Beam commissioning and upgrade progress for the CSNS-II RCS

Ming-Yang Huang

Institute of High Energy Physics, Chinese Academy of Sciences

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Outline

I. Introduction

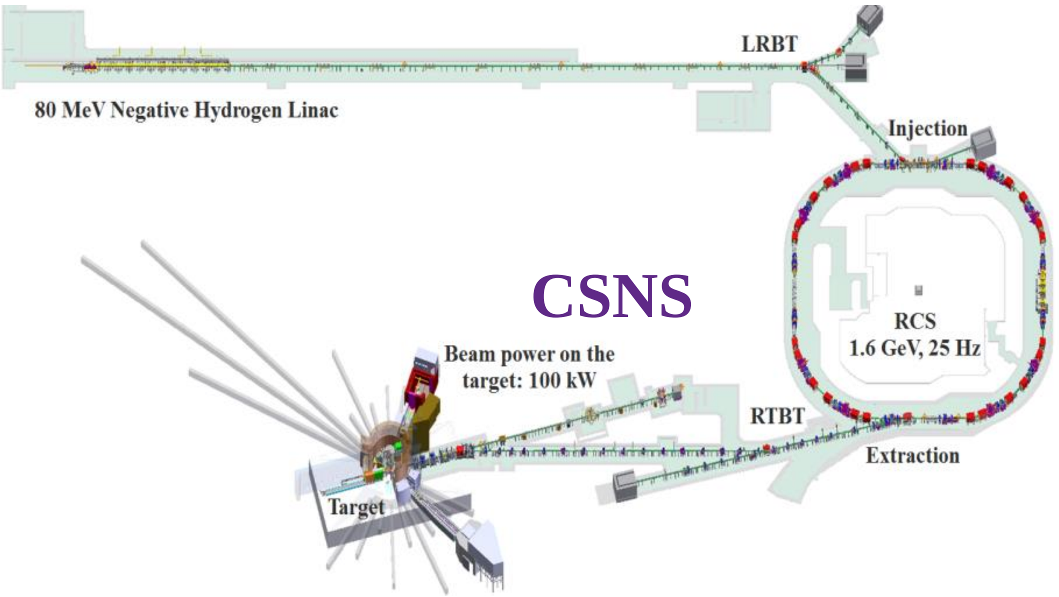
II. Beam commissioning for the RCS

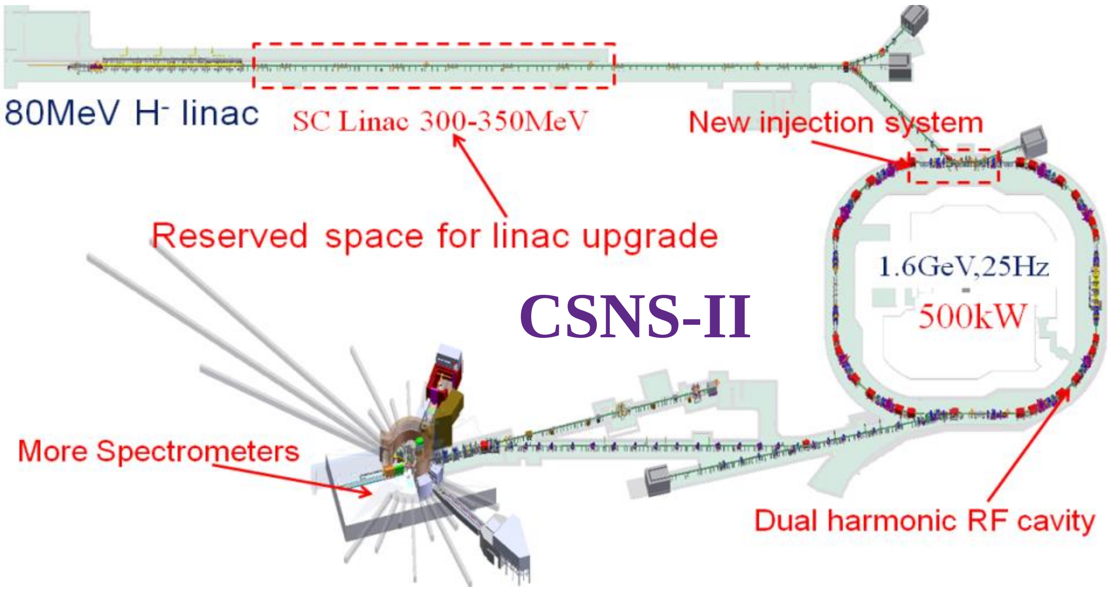
III. Upgrade progress for the CSNS-II RCS

