SuperKEKB commissioning taskforce report: AI/ML

2026/10/27

T.Koga
AT/ML beam tuning task force

ML/AI beam tuning task force

- ML/AI beam tuning task force has been established since May 2026, in order to enhance AI developments at SuperKEKB

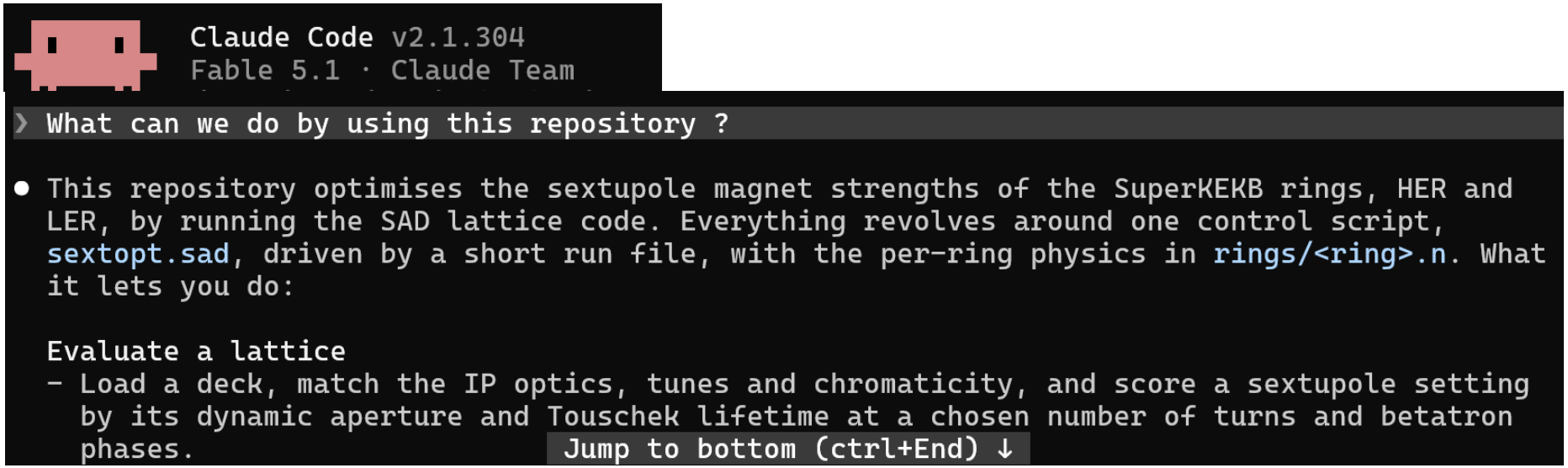
- Status from May to Oct. are summarized
  - ①offline lattice optimization by AI
    - optimization of sextupole to increase dynamic aperture
  - ②online beam parameter tuning by AI
    - IP knob, injection tuning tool
    - AI agent
  - ③ offline data analysis by AI
    - Luminosity fluctuation
    - HER emittance fluctuation

①Offline lattice optimization by AI

Simulation framework

- Simulation codes of SKEKB main ring are partially accumulated to git

- AI coding agent can perform following simulation by using SAD library
  - -lattice of main ring
  - -tune adjustment
  - -tracking simulation and sextupole magnet optimization
  - -beam injection @ main ring

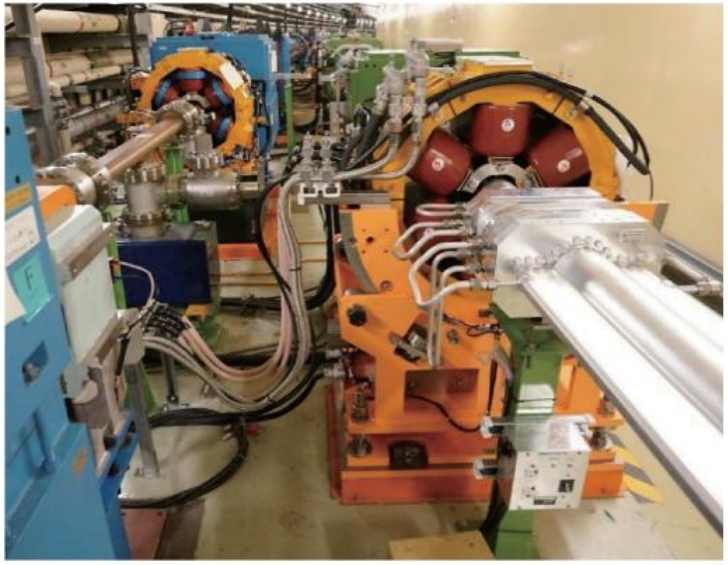


Sextupole optimization by simulation

- 54 pairs of sextupole magnets for chromaticity correction in each ring
  - -50 pairs in arc section with phase advance of π and
  - -4 pairs in interaction region, used for crab waist scheme

- The 50 pairs in arc are optimized to maximize DA
  - -due to nonlinear effects, analytical optimization is difficult → simulation
  - **-optimization problem with 50 parameters**

HF2014



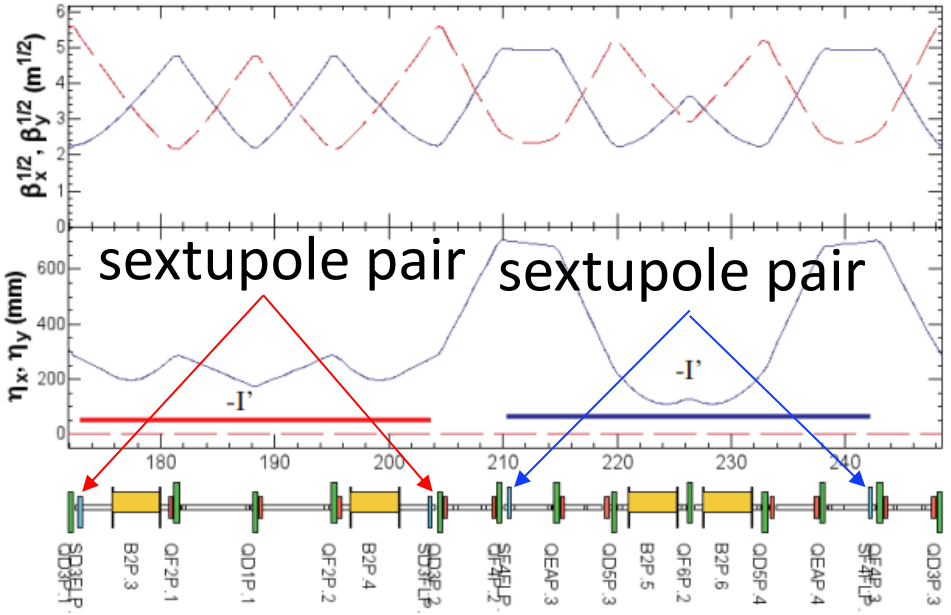


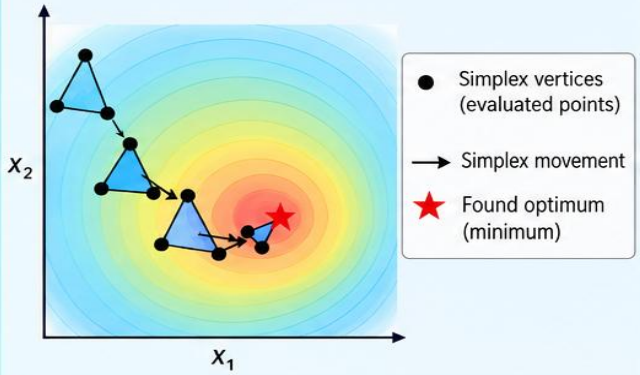
Figure 1: Arc cell in LER.

AI optimization algorithm

- So far, the sextupole have been optimized by downhill simplex to maximize dynamic aperture based on tracking simulation
- In this time, we newly use Modern AI optimization method, CMA-ES and surrogate model by AI agent (Claude fable 5.1)

Downhill Simplex Method
(Nelder–Mead)

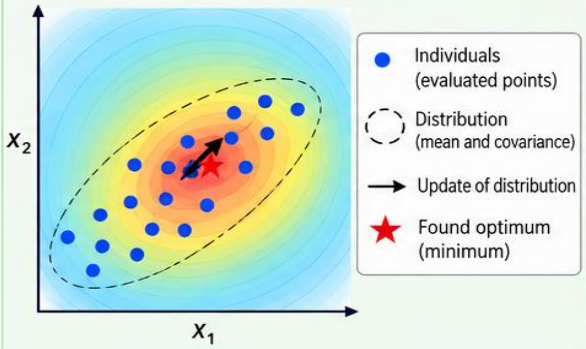
A derivative-free optimization method that moves a simplex (a polytope of vertices) through the search space to find a better point.



The simplex is modified by reflection, expansion, contraction, and shrinkage to move toward better points.

CMA-ES
(Covariance Matrix Adaptation Evolution Strategy)

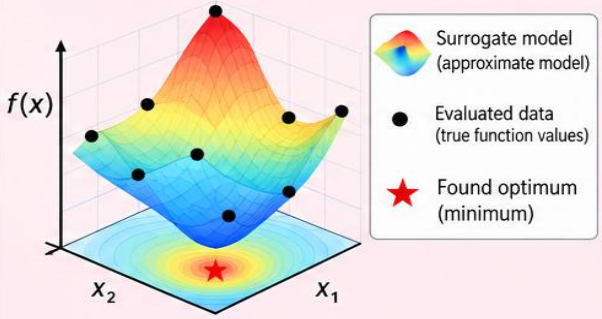
An evolutionary optimization method that evaluates multiple points (individuals) at once and adaptively updates their distribution (mean and covariance) to search for better regions.



The mean and covariance are adaptively updated so that the search focuses on promising directions and scales.

Surrogate Model
(Surrogate-based Optimization)

A method that builds an approximate model (surrogate model) from a limited number of expensive evaluations and uses this model to efficiently search for the optimum.



An approximate model is constructed from a limited number of evaluations, and optimization (e.g., maximization of an acquisition function) is performed on the model. New points are evaluated as needed to improve the model.

