Injector beam monitors

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for Injector Linac, SuperKEKB

The 23rd KEKB Accelerator Review Committee, Jun 9, 2019

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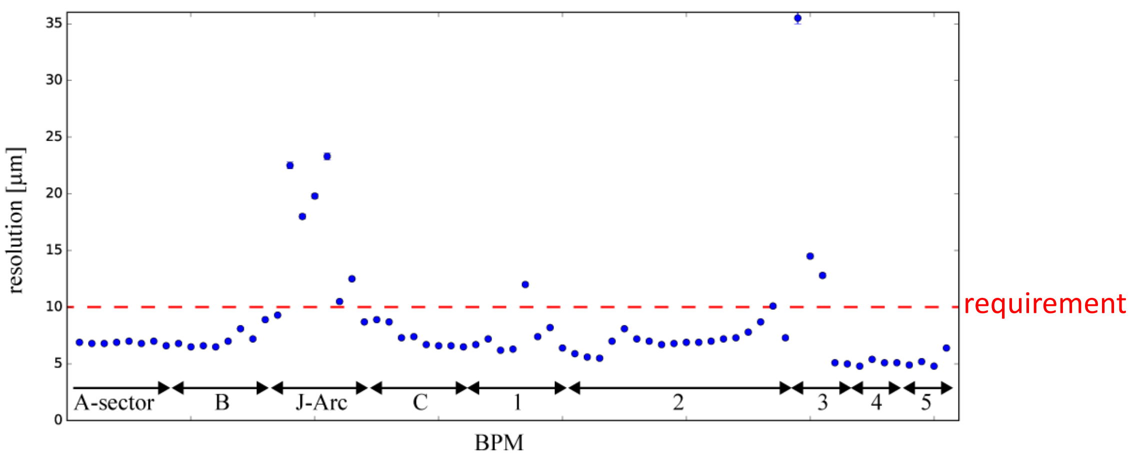
- Usability of the profile monitor

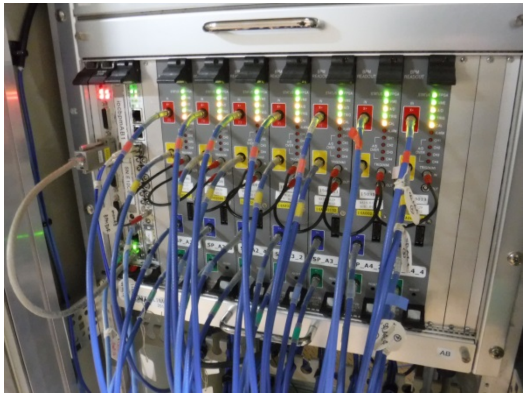
Beam Position Monitor (BPM)

BPM readout system in the Linac

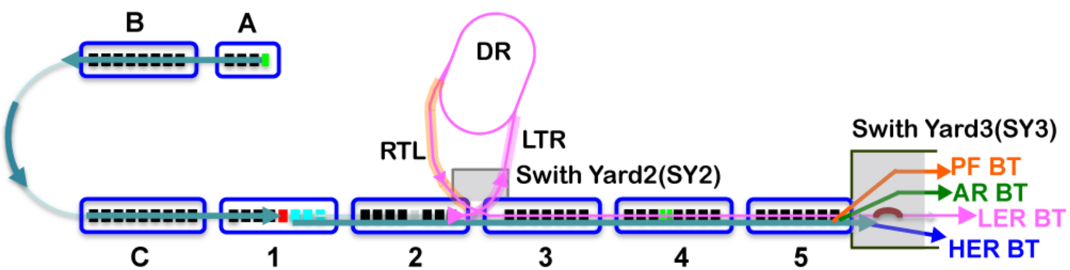
VME based BPM readout system is used in the linac. The BPM board has two band pass filters with bandwidth of 60 MHz (f_c=180 MHz), 16bit-250Msps ADCs and a calibration pulse generators. Position resolution of the system is smaller than requirement (σ<10 μm)



Position resolution of the BPM estimated by 3-BPM method



MVME5500 (CPU): 1
VME-EVR-230RF: 1
RAS board: 1
BPM readout board: 2-8 in a create



VME crate: 22, BPM board: 108

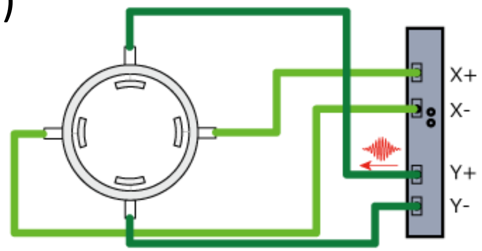
The oscilloscope system is used in LTR, RTL, HER/LER BT.

The system covers the whole of the linac (A-sector – SY3) and a part of the LTR (SY2) BT.

Calibration pulse

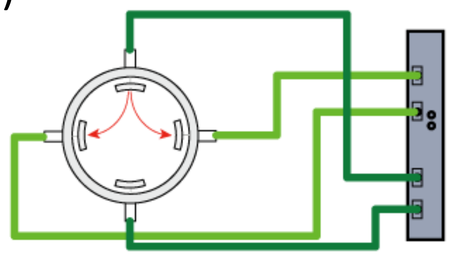
To calibrate gain balance between two signals from opposite electrodes and monitor the gain drift and cable connection, the BPM board can send a calibration pulse to an electrode.

1)



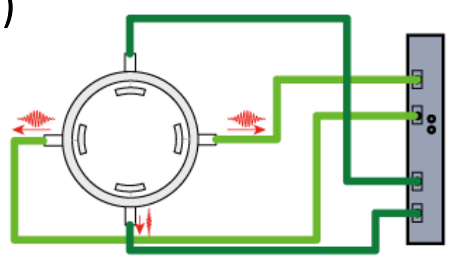
The calibration pulse is sent from the channel Y+.

2)



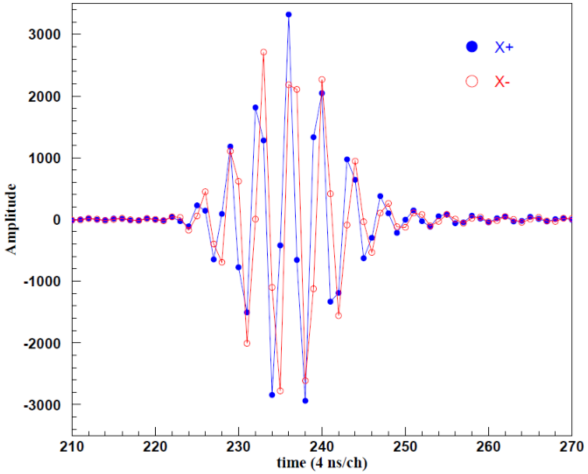
The calibration pulse induces signals on the adjacent electrodes.

3)



The amplitude of the signals are measured.

Calibration of the X direction



ADC response to the calibration pulse.

The signal strength of ch-*i* is given by

$$U_i = G_i \sqrt{\sum_j \left(V_{i,j} - V_{i,pedestal}\right)^2}$$

$V_{i,j}$: ADC value

The gain factor is calibrated by,

$G_{x+}=1,\ G_{x-}=U_{x+}/U_{x-}$

$G_{y+}=1,\ G_{y-}=U_{y+}/U_{y-}$

Usually, the gain calibration is performed at installation or replacing the board.

Acknowledgment: **Design of our BPM system is based on LCLS one.**
We thank Dr. Steve Smith and Dr. Andrew Yang for providing many information and meaningful suggestions.

Stability of the BPM System

The calibration pulse measurement are performed twice in a hour. It also runs machine shutdown time. Because the signal balance between electrodes affects the beam position, monitoring the balance is important.

