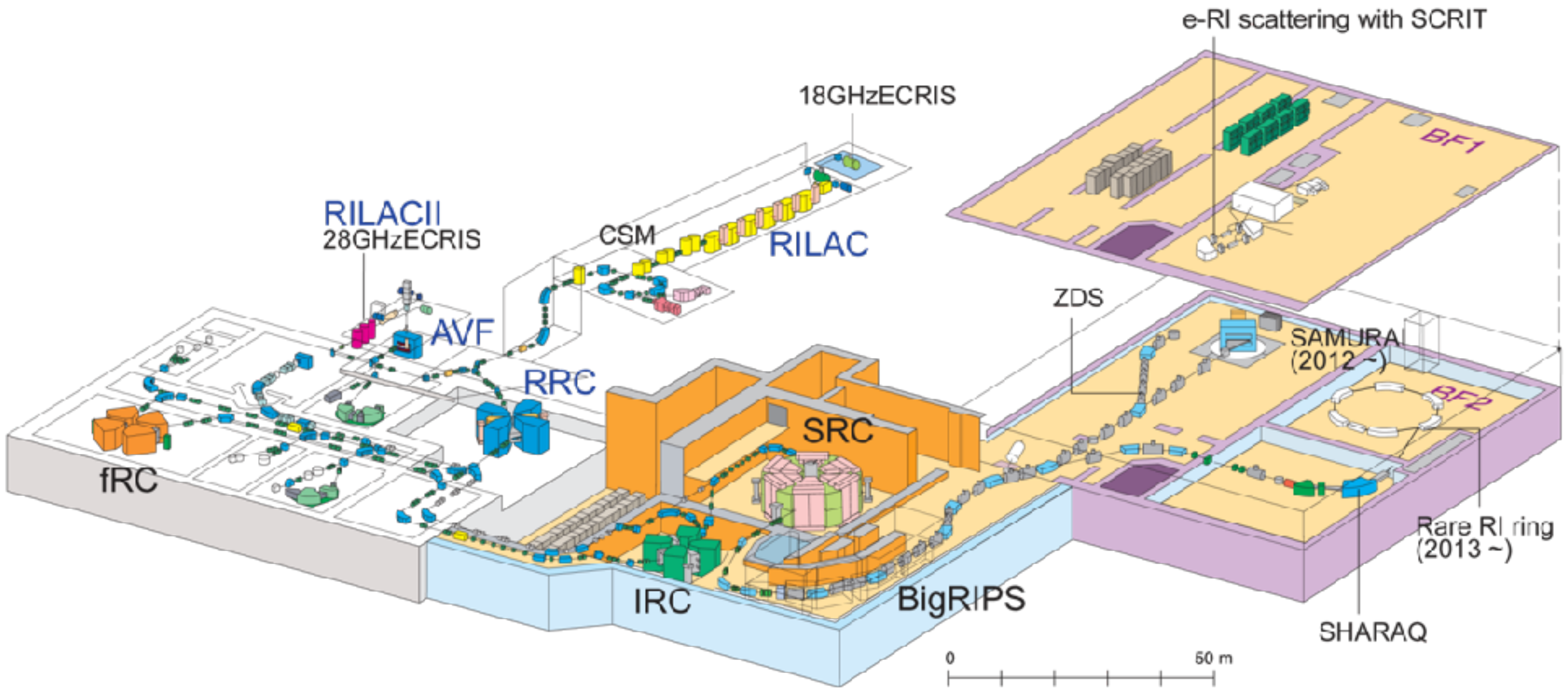
Development of automatic beam tuning system for high intensity heavy ion beams at RIBF

RIKEN Nishina Center for Accelerator-Based Science
Accelerator Group
Takahiro Nishi

Machine Learning Application for RIBF



Multistage accelerator complex
(5 cyclotrons, 2 LINAC, 5 Ion source)
Powerful fragment separator BigRIPS

Radioactive Isotope Beam Factory:

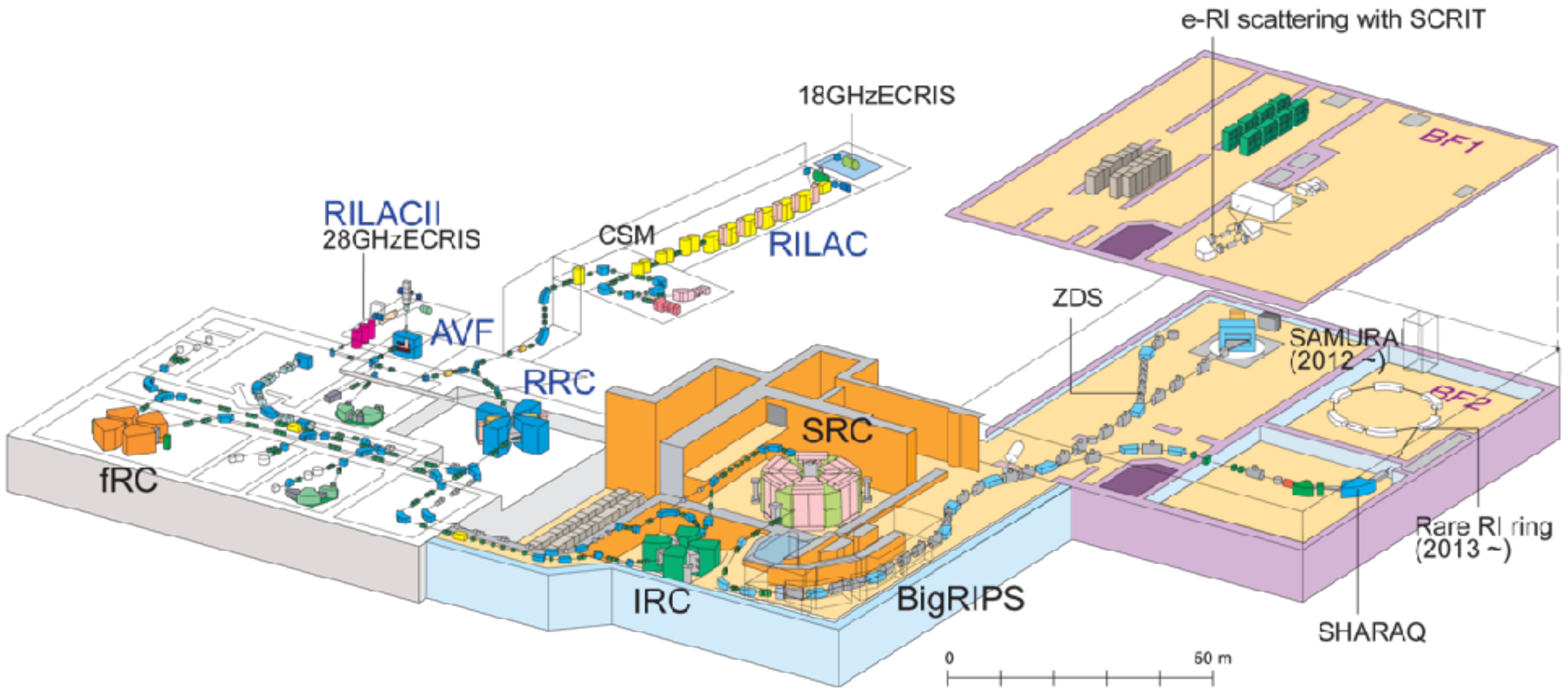
in operation since 2006

Accelerate all elements d (pn) to ^{238}U to ~ 345 MeV/u with high intensity (~ 10 kW / 100 enA)

Development related to AI at RIKEN

- ☐ Transport line
  (beam transport optimization)
- ☐ Ion source
  (beam current estimation with CCD camera)
- ☐ Beam diagnostics
  (beam distribution estimation)
- ☐ Others…

Machine Learning Application for RIBF



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Powerful fragment separator BigRIPS

Development related to AI at RIKEN

☐ **Transport line (beam transport optimization)**

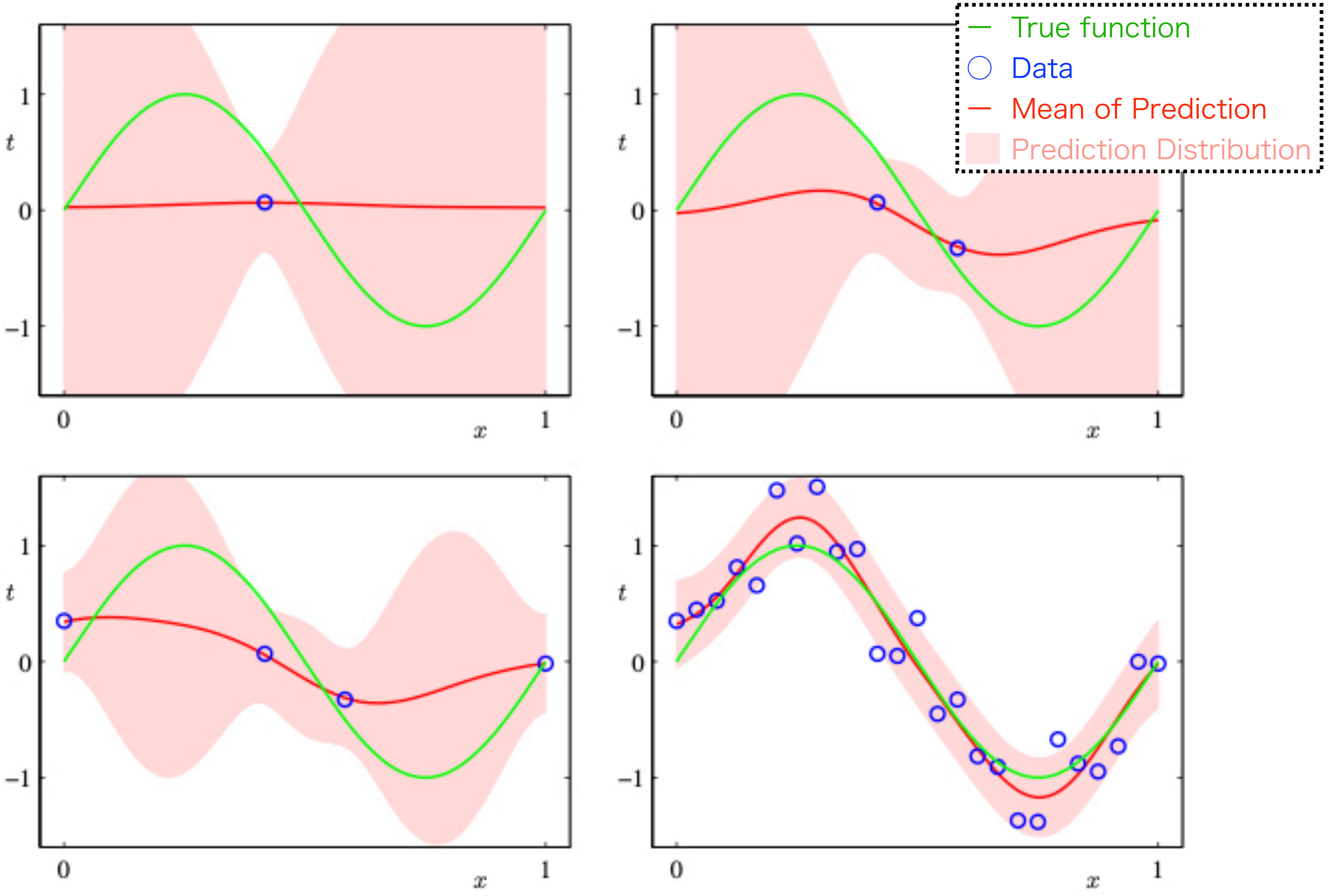
Future goal : **> 1 pμA** $^{86+}$U beam
local beam loss ~ **0.2%** can destroy the facility

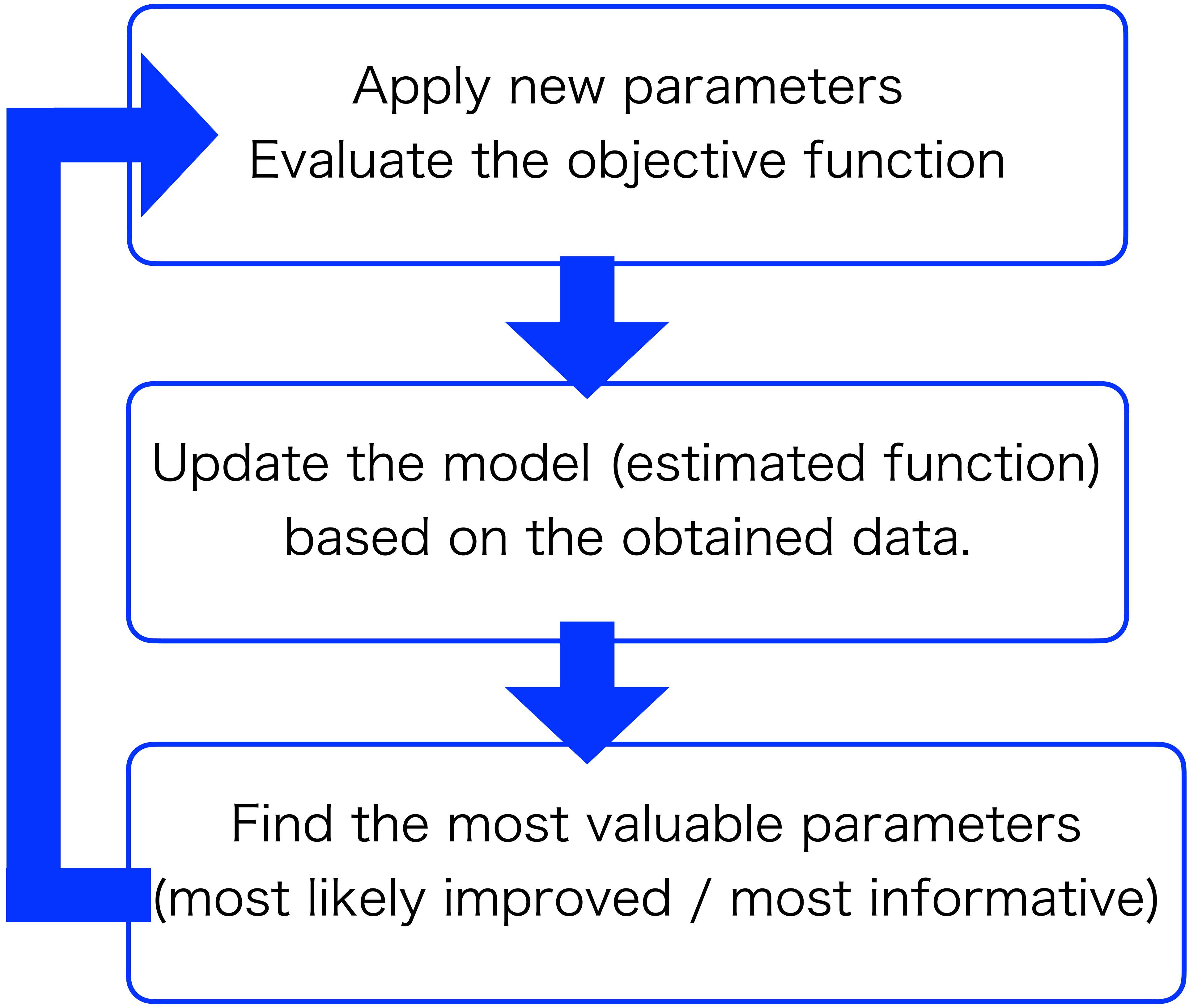
To realize high intense $^{86+}$U beam
(> 1puA / 100 kW), we should
・**suppress beam loss to 0.1 ~ 1%,**
・continuous adjustment

Optimization method	Bayesian Optimization using Gaussian Process Regression
Beam monitor for High intensity	Real Time Analysis of Charge Converted Particles
Safety	Safe Optimization with Line Bayesian Optimization

Optimization Method:
Bayesian Optimization using Gaussian Process Regression

<u>GPR: Estimate the “true function” based on the observed values with errors</u>

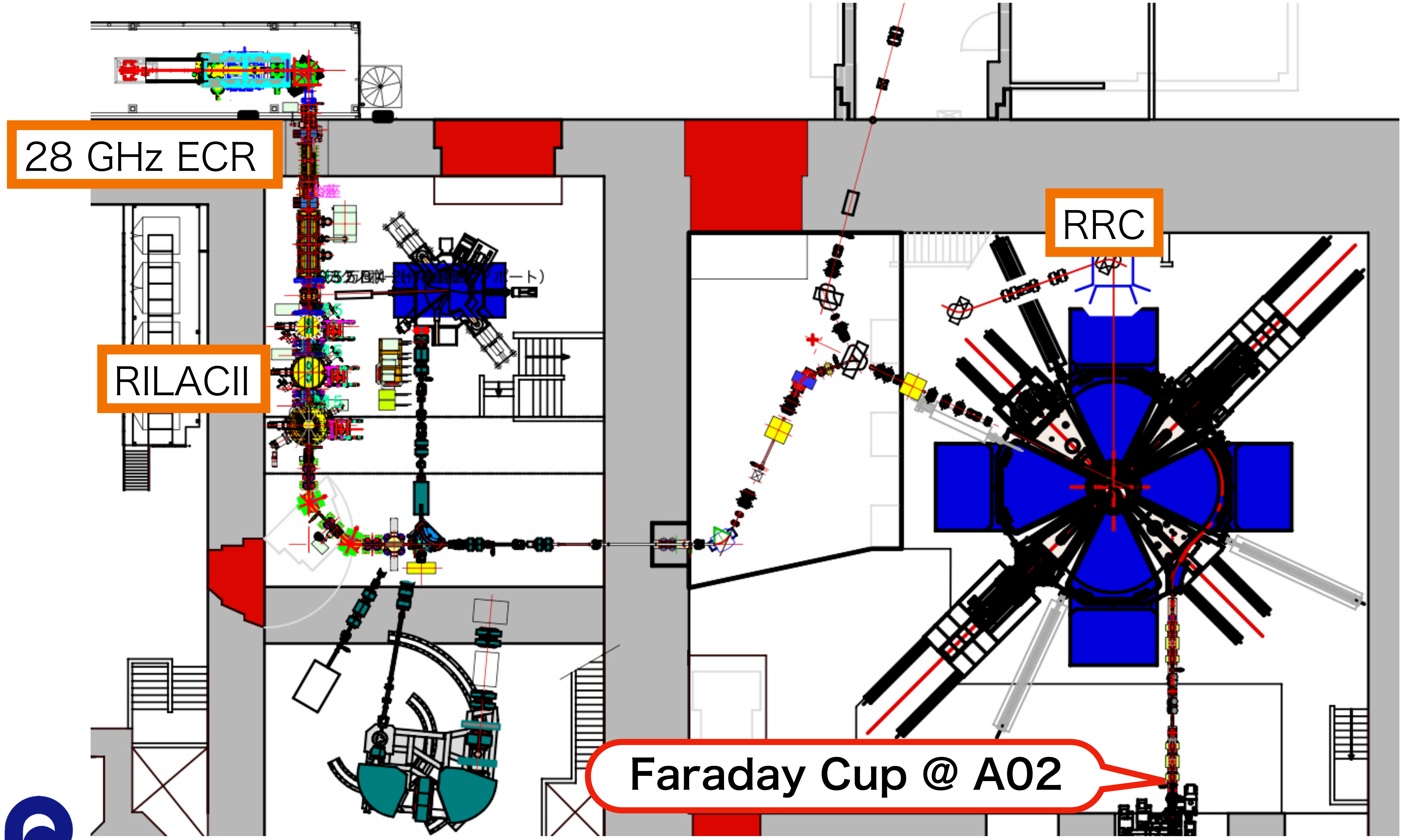




C. M. Bishop, Pattern Recognition
and Machine Learning, Springer (2006)

Bayesian Optimization at "Low Energy" Beamline

From Ion source exit to Cyclotron entrance, > **70** parameters. (Quadrupole, Steerer, Dipole…)
→ divided to 10 groups and optimized with each sections.

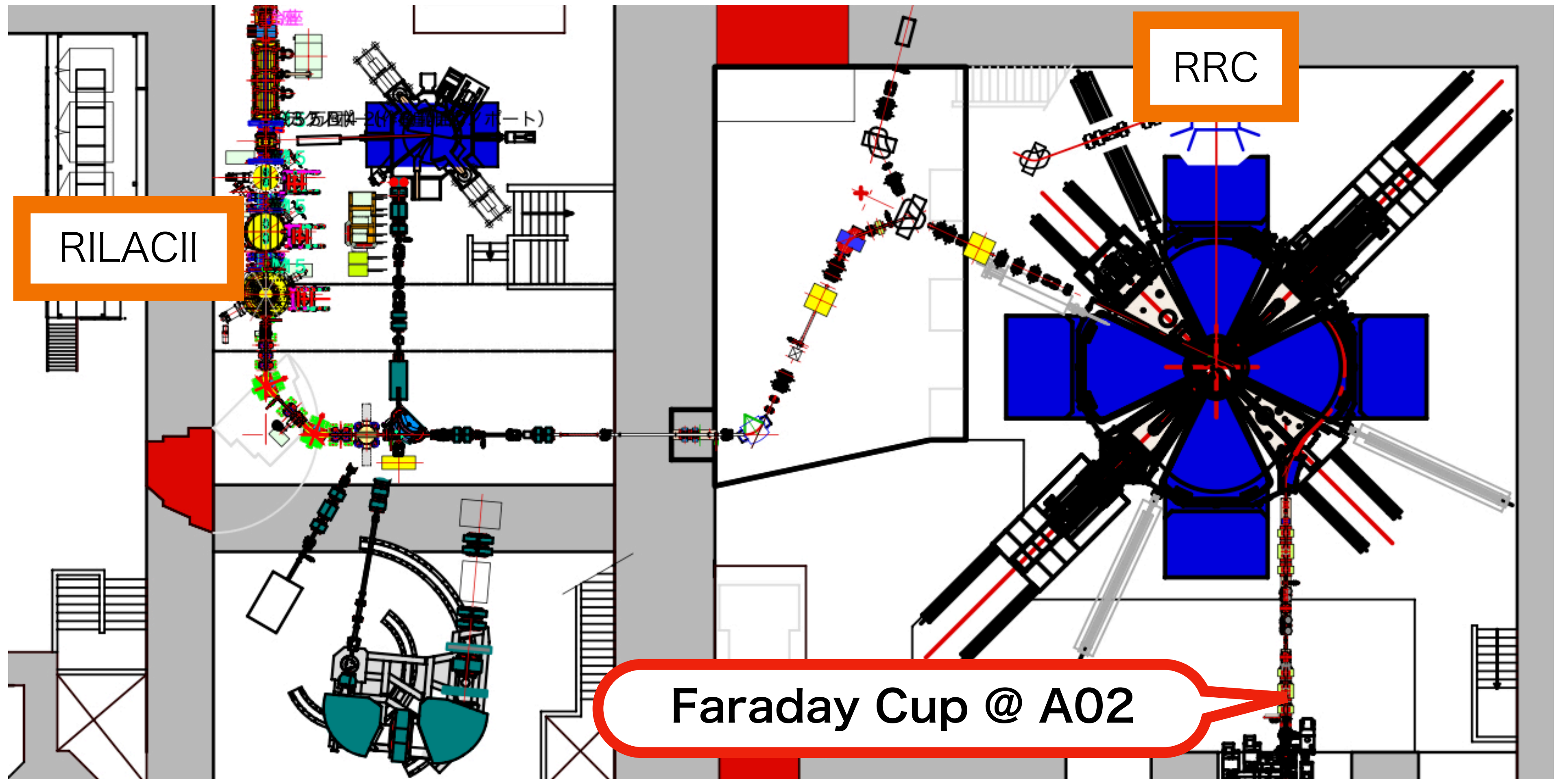


#	Quad	Steerer	Solenoid	Dipole	All
1	4	4	2	0	10
2	2	4	1	0	7
3	8	0	0	0	8
4	4	4	0	0	8
5	4	3	0	0	7
6	6	1	0	0	7
7	4	4	0	0	8
8	7	2	0	0	9
9	3	5	0	0	8
10	0	5	0	2	5

Bayesian Optimization at “Low Energy” Beamline

- Measurement: Averaged over 5 readings from the FC, taken every 0.2 seconds with fluctuation of a few enA
- 70 parameters / 335 trials → Total time: 40 minutes
- Beam current → Improved from 520–530 enA to 570–580 enA

  ~10% increase
- Minimum observed value was ~50 enA **~90% loss in worst case!**



Optimization method	**Bayesian Optimization using Gaussian Process Regression**
Beam monitor for High intensity	**Real Time Analysis of Charge Converted Particles**
Safety	**Safe Optimization with Line Bayesian Optimization**

