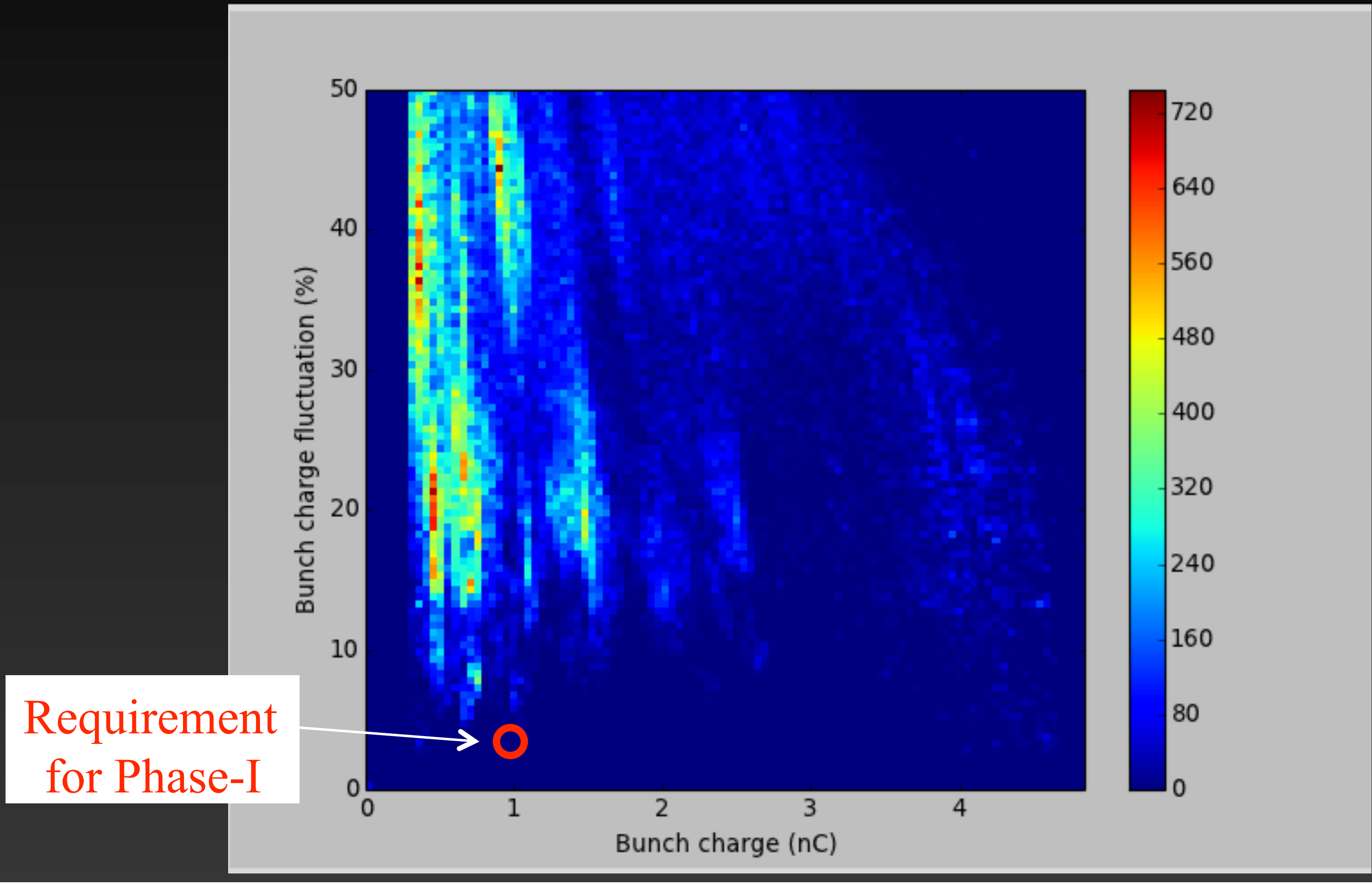
# Bunch charge and laser power

- Bunch charge (1st BPM) as a function of laser power.
- Clear correlation between them



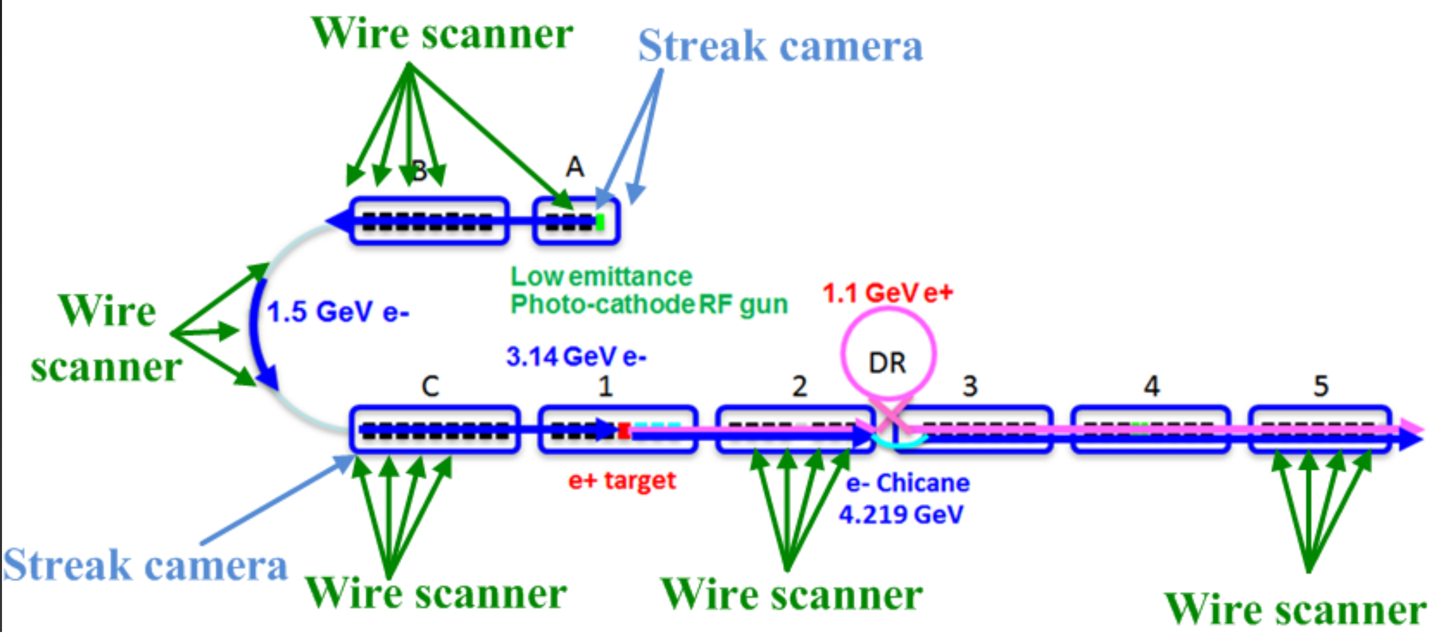
# Bunch charge fluctuation

- Bunch charge fluctuation as a function of bunch charge (2D histogram)
- Oct. of 2013 – Dec. of 2014



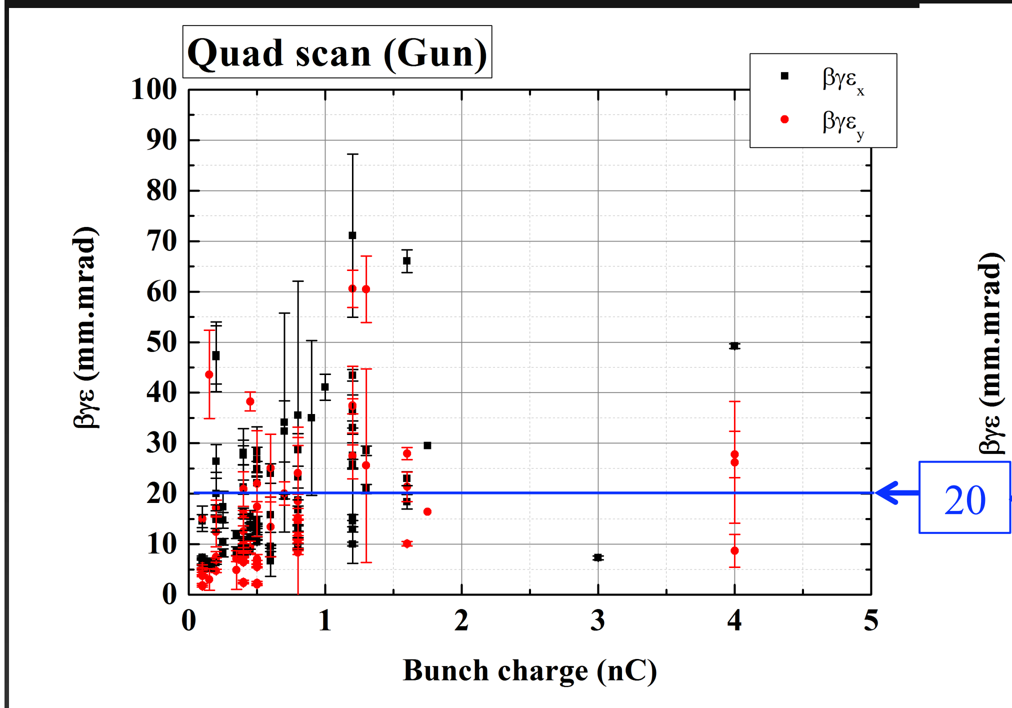
# Beam diagnostics

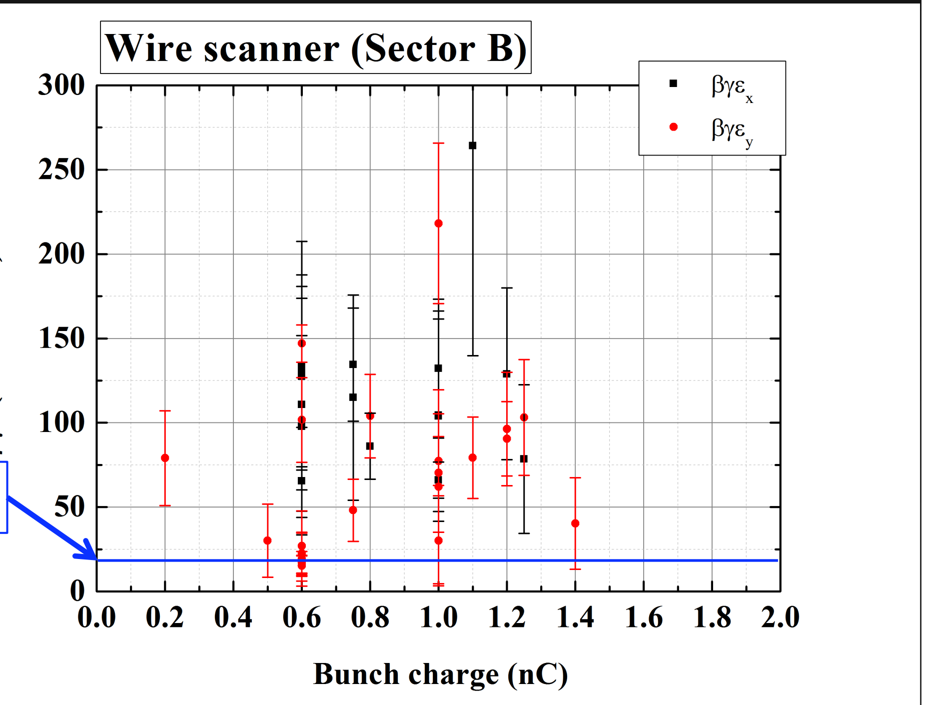
- Beam position measurement
  - BPMs x 90 (strip-line type electrodes)
- Beam profile/Emittance measurement
  - Fluorescent screen monitors x100
  - Single wire scanner x1
  - Multiple wire scanner x5
- Bunch length measurement
  - Streak camera x3



# Emittance measurement

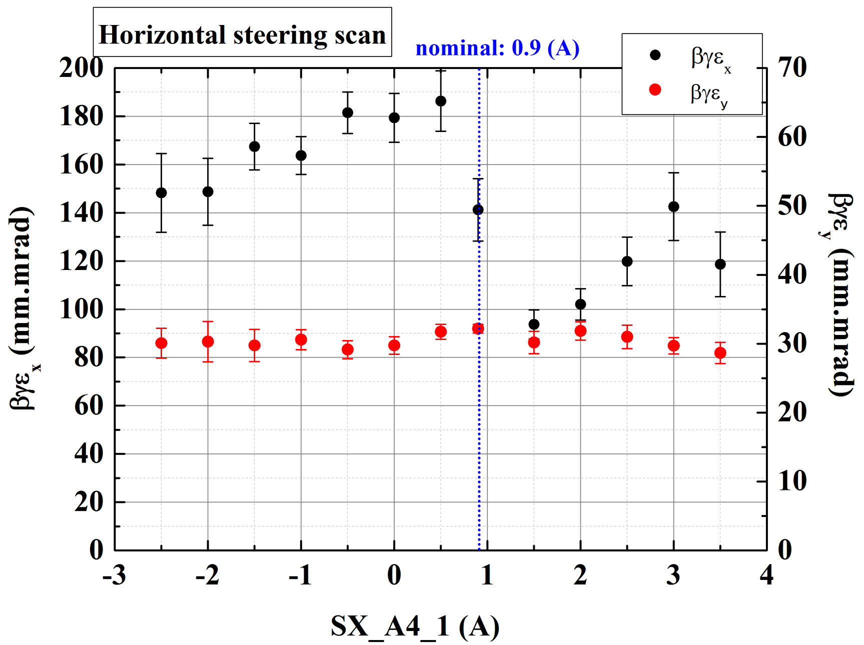
- Emittance as function of bunch charge (drop the results w/ large error )
- Small bunch charge (< 1 nC) shows good emittance at injector section.
  - < 10 mm·mrad (Vertical), < 15 mm·mrad (Horizontal)
- Results at SectorB show larger emittance than our goal.

