



Application of programmable trim quadrupoles in beam commissioning of CSNS/RCS

H.Y. Liu Y. Li

Institute of High Energy Physics, CAS

Geneva, Switzerland, 9-13 October 2023

HB2023

1

Background

2

Applications of QTs in CSNS/RCS

3

Summary

Airview map



中国散裂中子源装置地A点拍摄 (09.5.9)



中国散裂中子源工程进展照片 (2017.6)

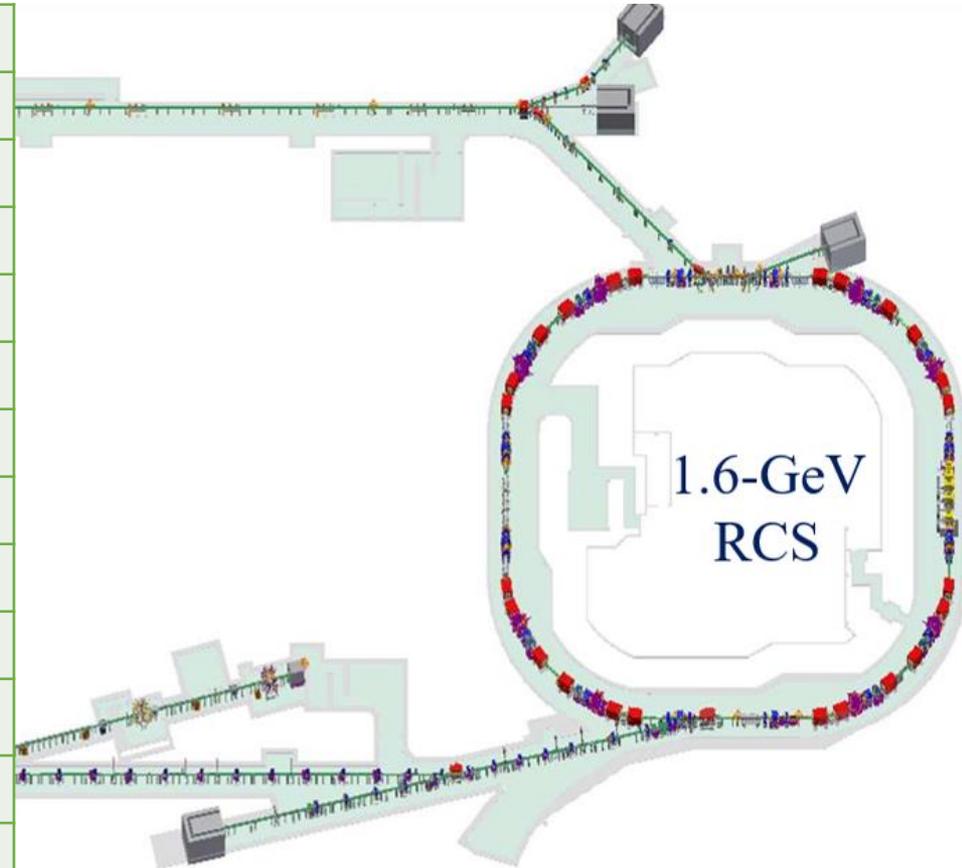


Project Design



- The phase-I CSNS facility consists of an 80-MeV H^- linac, a 1.6-GeV RCS, a target station, and 3 instruments.

Project Phase	I	II
Beam Power on target [kW]	100	500
Proton energy [GeV]	1.6	1.6
Average beam current [μ A]	62.5	312.5
Pulse repetition rate [Hz]	25	25
Linac energy [MeV]	80	300
Linac type	DTL	+Spoke/PIMS
Linac RF frequency [MHz]	324	324
Macropulse. ave current [mA]	15	40
Macropulse duty factor	1.0	1.7
RCS circumference [m]	228	228
RCS harmonic number	2	2
RCS Acceptance [π mm-mrad]	540	540
Target	1	1
Spectrometers	3	20



