SX2025 2025/10/8

Precise evaluation of time-varying quadrupole field errors through closed-orbit measurements in the J-PARC main ring

based on Phys. Rev. Accel. Beams 28, 012801 (2025).

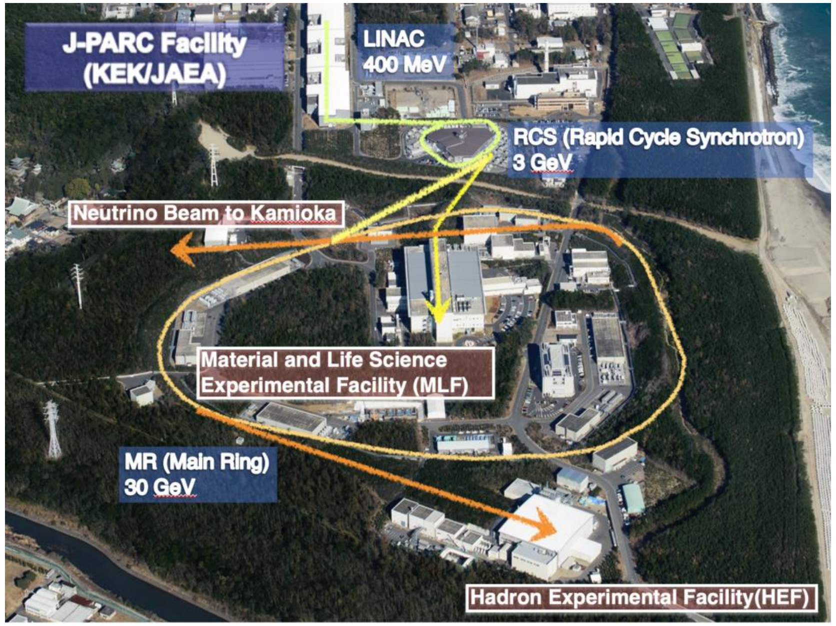
Takashi Asami (KEK)

Contents

Contents

- Introduction
- Method
- Precise evaluation of time-varying quadrupole field errors
- Conclusion

J-PARC main ring (MR)



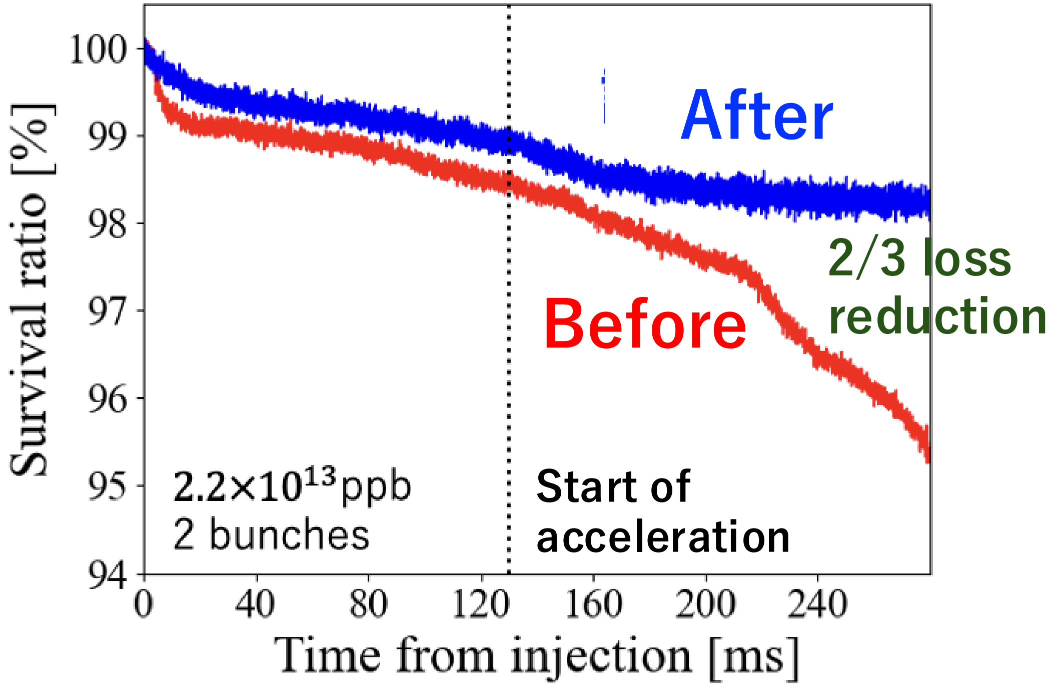
Parameter	
Particle	Proton
Kinetic energy	3 GeV ~30 GeV
Circumference	~1.6 km
Shape	Threefold symmetric
Extraction mode	FX (Neutrino), SX (Hadron)
Beam power (May 2025)	FX 830 kW, SX 92 kW

- The power upgrade plan for both FX and SX user operation is underway.
  FX 830 kW→1.3 MW   SX 92 kW→over 100 kW
- A critical challenge in power upgrade: radioactivation of components caused by **beam loss**.
- The amount of beam loss must be maintained below a certain threshold regardless of beam power. → **Beam loss mitigation is essential for both FX and SX operations.**

Quadrupole field errors (quad. errors)

- The primary source of beam loss of the MR is the “**betatron resonances.**”
- Quadrupole field distribution around the ring must be kept threefold symmetric, or the betatron resonances will be strengthened.[1]
- **In the MR, correcting non-symmetric quad. errors has been crucial for loss reduction.**

One example of beam loss mitigation by correction of quad. errors. (February 2023) →



Beam loss ratio: >4.5% → 1.5%.

This correction contributed to more than 2/3 beam loss reduction.

[1] For example, see *S. Y. Lee, “Accelerator physics.”*

Objective

- Precise evaluation/correction of quad. errors become increasingly crucial.
- A lot of successful attempts have been made to suppress such errors*.
- However, it was estimated that these efforts could unintentionally retain substantial quad. errors up to about $\Delta K/K$*=1%.
- **Objective: to establish and apply a method to precisely determine these remaining individual quad errors around the ring.**

* $\Delta K/K$: field deviation in relative error with designed field strength.

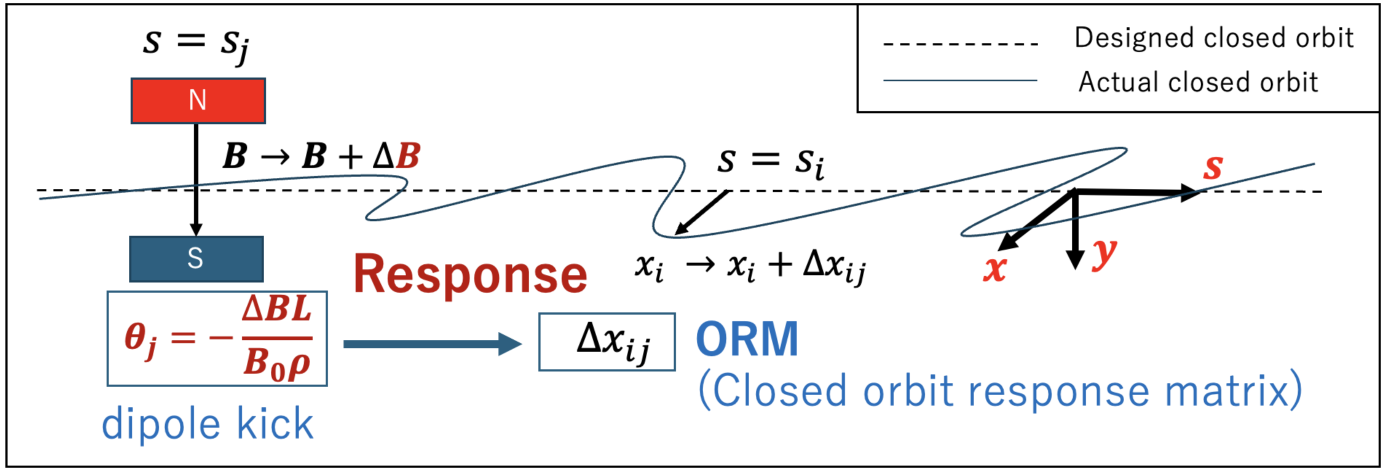
*Precise field measurements/calibration/shuffling before installation of the magnets, applying various optics tuning methods and their hardware, BPM upgrade(underway).

Contents

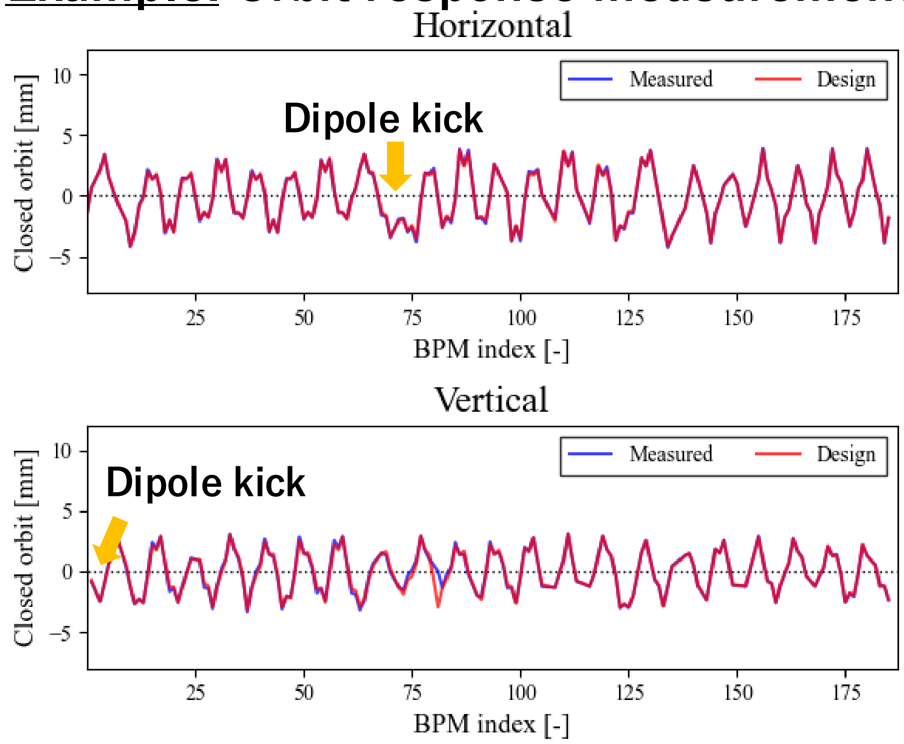
- Introduction
- Method
- Precise evaluation of time-varying quadrupole field errors
- Conclusion

Basic: Orbit Response Matrix (ORM)

A dipole kick at one location distorts the beam orbit around the ring.
→ The response function for this phenomenon: "ORM."



Example: Orbit response measurement.

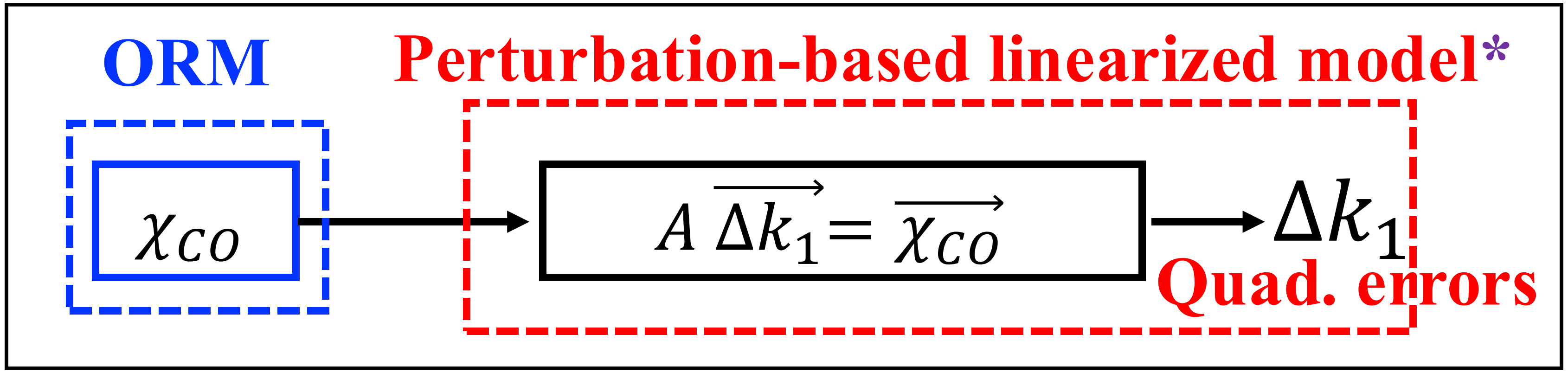


- ORM relies on quadrupole field errors.
- Therefore, quadrupole field errors are often determined by measuring and fitting ORM.
- In the MR, ORM can be measured using 186 beam position monitors (BPMs).

A precise method to evaluate quad. errors

For our objective, we established an ORM-based method called 'QCPLM.'

QCPLM (**Q**uadrupole **F**ield **A**nalysis by **C**losed orbits using **P**erturbation-based **L**inearized **M**odel)



- We experimentally benchmarked* (backup) that it evaluates quad. errors in 0.1% accuracy.
- This is enough to evaluate $\Delta K/K = 1\%$ quad. errors we concern.
- We used this to search for the remaining quad. errors in the ring → **next topic.**

*Please refer to the paper for more details of the method itself or its benchmark. We focus on the results using it.
(Note) This largely enhances the robustness of the fit; but we don't discuss further here.

