Injector Commissioning
(Phase I & II)

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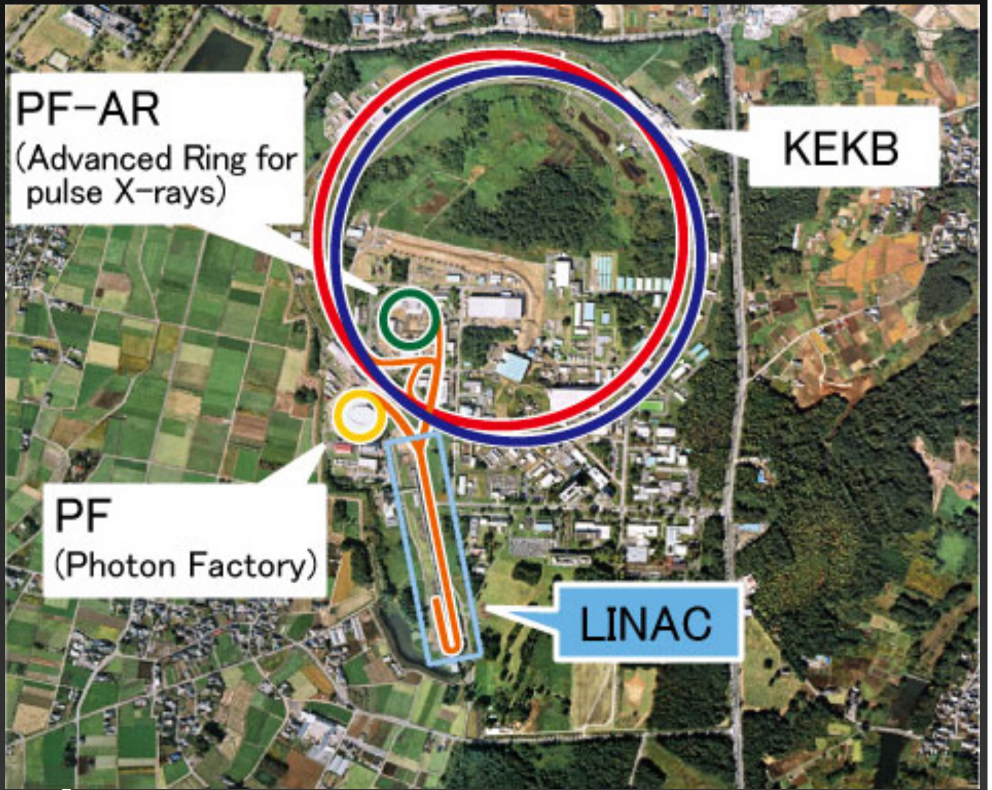
Injector overview

- Injector linac
  - Provide e-/e+ for 4 independent storage rings
  - 600-m-long, 25 Hz (Max. rep. 50 Hz)
  - Two bunch operation (96 ns interval)
- SuperKEKB
  - HER: 7 GeV, 1 nC
  - LER: 4 GeV, 1 nC

    Damping ring: 1.1 GeV
- Two light sources:
  - PF: e-, 2.5 GeV, 0.3 nC

    three times daily injection or top-up
  - PF-AR: e-, 3 GeV, 0.3 nC

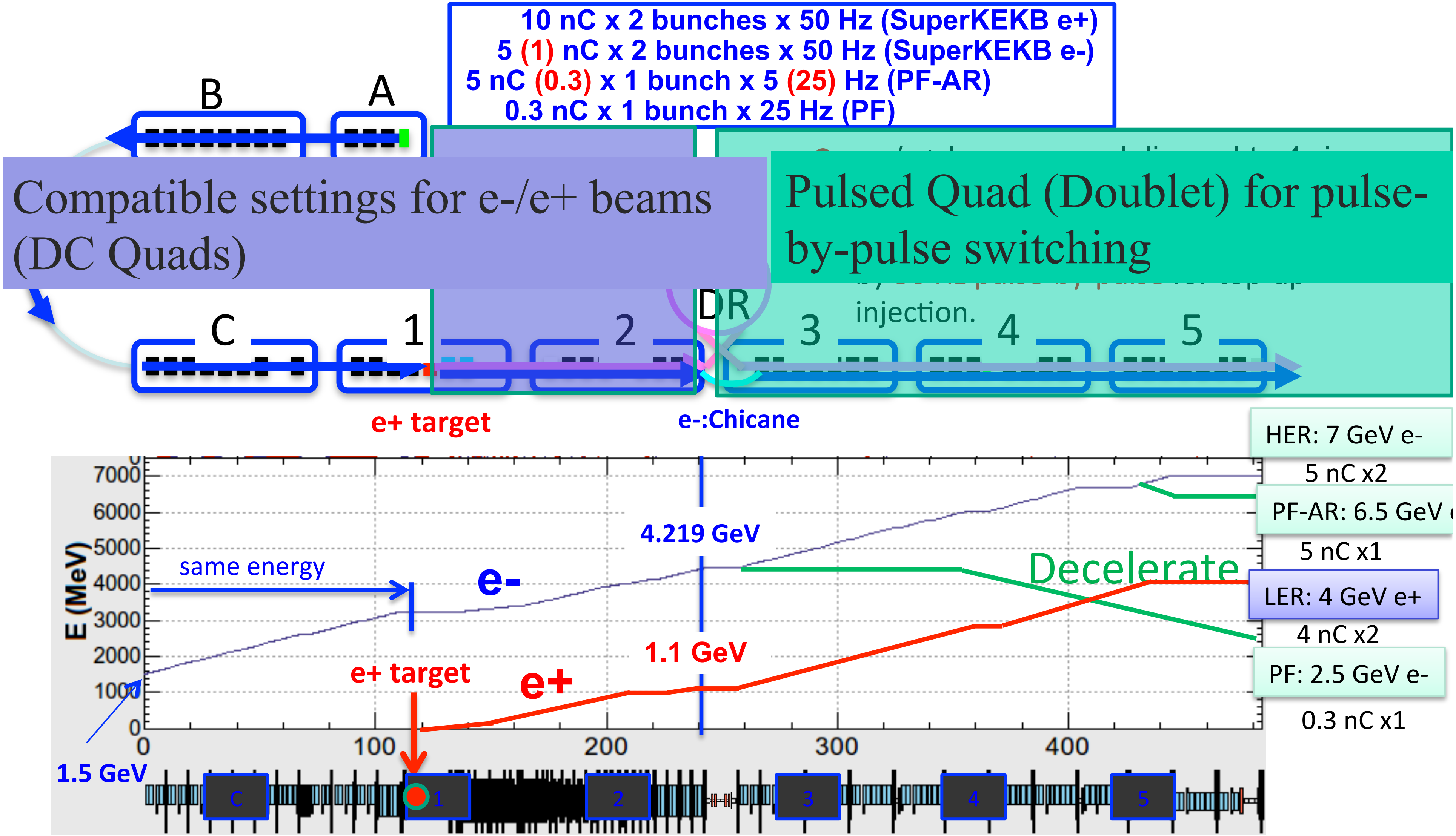
    three times daily injection



Requirements for SKEKB injector

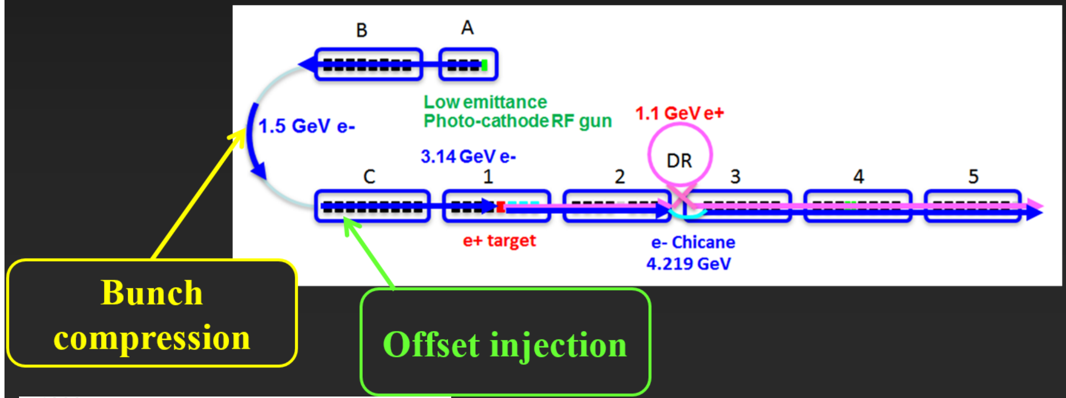
- Low emittance e-/e+ beam:
  - e-: 1 nC, 300 mm·mrad (KEKB) => 5 nC, 50 (H)/20 (V) mm·mrad (Phase III)
  - e+: 1 nC, 1500 mm·mrad (KEKB) => 4 nC, 100 (H)/20 (V) mm·mrad (Phase III)
  - (*) 1 nC (w/o low emittance) for Phase I, 2 nC (w/ low emittance) for Phase II
  - Low emittance photocathode rf gun. DR for e+. Fine component alignment (0.1 mm – 0.3 mm (σ)). Precise beam orbit measurement and control for low emittance preservation.
- High intensity e+:
  - Flux concentrator, Large aperture S-band accelerating structure
- Event based timing system (bucket selection for DR/MR)
- Fast rf monitor, high precision BPM readout, pulsed quads and steering magnets.
- Simultaneous top-up injection (short beam life time (～ 6 min.))
  - SKEKB HER/LER (+ damping ring), PF, and PF-AR

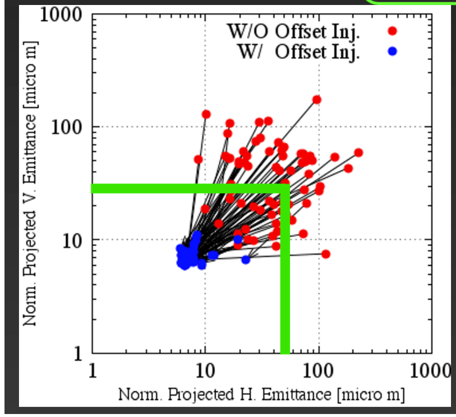
Operation scheme



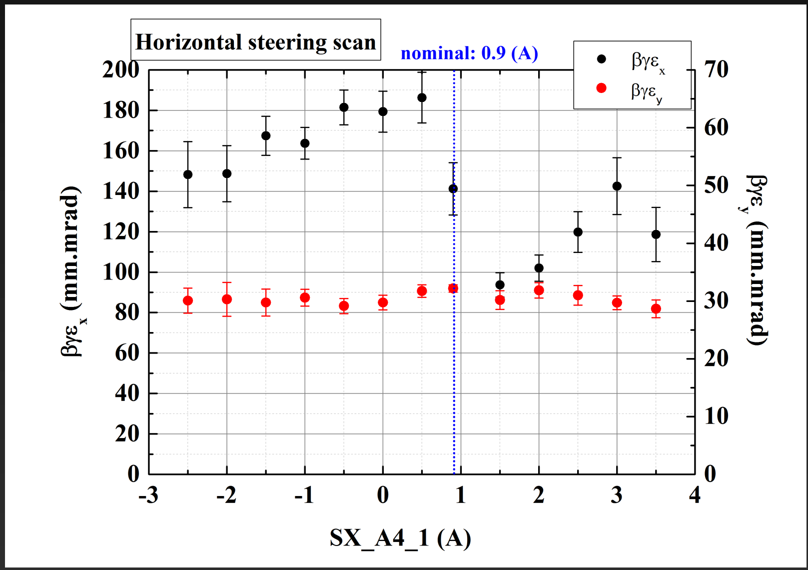
Low emittance preservation

- Low emittance e- beam transport w/o damping ring
- Emittance preservation w/ precise beam orbit control is key issue for e- beam.
- Simulation results show the feasibility of emittance preservation w/ bunch compression and offset injection. Beam study was also conducted.
- Beam study was also conducted at Sector A and B (125 m straight section)





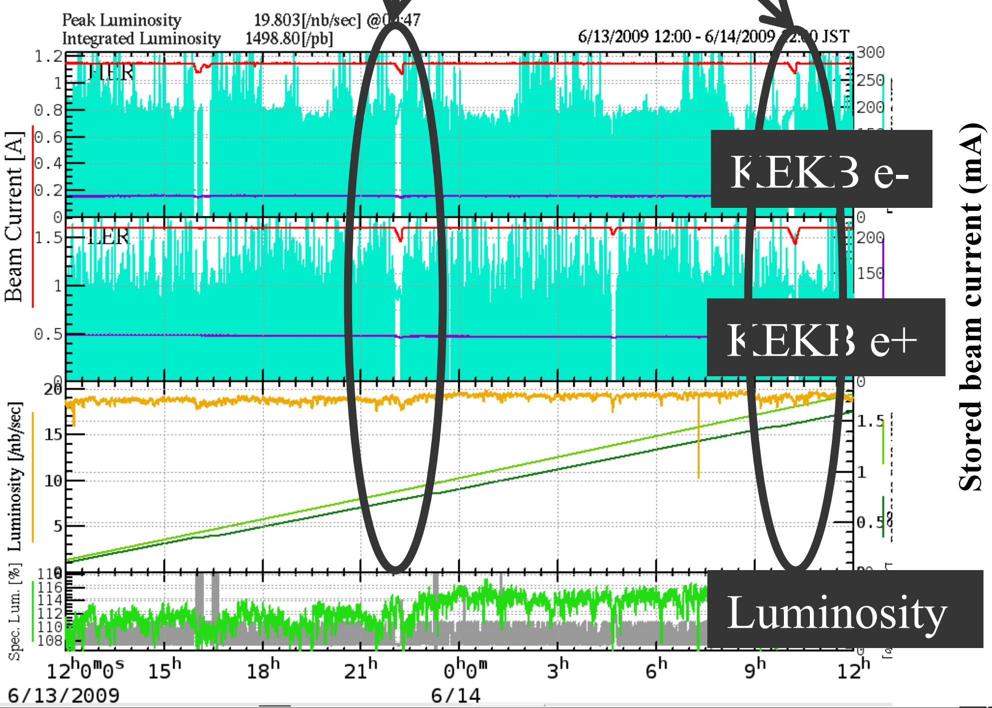
- Simulation -
- Quads and acc. w/ misalignment of 0.3 mm (σ)
- 50 different error seeds
- All seeds can be corrected.



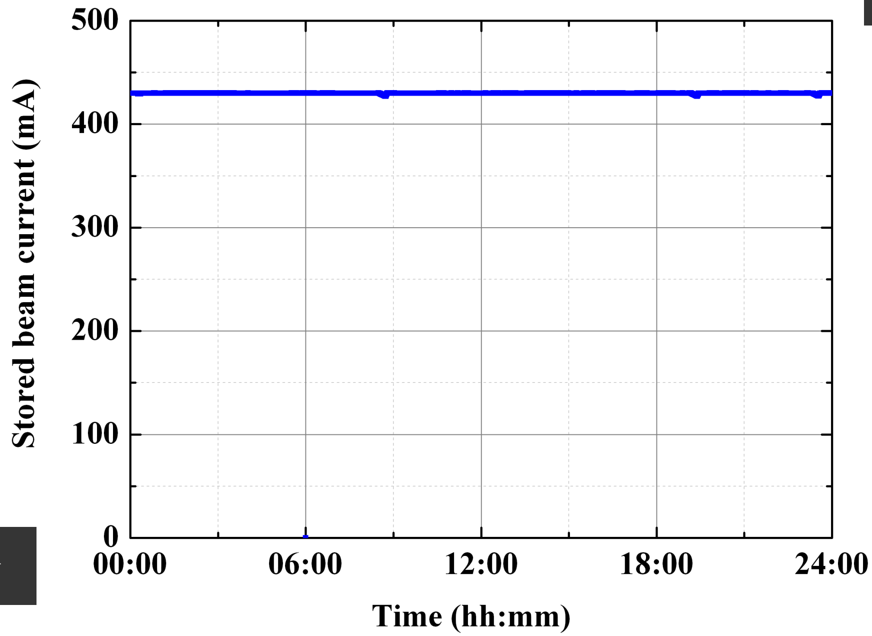
- Experiment -
- Control steering at Sector A
- Emittance was changed at Sector B

Simultaneous top-up injection for three rings

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

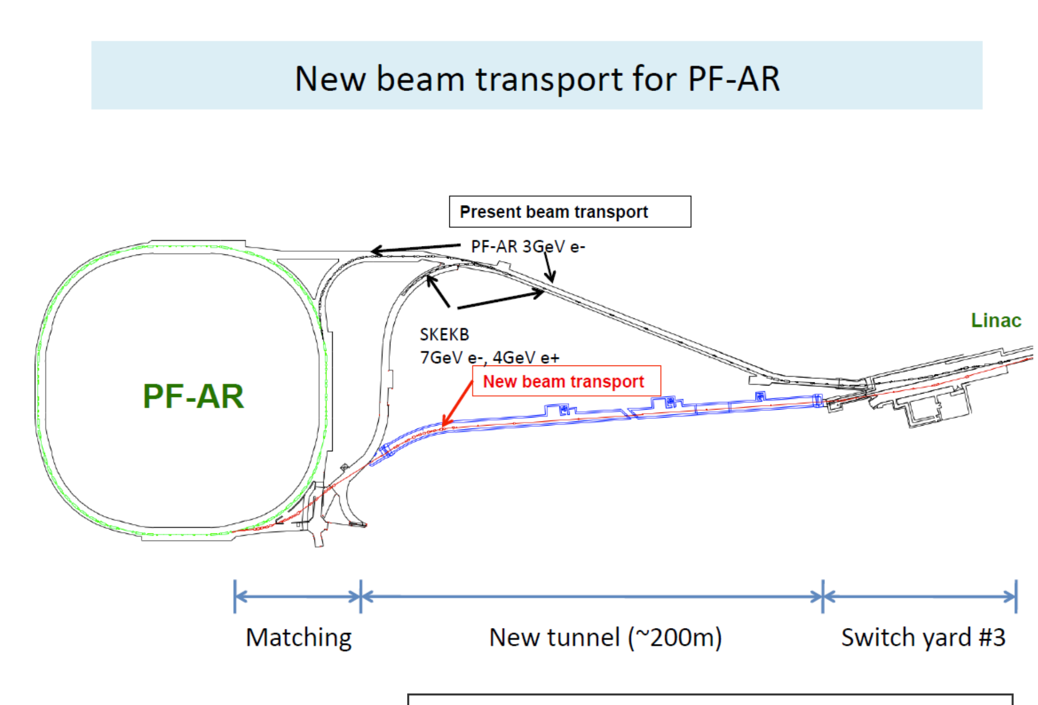


PF



Simultaneous top-up including PF-AR injection

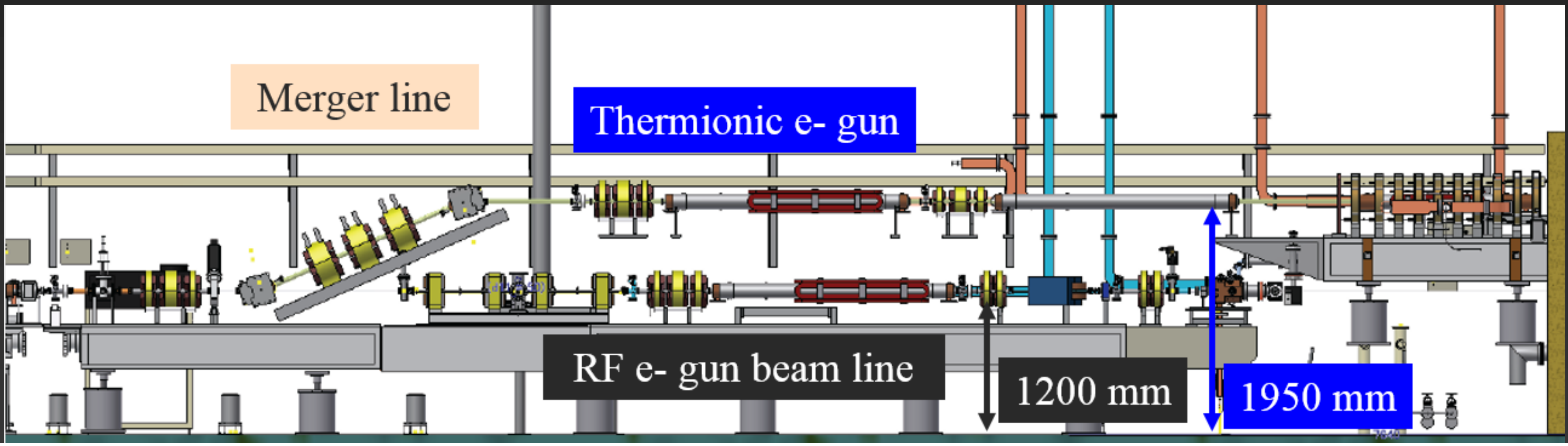
- PF-AR and KEKB share the long part of BT line.
- Existing tunnel space is very tight.
- New tunnel has been constructed in Mar. 2014.
- Pulsed bend will be installed at #3 switch yard of linac.
- New BT commissioning will be conducted in Feb. 2017.