History of the RCS beam power



RCS/DC+RCS/AC

2017.05.26~08.28

First beam
on target, first
neutron beam

2017.08.28

Increase beam
power to 10 kW

2017.11.09

Increase beam
power to 50 kW

2019.01.29

Increase beam
power to 80 kW

2019.09.27

Increase beam
power to 100 kW

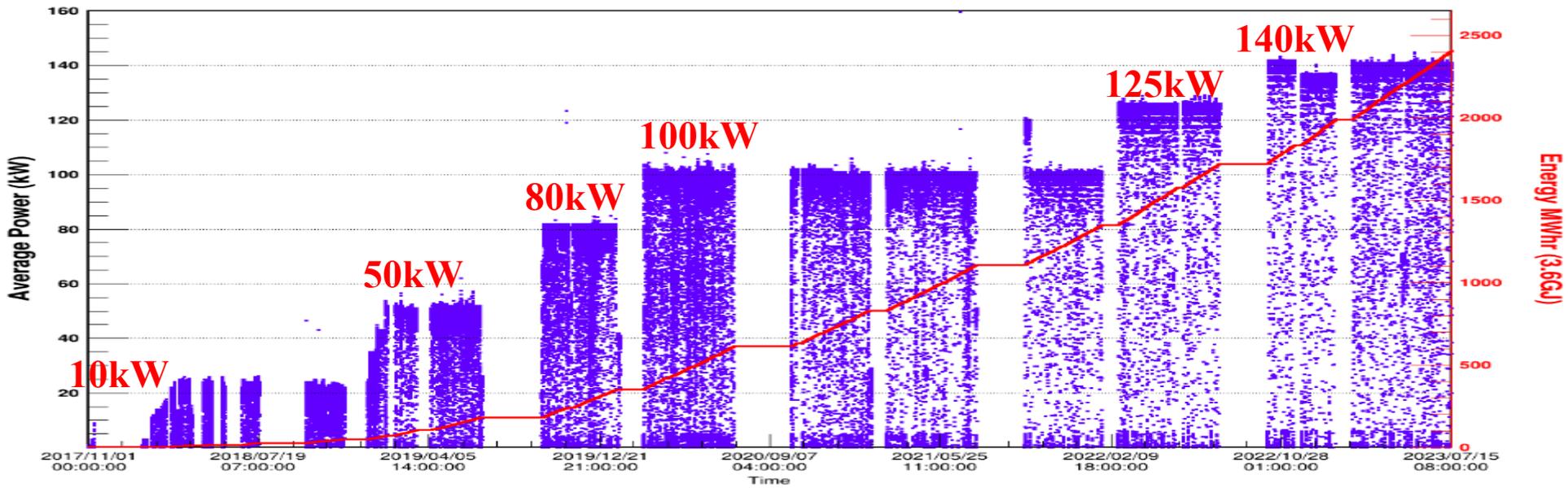
2020.02.28

Increase beam
power to 125 kW

2022.02.21

Increase beam
power to 140 kW

2022.10.07

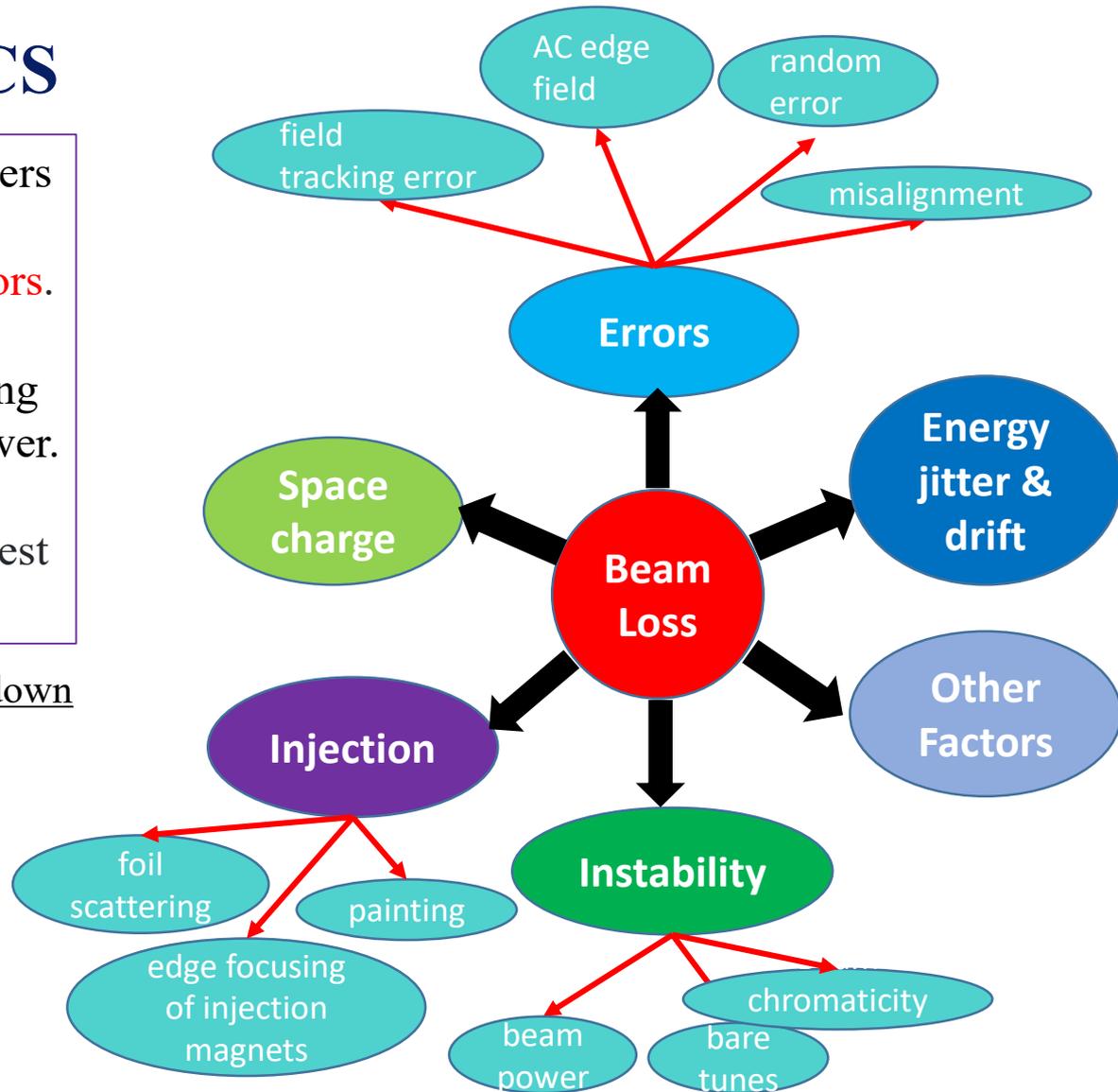


① Beam loss in RCS

- The beam optics parameters deviate from the design values due to **various errors**.
- **Space charge**, **instability**, and beam loss is increasing with the output beam power.
- The **radiation dose in the injection zone** is the highest in the ring.

injection section@1h after shutdown

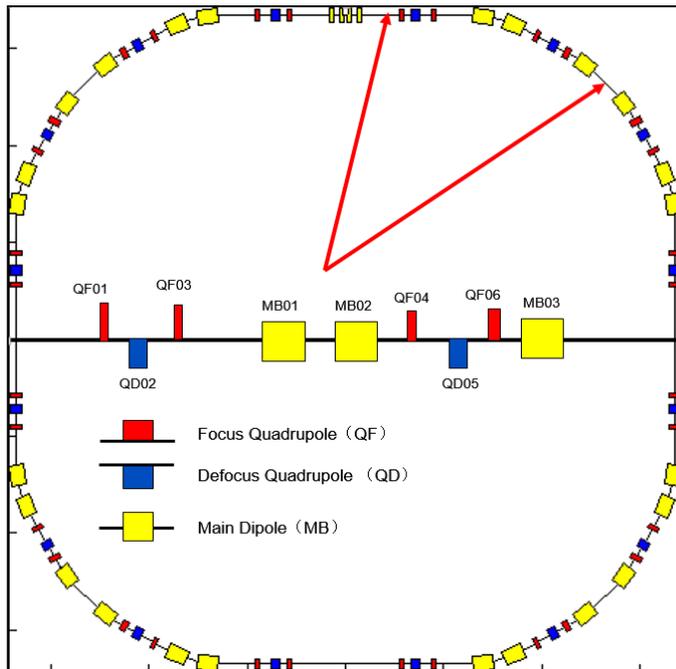
Beam power [kW]	Residual dose [mSv/h]
100	1.37
140	7.6



② Optics parameters correction

- 48 main quads are powered by 5 sets of power supplies
- The **harmonic injection** method was used in CSNS/RCS

$$f(t) = a + b \cdot \sin(w \cdot t + p) + b1 \cdot \sin(2 \cdot w \cdot t + p1) + b2 \cdot \sin(3 \cdot w \cdot t + p2) \dots$$
- The variation of the optics through the machine cycle is relatively smooth
- Tuning optics with main quads in short time is difficult, especially for **rapidly variation**



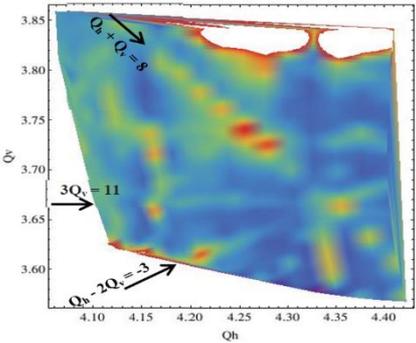
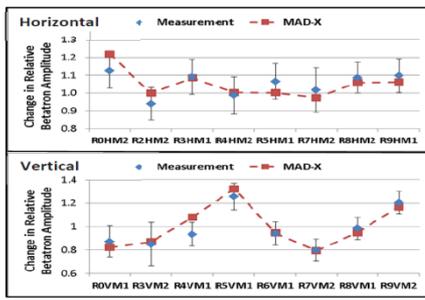
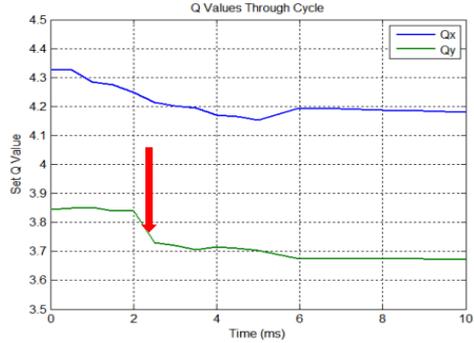
Magnet Harmonic		Q206A	Q272	Q206B	Q222	Q253
		DC (A)	720.7	794.1	642.9	618.2
25Hz	Amp(A)	531.4	568.5	466.3	446.4	538.7
	Phase(π)	1.5	1.5	1.5	1.5	1.5
50Hz	Amp(A)	15.24	8.57	8.211	4.537	8.876
	Phase(π)	0.145	0.79	0.58	0.52	0.67
75Hz	Amp(A)	3.727	7.745	4.813	1.767	6.738
	Phase(π)	0.7	1.53	1.445	1.308	1.43
100Hz	Amp(A)	2.623	3.744	1.1832	0.2227	2.454
	Phase(π)	0.85	0.02	0.23	1.74	0
125Hz	Amp(A)	2.901	1.495	0.3251	0.29	0.9701
	Phase(π)	1.7	0.46	1.99	0.054	0.294

Applications of QTs in other machines



■ ISIS

- There are 2 sets of 10 programmable trim quads in the ISIS ring.
- Applications: allow rapid variation of tune; measure β -functions; measure tune map.

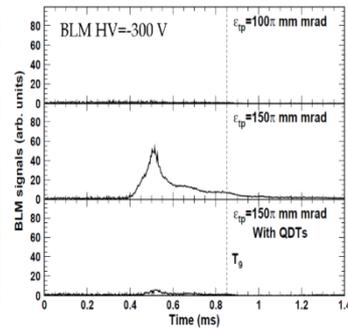


■ J-PARC

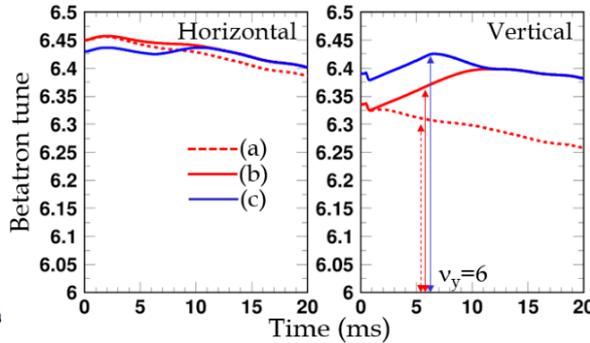
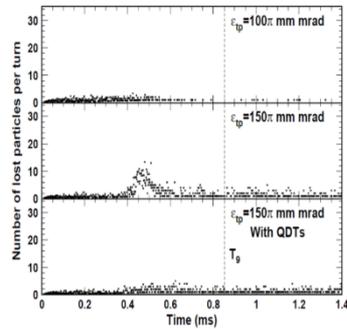
- 6 QTs with independent pulse-type power supplies; locate at dispersion-free region.
- Applications: compensate the β -beat; tunes optimization through the machine cycle.