IV. Summary

I. Introduction

- The CSNS facility consists of an 80 MeV H^- Linac, a 1.6 GeV RCS, two beam transport lines, a target station, and several instruments
- The design goal of beam power on the target for the CSNS is 100 kW which has been achieved in Feb. 2020
- Main goal of CSNS-II: increase the beam power on the target to 500 kW
- Main contents of CSNS-II accelerator upgrade: Linac upgrade; injection system upgrade; three dual harmonic cavity would be added to the RCS





CSNS brief history

- Feb. 2001 — Proposal for the CSNS Project
- Jan. 2006 — Prototyping R&D started
- Sep. 2008 — Proposal approved
- Sep. 2011 — Construction started
- May 2012 — Civil construction started
- Oct. 2014
- Jan. 2016 — DTL-1 Beam commissioning
- Apr. 2017 — Linac beam commissioning
- May. 2017 — RCS commissioning start
- Aug. 2017 — First beam on target, first neutron beam
- Mar. 2018 — Construction complete (6.5 years from start)
- Mar. 2020 — 100kW

CSNS beam history

Installation of a new dual harmonic RF cavity (Oct. 2022)

Detailed optimizations in many aspects (Mar. 2024)

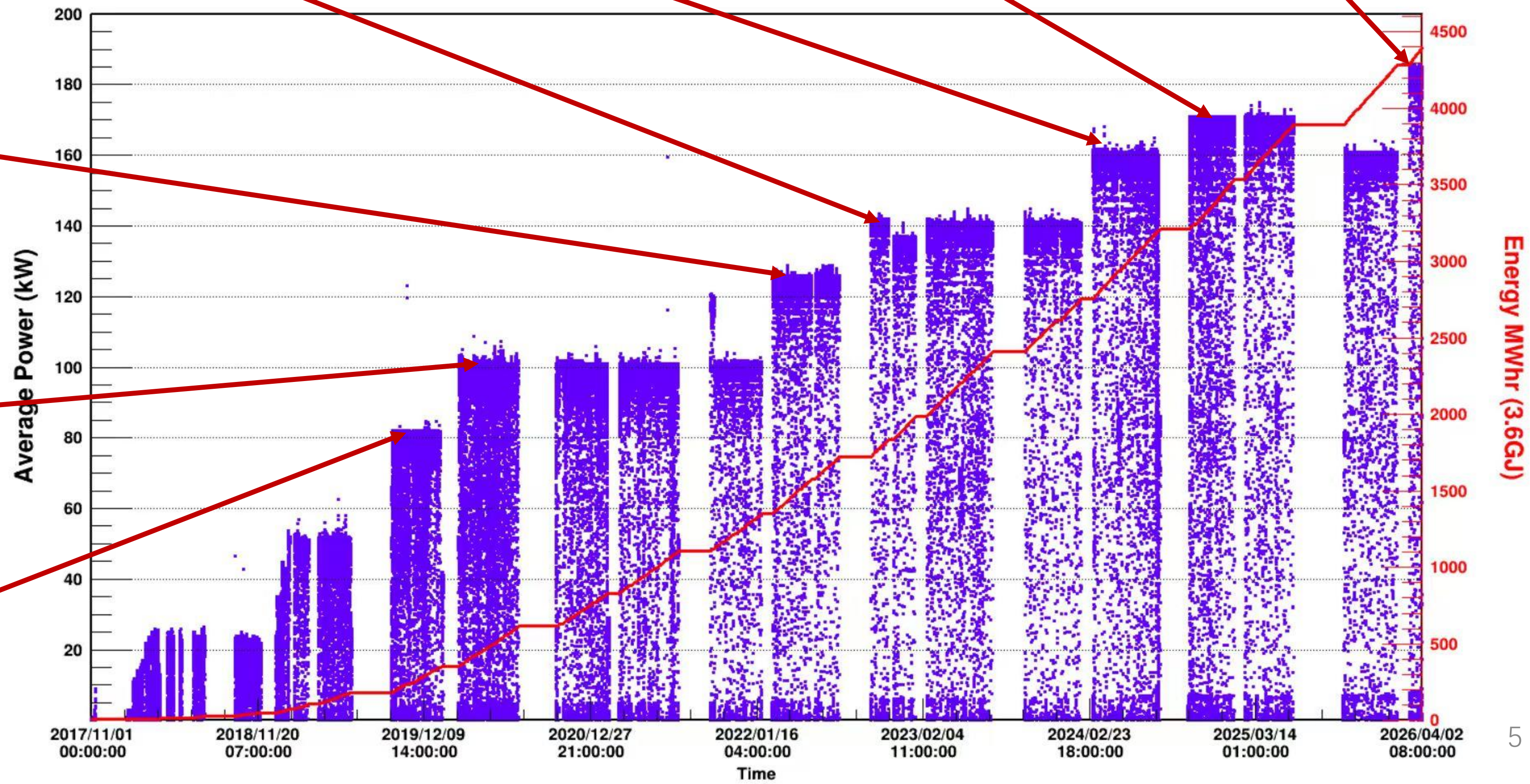
Optimization of vertical painting area (Oct. 2024)

