

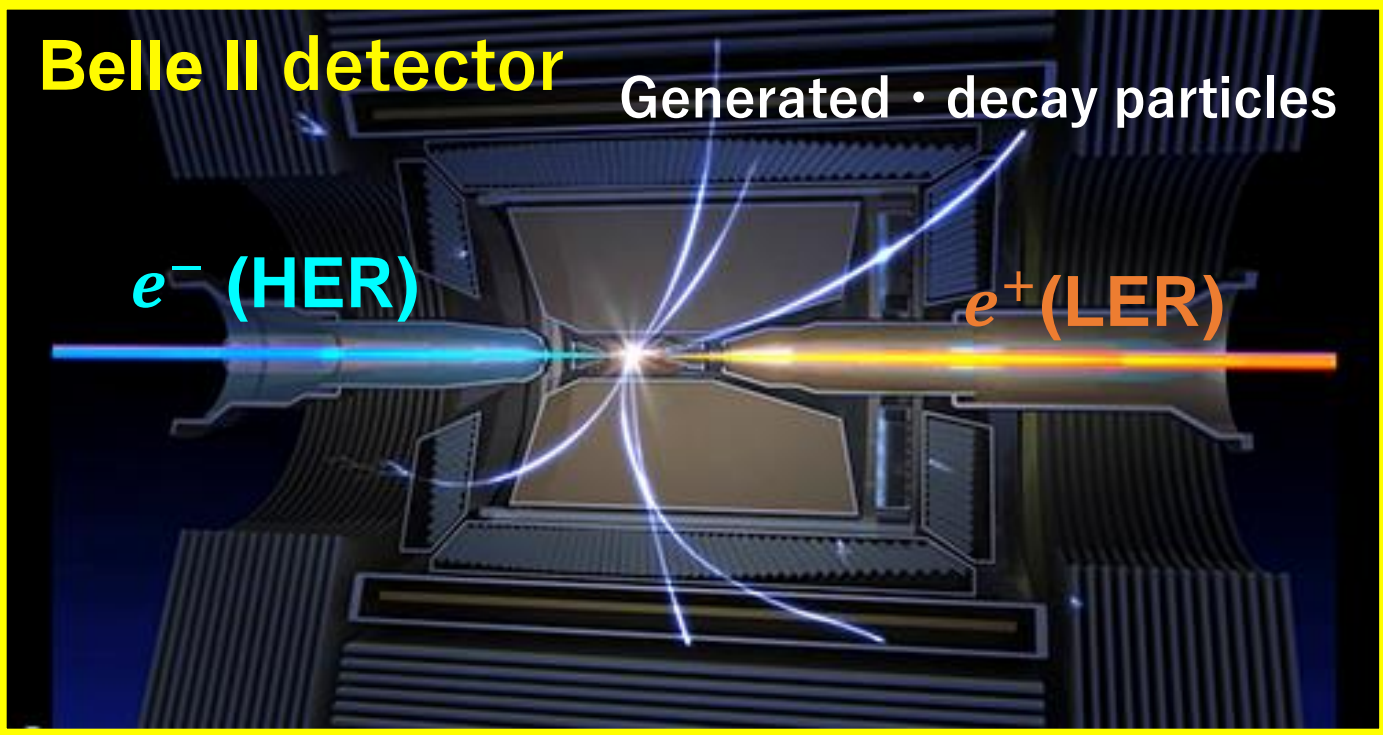
# Machine-learning-assisted beam tuning at the KEK Linac and prospects for SuperKEKB



