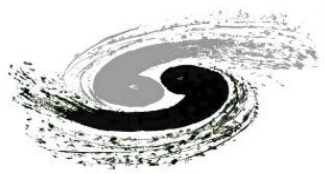


Recent progress in high-intensity beam commissioning in CSNS RCS

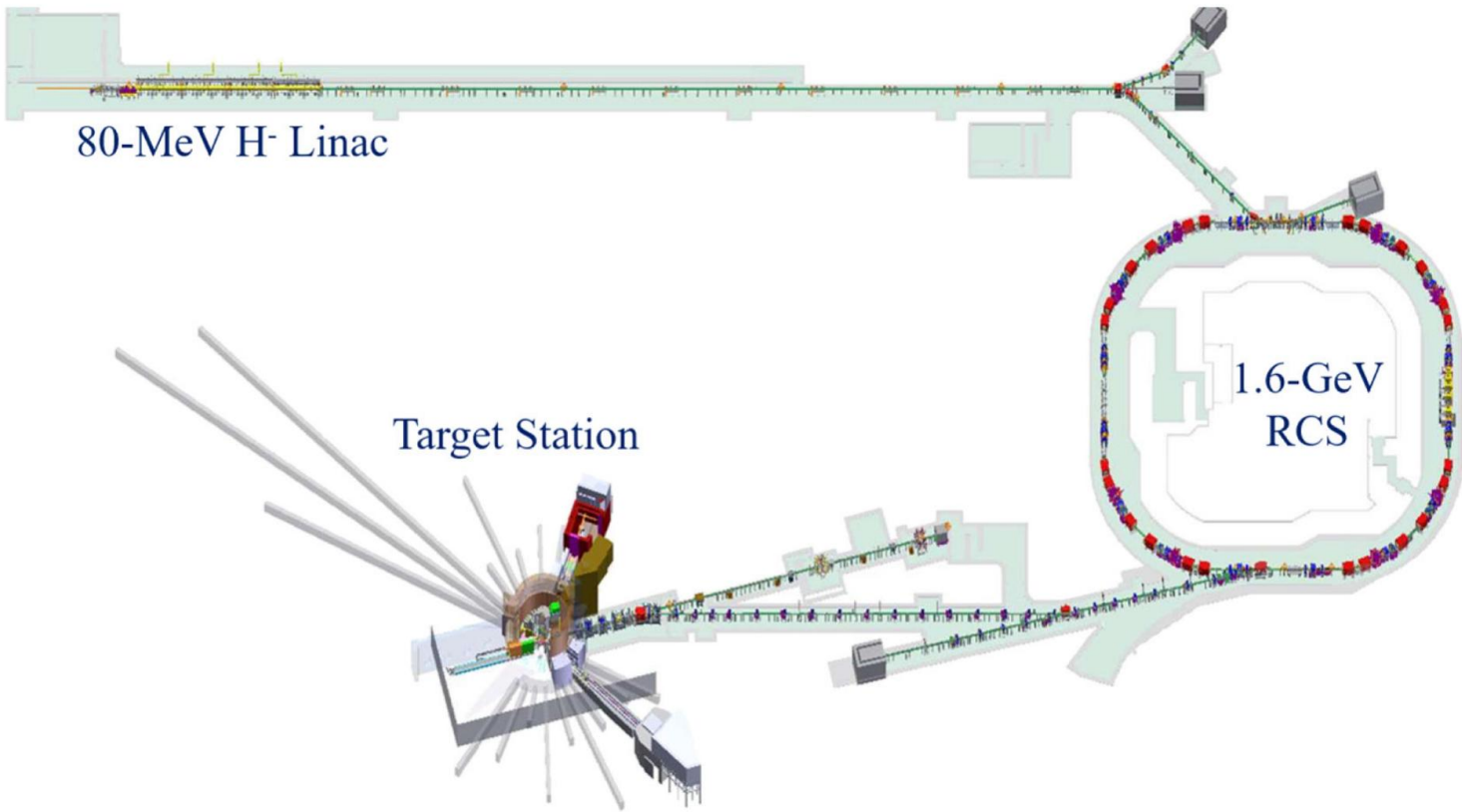
Yaoshuo Yuan
on behalf of AP group

OUTLINE

1. Introduction
2. Review of preparations
3. Beam commissioning below 100kW
4. Beam commissioning at 100 kW
5. Beam commissioning above 100 kW



Introduction



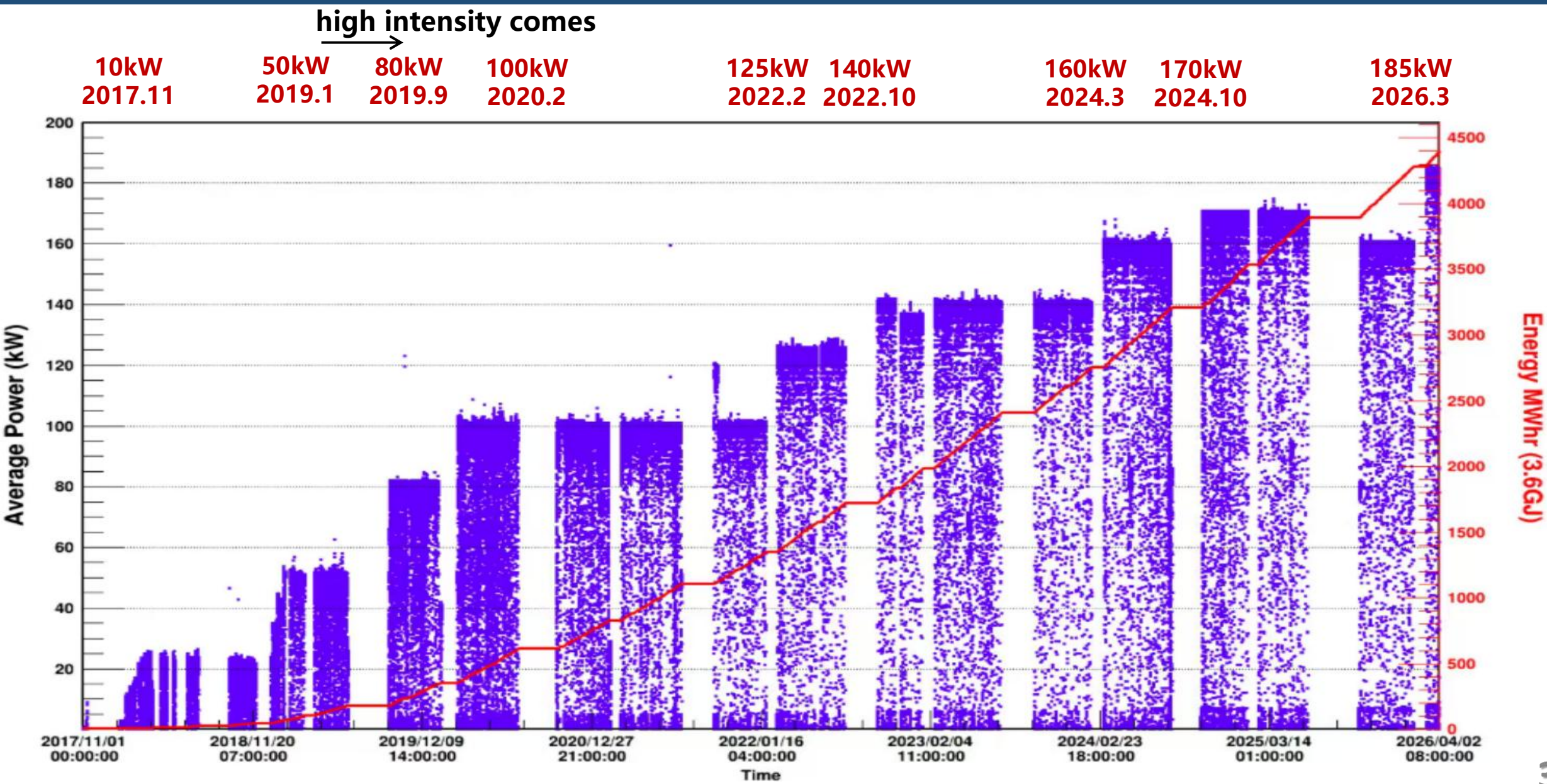
Layout of the CSNS RCS

Parameters	Units	Values
Circumference	m	227.92
Repetition Rate	Hz	25
Average current	μ A	62.5
Inj. Energy	GeV	0.08
Ext. Energy	GeV	1.6
Beam Power	kW	100
Dipole	-	24
Quadrupole	-	48
Sextupole		16
Octupole		4
Corrector	-	34
BPM	-	32
Nomianl Tunes (H/V)	-	4.86/4.78

Introduction

Year. Month	Main achievement	Description
2016	Beam commissioning starts	
2017.07	$E_{inj} = 61 \text{ MeV}$ $E_{ext} = 1.6 \text{ GeV}$	
2018.01	$E_{inj} = 80 \text{ MeV}$ $E_{ext} = 1.6 \text{ GeV}$	On-line sliced model
2019.01	Beam power 50 kW	Painting Inj.
2020.02	Beam power 100 kW	Designed value
2023	Beam power 140 kW	Trim quad (QT); one double rf cavity
2024	Beam power 170 kW	Two dual rf cavities
2026.3	Beam Power 185 kW	Parameters optimization
2026	Beam Power 200 kW (planning)	(4.81,4.87) to (4.42, 5.32)

Introduction



-
- Introduction
 - **Review of preparations**
 - Beam commissioning below 100kW
 - Beam commissioning at 100 kW
 - Beam commissioning above 100 kW

Preparations: Dipole and quadrupole sorting

- Required beam loss < **1 Watt/m**
- Expected magnetic field errors < **10^{-3}**
- Sorting method
 - Dipole: closed orbit distortion(COD)
 - Quadrupole: beta-beating

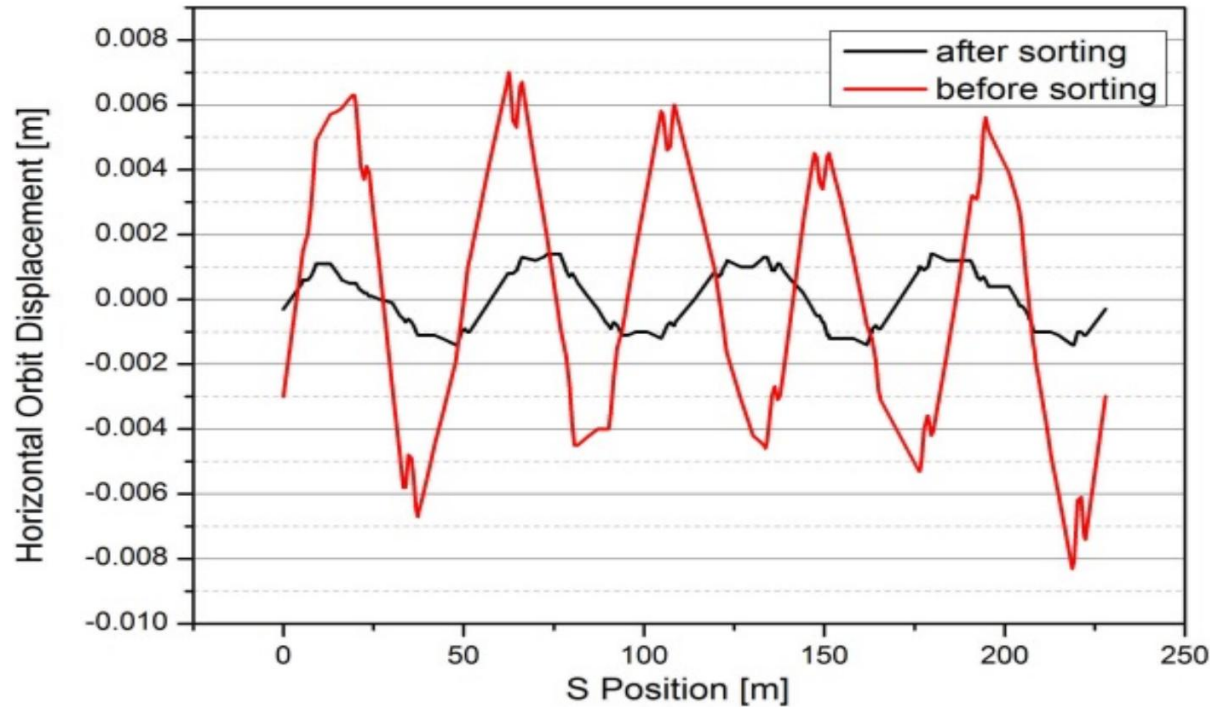
[1] Y.An, S.Xu, S.Wang, L.Huang, Magnet sorting of the CSNS/RCS dipoles and quadrupoles, IPAC15

[2] Y.An, S.Xu, S.Wang, Y.Li, J.Peng, H.Ji, Study of magnets sorting of the CSNS/RCS dipoles and quadrupoles HB2016