New injection system and painting method (Mar. 2026)

Slight modification of injection system, installation of new AC trim quadrupoles and AC sextupoles (Feb. 2022)

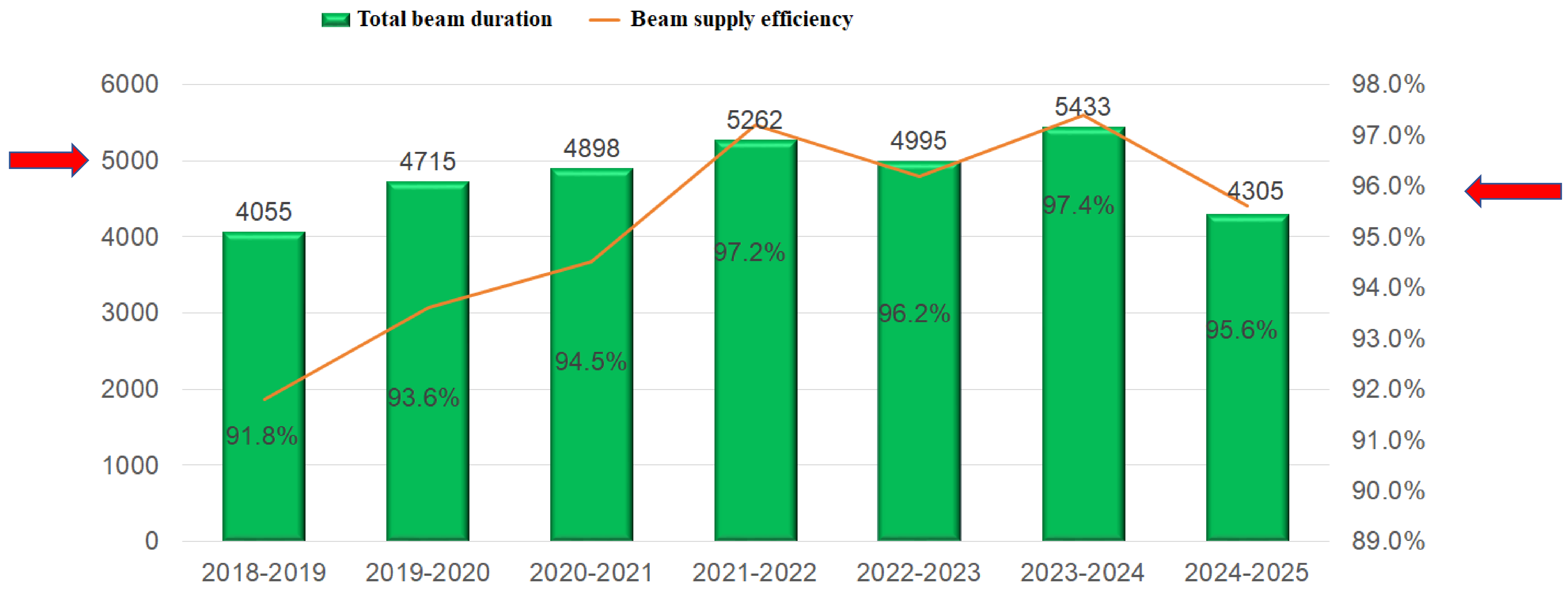
With the optimization of tune and chromaticity (Mar. 2020)