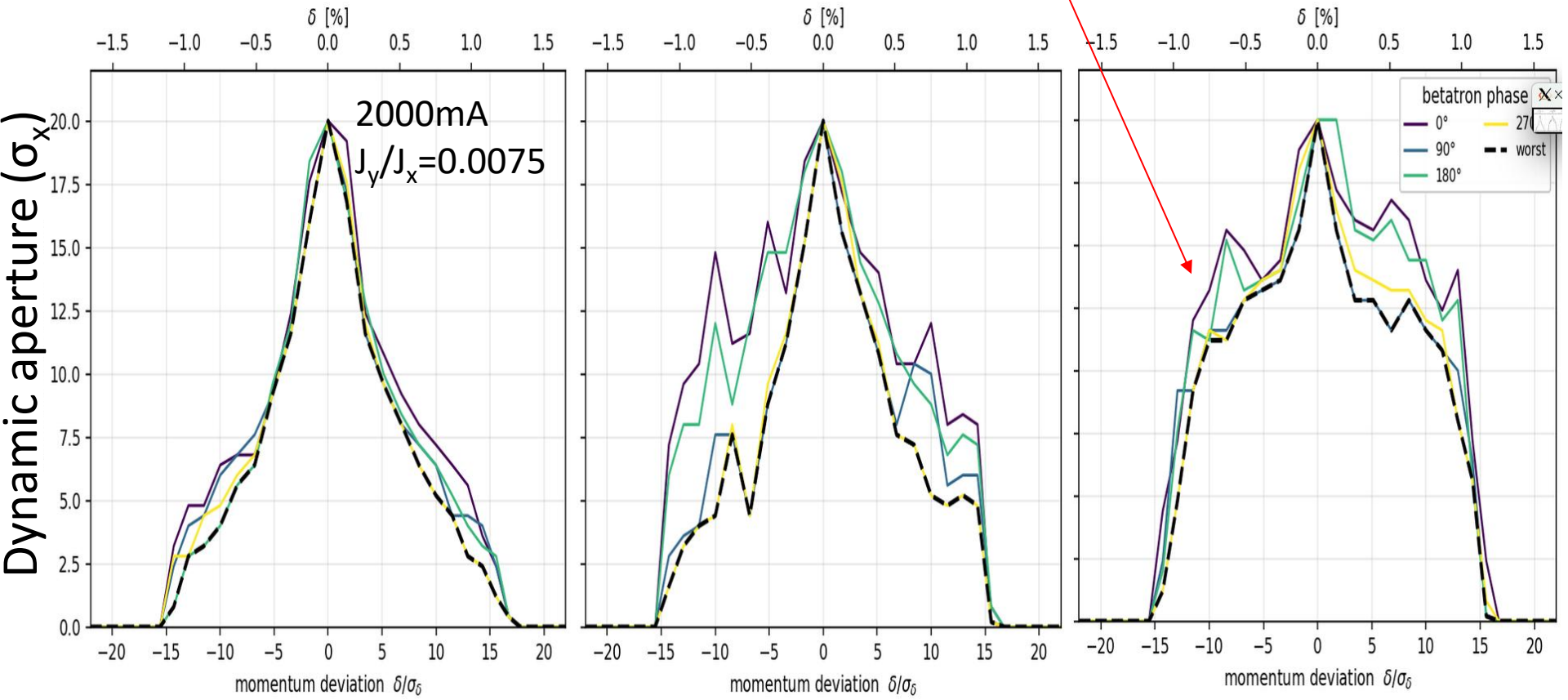
Optimized DA (LER)

- CMA-ES has ~70% better DA score than downhill simplex

initial lattice

downhill

CMA-ES+surrogate



DA score=-458

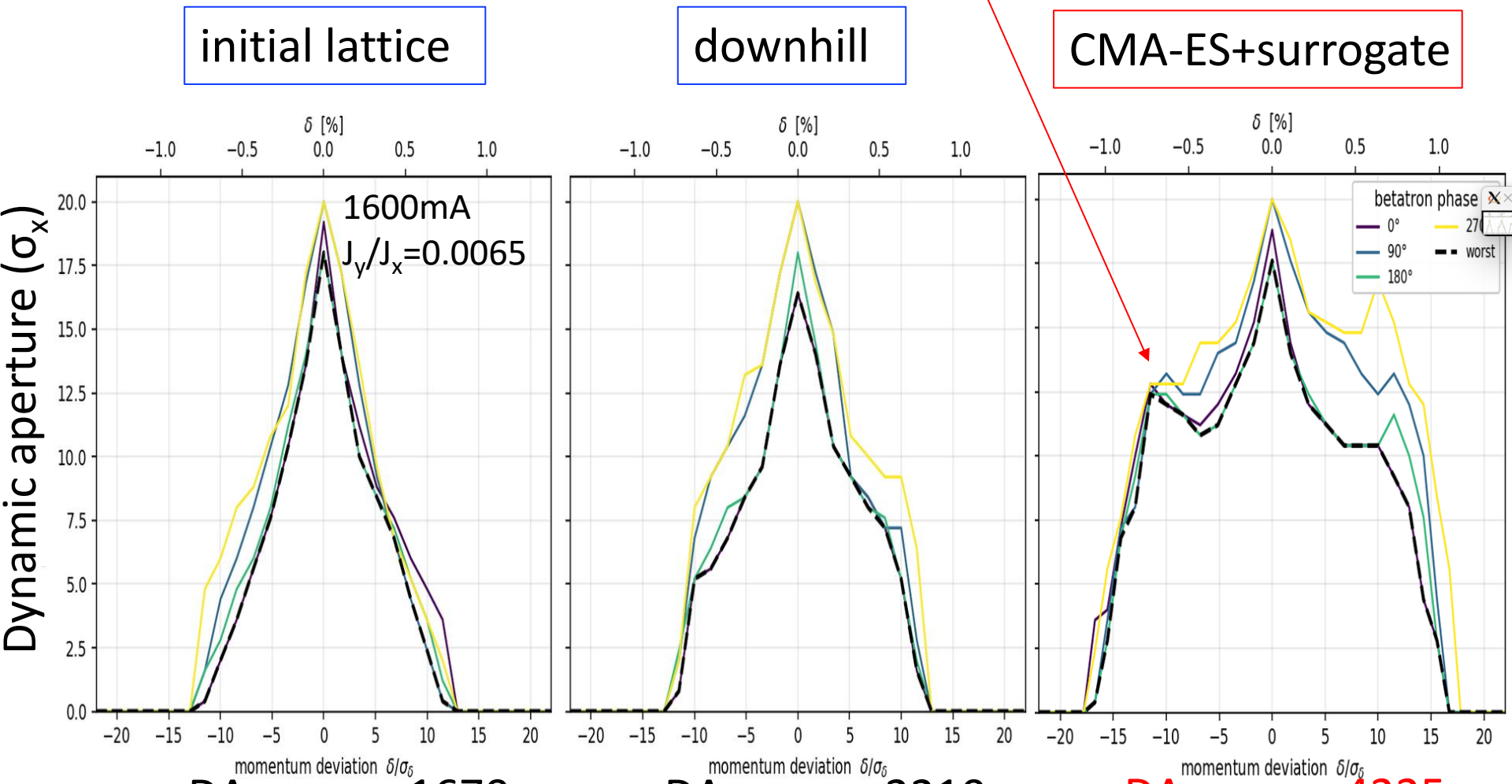
DA score=-530

DA score=-917

(smaller score is better)

Optimized DA (HER)

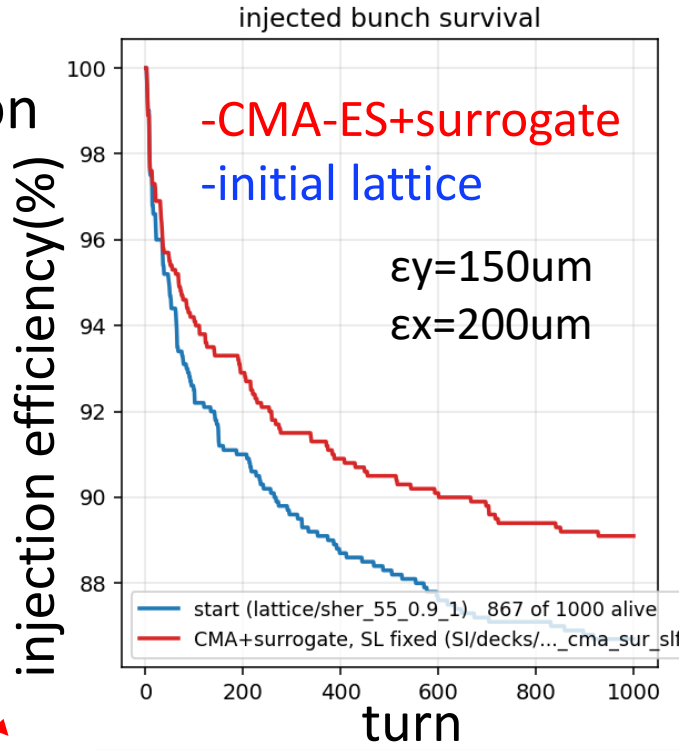
- CMA-ES has ~80% better DA score than downhill simplex



(smaller score is better)

Injection efficiency (HER betatron injection)

- Injection efficiency is evaluated by simulation
- CMA-ES+Surrogate has a few % better injection efficiency than initial lattice, especially at multi turns (beam-beam etc.)

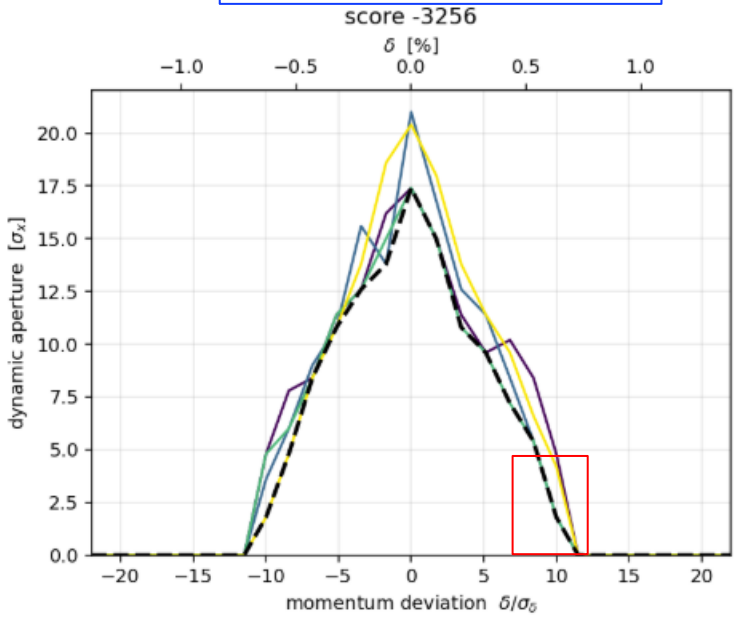


simulation configuration	cancel coil error	injection offset(mm)	collimator	beam-beam	injection efficiency (initial)	injection efficiency (CMA+sur)
1	off	-7.2	off	on	87%	89%
2	on	-7.2	off	on	76%	82%
3	on	-7.6	off	on	69%	75%
4	on	-7.6	on	on	69%	75%
5	on	-7.6	on	on (x2)	40%	50%