H. Takaki (KEKB review 2013)

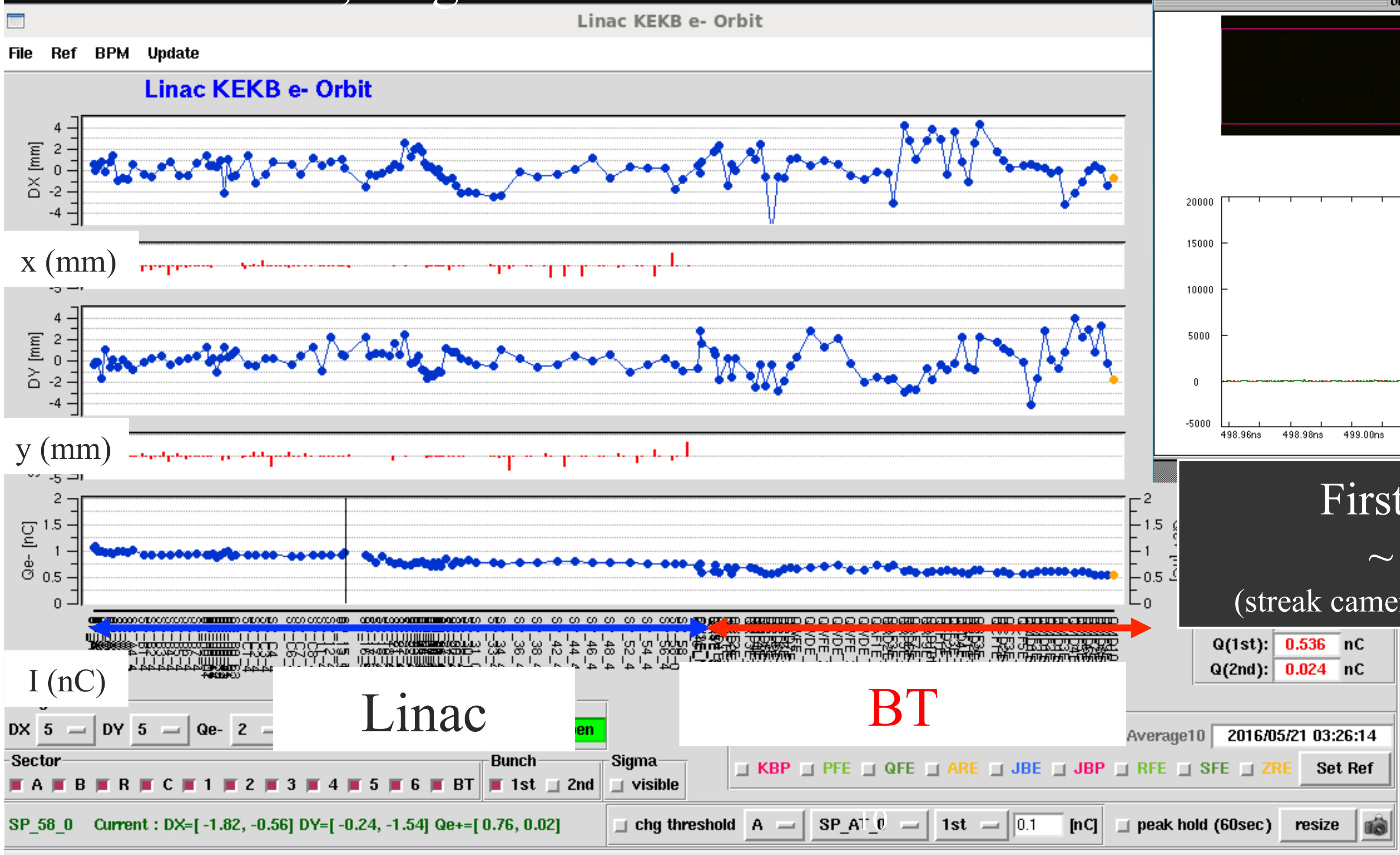
Injector commissioning for Phase I

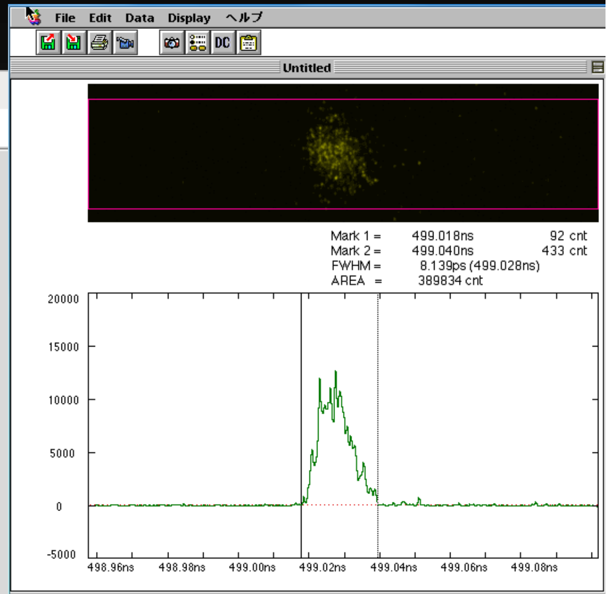
- Thermionic e- gun was reinstalled in end of April 2015.
  - e+ primary e- generation (10 nC). (rf gun achieved the maximum bunch charge of 5.6 nC)
  - Keep the beam line for rf gun in original position.
  - Beam line level of thermionic gun was changed from 1200 mm to 1950 mm.
  - Spare magnets have been reused for the thermionic gun beam line.
- Thermionic e- gun commissioning has been successful in May 2015.
- MR (both of HER and LER) injection by thermionic e- gun started in this February.
- June 8th ~:
  - HER injection: rf e- gun, LER injection: thermionic e- gun



Thermionic e- gun (HER injection)

- Typical operation:
  - 1 nC (gun), 1 nC (linac end), 0.5 nC (BT end)
  - 12.5 Hz, single bunch

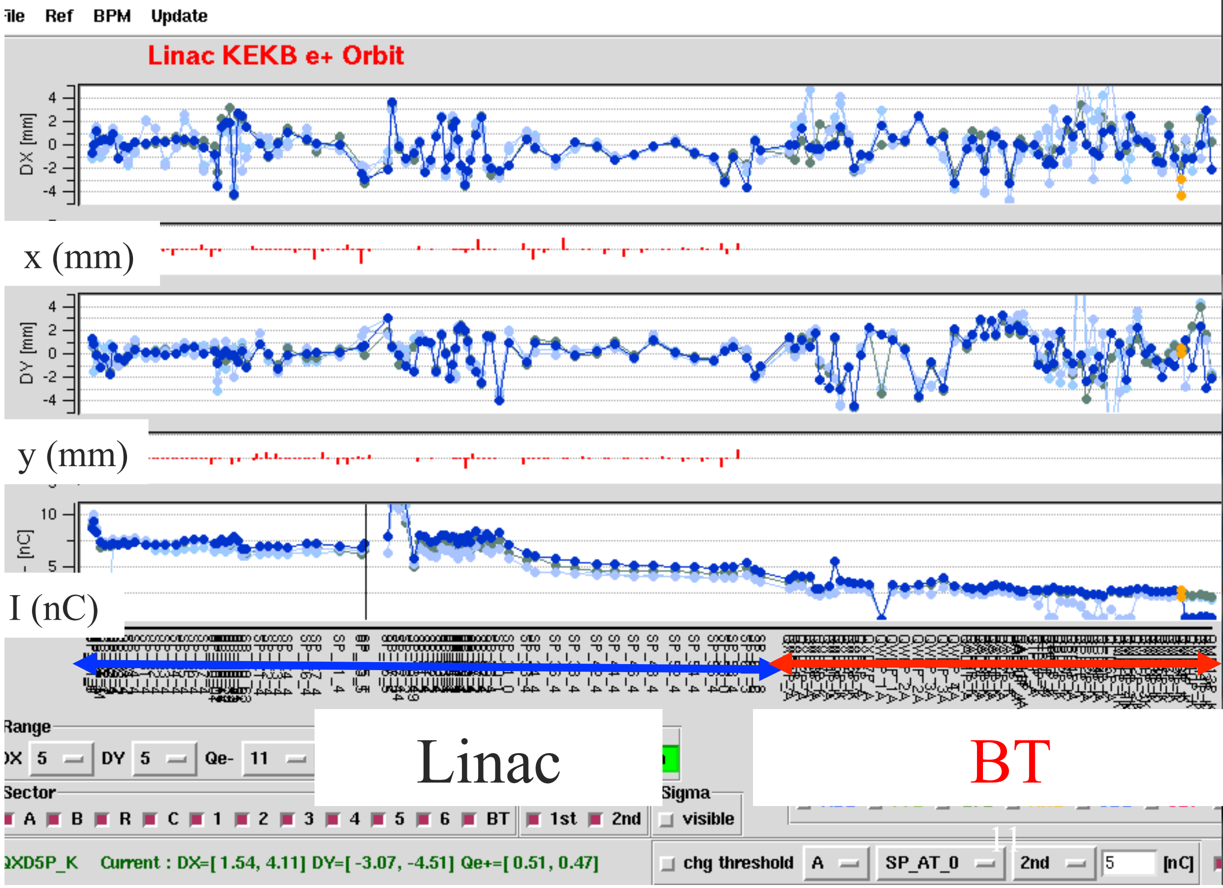


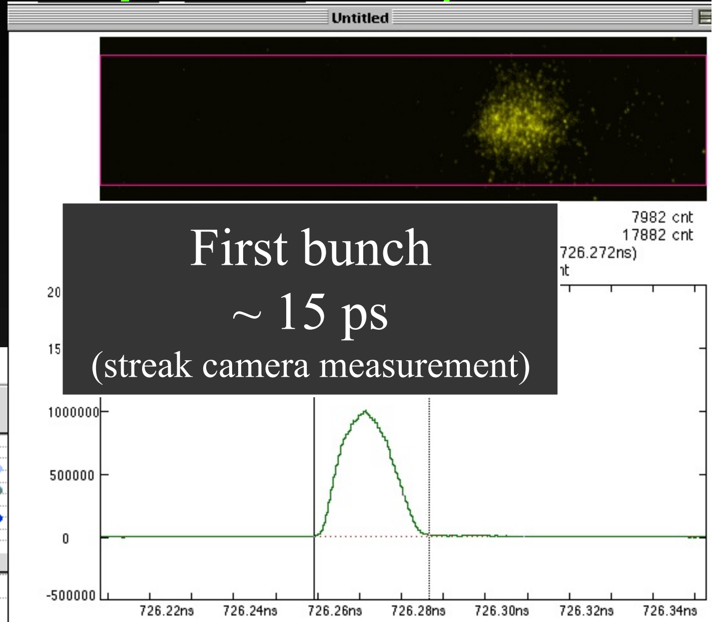


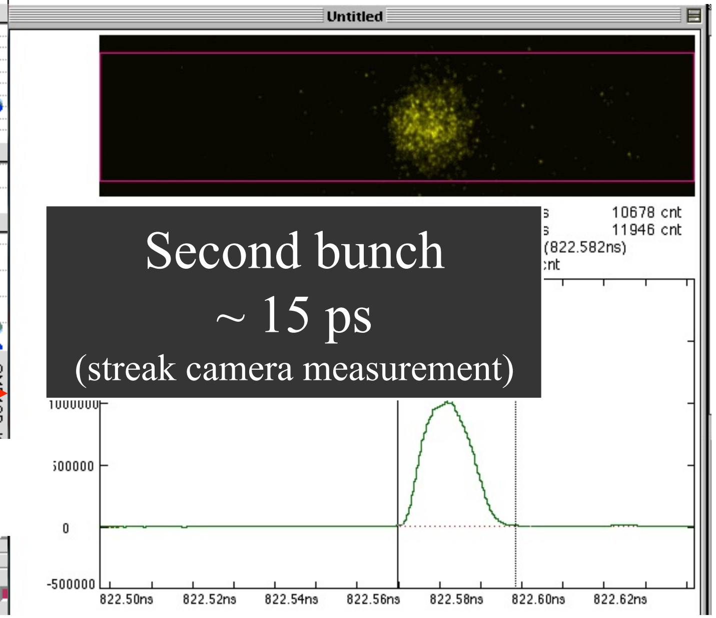
First bunch
~ 8 ps
(streak camera measurement)

Thermionic e- gun (LER injection)

- Typical operation:
  - Primary e-: 10 nC (gun), 7 nC (target)
  - e+: 0.7 nC (linac end), 0.4 nC (BT end)
  - 25 Hz, two bunch

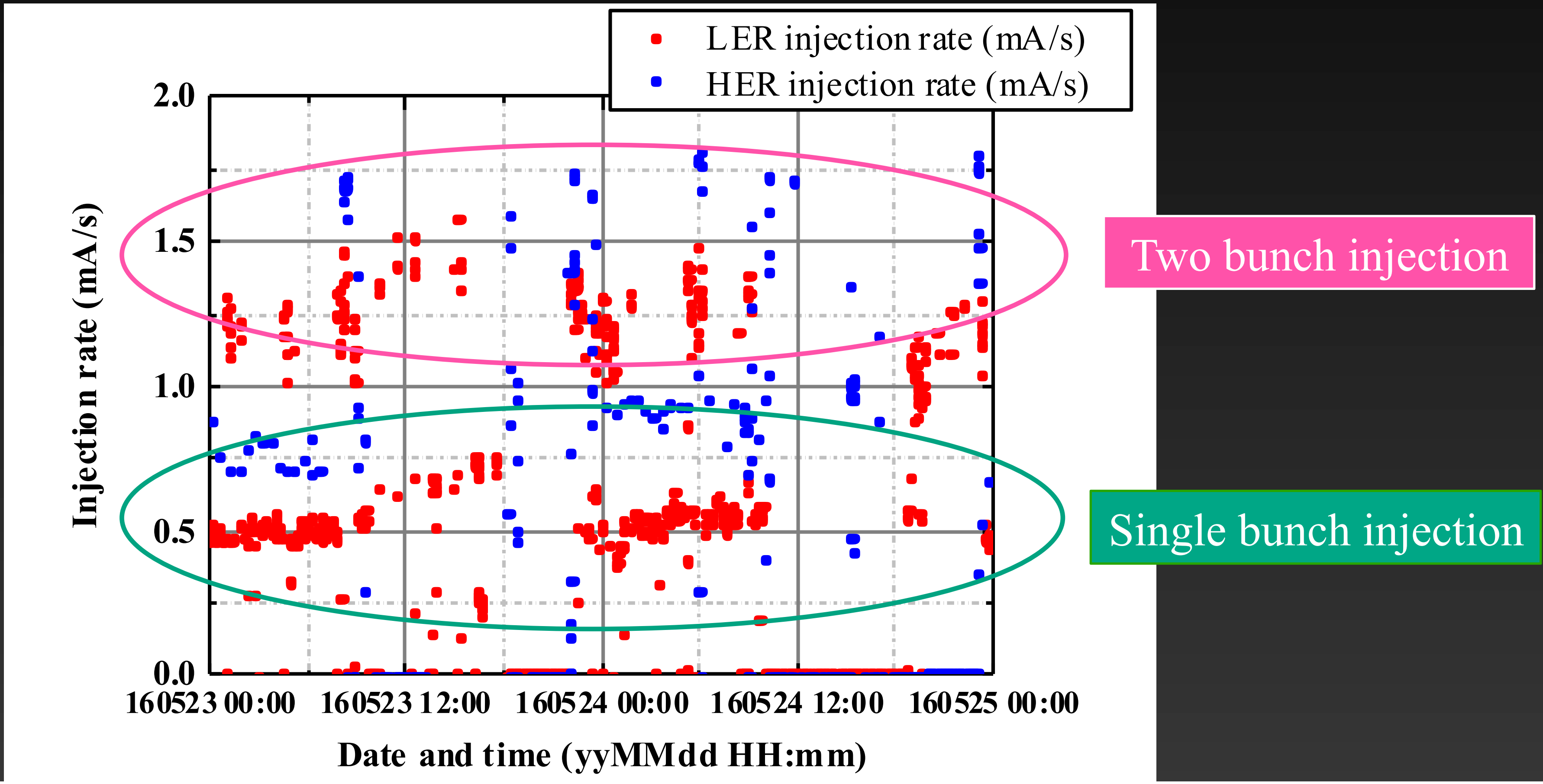






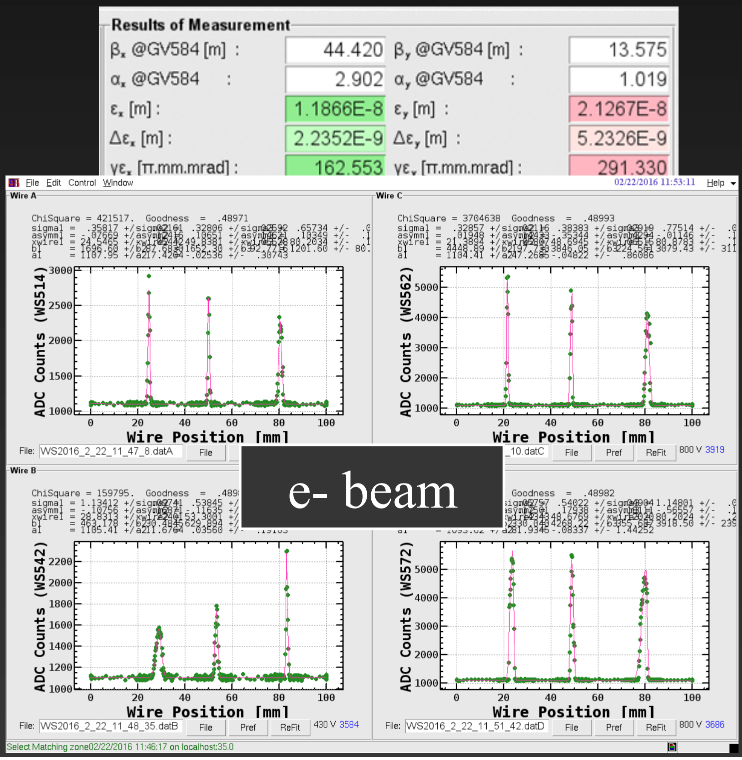
Thermionic e- gun (Injection rate)