By switching from anti-correlated to correlated painting (Sep. 2019)

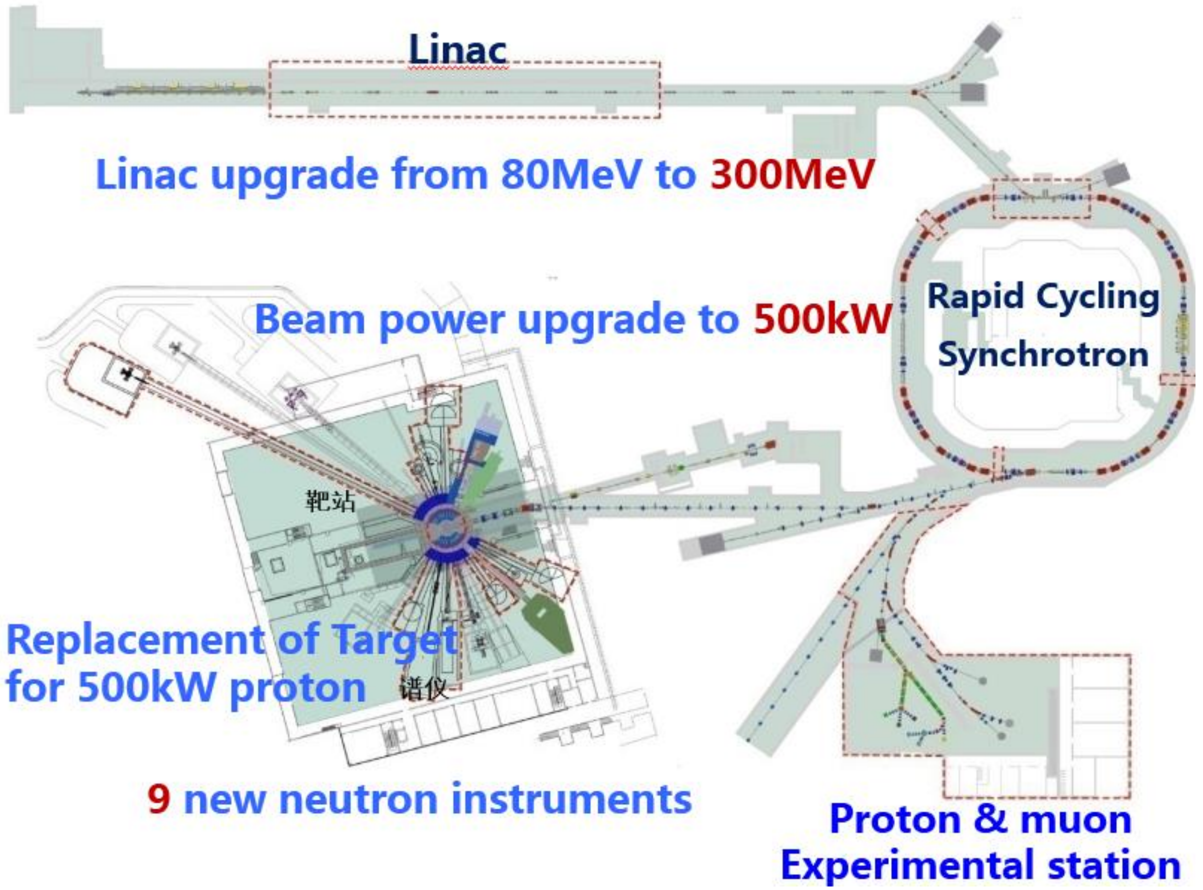


Operation of the CSNS

- Comparison of operational indicators across seven operational years since the opening for operation



