

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

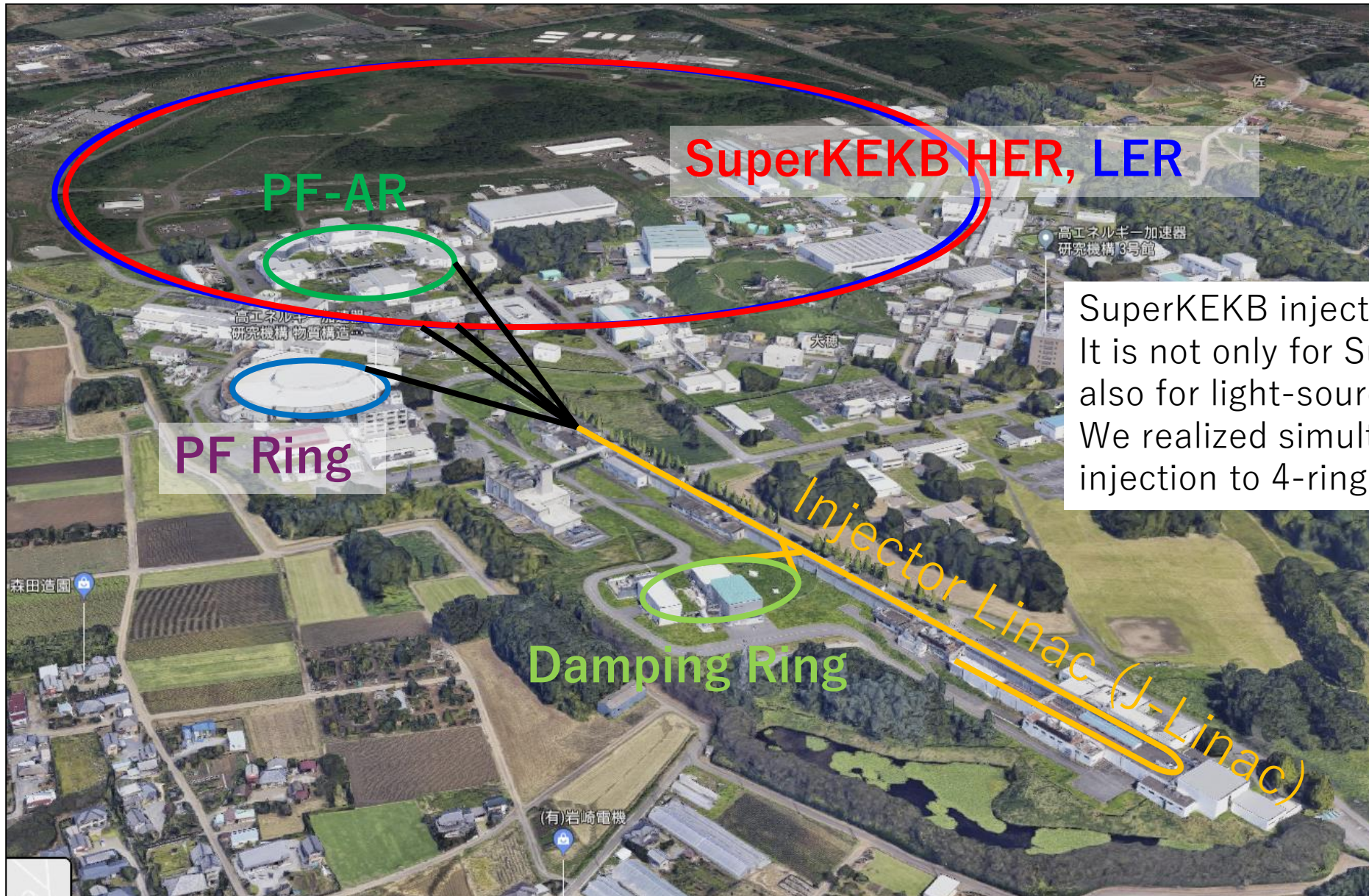
T. Natsui, T. Kamitani, K. Yokoyama, Y. Okayasu, M. Satoh, D. Wang

KEK

Introduction

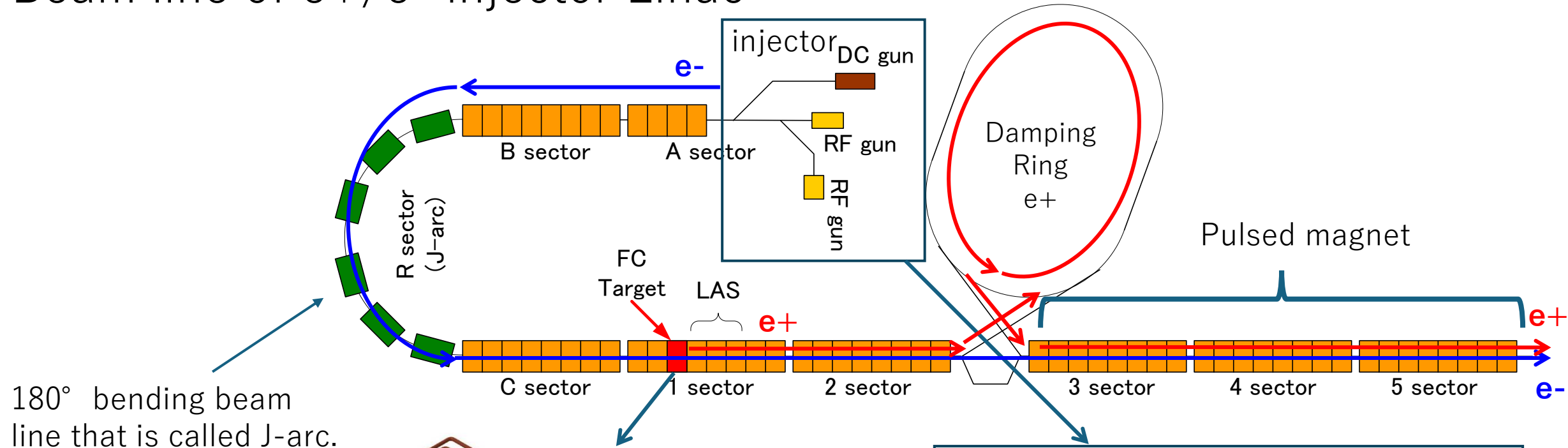
KEK Injector Linac

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

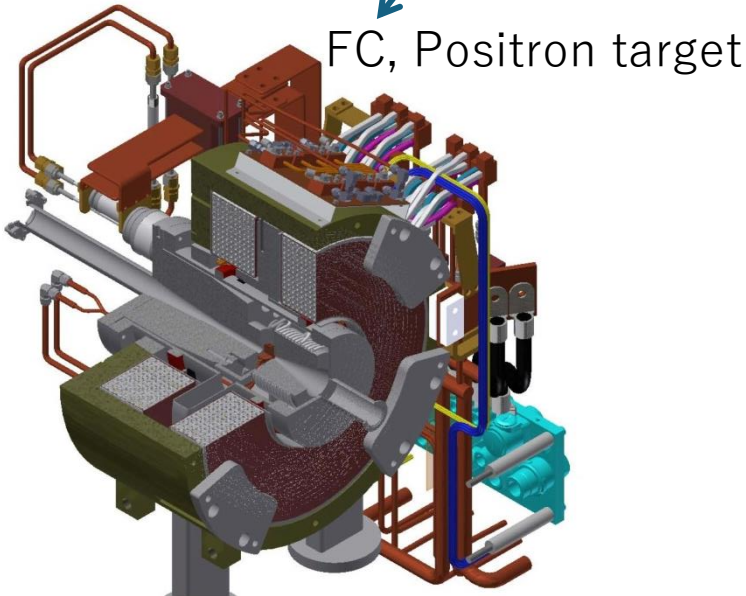


SuperKEKB injector is called J-Linac. It is not only for SuperKEKB rings but also for light-source rings. We realized simultaneous top-up injection to 4-ring.

Beam line of e⁺/e⁻ injector Linac



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



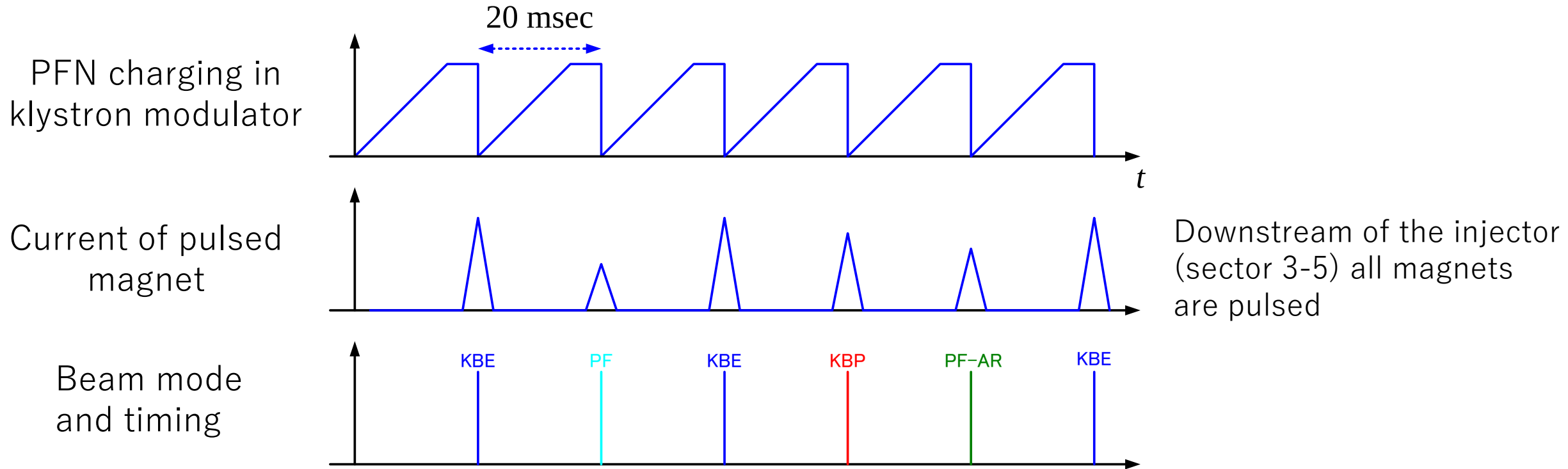
Thermionic gun and SHB

The schematic shows a thermionic gun with a Cathode, Grid, and Anode. The Cathode is connected to a negative bias voltage, and the Anode is connected to a positive voltage. The Grid is connected to a negative voltage. The electron beam is shown as a stream of electrons between the Cathode and the Anode. Two waveforms are shown: a 2 ns pulse with a bias of -100 ~ -500V, and a 4 us pulse with a bias of -200 kV.

RF gun

4

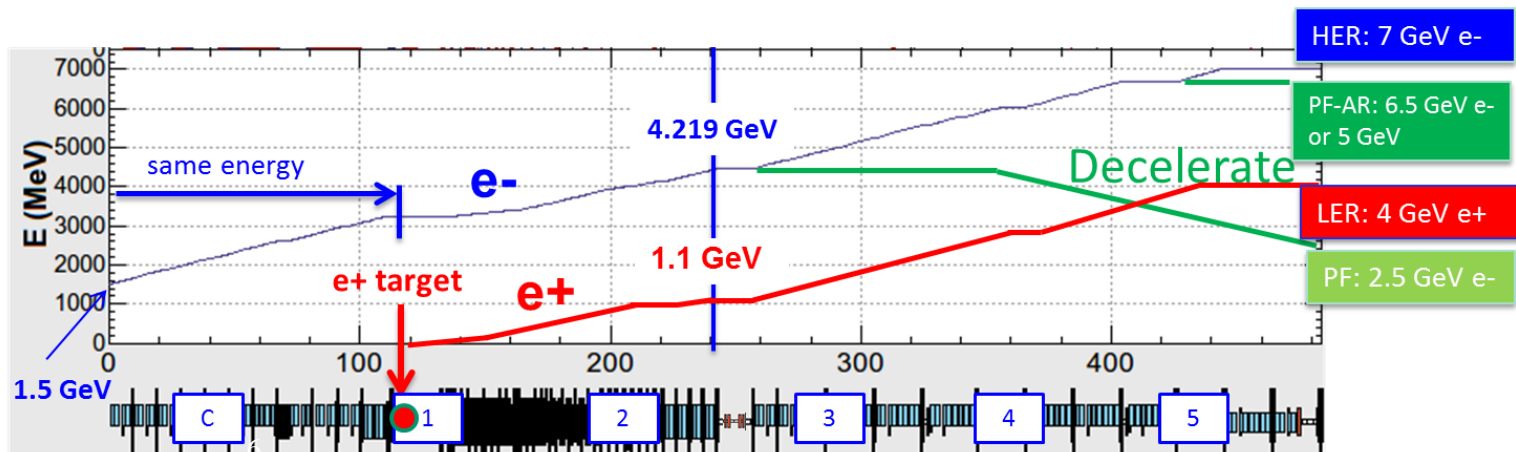
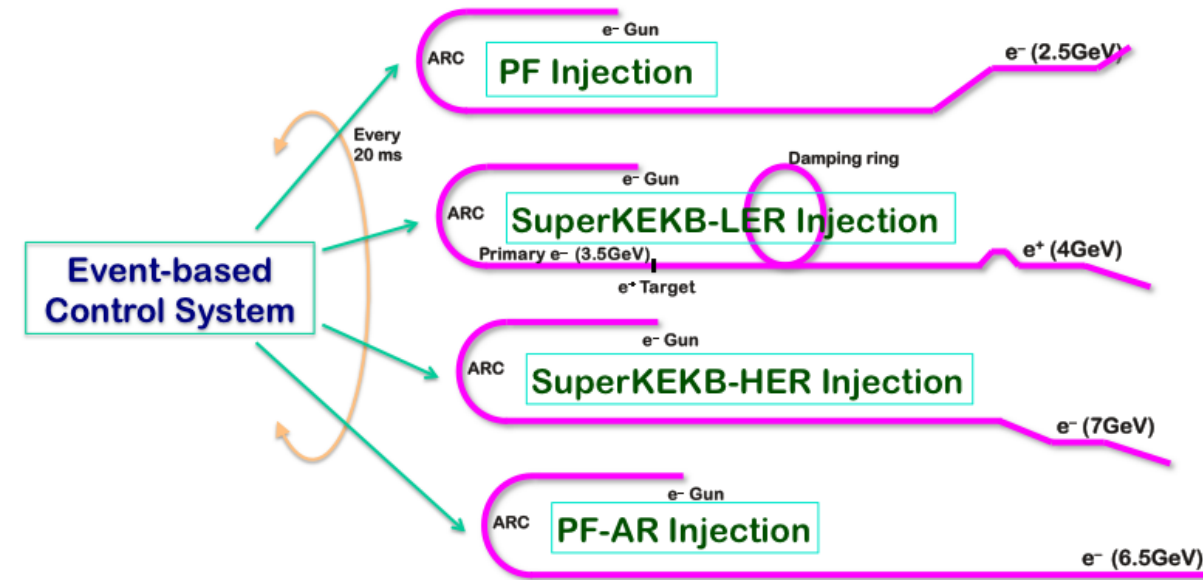
Beam timing and beam mode switching



