

SuperKEKB commissioning taskforce report: AI/ML

2026/10/27

T.Koga

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
 - ① offline lattice optimization by AI
 - optimization of sextupole to increase dynamic aperture
 - ② online 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



Claude Code v2.1.304
Fable 5.1 · Claude Team

> What can we do by using this repository ?

- This repository optimises the sextupole magnet strengths of the SuperKEKB rings, HER and LER, by running the SAD lattice code. Everything revolves around one control script, `sextopt.sad`, driven by a short run file, with the per-ring physics in `rings/<ring>.n`. What it lets you do:

Evaluate a lattice

- Load a deck, match the IP optics, tunes and chromaticity, and score a sextupole setting by its dynamic aperture and Touschek lifetime at a chosen number of turns and betatron phases.

Jump to bottom (ctrl+End) ↓

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](#)

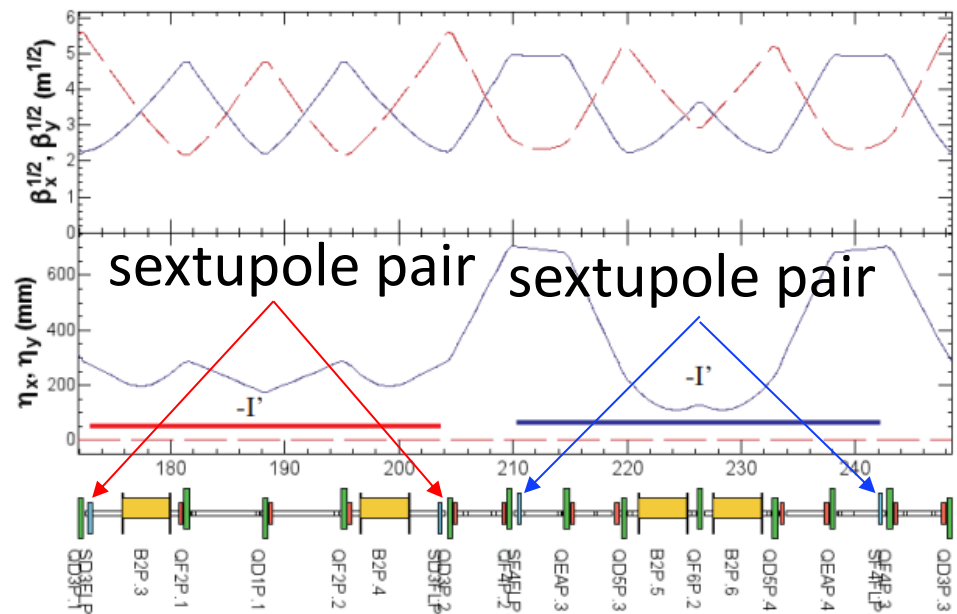
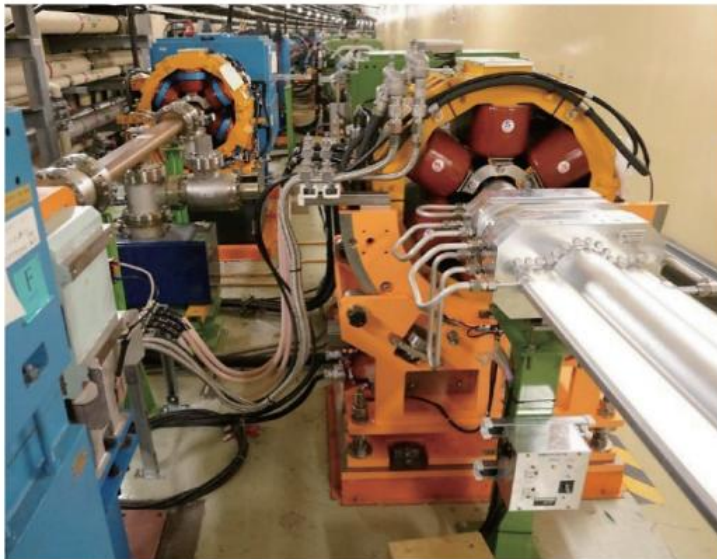


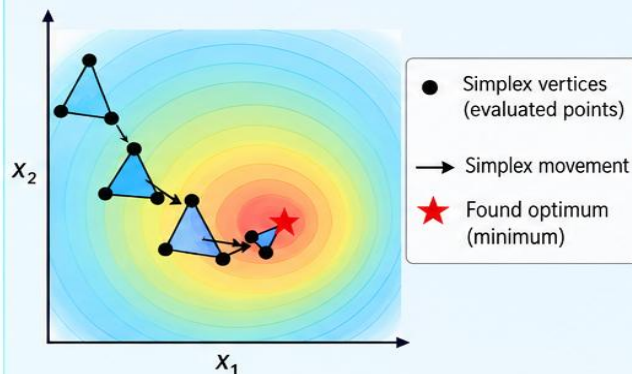
Figure 1: Arc cell in LER.

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.

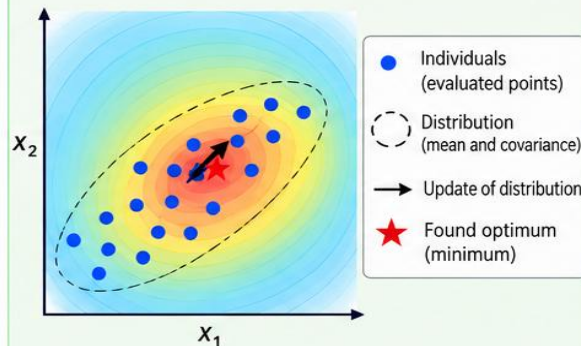


The simplex is modified by reflection, expansion, contraction, and shrinkage to move toward better points.

CMA-ES

(Covariance Matrix Adaptation Evolution Strategy)

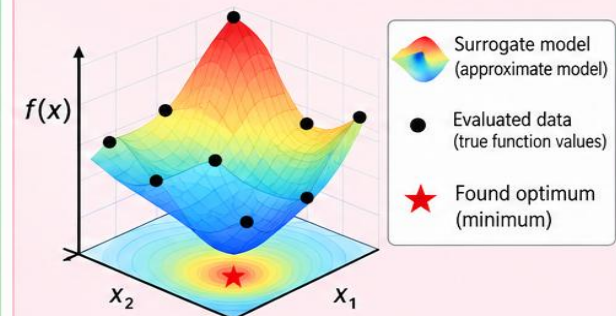
An evolutionary optimization method that evaluates multiple points (individuals) at once and adaptively updates their distribution (mean and covariance) to search for better regions.



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

Surrogate Model (Surrogate-based Optimization)

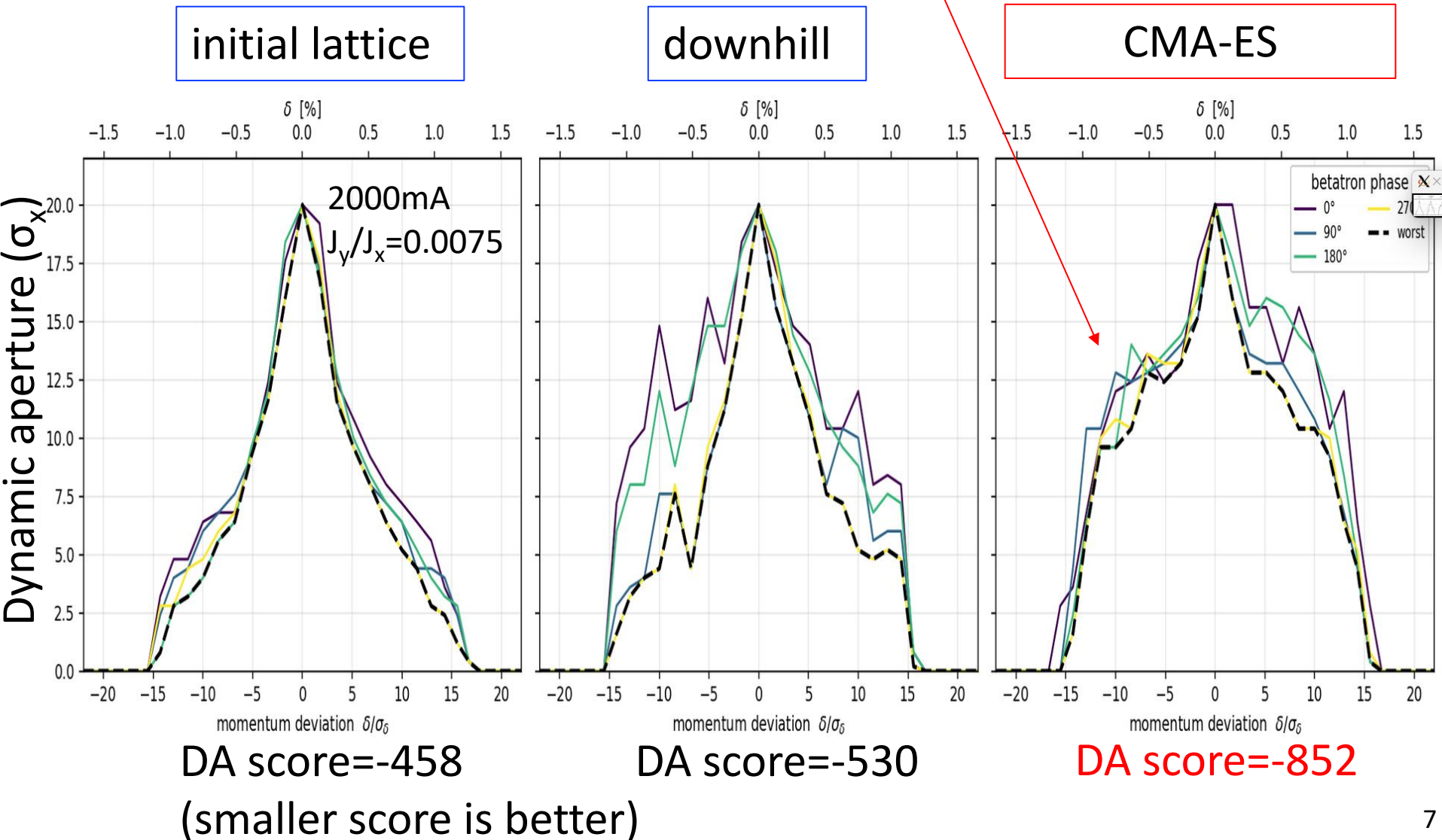
A method that builds an approximate model (surrogate model) from a limited number of expensive evaluations and uses this model to efficiently search for the optimum.