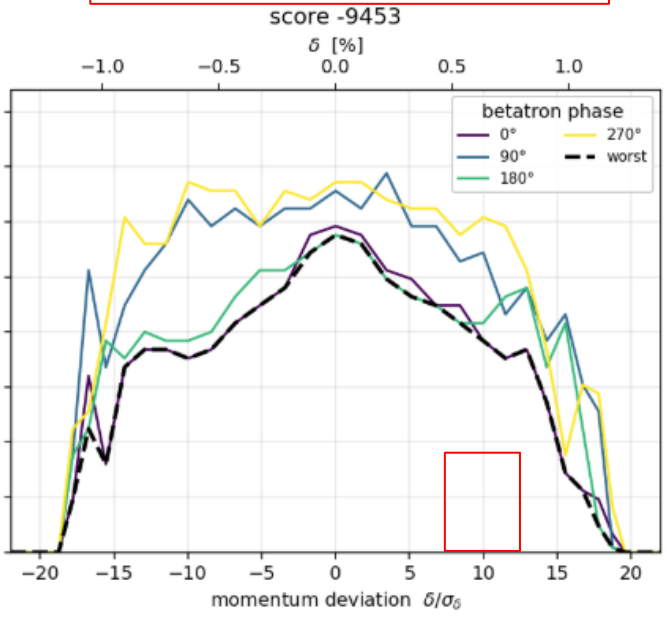
Injection efficiency (HER synchrotron injection)

- Dynamic aperture is enlarged at off-momentum direction mainly
- We do not plan synchrotron injection in 2027,
  but possible improvement in future

initial lattice



CMA-ES+surrogate



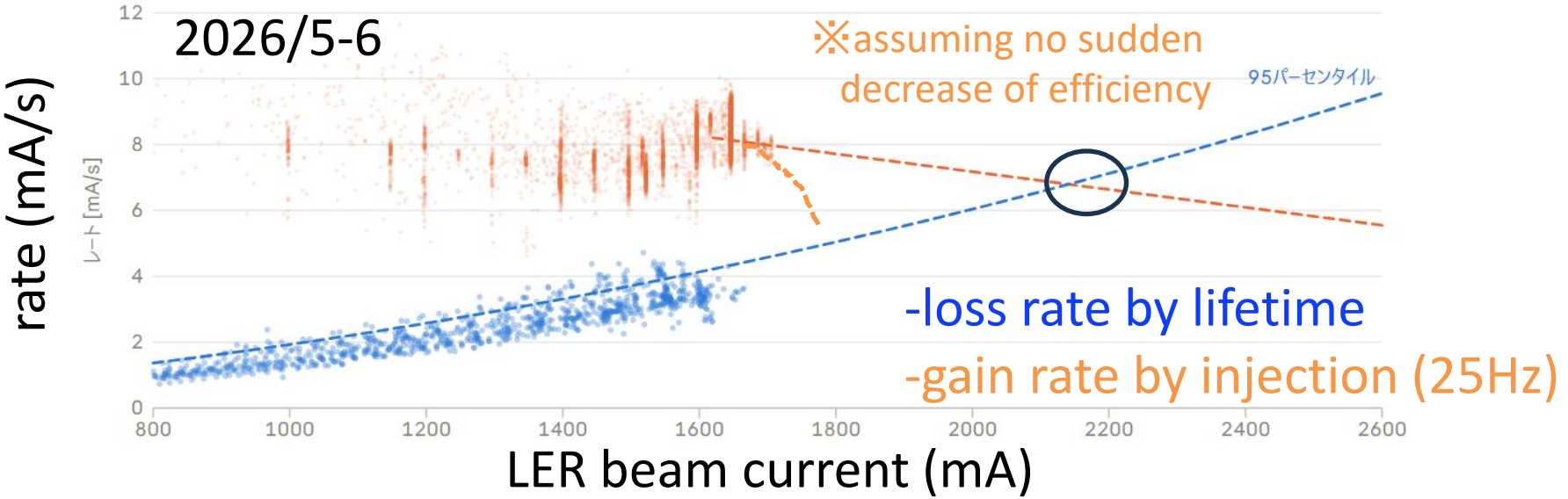
with cancel coil error
without collimator
synchrotoron injection

☐~2.5σ of injected beam

Impact to luminosity and beam current

- Based on simulation, most optimistically,
  - -Touscheck lifetime improves by ~80% (total LER lifetime improve ~20%)
  - -Injection efficiency improves by ~5%

→Beam current increase by ~200mA by very rough extrapolation below



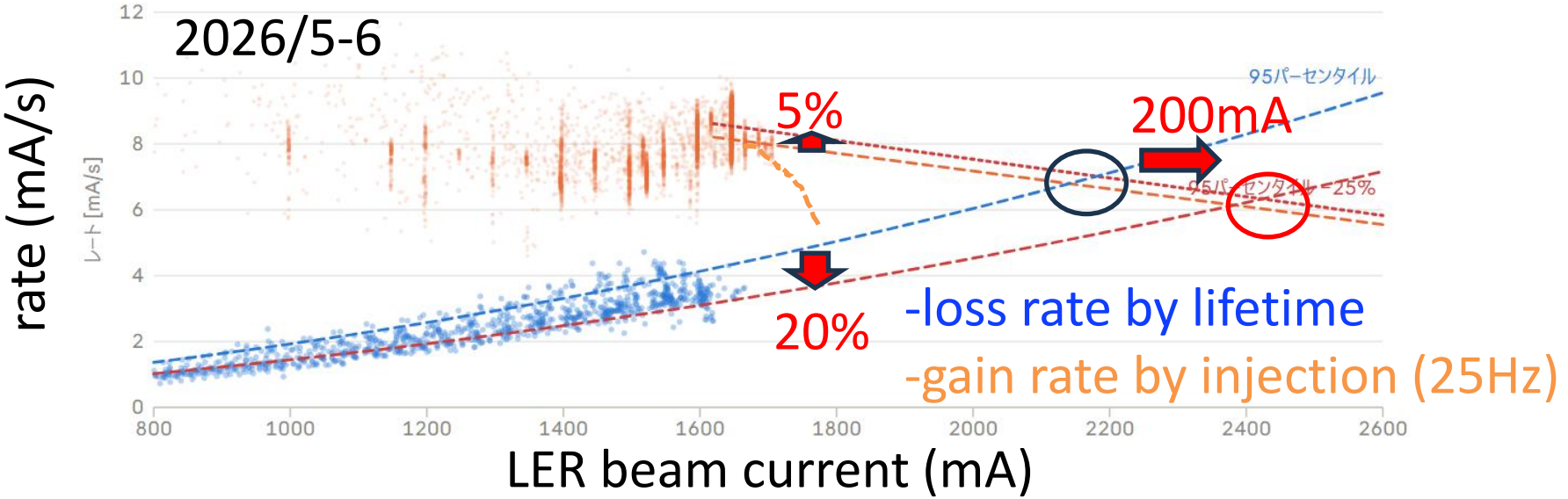
※According to experiences, even if the lifetime is good in simulation, it does not necessarily improve performance in the actual machine.

- We plan to prepare a few candidates of sextupole setting and study the performances in the actual machine in 2027.

Impact to luminosity and beam current

- Based on simulation, most optimistically,
  - -Touscheck lifetime improves by ~80% (total LER lifetime improve ~20%)
  - -Injection efficiency improves by ~5%

→Beam current increase by ~200mA by very rough extrapolation below



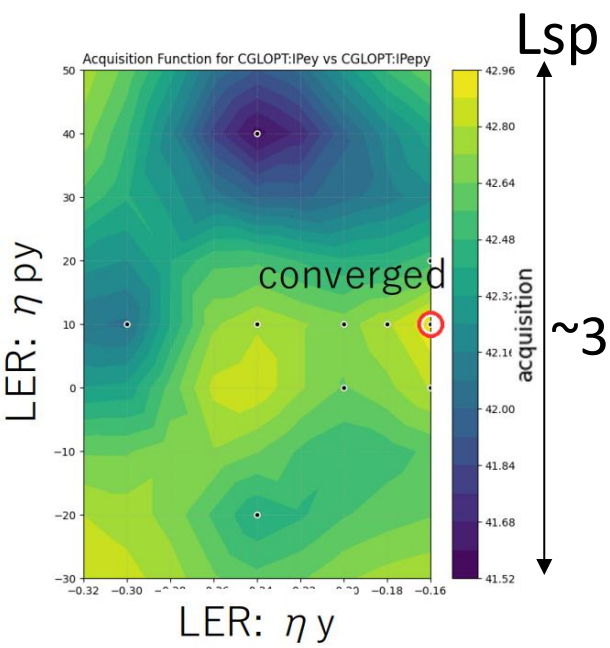
※According to experiences, even if the lifetime is good in simulation, it does not necessarily improve performance in the actual machine.

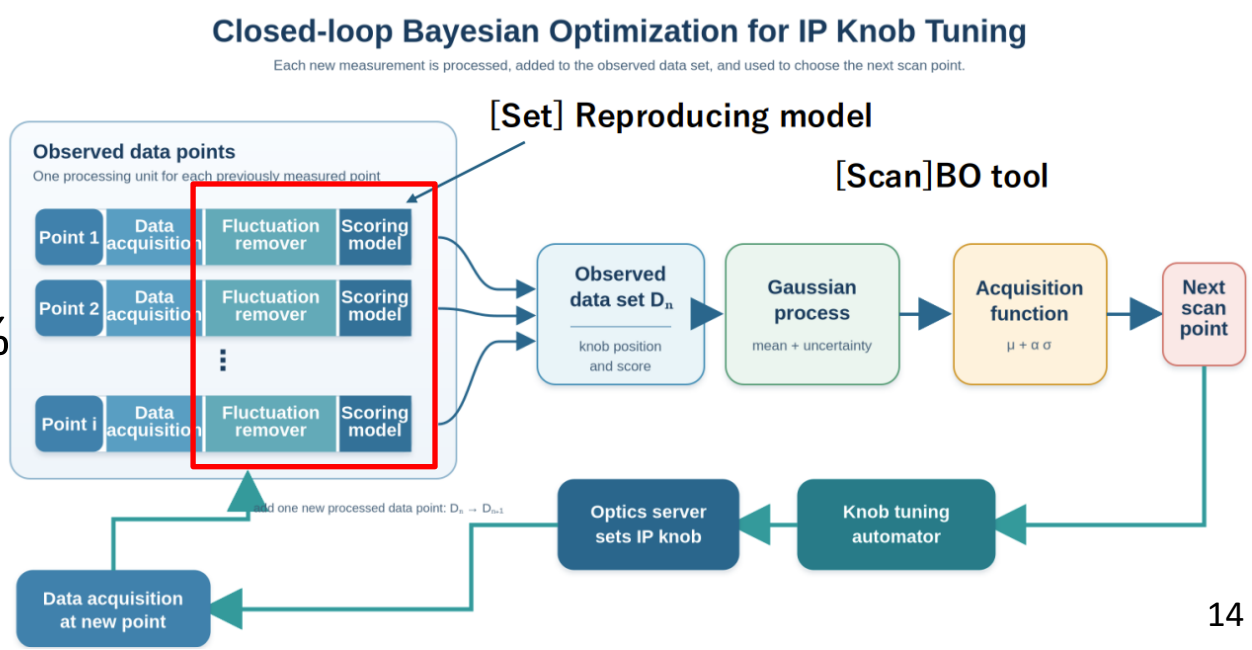
- We plan to prepare a few candidates of sextupole setting and study the performances in the actual machine in 2027.