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

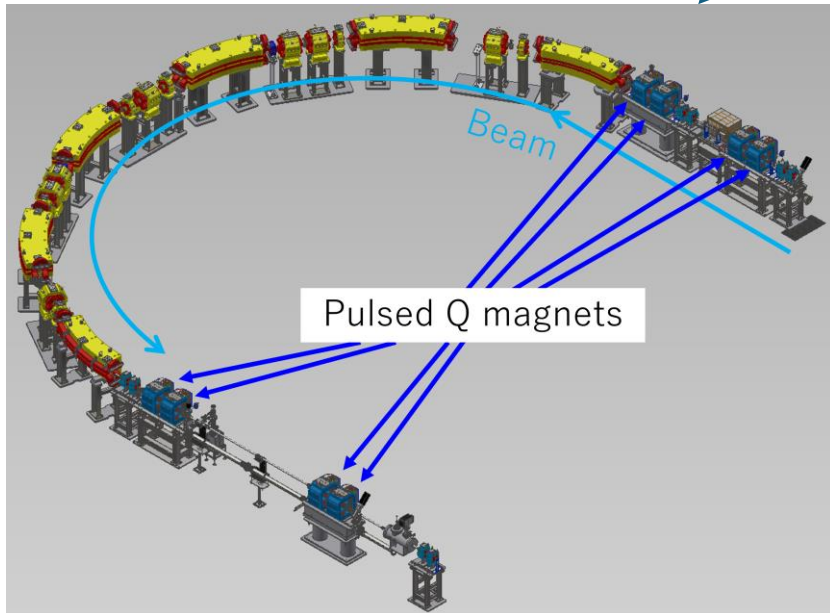
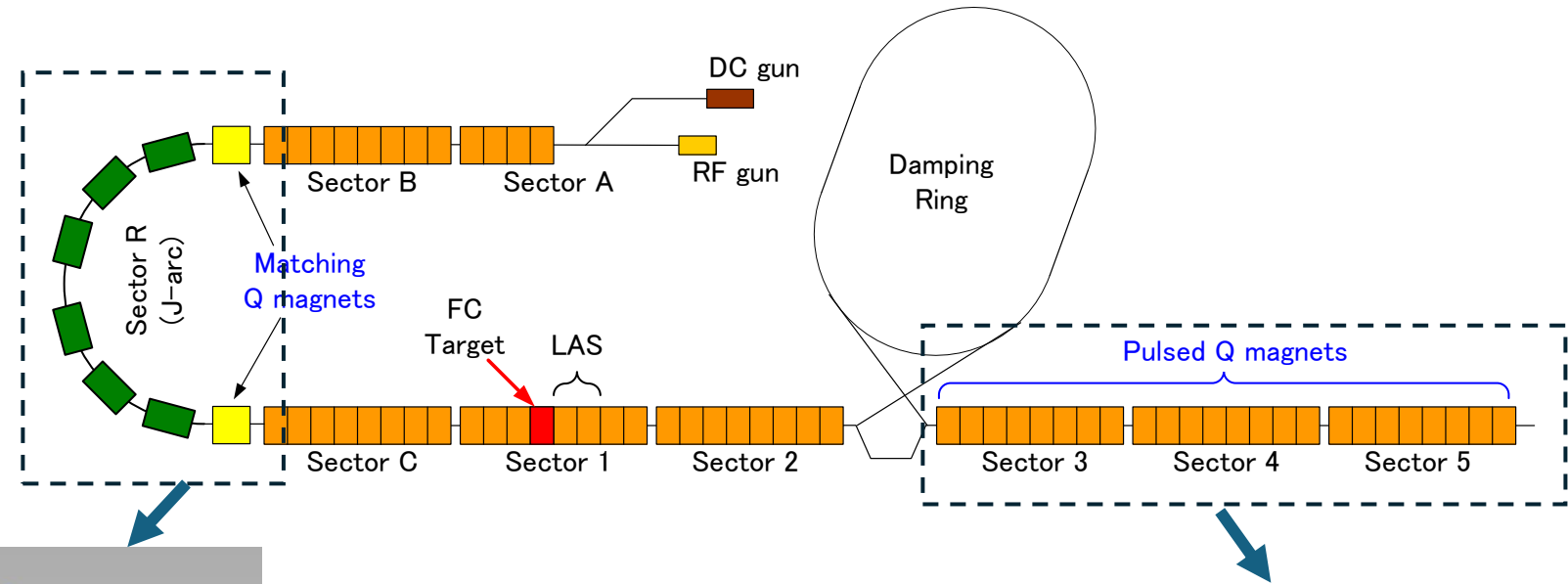
Steering magnet

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

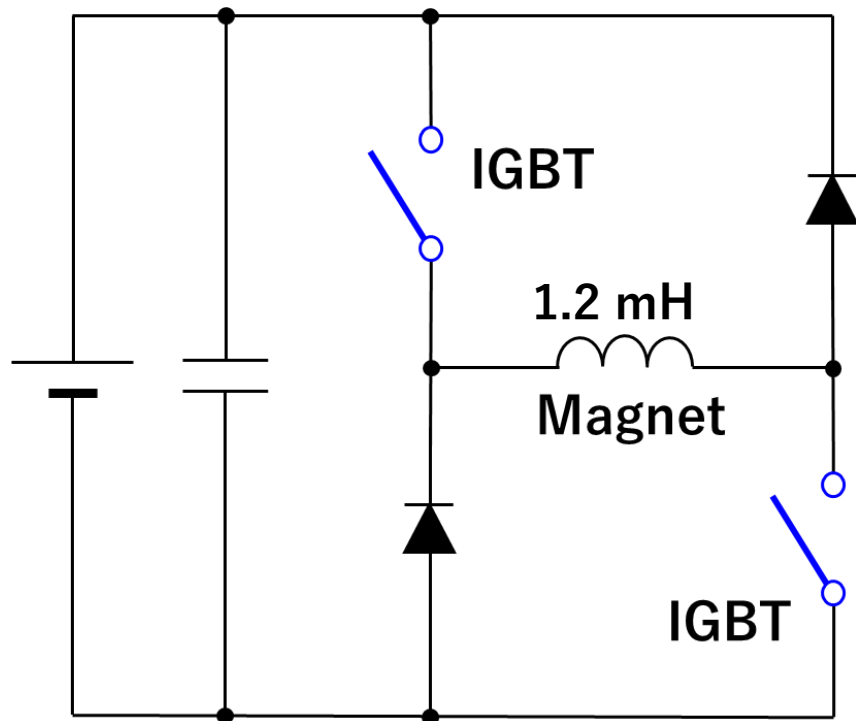
This magnet was designed to have an inductance of about 1 mH.

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

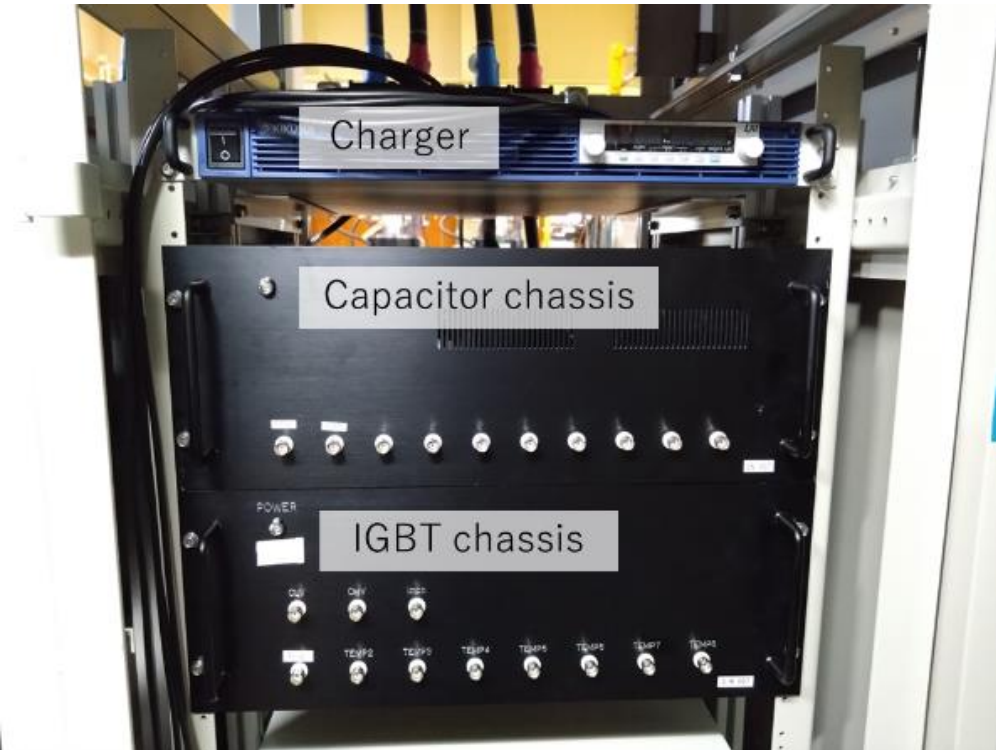


Development of Pulse driver for the Large-aperture Q magnet

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.



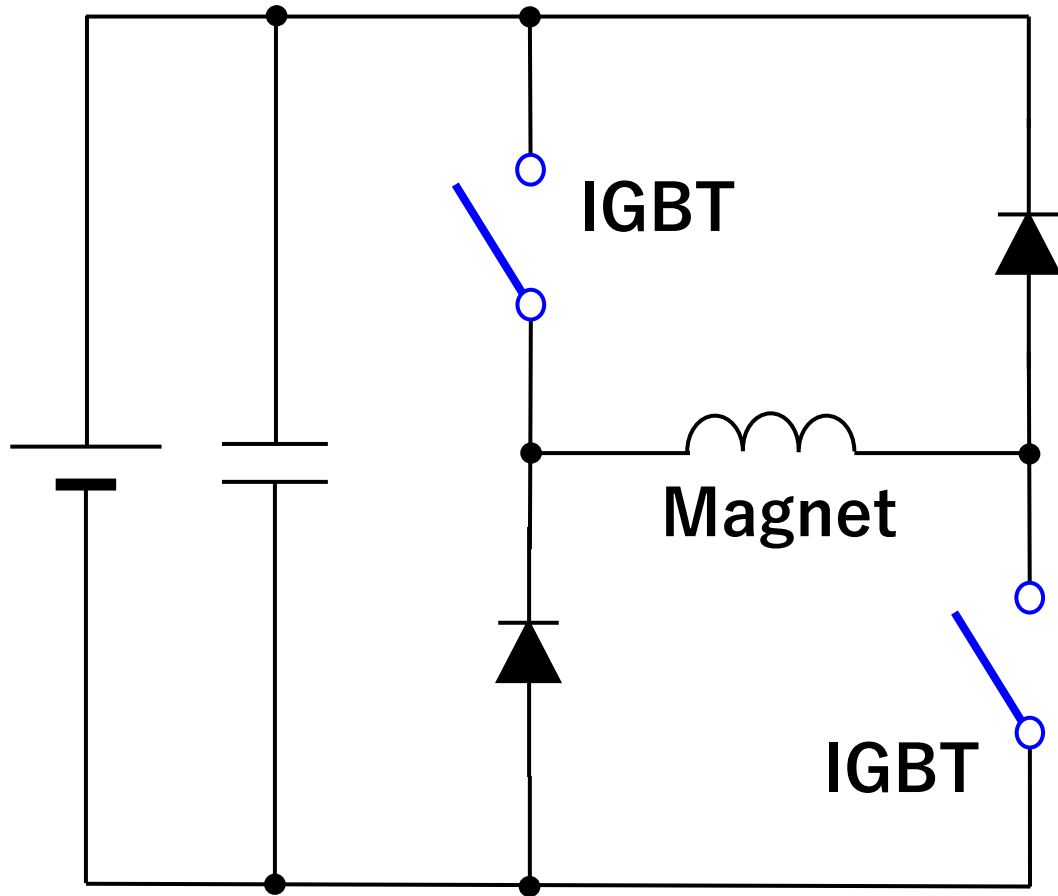
Basic circuit



Pulse driver is housed in a compact chassis

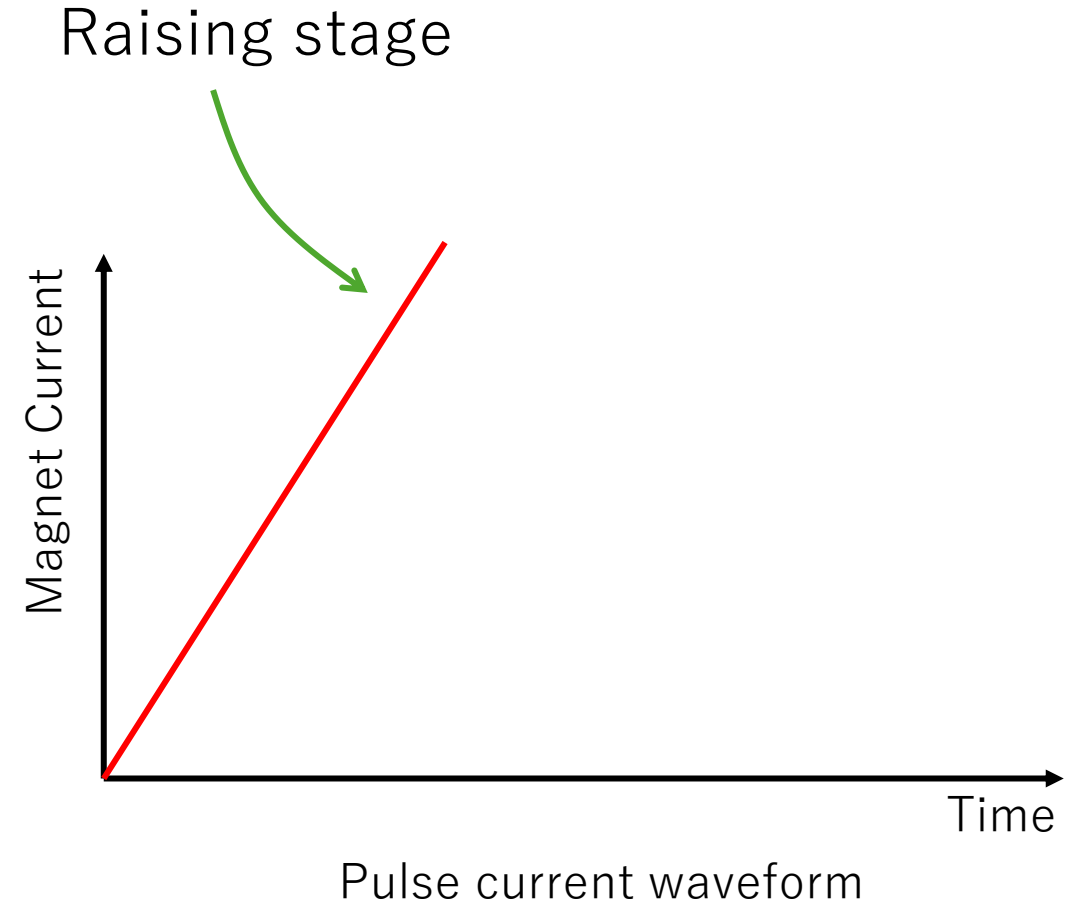
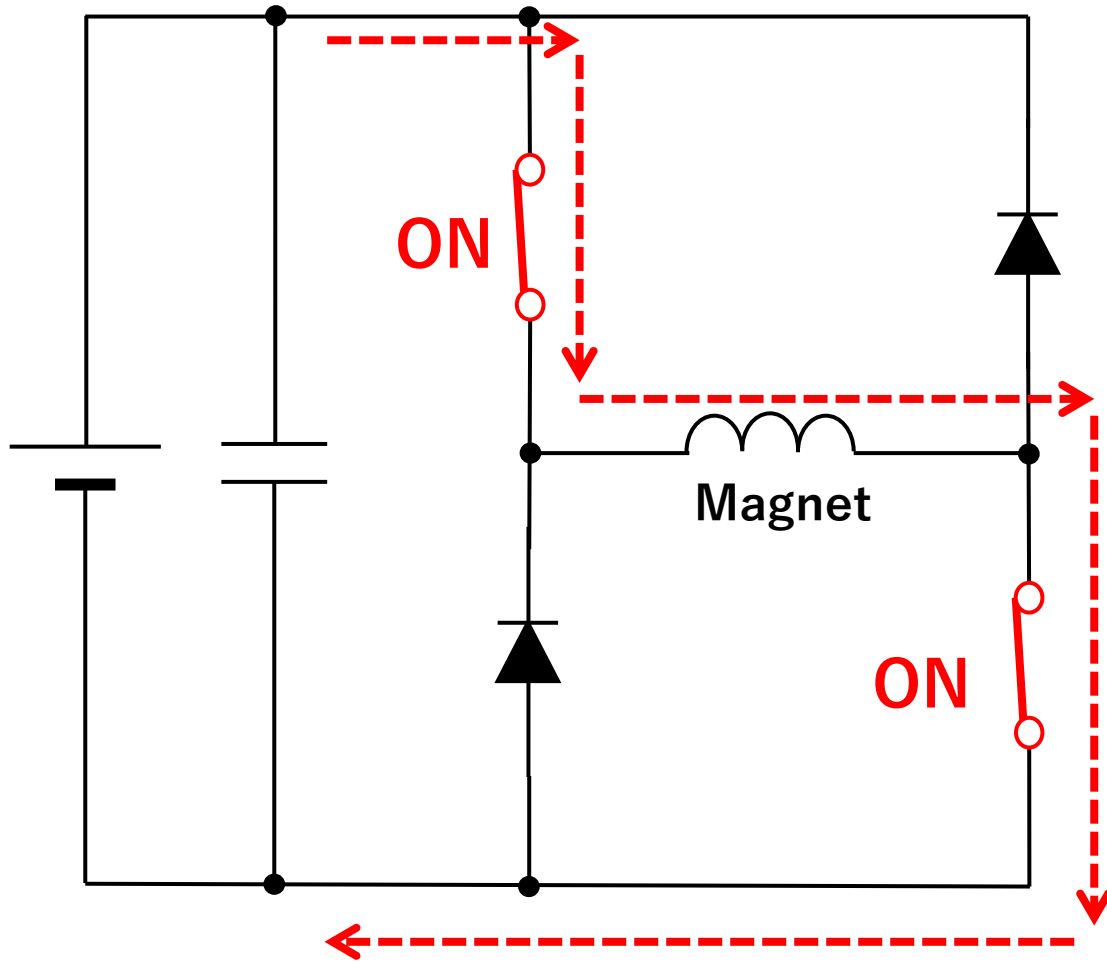
Circuit Operating Principle