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.

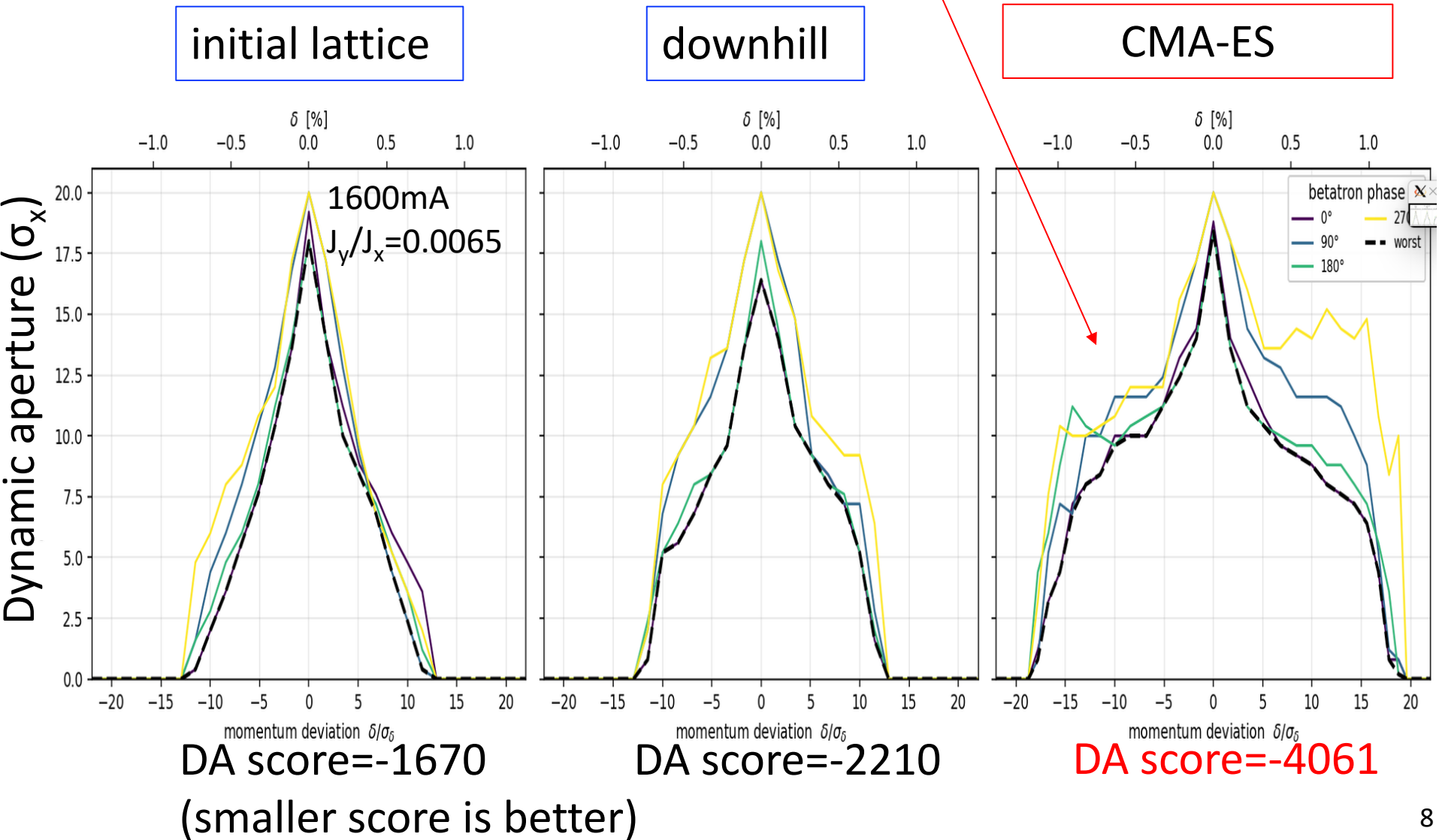
Optimized DA (LER)

● CMA-ES has ~60% better DA score than downhill simplex



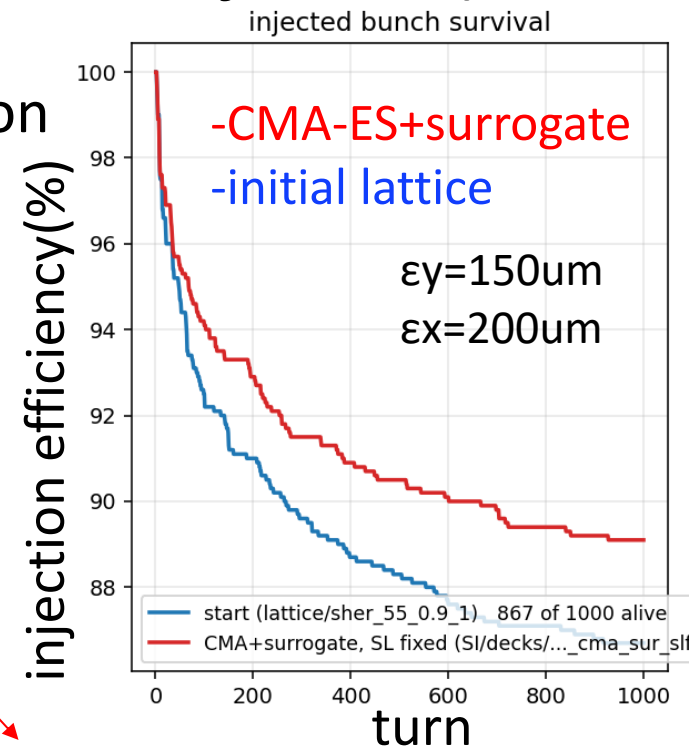
Optimized DA (HER)

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



Injection efficiency (HER betatron injection)

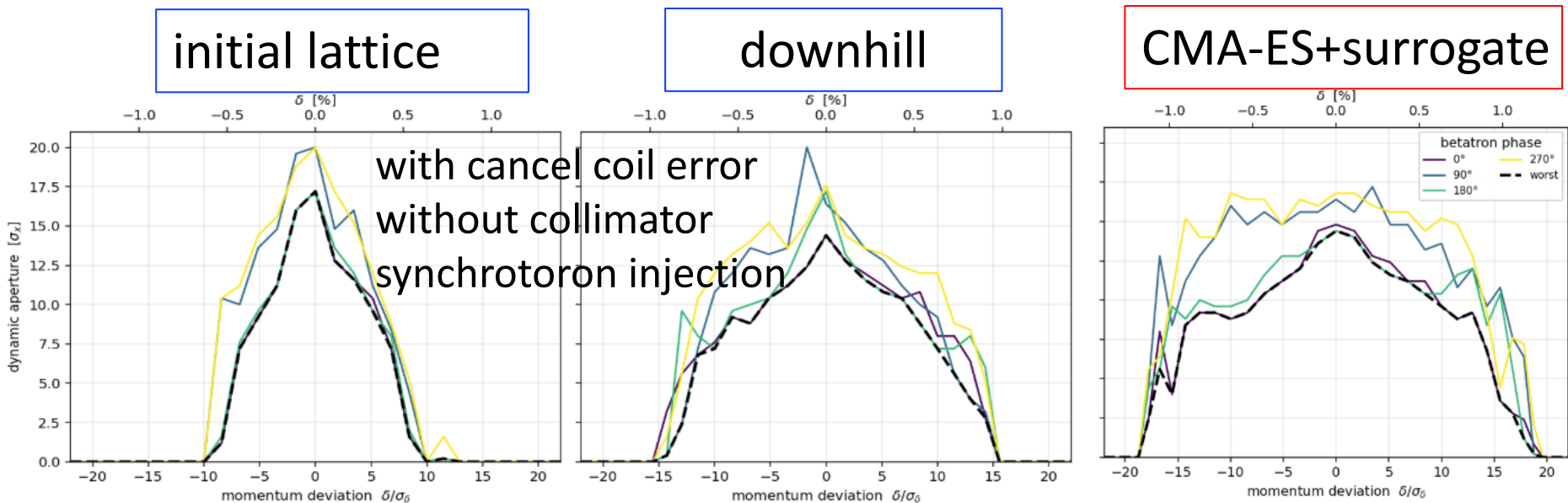
- Injection efficiency is evaluated by simulation
- CMA-ES+Surrogate has a few % better injection efficiency than initial lattice