UTokyo  
KEK.Acc

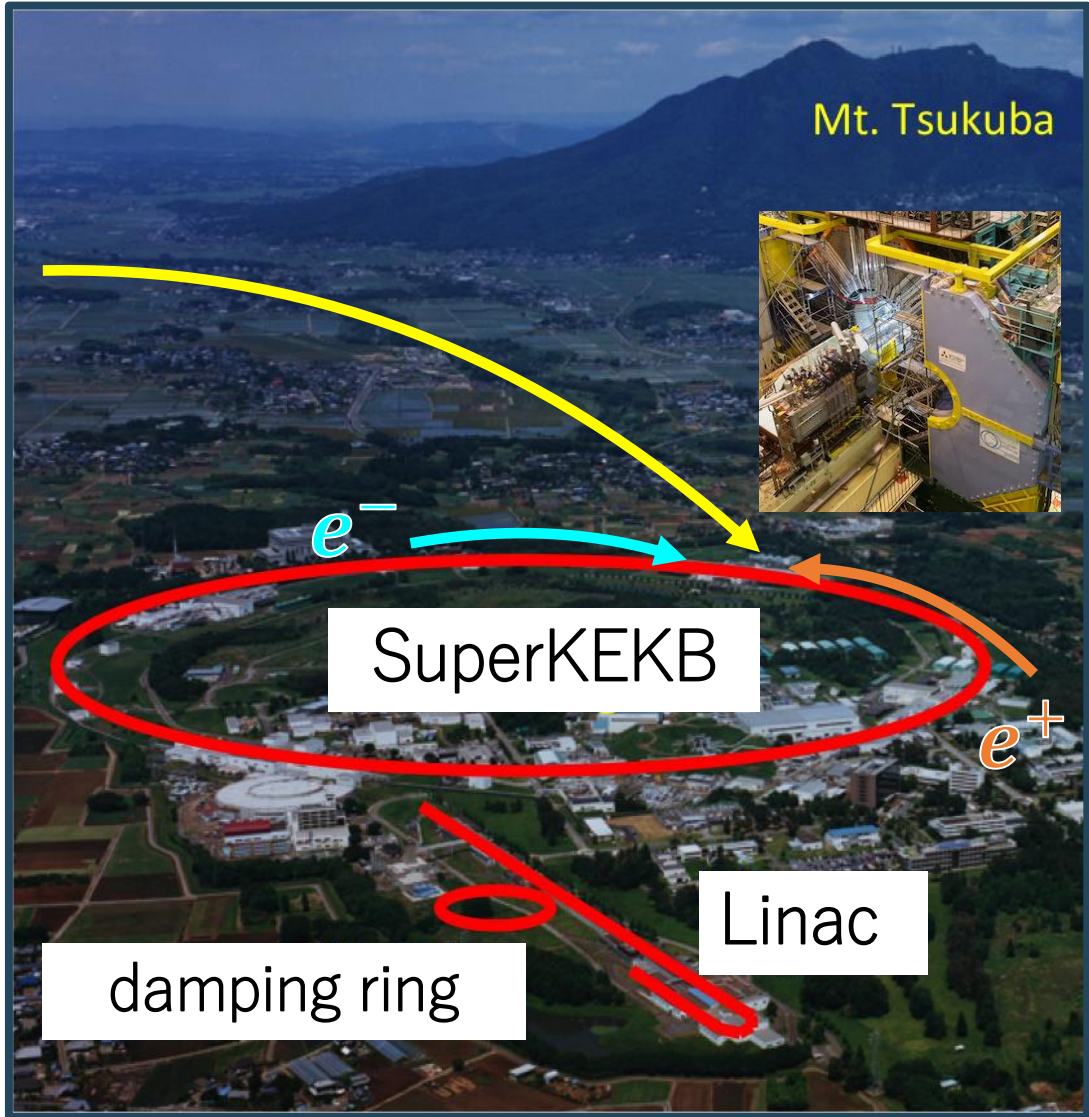
**Shinnosuke Kato**  
Gaku Mitsuka

# Luminosity is important in the search for a new physics



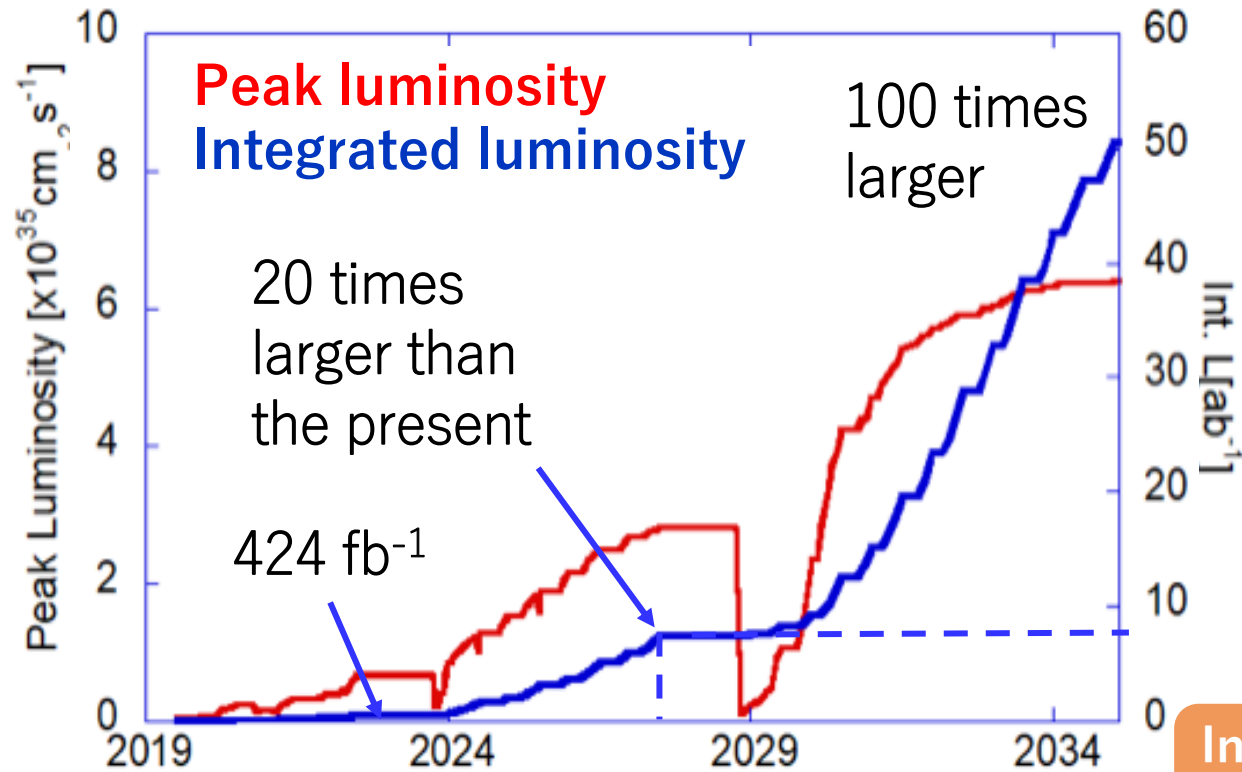
$$N = \sigma [\text{cm}^2] \int L [\text{cm}^{-2}\text{s}^{-1}] dt [s]$$

Accumulating statistics N to search for a new physics  
 → Requires high peak luminosity and long-term stability



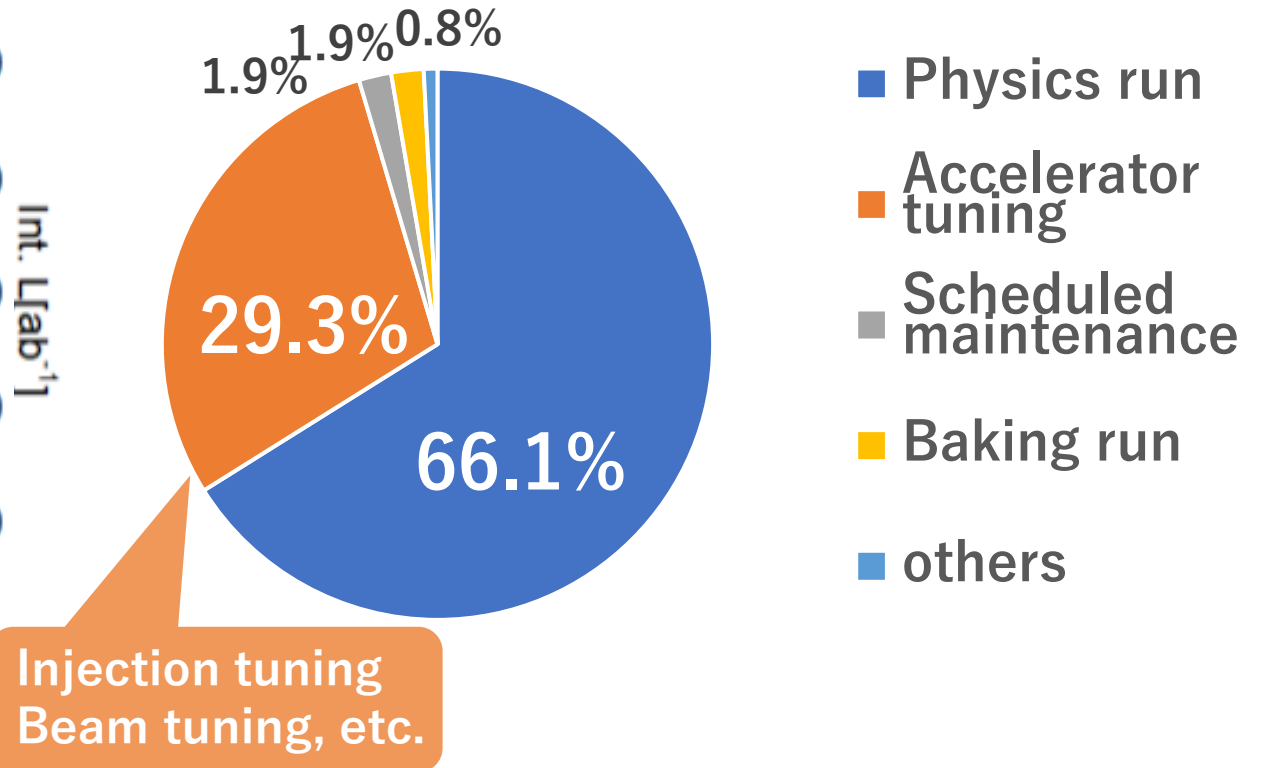
# Motivation to introduce machine learning

## Target profile of luminosity



## Belle II / SuperKEKB Run time breakdown

(Feb. 21 - Jun. 22, 2022)