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



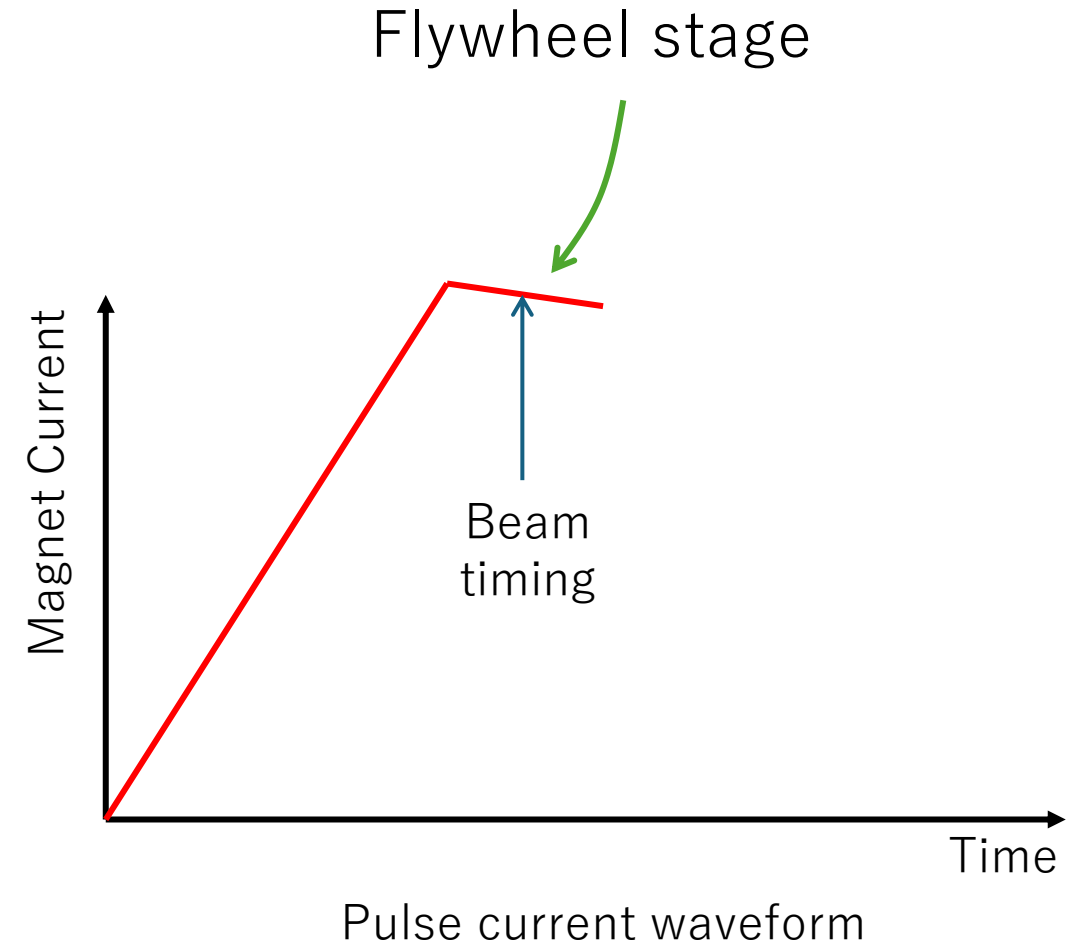
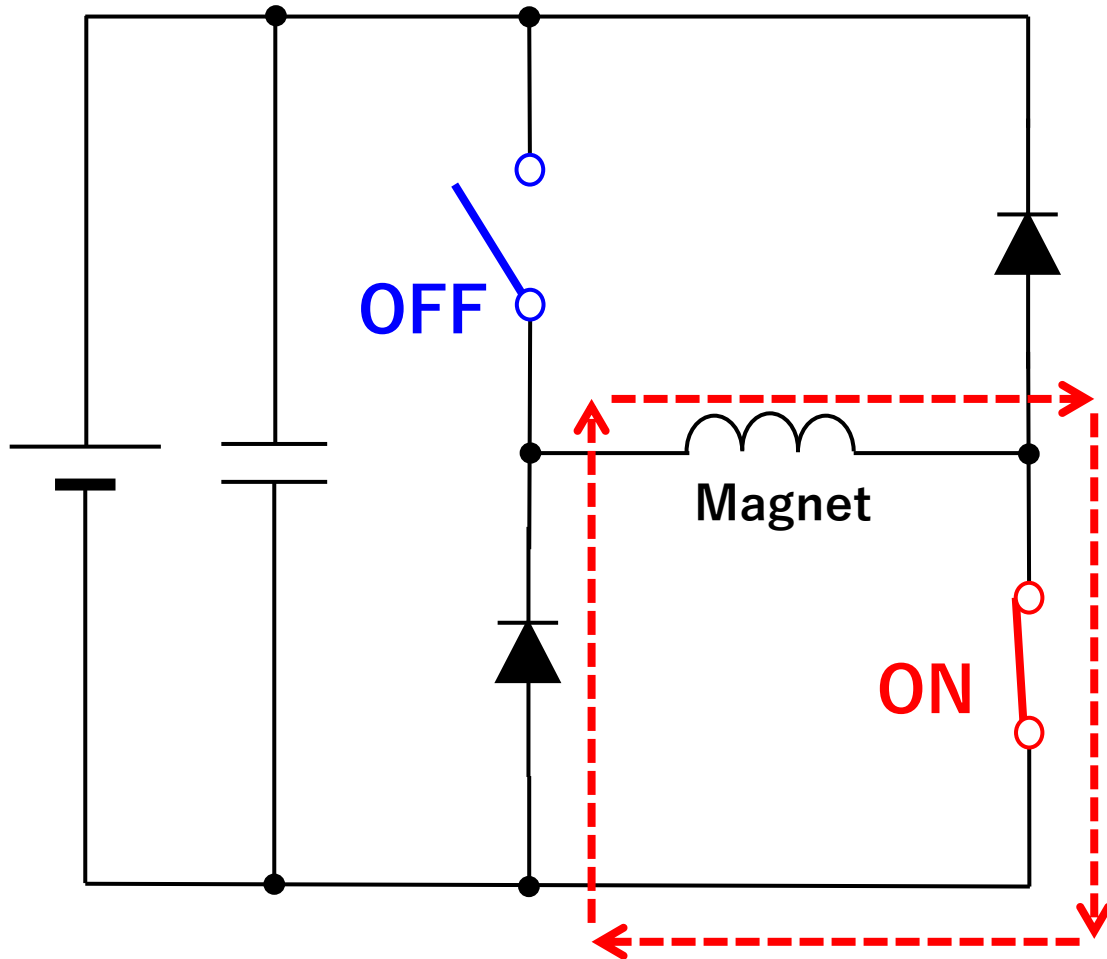
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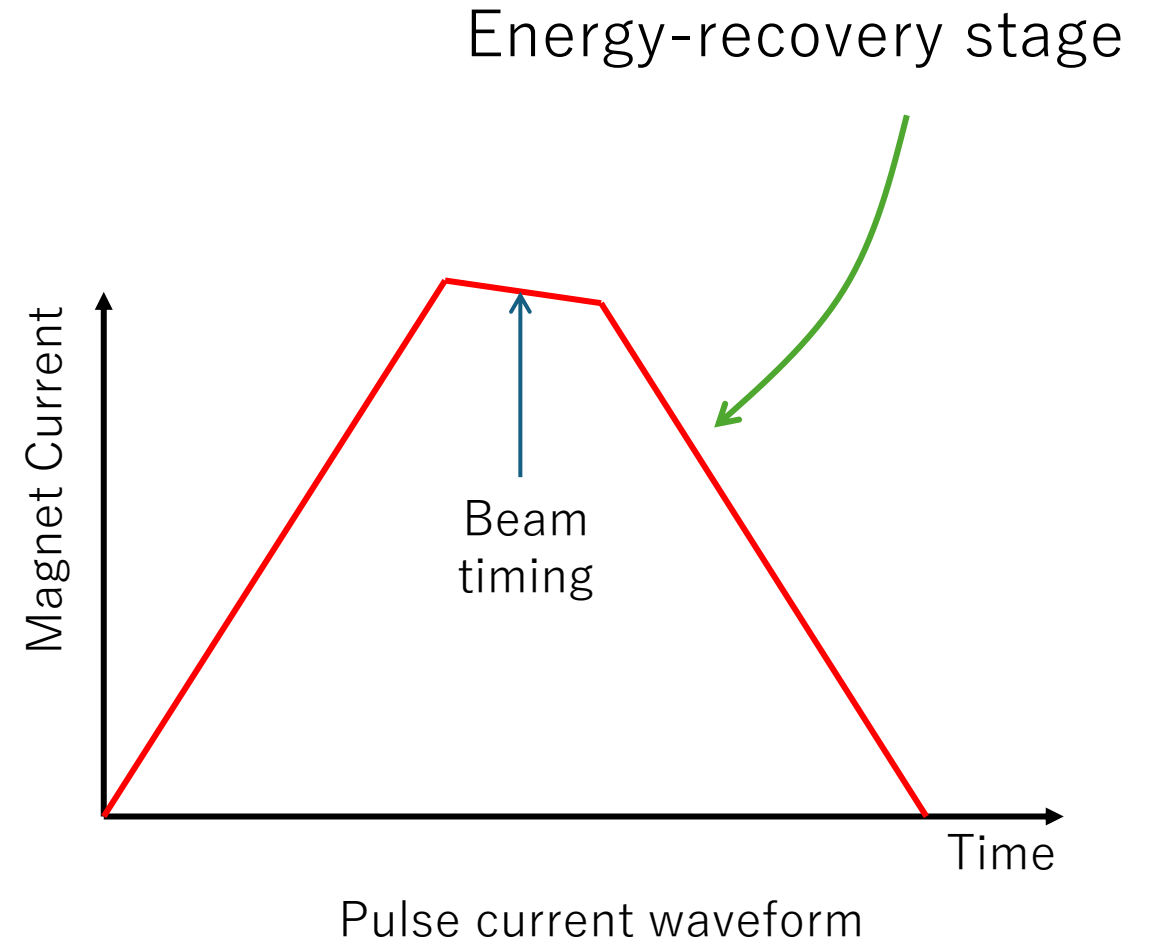
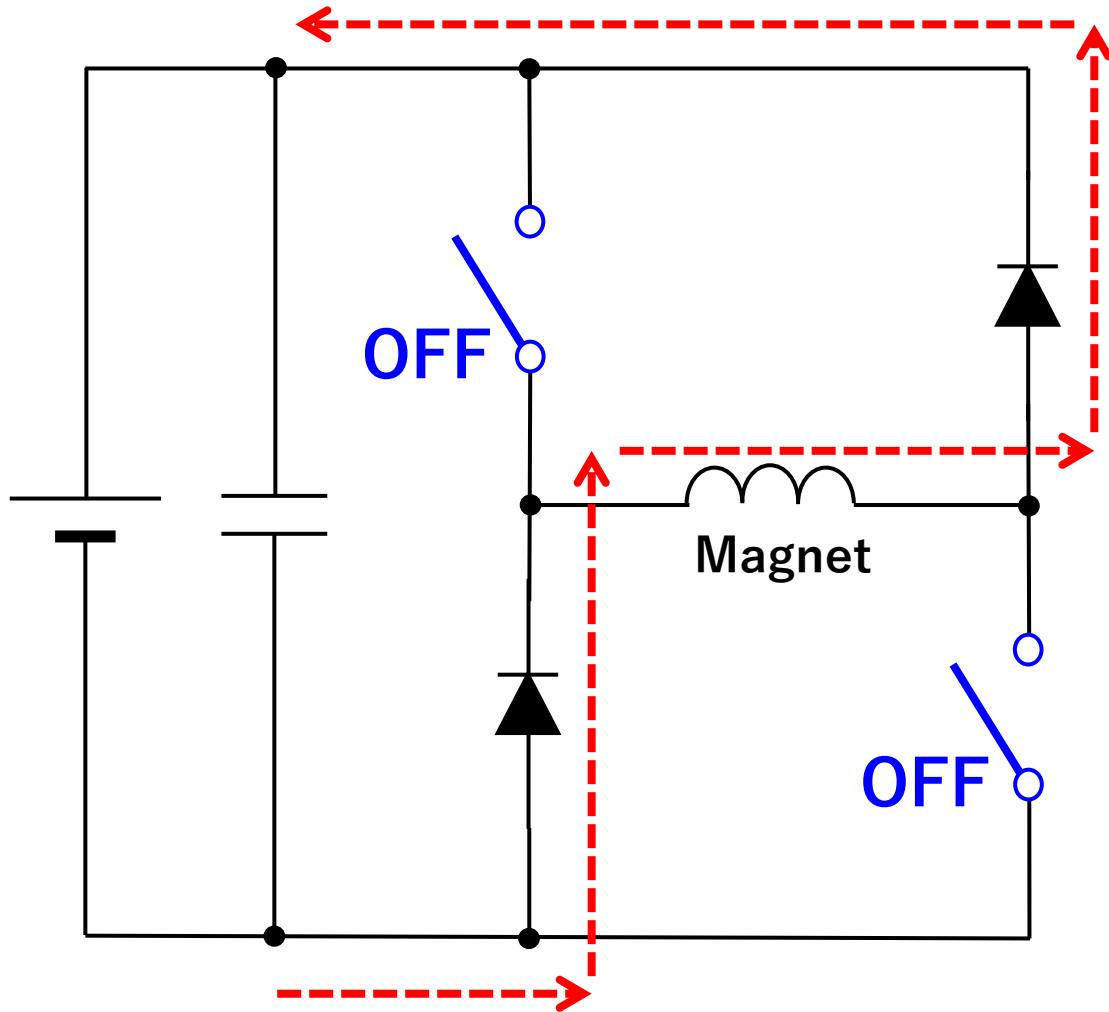
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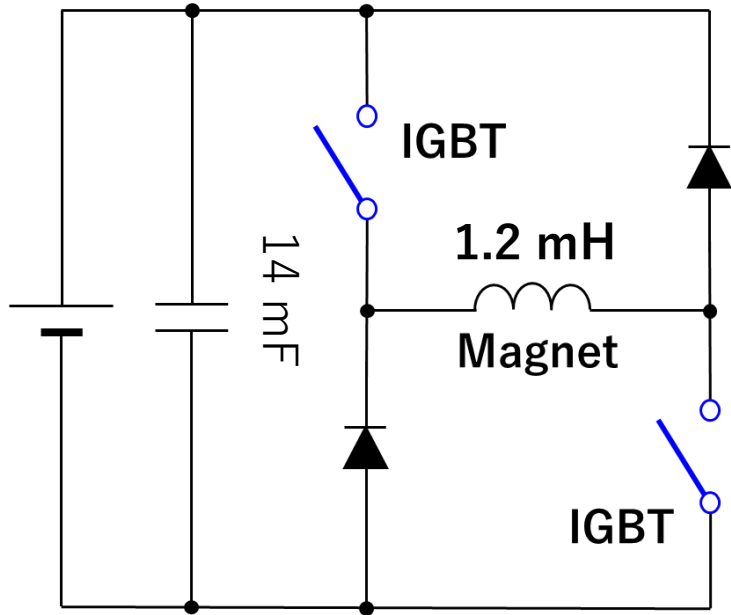
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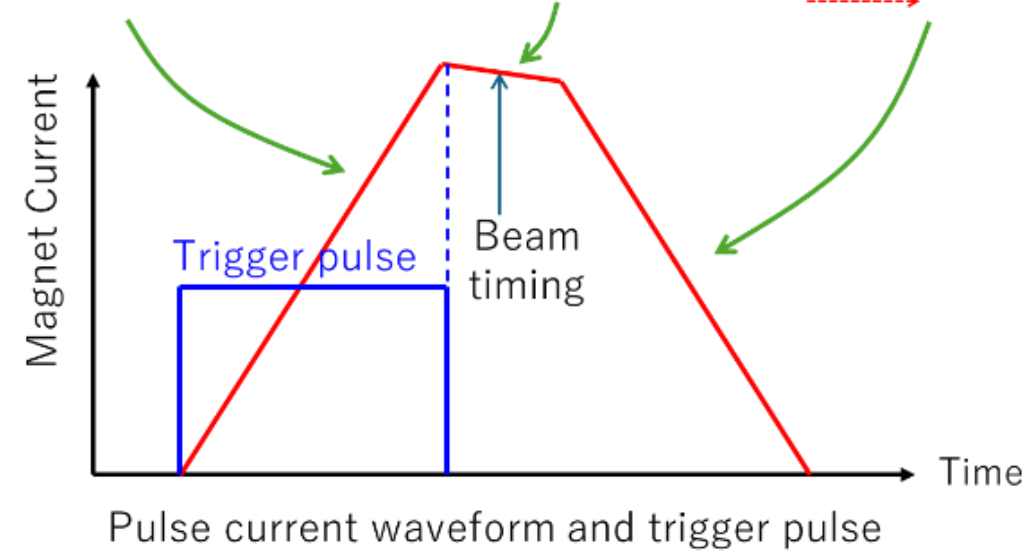
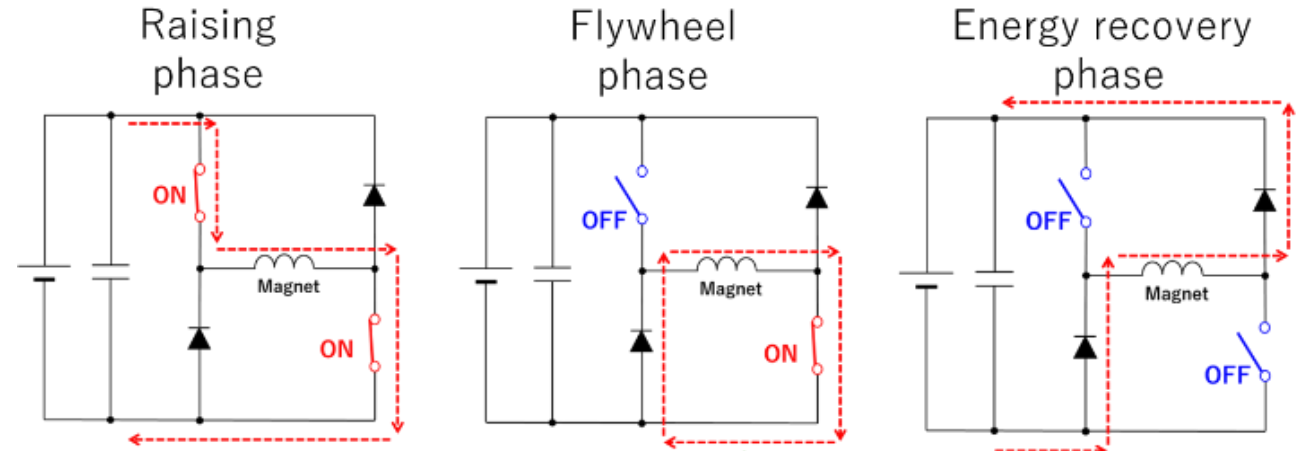