◆ Measurement (BLM signals at the collimator section)



◆ Numerical simulation



Design of trim quads

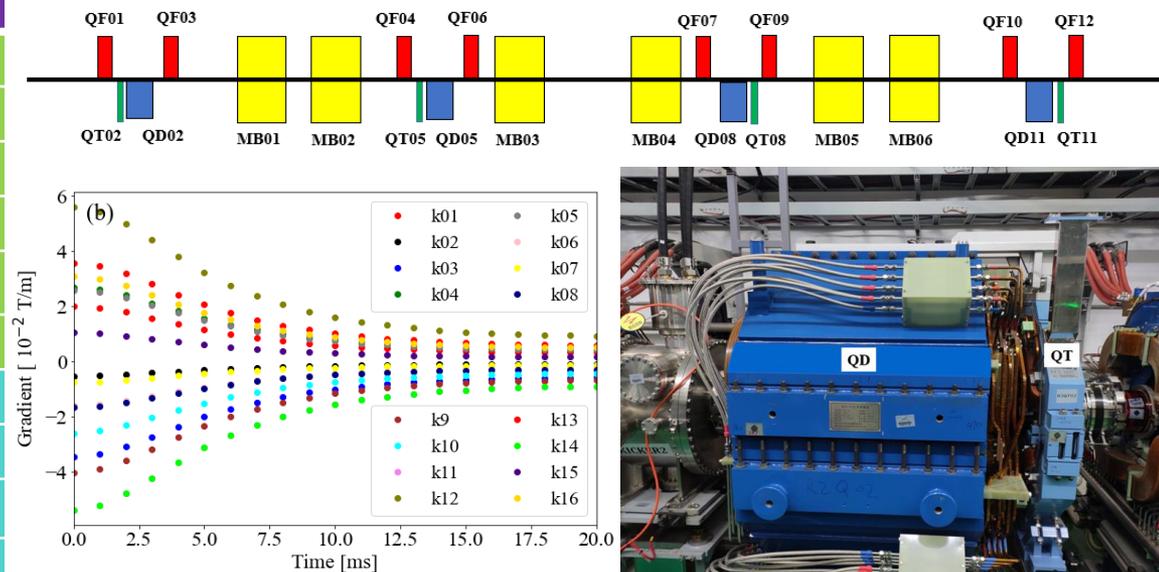
■ Design factors

- Beta-beat correction (first 5ms)
- Tunes optimization (at least 10ms)

■ Final parameters

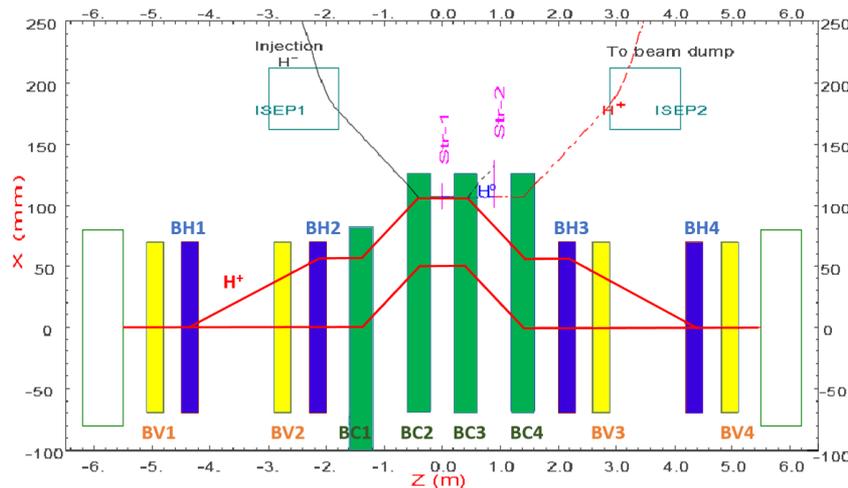
- 16 QTs are designed to be independently powered allowing a fine tuning of the β -functions and bare tunes at 21 time points through ramping time of 20 ms.
- The maximum rate of current change for the QTs is 300 A/ms, ensuring fast modulation of the tunes even in the high-energy region.

Parameters [unit]	Value
Magnets No.	16
Magnet length [mm]	150
Bore radius [mm]	272
Maximum Gradient [T/m]	1.18
Good field radius [mm]	126
Higher-order field error [%]	0.5
Power Supply No.	16
Peak current [A]	550
Peak rate of current change [A/ms]	300
Dynamic tracking accuracy[%]	2



① Super-periodicity restoration

1: Injection system

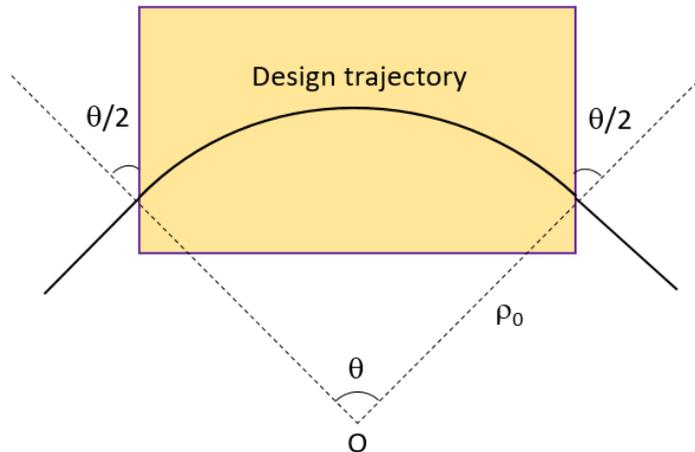


- The **transverse injection painting scheme** is widely adopted in many high-intensity hadron synchrotrons to alleviate space charge effects.
- The CSNS injection system consists of **12 rectangular dipole magnets**.
- BH1~BH4 and BV1~BV4 are pulse-type bump magnets, which are used to generate dynamic orbit bumps.
- BC1~BC4 provide additional fixed horizontal orbit bumps. The four BCs are designed as **DC type** chicane magnets to avoid the use of complex vacuum chambers.
- The **edge focusing effect** of the DC injection bump magnets breaks the 4-fold symmetry of the RCS.

Magnet Type	Length (m)	B_{\max} (T)	θ_{\max} (mrad)	Number
BH	0.3	0.114	26.0	4
BV	0.3	0.09	20.2	4
BC	0.35	0.285	60	4

① Super-periodicity restoration

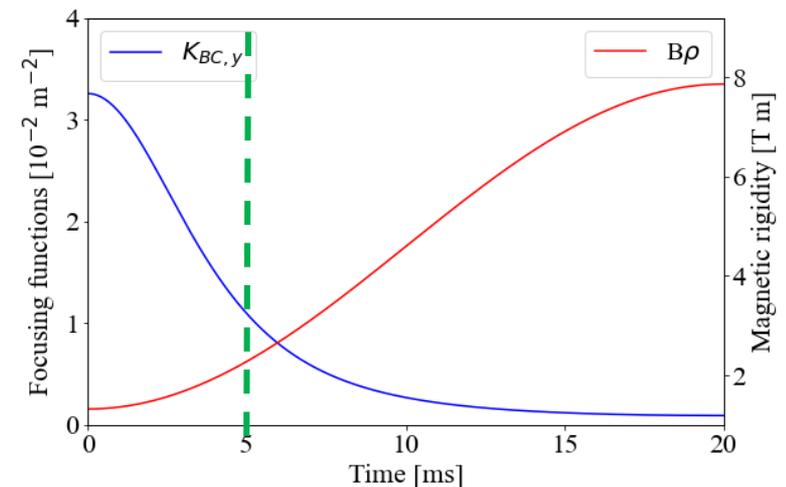
2: Edge focusing of injection bump magnets



- The edge focusing effect of the horizontal bump magnet causes the focusing effect **only in the vertical plane** and the horizontal focusing is completely canceled by the intrinsic focusing property on the bending plane.
- The **vertical edge focusing strength is relatively large in the first 5 ms**.

$$M_x = \begin{bmatrix} 1 & 0 \\ \frac{\tan \frac{\theta}{2}}{\rho_0} & 1 \end{bmatrix} \begin{bmatrix} \cos \theta & \rho_0 \sin \theta \\ -\frac{\sin \theta}{\rho_0} & \cos \theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{\tan \frac{\theta}{2}}{\rho_0} & 1 \end{bmatrix} = \begin{bmatrix} 1 & \rho_0 \sin \theta \\ 0 & 1 \end{bmatrix}$$