Variation of the ratio of the signals from the opposite electrodes

$$\Delta r = r - \bar{r} \qquad r = \frac{U_{x-}}{U_{x+}}$$

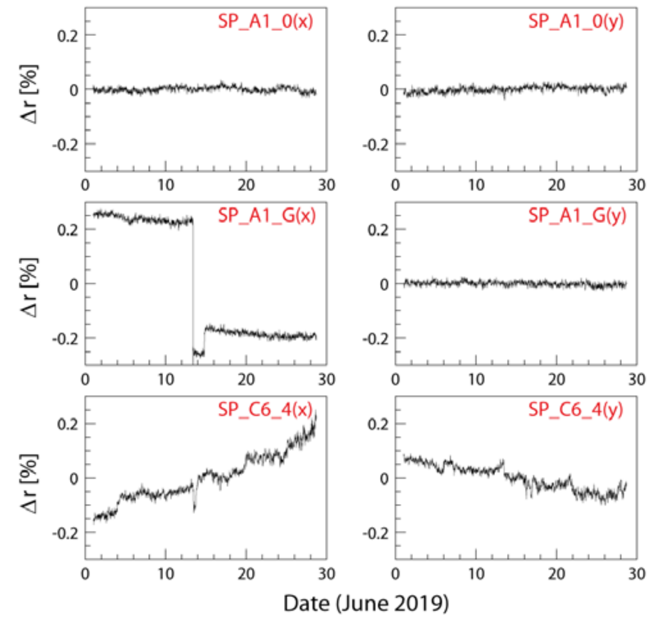
Position drift due to the variation of the gain balance can be approximated by

$$\Delta x \approx a\frac{\Delta r}{1+r} \approx 0.5a\Delta r \qquad a \approx \begin{cases} 8.5\ [\mathrm{mm}](\text{for Sector: A}-2), \\ 5.2\ [\mathrm{mm}](\text{for Sector: }3-5) \end{cases}$$

Stable ⇔

Sudden change ⇔

Drift ⇔



Transit of the signal ratio between opposite electrodes to the calibration pulse in a month.

Stability of BPMs (4 electrodes only)

Maximum variation of the gain balance in a month [%]	<0.1	0.1-0.2	0.2-0.3	>0.4
Number of BPMs (101 BPMs)	33	23	18	27

The reason of the sudden change (without cable re-connection) and the drift is not clear.
➔ We have to find the reason.
The beam position shift or drift (<~20 μm) stems from the change of the signal balance doesn't affect the beam operation yet, but we will develop alert or feedback system.

Synchronized data acquisition

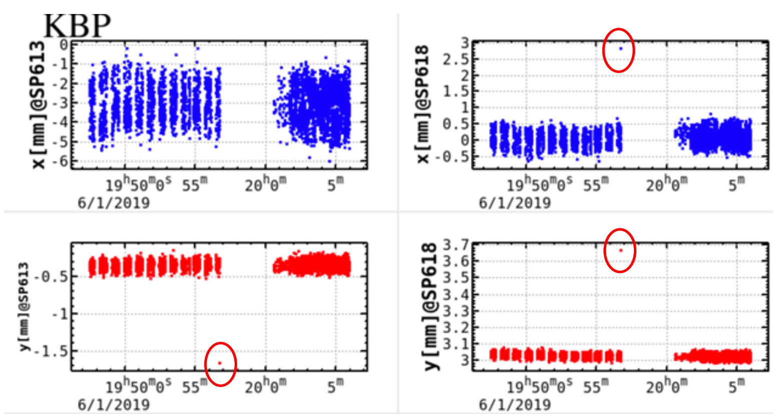
The event timing system allows the beam mode control (HER/LER/PF/PF-AR) and synchronized data acquisition of the BPM, the RF system and pulsed magnet system through the shot-ID.

The synchronized data are put in a PV(Waveform record including the shotID and the beam mode).

- 103 BPMs (Position, Charge) → LIiBM:BPM_SYNC:DATA:[BeamMode]
- 59 RF Monitors (Amplitude, Phase) → LIiRM:RFM_SYNC:DATA
- 98 Pulsed Magnets (Current) → LIiMG:PM:sync_data:IREAD

Every shot of the those data are archived.

➔ **We can analyze correlation of those data and check an irregular event.**



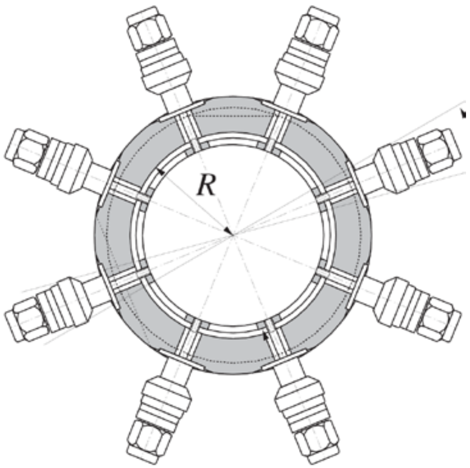
An irregular beam orbit caused a LER abort (Y. Seimiya).
(* Most of abort has another reason.)

The RF pulse shortening was found.
(T. Miura)

Quadrupole moment measurement of the beam

Monitoring the energy spread during the operation is very important to keep the beam quality, but the screen monitor can't be used for this purpose due to it causes the emittance growth.

➔ Non-destructive energy spread monitor is required.



Quadrupole moment of the beam depends on the beamsize.

$$J_q = \frac{1}{R}\left(\left\langle x^2\right\rangle - \left\langle y^2\right\rangle + \left\langle x\right\rangle^2 - \left\langle y\right\rangle^2\right)$$

$$J_q \approx \frac{\sum_{i=1}^{N} V_i \cos 2\theta}{\sum_{i=1}^{N} V_i}$$

V_i: pickup voltage

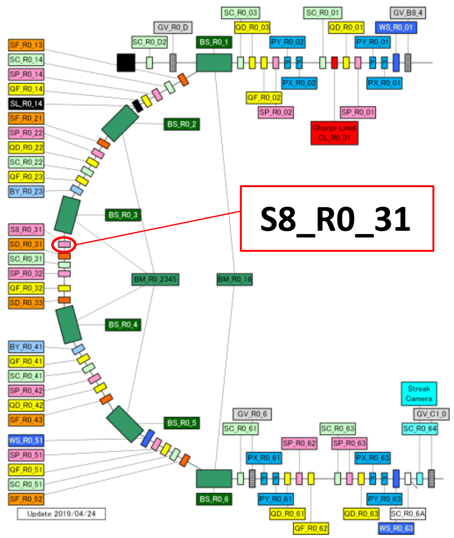
T. Suwada, M. Sato and K. Furukawa
Phys. Rev. Accel. Beams **6**, 032801(2003)

➔ **By monitoring the quadrupole moment at a point with a large dispersion function, the change of the energy spread/distribution can be measured non-destructively.**
(The actual beam size can't be estimated by this way because the quadrupole moment also depends on the beam distribution.)

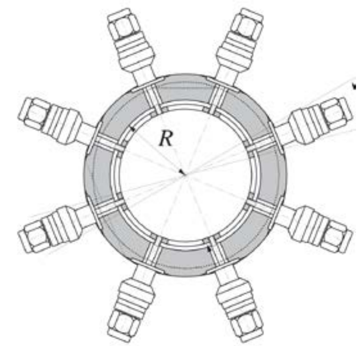
The quadrupole moment was used at KEKB era, but calculation of the quadrupole was not prepared on the new BPM readout system.
➔ A software IOC to calculate the quadrupole moment was developed.

