SuperKEKB positron beam tuning using ML

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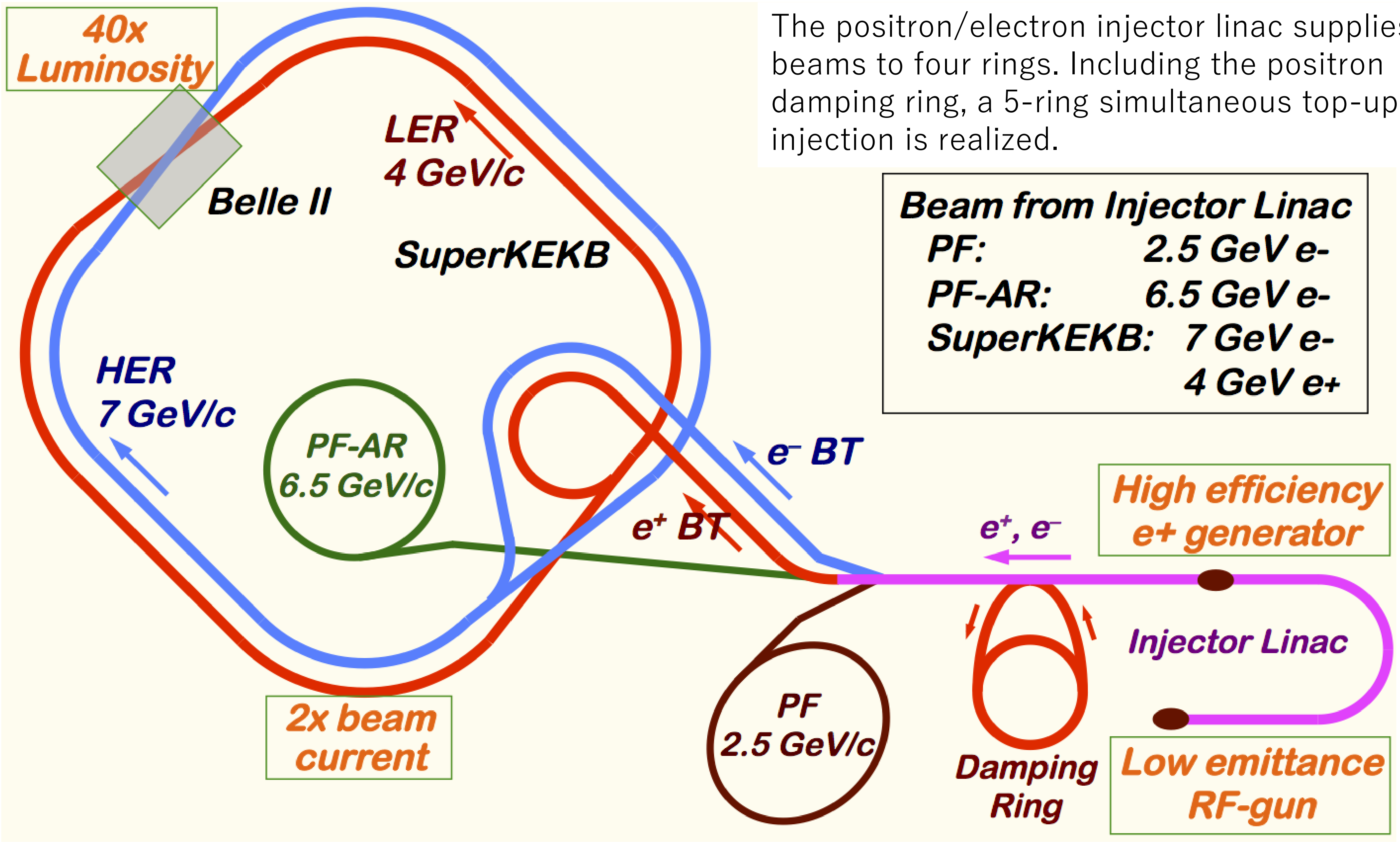
KEK

Back ground

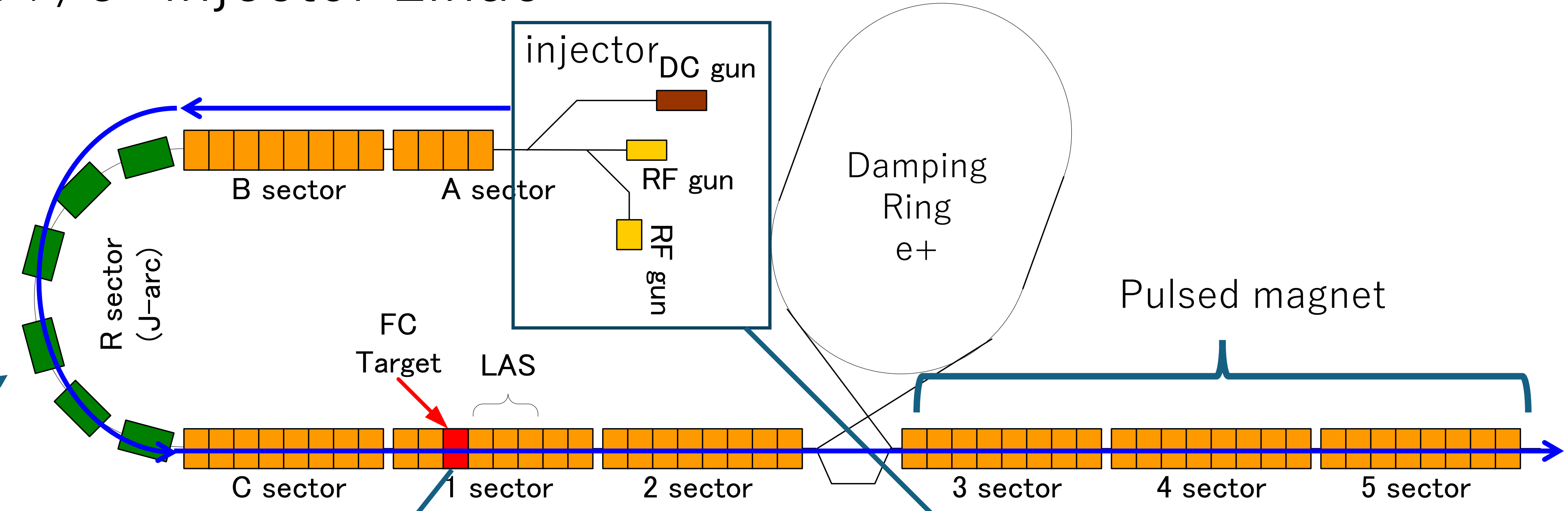
KEK positron/electron injector

Accelerator at KEK Tsukuba

The positron/electron injector linac supplies beams to four rings. Including the positron damping ring, a 5-ring simultaneous top-up injection is realized.

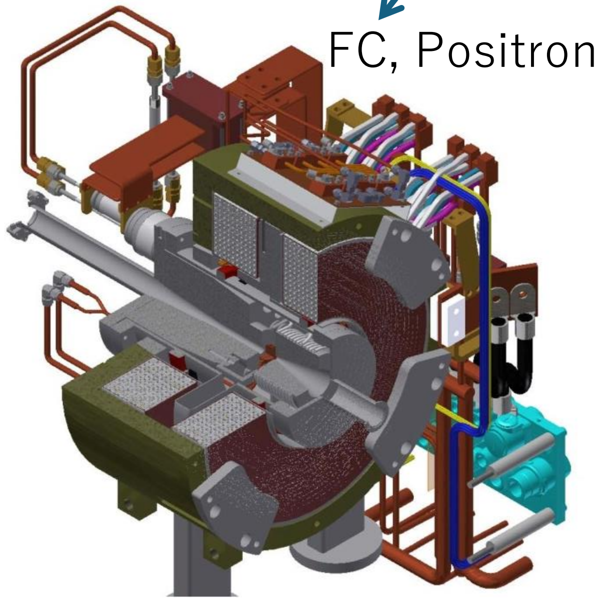


Beam line of e+/e- injector Linac

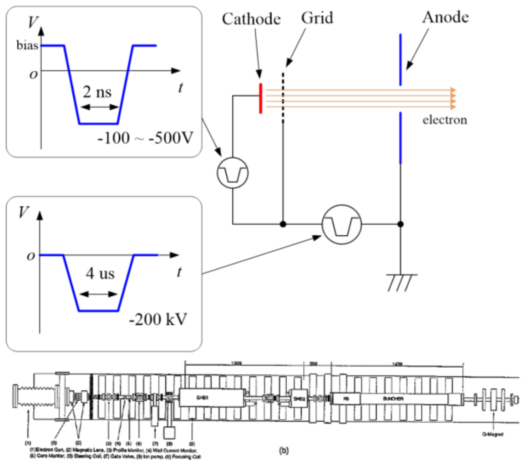


180° bending beam line that is called J-arc.