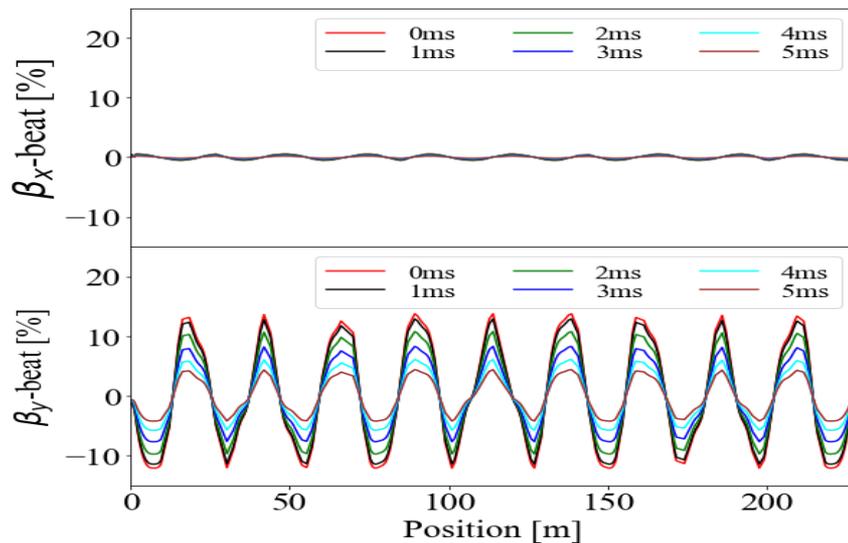
$$M_y = \begin{bmatrix} 1 & 0 \\ -\frac{\tan \frac{\theta}{2}}{\rho_0} & 1 \end{bmatrix} \begin{bmatrix} 1 & \rho_0 \theta \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{\tan \frac{\theta}{2}}{\rho_0} & 1 \end{bmatrix} = \begin{bmatrix} 1 - \theta \tan \frac{\theta}{2} & \rho_0 \theta \\ \frac{\theta \tan^2 \frac{\theta}{2}}{\rho_0} - \frac{2 \tan \frac{\theta}{2}}{\rho_0} & 1 - \theta \tan \frac{\theta}{2} \end{bmatrix}$$



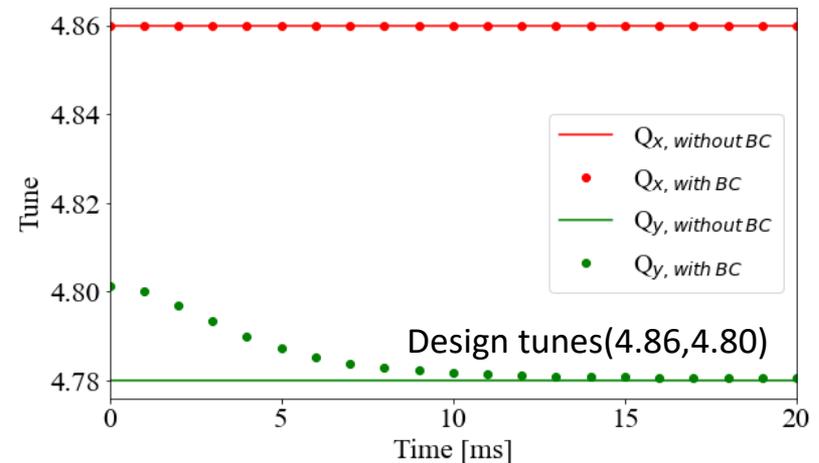
① Super-periodicity restoration

3: Edge focusing effects

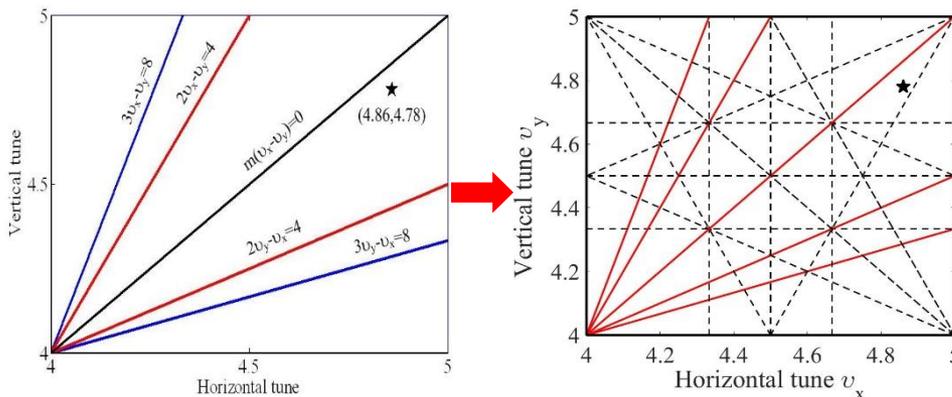
β -beating@MAD-X



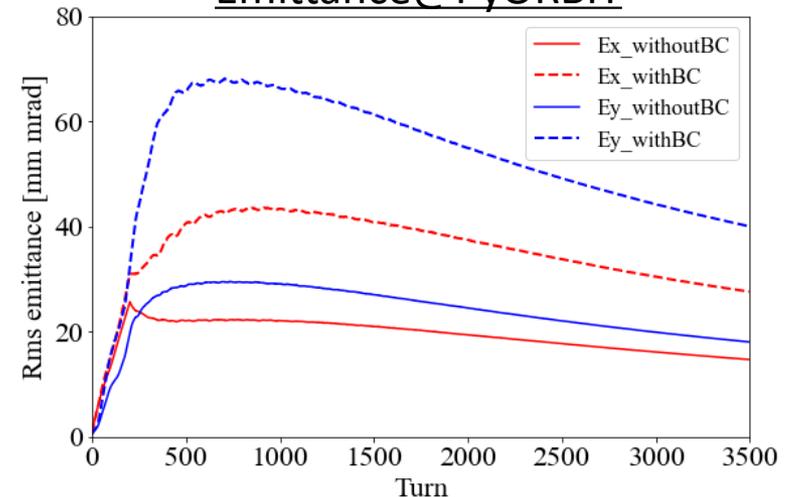
tunes@MAD-X



resonance line



Emittance@PyORBIT



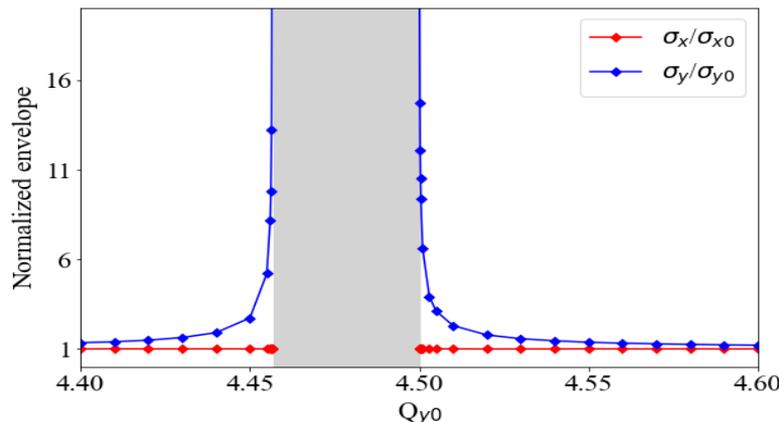
① Super-periodicity restoration

4: Half-integer resonance caused by edge focusing effects

without space charge

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

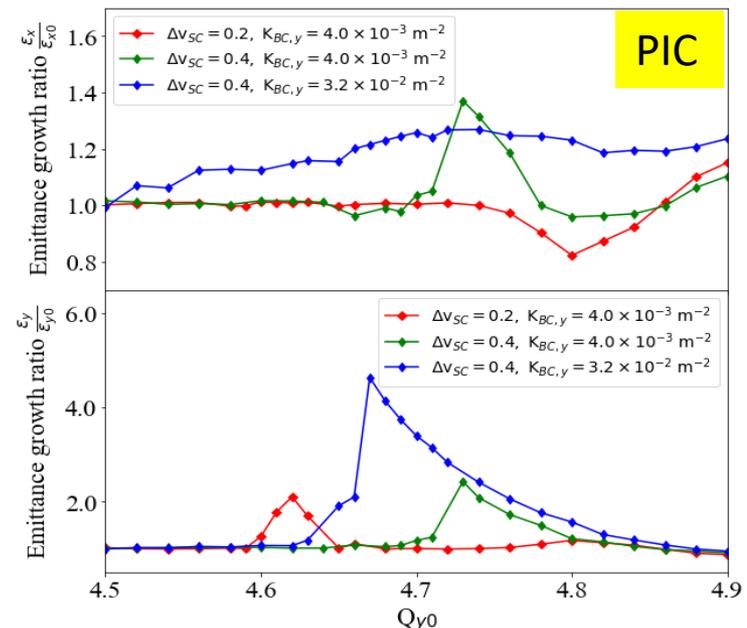
$$\frac{\Delta\beta_y(s)}{\beta_y(s)} = -\frac{\nu_{y0}}{2} \sum_{p=-\infty}^{\infty} \frac{J_p e^{jp\phi}}{\nu_{y0}^2 - (p/2)^2}$$



- For the CSNS/RCS with the design bare tune (4.86,4.80), the resonance width $J_9 = 0.042$.
- The envelope growth keeps constant in the horizontal plane, but increases rapidly in the vertical plane as Q_{y0} approaching to 4.5.