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

Injection efficiency (HER synchrotron injection)

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

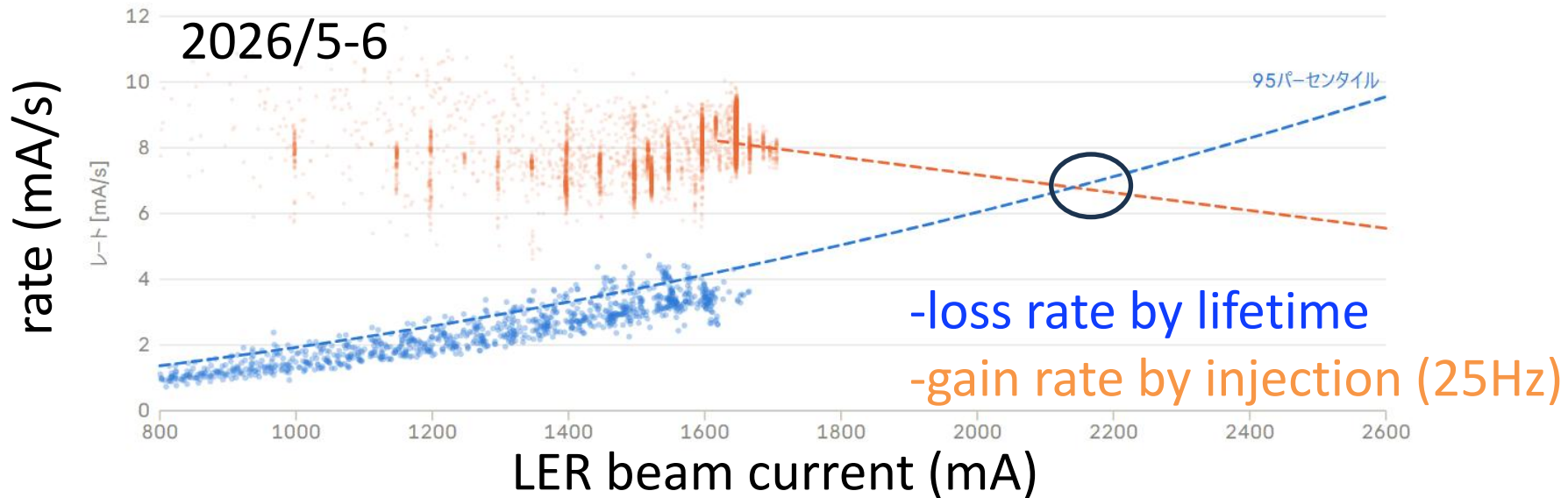


Impact to luminosity and beam current

● Based on simulation, most optimistically,

- Touscheck lifetime improves by $\sim 80\%$ (total LER lifetime improve $\sim 20\%$)
- Injection efficiency improves by $\sim 5\%$

→ Beam current increase by $\sim 200\text{mA}$ 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.

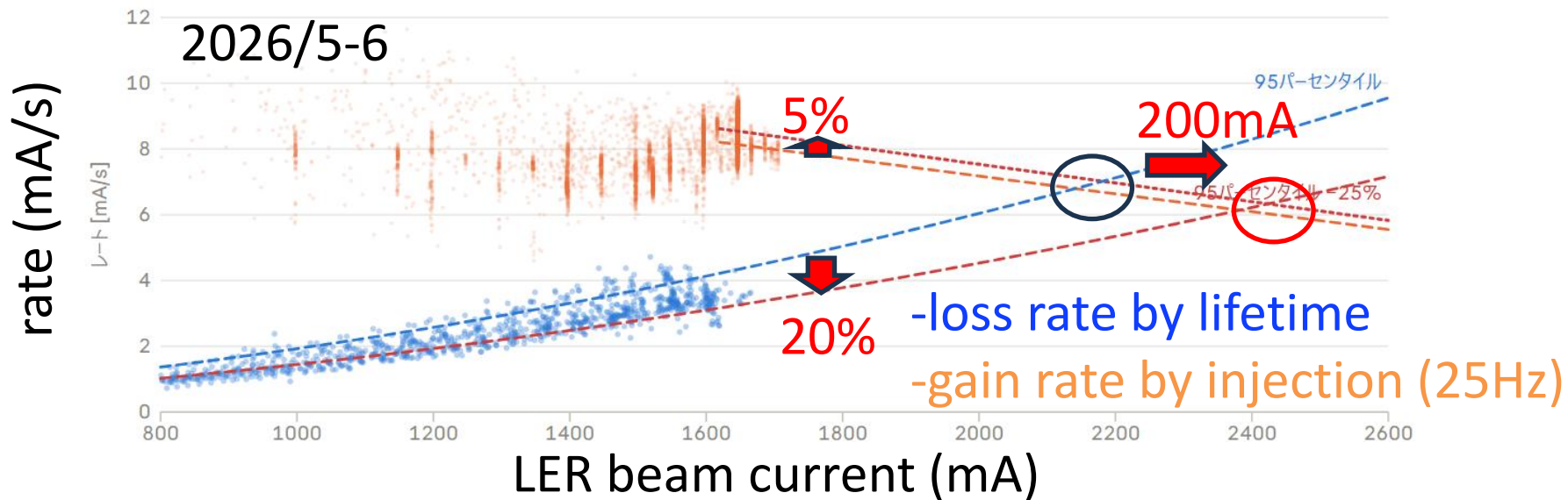
● We plan to prepare a few candidates of sextupole setting and study the performances in the actual machine in 2027.

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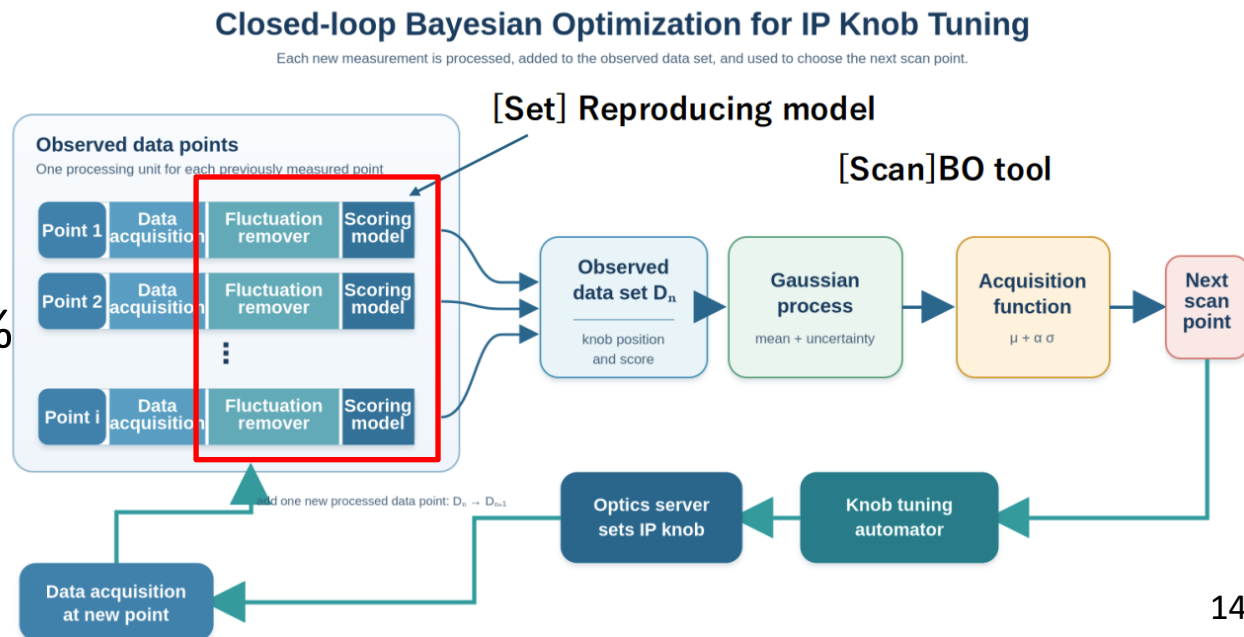
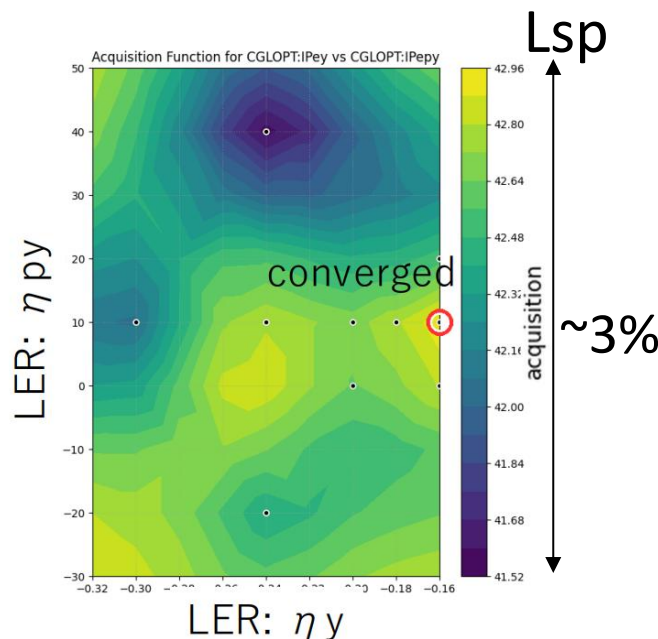
✗ According to experiences, even if the lifetime is good in simulation, it does not necessarily improve performance in the actual machine.