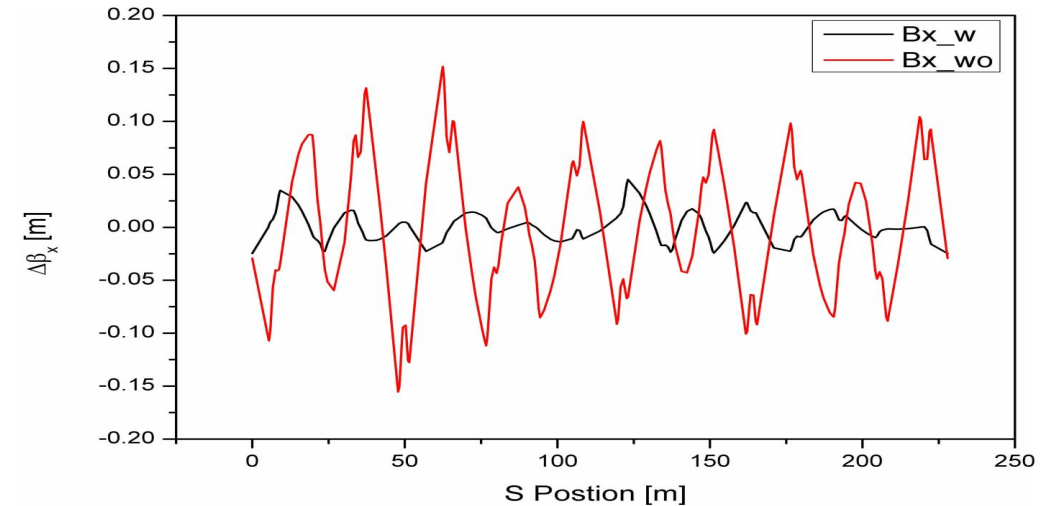
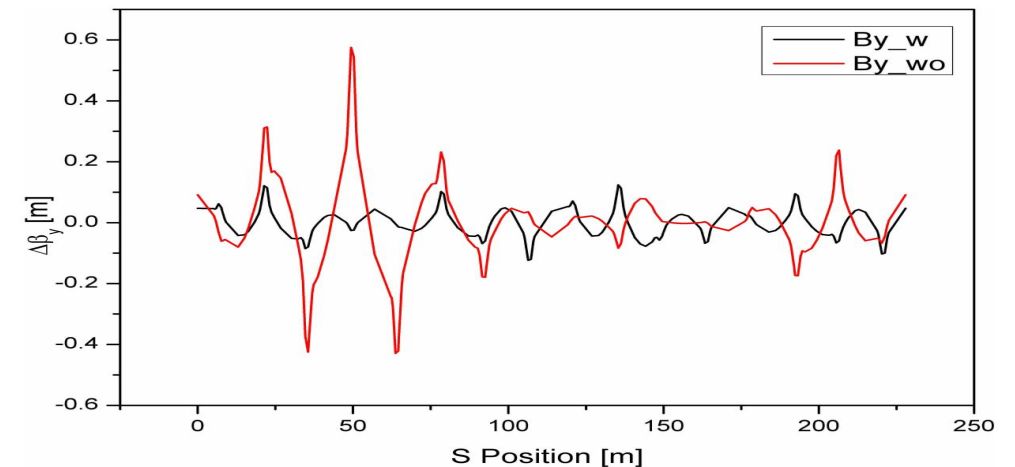
Preparations: Dipole and quadrupole sorting

➤ Sorting optimization results:

- COD decreased from 8 to 1.5 mm.

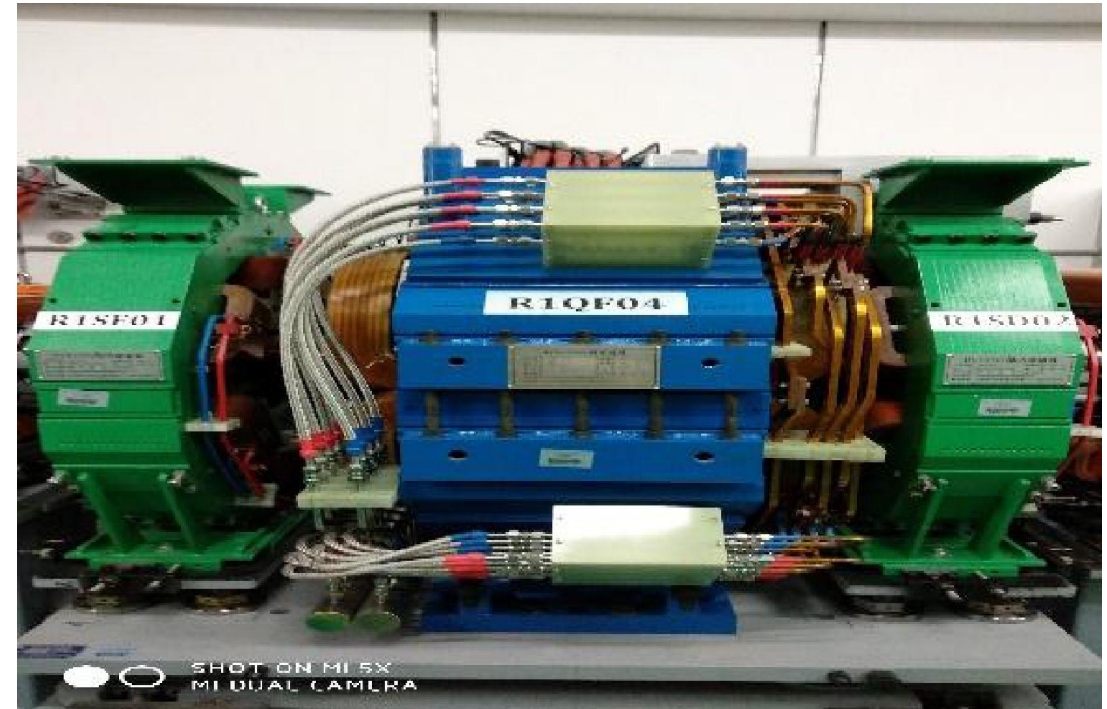


- Beta-beating from 15% to <5%



Preparations: Sliced model for magnets

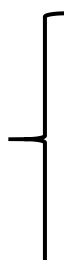
- The magnet elements are **tightly arranged** in CSNS RCS
 - ➔ **field interference effect**
- Magnets **with large aperture** due to large space charge
 - ➔ **fringe field effect**
- 2.3% reduction in the integrated field strength of quads



[1] S.Y. Xu, et al., Commissioning status of CSNS/RCS, HB2018

[2] J. Chen, S. Xu, X. Lu, Y. An, Y. Li and S. Wang, Study on the fringe field and the field interference effects of quadrupoles in the rapid cycling synchrotron of the china spallation neutron source, NIM-A (2019)

Preparations: Sliced model for magnets

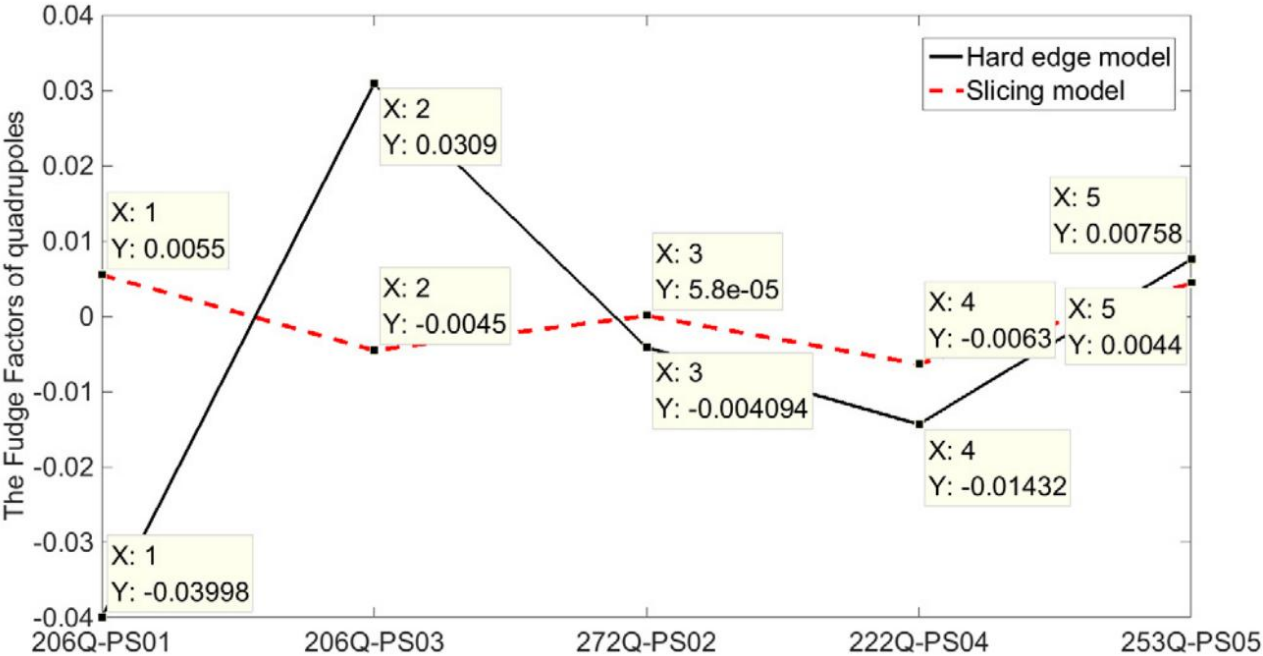
- A sliced model is established with 
 - edge focusing
 - fringe field interference

Quadrupole Type	Slice number
206Q	9
222Q	9
253Q	11
272Q	11

- Fringe field and the Field interference has been added to the online model OPEN XAL.

Preparations: Sliced model for magnets

- The fudge factor for
 - Hard edge model: ~4%
 - **Sliced model after re-matching <1%**



- Lattice is re-matched, the measured tunes is closer to design value

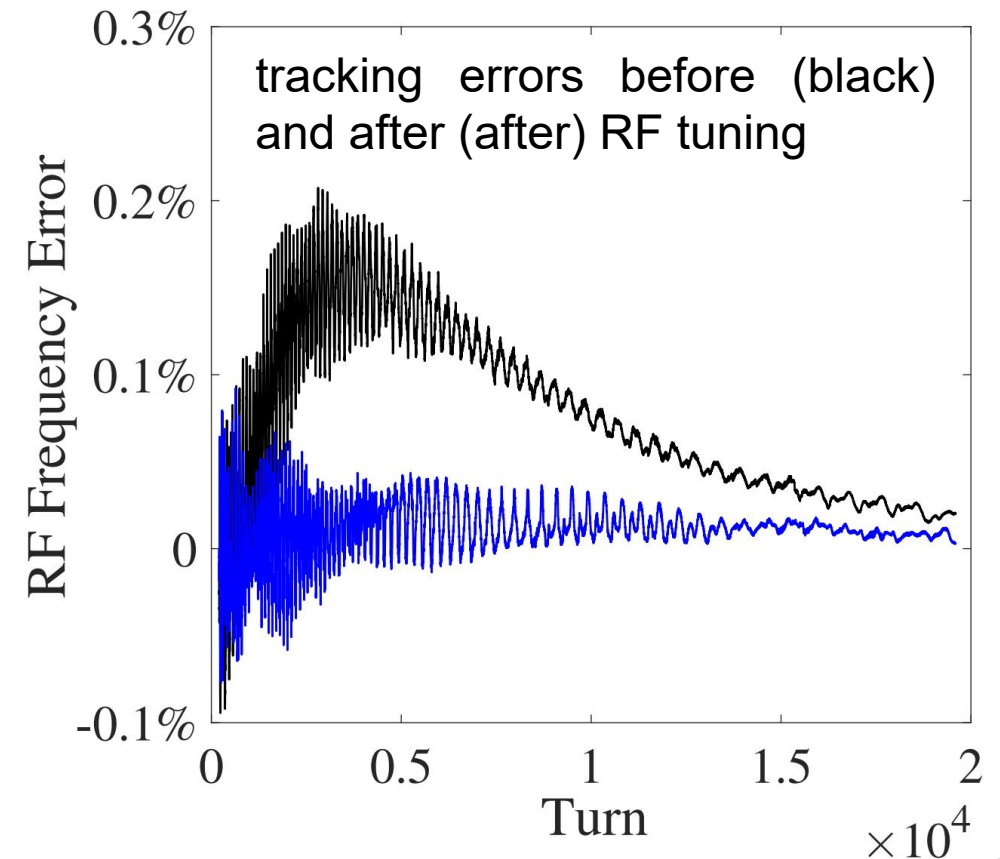
Description	Tune x	Tune y
Design model	4.86	4.78
Without fringe field in Openxal	4.946	4.979
With fringe field in OpenXAL	4.863	4.785
Measured Tune	4.857	4.779

