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

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Outline

1 Background

2 Applications of QTs in CSNS/RCS

3 Summary

Airview map

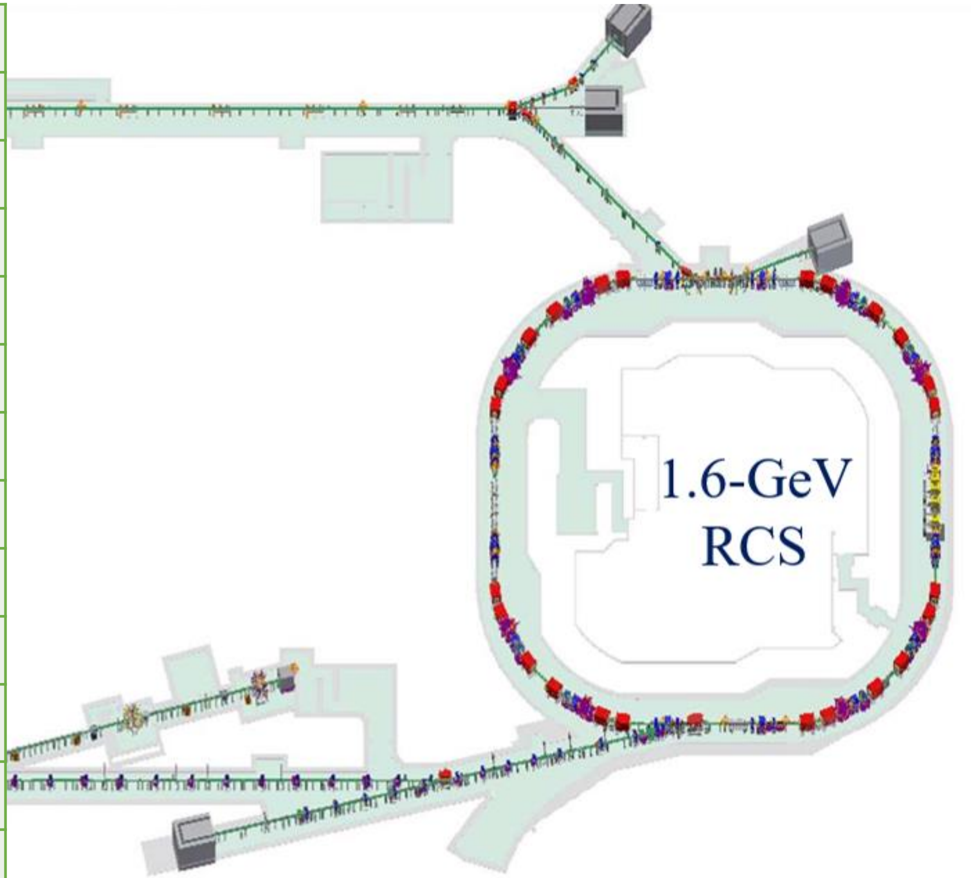

中国散裂中子源装置地A点拍摄（09.5.9）


中国散裂中子源工程进展照片（2017.6）
RCS
Target
Linac

Project Design

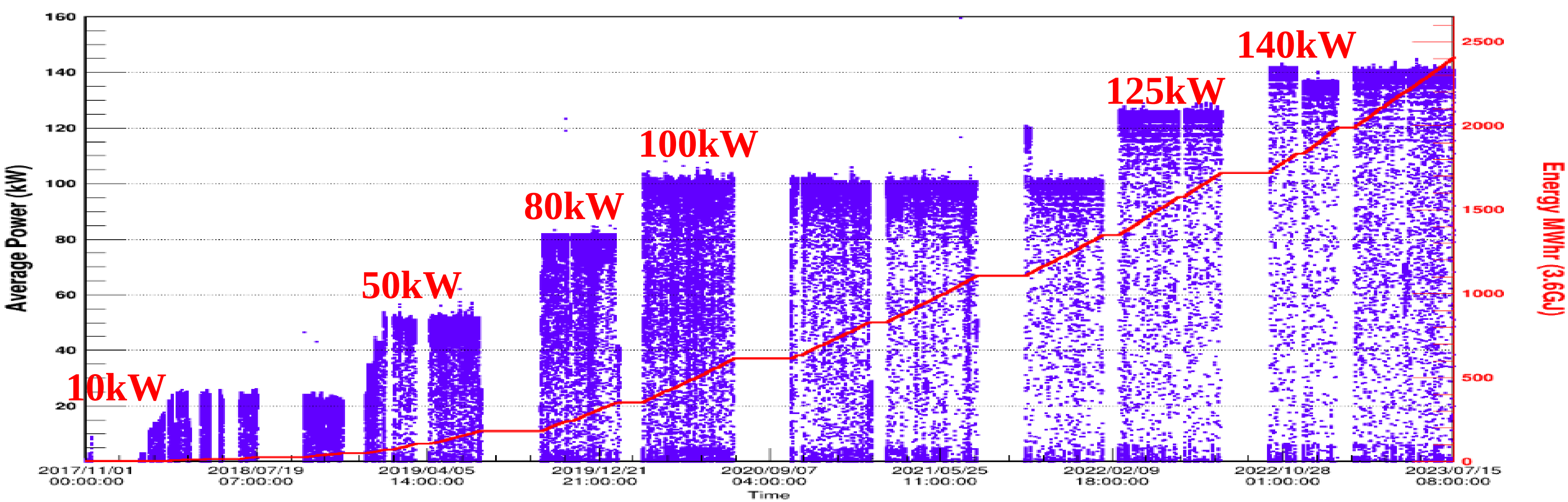
- **The phase-I CSNS facility consists of an 80-MeV H^- linac, a 1.6-GeV RCS, a target station, and 3 instruments.**

Project Phase	I	II
Beam Power on target [kW]	**100**	**500**
Proton energy [GeV]	**1.6**	**1.6**
Average beam current [μA]	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 [πmm-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