with space charge

$$2Q_{y0} - \Delta\Omega_{SC,y}^{(2)} = 2Q_{y0} - 2C_2\Delta Q_{SC,y} = 9$$



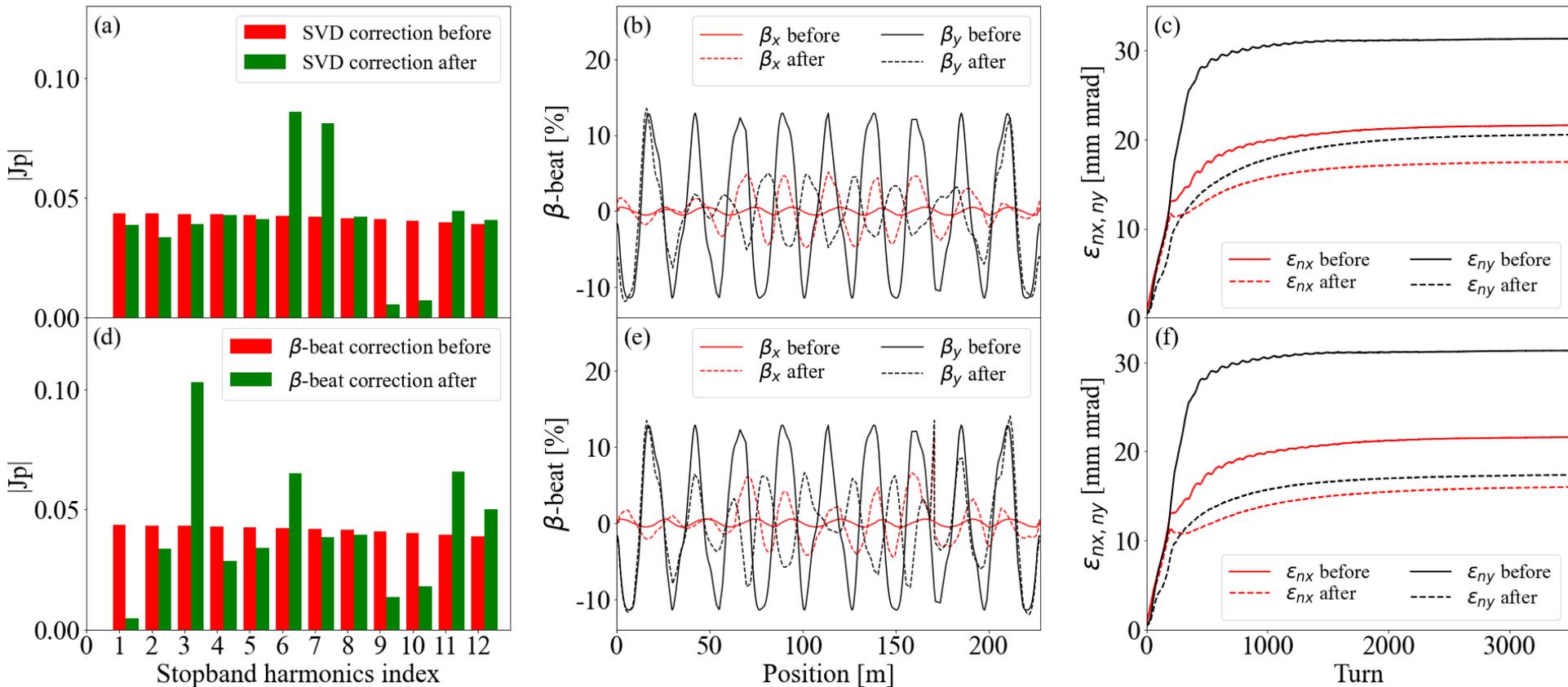
- The emittance growth mainly occurs on the vertical plane.
- The resonance strength is proportional to the edge focusing and space charge.

① Super-periodicity restoration

5: Two QT-based schemes

- ① SVD harmonics correction $\rightarrow J_9$ & J_{10}
- ② β -beat correction $\rightarrow \beta$ function

Most of the stopband harmonics and β -beat are largely reduced. The emittance growth is decreased significantly via using the two correction schemes.

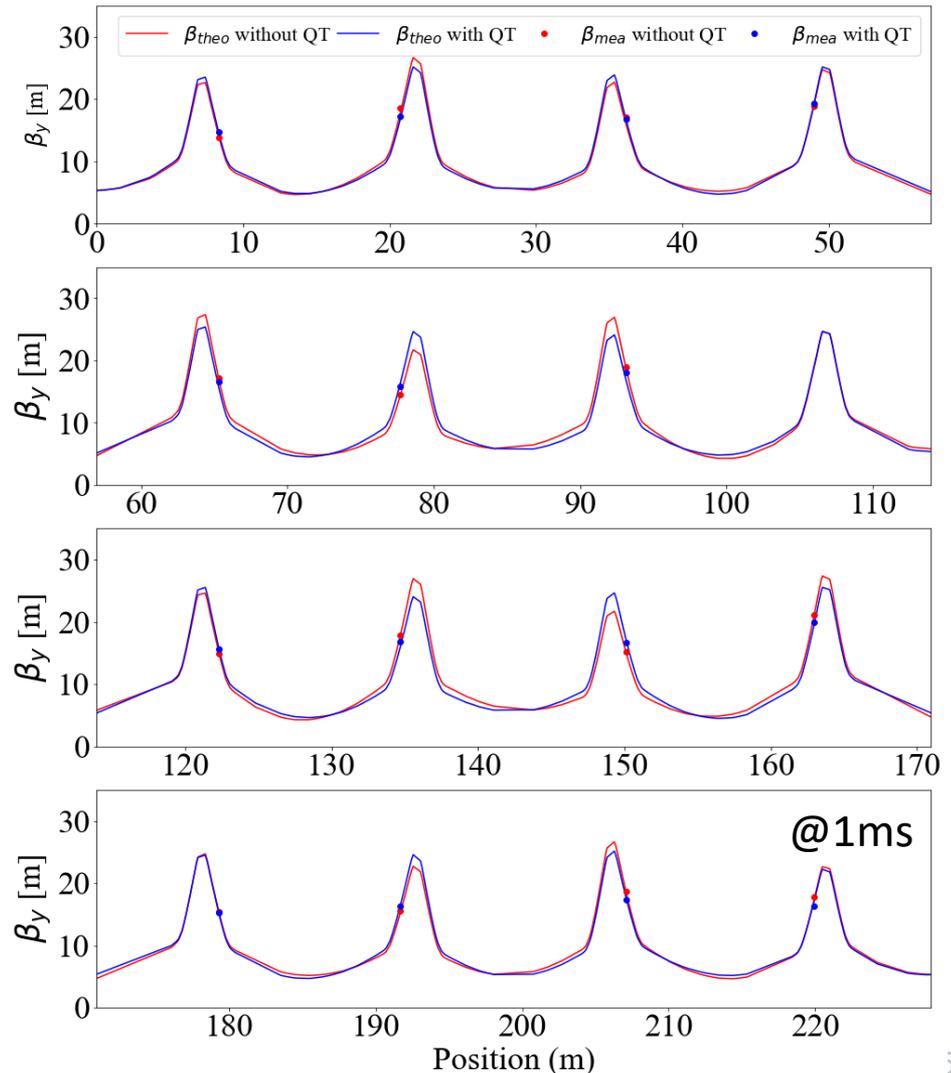


① Super-periodicity restoration

6: Experimental results

① β -function

- Orbital response matrix method is adopted.
- The measured β_y -function is in good agreement with the theoretical β_y -function.
- The maximum β_y -function is significantly reduced and most of the β -beat was effectively corrected by QTs to less than 5%, which proves that QTs have a significant correction effect on β -beat.

