Injector Upgrade Plan

F. Miyahara (KEK, Acc. Lab.) for Injector Linac Group

The upgrades performed in 2024 and the plans for the future will be reported.

Contents

1. Fast Kicker to correct 2nd bunch orbit
2. Beam diagnostic Line with pulsed magnets
3. Beam tuning programs with machine learning
4. Big data analysis
5. HER BT Energy Compression System (ECS)
6. Summary

Fast Kicker to correct 2nd bunch orbit

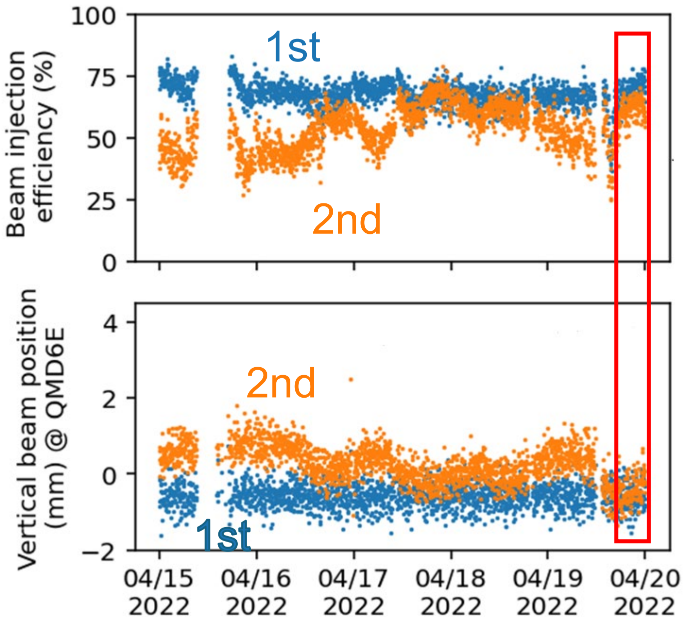
Fast Kicker for Second Bunch

T. Natsui

Background:

- To suppress emittance growth, 1st and 2nd bunch beams must pass through the center of accelerating structures
- To achieve the same injection efficiency as the 1st bunch, the beam orbit of the 2nd bunch must be same as 1st bunch

However, the orbit of the 1st and 2nd bunches differ right after the electron gun



Injection efficiencies and orbit trend of the 1st and 2nd bunches (HER).

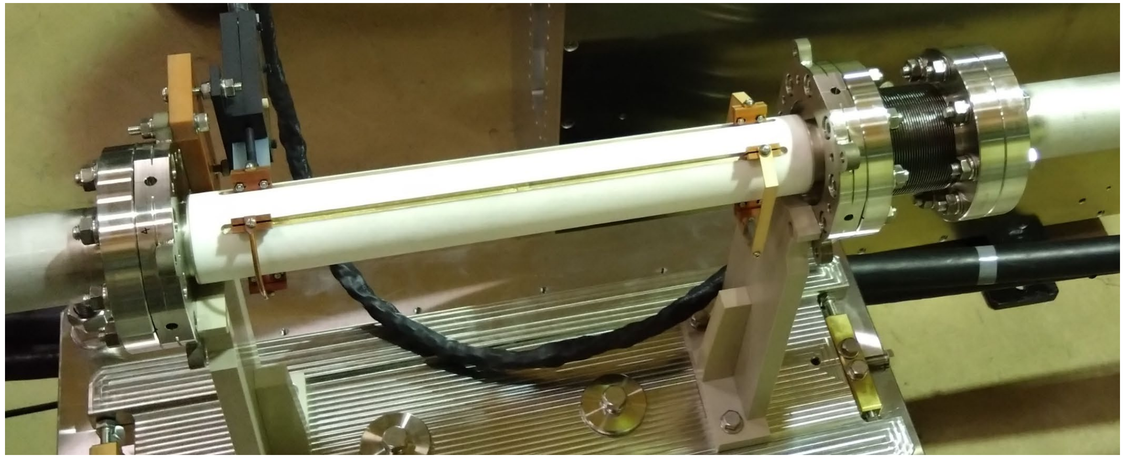
Solution:

Installation of a steering magnet capable of kicking only the 2nd bunch

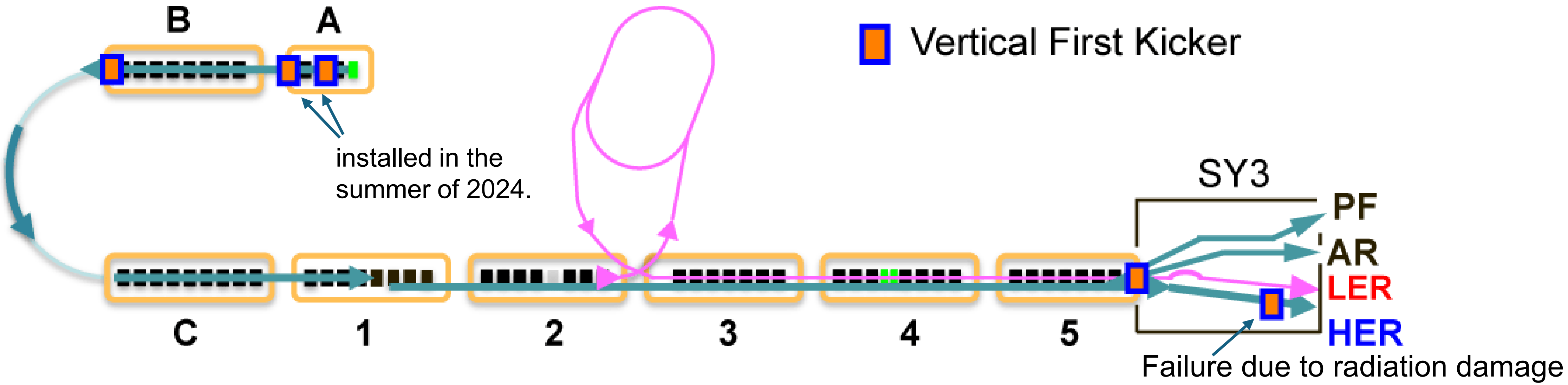
Requirements:

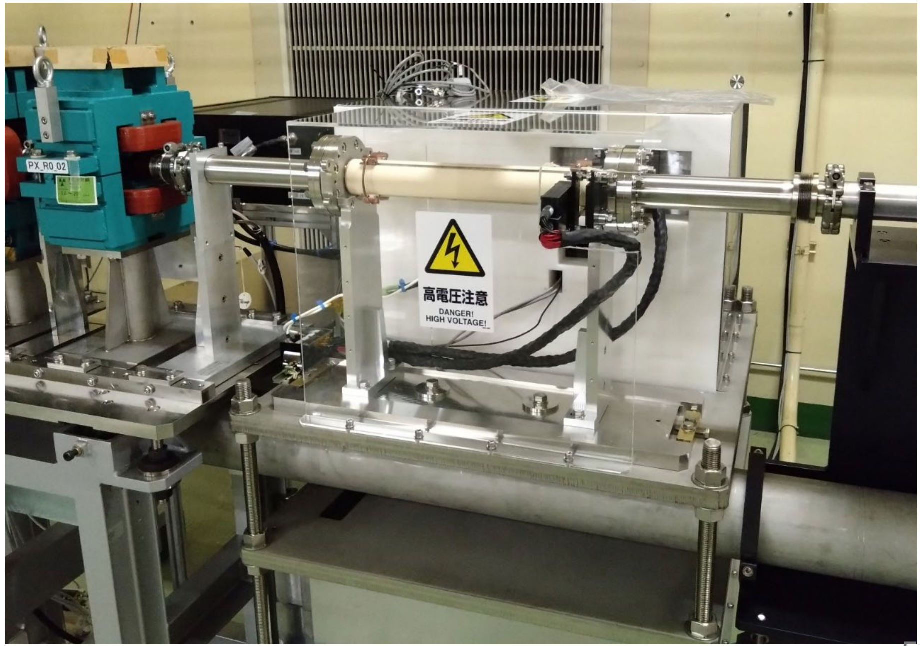
Current response faster than the 96 ns bunch spacing

T. Mitsuda, T. Natsui, Y. Enomoto, Y. Okayasu



Fast Vertical Kickers in the Linac





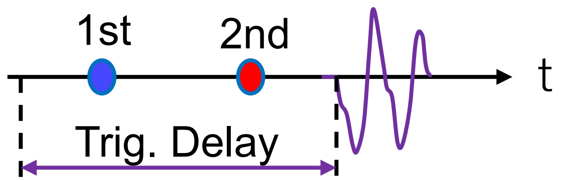
List of fast vertical kickers

Name	Location	Beam
FY_A2_2	A-sector	e- (HER), e- for e+ production
FY_A4_4	A-sector	e- (HER), e- for e+ production
FY_R0_02	J-Arc	e- (HER), e- for e+ production
FY_58_4	5-sector	e- (HER), e+ (LER)
~~FY_61_E~~ #	SY3	e- (HER)

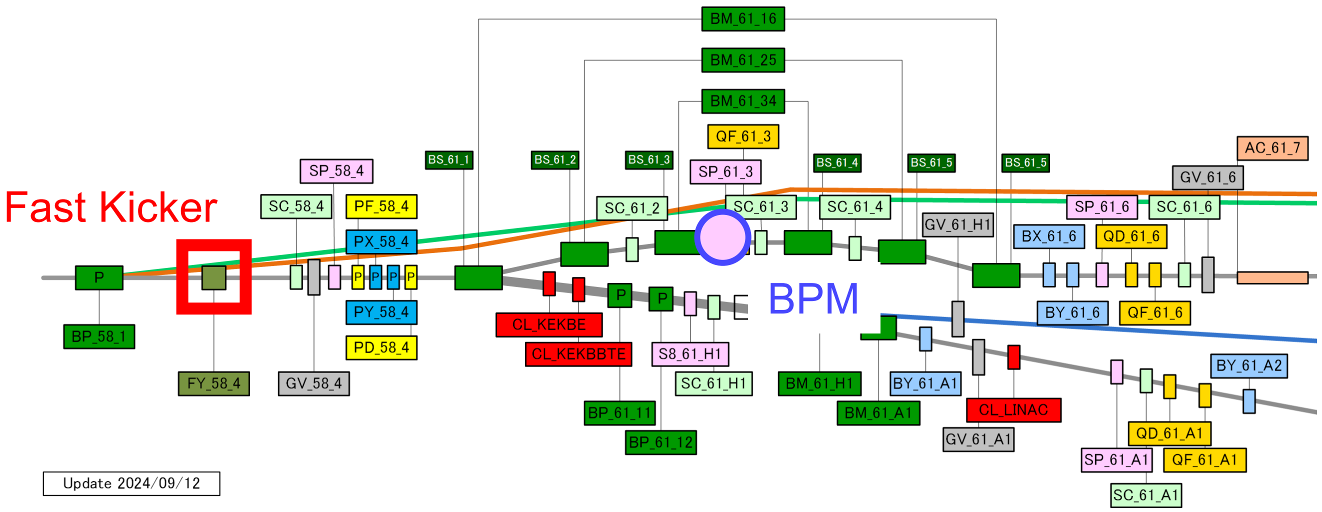
Power semiconductor device was broken due to radiation.

➔ We are looking for a new location with lower radiation levels that is suitable for installation and effective.

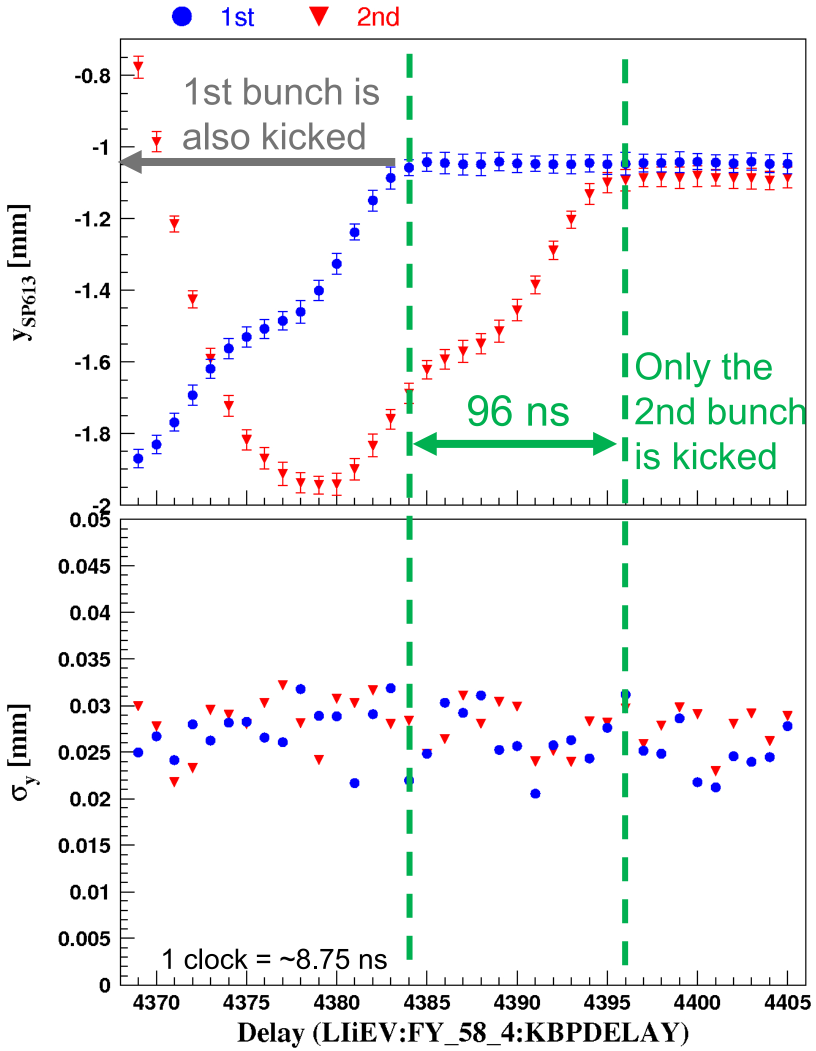
Beam test using a Fast Kicker



The beam position displacement and jitter were measured using the fast kicker



Beam test at Linac end



The y-position and position jitter as a function of the trigger delay of the fast kicker

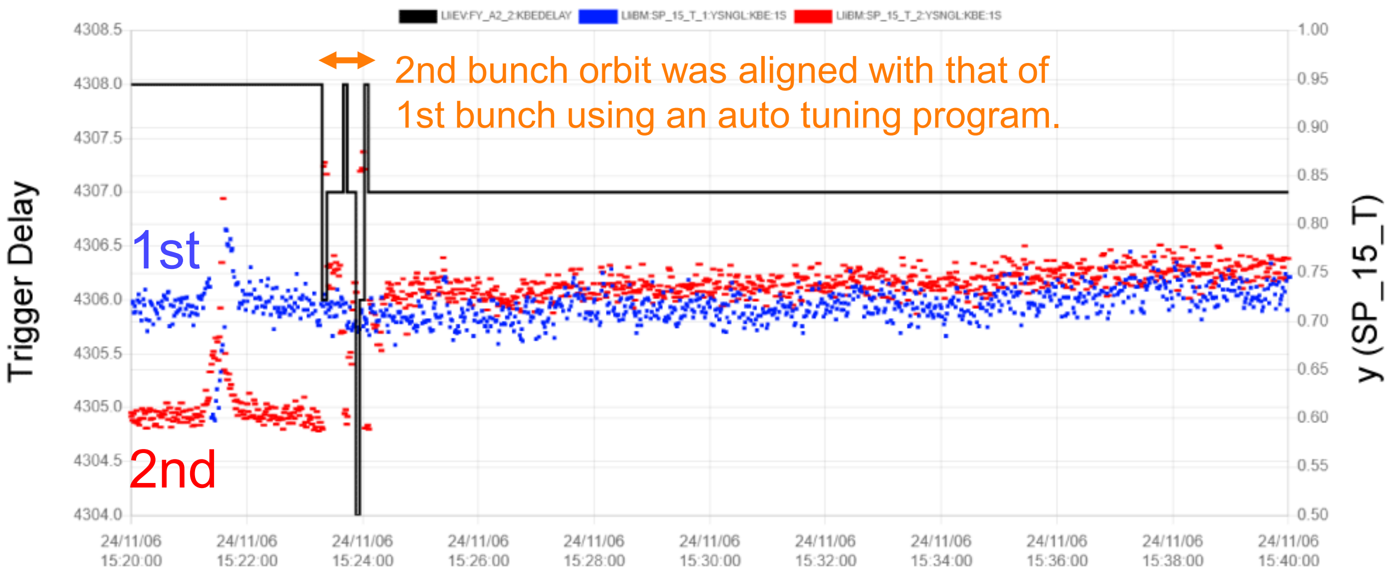
- ✓ Kicking only the 2nd bunch is possible
- ✓ It is also possible to kick both the 1st and 2nd bunches
- ✓ The beam position jitter remains constant regardless of the kick angle (The current output is stable)#

In last year's KEKB Review, it was reported that initial tests showed significant jitter, which was found to be caused by trigger timing jitter from the bucket selection. By implementing timing corrections, this jitter was eliminated.

Use case of the Fast Kicker

1) Orbit correction for the 2nd bunch

- Orbit correction for 2nd bunch of e- beam (HER) using FY_A2_2



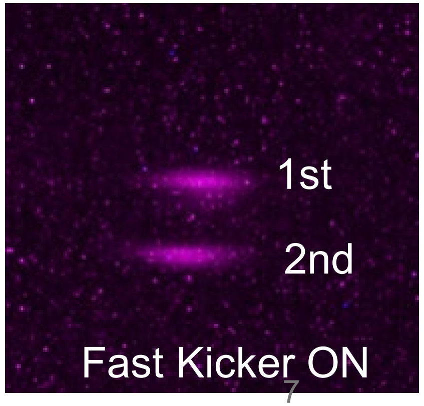
Trigger Delay and vertical e- beam (HER) position before the target

2) Beam diagnostics with separated two bunches

- The beam profiles of the first and second bunches can be measured simultaneously.

- The emittance and energy spread of the first and second bunches can be evaluated.