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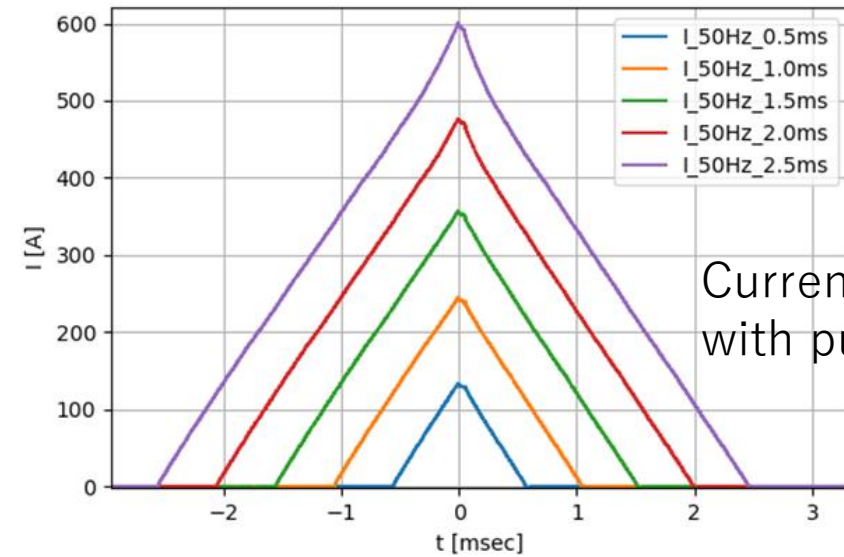
Basic circuit



Operating Principle and Waveforms

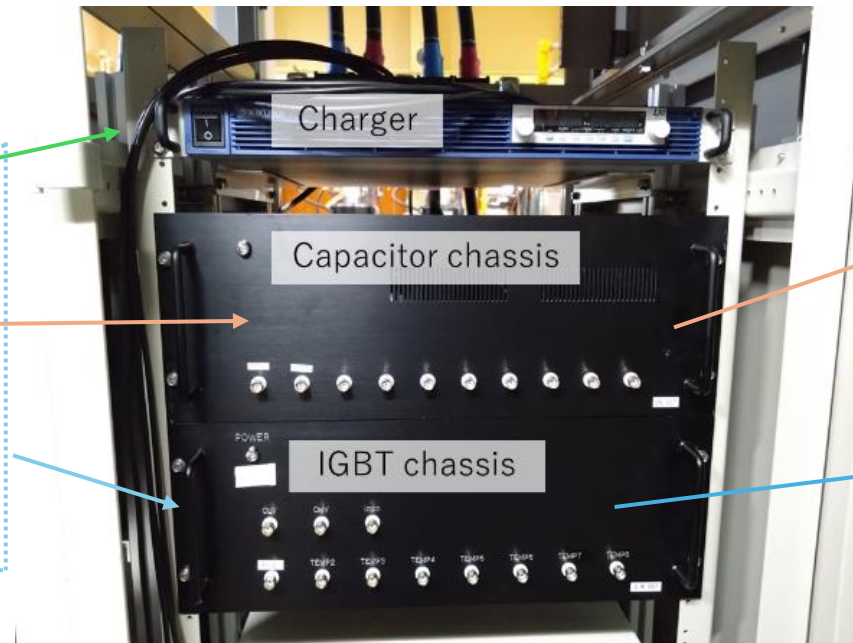
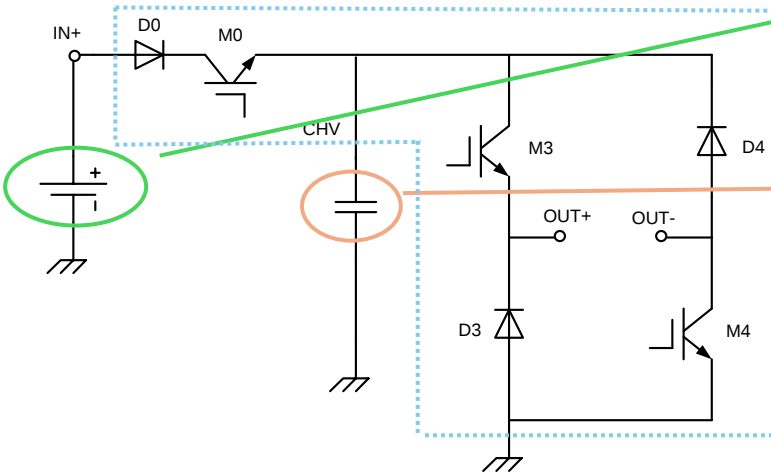
Development of Pulse driver for Large-aperture Q magnet

This simple and robust circuit provided sufficient pulse current.

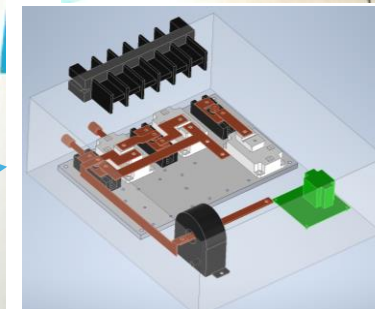


Current was controlled with pulse width.

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

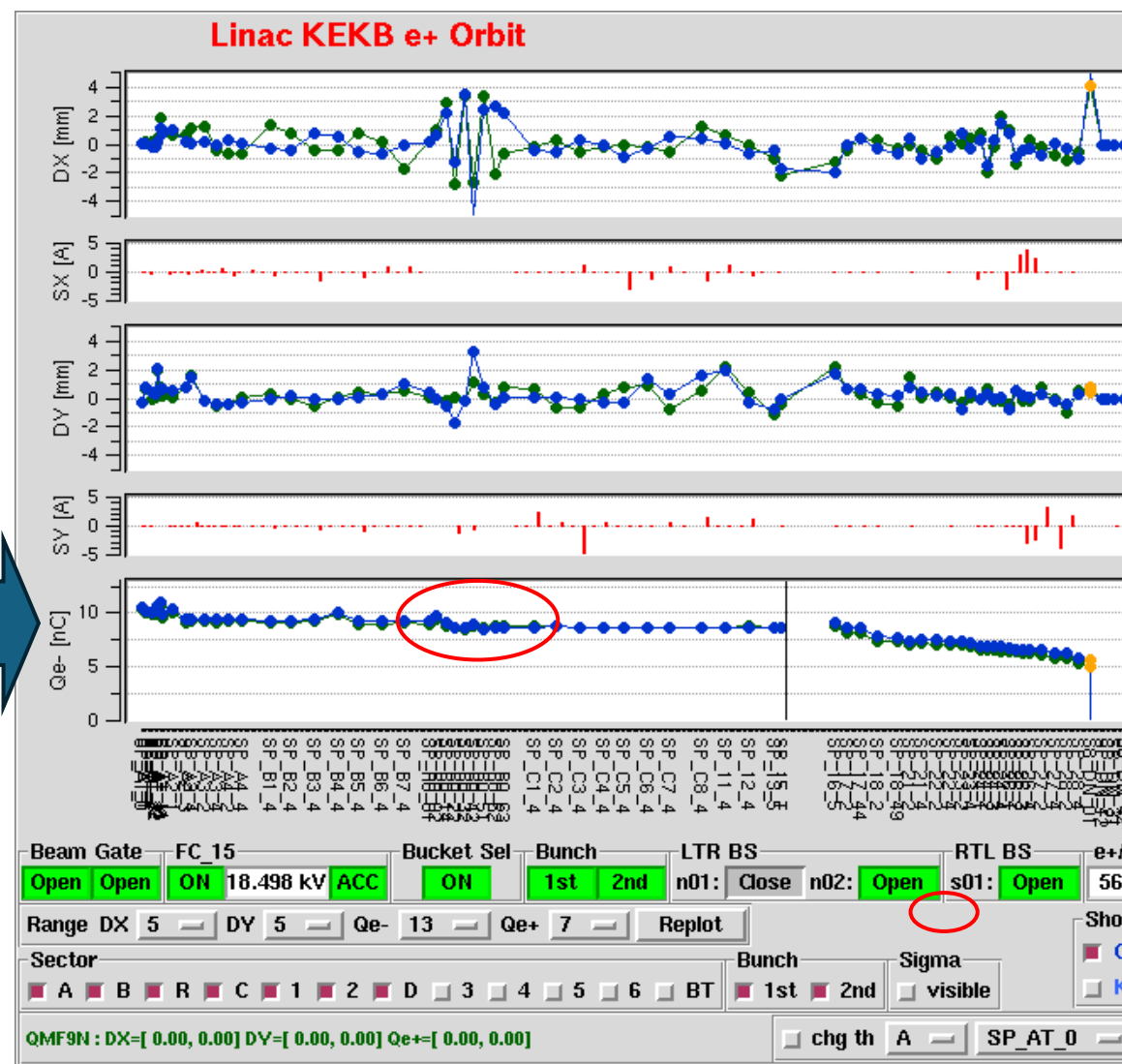
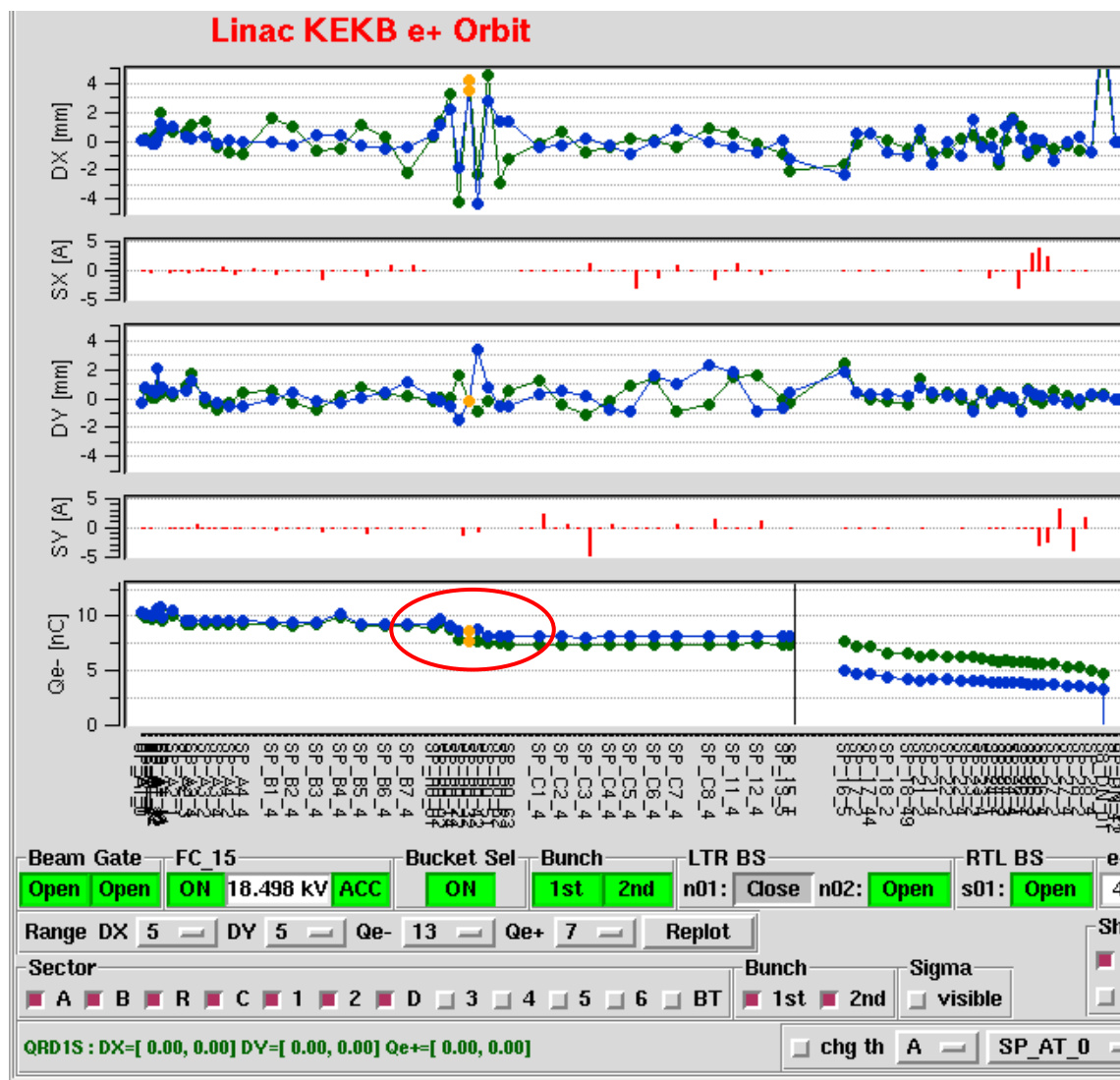