②Online beam tuning by AI

IP knob tuning by Bayesian optimization

- IP knob (R_1,R_2 etc.) tuning tool has been developed since 2025, in order to maximize luminosity constantly: a few % impact to Lsp
- 2D and 4D parameter tuning by Bayesian optimization in 2026ab
- New functions for 2027
  - -Fluctuation remover: estimate change of luminosity by external environment
  - -Scoring model: choose best point including BG, beam size, injection efficiency
  - -Optimization by RL Agent



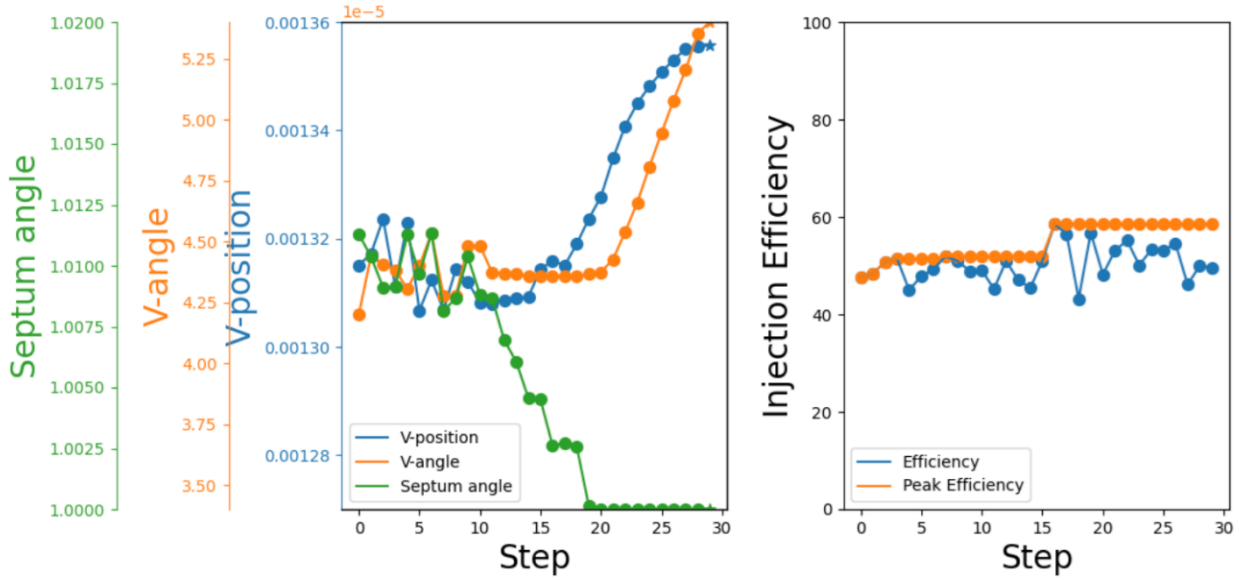


injection tuning by Bayesian optimization

- Injection (y-angle etc.) tuning tool has been developed since 2023
- 3D parameter tuning by Bayesian optimization in 2024
- New functions for 2027
  - -add more tuning parameters (manual Q matching etc.)
  - -add constraint from background

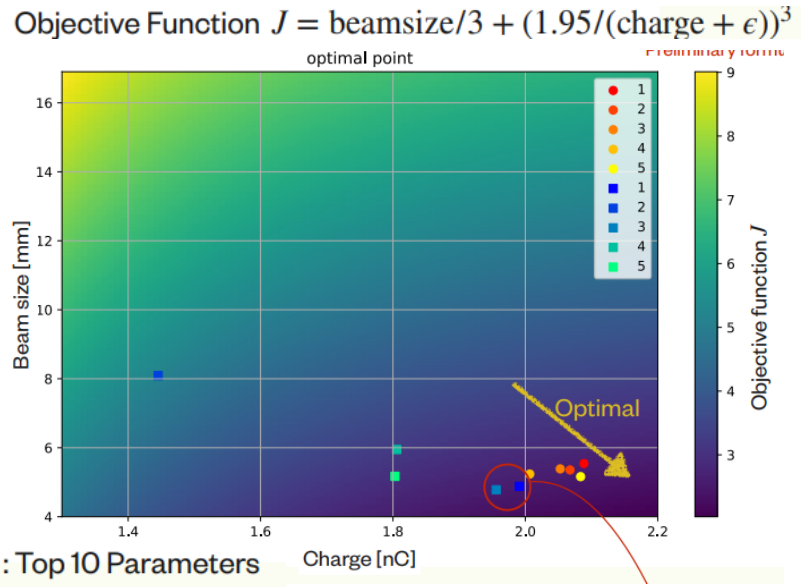
BPAC recommendation

R16.5: The ARC suggests extending the machine learning (ML)-based injection tuning approach by incorporating the objective of reducing detector backgrounds. This effort should involve optimizing not only the linac and transport line, but also explore the inclusion of additional tuning knobs in the ring.

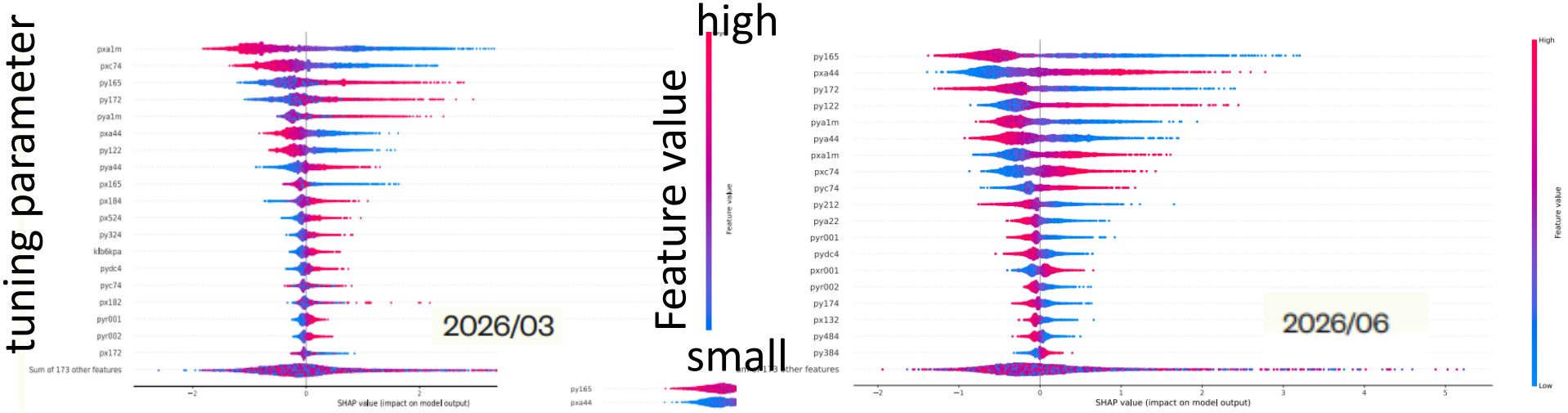


LINAC tuning and parameter importance

- GBTD+SHAP analysis to identify important tuning parameter
  - -1. initialize magnet parameter randomly
  - -2. Bayesian Optimization for tuning and data sampling
  - -3. SHAP analysis to identify importance



- Consistent results with expert's experience



SHAP value (impact on objective function)

beam tuning by AI agent

- Let AI agent knows below information from database:
  - -lattice
  - -operation log
  - -past parameter tuning history
  - -parameter tuning tool (IP knob, injection tool etc.)



- AI agent is consulted to optimize beam parameter.
  (ex. “please optimize parameter to increase injection efficiency”)

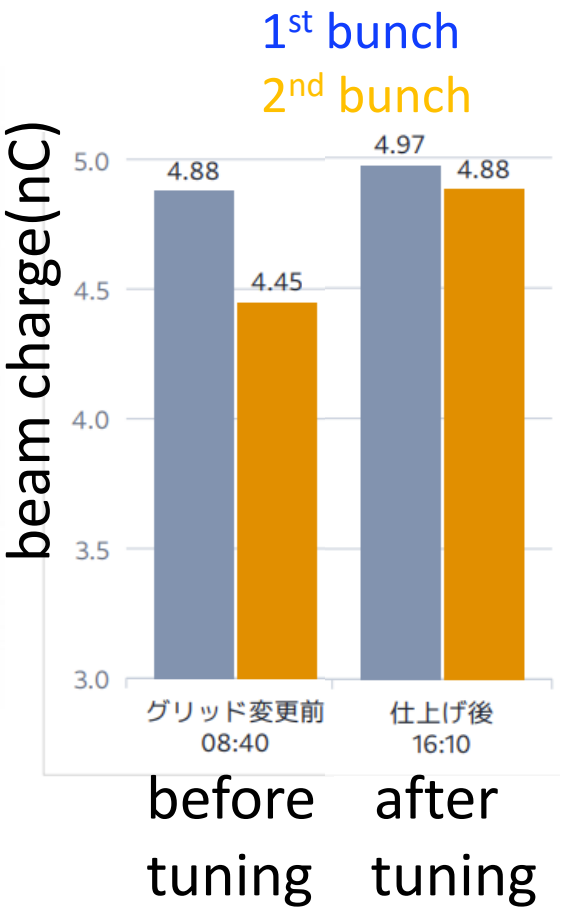
- Then AI agent will suggest recommended parameters and scan range, and operator/shifter will change parameter.