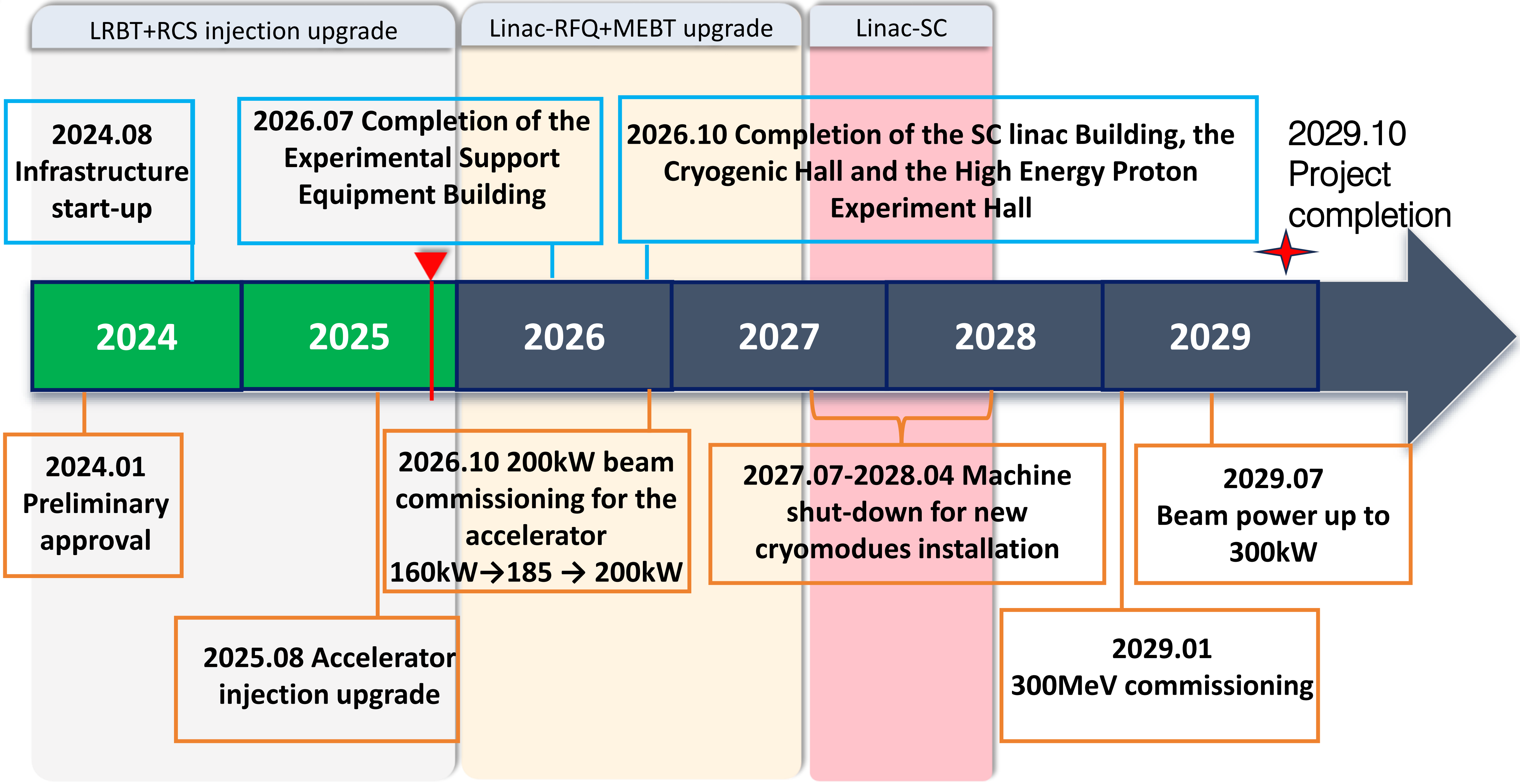
Second phase of the CSNS (CSNS-II)



- **Linac（80 MeV）+ RCS upgrade 150~200 kW**
  - ✓ New dual harmonic RF system
  - ✓ AC trim quadrupoles, sextupoles and octupoles
- **Linac （300 MeV+）+ upgraded RCS 500 kW**
  - ✓ New injection system
  - ✓ SC Linac to 300 MeV

- **Project Budget: 2.9 BCNY, Funded by central and Guangdong local government**
- **Construction: 2024.1~2029.9 （5 years and 9 months）**