1 mF capacitor x14 in Capacitor chassis



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

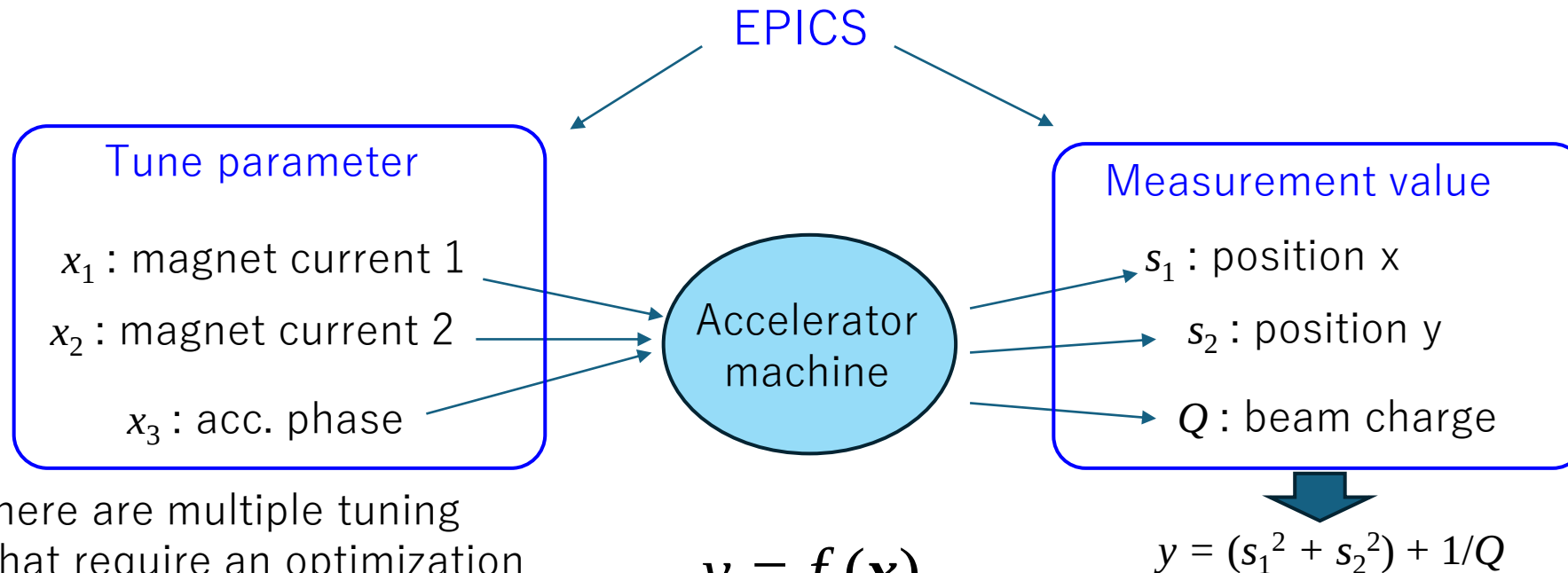
The loss of positron primary beam has been eliminated since the introduction of pulsed Q magnet at J-arc



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

Automatic tuning
using Machine Learning

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.



In practice, there are multiple tuning parameters that require an optimization algorithm for the multivariable function $f(x_1, x_2, x_3, \dots, x_n)$.

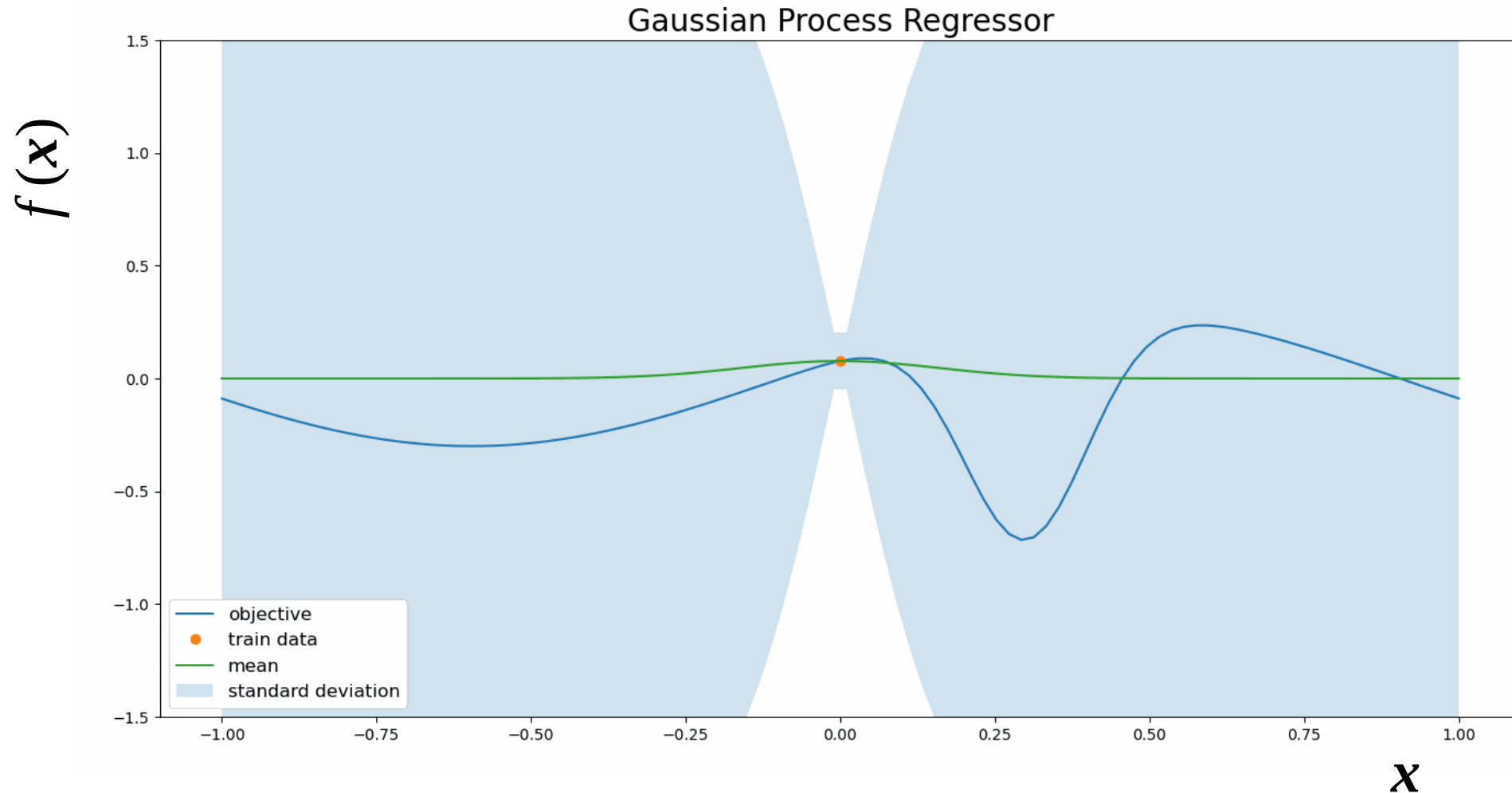
$$y = f(x)$$

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

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

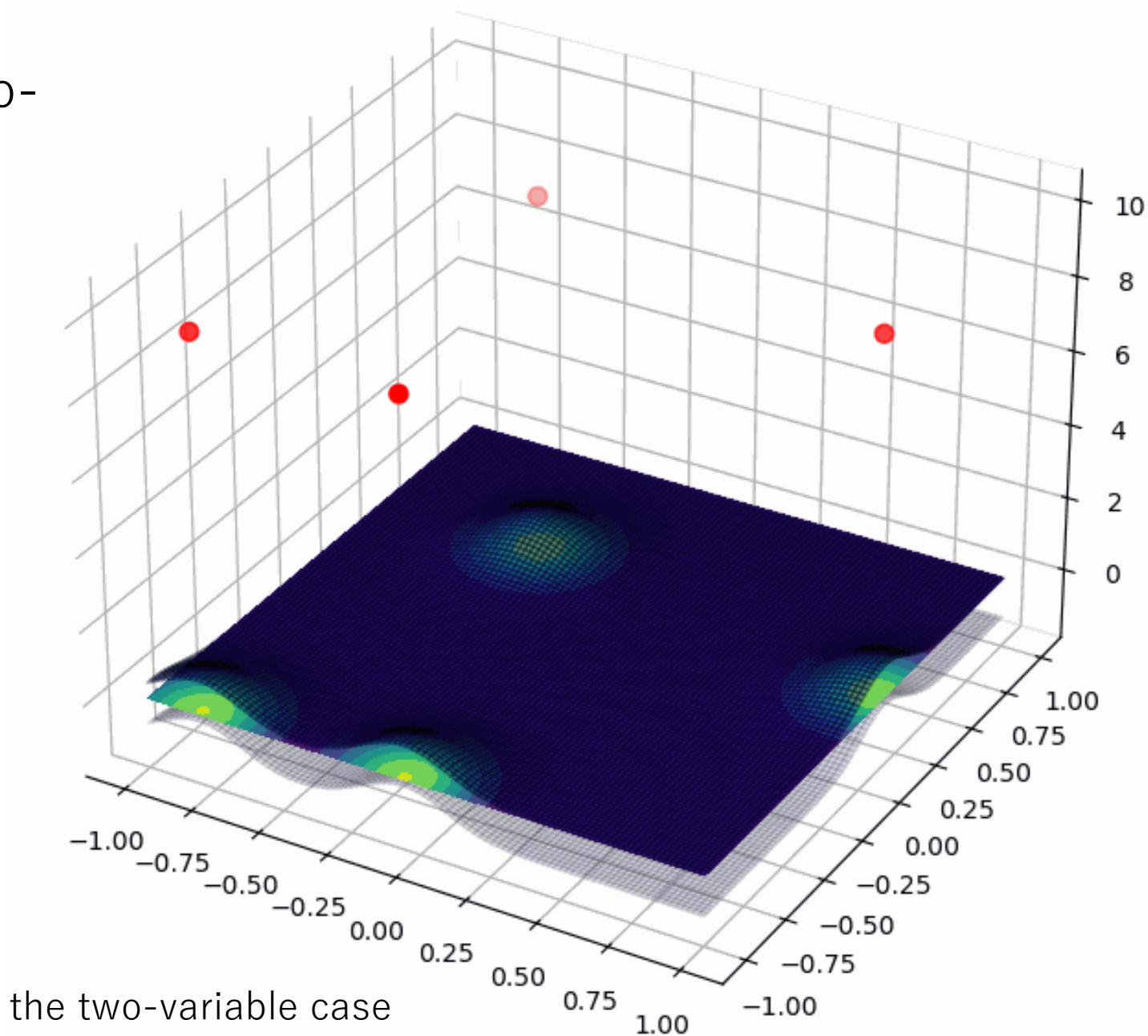
Gaussian Processes and Bayesian Optimization

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.