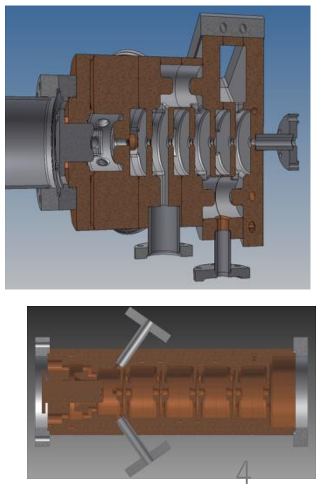
FC, Positron target



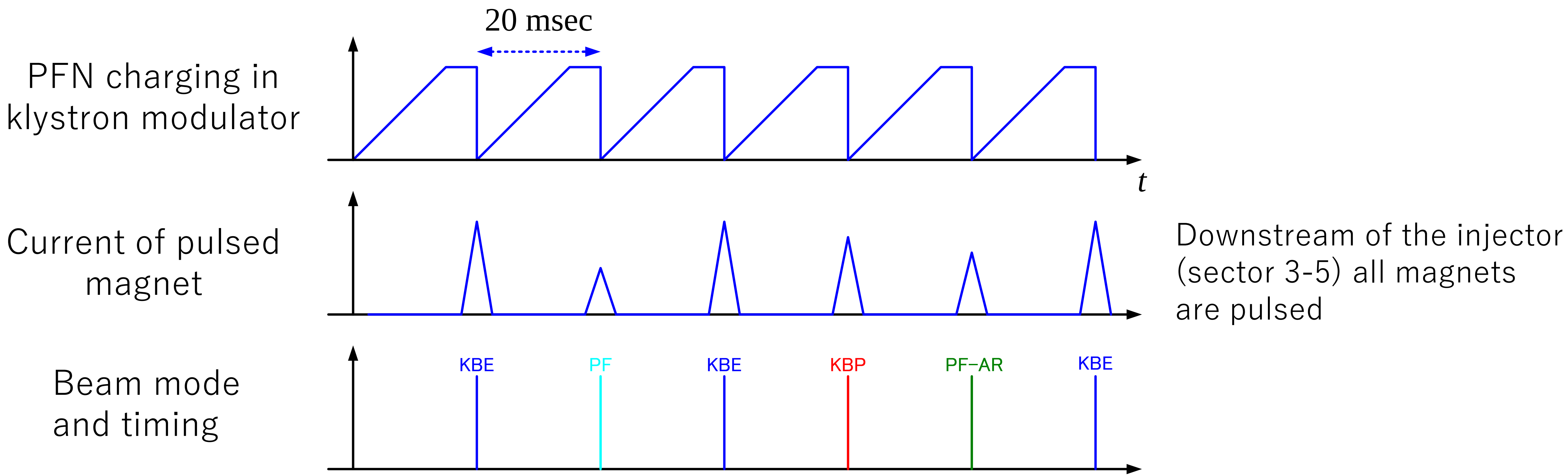
Thermionic gun and SHB



RF gun



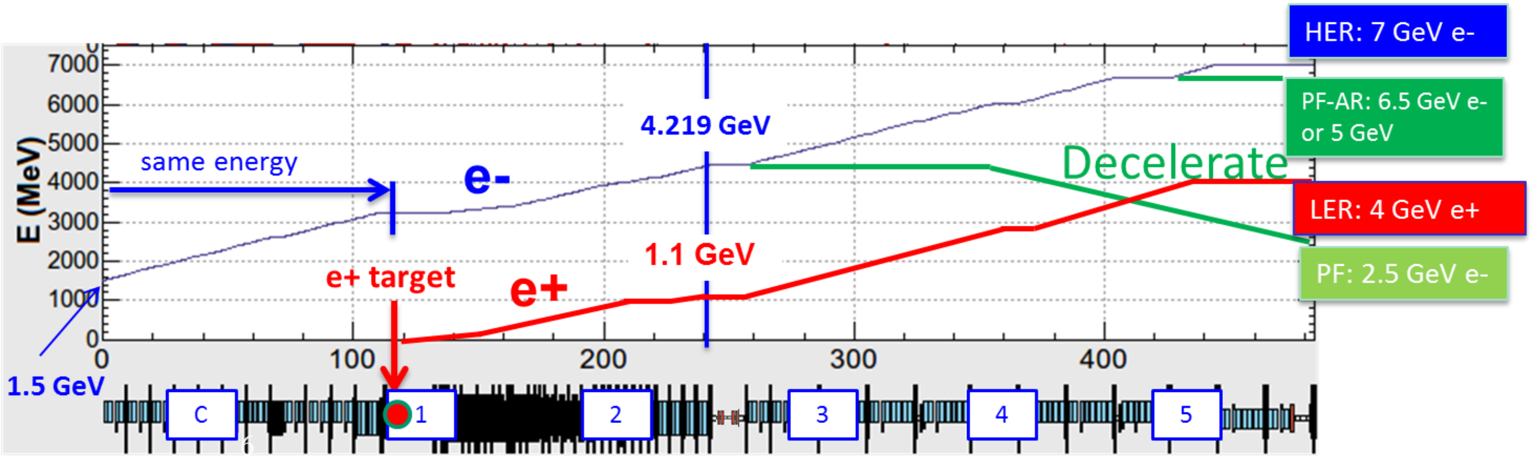
Beam timing and beam mode switching

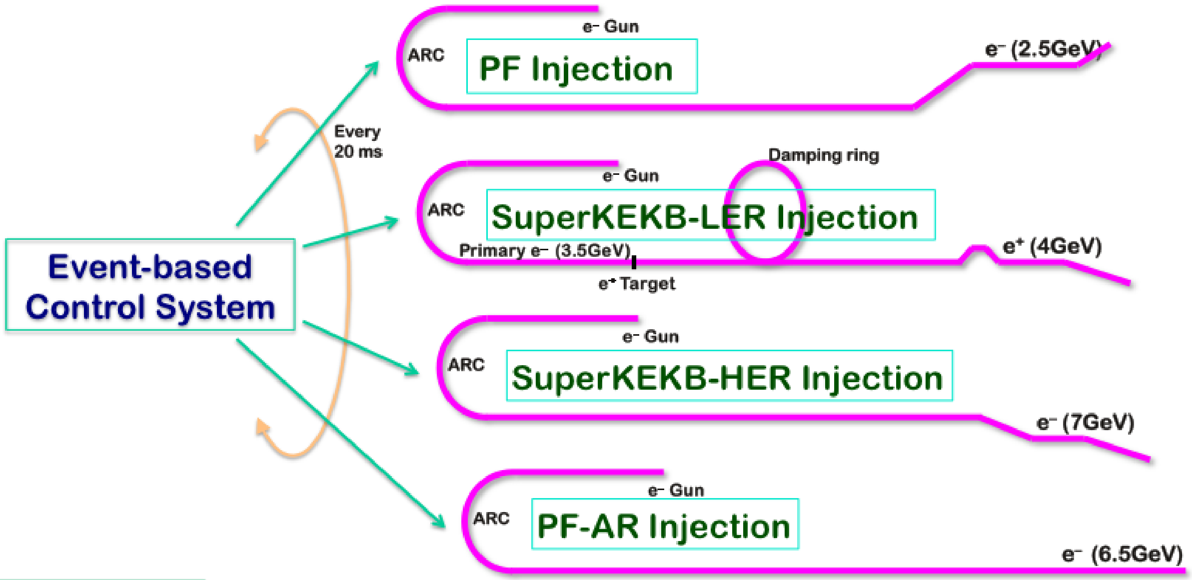


The interval between beams is 20 msec (50 Hz). The time between beams is used for PFN charging, and the other pulsed devices are at idle. A different beam mode can be launched every 20 msec.
(HER e-, LER e+, PF e-, PF-AR e-)

Pulse 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	4
LER	e+	4	4
PF	e-	2.5	0.3
PF-AR	e+	6.5	0.3

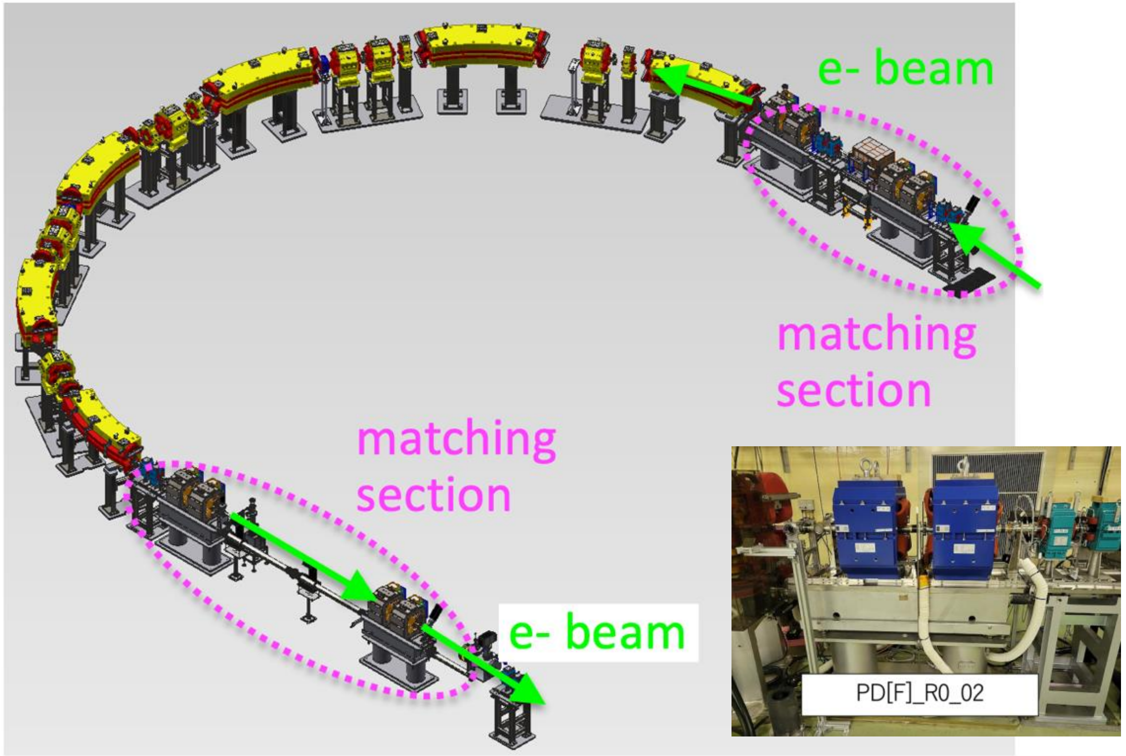




So, beam tuning has become increasingly complex in recent years

In the fall of 2023, large pulse magnets have been installed not only in the 3-5 sector but also in the J-arc area, allowing independent adjustment of each beam mode. Independent tuning of each mode is important for SuperKEKB, which requires beams with large charge and low emittance.