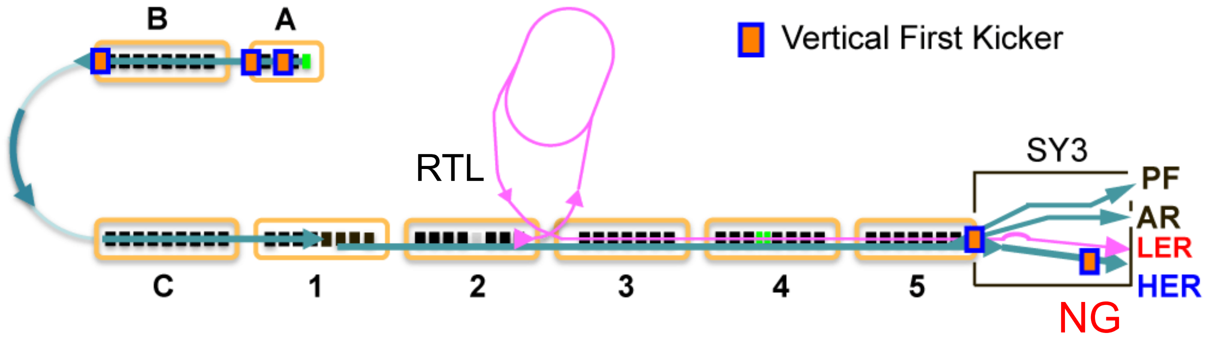
e- beam profile at BT



e- beam profile at BT

Upgrade plans of fast kickers

Current Status:



- Only one Fast Kicker is available for positron beam correction (one unit is out of order)
- There are no horizontal fast kickers in Linac#

A stripline-type horizontal fast kicker is installed in the RTL.

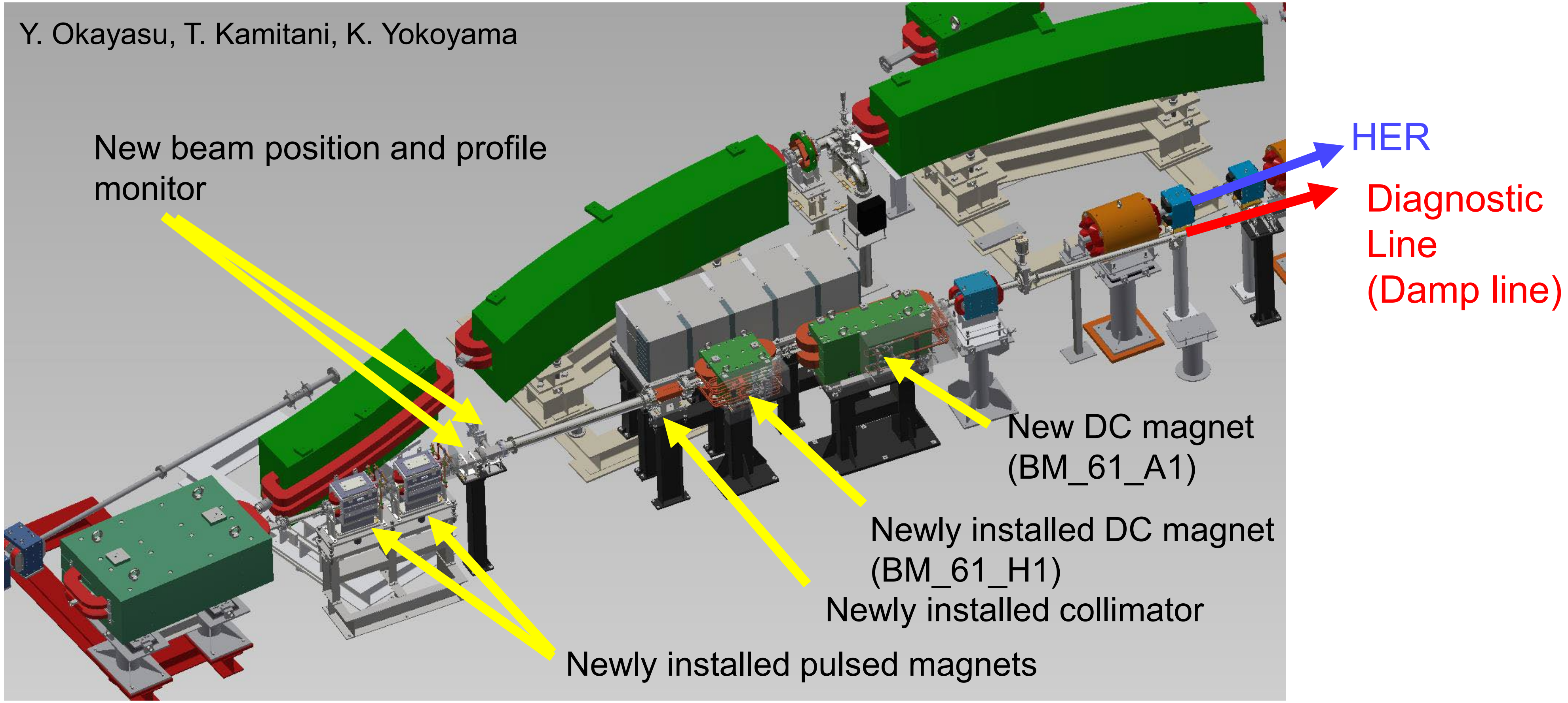
Plans:

- **The failed Fast Kicker is planned to be relocated to 4-sector end**
- **We aim to install at least two horizontal Fast Kickers and, if possible, a total of tree.**
  (Two will be installed upstream of the target, and the remaining one downstream of the DR)

Beam diagnostic line with pulsed magnets

Beam diagnostic line with pulsed magnets

A beam diagnostic line using a pulsed magnet was developed to periodically (≤ 1 Hz) guide the beam to the dump line for diagnostics even during HER injection.

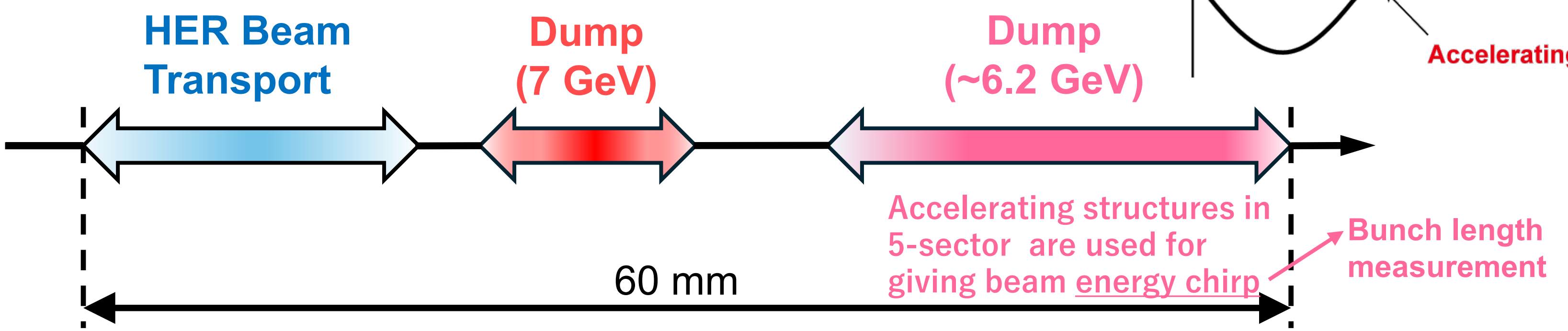


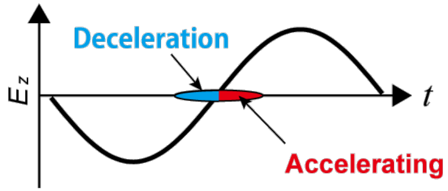
New pulsed diagnostic line (2024 Summer)

Newly installed beam diagnostics devices and beam modes

E. Miyahara, T. Suwada

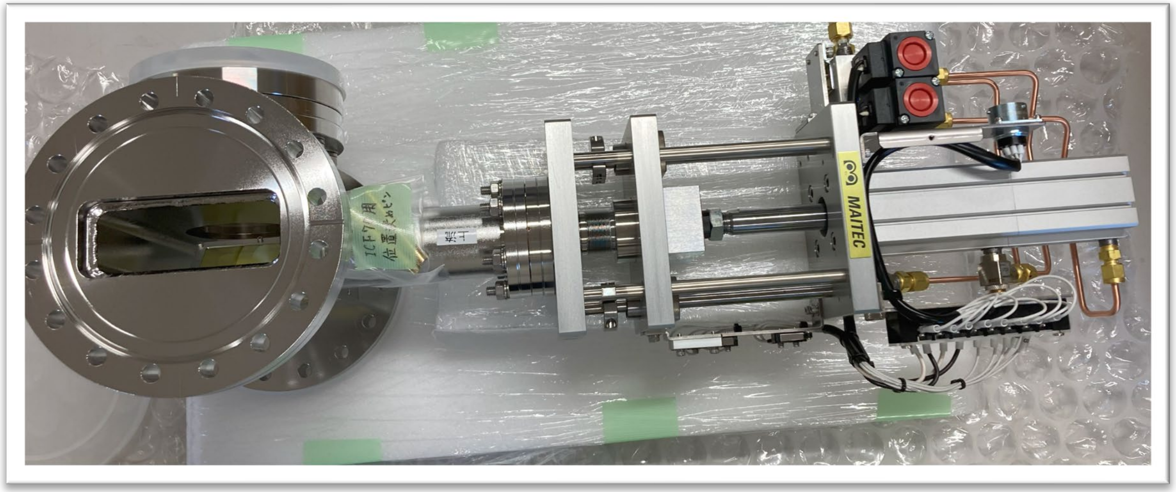
The beam monitors were replaced with a new ones to cover the entire beam orbit



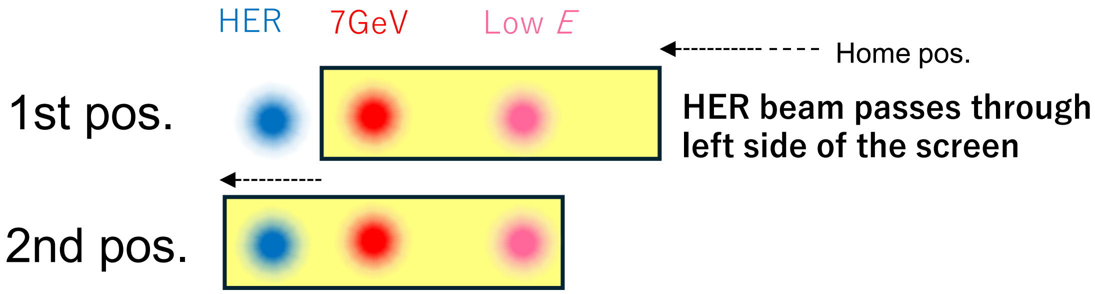


The horizontal range of the beam passing through the new monitor

An 8-electrode position monitor with a wide dynamic range.



Screen monitor with two adjustable insertion positions



The insertion position of the screen and the beam position

A screen monitor with two adjustable insertion positions. In the first position, it allows continuous measurement of the diagnostic line beam without interfering with the HER beam.

Utilization of the beam diagnostic line

Use of the beamline:

- Diagnostics of a beam same as HER injection beam
- For diagnosing the bunch length, utilizing 5-sector acc. structures to apply an energy chirp
  → Beam energy at Linac end is ~6.2 GeV
- Test experiment using a beam dump

Beam test:

- ✓ Preparation of beam modes for beam diagnostics → OK
- ✓ Passing 7 GeV e- beam to the HER BT→ OK
- ✓ Passing 7 GeV e- beam to the Diagnostic (Damp) line → OK
- ✓ Passing 6.2 GeV e- beam to the Diagnostic (Damp) line → OK

During operations starting from September 2024, there was not enough power and time to perform sufficient beam tests using the diagnostic line.
From the 2025 operations, full-scale use of the beamline will be promoted.

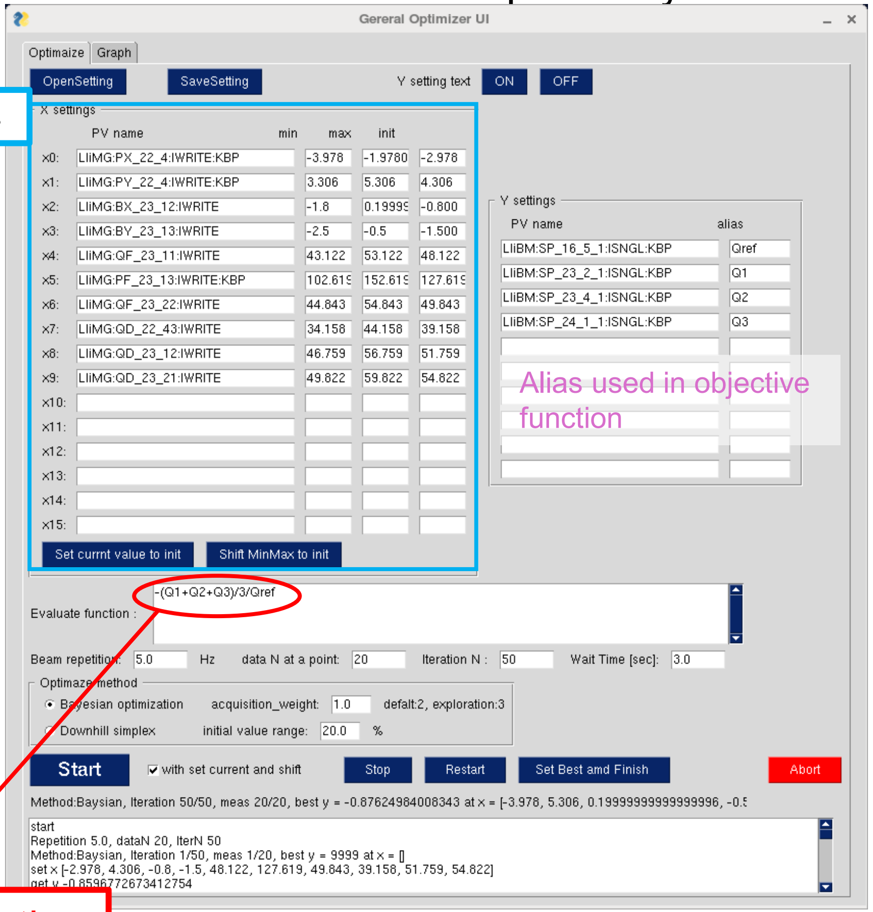
Beam tuning programs with machine learning

General optimization program using Bayesian Optimization

A general optimization program utilizing machine learning has been developed and is being actively used for various beam tuning

Development by T. Natsui

Parameters

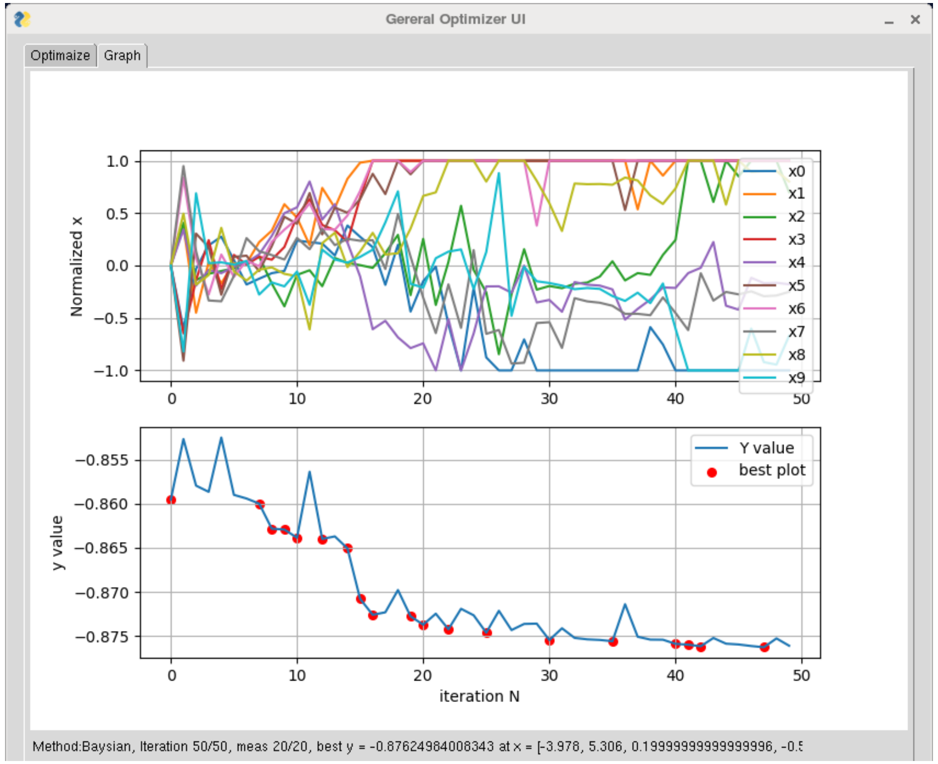


Example of an optimization

Objective Function

Example: Maximizing beam transmission

f = -(Q(BPM1)+Q(BPM2)+Q(BPM3))/Q(BPM0)



The process of the objective function decreasing during an optimization.

Since Kurata-san developed a similar alternative program, two optimization programs are now available for use.

Utilization of the optimization program

Typical use cases for machine learning programs

Purpose	Execution time	Execution interval or execution count
Maximization of positron yield at positron capture section exit	A few minute (When slightly deviating from the optimal conditions)	A few times in a day (**Automatically execute when the yield decrease**)
Maximization of the e+ beam transmission rate from positron capture section exit to SY2 (End of 2-sector)	~a few days (~160 params. Execute the beamline in multiple parts)	Only once
Maximization of the e+ beam transmission rate from Linac (SY2) to Damping Ring	~20 min	Several times a day after Linac startup
Align the vertical orbit of the electron 2nd bunch with that of the 1st bunch using fast kicker	A few minute	A few (Because each beam was stable before the gun problem)
Minimization of emittance in the HER BT through beam orbit adjustments in the Linac	~30 min	A few times a month
Increase the beam transmission rate for both the 1st and 2nd bunches in the Linac	~20 min	Several times a day after Linac startup

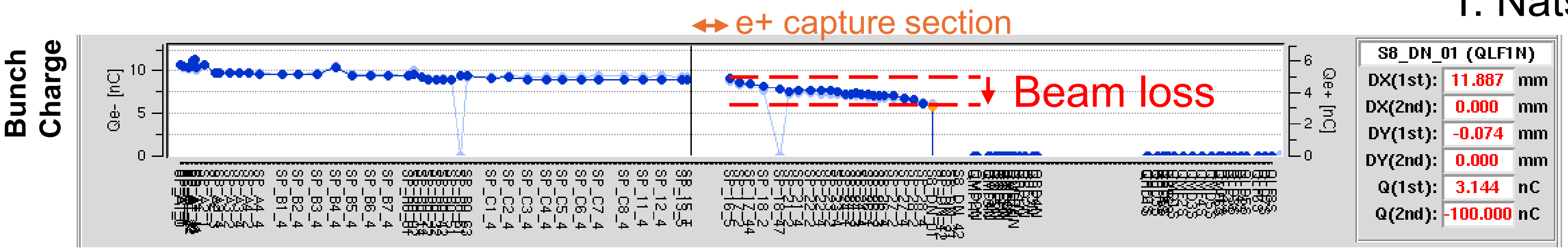
Operators may also use it independently.

