IPAC 2025
WEXN1

Upgrade of KEK Electron/Positron Injector Linac Using Pulsed Magnets and Machine Learning

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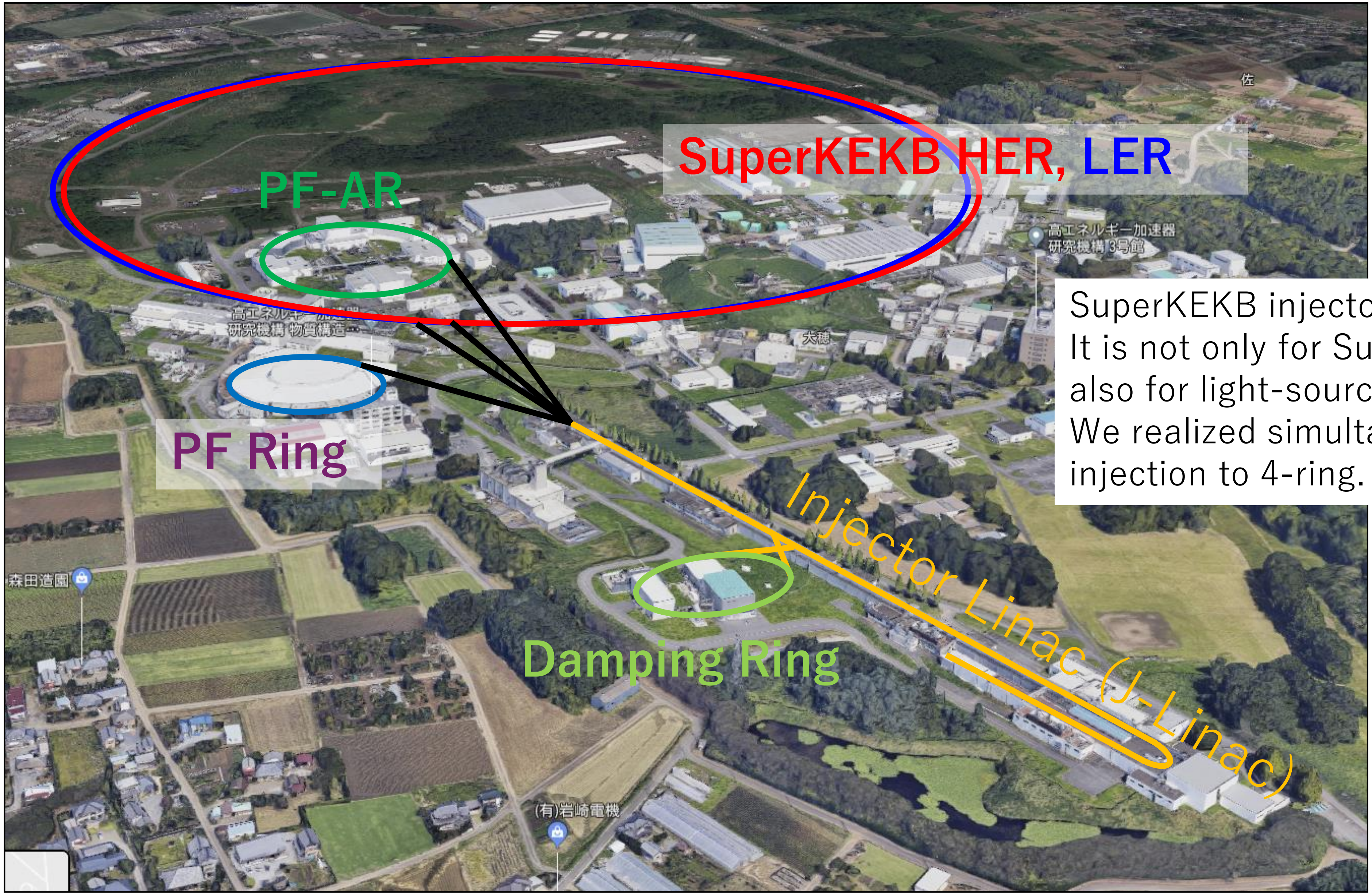
KEK

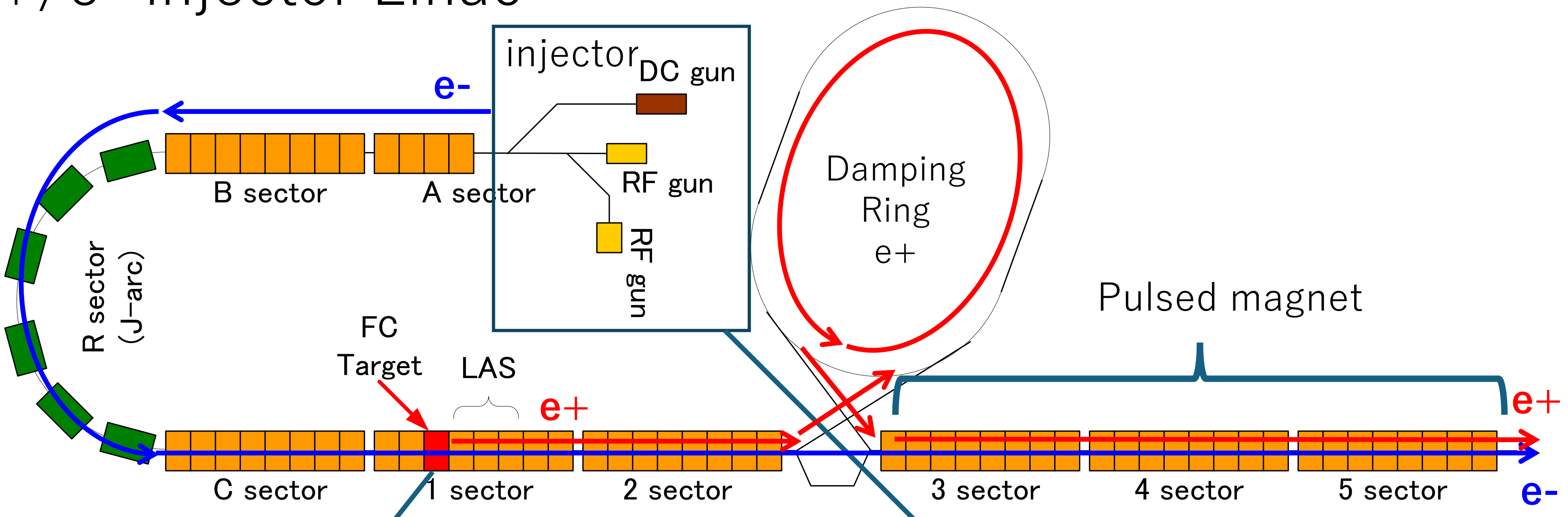
Introduction
KEK Injector Linac

Accelerators in KEK Tsukuba (Injector linac and four storage rings)



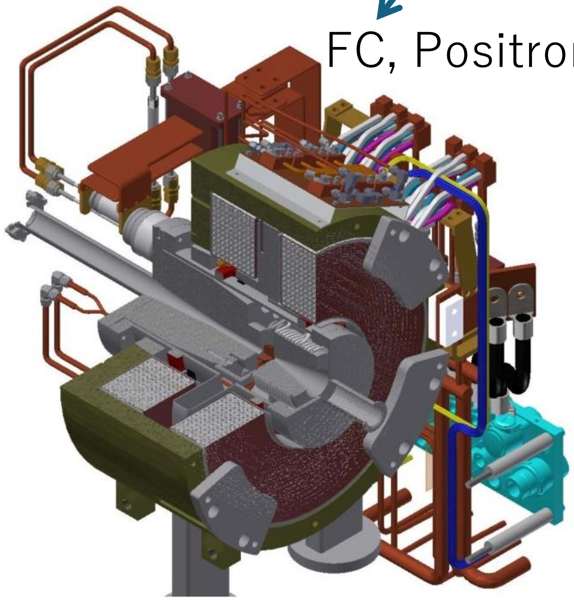
SuperKEKB injector is called J-Linac.
It is not only for SuperKEKB rings but also for light-source rings.
We realized simultaneous top-up injection to 4-ring.

Beam line of e+/e- injector Linac

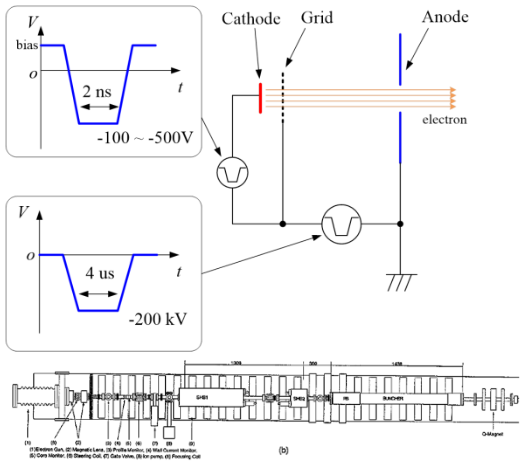


180° bending beam line that is called J-arc.

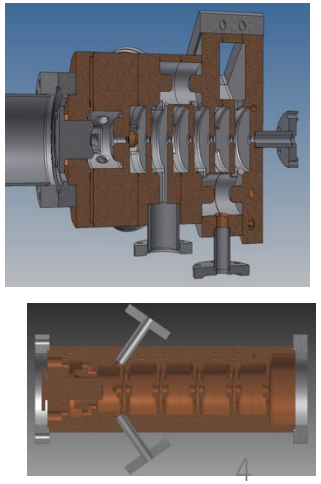
FC, Positron target



Thermionic gun and SHB



RF gun

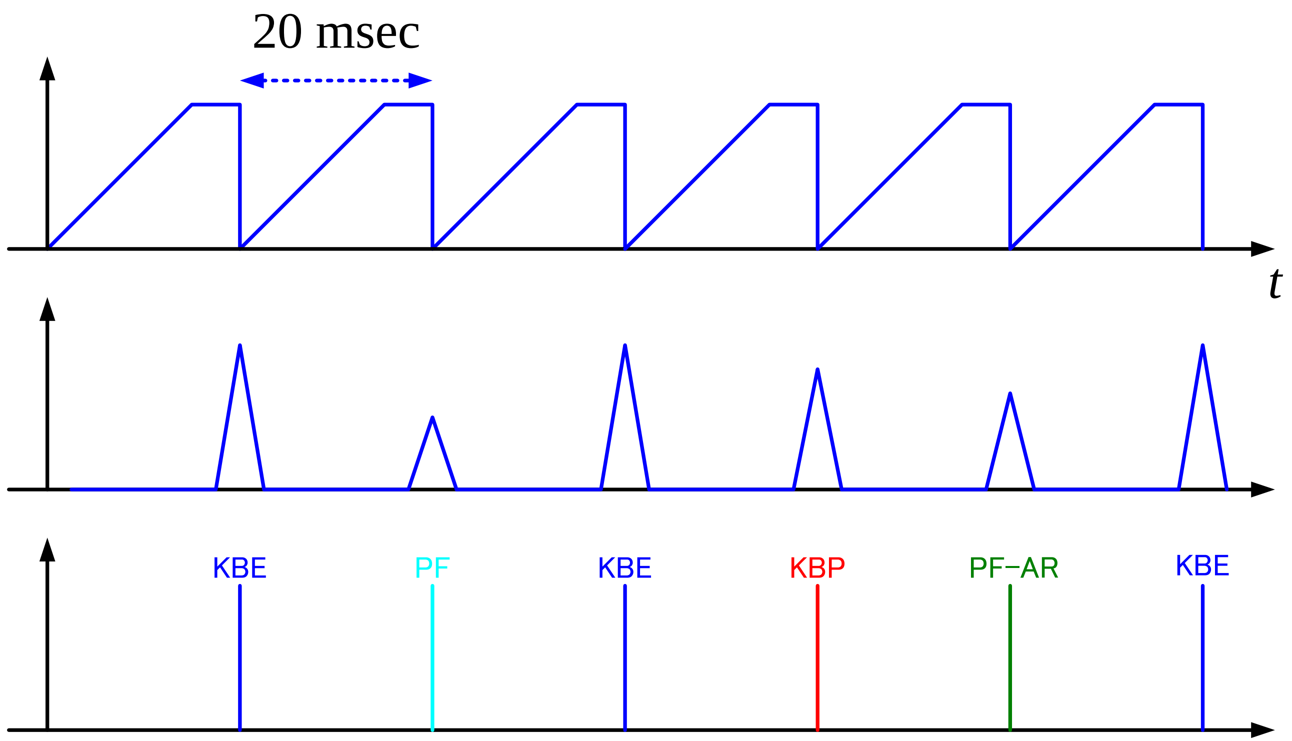


Beam timing and beam mode switching

PFN charging in
klystron modulator

Current of pulsed
magnet

Beam mode
and timing

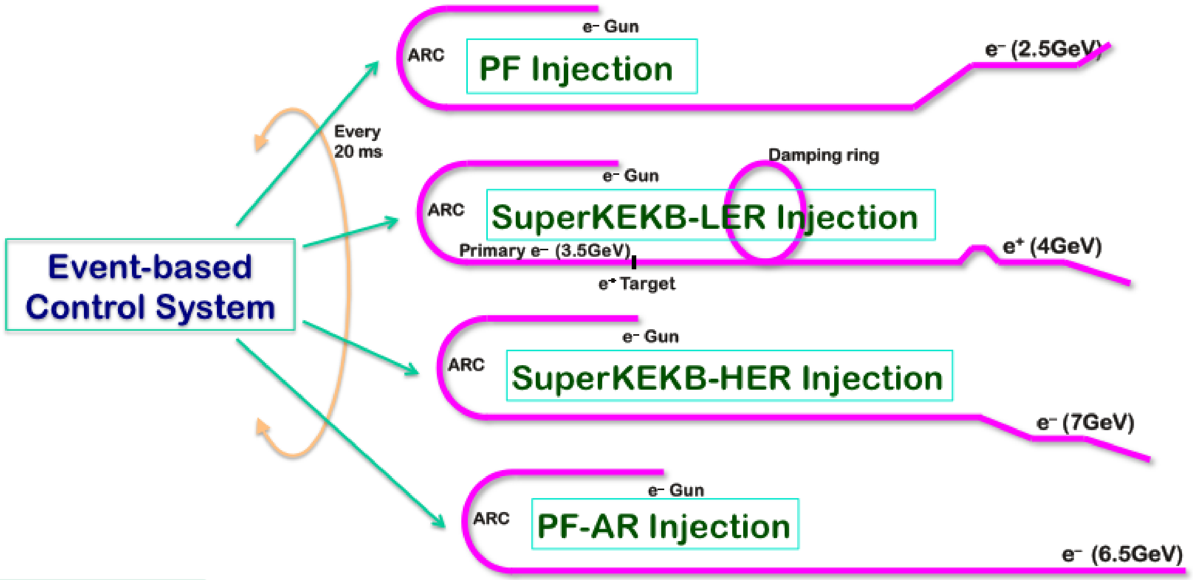


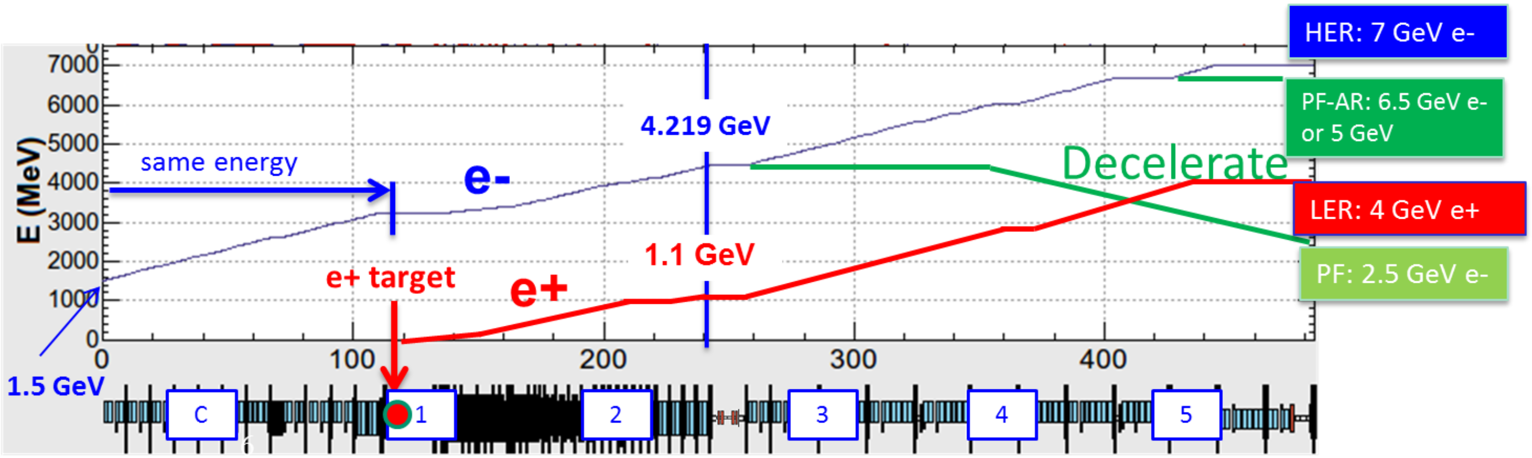
Downstream of the injector (sector 3-5) all magnets are pulsed

The interval between beams is 20 msec (50 pps operation).
Use pulsed magnets to change the optics every 20 msec.
A different beam mode can be launched every 20 msec.
(HER e-, LER e+, PF e-, PF-AR e-)

Pulsed magnet, RF phase, etc. are switched every 20 msec. There appear to be multiple injectors from each ring.
It is called Virtual Accelerator

	e+ or e-	Energy [GeV]	Charge [nC]
HER	e-	7.0	4.0
LER	e+	4.0	4.0
PF	e-	2.5	0.3
PF-AR	e+	6.5	0.3





It appears as if there are four beamlines.