We want to reduce **accelerator tuning time** using machine learning

# Linac study for SuperKEKB injection tuning

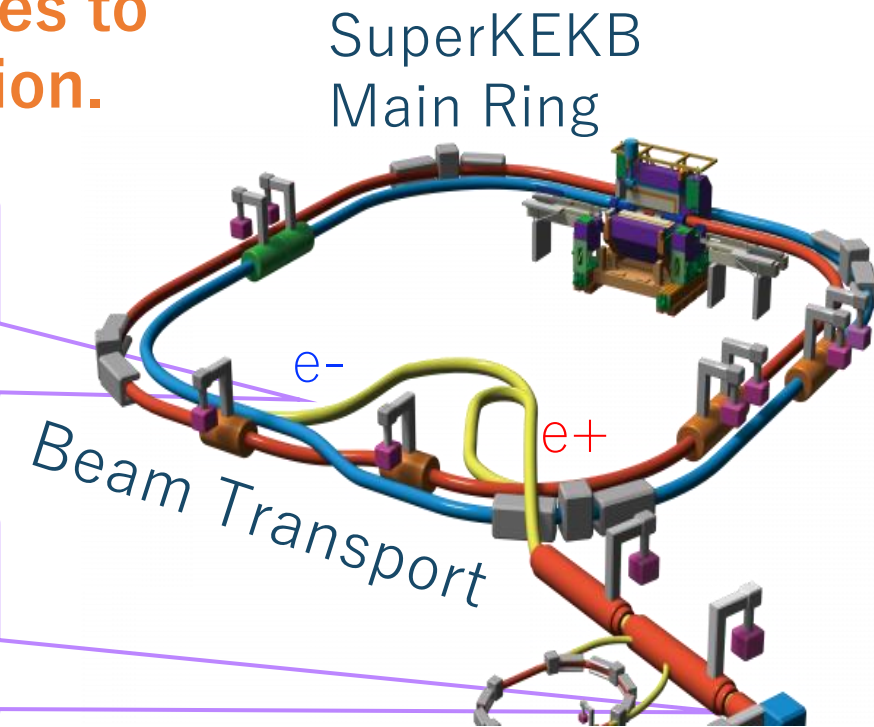
SuperKEKB main ring continues to inject beams during the collision.

Injection tuning (expected to save tuning time, 2024~)

- Support for improving injection efficiency by ML
- Run operators usually adjust by 4~6 parameters

KEK Linac  $e^+$  beam study (Dec. 2023)

- Maximize  $e^+$  beam charge using ML
- Adjust beam orbit using 6 parameters



For machine learning.....

- **How quickly** can we optimize the beam?

# Outline

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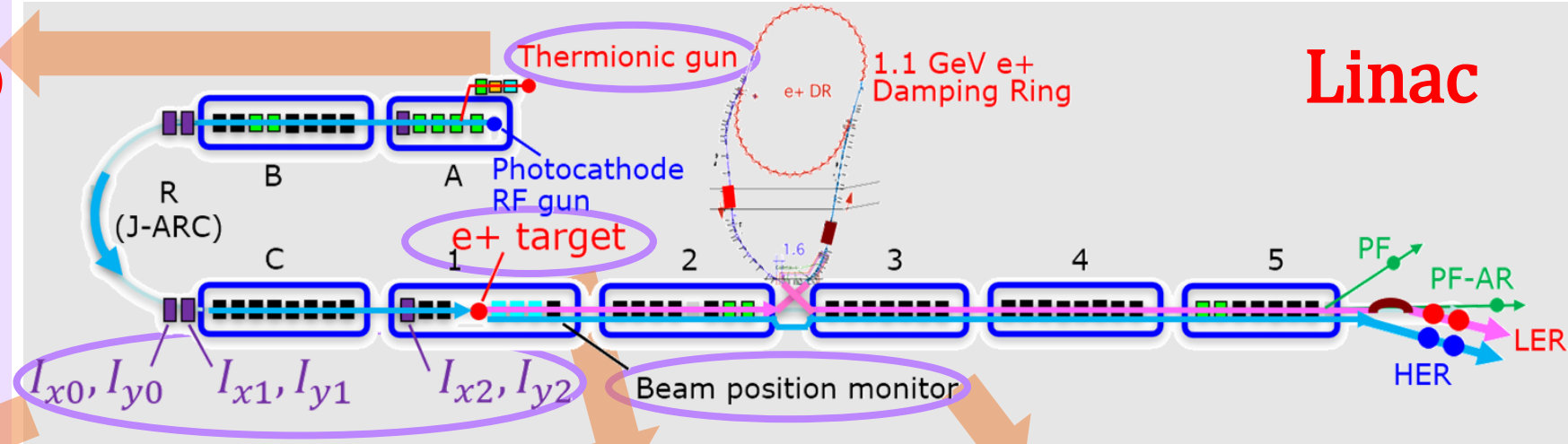
- **KEK Linac  $e^+$  beam study**
  - Experiment setup of this study
  - Explanation of Bayesian optimization
  - Initialization details
  - Results
    - Single run
    - Peak hold
    - Toward injection tuning at the SuperKEKB operation
      - Waiting time
      - One-stroke function
- **Summary and prospects**



# Components used in the Linac study

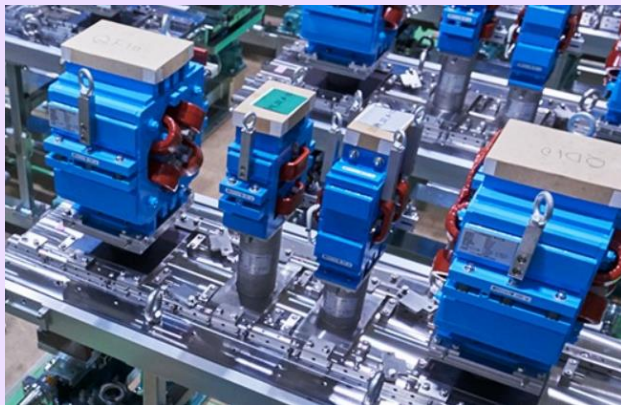
Thermionic electron gun

(Generate  $e^-$  beam for  $e^+$  beam)



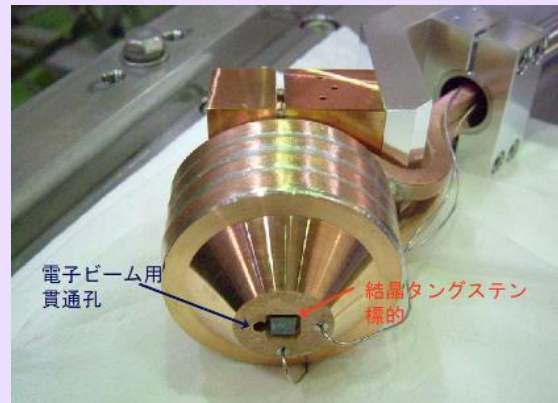
Pulse steering magnets

(Adjust beam trajectory)



Tungsten Target

(Generate  $e^+$  beam)



Beam position monitor

(Measure the beam charge)



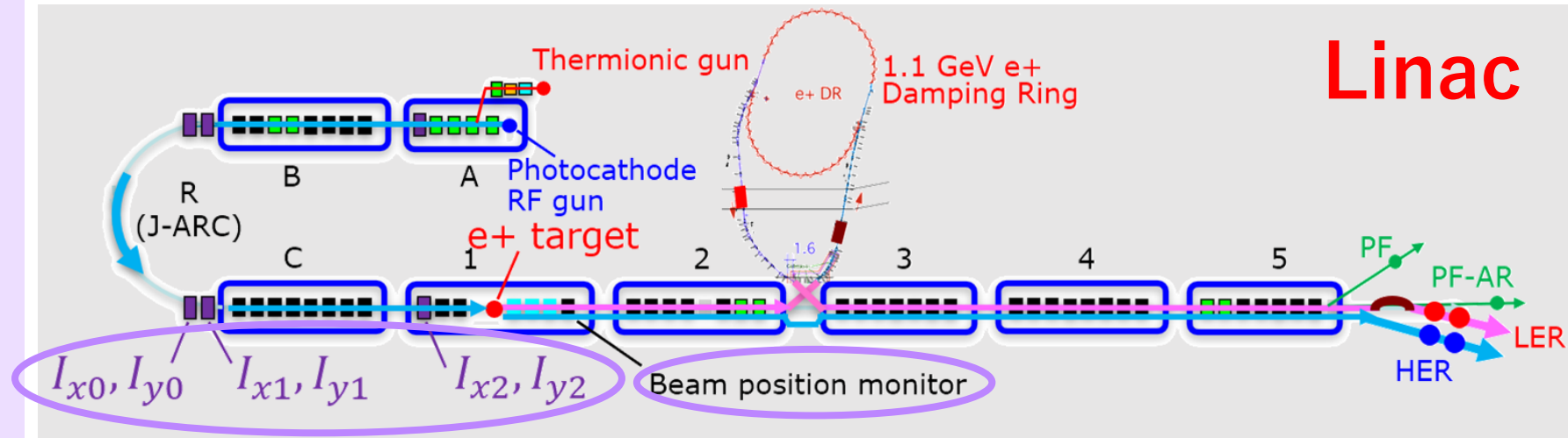
# How does Bayesian optimization maximize beam charge?