● 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

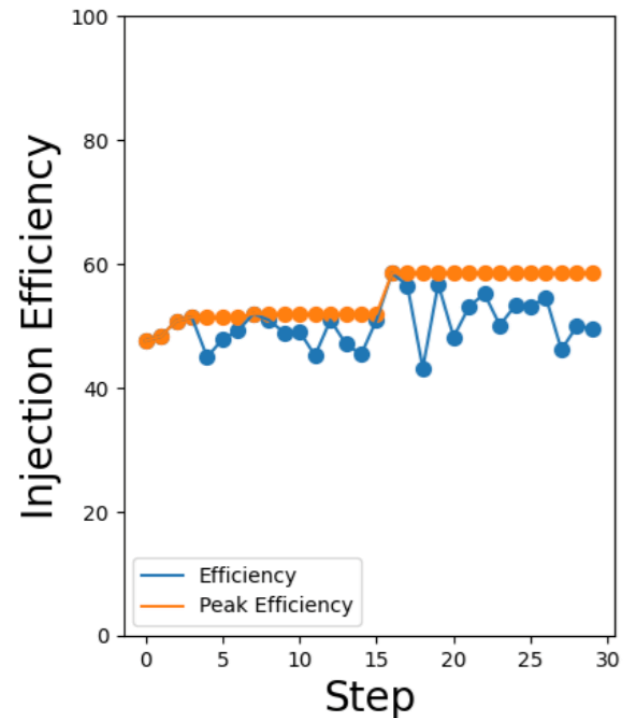
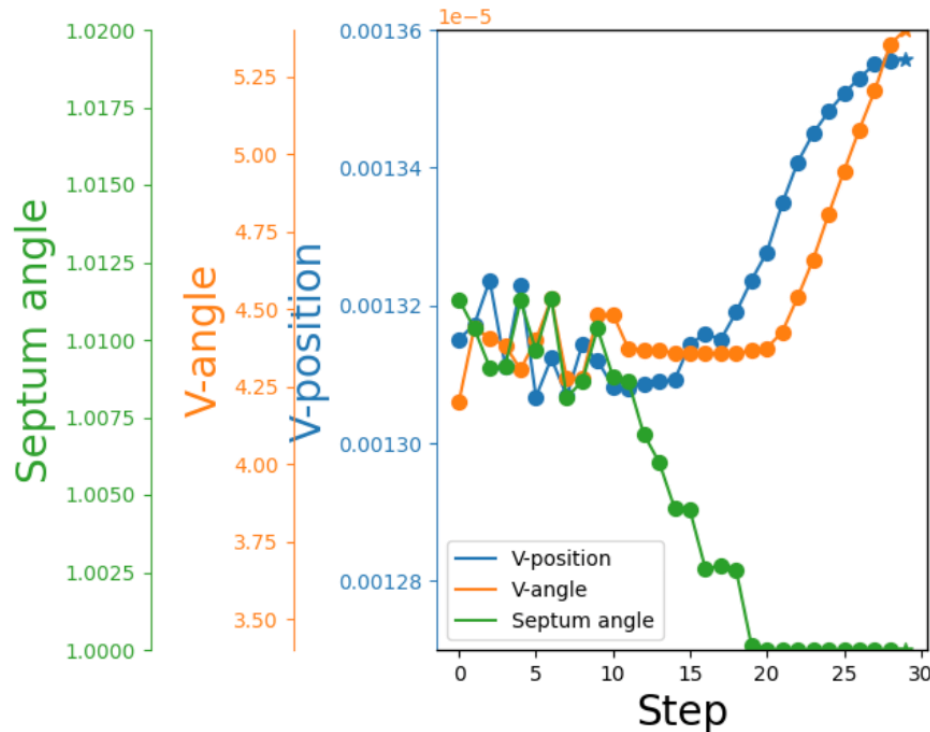
- IP knob (R_1, R_2 etc.) tuning tool has been developed since 2025, in order to maximize luminosity constantly: a few % impact to Lsp
- 2D and 4D parameter tuning by Bayesian optimization in 2026ab
- New functions for 2027
 - Fluctuation remover: estimate change of luminosity by external environment
 - 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



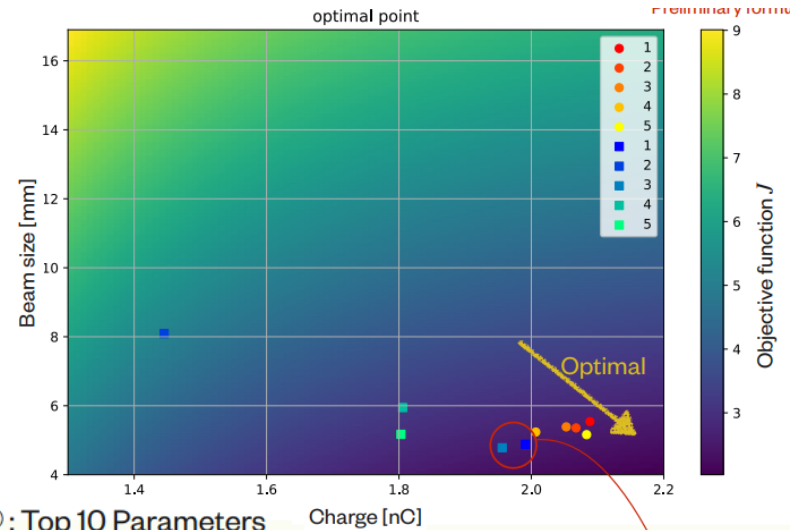
LINAC tuning and parameter importance

● GBTD+SHAP analysis to identify important tuning parameter

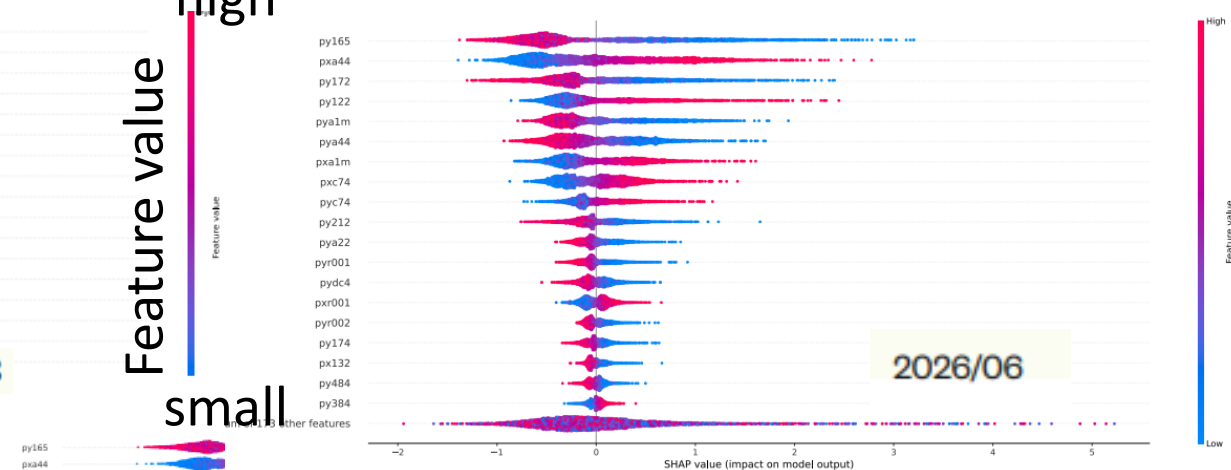
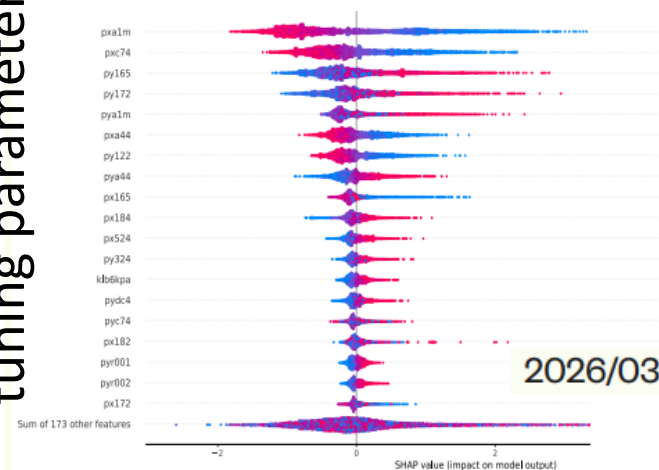
- 1. initialize magnet parameter randomly
- 2. Bayesian Optimization for tuning and data sampling
- 3. SHAP analysis to identify importance

● Consistent results with expert's experience

$$\text{Objective Function } J = \text{beamsize}/3 + (1.95/(\text{charge} + \epsilon))^3$$



tuning parameter

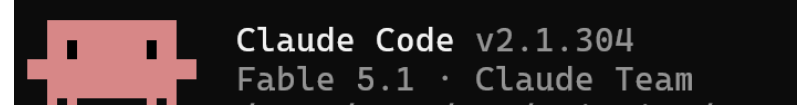


SHAP value (impact on objective function)

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.)