Contents

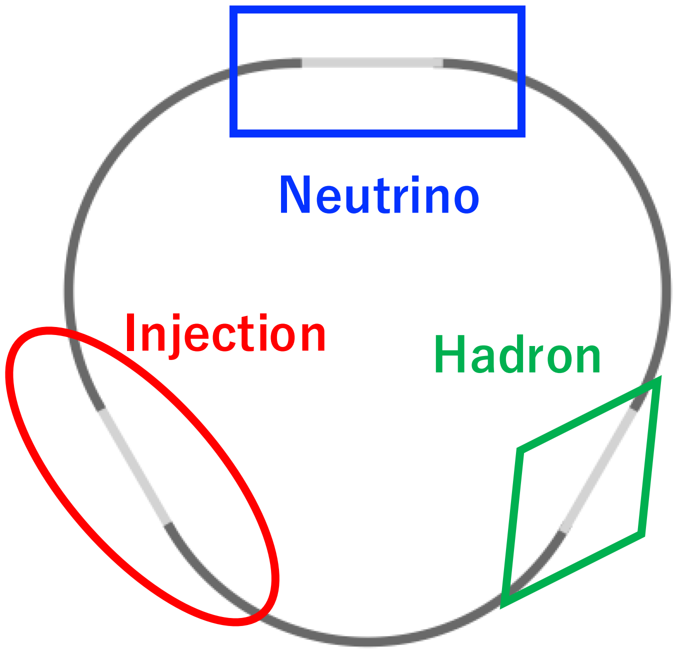
Background: the eddy current effects

In the MR, there are various types of beam ducts near injection/extraction area.

- Ramping of the magnet during acceleration induces **eddy currents** in these beam ducts.
- Their arrangement **does not consistently maintain threefold symmetry**.

→ Eddy currents could break optics' symmetry.

→ One of the most significant concerns in the MR.



We surveyed time-varying quadrupole field errors using QCPLM, targeting the determination of the eddy current effects.

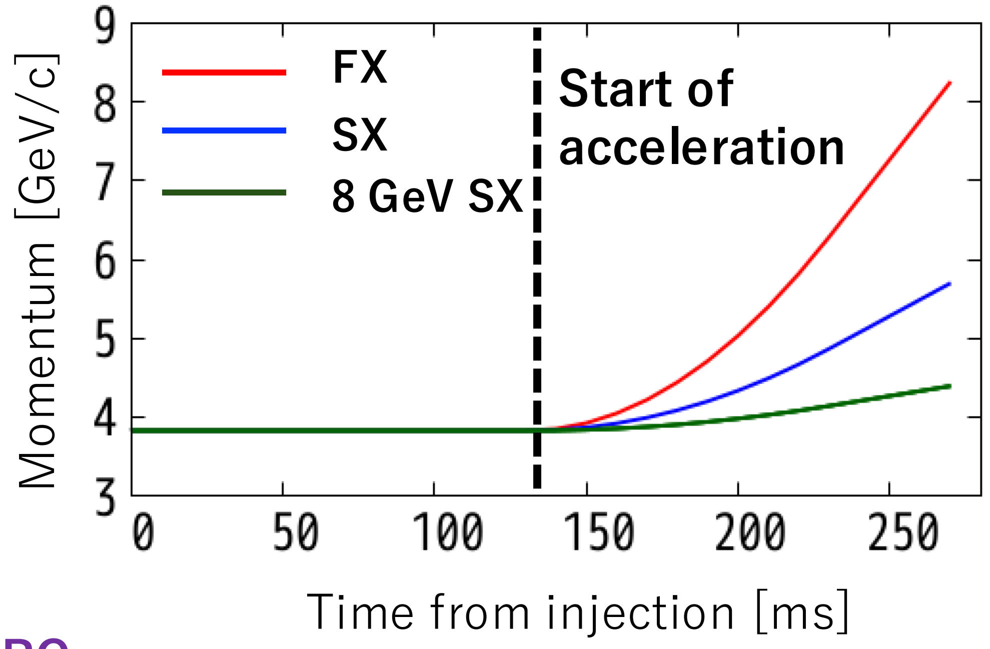
Details of the survey

- MR operates in three modes with distinct momentum variations: FX, SX, “8GeV SX”*.
- **They should have difference in the strength of the eddy current effects.**
- **We conducted a survey in each of the operation modes.**

Parameters for each operation modes (@ December 2023)

Operation modes	Extraction energy	Ramping
FX	30 GeV	0.65 s
SX	30 GeV	1.4 s
“8 GeV SX” *	8 GeV	0.9 s

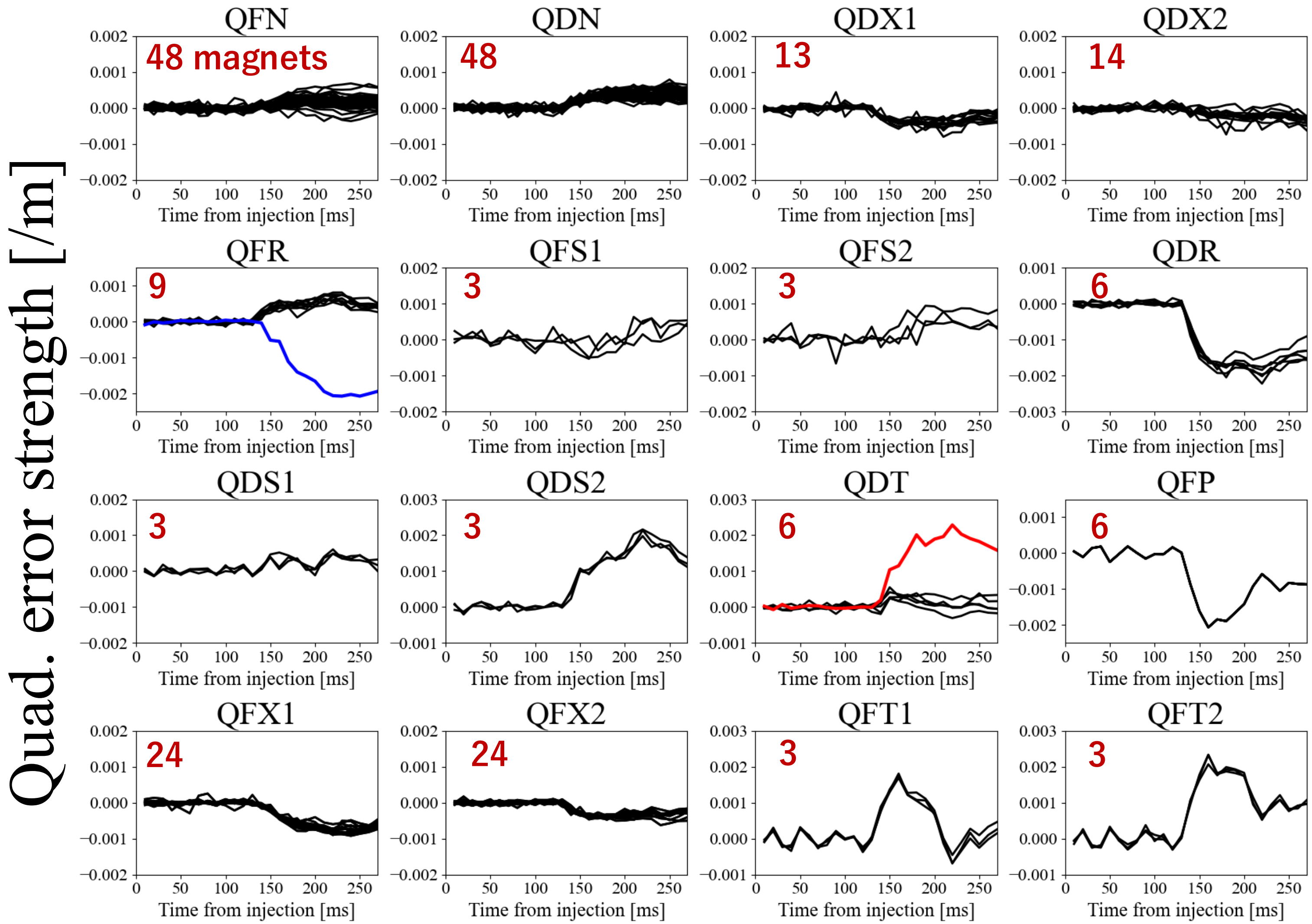
They have different extraction energy , acceleration time, and therefore different momentum variations.



***A special SX optimized for the “COMET” experiment in J-PARC.**

Results for FX

PS family : Group of magnets driven by same power supply. (16 PS families in total)

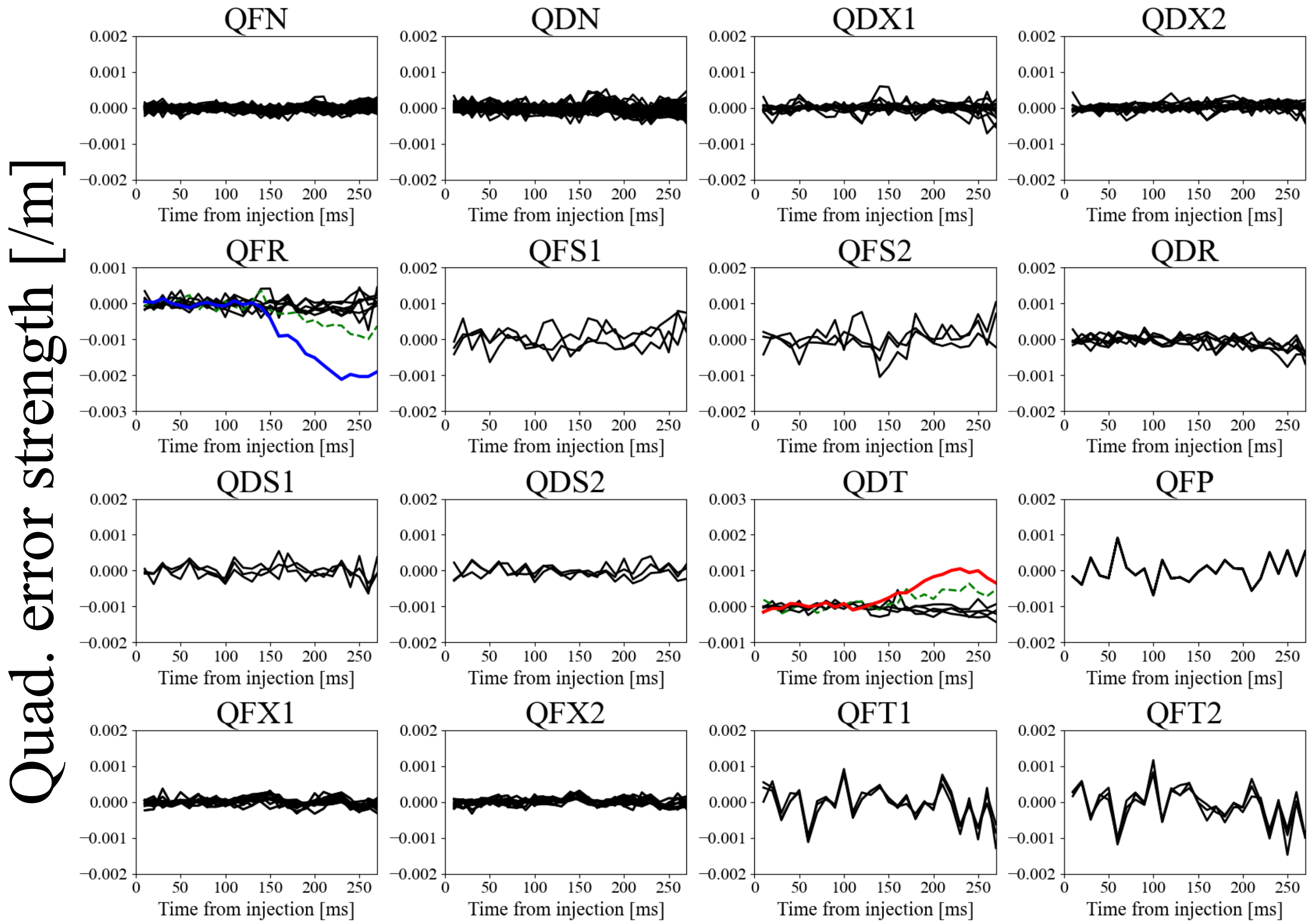


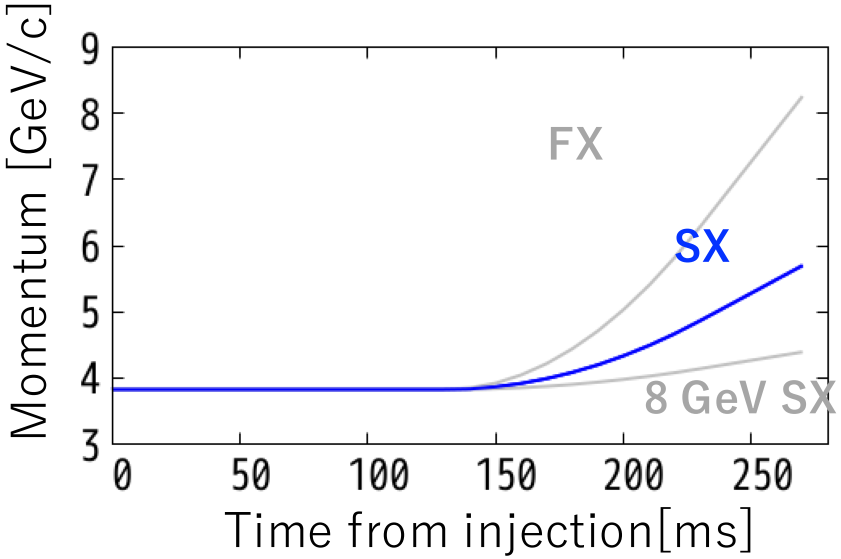
- Each panel shows each PS family.
- Vertical: Strength, Horizontal: time
- The lines indicate the measured field strength for each of the 216 magnets.

- The magnets shown by black lines exhibit consistent time variation among their PS family.
- However, **one QFR magnet (colored blue)** and **one QDT magnet (colored red)** exhibit distinct time variations.
- Their strength: $\Delta K/K$ >1% at max point.