## Tuning parameters

Applied current of  
6 steering magnets :  
 $I_{x0}, I_{y0}, I_{x1}, I_{y1}, I_{x2}, I_{y2}$  (A)

## Evaluation parameter

Beam charge measured  
by BPM:  $Q$  (nC)



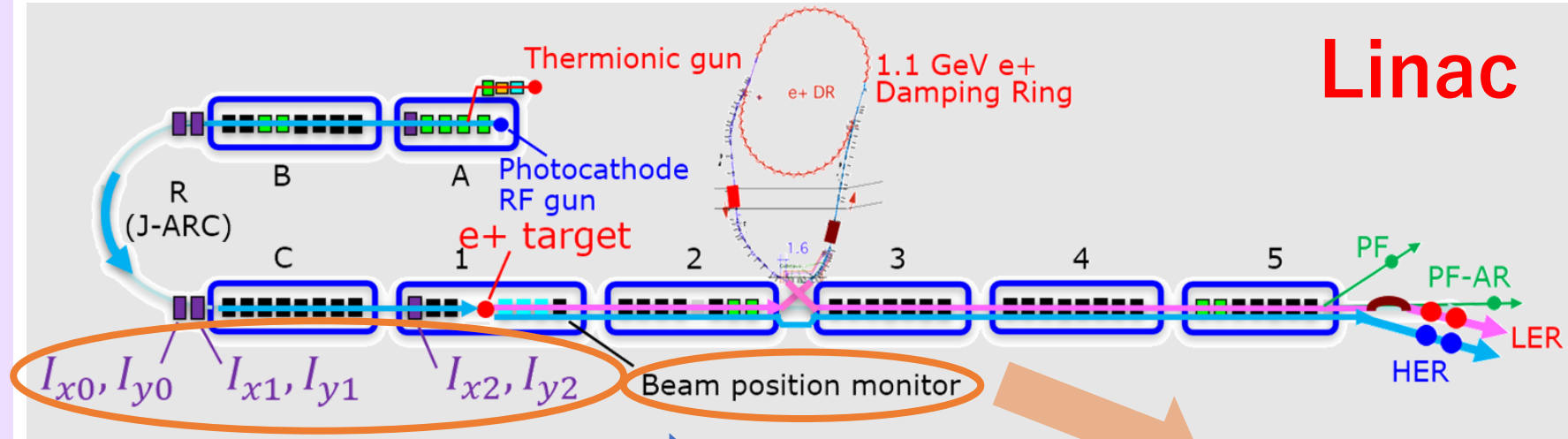
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## Evaluation parameter

Beam charge measured by BPM:  $Q$  (nC)



③ Put this value on applied current



① Get the beam charge

② Estimate best current at that time to maximize charge

**Bayesian optimization (BoTorch)**

Accumulate the data

Trial1	$I_{x0} \sim I_{y2}$	$\leftrightarrow Q$
Trial2	$I'_{x0} \sim I'_{y2}$	$\leftrightarrow Q'$
⋮	⋮	⋮



# How does Bayesian optimization maximize beam charge?

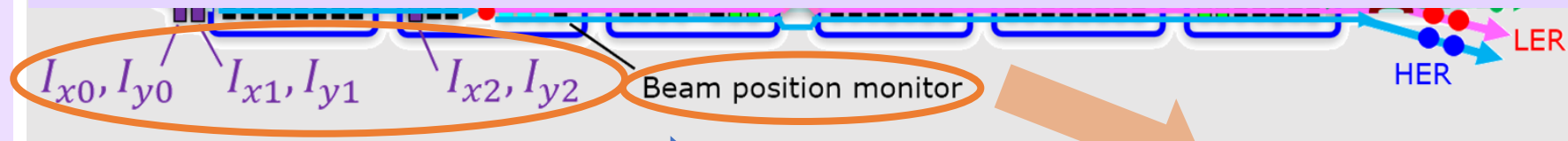
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Applied current of  
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 $I_{x0}, I_{y0}, I_{x1}, I_{y1}, I_{x2}, I_{y2}$  (A)

## Evaluation parameter

Beam charge measured  
by BPM:  $Q$  (nC)

- This iteration is called a **"trial"**.
- We call 100 trials as **"1 run"**.
- Measure "run" under **various initialization**. (next page)



③ Put this value  
on applied current



① Get the  
beam charge

② Estimate best  
current at that time  
to maximize charge

Accumulate the data

Trial1  $I_{x0} \sim I_{y2} \leftrightarrow Q$

Trial2  $I'_{x0} \sim I'_{y2} \leftrightarrow Q'$

$\vdots$

**Bayesian  
optimization  
(BoTorch)**

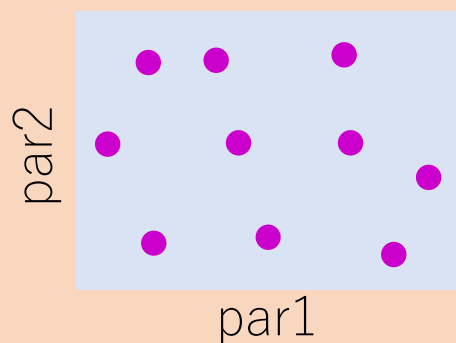


# Initialization details

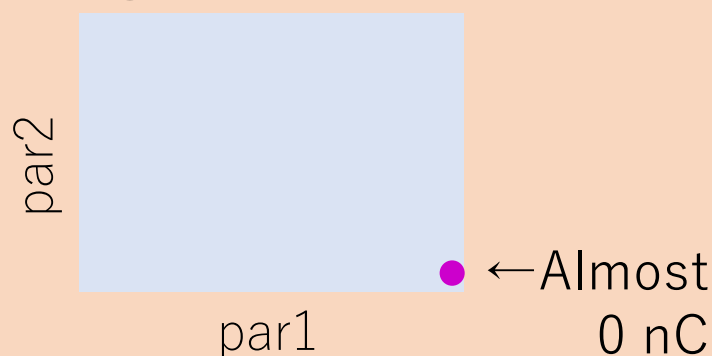
- We tested 3 types of Initializations.