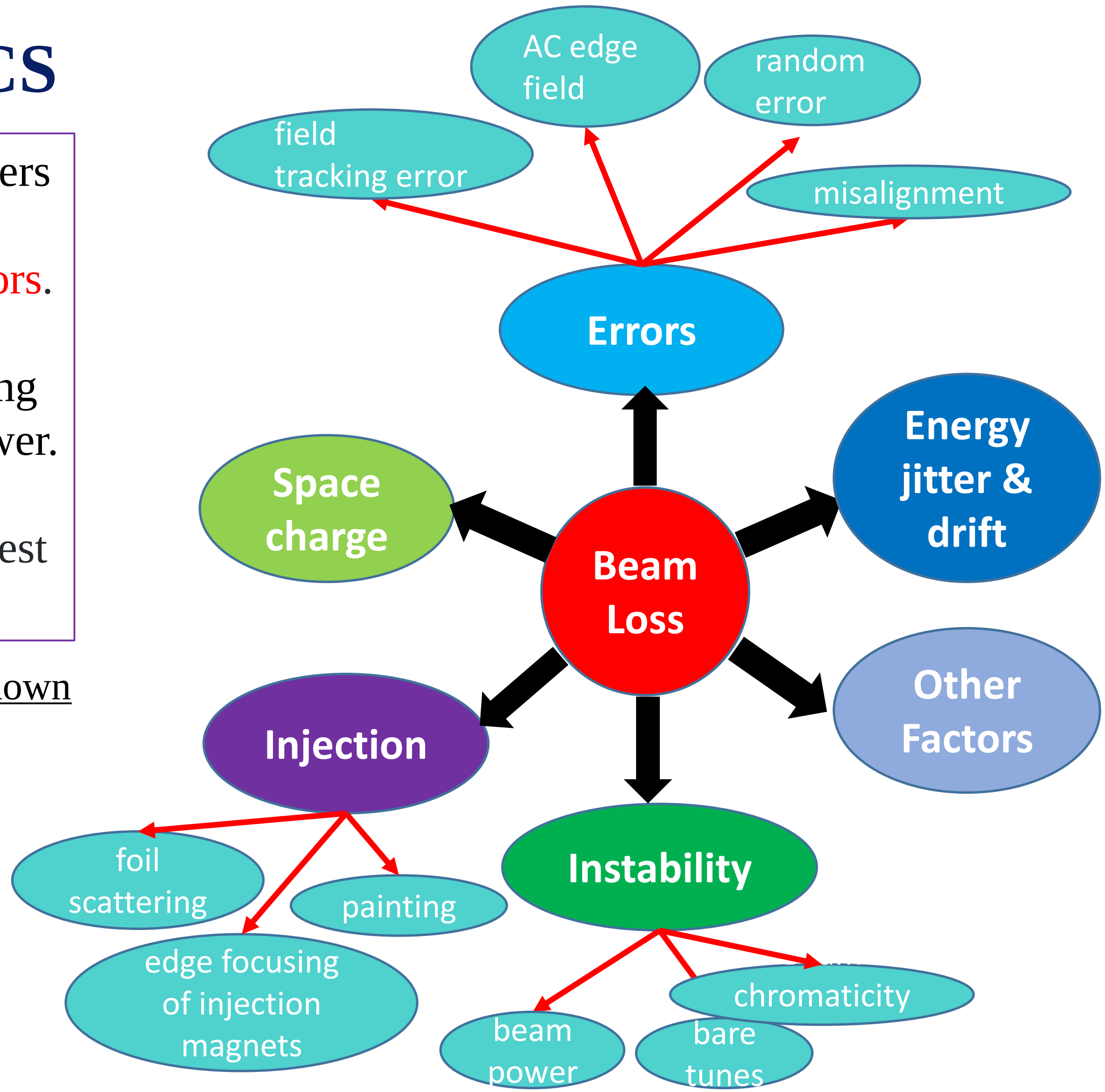
Issues in the beam commissioning

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.

<u>injection section@1h after shutdown</u>

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



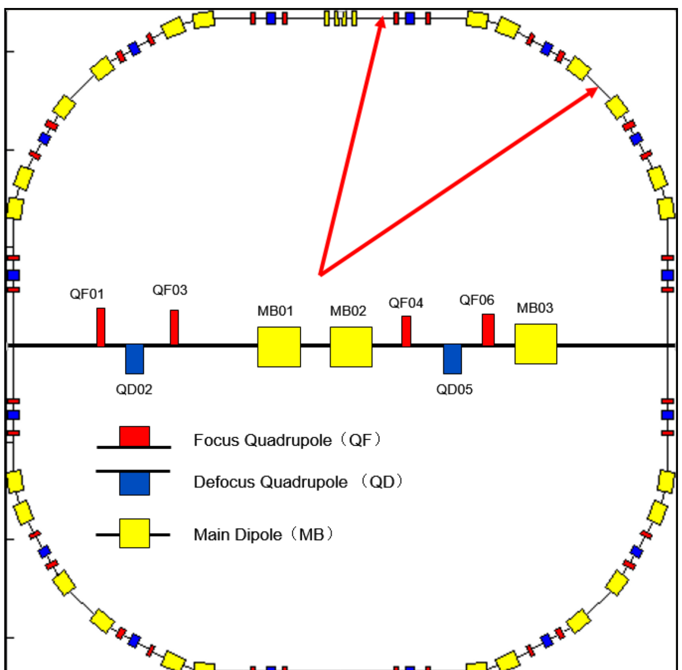
Issues in the beam commissioning

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*sin(w*t+p)+b1*sin(2*w*t+p1)+b2*sin(3*w*t+p2)……

- The variation of the optics through the machine cycle is relatively smooth
- Tuning optics with main quads in short time is difficulty, especially for rapidly variation

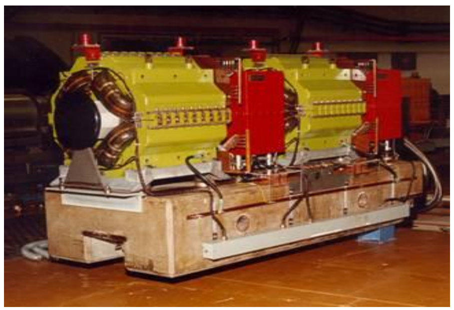


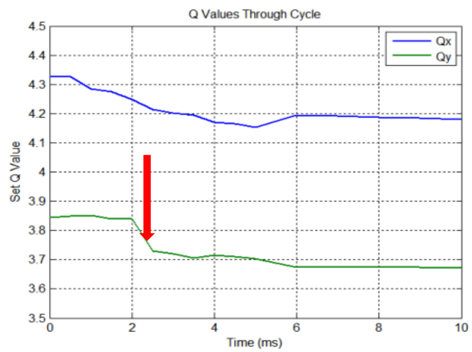
Harmonic \ Magnet		Q206A	Q272	Q206B	Q222	Q253
DC (A)		720.7	794.1	642.9	618.2	747.6
25Hz	Amp(A)	531.4	568.5	466.3	446.4	538.7
	Phase(π)	1.5	1.5	1.5	1.5	1.5
50Hz	Amp(A)	15.24	8.57	8.211	4.537	8.876
	Phase(π)	0.145	0.79	0.58	0.52	0.67
75Hz	Amp(A)	3.727	7.745	4.813	1.767	6.738
	Phase(π)	0.7	1.53	1.445	1.308	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

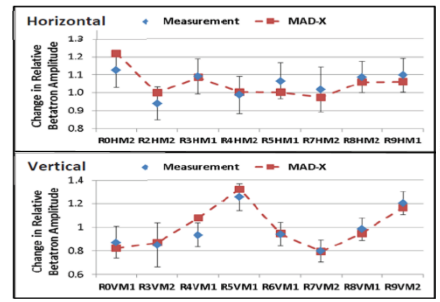
Applications of QTs in other machines

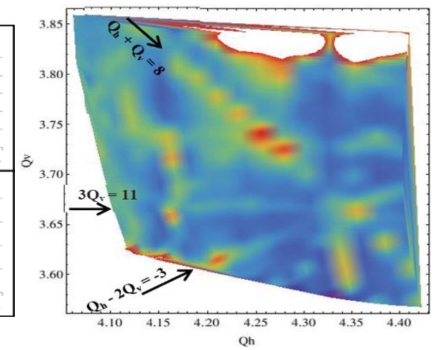
ISIS

- 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.