Thus, more and more tuning parameters are being increased. However, since time and manpower remain the same, some new mechanism was needed to extract machine performance.



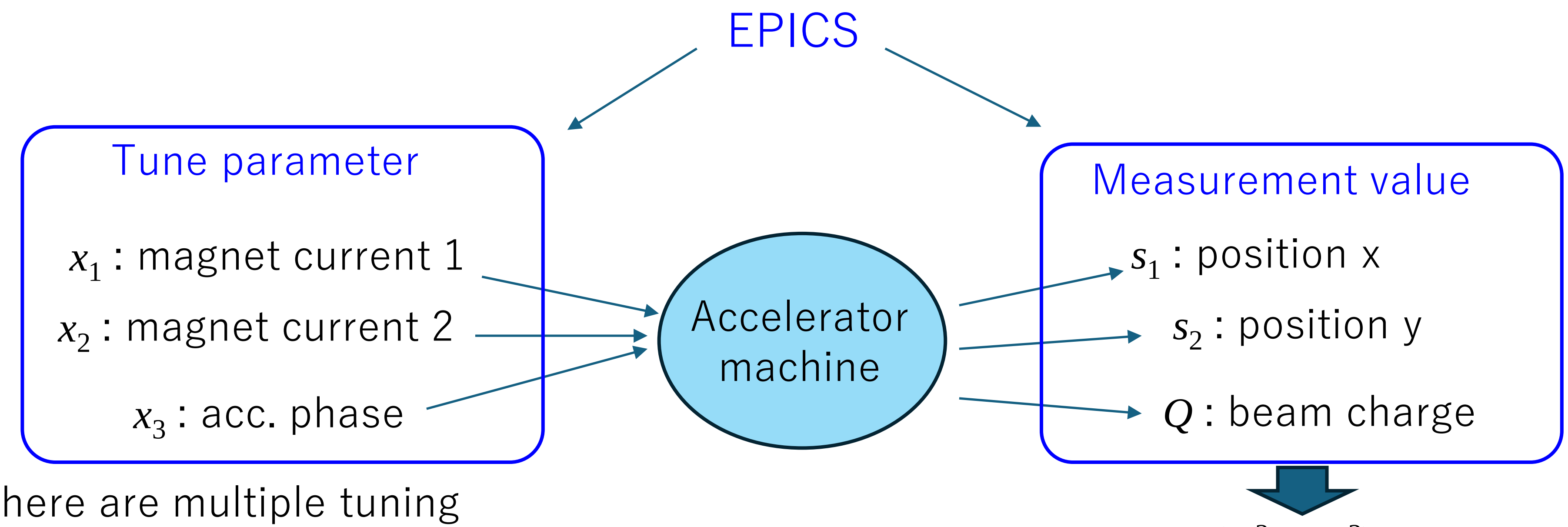
Large pulse magnets were also introduced upstream and downstream of J-arc. Although each beam can now be matched independently, the degree of freedom has increased, and the degree of difficulty of adjustment has also risen.

Automatic tuning using machine learning

Principle of Automatic tuning

Bayesian Optimization and Downhill simplex method. Automatic Tuning of Accelerator Operation as a Minimization Problem.

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.



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

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

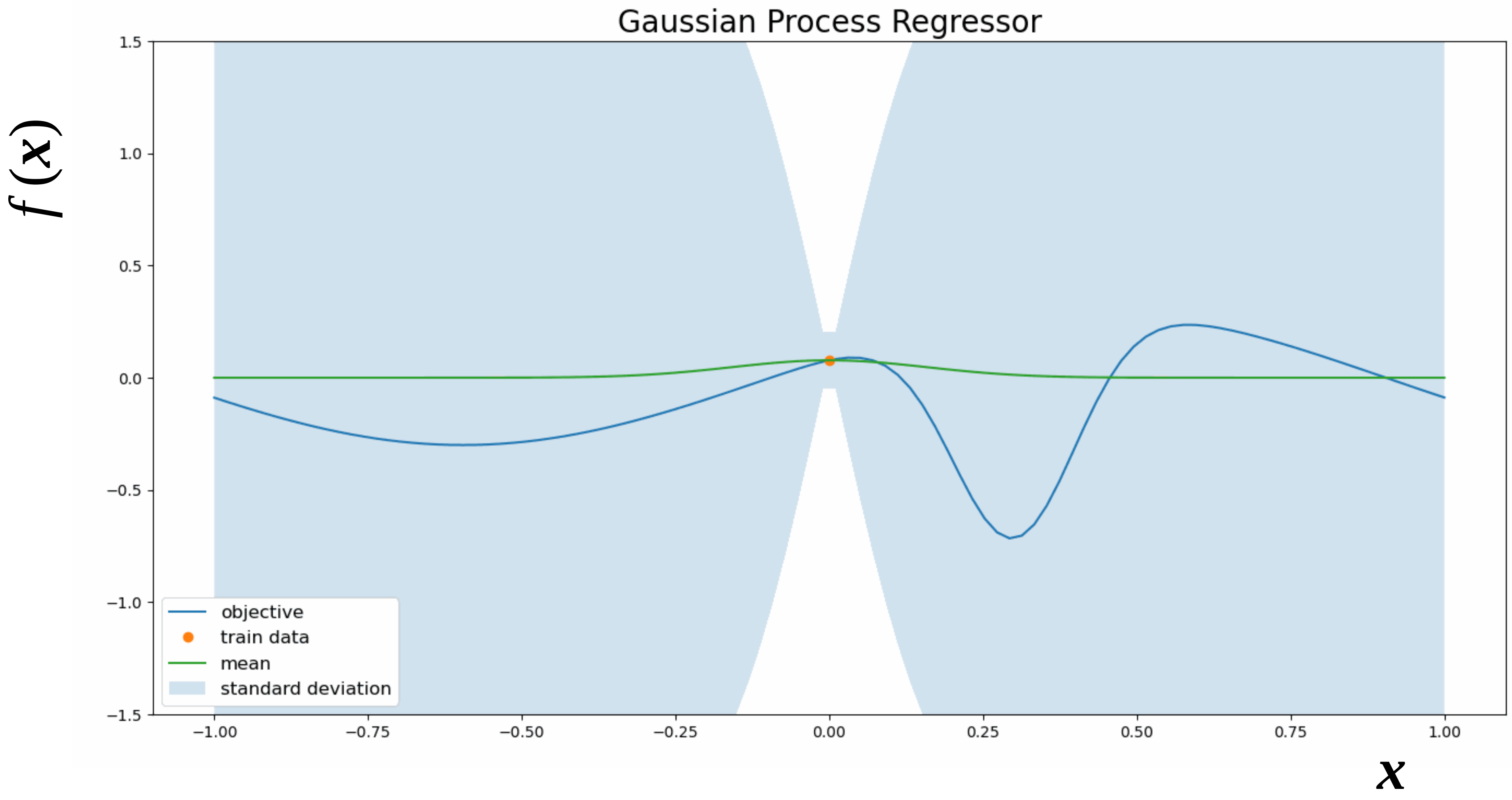
In practice, there are multiple tuning parameters that require an optimization algorithm for the multivariable function f(x1, x2, x3, ... xn).