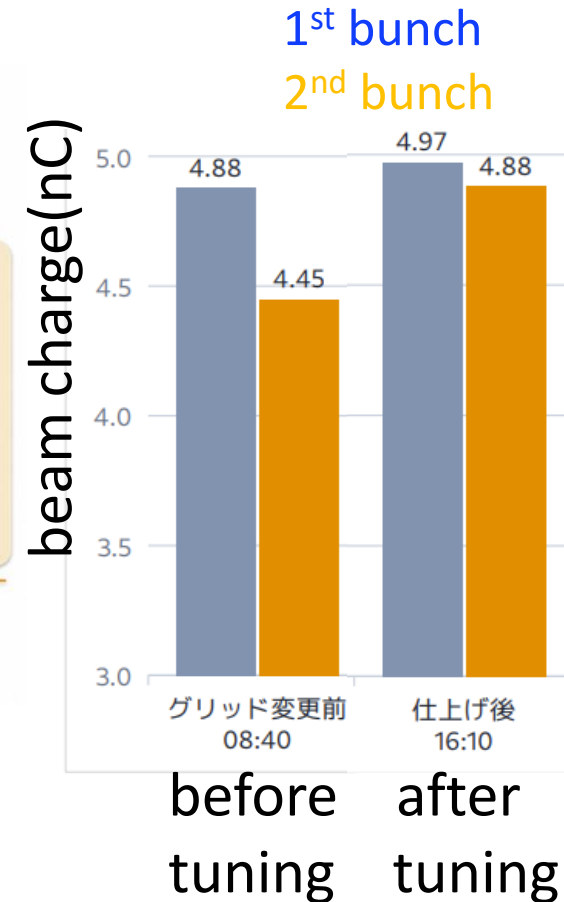
- AI agent is consulted to optimize beam parameter.
(ex. “please optimize parameter to increase injection efficiency”)
- Then AI agent will suggest recommended parameters and scan range,
and operator/shifter will change parameter.
- ✗ AI agent will not directly change machine parameter for safety

beam tuning by AI agent: LINAC demonstration

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

Adjustment Workflow: Proposal → Execution by Humans → Iteration

We repeat this workflow six times in one day.



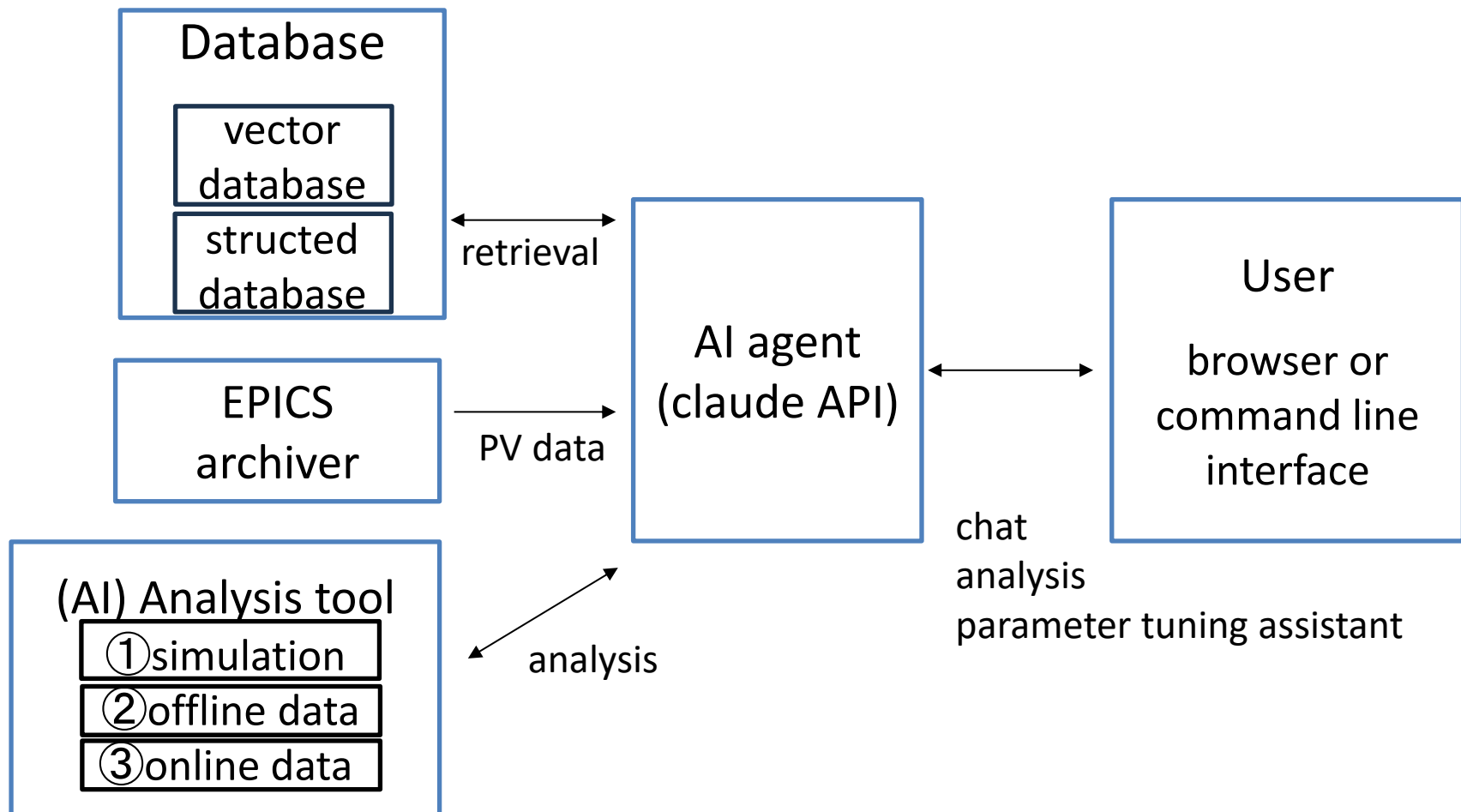
- We would like to try similar tuning at Main ring in 2027
 - injection tuning and IP knob tuning

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
- operation log (w/o personal information)
- SAD library
- OHO seminar document
- lattice
- 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

The screenshot shows a web browser displaying the 'pv_db' interface for SuperKEKB EPICS PV descriptions. The browser address bar shows the URL: `btrgpc17.kek.jp:8001/?has_desc=true&page=1`. The interface includes a search bar with the text 'Search all fields at once (all words must match)' and a 'Search' button. Below the search bar, there is a toggle for 'Only PVs with a description'. The main content area displays a table of PVs, with columns for 'PV name', 'Description', and 'Unit'. The table shows 22,604 PVs, with the first 50 displayed. The table includes entries like 'ABT_TEST:D07M:ABORT0:CH1.ACNT' and 'B2_BEAST:OPT:HER:hor:betak'. A 'Columns' dropdown menu is open, showing options for 'PV name', 'Description', 'Unit', 'Group', 'Status', 'Location', 'Comment', and 'Link'. The 'Unit' column shows values like 'count', 'e+15 V/C', and 'e+15 V/C'.