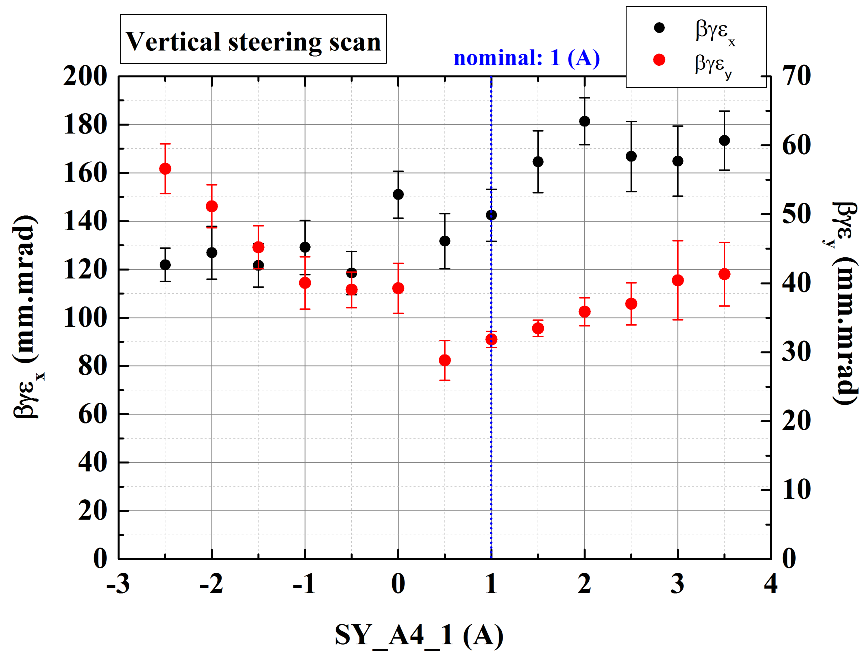


# Offset Injection (experiment)

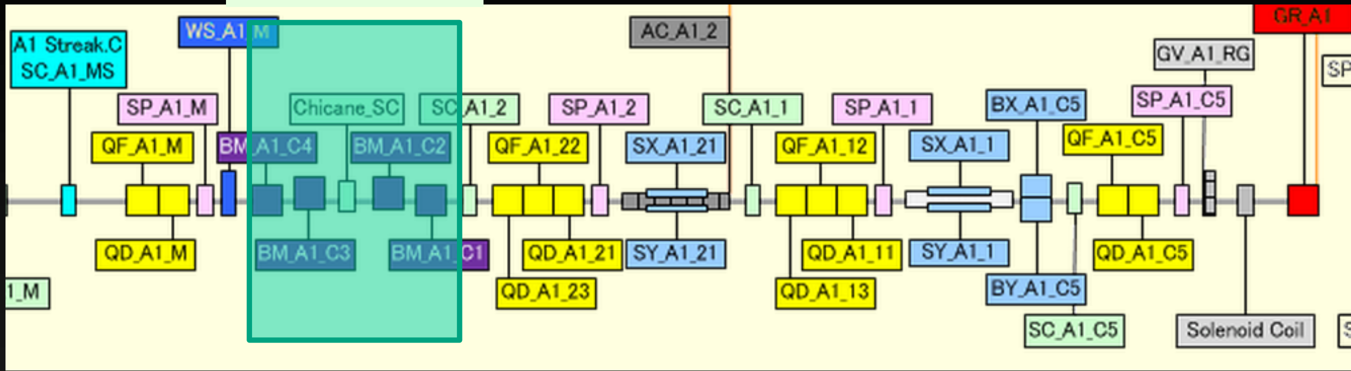
- Feasibility of offset injection was studied w/ bunch charge of 0.3 nC.
- Changing the excitation current of steering magnet at Unit-A4.
- Emittance was measured multiple wire scanner at SectorB end.
- We will conduct this measurement w/ various bunch charges.



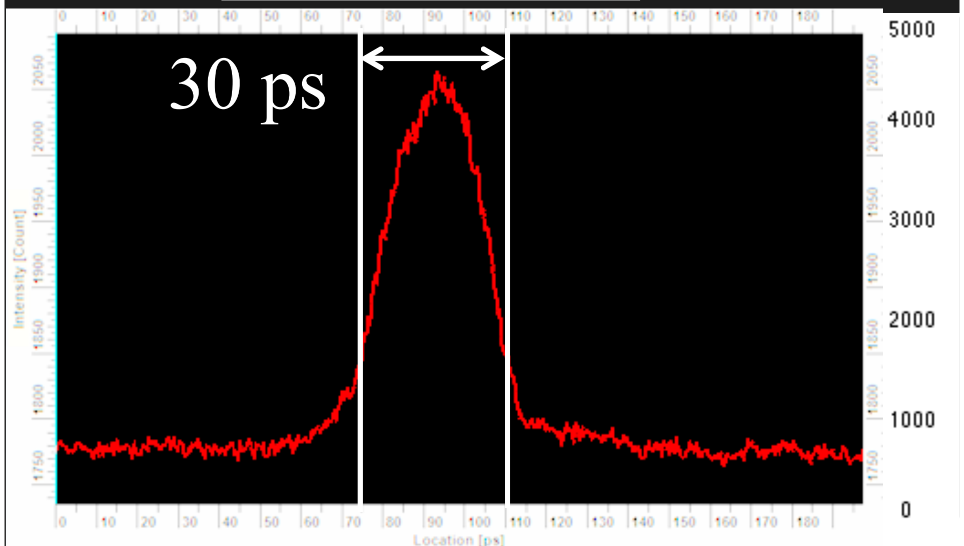



# Bunch compression at Unit-A1

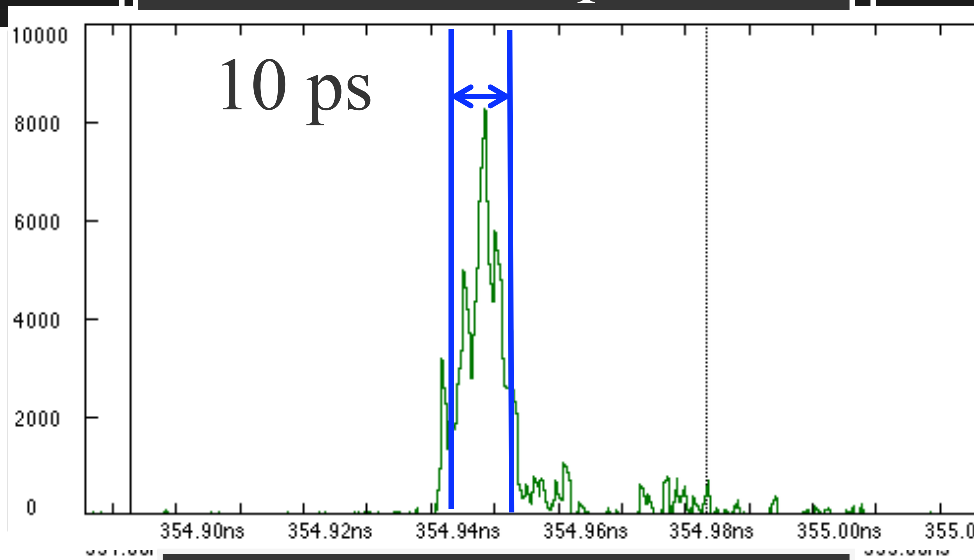
Chicane




Laser length



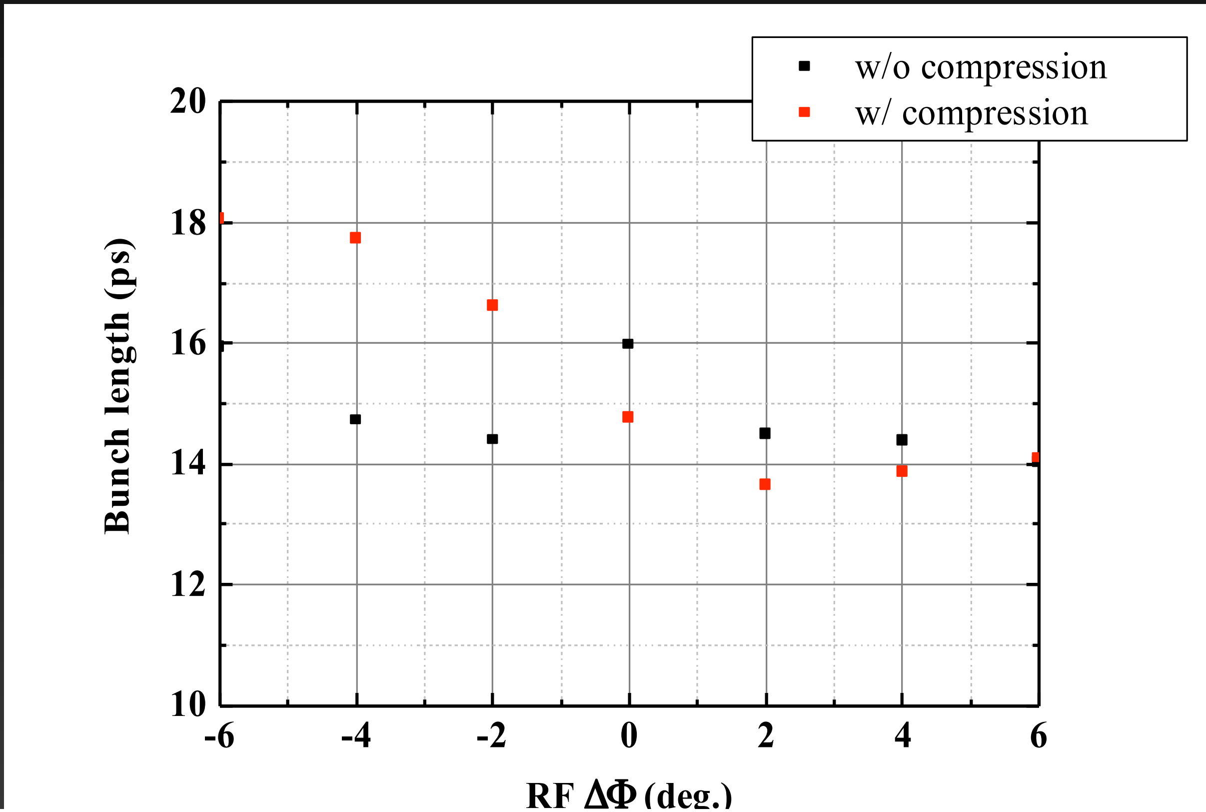

w/ bunch compression

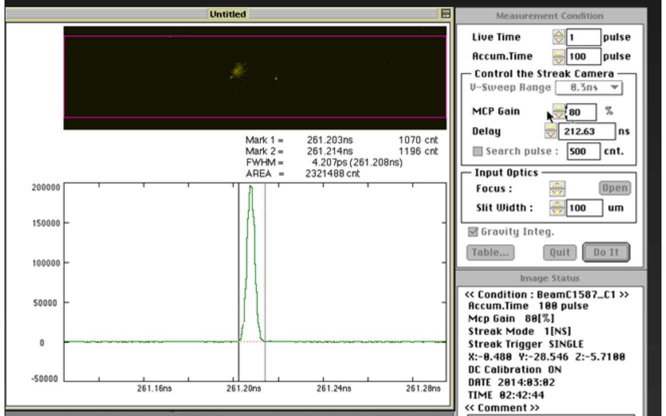



A1 RF Φ -30°: 10 ps

# Bunch compression @ J-ARC

- Isochronous (w/o bunch compression), $R_{56}$ = -0.3 m (w/ bunch compression) w/ different RF Φ in SectorA/B
- Clear bunch compression has not yet been measured.
- Emittance measurement by multiple wire scanner at Sector2 w/ and w/o J-ARC bunch compression.