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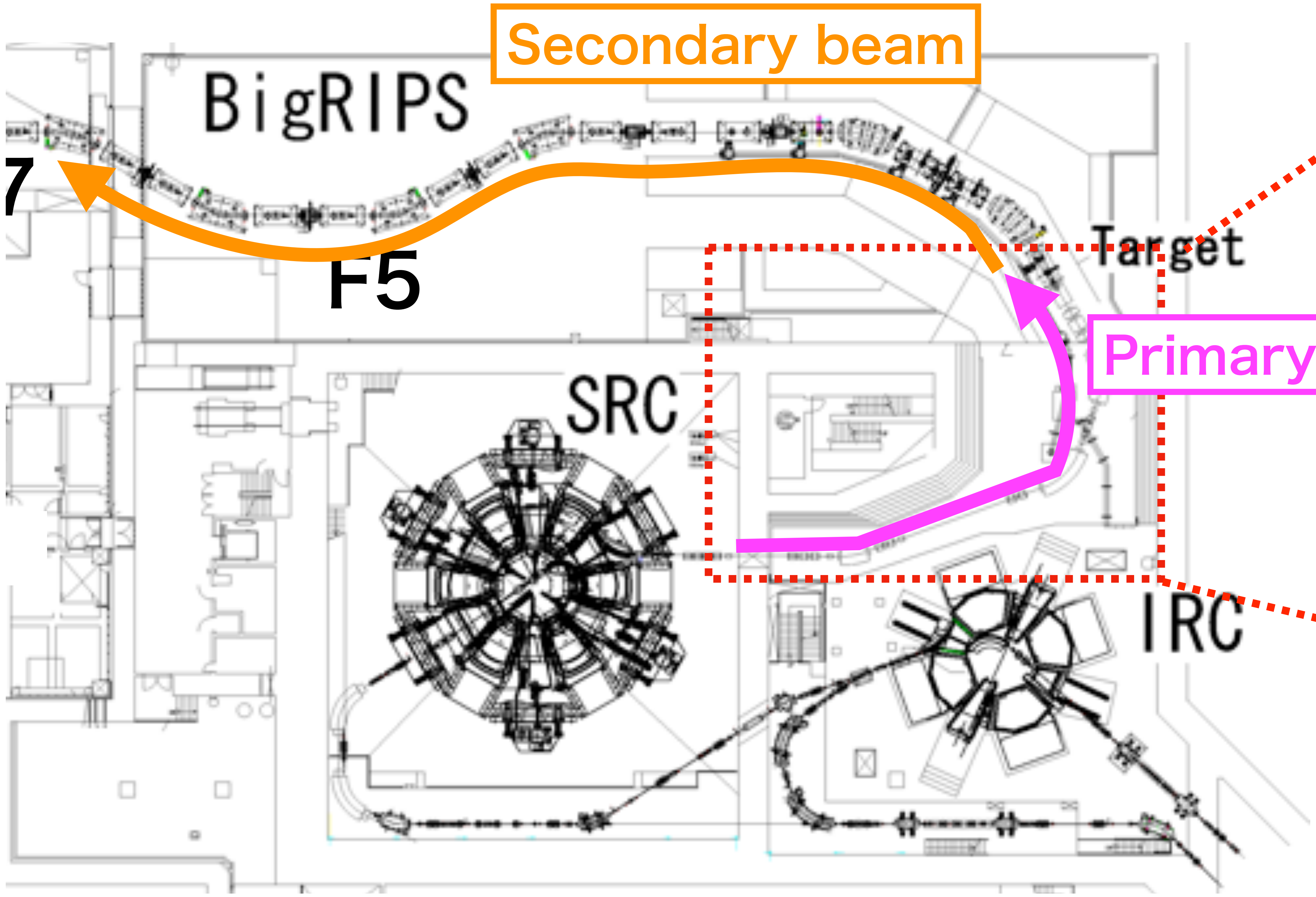
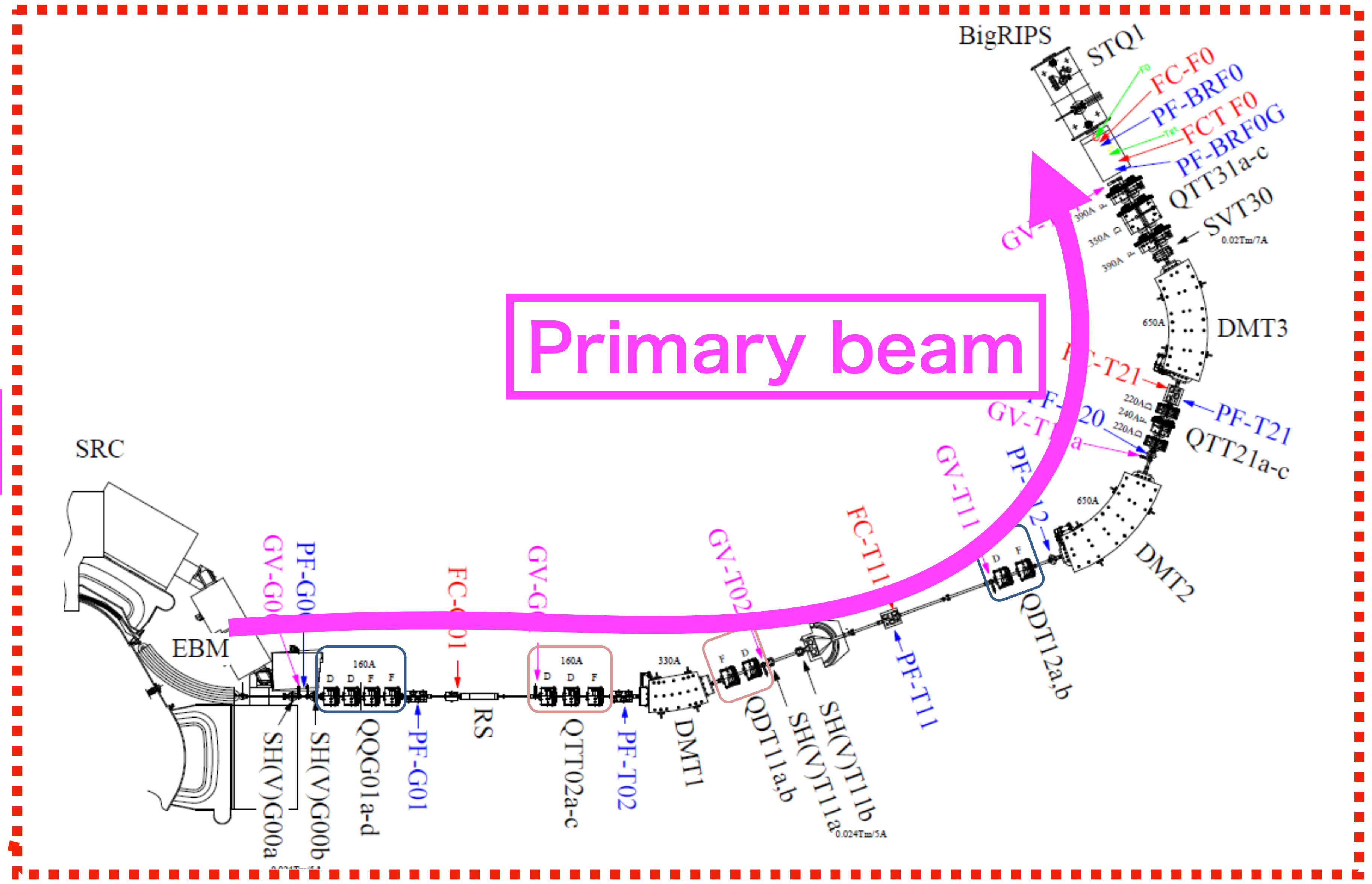
Bayesian Optimization at "High Energy" Beamline





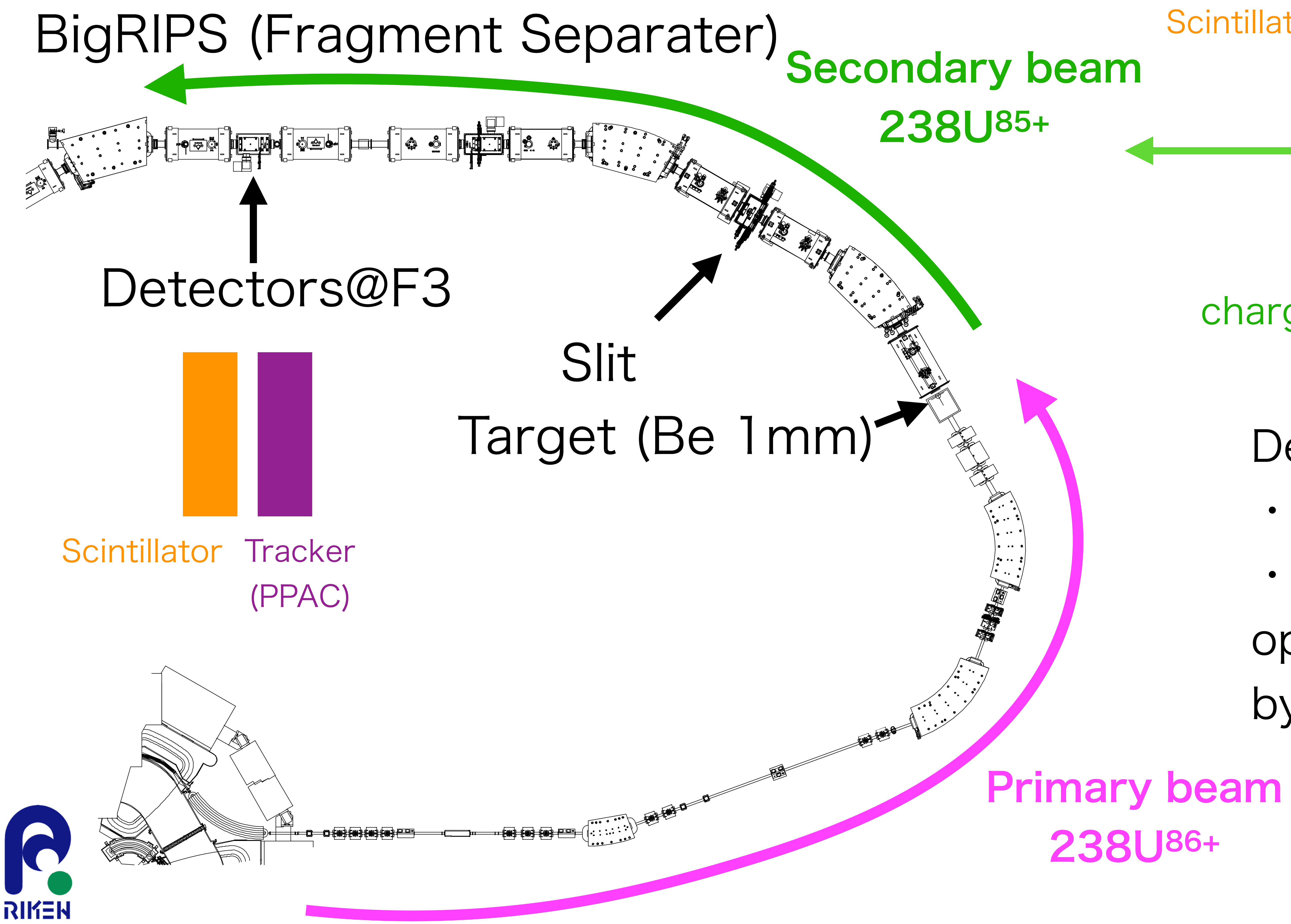
T-Course: Primary beam line between SRC to first target

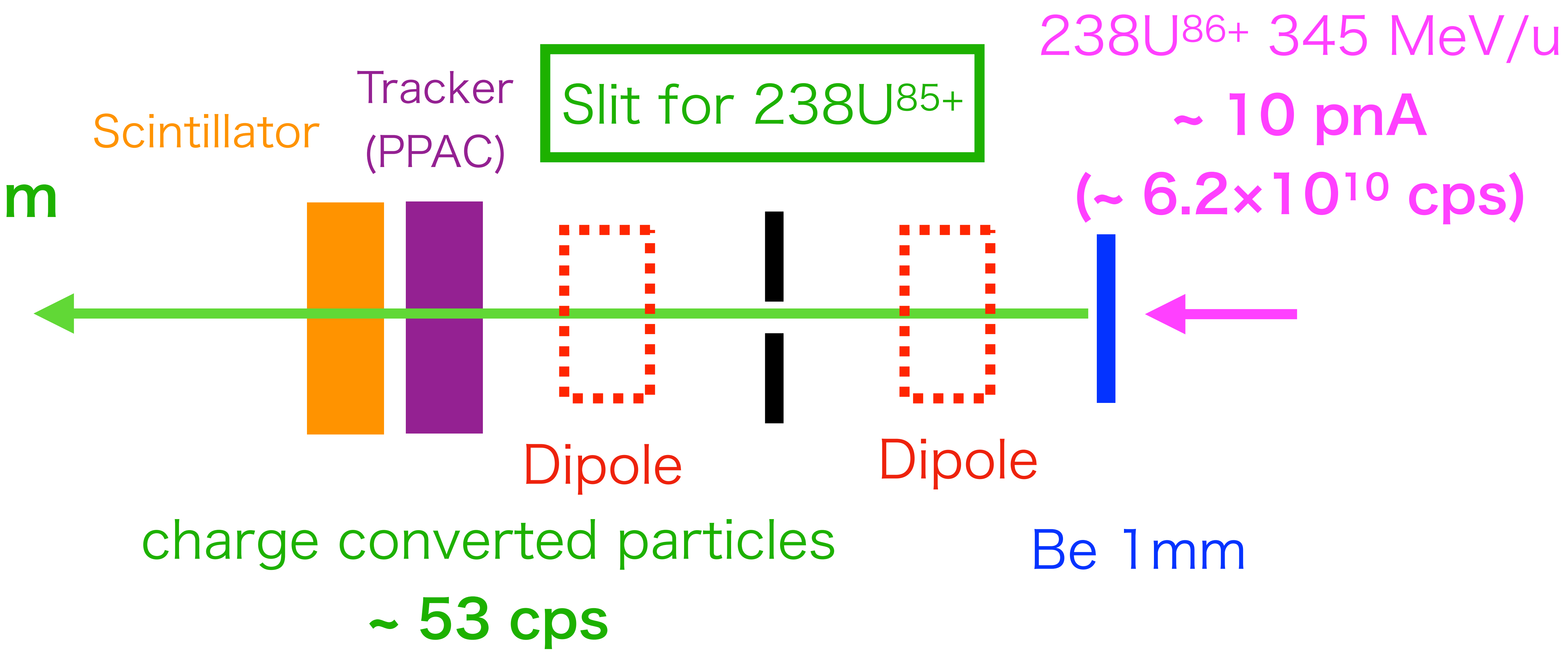
- Beam loss ~ "a few %" for $^{86+}$U beam in normal operation
- Simultaneous optimization of transmission / spot shape

To realize high intense $^{86+}$U beam (> 1 puA / 100 kW), we should

- suppress beam loss to 0.1 ~ 1%,
- **keep spot small (σ ~ 1mm).**

Development of probe for High Intensity Beam Monitor using charge converted particles





Detector in downstream

・Scintillator (for Transmission)

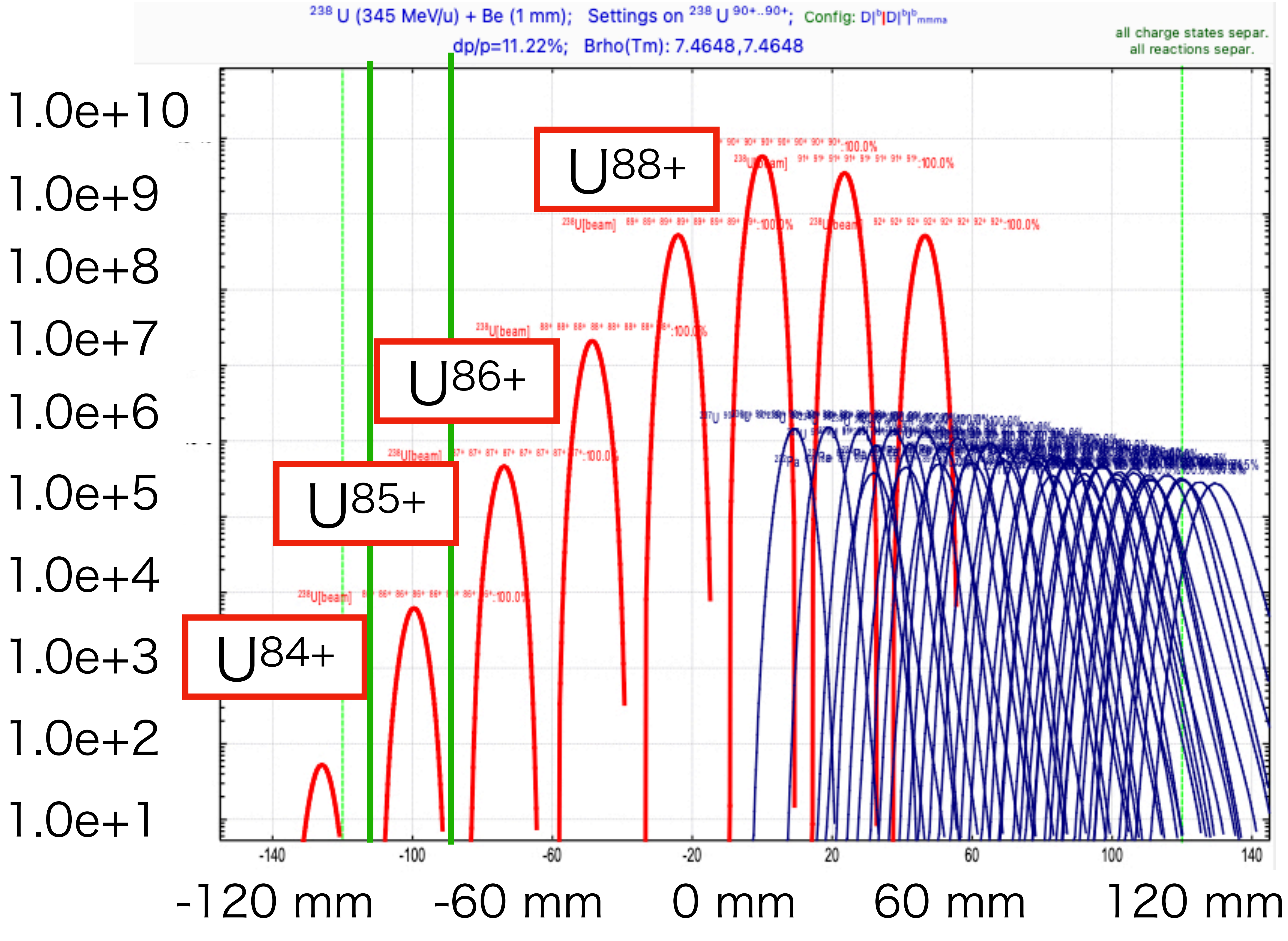
・Gas tracker (for spot)

optimize **10 pnA** primary beam $^{238}U^{86+}$ by the measurement of **50 cps** $^{238}U^{85+}$

Development of probe for High Intensity Beam

charged particle dist. at **Slit**

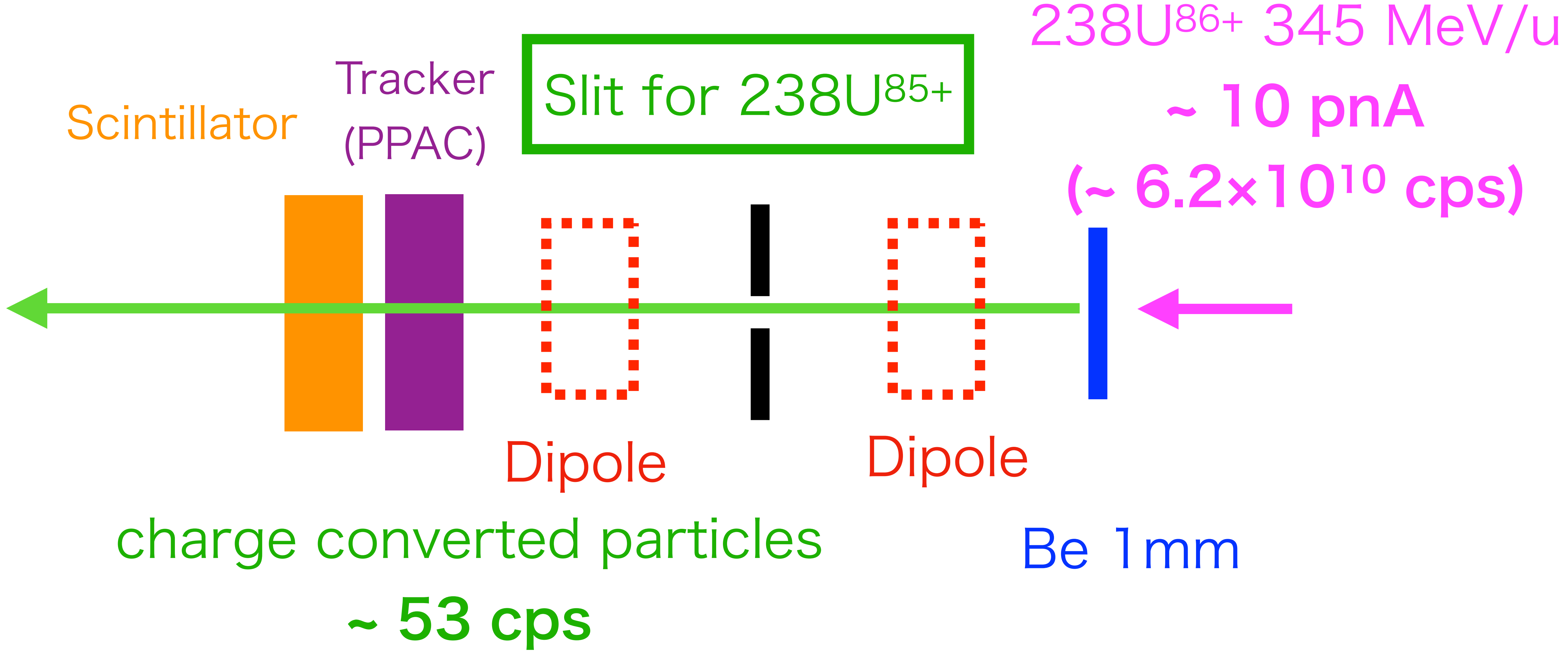
in downstream of 1st target (F1)



position at slit [mm]

Intensity : Scintillator in downstream (F3)

Spot : PPAC in downstream (F3)



Convert charge state of beam by Be 1mm target
Make low intense beam

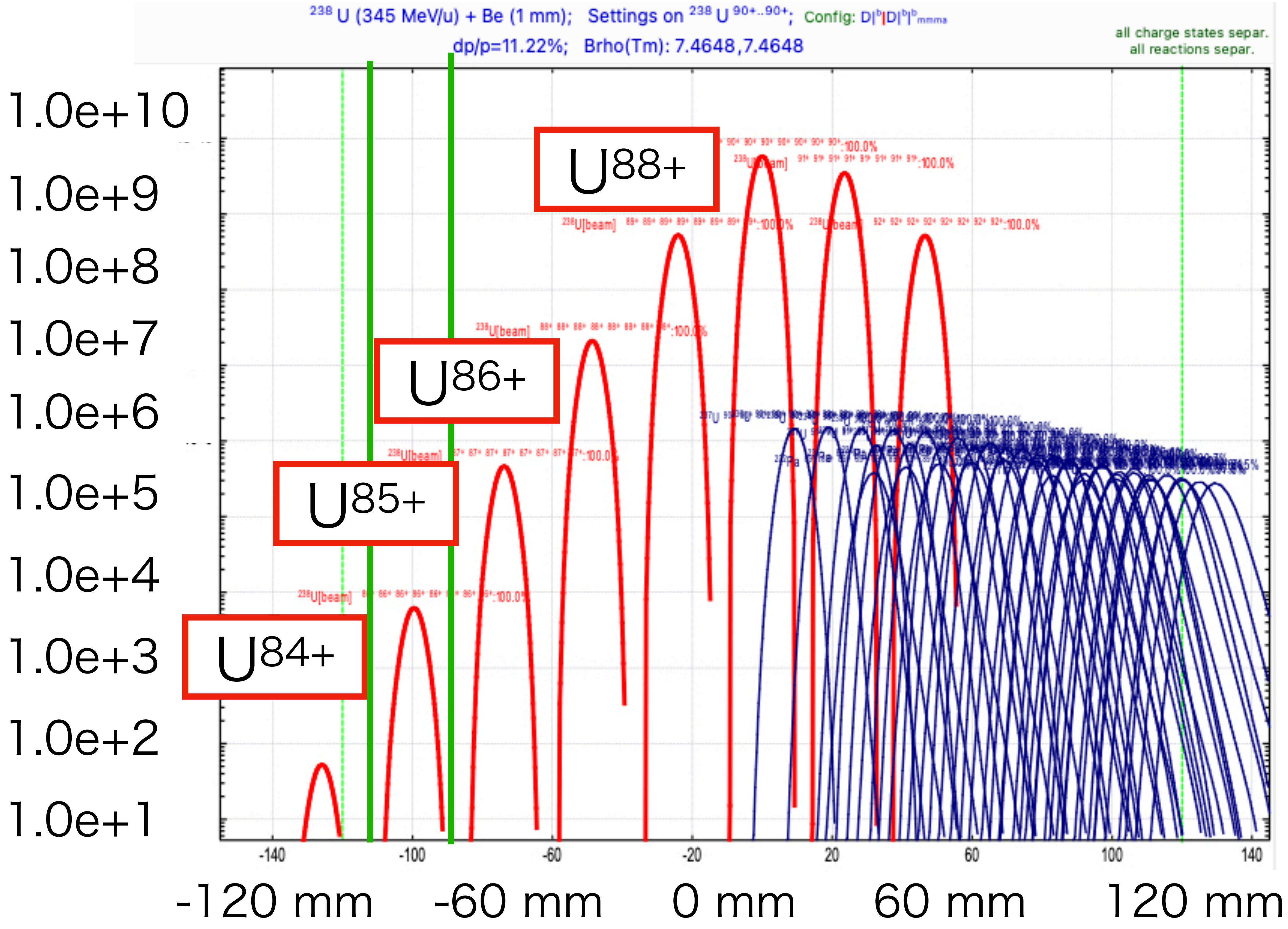
Primary intensity	Secondary beam charge	Expected rate of secondary beam
10 pnA	$^{238}U^{88+}$	2.1e+7 cps
10 pnA	$^{238}U^{86+}$	6.2e+3 cps
10 pnA	$^{238}U^{85+}$	53 cps