- Introduction
 - Recap: Preparations
 - **Recap: Beam commissioning <100kW**
 - Beam commissioning at 100 kW
 - Beam commissioning >100 kW
- 
- RF system and magnets matching
 - Correction of dynamic magnetic error
 - COD correction
 - Beam optics correction

Beam commissioning with low intensity (<100 kW)

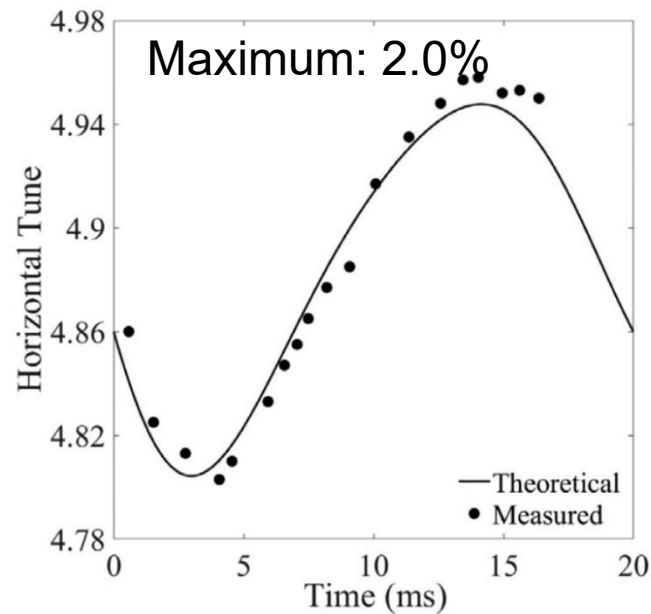
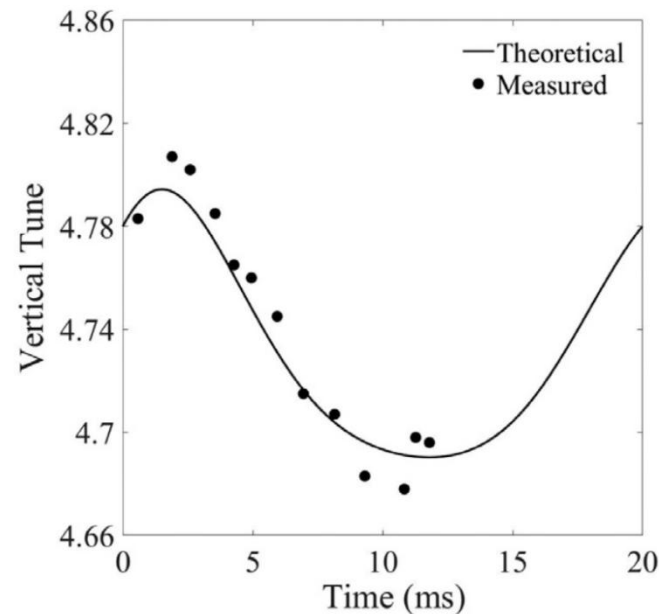
➤ Matching between magnets & RF system

- Mismatch can cause orbit deviation Δx in arc section $D_x \approx 1.7$ m
- Matching has been done by using 8 BPMs in the arc section
- Matching result: the average beam displacement at the 8 BPMs are almost zero

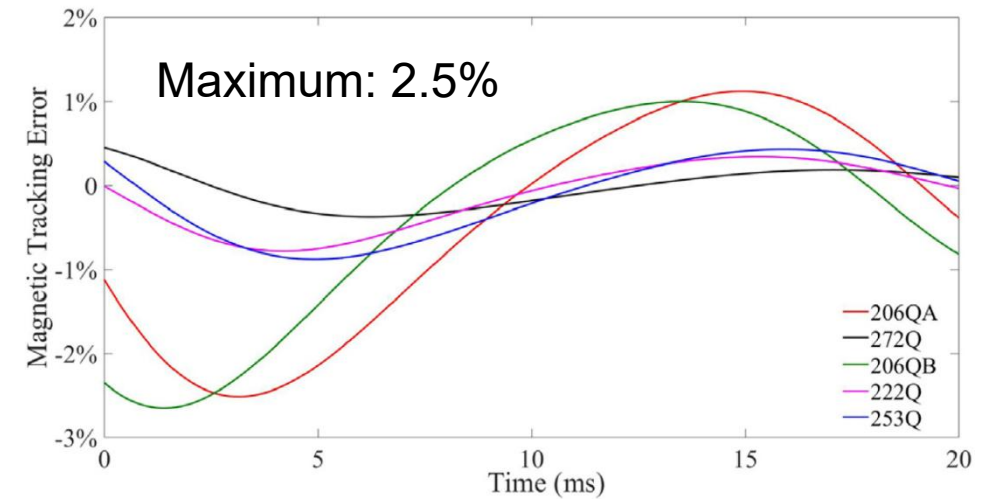


Beam commissioning with low intensity (<100 kW)

- Due to **eddy current effect** and **magnetic saturation**, different magnets have different magnetic tracking error during the 20-ms ramping period.
- Causing time-dependent tune shift and severe beam loss



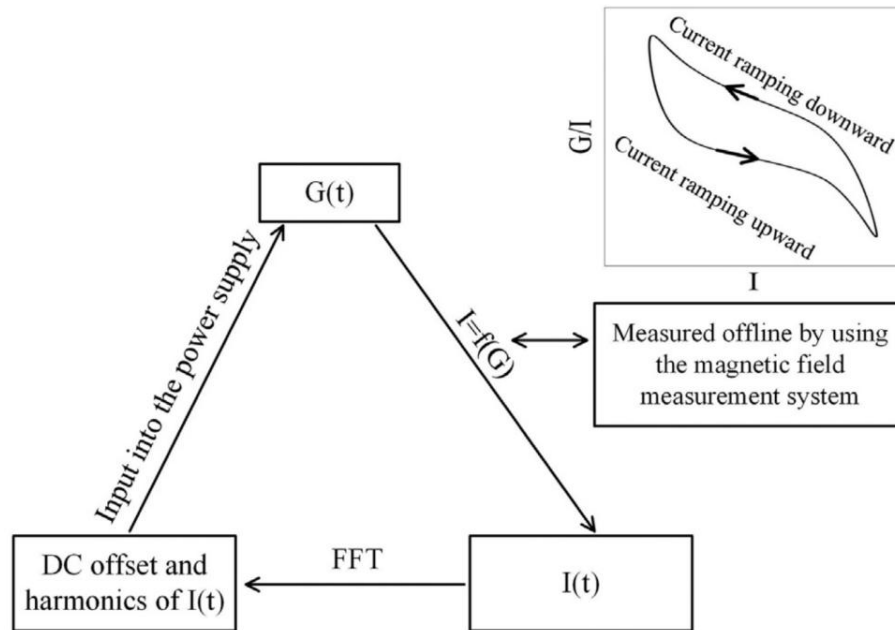
Tune variation induced by magnetic field tracking error



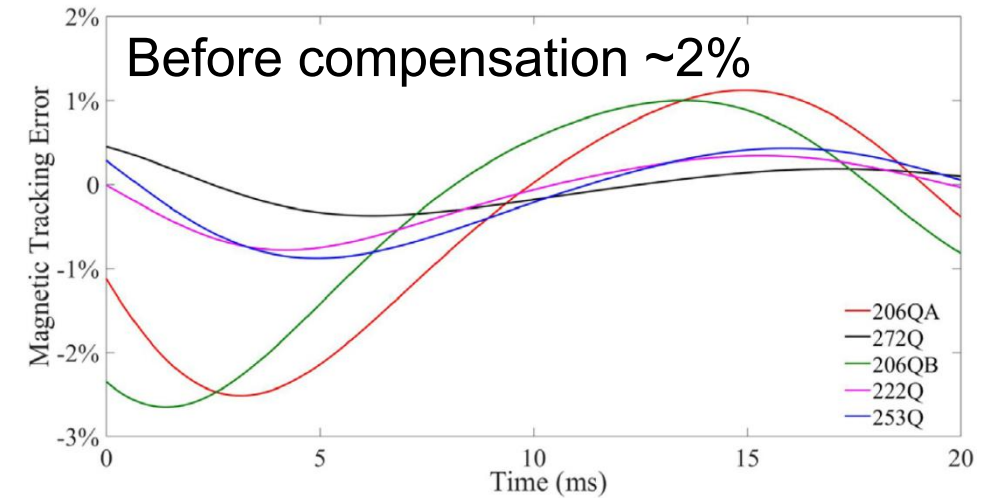
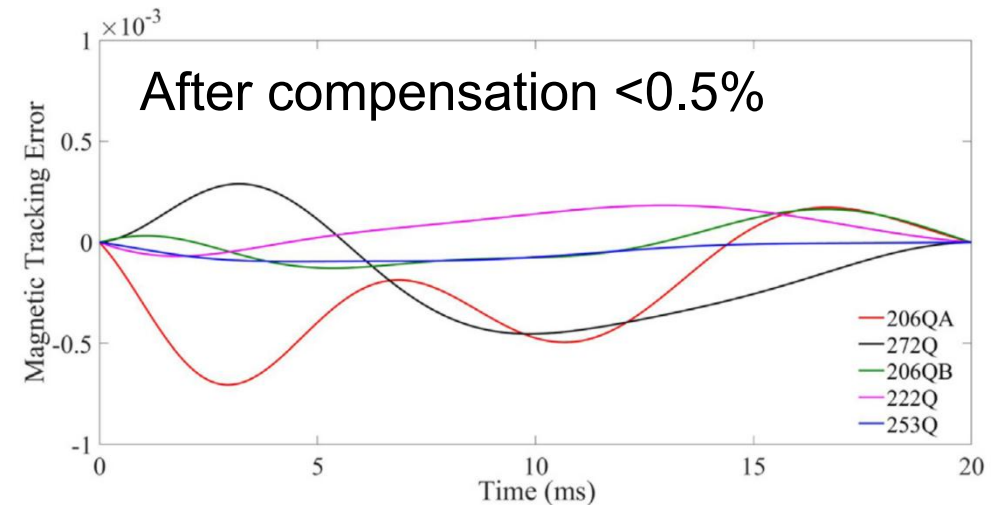
Maximum magnetic field variation

Beam commissioning with low intensity (<100 kW)

- Wave form compensation based on **transfer function** and FFT are performed
- Maximum tracking error from 2.5% reduced to 0.08%