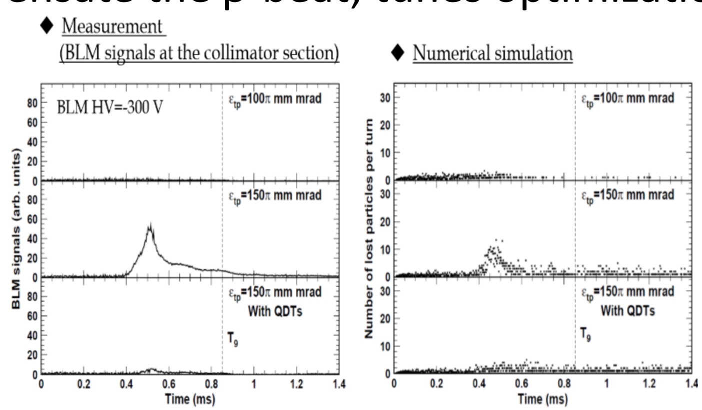


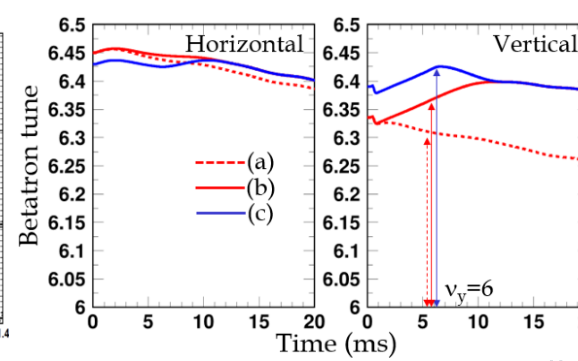




J-PARC

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





Design of trim quads

SNS

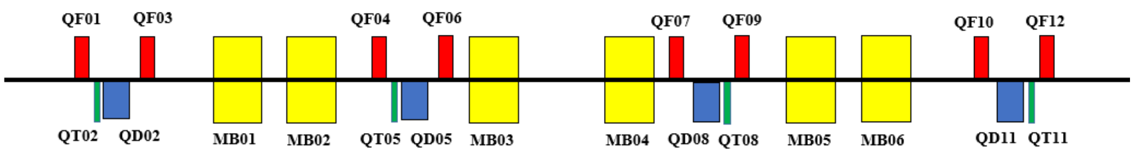
Design factors

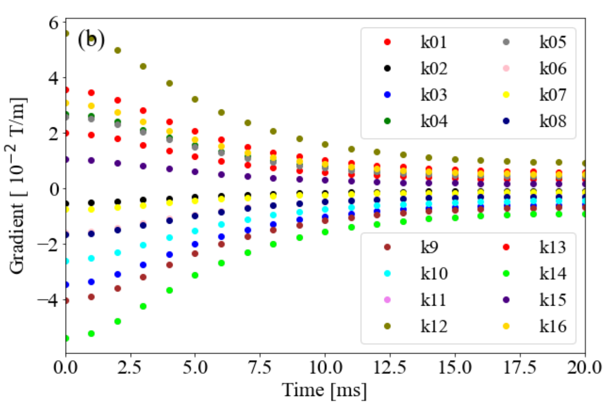
- Beta-beat correction (first 5ms)
- Tunes optimization (at least 10ms)

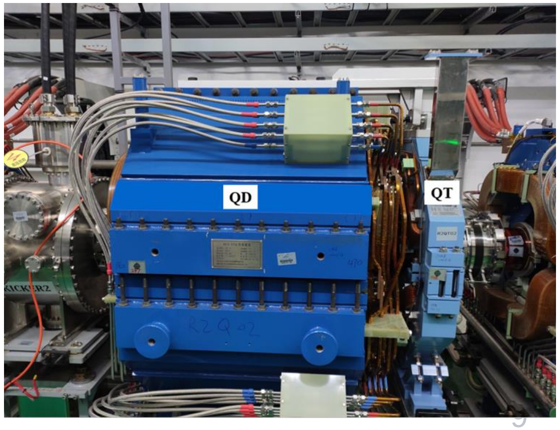
Final parameters

- 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



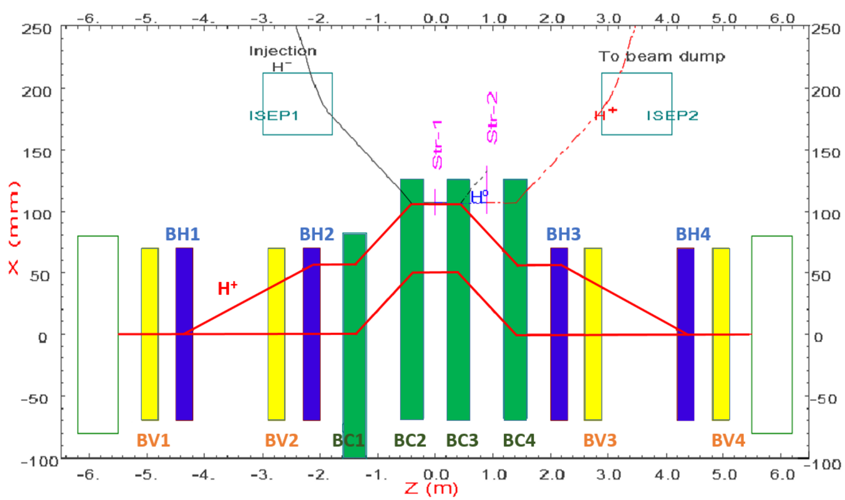




Applications of QTs

① Super-periodicity restoration

1：Injection system



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

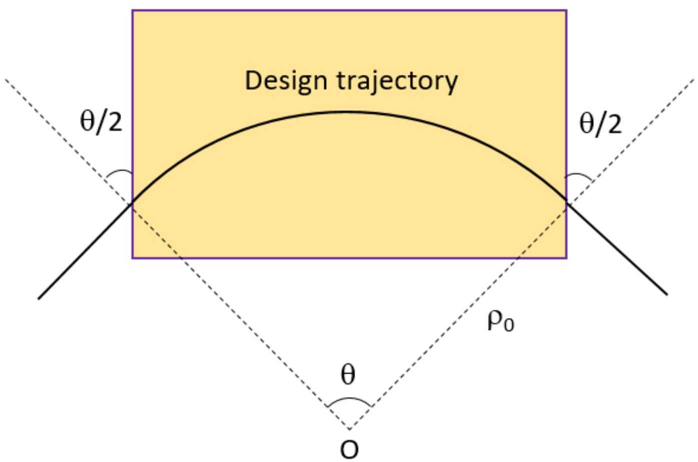
- The transverse injection painting scheme is widely adopted in many high-intensity hadron synchrotrons to alleviate space charge effects.
- The CSNS injection system consists of 12 rectangular dipole magnets.
- BH1~BH4 and BV1~BV4 are pulse-type bump magnets, which are used to generate dynamic orbit 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.

Applications of QTs

SNS

① Super-periodicity restoration

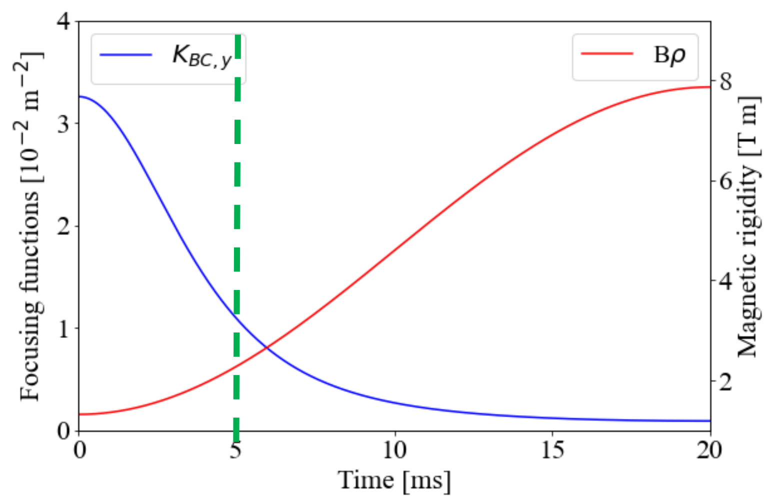
2：Edge focusing of injection bump magnets



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

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

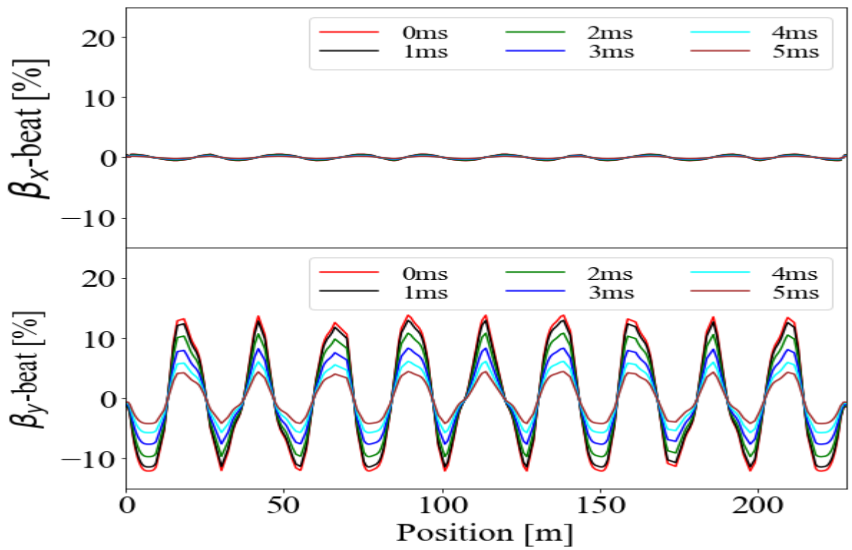
- The edge focusing effect of the horizontal bump magnet causes the focusing effect only in the vertical plane and the horizontal focusing is completely canceled by the intrinsic focusing property on the bending plane.
- The vertical edge focusing strength is relatively large in the first 5 ms.