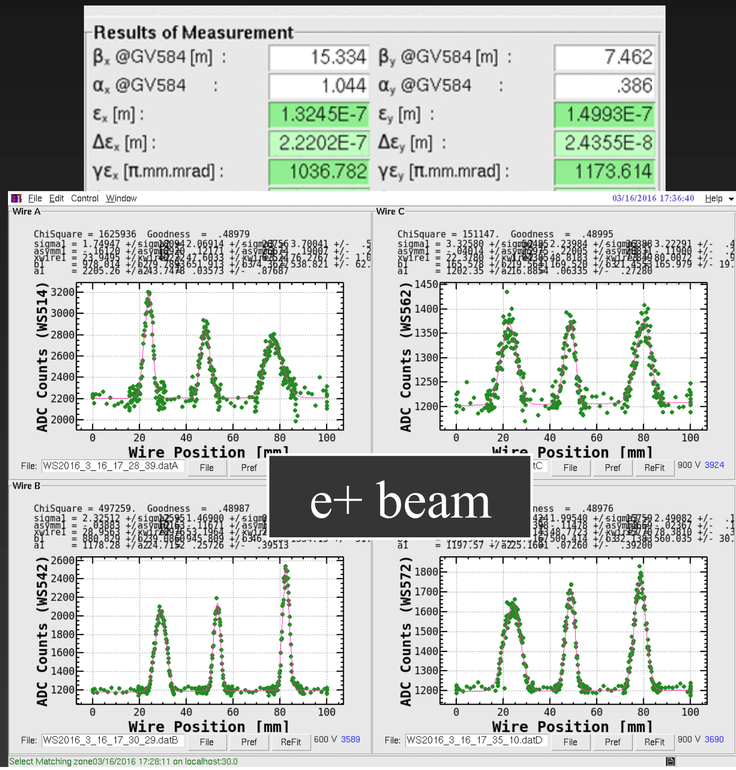
- LER:
  - Injection rate: ~ 0.5 mA/s, efficiency: 70% ~ 100%
- HER:
  - Injection rate: ~ 0.8 mA/s, efficiency: 80% ~ 100%



Thermionic e- gun (emittance)

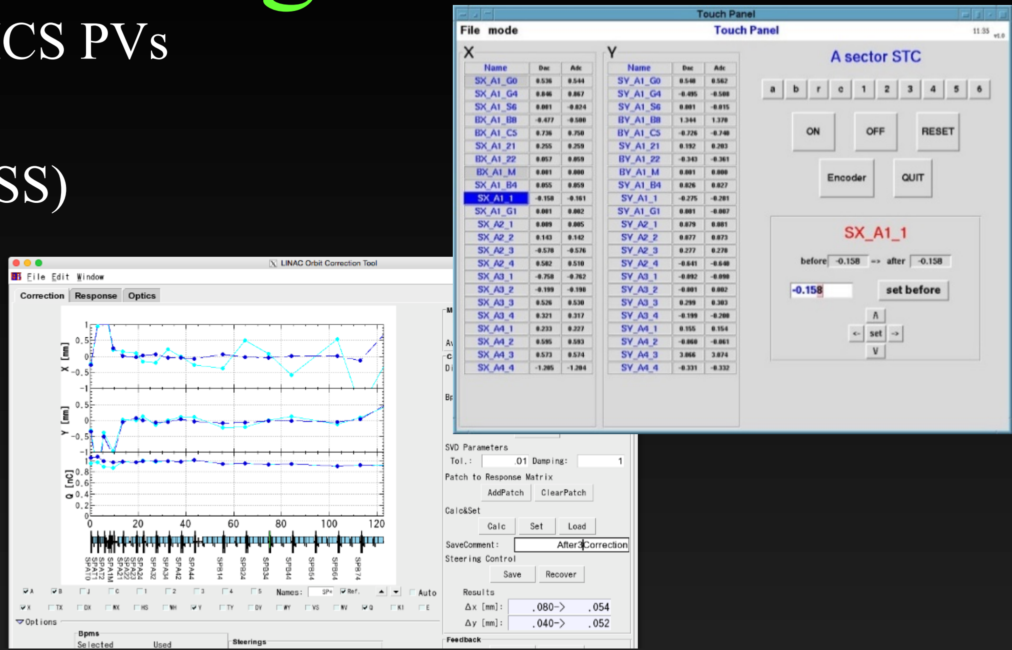
- Emittance was measured by the multiple wire scanner situated at Sector 5.
- e- beam: $\varepsilon_{nx} \sim 160$, $\varepsilon_{ny} \sim 300$ (mm·mrad)
- e+ beam: $\varepsilon_{nx} \sim 1000$, $\varepsilon_{ny} \sim 1200$ (mm·mrad)





Commissioning tools

- All parameters can be access via EPICS PVs
  - ~ 150 IOCs
- Parameter logging: Archiver (CA, CSS)
  - 42000 PVs
  - CLI and Web-based data browser
- EPICS CSS alarm
- Tools based on SAD, Python, CSS
- Parameter management tool



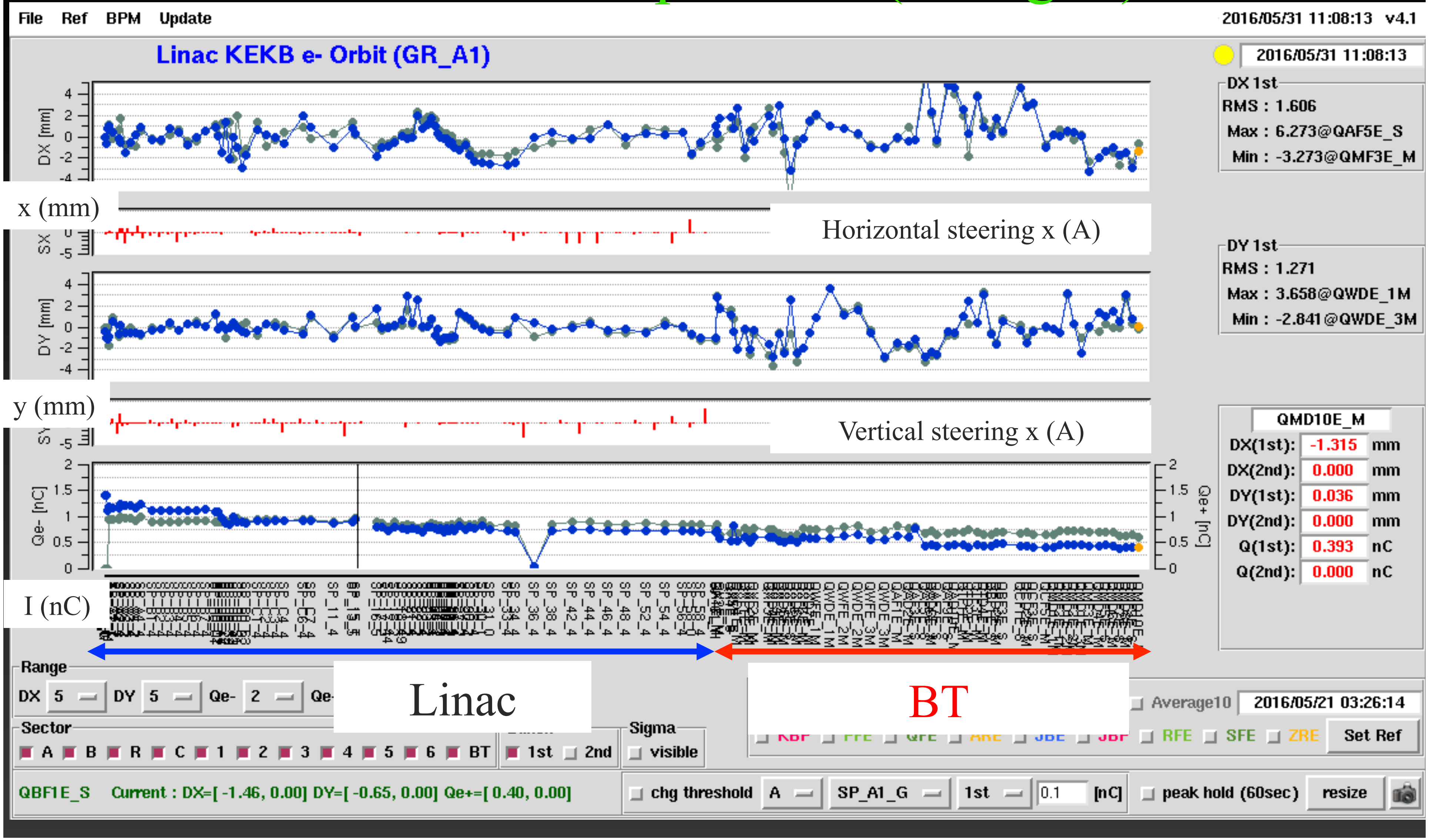
- Orbit correction and feedback software is almost ready (both of model and measured response can be applicable to correction).
- Energy feedback EPICS IOC is almost ready for operation.
- Energy spread monitor and feedback will be prepared in this autumn.
- Synchronized measurement over 91 BPMs is ready. Similar tools for fast rf monitor is also ready. Combination of them could be a strong analysis tools.

MR injection from rf e- gun

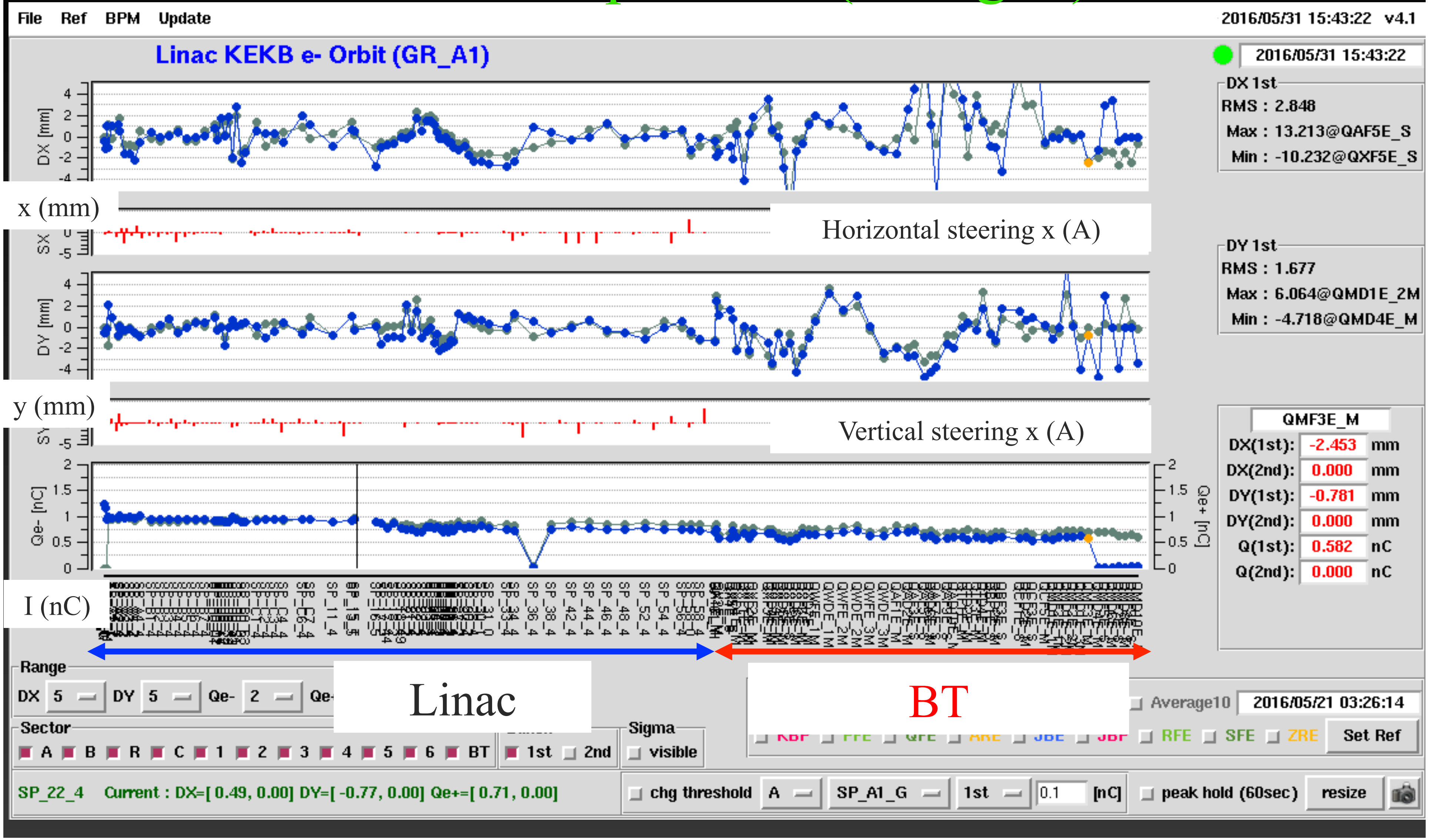
- MR injection w/ rf gun was success at the first time (May 31, 2016).
- Bunch charge is around 1 nC w/o emittance preservation.
- e- beam emittance was measured by the Quads scan (Qscan) and multiple wire scanner (WS).
- Qscan can be conducted by using a profile monitor and a GbE network attached camera w/ external trigger input.

Measured location	Horizontal ε_n (mm·mrad)	Vertical ε_n (mm·mrad)
Unit A1 chicane (Qscan)	28.3	26.4
A1_M (Qscan)	20.3	17.7
Dump @ Sector B (Qscan)	48.5	21.7
Sector C (WS)	100 ± 138	34.2 ± 16.5
Sector 5 (WS)	106 ± 24.9	76.5 ± 38.9
BT (WS)	211 ± 110.6	133 ± 22.2

Beam orbit
w/o bunch compression (rf e- gun)



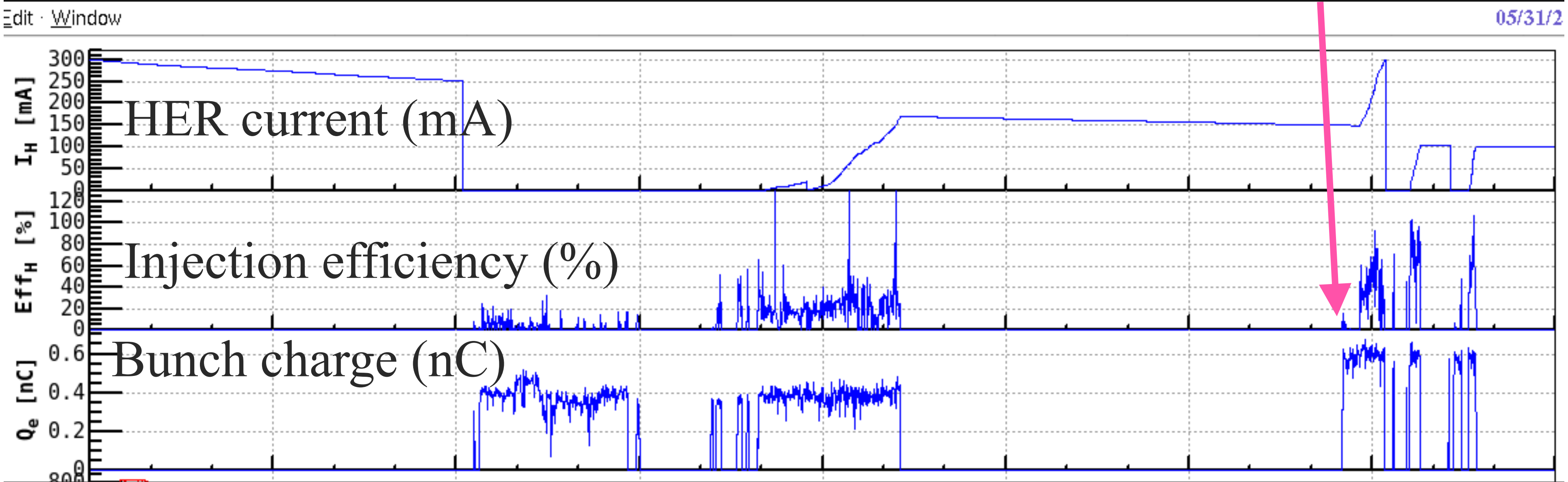
Beam orbit
w/ bunch compression (rf e- gun)



Main ring injection w/ rf e- gun

- After bunch compression w/ chicane of unit A1, the injection efficiency reaches almost 100%.