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)

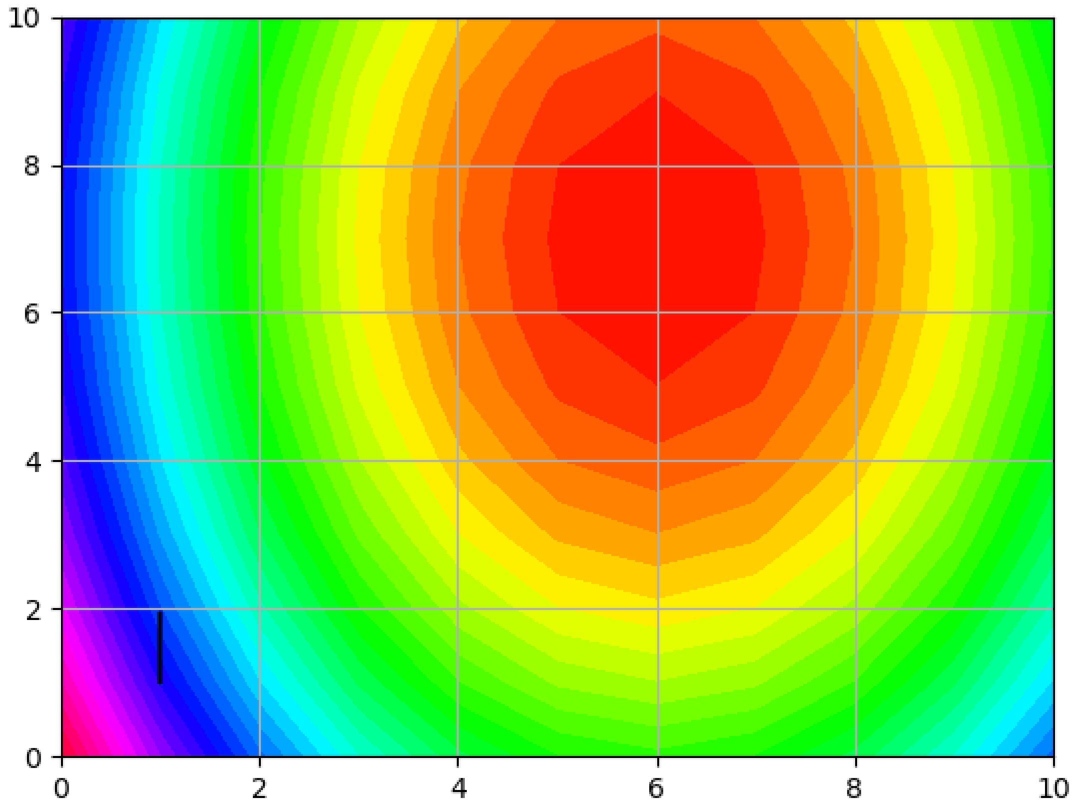
Gaussian Processes and Bayesian Optimization

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.



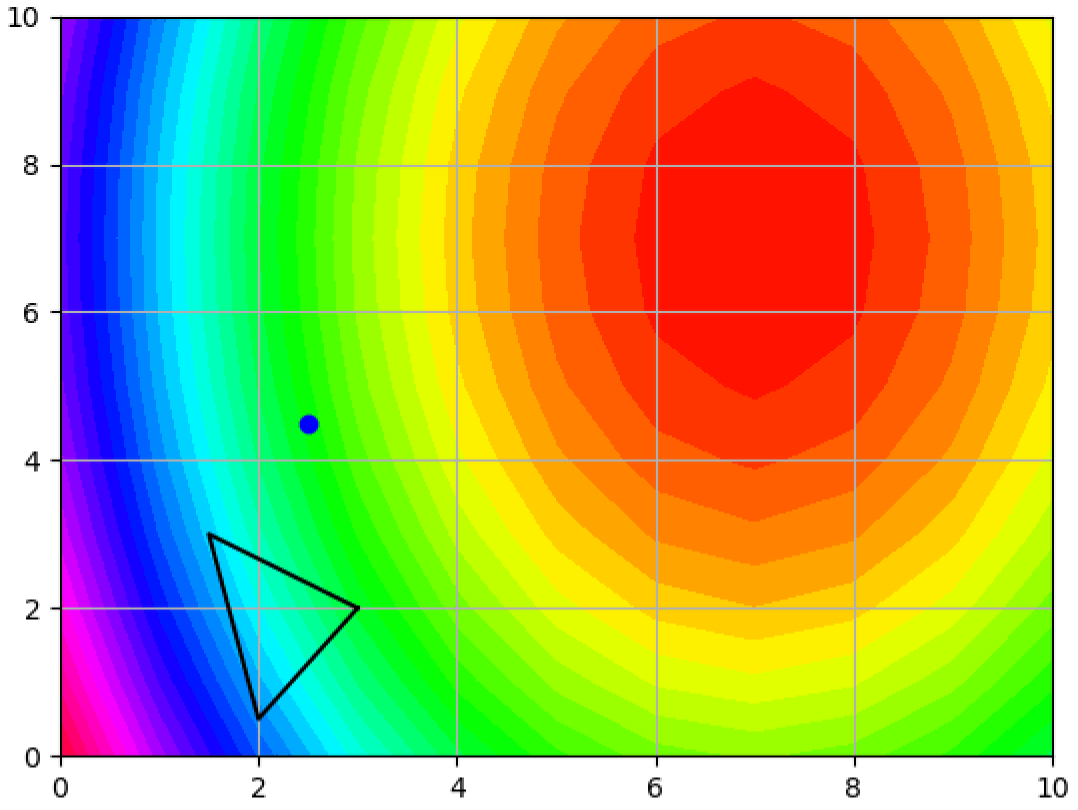
Bayesian optimization and downhill simplex method

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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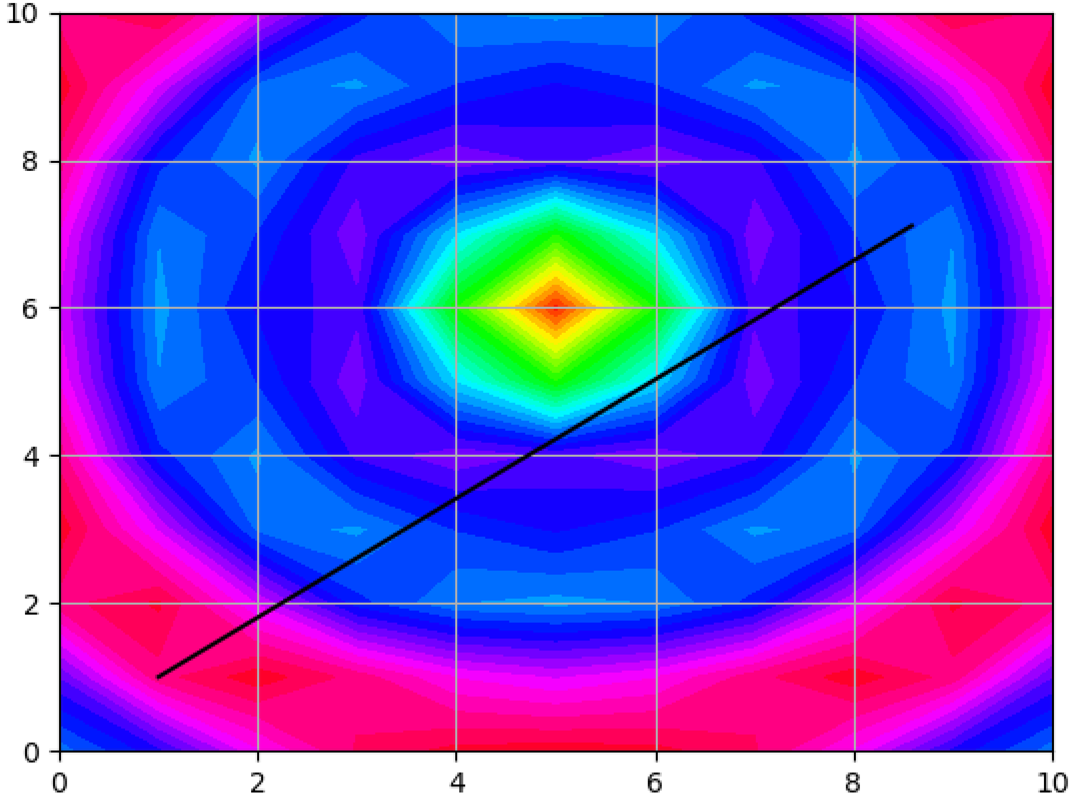

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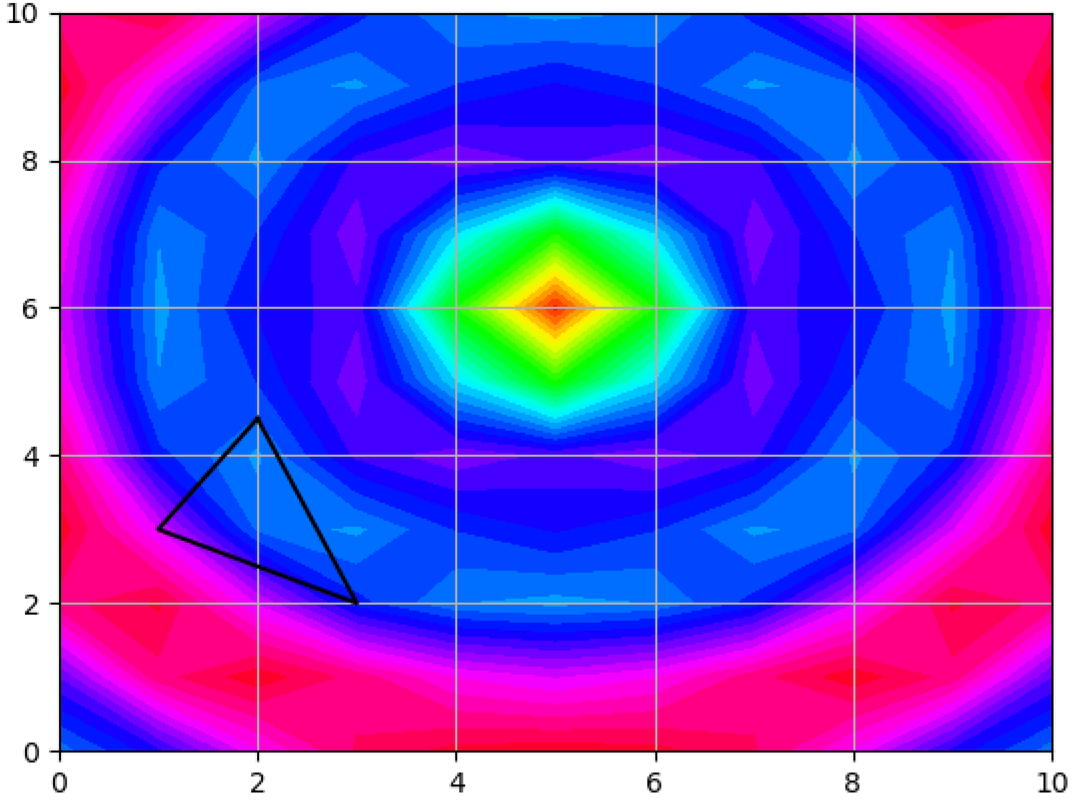