Pulsed Q and steering magnet at sector 3-5

Quadrupole
Steering

Typical magnet set at 3-5 sector of LINAC

Quadrupole magnet

Parameter	spec
Reputation	50 pps
Max. Pulse Current	300 A
Max. Average Current	100 A
Max. Field Gradient	60 T/m
Bore diameter	20 mm

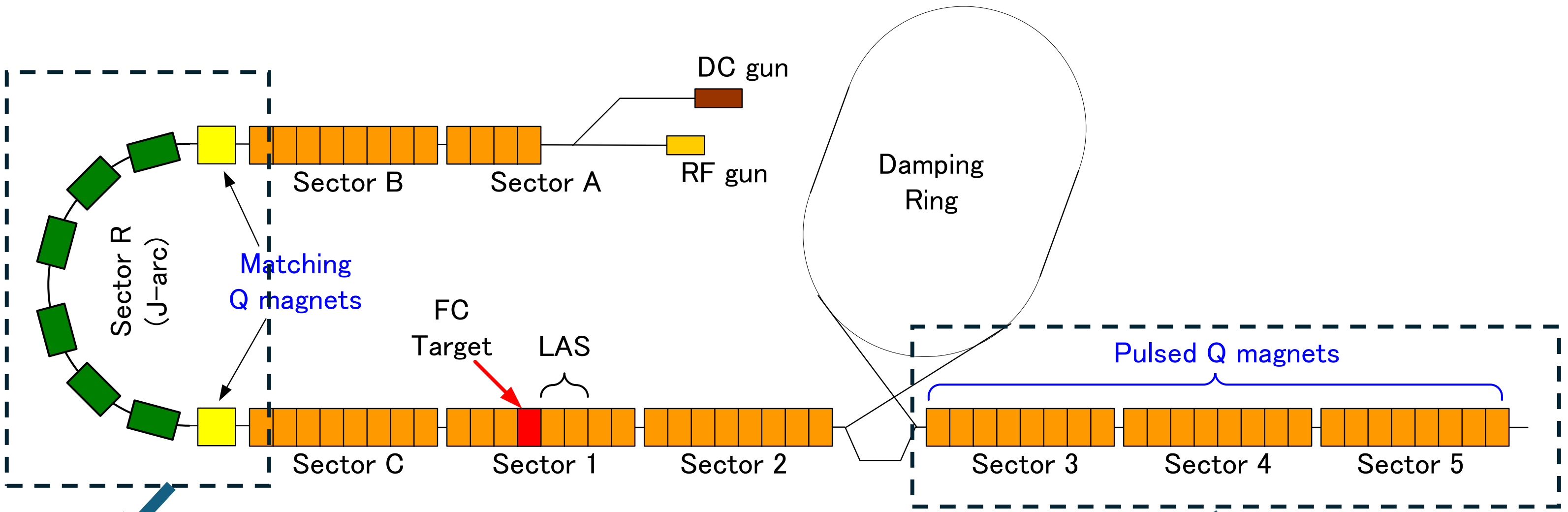
Steering magnet

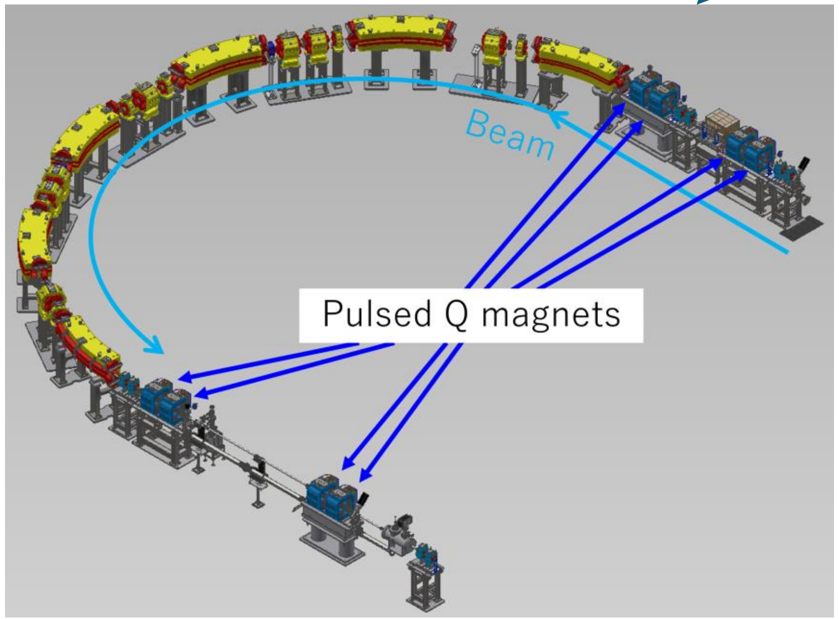
Parameter	spec
Reputation	50 pps
Max. Pulse Current	10 A
Max. Field strength	44.3 mT
Pole gap	20 mm
Pole length	80 mm

Upgrade of Pulsed Q Magnet and New Pulse Driver

New Large-aperture pulsed Q magnet in J-arc

In 2023, the large Q magnets were replaced with pulsed Q magnets.





Pulse magnets were already in use in the downstream section of the linac. (In 2017, installed)

Specification of the Pulsed Q magnet

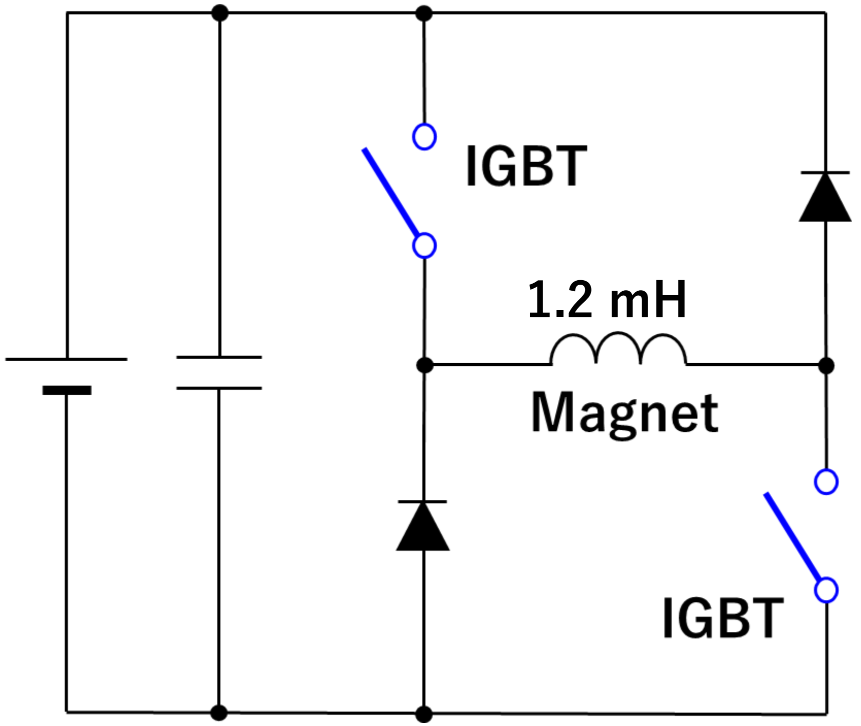
	PM_32_4 (3-5 sector)	New PM_R0_01 (J-arc)
L@ 1 kHz	1.0 mH	1.2 mH
Max Current	330 A	**600 A**
Gap	ϕ 20 mm	ϕ 44 mm
Length	200 mm	300 mm
Magnetic field	60 T/m	20 T/m

This magnet was designed to have an inductance of about 1 mH.

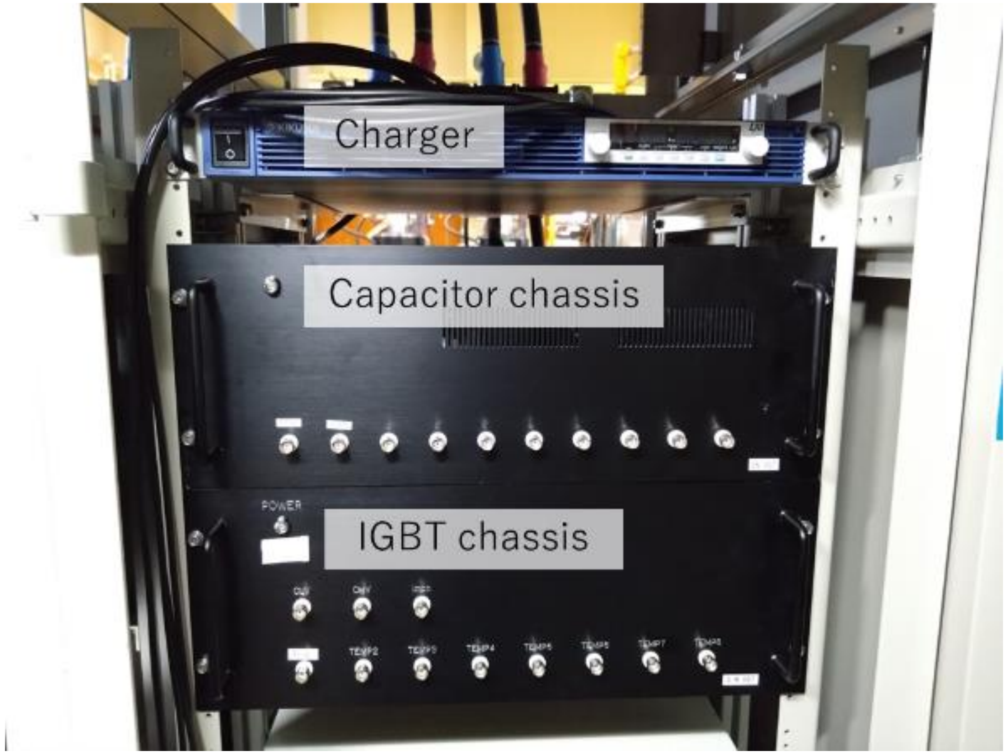
Existing pulsed Q magnet. 330 A, 200 V pulse driver was used.

Development of Pulse driver for the Large-aperture Q magnet

The large-aperture Q magnet requires a 400 V, 600 A-class pulse driver. A simple circuit was used to configure the pulse driver because it requires a very large amount of power. This circuit enables energy recovery.



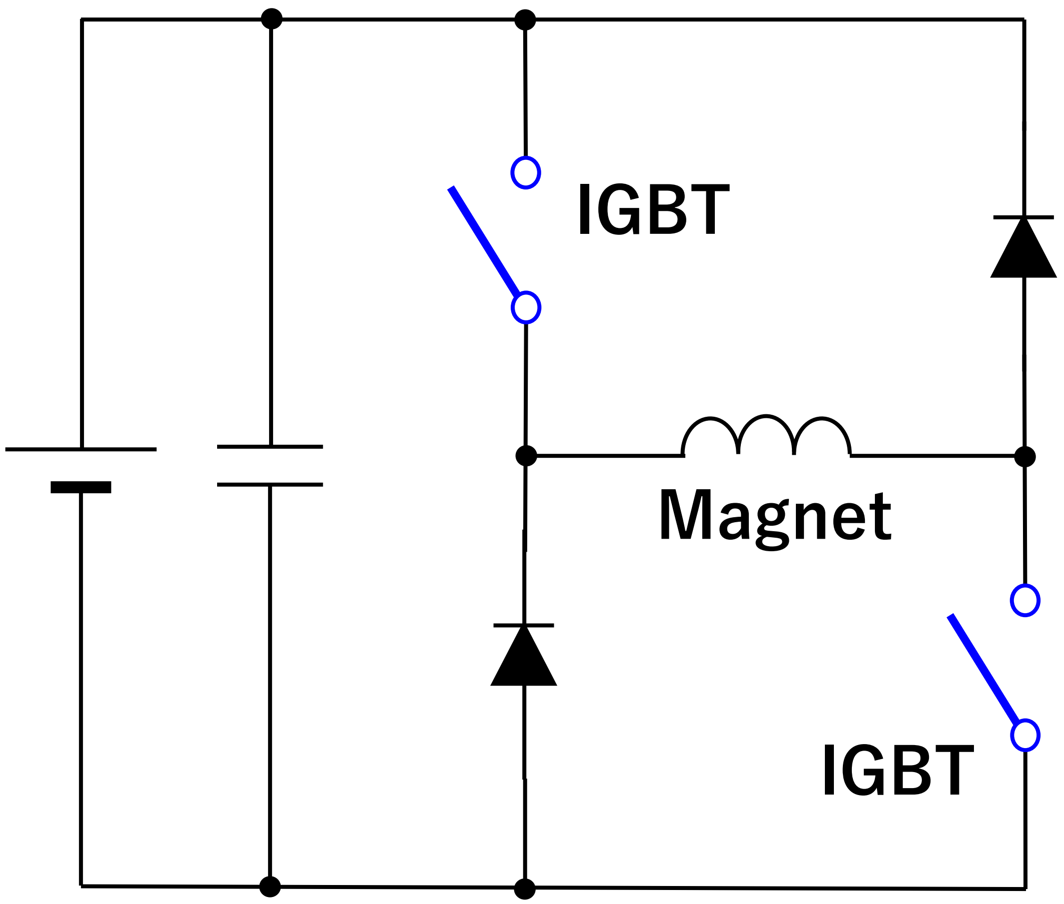
Basic circuit



Pulse driver is housed in a compact chassis

Circuit Operating Principle

The H-bridge circuit is used for energy recovery. A robust pulse power supply is achieved with a simple circuit and trigger control.