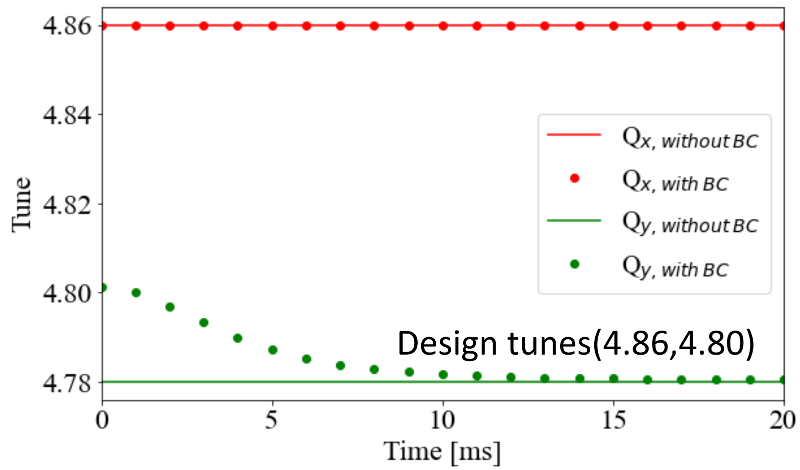
① Super-periodicity restoration

3：Edge focusing effects

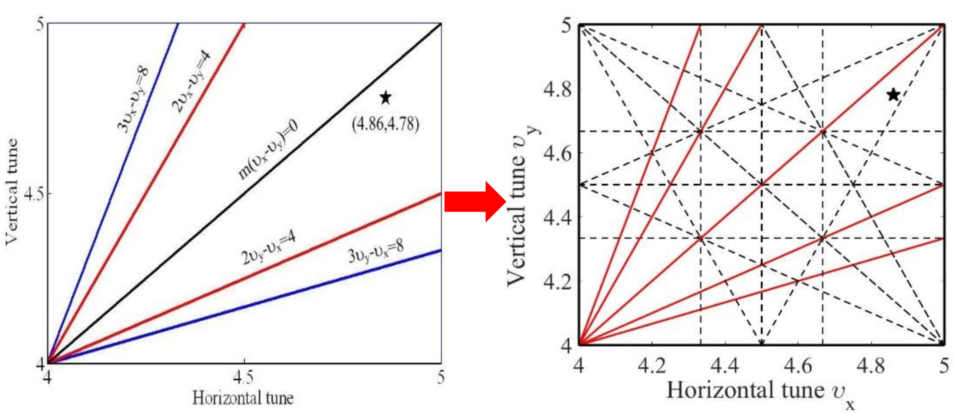
β-beating@MAD-X



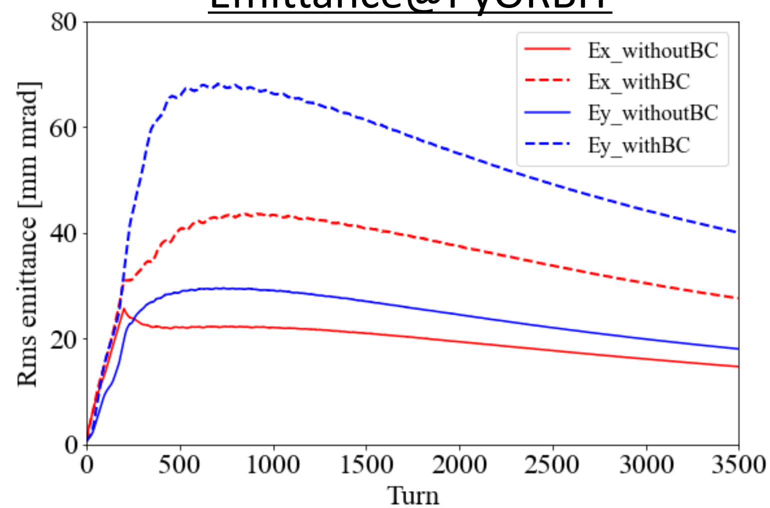
tunes@MAD-X



resonance line



Emittance@PyORBIT



Applications of QTs

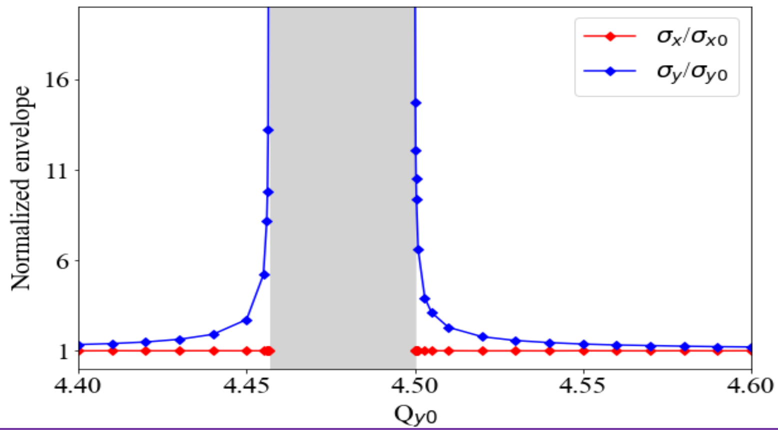
① Super-periodicity restoration

4: Half-integer resonance caused by edge focusing effects

without space charge

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

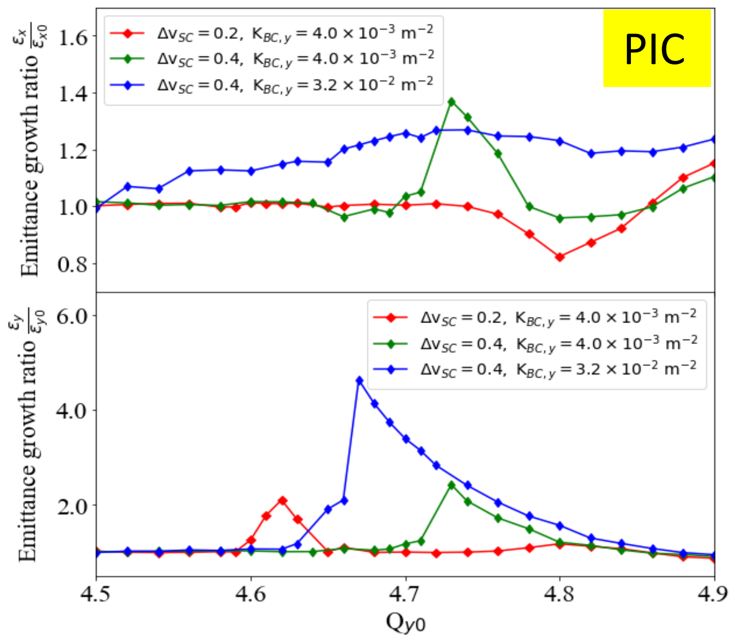
$$\frac{\Delta\beta_y(s)}{\beta_y(s)} = -\frac{\nu_{y0}}{2}\sum_{p=-\infty}^{\infty}\frac{J_p e^{jp\phi}}{\nu_{y0}^2-(p/2)^2}$$