***The time-independent offset components were subtracted beforehand to observe the eddy currents.**

Results for SX

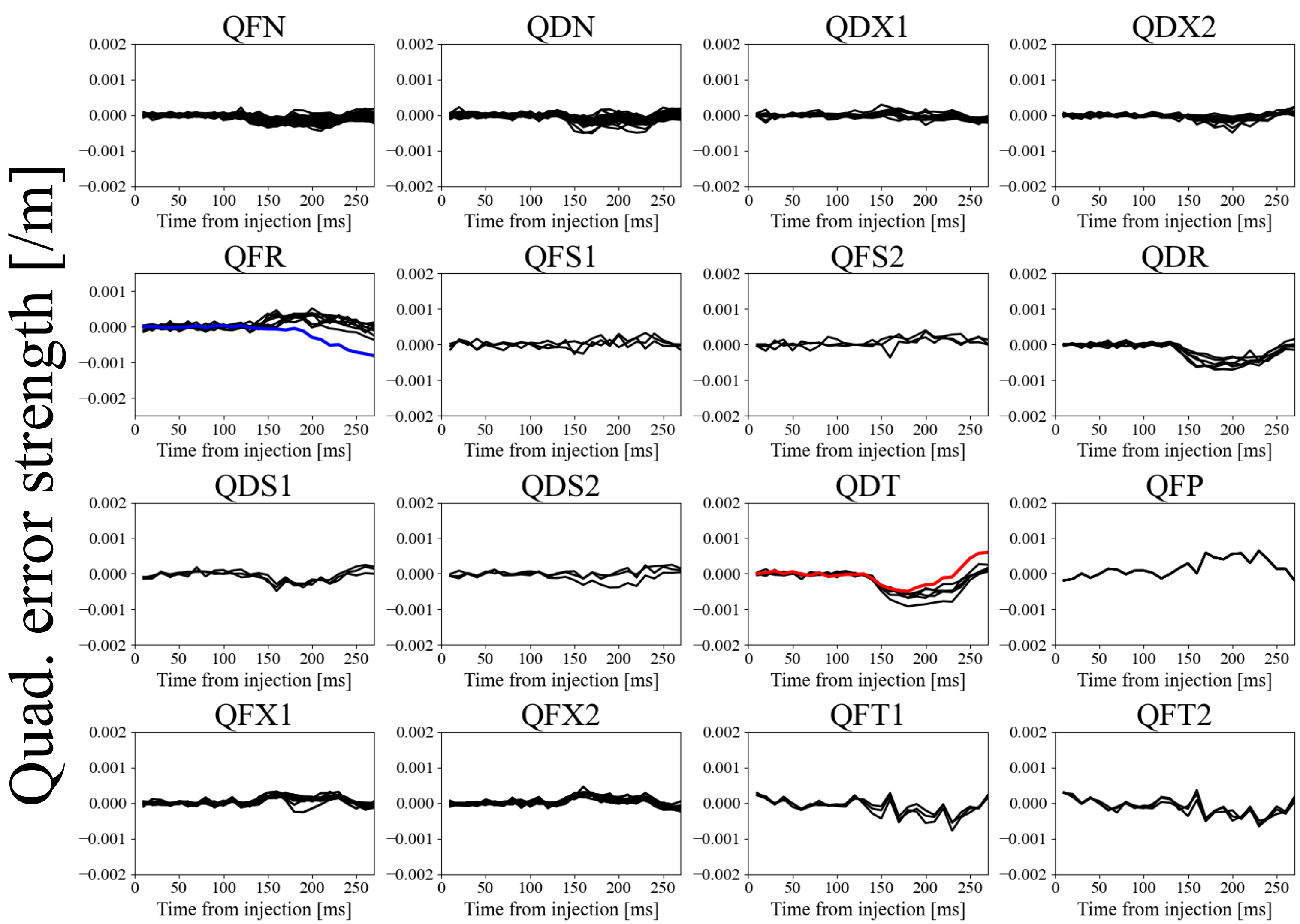


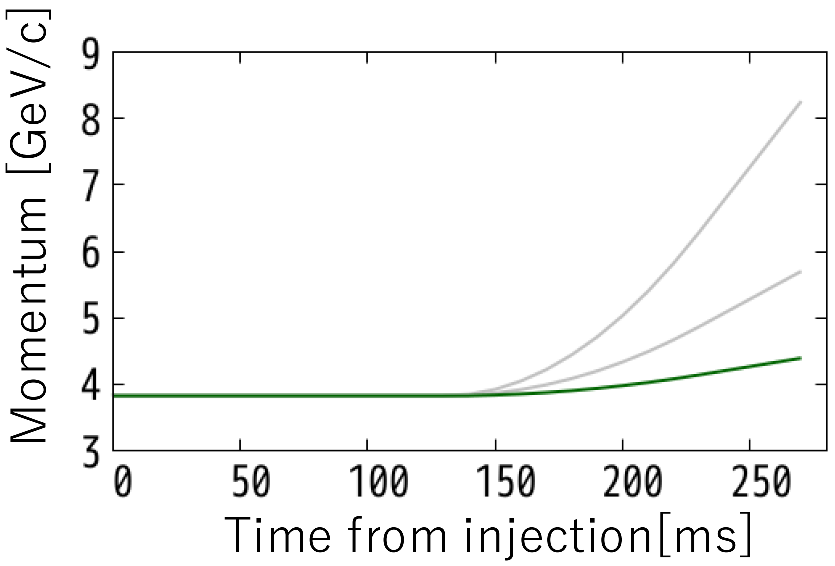


The blue and red lines are still present in the results, but smaller than FX.

Green dashed lines: determined to be the leakage fields from the septum magnets.

Results for 8 GeV SX



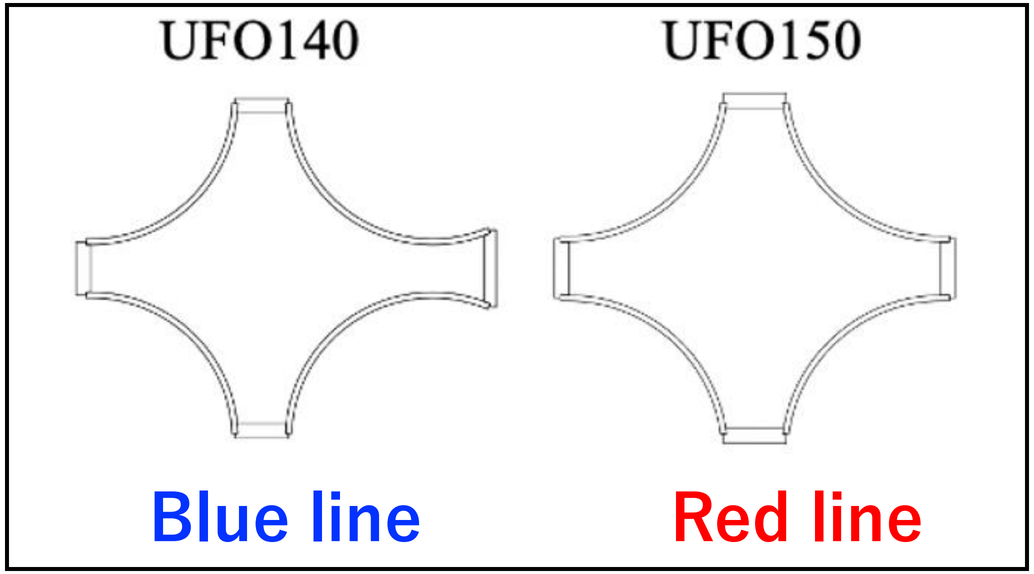


- ➢ The gentlest acceleration gradient among modes.
- ➢ Quad. field response of blue and red lines became much smaller.

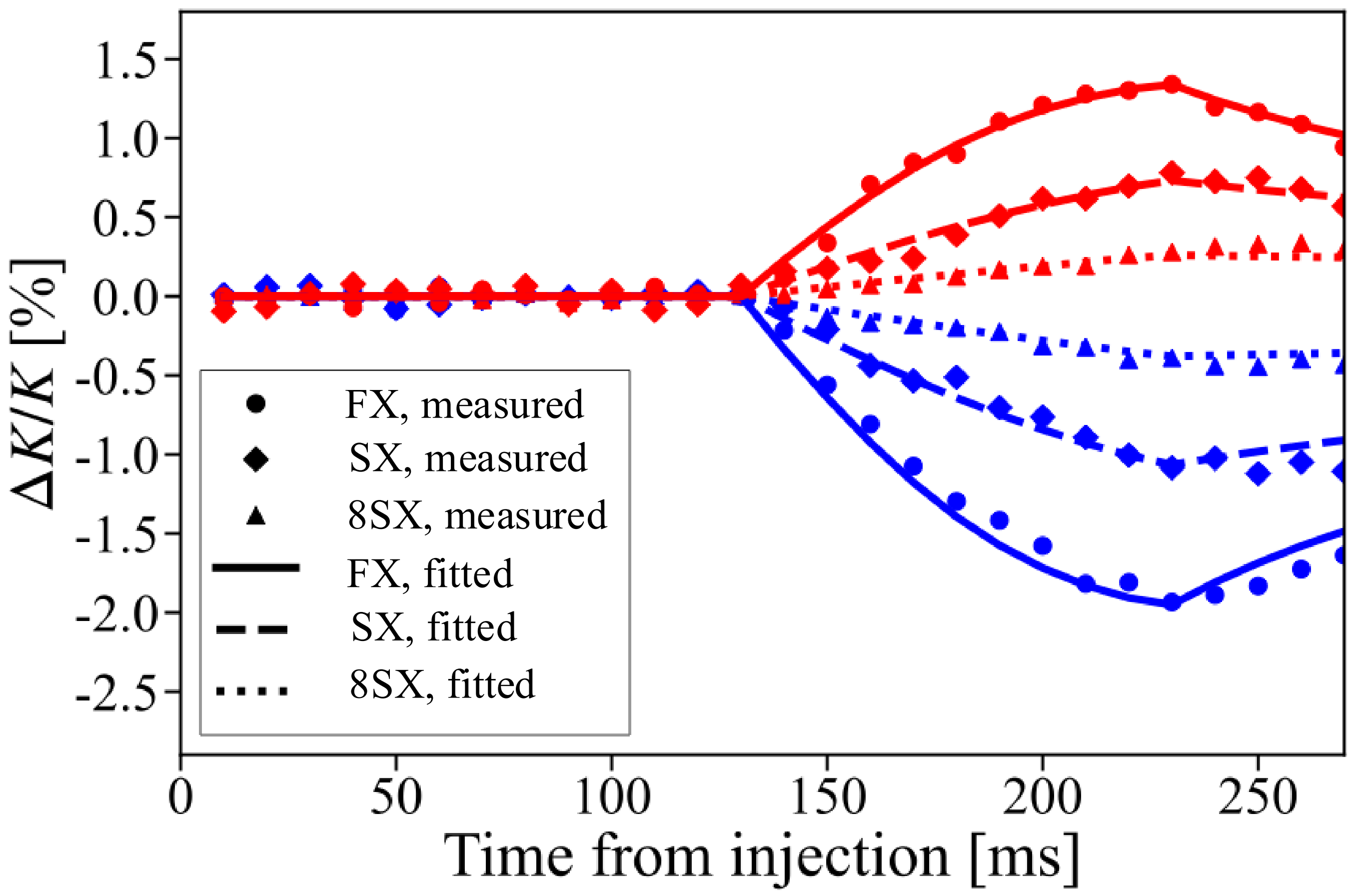
Discussion

- At these two magnets with distinct time variation, there are unique beam ducts called “UFO ducts,” to accommodate the extraction trajectory.
- The UFO ducts are solely located at these two locations. → **Therefore, eddy current effects in these UFO ducts were highly suspected.**

Cross-section of the UFO ducts.



Examination by model fitting



Simple model of field response by the eddy current effects:

$\Delta(B'L/B\rho)$

$$\Delta K(t) \sim c_f \frac{1}{p(t)} \frac{dp(t)}{dt}$$

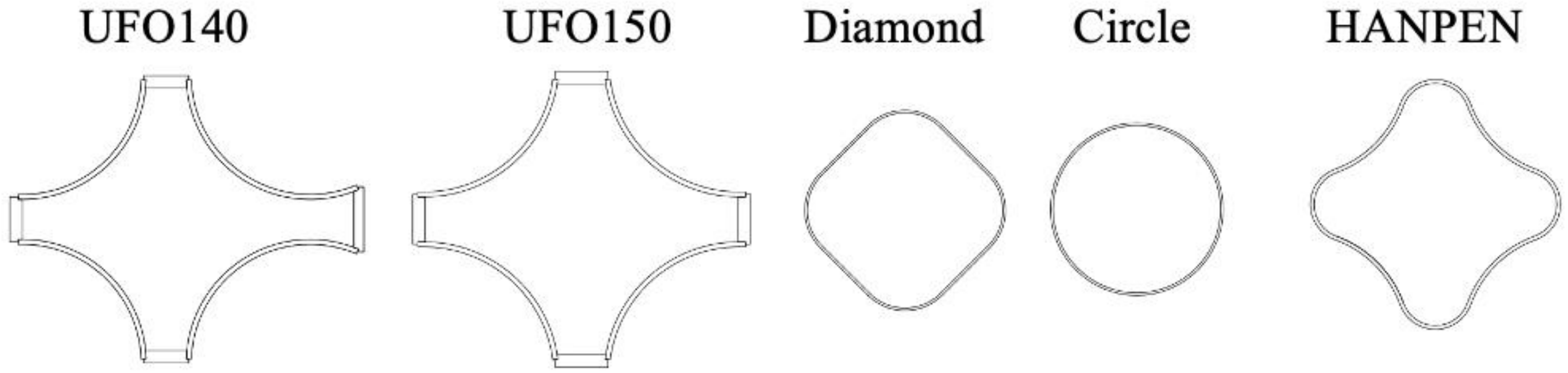
Form factor c_f :
Only depends on material and shape.
Not depending on time, momentum, or operation mode.