1. Maximization of e+ beam transmission rate up to SY2

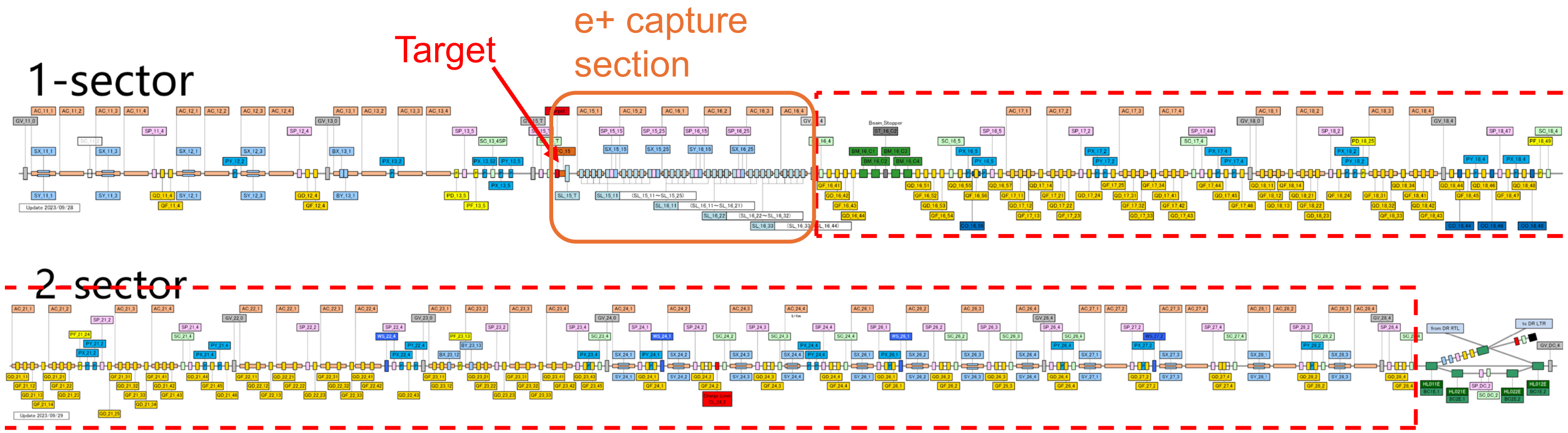
Briefly reported in the last review

The challenges that led to the development of machine learning program

T. Natsui



In simulations, the transmission rate from capture section exit to 2-sector end was nearly 100%, but in the experiment, there was about a 40% loss, which could not be improved through manual adjustments.



Linac layout from the target to switch yard to Damping Ring

Quadrupole

Dipole (steering)

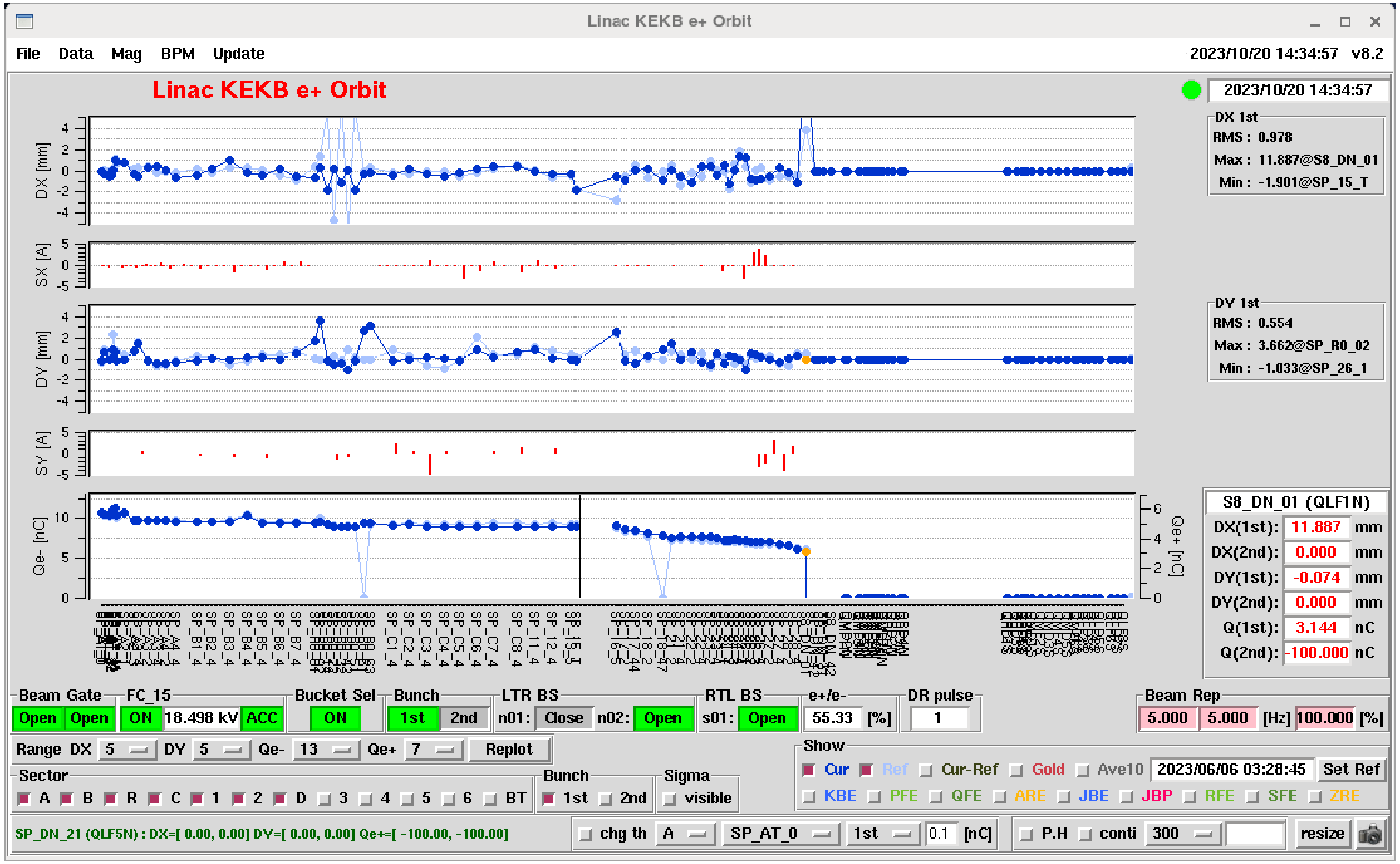
~160 parameters

Manual tuning is almost impossible

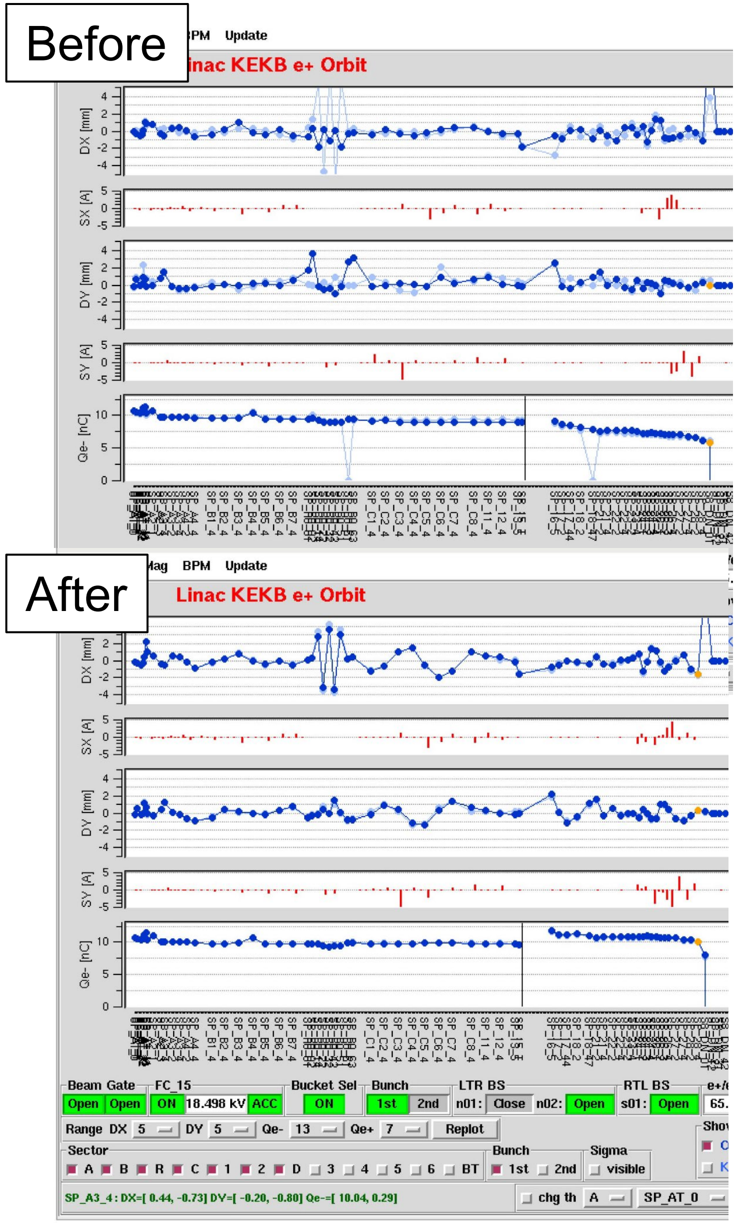
The application of machine learning was divided into multiple sections, and the transmission rate was sequentially increased from upstream.

1. e+ beam transmission rate after the optimization

T. Natsui



Progression of tuning process



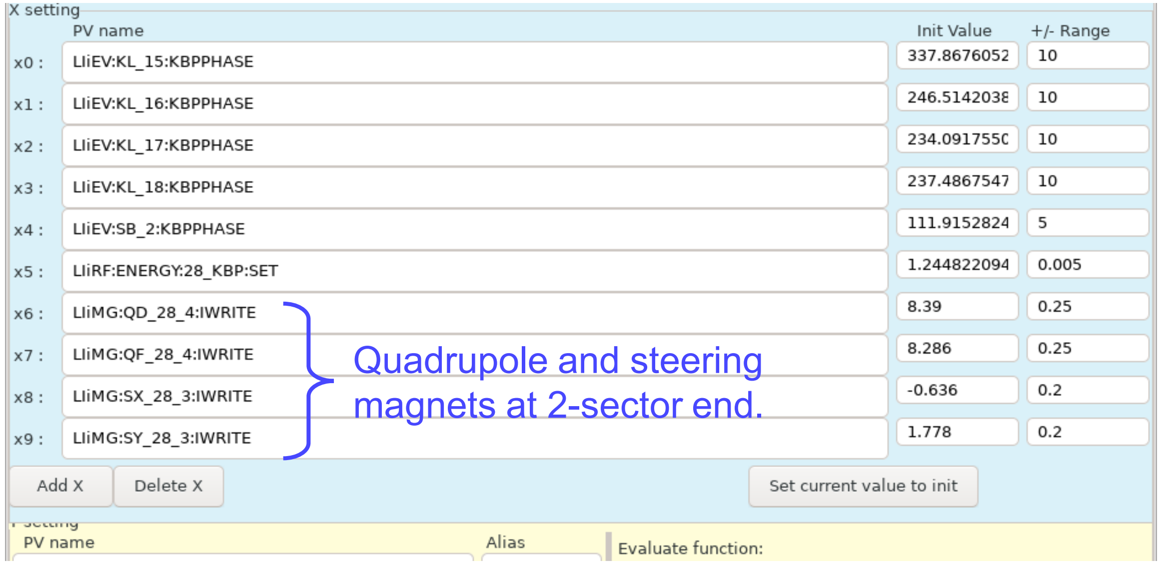
This tuning process (~160 parameters) takes a few days, so we have only done it once so far.

2. Maximization of e+ beam transmission rate from Linac to DR

The cause of the beam loss is likely the energy spread

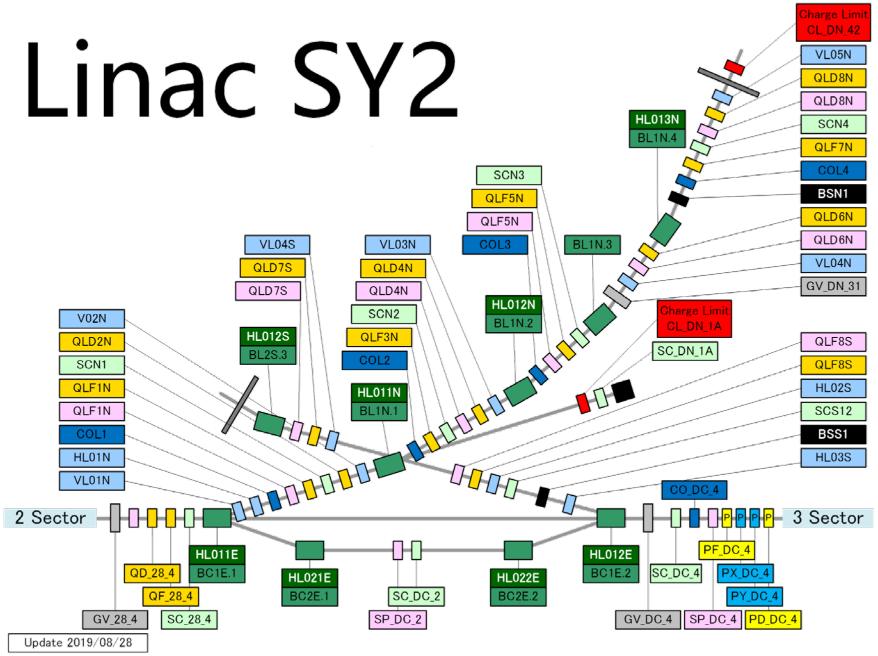
Tuning parameters:

RF phases at 1-sector to 2-sector



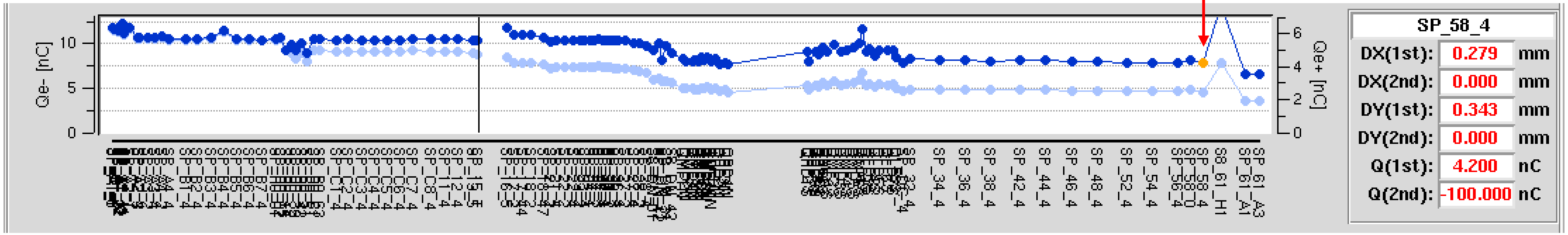
Quadrupole and steering magnets at 2-sector end.