Pulse current waveform

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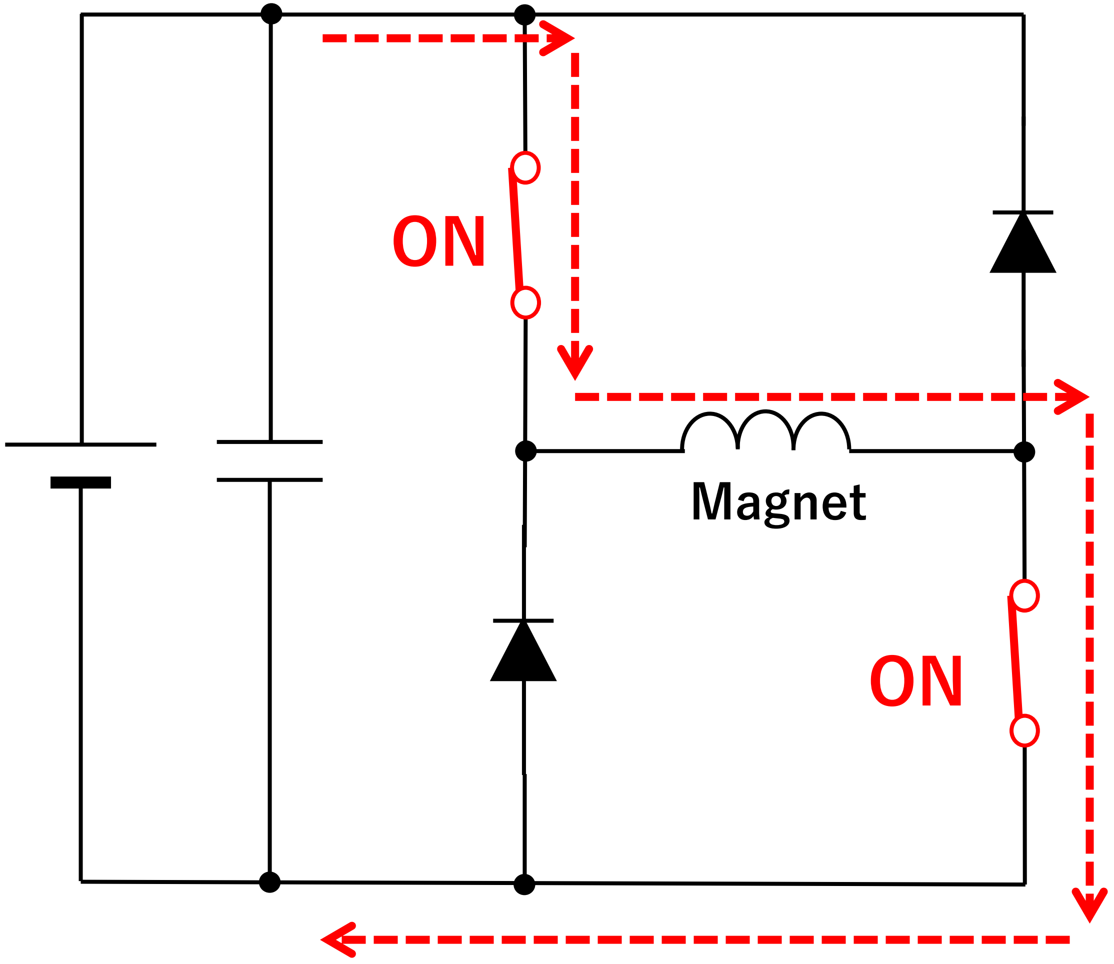

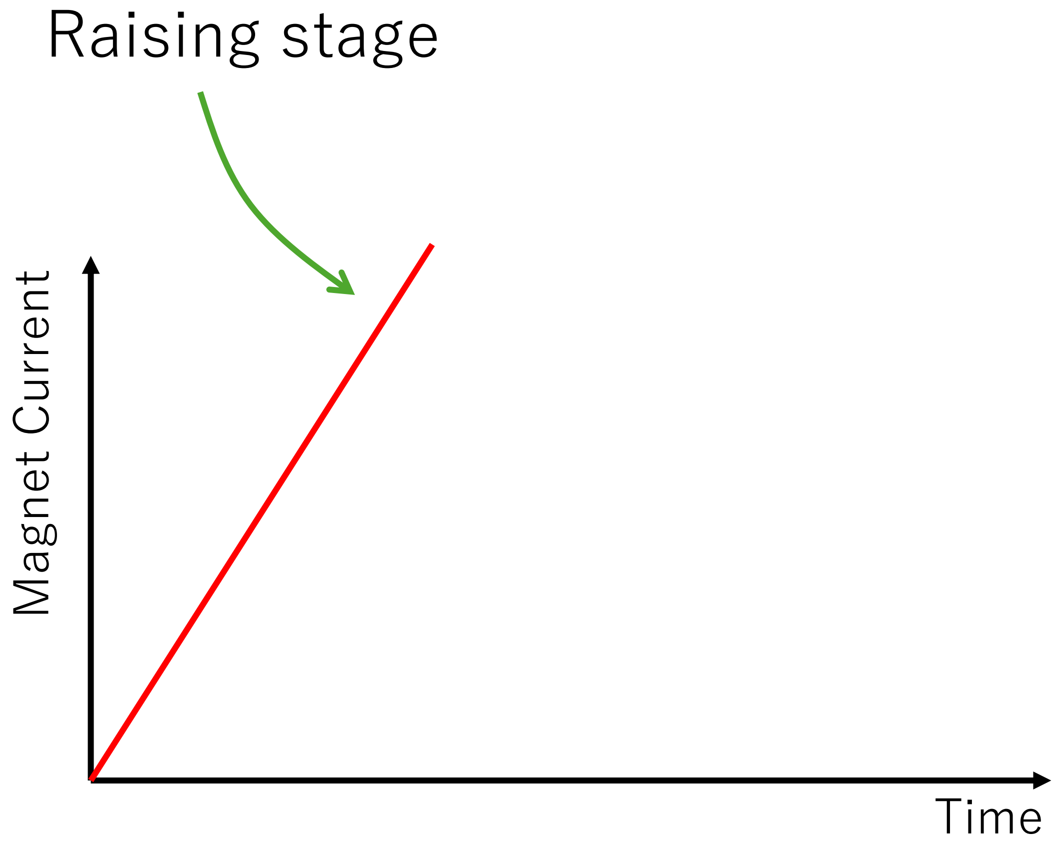

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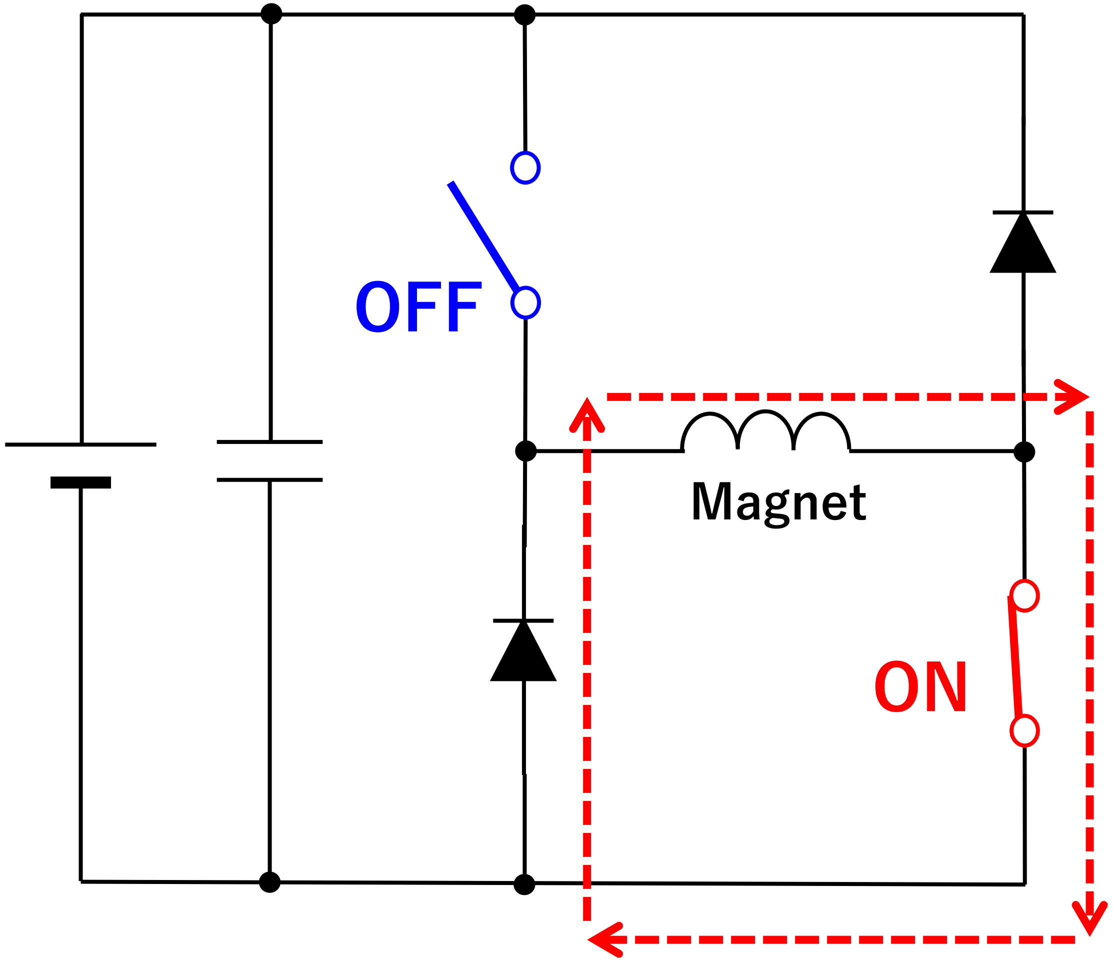

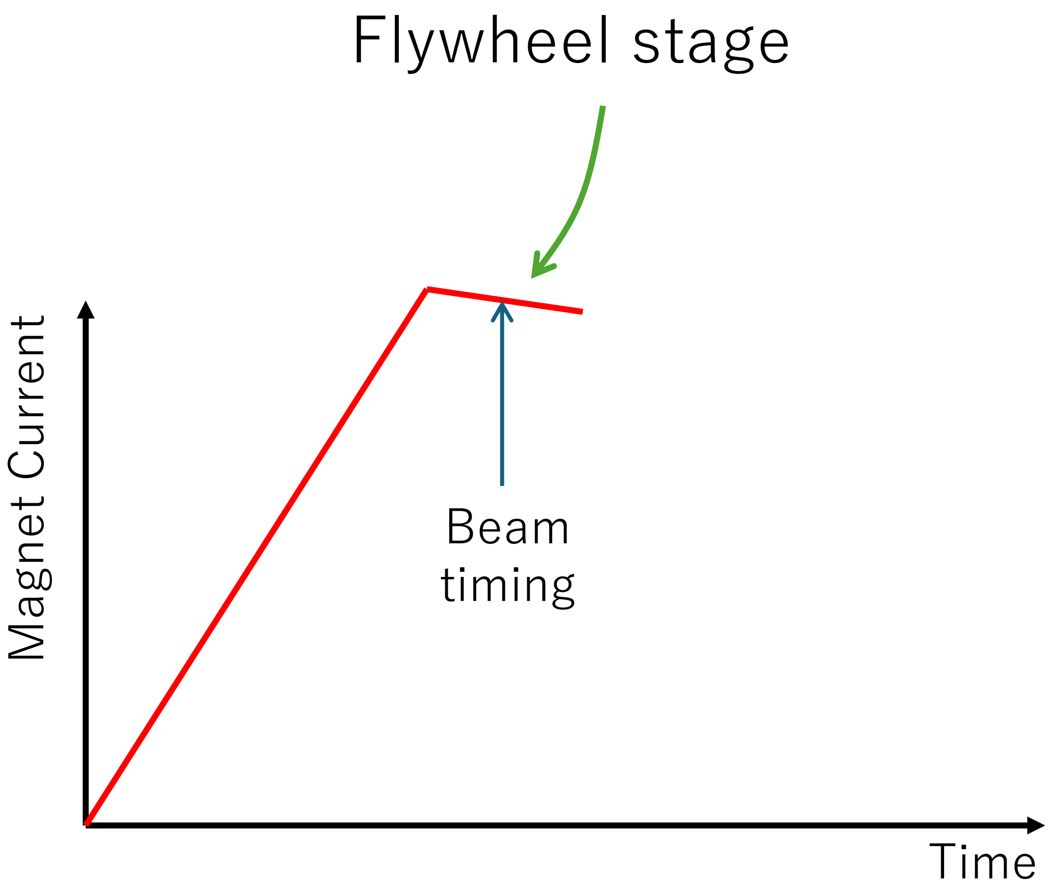

Pulse current waveform

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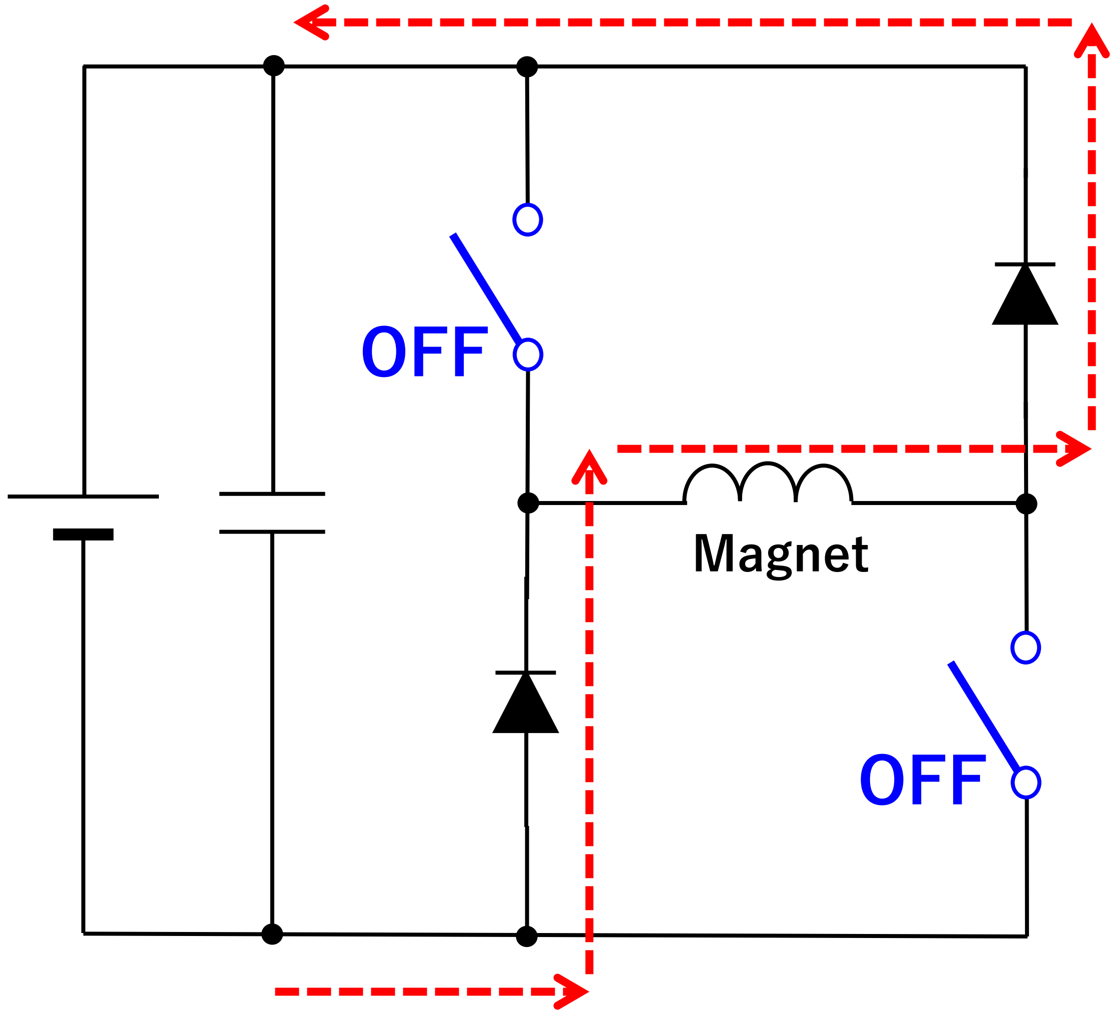