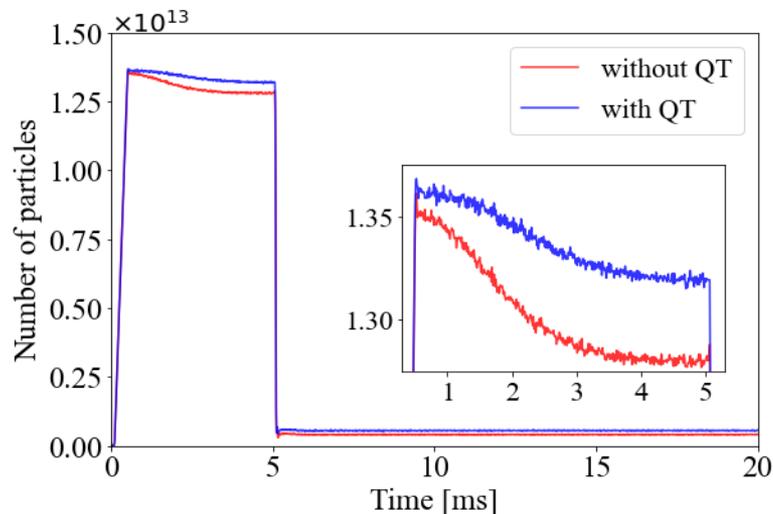


① Super-periodicity restoration

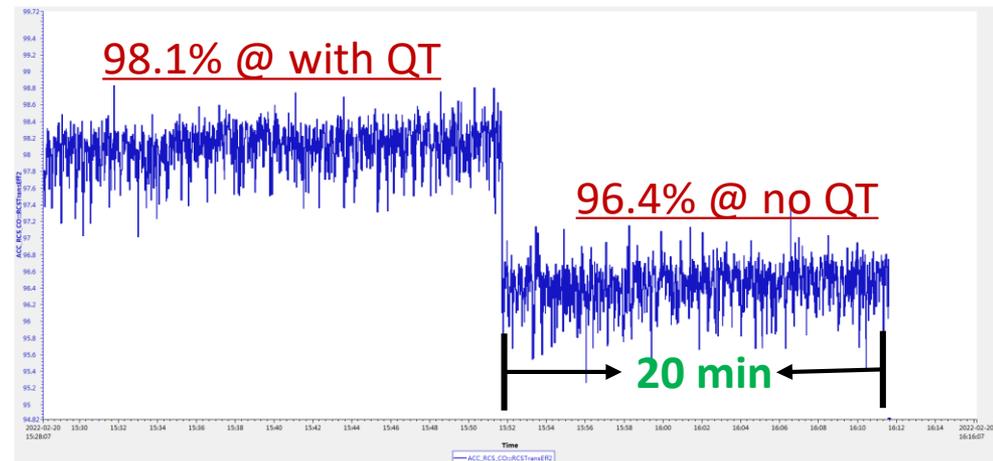
6: Experimental results

② Beam loss and beam power

(4.86,4.80) @90 kW



Operating mode @125 kW

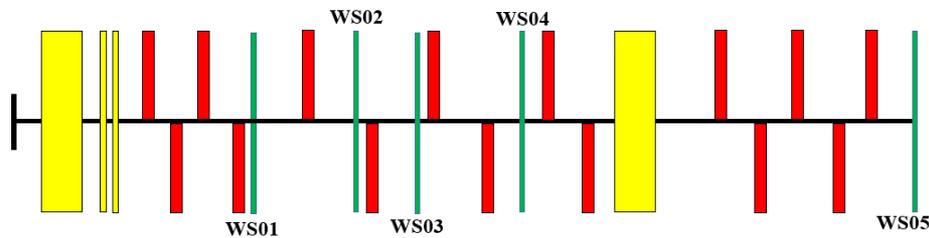


- More particles survive in the beams in the presence of QTs than that without QTs, with a reduction ratio of beam loss by 2% – 3%.

① Super-periodicity restoration

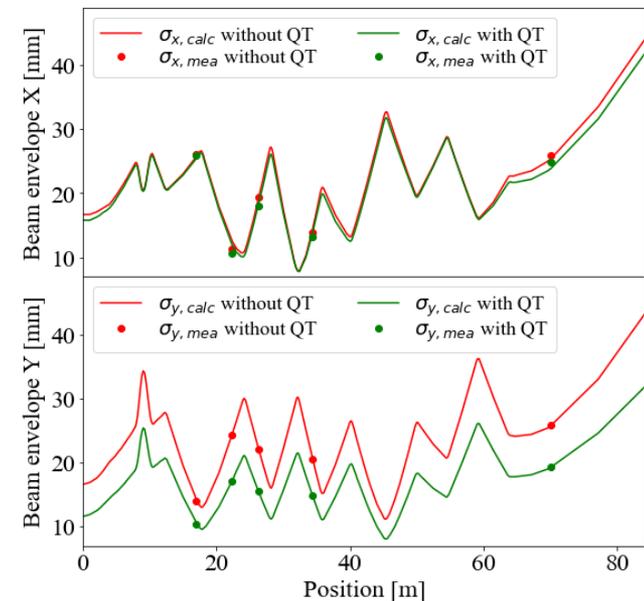
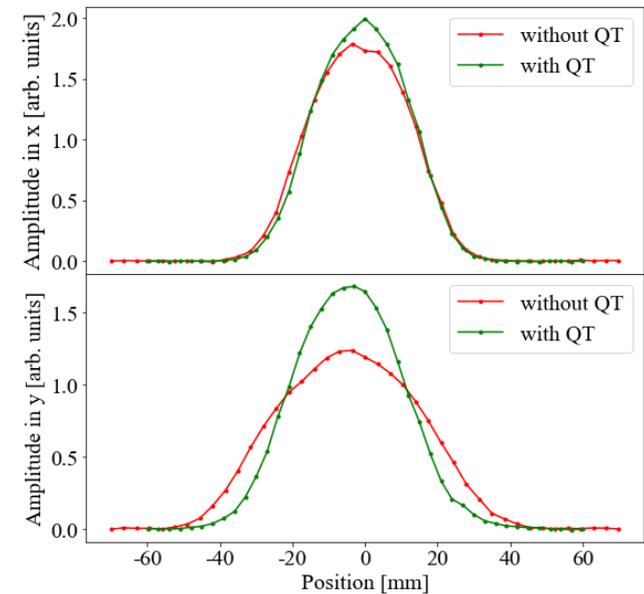
6: Experimental results

③ Beam Emittance



Cases	$\epsilon_{nx, mea}$	$\epsilon_{ny, mea}$	$\epsilon_{nx, sim}$	$\epsilon_{ny, sim}$
without QT	31.08	33.77	22.28	32.83
With QT	27.68	17.09	19.13	16.61

- Five wire scanners are installed on RTBT transport line for the emittance measurement of the extracted beams from the RCS.
- The extracted beam at 5 ms has a Gaussian-like distribution.
- Beam envelope and emittance in the vertical plane decreases significantly with QTs.

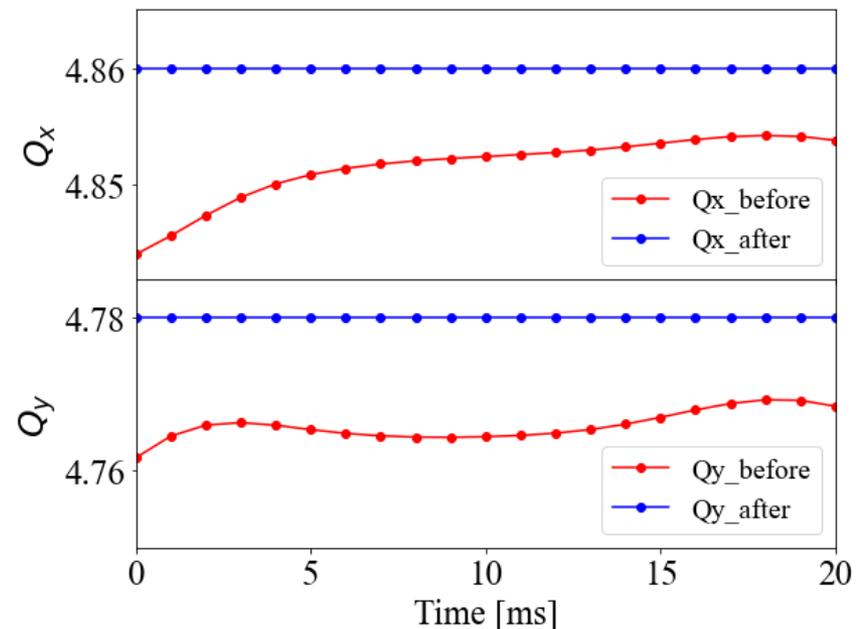


② Tunes optimization

- Due to the harmonic injection method with the main quads, the variation of the tunes through the machine cycle is relatively smooth, and the tuning capability with main quads in short time is limited, especially for rapidly variation.
- However, the installation of QTs enables fast variation of tunes for a specific energy range or tuning throughout the machine cycle.

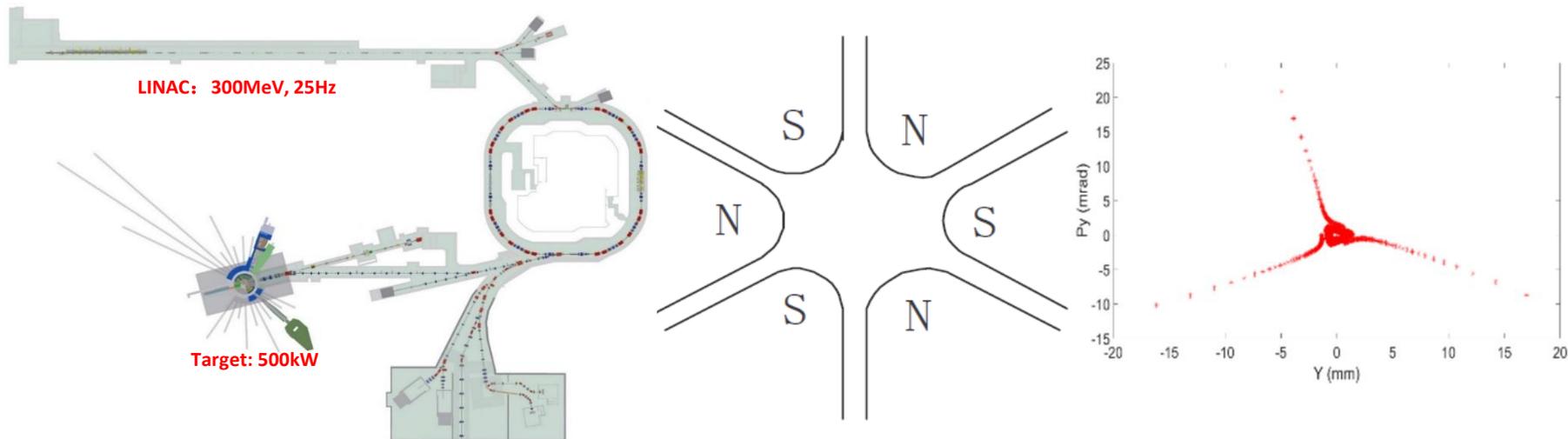
eg1: Correction of AC dynamic edge fields for main quads

- Due to the dynamic edge fields of the main quads through machine cycle on the CSNS/RCS ring, the tunes of the entire ramping time deviates from the design value.
- By using QTs, the tunes can be compensated to the design value through the 20-ms ramping time.