※AI agent will not directly change machine parameter for safety

beam tuning by AI agent: LINAC demonstration

- 2026/10: Successfully increase 2nd bunch charge from 4.45 to 4.88



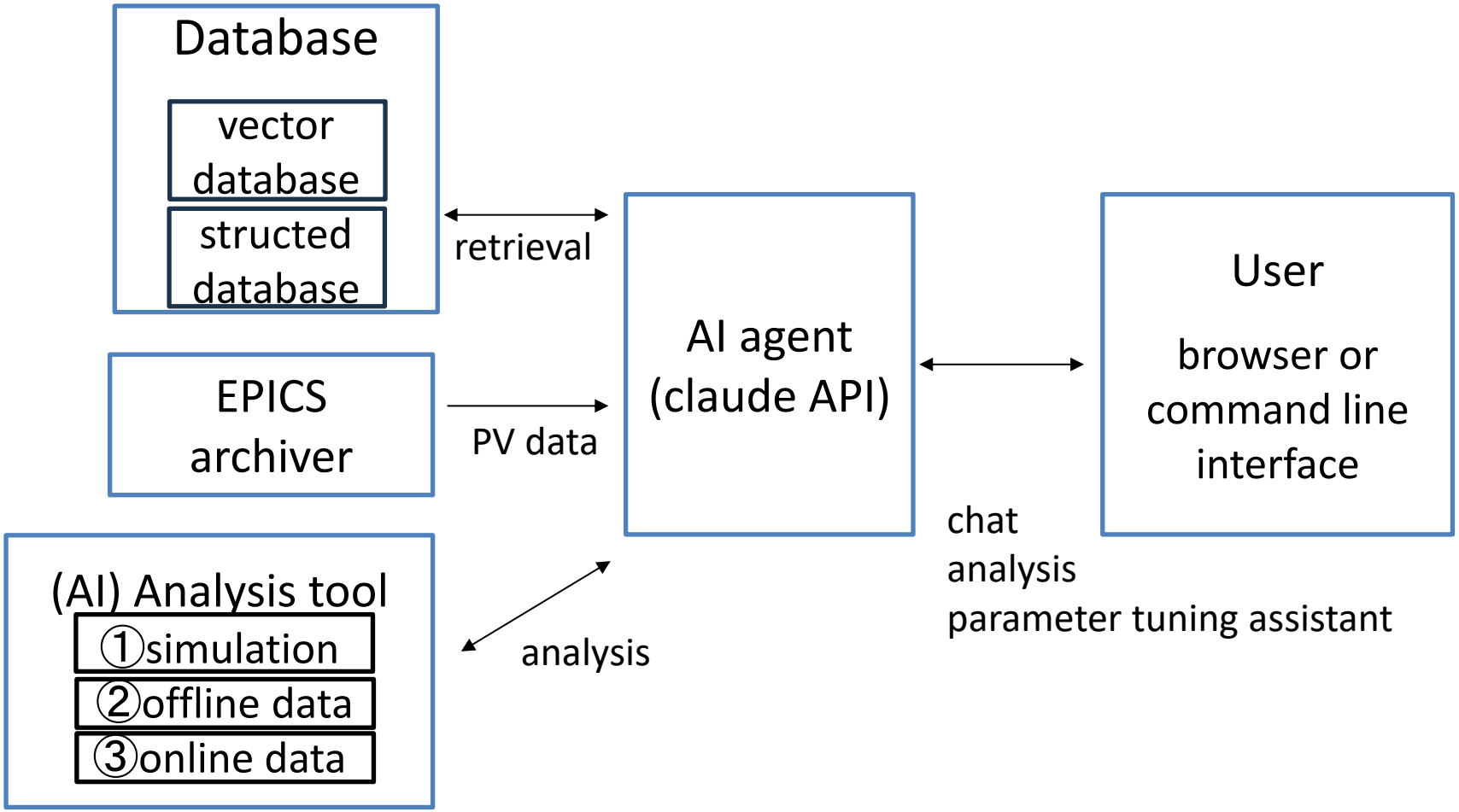


- We would like to try similar tuning at Main ring in 2027
  - -injection tuning and IP knob tuning

③Offline data analysis by AI

SuperKEKB AI assistant framework

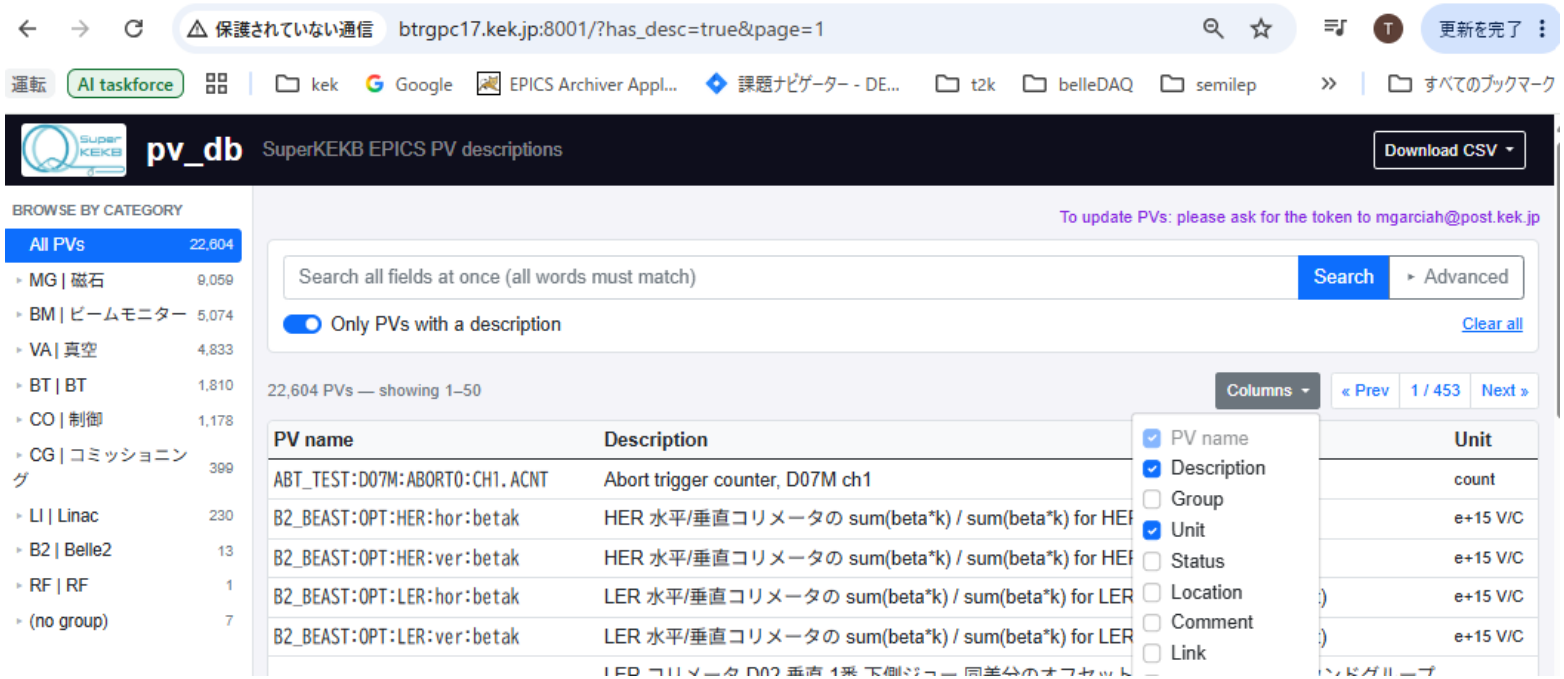
- Integrated AI agent framework is developed for SuperKEKB
  - -① offline tuning by simulation
  - -② online tuning/monitoring by actual machine
  - -③ offline data analysis



Database

- Below input documents are prepared and converted to database:
  - -SKEKB TDR
  - -SAD library
  - -lattice
  - -operation log (w/o personal information)
  - -OHO seminar document
  - -EPICS PV definition

- EPICS PV definition database is newly developed
  - -information is accumulated from all hardware groups
  - -useful not only for AI but also for human



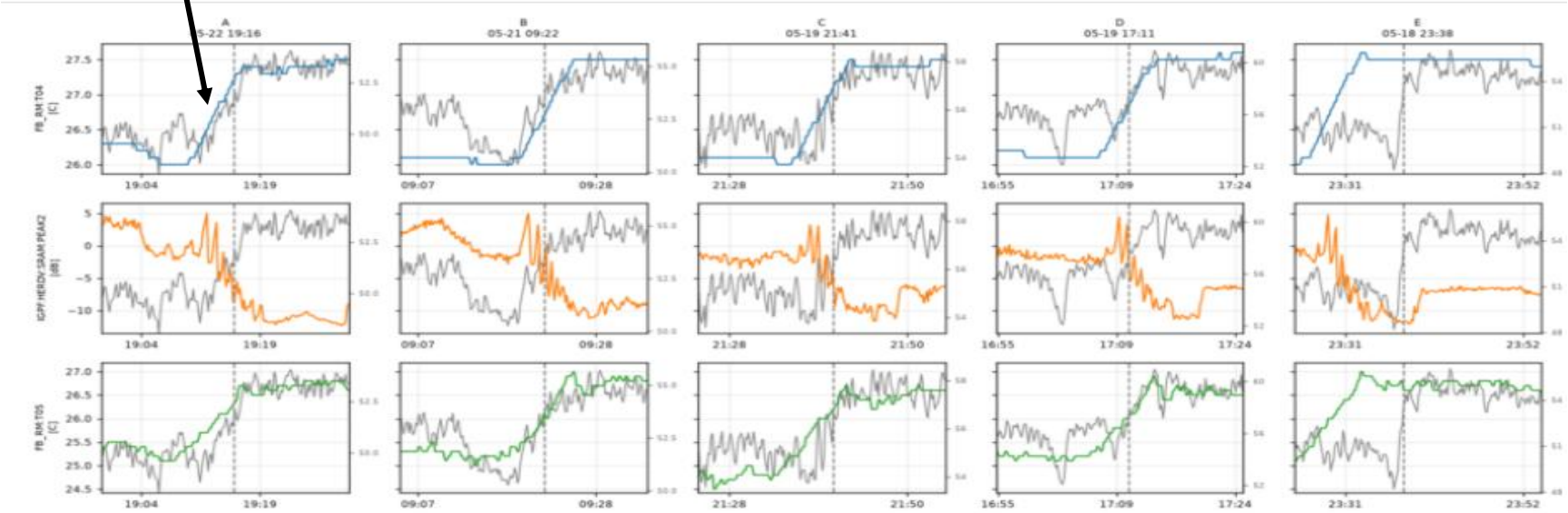
offline analysis: luminosity fluctuation

- AI agent can perform any EPICS PV analysis by using framework
  -iterative conversation with natural language
- Example1: “Please investigate the causes of luminosity fluctuations when no tuning parameters are being changed.”
- Highly correlated PVs are listed up by AI agent

~5% luminosity fluctuation
without touching anything

-gray: luminosity

-others: high correlated PVs



offline analysis: luminosity fluctuation

- AI agent can perform any EPICS PV analysis by using framework
  -iterative conversation with natural language
- Example1: “Please investigate the causes of luminosity fluctuations when no tuning parameters are being changed.”
- Highly correlated PVs are listed up by AI agent

feedback and Fuji feedback room temperature PV

#	PV	What it measures	Moved at how many of the 8	Step size	Verdict
1	FB_RM:T04	Thermometer 04, **Fuji feedback room** (°C, common infrastructure)	8 of 8, always **up**, within ±2.5 min at 7, ~8 min early at 5/18 23:40	+1.0 to +1.4 °C (26.1–26.5 → 27.3–27.5)	Strongest common signature; steps at the luminosity's own minute
2	IGPF:HERDV:SRAM:PEAK2	HER, dB — **no description written**; name matches the iGp bunch-by-bunch feedback processors ("HER vertical", spectrum peak)	8 of 8, always **down**; within ±1 min at 7, ~7 min early at 5/18 23:40	−5.6 to −12.5 dB	A large, repeatable drop in a measured spectral peak at every event
3	FB_RM:T05	Thermometer 05, Fuji feedback room (°C)	8 of 8, always up	+1.2 to +1.7 °C (24.8–25.6 → 26.4–26.8)	Same signature as T04, same seconds
4	FB_RM:T02	Thermometer 02, Fuji feedback room (°C)	8 of 8, always up	+0.5 to +0.7 °C (23.3–23.7 → 24.0–24.2)	Same signature, smaller amplitude