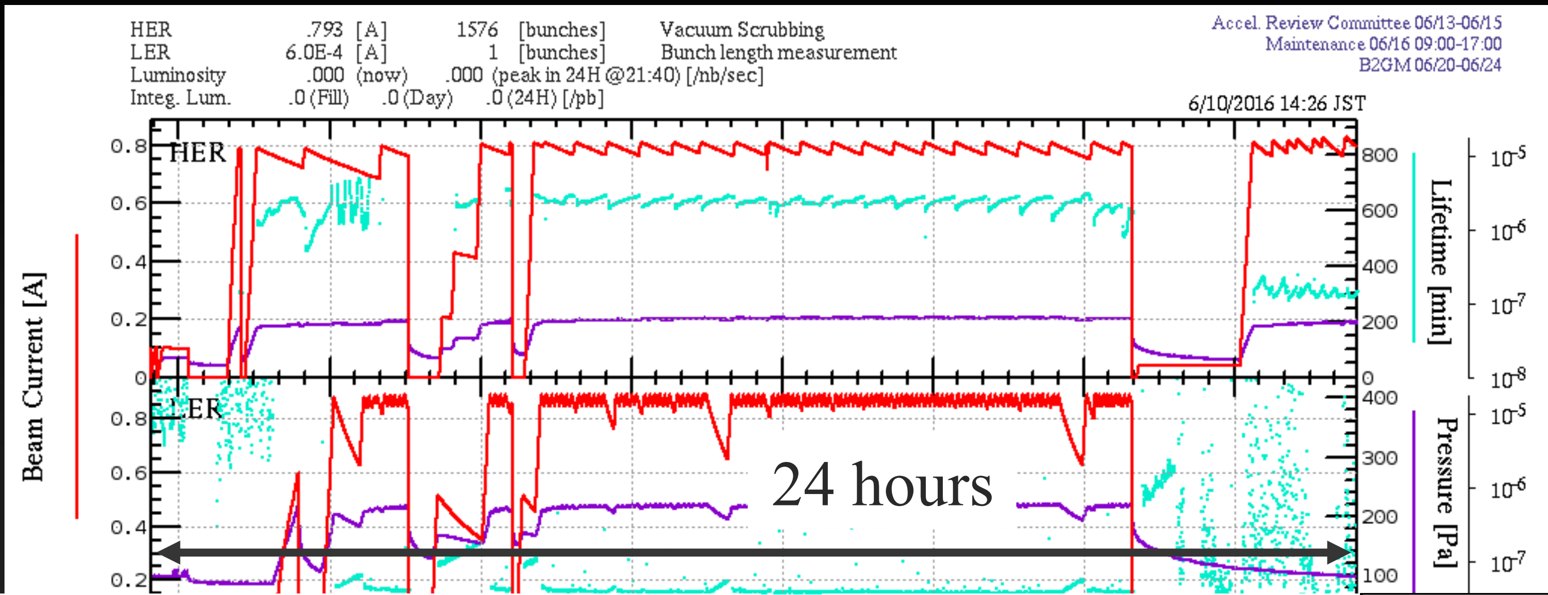
Injection tuning

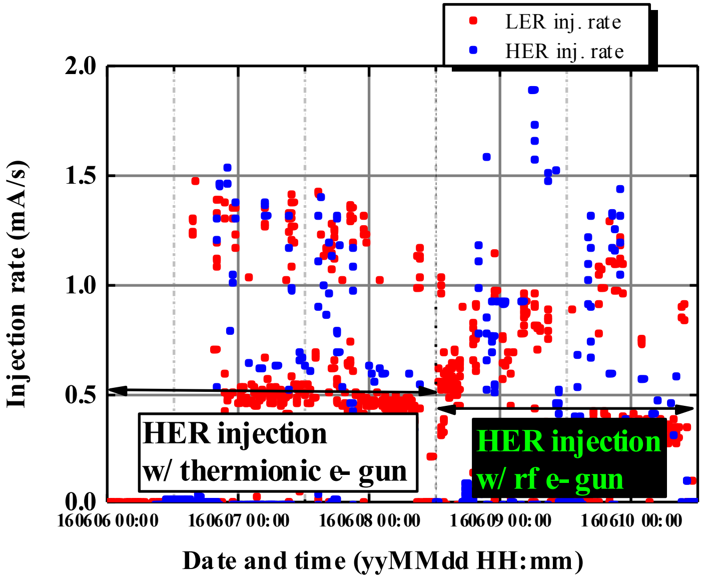


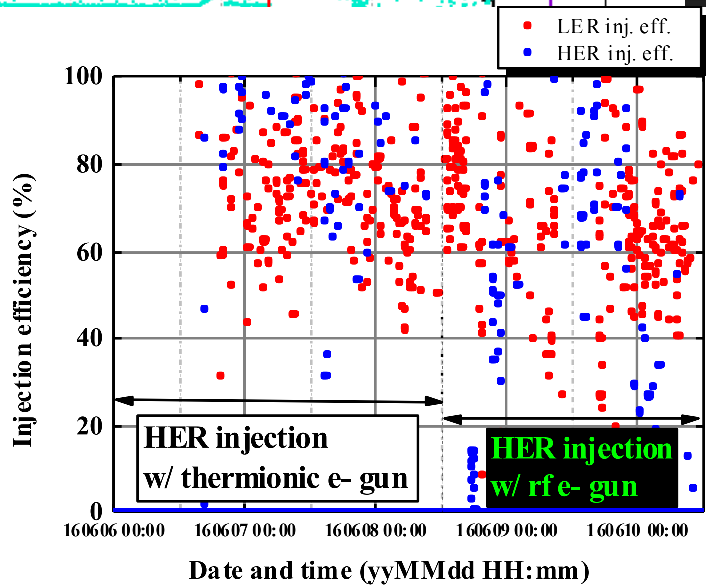
w/o bunch compression

w/ bunch compression

Stable HER injection w/ rf e- gun

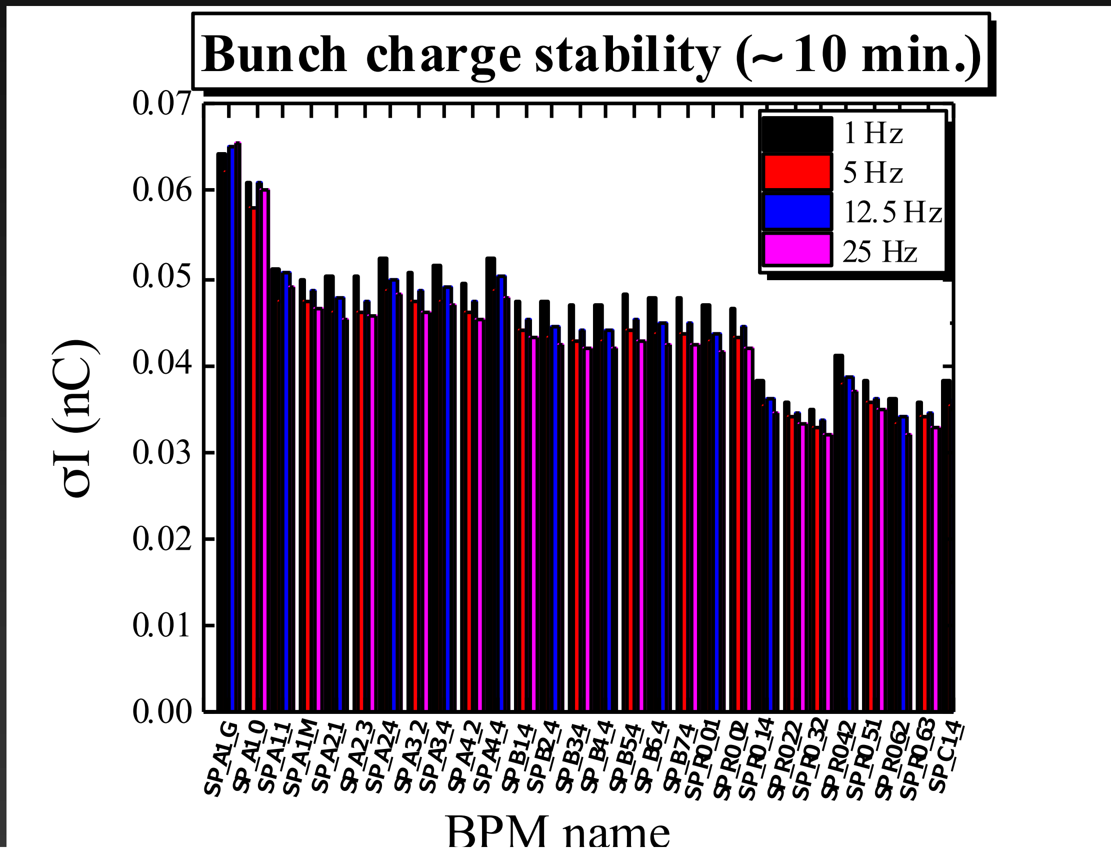






Bunch charge stability (rf e- gun)

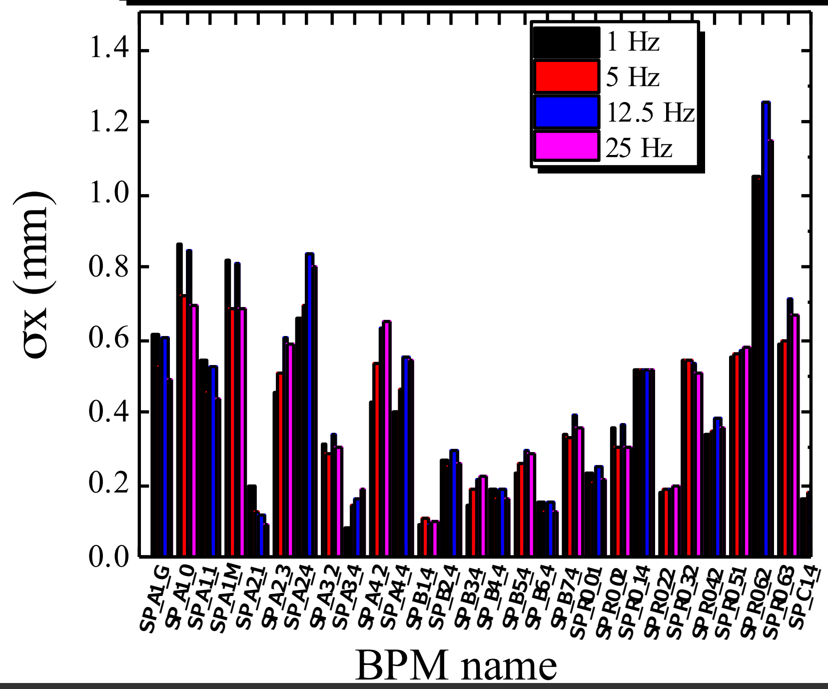
- RF e- gun has been utilized for HER injection since last Wednesday (June 8th) w/o any significant trouble.
- Bunch charge fluctuation is about 4% ~ 5%. (~ 20% in 2014)
  - 1% ~ 2% (thermionic e- gun)
- Bunch charge stability is almost same for different beam repetition.



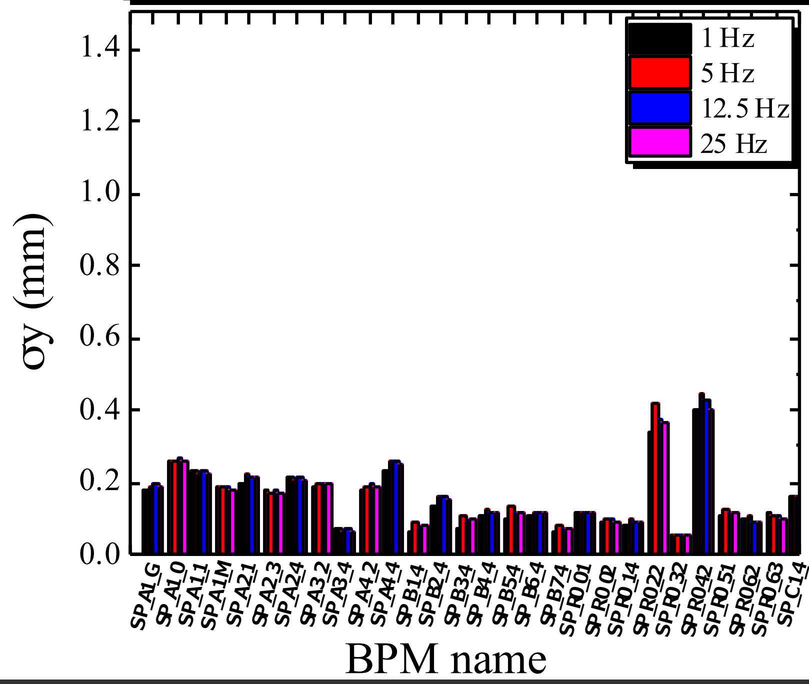
Position stability (rf e- gun)

- Position fluctuation is almost same for different beam repetition.
- Beam position fluctuation in horizontal direction is larger than one in vertical direction.
- $\sigma_{x,y}$: 0.1 mm ~ 0.2 mm (thermionic e- gun)

Horizontal position stability (~10 min.)



Vertical position stability (~10 min.)



Summary and plan

- Reinstallation of thermionic e- gun was completed in May of 2015.
- MR Phase I commissioning successfully started w/ thermionic e- gun for HER and LER injection.
- MR injection w/ rf e- gun was success at the first time (May 31, 2016).
- Rf gun has continuously been utilized for daily operation since last Wednesday. Bunch charge stability has been much improved.
- Towards Phase II (Oct. 2017):
  - Low emittance beam (2 nC, 20 mm·mrad)
    - rf e- gun (2 nC, 10 mm·mrad)
    - Pre-alignment and countermeasure for ground motion
    - Low emittance preservation study in this autumn
      - BPM readout will be replaced by the high precision one (VME module) in this autumn. (12/91 have been already replaced.)
    - Development of commissioning tools especially for low emittance preservation

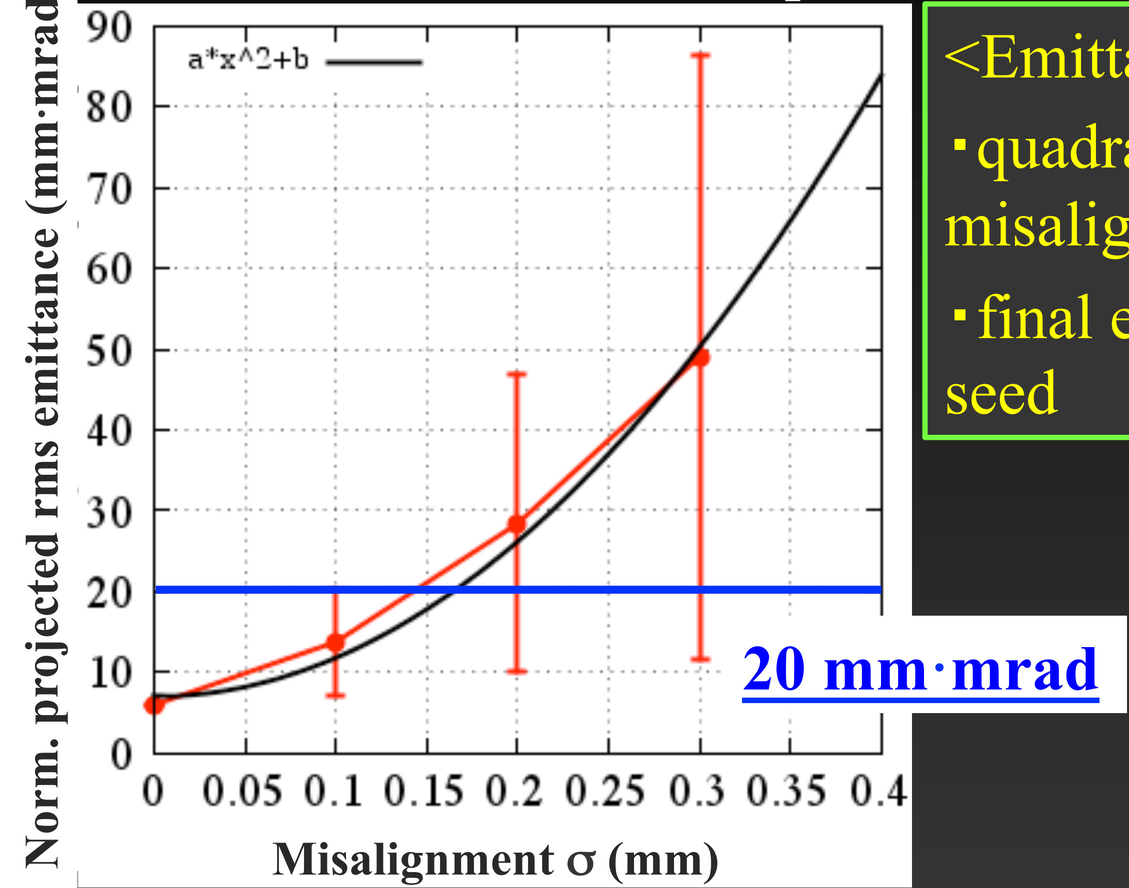
Summary and plan (cont'd)

- Towards Phase II (Oct. 2017):
  - Positron generation
    - Flux concentrator: New one (work hardening process) will be installed in this Nov. for 12 kA operation.
  - Simultaneous top-up (HER, LER (+ damping ring), PF, PF-AR)
    - Commissioning of New PF-AR BT (Feb. 2017)
    - Pulsed Quads will be tested by real beam soon. Control and monitor system is under preparation. All pulsed Quads (30) and steering magnets (36) will be installed in the next summer.
    - Safety system upgrade for simultaneous top-up operation

Backup

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

Energy spread requirement

- For the synchrotron phase space injection, small energy spread (0.1%) is required.
- A rectangular beam distribution in the longitudinal direction is required for the beam with bunch charge of 5 nC (Phase III).
- Laser shaping technique (temporal manipulation)

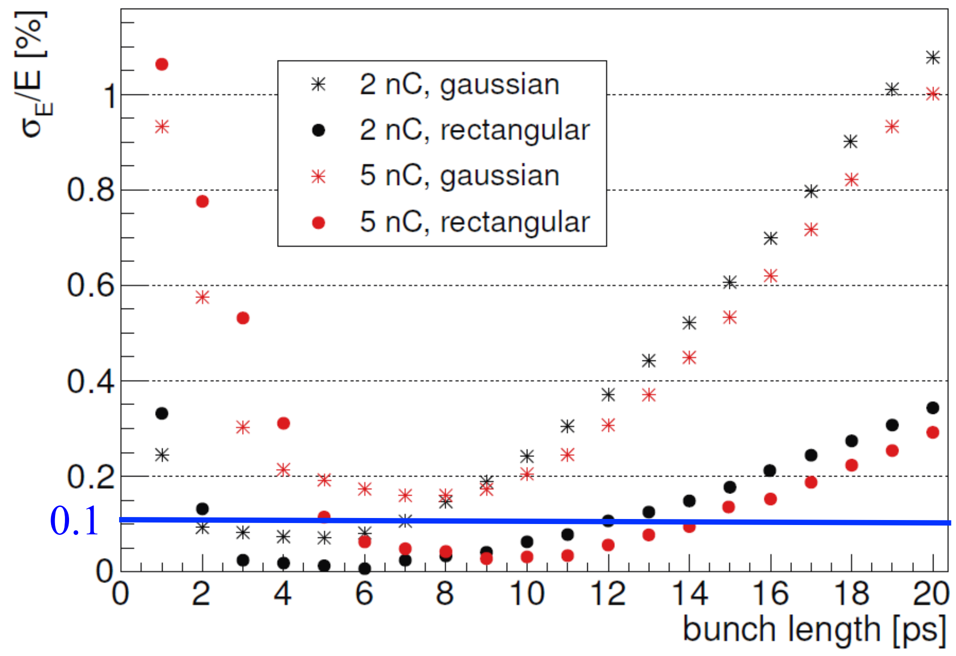
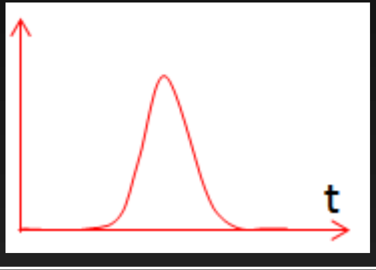
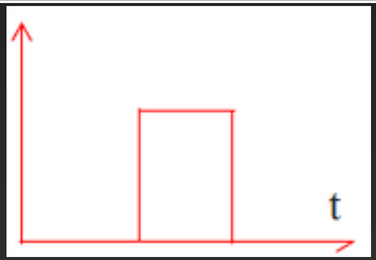


Figure 7: Energy spread at the end of 5-sector as a function of the bunch length with optimal RF phase.