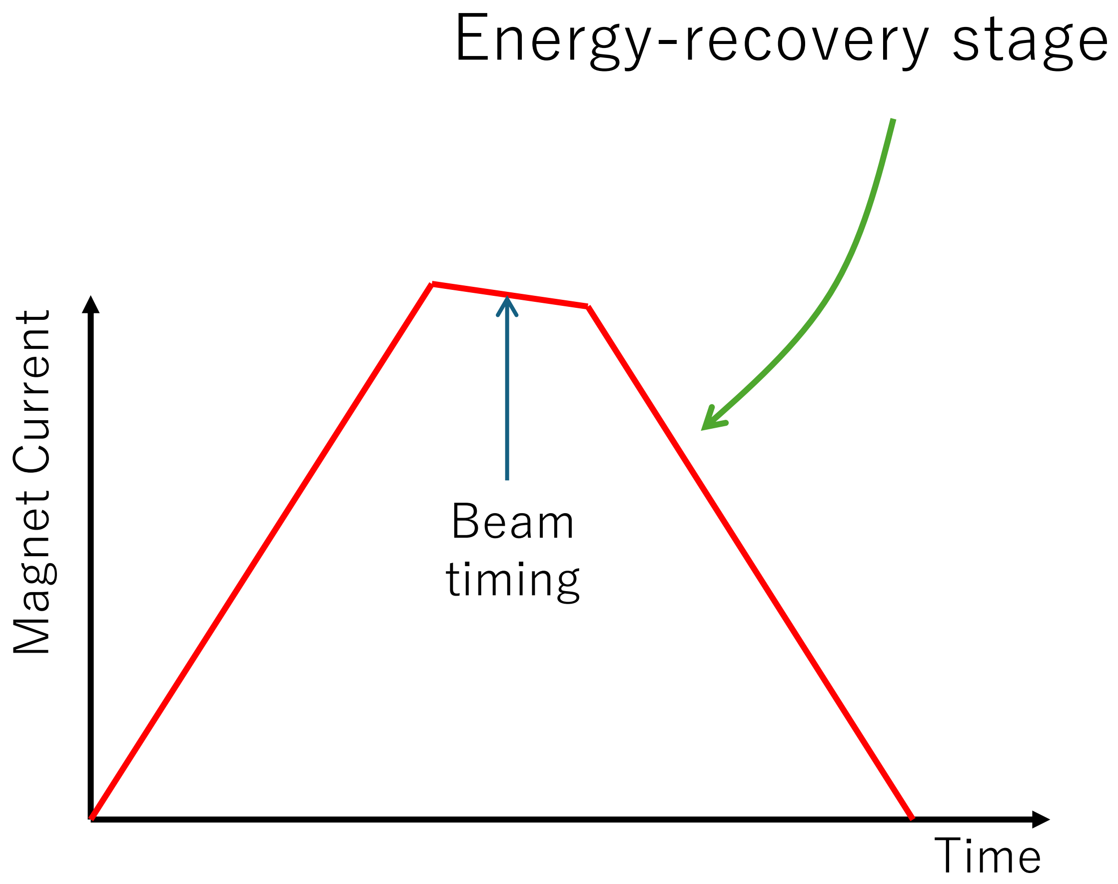

Pulse current waveform

Circuit Operating Principle

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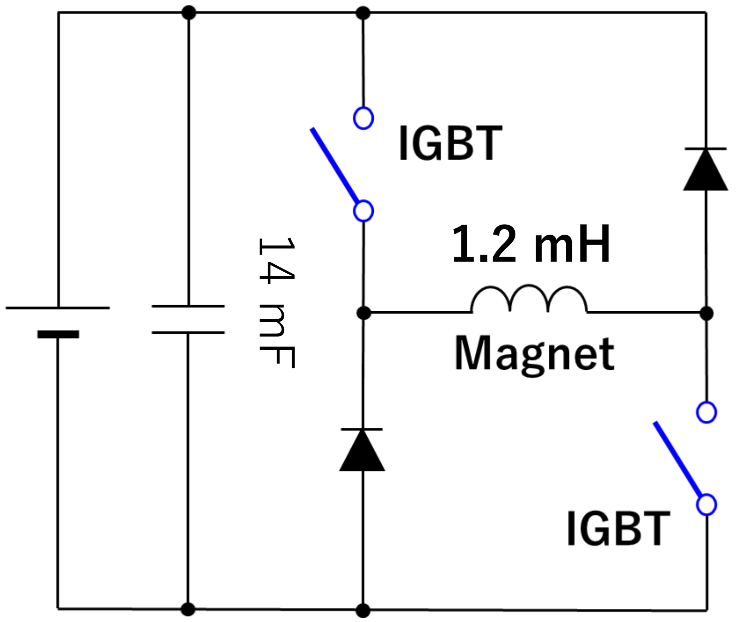
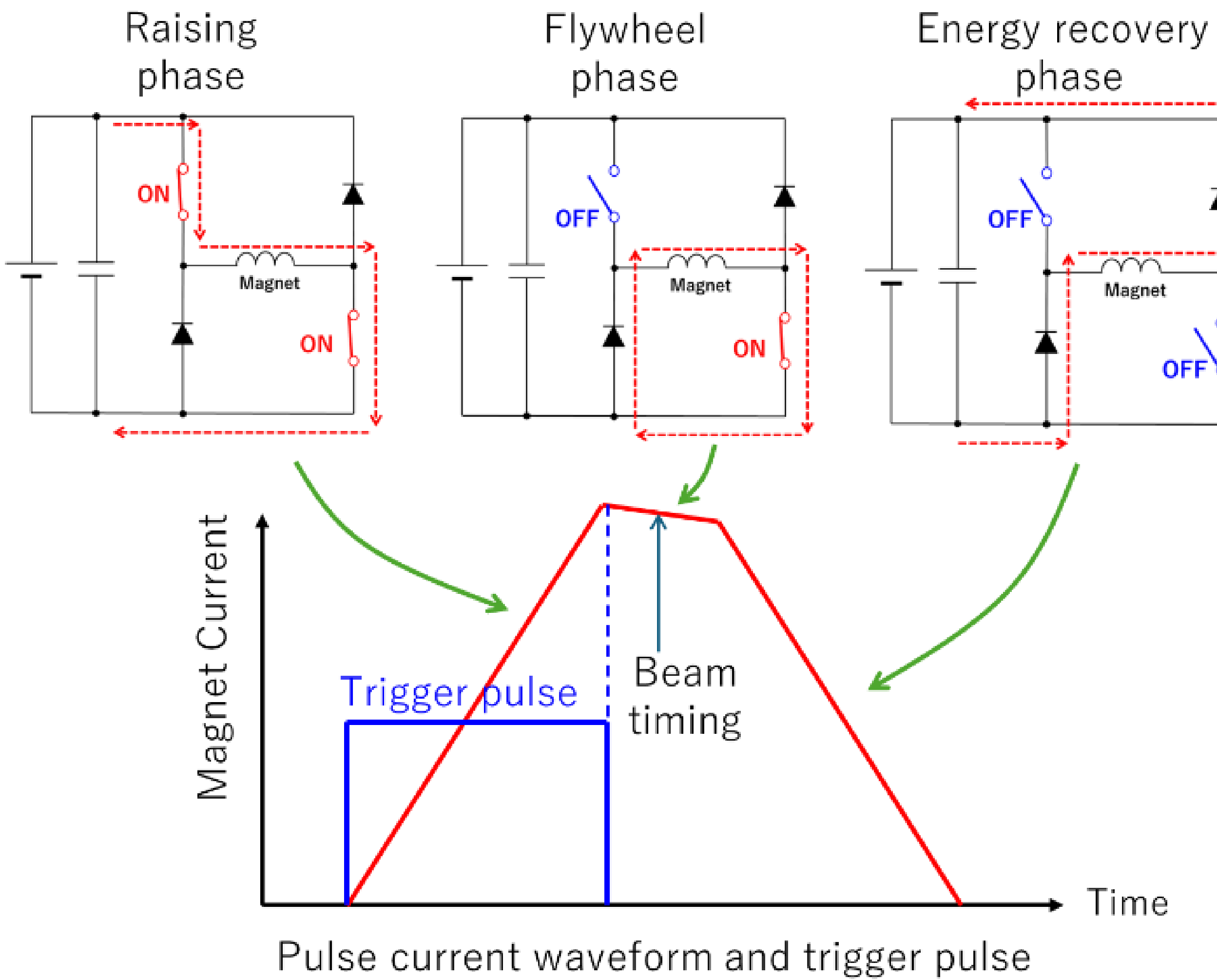


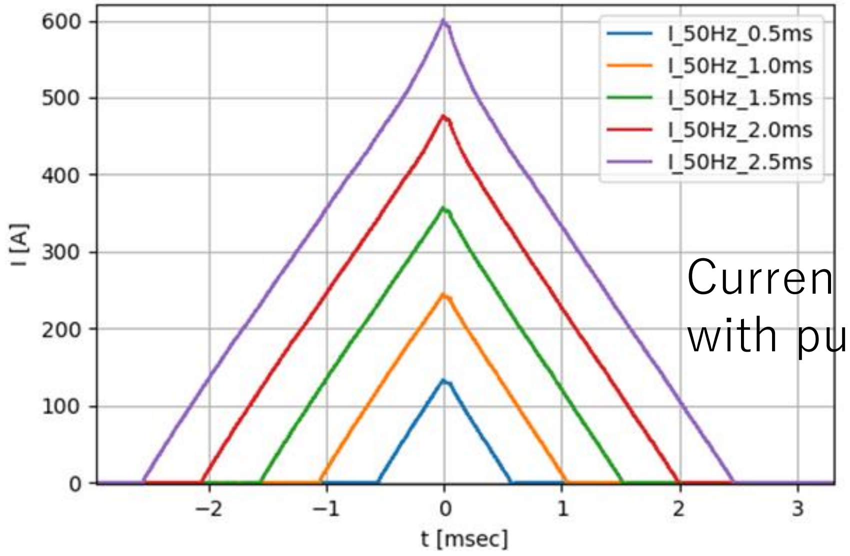
Basic circuit



Operating Principle and Waveforms

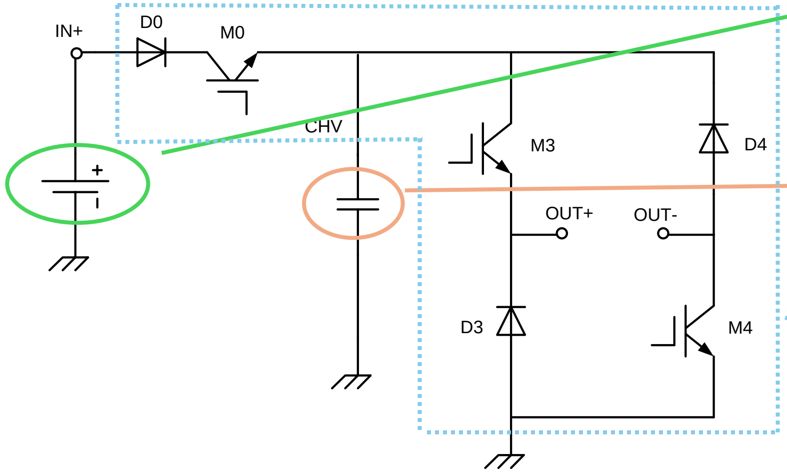
Development of Pulse driver for Large-aperture Q magnet

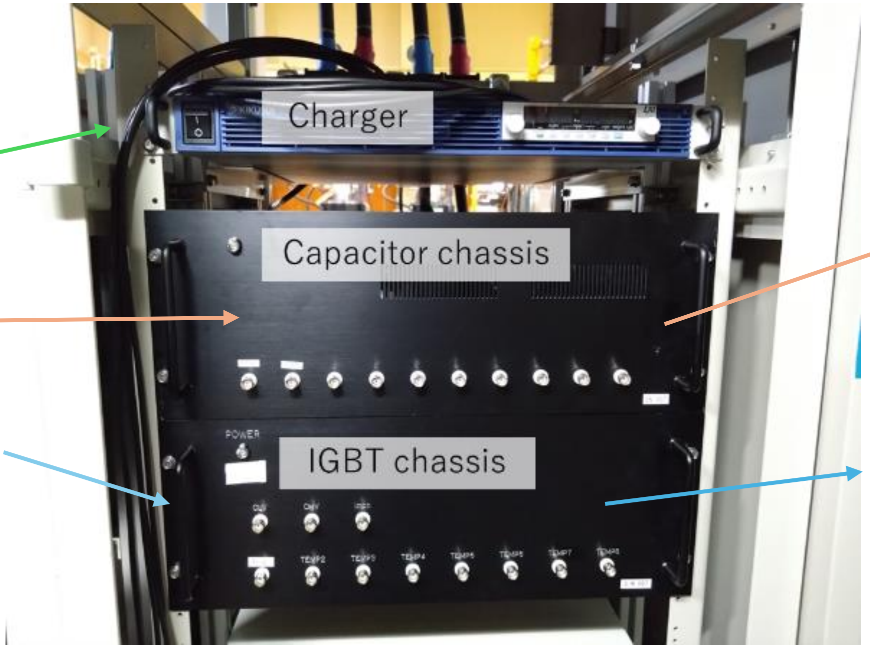
This simple and robust circuit provided sufficient pulse current.

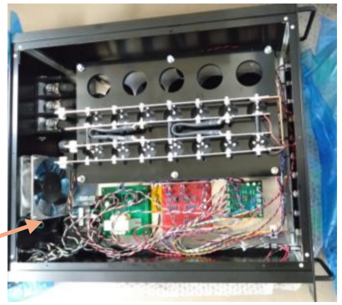


Curren was controlled with pulse width.

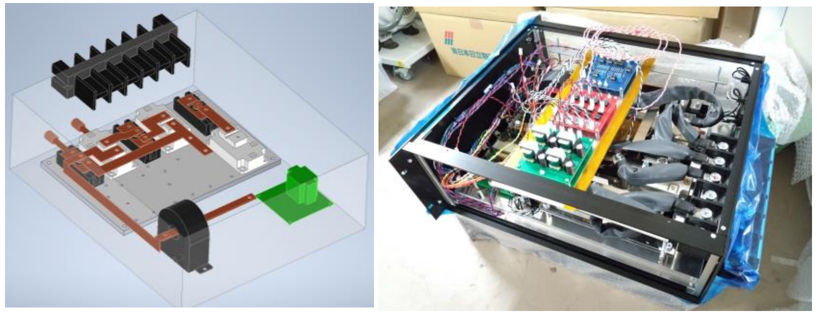
The pulse driver is housed in two 19-inch rack 4U units.