※ calc. by LISE++ / mode: Global + J

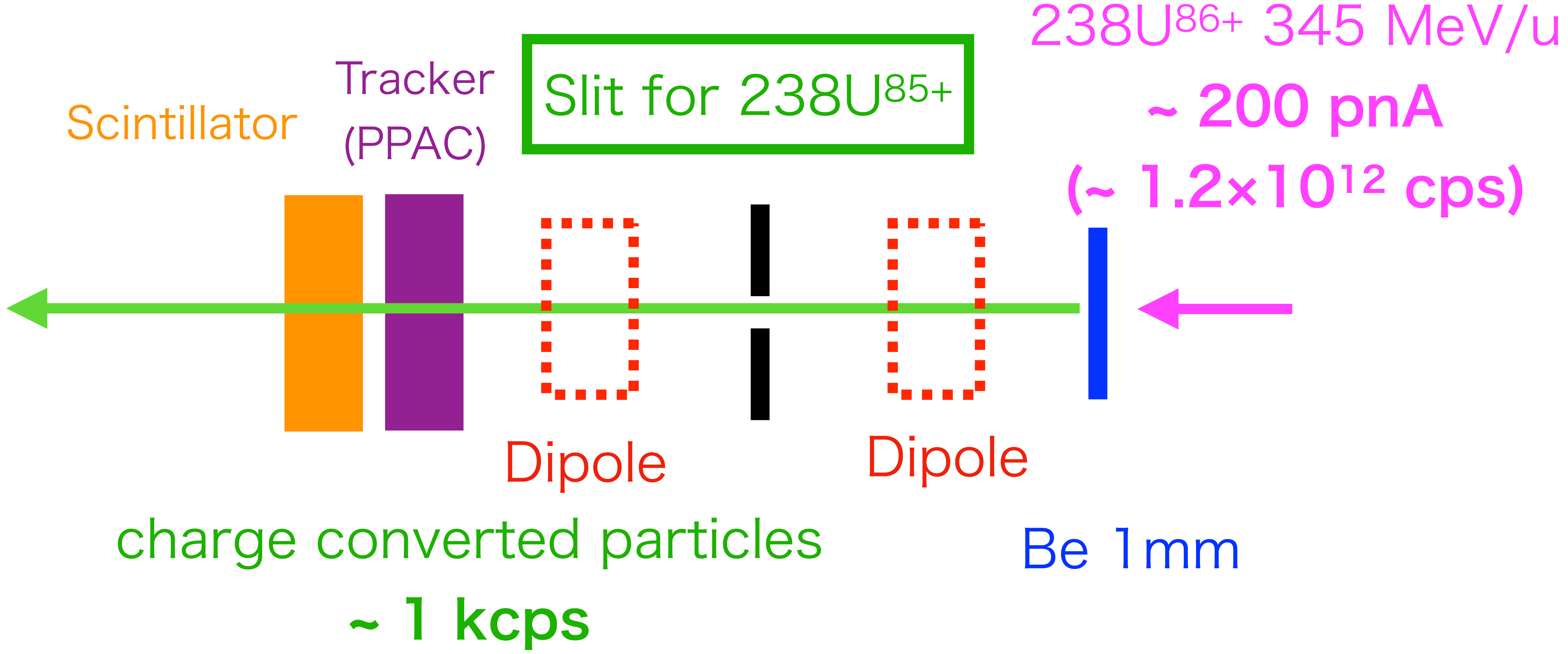
Development of probe for High Intensity Beam

charged particle dist. at **Slit**

in downstream of 1st target (F1)



position at slit [mm]



Convert charge state of beam by Be 1mm target

Make low intense beam

Intensity : Scintillator in downstream (F3)

Spot : PPAC in downstream (F3)

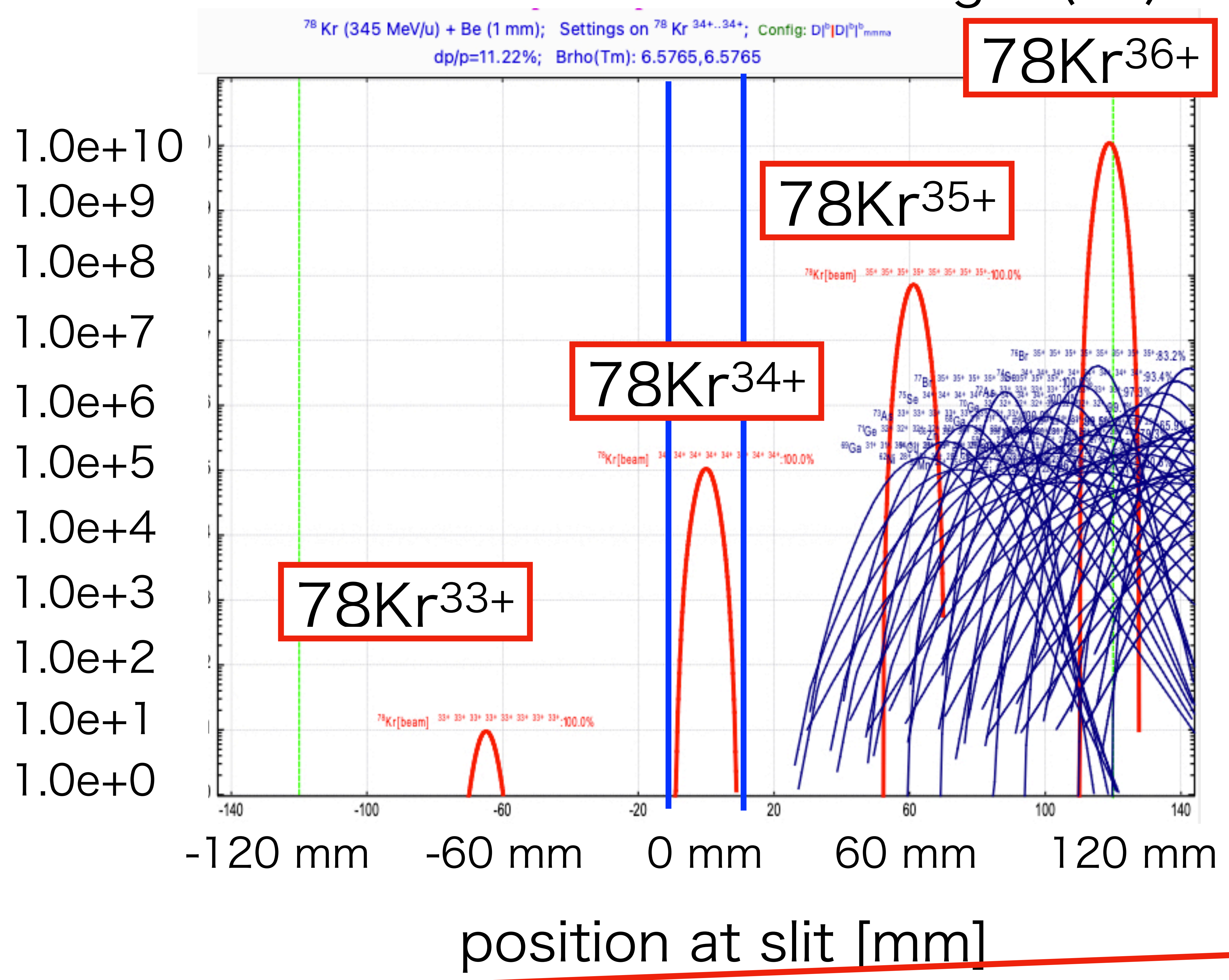
Primary intensity	Secondary beam charge	Expected rate of secondary beam
5.0e-4 pnA	$^{238}U^{88+}$	**1 kcps**
0.02 pnA	$^{238}U^{86+}$	**1 kcps**
200 pnA	$^{238}U^{85+}$	**1 kcps**

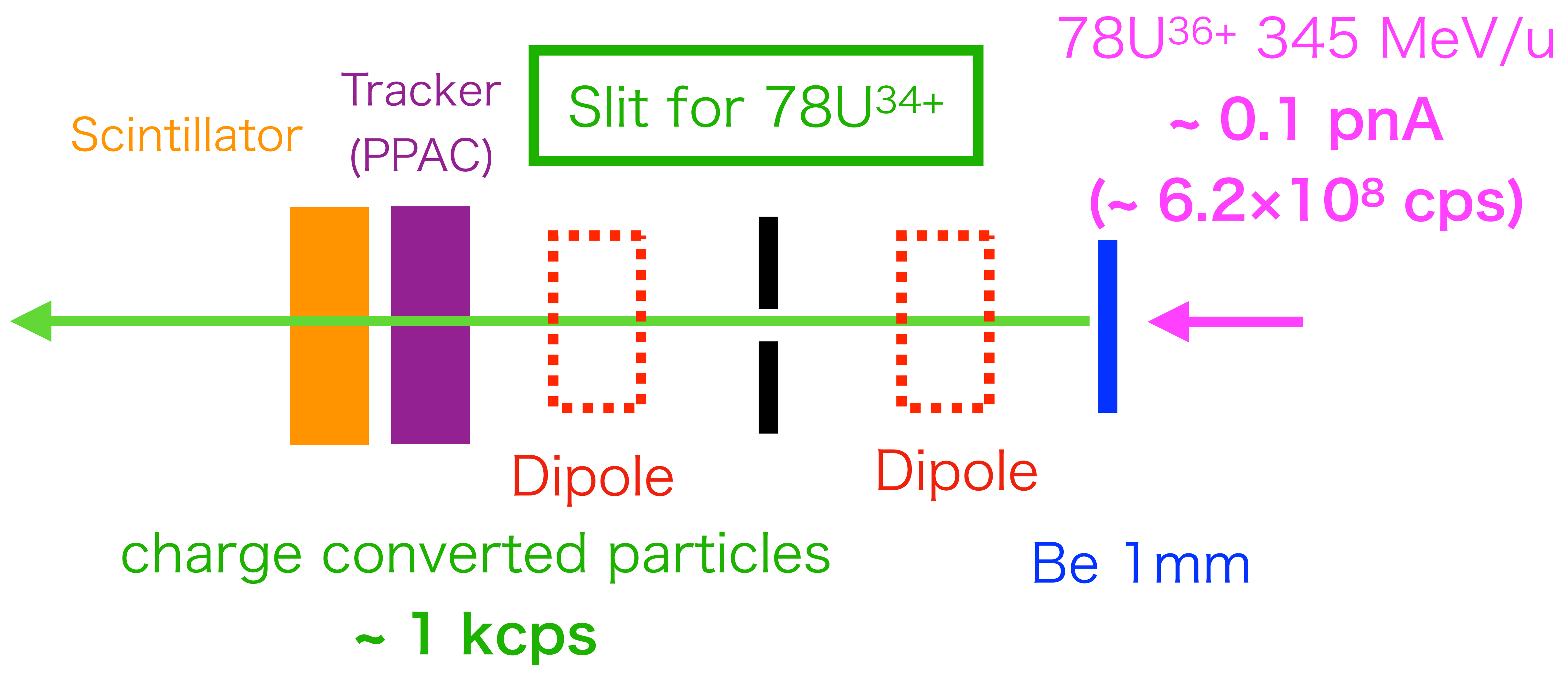
※ calc. by LISE++ / mode: Global + J

Development of probe for High Intensity Beam

charged particle dist. at **Slit**

in downstream of 1st target (F1)





Convert charge state of beam by Be 1mm target
Make low intense beam

Intensity : Scintillator in downstream (F3)
Spot : PPAC in downstream (F3)

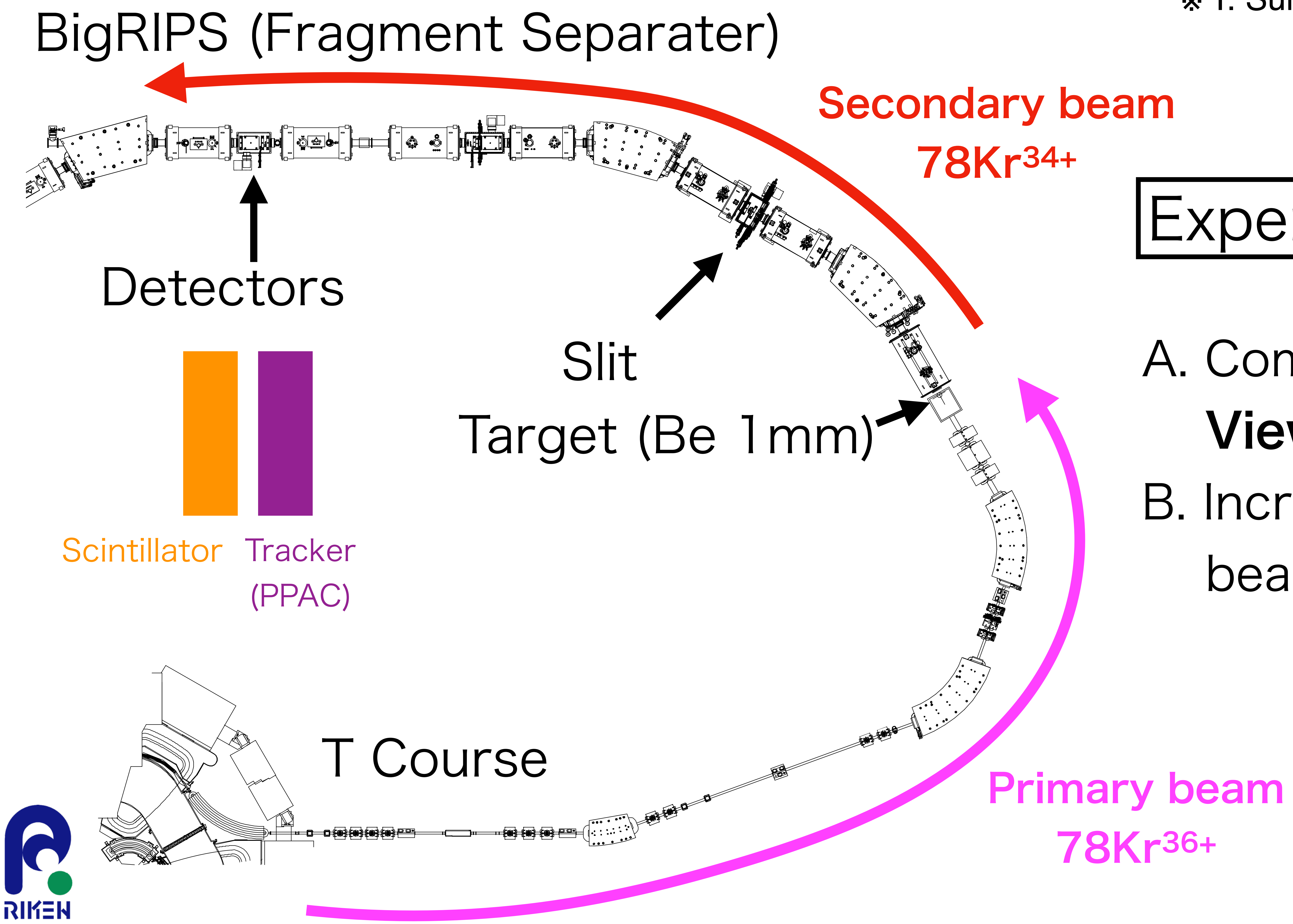
Primary intensity	Secondary beam charge	Expected rate of secondary beam
0.00013 pnA	$^{78}Kr^{35+}$	**1 kcps**
0.1 pnA	$^{78}Kr^{34+}$	**1 kcps**
1000 pnA	$^{78}Kr^{33+}$	**1 kcps**

※ calc. by LISE++ / mode: Global + J

Auto Tuning with High Intensity / High Energy Beam

Real time tracker system is realized and connected to EPICS by **BYACO**※

※ T. Sumikama *et al*, RIKEN Accel. Prog. Rep 54, 82 (2021)



Experiment items

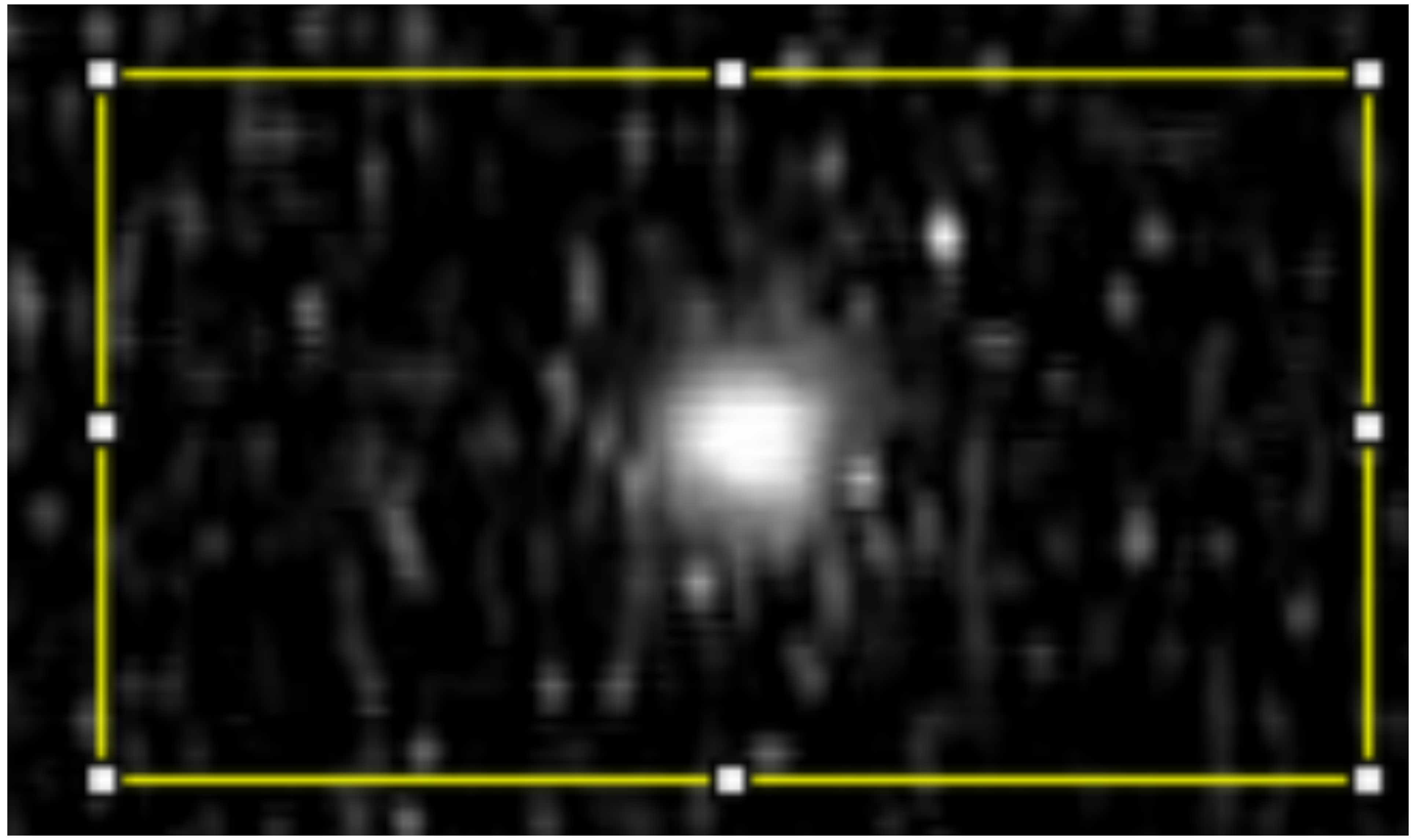
A. Compare beam spot measured by **Viewer** and **PPAC**

B. Increase the beam intensity and optimize beam optics using PPAC / Scintillator

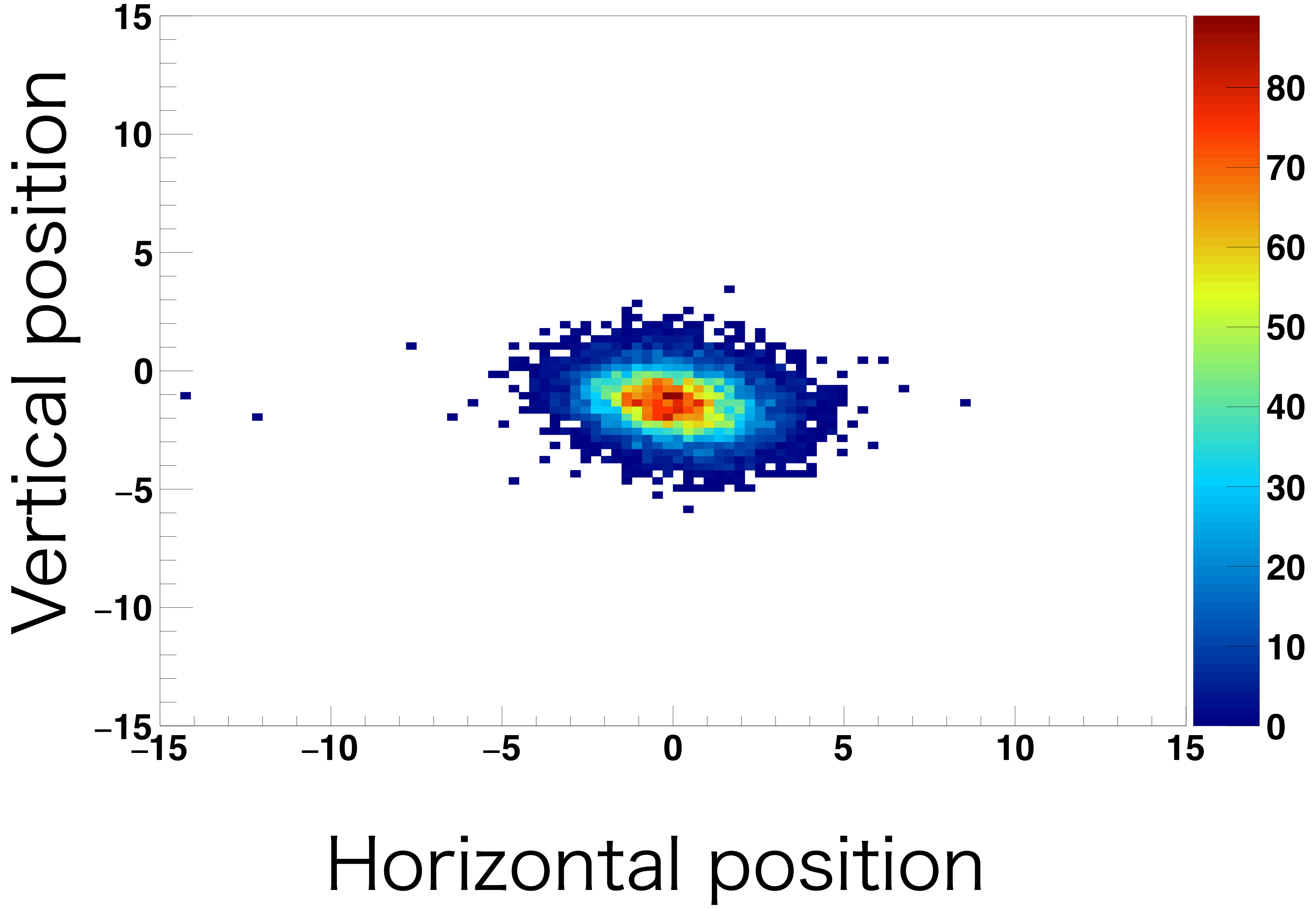
A. Compare Beam Spot measured by Viewer and PPAC

Change optics and compare
- fluorescent viewer image of primary beam ($^{78}Kr^{36+}$)
- position distribution of secondary beam ($^{78}Kr^{34+}$) tracked by PPAC (gas detector)

Fluorescent viewer ($^{78}Kr^{36+}$)



PPAC@F3 ($^{78}Kr^{34+}$)



※ In this measurement, Fluorescent viewer was removed and Be 1mm was inserted.