② Tunes optimization

eg2: Fast extraction with third-order resonance

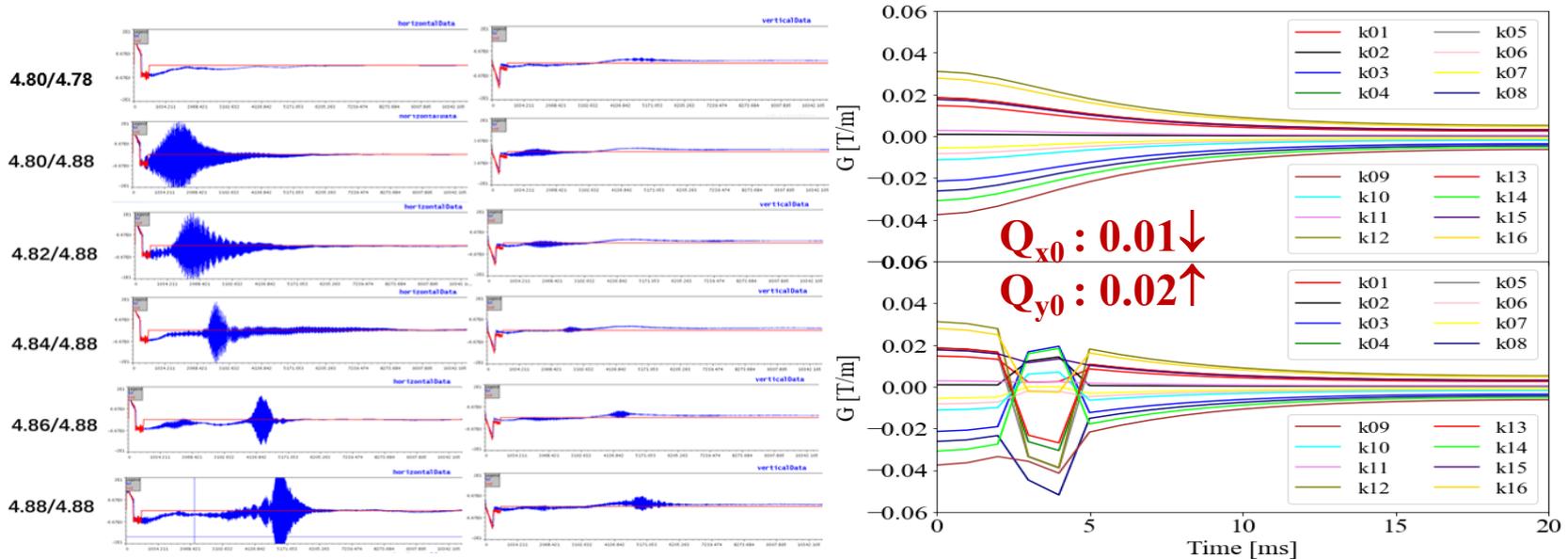


- The extraction of third-order resonance has important applications in proton imaging, spatial irradiation, cancer treatment, and other areas.
- The Q_y of CSNS/RCS was adjusted from 4.69 to 4.66 within $10 \mu\text{s}$ using QTs.
- Then sextupole magnets were used to drive third-order resonance.

② Tunes optimization

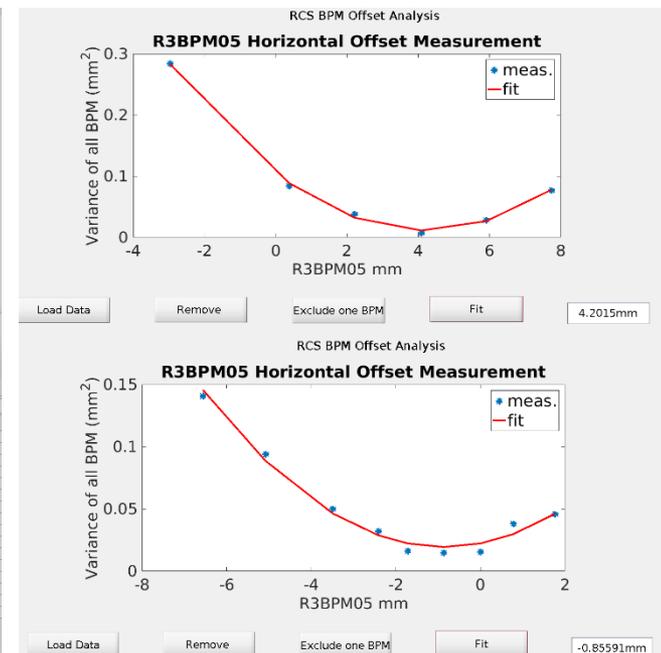
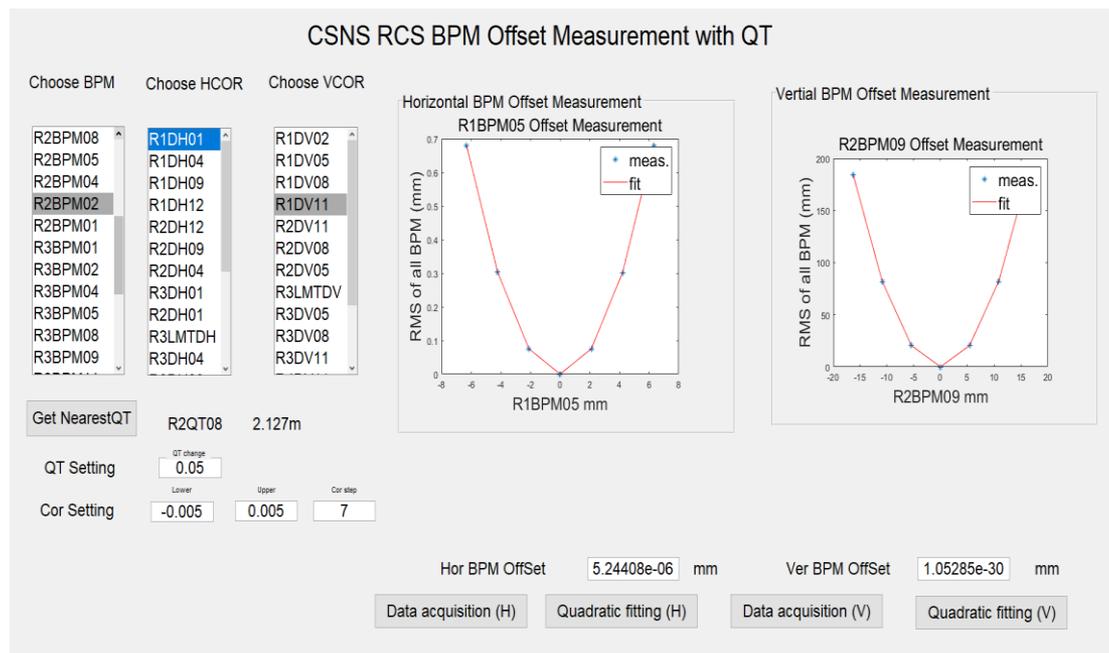
eg3: Suppressing beam instability

- It was found a very strong horizontal betatron oscillations occurs under certain bare tunes and beam powers.
- The beam instability can be suppressed with little oscillations by sextupole magnets.
- The beam instability can be further reduced by fine tuning the QTs. After the tuning, the beam became stable and met the requirements for routine operation.



③ BBA measurement

- BBA was successfully applied in many accelerators to measure BPM offsets.
- BBA could not be applied in CSNS/RCS without individual controlled quads.
- For high-intensity beams, it is crucial to control the COD within a small range, so it is urgent to know the true COD in CSNS/RCS.
- BPM offsets were measured smoothly after installing 16 QTs. The distance (center to center) between BPM05/BPM08 and QT is less than 0.3 m.
- During the beam experiment, RCS runs in the storage mode.