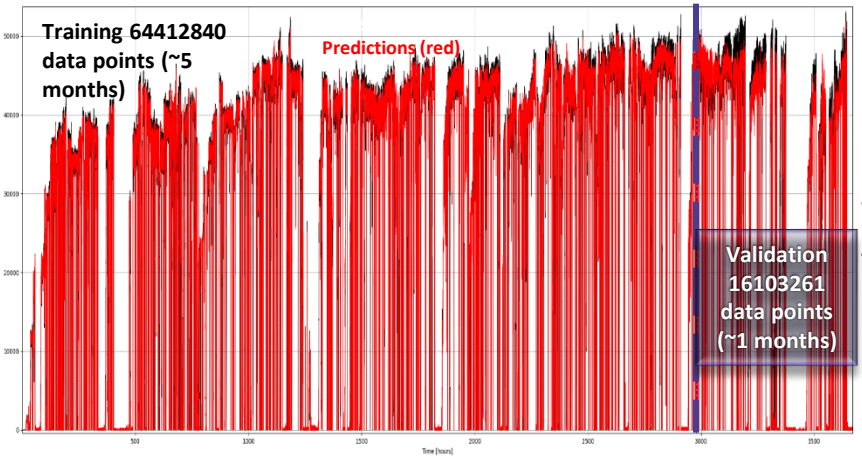
feedback PV

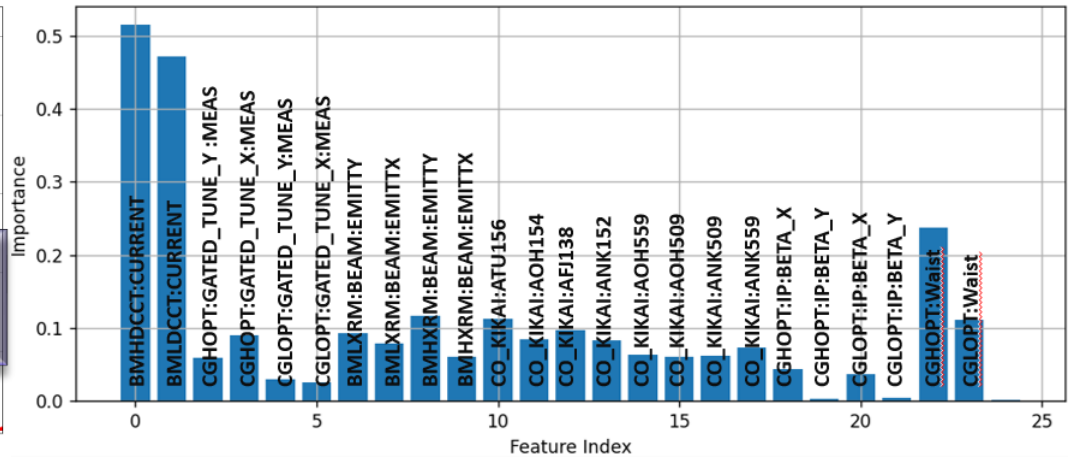
- In 2026, we took ~3month to notice these correlations
  → quick feedback to hardware experts will be possible

Luminosity Prediction via ML Surrogate Model (long term)

PI: D. Oumbarek Espinos

- Surrogate ML model developed to predict luminosity from 23 monitored parameters.
- Extremely good accuracy achieved.
- Information about which parameters affect more the luminosity.
- Allowed to detect non-measured magnet deviations.





$RMSE$ (standardized units)	$RMSE$ $(\times 10^{34} cm^{-2} s^{-1})$	NRMSE (%)	R^2
0.106	0.1905	3.58	0.992

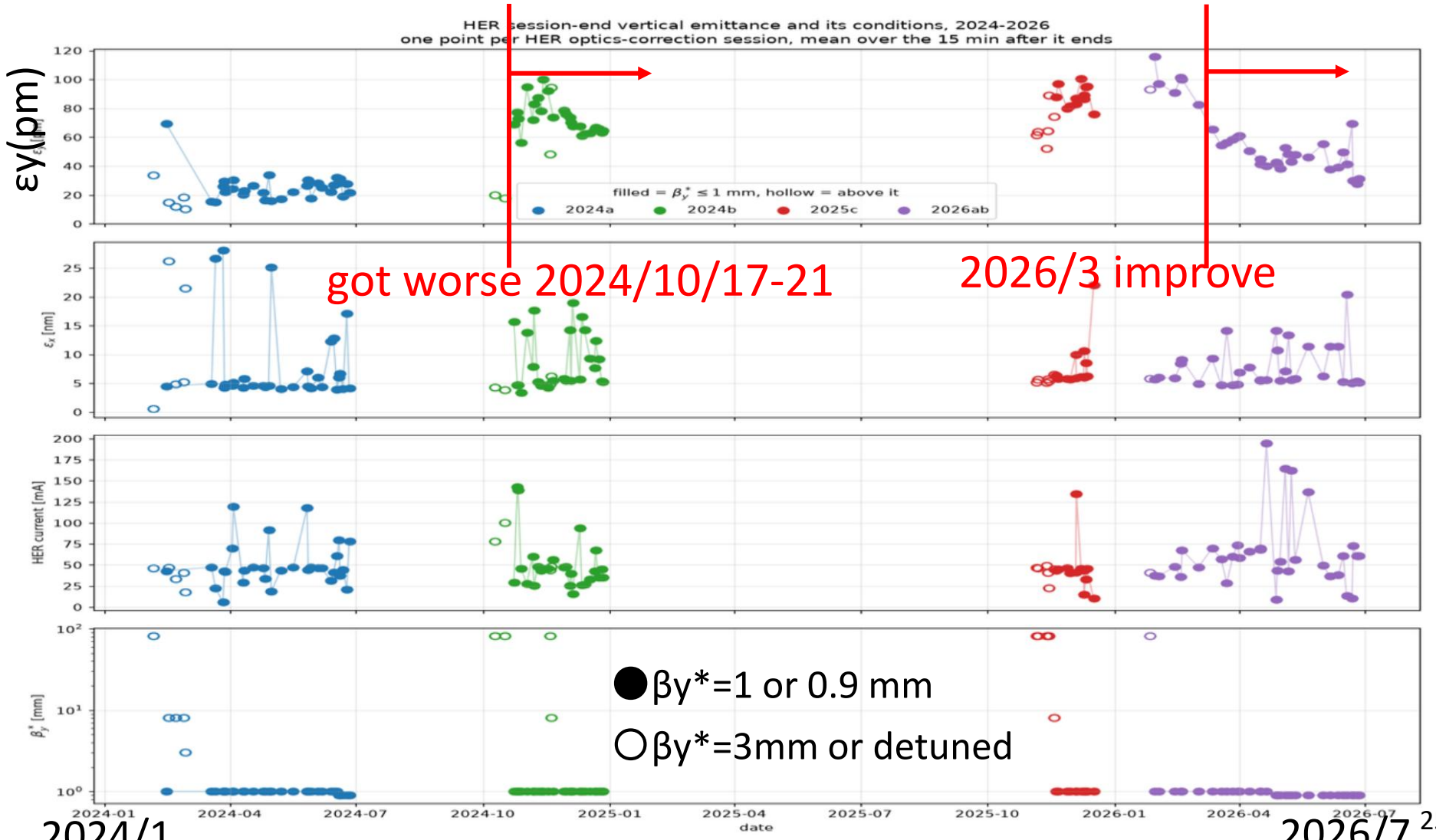
Luminosity Error	0 – 0.01	0.01 – 0.05	0.05 – 0.1	0.1-0.2	0.2-0.3
Prediction %	22.1 %	21.2	10.1	19.8	14.9

"A SuperKEKB Luminosity ML Surrogate Model for Diagnostic and Prediction", D. Oumbarek Espinos, M. Masuzawa and M. Tawada. (Under preparation).

offline analysis: HER emittance

- Example2: “Please investigate HER emittance fluctuation issue”

  -AI agent automatically summarize the emittance history in 2024-2026 quickly

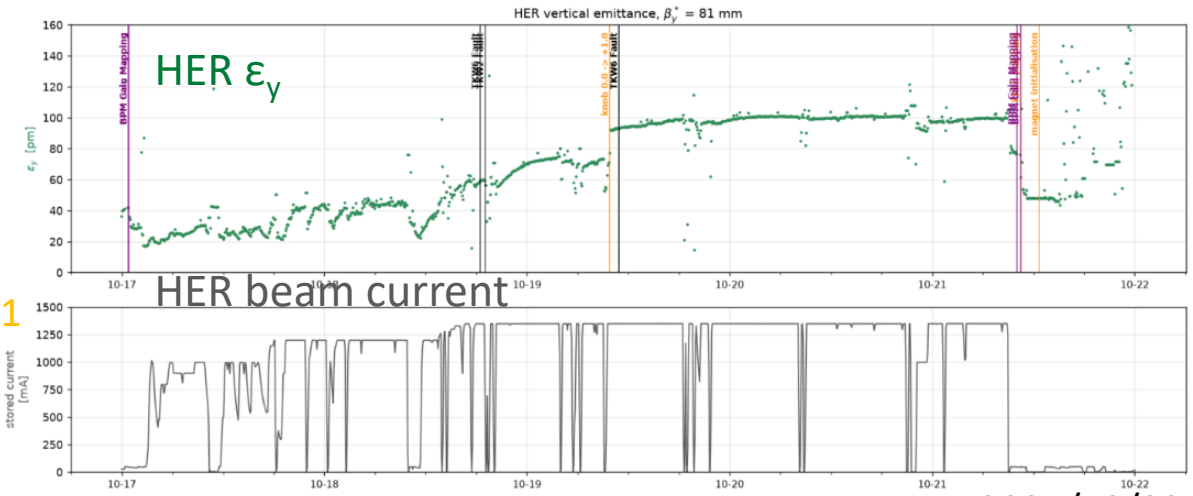


offline analysis: HER emittance

- Example2: “Please investigate HER emittance fluctuation issue”

-problematic period is checked with operation log

-10/17 BPM gain mapping
-10/19 9:48- emittance control knob+1
-10/21 10:26 BPM gain mapping
-10/21 12:23 magnet initialization



2024/10/17

2024/10/22

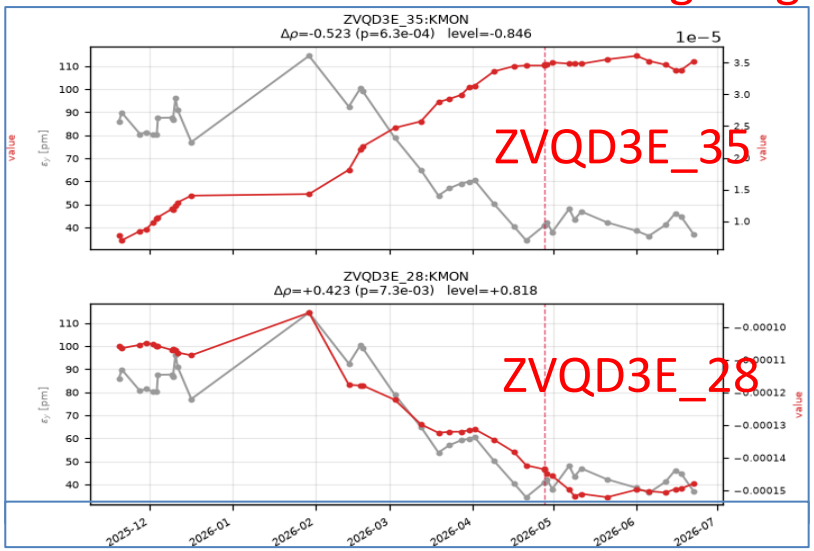
-HER ε_y

-steering magnet

-highly correlated PVs with the emittance is searched among ~100k PVs

-2024c: none
-2026: some steering magnets, skew Q

-We can not conclude the reason by AI, but quick feedback will be possible.