8 electrodes BPM in the linac, HER and LER BT

J-Arc

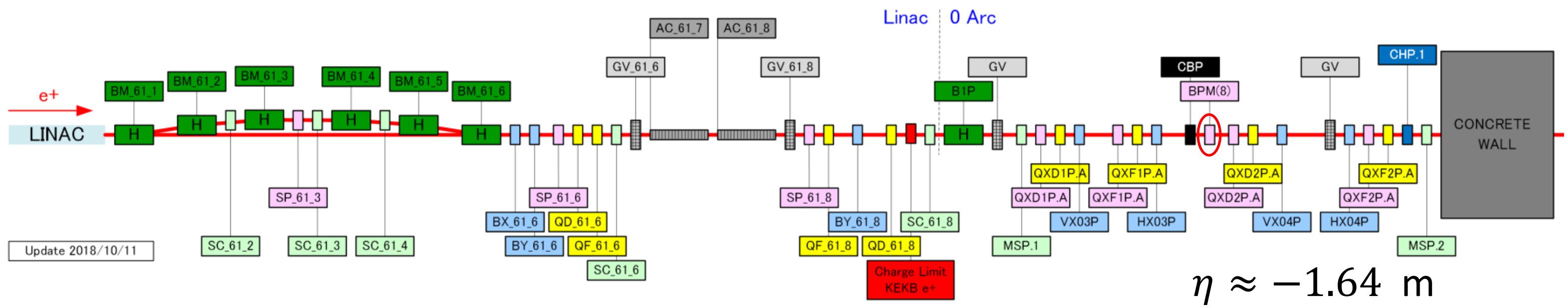


$\eta \approx 0.85$ m



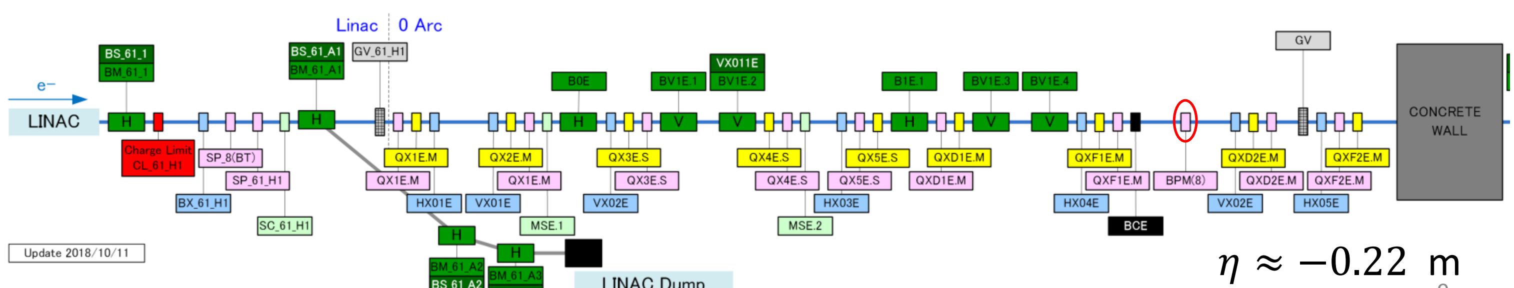
8 electrodes stripeline BPM

LER BT



$\eta \approx -1.64$ m

HER BT

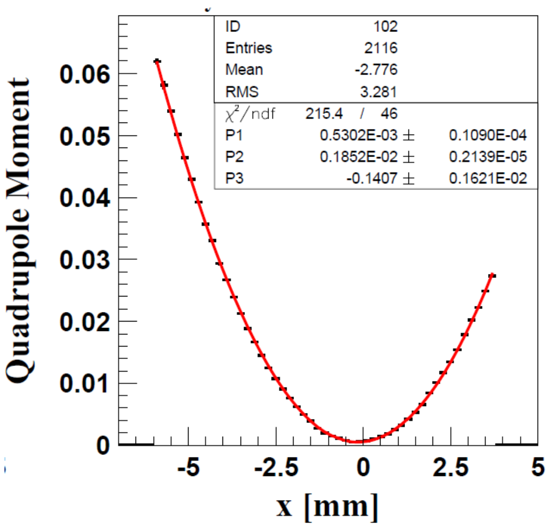


$\eta \approx -0.22$ m

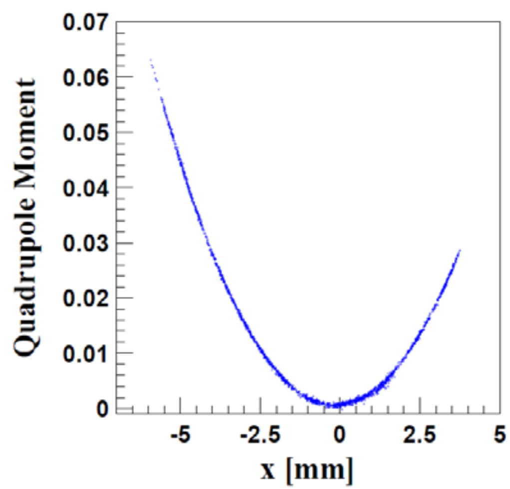
Correction of the beam position

The quadrupole moment depends on the beam position and the beam is jittered every shot.
A quadratic function to cancel the beam position term was applied.

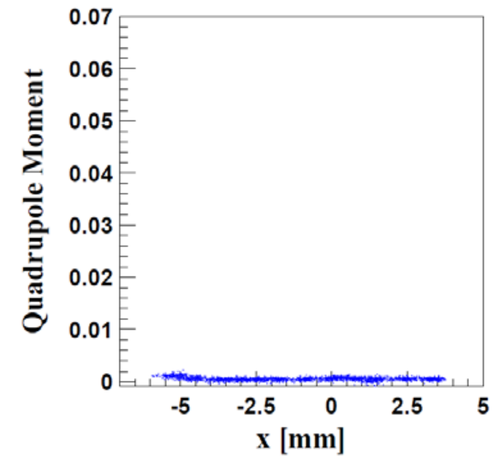
$$J_q = \frac{1}{R}\left(\langle x^2 \rangle - \langle y^2 \rangle + \underbrace{\langle x \rangle^2 - \langle y \rangle^2}_{\text{position term}} \right)$$



Position dependency measured by changing the strength of the steering magnet upstream of the BPM. The red line represents the fitting function.