Downhill simplex method

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

Example of Automatic Tuning

Operation Panel

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

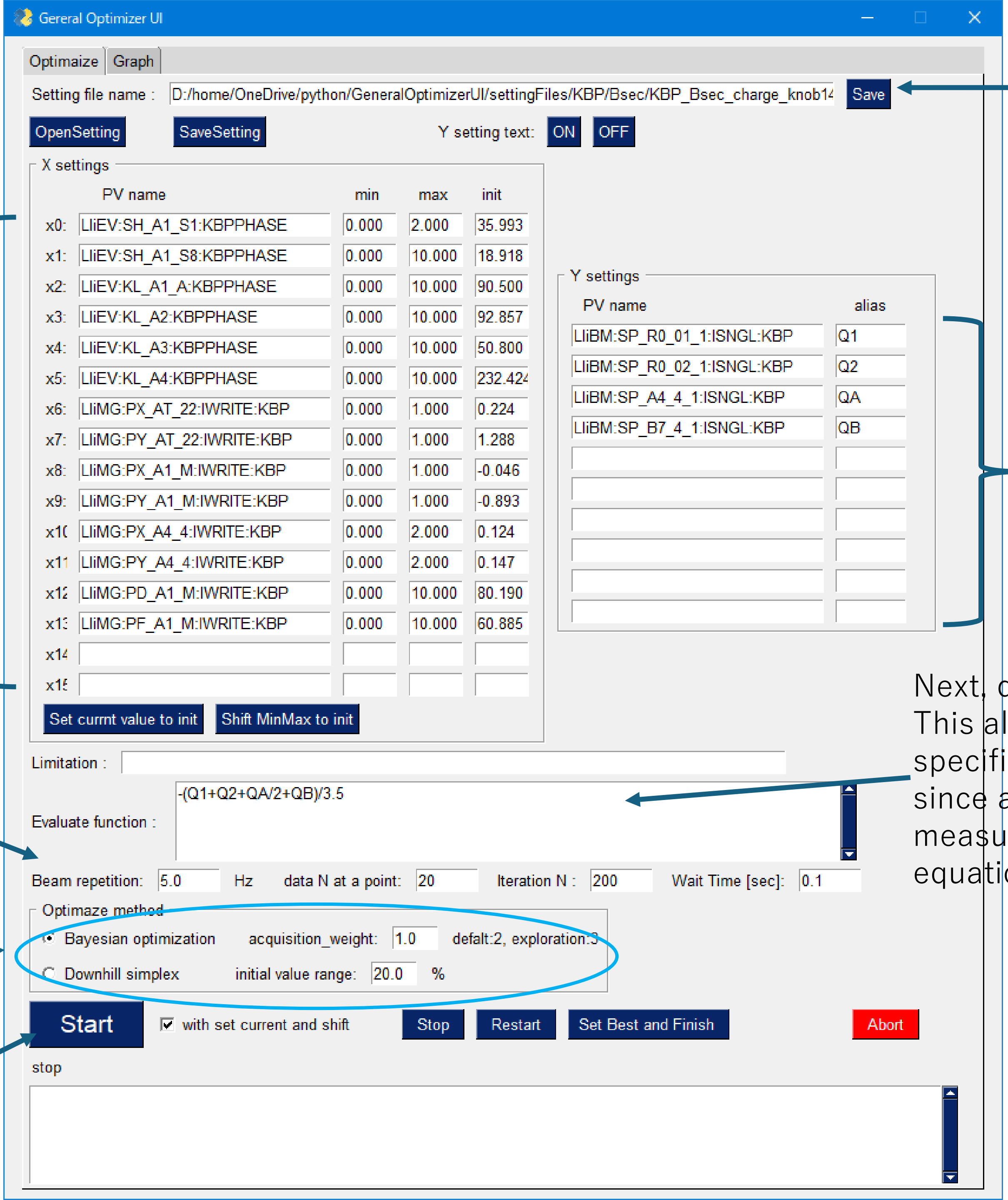
Select tuning knob. We can use any variable EPICS records and select minimum and maximum value for tuning range.

x

Basic setting.
Number of iteration and so on.

Select optimization method.
Bayesian or Downhill.

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



Basically, we just choose previous setting file.

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

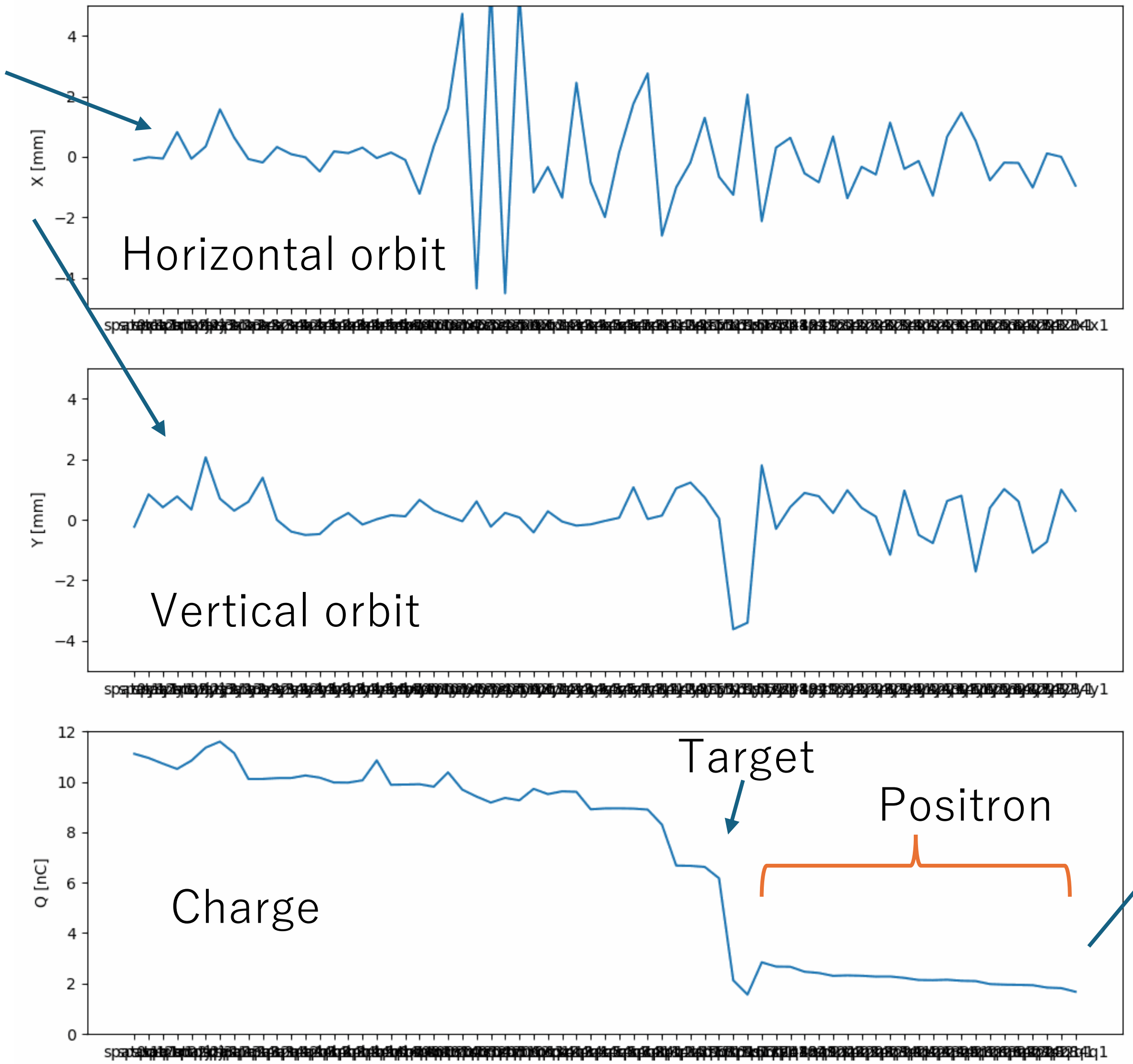
Next, define the values to be minimized. This allows for a very flexible specification of the objective function, since any combination of measurements can be defined in the equation.