Gaussian shape

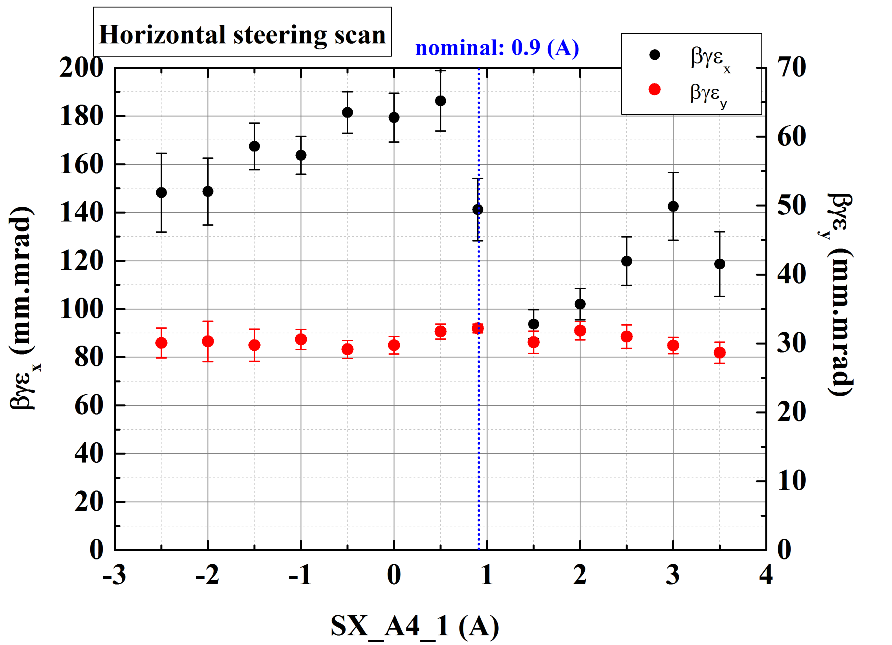


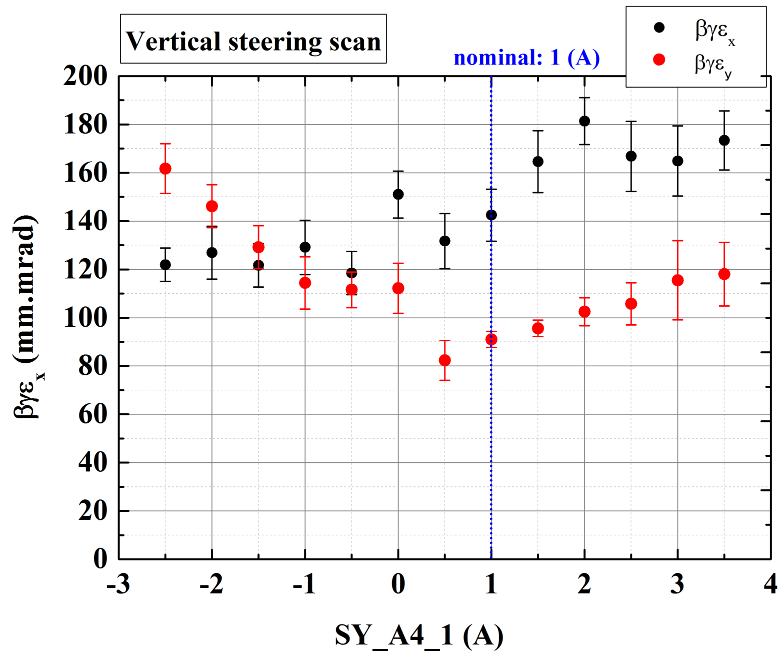
Rectangular shape

S. Kazama et al., IPAC'15, MOPWA053

Offset injection (experiment)

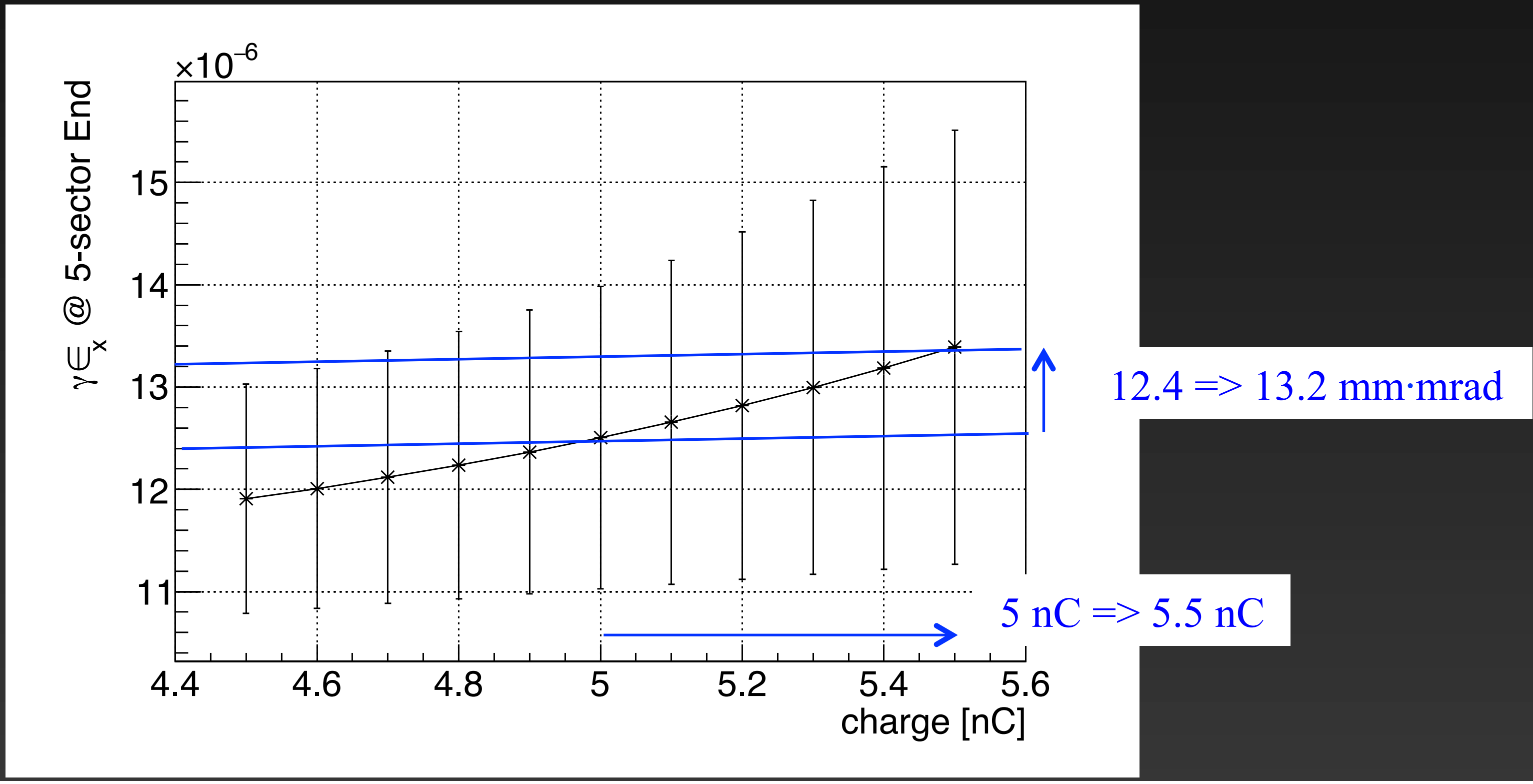
- Feasibility of offset injection was studied w/ bunch charge of 0.3 nC (thermionic gun).
- Changing the excitation current of steering magnet at Unit A4.
- Emittance was measured multiple wire scanner at Sector B end.
- We will conduct this measurement w/ rf gun.





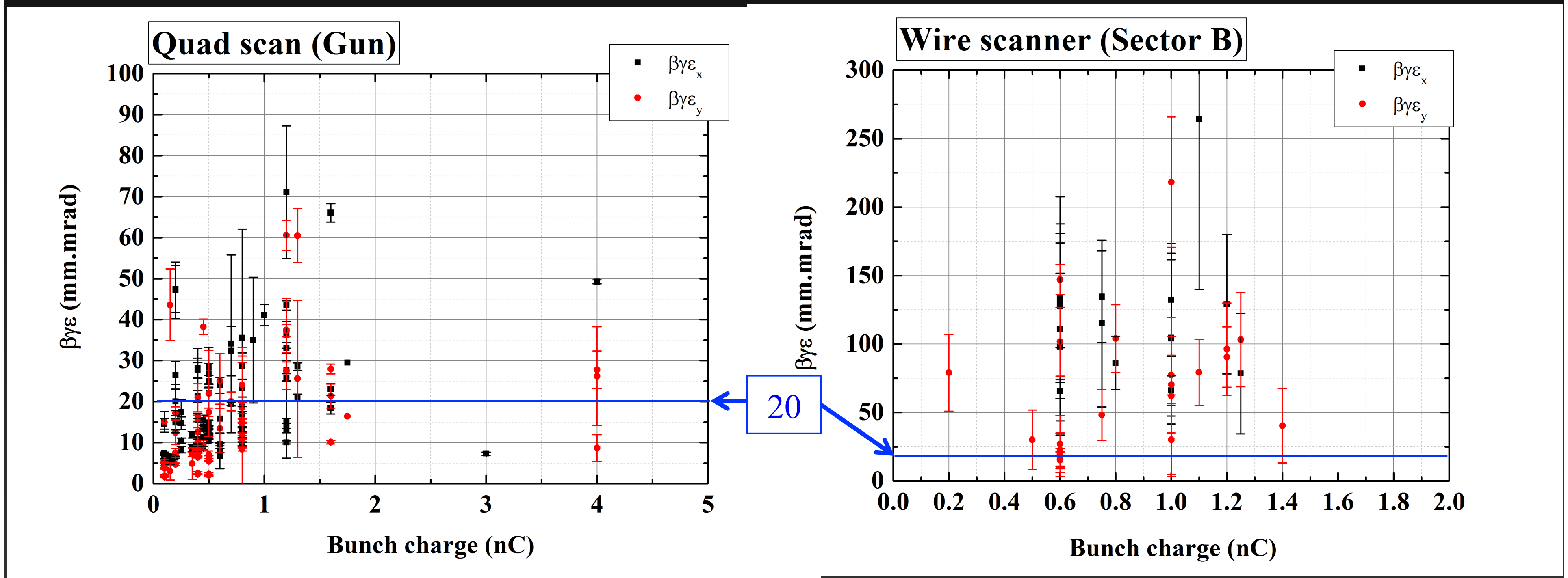
Emittance w/ bunch charge fluctuation

- Emittance simulation w/ 10 misalignment seeds (accelerating structure).
- Sector C to Sector 5 (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.



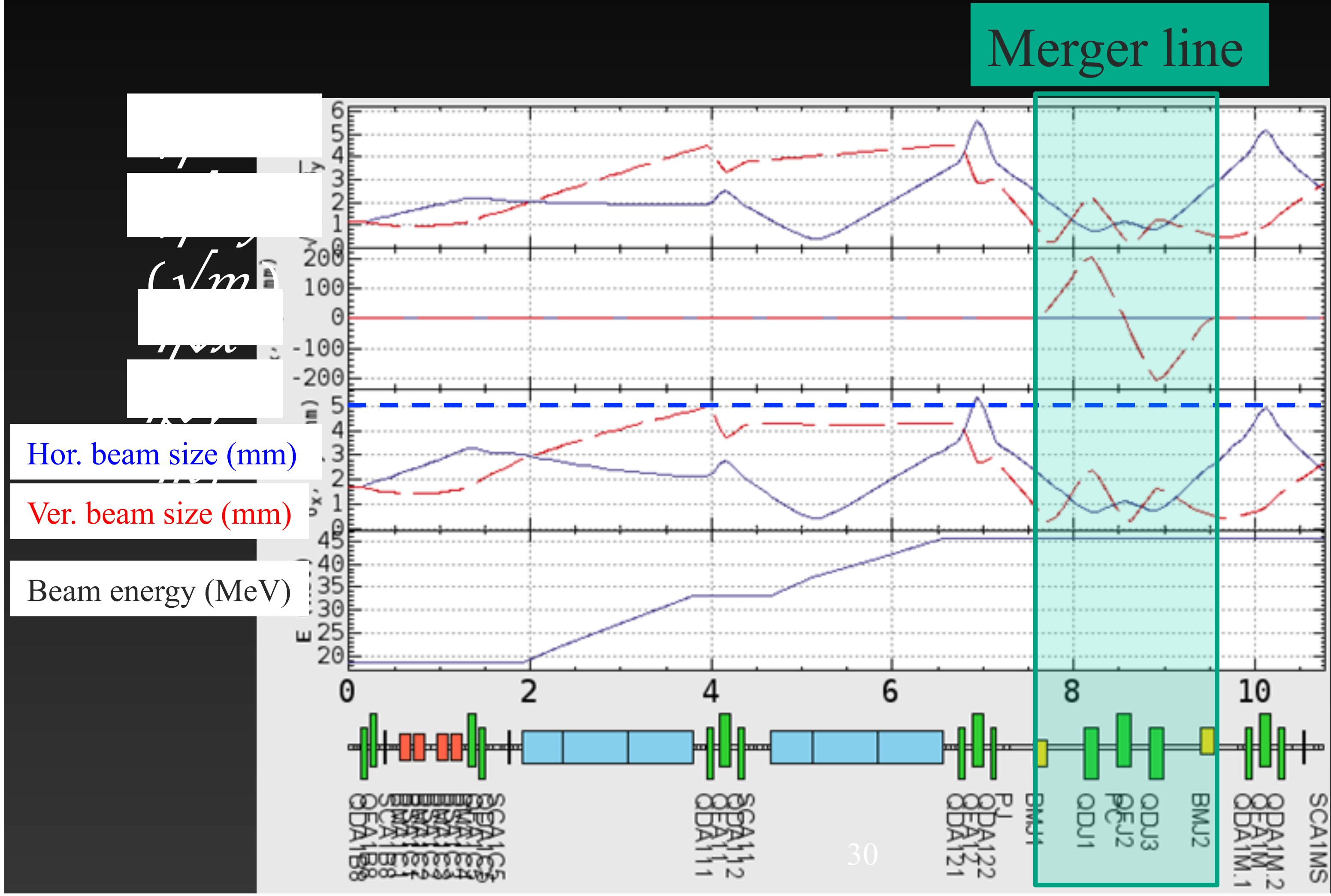
Emittance measurement

- 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.



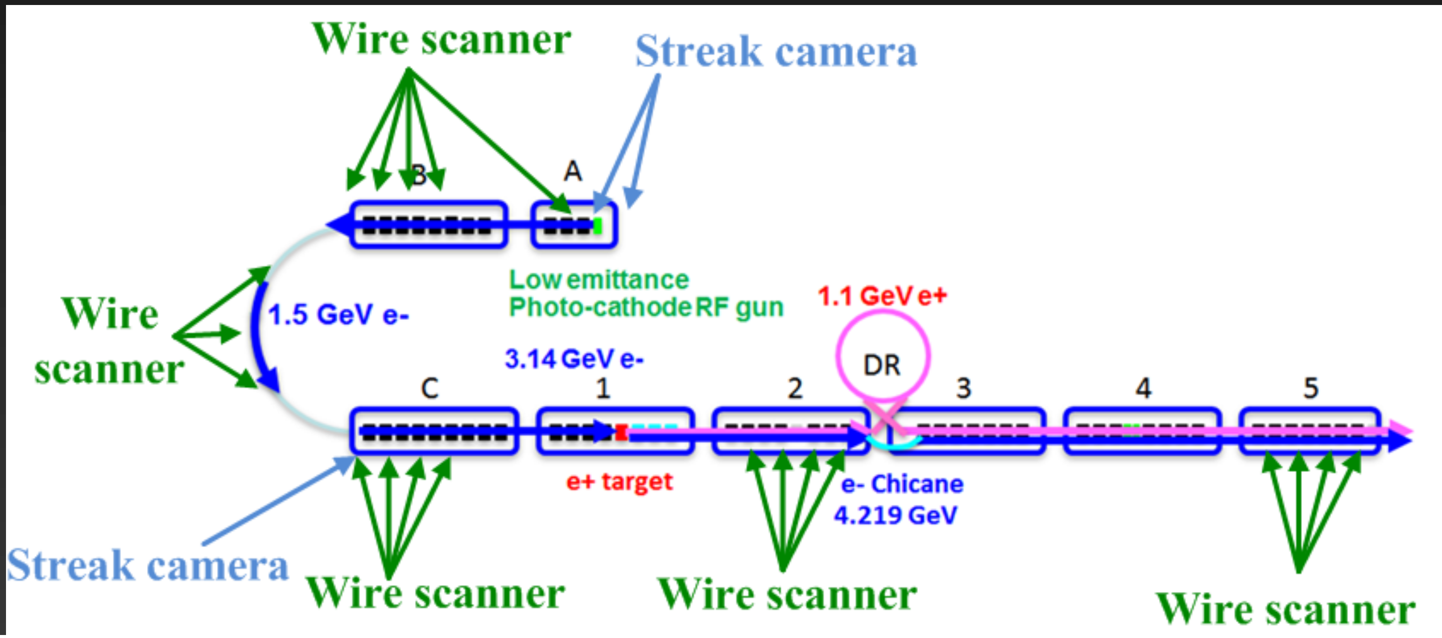
Optics design

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

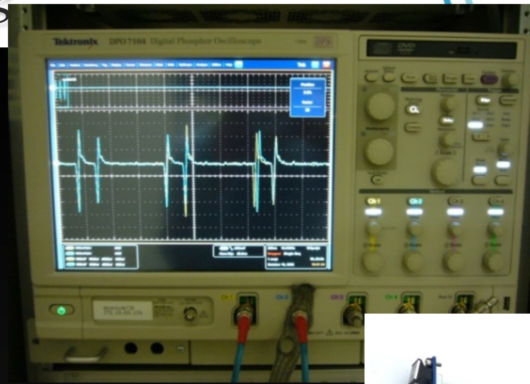


Beam diagnostics

- Beam position measurement
  - BPMs x 91 (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



New BPM readout system



- Current system:
  - Windows-based digital oscilloscope
    - 10 GSa/s, 8 bit, 1 GHz bandwidth, 4 channels
    - Twenty four systems process the signals from 92 BPMs
    - Position measurement precision: 25～50 μm (3-BPM method)

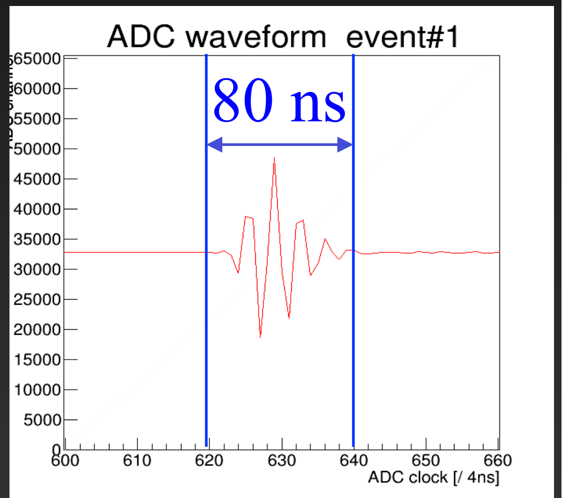
- New system:
  - VME module w/ band-pass sampling scheme
    - 250 MSa/s, 16 bit ADC,
    - BPF (fc: 180 MHz, BW: 60 MHz, 22 MHz)
    - Signal can be well damped within 80 ns

    (first and second bunch interval: 96 ns)

  - Measurement precision: 3 μm

  104 modules have been manufactured.

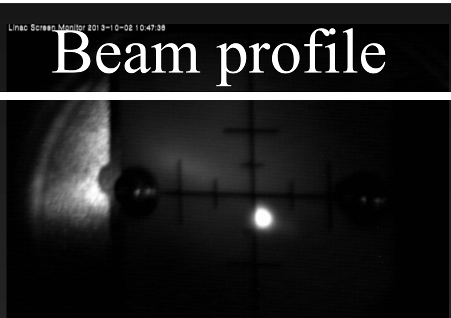
  12 modules have been successfully utilized for daily operation.