- 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

$$2Q_{y0} - \Delta\Omega^{(2)}_{sc,y} = 2Q_{y0} - 2C_2\Delta Q_{sc,y} = 9$$



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

Applications of QTs

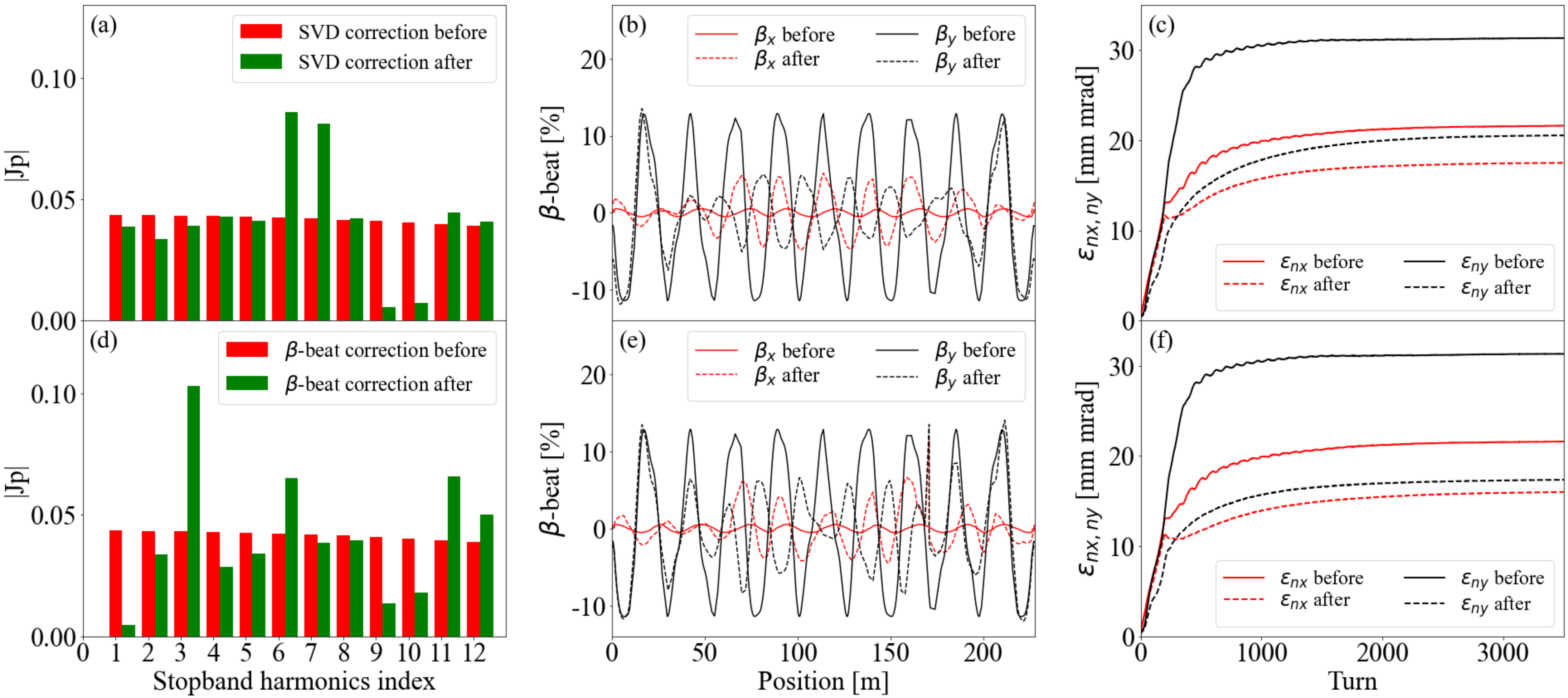
① Super-periodicity restoration

5：Two QT-based schemes

① SVD harmonics correction ->J_9 & J_{10}

② β-beat correction ->β function

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



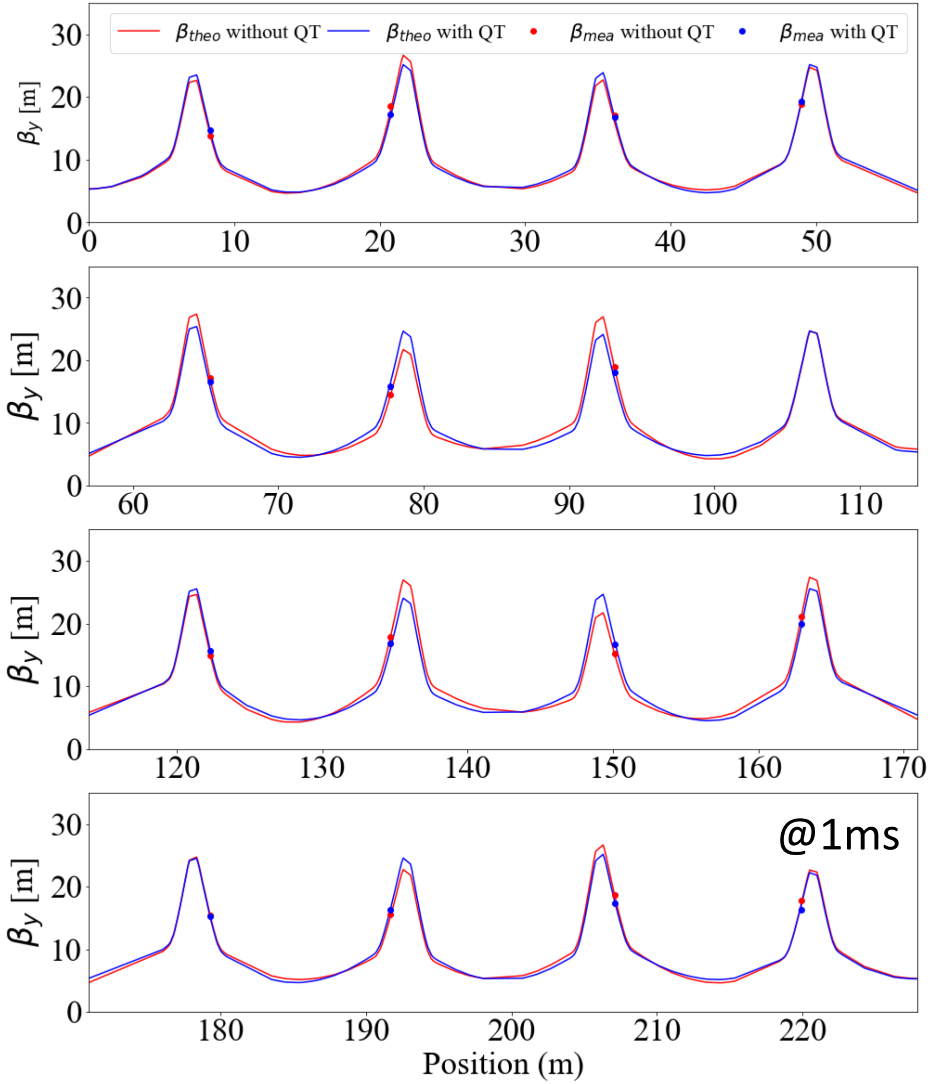
Applications of QTs

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.