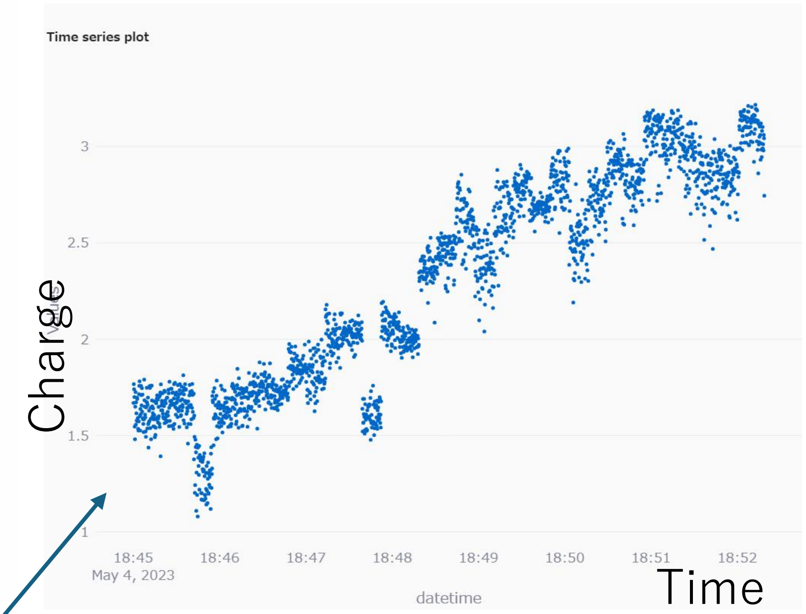
$f(x)$

Example 1

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

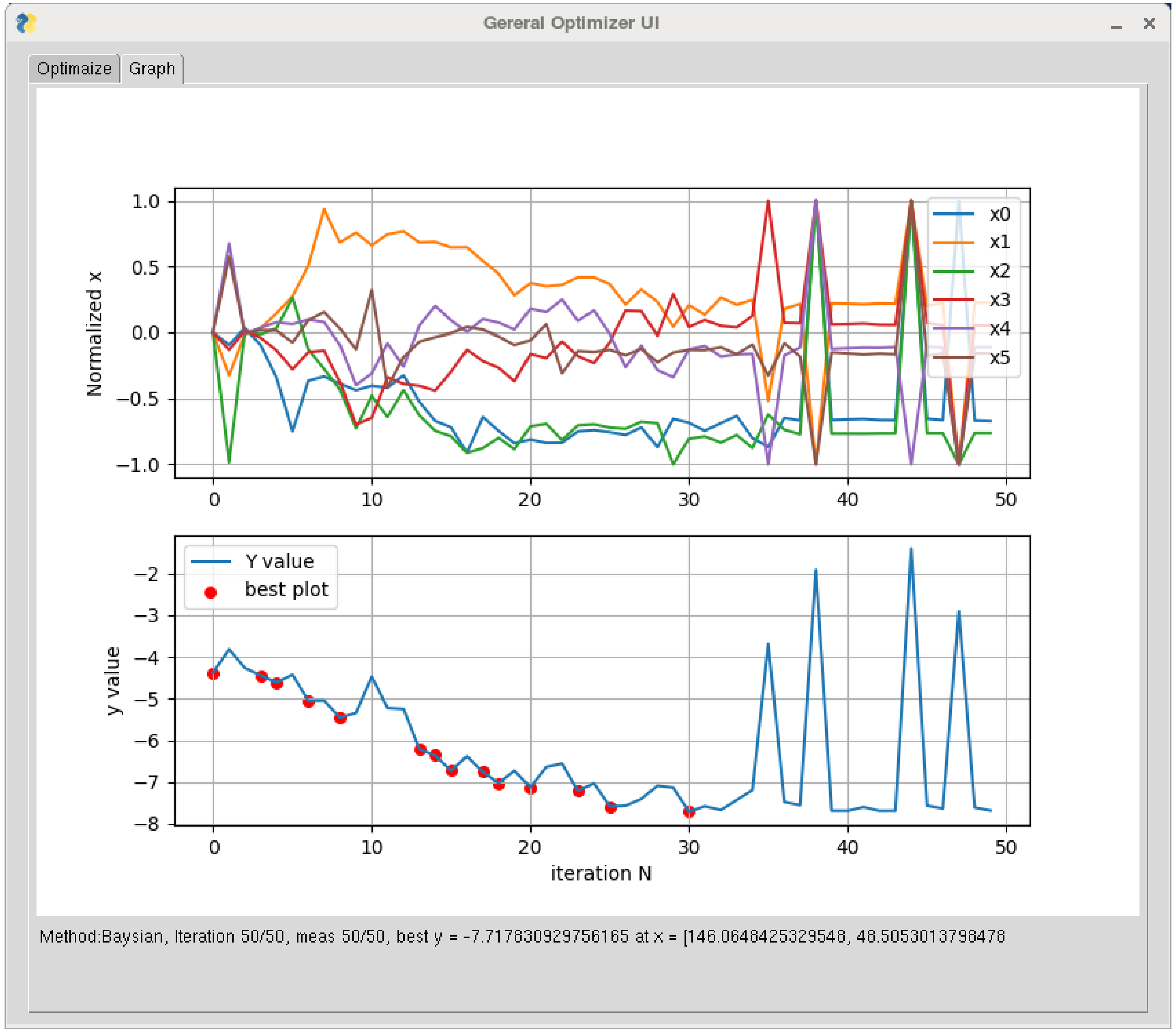
BPM data in linac while auto tuning.





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

Example 1



SH_A1_S1 (KBP) 146.7° → 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

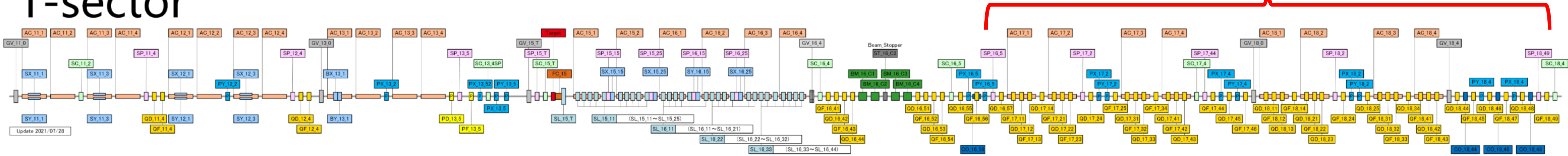
The problem was the large beam loss of positron in the capture section. The transmission was lower than the simulation results, but the cause had not been identified.

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.