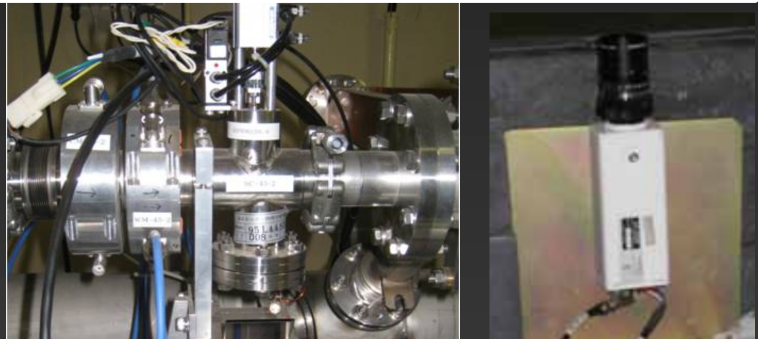
Profile monitor

- 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.

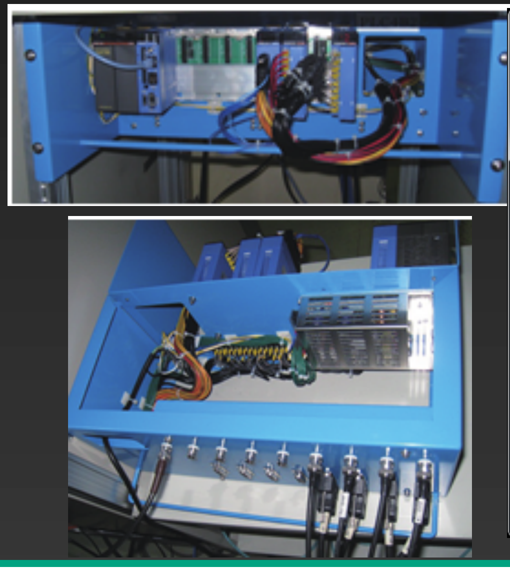
Beam profile

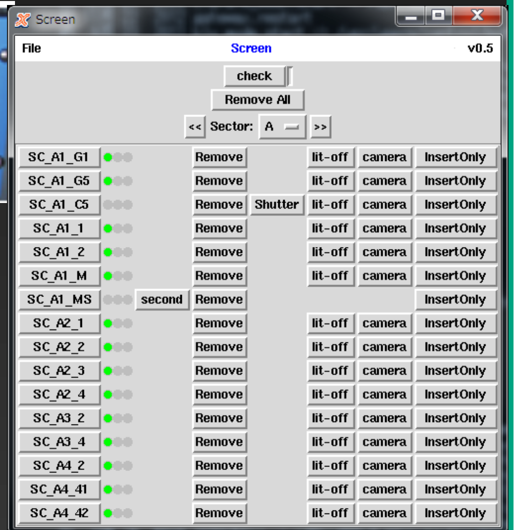


Monitor and CCD camera



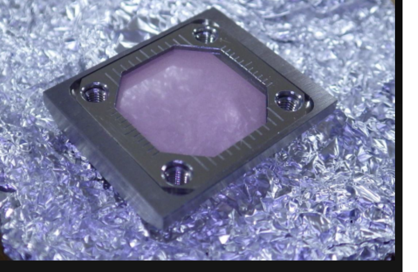
Controller and HLA

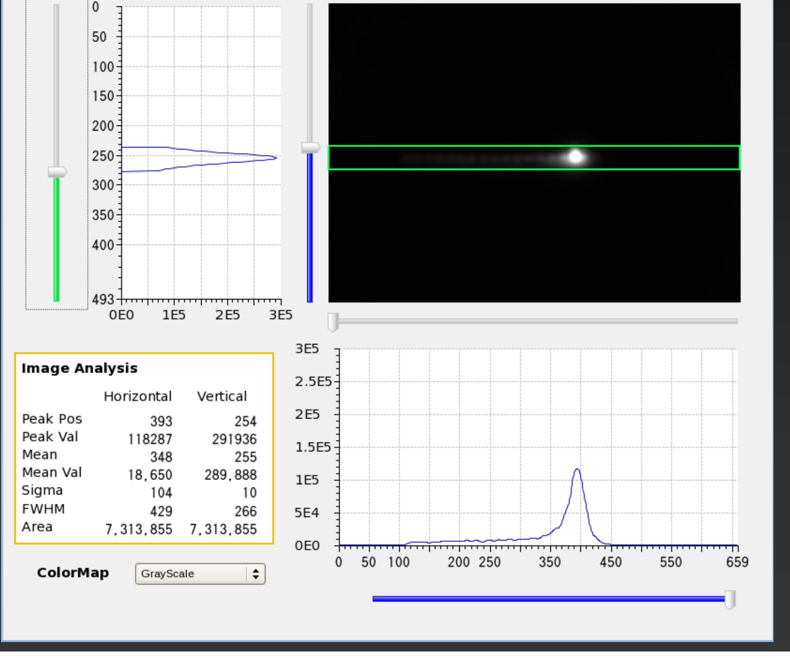


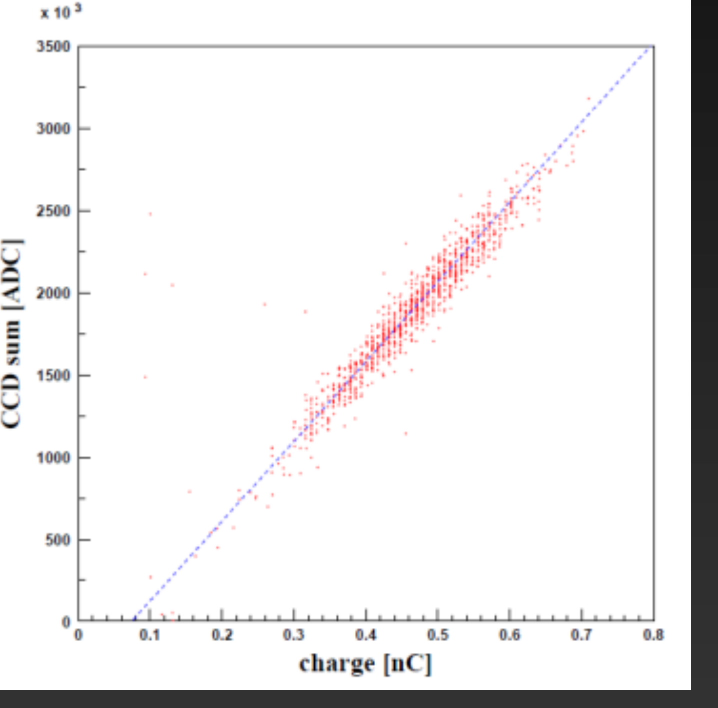


Profile monitor (cont'd)

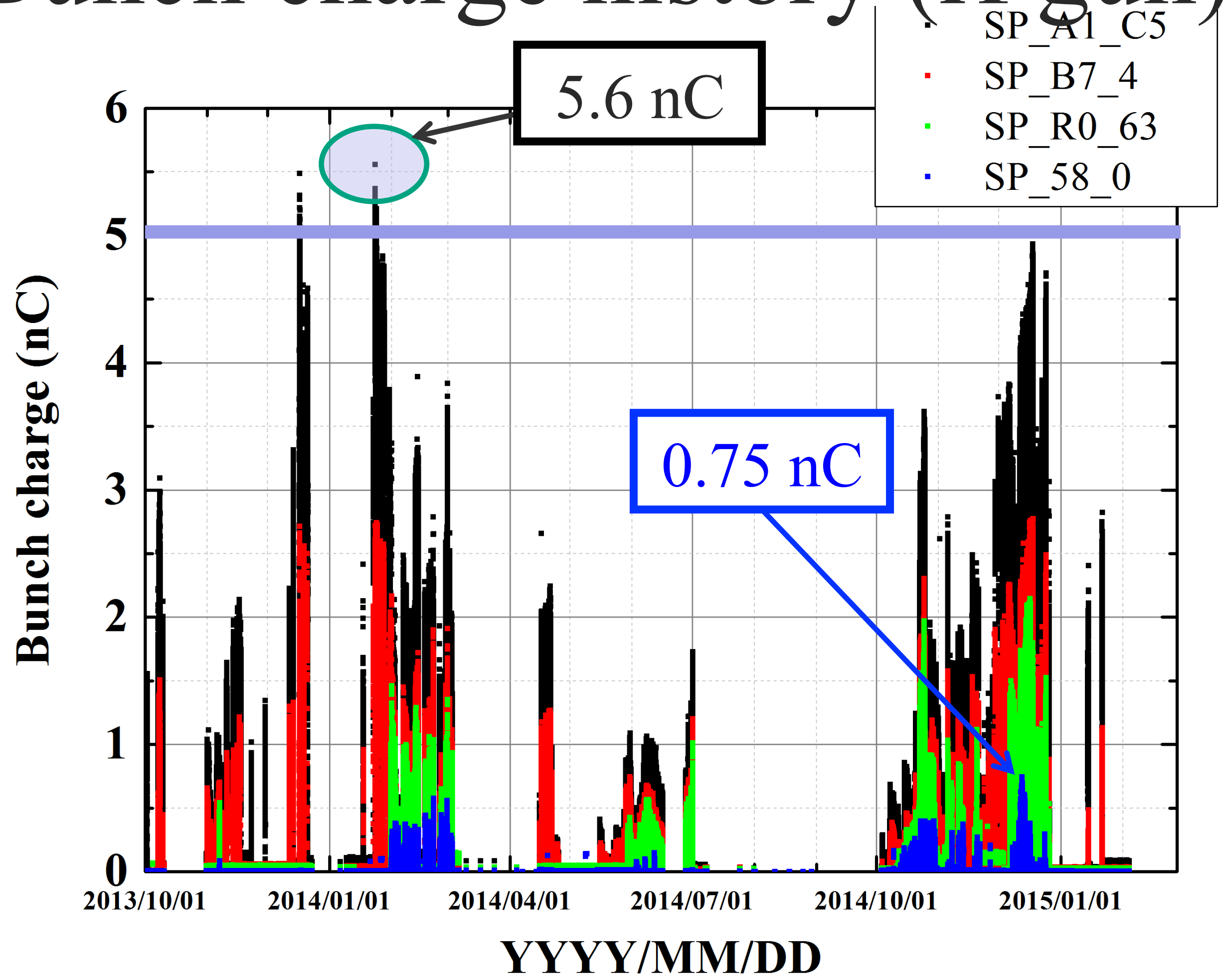
- 7/97 were replaced by 30-μm-thick one for precise beam size/emittance measurement (Quadrupole scan).
- CCD cameras have been replaced by new one.
  - Allied Vision: GC650 w/ GbE
  - Ext. trigger input
  - EPICS IOC, CSS for HLA

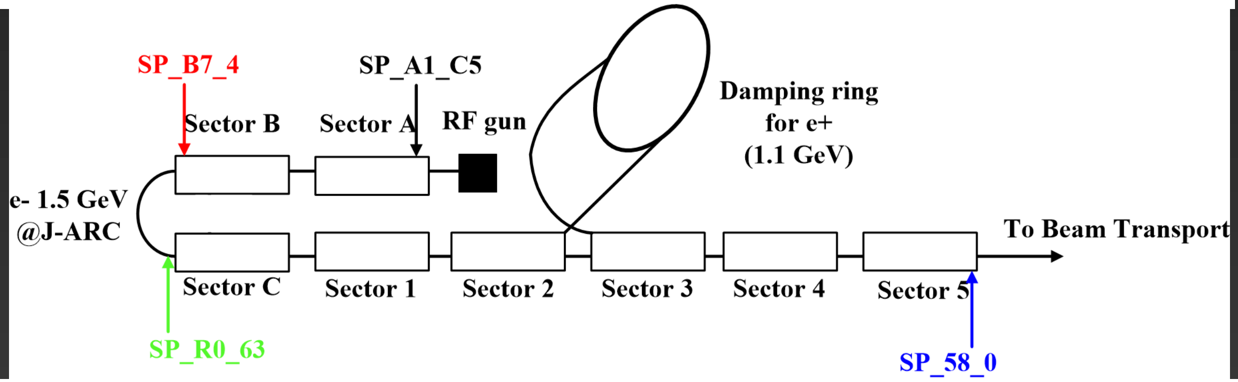




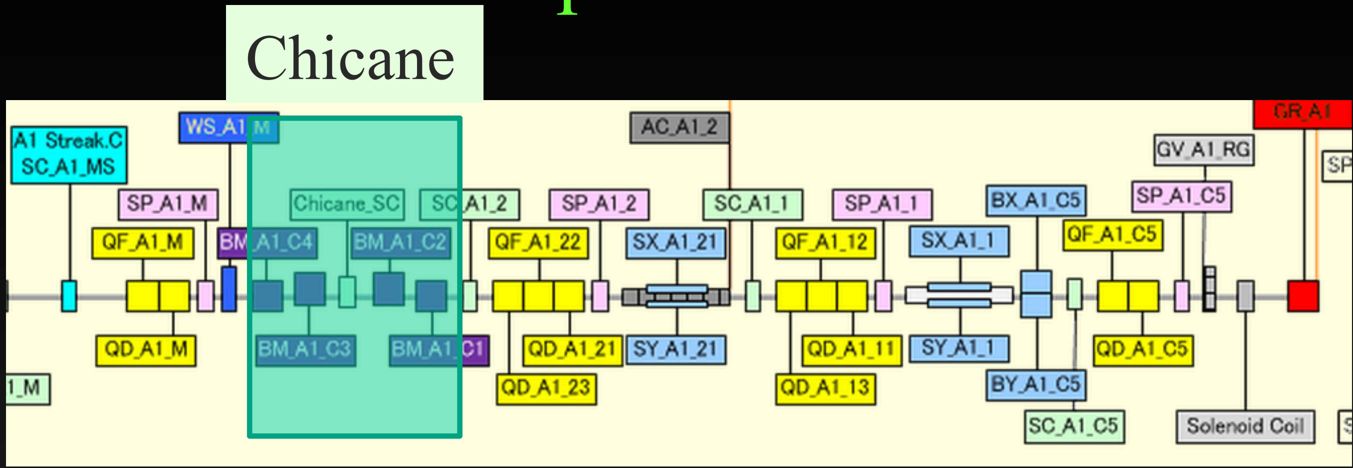


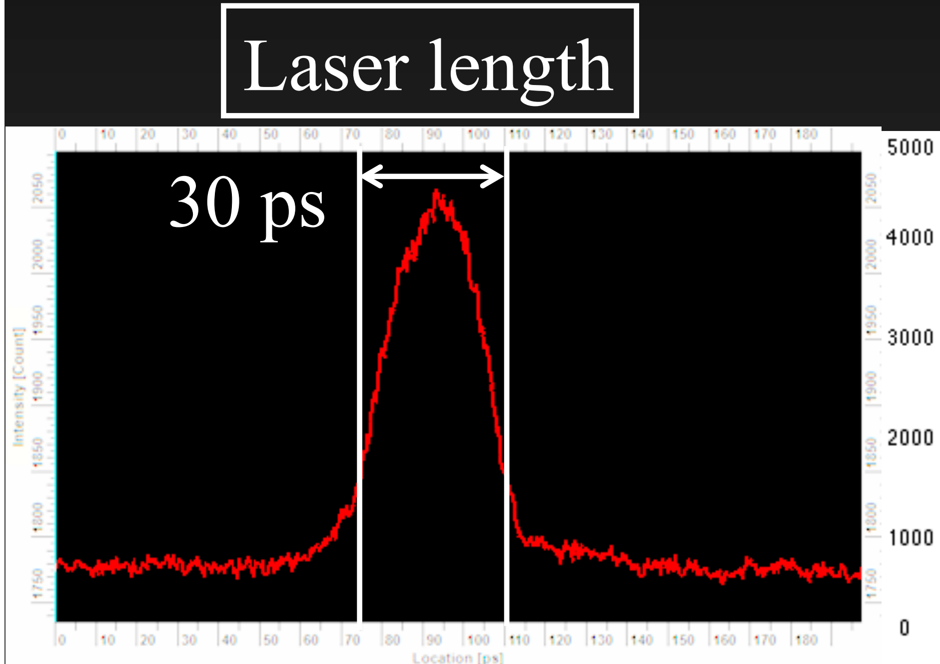
Bunch charge history (rf gun)