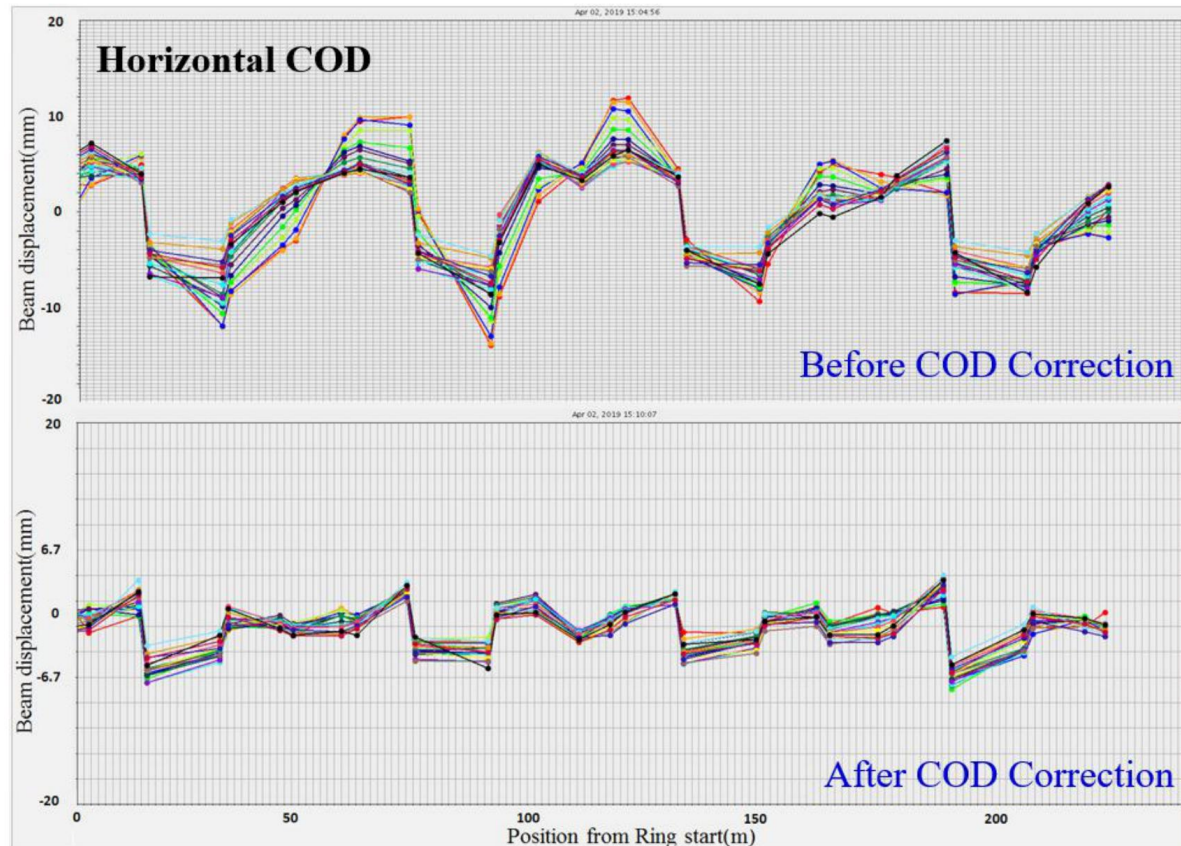
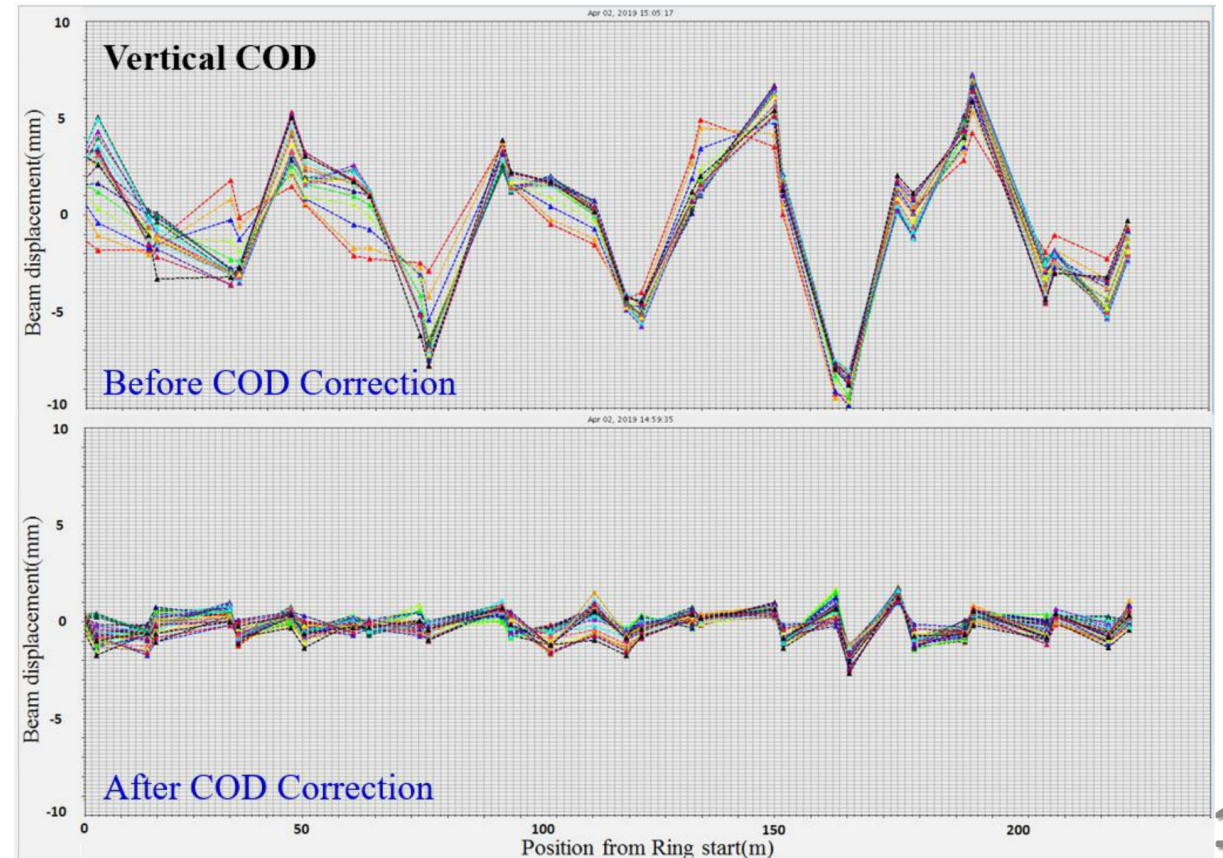


Flow process for waveform compensation



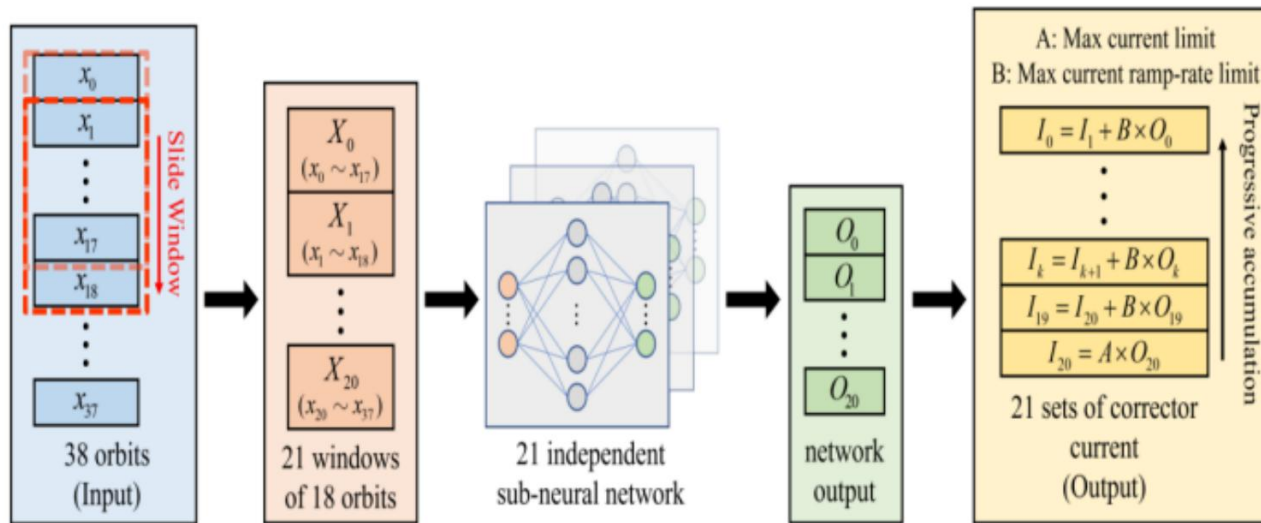
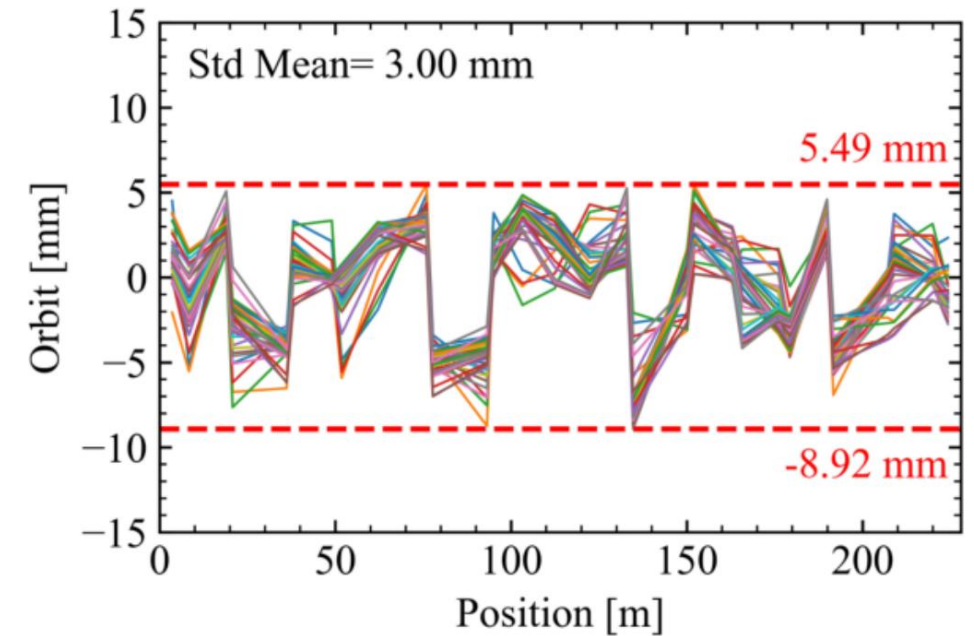
Beam commissioning with low intensity (<100 kW)

- COD has been largely corrected based on the two procedures above
- The synchronization between the BPM and the dipole corrector has been optimized.



Beam commissioning with low intensity (<100 kW)

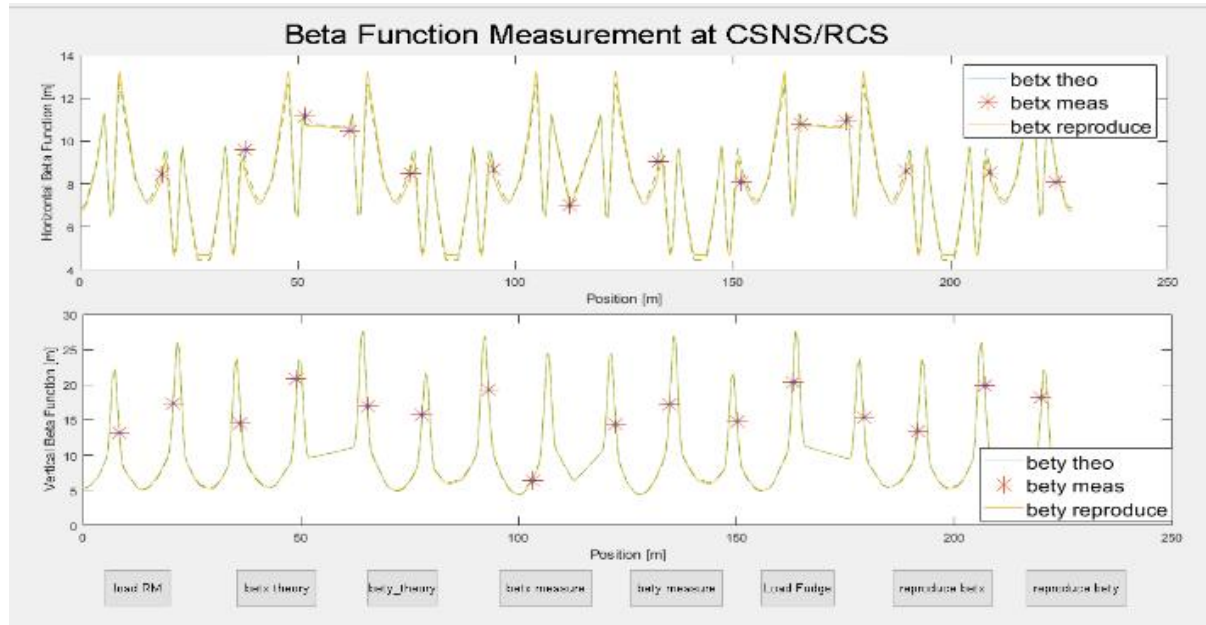
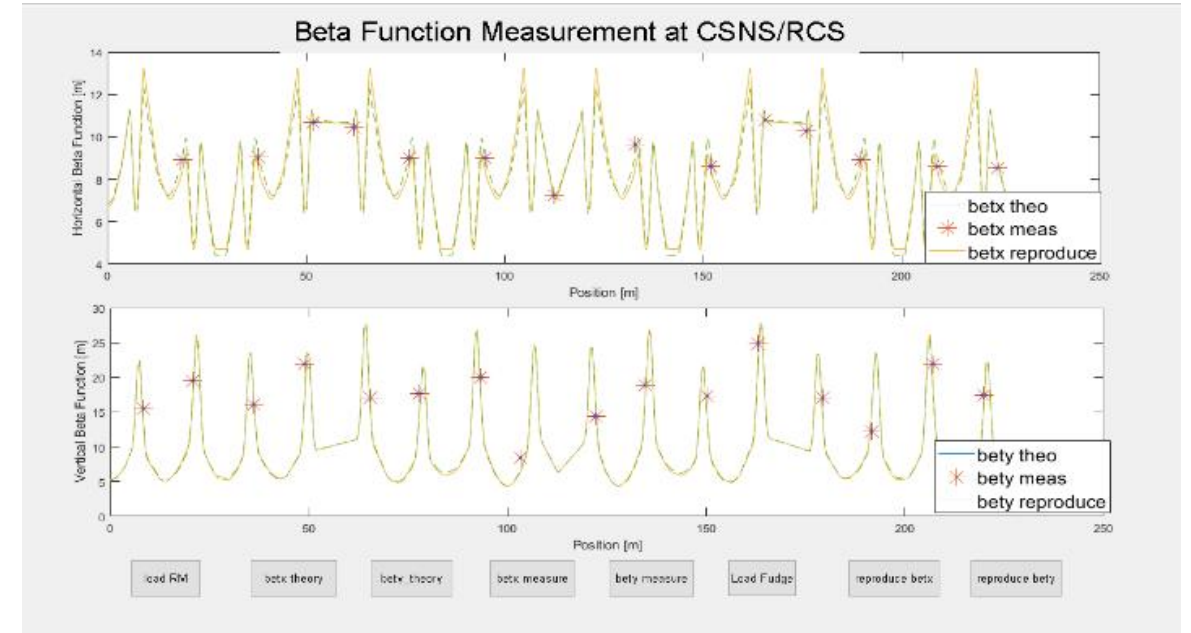
- Residual COD has been corrected via 34 steering magnets
- Vertical COD $\leq 3\text{mm}$; horizontal COD $\leq 5\text{mm}$
- Recently, machine-learning are adopted to COD correction.