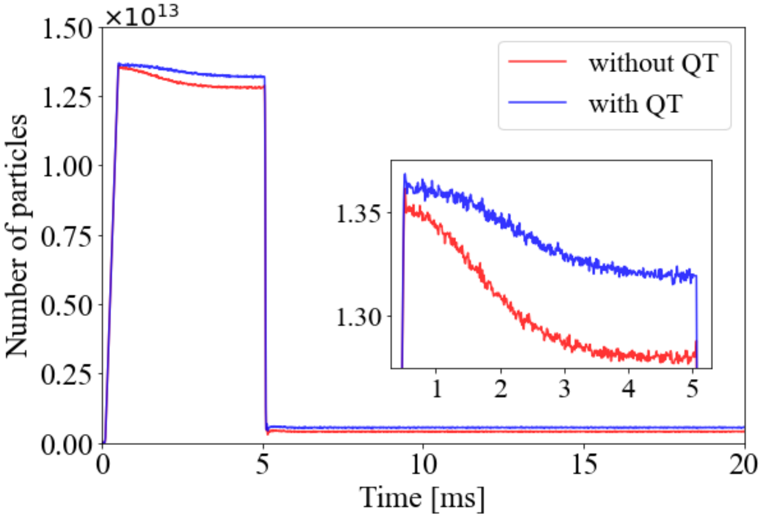
Applications of QTs

① Super-periodicity restoration

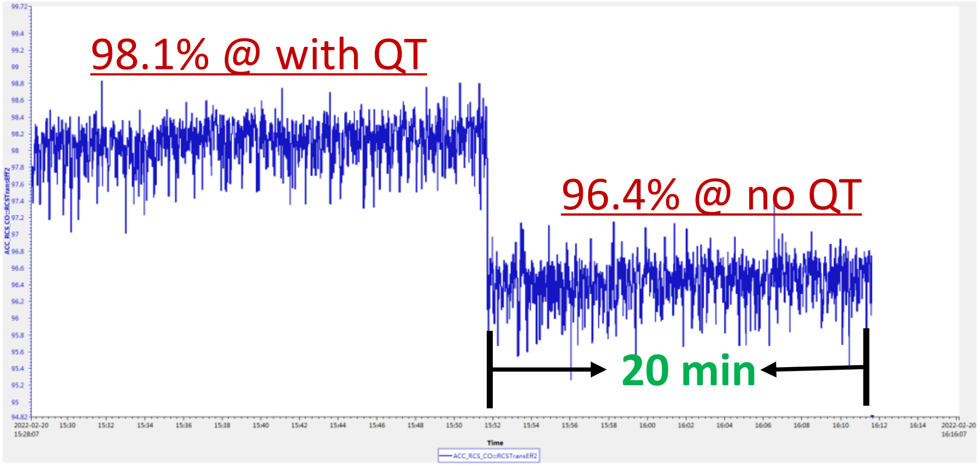
6： Experimental results

② Beam loss and beam power

(4.86,4.80) @90 kW



Operating mode @125 kW



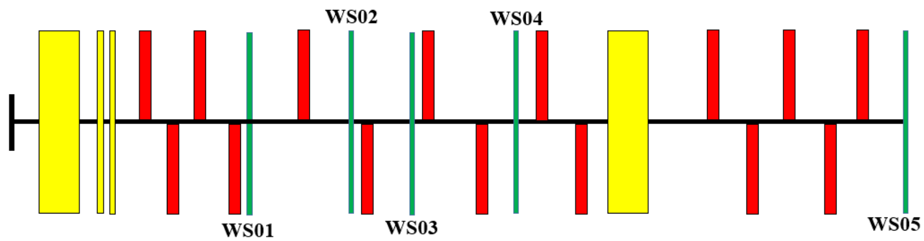
- More particles survive in the beams in the presence of QTs than that without QTs, with a reduction ratio of beam loss by 2% – 3%.

Applications of QTs

① Super-periodicity restoration

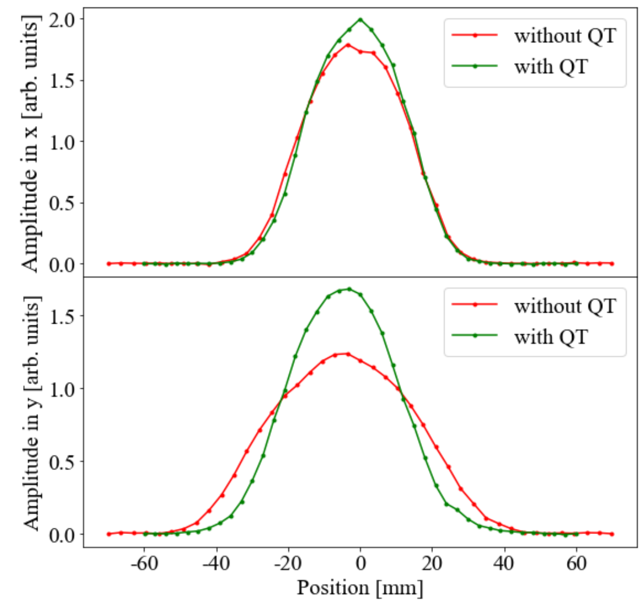
6： Experimental results

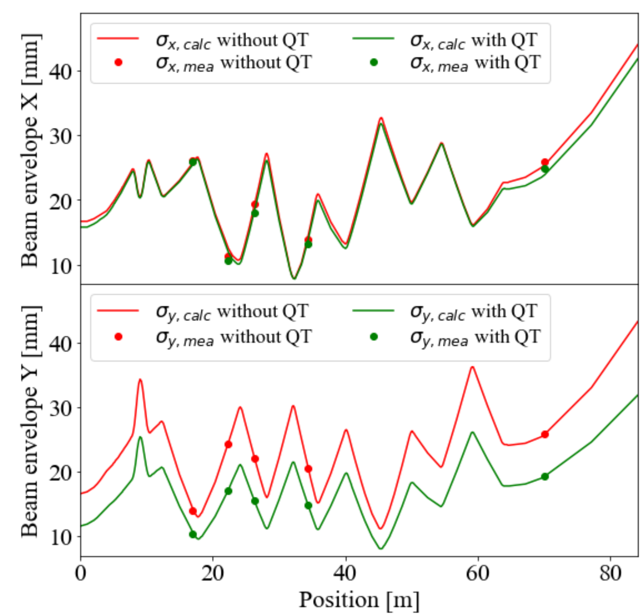
③ Beam Emittance



Cases	$\varepsilon_{nx,\,mea}$	$\varepsilon_{ny,\,mea}$	$\varepsilon_{nx,\,sim}$	$\varepsilon_{ny,\,sim}$
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.





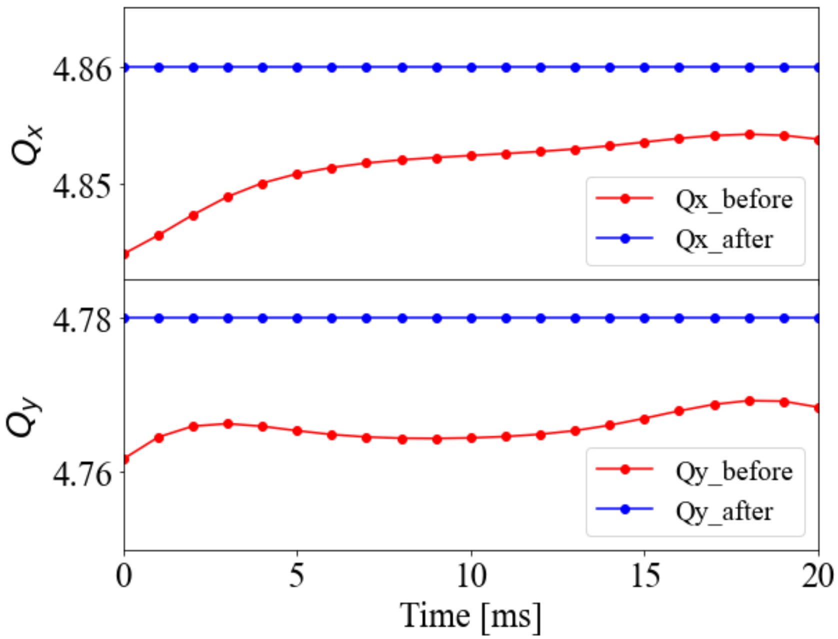
Applications of QTs

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.

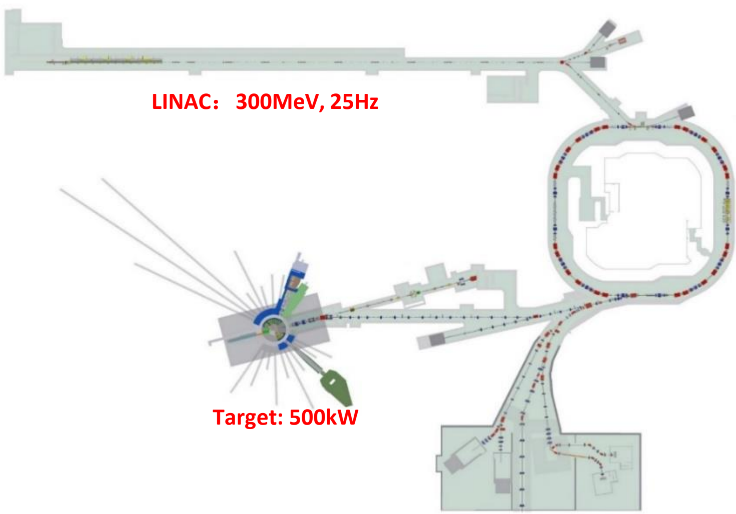
eg1： Correction of AC dynamic edge fields for main quads

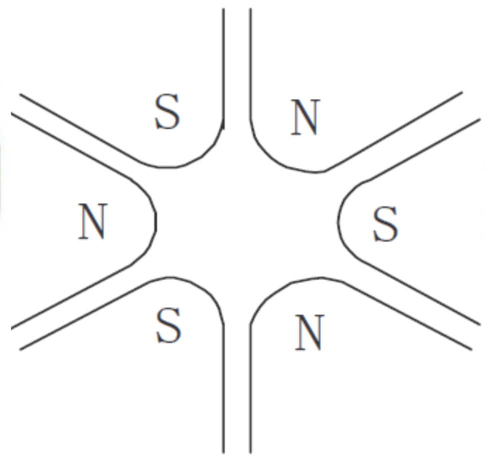
- Due to the dynamic edge fields of the main quads through machine cycle on the CSNS/RCS ring, the tunes of the entire ramping time deviates from the design value.
- By using QTs, the tunes can be compensated to the design value through the 20-ms ramping time.