## Poor knowledge

Random Initialization



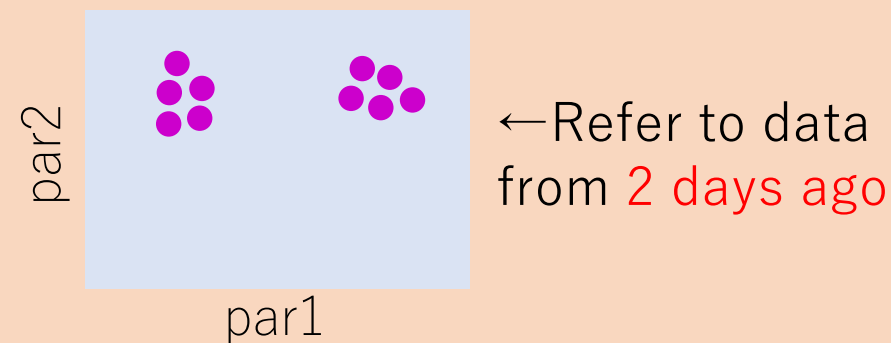
Initialized at the edge of domain



For the case that **we only poorly know the machine parameters** suitable for the present condition.

## Best knowledge

Use best parameters from previous run



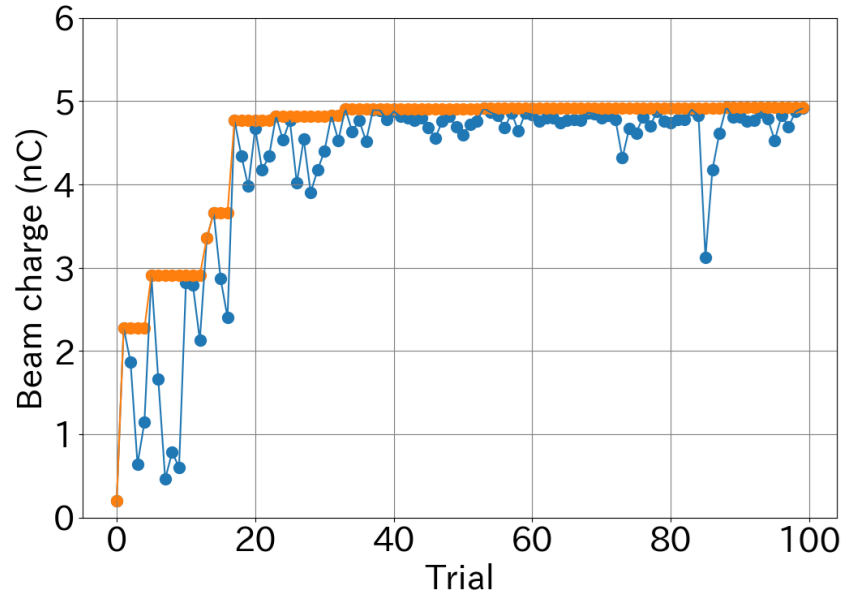
For the case that **we know the best parameters** suitable for the present condition.

Operator tuned value  
(Dec. 12) **4.9 nC**

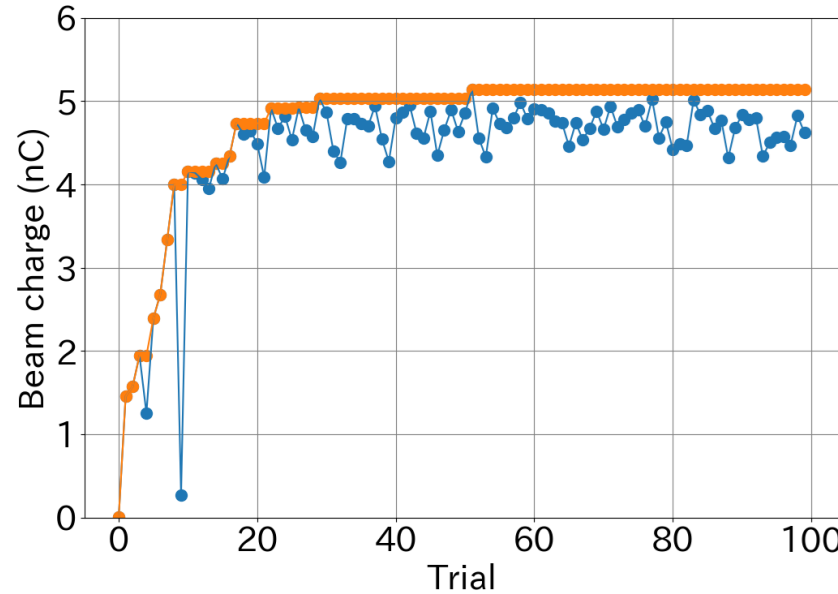
# Single run results

Operator tuned value  
(Dec. 14) **5.2 nC**

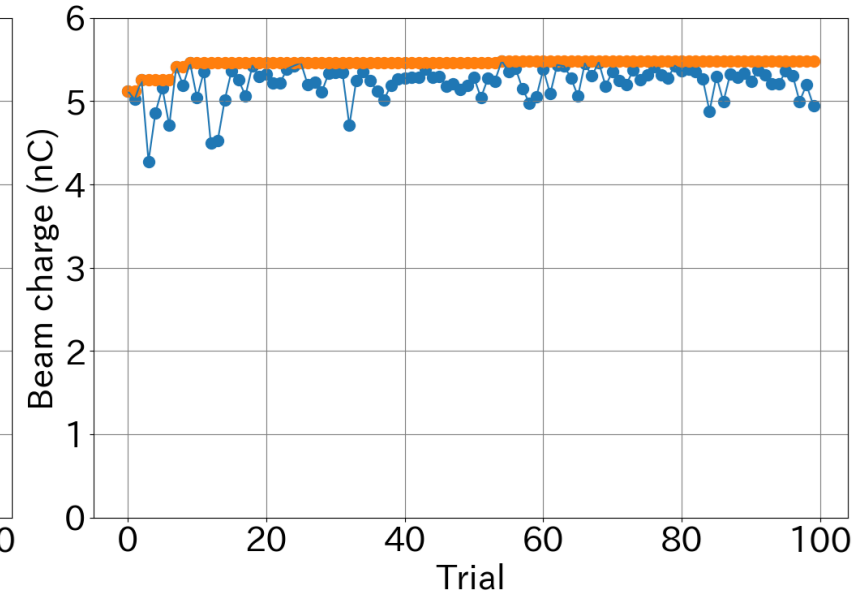
Random number(Dec. 12)



Edge of domain(Dec. 14)



Best parameters(Dec. 14)



**Blue** : Beam charge at each trial      **Orange** : Peak hold (Maximum at that time)

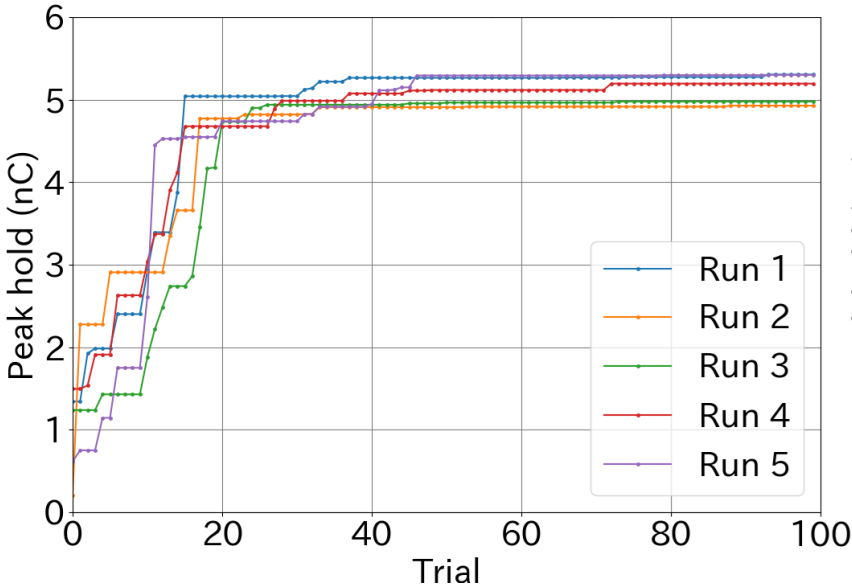
**The optimization worked well for all initialization conditions.**