Linac SY2



Linac End

T. Natsui



Charge variation along the beamline after tuinig

(In the J-ARC, LTR and RTL, there are BPMs where charge calibration has not been performed correctly)

4.2 nC was achieved at the Linac end

The highest record so for

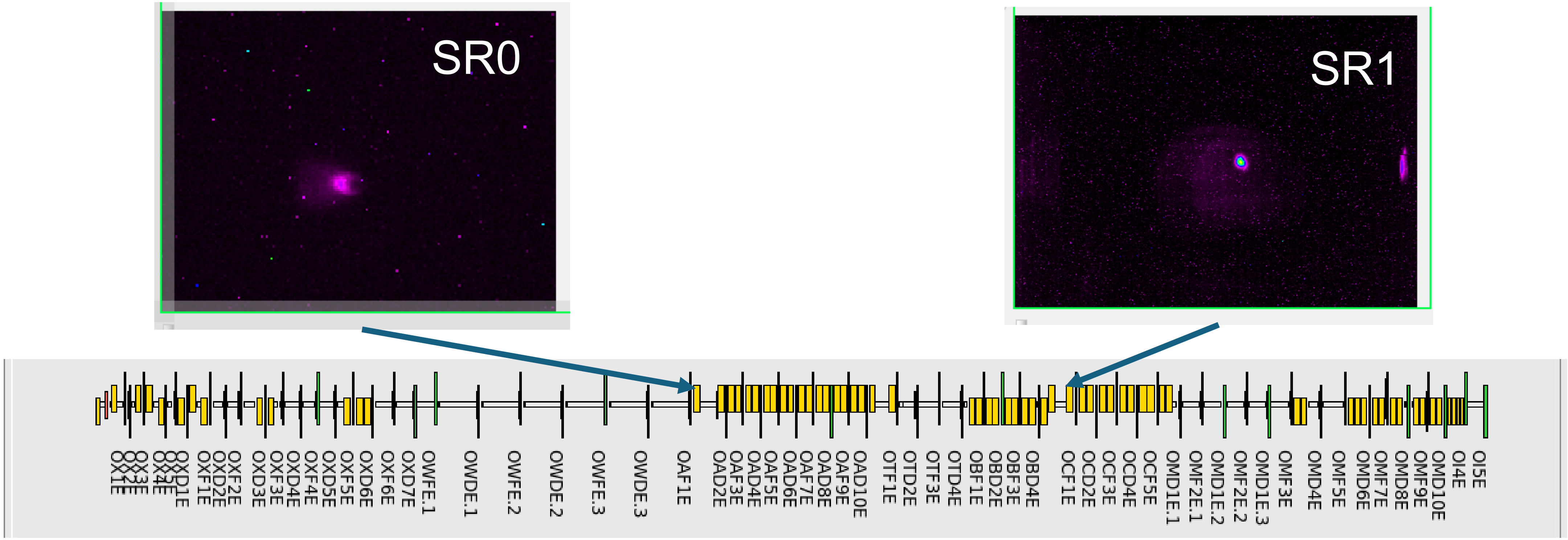
3. Minimization of e- beam emittance at HER BT

M. Kurata

Auto-tuning for reduction of the emittance using SR monitors

Low-emittance beam is important for injection to main ring with high injection efficiency

Empirically, adjusting the beam orbit to reduce the beam sizes observed by the SR monitors leads to a reduction in emittance



Electron BT beam line

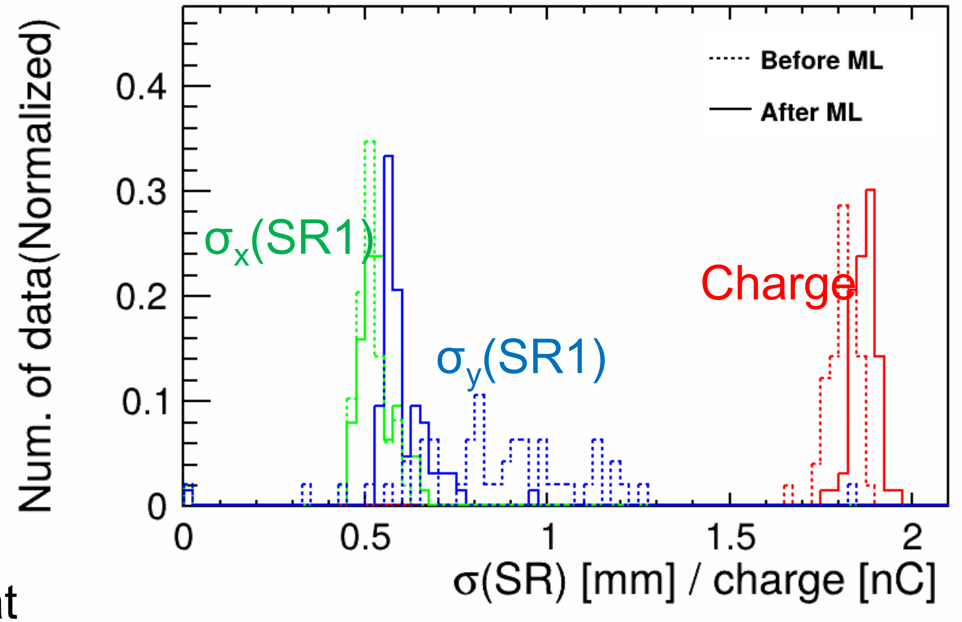
(Since there is no SR monitor in the LTR BT, this tuning cannot be performed with the positron beam)

3. Beam size and emittance after the optimization

M. Kurata

Tuning parameters:

- Steering magnets at J-ARC Exit (PX_R0_61, PY_R0_61, PX_R0_63, PY_R0_63)
- Steering magnets before the positron target with hole (PX_13_5, PY_13_5)



Comparison of emittance at BT before and after tuning

1^{st} bunch	$\varepsilon_{n,x}$ [μm]	$\varepsilon_{n,y}$ [μm]
Before ML	64.9±8.6	45.6±11.0
After ML	**29.2±5.1**	**46.9±13.0**

By minimizing the beam size at two SR monitors, the emittance was also reduced.

Using synchrotron radiation allows for non-invasive measurement that can be performed at any time

Plan: Tuning programs with machine learning

- **The effective tuning program will be worked continuously**

  A system is needed to monitor whether it is working correctly and ensure it does not interfere with other tuning or feedback programs.

- **To facilitate the development of tuning or feedback programs, it is essential to find parameters that are effective for beam emittance, stability, or the objective function**

  In addition to the physical perspective, we will also consider key parameters found through big data analysis (currently under trial) and the opinions of experienced operators.

- **Share information about any monitors or equipment required for tuning and proceed with their implementation**

Big Data Analysis

Big data Analysis

Synchronized data (position, charge) from all BPMs in the Linac and BT are archived.
It has become possible to compare these with various measured values (EPICS PVs) stored in the Archiver Appliance.

Shot by shot data

- Linac BPMs
- Linac RF Monitors
- Linac pulsed magnets

- BT BPMs

EPICS PVs (sampling data)

Linac Data:
Laser (power, position, …),
Thermionic-gun (Heater/Vias voltage, …),
RF phase, Temperature,
…

SuperKEKB Data:
Injection efficiency, beam current,
Kicker / Septum, Beam loss,
SR monitor at BT, Tune, Temperature,
…

Synchronized data for these datasets can be output

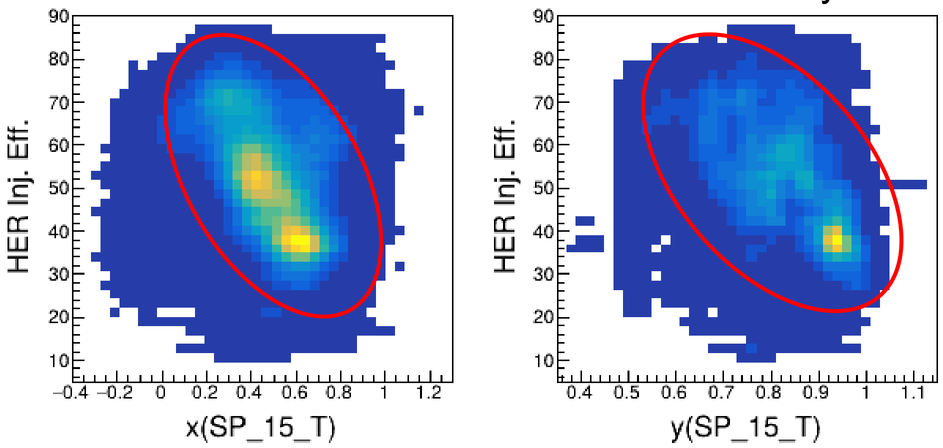
Tool for finding critical parameters:

- **Parameters that significantly affect injection**
- **Parameters for maintaining emittance**
- **Factors causing beam instability**
- **Cause of abnormal beam (cause an beam abort)**
- **…**

Example of Big Data analysis and Future Plans

- Injection efficiency and beam orbit before the target (e- beam passes through the target hole)

F. Miyahara



Electron beam position at the entrance of the positron target and HER injection efficiency (100th turn)

The emittance improvement achieved through upstream orbit correction using SR monitor-based tuning with machine learning is consistent with the results.

Such clear correlations cannot be seen in asynchronous data.

Future plans

- Exploring critical parameters using Explainable AI
- Faster data generation
- Increasing the number of people performing data analysis

🡐 Iwasaki-san's group from Osaka Metropolitan Univ. is conducting analysis using SHAP (Shapley Additive Explanations)

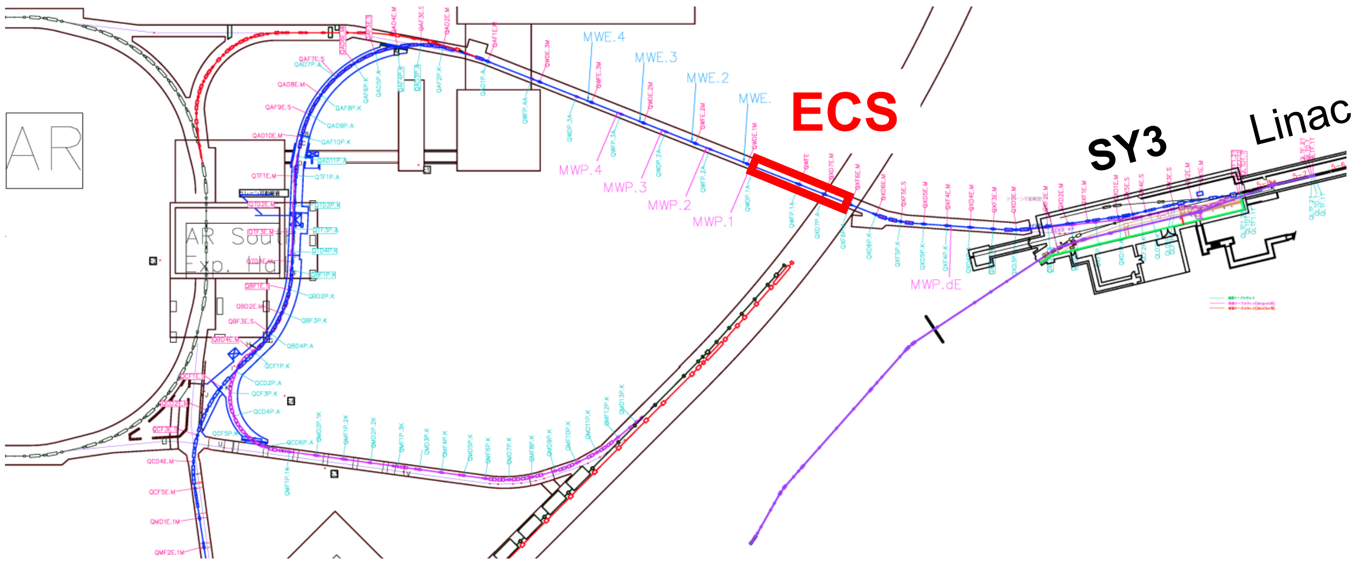
HER BT Energy Compression System (ECS)

HER BT Energy Compression System (ECS)

Background of HER BT ECS introduction

1. As the bunch charge increases (current: 2 nC → 4 nC) , emittance growth due to short-range transverse wakefields will become a significant issue.
2. Bunch compression is effective in suppressing the short-range transverse wakefields.
3. However, bunch compression increases the energy spread due to longitudinal wakefields.

ECS consists of four 3-meter accelerating structures will be installed in the BT section.

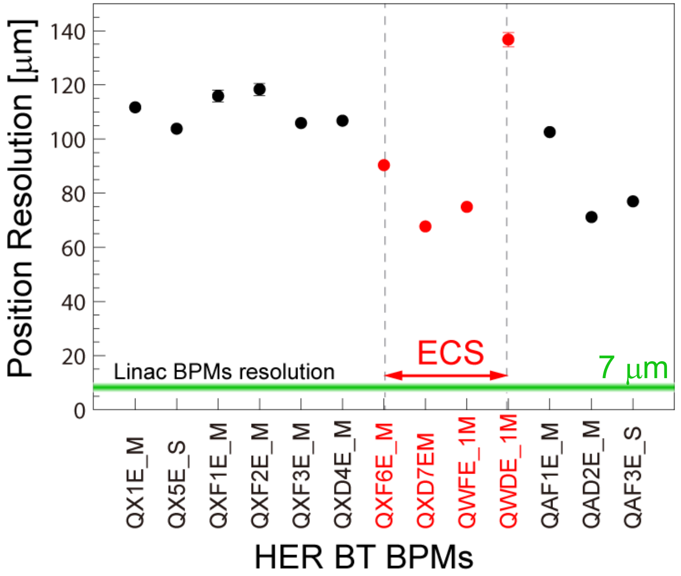


Construction of the ECS is under way

- The installation of waveguides is approximately complete
- The installation of accelerating structure is in progress

BPM readout system for ECS

To suppress emittance growth caused by wakefields in the accelerating structures, it is necessary to accurately measure the beam position and adjust it to pass through the center.



Position resolutions of BT BPMs evaluated using 3-BPM method.

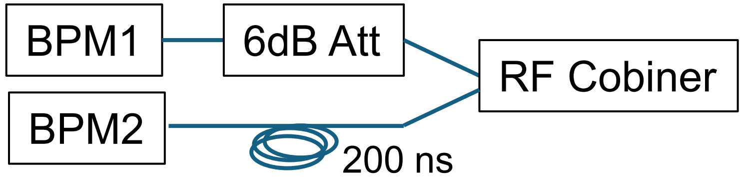
The BT BPM processes signals from multiple BPMs with a single oscilloscope, resulting in a low number of samples. Additionally, since the ADC is 8-bit, the resolution is not optimal.

It would be better to use the Linac readout system.
However, the stock of the readout boards for the Linac is insufficient, and since the FPGA used in the board has been discontinued.
It is not possible to produce new boards.

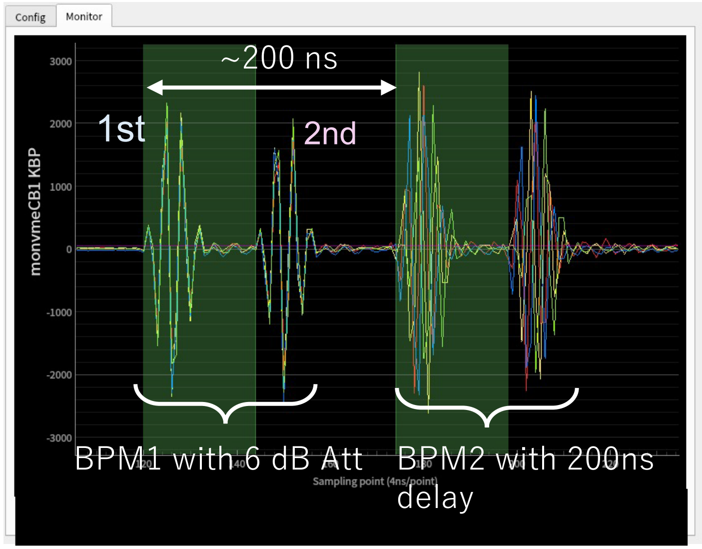
The Linac BPM has 1024 channels of data with a 4 ns time step, making it possible to process data from multiple BPMs on the EPICS IOC.

A beam test was performed to measure two BPMs using a single BPM readout board.

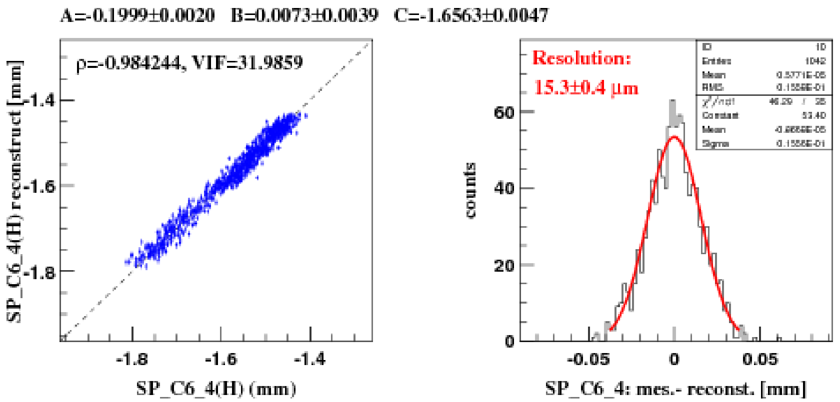
The BPM readout test and Layout for ECS BPMs measurement



The first BPM signal and the second BPM signal, with a 200 ns cable delay inserted, were combined using an RF combiner and input into the BPM board.



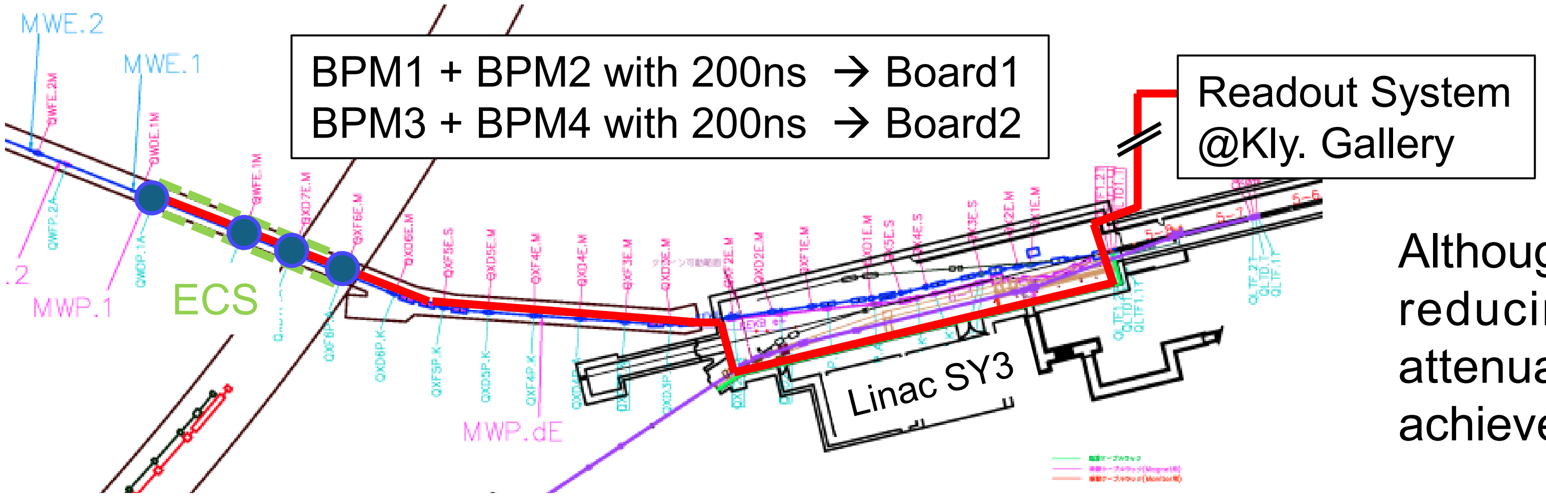
Raw signals from two BPMs (after passing through the filter).



The predicted position from the other two BPMs, the measured position, and the difference between them.

A resolution of 15 μm was achieved without performing gain adjustment
(4 electrodes: left, right, up, down)

Layout of BPM measurement



Cabling for the four BPMs in the ECS section and the readout system.

Although there is attenuation due to the cables, reducing the value of the board's internal attenuator allows for signals large enough to achieve high-resolution measurements.

Summary

1. **Fast Kicker to correct 2nd bunch orbit**
   It has been confirmed that the 2nd bunch can be stable controlled.
   We would like to add it where necessary.

2. **Beam diagnostic Line with pulsed magnets**
   The transport to both the HER BT and the diagnostic line was successful without any issues.
   Moving forward, we will begin utilizing it.

3. **Beam tuning programs with machine learning (Bayesian optimization)**
   It has been extremely beneficial for improving beam performance. The positron beam achieved the highest transmission rate to date, and the HER beam enabled emittance reduction while conducting non-destructive monitoring.