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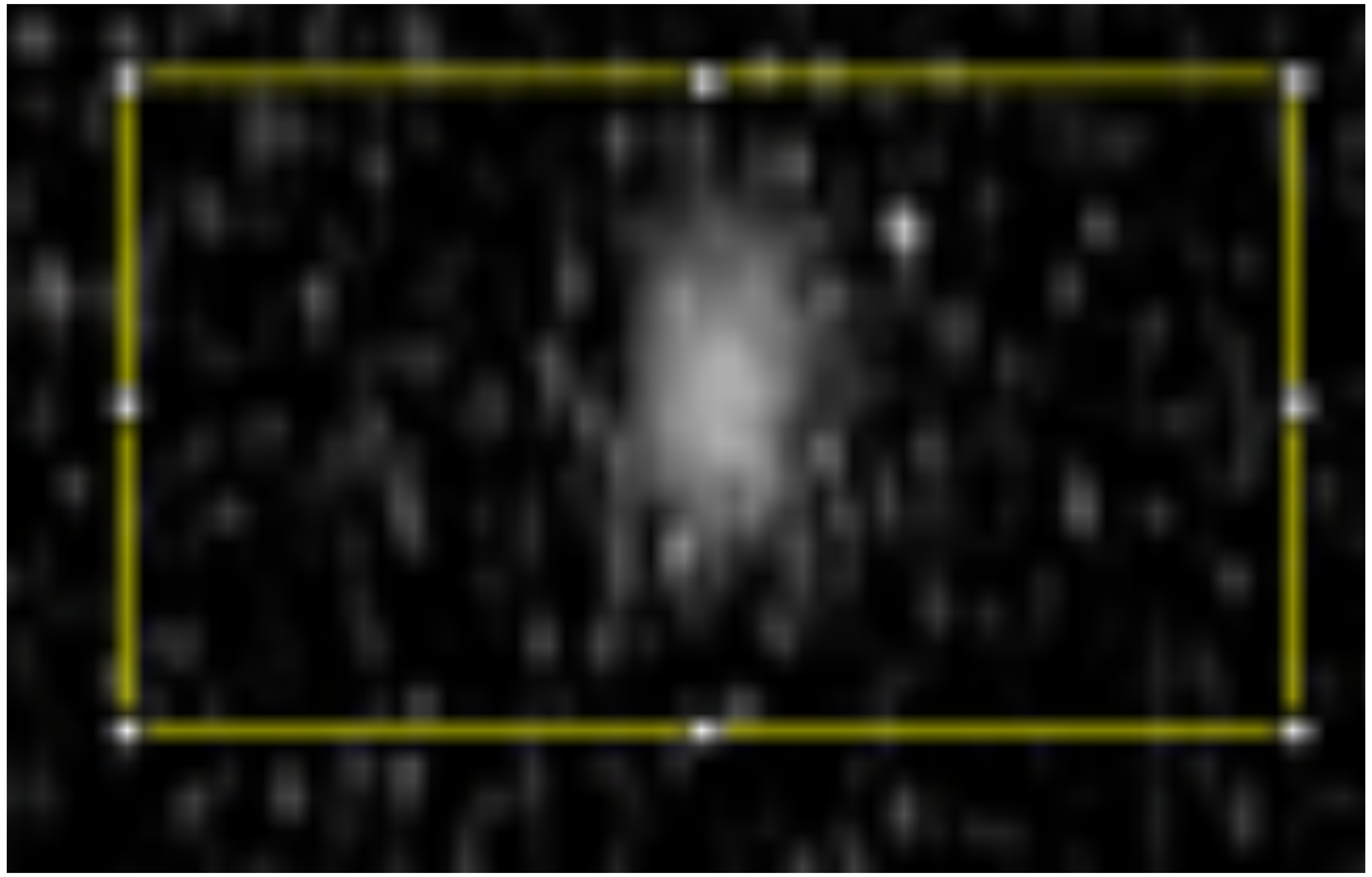

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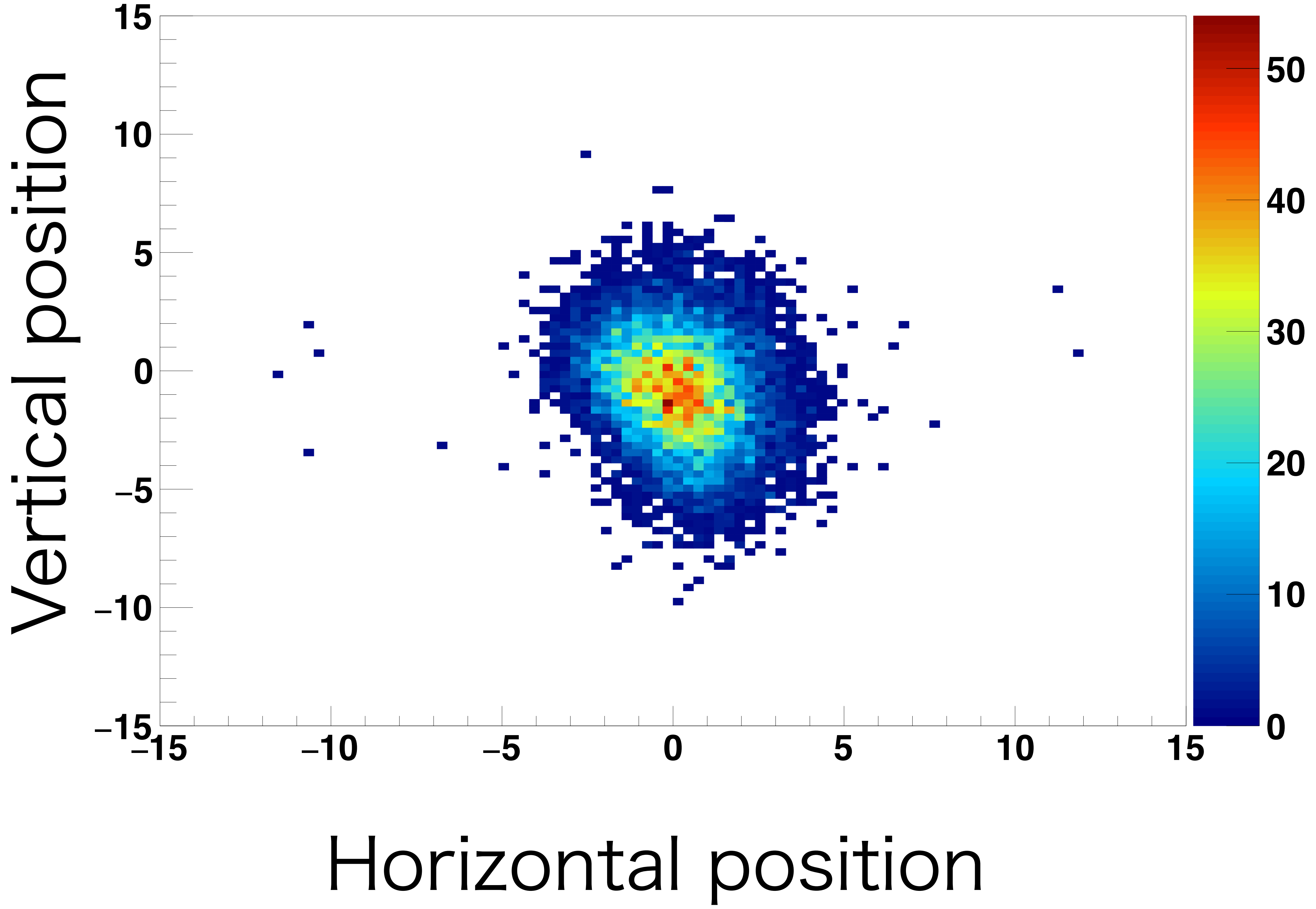

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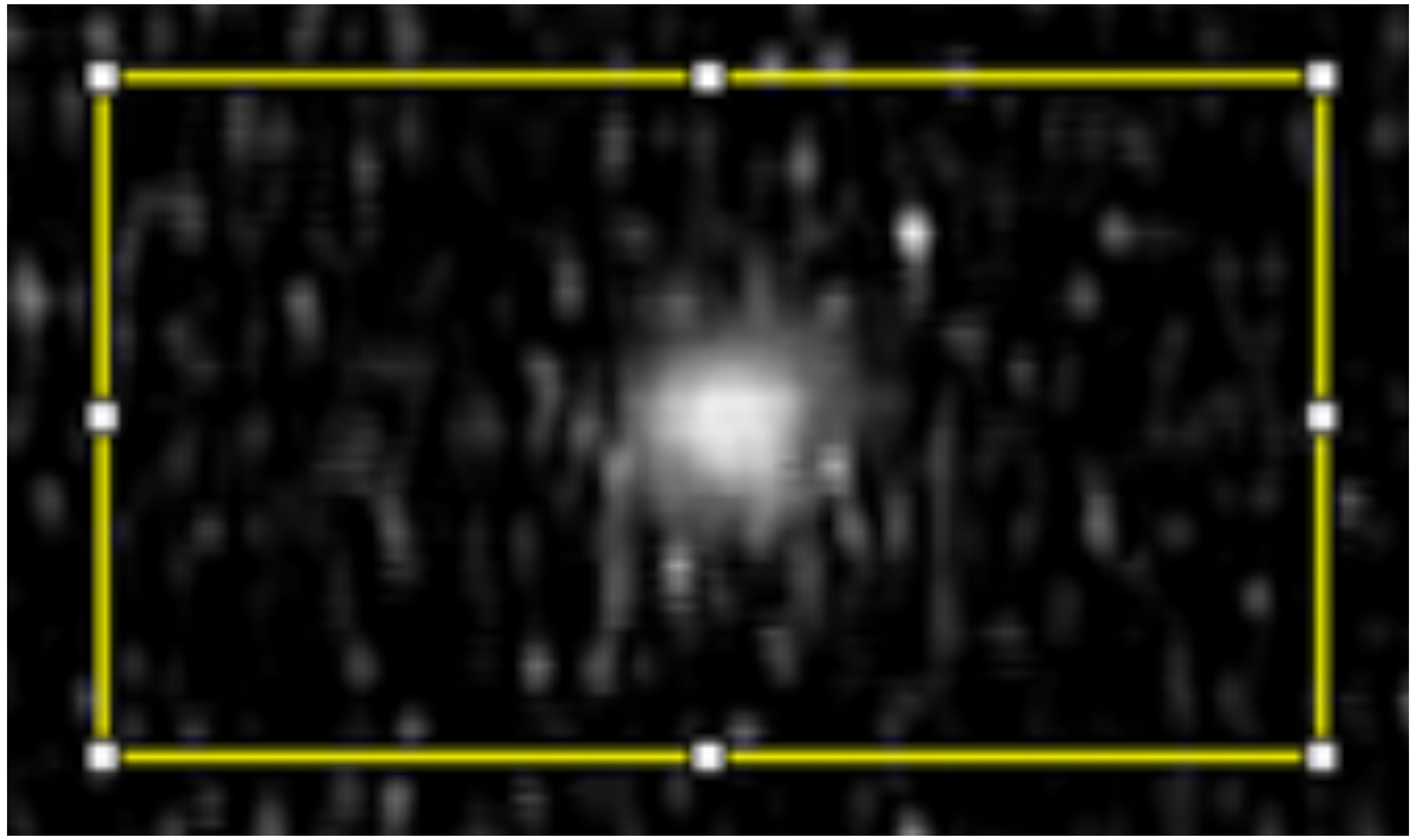

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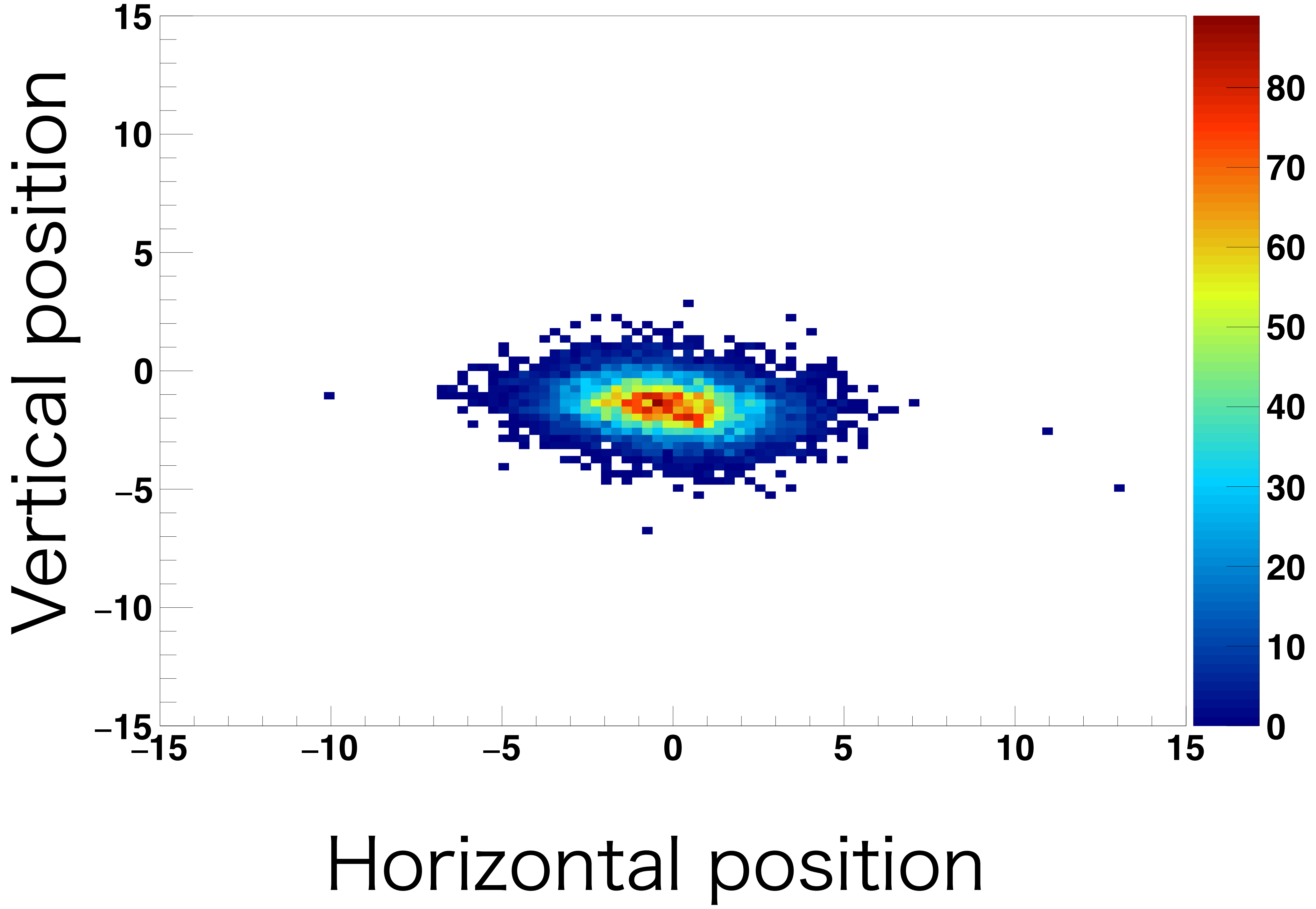

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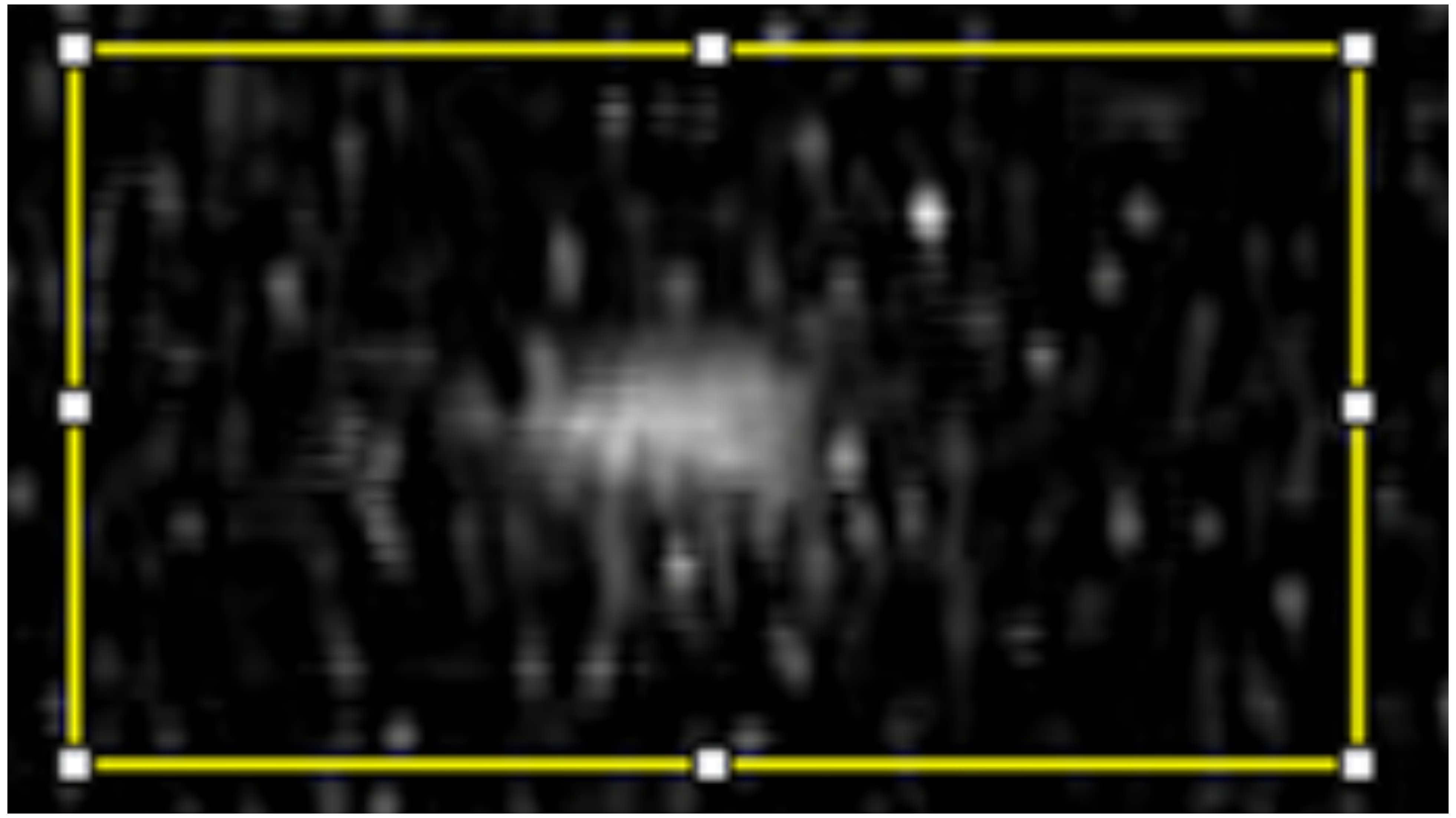
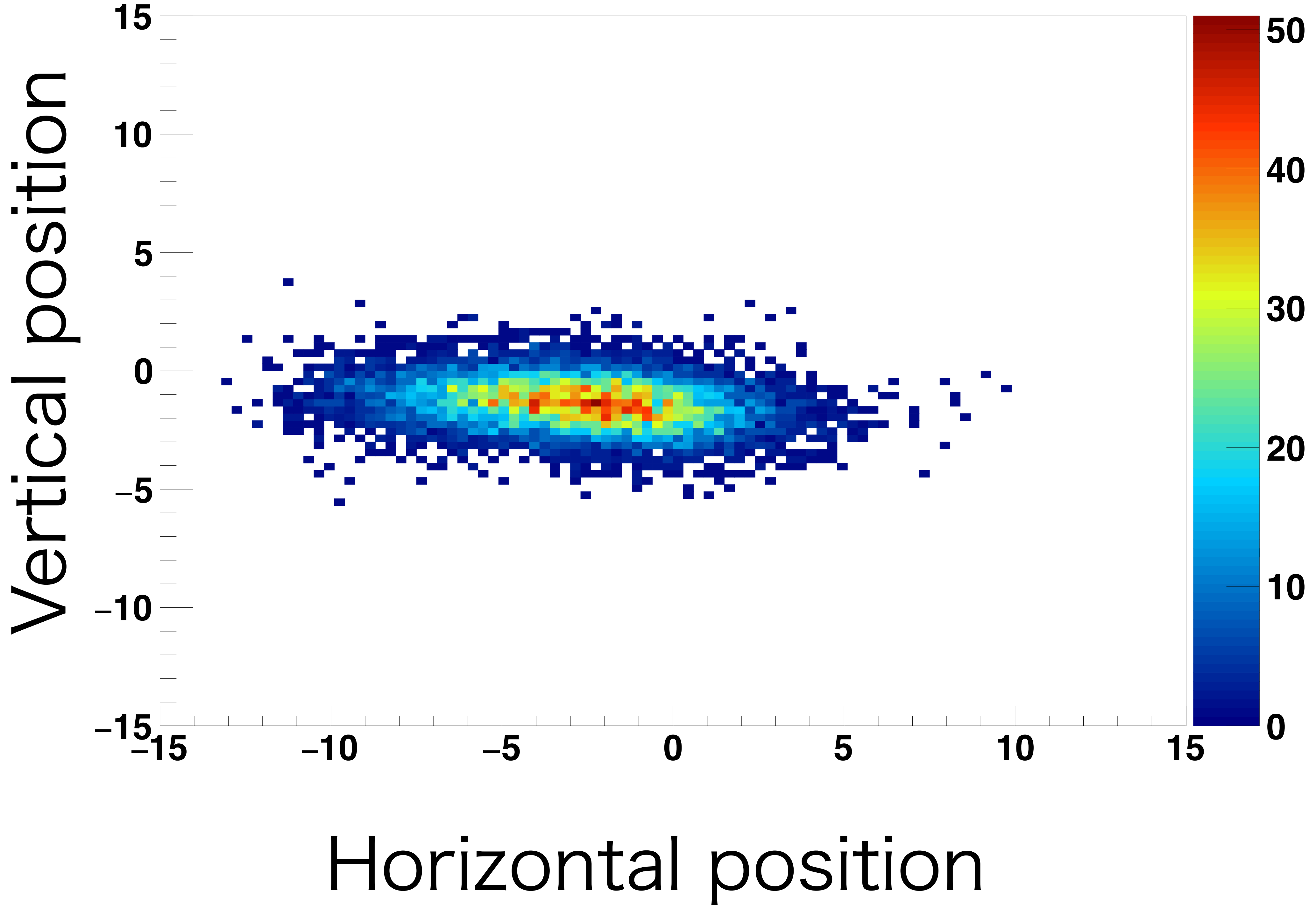


PPAC@F3 ($^{78}Kr^{34+}$)



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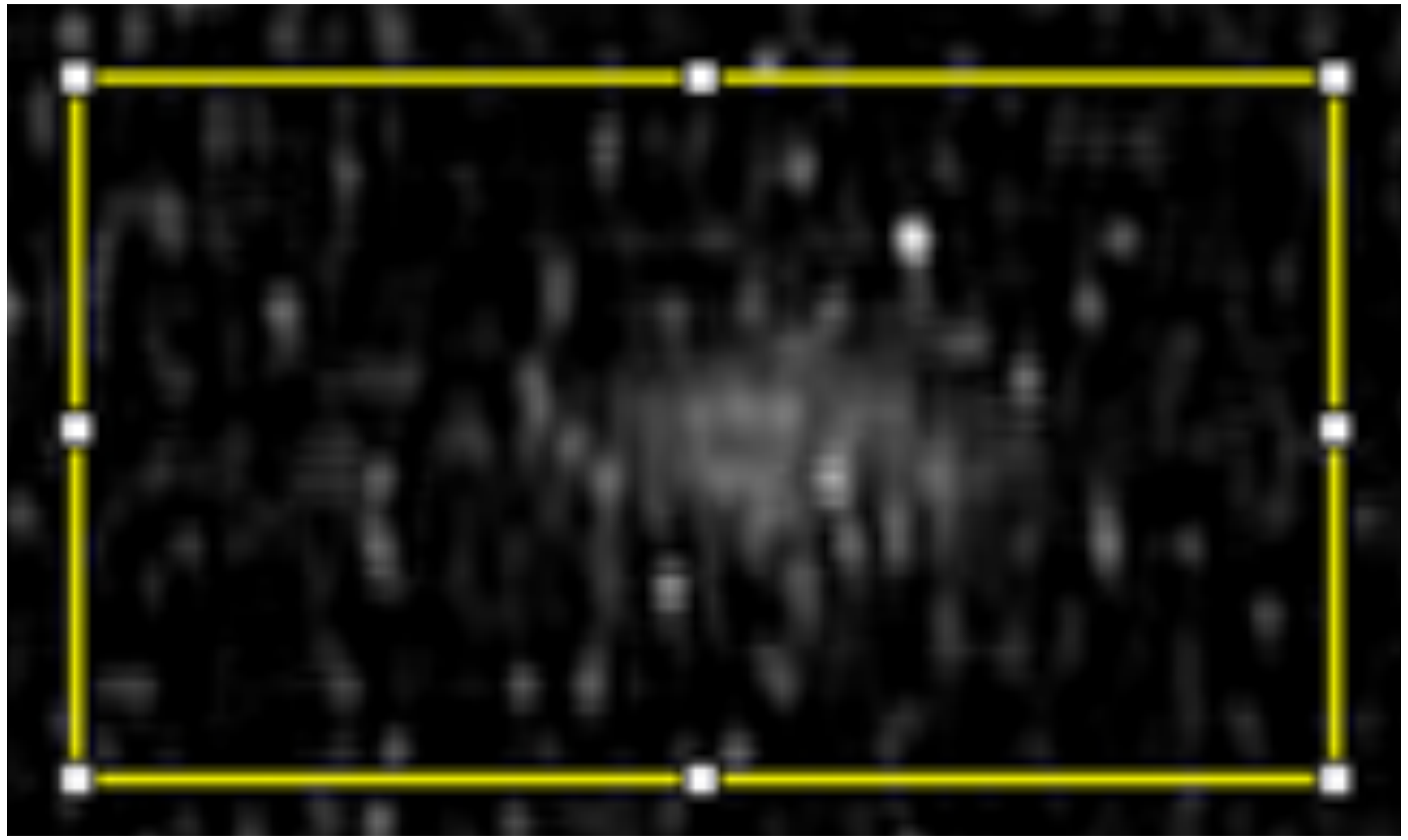
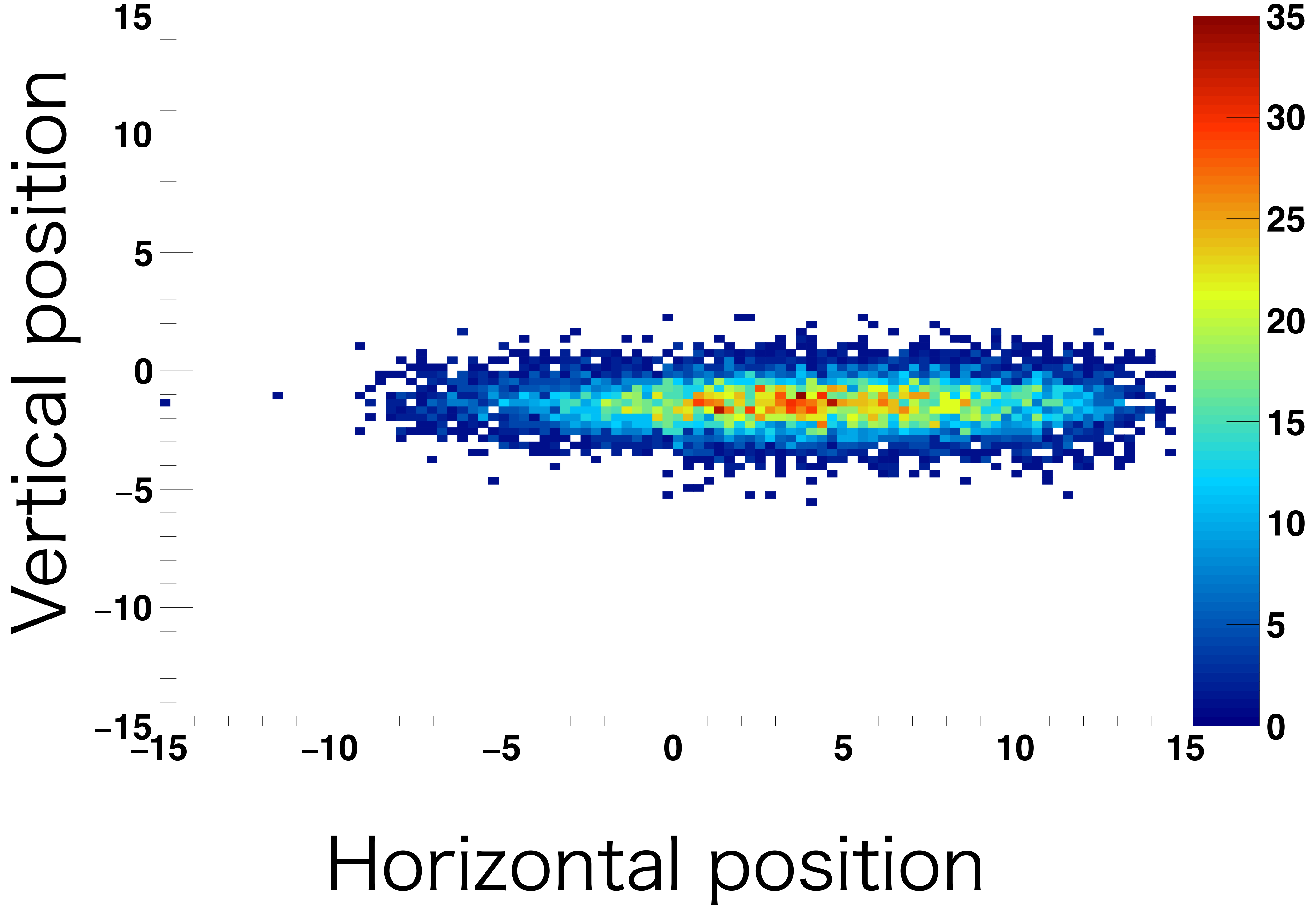