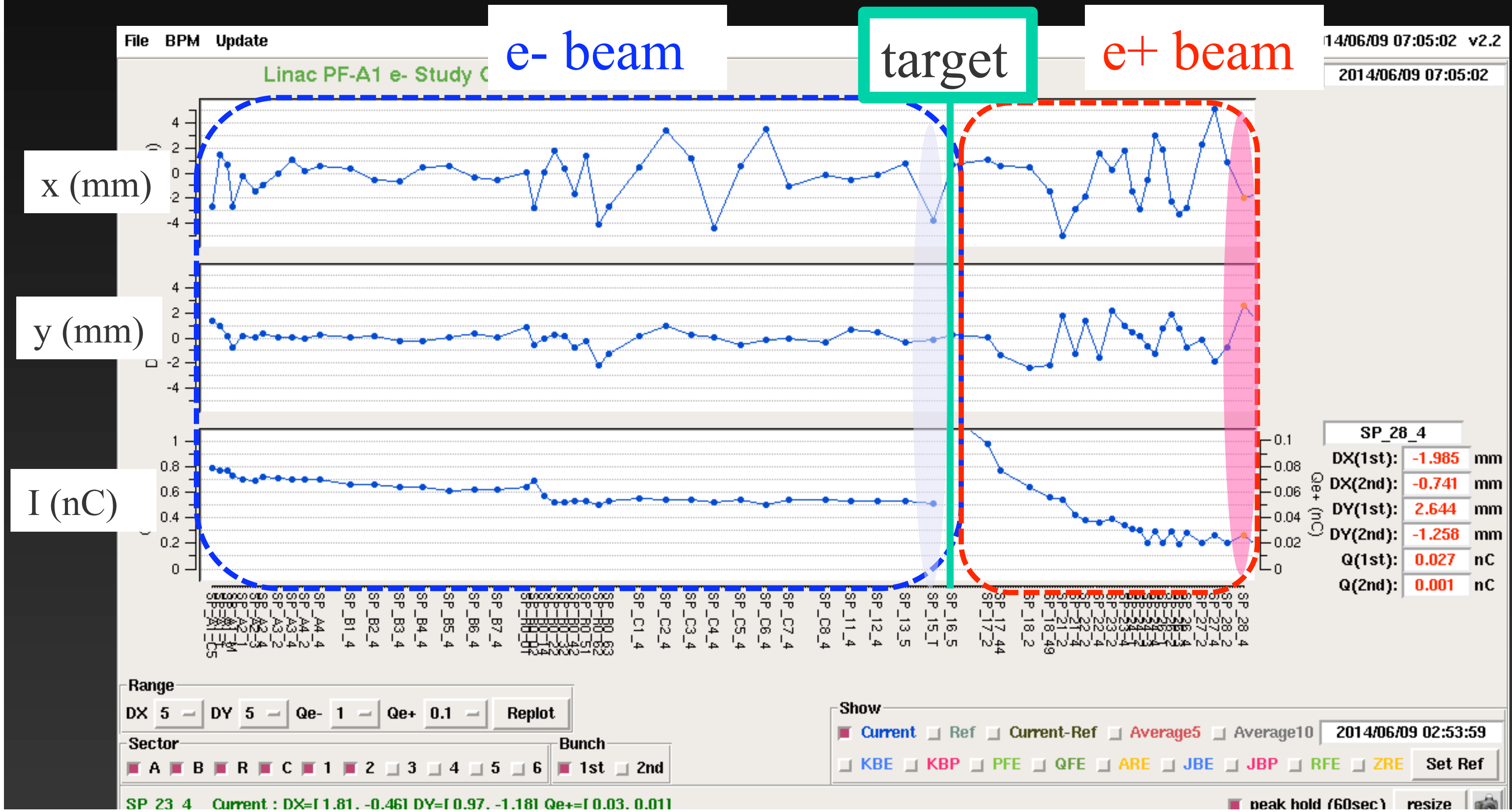


Streak camera at SectorC

# e+ beam measurement

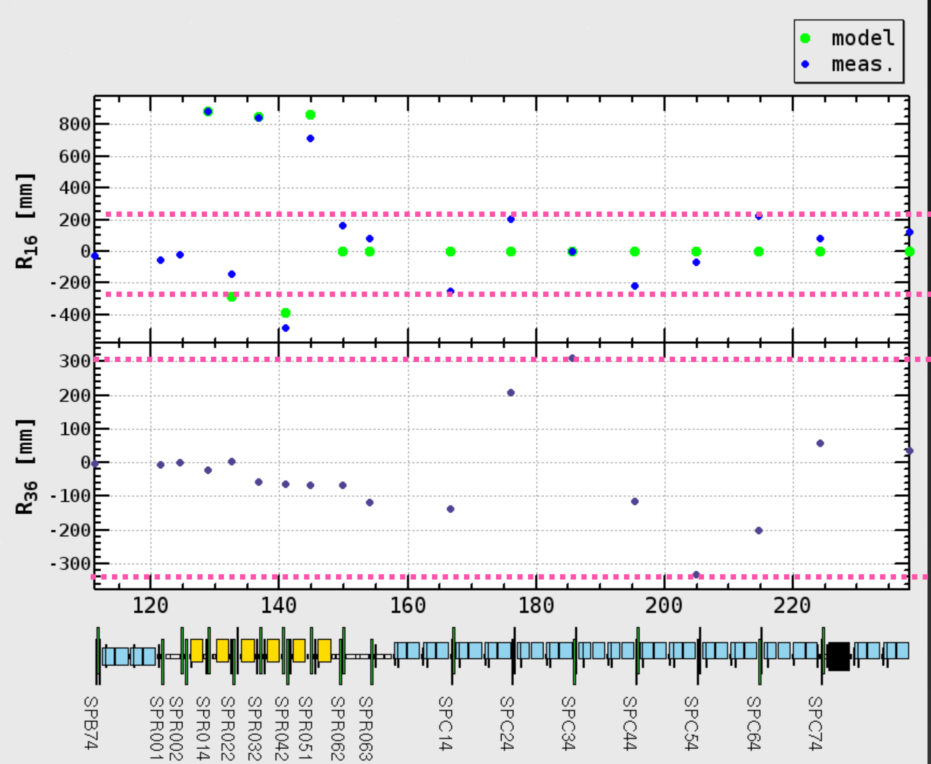
- First e+ beam was measured by current system at Jun. 9th 2014.
- Primary e- beam charge: 0.5 nC
- e+ charge: 0.02 nC @ SP_28_4



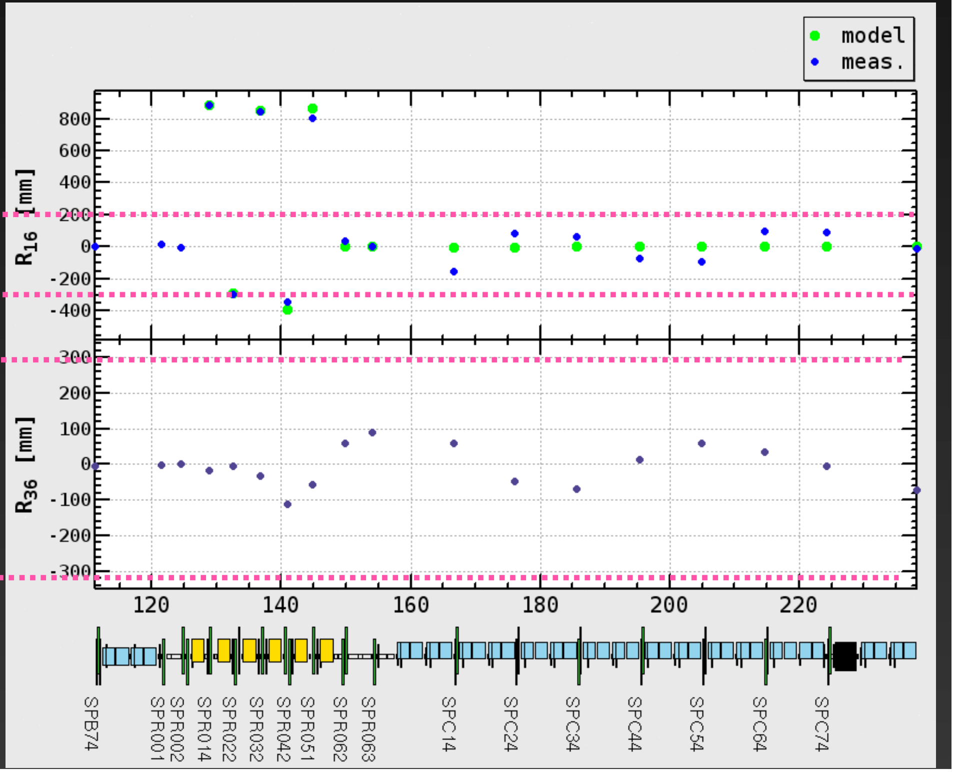
# $R_{16}$, $R_{36}$ elements at J-ARC

- $R_{16}$, $R_{36}$ values were measured at J-ARC and SectorC.
- w/ and w/o fudge factors ($B' = A_{fudge} \times B'_{model}$)
- Find suitable fudge factors
  - Typical fudge factors used for KEKB operation are 1% ~ 5%.