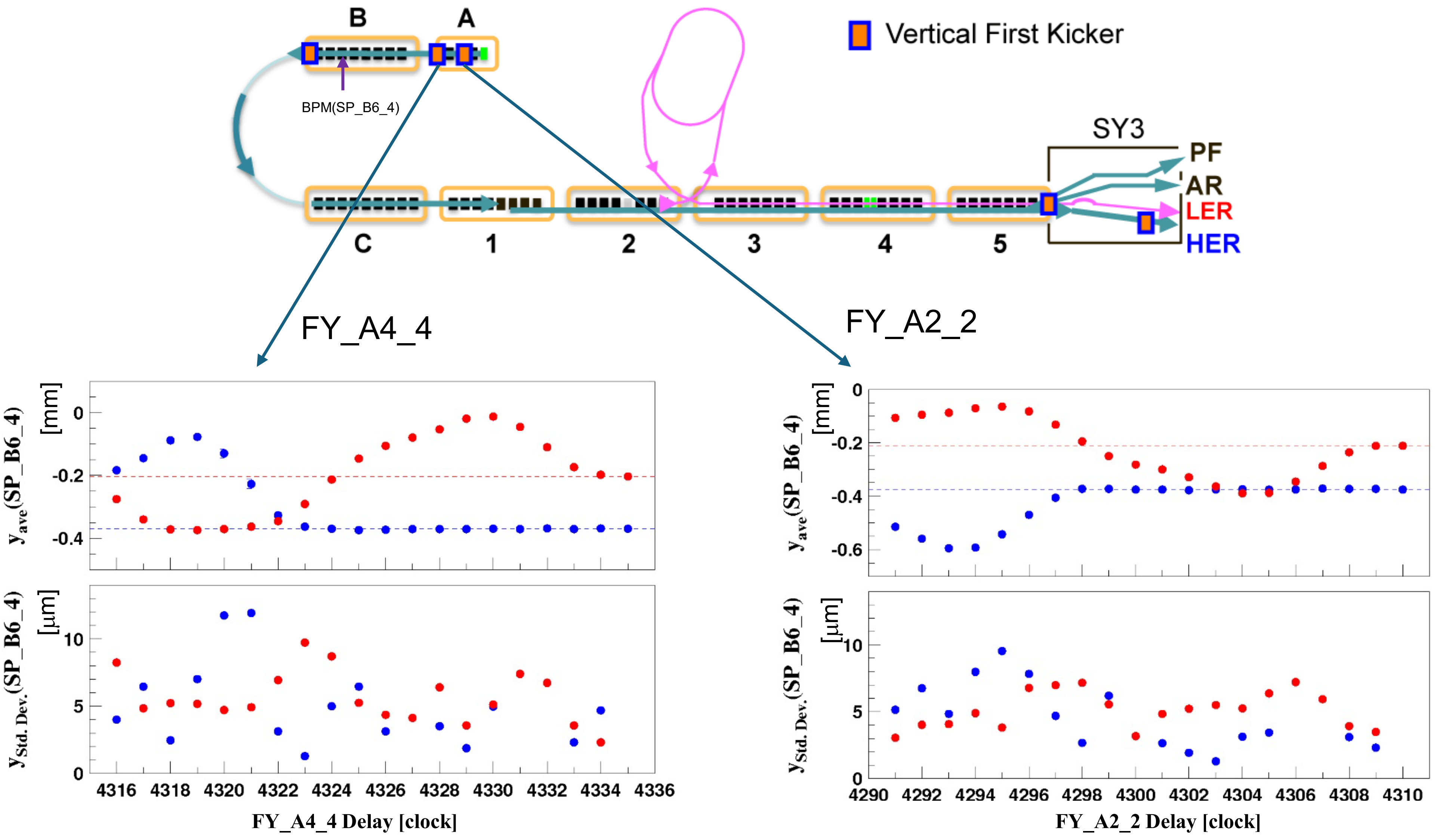
4. **Big data analysis**
   Synchronized data output from the injector to the ring has been enabled. Detailed analysis and the exploration of key parameters using machine learning will be advanced.

5. **HER BT Energy Compression System (ECS)**
   It is necessary to increase the charge of the electron beam. Construction is progressing smoothly.

Thank you

Appendix

Response of Fast Vertical @ 2-sector



In the upstream section, there were a slight tendency for jitter to increase.
Energy spread might also be a contributing factor.

T. Natsui

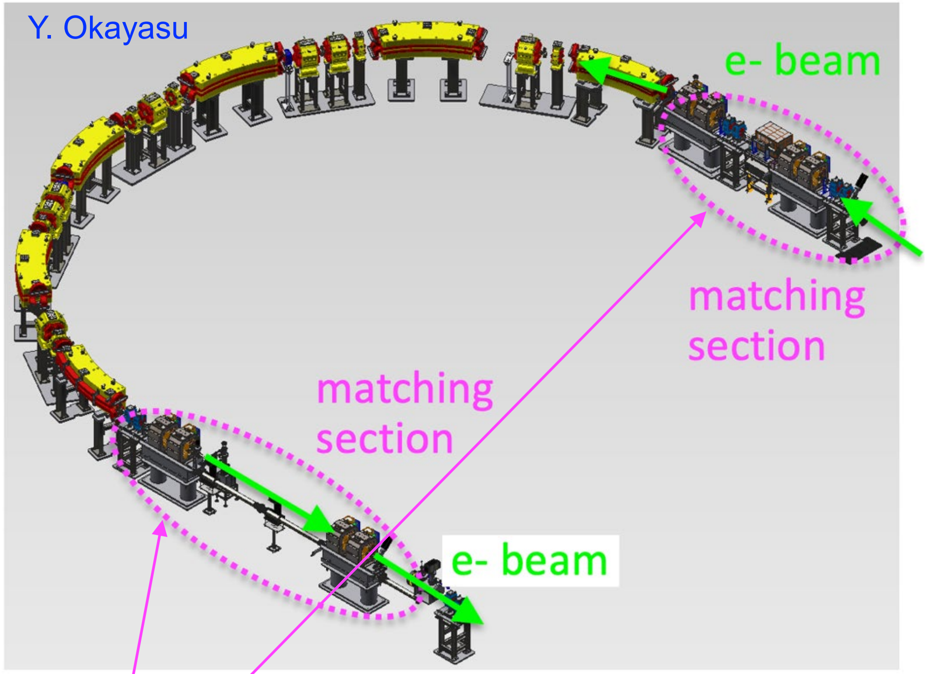
Large-aperture pulsed quadrupole magnets (1): J-ARC

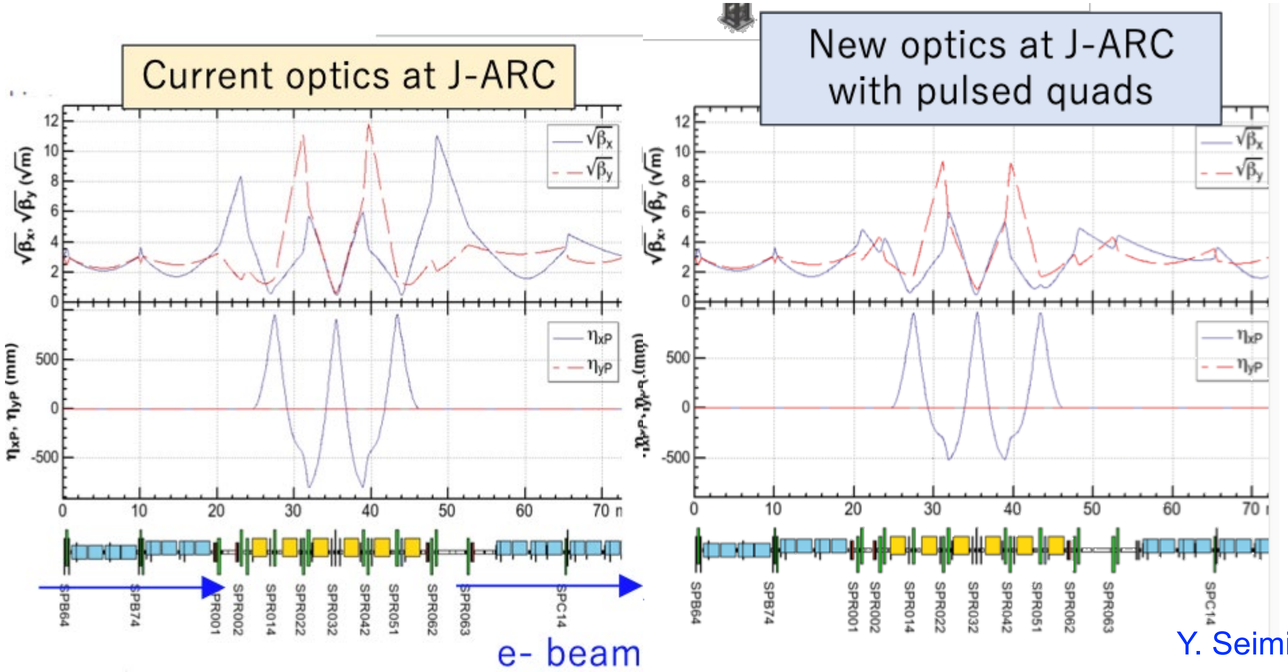
Background:

- The transmission of e- beam for LER through J-ARC should be maximized as much as possible (less beam loss).
- The optics of e- beam for HER should be matched after the J-ARC exit.

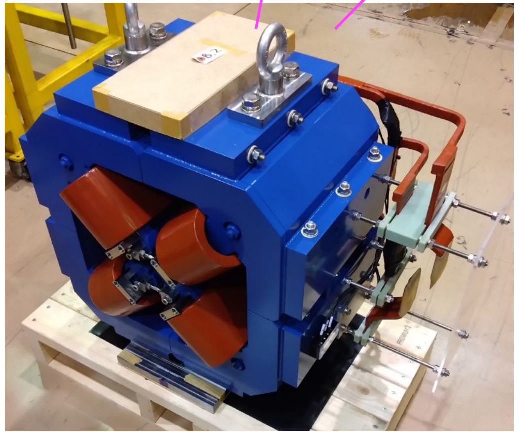
Solution:

- ➢ Large-aperture pulsed quadrupole magnets can separately control beam optics for each beam mode.
- ➢ Lower beta and lower dispersion optics can reduce beam loss in J-ARC.





Y. Seimiya



K. Yokoyama

Seven pulsed quadrupole magnets was installed.
Maximum current: 600 A

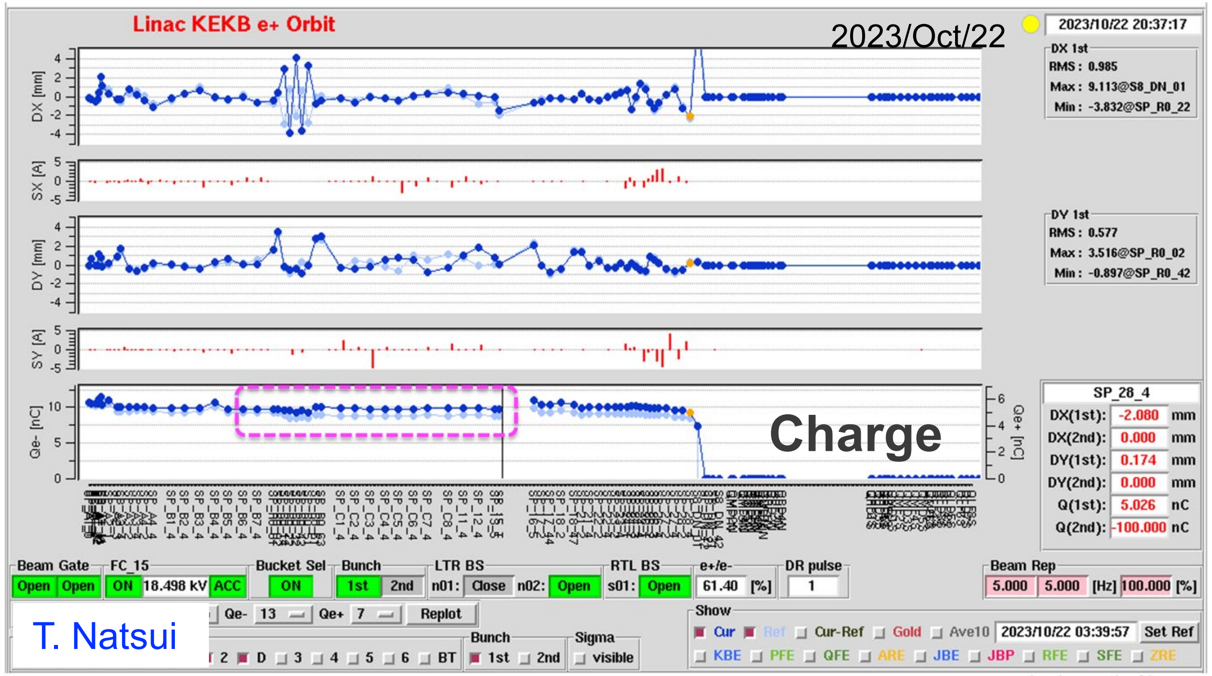
600 A, 400 V class pulse drivers also installed.

Large-aperture pulsed quadrupole magnets (2): J-ARC

T. Natsui

e- for the LER

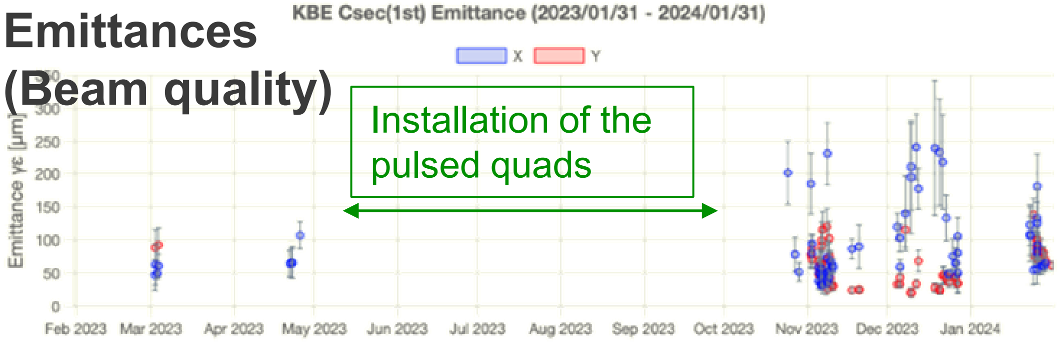
- Beam transmission of the e- beam for LER in J-ARC is achieved almost 100% (almost no beam loss)
- This is the result of automatic beam tuning and optics matching in each beam mode.



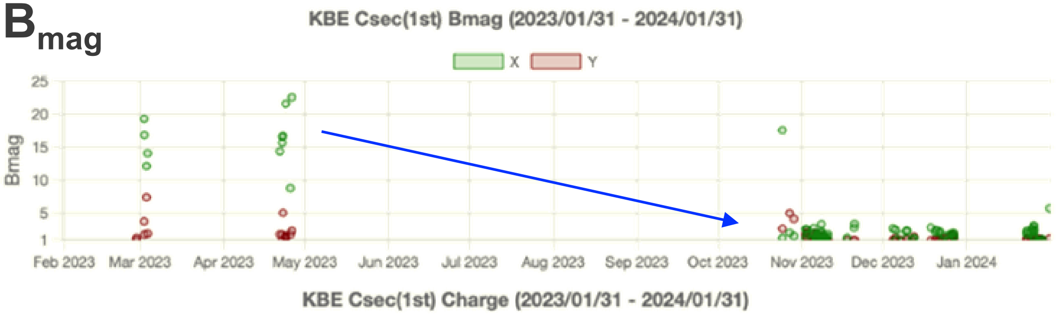
e- for the HER

- After installing pulsed quads, e- beam optics at J-ARC exit can be matched to the design ones (B_{mag} ~ 1).

Emittances (Beam quality)

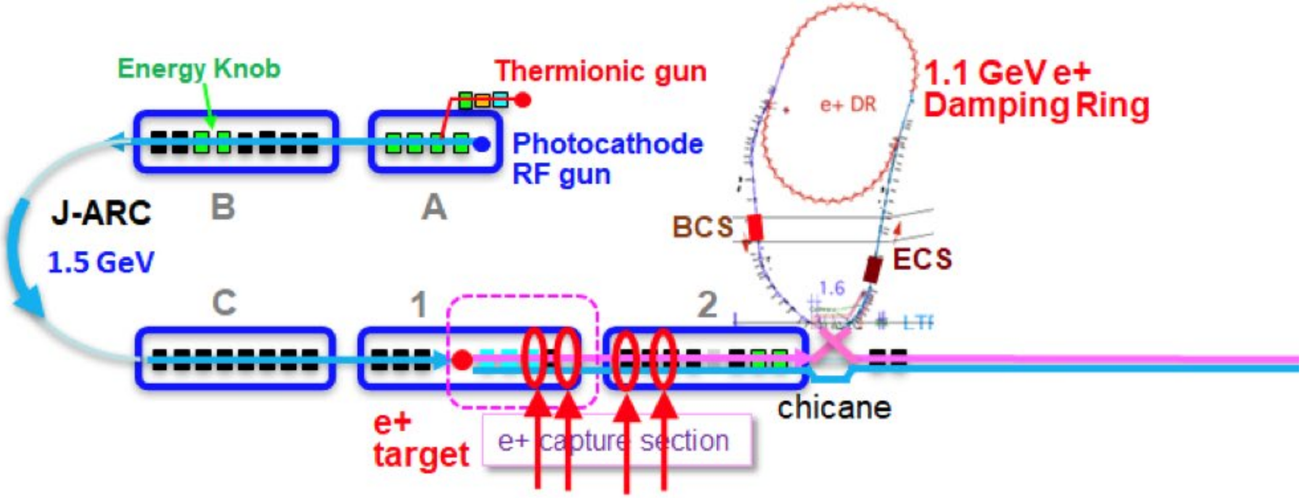


B_{mag}



T. Natsui

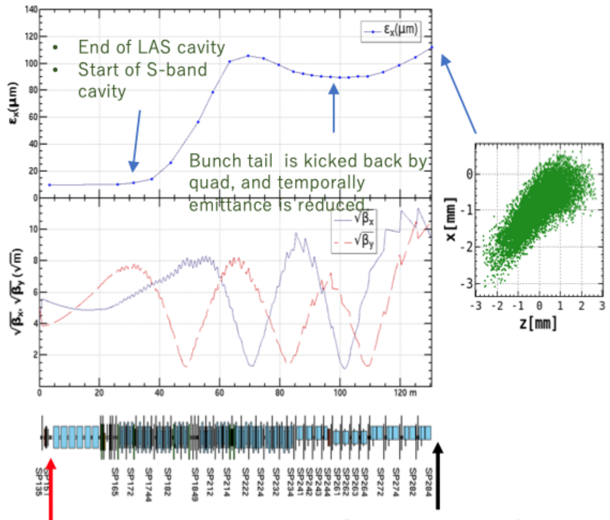
Large-aperture pulsed quadrupole magnets (3): Sec. 1 & 2



Replaced four DC quadrupole magnets with pulsed ones

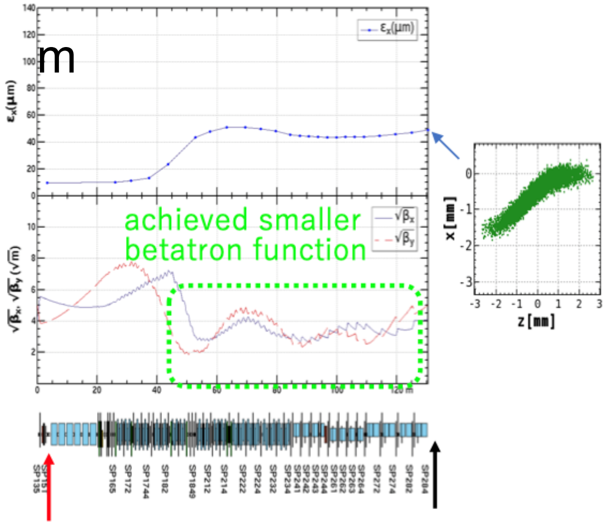
T. Kamitani

$\Delta\gamma\varepsilon x \sim 100$ um, $\overline{\beta x} = 45.2$ m



Before optimization

$\Delta\gamma\varepsilon x \sim 40$ um, $\overline{\beta x} = 16.3$ m



After optimization

Simulations revealed that replacing four DC quadrupoles (common to all beam modes) with pulsed quadrupoles enables the setup of an optics with smaller beta functions for HER beam, thereby suppressing emittance growth.