Choosing only one parameter c_f for each magnet of the two magnets, and we get the left fit results.

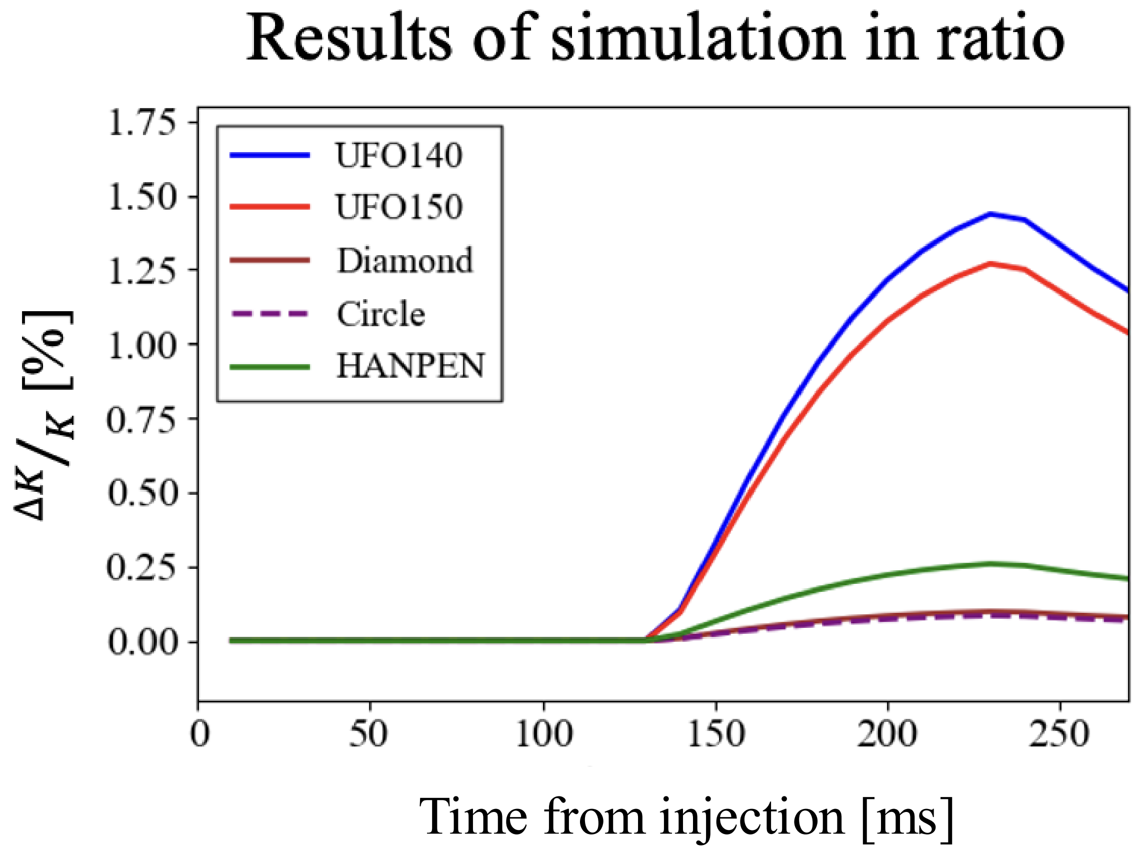
Strongly supports the eddy current effects.

Examination by 3D EM simulation approach

- To further examine the eddy current effects, we performed 3D electromagnetic field simulations using **CST Studio Suite**.
- The duct shapes are classified into five categories as shown below, and each of them was considered in the simulation.
- The evaluation focused on the **quadrupole magnetic field response**.



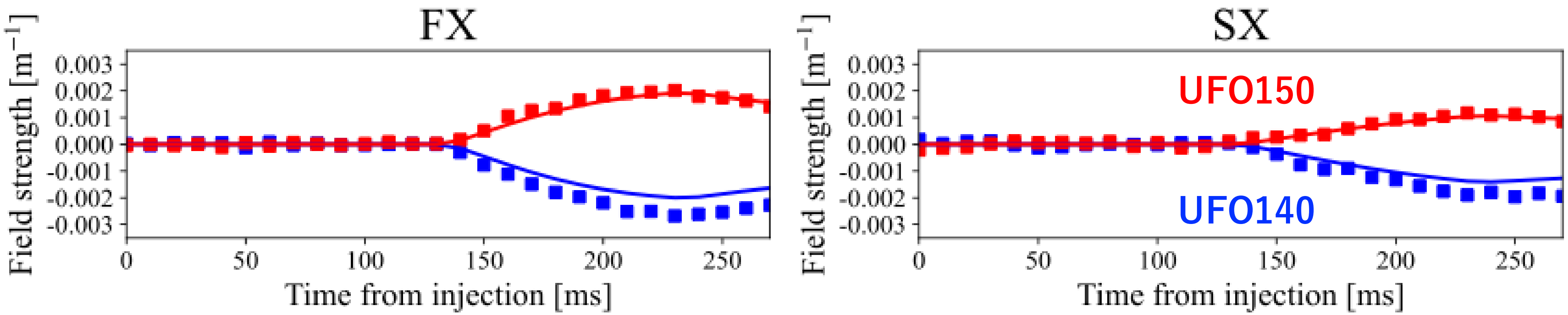
Results of EM simulation

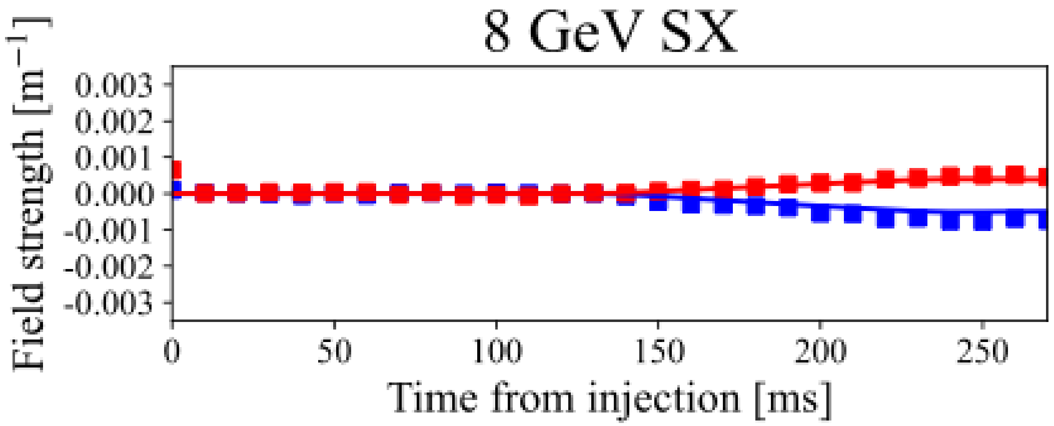


Considered coil currents for FX as input.

Only the UFO ducts showed more than 1% field errors.

3D EM vs QCPLM



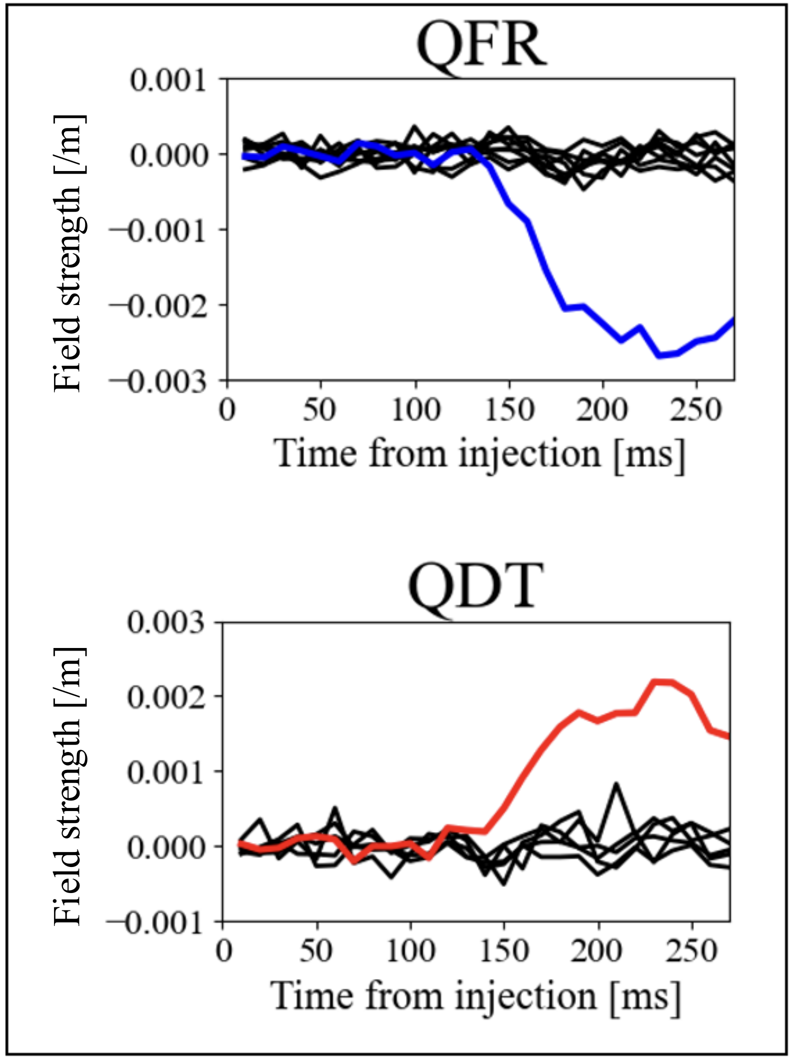


Scatter: QCPLM
Lines: EM simulation

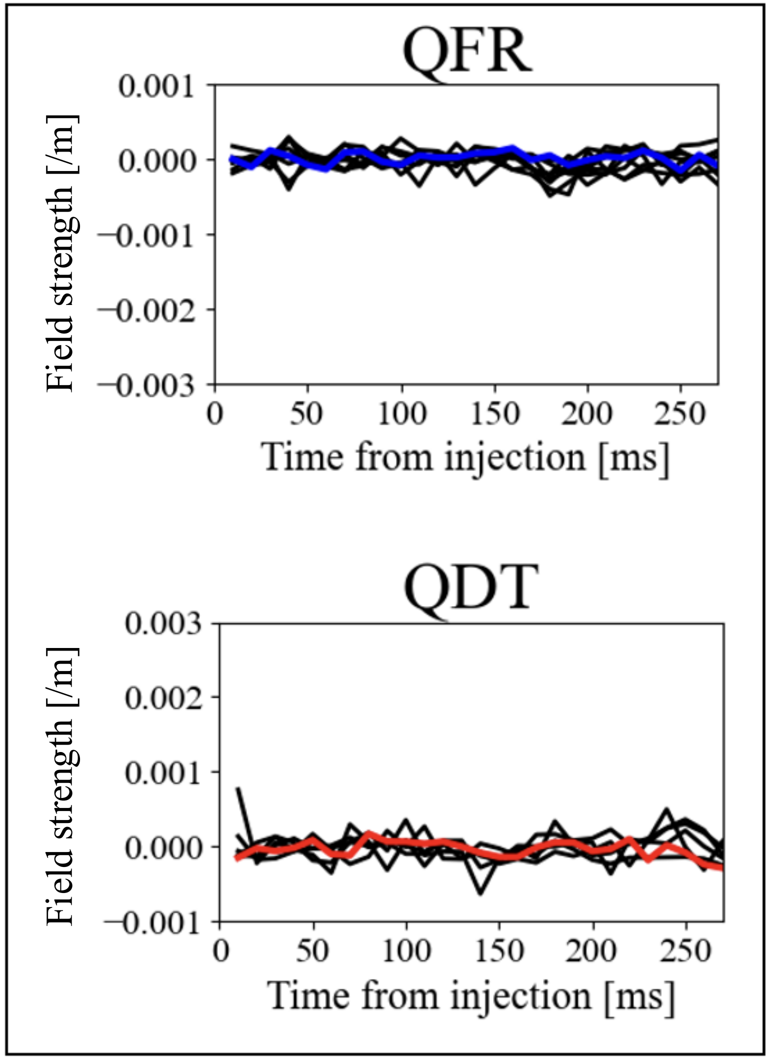
- QCPLM and 3D EM simulation results agree well.
- **We determined the quad. field errors by eddy currents for the first time in the MR.**