- [1] Y. An, et al., Local Orbit Correction Application for CSNS/RCS High Intensity Commissioning, IPAC21
- [2] Y. Li, et al., Closed orbit and realignment in the CSNS RCS, IPAC26
- [3] X. Lu, et al., Machine learning-based orbit correction in the RCS of CSNS, IPAC26

Beam commissioning with low intensity (<100 kW)

- Beam optics correction are measured based on the orbit response matrix method.

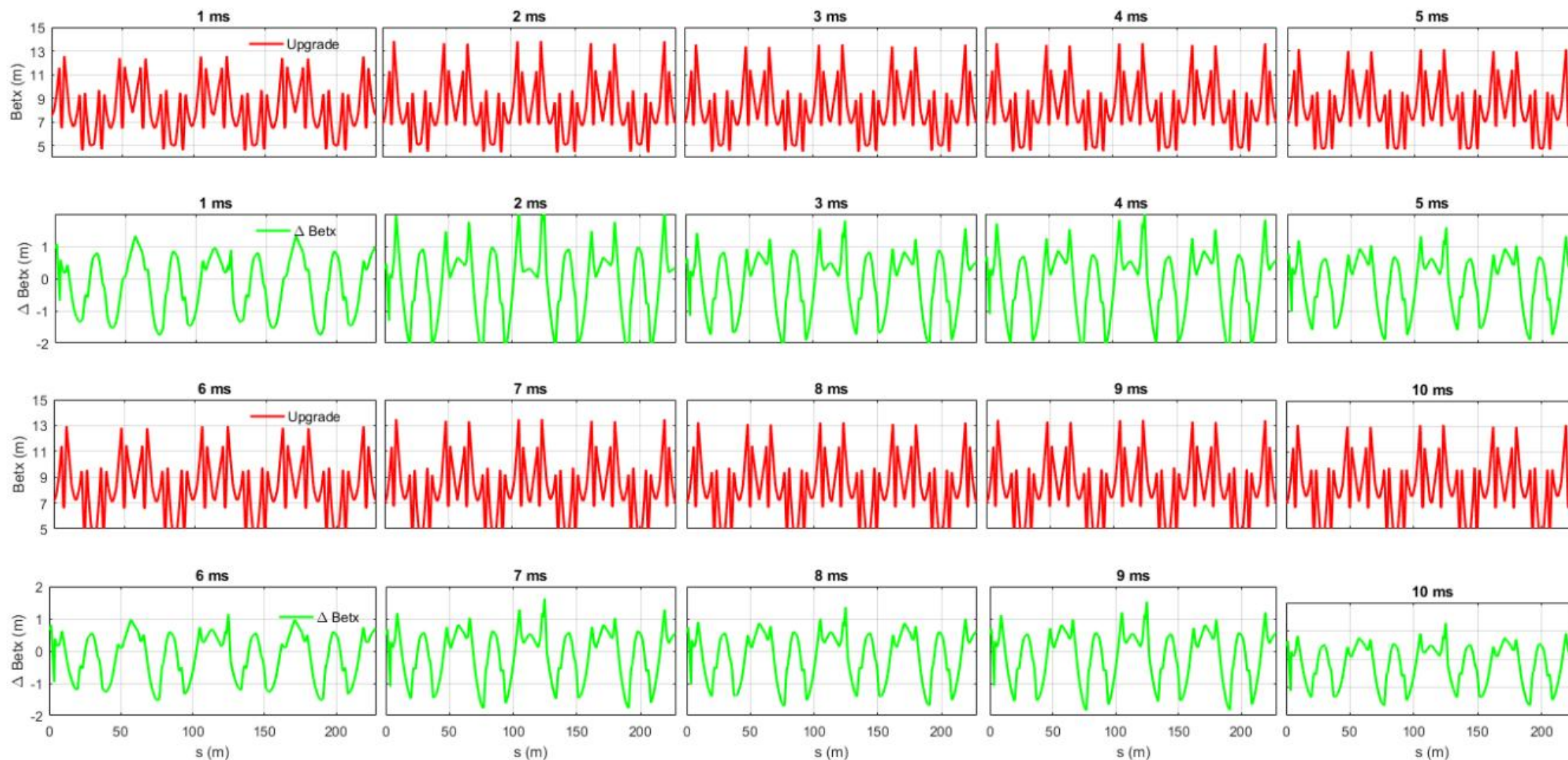


Correction of β -functions

[1] Y. An, et al., Optics correction techniques and their application in the CSNS/RCS, IPAC26

[2] Y. An, et al., Application of Orbit Response Matrix Method at CSNS/RCS, IPAC21

Beam commissioning with low intensity (<100 kW)



Reconstruction of the beta function before and after 2025 shutdown based on the LOCO model

- Introduction
- Recap: Preparations
- Beam commissioning <100kW
- **Beam commissioning with 100 kW**
- Beam commissioning >100 kW

Damping of the half-integer
resonance and impedance instability

Optimization of injection curve

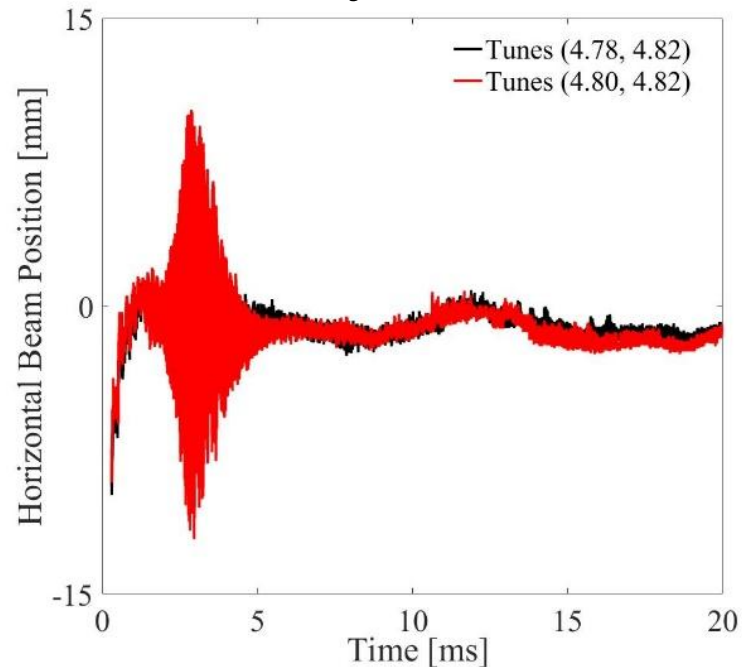
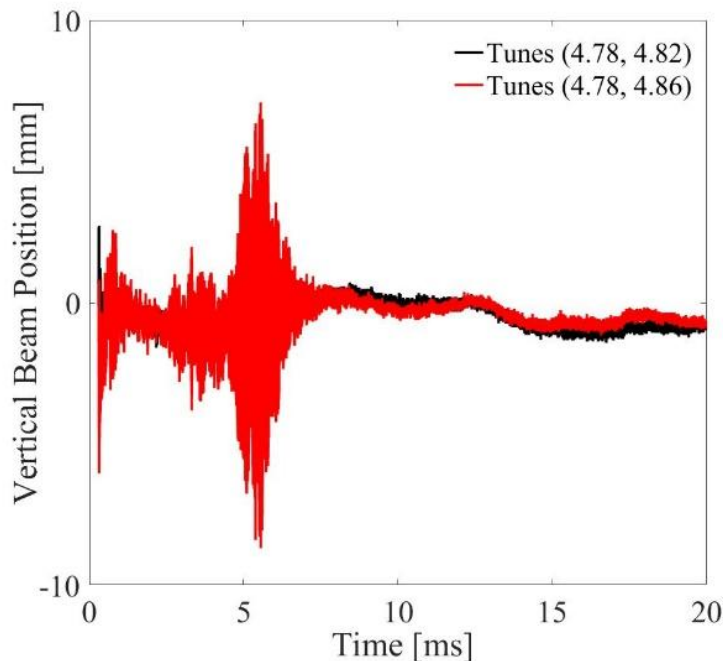
Tune optimization



Discussion on collimation system, tune optimization and beam loss control: see Shouyan Xu's talk on 02 Oct.

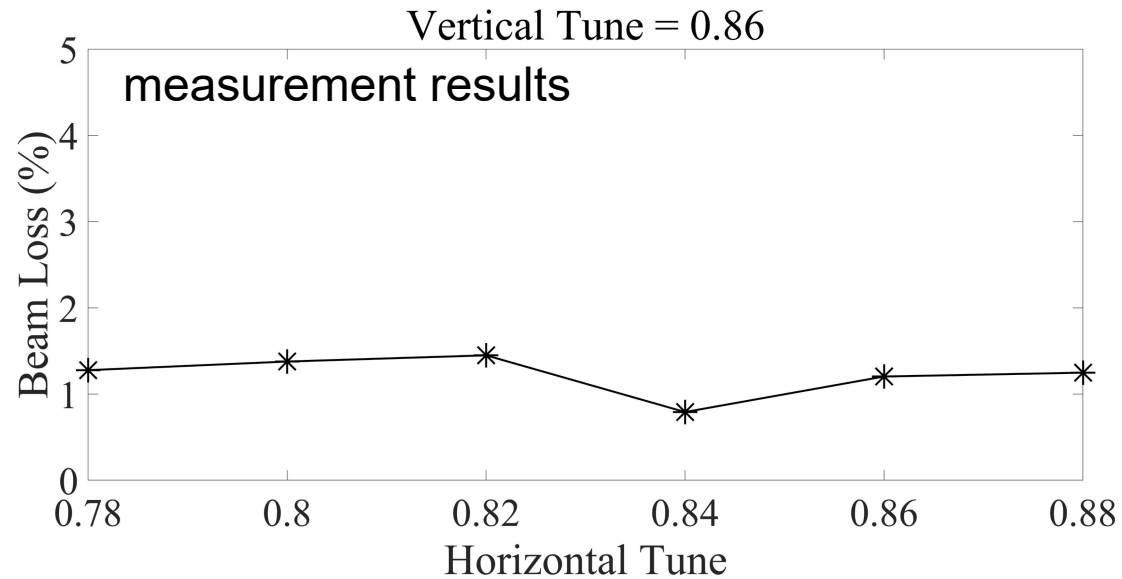
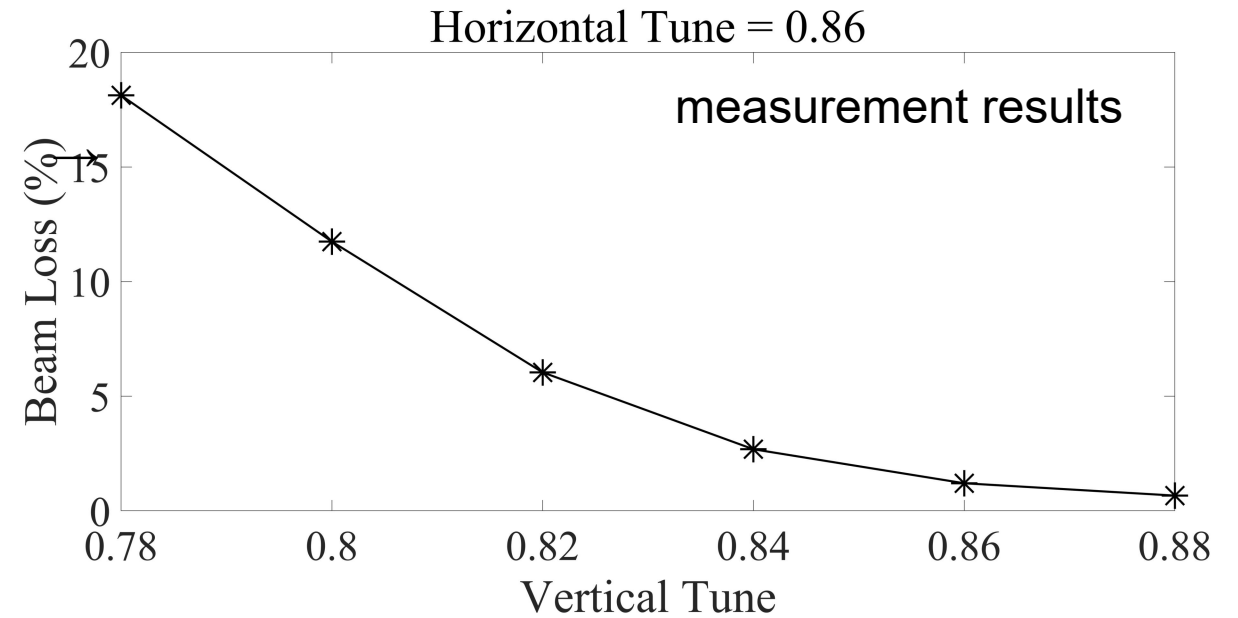
Beam commissioning with high intensity (100 kW)