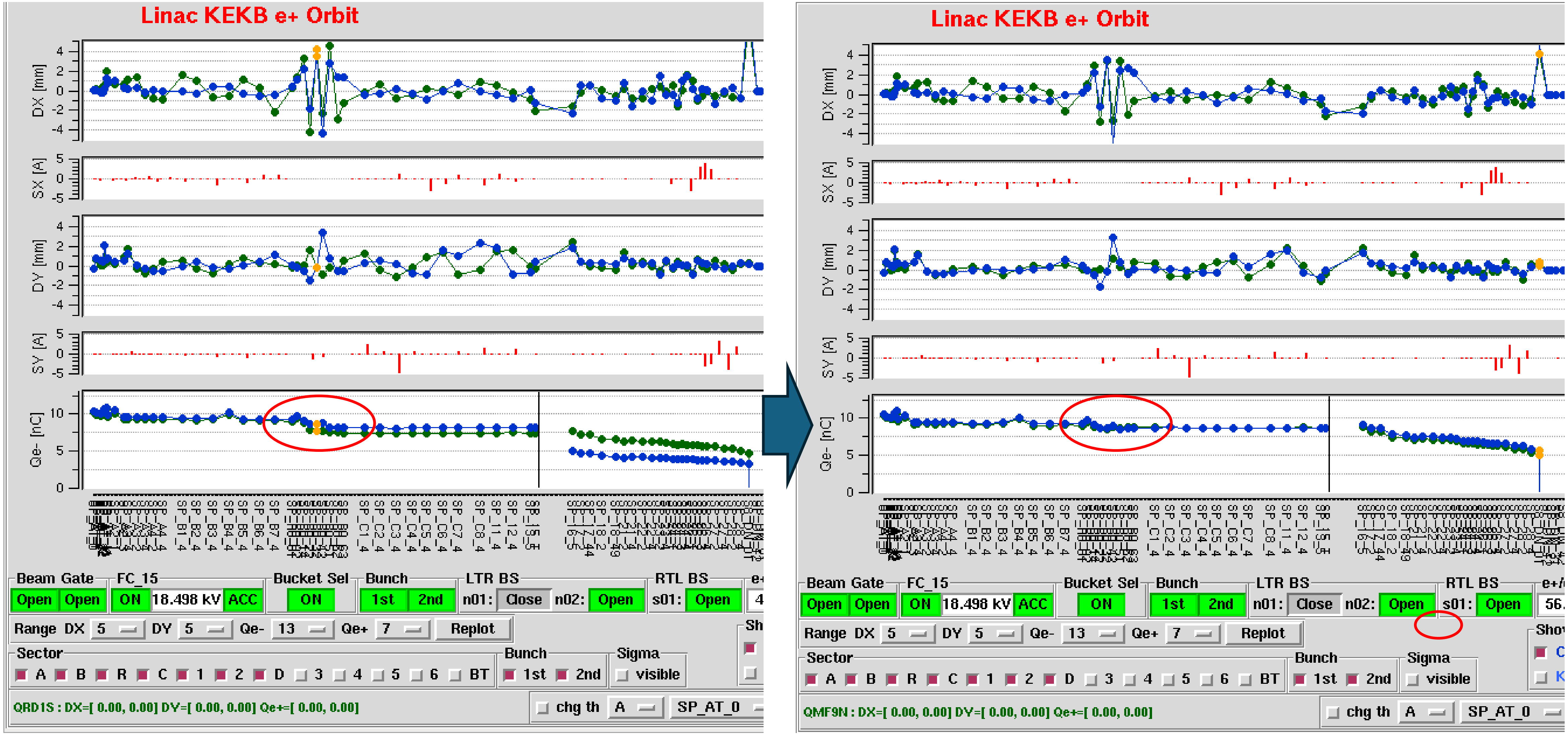


1 mF capacitor x14 in Capacitor chassis



IGBT x3, Diode x3, and control circuit, in IGBT chassis.

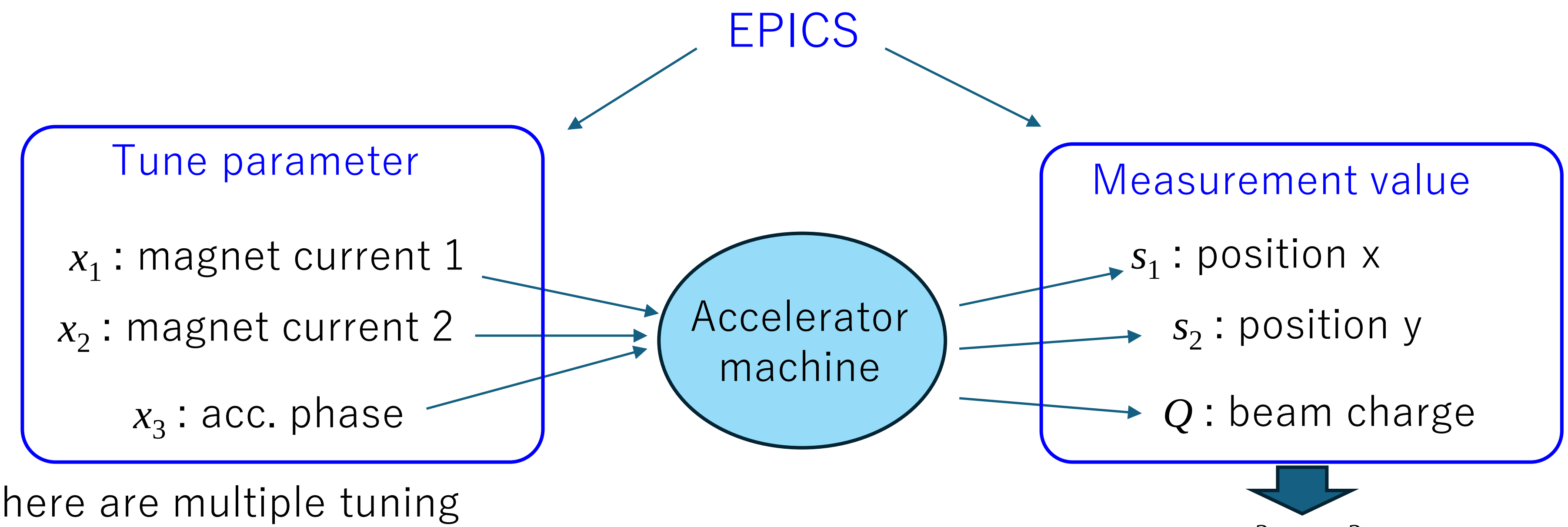
The loss of positron primary beam has been eliminated since the introduction of pulsed Q magnet at J-arc



The pulse driver demonstrates adequate stability to attain beam matching for each beam.

Automatic tuning
using Machine Larning

What is machine tuning? It is “to change the parameters of the equipment to bring it closer to a better state”. It is important to consider the parameters and the resulting values as a multi-variable function for automatic tuning. For example, if the current value I[A] of the magnet is "x" and f(x) is the inverse of the beam charge Q[nC], the problem is to find x where f(x) is the minimum.



$$y = (s_1^2 + s_2^2) + 1/Q$$

In practice, there are multiple tuning parameters that require an optimization algorithm for the multivariable function f(x1, x2, x3, ... xn).

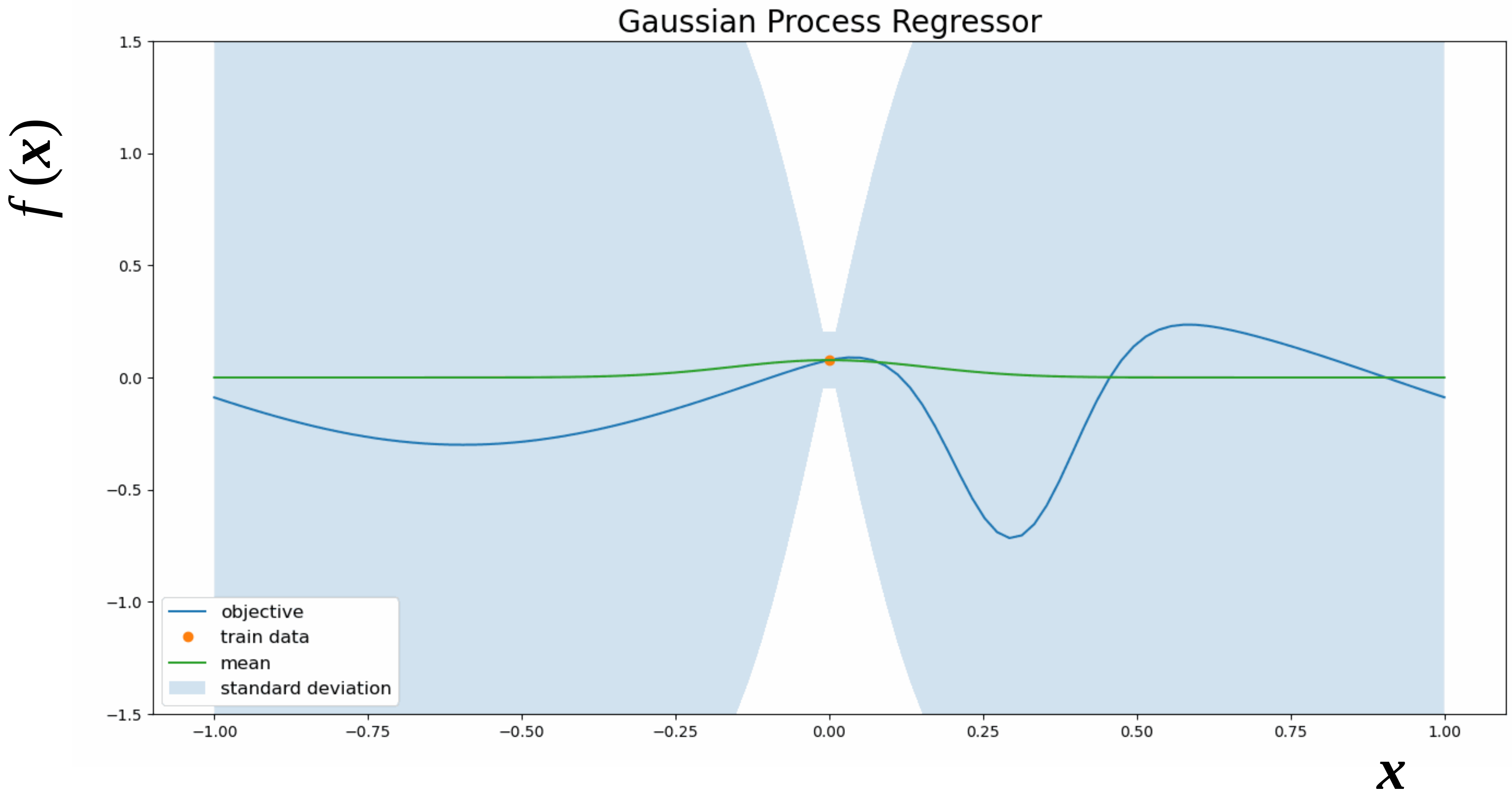
$$y = f(\boldsymbol{x})$$

Defines a numerical value to be minimized by computing the measured value.

For this type of minimization problem, Bayesian optimization or the Downhill Simplex method (Nelder-Mead method) can be used. (f(x) is unknown)

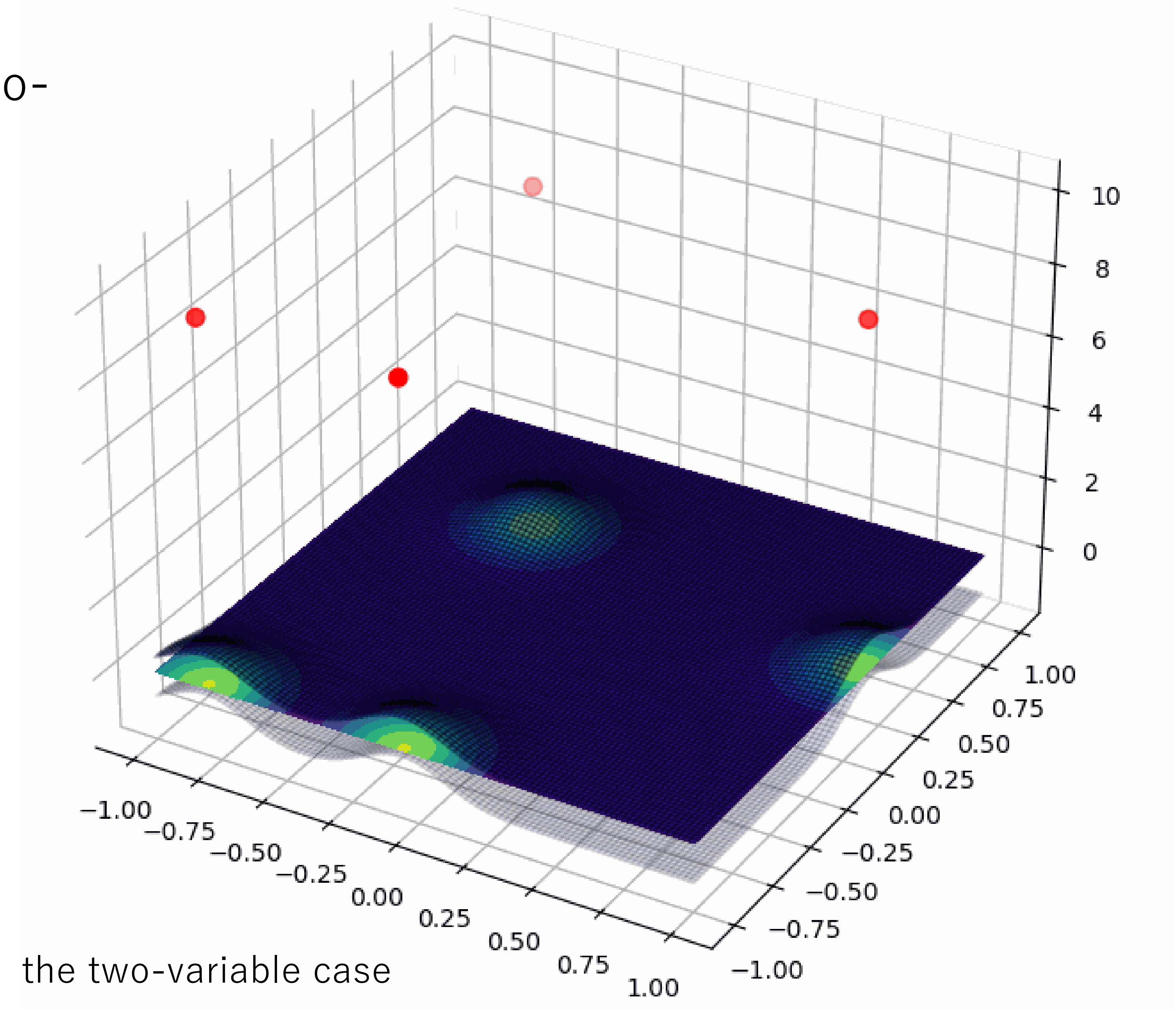
Gaussian Processes and Bayesian Optimization

The Gaussian process is a method for predicting the entire function from a small number of observation points with a distribution of errors. Bayesian optimization is a method that determines the next point to be observed based on the prediction and the error range, and searches for the point of minimum (maximum) value of the function.