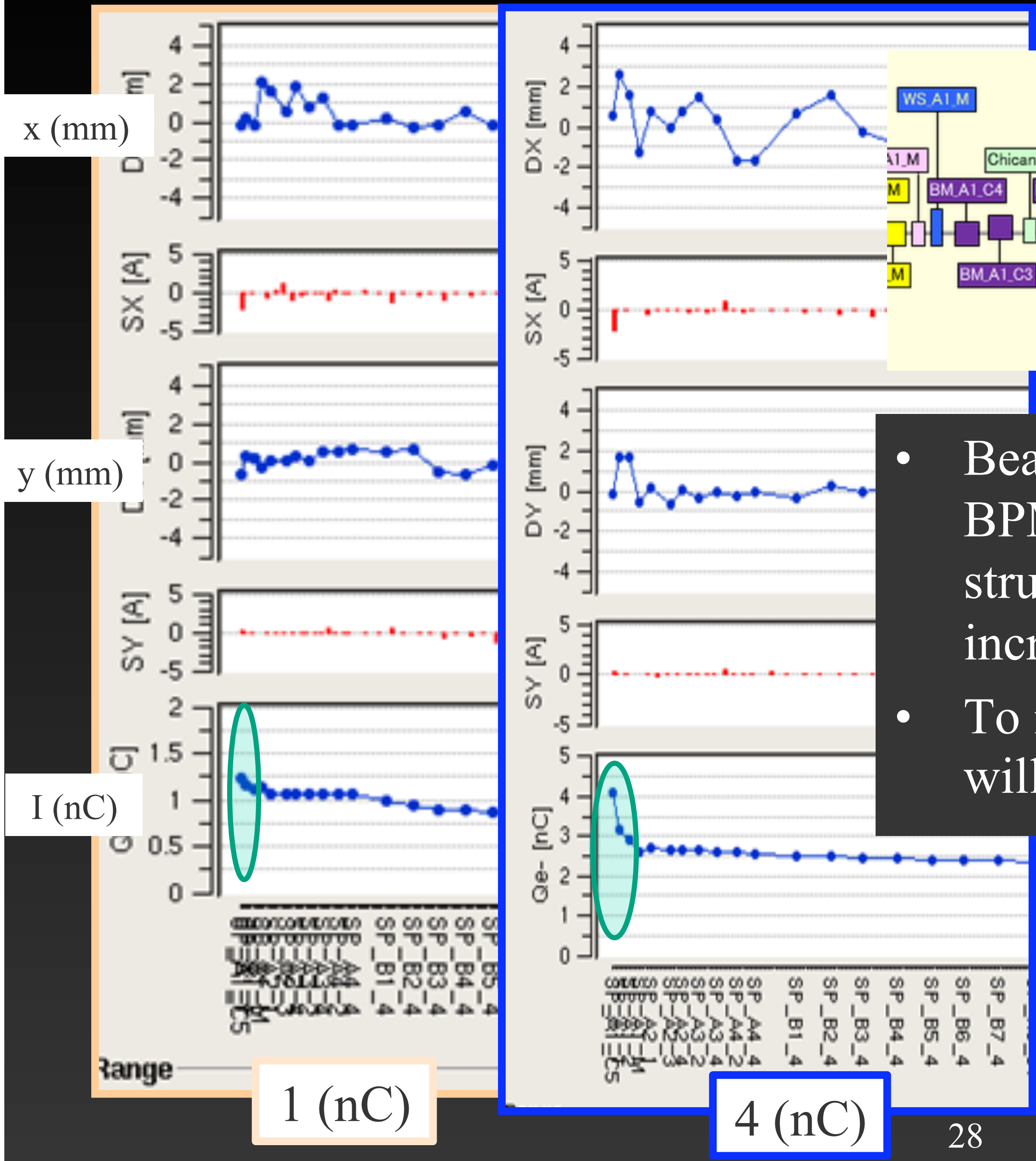
Design value

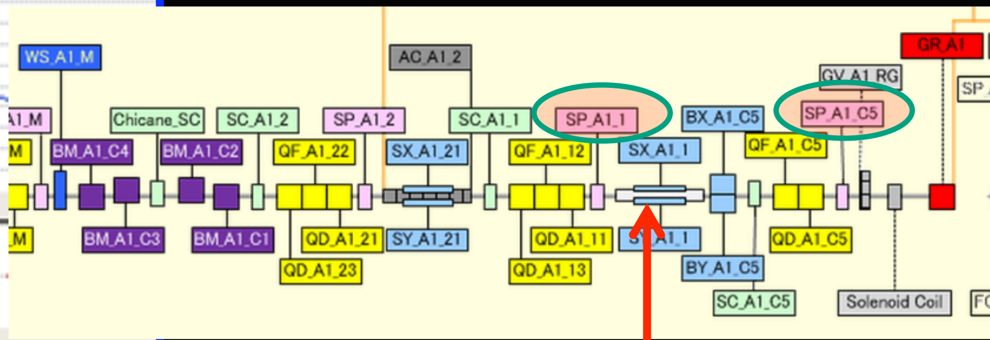



w/ fudge factors



# Beam loss at first acc. structure

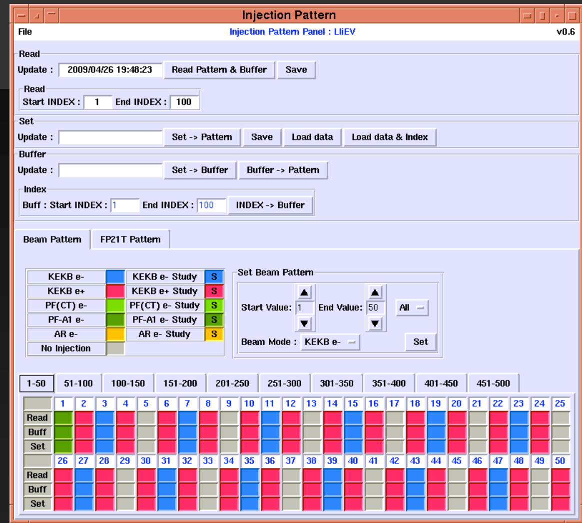


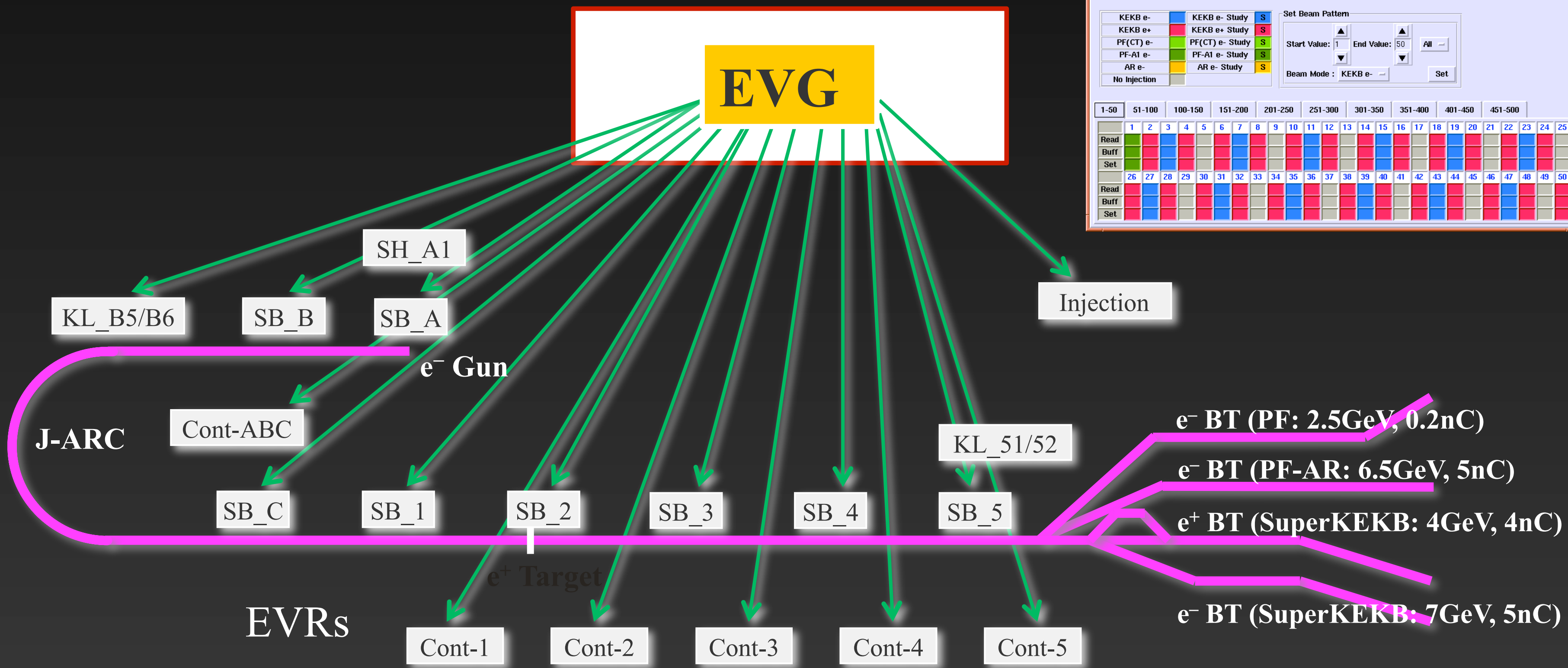

- Beam transmission rate is reduced at 2nd BPM (downstream 1st accelerating structure) when bunch charge from gun increases.
- To improve it, 1st accelerating structure will be removed soon.

# Timing system

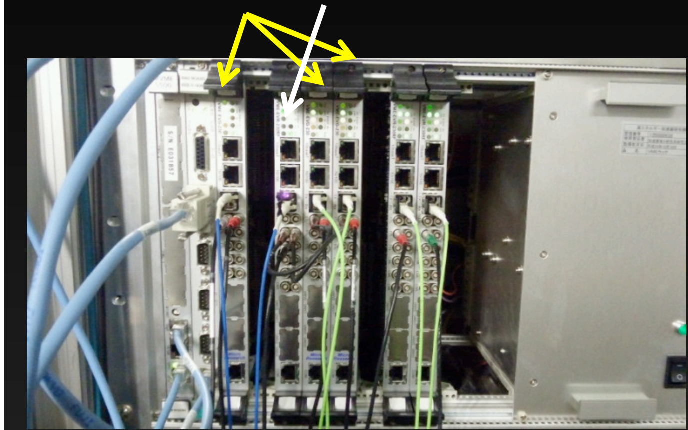
- Event generator (EVG)/Event receiver (EVR) based on VME64x. (Micro-Research Finland)
- EVG (EVG-230) x1, EVR (EVR-230RF) x24
- Arbitrary injection pattern can be set via HLA.