PPAC@F3 ($^{78}Kr^{34+}$)



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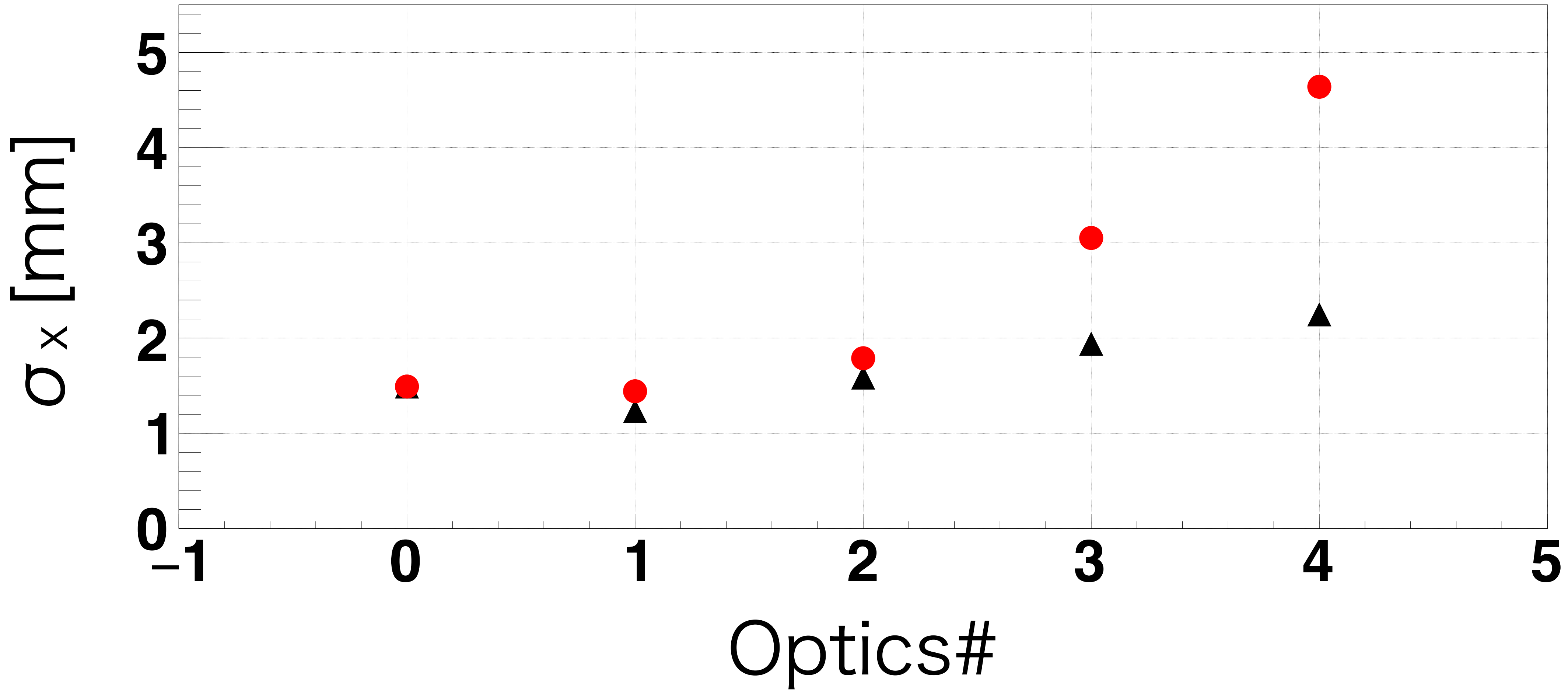
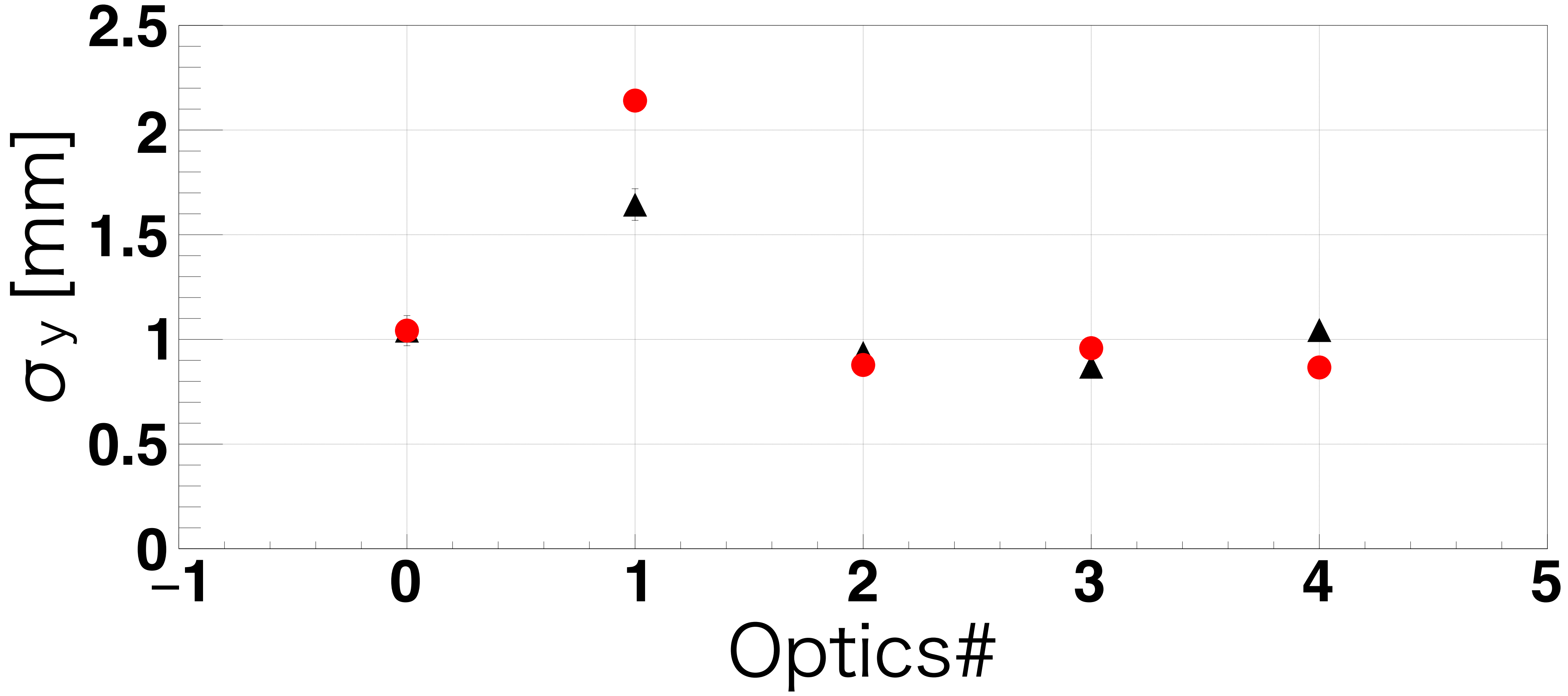


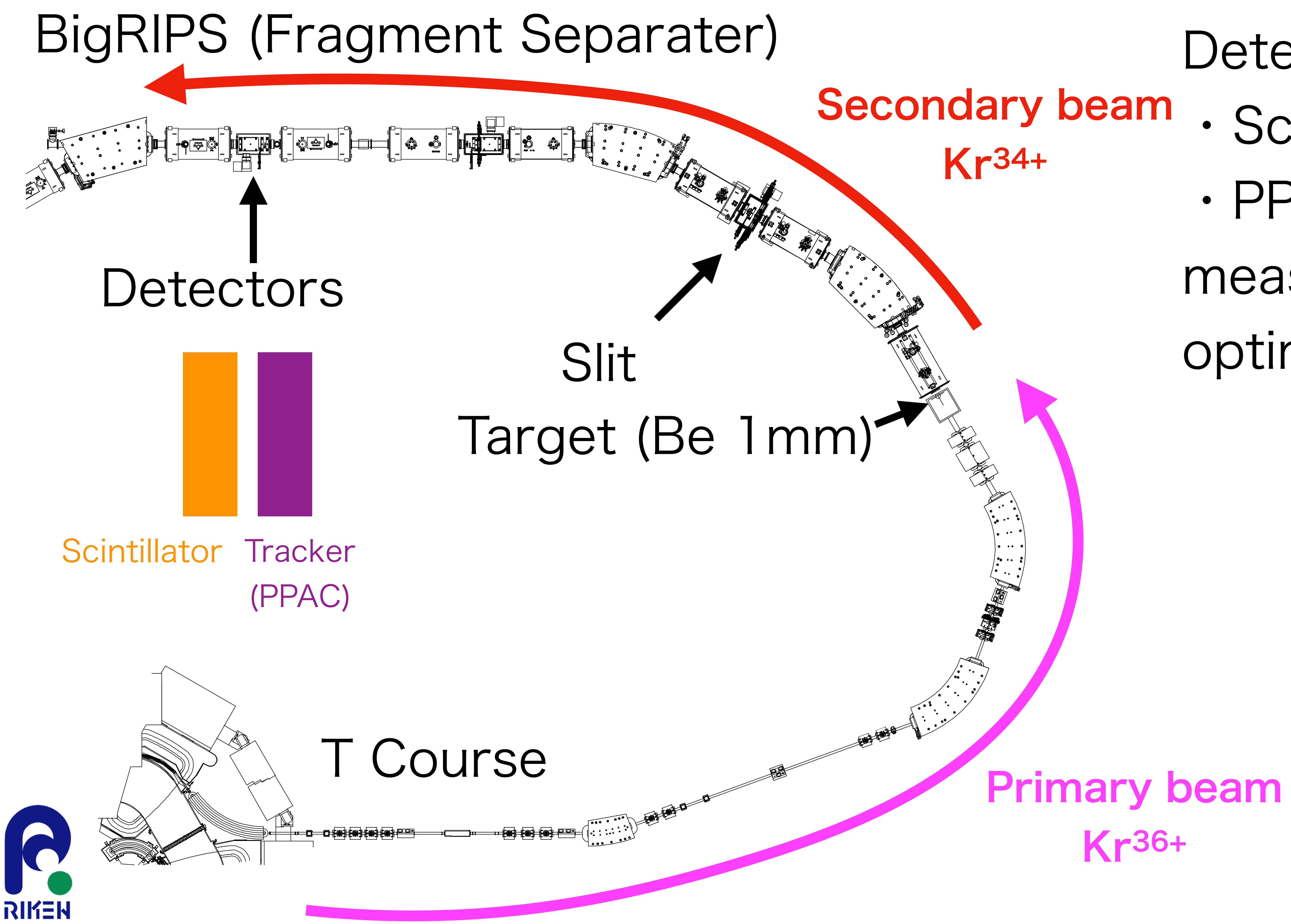


Red : Viewer
Black: PPAC
※ Values of Viewer and PPA are calibrated by optics 0 data.

Data of viewer and PPAC
→ (qualitatively) consistent
※ When the spot become wide,
non linearity may not be negligible

Tracking distribution of secondary beam is a good probe for the primary beam spot!!

B. Auto Tuning with “High Intensity“ Primary Beam



Detector in downstream

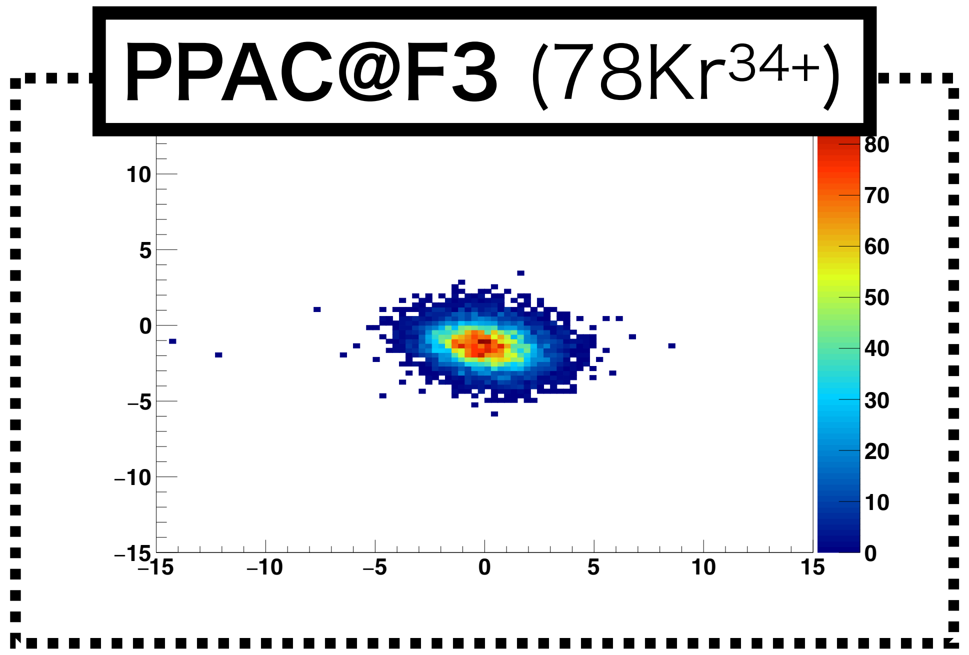
- Scintillator (for Transmission)
- PPAC (for spot)

measure $78Kr^{34+}$ **10 kcps**

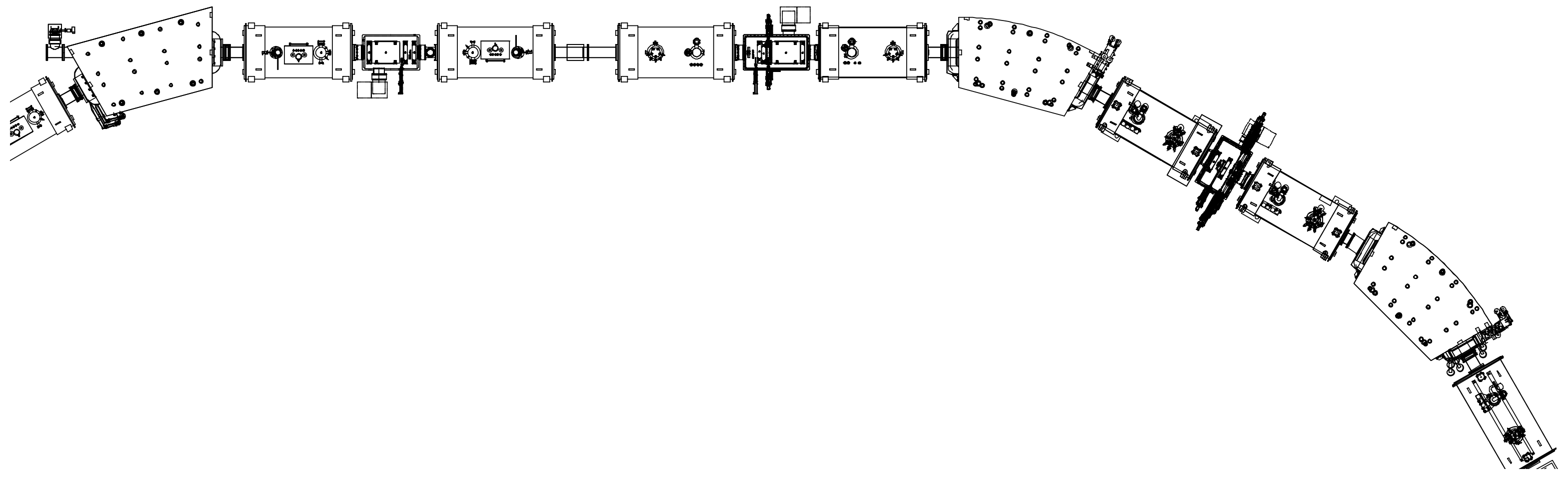
optimize **0.7 pnA** primary beam $78Kr^{36+}$

B. Auto Tuning with “High Intensity“ Primary Beam

Real time tracker system : BYACO



BigRIPS
Spectrometer Side



※ Analyzed results are also transferred via EPICS

Waiting…

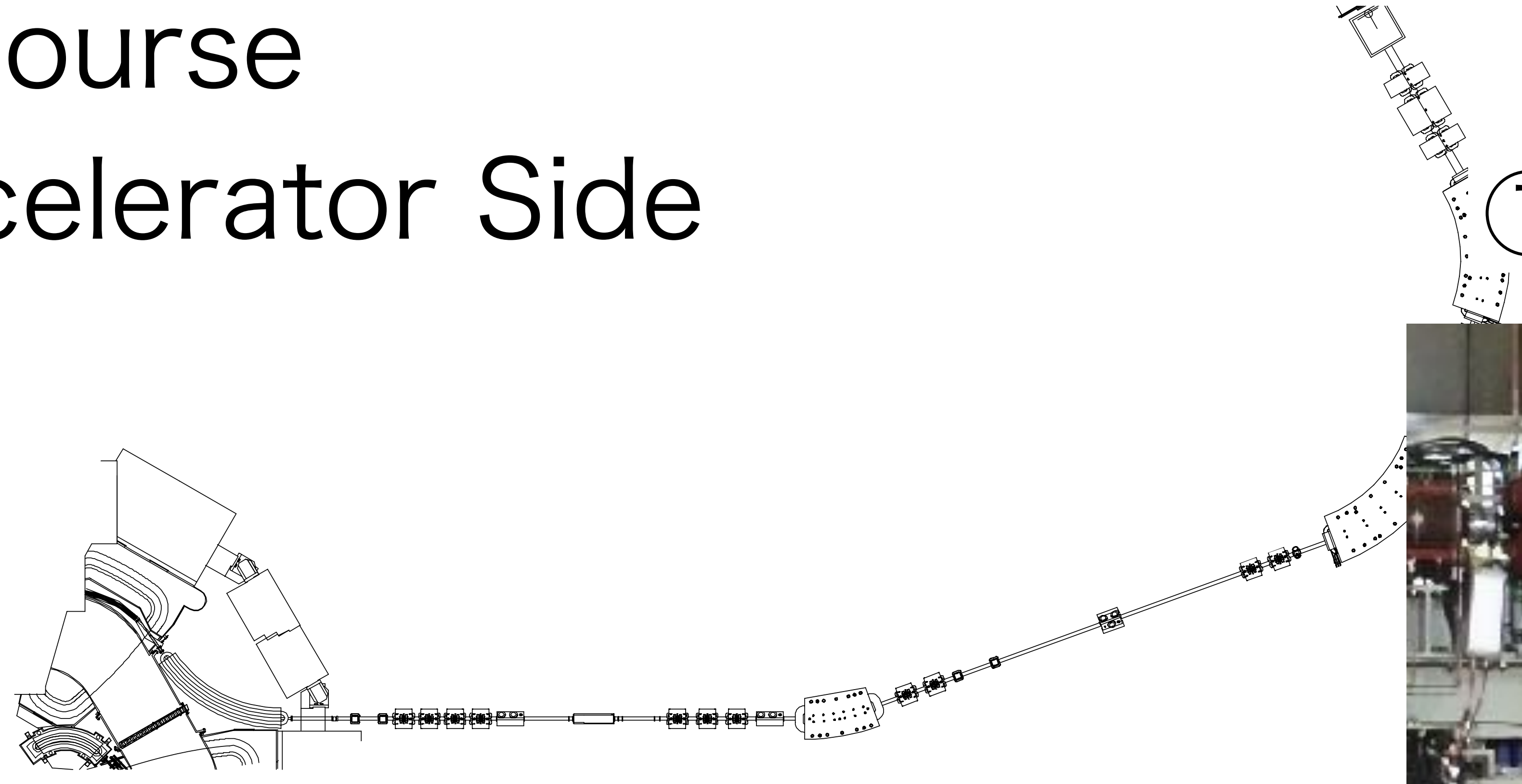
② Start DAQ → ③ Finish Analysis

EPICS PV: Flag_ML

1

0

T Course
Accelerator Side



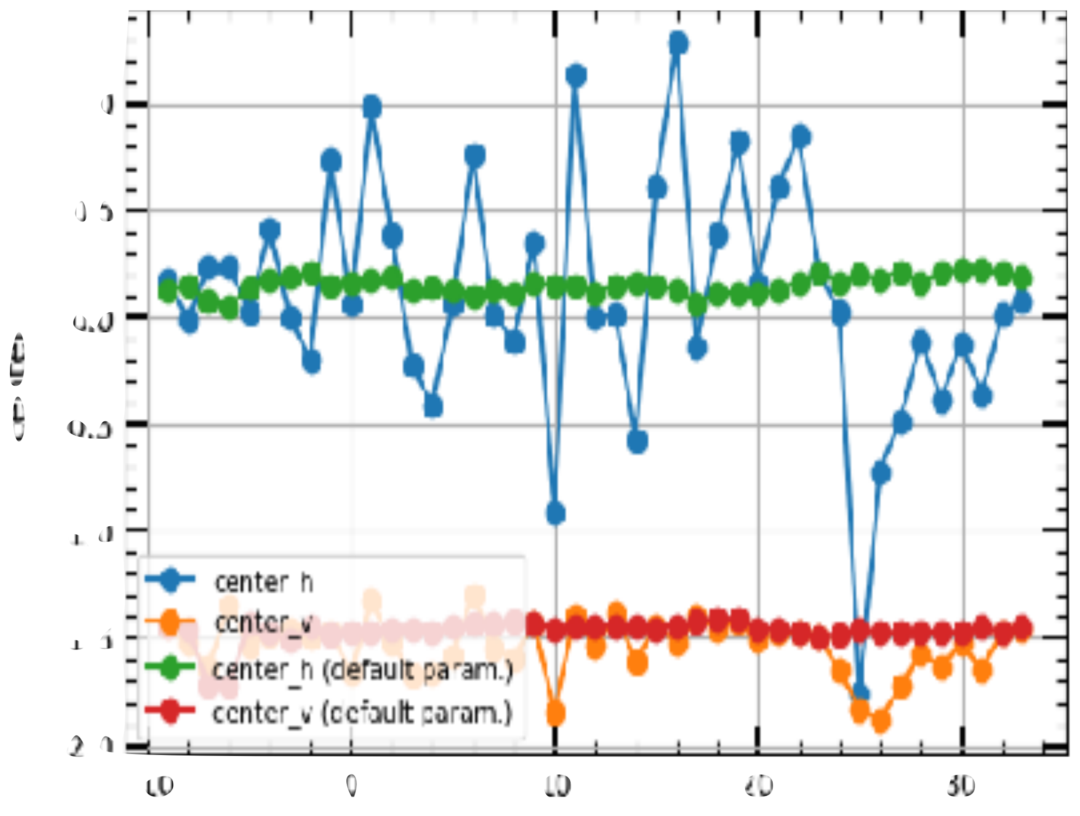
① Set Magnet

Waiting…

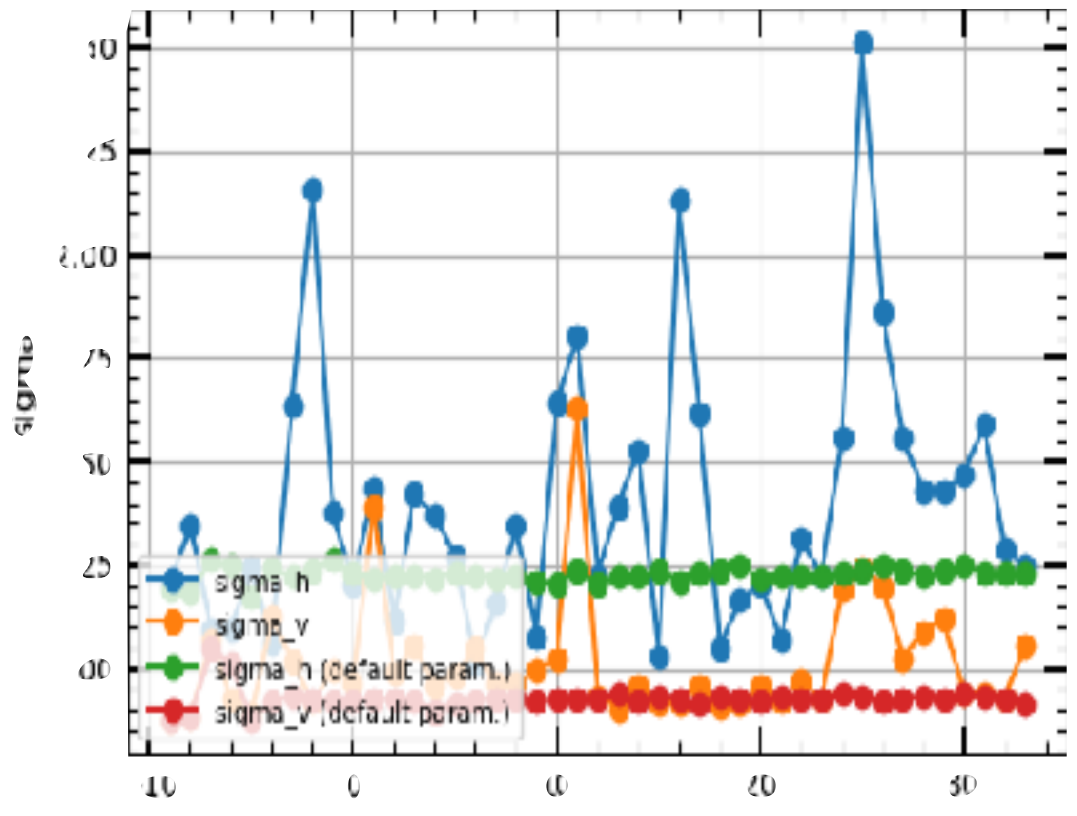
④ Evaluate
Analyzed Result

⑤ Recreate Model
Chose Next Param.