The Gaussian process and Bayesian optimization in the two-variable case

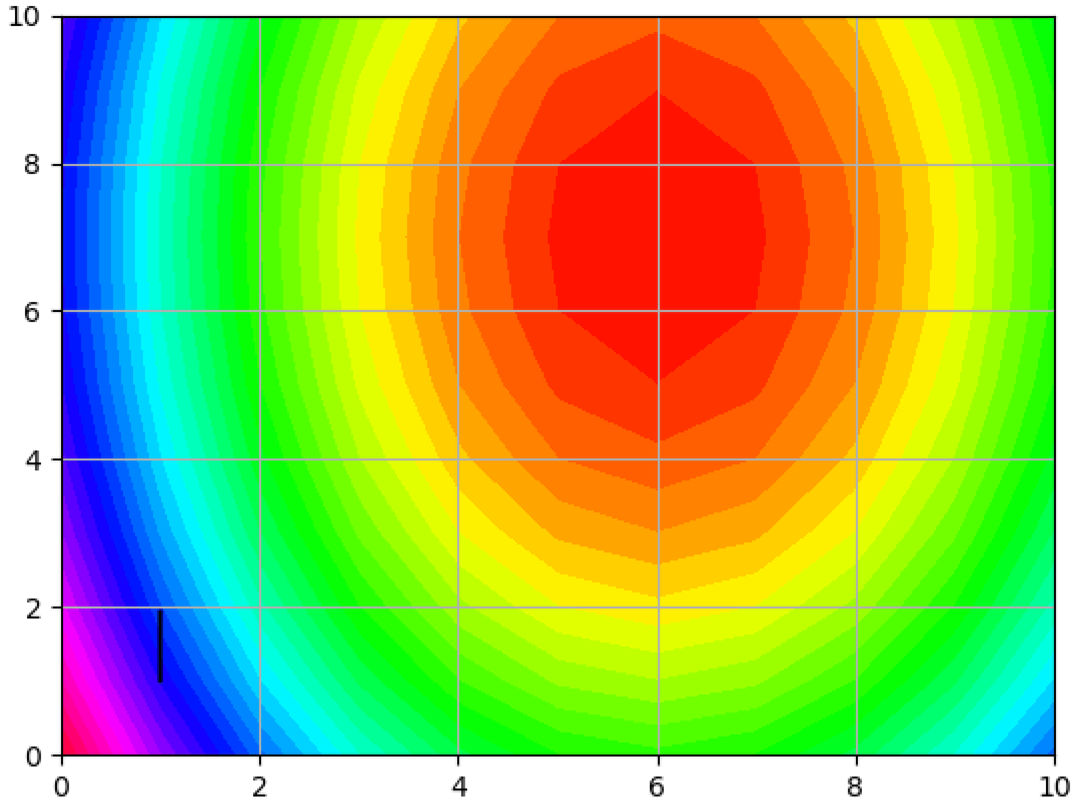
Multi-dimensional function prediction (fitting) is also available.



the two-variable case

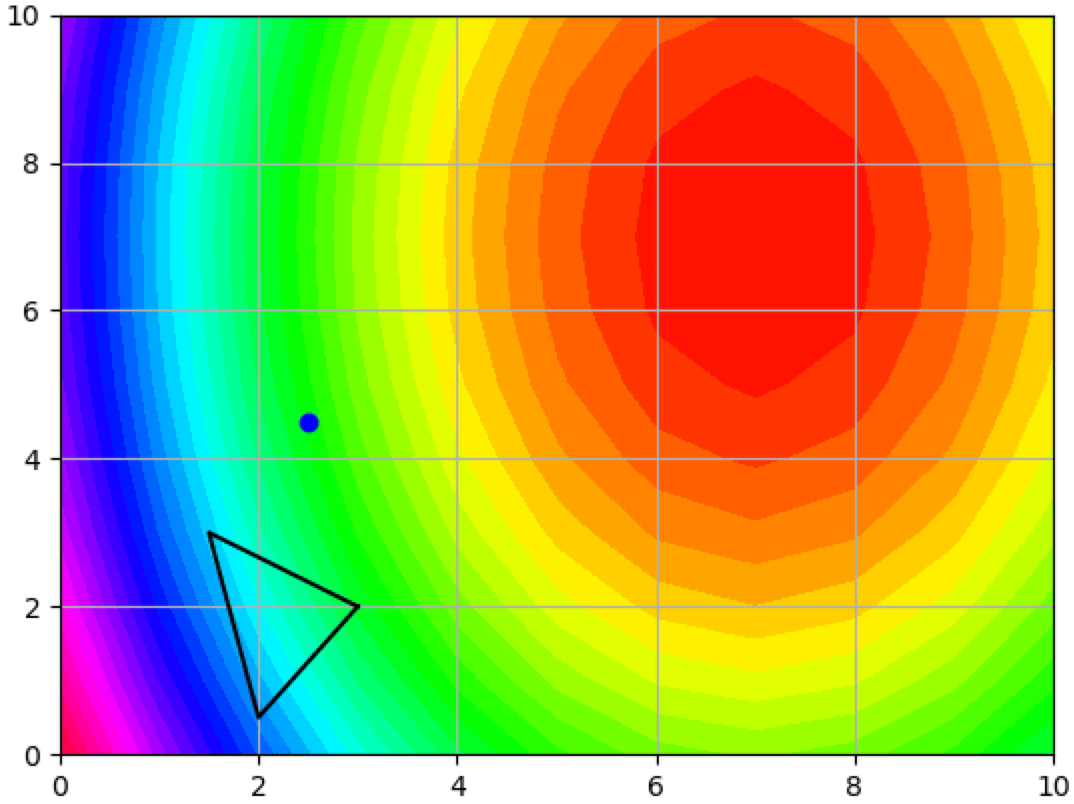
Bayesian optimization and downhill simplex method

Bayesian optimization is an algorithm that finds the optimal solution by predicting the entire function considering uncertainty. In contrast, the Downhill simplex method is an algorithm that converges to the optimal solution with a simple move and flip operation that considers the number of search dimensions plus one point.



Bayesian optimization

Move to anticipate the function of the entire search area without falling into local solutions.



Downhill simplex method

Seek optimum point if smooth function, may fall into local solutions.

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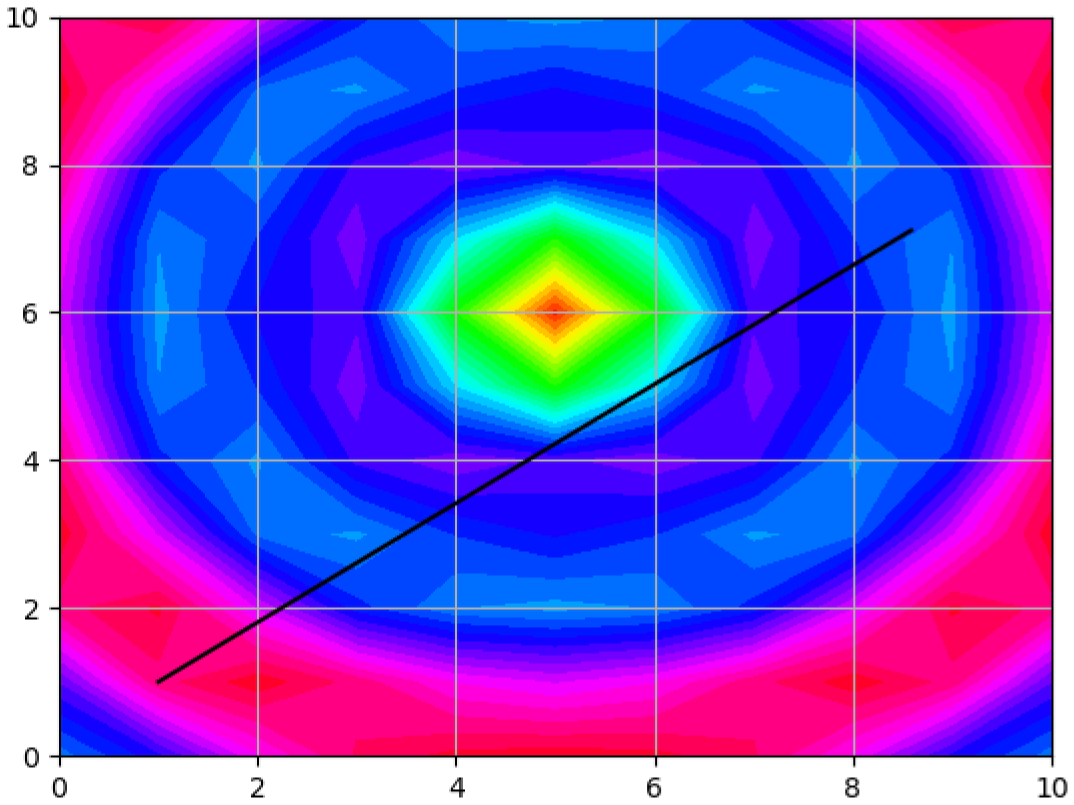

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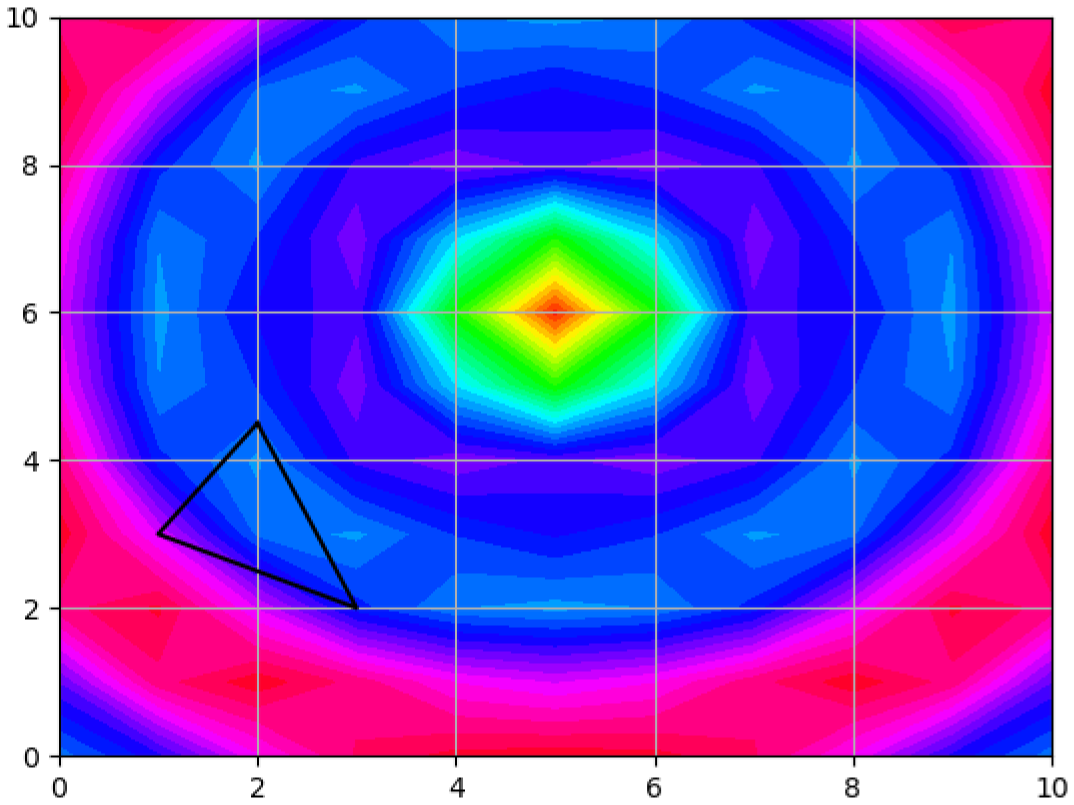


Downhill simplex method

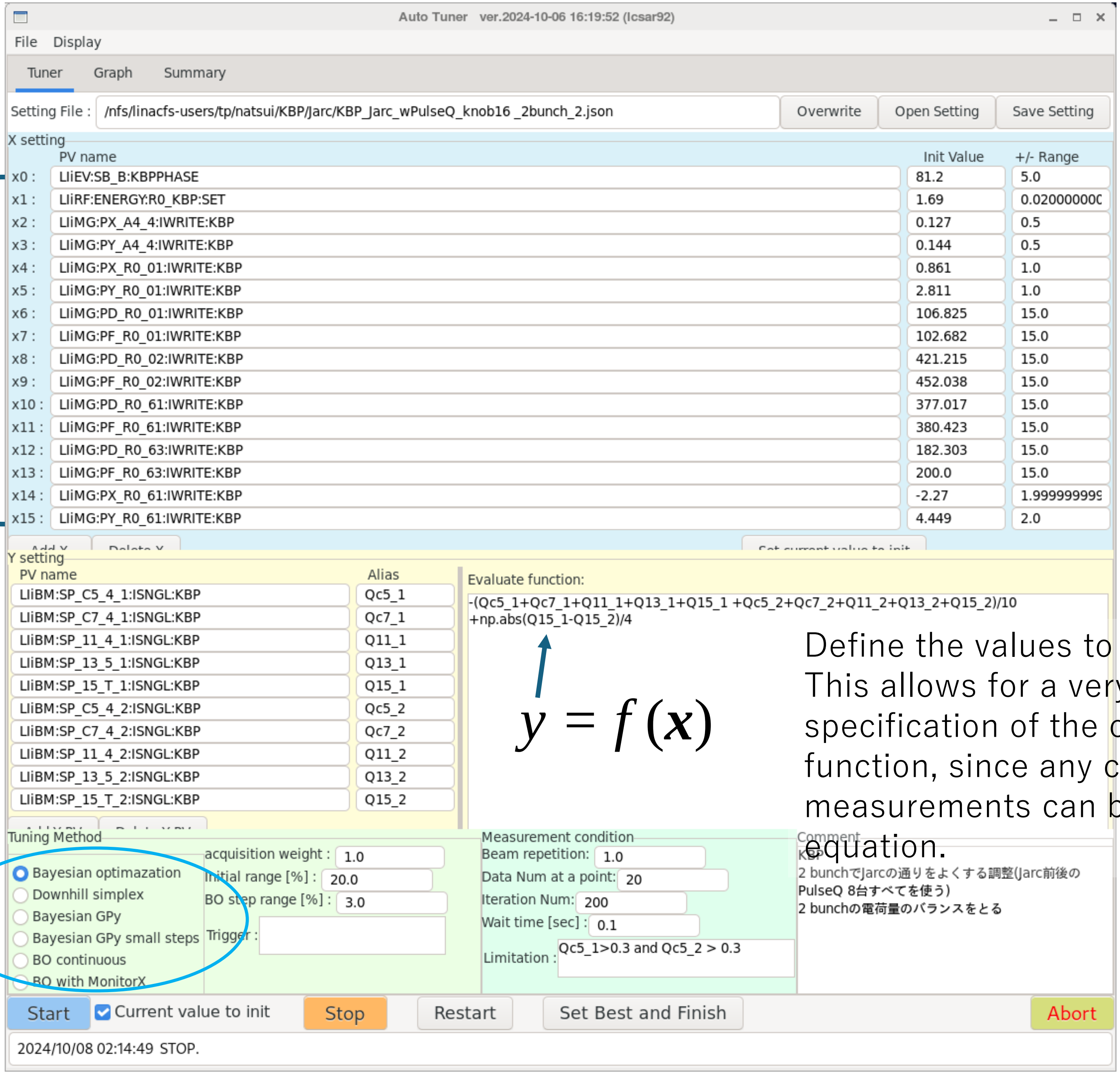
Seek optimum point if smooth function, may fall into local solutions.

Automatic tuning using Machine Larning

Implementation and Practical Examples

Operation Panel

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.

$$y = f(\boldsymbol{x})$$

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.