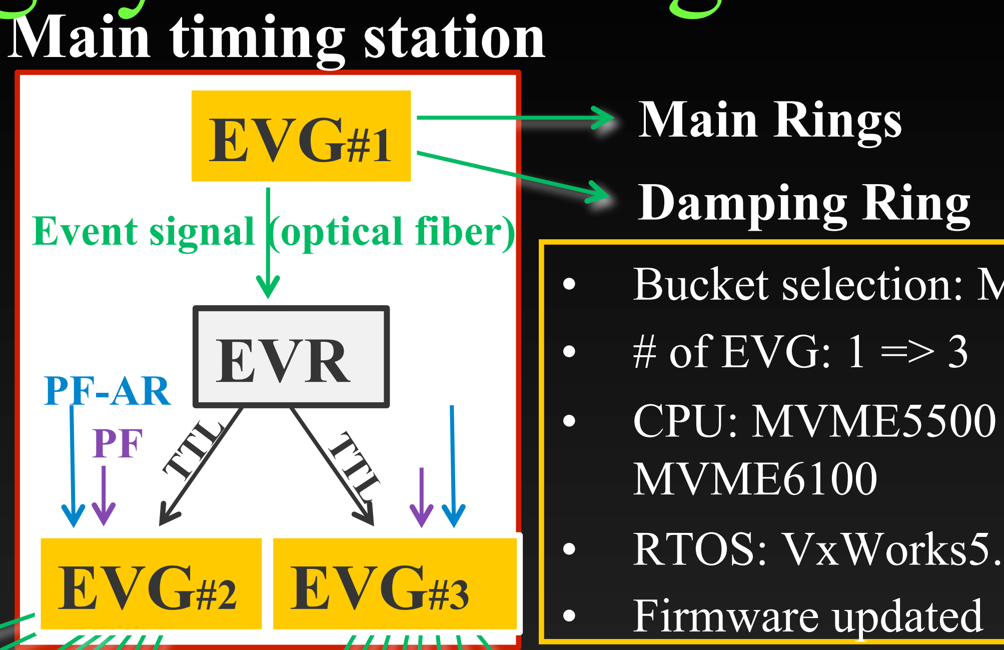



## Main timing station

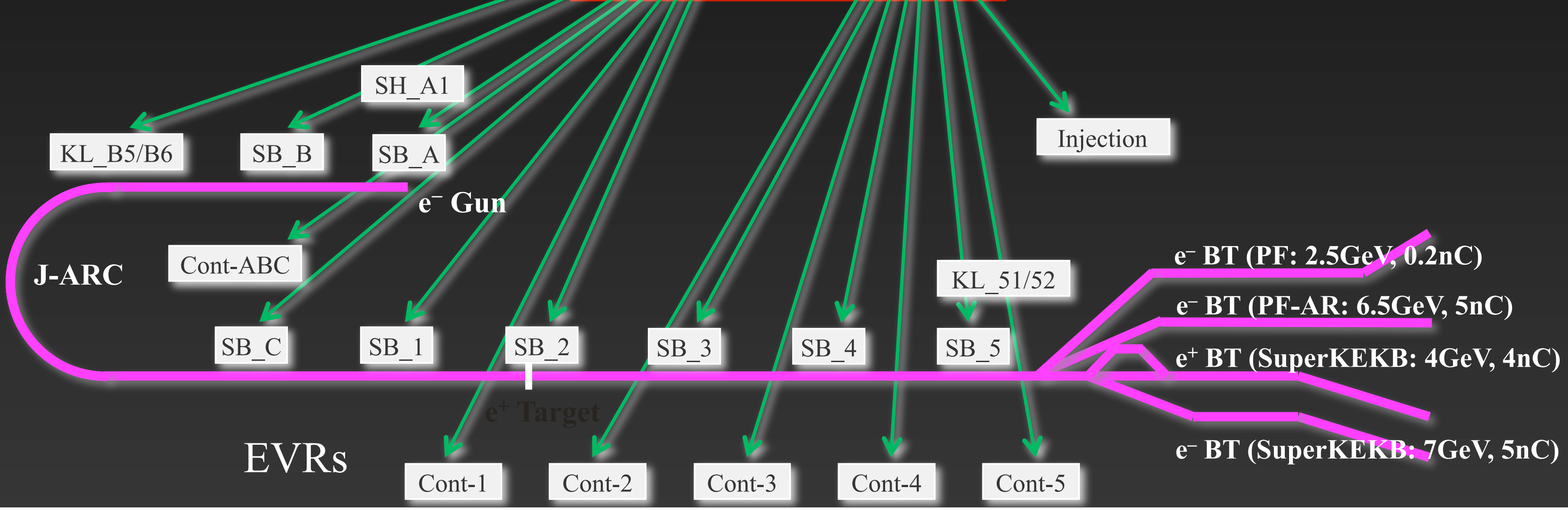


# New timing system configuration



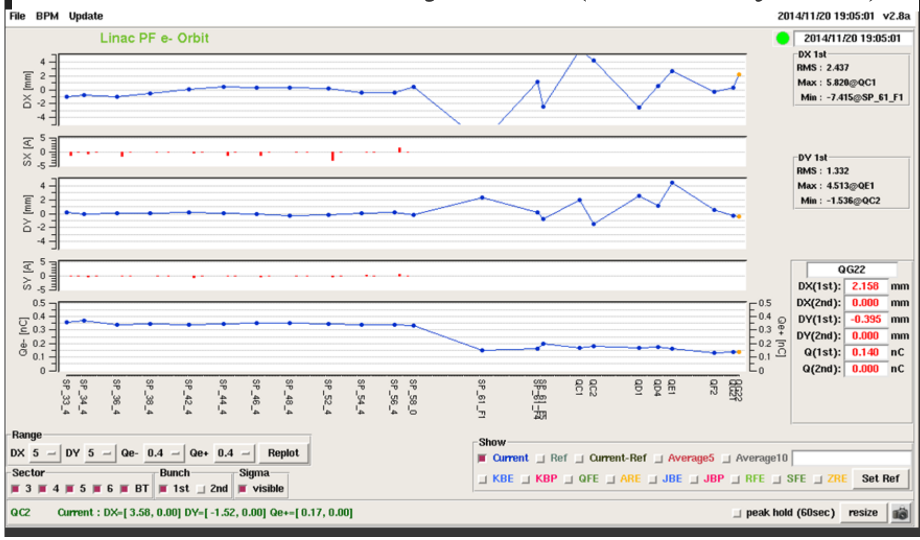

- Bucket selection: MR, DR
- # of EVG: 1 => 3
- CPU: MVME5500 => MVME6100
- RTOS: VxWorks5.5 => 6.8
- Firmware updated



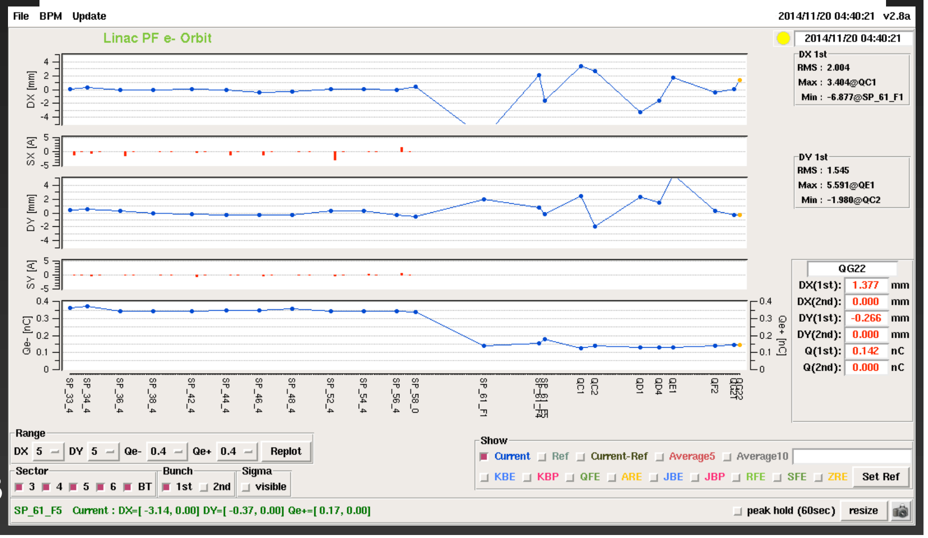
# Beam injection study
## (new timing system configuration)

- PF/PF-AR injection study were conducted w/ new EVG configuration and software.
- Beam orbit and injection rate is quite similar between current and new system configuration.
- Wire scanner/BPM works well.
- Long-term stability will be tested after this Apr.

Beam orbit for PF injection (current system)

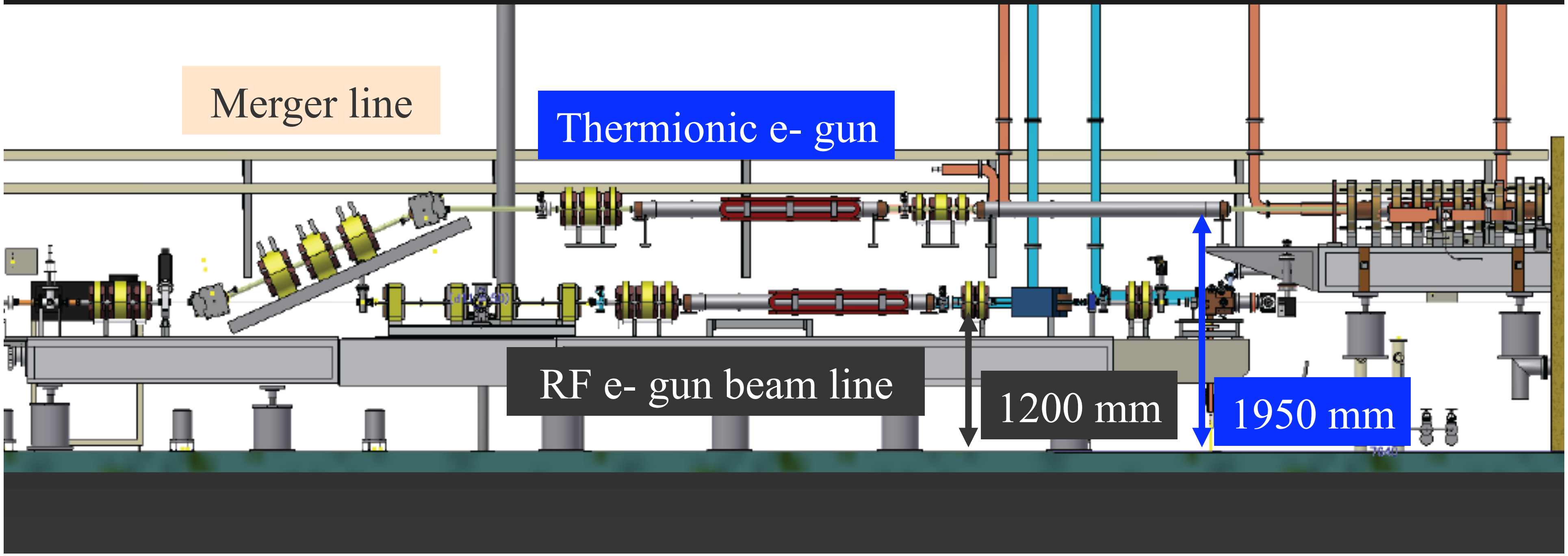



Beam orbit for PF injection (new system)



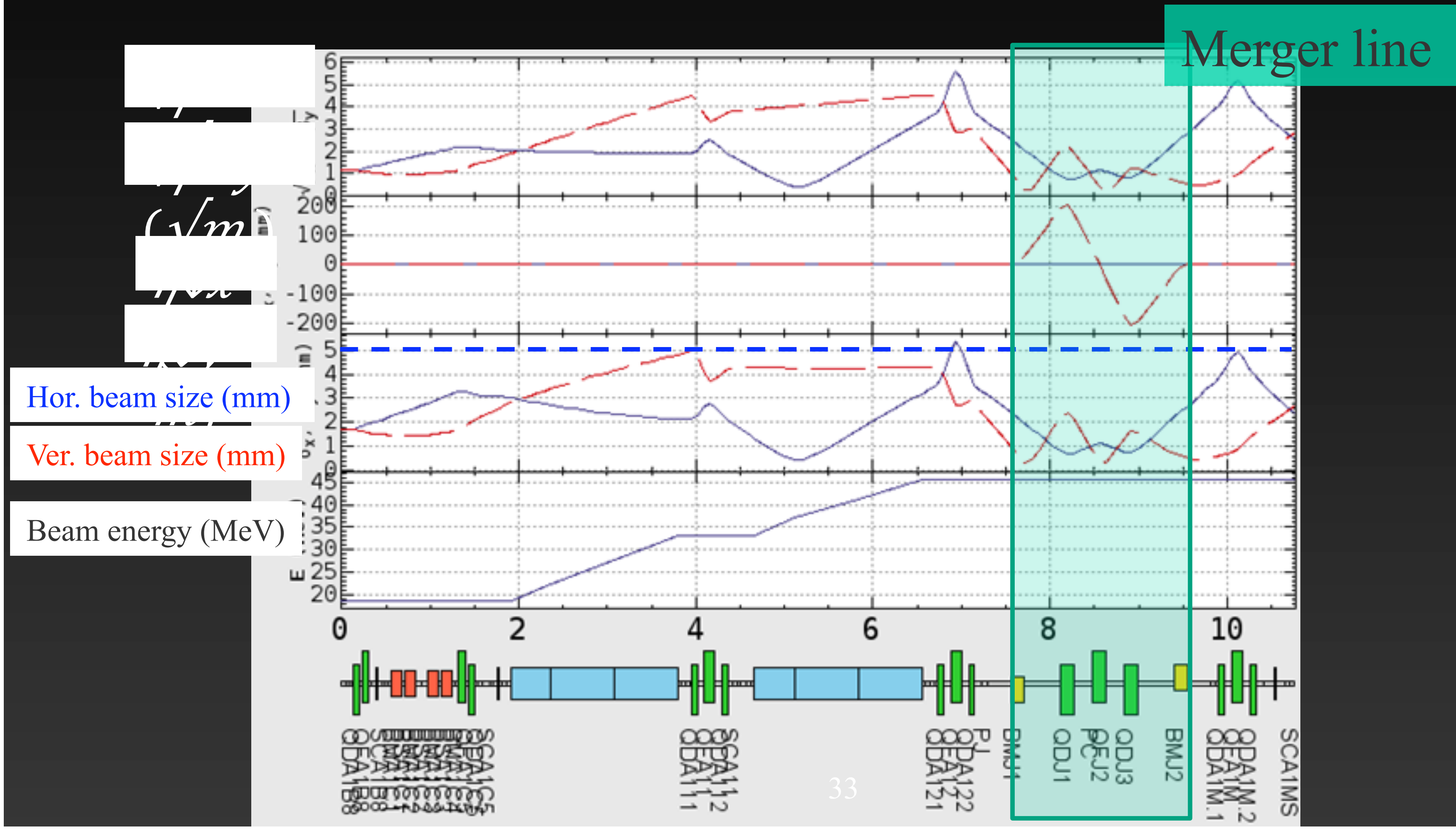
# Unit A1 (reconfiguration)

- Thermionic e- gun will be temporarily back in end of this Apr. (for radiation control license and e+ primary e- generation of 10 nC)
  - Keep the beam line for rf gun in current position.
  - Beam line level of beam line will be changed from 1200 mm to 1950 mm.
  - Spare magnets will be used for new beam line.
- Thermionic e- gun commissioning will be started in early May.



# Optics design

- Quadrupole triplets will be installed in merger line.
- Beam size is not so large in comparison with bore radius of vacuum chamber .



# Issues

- Injector commissioning
  - Oct. and Dec. of 2013/ Apr. ~ Jun. of 2014/ Oct. ~ Dec. of 2014
  - Not enough time for commissioning
  - e+ commissioning:
    - Installation of flux concentrator delayed from Dec. of 2013 to May of 2014.
    - Twice accidents in Dec. of 2013 and Dec. 2014 (cable burned)
    - First e+ beam was measured in Jun. of 2014.
    - Progress of LAS rf conditioning is slow.
    - Not enough primary e- bunch charge at target (≤ 1 nC)
  - e- commissioning:
    - Discharge of rf gun cavity. Not enough power for rf gun cavity (12 MW/20 MW)
    - Shot-by-shot beam stability of charge and position/angle from gun is not yet enough. Difficulty to keep the high bunch charge in long term period.
    - Beam loss at Unit-A1 (chicane) and J-ARC

# Summary and Plan

- Beam commissioning w/ A1 rf gun started in Oct. of 2013.
  - Not enough time for commissioning
  - **5.6 nC (from rf gun), 0.75 nC (Linac end)**
  - Stability is still issue. (Shot-by-shot and long term)
- Unit-A1 reconfiguration will be completed before end of Apr. Thermionic e- gun commissioning in May.
- Beam commissioning w/ thermionic e- gun (May, June)
  - Measure Quadrupole center to BPM center offset
  - Reduce beam loss at Unit-A1/J-ARC
  - Development of commissioning tools and tests (beam based alignment/ emittance preservation)
  - Pulsed Quads (x2) and steering (x2) will be tested in Sector2.
- Prepare stable e-/e+ beams (1 nC w/o low emittance) before MR commissioning Phase-I.