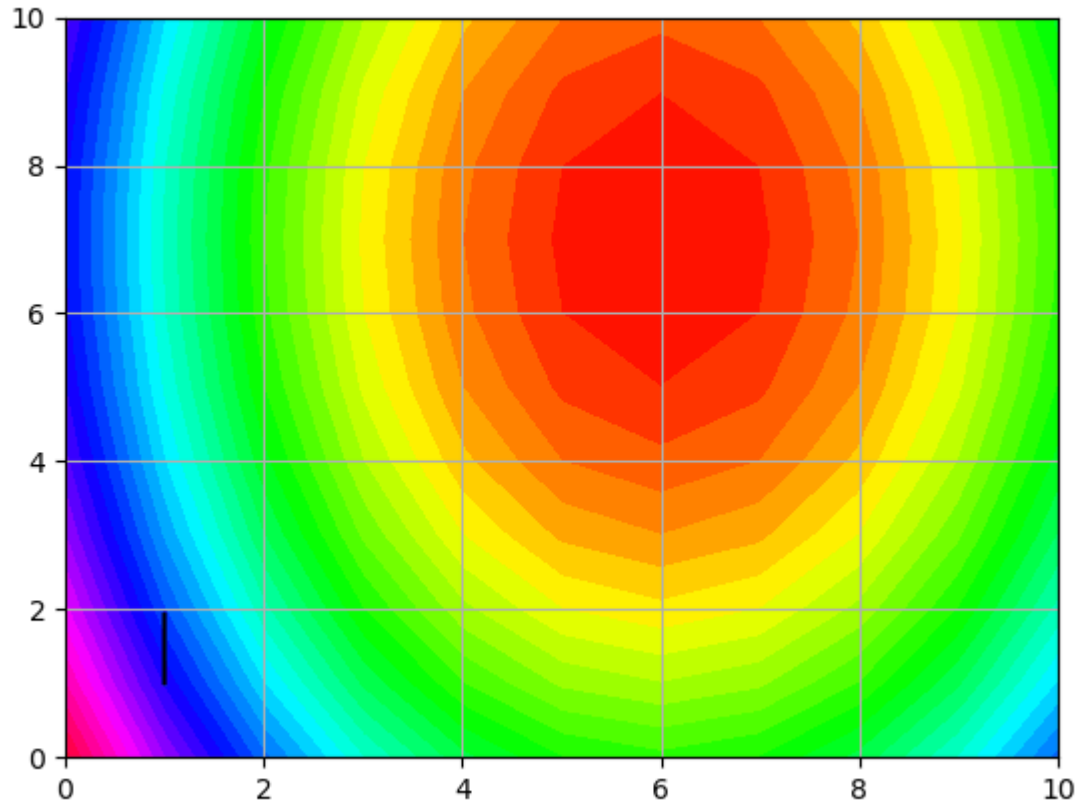
The Gaussian process and Bayesian optimization in the two- variable case

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



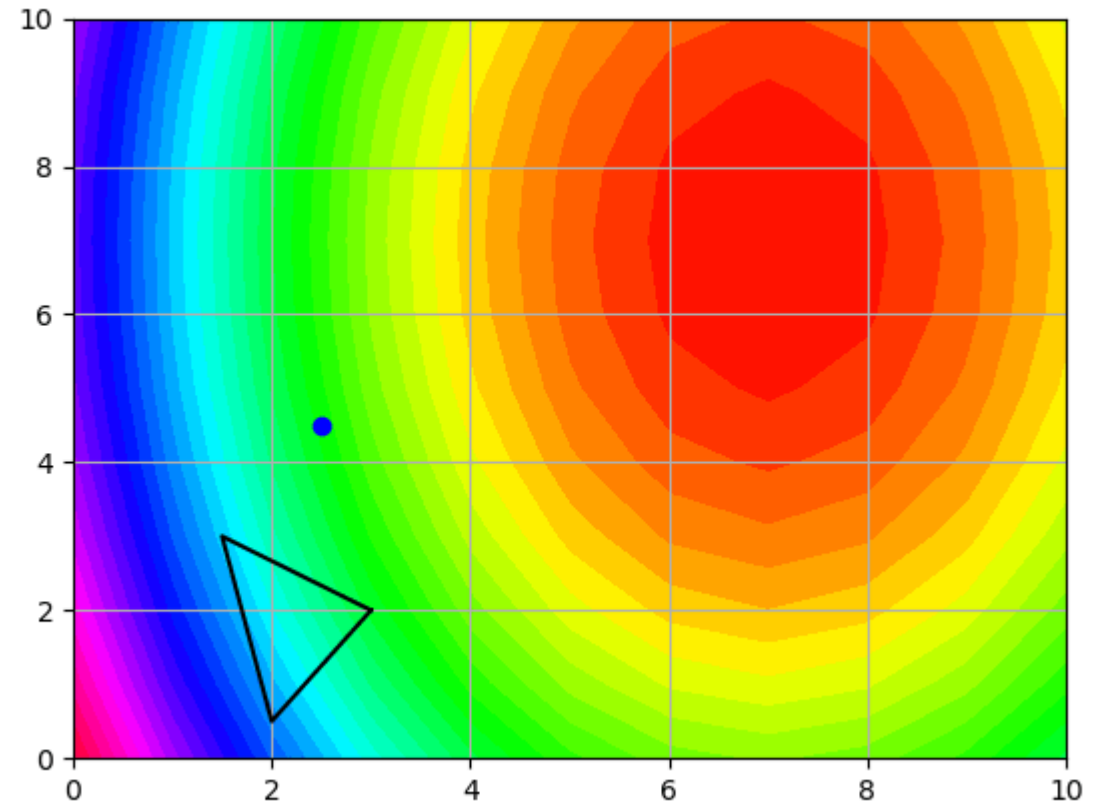
Bayesian optimization and downhill simplex method

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.

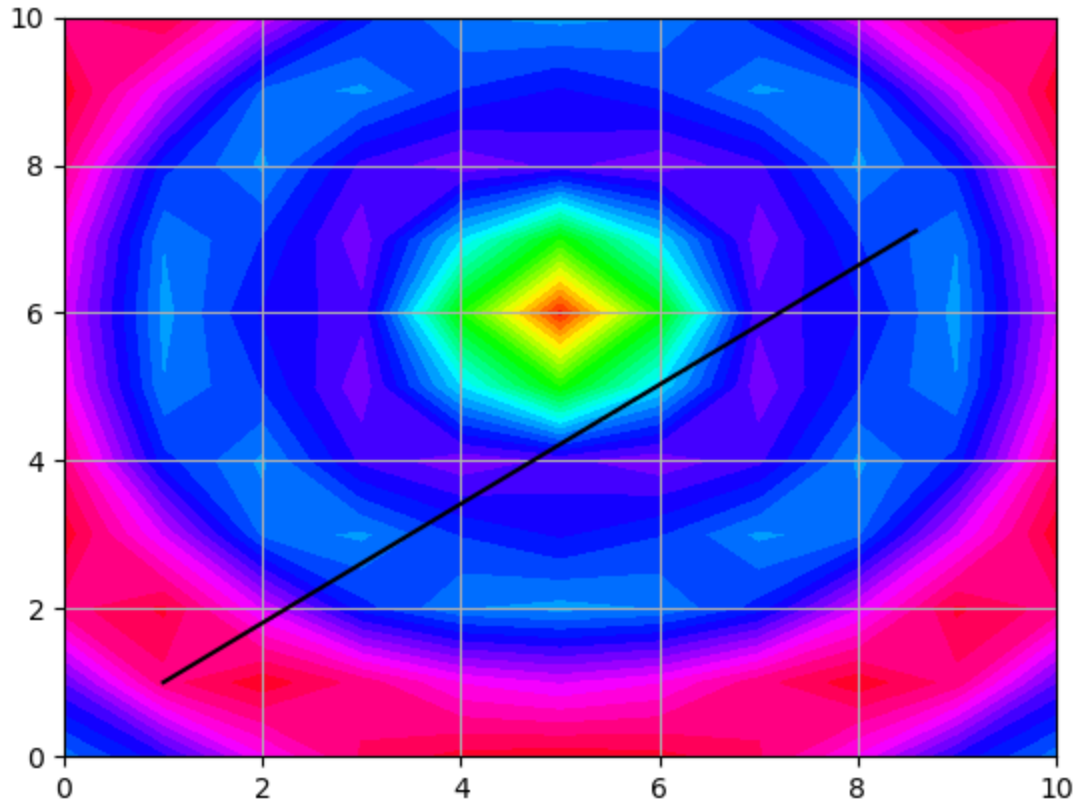


Downhill simplex method

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

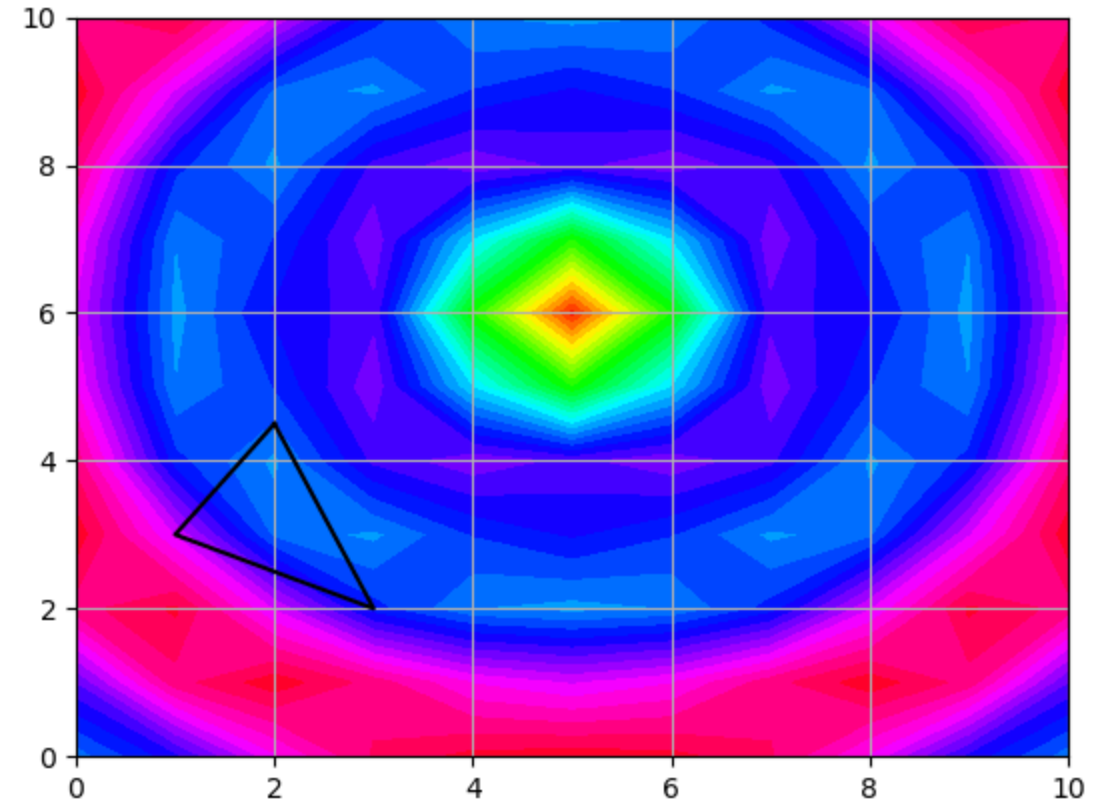
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Bayesian optimization

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.

Automatic tuning using Machine Learning

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.

x

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

$$y = f(x)$$

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.

The screenshot shows the 'Auto Tuner' software interface. The 'Tuner' tab is active, displaying a table of 'X setting' (tuning knobs) and a table of 'Y setting' (monitor EPICS records). The 'X setting' table has columns for 'PV name', 'Init Value', and '+/- Range'. The 'Y setting' table has columns for 'PV name' and 'Alias'. The 'Tuning Method' section shows 'Bayesian optimization' selected. The 'Evaluation function' is defined as $-(Qc5_1 + Qc7_1 + Q11_1 + Q13_1 + Q15_1 + Qc5_2 + Qc7_2 + Q11_2 + Q13_2 + Q15_2) / 10 + np.abs(Q15_1 - Q15_2) / 4$. The 'Measurement condition' section shows 'Beam repetition: 1.0', 'Data Num at a point: 20', 'Iteration Num: 200', 'Wait time [sec]: 0.1', and 'Limitation: Qc5_1 > 0.3 and Qc5_2 > 0.3'. The 'Start' button is highlighted with a blue arrow.

X setting	PV name	Init Value	+/- Range
x0	LiEV:SB_B:KBPPHASE	81.2	5.0
x1	LiRF:ENERGY:RO_KBP:SET	1.69	0.02000000C
x2	LiMG:PX_A4_4:IWRITE:KBP	0.127	0.5
x3	LiMG:PY_A4_4:IWRITE:KBP	0.144	0.5
x4	LiMG:PX_R0_01:IWRITE:KBP	0.861	1.0
x5	LiMG:PY_R0_01:IWRITE:KBP	2.811	1.0
x6	LiMG:PD_R0_01:IWRITE:KBP	106.825	15.0
x7	LiMG:PF_R0_01:IWRITE:KBP	102.682	15.0
x8	LiMG:PD_R0_02:IWRITE:KBP	421.215	15.0
x9	LiMG:PF_R0_02:IWRITE:KBP	452.038	15.0
x10	LiMG:PD_R0_61:IWRITE:KBP	377.017	15.0
x11	LiMG:PF_R0_61:IWRITE:KBP	380.423	15.0
x12	LiMG:PD_R0_63:IWRITE:KBP	182.303	15.0
x13	LiMG:PF_R0_63:IWRITE:KBP	200.0	15.0
x14	LiMG:PX_R0_61:IWRITE:KBP	-2.27	1.999999999
x15	LiMG:PY_R0_61:IWRITE:KBP	4.449	2.0

Y setting	PV name	Alias
	LiBM:SP_C5_4_1:ISNGL:KBP	Qc5_1
	LiBM:SP_C7_4_1:ISNGL:KBP	Qc7_1
	LiBM:SP_11_4_1:ISNGL:KBP	Q11_1
	LiBM:SP_13_5_1:ISNGL:KBP	Q13_1
	LiBM:SP_15_T_1:ISNGL:KBP	Q15_1
	LiBM:SP_C5_4_2:ISNGL:KBP	Qc5_2
	LiBM:SP_C7_4_2:ISNGL:KBP	Qc7_2
	LiBM:SP_11_4_2:ISNGL:KBP	Q11_2
	LiBM:SP_13_5_2:ISNGL:KBP	Q13_2
	LiBM:SP_15_T_2:ISNGL:KBP	Q15_2

Tuning Method: ☒ Bayesian optimization, ☐ Downhill simplex, ☐ Bayesian GPy, ☐ Bayesian GPy small steps, ☐ BO continuous, ☐ BO with MonitorX

Measurement condition: Beam repetition: 1.0, Data Num at a point: 20, Iteration Num: 200, Wait time [sec]: 0.1, Limitation: Qc5_1 > 0.3 and Qc5_2 > 0.3