Correction of the eddy current effects

Before correction



After correction

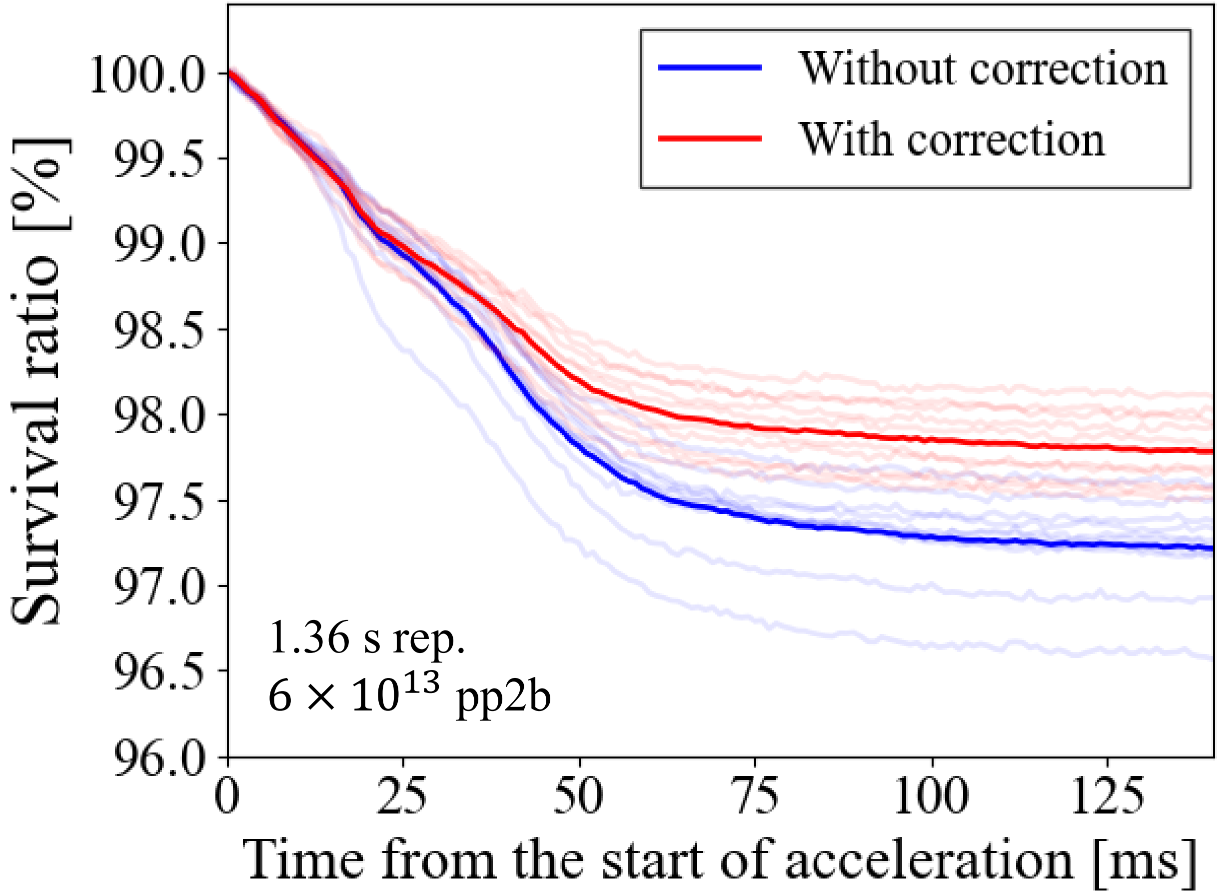


We attempted to correct the effects using secondary coils (trim coils) of quadrupole magnets.

Succeeded to correct them.

Beam loss response by the correction

Beam survival ratio during acceleration (850 kW equiv. FX)



Beam survival ratio during acceleration 97.5% → 98%.

→ **successfully mitigated 20%**

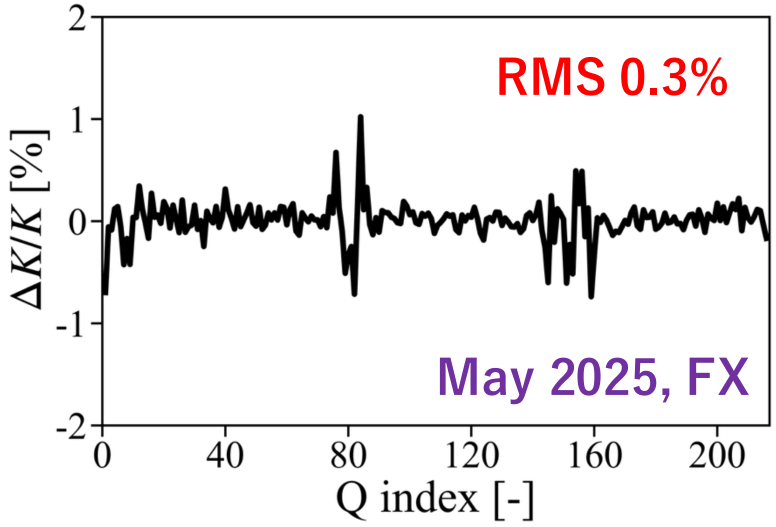
(**Detailed Conditions**)

- Data was acquired for 10 shots per condition.
- Thin lines represent the measured values for 10 shots.
- Solid lines represent the average value.
- Normalized based on the loss amount at the start of acceleration.

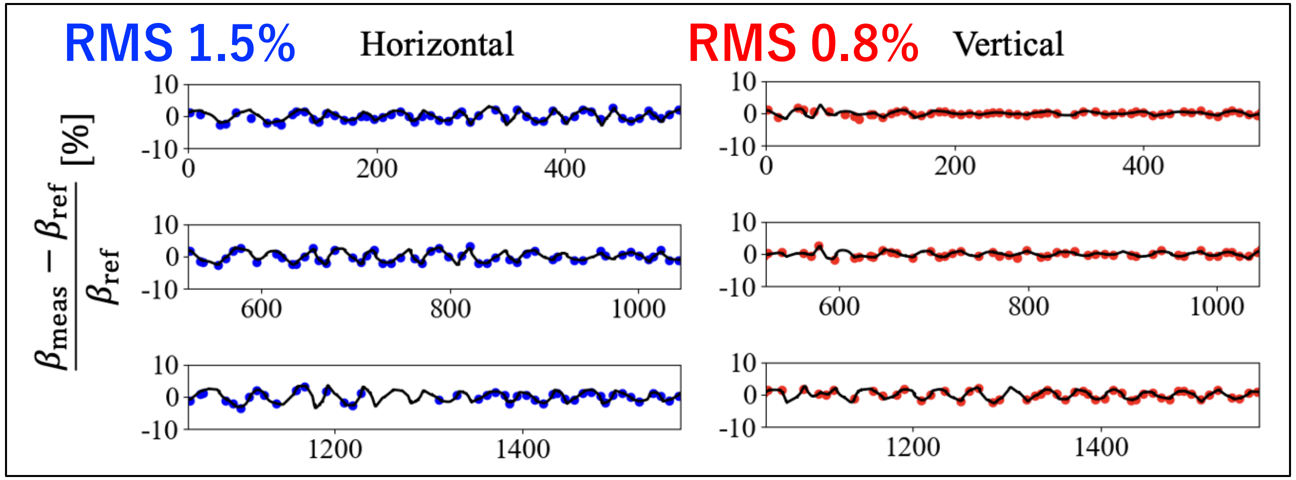
Recent optics tuning

- The optics measurement scheme developed in this work is employed in routine optics tuning, often leading to loss reductions of tens of percent.
- Typical tuning results: $\mathrm{rms}[\Delta K/K] \sim 0.3\ [\%]$ and $\mathrm{rms}[\Delta\beta/\beta] \sim 1.5\ [\%]$.

Quadrupole field error (injection period)



Beta-beat (injection period)



May 2025, FX, 1×10^{12} ppb (for optics tuning)

Contents

Conclusion

1. We established a precise method to evaluate the time-varying quadrupole field errors for the MR.
2. We identified previously undetermined quadrupole field errors and established its correction method.
3. The methods developed in this works are employed in the routine optics tuning.

Backup

Experimental benchmark of QCPLM

Theme：

Can we precisely determine time-varying quad errors intentionally given in the ring?

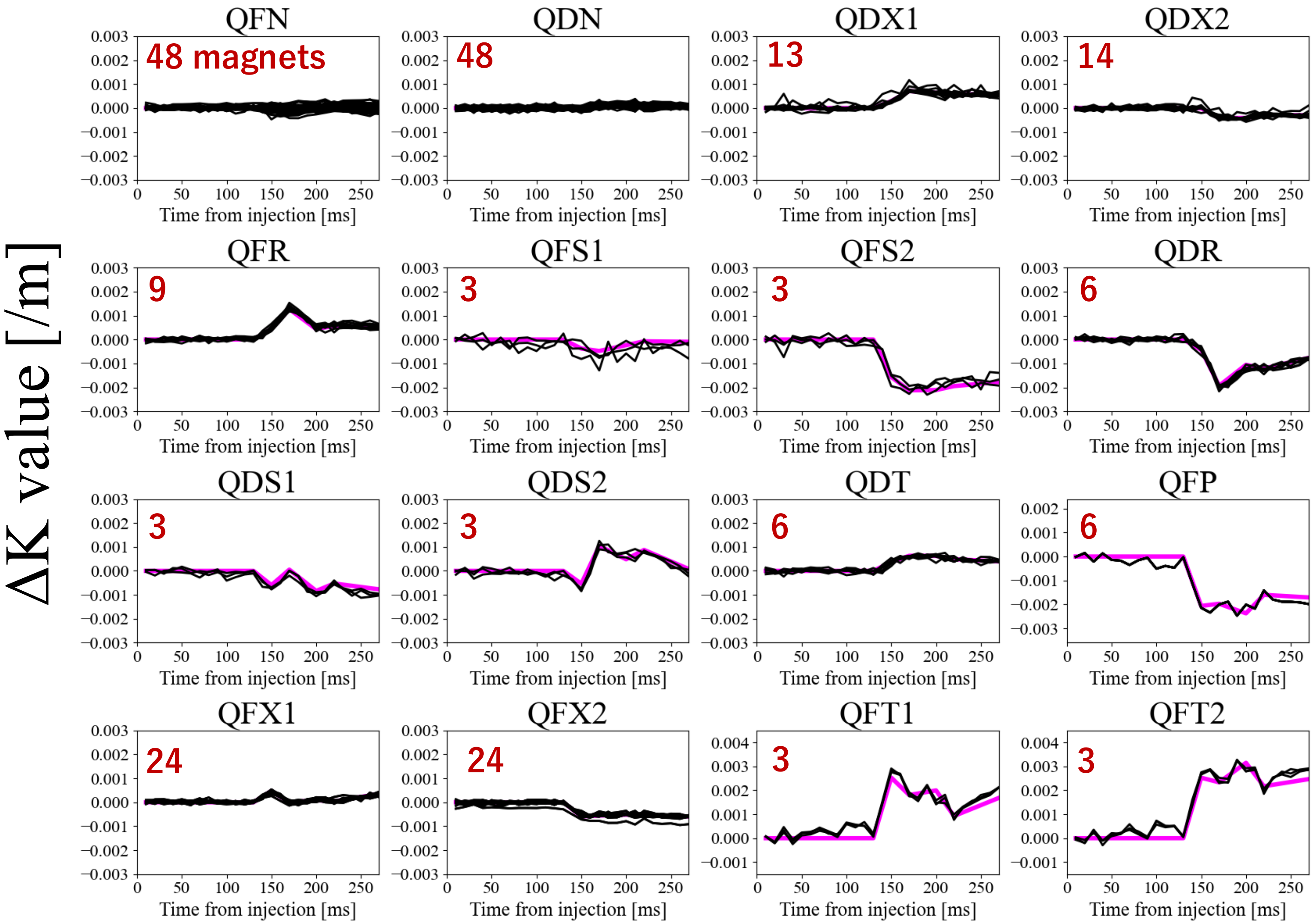
Method：

- First, we measured the ORM.
- Then, we changed the currents of 16 power supplies of quadrupole magnets and reacquired ORM. **There are 216 quad magnets driven by 16 power supplies.**
- We determined the field difference of all 216 individual quadrupole magnets under these two conditions using QCPLM.

The results were compared with the set value for the power supplies.

Results

PS family：Group of magnets driven by same power supply.



- Each panel shows each PS family.
- The black lines indicate the measured field difference among the two conditions for each 216 magnet.
- The magenta lines show the reference values set to PSs.

Accuracy

Measured

Set values

$$\sigma_K \equiv \mathrm{RMS}\left[\frac{\Delta K_{meas}}{K} - \frac{\Delta K_{ref}}{K}\right]$$

$= 0.1\%$

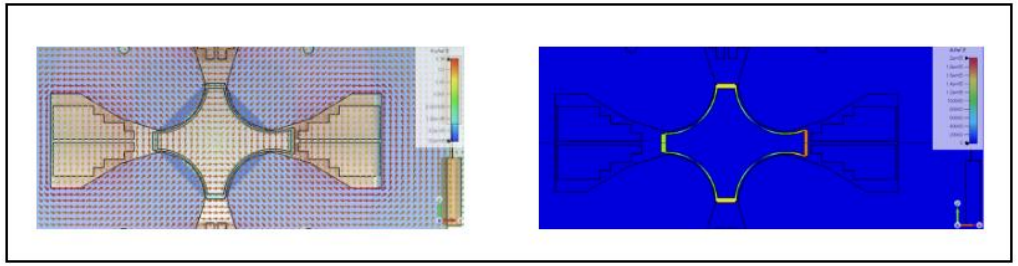
Enough to evaluate 1 % errors which we concern.

We carried out QCPLM to find the undetermined quadrupole field errors.

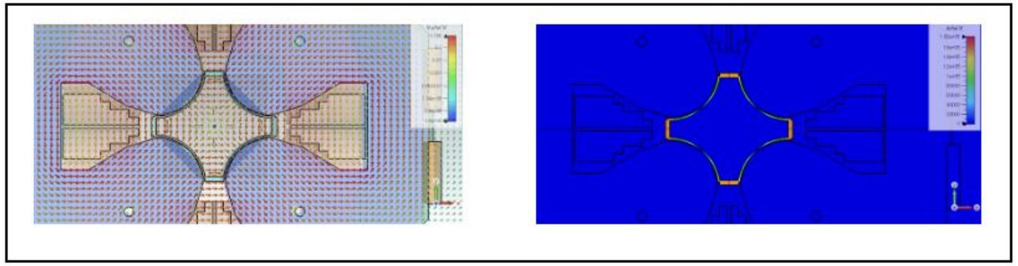
Simulation models

Five types of ducts with different **materials and thicknesses**.