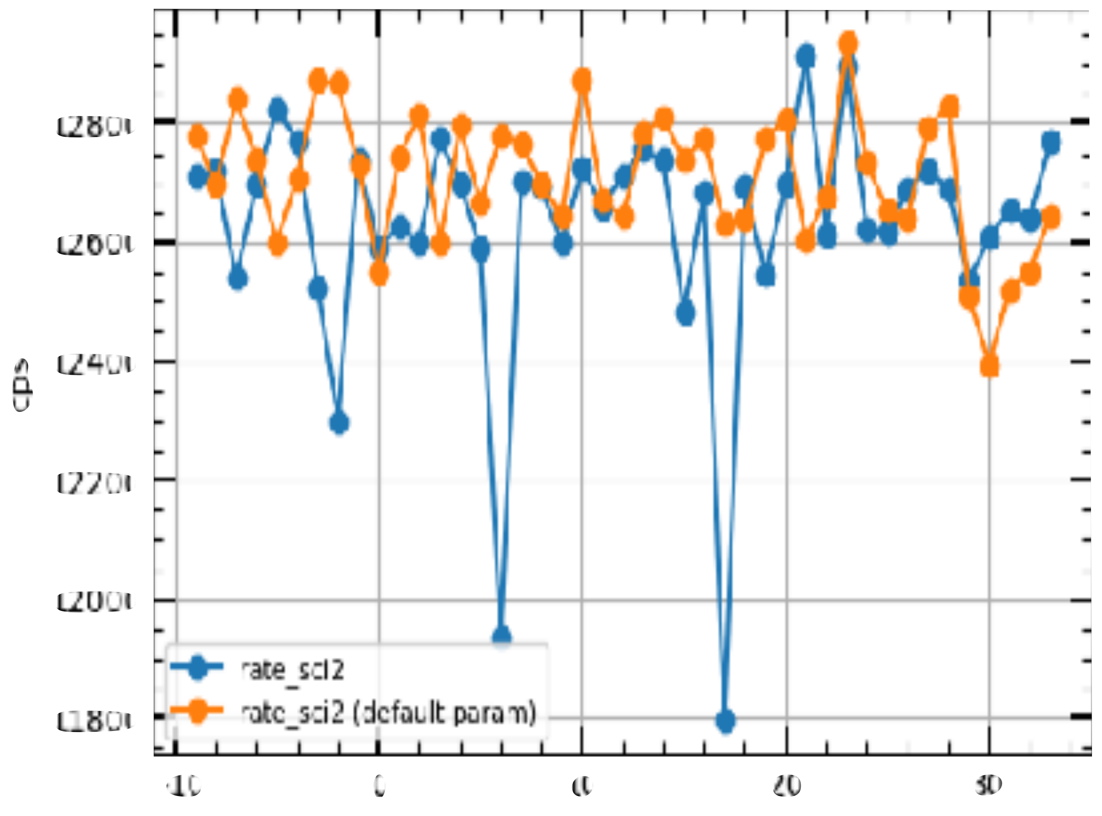
B. Auto Tuning with “High Intensity“ Primary Beam



$Pos_{h,v}$ vs Trial

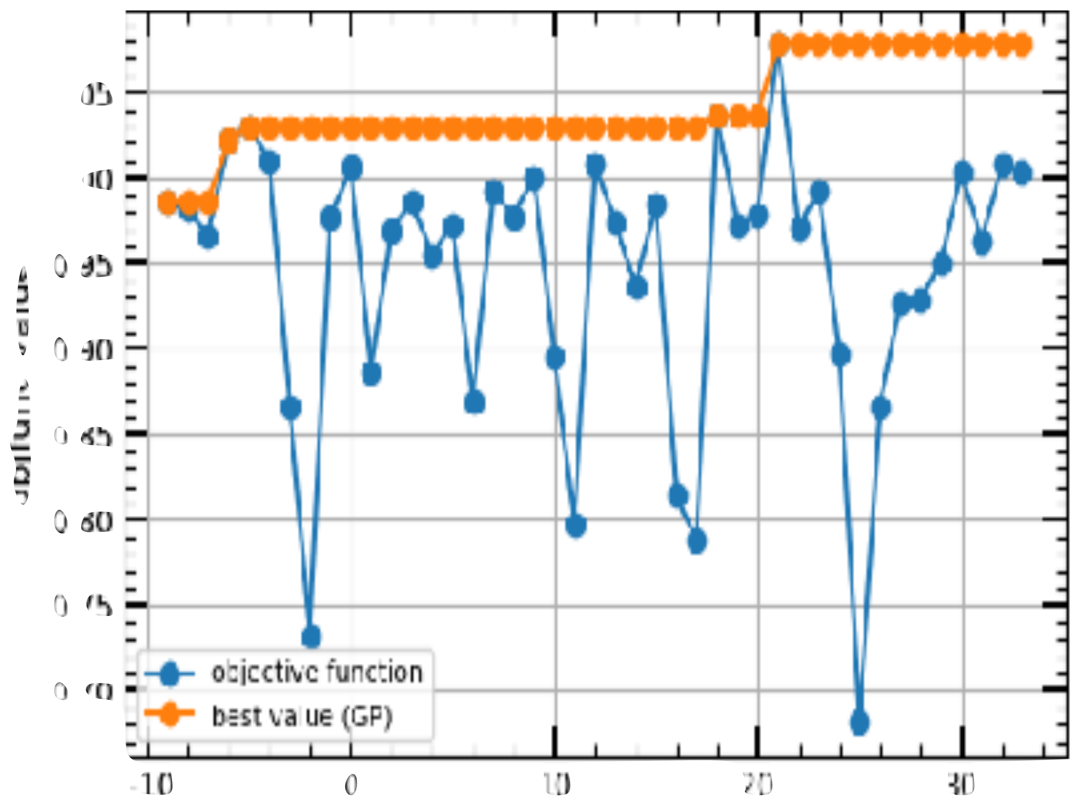


$\sigma_{h,v}$ vs Trial

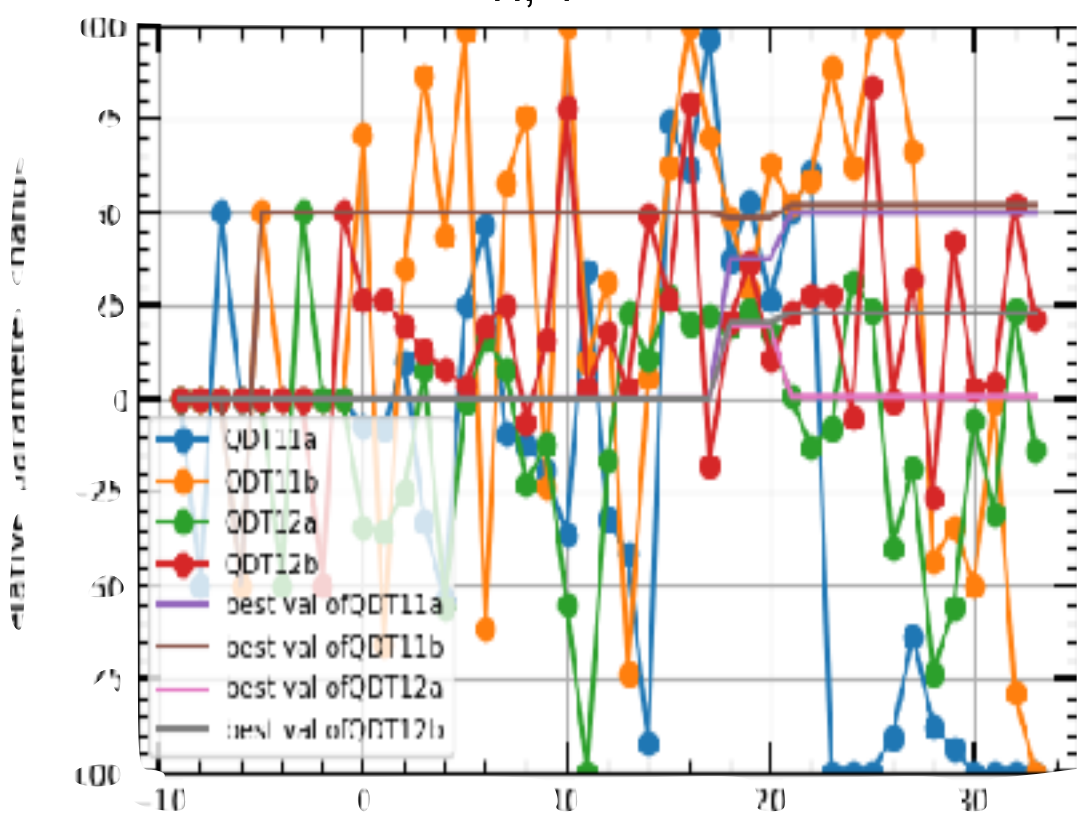


Count rate vs Trial

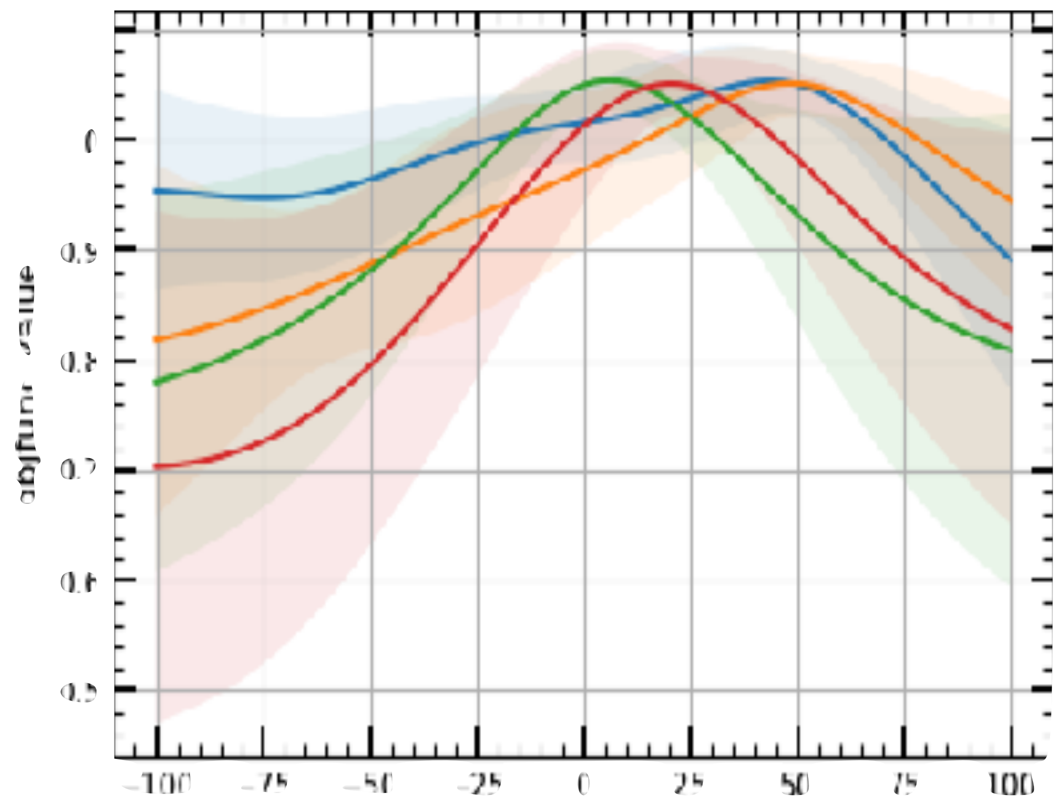
- ~ 4 params. (Quadrupoles)
- 1 trial ~ 25 s
- 1 set ~ 30 min
- ~ 0.7 pnA



Objective function vs Trial



Current of Q vs Trial

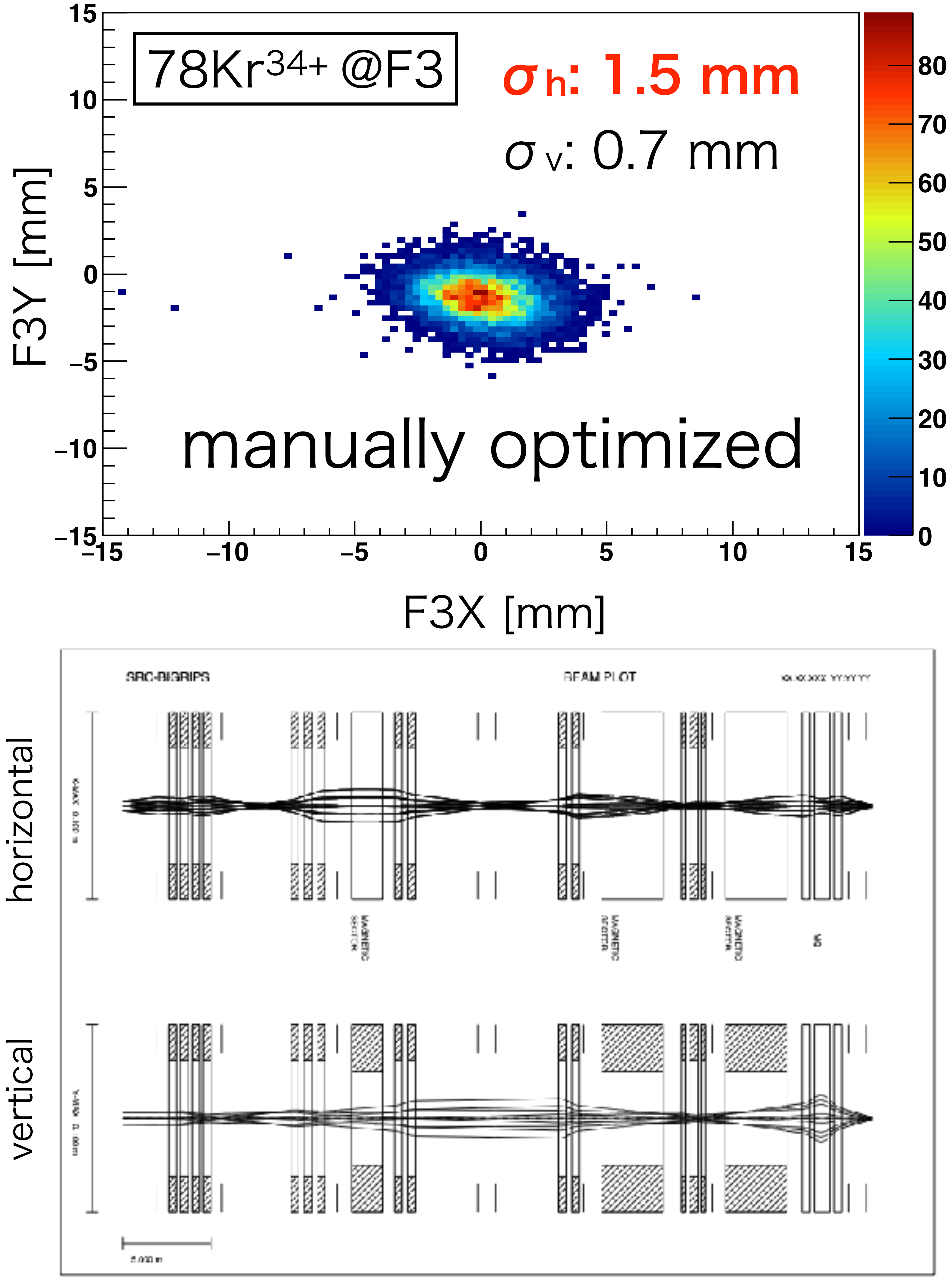


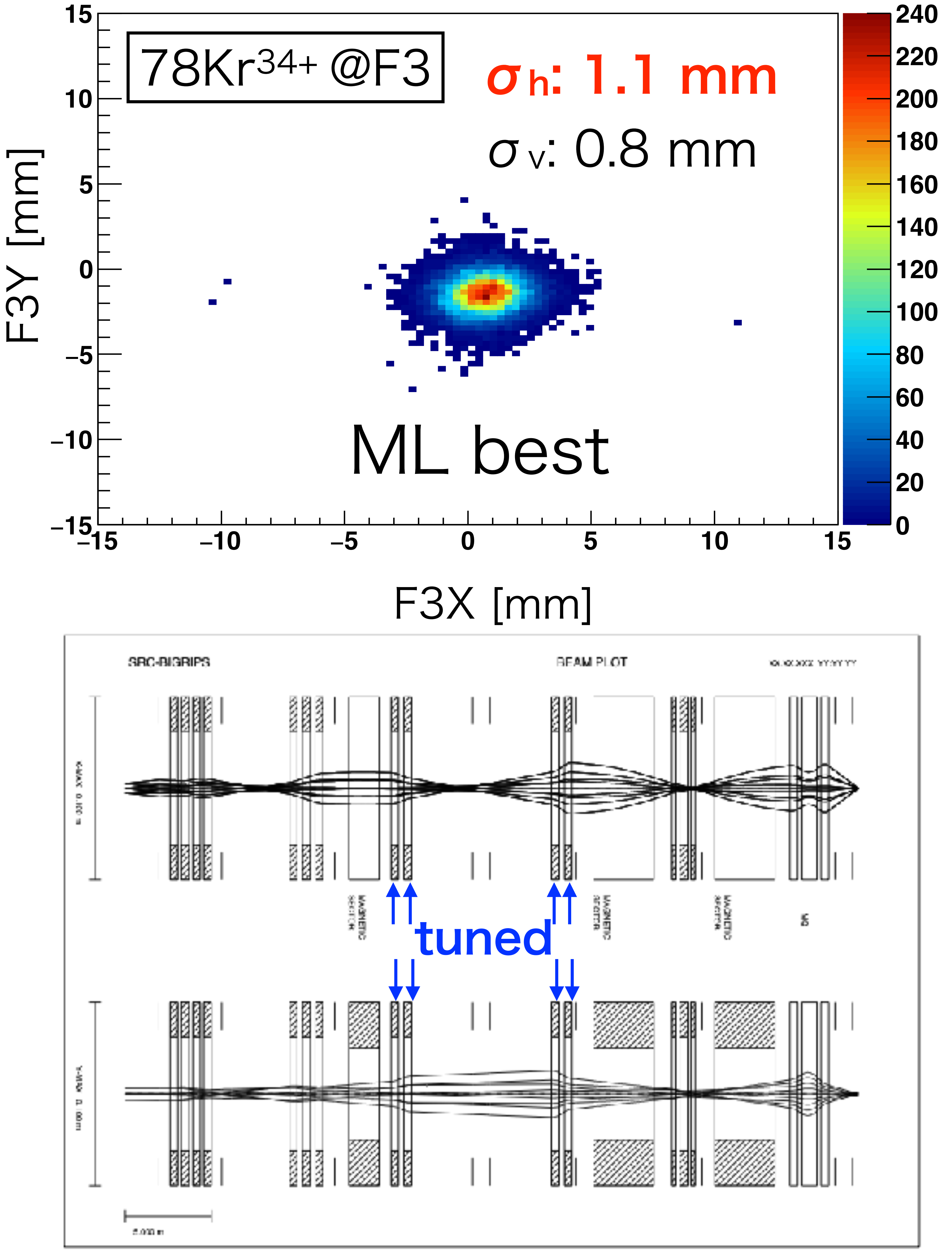
Objectives vs Current of Q

※ time of one trial is limited by measurements by detectors

Result of Auto Tuning with High Intensity Beam

Compare with manually optimized vs ML optimized optics





the spot size ↘ by 30%
keeping the transmission
in ~ 30 min. optimization
with 4 quadrupoles.

This method enable us to optimize the upstream beamline to maximize any results obtained from analyzing data from the detectors.

Optimization method	**Bayesian Optimization using Gaussian Process Regression**
Beam monitor for High intensity	**Real Time Analysis of Charge Converted Particles**
Safety	**Safe Optimization with Line Bayesian Optimization**

Safe-Line Bayesian Optimization: Safe function

Objective

$$\max_{x\in\chi} f(x) \ (\text{or} \ \min f(x)) \quad \text{s.t.} \begin{cases} g_1(x) \le 0 \\ \vdots \\ g_l(x) \le 0 \end{cases}$$

Approaches in the safe optimization

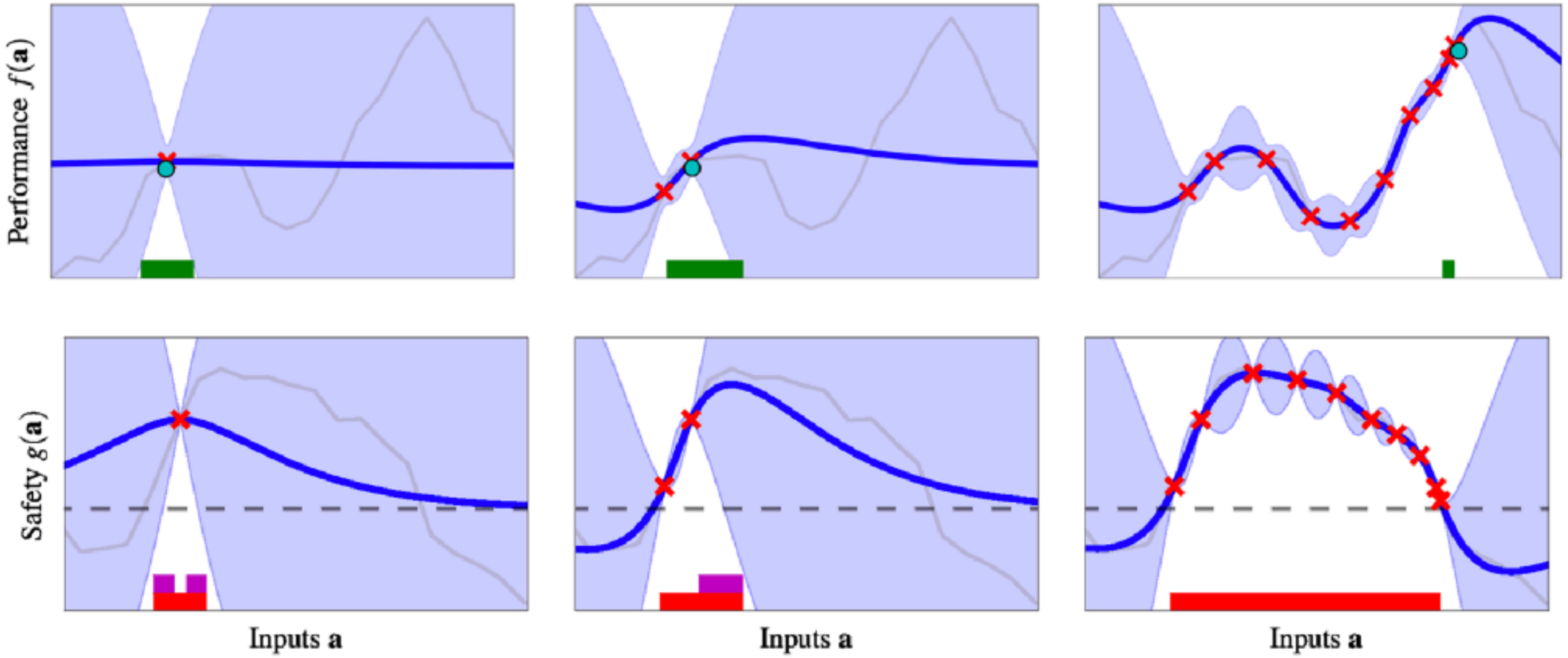
Prepare distinct GP models for both the objective and the constraints
Evaluate within the safe set only

$$x_t = \arg\max_{x\in S_t^\tau} \mathrm{UCB}_f(\hat{m}_t, x, \delta)$$

$$s.t.\ S_t^\tau = \{x \in \chi : \max_{i\in[l]} \mathrm{UCB}_{g_i}(\hat{m}_t, x, \delta) \le -\tau\}$$

Margin

[1] F. Berkenkamp, A. Krause, and A. P. Schoellig, vol. 112, no. 10. Springer US, 2023.



(a) Initial, safe parameters. (b) Safe exploration. (c) After 10 evaluations: safe maximum found.

- Create the model of the “safety function” as well
- Explore new params. in the regions where the safety function exceeds a certain threshold
- Update both the objective function and the safety function through measurements

Safe-Line Bayesian Optimization: Line BO

Line BO

Instead of optimizing in a multidimensional space, optimization is performed along a specific direction (1D) in the parameter space. This is followed by changing the direction from the optimal point and repeating the optimization process.