# backup

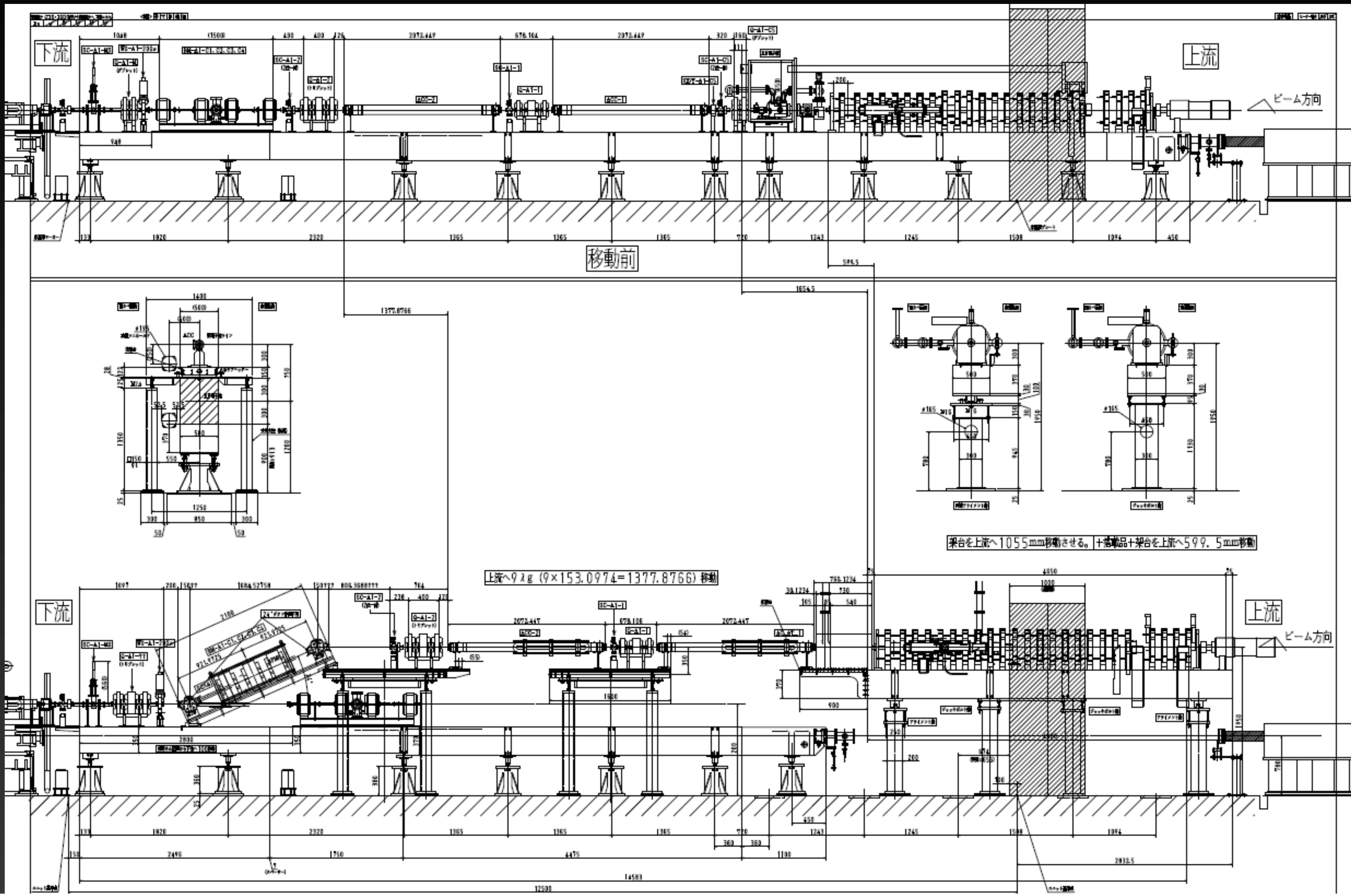
# e- beam parameters

| | SuperKEKB | KEKB |
|---|---|---|
| Energy (GeV) | 7.0 | 8.0 |
| HER stored current (A) | 2.6 | 1.1 |
| HER beam lifetime (min.) | 6 | 200 |
| Maximum beam repetition (Hz) | 50 | 50 |
| Max. # of bunch in an rf pulse | 2 | 2 |
| Emittance (mm·mrad) | 50/20 (Hor./Ver.) | 100 |
| Charge (nC) | 5 | 1 |
| Energy spread (%) | 0.1 | 0.05 |
| Bunch length σz (mm) | 1.3 | 1.3 |
| Damping ring | - | - |
| Simultaneous top-up injection | 4 rings (SuperKEKB e-/e+, PF, PF-AR) | 3 rings (KEKB e-/e+, PF) |

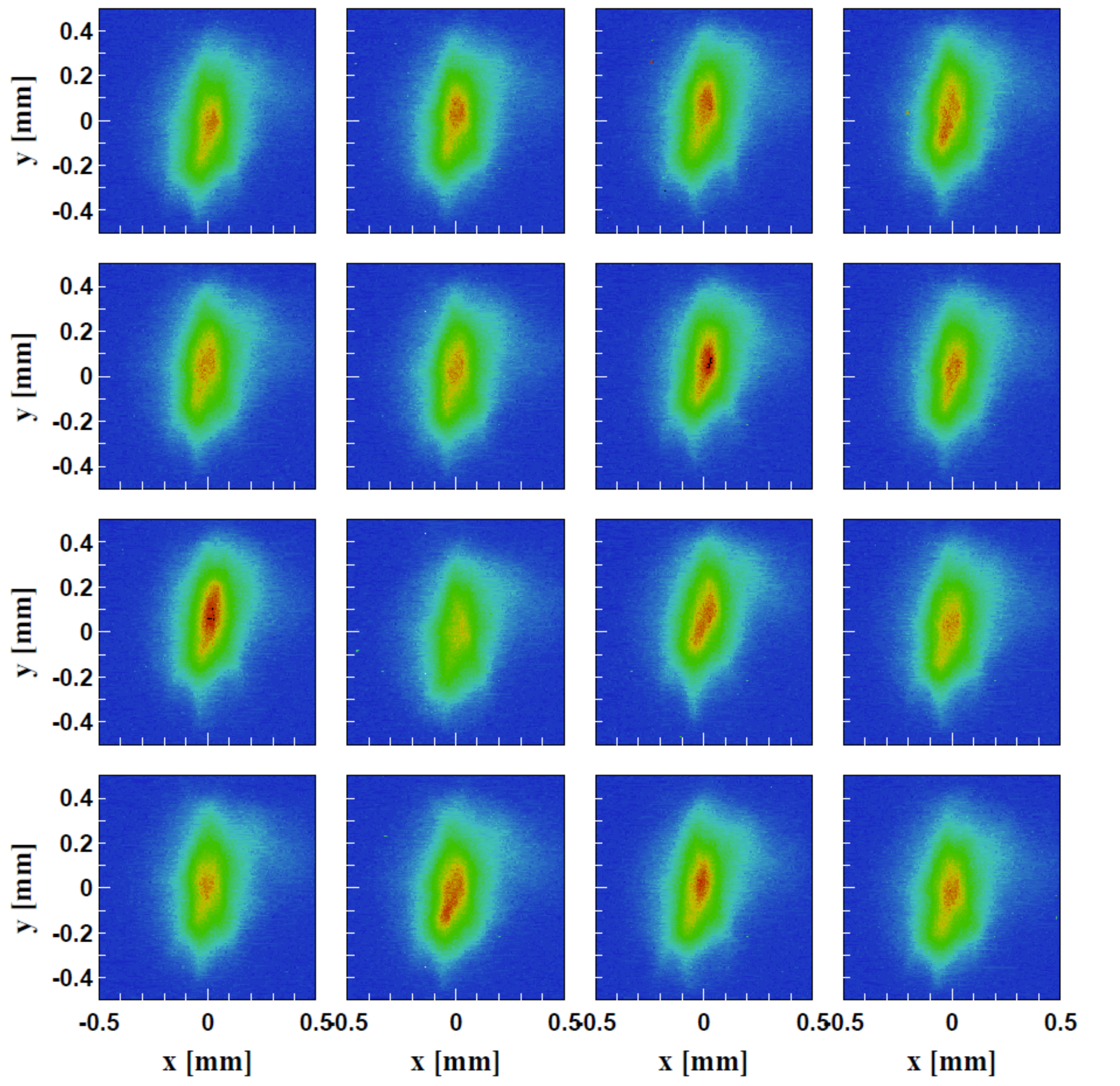
# e+ beam parameters

| | SuperKEKB | KEKB |
|---|---|---|
| Energy (GeV) | 4 | 3.5 |
| LER stored current (A) | 3.6 | 1.6 |
| LER beam lifetime (min.) | 6 | 133 |
| Maximum beam repetition (Hz) | 50 | 50 |
| Max. # of bunch in an rf pulse | 2 | 2 |
| Emittance (mm·mrad) | 100/20 (Hor./Ver.) | 2100 |
| Charge (nC) | 4 | 1 |
| Energy spread (%) | 0.07 | 0.125 |
| Bunch length σz (mm) | 0.7 | 2.6 |
| Damping ring | ○ | - |
| Simultaneous top-up injection | 4 rings (SuperKEKB e-/e+, PF, PF-AR) | 3 rings (KEKB e-/e+, PF) |