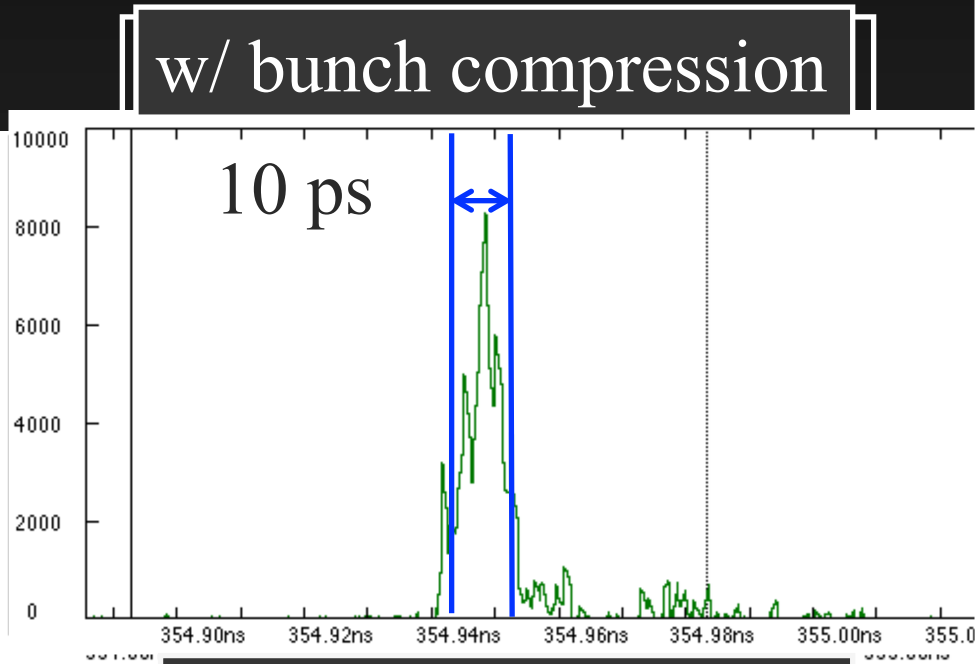




Bunch compression at Unit-A1

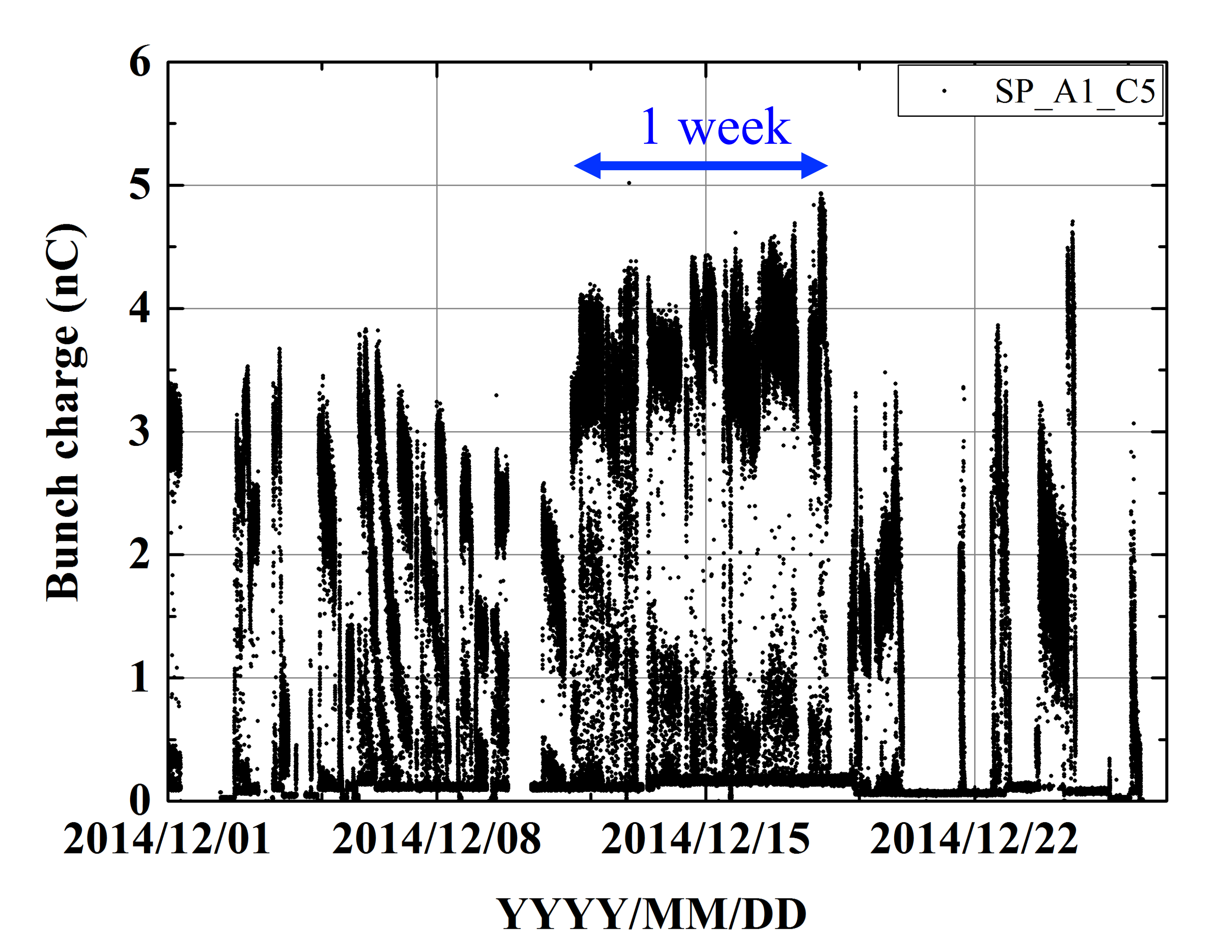




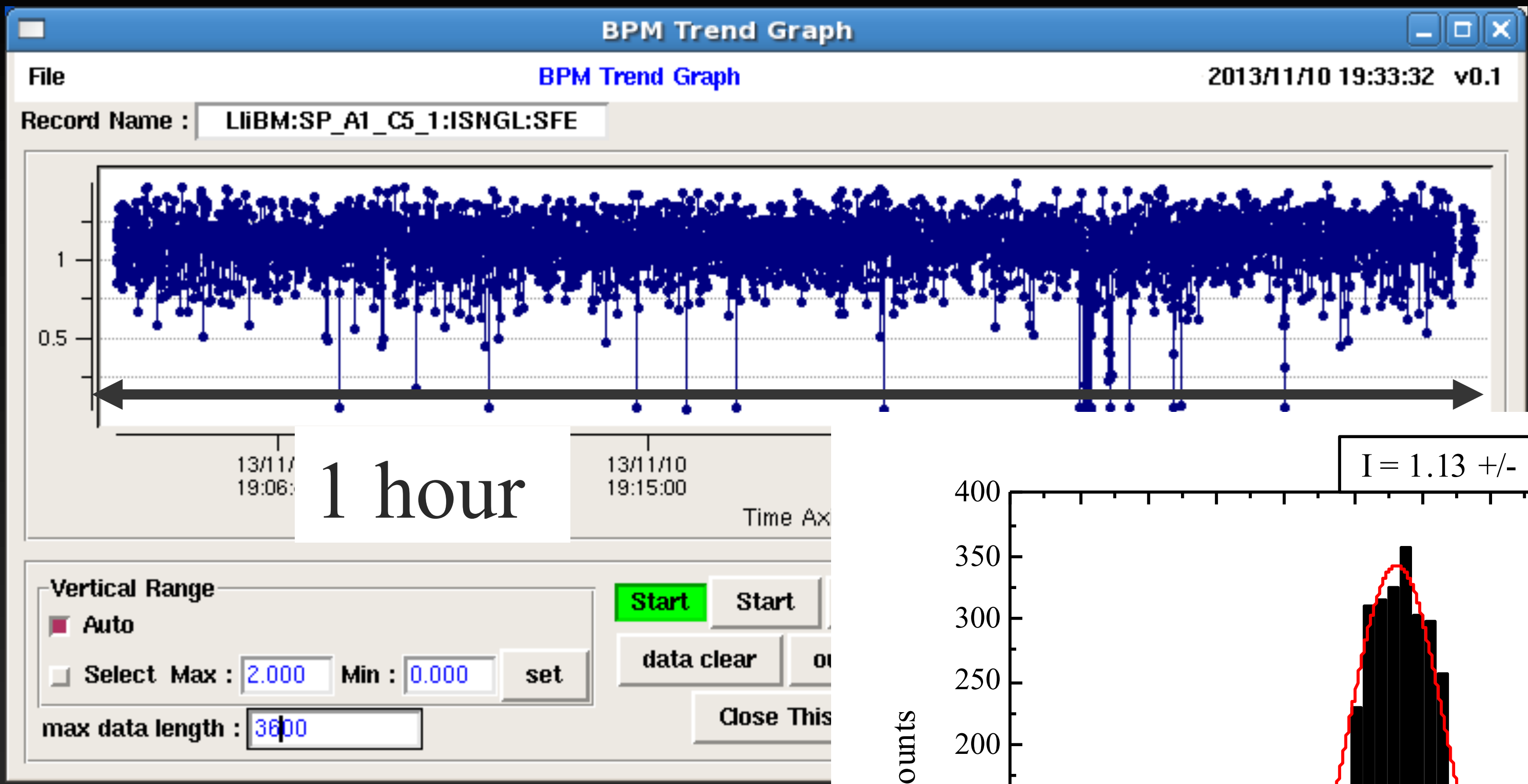


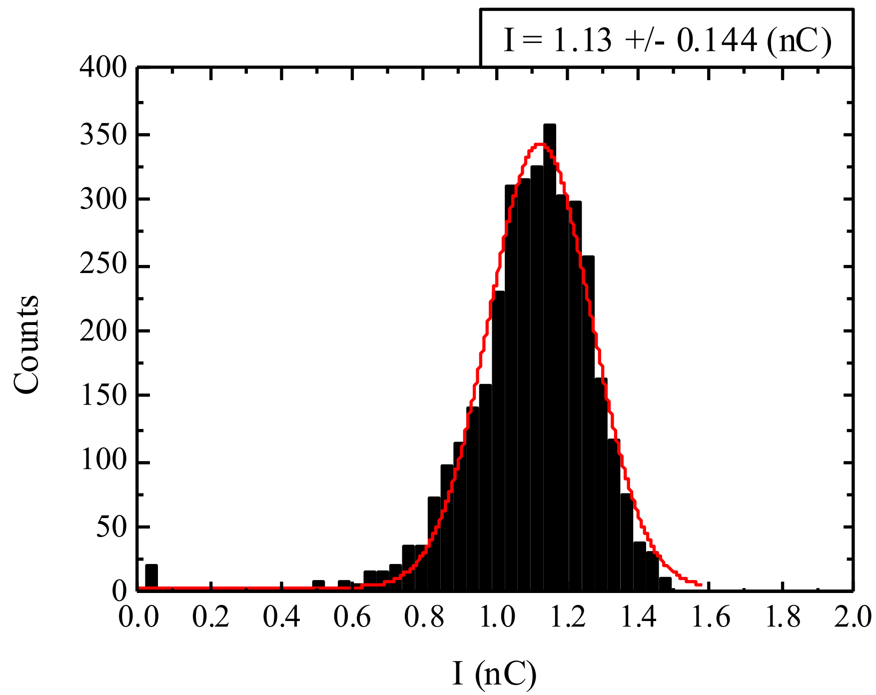
A1 RF Φ -30°: 10 ps

Bunch charge from rf gun in last Dec.



Typical beam charge stability

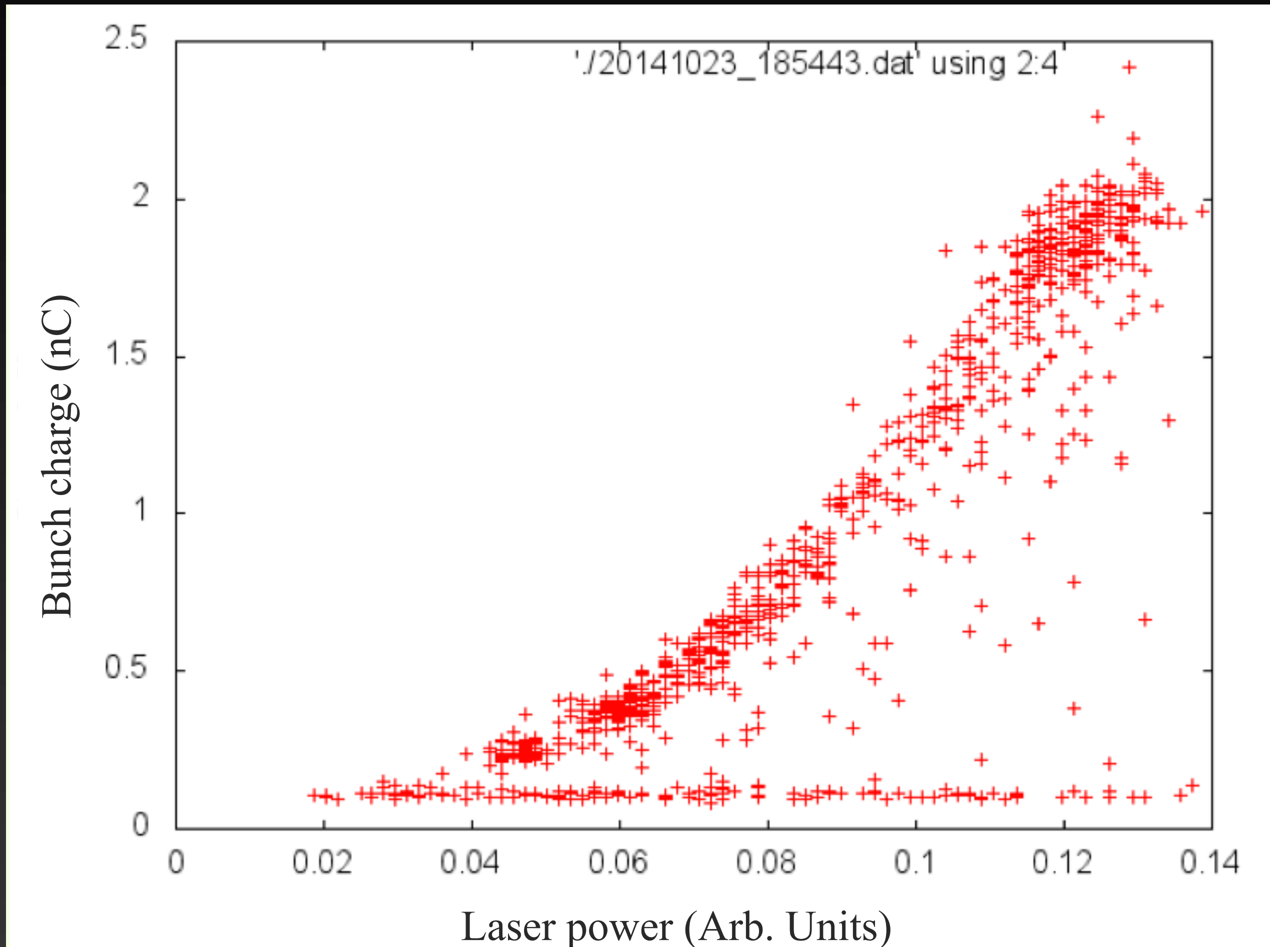




σ_I: 10% ~ 20%
~ 2.5% (KEKB operation)

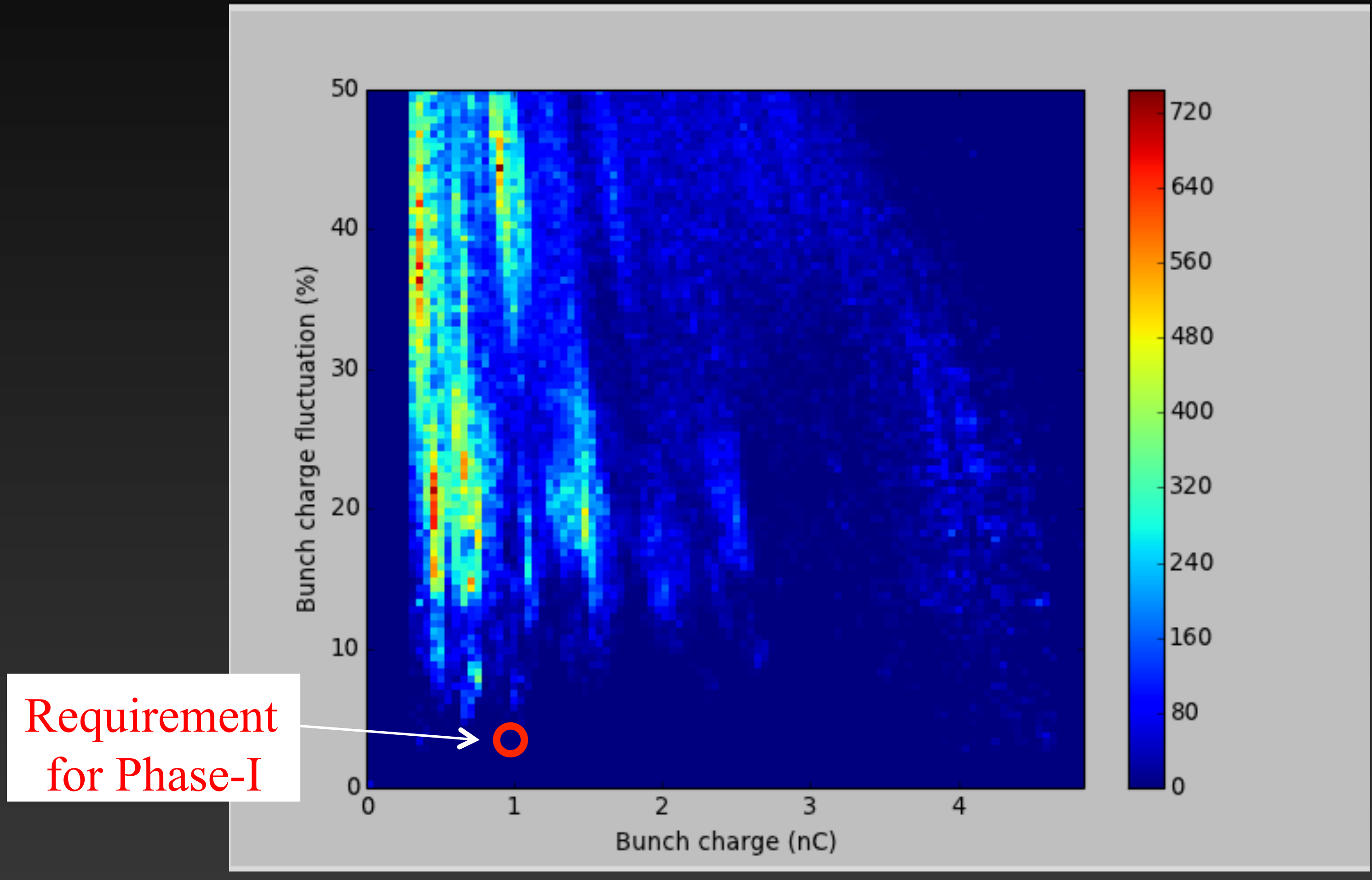
Bunch charge and laser power

- 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



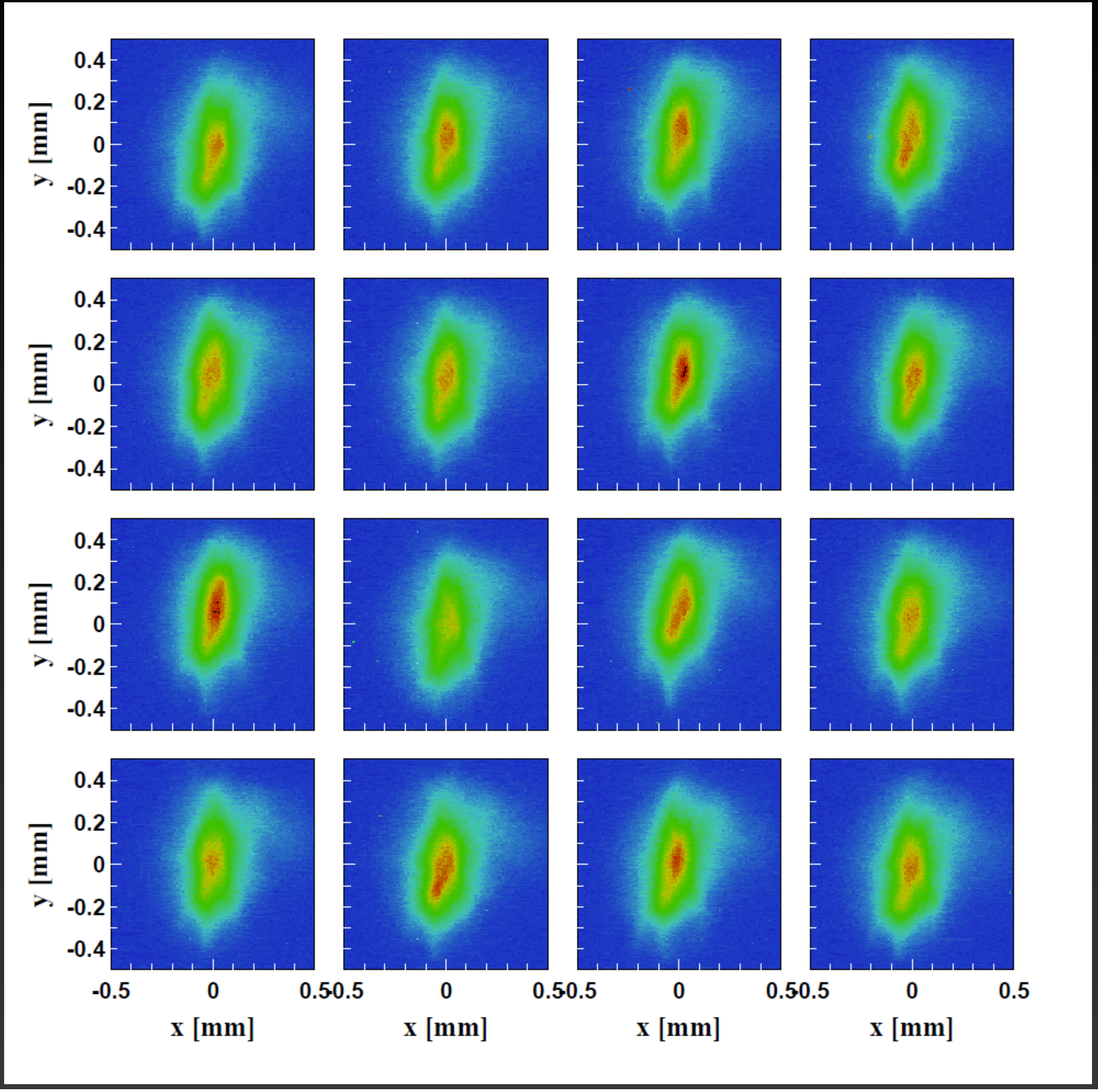
e- beam parameters

	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.)	310
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