(A) CoordinateLineBO

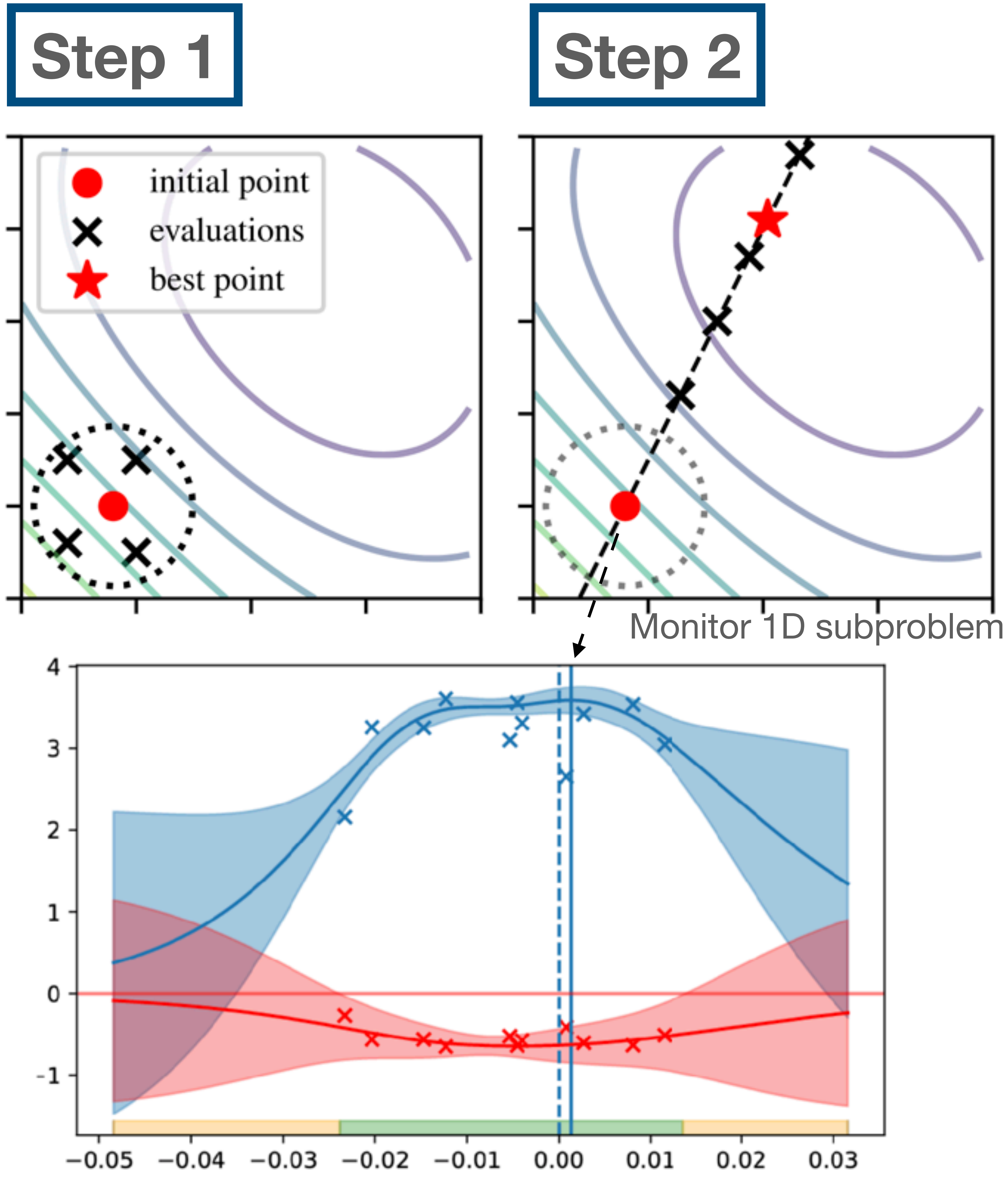
The direction is chosen to align with each parameter axis

(B) Descent (Ascent) LineBO

The direction is chosen to align with steepest gradient

(C) RandomLineBO

The direction is chosen randomly

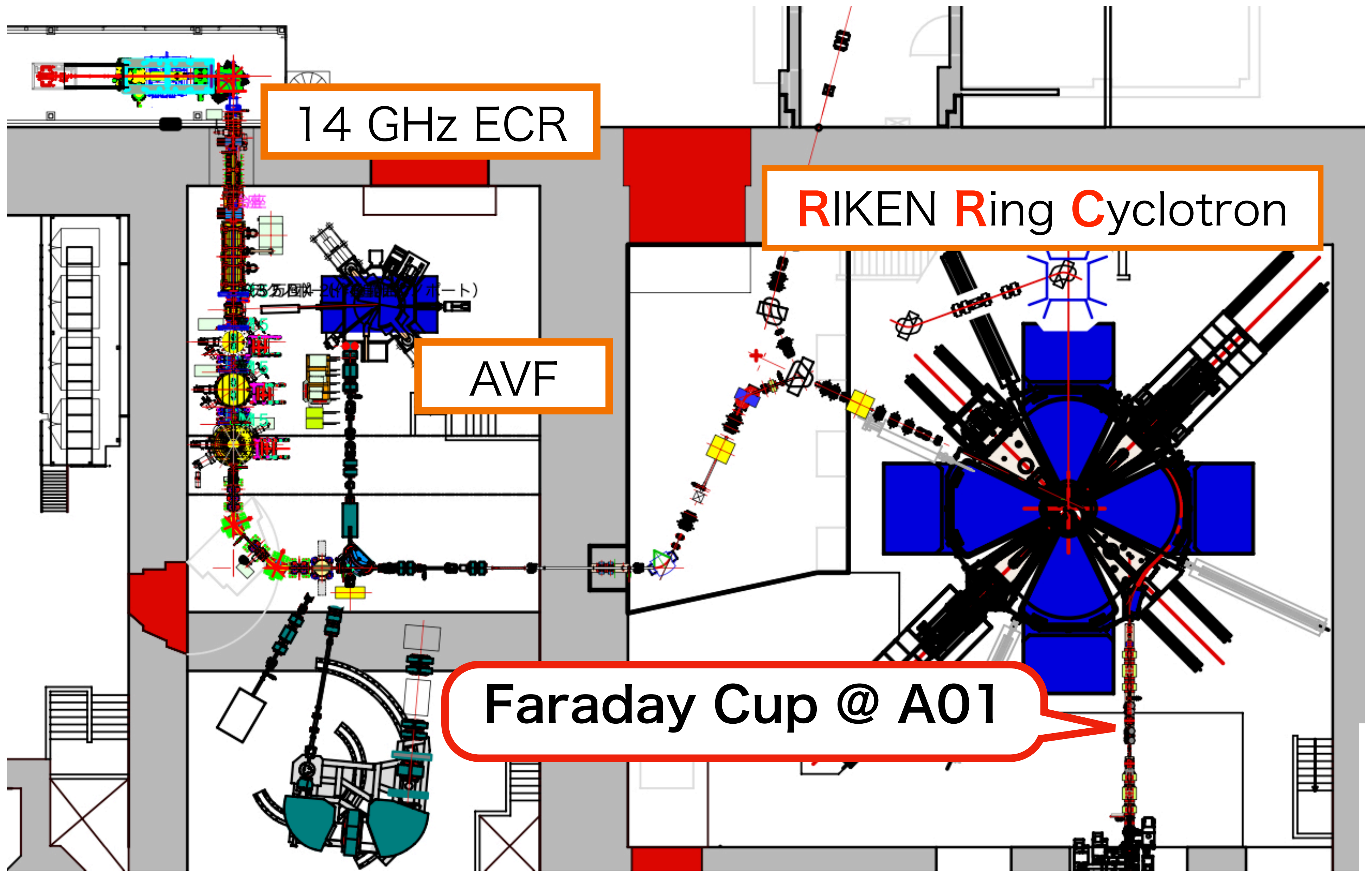


(c) User feedback

J. Kirschner, M. Mutný, N. Hiller, R. Ischebeck, and A. Krause, *36th Int. Conf. Mach. Learn. ICML 2019*, vol. 2019-June, no. Icml, pp. 5959–5971, 2019.

Demonstration of Safe-Line BO at "Low" Energy Beamline

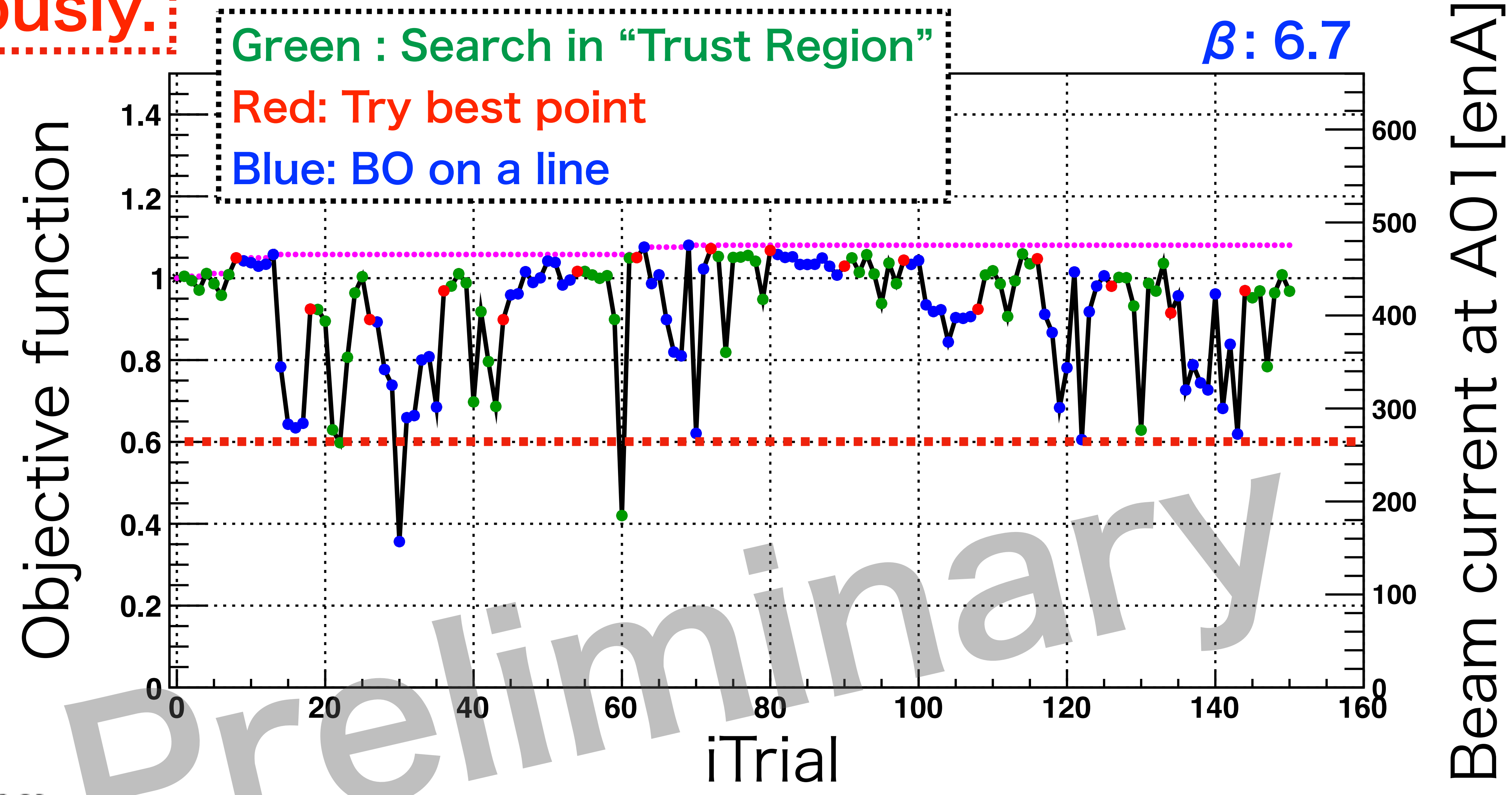
From Ion source exit to Cyclotron entrance,
~ **24 Quadrupoles**.
→ Line BO can treat these params **simultaneously.**

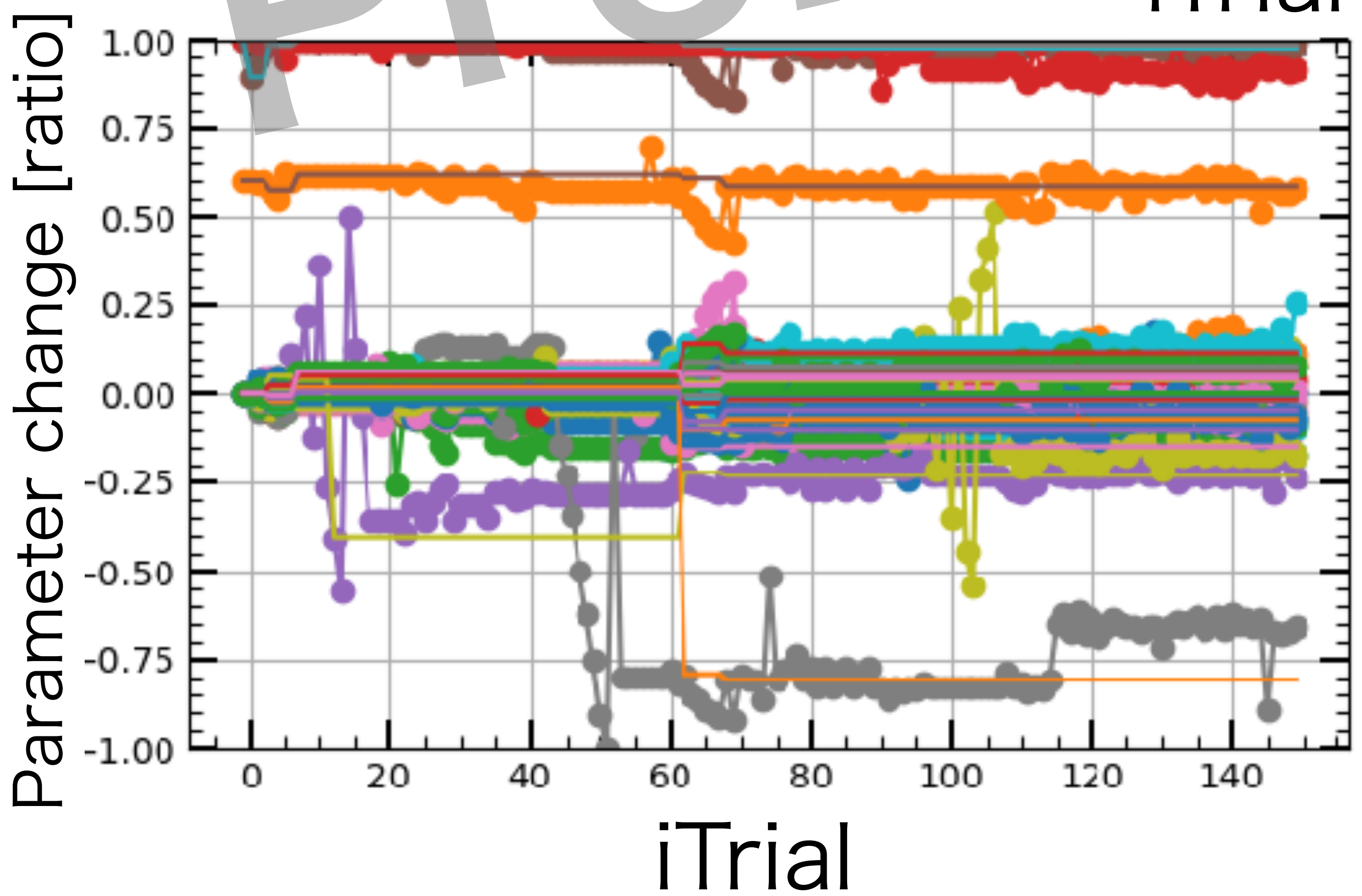


※ Exp. was performed in Oct. 9th.

Objective function: FC current / FC current (start)

Constraint : Objective function > 0.6



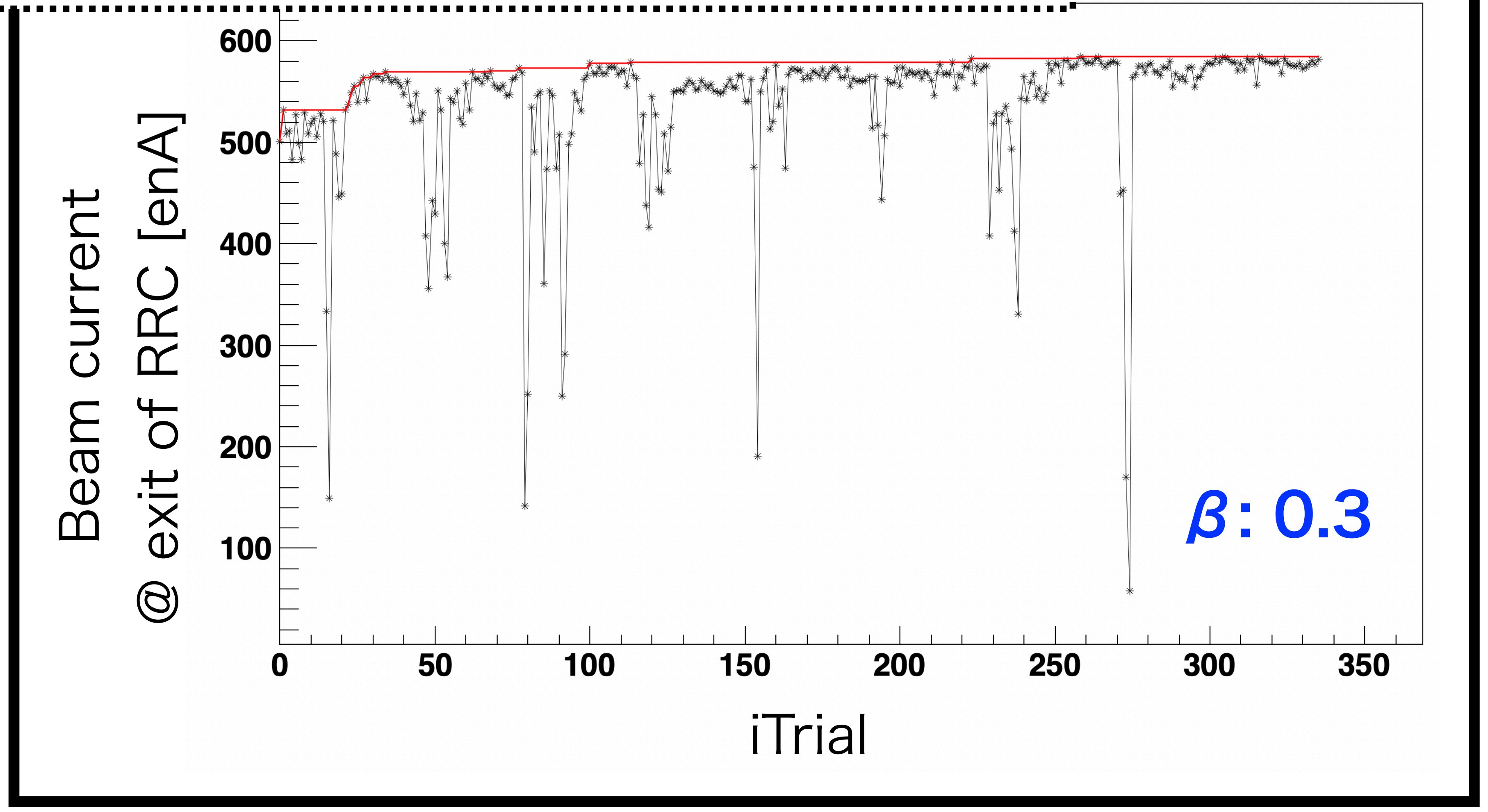


- The search mostly stayed within the constraint, but **sometimes went below it.**

Demonstration of Safe-Line BO at "Low" Energy Beamline

From Ion source exit to Cyclotron entrance,
~ **24 Quadrupoles**.
→ Line BO can treat these params **simultaneously.**

c.f. Normal BO for RILACII to AVF



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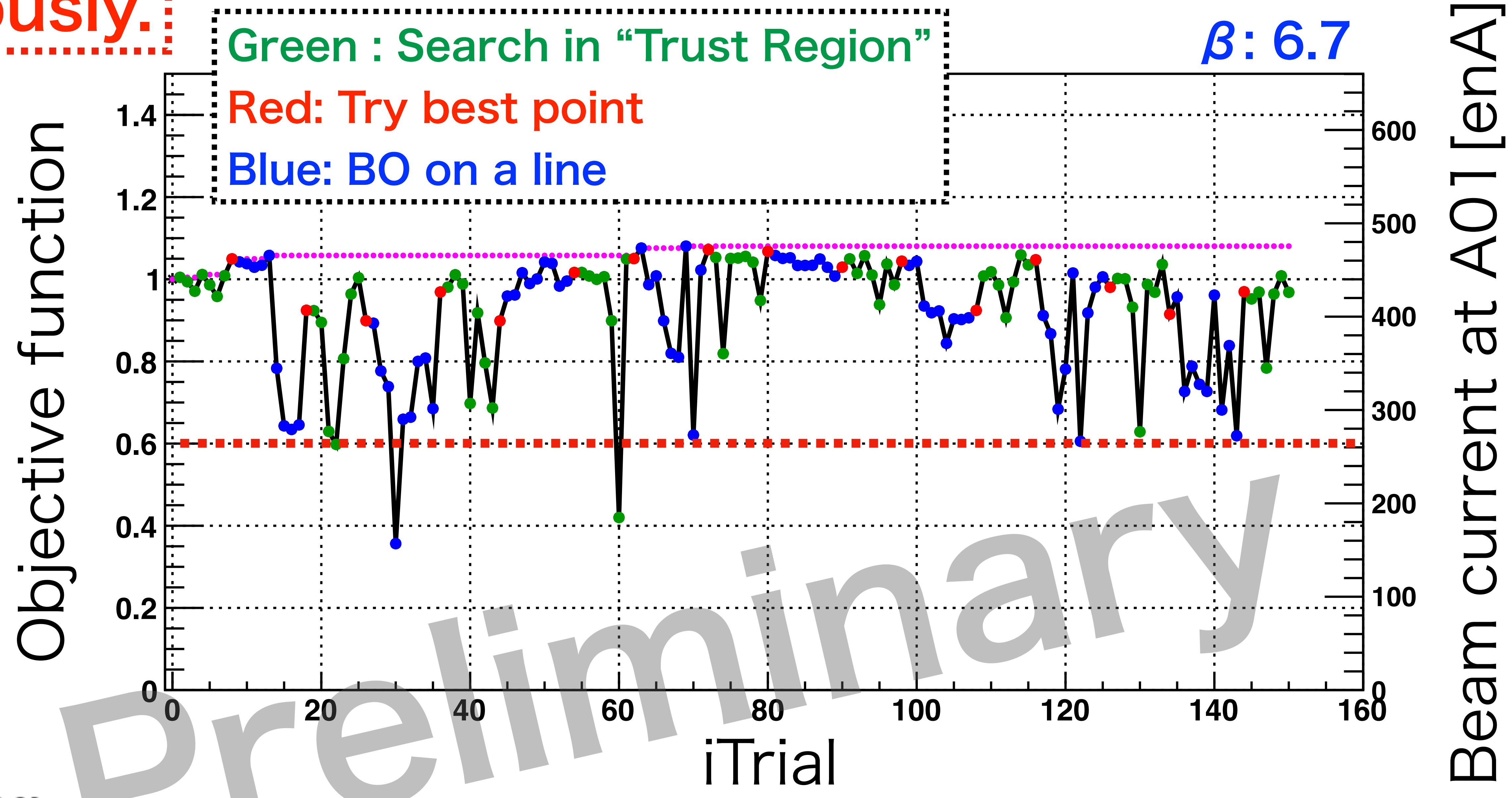