Before correction

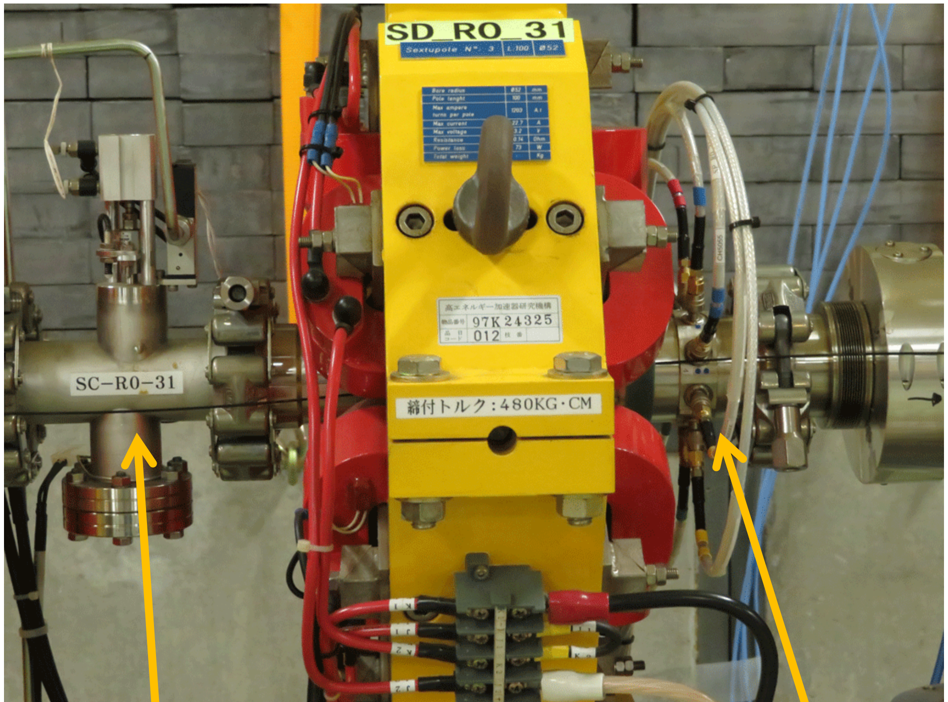


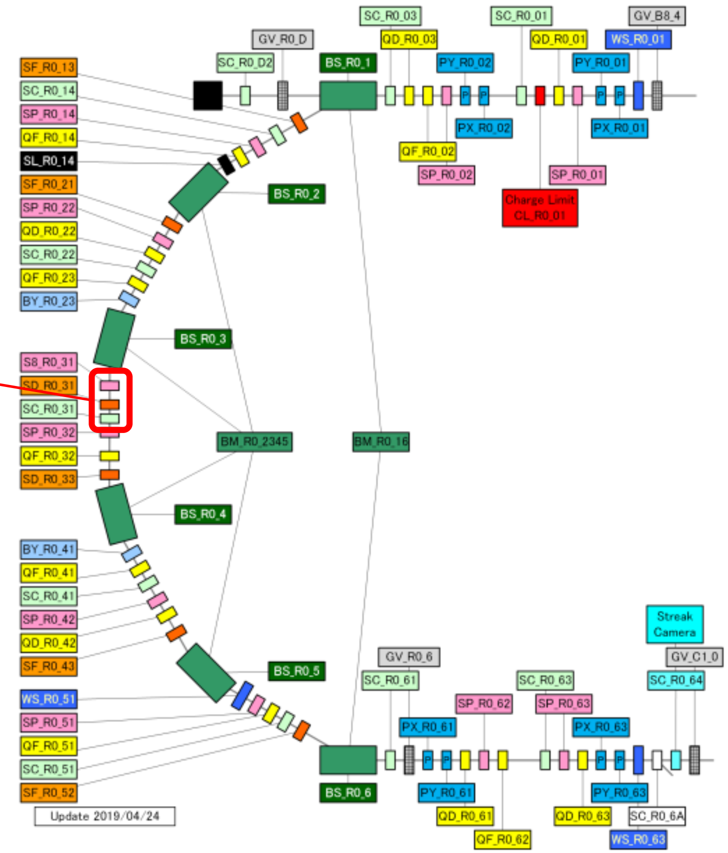
After correction

Beam position and quadrupole moment before (left) and after (right) correction.

The correction works very well.

Beam size and Quadrupole moment@J-ARC



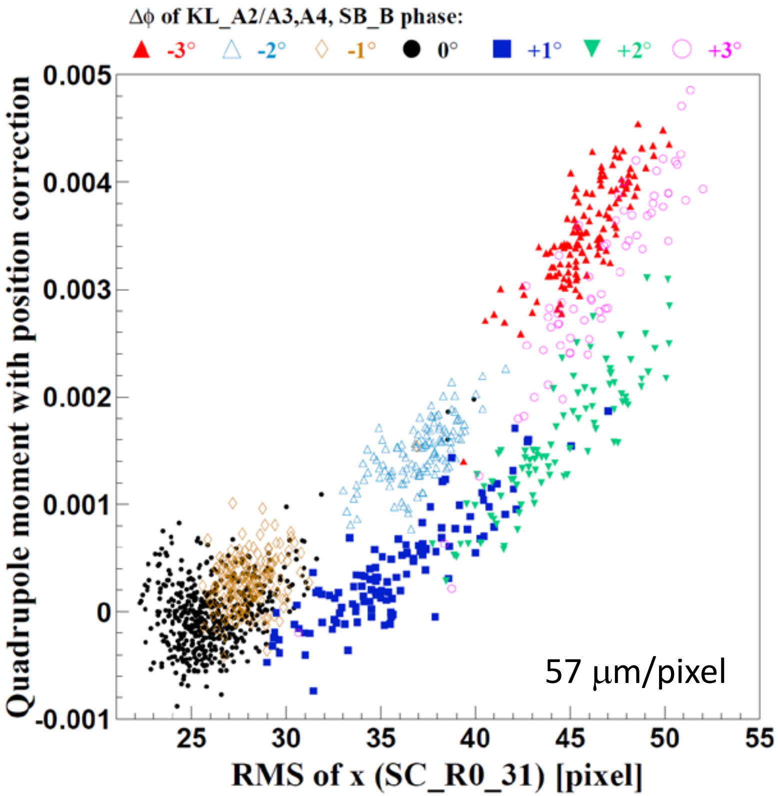


Screen Monitor (SC_R0_31)

8 electrodes BPM (S8_R0_31)

To confirm response of the quadrupole moment of the beam, synchronous measurements of the quadrupole moment and the beam profile had been performed.