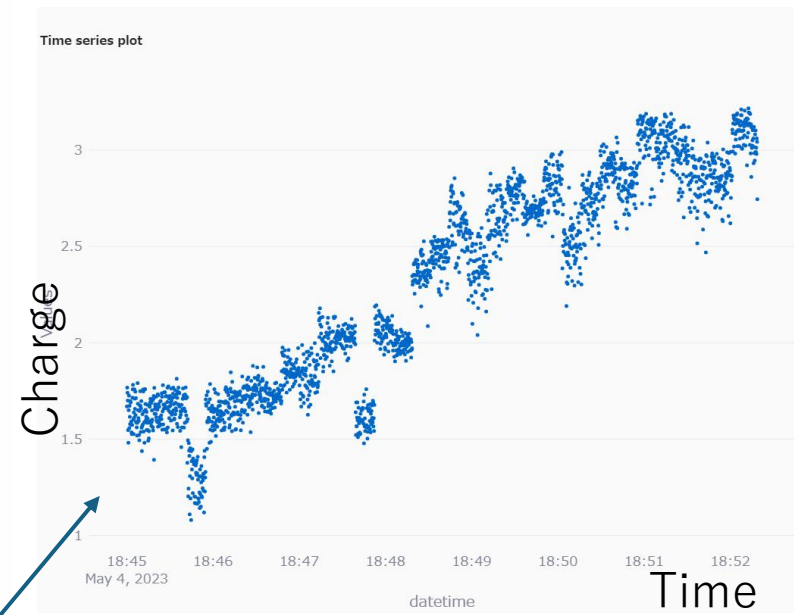
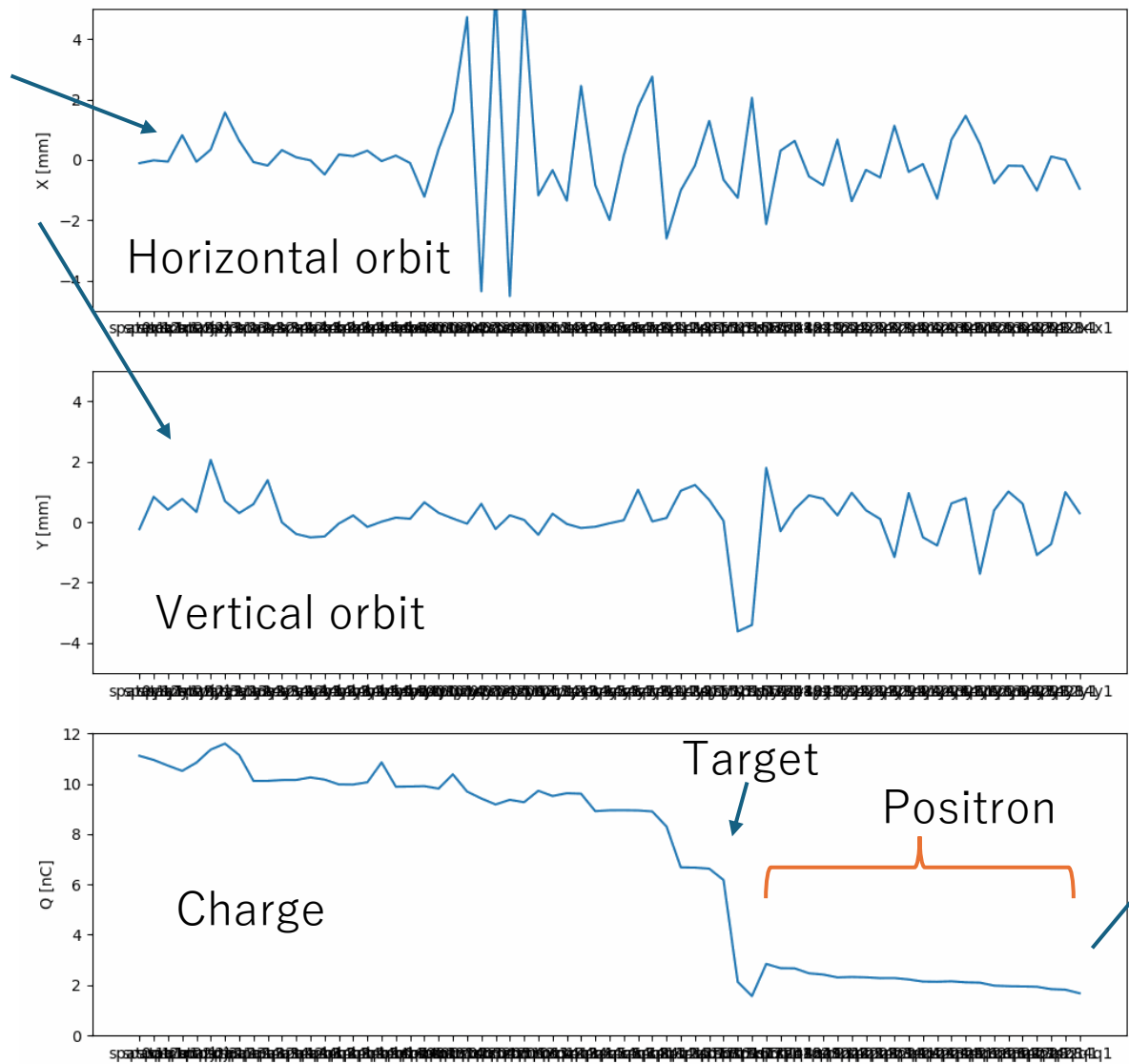
Comment: 2 bunchでJarcの通りをよくする調整(Jarc前後のPulseQ 8台すべてを使う) 2 bunchの電荷量のバランスをとる

Start button: Start, Current value to init, Stop, Restart, Set Best and Finish, Abort

Example 1

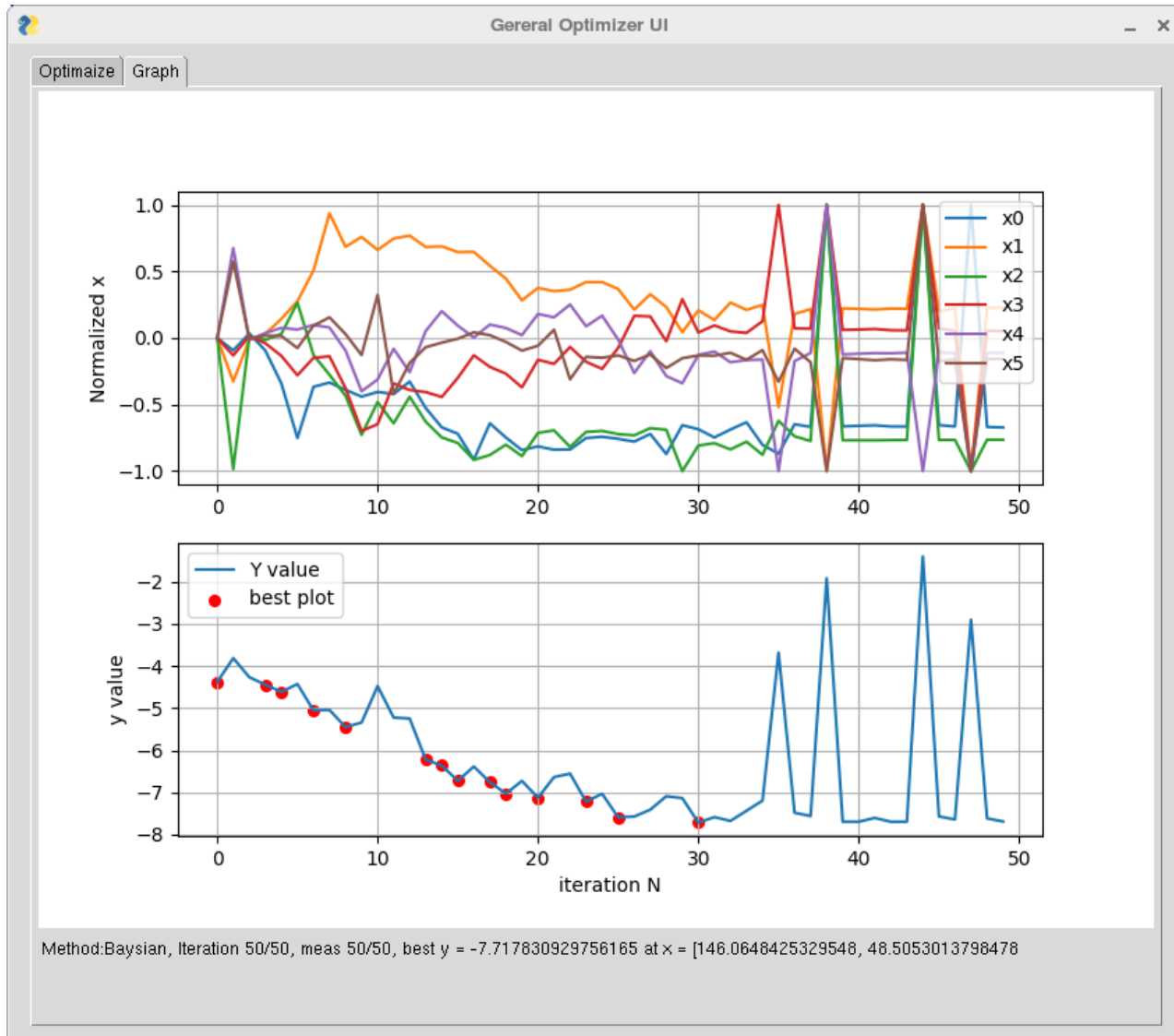
Searching for parameters that will increase positron production by shaking the orbit in the upstream.
(Changing magnet current and RF phase.)

BPM data in linac while auto tuning.



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

Example 1



SH_A1_S1 (KBP) $146.7^{\circ} \rightarrow 146.1^{\circ}$ (-0.6°)
SH_A1_S8 (KBP) $48.0^{\circ} \rightarrow 48.6^{\circ}$ ($+0.6^{\circ}$)
PX_AT_22-KBP $0.364\text{A} \rightarrow 0.170\text{A}$ (-0.194A)
PY_AT_22-KBP $1.435\text{A} \rightarrow 1.451\text{A}$ ($+0.016\text{A}$)
PX_A1_M-KBP $0.009\text{A} \rightarrow -0.018\text{A}$ (-0.027A)
PY_A1_M-KBP $-1.137\text{A} \rightarrow -1.176\text{A}$ (-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.

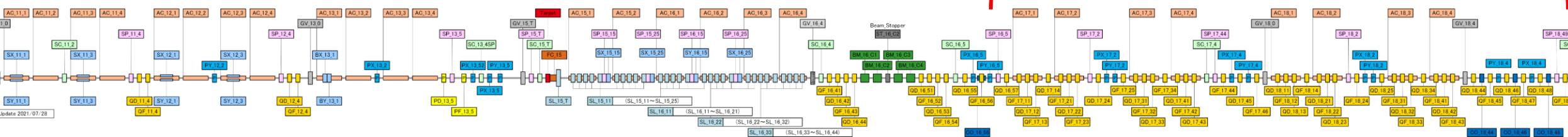
It was thought that the Q-magnets and steering magnets would need to be adjusted to improve this situation. However, about 200 parameters had to be adjusted, making it impossible to do so manually.

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.



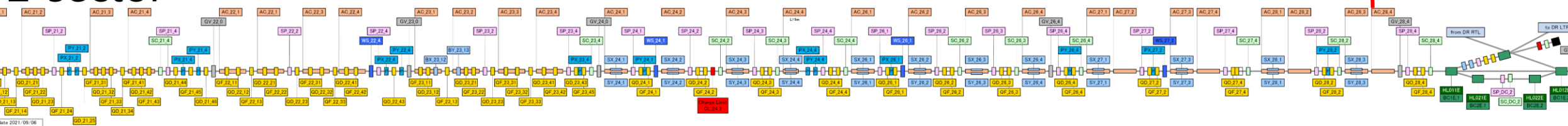
1-sector

Sector-1 tuning region

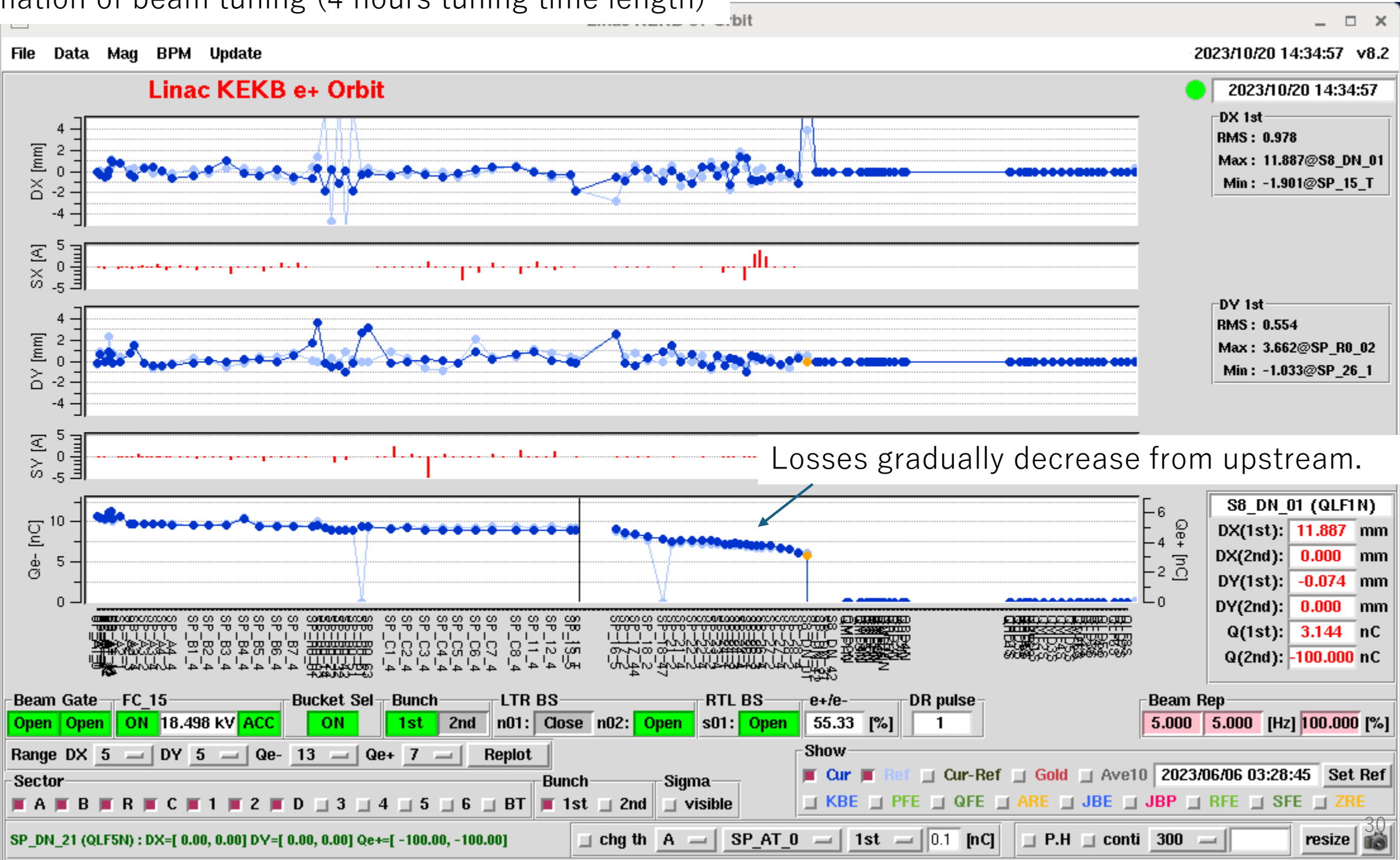


Sector-2 tuning region

2-sector



Animation of beam tuning (4 hours tuning time length)