# Design drawing of A1 beam line

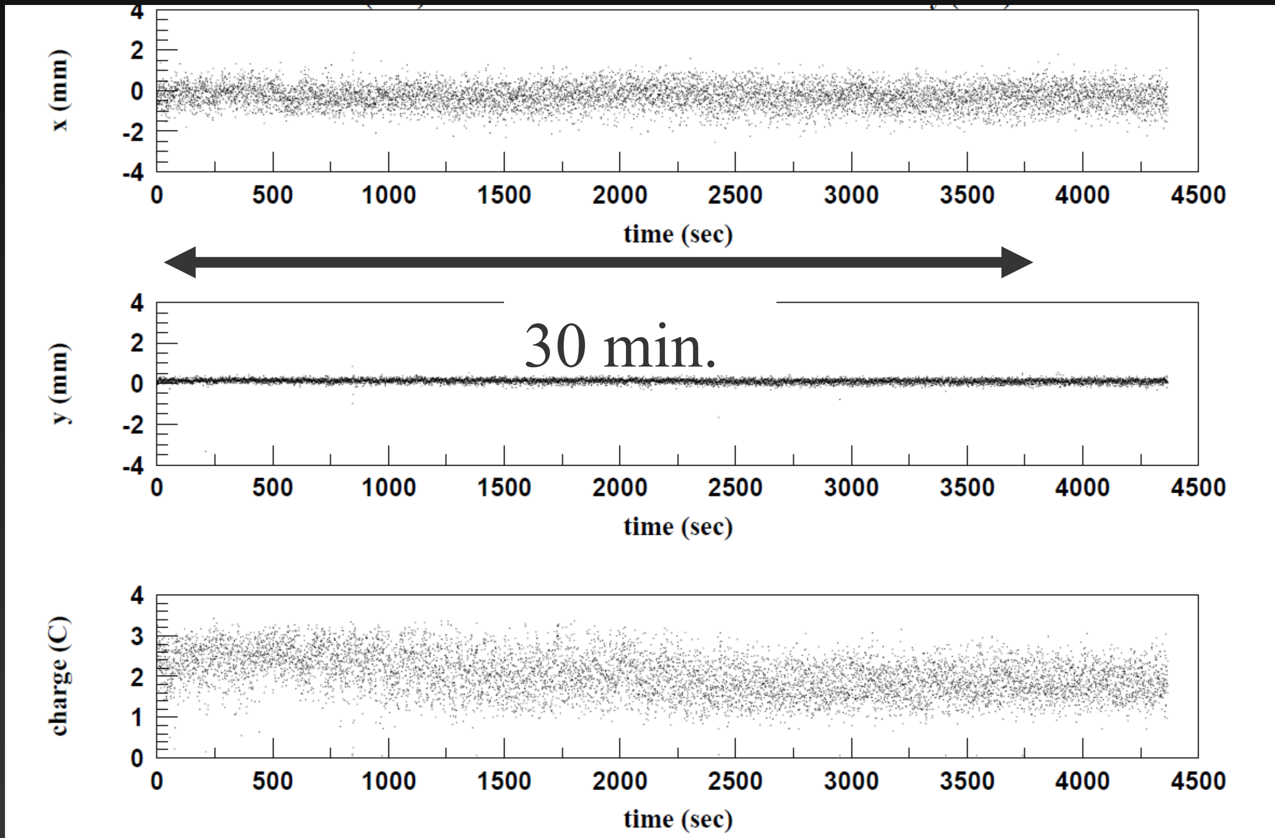


# Shot-by-shot beam profile stability



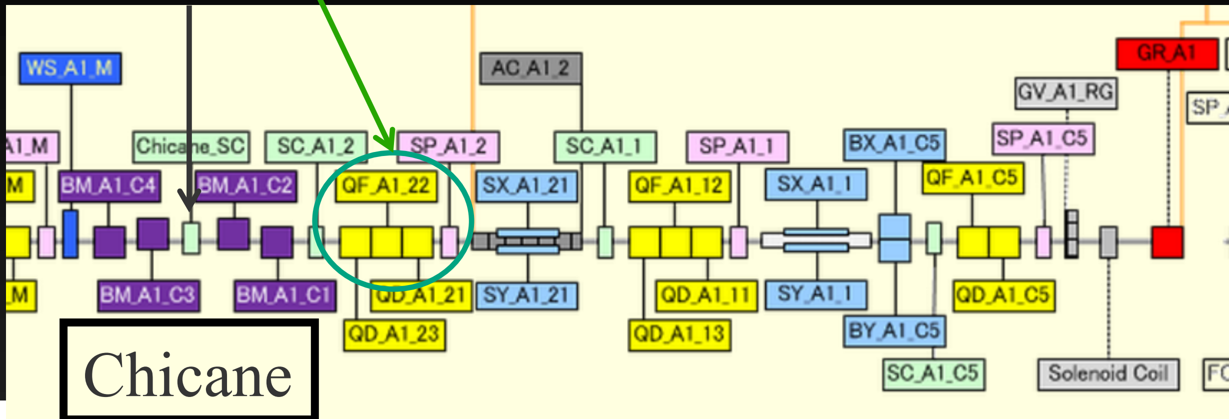
# Beam position stability @ SP_A1_C5

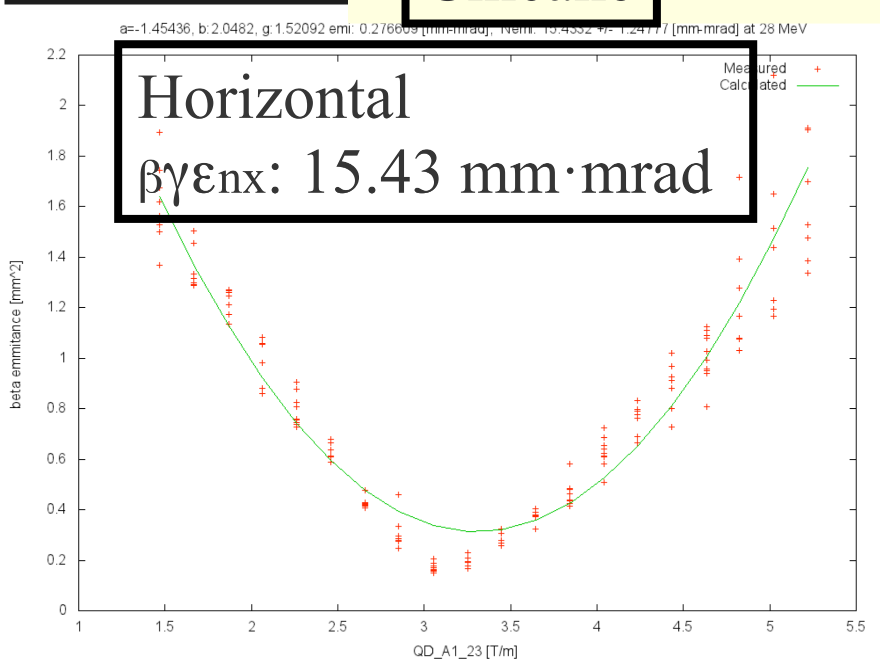
- Measured beam position at first BPM (SP_A1_C5)
  - σx ~ 0.57 mm
  - σy ~ 0.11 mm
- Fluctuation of horizontal beam position is larger than vertical one.

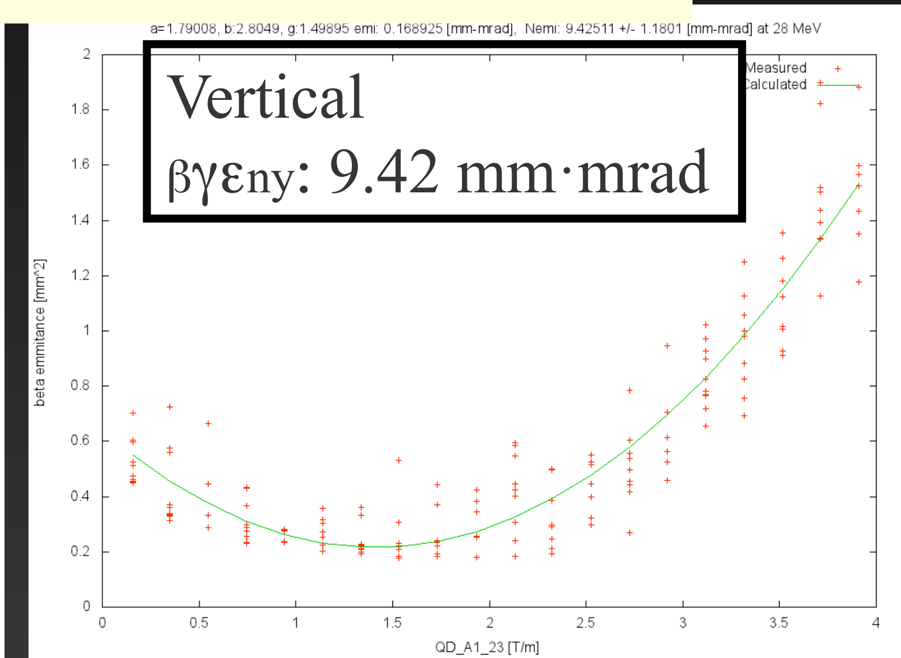


# Emittance measurement example (Unit-A1)

- Quadrupole scan
- Screen monitor at chicane

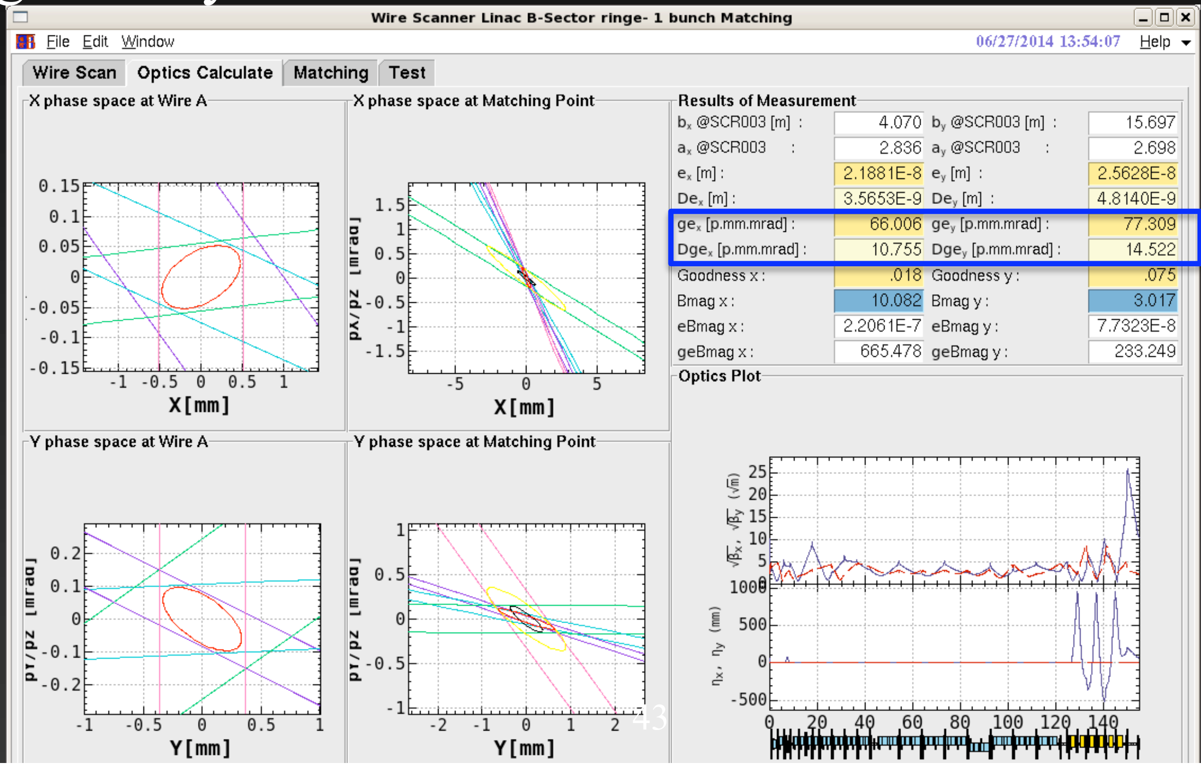


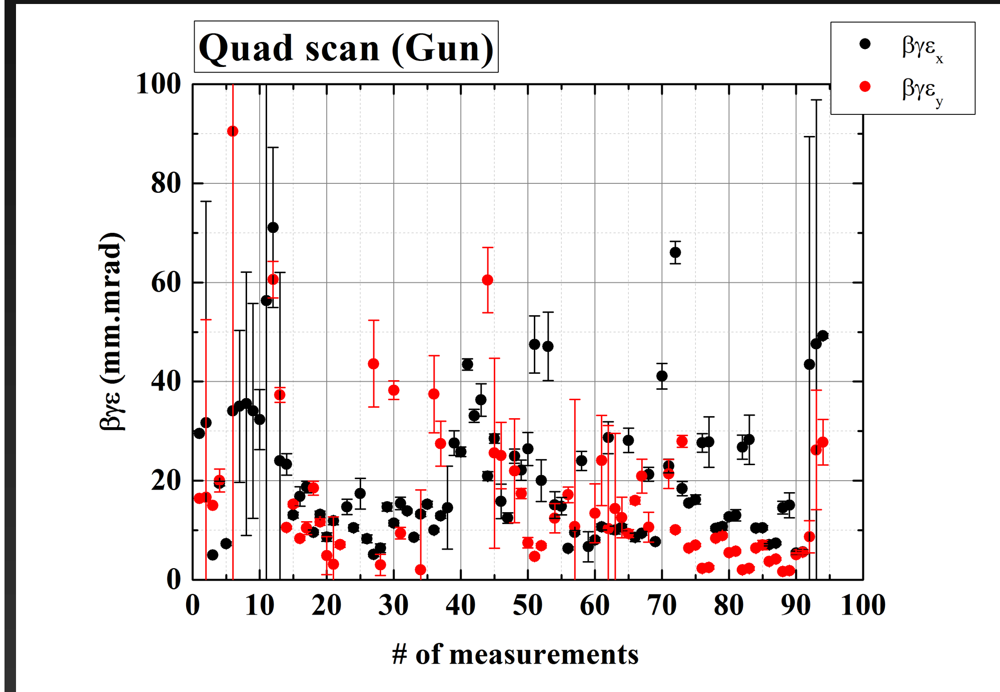
# Emittance measurement example (Sector B)

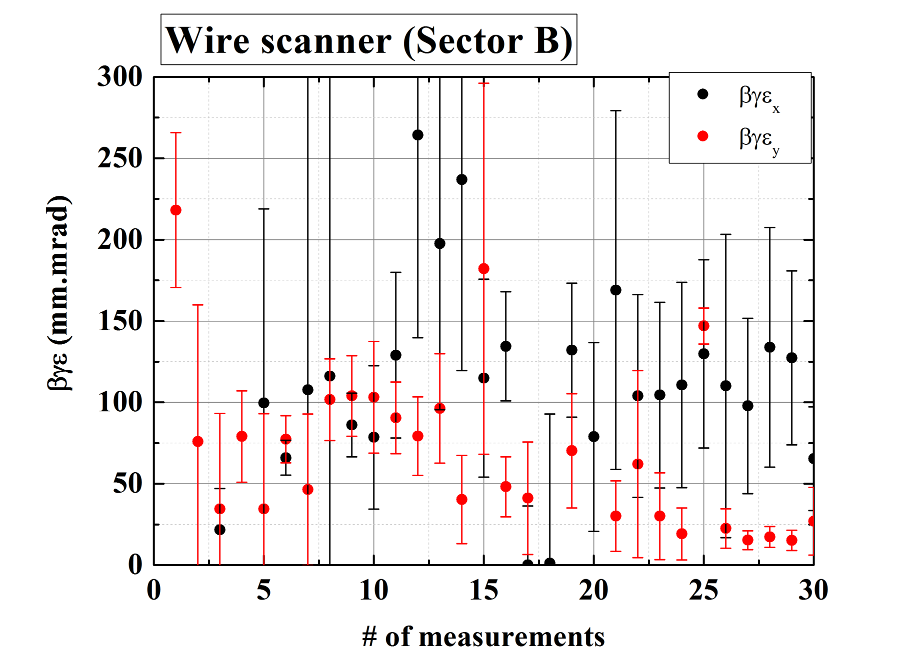
- Multiple wire scanner at the end of Sector B
- Typical result (1 nC):
  - $\varepsilon_{n,x}$: 66.006 ± 10.755 mm·mrad
  - $\varepsilon_{n,y}$: 77.309 ± 14.522 mm·mrad
- Charge stability is not so small. Software is under development for subtracting shot-by-shot beam fluctuation.