Beam size and Quadrupole moment@J-ARC

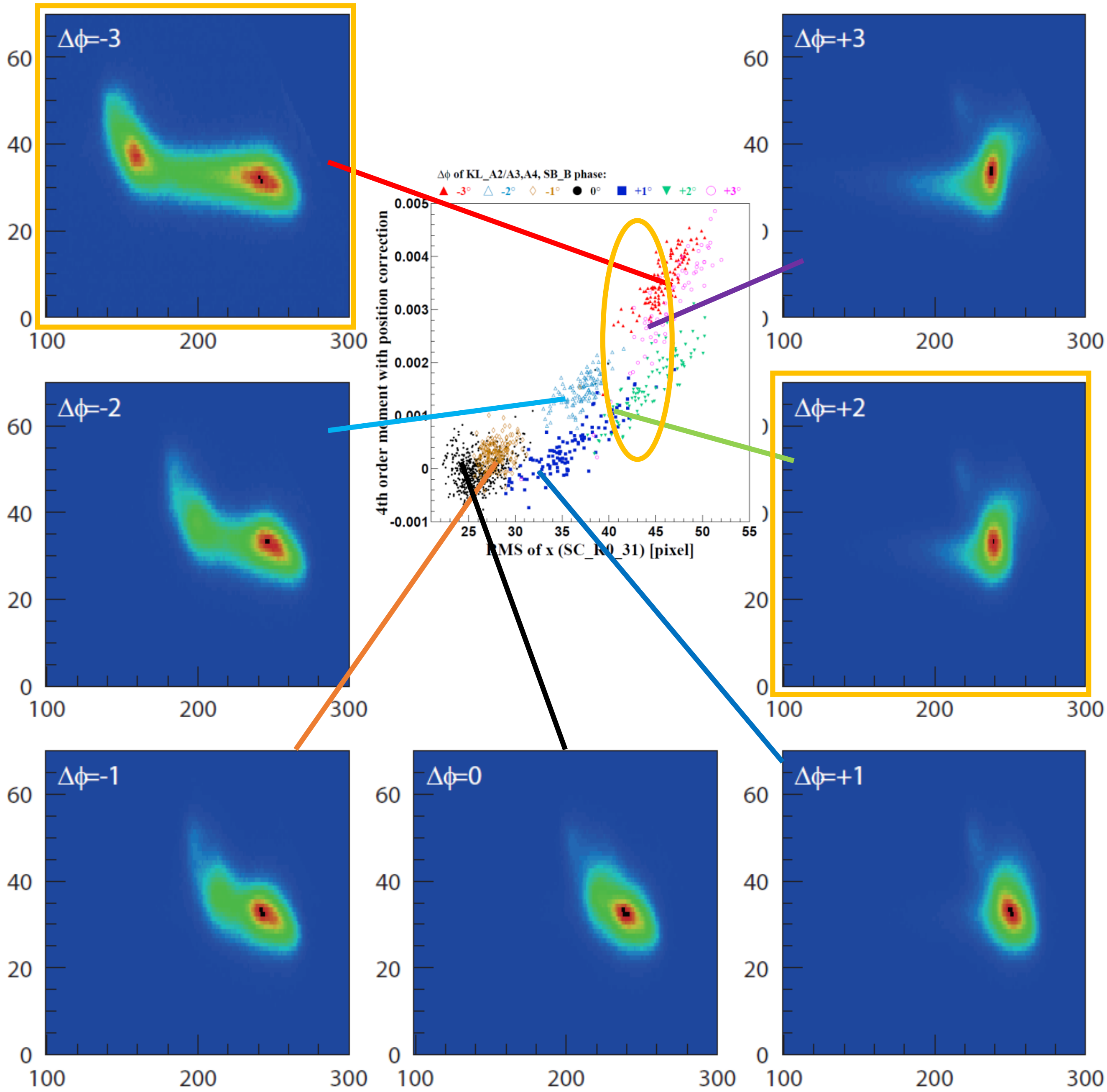


The quadrupole moment and the beamsize measured by the screen monitor.
The klystron phase was varied to change the distribution.

- The quadrupole moment proportional to square of the beam size, but second-order coefficient depends on the beam distribution (⇔klystron phase).
- Beamsize minimum corresponds to the quadrupole moment minimum.
- Variance is not small.
  → Statistical average should be used.

By using statistical average of the quadrupole moment, non-destructive measurement of the change of the beam profile or energy spread, that depend on the laser or the klystron phase or something, becomes possible.

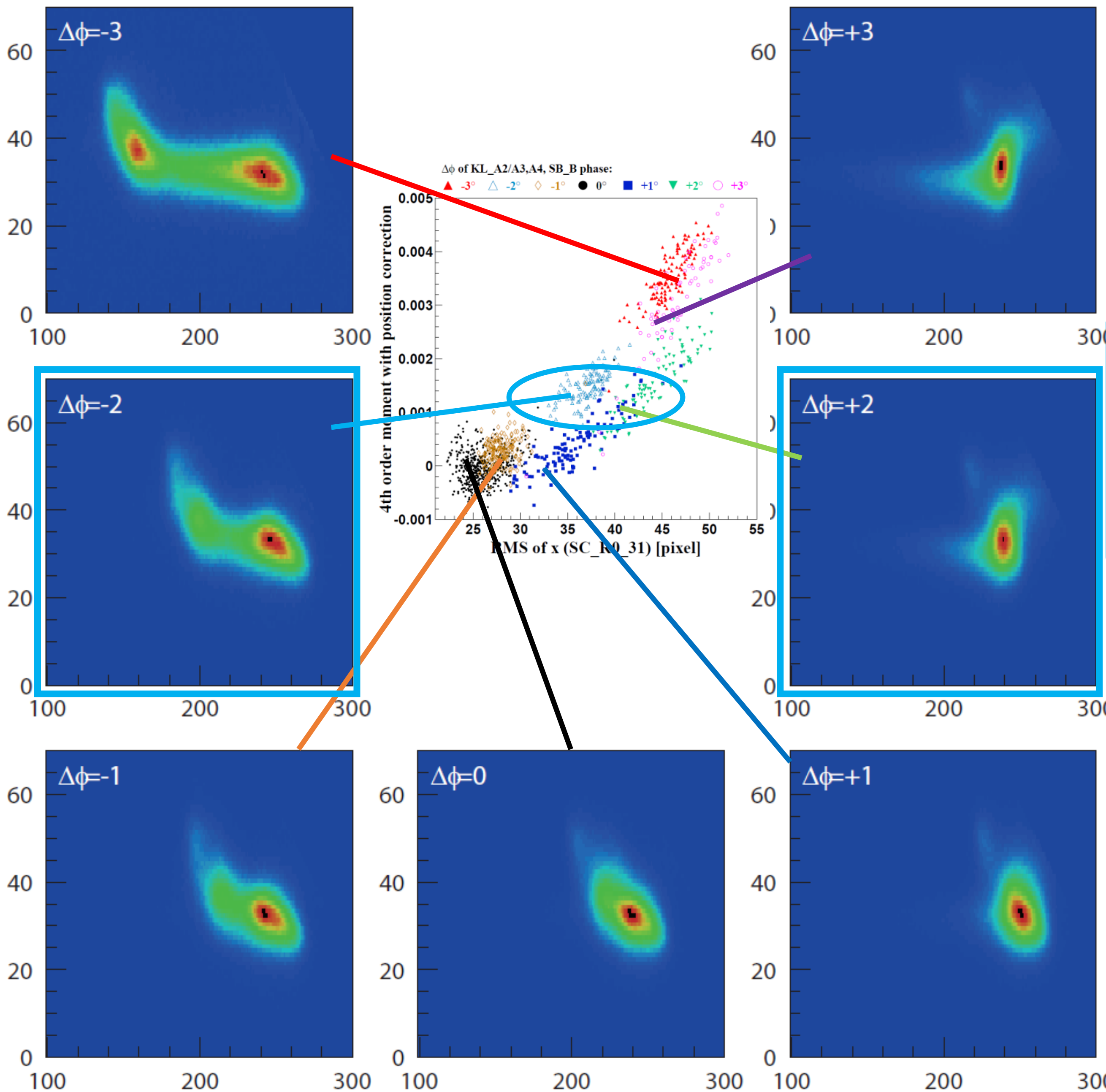
Quadrupole moment and beam profile



The beam sizes (RMS) of those figures are almost same.