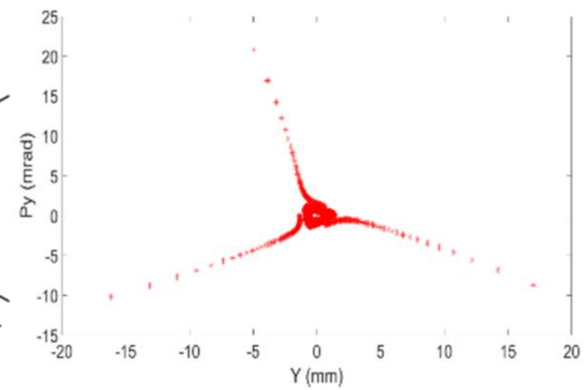


② Tunes optimization

eg2： Fast extraction with third-order resonance







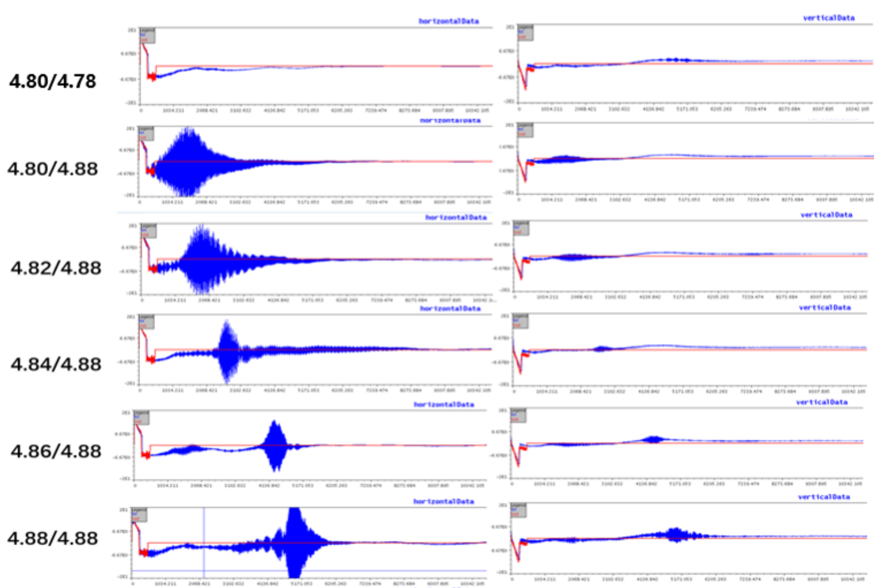
- The extraction of third-order resonance has important applications in proton imaging, spatial irradiation, cancer treatment, and other areas.
- The Q_y of CSNS/RCS was adjusted from 4.69 to 4.66 within **10 μs** using QTs.
- Then sextupole magnets were used to drive third-order resonance.

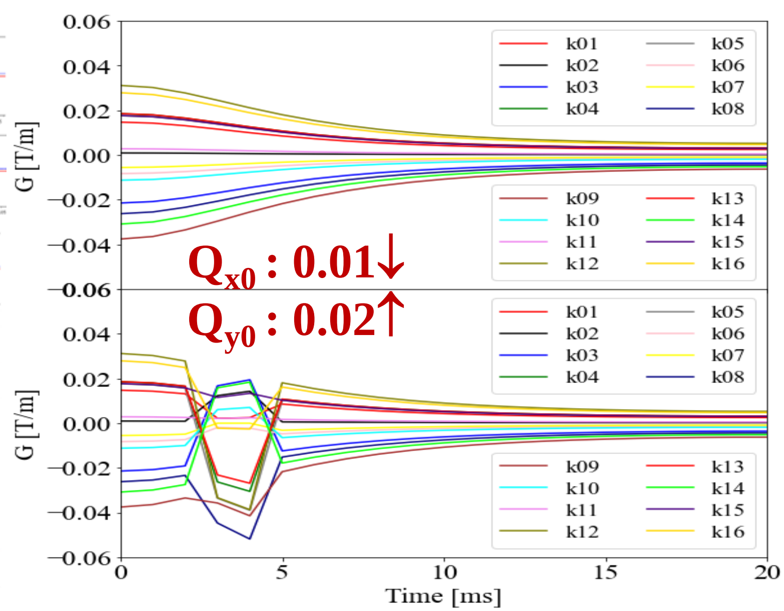
Applications of QTs

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.

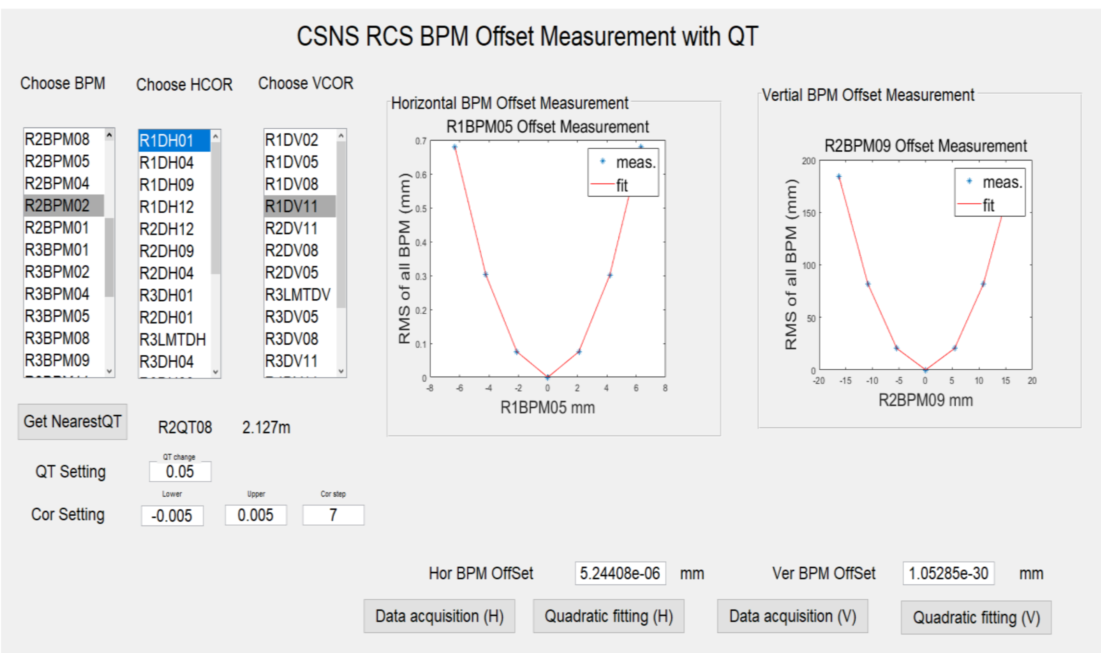


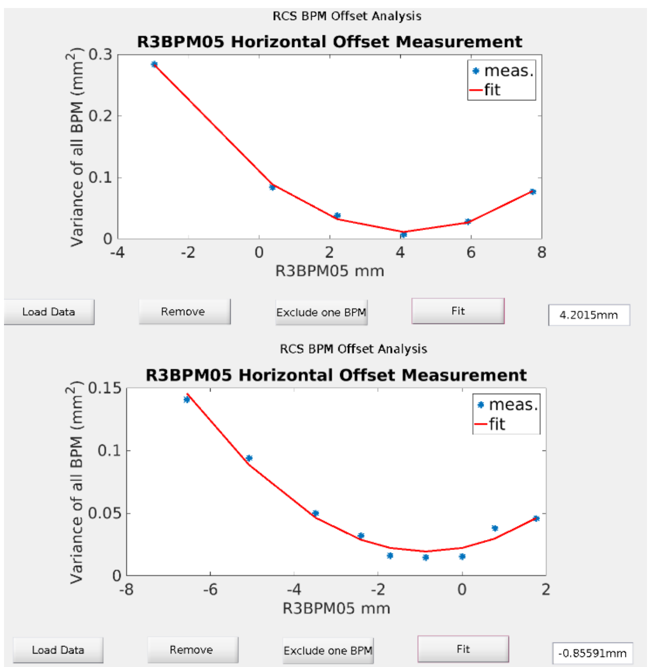


Applications of QTs

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.