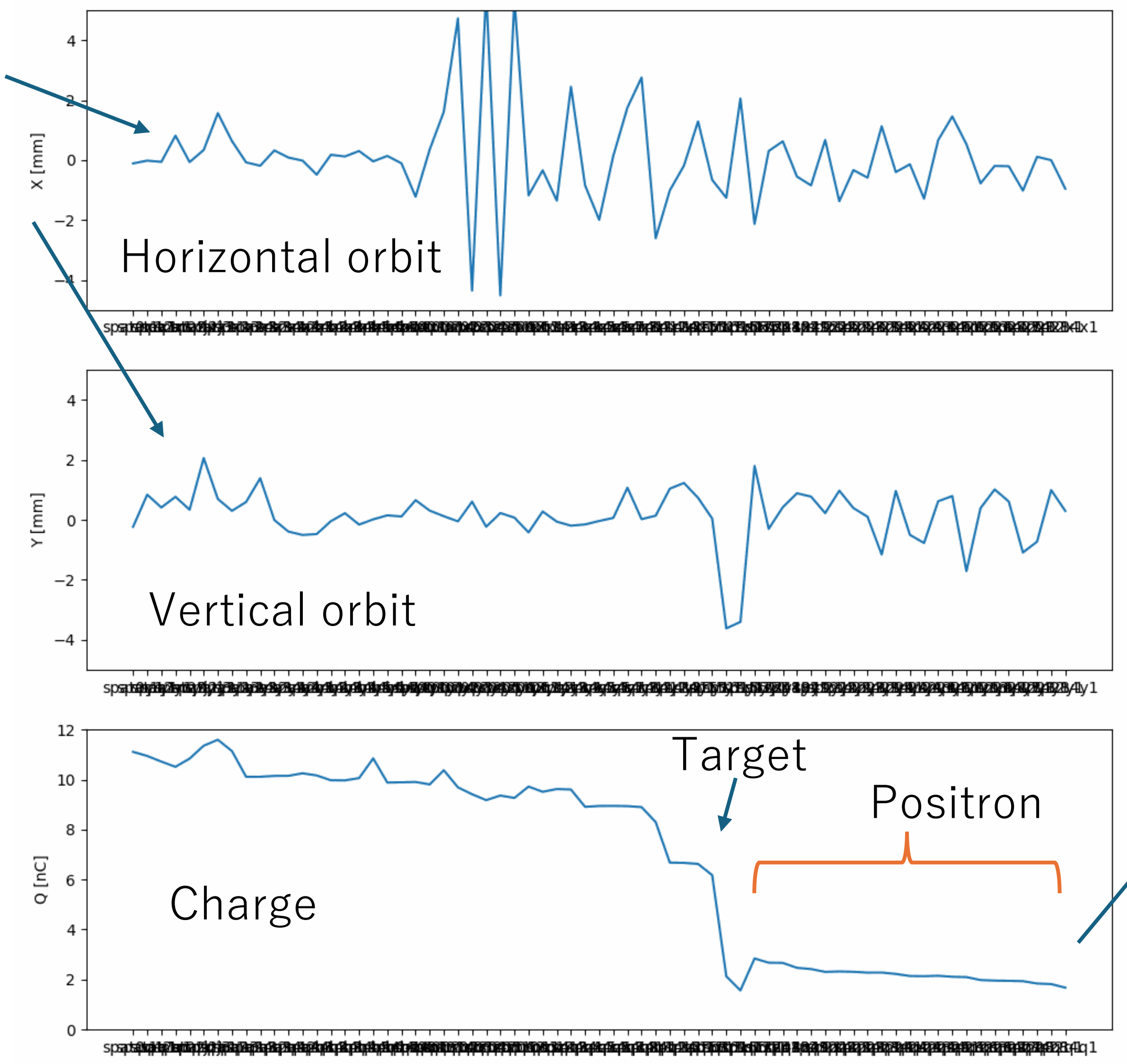
Select optimization method.
Bayesian or Downhill.

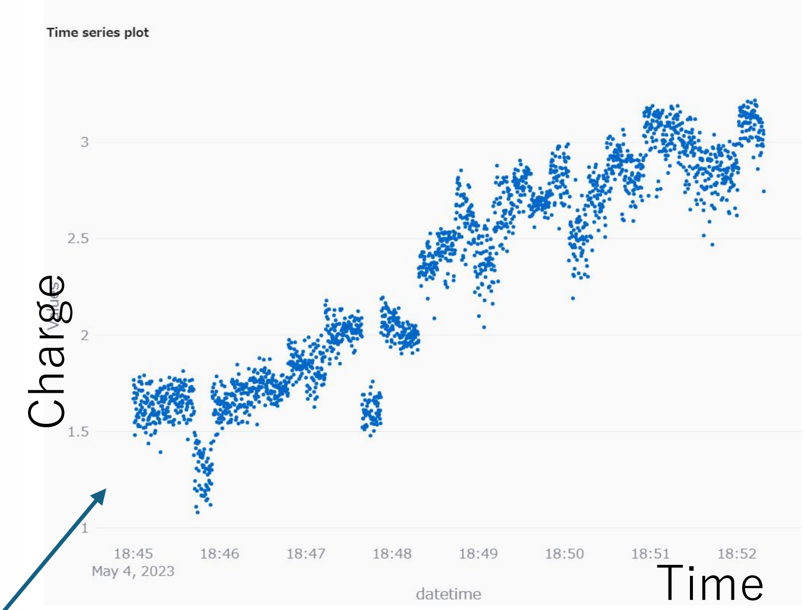
Operator will select setting file and just push this Start button.

Example 1

BPM data in linac while auto tuning.

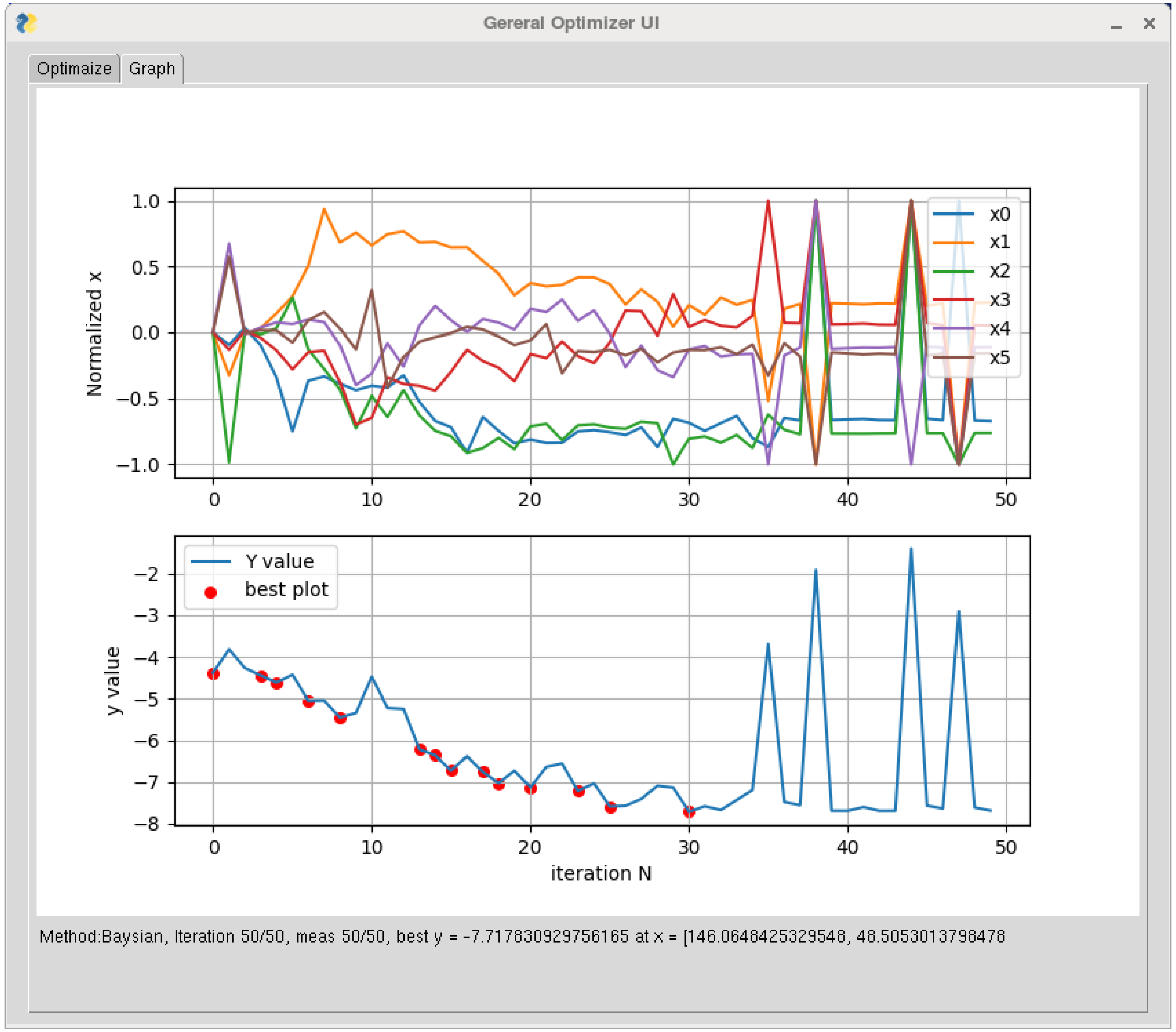
Searching for parameters that will increase positron production by shaking the orbit in the upstream.
(Changing magnet current and RF phase.





It took about 10 minutes to double the amount of positron charge.

Example 1



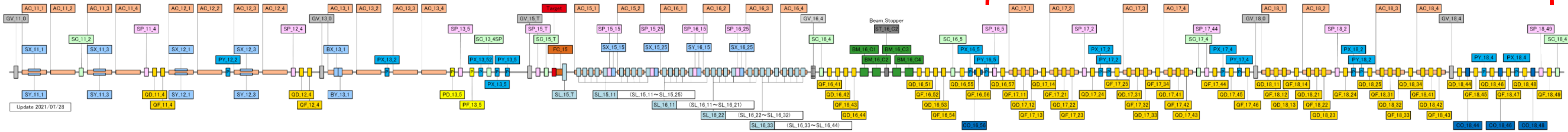
SH_A1_S1 (KBP) 146.7° → 146.1° (-0.6°)
SH_A1_S8 (KBP) 48.0° → 48.6° (+0.6°)
PX_AT_22-KBP 0.364A → 0.170A (-0.194A)
PY_AT_22-KBP 1.435A → 1.451A (+0.016A)
PX_A1_M-KBP 0.009A → -0.018A (-0.027A)
PY_A1_M-KBP -1.137A → -1.176A (-0.039A)

Example 2

The problem was the large beam loss of positron in the capture section. The transmission was lower than the simulation results, but the cause had not been identified.
It was thought that the Q-magnets and steering magnets would need to be adjusted to improve this situation. However, about 200 parameters had to be adjusted, making it impossible to do so manually.
The parameters were adjusted with automatic tuning from the upstream with divided regions. Parameter tuning was fully automated, resulting in a significant improvement in the transmission of the positron beam.