Operator tuned value  
(Dec. 12) **4.9 nC**

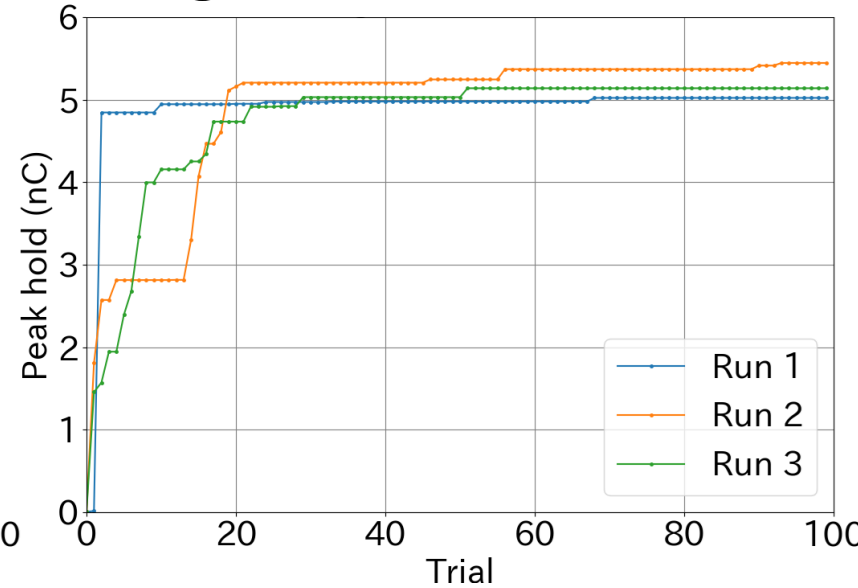
# Peak hold results

Operator tuned value  
(Dec. 14) **5.2 nC**

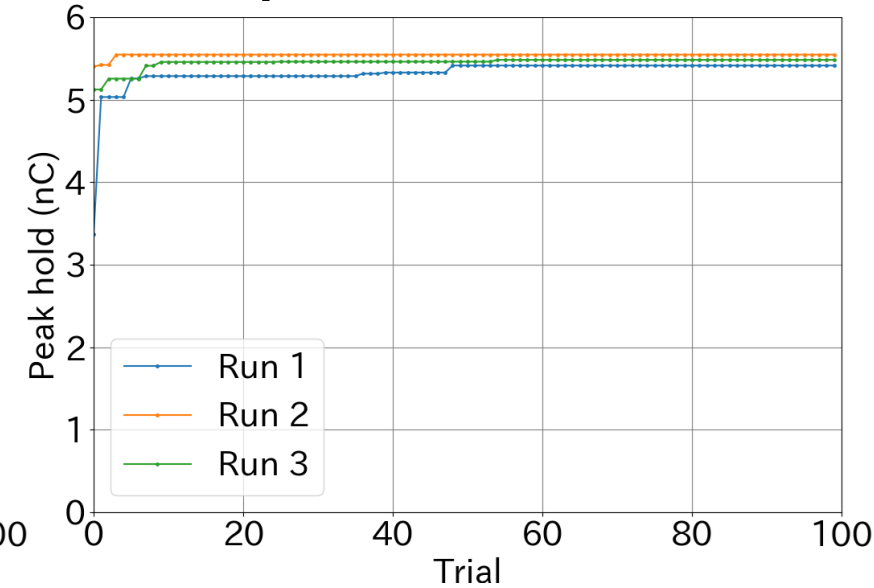
Random number(Dec. 12)



Edge of domain(Dec. 14)



Best parameters(Dec. 14)



- Optimization worked well on **all runs**.
- In poor knowledge, the beam charge was optimized at about **30trial (5min)**.
- Initialization with best parameters optimize **very quickly (less than a minute)**.



# Outline

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- **KEK Linac  $e^+$  beam study**

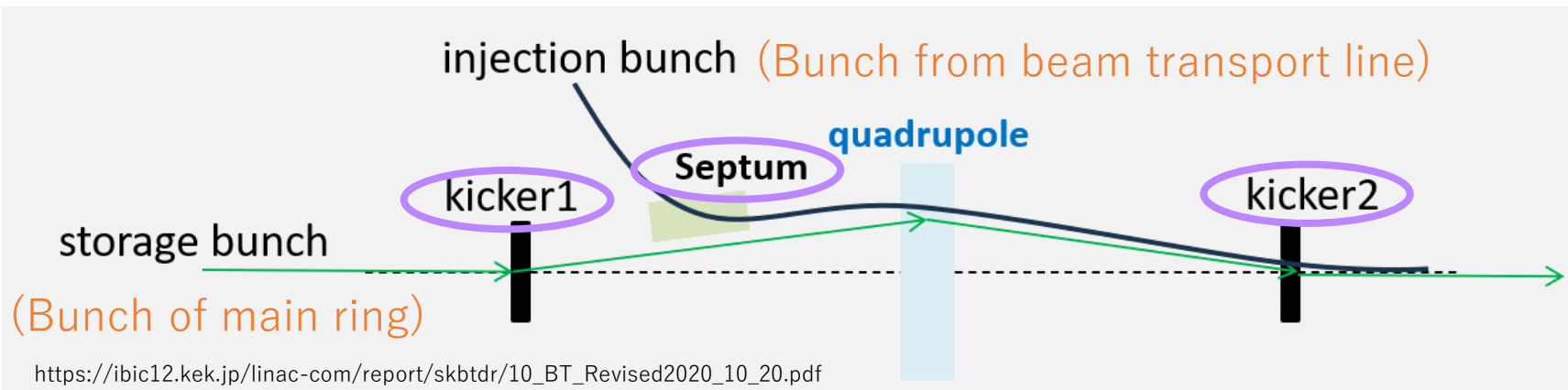
- Experiment setup of this study
- Explanation of Bayesian optimization
- Initialization details

- Results

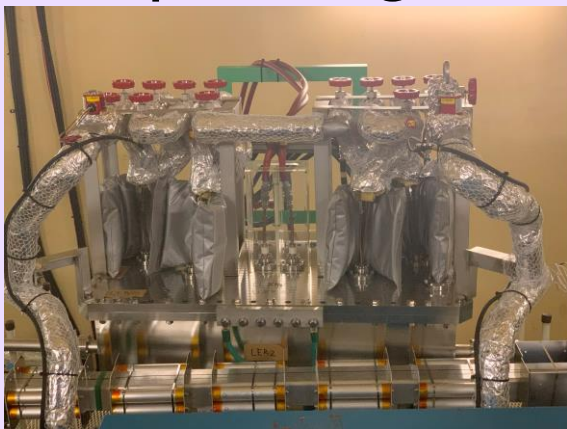
- Single run
- Peak hold
- Toward injection tuning at the SuperKEKB operation
  - Waiting time
  - One-stroke function