PV name	Description	Unit
ABT_TEST:D07M:ABORT0:CH1.ACNT	Abort trigger counter, D07M ch1	count
B2_BEAST:OPT:HER:hor:betak	HER 水平/垂直コリメータの $\sum(\text{beta}^*k) / \sum(\text{beta}^*k)$ for HER	e+15 V/C
B2_BEAST:OPT:HER:ver:betak	HER 水平/垂直コリメータの $\sum(\text{beta}^*k) / \sum(\text{beta}^*k)$ for HER	e+15 V/C
B2_BEAST:OPT:LER:hor:betak	LER 水平/垂直コリメータの $\sum(\text{beta}^*k) / \sum(\text{beta}^*k)$ for LER	e+15 V/C
B2_BEAST:OPT:LER:ver:betak	LER 水平/垂直コリメータの $\sum(\text{beta}^*k) / \sum(\text{beta}^*k)$ for LER	e+15 V/C

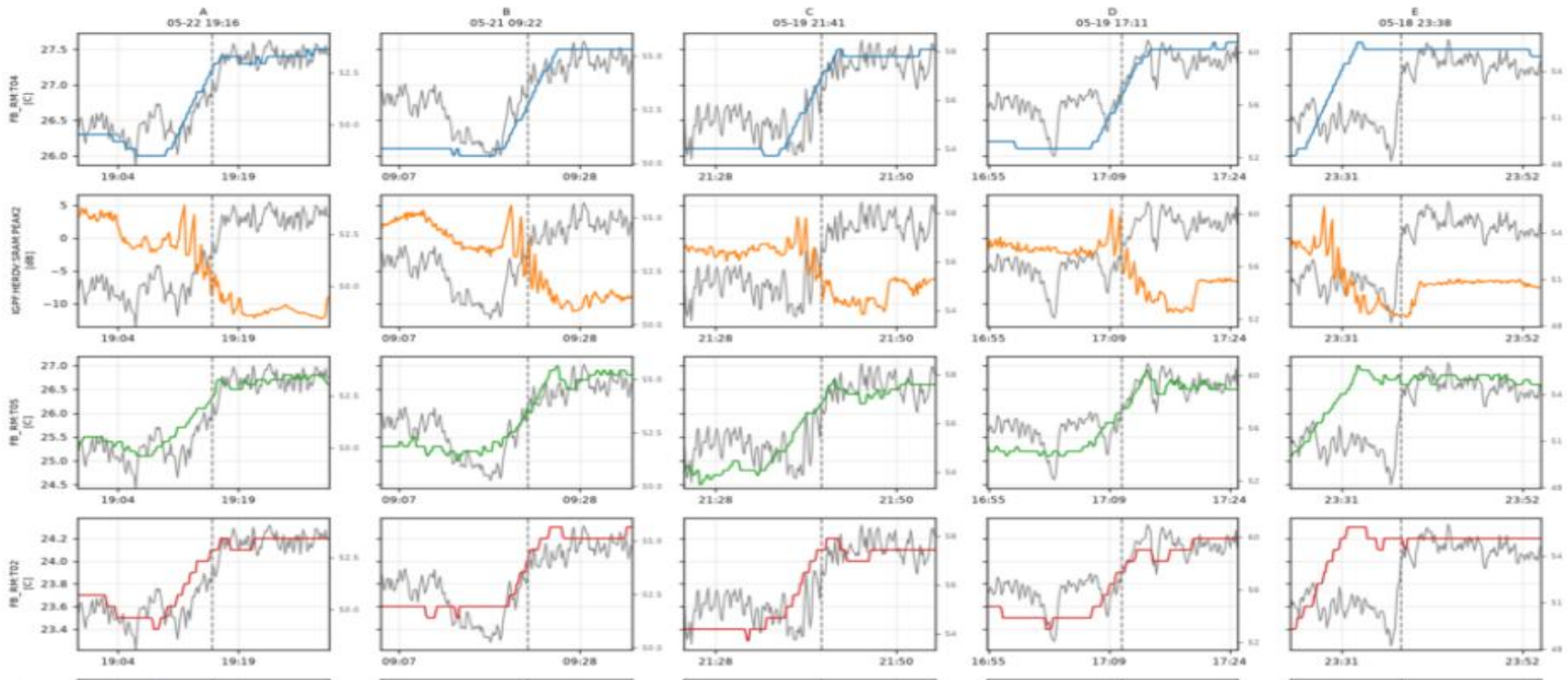
offline analysis: luminosity fluctuation

- 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

-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 $\rightarrow$ 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 spectrum peak, the very 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 $\rightarrow$ 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 $\rightarrow$ 24.0–24.2)	Same signature, smaller amplitude

feedback PV

- In 2026, we took ~3month to find these relation
 - $\rightarrow$ This tool can shorten the time: quick feedback to hardware experts

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
 - ① offline lattice optimization by AI
 - Koga(30%)
 - ② online beam parameter tuning by AI
 - LINAC: Natsui(10%), Sakai(10%)
 - IP knob: Takizawa(100%), Hara(10%), Sarthak(100%)
 - Injection: Hrishikesh(100%)
 - ③ offline 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

-①offline lattice optimization by AI

-Multiobjective optimization of sextupole

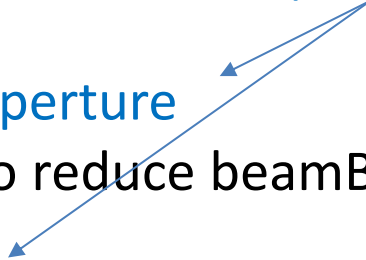
-study data/simulation difference of dynamic aperture

-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

maybe too difficult
for student (but important)



-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

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- Status from May to Oct. are summarized

- ① offline lattice optimization by AI
 - optimization of sextupole to increase dynamic aperture

luminosity
increasement
by improving life
and inj. efficiency

- ② online beam parameter tuning by AI
 - IP knob, injection tuning tool
 - AI agent

constantly keep
highest luminosity
condition

- ③ offline data analysis by AI
 - Luminosity fluctuation
 - HER emittance fluctuation

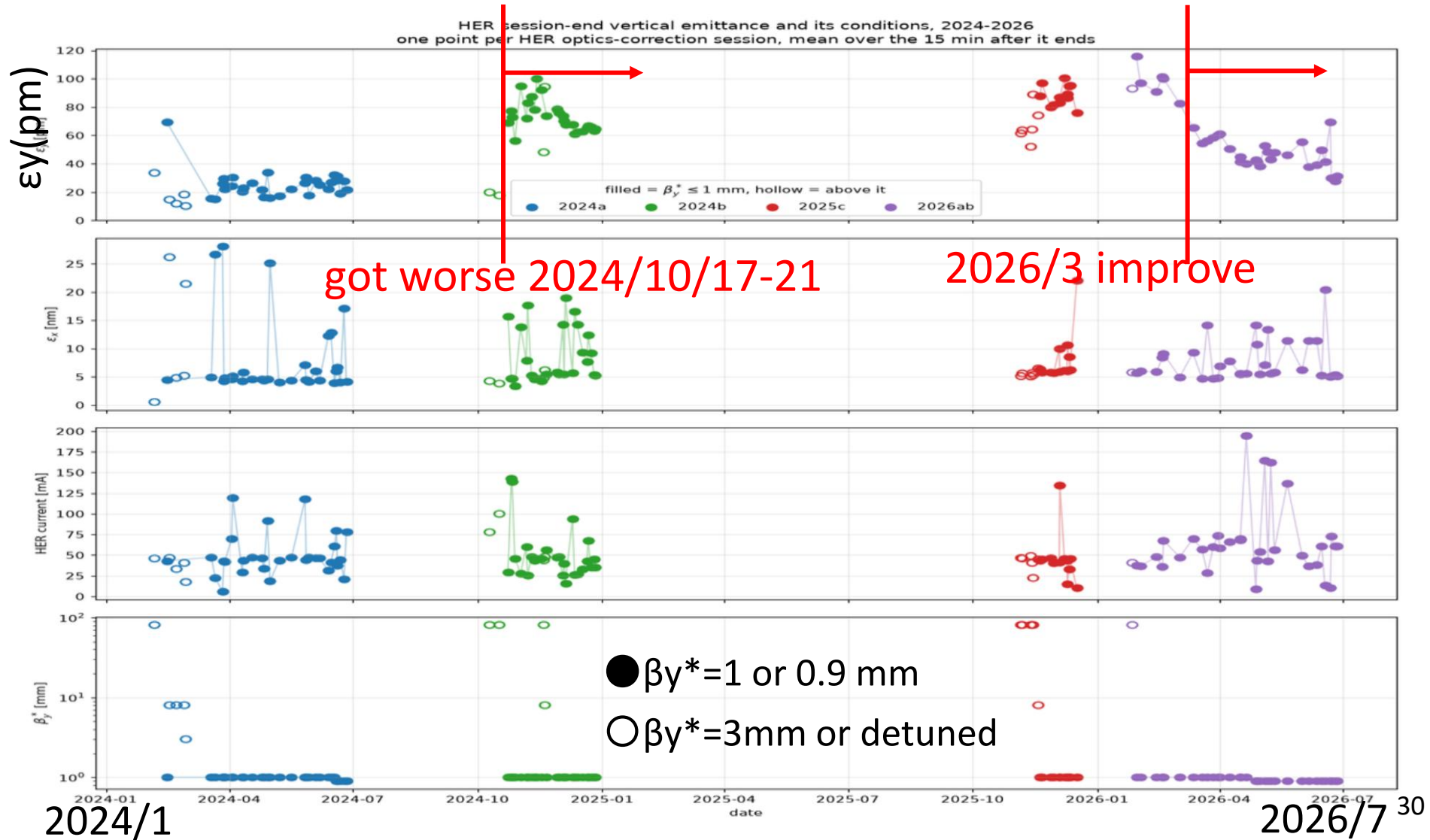
investigate outstanding issue by AI
for possible missed discovery
and countermeasure

backup

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”