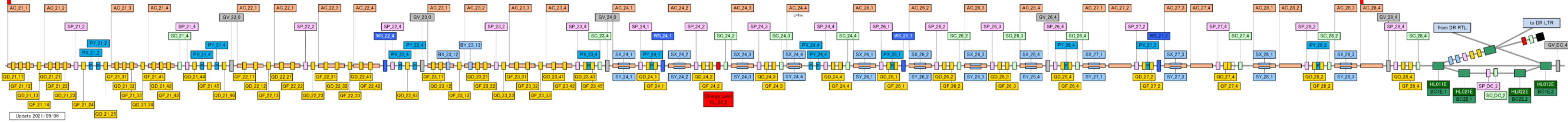
Sector-1 tuning region

1-sector

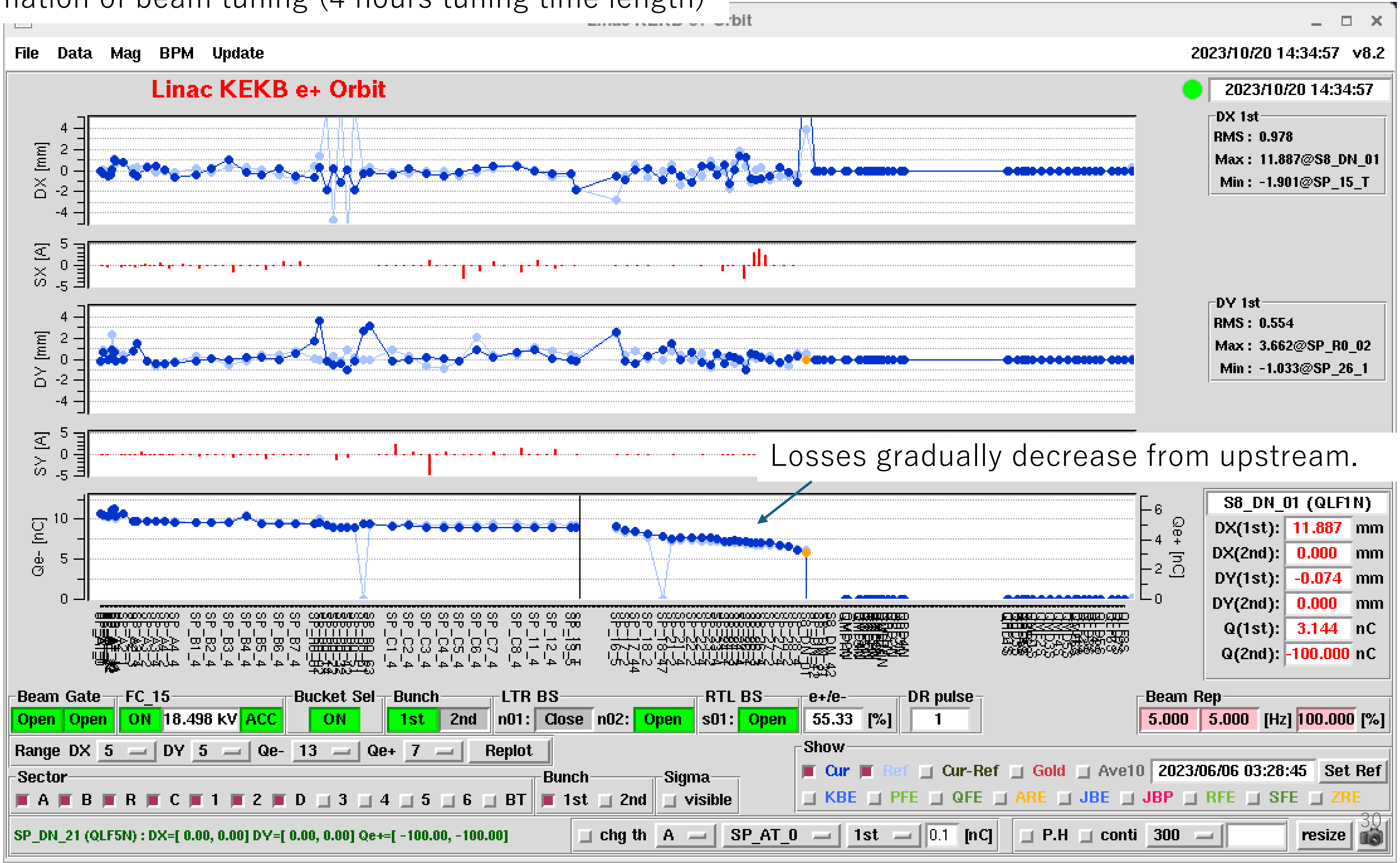


Sector-2 tuning region

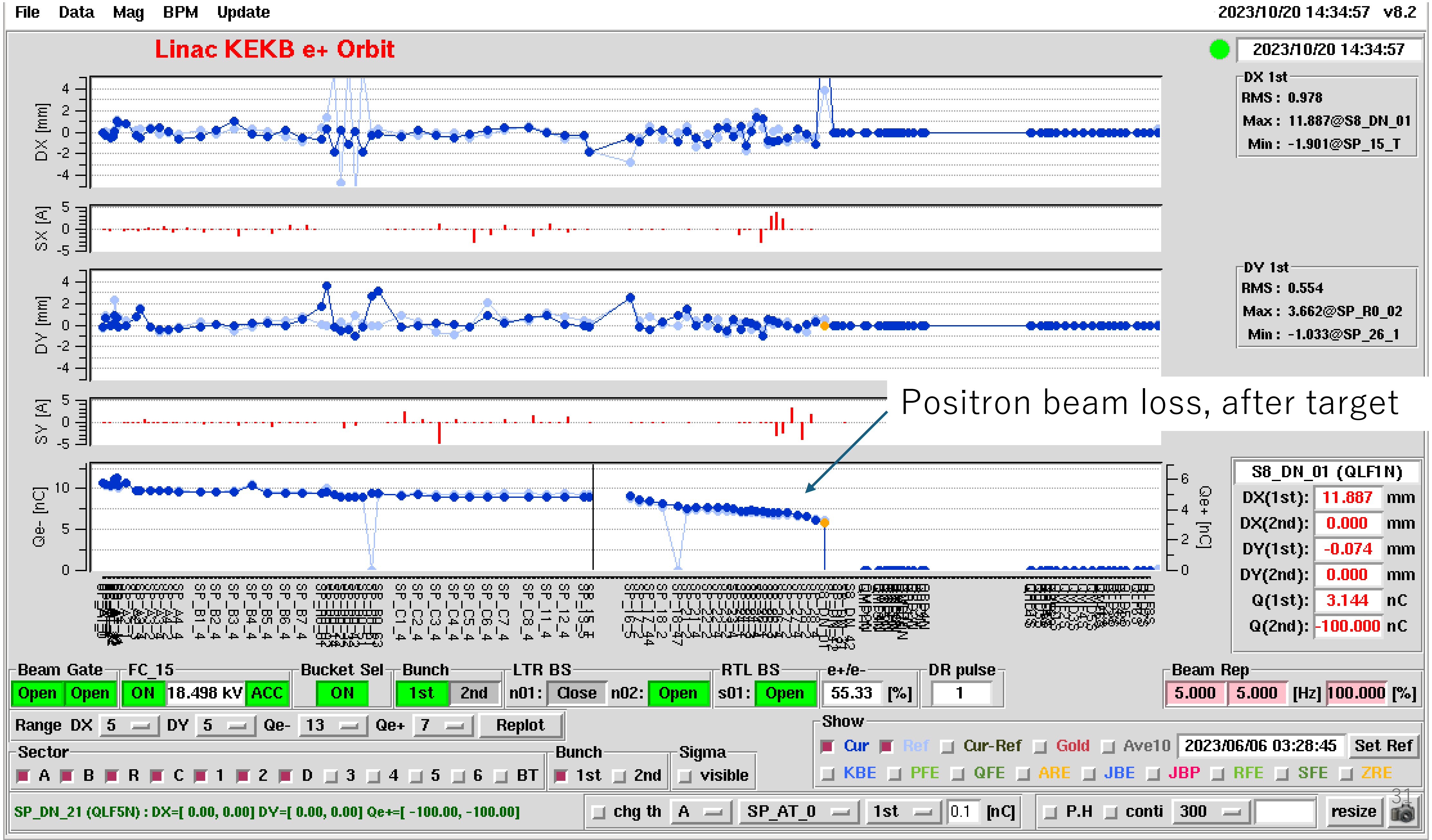
2-sector



Animation of beam tuning (4 hours tuning time length)

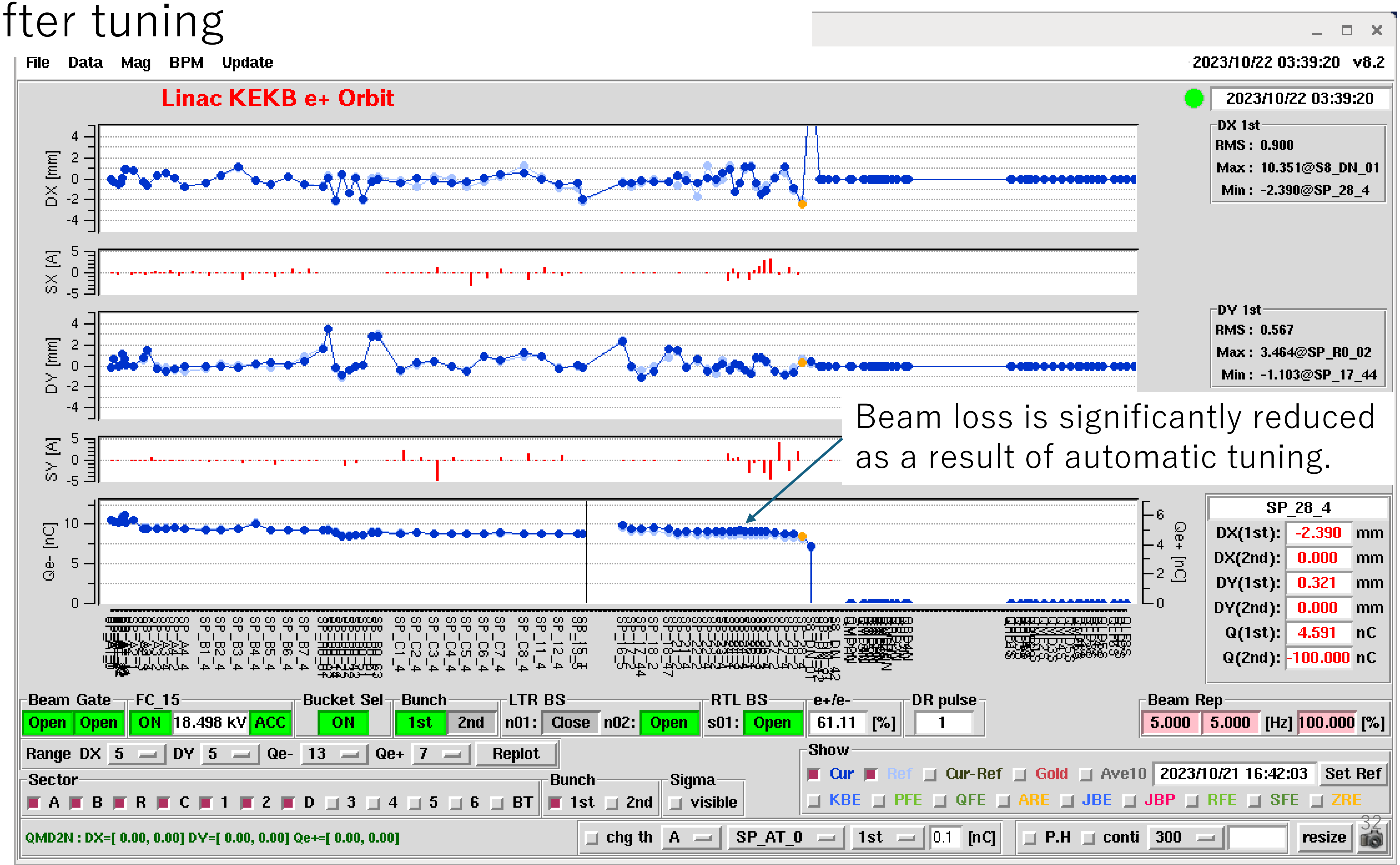


Before tuning



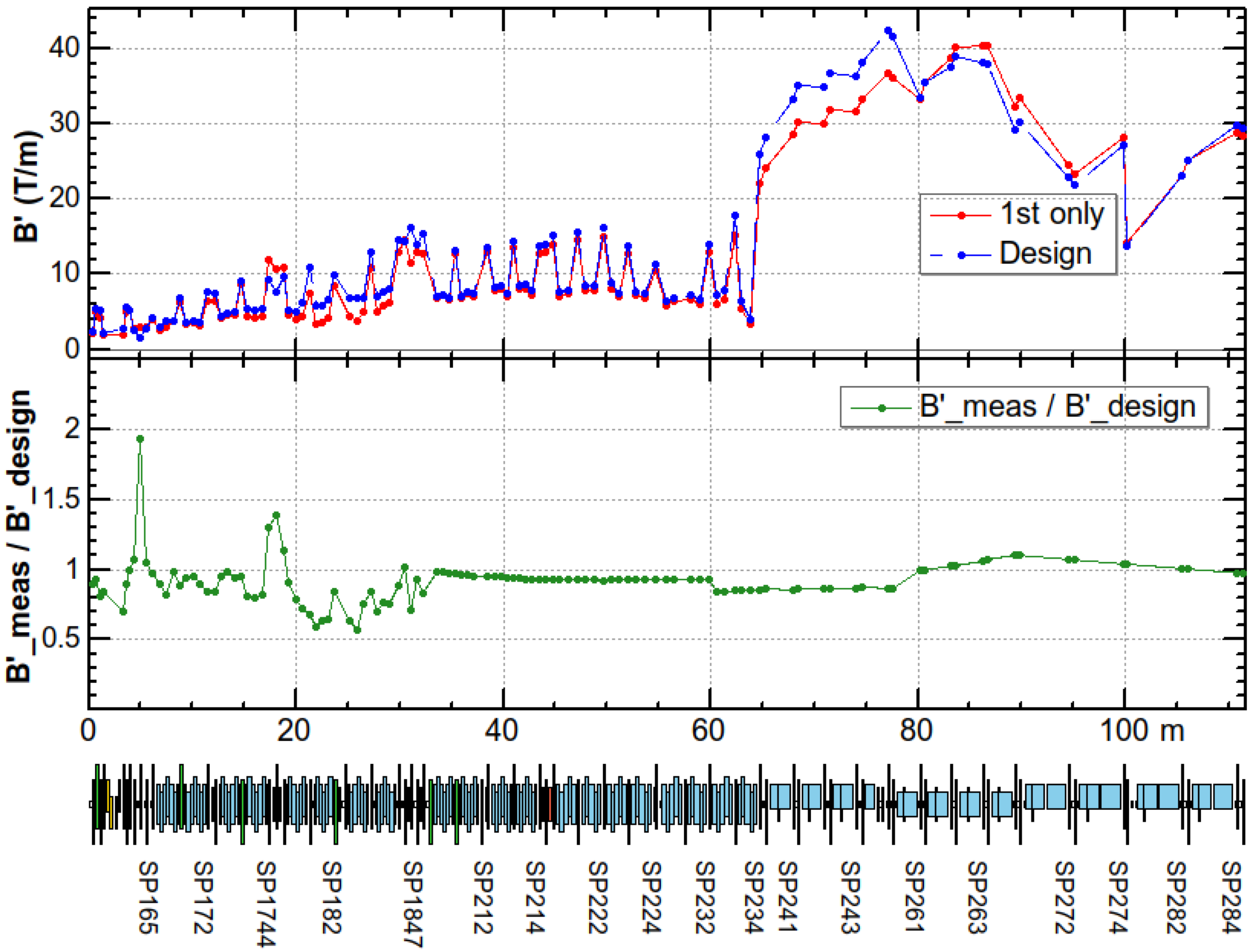
Positron beam loss, after target

After tuning



Beam loss is significantly reduced as a result of automatic tuning.

Design and tuned Q magnet field in positron beam line



- The error due to energy is estimated to be about 10%. Magnetic field errors are usually smaller than that.
- Similar to the design in some areas, but values differ by more than 20%, especially near Target.
- The large energy error near the target is thought to be a contributing factor.
- Due to misalignment effects, the Q magnet acts as a steering magnet?

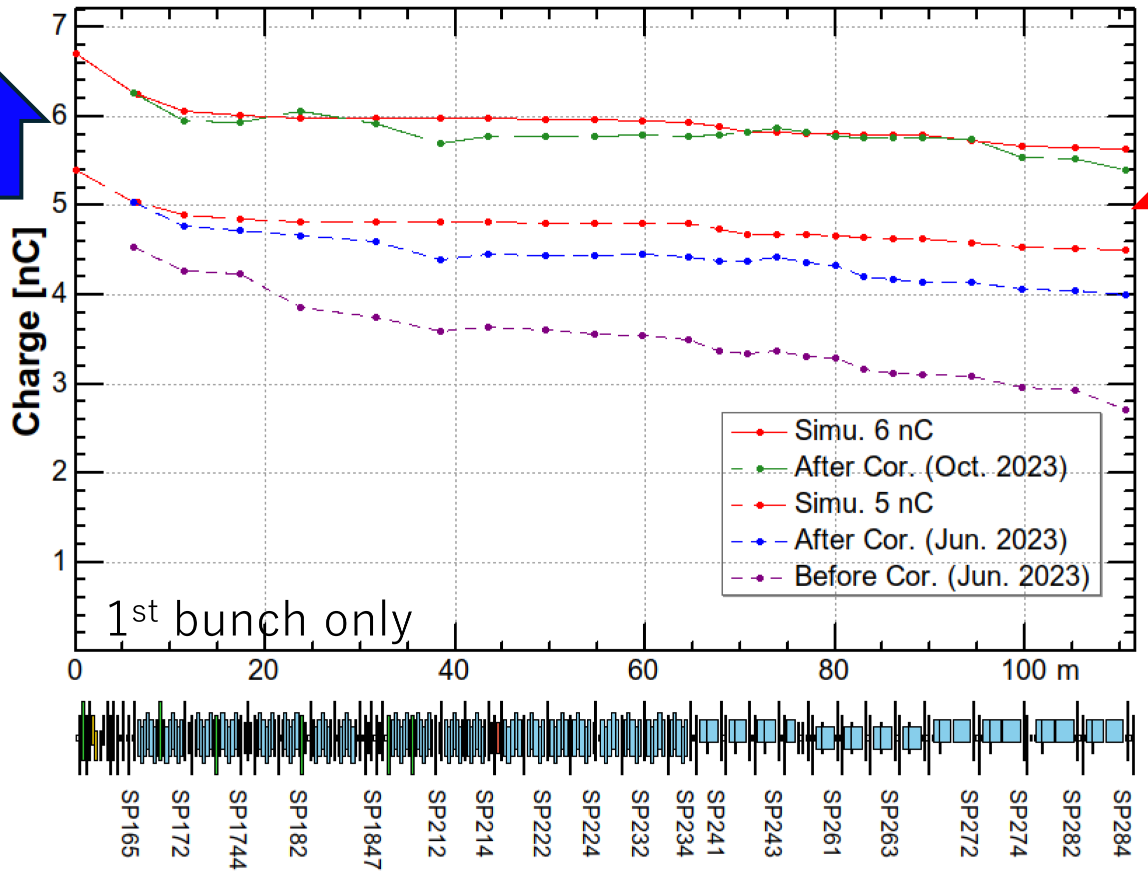
Although the adjustment itself was made with the improvement of charge quantity as an index, a trend of discrepancy with the design became visible as a result.

清宮氏提供データ

Automatic tuning significantly improves positron charge

Achieved a positron charge (before damping BT) almost equal to the calculated value. (2023/10/25)

- **New Pulse Q-magnet**



Automatic tuning reduces beam loss

The amount of beam charge was approximately doubled by increasing the number of pulse magnets and by automatic adjustment.

清宮氏提供データ

Summary

- In KEK injector linac, many pulsed magnets is installed. In particular, the large-aperture pulsed Q magnet introduced in 2023 contributed to increase positron beam charge.
- The 600 A pulse driver developed for the large-aperture pulsed Q magnet also operated stably.
- Automatic tuning using machine learning has been very useful for KEK injector, which has to adjust multiple beam modes simultaneously.
- Automatic tuning using Bayesian optimization or the Downhill Simplex method works well with the EPICS control system and can be used for all purposes.
- The automatic tuning software we developed was used in a variety of situations. It often achieved better results than manual tuning.