Y. Seimiya

Operation Panel Implementation

I use GPyOpt.
It is python library for Bayesian optimization.

Select tuning knob. We can use any variable EPICS records and select minimum and maximum value for tuning range.

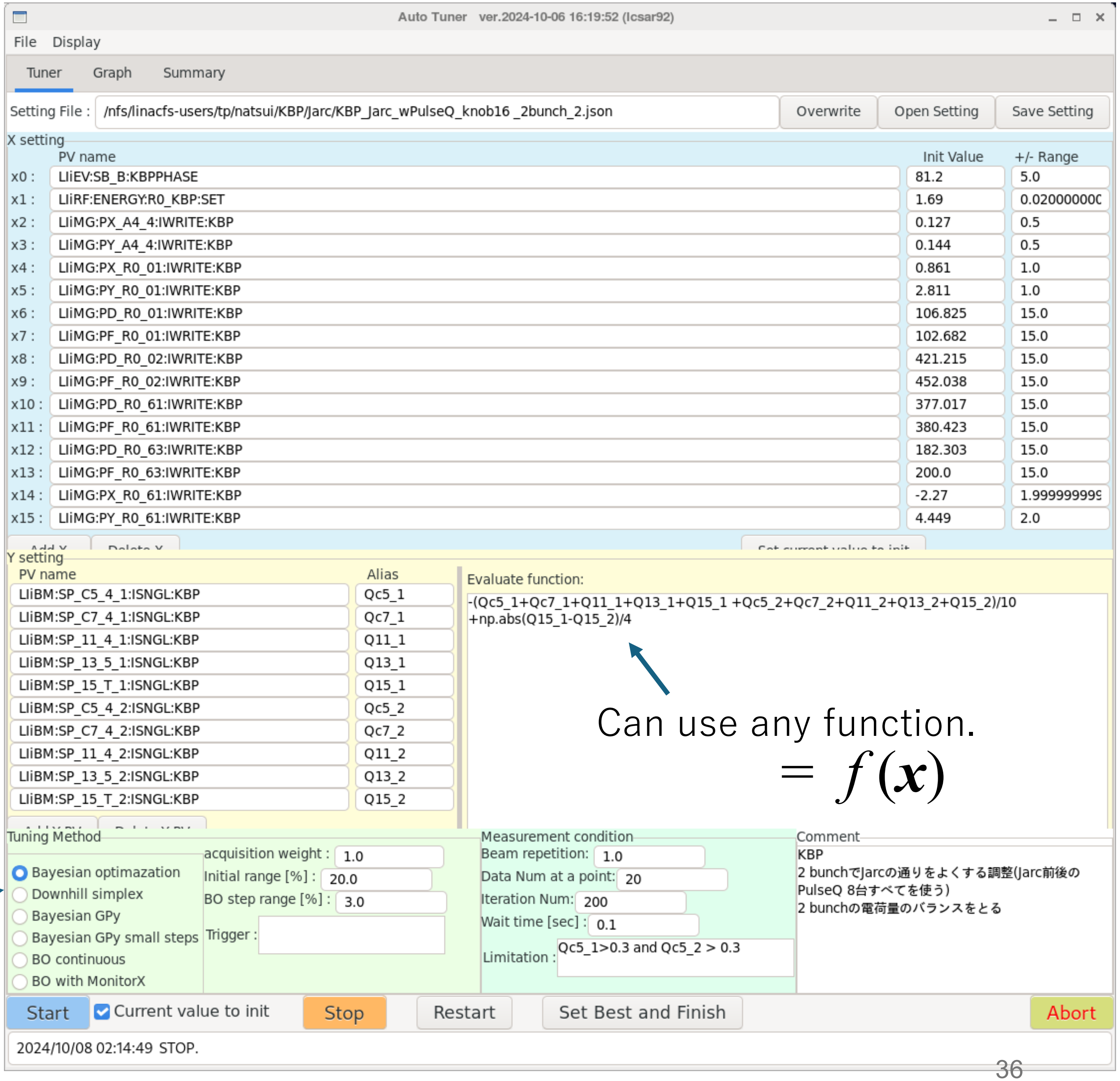
$\boldsymbol{x}$

Select monitor EPICS records.
We use arias name for evaluation function.

And define the values to be minimized. This allows for a very flexible specification of the objective function, since any combination of measurements can be defined in the equation.

Select optimization method.

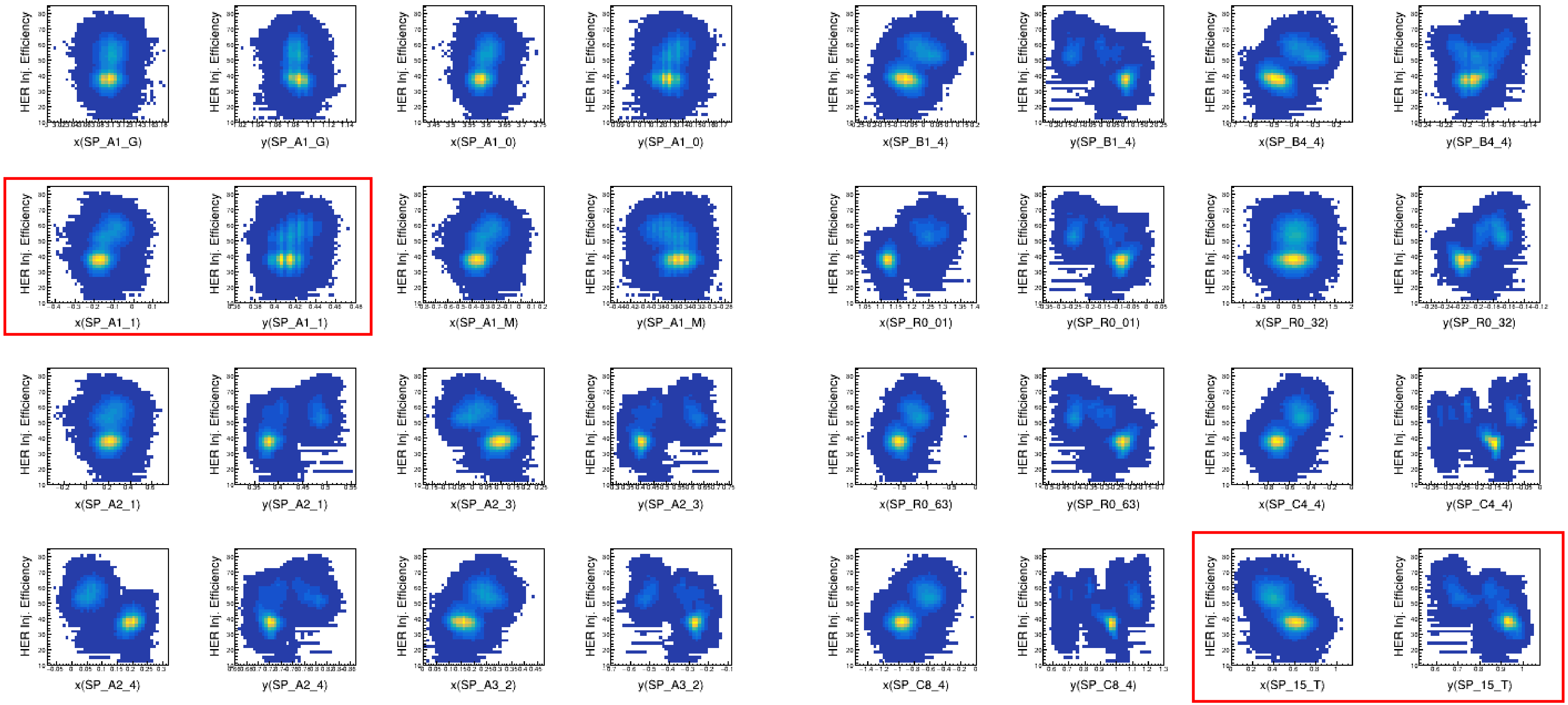
Operator will select setting file and just push this Start button.



Can use any function.

$= f(\boldsymbol{x})$

Injection efficiency and beam position (2024/6/30)

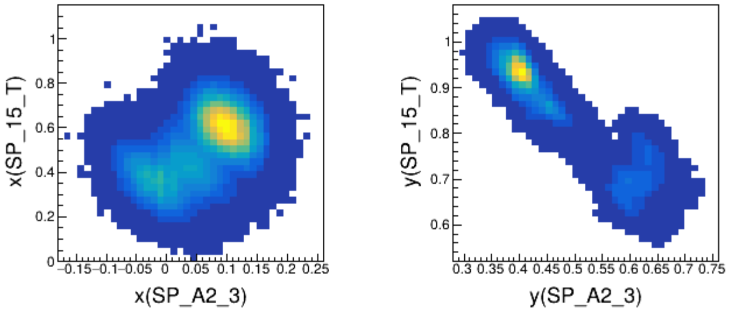


Correlation starts to appear around SP_A1_M, with a clear correlation observed just before the target.

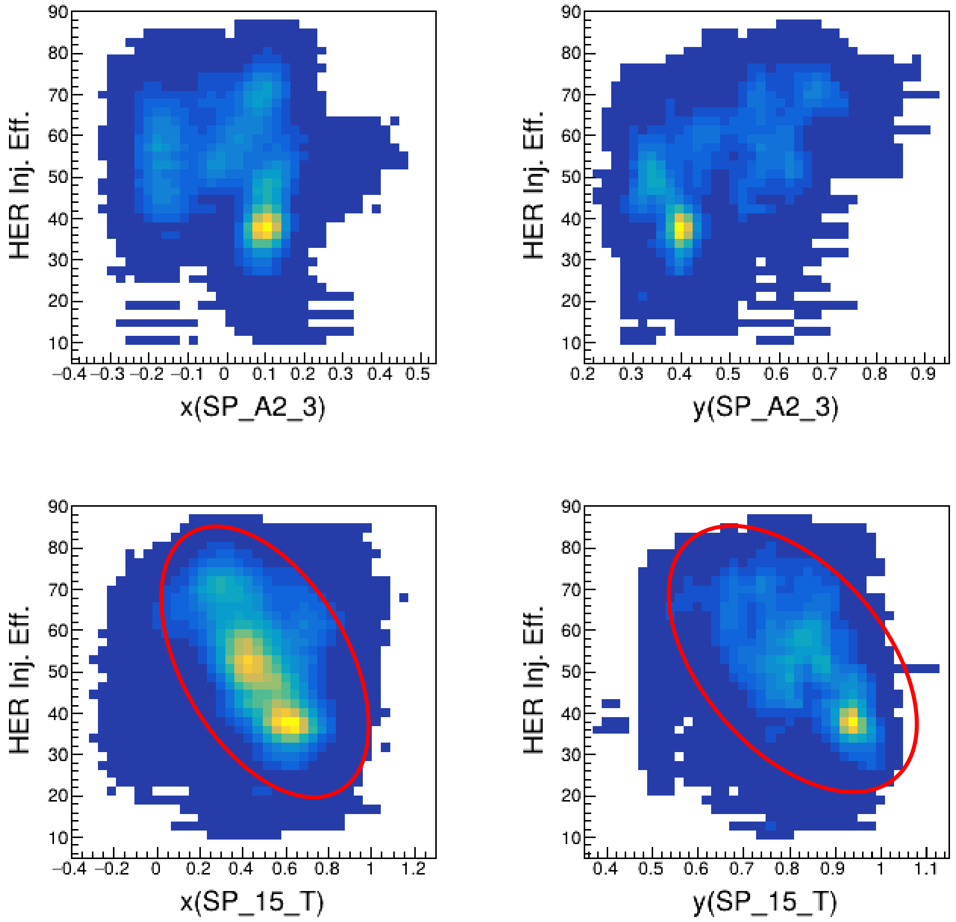
In reality, it is unclear whether SP_15_T is directly correlated with injection efficiency and the upstream section is only correlated with the position of SP_15_T, or if both the upstream section and the area before the target contribute equally to injection efficiency.

Correlation of pre-target and upstream areas, identification of locations that work for injection efficie

Correlation between SP_15_T (Target) and SP_A2_3 (Upstream: A-sector)



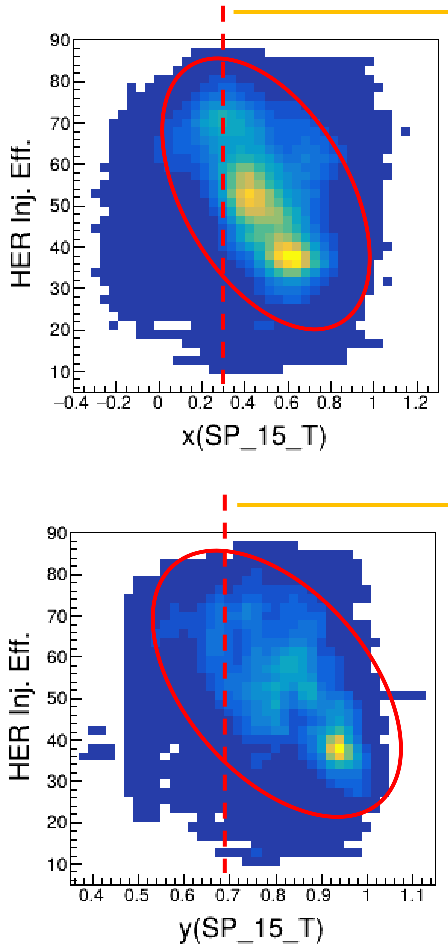
Correlation between upstream and pre-target position and incident efficiency for 5 days.



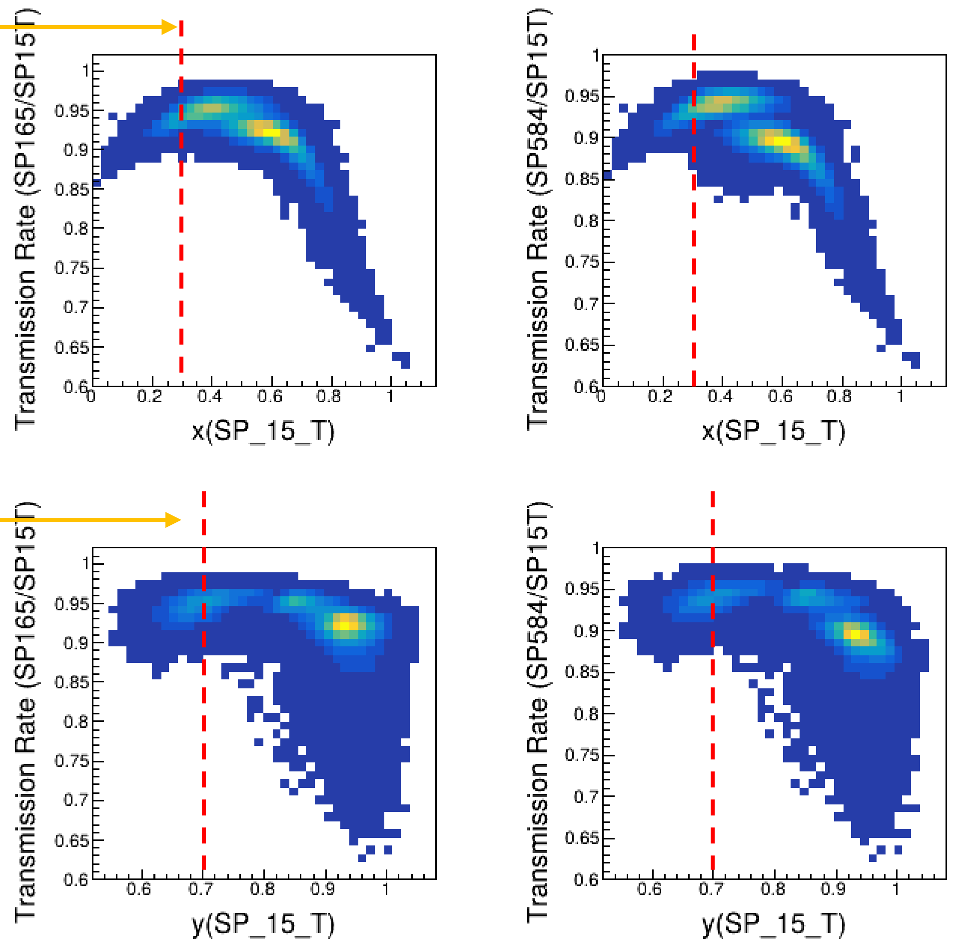
The correlation varies depending on the time of day.

A linear correlation appears between SP_15_T and injection efficiency

Is the beam being reduced at the target in locations with high injection efficiency?