- Beam instability has been observed during 50kW to 100kW beam commissioning with $Q_x > 4.80$ or $Q_y > 4.86$
- It depends on beam intensity, tune, and chromaticity
- It was recently confined as transverse coupled bunch instability
- The instability is more severe in the vertical plane



Beam commissioning with high intensity (100 kW)

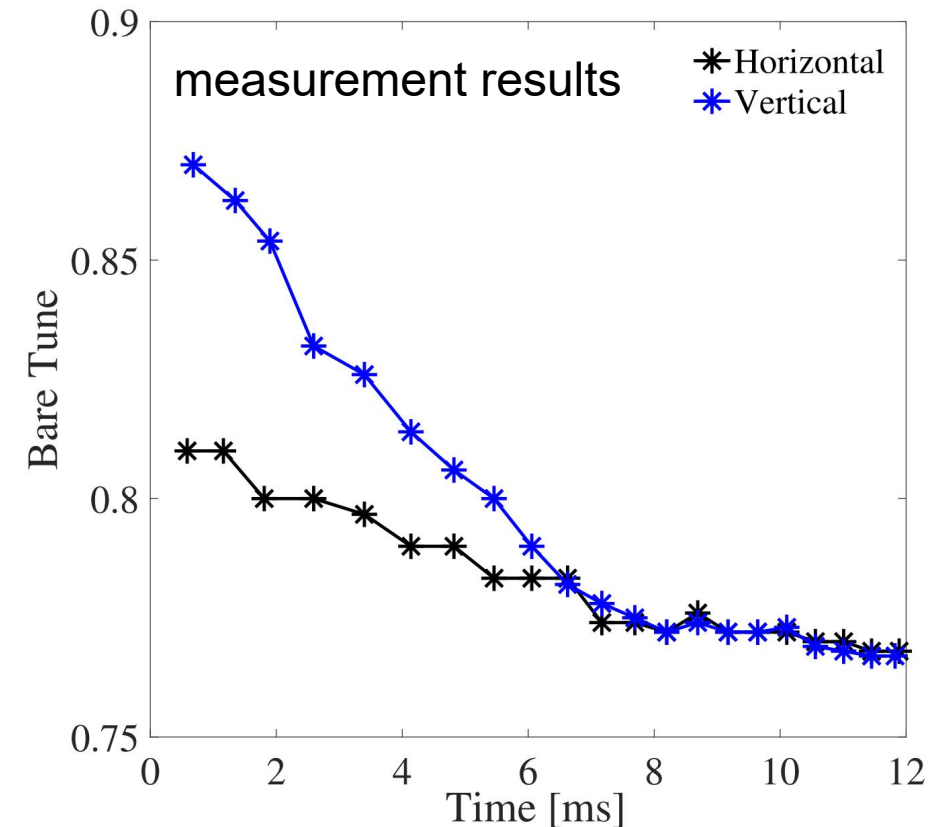
- Half-integer resonance are more severe in y, since space charge in y is stronger



far away from half-integer resonance

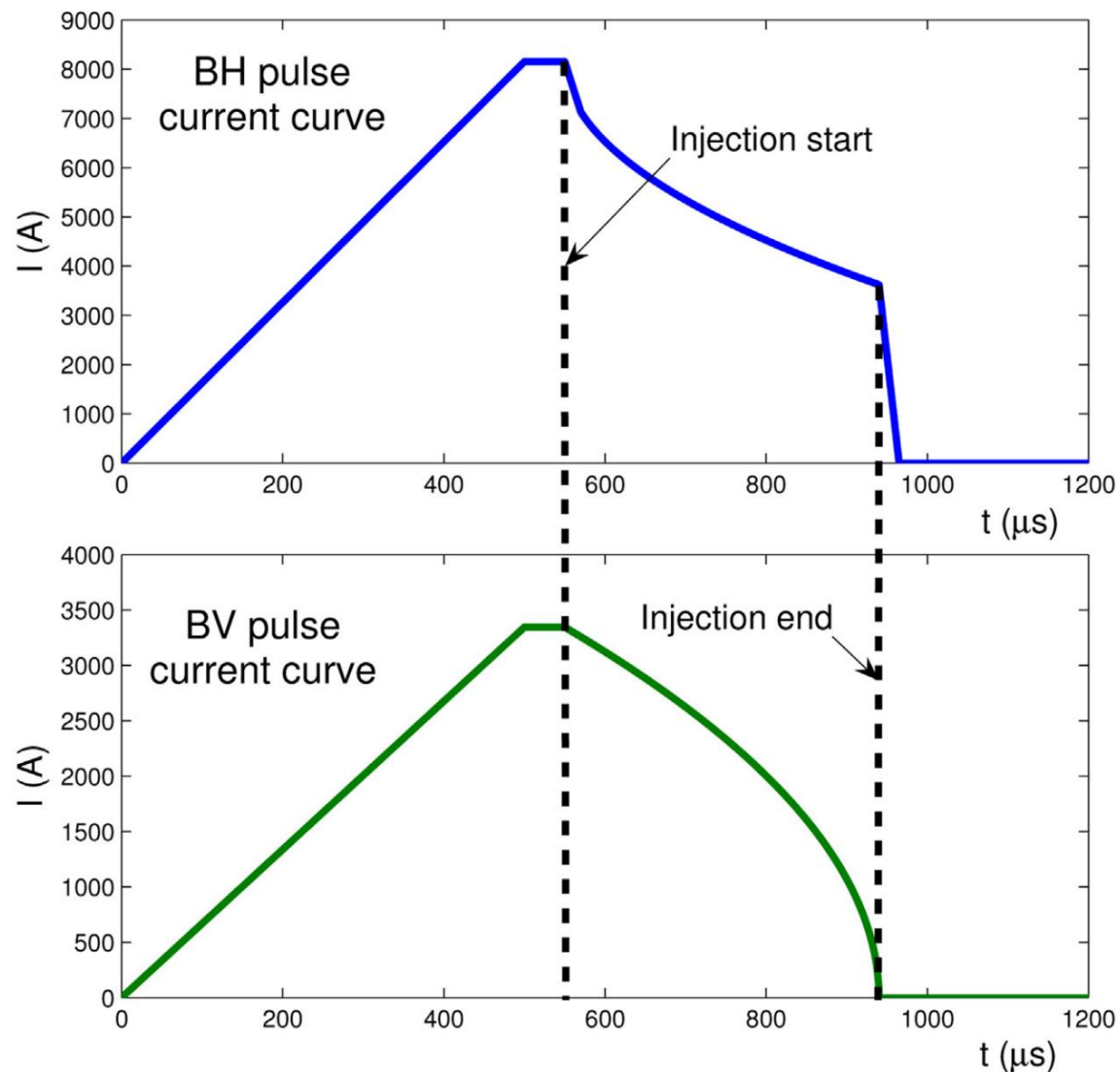
Beam commissioning with high intensity (100 kW)

- Tune optimization during the 20-ms ramping:
 - Firstly: far away from half-integer
 - Then: decrease the tune to dampen the beam center oscillation
- Installation of DC sextupole to modify chromoticity from -4.0, -8.2 to -6, -6



Beam commissioning with high intensity (100 kW)

- Optimized injection curve in x (upper) and y (lower)



- Optimized painting range

- Horizontal:

$$X = X_{\max} - (X_{\max} - X_{\min}) \sqrt{\frac{t}{T_{\text{inj}}}}, \quad X' = 0.$$

Designed: $X_{\max} - X_{\min} = 33 \text{ mm}$

Optimized: 31 mm

- Vertical:

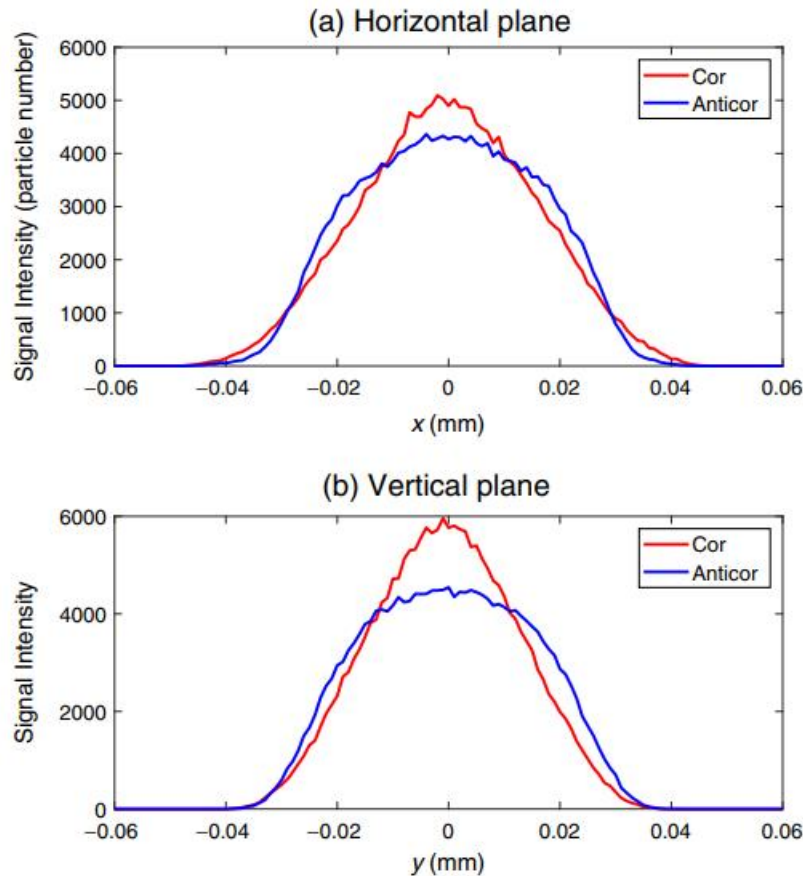
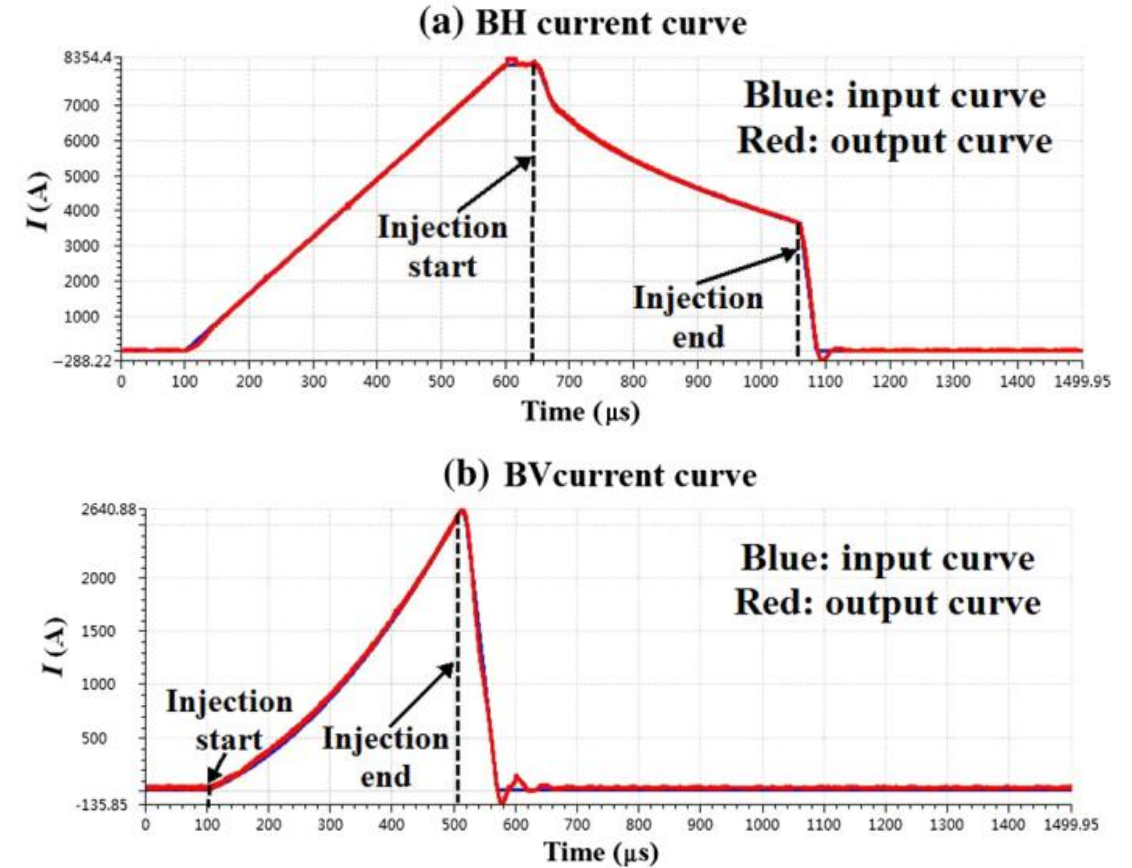
$$Y = -Y_{\max} \times \sqrt{1 - \frac{t}{T_{\text{inj}}}}, \quad Y' = 0$$

Designed: $Y_{\max} = 24 \text{ mm}$

Optimized: <16 mm

Beam commissioning with high intensity (100 kW)

- Correlated painting scheme adopted in the beam commissioning from 50 to 100kW.