- **Summary and prospects**

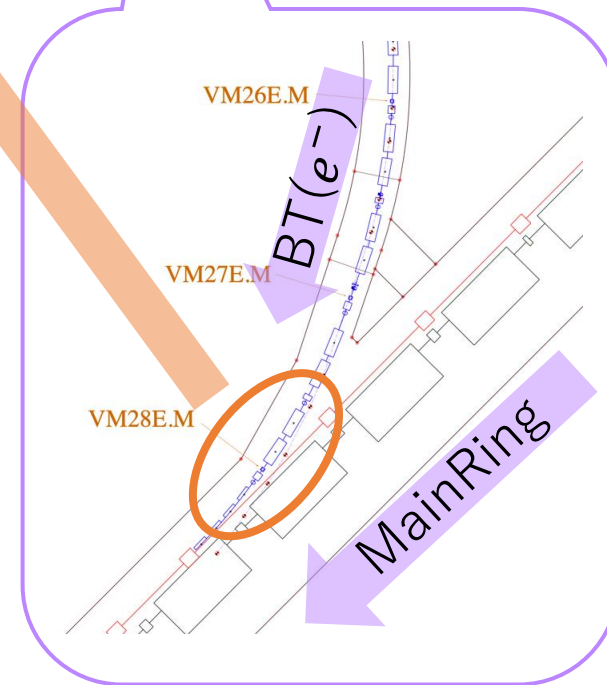
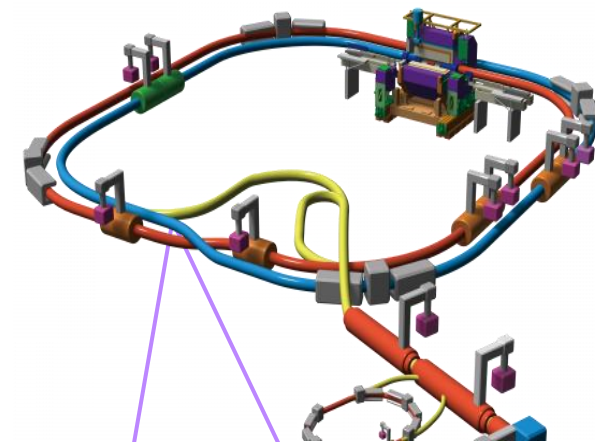
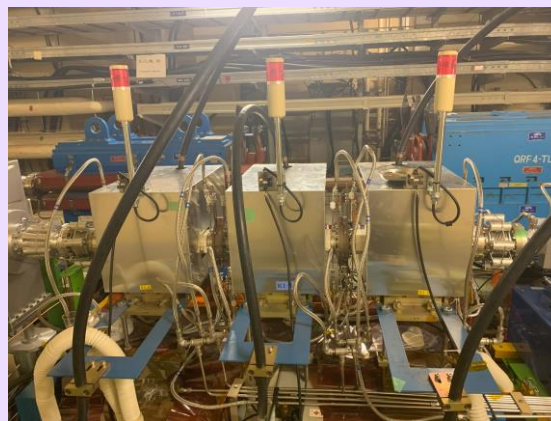
# Injection tuning at the SuperKEKB operation



## Septum magnet



## Kicker magnet



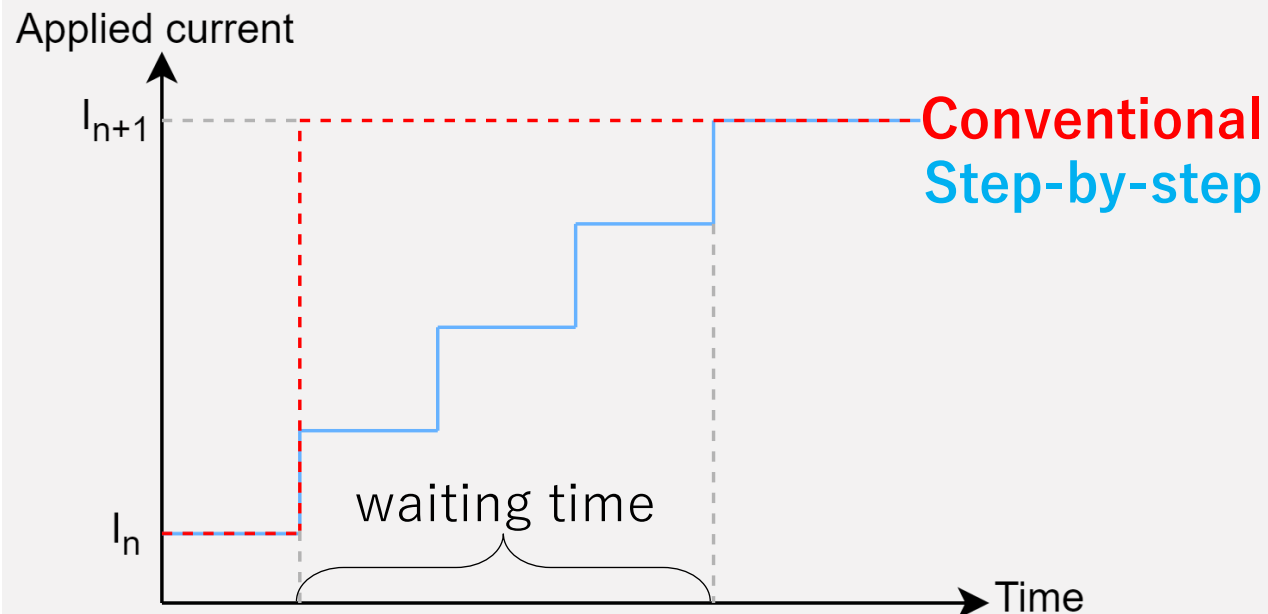
Gradual changes in the magnetic fields are preferred for these magnets at the beam-transport line from the machine safety point of view.

# Improvements toward injection tuning

- We introduced the **step-by-step mechanism** by allowing a few seconds of waiting time after changing the magnet setting.
- Optimization according to **the one-stroke function** can reduce the waiting time.