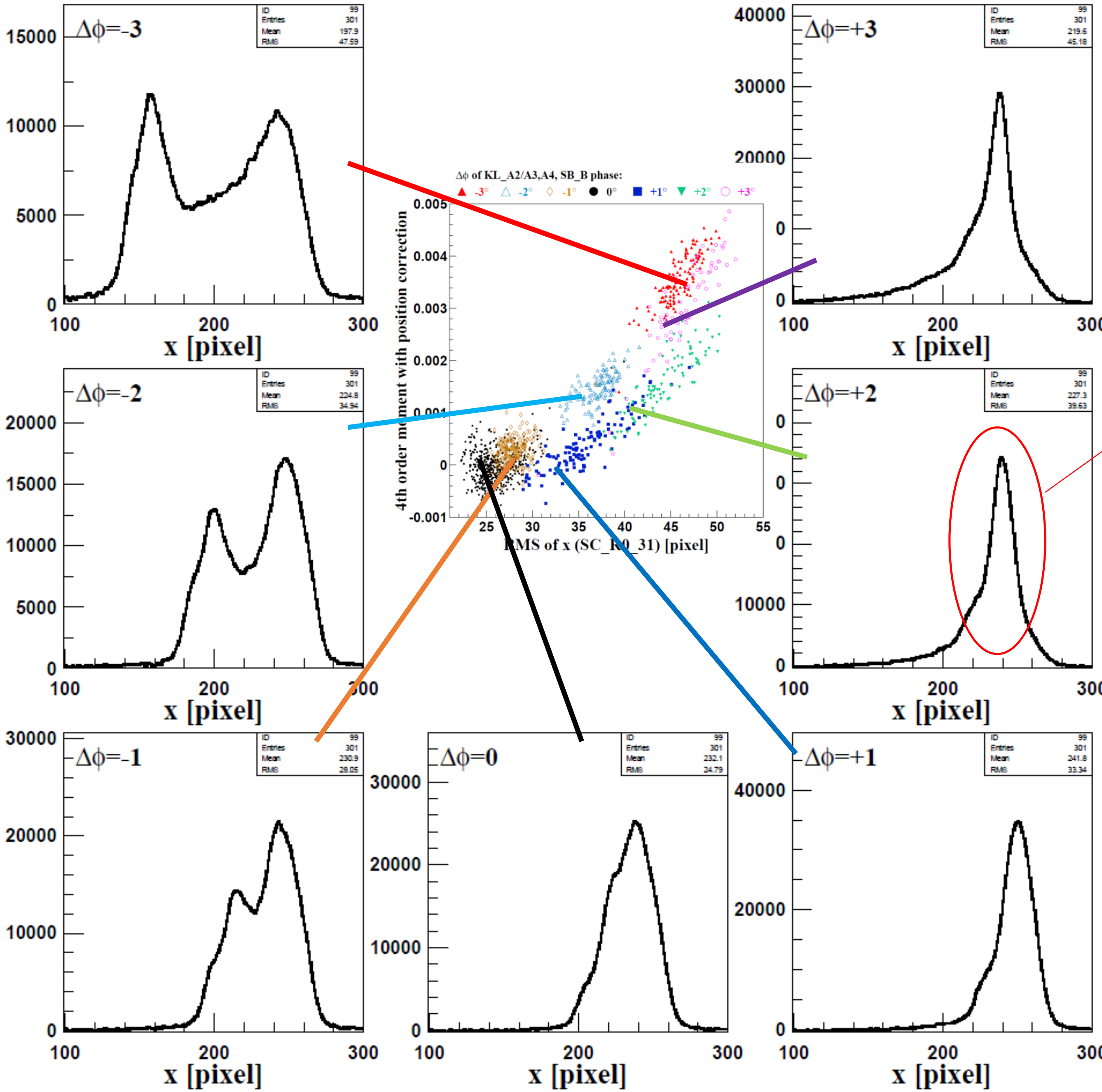
But the distribution and the quadrupole is completely different.

Quadrupole moment and beam profile



The quadruple moments are almost same, but distribution and beam sizes are completely different.

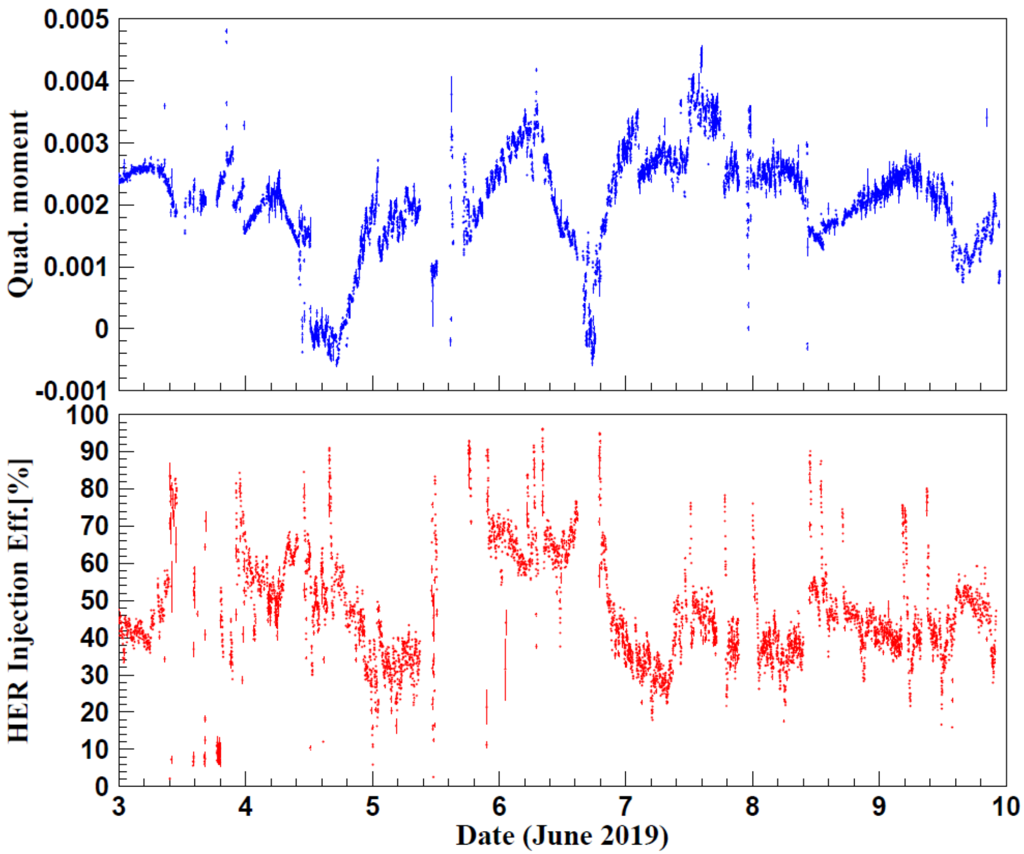
Quadrupole moment and Horizontal beam profile



The core of the distribution is very narrow, but the quadrupole is not small due to a long tail.

We can only monitor the change of the distribution (≈energy spread)

Quadrupole Moment and HER Injection



Quadrupole moment of the electron beam and Injection efficiency (average of 1 minute).

- Clear correlation between the quadrupole moment and the injection efficiency.
- The reason of the drift of the quad. is not clear yet.
  ➔Laser? RF? …
  We have to find the source and develop feedback systems.

The quadrupole moment of the beam at the J-Arc can be a good tool for improvement of the beam injection to the ring.

Summary of the BPM in the Linac

- The position resolution of 5-7 μm is smaller than the requirement.
- Synchronized data acquisition of BPM, RF and pulsed Magnet is very useful.
- Most of the BPM readout boards are stable (gain variation < 0.4% ⇔ Δx, Δy<20 μm), but 30% of the boards have more than 0.4% gain variation.
- Change of the energy spread can be monitored by measuring the quadrupole moment of the beam with 8 electrodes BPM at a large dispersion function point. That affects beam injection efficiency to the ring.

TODO

- Finding the reason of the unstability of BPM boards(~30%).
- Development of an alert or a feedback system to the large variation of the gain balance.
- Finding the source of the drift of the quadrupole moment (≈ energy spread) of the e- beam.
- Install new BPMs in the e+ capture section (🡐 Enomoto's talk).