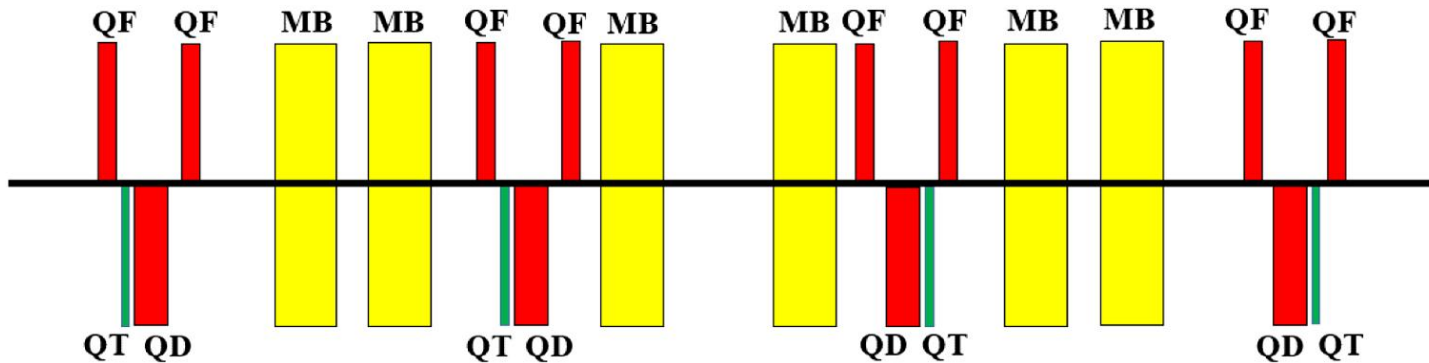
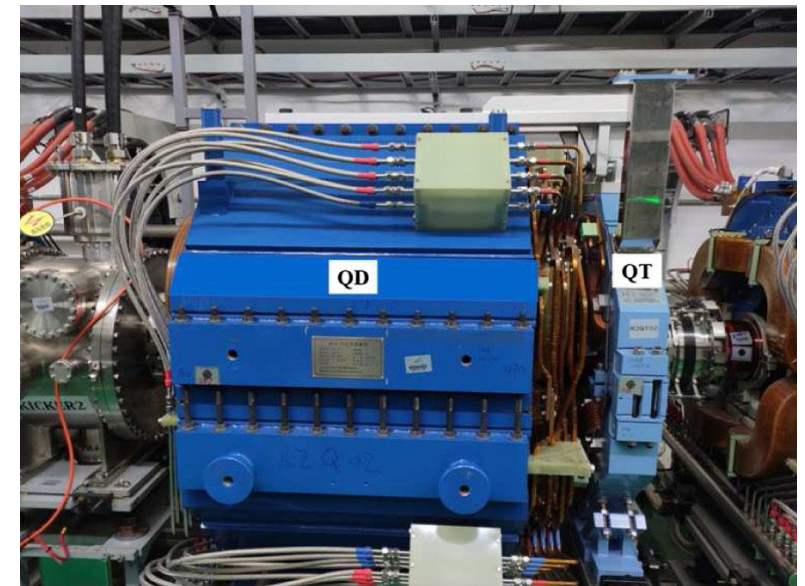


- [1] Ming-Yang Huang, et al., Study on the anti-correlated painting injection scheme for the Rapid Cycling Synchrotron of the China Spallation Neutron Source, NIM-A 2021
- [2] Ming-Yang Huang, et al., Performance of the correlated painting based on the mechanical structure of the anticorrelated painting scheme, PRAB, 2022

- Introduction
 - Preparations
 - Beam commissioning <100kW
 - Beam commissioning with 100 kW
 - **Beam commissioning beyond 100 kW**
- 
- 100 to 140 kW: trim quads
 - 140 to 170 kW: Matched inj. method; AC sextupoles
 - 170 to 185 kW: parameters detailed optimization

Beam commissioning beyond 100 kW: towards 140 kW

- Beyond 100 kW, severe beam loss and emittance growth was observed after injection.
 - ➡ The broken RCS superperiodicity caused by the edge focusing effect injection bump magnets
- In 2021, 16 QTs have been installed in CSNS RCS to reduce β -beating and restore the periodicity

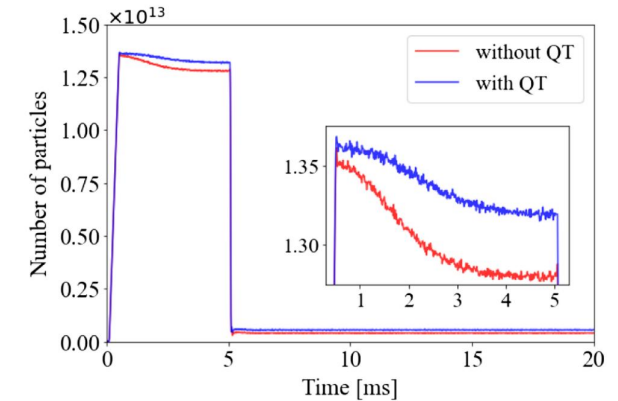
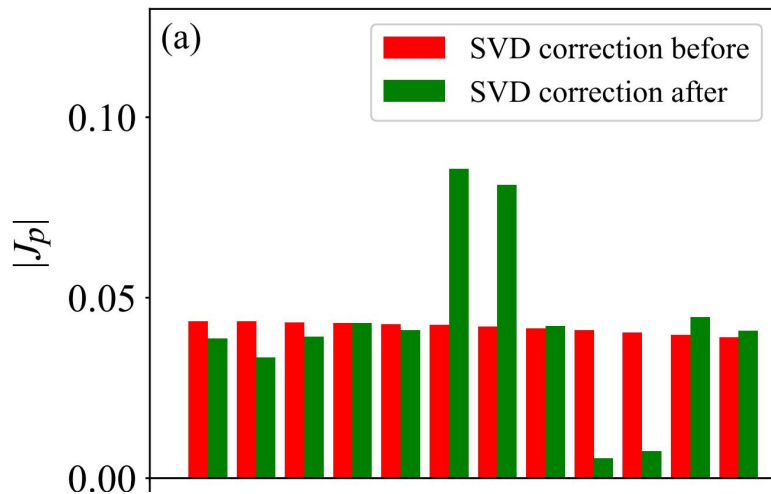
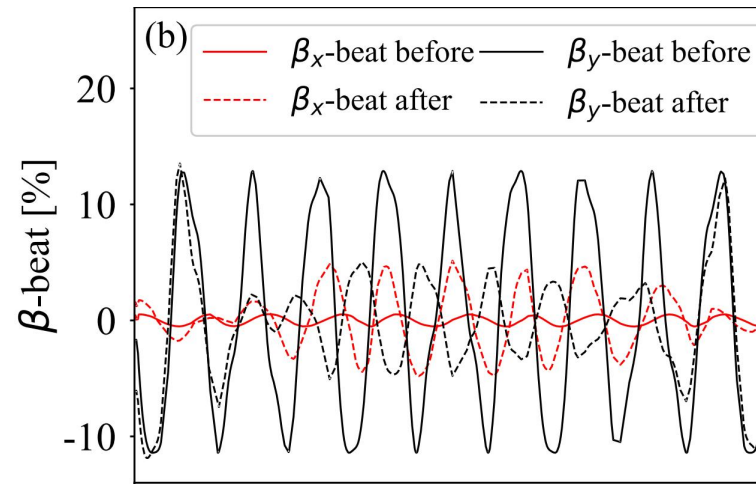
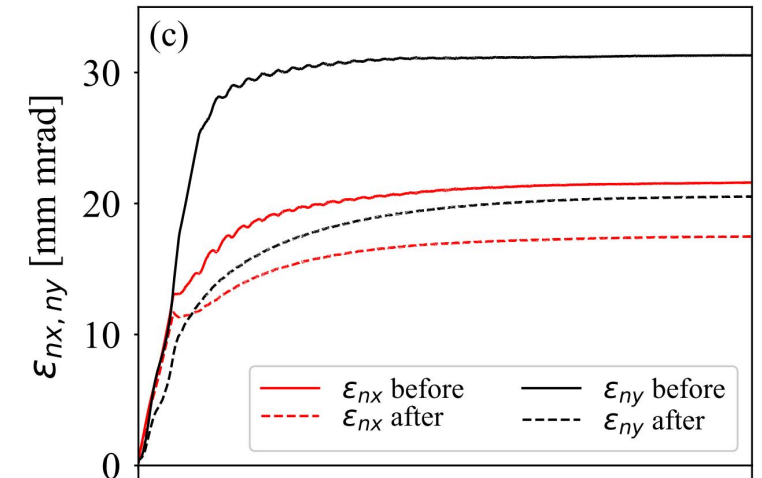


Beam commissioning beyond 100 kW: towards 140 kW

- Harmonic analysis has been performed to identify the major half-integer stopband harmonic

$$J_p = \frac{1}{2\pi} \oint \beta_y(s) K_{\text{BC},y}(s) e^{-jp\phi_y} ds \quad p = 8 \text{ and } 9$$

- Harmonic correction method are used to reduce J_9 and J_{10}

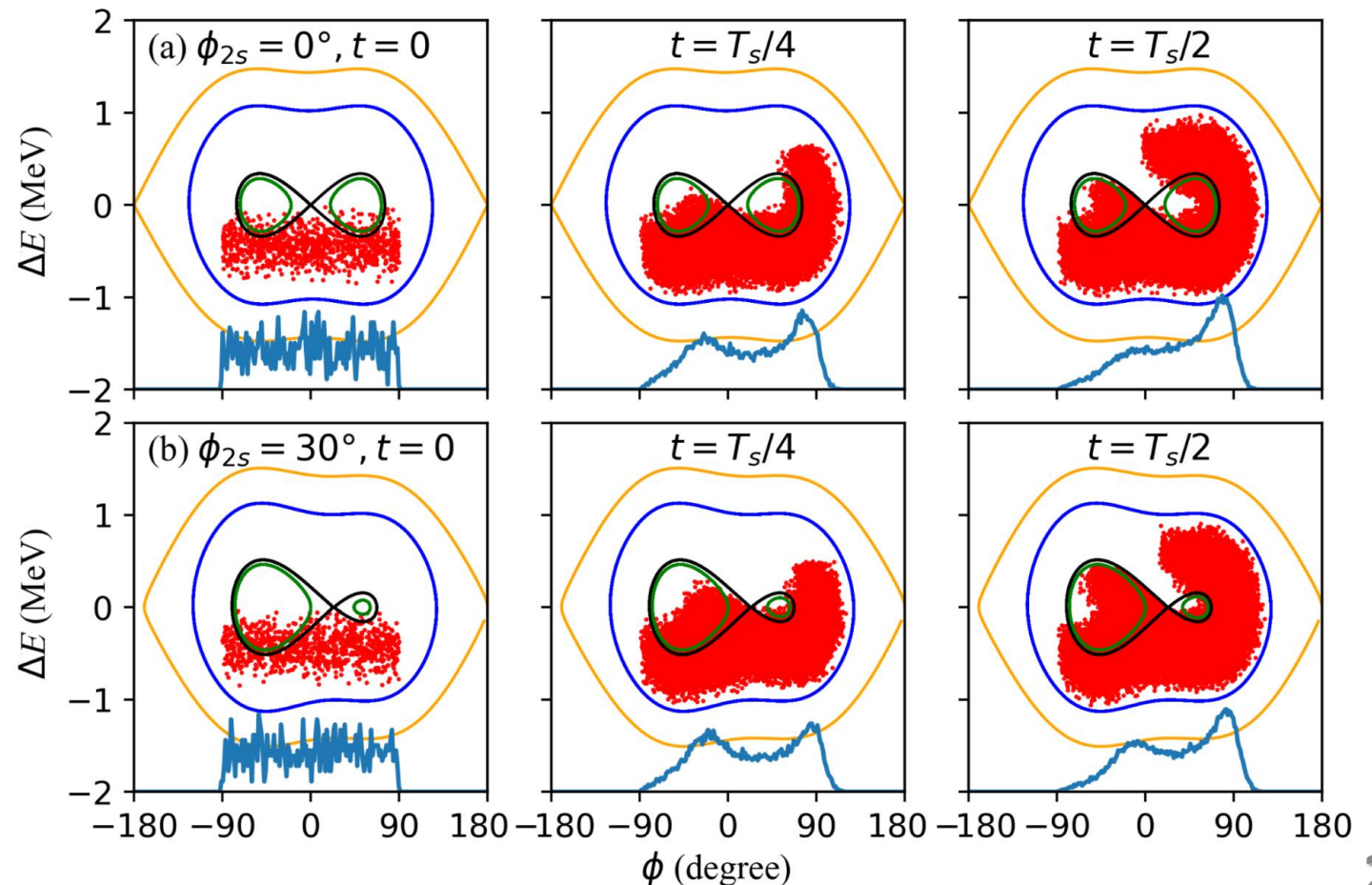


Beam commissioning beyond 100 kW: towards 170 kW

➤ Further improved via phase sweep method (with a non-zero second harmonics synchronous phase ϕ_{2s})