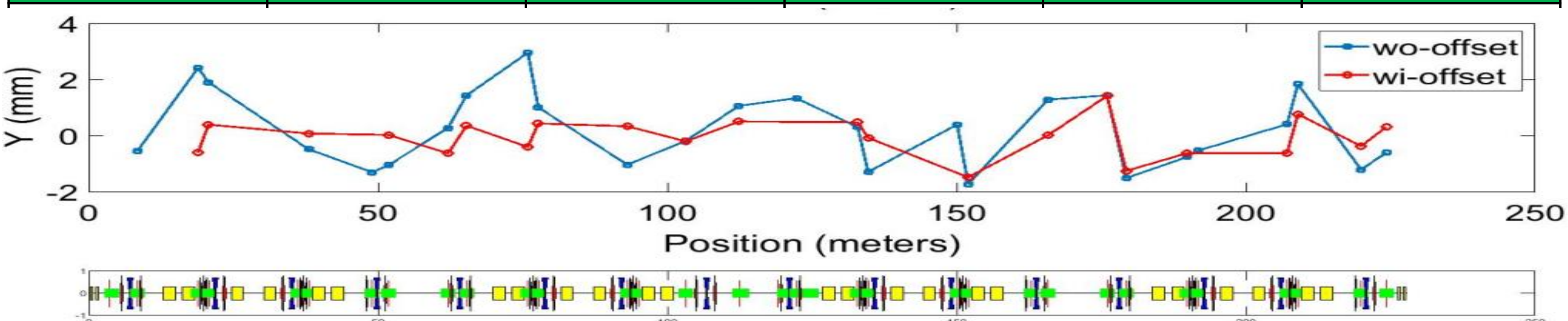
Applications of QTs

SNS

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

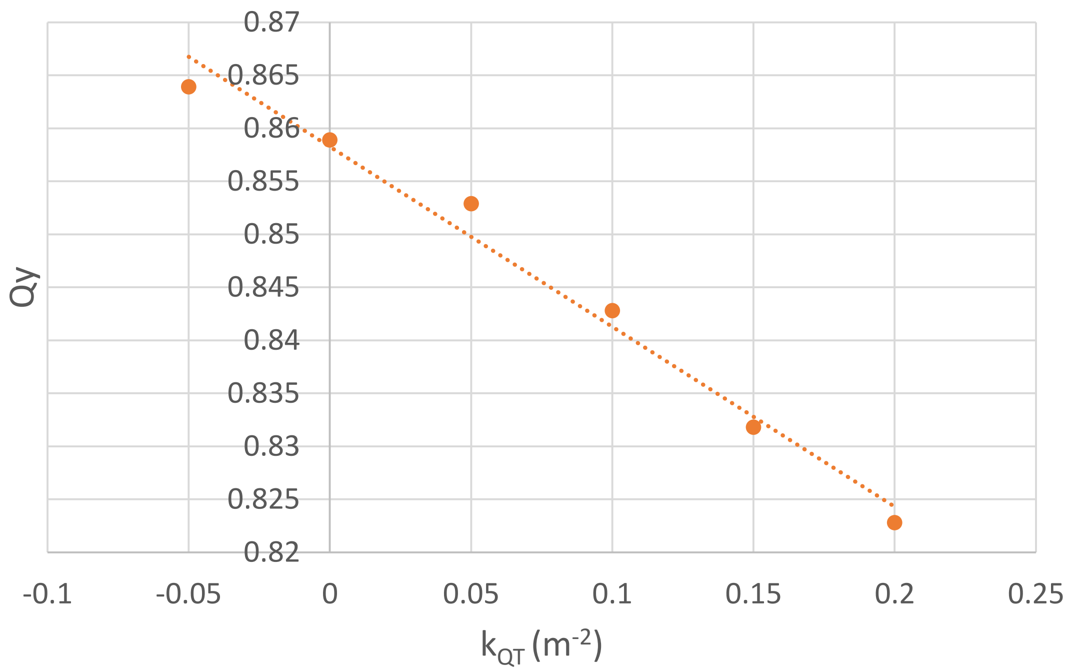


Applications of QTs

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.

$$\Delta\upsilon = \frac{1}{4\pi}\oint \beta(s_1)k(s_1)ds_1 \Rightarrow <\beta_{x,y}> = 4\pi\frac{\Delta\upsilon_{x,y}}{\Delta KL}$$



Applications of QTs

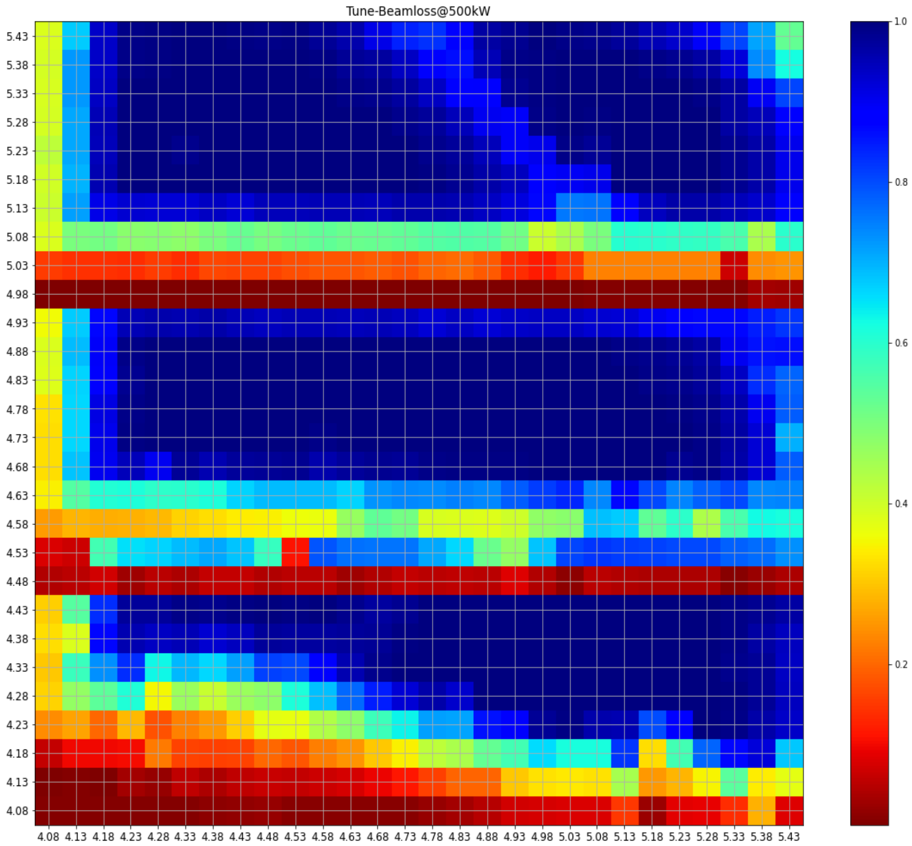
⑤ Tune map measurement

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



Summary

- 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 !