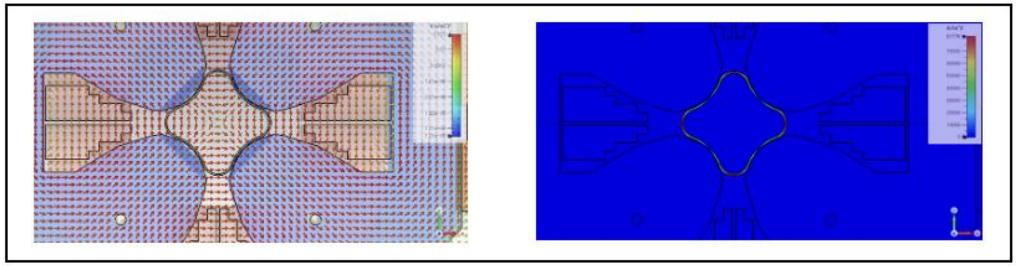
UFO140 Ti, 4mm



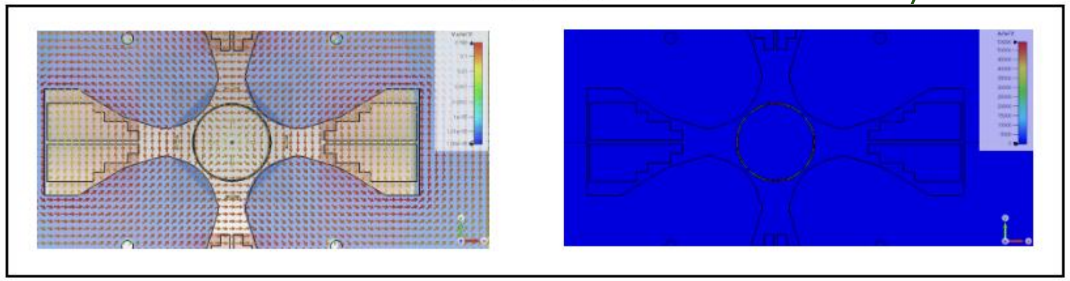
UFO150 Ti, 4mm



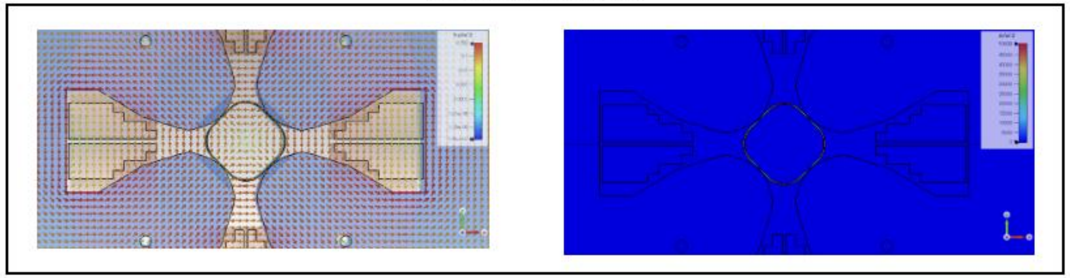
HANPEN Ti, 3mm



Circle Ti, 2mm



Diamond SUS316L, 2mm

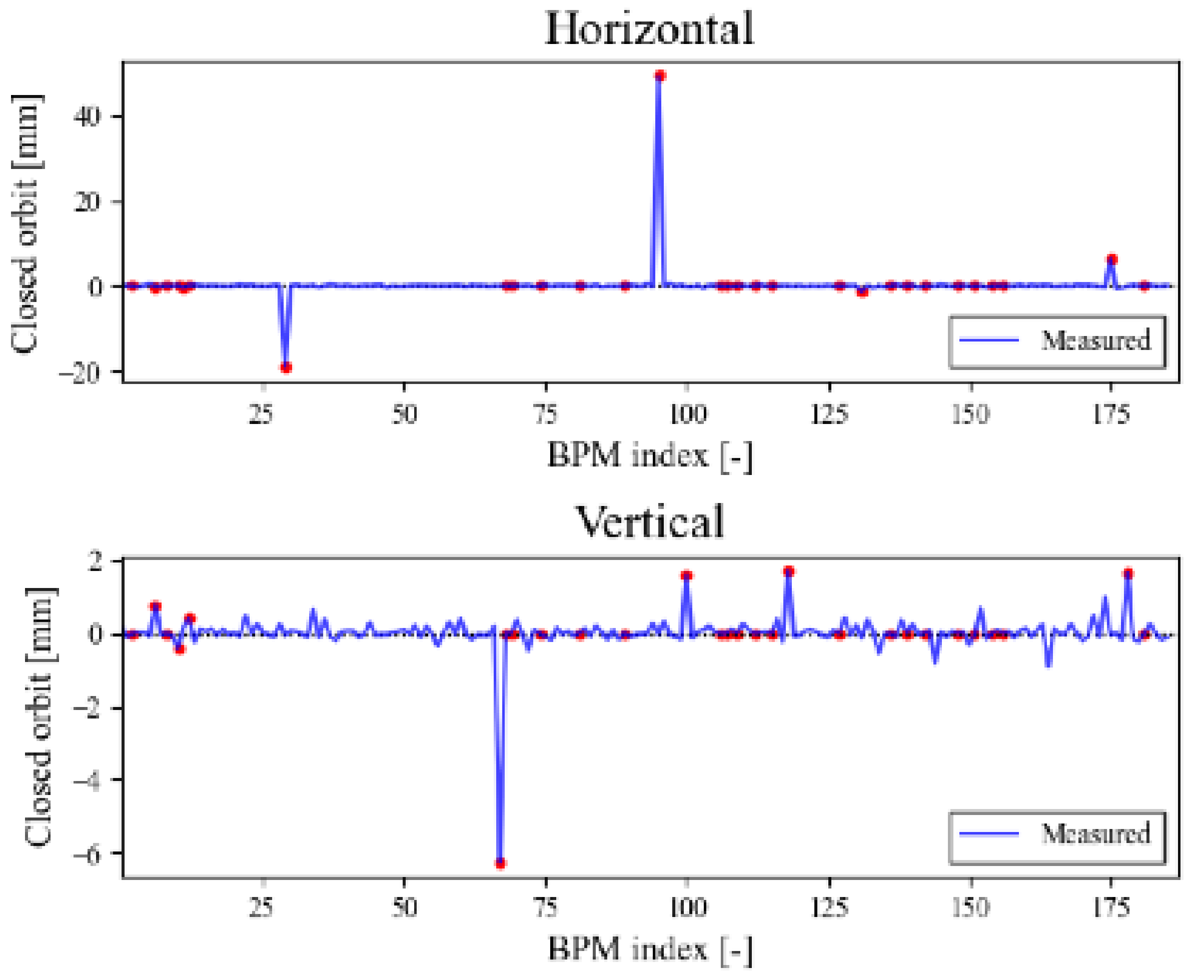


Malfunctioning BPMs

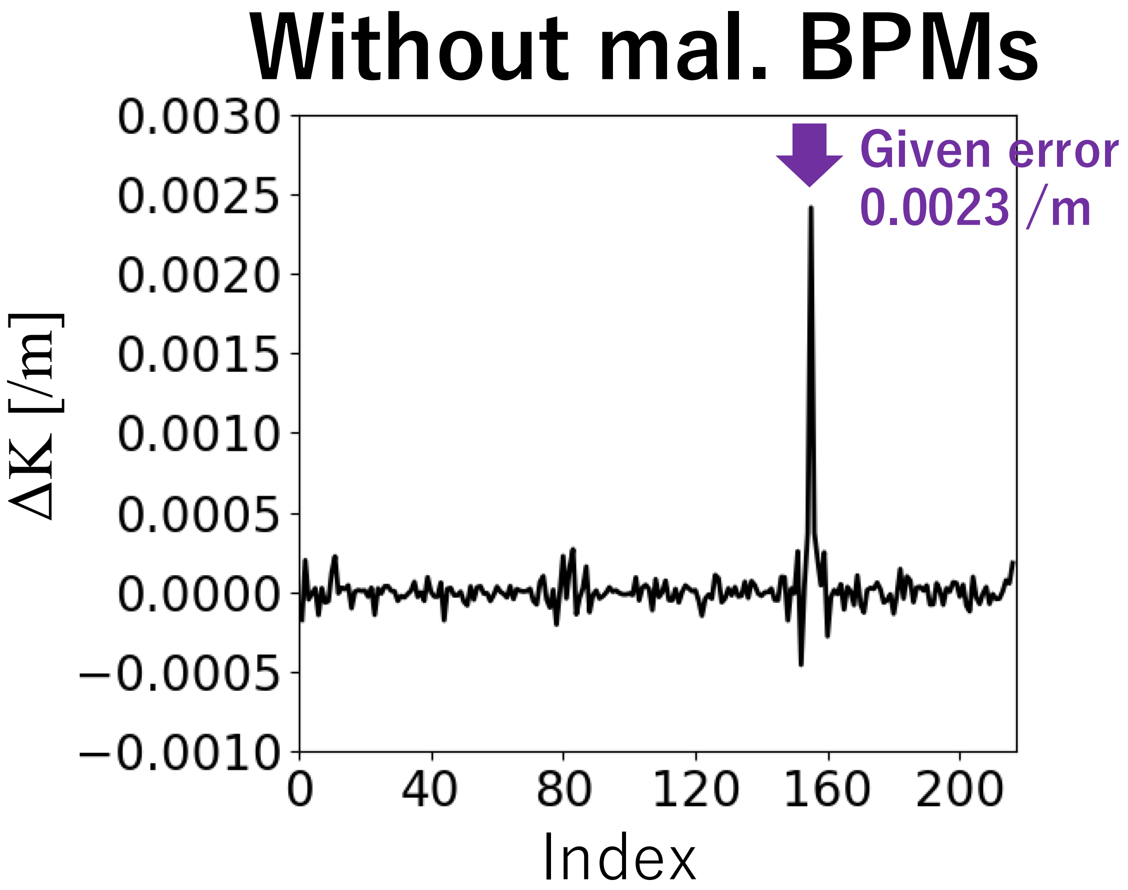
Recently, many BPMs in MR exhibit unreliable readings due to the aging of the BPM circuit. Upgrade of the system is underway.

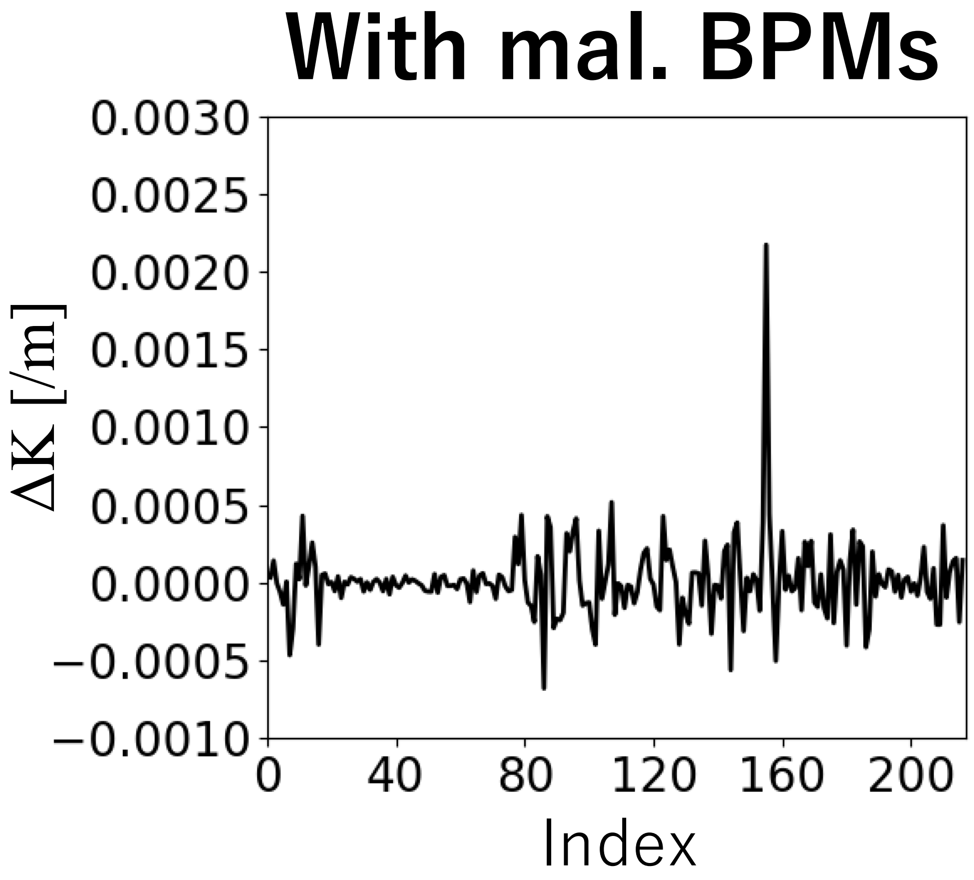
Ones with red points are determined to be malfunctioning.

We must observe <100 um order orbit deviation, but we have no method to distinguish all the other BPMs with "reliable" readings are in fact reliable at this accuracy.
→ Robustness is necessary.