# Emittance measurement

- Emittance of rf gun and SectorB were measured by Quad scan and multiple wire scanner, respectively.
- Results measured in Nov. and Dec. of 2014.
- Vertical emittance is smaller than horizontal one.



# Two bunch operation example


1st bunch charge

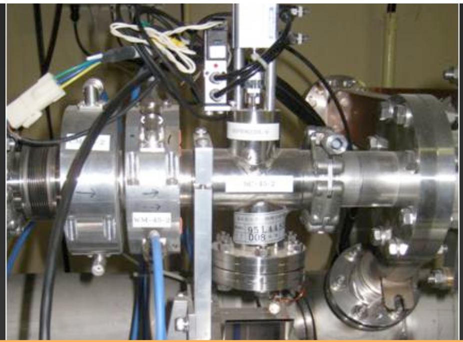
2nd bunch charge

# Profile monitor

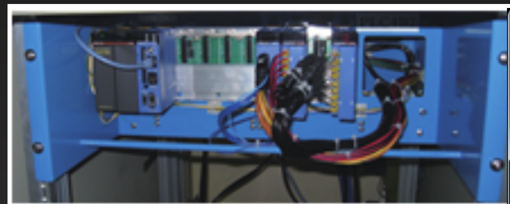
- Screen material is made of 99.5% $Al_2O_3$ and 0.5% $CrO_3$ (AF995R, Demarquest Co.). (t: 1 mm)
- Linux/PLC (x31) control profile monitor (insert/remove, video signal select, limit switch, LED illumination, pneumatic air pressure).
- EPICS IOC is running on Linux/PLC. HLA is implemented by Python.

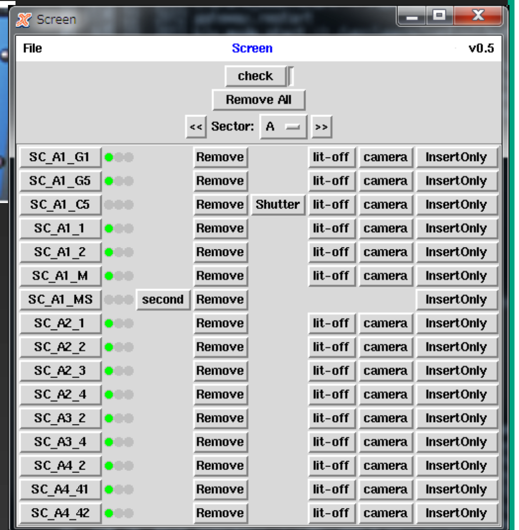
Beam profile

Monitor and CCD camera



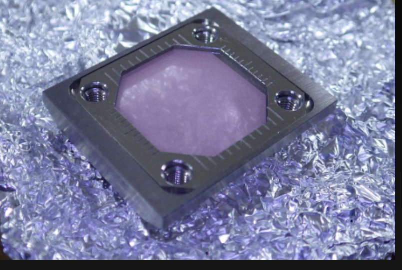
Controller and HLA

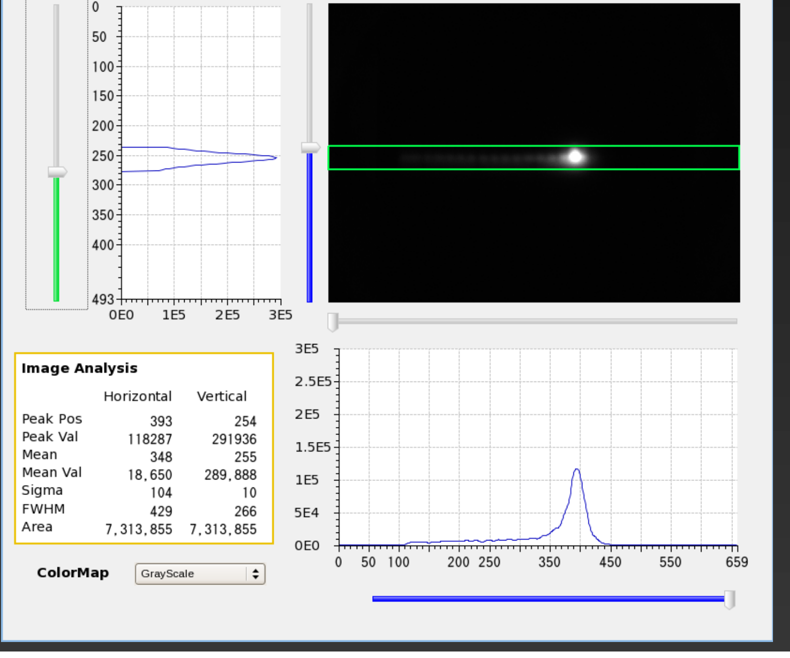


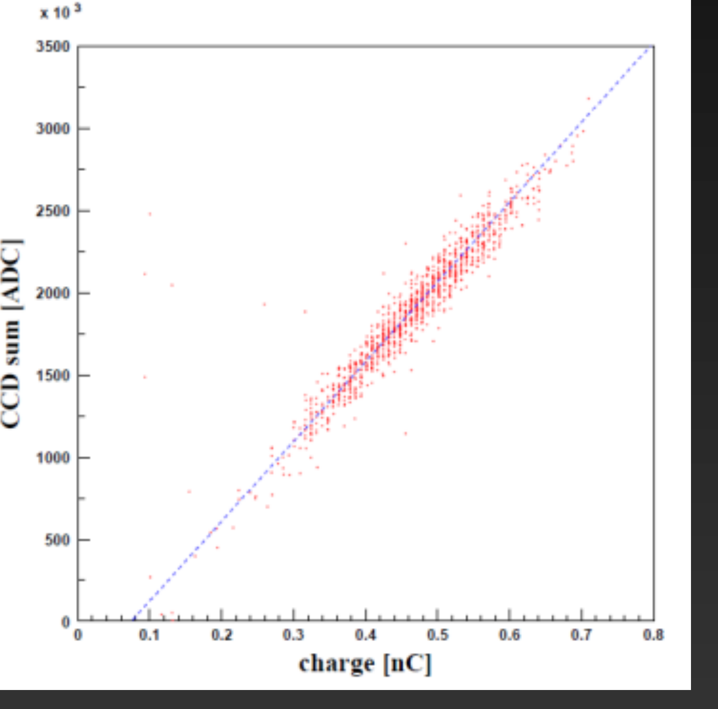


# Profile monitor (cont'd)

- 7/97 were replaced by 30-µm-thick one for precise beam size/emittance measurement (Quadrupole scan).
- CCD cameras have been replaced by new one.
  - Allied Vision: GC650 w/ GbE
  - Ext. trigger input
  - EPICS IOC, CSS for HLA

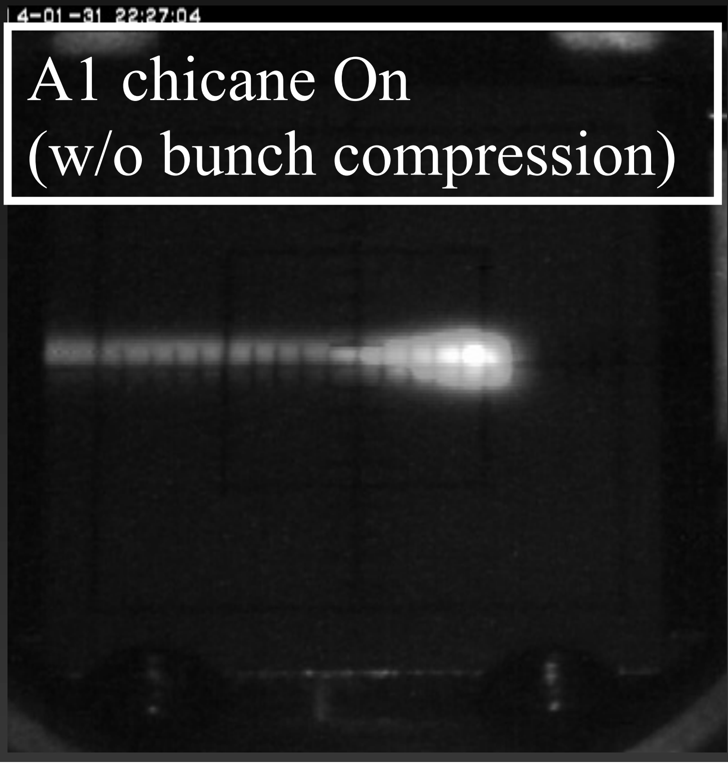


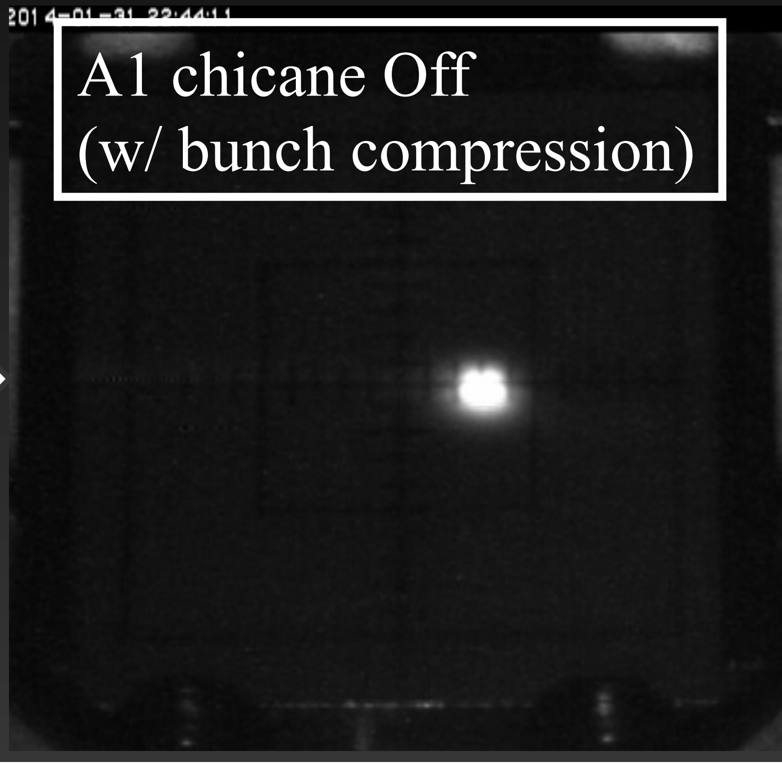


# Energy spread measurement @ J-ARC

- Measure beam energy spread by screen monitor (middle of J-ARC) w/ and w/o bunch compression at A1 chicane.
- Bunch compression at A1 unit is effective for energy spread compensation.



# Summary of e- commissioning

| Item | Requirement | Current status |
|---|---|---|
| Beam charge (nC) | 5 (10 for e+ primary) | 5.6 (first BPM)<br>0.58 (Linac end) |
| Beam energy (GeV) | 7 | 7 |
| Normalized emittance (mm·mrad) | 50/20 (Hor./Ver.)<br>(at the end of Linac) | 20/7 (Hor./Ver.)<br>(from RF gun) |
| Bunch charge stability | 2.5% (KEKB), 1% (PF/PF-AR) | 10% ~ 20% |
| Bunch compression (Unit-A1) | 30 ps => 10 ps | 30 ps => 10 ps |
| Bunch compression (J-ARC) | 10 ps => 5 ps | n/a |
| Temporal manipulation of laser | Uniform shape | n/a |
| Emittance preservation | 20 mm·mrad (Linac end) | n/a |
| Max. beam repetition | 50 | 25 |
| # of bunches | 2 | 2 |
| Operation | Simultaneous top-up | n/a |