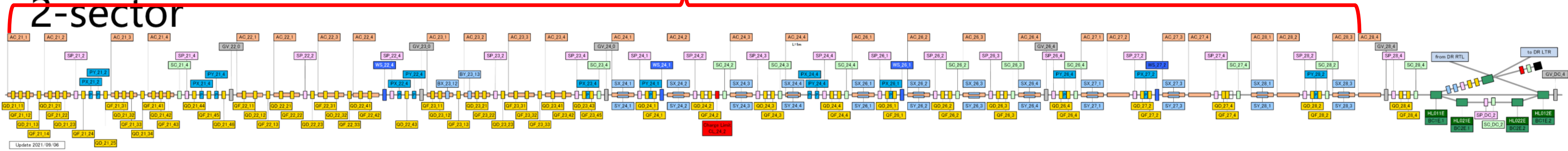
Sector-1 tuning region

1-sector

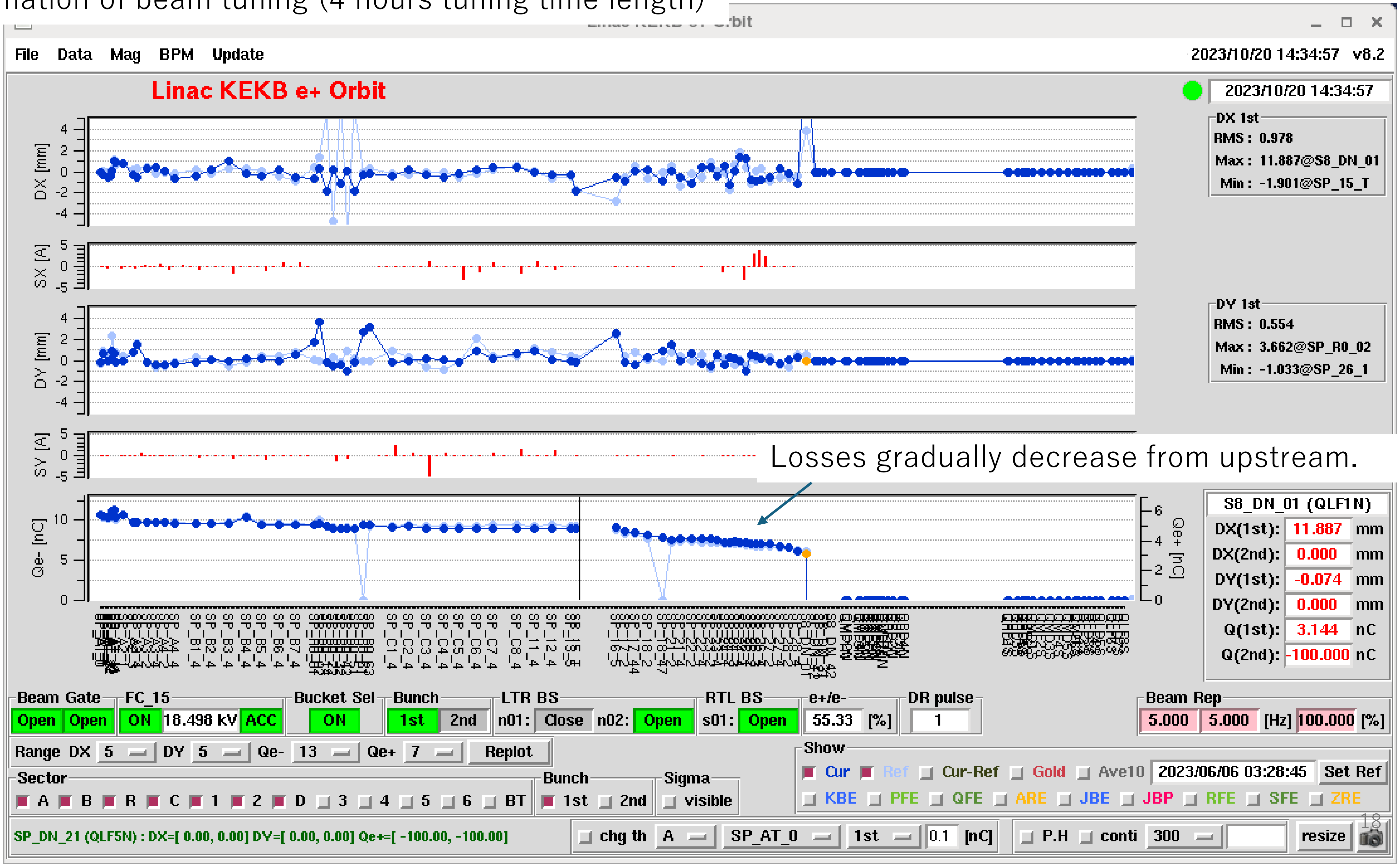


Sector-2 tuning region

2-sector

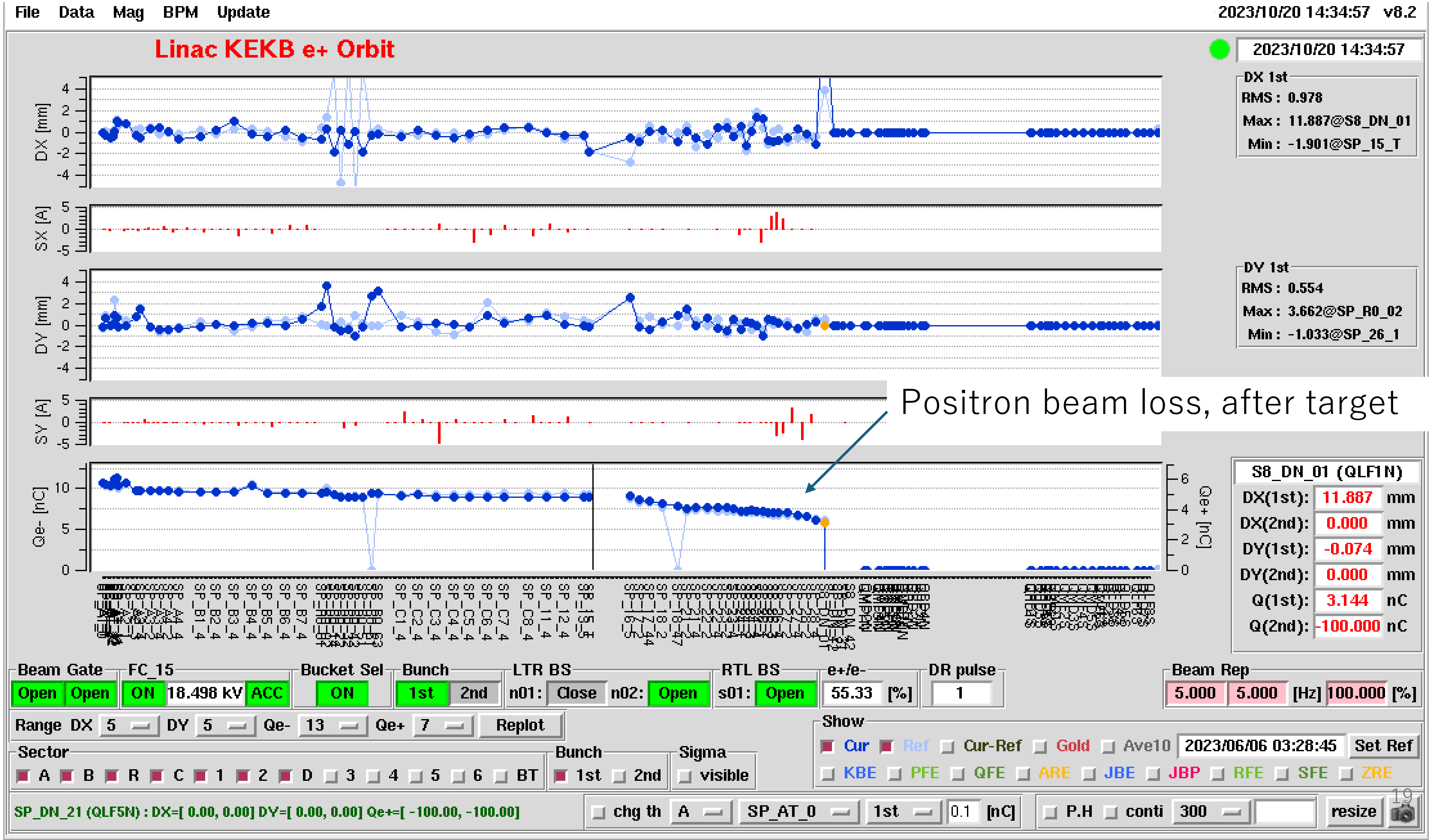


Animation of beam tuning (4 hours tuning time length)

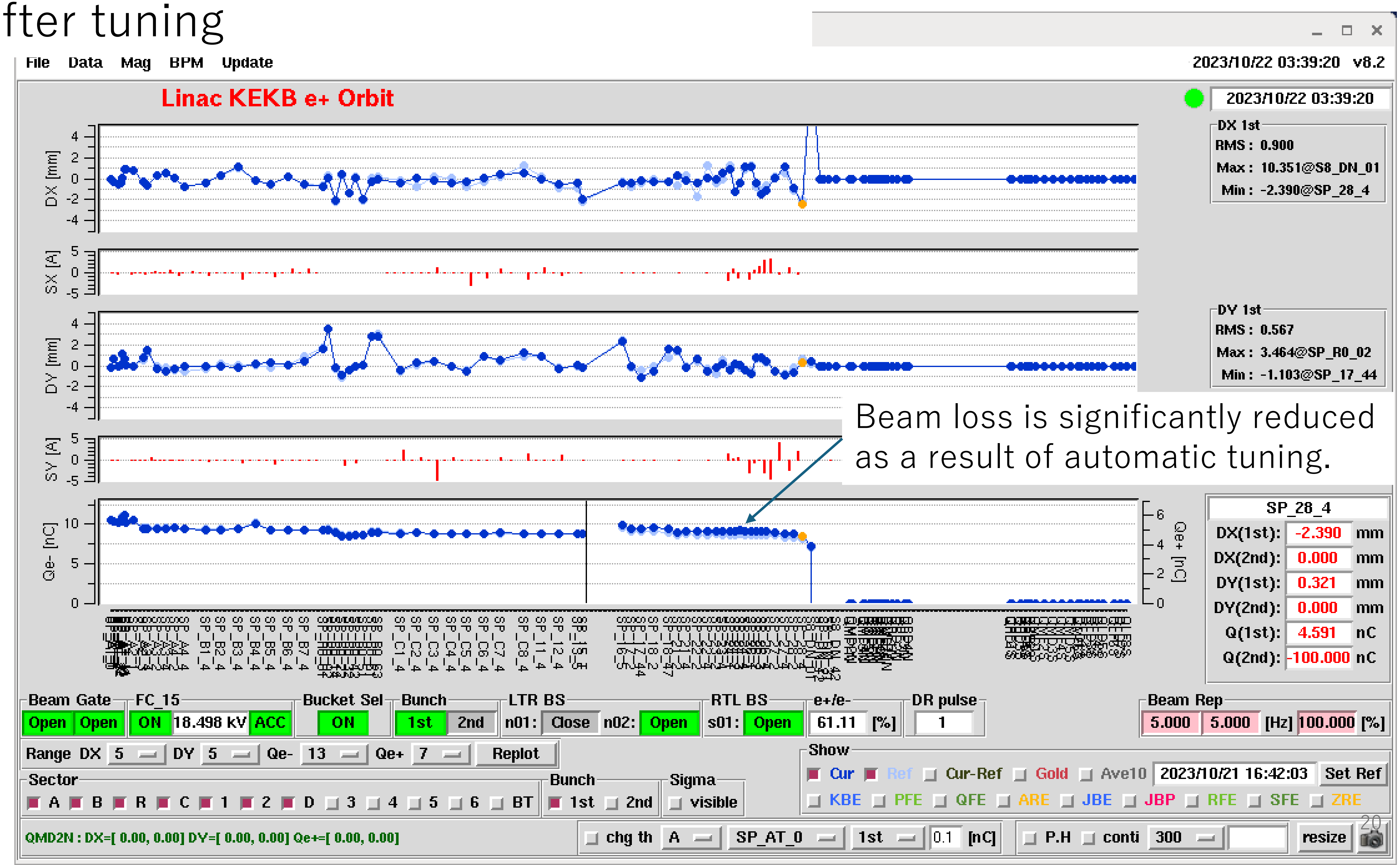


Losses gradually decrease from upstream.