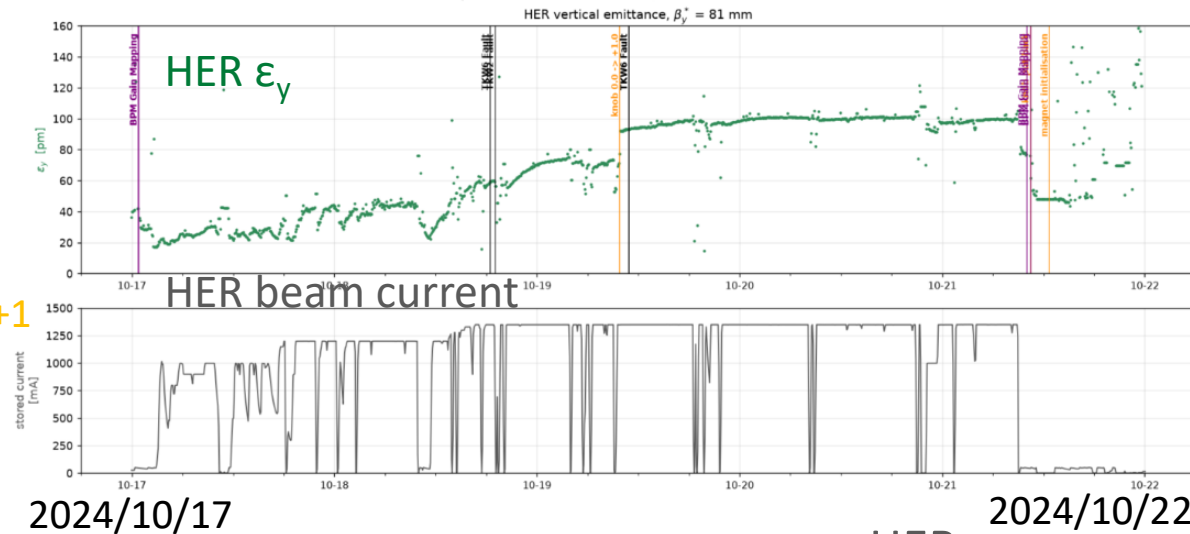
-problematic period
is checked with
operation log

-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

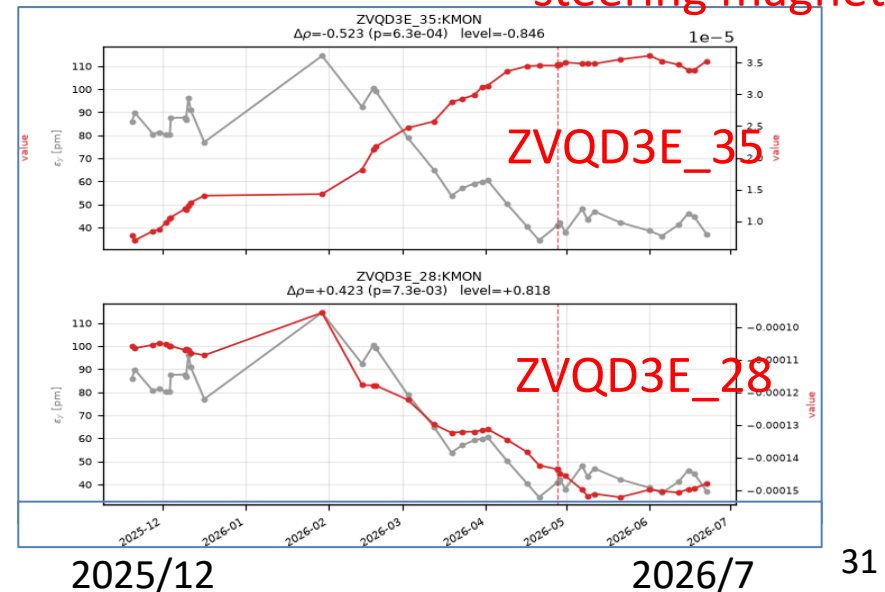


-highly correlated PVs with the
emittance is searched among ~100k PVs

-2024c: none

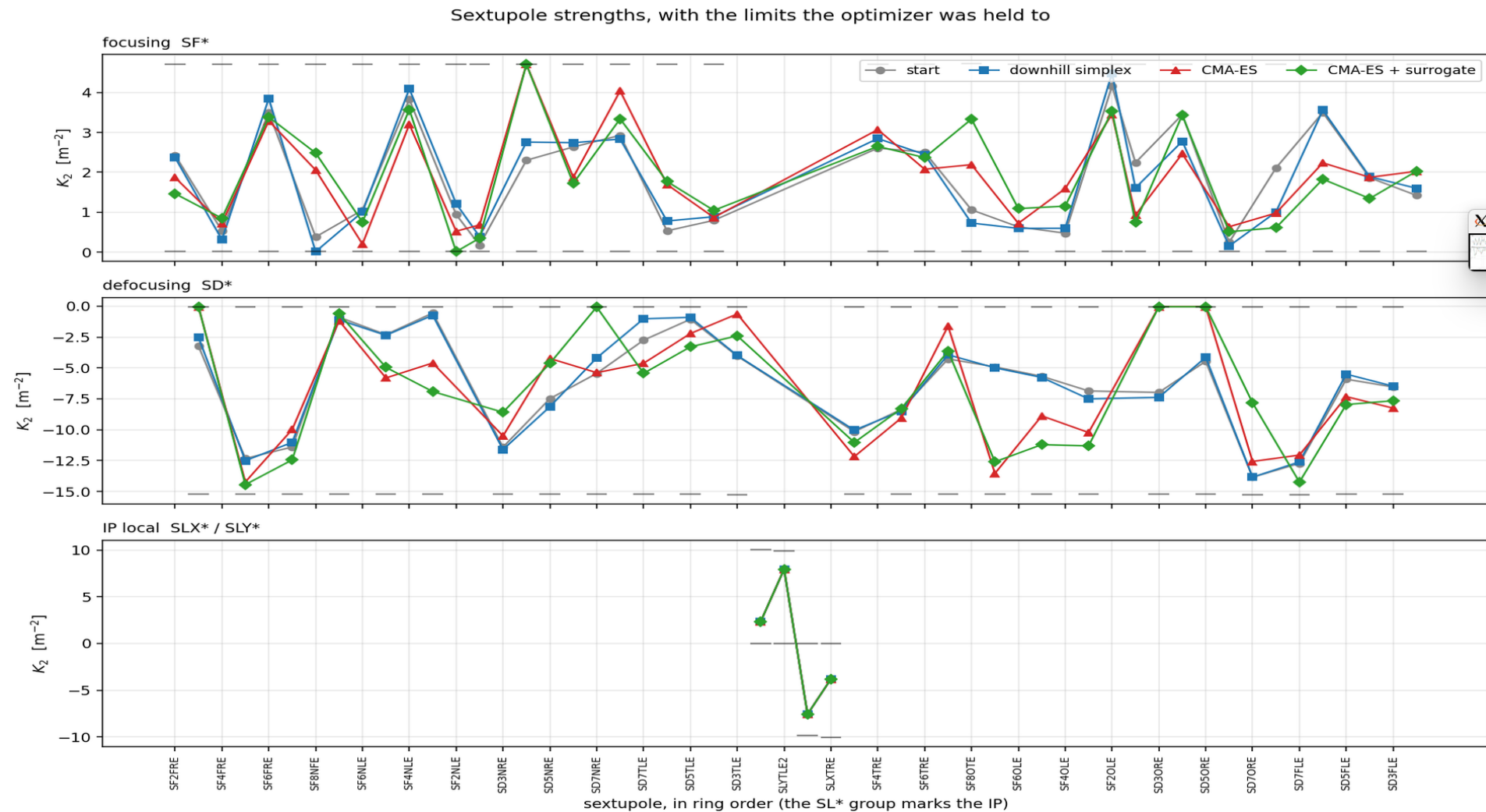
-2026: some steering magnets, skew Q

-We can not conclude the reason yet,
but quick feedback to hardware expert
will be possible.