Beam position (SP_15_T)
and injection efficiency



The position and beam transmission rate at SP_15_T.
Left: Target to capture section exit (SP165)
Right: Target to Linac End (SP584)

The positions with high injection efficiency have not reduced the beam.

BTe accelerating structure installation

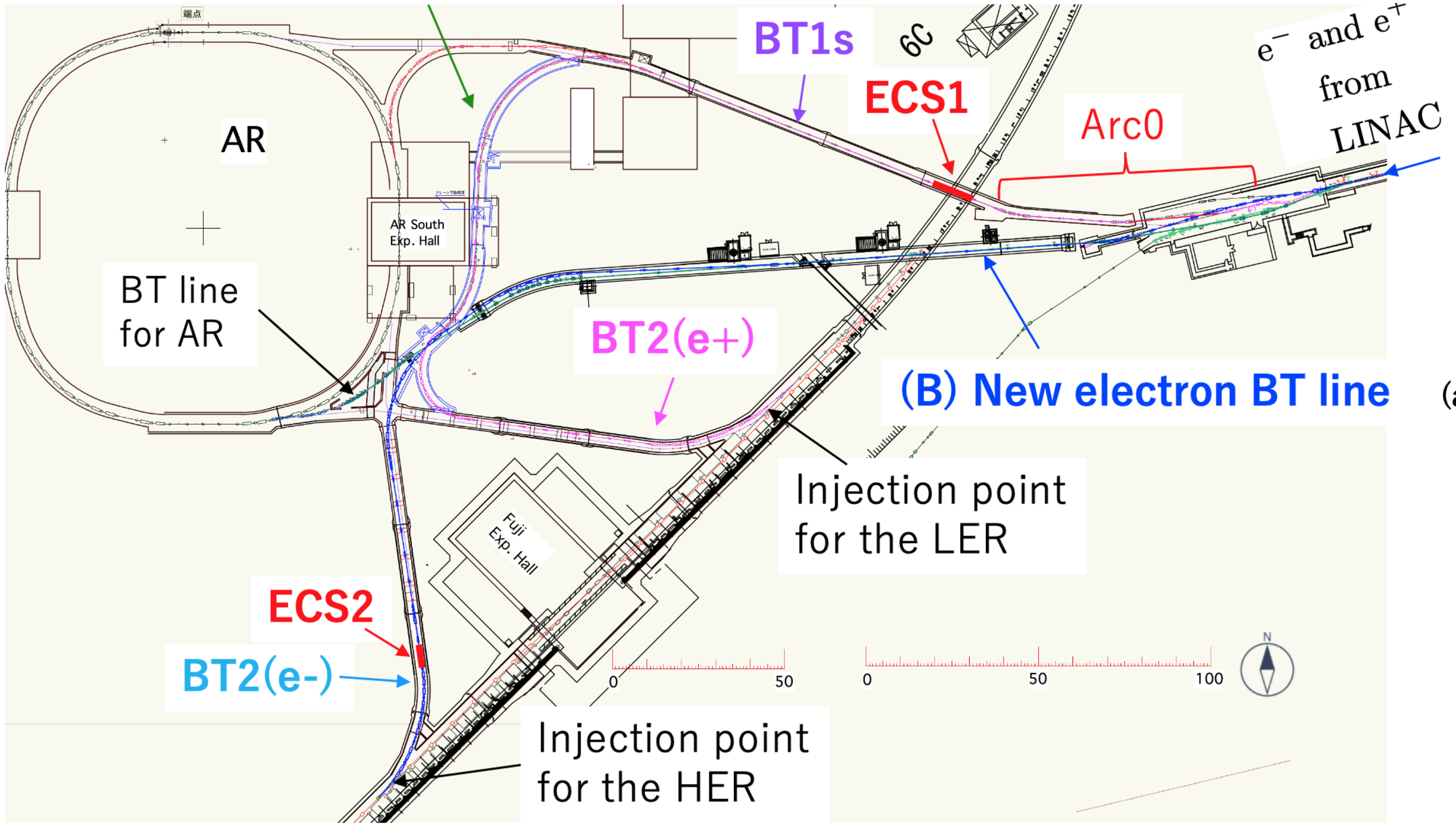
M. Yoshida

- Bunch compression to reduce short range transverse wakefield
  → Longitudinal wakefield causes large energy spread
- Harmful fine structure due to longitudinal wakefield

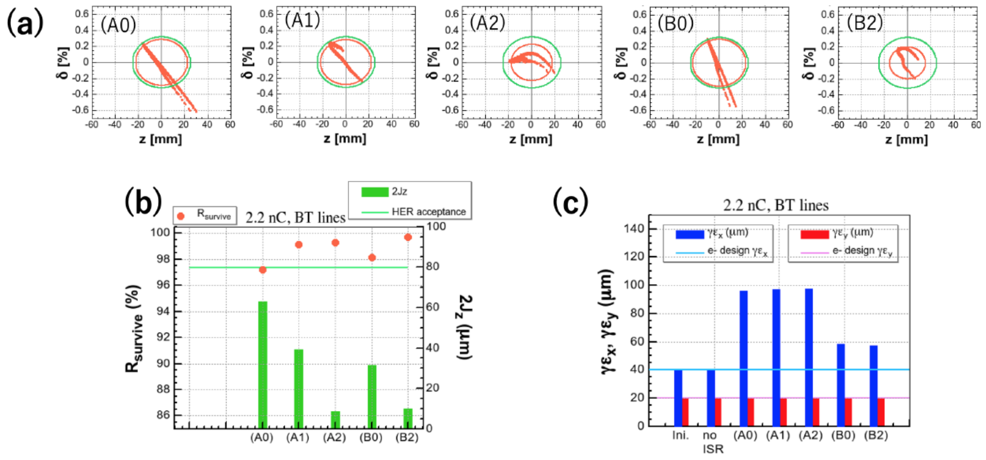
  => BTe-ECS is effective for lower energy spread and smoothing
- Energy jitter reduction
- Additional voltage for 6S resonance and multi-bunch(7-bunch for future) operation.

- 3m(longer) acceelerating structures are transferred from Harima
  by Ego-san’s effort

BTe-ECS (FY2024) to improve injection efficiency



	BT line	ECS	R_{56} [m]	V_c^{Total} [MV]
(A0)	Present	—	-0.11(Arc0)	—
(A1)	Present	"ECS1"	-1.0(Arc0)	72
(A2)	Present	"ECS2"	-4.3	34
(B0)	New	—	—	—
(B2)	New	"ECS2"	-1.6	70