Before tuning

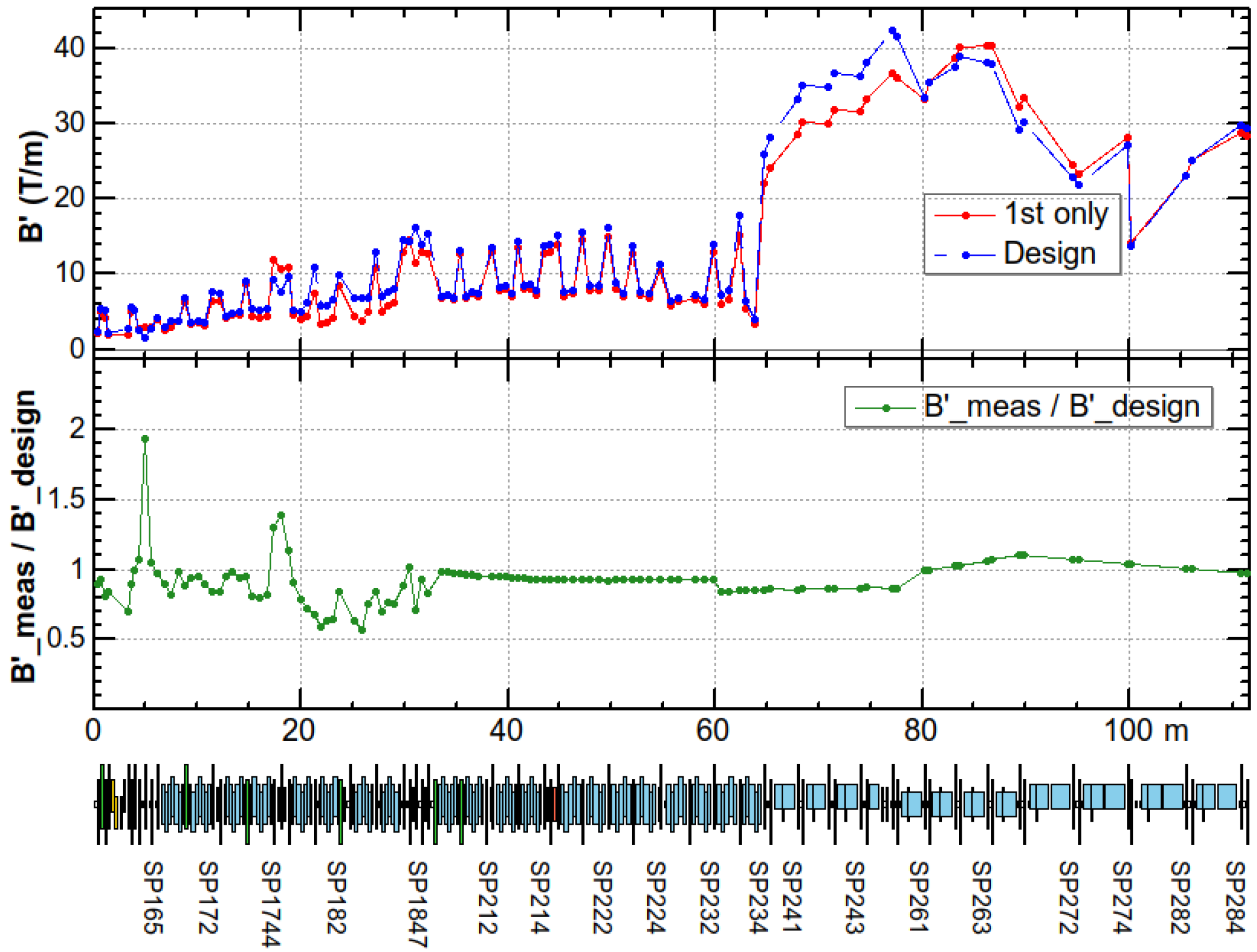


After tuning



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?

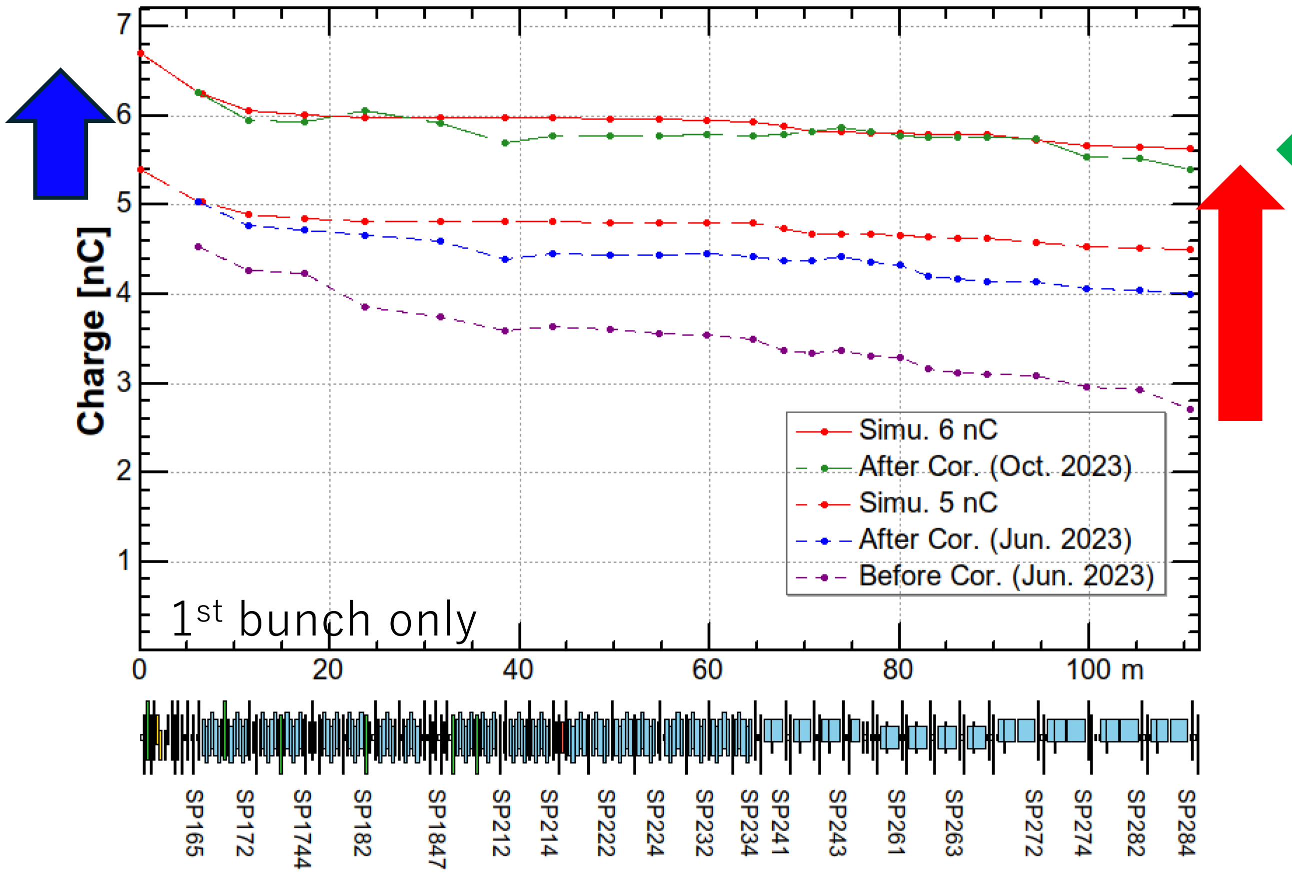
Although the adjustment itself was made with the improvement of charge quantity as an index, a trend of discrepancy with the design became visible as a result.

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 the KEK injector linac, there are many tuning parameters for four-ring injection, and the number of tuning knobs has been increasing in recent years due to the increase in the number of pulsed magnets.
- Automatic tuning was introduced to ensure sufficient tuning in a small amount of manpower and time.
- We use Bayesian optimization and Downhill simplex method as optimization algorithms.
- In accelerator facilities where many adjustment knobs are controlled by a control system such as EPICS, such automatic adjustment is very useful.
- In fact, the automatic tuning contributed significantly to the increase in positron production.
- In the future, we would like to make the automatic tuning easier to use and apply it to routine beam stabilization.