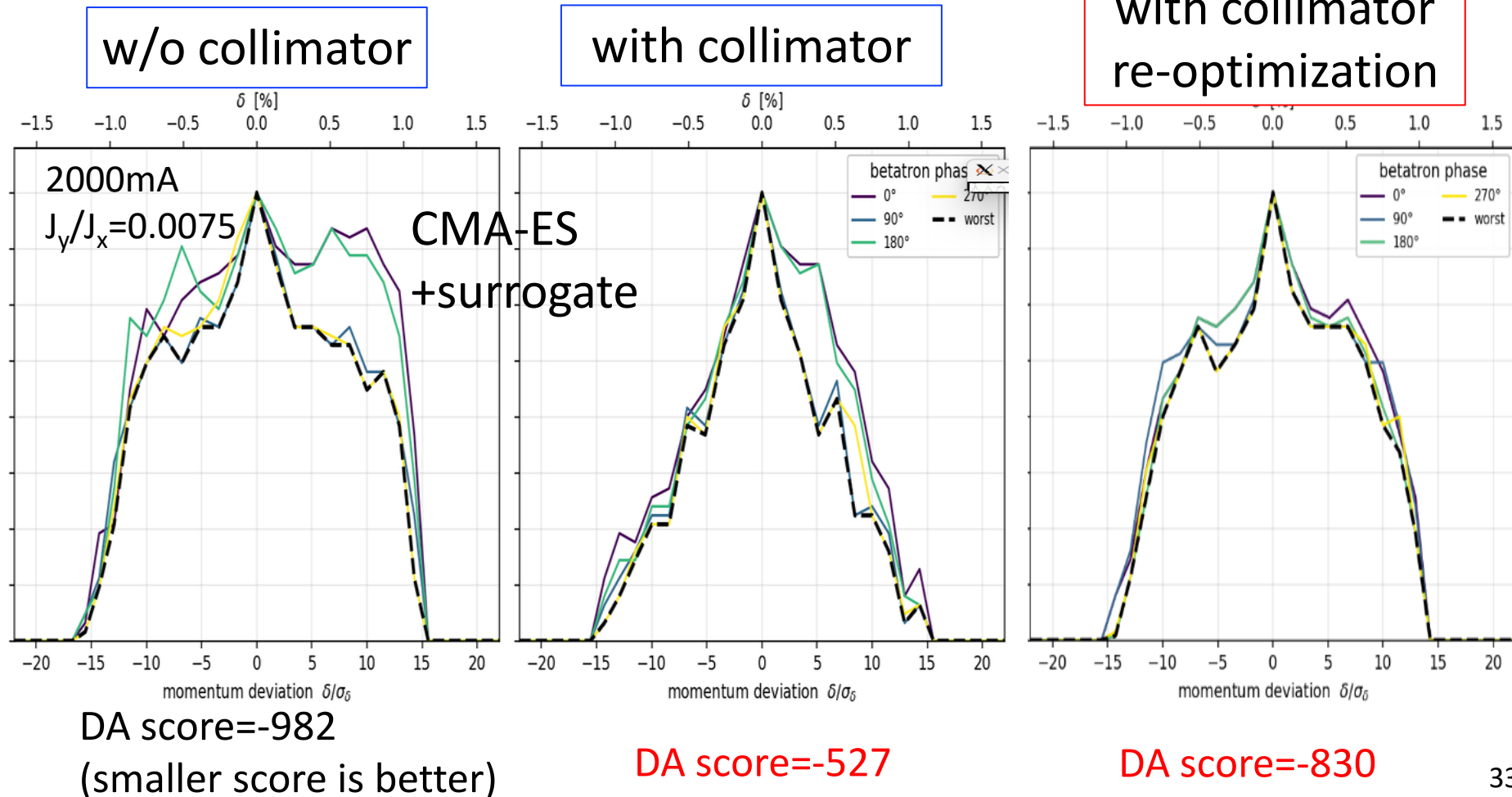
Optimized sextupole field (example of LER)

● Different optimal points are found by new optimization algorithm



Effect from collimator

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

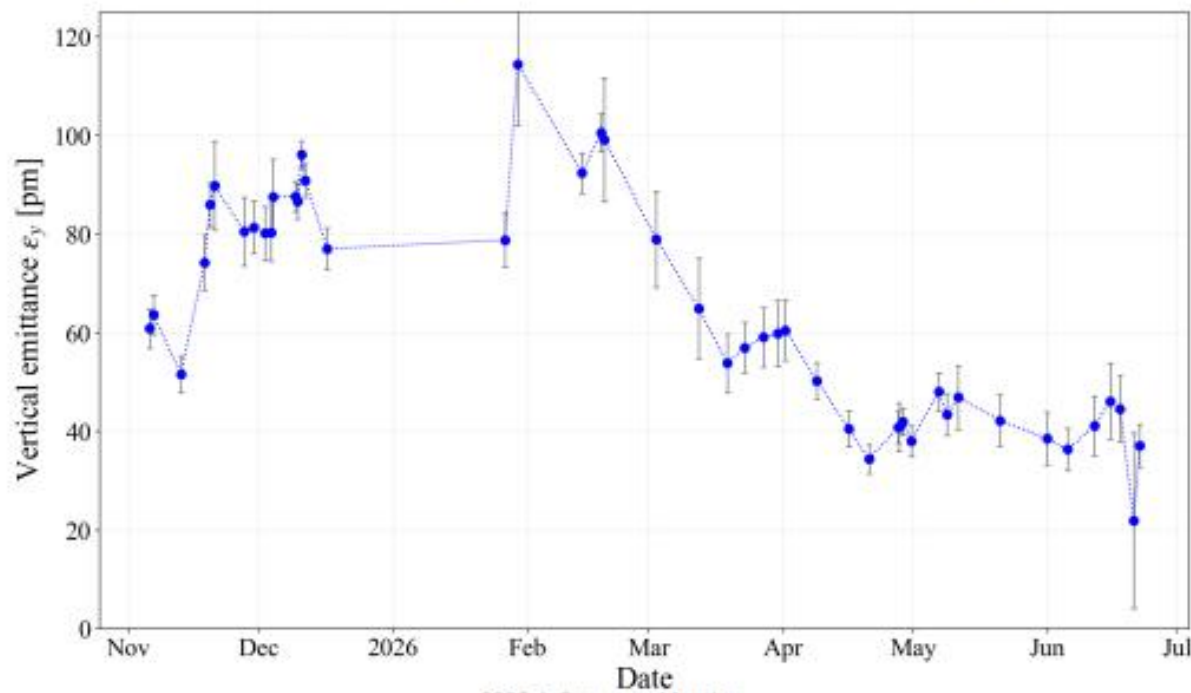


Example of emittance variation analysis

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

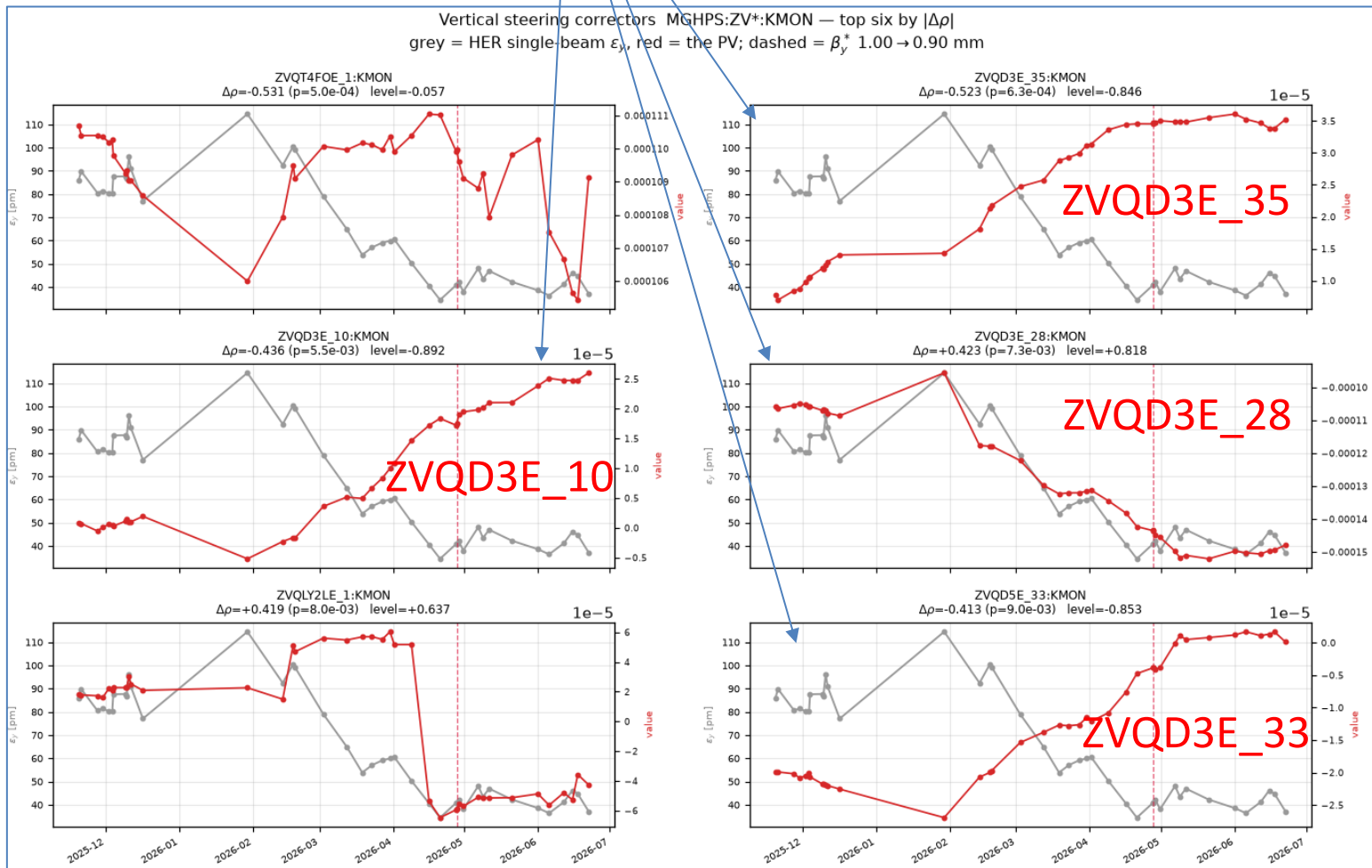
HERの垂直エミッタンスの変遷

- 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