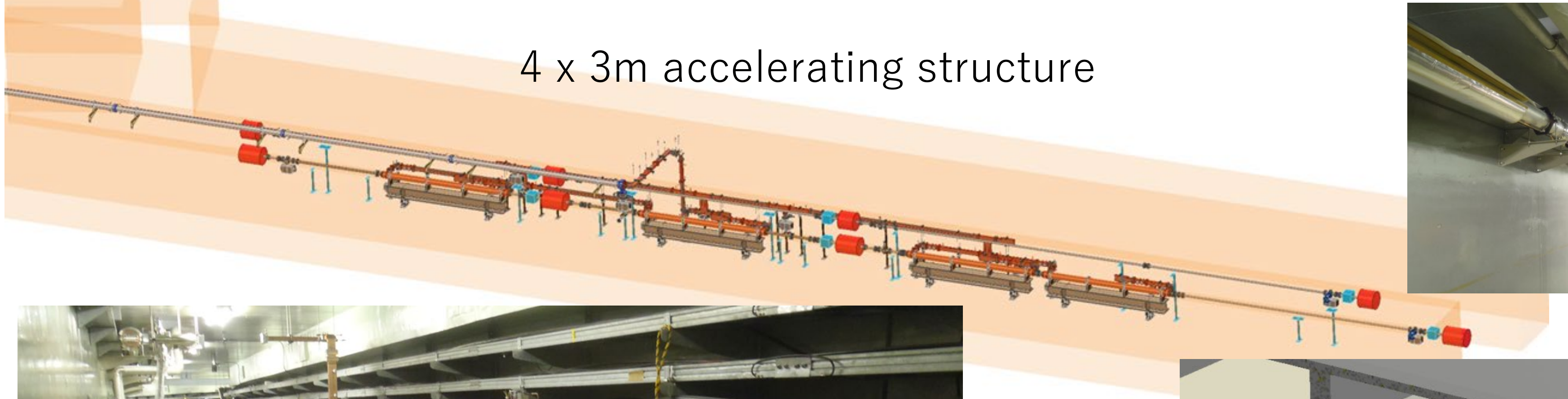


ECS1 was chosen due to building difficulty of ECS2

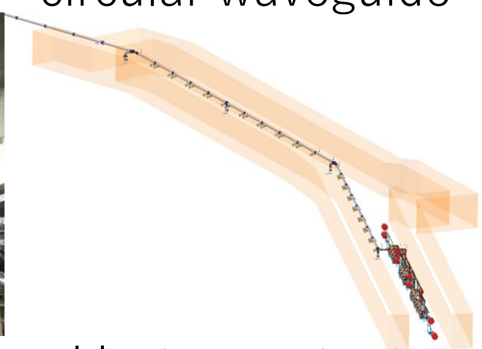
BT-ECS at BT1

M. Yoshida

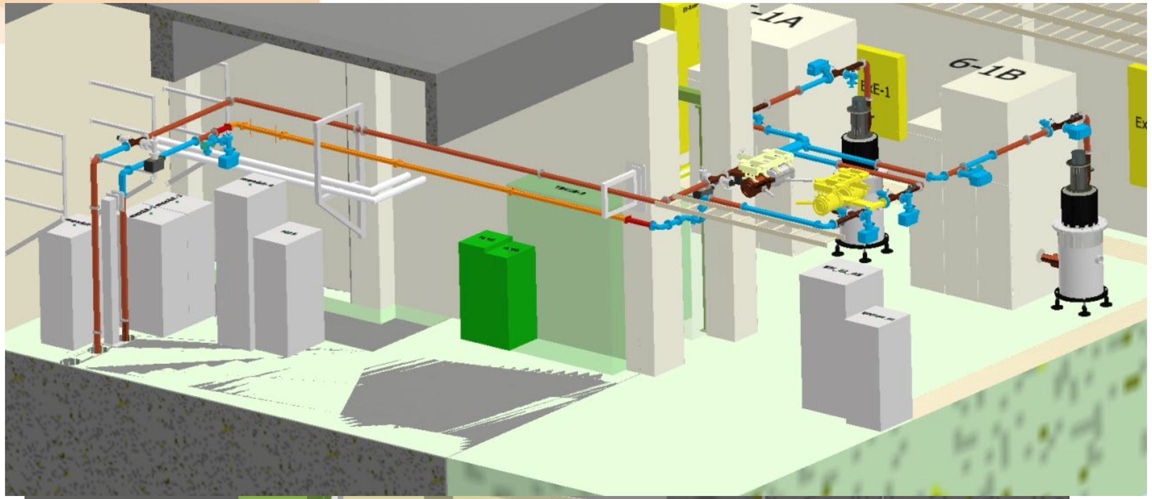
4 x 3m accelerating structure



Low loss circular waveguide

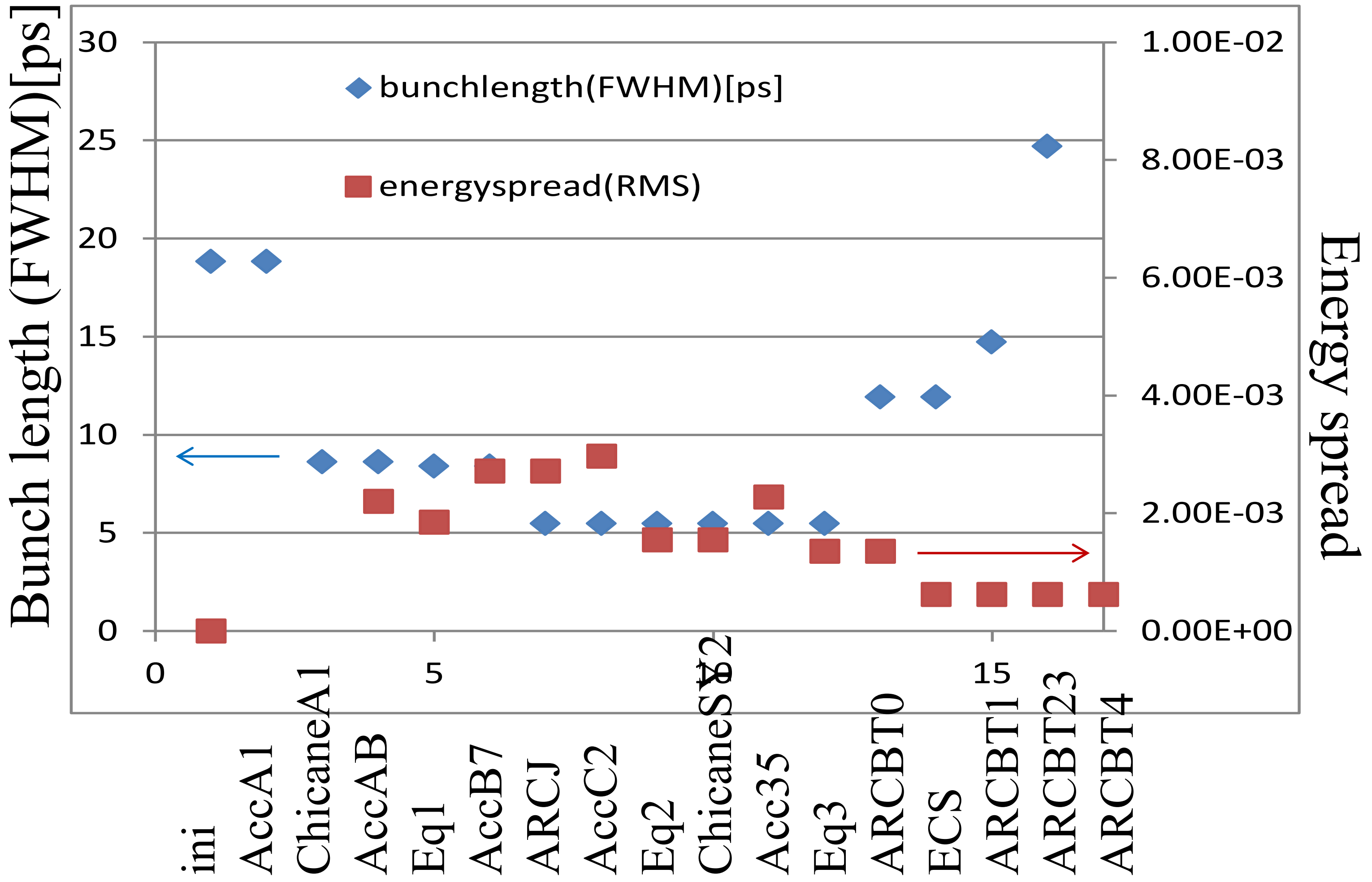


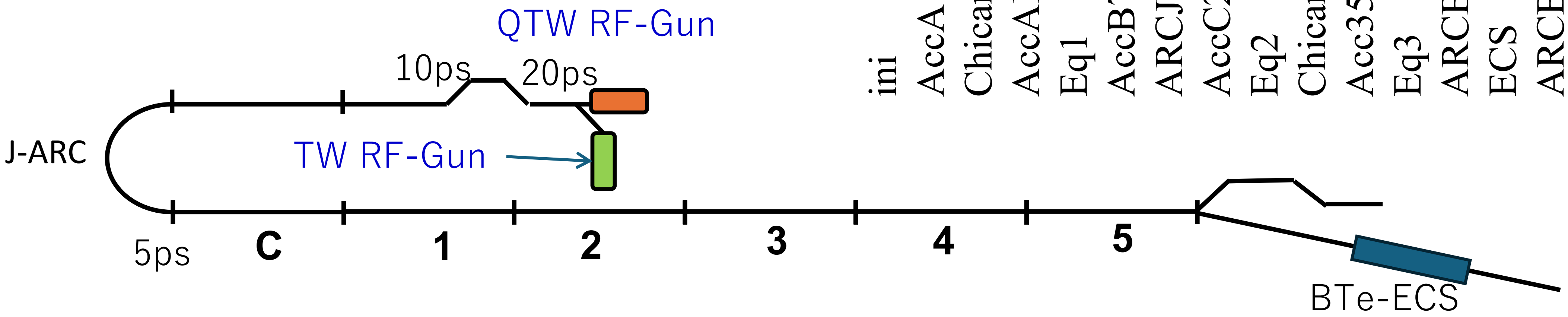
Combine two klystron outputs



Bunch length & Energy spread

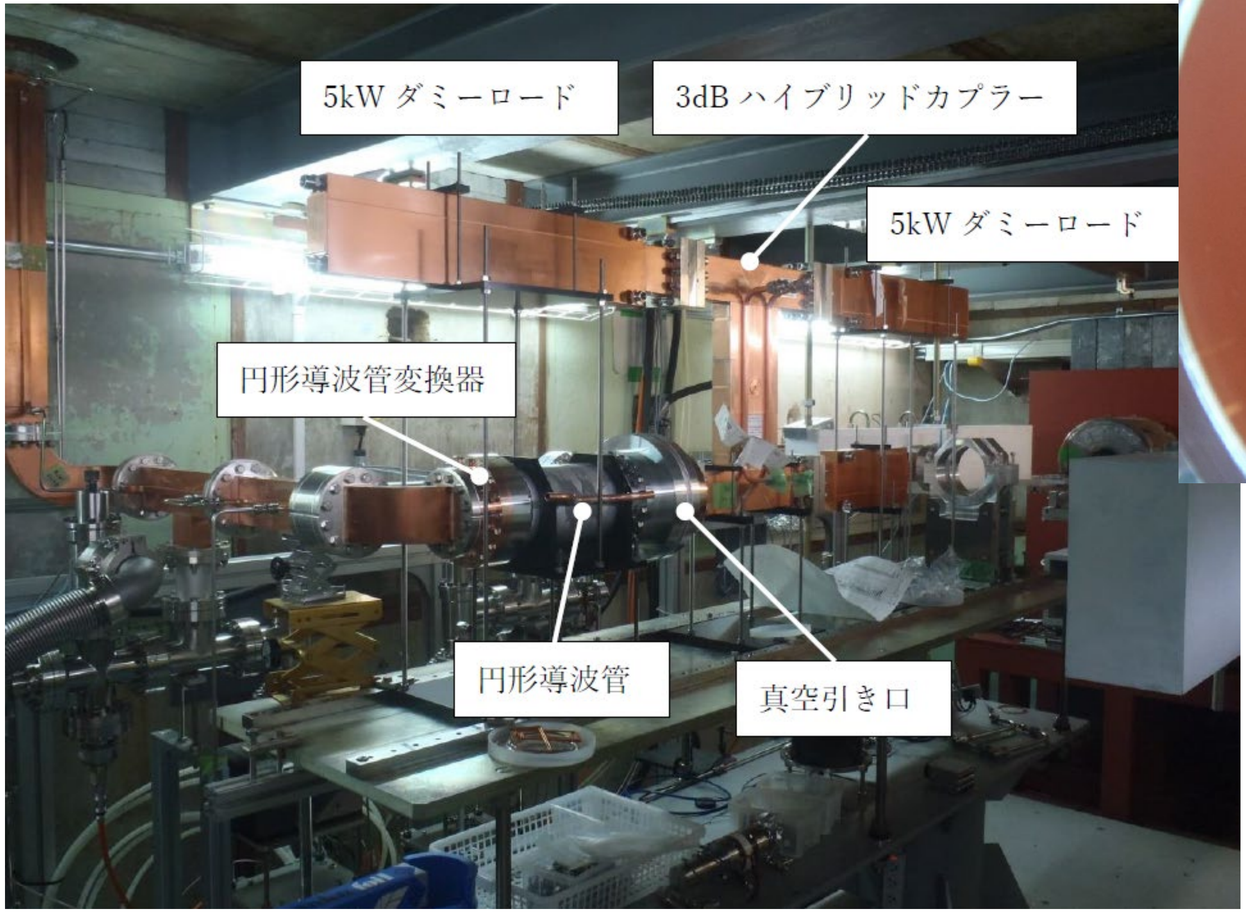
M. Yoshida

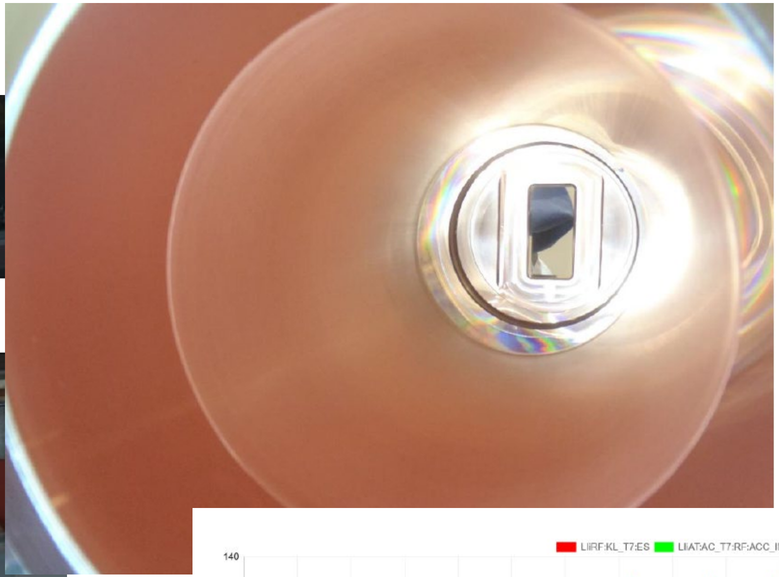




High Power Test for Cylindrical Waveguide

M. Yoshida





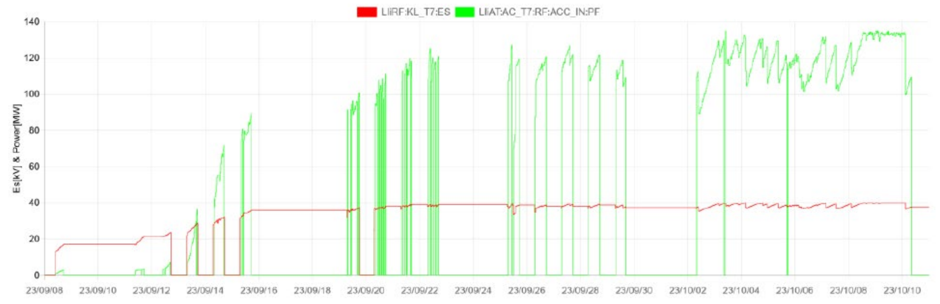


図 7：RF 入力パワーグラフ

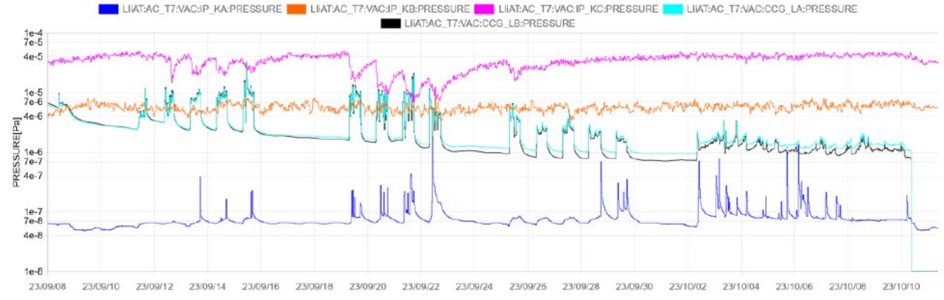


図 8：ハイパワー試験時真空度グラフ

M. Yoshida

Copper Coating Stand

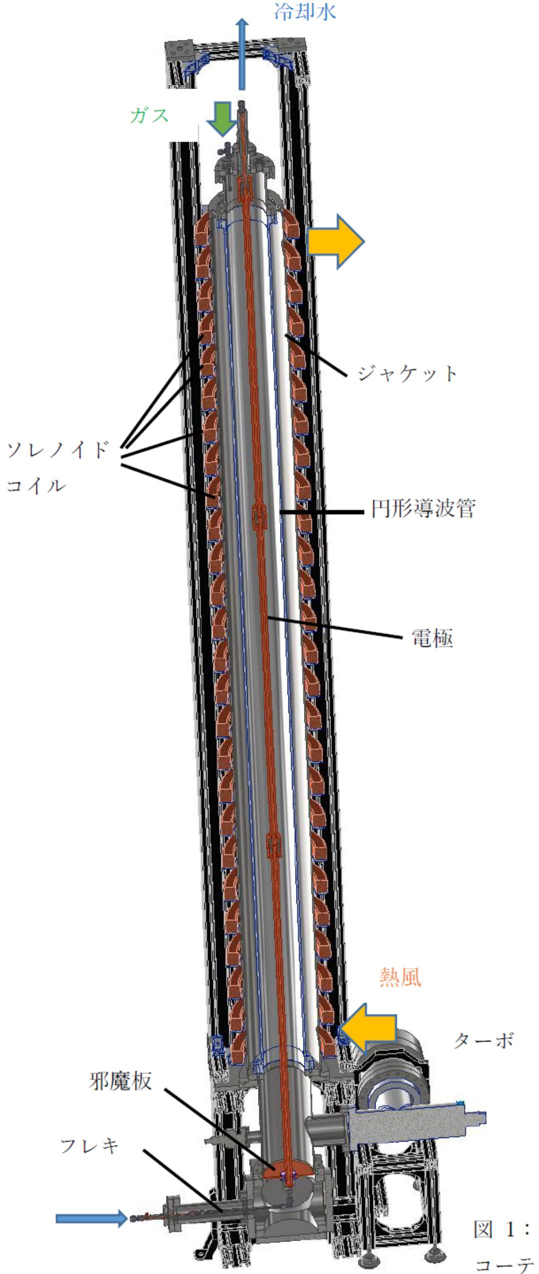
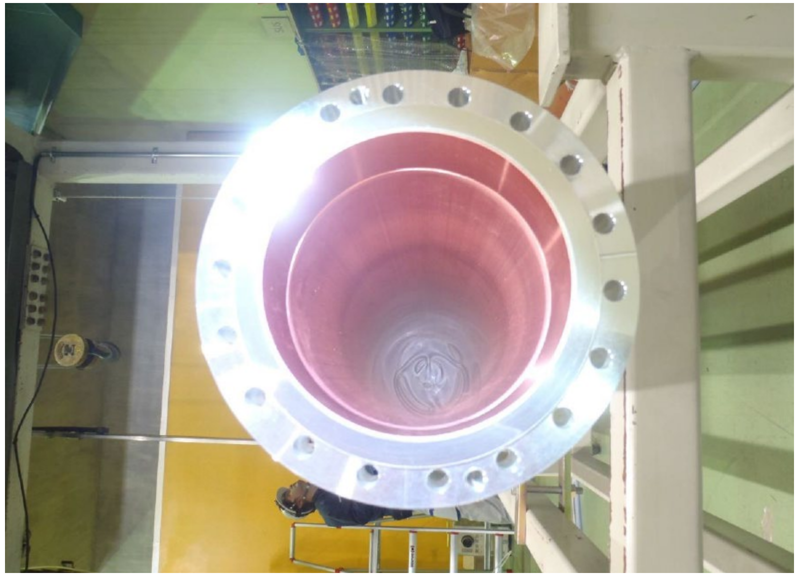
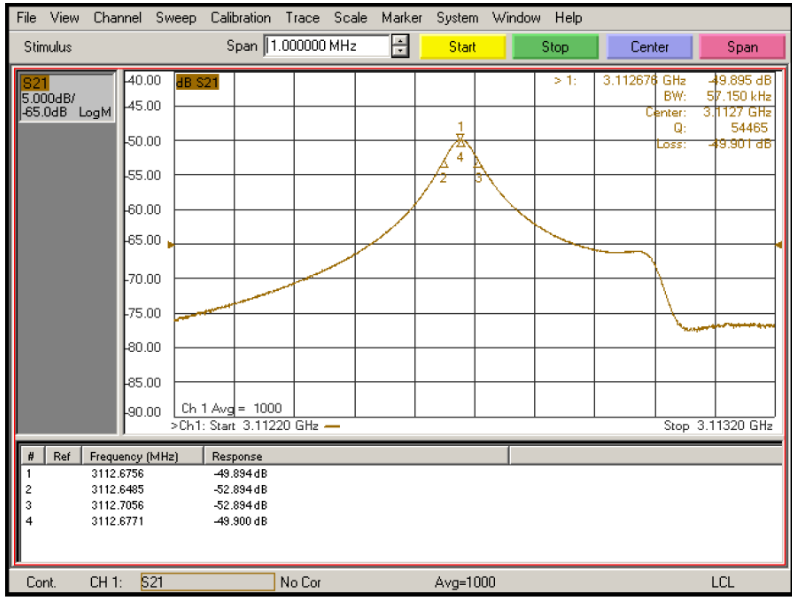


図 1：長尺円形導波管銅
コーティング治具 3D 図



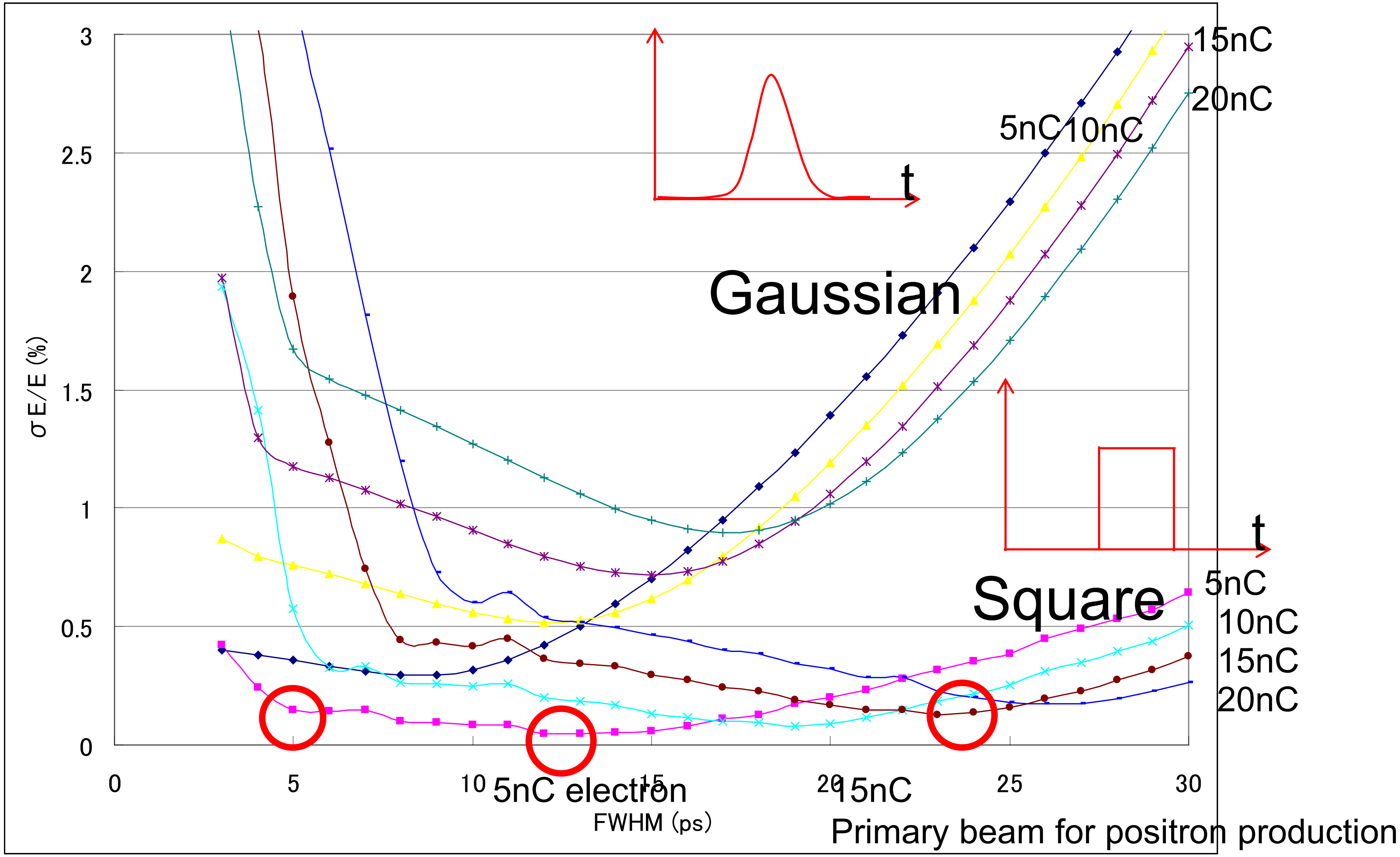
理論値 53400 に対して計測値 54400 であった。



M. Yoshida

Energy spread reduction by pulse shaping

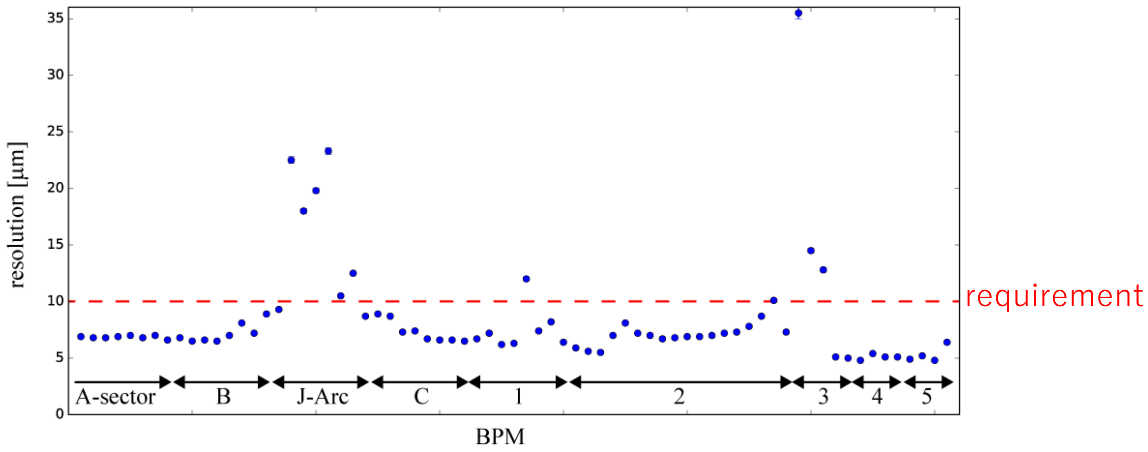
Energy spread of 0.1% is required for SuperKEKB synchrotron injection.



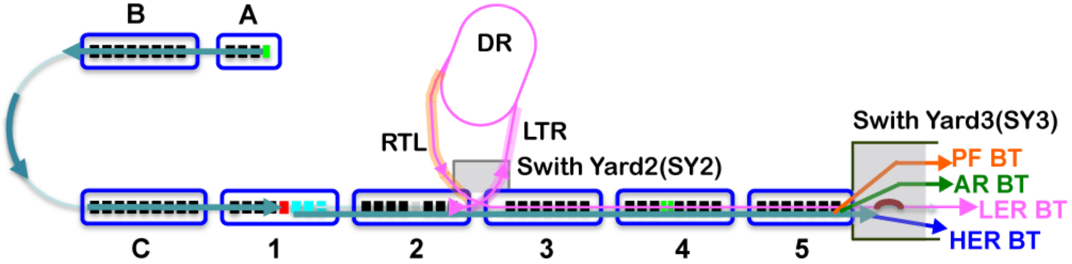
When bunch compression is performed to suppress vertical emittance, the energy spread exceeds 0.2%.

BPM readout system in the Linac

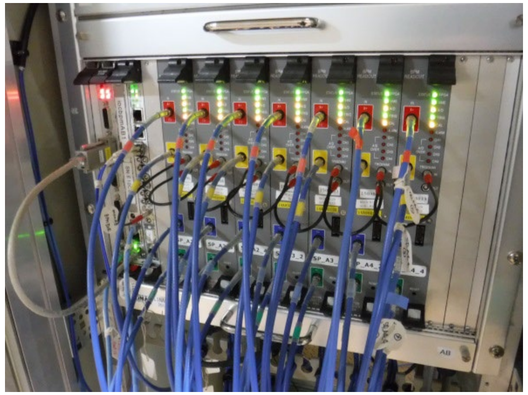
VME based BPM readout system is used in the linac. The BPM board has two band pass filters with bandwidth of 60 MHz (f_c=180 MHz), 16bit-250Msps ADCs and a calibration pulse generators. Position resolution of the system is smaller than requirement (σ<10 μm)



Position resolution of the BPM estimated by 3-BPM method



VME crate: 22, BPM board: 108



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

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.

BT BPM raw signals measured by Oscilloscope

Some BPMs have overlapping signals during two-bunch operation.