2025/12

2026/7

Human resource and organization

Human resource and organization

- ML/AI beam tuning task force has been established since May 2026, in order to enhance AI developments at SuperKEKB

- Both SKEKB and Belle II members are joining, by holding regular task force meeting every other week, with 10~15 attendances

- Major activities and active persons in charge

-①offline lattice optimization by AI
  -Koga(30%)

-②online beam parameter tuning by AI
  -LINAC: Natsui(10%), Sakai(10%)
  -IP knob: Takizawa(100%), Hara(10%), Sarthak(100%)
  -Injection: Hrishikesh(100%)

-③offline data analysis by AI
  -Koga, Mehraj(100%), Driss(10%)

-SKEKB staff
-Belle II staff
-Belle II master student
(xx%) is FTE

Specialist, computing resource, funding

- At present, accelerator and particle physics experts are main members. We are looking for software and AI experts.

- AI TF does not have any specific materials yet. We need
  - -CPU server for operation and online monitoring
  - -CPU server for offline analysis ← for now Belle II's server is borrowed
  - -GPU server for local LLM ← discussing to borrow Belle II's server
  - -AI agent account ← partially covered by existing funding (Kokusai sendo)

- We are applying a few Japanese fundings to buy the materials
  - -Japanese Kakenhi Kiban B: under review
  - -Japanese AI for Science (SPReAD): failed
  - -Japanese AI for Science (ARISE): participate in selected Nojiri-san's subgroup
  - -JST BOOST: selected for FPGA x AI developments (2027-)

Possible research topics for student

- ML/AI TF is a new group, and new comers are really welcome !

- Possible topic for new student

maybe too difficult
for student (but important)

  - ①offline lattice optimization by AI
    - Multiobjective optimization of sextupole
    - study data/simulation difference of dynamic aperture
    - Optimization of phase advance at collimator to reduce beamBG
    - beam-beam simulation, model development
    - re-design of lattice with possible new hardware by AI agent
  - ②online beam parameter tuning by AI
    - automatic beam diagnostic system for 24hour by AI agent
    - new optimization algorithm (latent world etc.)
  - ③offline data analysis by AI
    - system to quickly analyze any problem/mystery during operation
    - causal inference
    - tackling long-standing issue (BT emittance, SBL, etc.)

Summary

- ML/AI beam tuning task force has been established since May 2026, in order to enhance AI developments at SuperKEKB

- Status from May to Oct. are summarized
  - -①offline lattice optimization by AI
    - -optimization of sextupole to increase dynamic aperture
  - -②online beam parameter tuning by AI
    - -IP knob, injection tuning tool
    - -AI agent
  - -③offline data analysis by AI
    - -Luminosity fluctuation
    - -HER emittance fluctuation

luminosity increasement by improving life and inj. efficiency

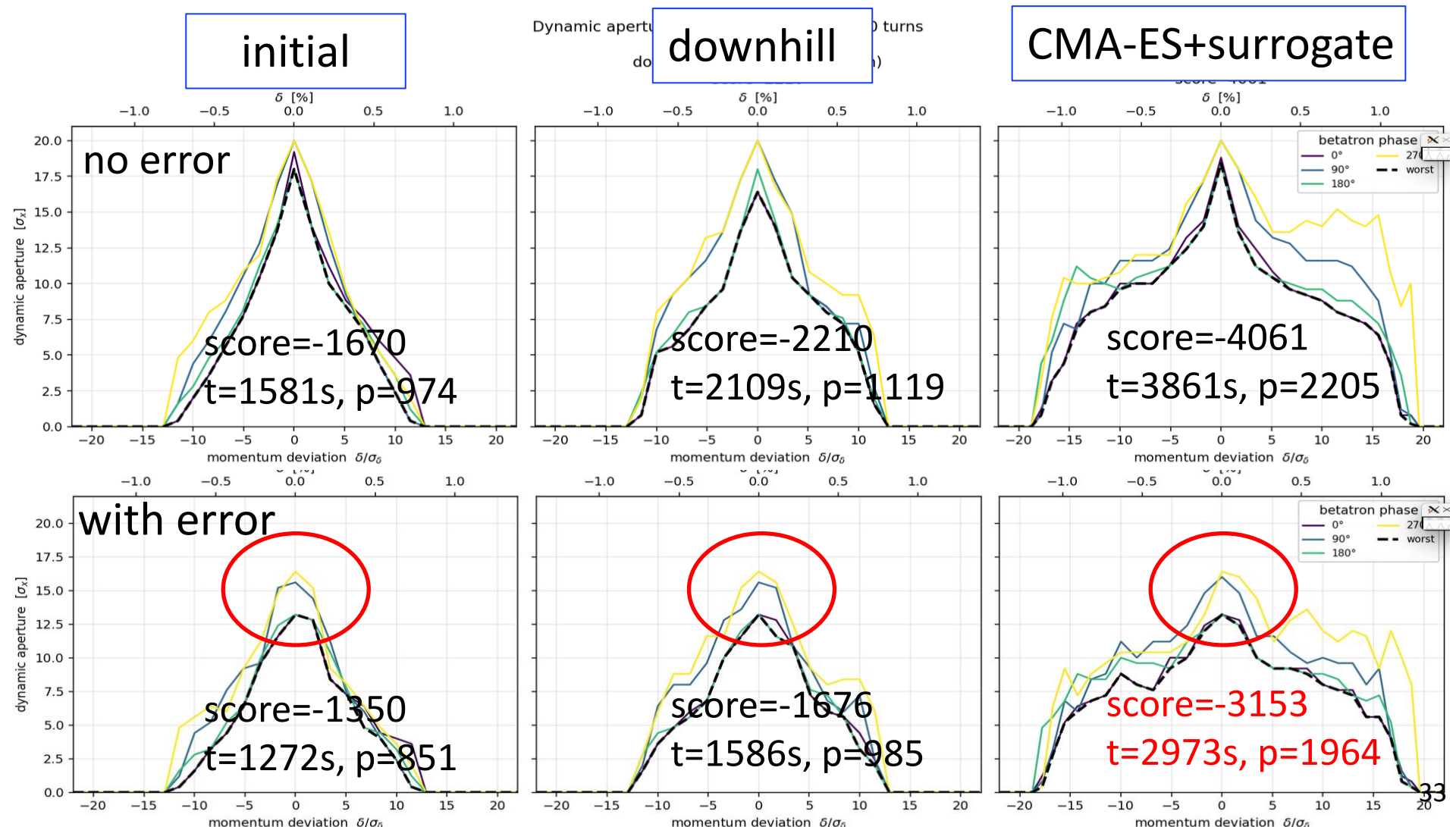
constantly keep highest luminosity condition

investigate outstanding issue by AI for possible missed discovery and countermeasure

backup

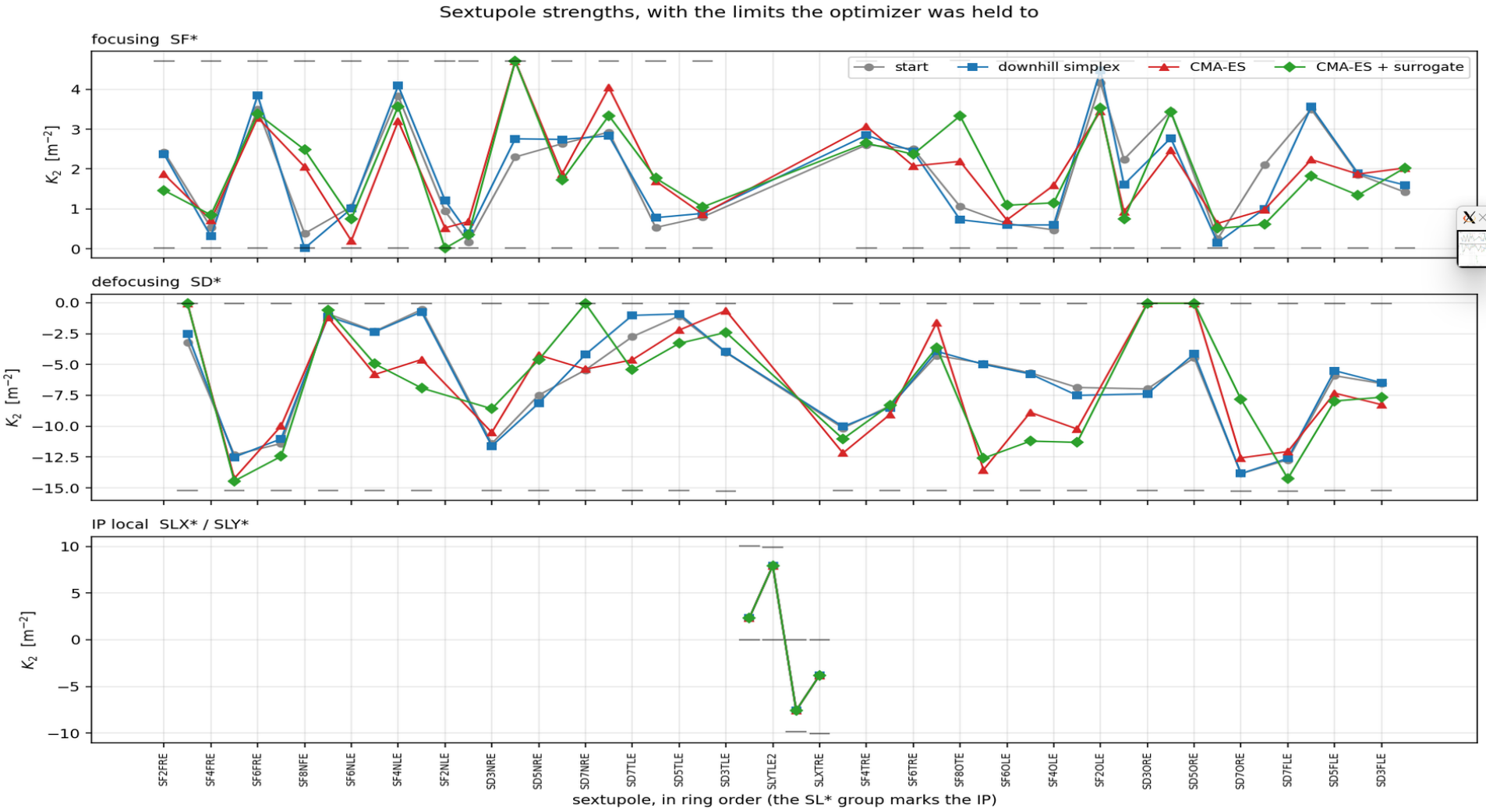
HER cancel coil error

- comparison of cancel coil error on/off
  - -optimization is done with the error off
- aperture is reduced at on-momentum