➤ ϕ_{2s} characterizes the capability of accumulating particles of the inner buckets

➤ Bunching factor can be improved via multi-turn painting scheme



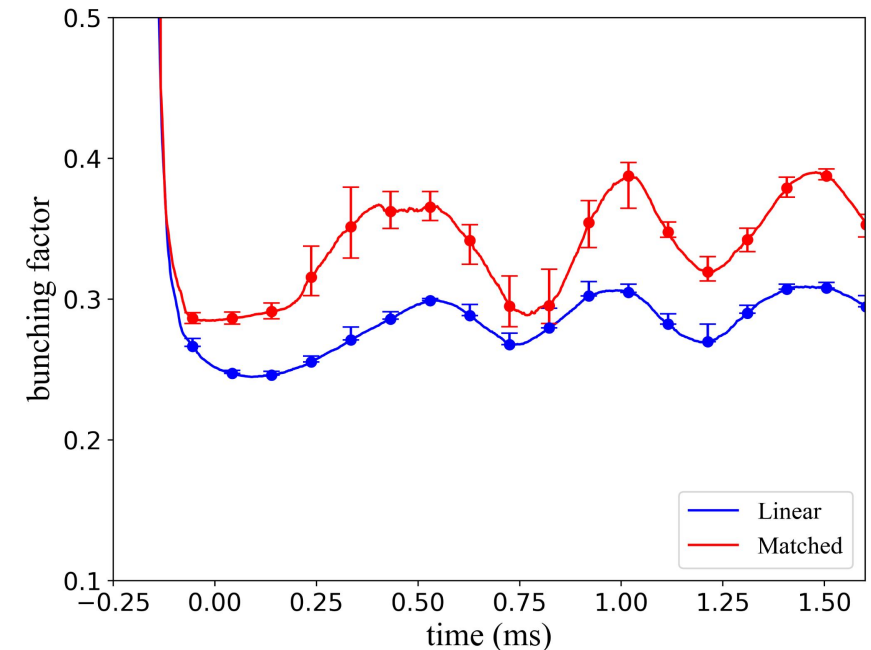
Beam commissioning beyond 100 kW: towards 170 kW

➤ Matched phase space method

- First stage: Maximize the synchrotron frequency in $\frac{1}{4}$ synchrotron period
- Second stage: Match the synchrotron motion during injection to be an integer

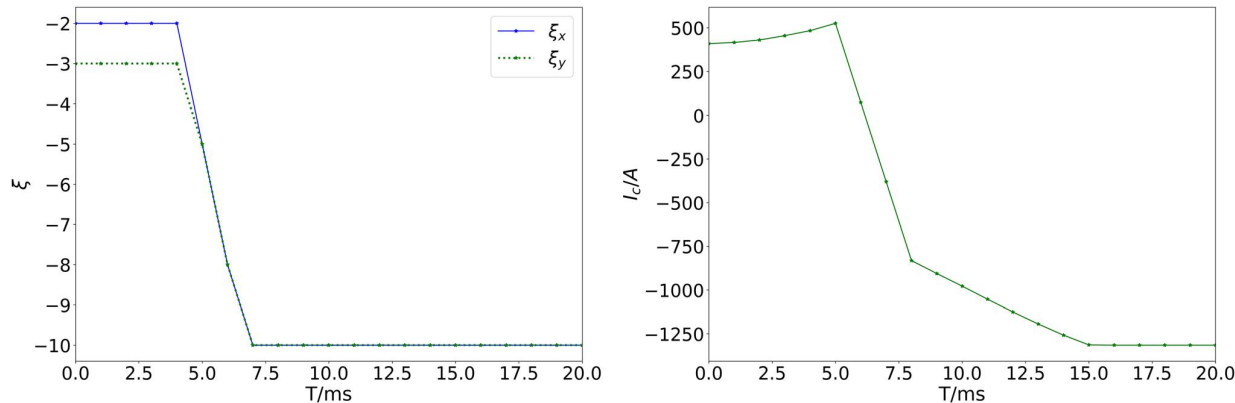
$$\underbrace{n_0 \nu_{s2,\max}}_{\text{first stage}} + \underbrace{\int_{n_0}^{n_{\text{inj}}} \frac{1}{2} [\nu_{s1}(n) + \nu_{s2}(n)] dn}_{\text{second stage}} = \boxed{m} \text{ integer}$$

- ## ➤ Bunching factor with matched sweep method is larger than thaty with the linear sweep method.



Beam commissioning beyond 100 kW: towards 170 kW

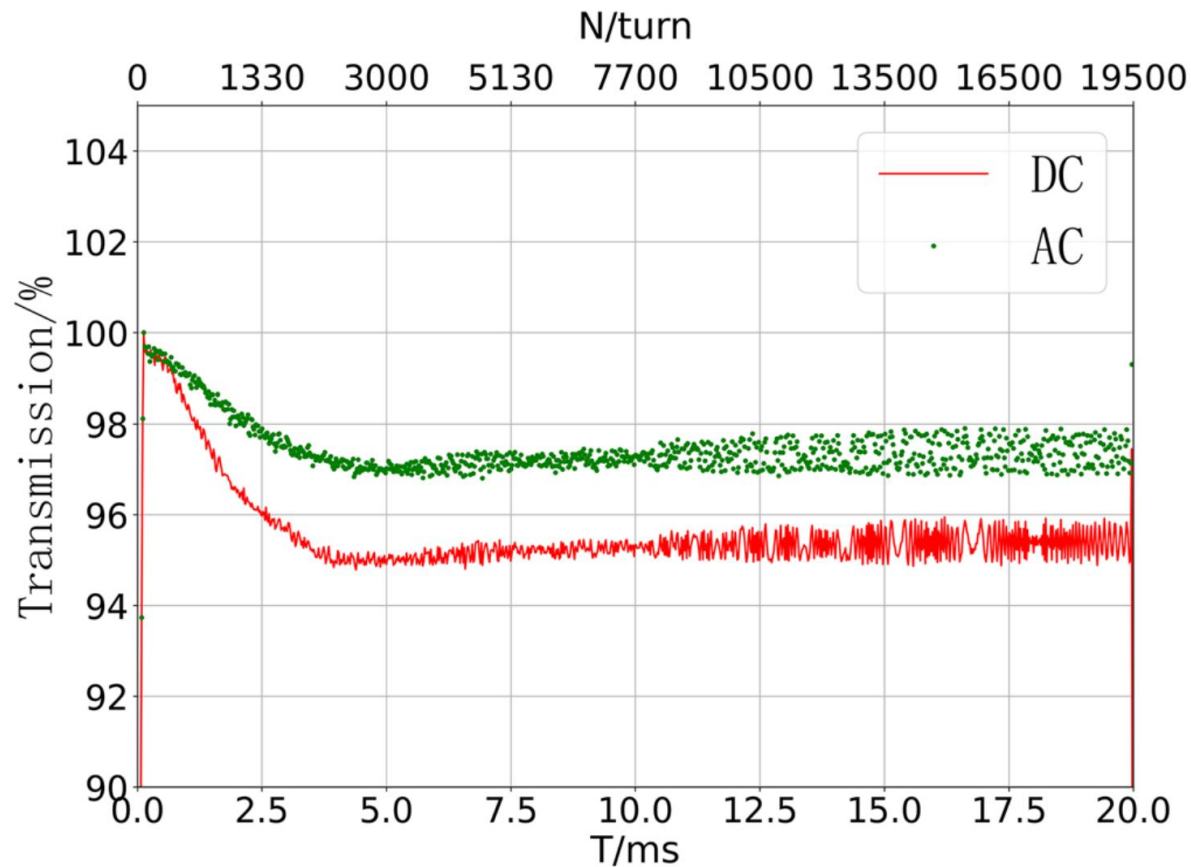
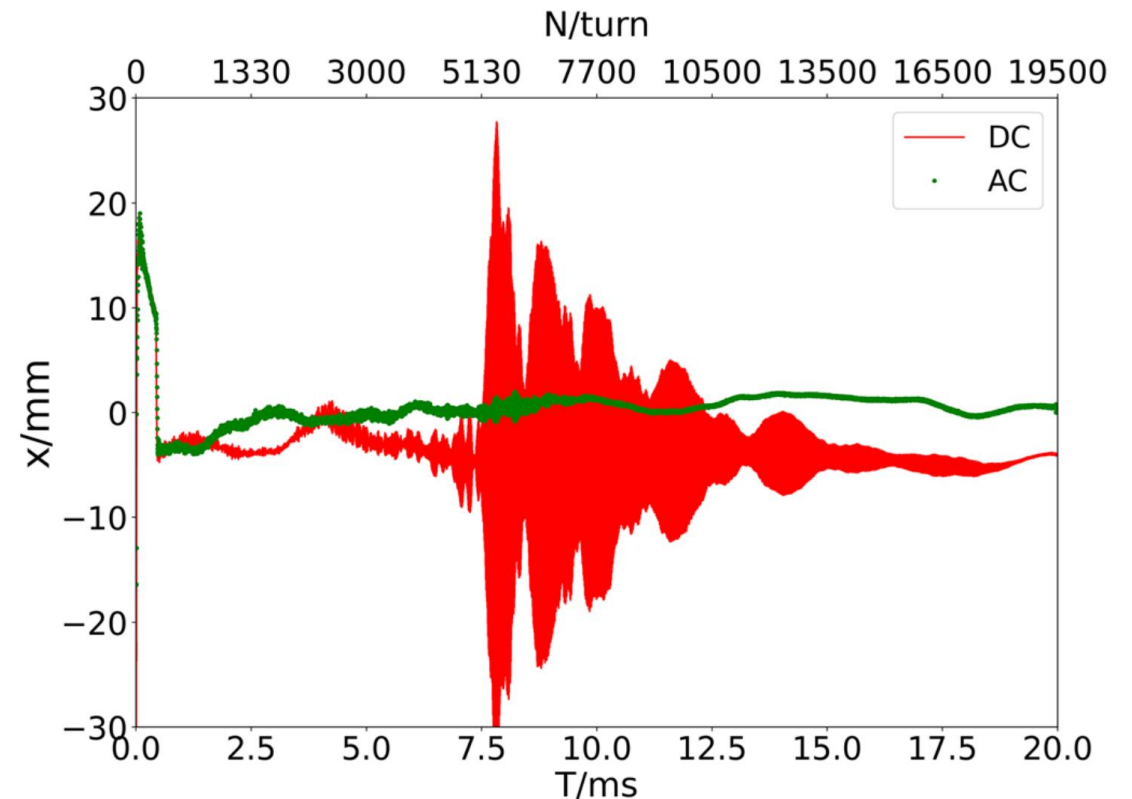
- 16 AC sextupoles have been installed in CSNS RCS to replace the 16 DC sextupoles.
- Chromaticity can be well-controlled with the AC sextupoles during 20ms period



Left: Programmed chromaticity during 20-ms ramping period; Right: the corresponding current of the AC sextupole power supply

Beam commissioning beyond 100 kW: towards 170 kW

- Particle transmission rate has been increased by 2% from 96% to 98%
- The instability has been dampened



Beam commissioning beyond 100 kW: towards 185 kW

- In 03, 2026, Bayesian optimization are adopted to further increase beam power to 185kW, including
 - Working point curve during 20-ms ramping period;
 - Parameters of RF system;
 - Parameters of dipoles, quads and correctors;

Beam commissioning beyond 100 kW: towards 200 kW

- Recent attempt: working point are shifted from (4.81,4.87) to (4.42, 5.32) to avoid impedance-driven instability
- Linac beam current has been increased to over 30 mA.
- Temperature rise of the stripping foil has been successfully controlled with horizontal angle painting
- Simultaneously accommodate both correlated and anti-correlated painting by employing horizontal angle painting and vertical bump painting, this scheme can

Conclusion

- Proton beam power in CSNS has been increased step by step
- Low intensity beam commissioning (<50kW) : COD correction, beam optics commissioning
- High intensity beam commissioning has been made with the adoption of the dual rf system, AC sextupoles, optimization of injection system and the trim quads
- Efforts to apply machine learning to beam commissioning

Thanks for your attention!