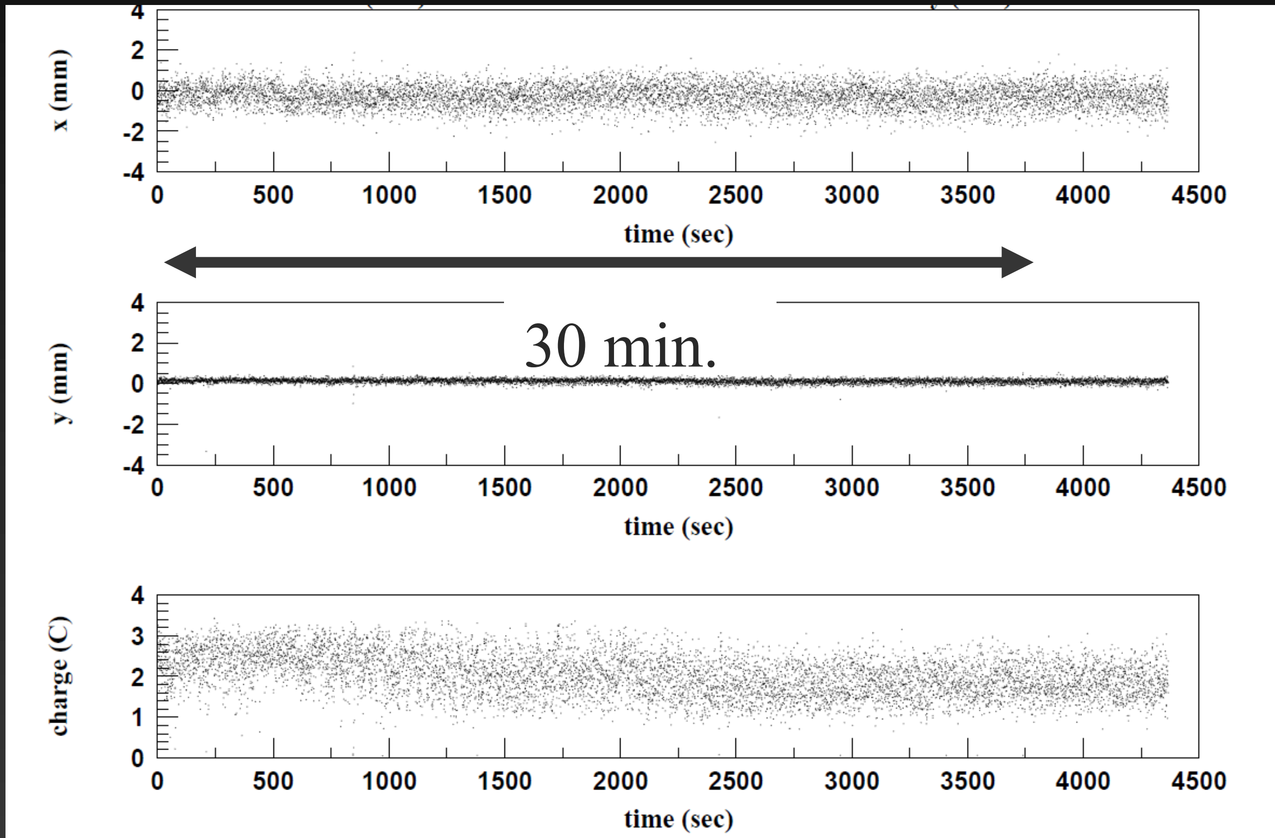
	SuperKEKB	KEKB
Energy (GeV)	4	3.5
LER stored current (A)	3.6	1.6
LER beam lifetime (min.)	6	133
Maximum beam repetition (Hz)	50	50
Max. # of bunch in an rf pulse	2	2
Emittance (mm·mrad)	100/20 (Hor./Ver.)	1400
Charge (nC)	4	1
Energy spread (%)	0.07	0.125
Bunch length σz (mm)	0.7	2.6
Damping ring	○	-
Simultaneous top-up injection	4 rings (SuperKEKB e-/e+, PF, PF-AR)	3 rings (KEKB e-/e+, PF)

Shot-by-shot beam profile stability



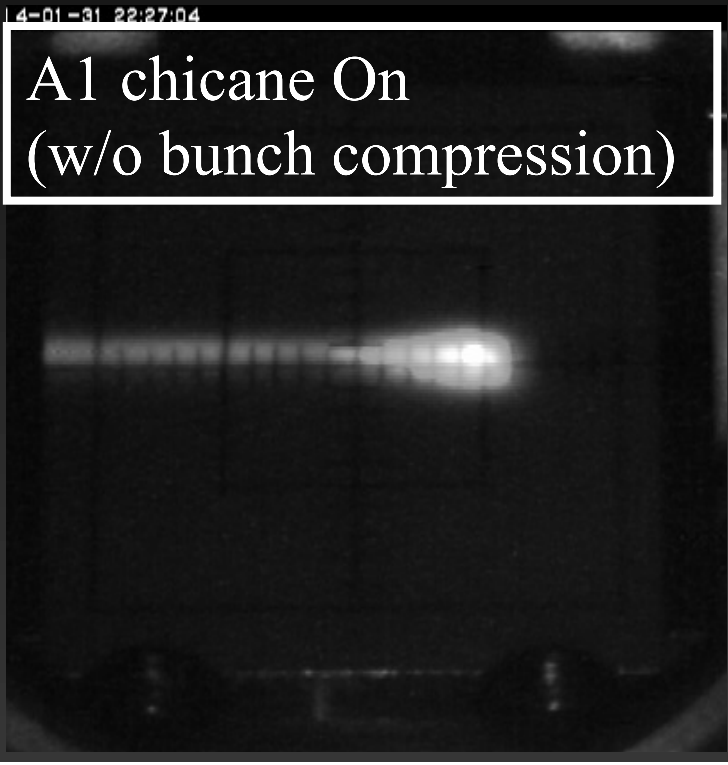
Beam position stability @ SP_A1_C5

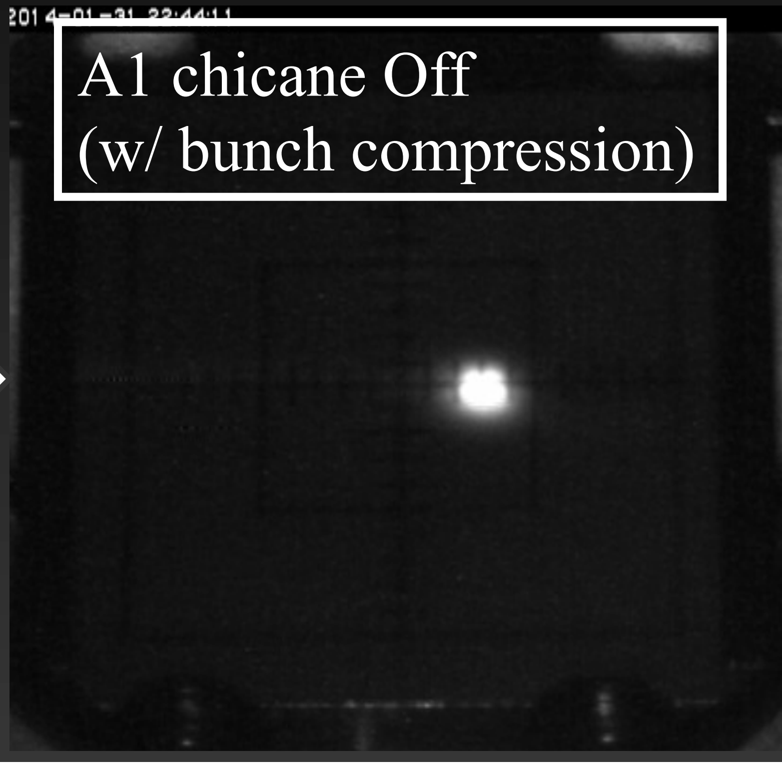
- Measured beam position at first BPM (SP_A1_C5)
  - σx ~ 0.57 mm
  - σy ~ 0.11 mm
- Fluctuation of horizontal beam position is larger than vertical one.



Energy spread measurement @ J-ARC

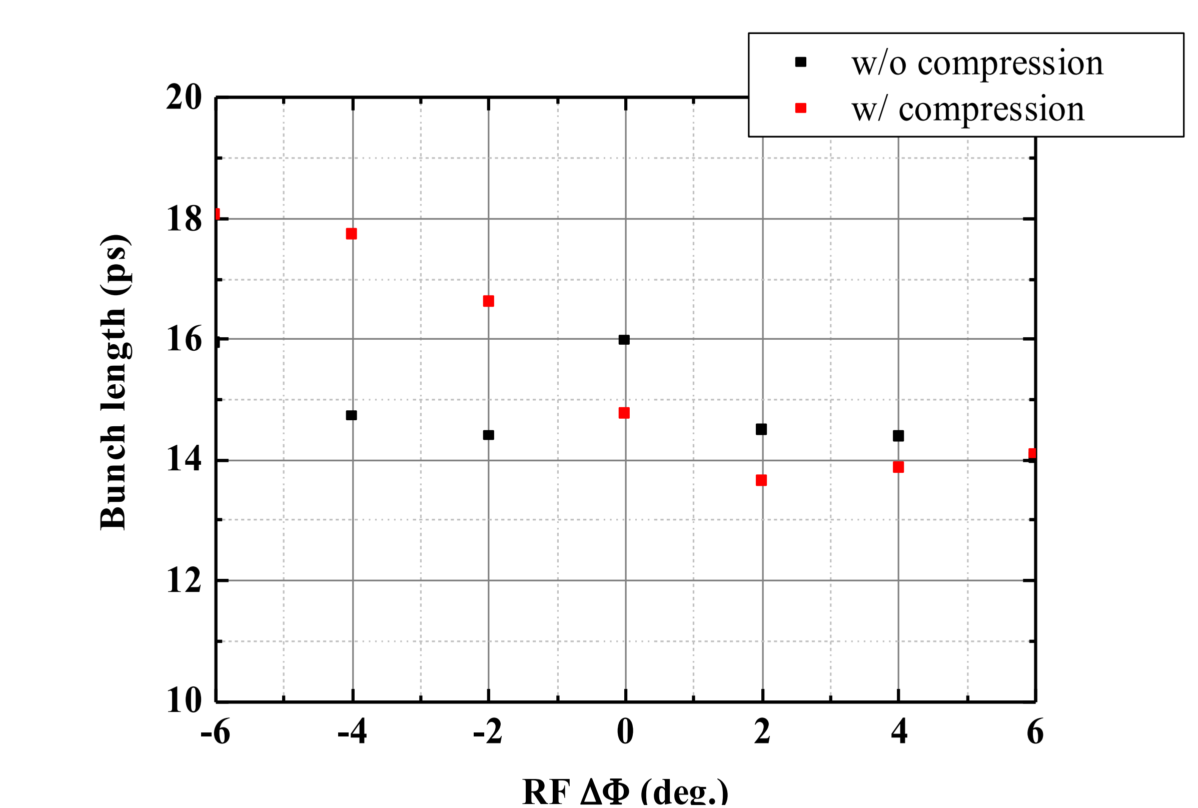
- Measure beam energy spread by screen monitor (middle of J-ARC) w/ and w/o bunch compression at A1 chicane.
- Bunch compression at A1 unit is effective for energy spread compensation.

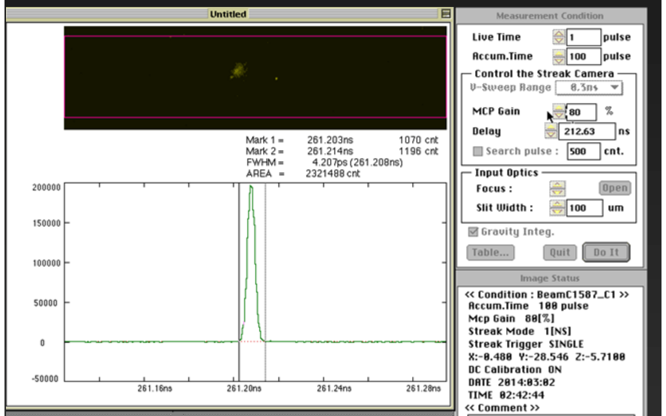




Bunch compression @ J-ARC

- 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.

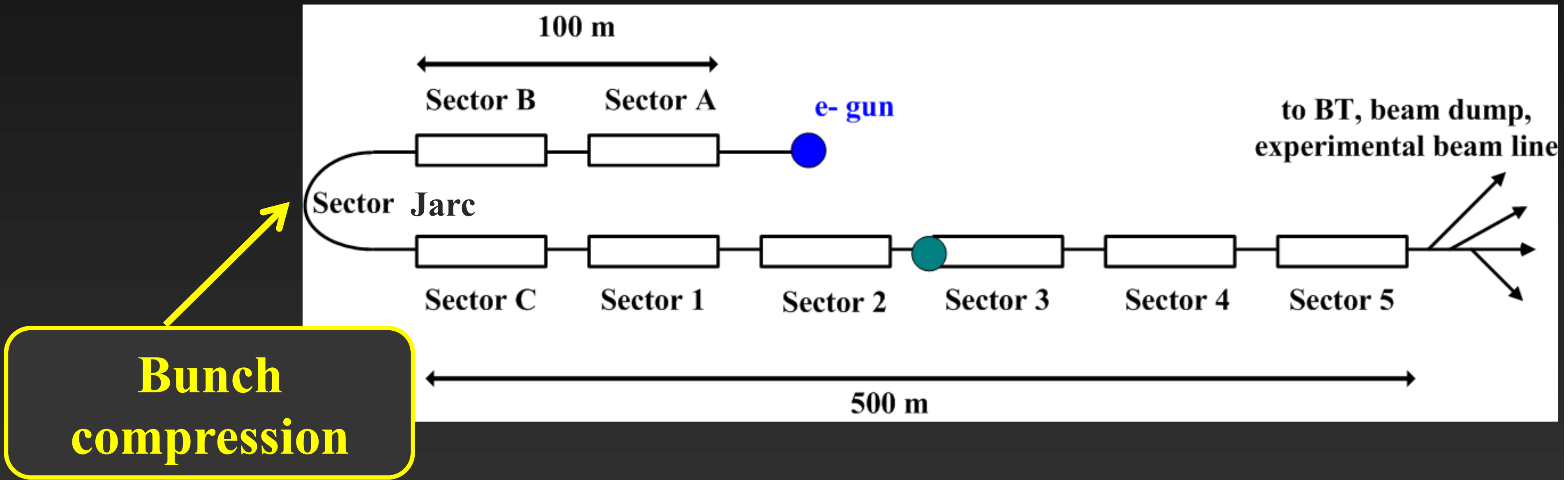




Streak camera at SectorC

Bunch compression at J-ARC

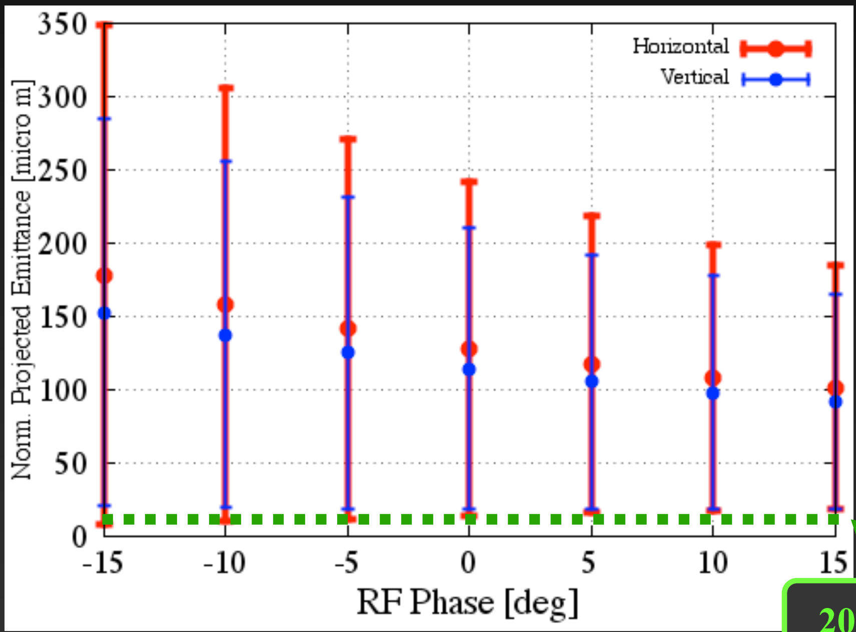
- Mitigate transverse wakefield and emittance growth
- Initial bunch length 10 ps => 5 ps (bunch compression at J-ARC)
  - First stage compression at A1 unit (30 ps => 10 ps)
- Control R56 and energy spread at J-ARC



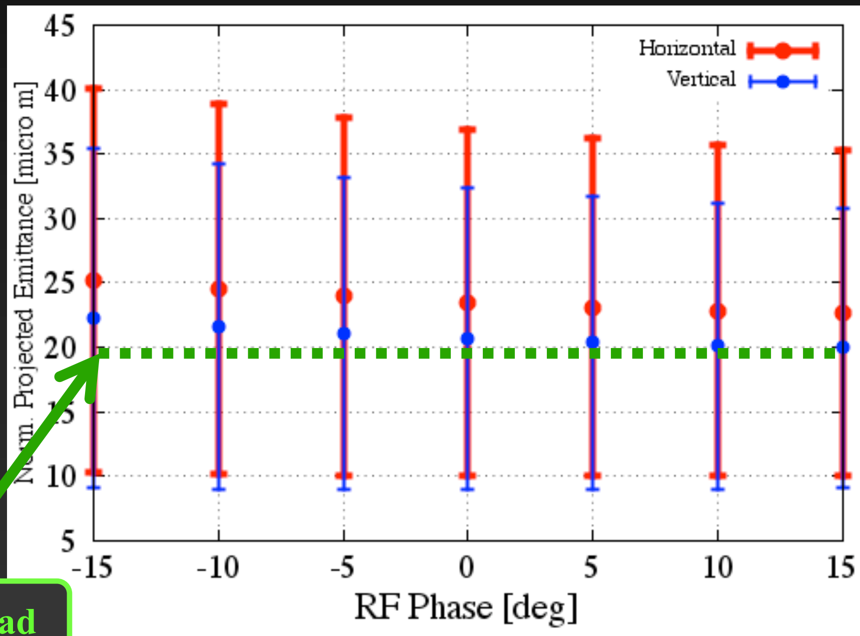
Emittance (misalignment σ = 0.3 mm)

- Bunch compression is effective.
- However, still not enough for 20 mm·mrad.

R56 = 0 (w/o compression)



R56 = -0.30 (w/ compression)



20 mm·mrad

Bunch compression at A1 unit

- To mitigate space charge effect, bunch length is compressed from 30 ps to 10 ps.