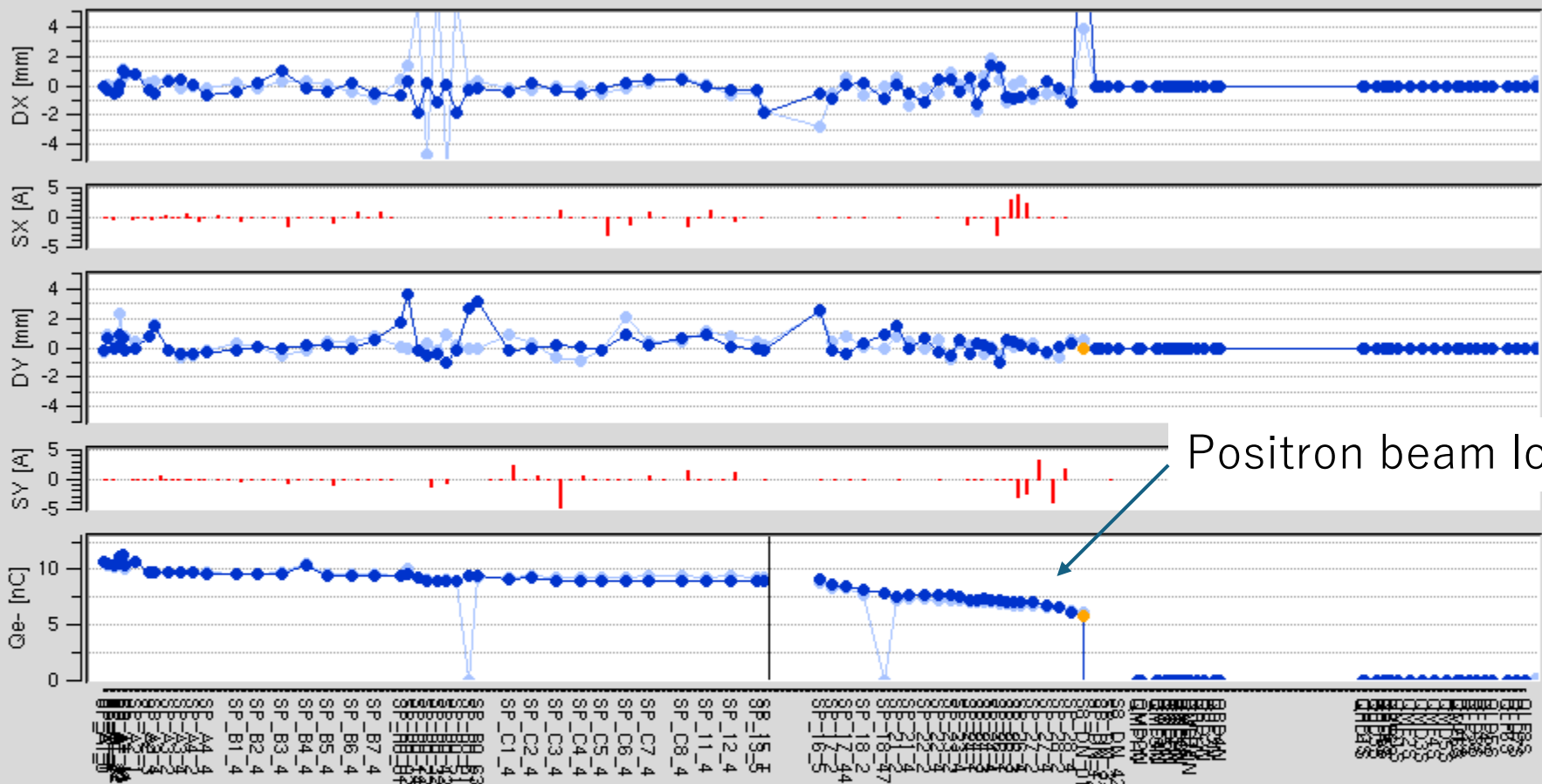


Before tuning

File Data Mag BPM Update

2023/10/20 14:34:57 v8.2

Linac KEKB e+ Orbit



2023/10/20 14:34:57

DX 1st
RMS : 0.978
Max : 11.887@S8_DN_01
Min : -1.901@SP_15_T

DY 1st
RMS : 0.554
Max : 3.662@SP_R0_02
Min : -1.033@SP_26_1

S8_DN_01 (QLF1N)
DX(1st): 11.887 mm
DX(2nd): 0.000 mm
DY(1st): -0.074 mm
DY(2nd): 0.000 mm
Q(1st): 3.144 nC
Q(2nd): -100.000 nC

Beam Gate FC_15
 18.498 kV ACC

Bucket Sel Bunch 1st 2nd

LTR BS n01: n02: RTL BS s01:

e+/e- 55.33 [%] DR pulse 1

Beam Rep 5.000 5.000 [Hz] 100.000 [%]

Range DX 5 DY 5 Qe- 13 Qe+ 7 Replot

Sector ☒ A ☒ B ☒ R ☒ C ☒ 1 ☒ 2 ☒ D ☒ 3 ☒ 4 ☒ 5 ☒ 6 ☒ BT

Bunch ☒ 1st ☐ 2nd Sigma ☐ visible

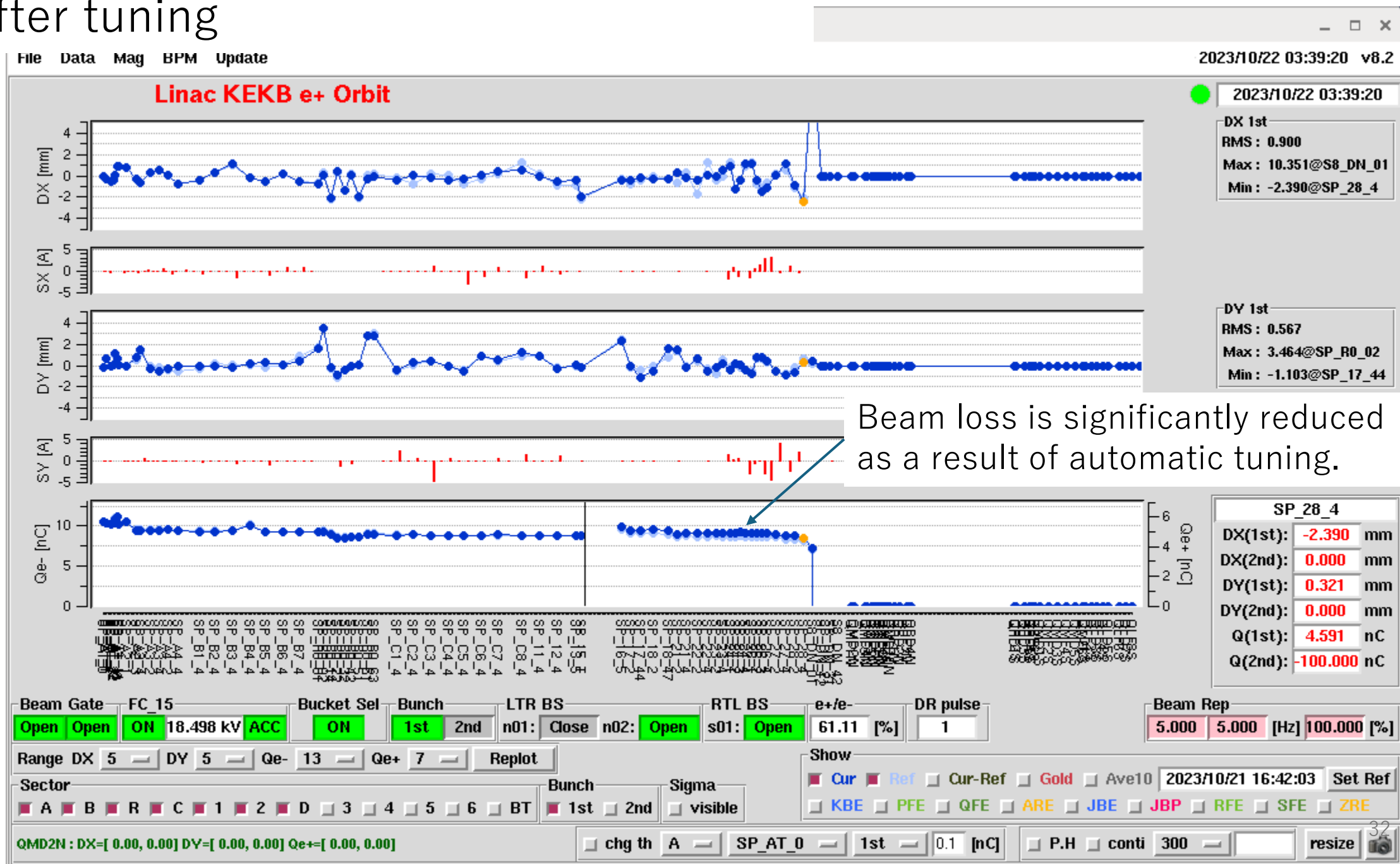
☒ Cur ☒ Ref ☐ Cur-Ref ☐ Gold ☐ Ave10 2023/06/06 03:28:45

☐ KBE ☐ PFE ☐ QFE ☐ ARE ☐ JBE ☐ JBP ☐ RFE ☐ SFE ☐ ZRE

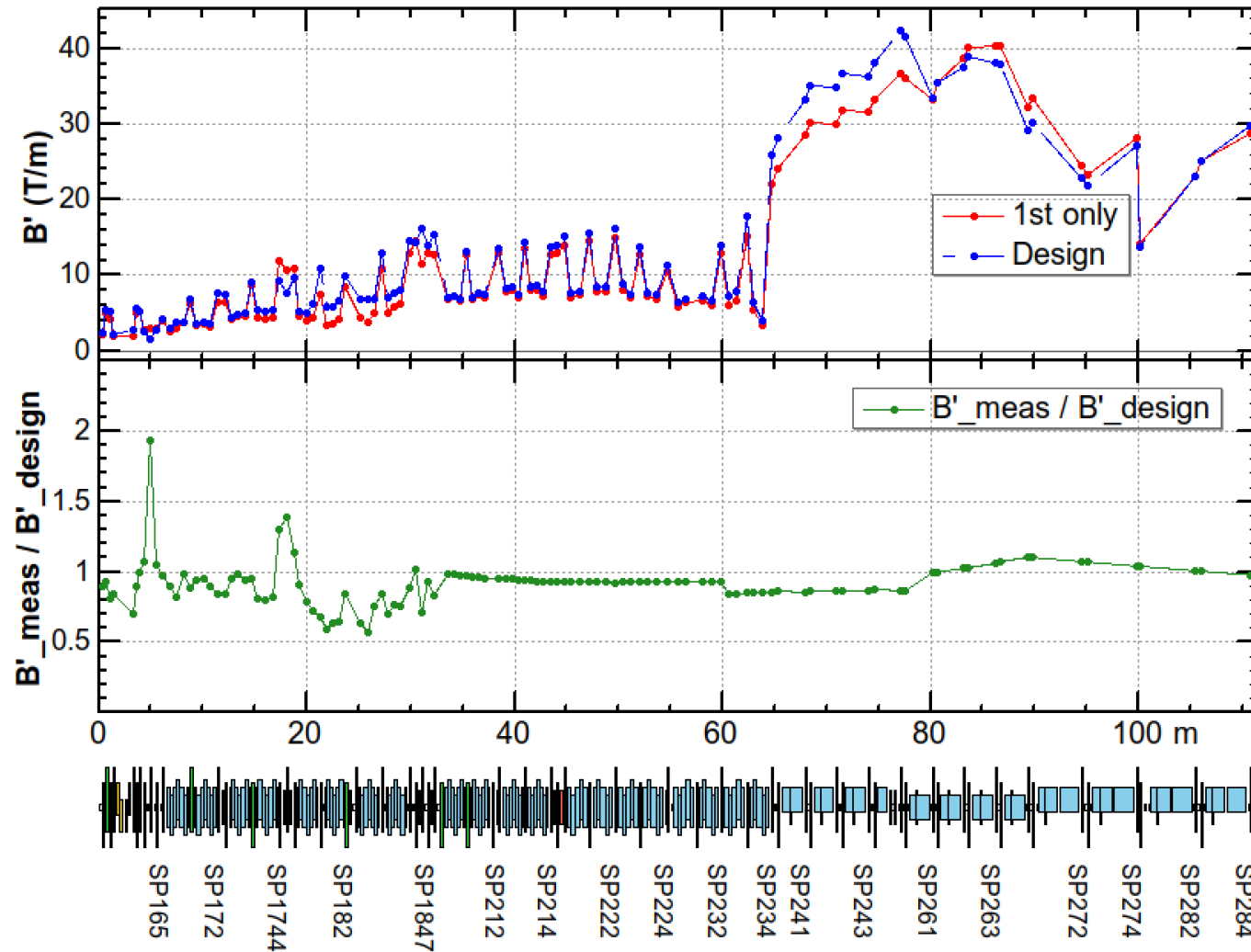
SP_DN_21 (QLF5N) : DX=[0.00, 0.00] DY=[0.00, 0.00] Qe+=[-100.00, -100.00]

A 1st 0.1 [nC] 300

After tuning



Design and tuned Q magnet field in positron beam line



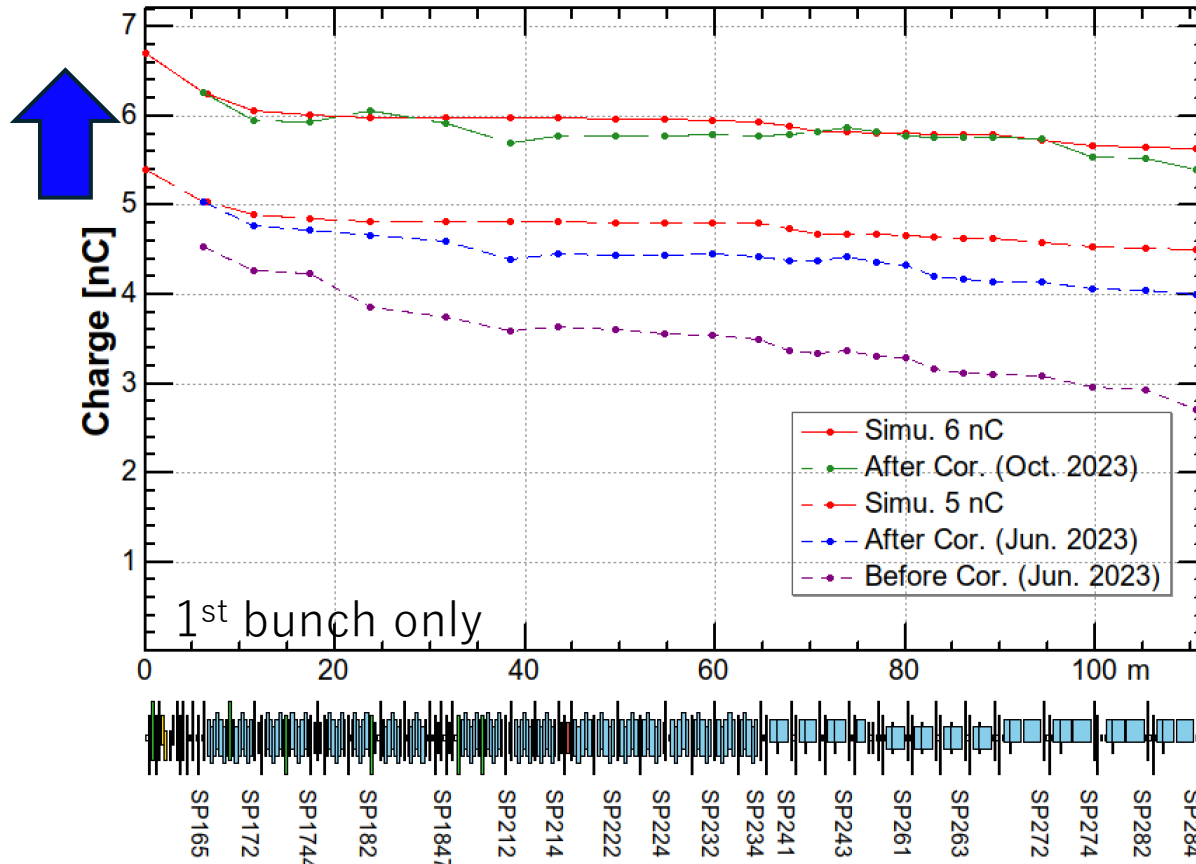
- The error due to energy is estimated to be about 10%. Magnetic field errors are usually smaller than that.
- Similar to the design in some areas, but values differ by more than 20%, especially near Target.
- The large energy error near the target is thought to be a contributing factor.
- Due to misalignment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

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.

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.