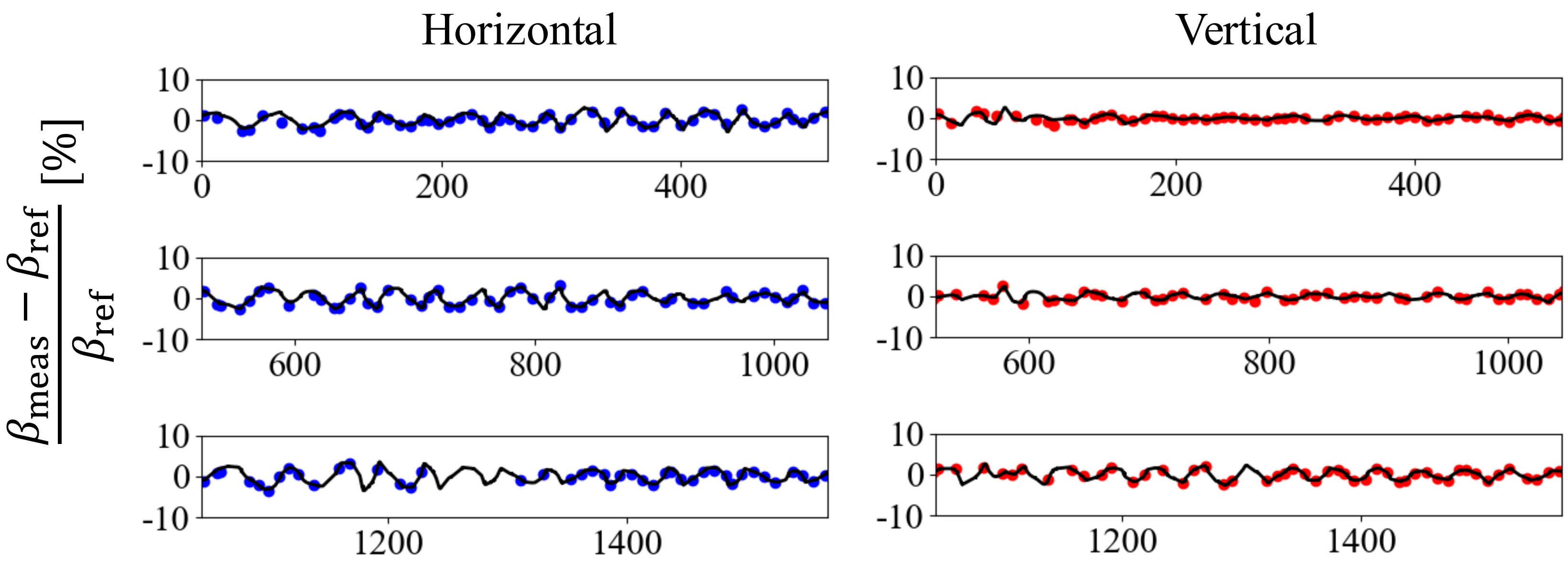


1. We intentionally gave significant quadrupole field errors at one location of the ring.
2. For benchmark, we considered specifying its location using QCPLM.
3. Analysis is usually conducted excluding malfunctioning BPMs beforehand.
4. This time, we conducted same analysis without excluding malfunctioning BPMs, using wrong BPM positions.





Betatron functions and quad. errors



Lines :

Calculated from Δ K/K deduced from QCPLM using SAD.

Scatter :

Direct evaluation by nonlinear fitting ORM considering beta, phase, and tune as free parameters.

A linearized model is enough to evaluate quadrupole field errors.

Mode selection

We can collect the modes corresponding to the quad errors.

SVD: $A = UDV^T = \sigma_1 \overrightarrow{u_1}\overrightarrow{v_1}^T + \sigma_2 \overrightarrow{u_2}\overrightarrow{v_2}^T + \sigma_3 \overrightarrow{u_3}\overrightarrow{v_3}^T + \cdots$

$U = (\overrightarrow{u_1} \quad \overrightarrow{u_2} \quad \cdots \quad \overrightarrow{u_r})$

$V = (\overrightarrow{v_1} \quad \overrightarrow{v_2} \quad \cdots \quad \overrightarrow{v_r})$

$V^T V = I_r,\ U^T U = I_r$

$D = \mathrm{diag}(\sigma_1, \sigma_2, \ldots, \sigma_r)$

σ_j are SVs ($\sigma_j > \sigma_{j+1} > 0$)

r is the rank of R.

$A\,\overrightarrow{\Delta K} = \overrightarrow{x_{COD}}$

measurement errors

$\overrightarrow{x_{COD}}^{(meas)} = \alpha_1 \overrightarrow{u_1} + \alpha_2 \overrightarrow{u_2} + \alpha_3 \overrightarrow{u_3} + \cdots + \alpha_r \overrightarrow{u_r} + \vec{\boldsymbol{\varepsilon}}$

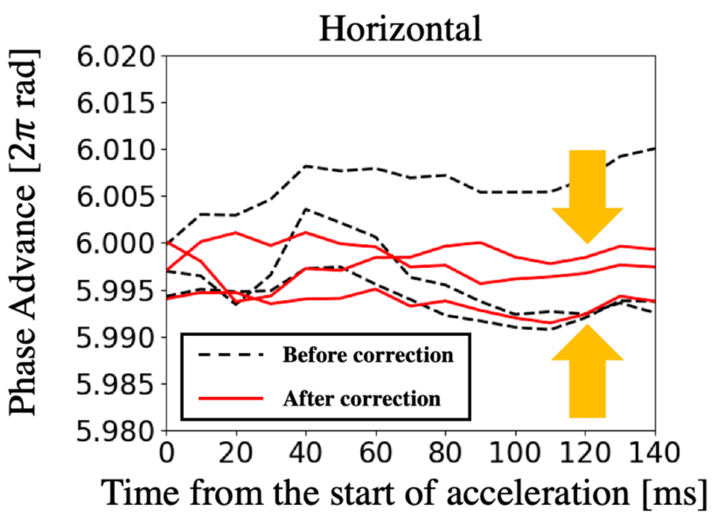
$\overrightarrow{u_j} \cdot \vec{\varepsilon} \sim 0$ is small if we make the dimension of $\overrightarrow{x_{COD}}$ large enough.

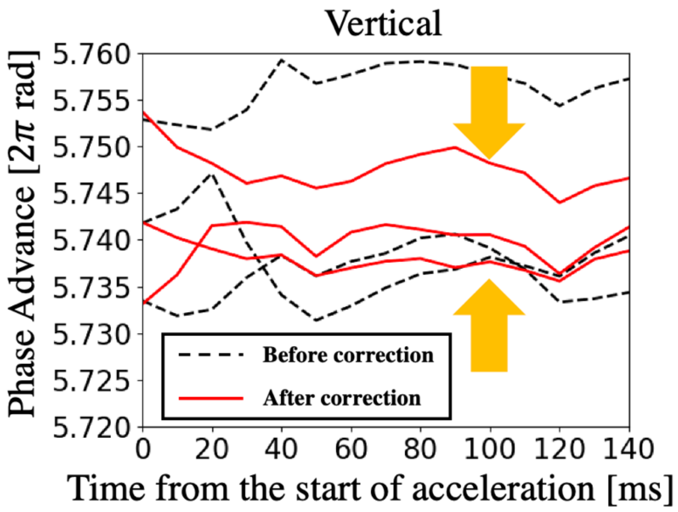
$\alpha_j \approx \overrightarrow{u_j} \cdot \overrightarrow{x_{COD}}^{(meas)}$

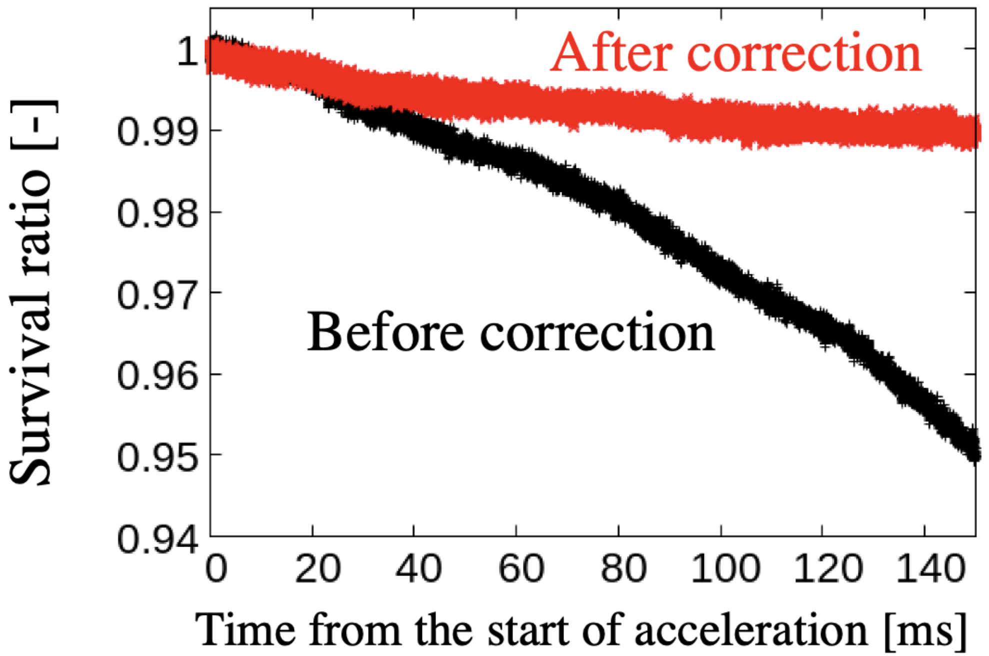
Mode selection $\overrightarrow{\Delta K} = \sum_j \overrightarrow{v_j} \left(\frac{\overrightarrow{u_j} \cdot \overrightarrow{x_{COD}}}{\sigma_j} \right)$