Optimized sextupole field (example of LER)

- Different optimal points are found by new optimization algorithm



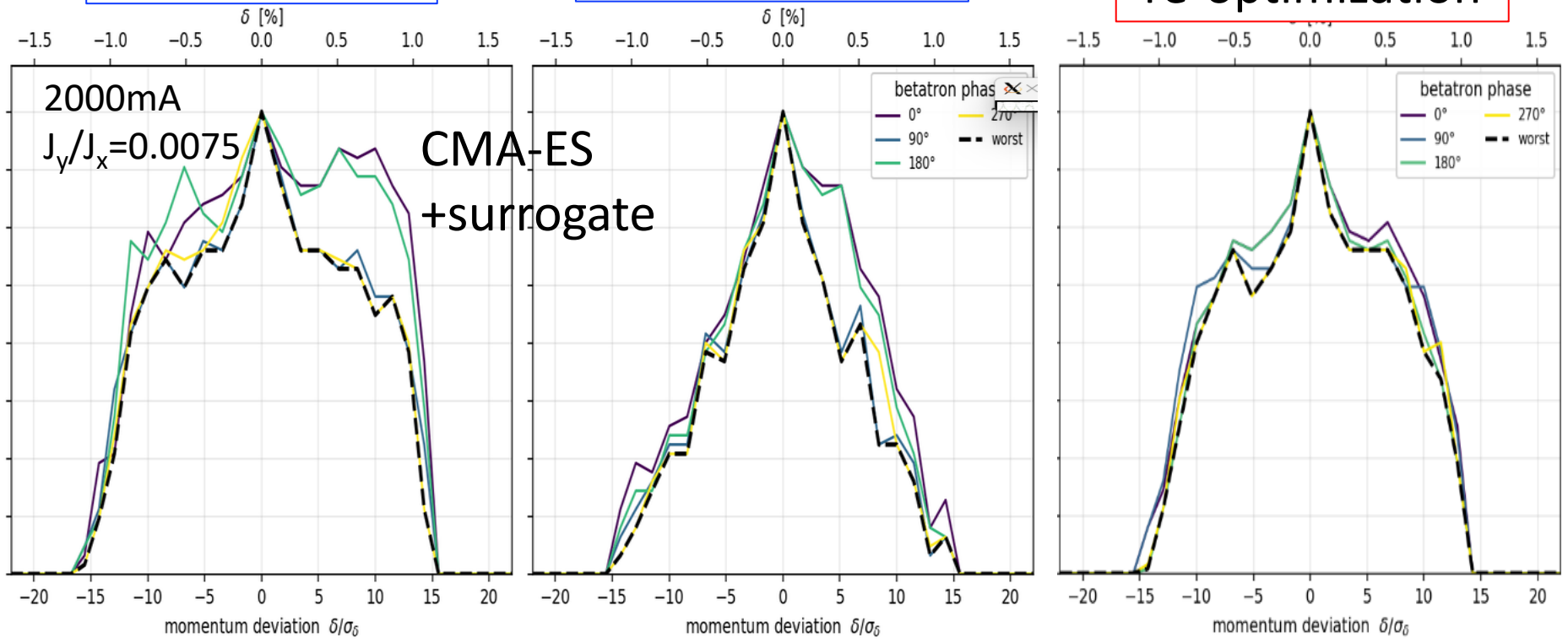
Effect from collimator

- Optimized DA is largely reduced by collimator (score: -982→-527)
  -optimization has been performed without collimator
- By re-optimization with collimator, DA is recovered (score: -830)

w/o collimator

with collimator

with collimator
re-optimization



DA score=-982
(smaller score is better)

DA score=-527

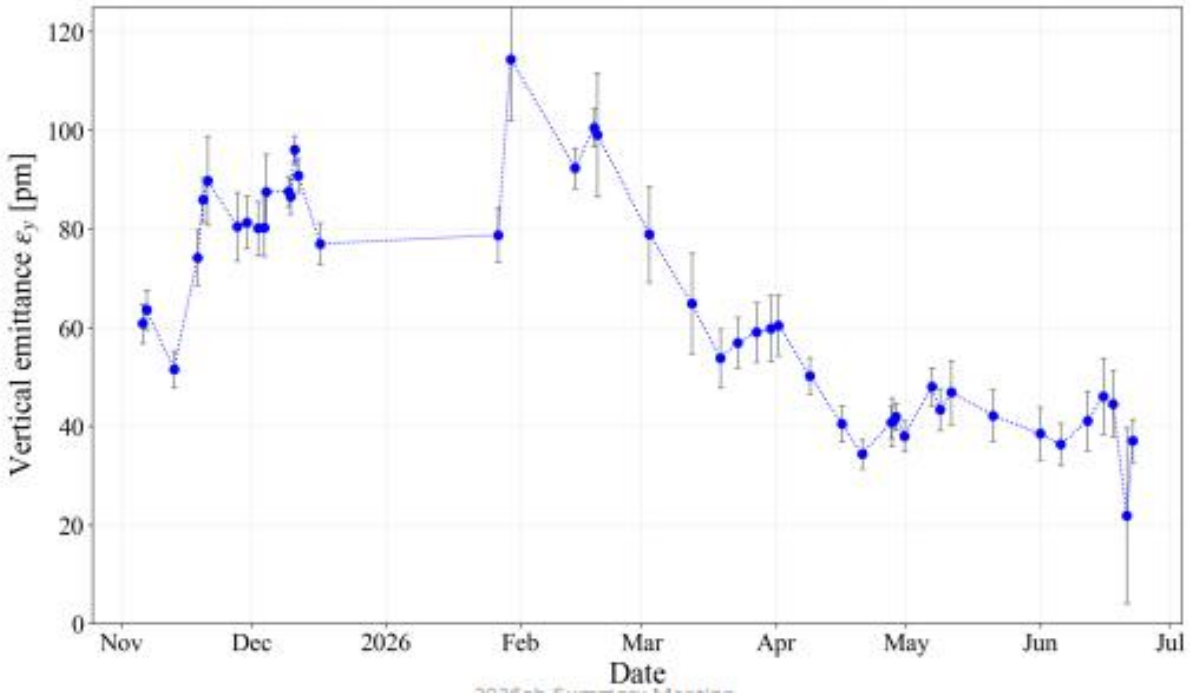
DA score=-830

Example of emittance variation analysis

- AI agent can perform any EPICS PV analysis by using framework
- Analysis example of HER emittance variation issue

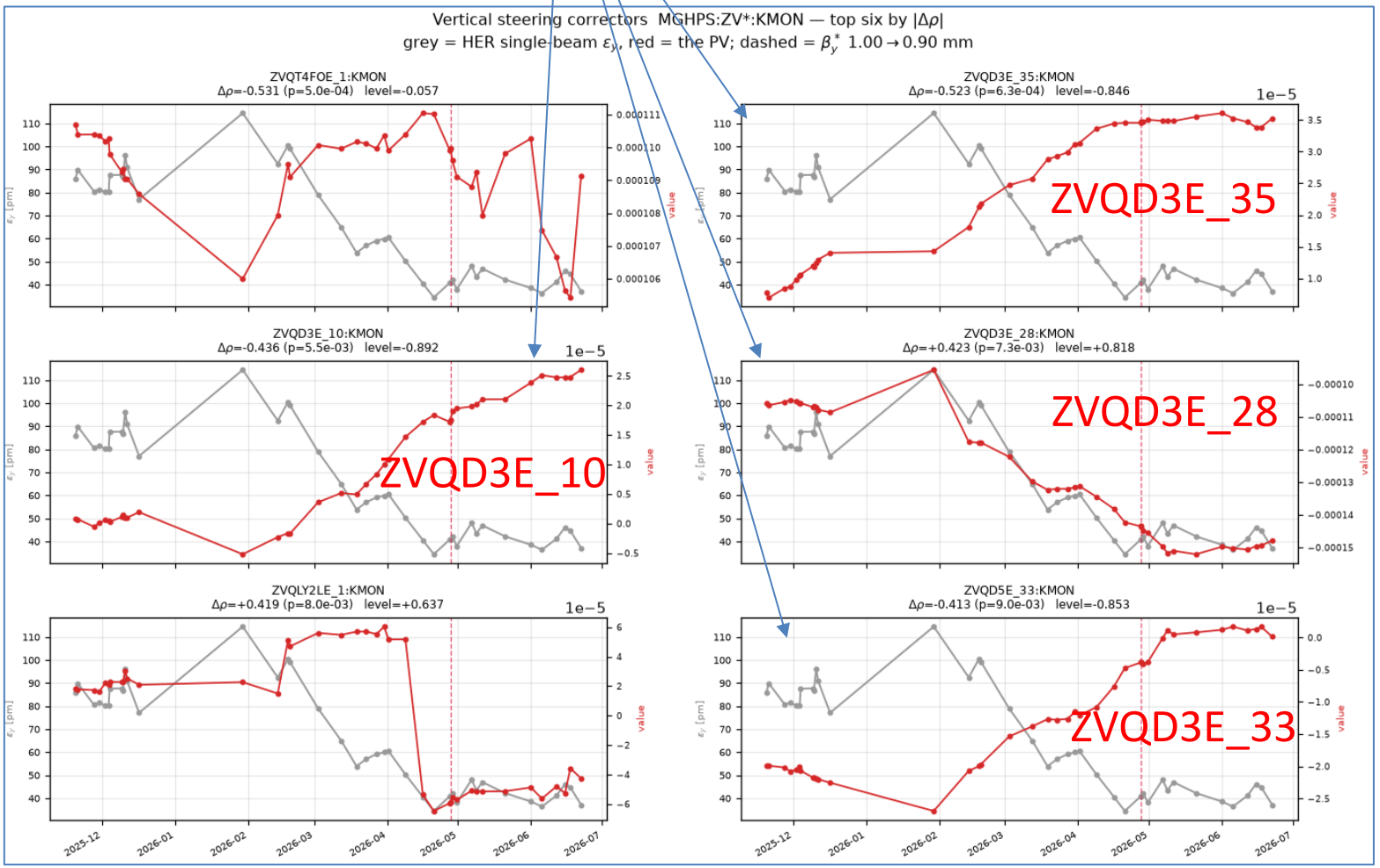
HERの垂直エミッタンスの変遷

- 3/19以降、日々の調整でHERの垂直エミッタンスが下降トレンドにあるように感じていた。
- 運転終了後、実際にプロットしてみると、確かに徐々に低下していることが分かる。



Correlation with vertical steering magnet

- AI found part of vertical steering magnet (ZVQD3E_*, ZVQD5E_*) have significant correlation to the vertical emittance
- It was feedback to optics expert. Further analysis in 2024- is on-going.



-emittance

-magnet