Beam Profile Monitor (Screen Monitor)

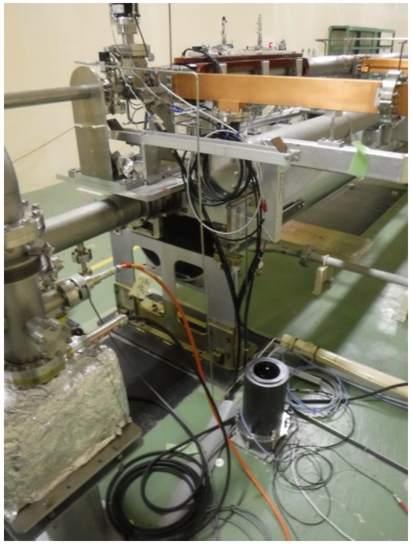
Screen Monitors in the Linac

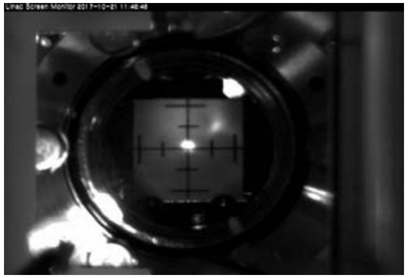
Screen monitor is very important to achieve production and transportation of the low emittance electron beam.

- ◆ Downstream of the rf-gun
  - → • Optimization of the laser and the rf gun
  - • intrinsic beam emittance
    (without the beam position jitter and the emittance growth)
- ◆ Key point (e.g. top of the sector) in the linac
  - → • Making a guess of a source of the emittance growth
- ◆ Point with a large dispersion function
  - → • Energy spread

There are about 100 screen monitors, but they have some problems.

- Conventional system is simple but it has poor resolution (~80 μm FWHM).
- Aluminum ceramic (Al_2O_3:Cr_2O_3) is used as the screen material.
  It is fabricated by sintering and has a very long decay time (~ms).
  That degenerate the resolution.
  (⇔ The long decay time enable dynamic range control of the intensity by changing exposure time of the camera.)
- Some screens have target guide lines, that disturbs beam profile measurements.
- The CCD camera without external trigger.
  → The intensity is random, because the screen shot is not synchronized with the beam.

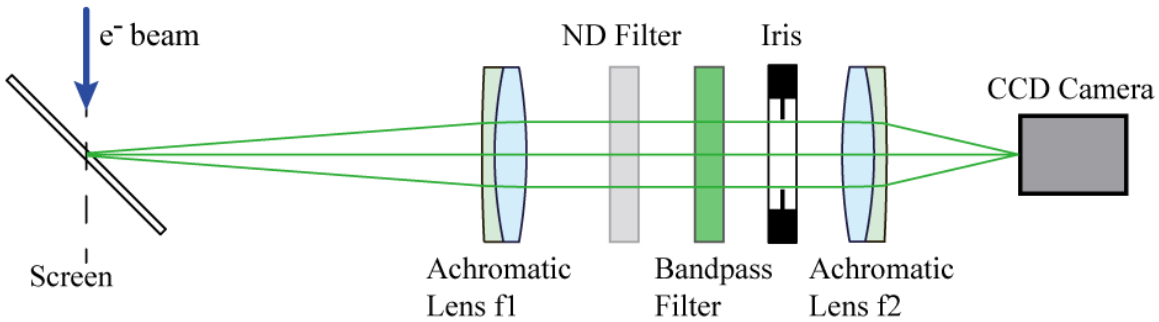




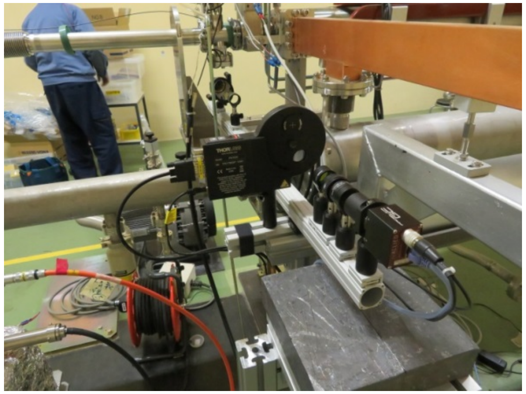
Conventional (old) screen monitor system.

➔ A new high resolution screen monitor system is required.

High Resolution Screen Monitor (new)



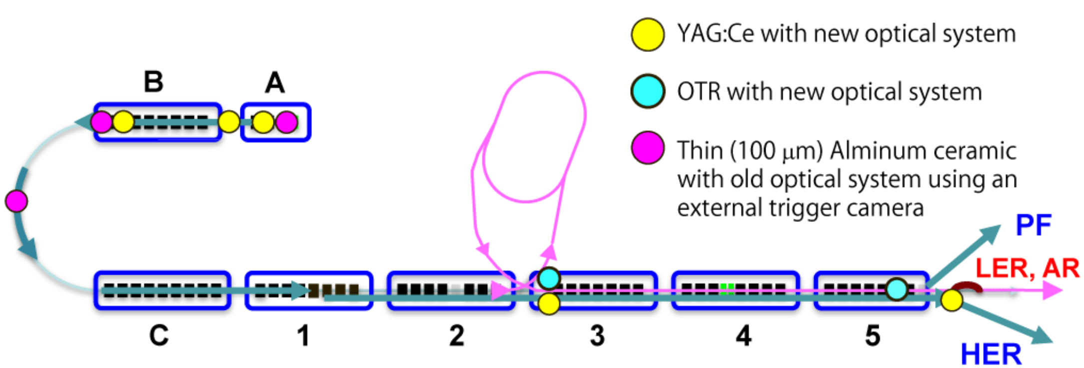
Layout of the optical system



Screen SC_A4_42 (Lead shield shield is removed in this picture)

component of the screen monitor system

Screen	YAG:Ce crystal (t=100 μm) or Optical Transition Radiation (OTR) screen (70μm silicon wafer with Al coating)
Optical System	Achromatic lens x 2(f=750, f=250 mm), Bandpass Filter, ND Filter with motorized filter wheels(variable), Iris, Mirror (depend on the direction of the view port), Lead shield
CCD Camera	GigE camera with external trigger (Sensor: 1/3-inch type, Resolution: 659x493 or 1024x768)



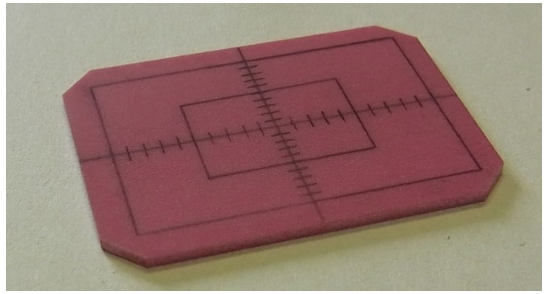
Location of the new screen monitors (~June 2019)

Some thin aluminum ceramic screens are used at some points, because it is useful to control dynamic range.

The resolution of the optical system is about 10 μm FWHM (estimated by spread of a sharp edge).
It is much smaller than the beam size in the linac (σ_e->~100, σ_{e+}>~50 μm).