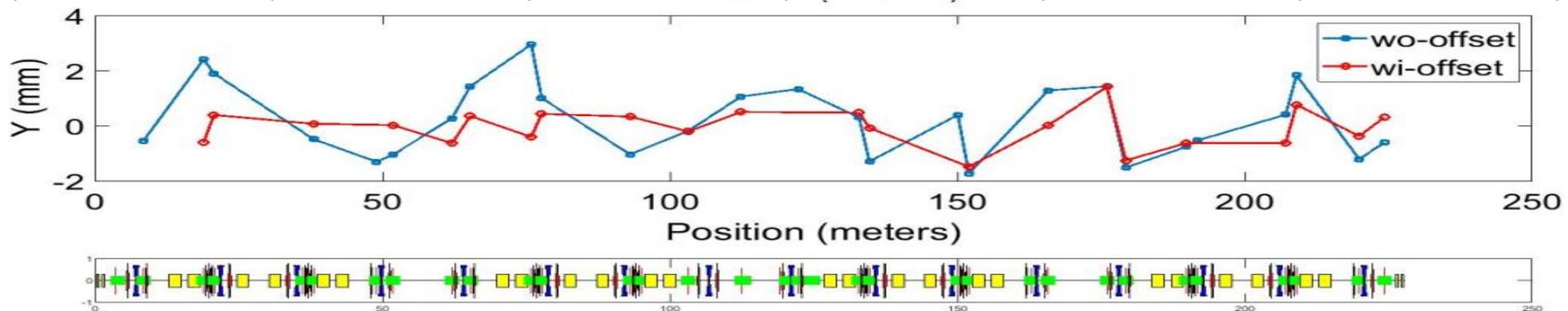
Applications of QTs



③ BBA measurement

- Several BPM offsets are around **4 mm**.
- The COD is smaller after orbit correction with the BPM offsets.

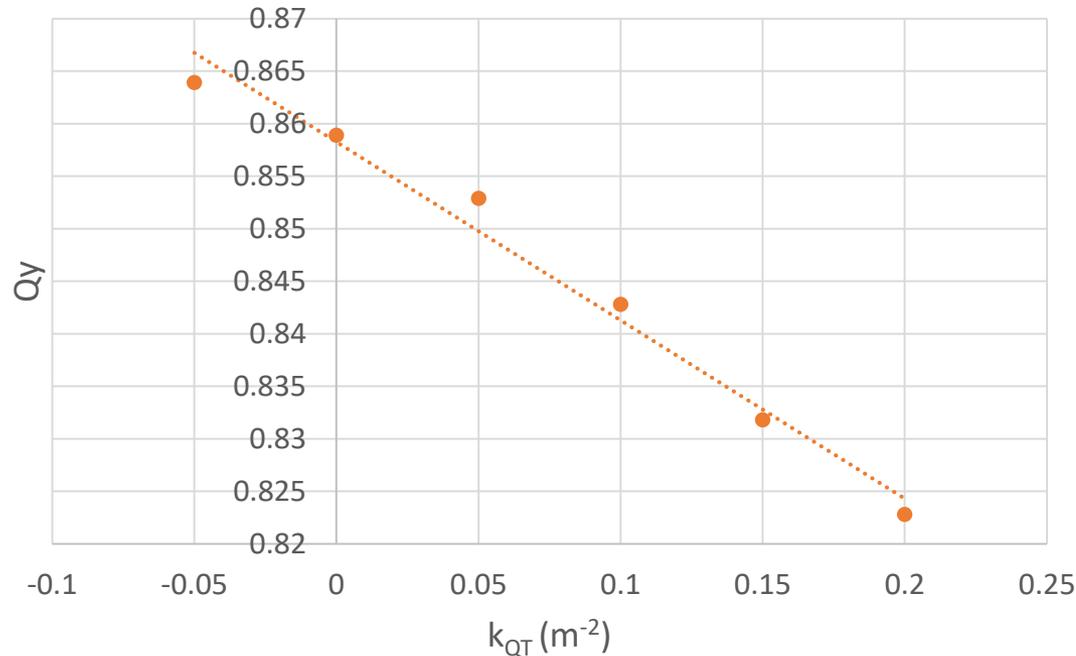
BPM	offset_X	offset_Y	BPM	offset_X	offset_Y
R1BPM01	2.9		R3BPM01		
R1BPM02	4.2		R3BPM02	0.28	
R1BPM04			R3BPM04		
R1BPM05	2.95	-2.52	R3BPM05	4.2	-0.6
R1BPM08	0.54	-1.23	R3BPM08		
R1BPM09	4.6		R3BPM09		
R1BPM11		-0.66	R3BPM11		-0.5
R1BPM12	0.7	-2	R3BPM12		-4.5
R2BPM12		-0.18	R4BPM12		
R2BPM11	1.56		R4BPM11		
R2BPM09			R4BPM09		
R2BPM08	2.45	-3.76	R4BPM08	2.4	-0.96
R2BPM05	1.02	-0.38	R4BPM05	0.46	-0.6



④ Beta function measurement

The beta function can also be measured with QTs based on the tune shift caused by the variation of QT strength.

$$\Delta\nu = \frac{1}{4\pi} \oint \beta(s_1)k(s_1)ds_1 \quad \longrightarrow \quad \langle \beta_{x,y} \rangle = 4\pi \frac{\Delta\nu_{x,y}}{\Delta KL}$$



⑤ Tune map measurement

Purpose:

- ✓ Find candidate tunes for CSNS-II
- ✓ Study nonlinear behaviors

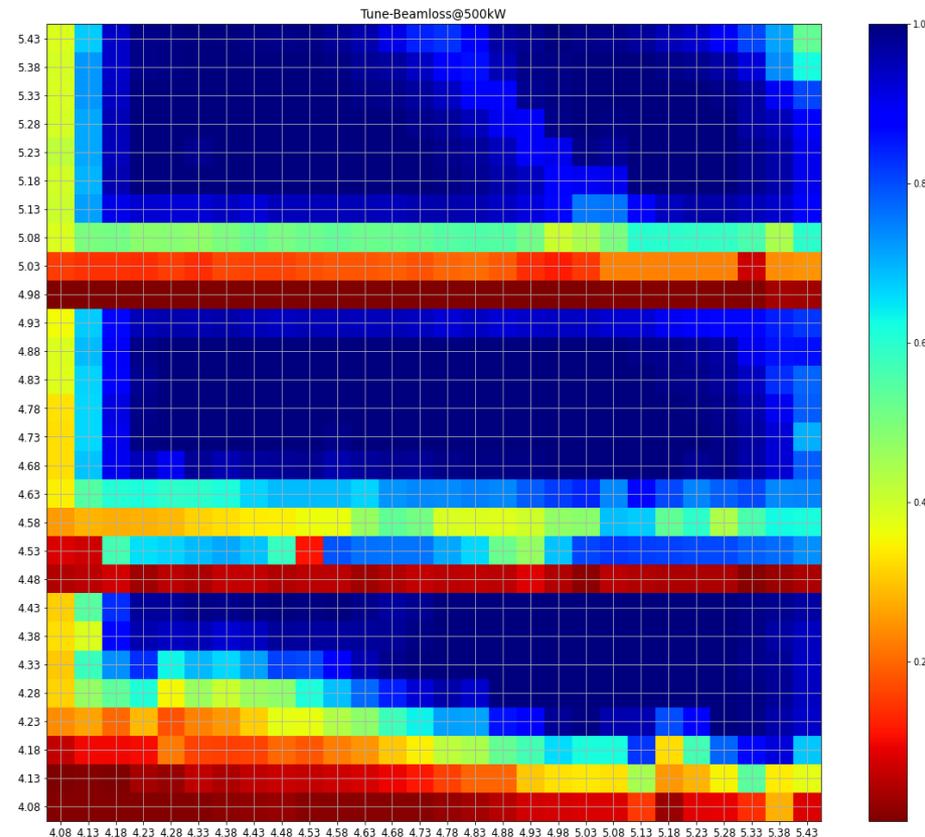
Simulation:

- ✓ PyORBIT code
- ✓ Scan range $4.0 < Q_{x,y} < 5.0$ (0.05)
- ✓ Only with space charge
- ✓ Structural resonances and half-integer resonances are important factors contributing to beam loss

Future plan:

- ✓ Simulate with all kinds of errors
- ✓ Beam experiments
- ✓ Automatically adjust QTs

Simulated CSNS-II tune map



- To address issues such as rapid manipulation of the working point, correction of twiss parameters, and restoration of the lattice, 16 programmable trim quads were successfully installed in CSNS/RCS.
- The experimental results on lattice restoration show that the β -function is effectively compensated, the beam loss and the emittance growth are significantly reduced with QTs.
- The trim quads will play an increasingly crucial role in the process of increasement of beam power.



Thank you!