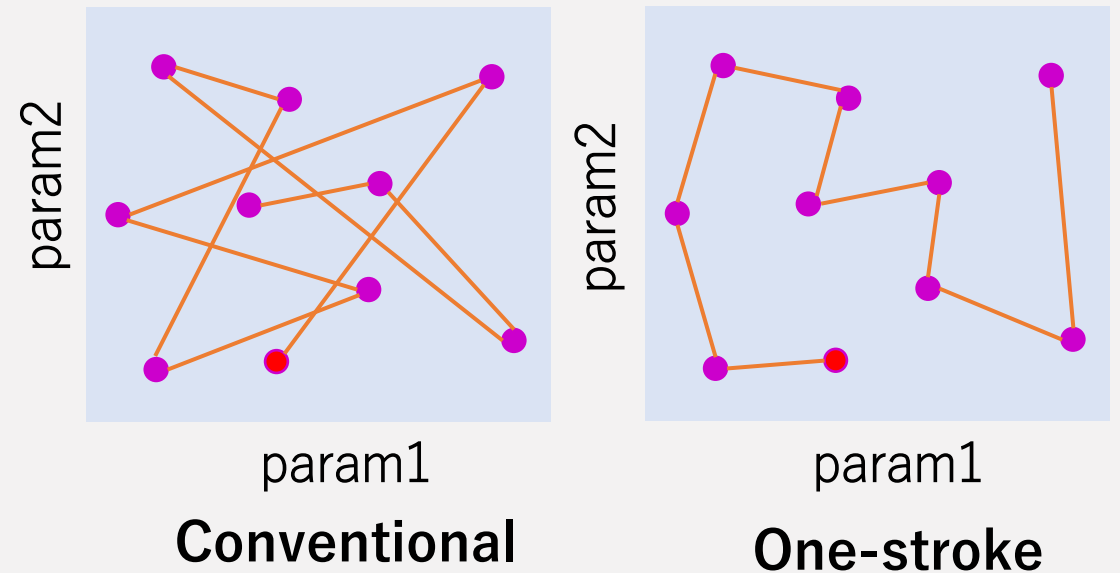
## ➤ Step-by-step mechanism

→ Increased waiting time but no sudden change in current



## ➤ One-stroke function

→ Expected to reduce waiting time

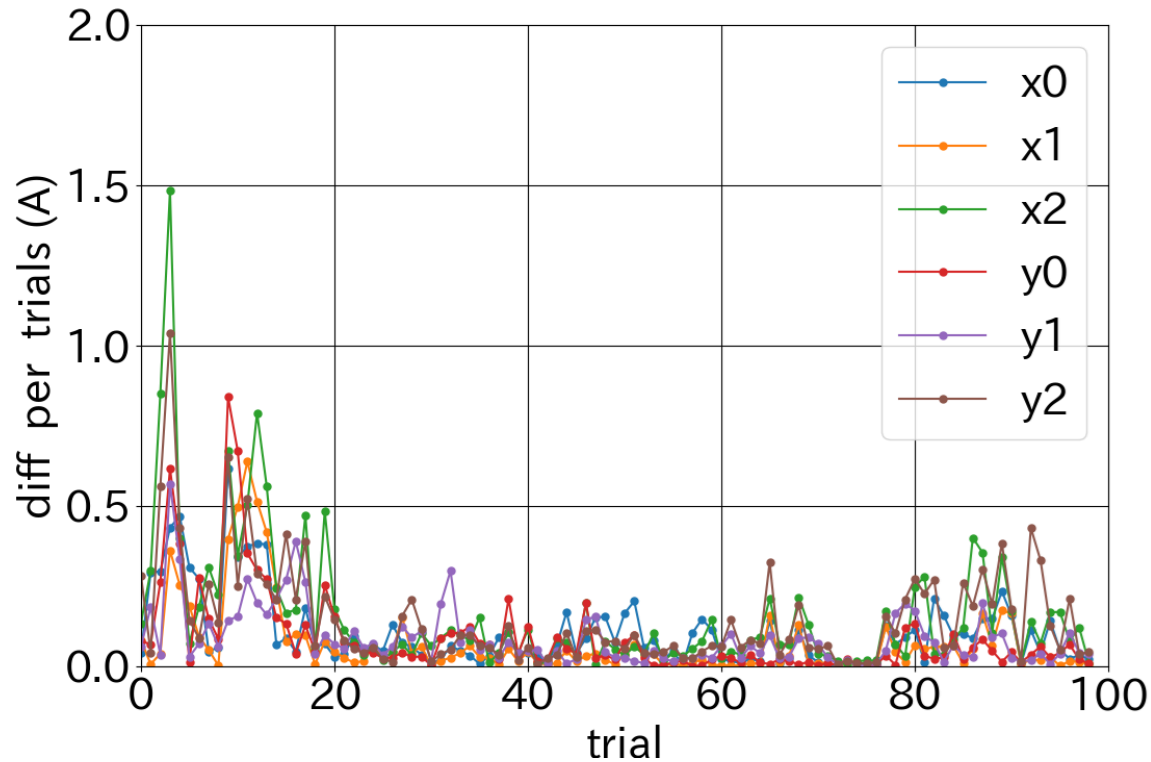


(Ryan,2021, [https://ml4physicalsciences.github.io/2021/files/NeurIPS\\_ML4PS\\_2021\\_82.pdf](https://ml4physicalsciences.github.io/2021/files/NeurIPS_ML4PS_2021_82.pdf))

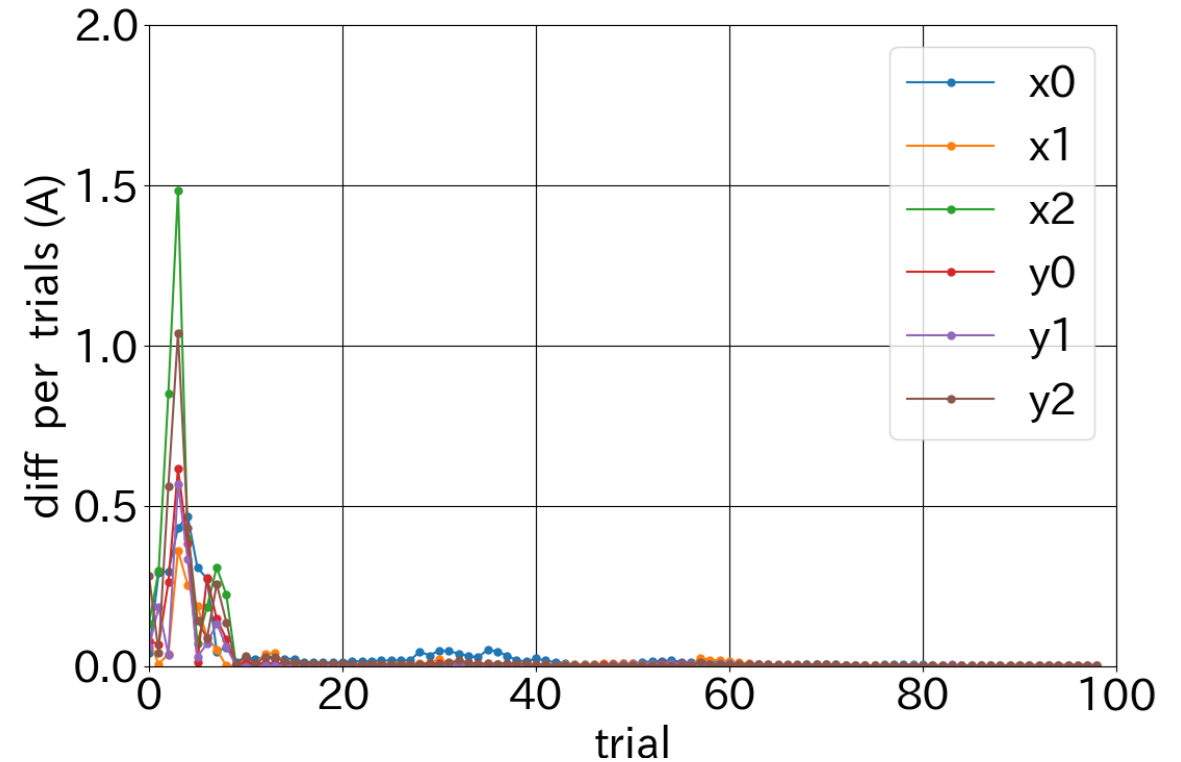
# Check the operation of one-stroke function

Diff per trials =  $|I_t - I_{t-1}|$  ( $I_t$  : applied current of each magnet  $t$  : trial )

## Conventional



## Use one-stroke



**We verified that the one-stroke function works correctly.**



# Summary and prospects

## ➤ Summary

- We maximized positron beam charge using Bayesian optimization by adjusting the electron beam orbit for positron production in KEK Linac.
- Under the initialization with **poor knowledge**, the beam charge was maximized in about **5 minutes**. It is expected that optimization can be done for the case that we only poorly know the magnet parameters suitable for the present condition.
- Under the initialization with **best knowledge**, the beam charge was optimized in **less than a minute** using the best parameters from two days ago. It is expected that optimization can be done **quickly** for the case that we know the best parameters suitable for the present condition.
- The implemented functions are expected to work for SuperKEKB injection tuning.

## ➤ Prospects

- Machine learning assisted injection tuning is ready for the upcoming SuperKEKB commissioning **from the end of January**.

# Backup

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