Phase advance

Optics' symmetry

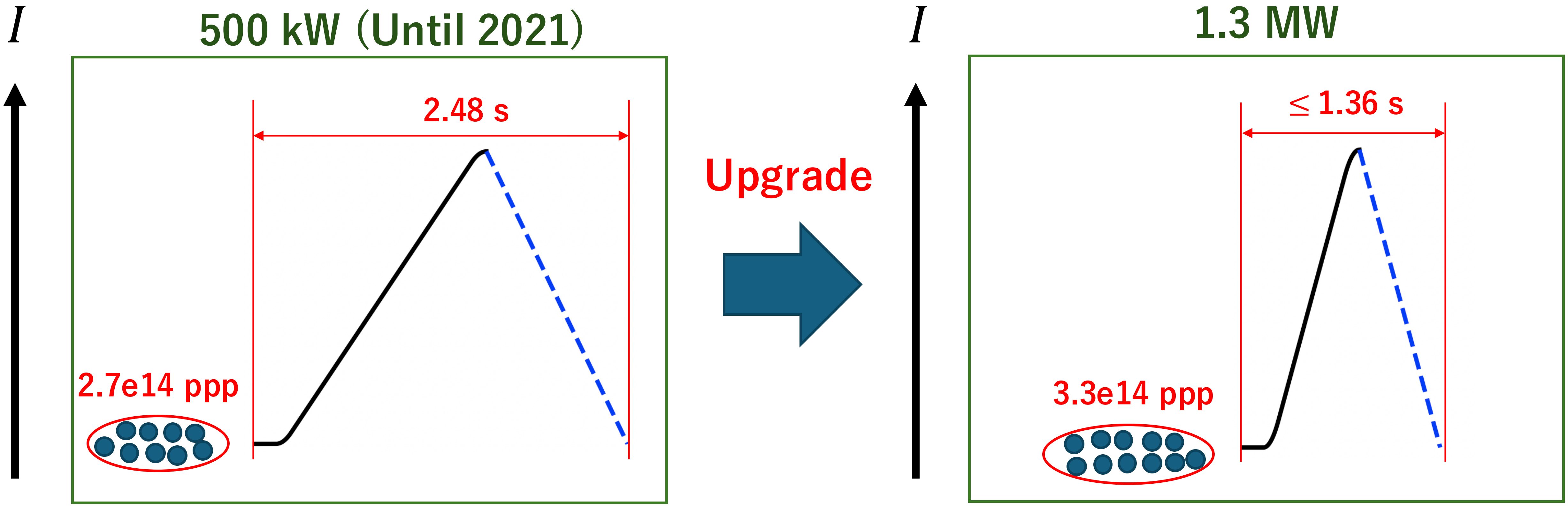






2 bunches 4.4×10^{12} ppp

1.3 MW upgrade of J-PARC MR

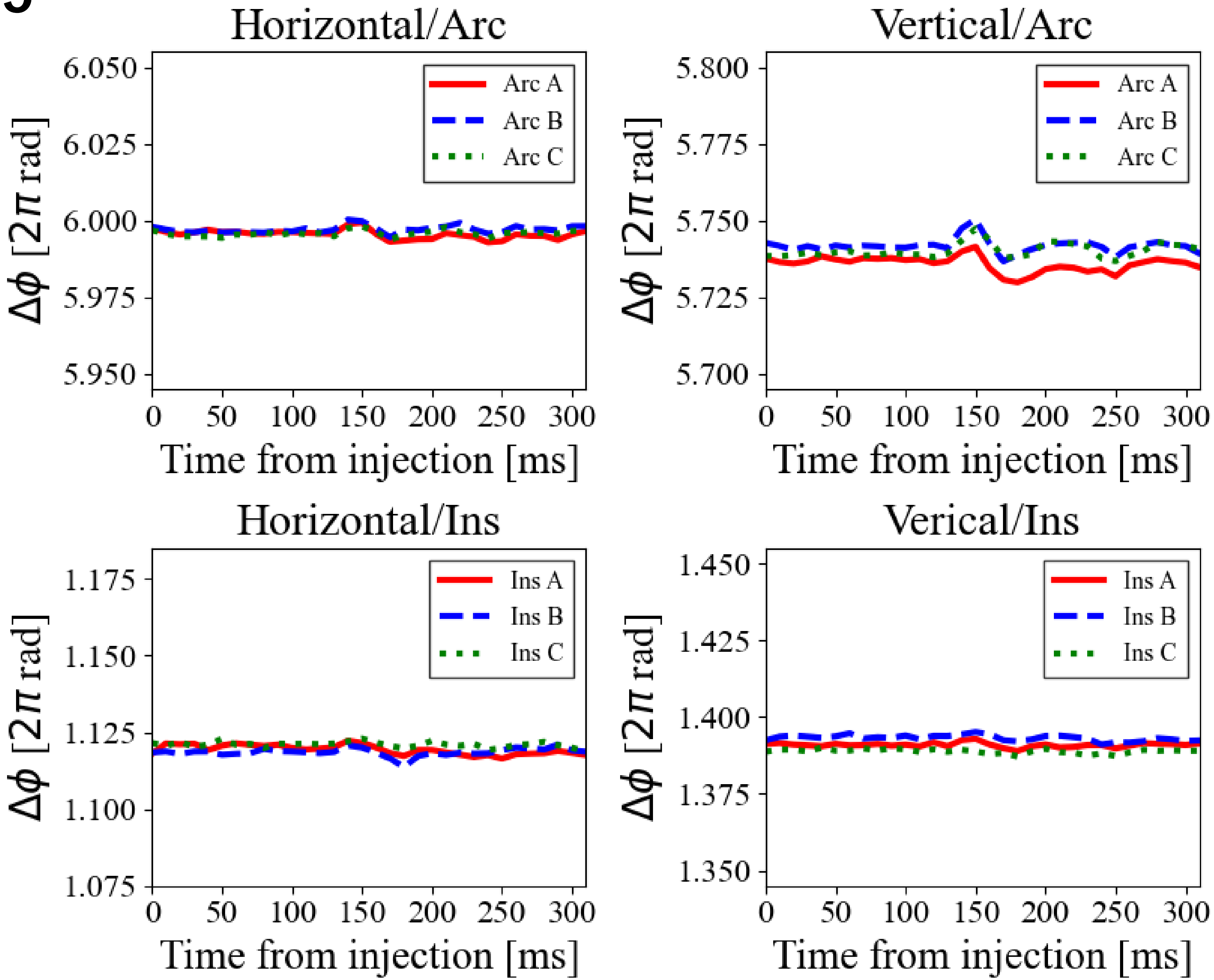


Shortening repetition period and Increasing number of protons

KEYs till 2/15

Optics
BEFORE 2/16
Re-correction

NU 650 kW
Loss 650+450+100 W



T. Asami
2/15 meas.

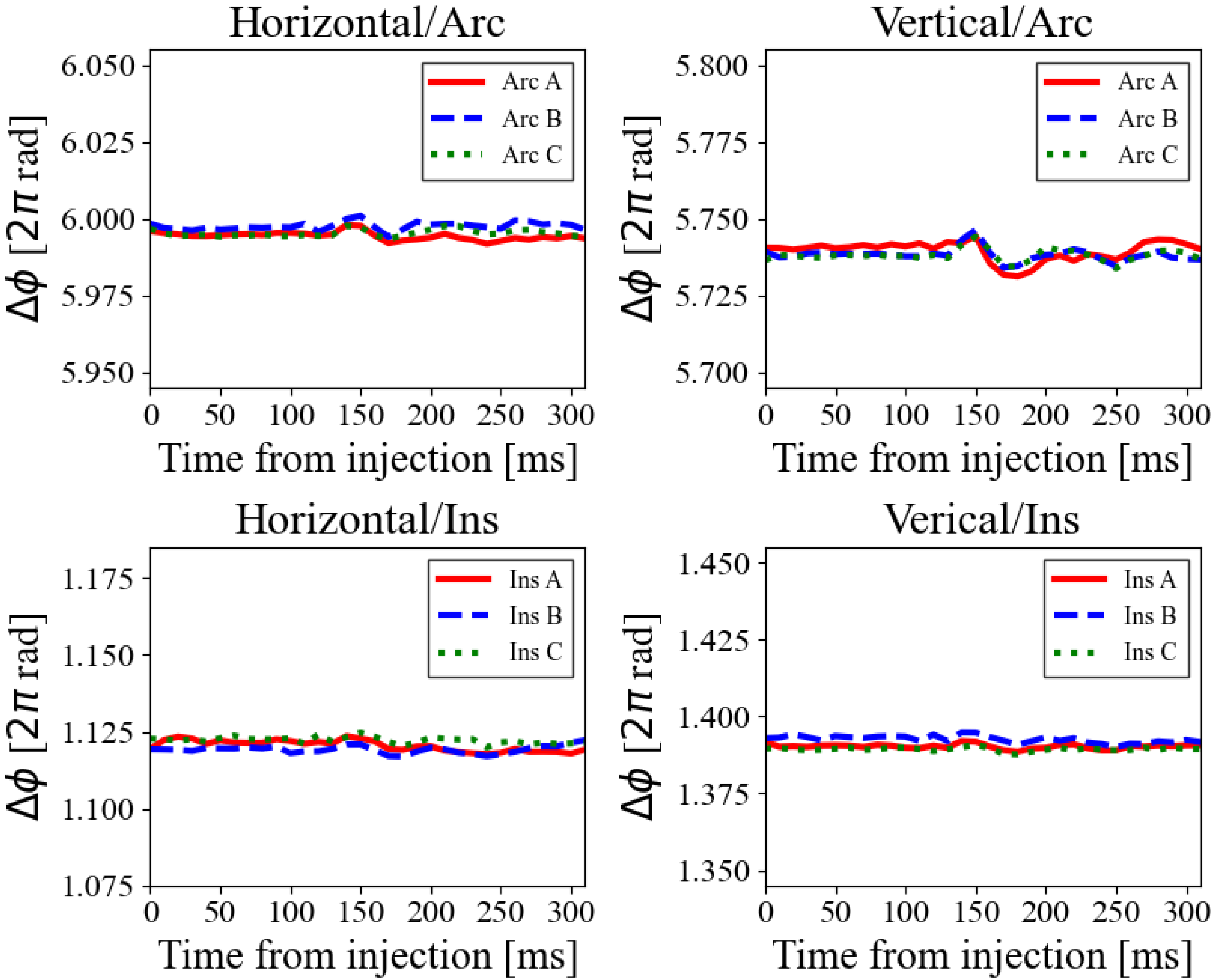
Courtesy Y. Sato

KEY 1, 2

Optics
AFTER 2/16
Re-correction

NU 655 kW
Loss 370+300+100 W

NU 715 kW
Loss 500+400+150 W



T. Asami
2/26 meas.

Courtesy Y. Sato

T. Yasui, Y. Sato

KEY 3

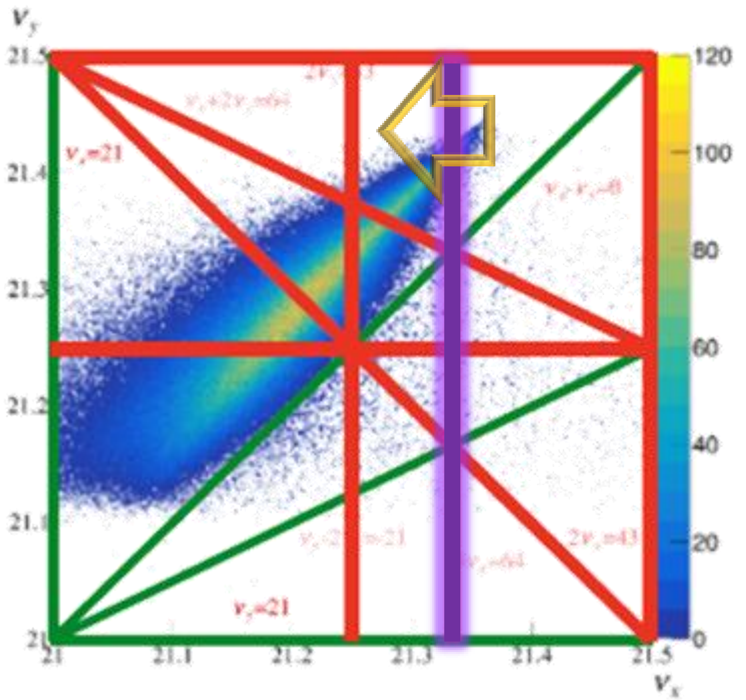
Optimize
Acc tune tracking
on 2/22

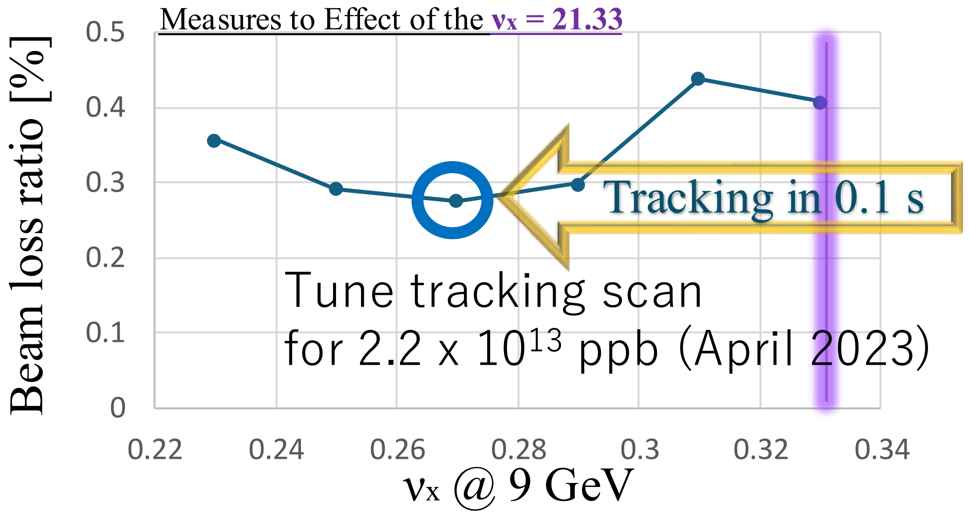
NU 648 kW
Loss 270+300+100 W

NU 707 kW
Loss 320+370+100 W

1741831

- **Opt. Tune tracking in ACC time: quick cross 3+0 line in 30 ms**
  ➔ Less Mid-Acc loss





ν_x = 21.27 is more stable for broken symmetry in horizontal

FX best operation point is (ν_x, ν_y) = ~(21.35, 21.41) at 3 GeV.
The **ν_x = 21.33** is corrected with trim-sextupoles below 6 GeV, but the resonance effect is still severe during accelration.

April 2023 to Feb 22, 2024:

ν_x = 21.35@ < 4 GeV => 21.27@9 GeV

Feb 22, 2024 ~:

ν_x = 21.35@ < 3.8 GeV => 21.27@5 GeV

Courtesy Y. Sato

Importance of optics tuning

Since the right-hand side is not a multiple of 3, resonance does not ideally occur.

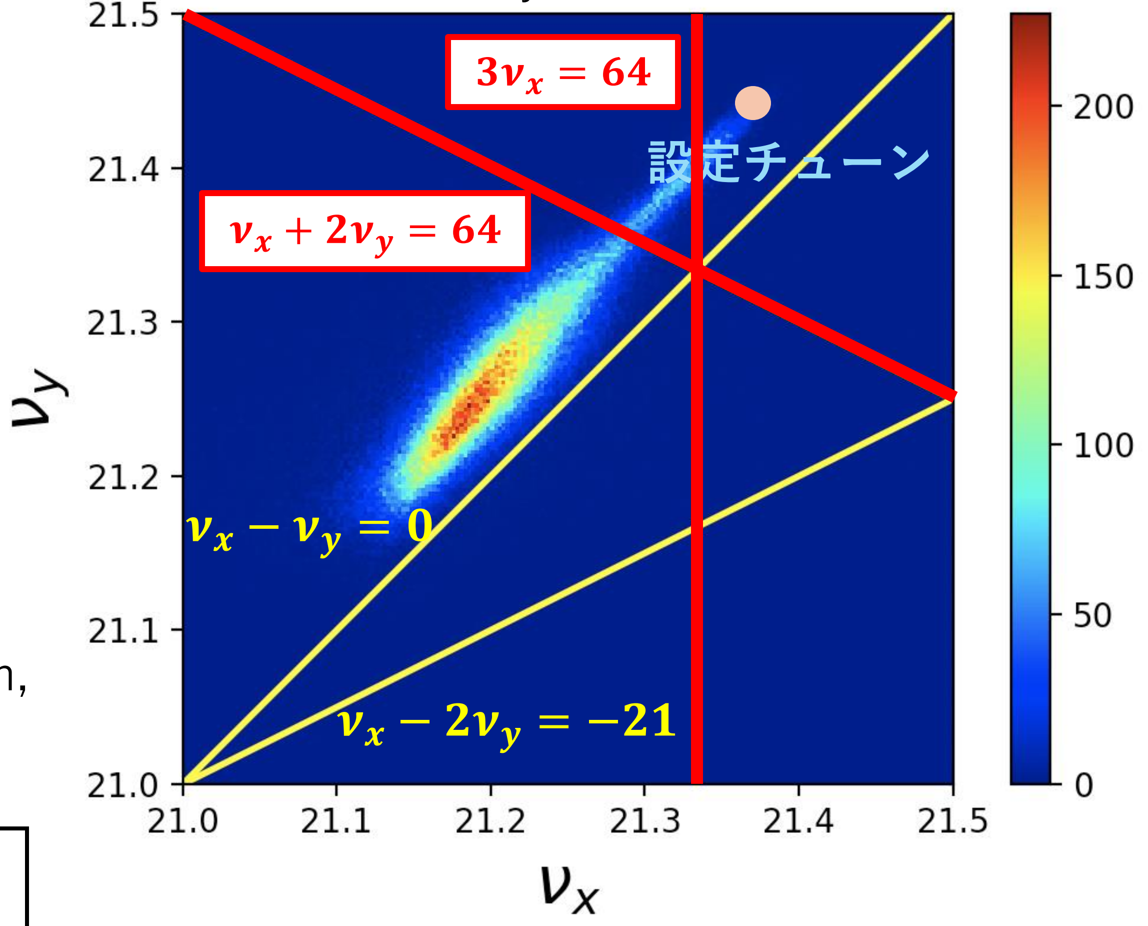
$m\nu_x + n\nu_y = Nl$ N: **Optics' symmetry**

Betatron resonance

MR is designed to be N=3

e.g., $\beta(s) = \beta\left(s + \frac{C}{3}\right)$ C: **circumference**

- If there exist field errors without three-fold symmetry, numerous resonance conditions appear for arbitrary N.
- Due to space-charge effects, the tune has a distribution, making it difficult to avoid all resonance conditions.



* Tracking simulation by "GPUSim" (4.0e13 ppb)

GPUSim: Y. Kurimoto, doi:10.1109/TNS.2021.3084214

The main cause of beam loss is betatron resonances.

→ To mitigate them, pursuing optical symmetry is crucial.

→ **Therefore, precise optics tuning are indispensable.**