Screen Materials

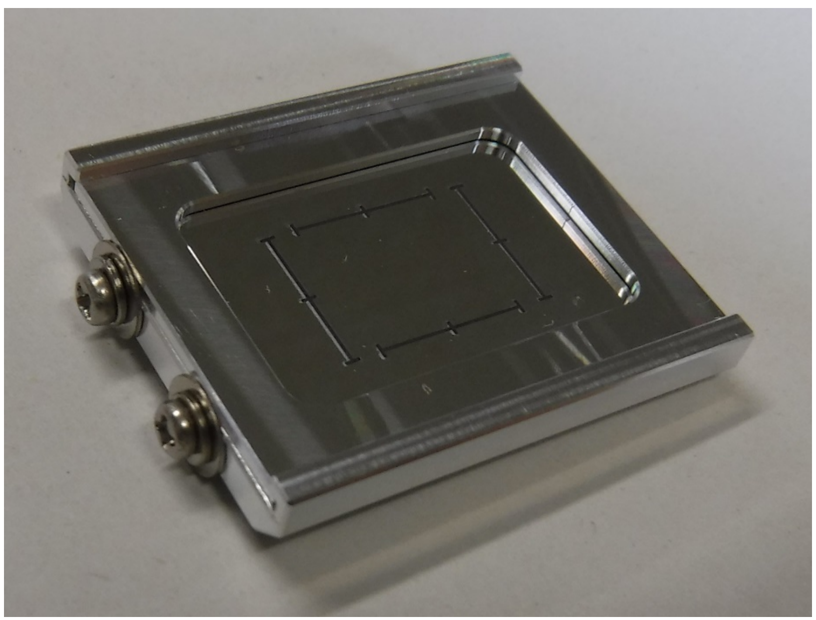
Thin type (t=0.1 mm)



Conventional (Old) type with target guide lines (t= 1 mm)

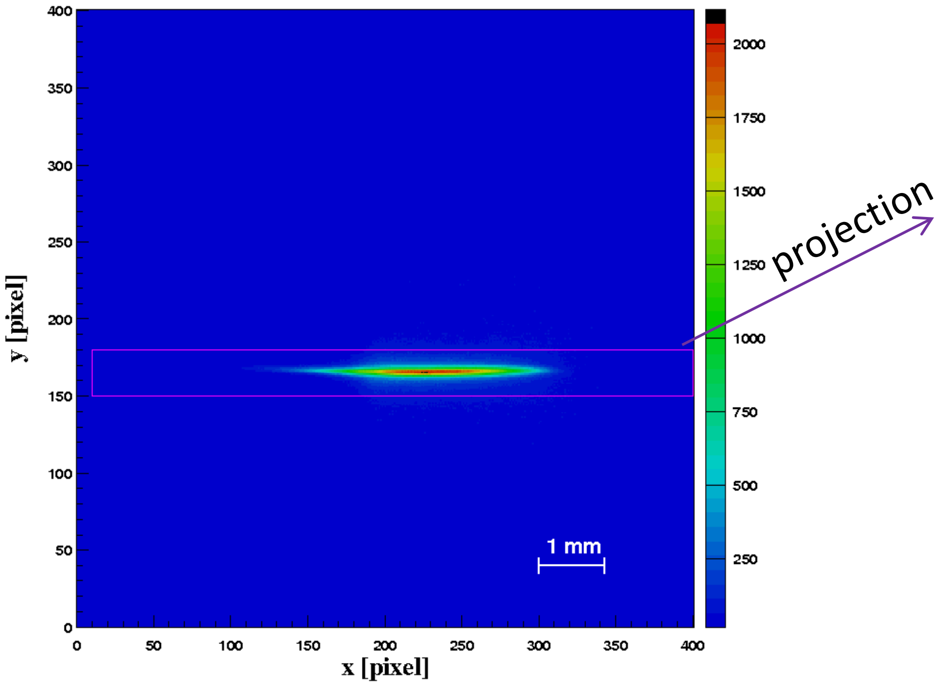
Aluminum Ceramic (Al_2O_3:Cr_2O_3)

YAG:Ce (t=0.1 mm)



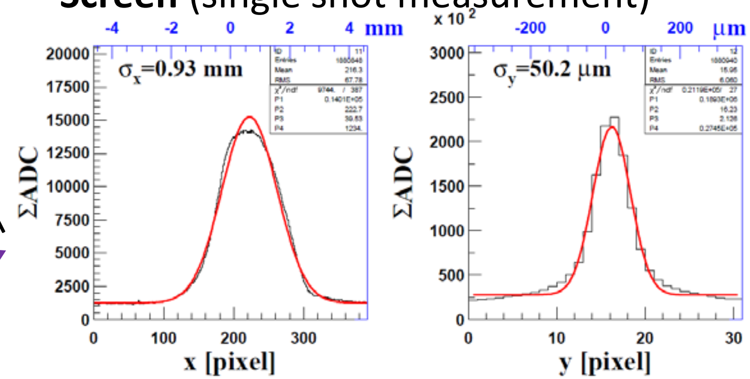
OTR Screen (t=0.07 mm)

Positron beam profile at Linac End (SC_57_2)

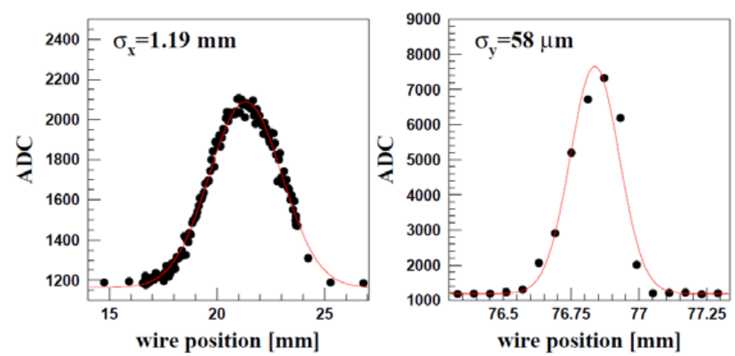


Positron beam profile measured by the OTR screen at the linac end.

Screen (single shot measurement)



Wire Scanner (multi shot measurement)



Horizontal (left) and Vertical (right) beam profile measured by screen and wire scanner.

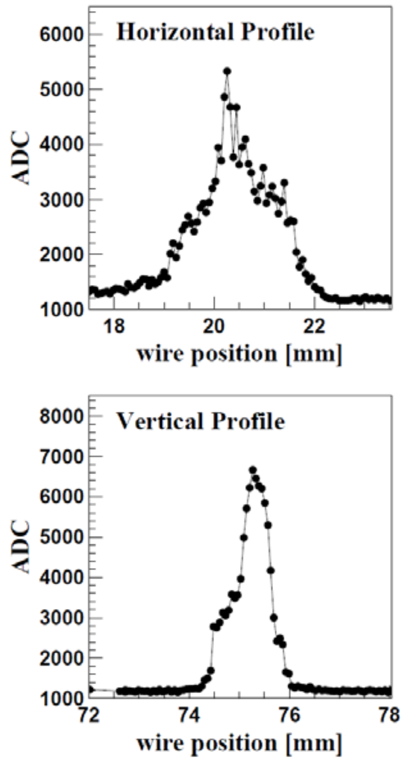
Beam size estimated by the screen and the wire scanner

	σ_x [mm]	σ_y[mm]
screen	0.93	0.050
wire	1.19	0.058

The beam profile measured by screen shows good resolution and consistent with wire scanner measurement.

Electron beam profile at Linac End (SC_57_2)

Wire Scanner



In this case, the electron beam split into two core beams.
The horizontal profile measured by wire scanner shows fluctuation due to multi shot measurement with the beam jitter and the variation of the profile.
Only 2-dimentional profile helps understanding of the situation.

In case of 2 core beam at the linac end, by tuning of the beam orbit after the 2-sector, double core beams are assembled in single core.

High resolution screen monitor is important to improve the beam quality

Summary of the Screen Monitor

- New high resolution screen monitors were installed.
- The resolution of the optical system is ~10 μm FWHM which much smaller than the beam size (σ_{e-}>~100, σ_{e+}>~50 μm).
- A beam size measured by the screen monitor is consistent with the wire scanner measurement.
- Two dimensional beam profile can be a good tool to improve the beam quality.

TODO

- Beam profile measurement with the screen monitor is destructive and it disturbs beam injection to the rings (HER, LER, PF, PF-AR)
  ➔ • Install a new screen to HER/LER BT.
     • Replace the screen material to very thin material (e.g. aluminized Mylar).

- Development of a universal data acquisition system with auto gain control (variable ND filter, exposure time).

- Development of a feedback system using the screen monitor.