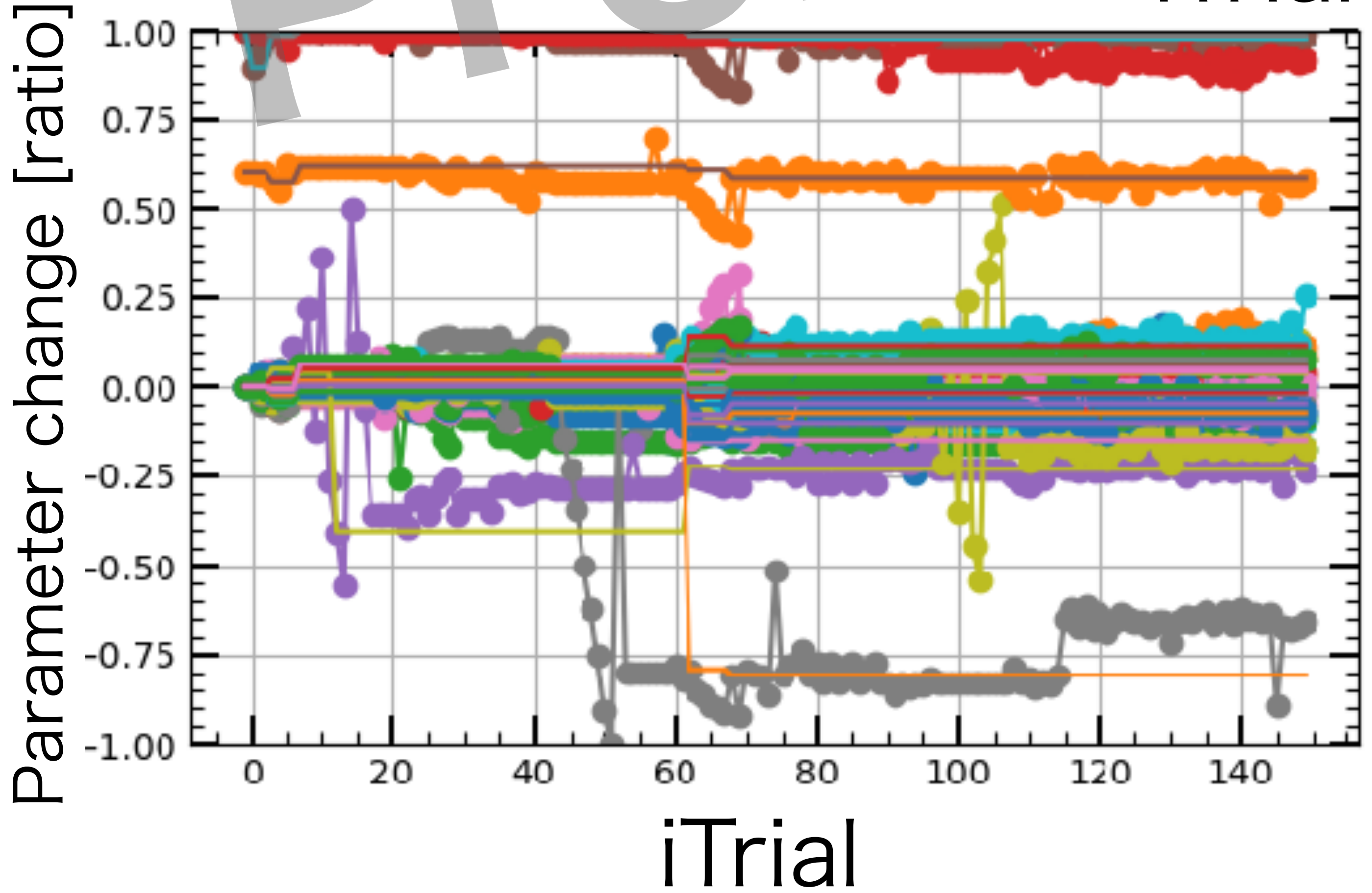

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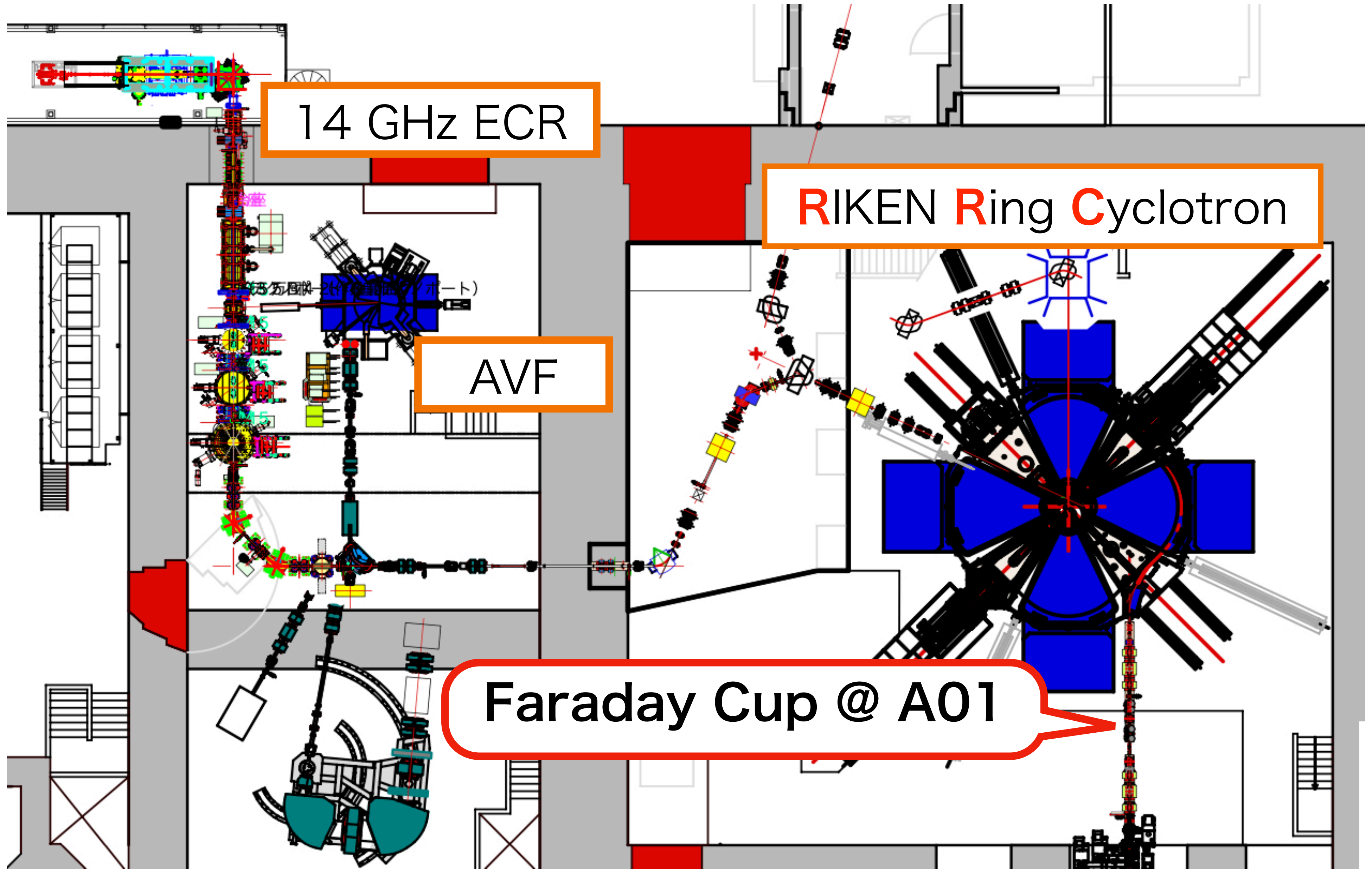
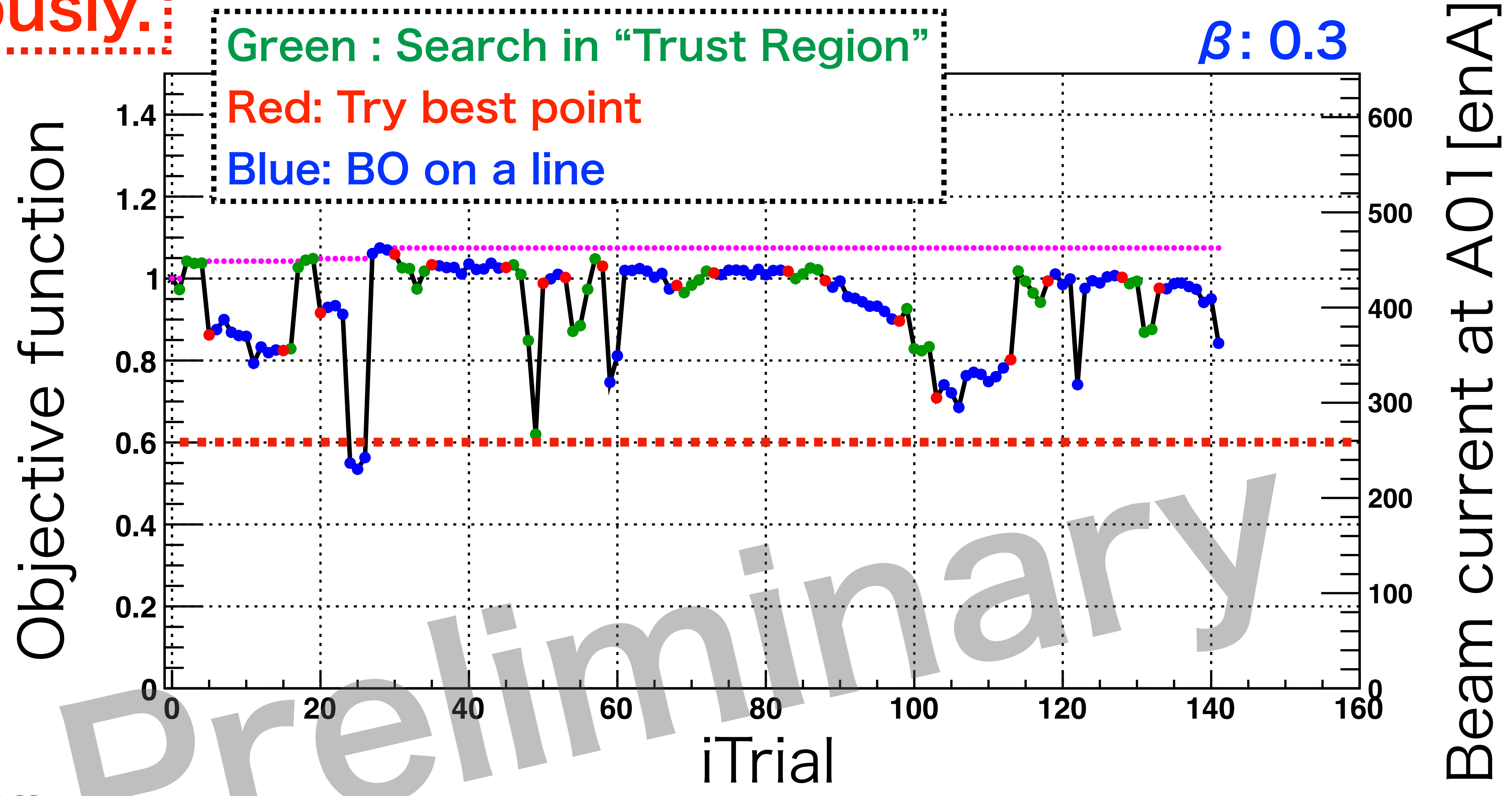
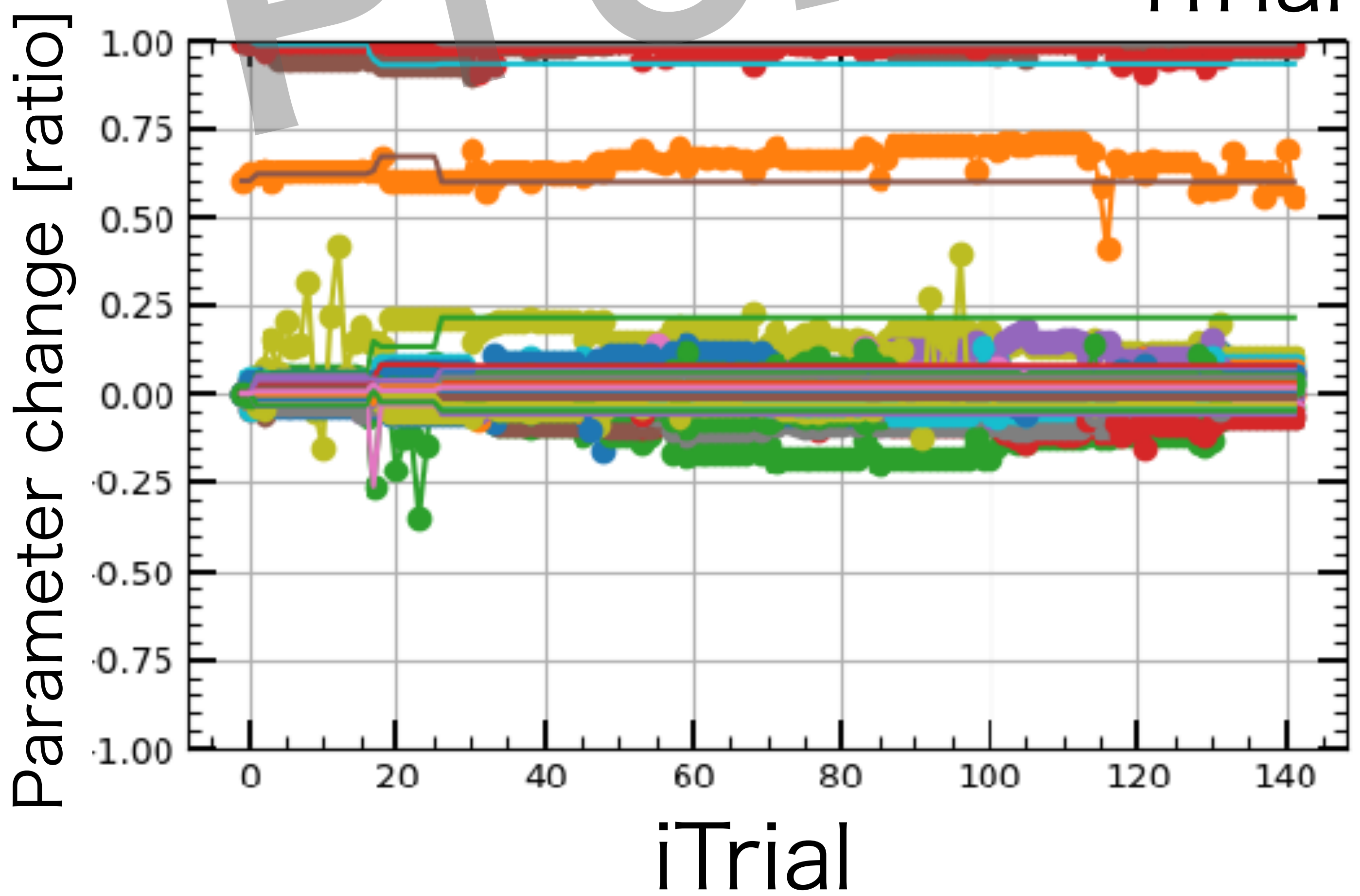


※ Exp. was performed in Oct. 9th.

Objective function: FC current / FC current (start)

Constraint : Objective function > 0.6





- The search mostly stayed within the constraint, but sometimes went below it.
- Behavior depended on BO hyperparameters (e.g., β).

Demonstration of Safe-Line BO at "Low" Energy Beamline

From Ion source exit to Cyclotron entrance,
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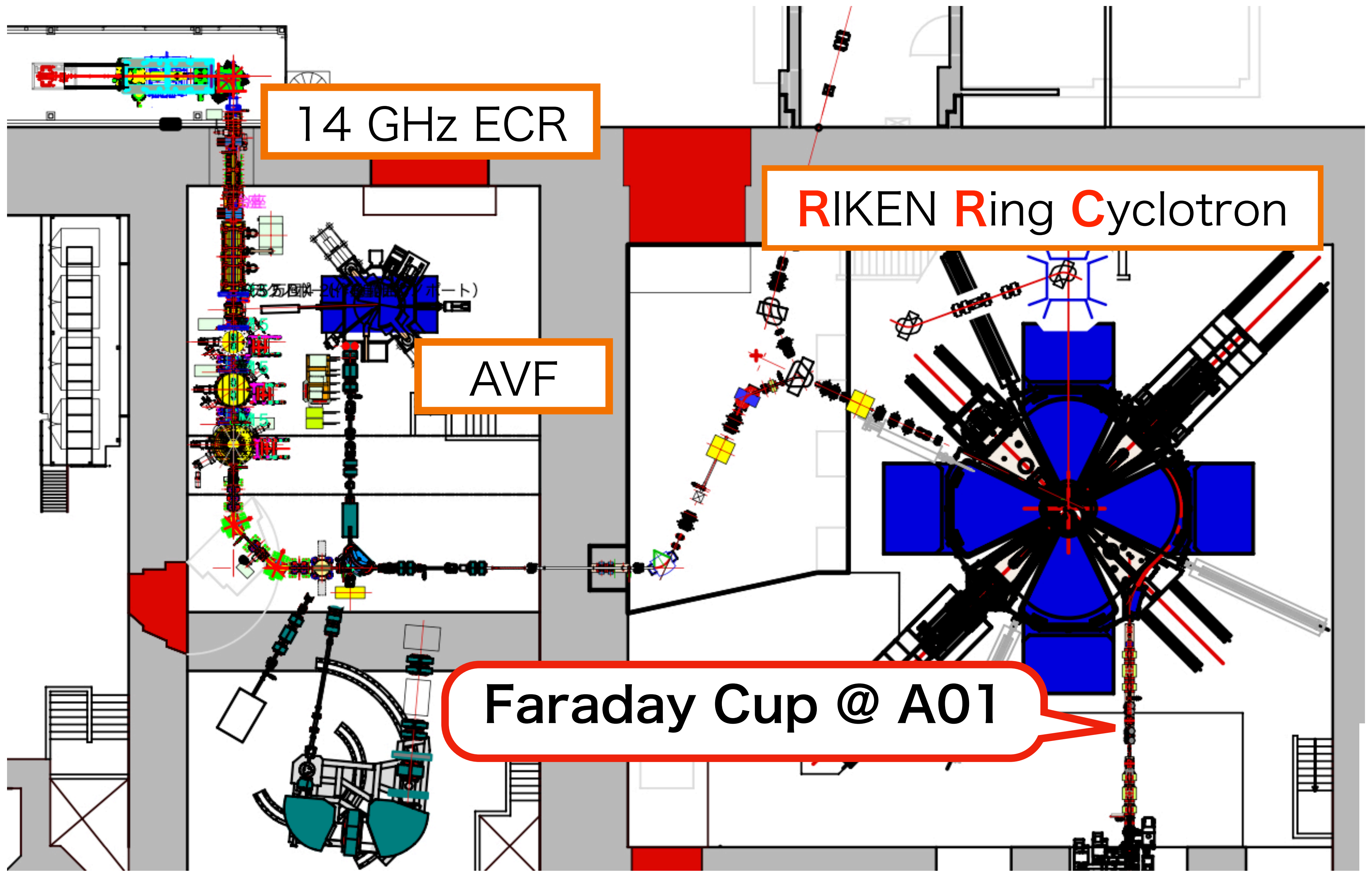
→ Line BO can treat these params **simultaneously.**



※ Exp. was performed in Oct. 9th

Objective function: FC current / FC current (start)

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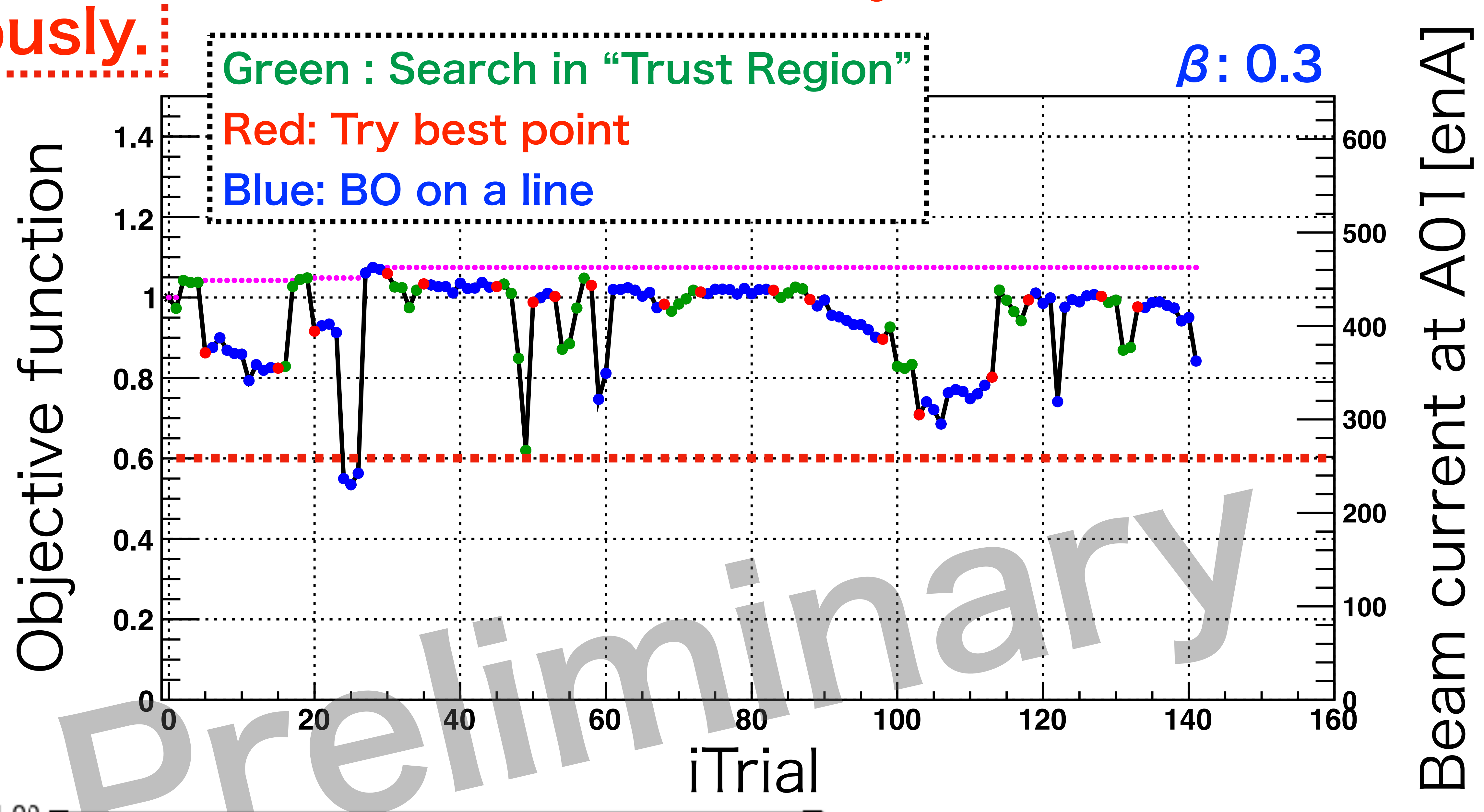

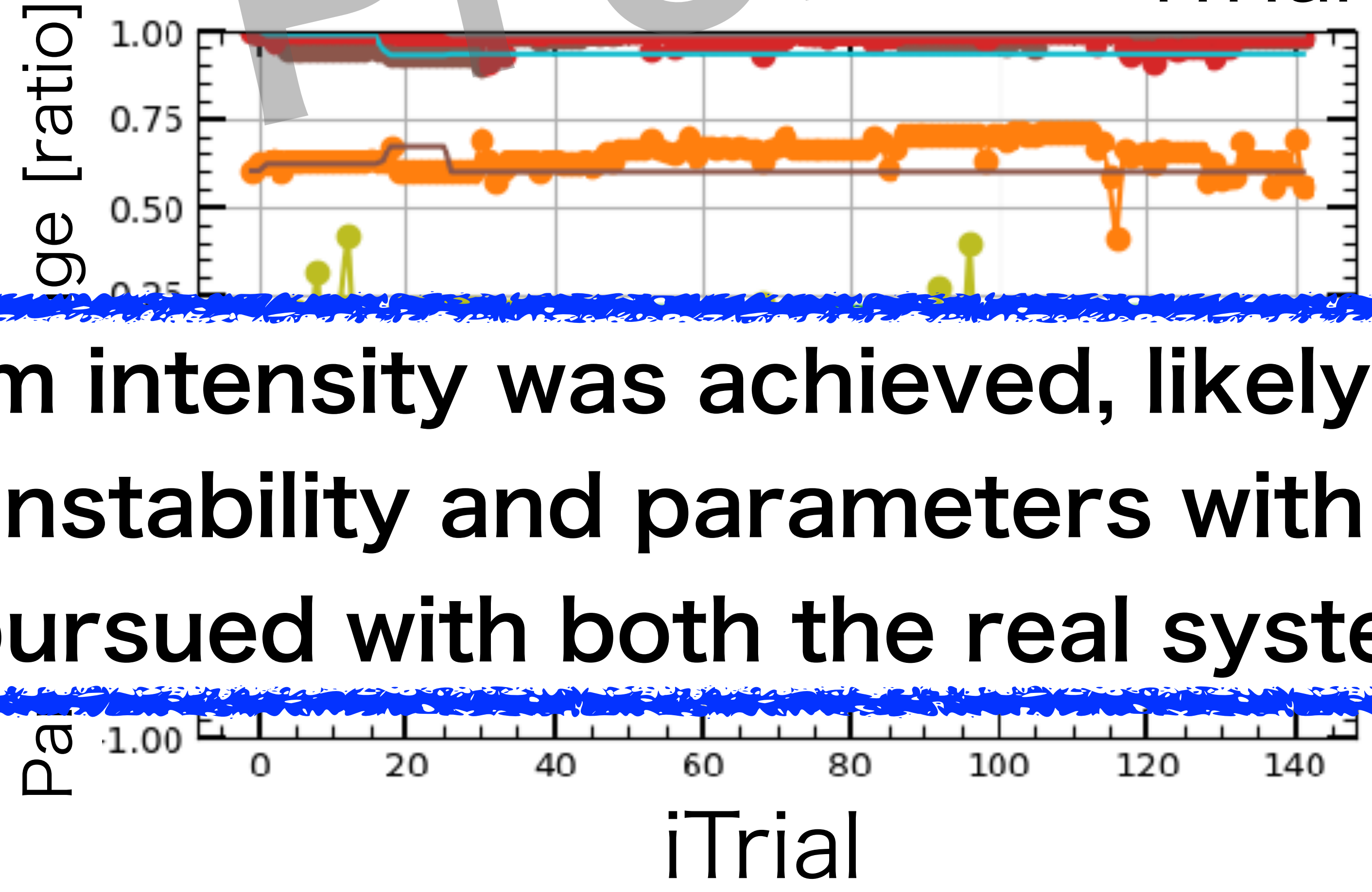

· The search mostly stayed within the constraint, but sometimes went below it.

- **No significant increase in beam intensity was achieved, likely due to experimental issues such as beam current instability and parameters with hysteresis.**
- **Further improvement will be pursued with both the real system and simulations.**

RIKEN NiSHiNA CENTER

Summary

- At RIKEN RIBF, auto beam tuning system using Bayesian Optimization are under development to handle future high-intensity heavy ion beams precisely.
- When BO is used in beam dynamics control, it is very important to develop not only algorithms but also safety scheme and diagnostics for high intensity beam.
- So far we achieved ~ 4 parameters simultaneous optimization with 0.7 pnA primary beam to improve transmission efficiency and beam spot size, measuring charge converted particles at downstream separator BigRIPS.
- For safety optimization, we are also developing new algorithm using Safe-LineBO.

Collaborators

Real Time Analysis of Charge Converted Particles

Naoki Fukuda, Yohei Shimizu, Toshiyuki Sumikama, Hiroshi Suzuki, Hiroyuki Takeda, Yasuhiro Togano, Akito Uchiyama and Masahiro Yoshimoto

Implementation of Safe LineBO

Hiroyuki Ekawa, Hiroki Fujii and Yasuyuki Morita