CSNS-II Time Schedule



II. Beam commissioning for the RCS

1. Low-intensity beam commissioning
2. Intense beam issues

    2.1 Space charge effects

        (1) Tune pattern optimization

        (2) Method to achieve the correlated painting

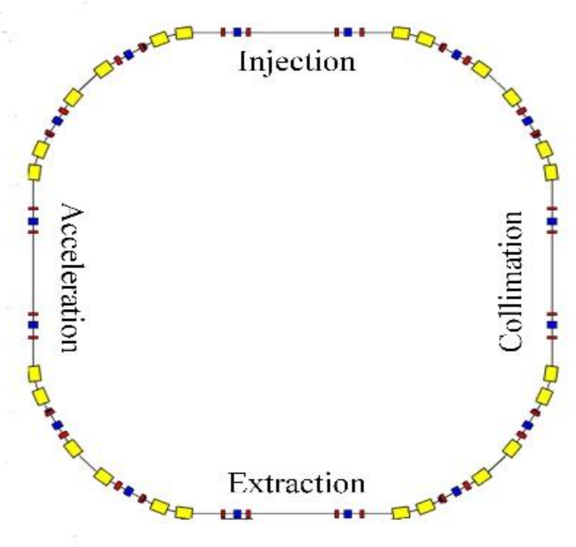
        (3) Super-periodicity restoration

        (4) Optimization of the bunching factor

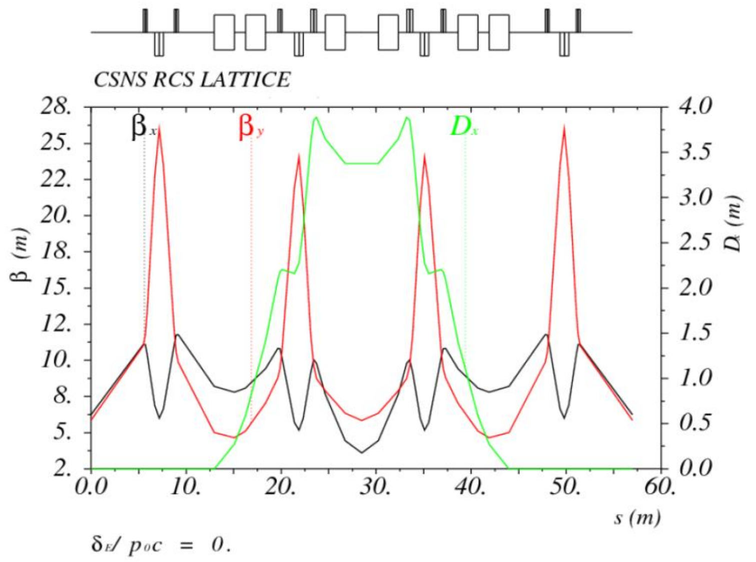
    2.2 Beam instability

Introduction of the CSNS RCS

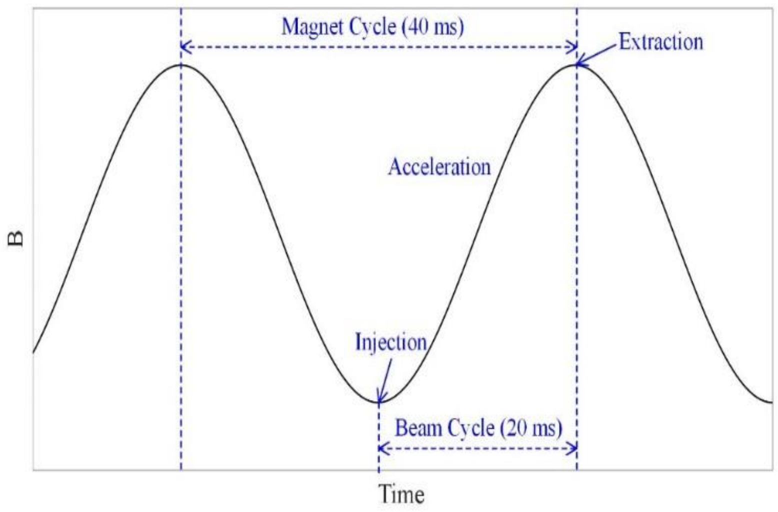
Output Beam Power [kW]	100
Injection Energy [MeV]	80
Extraction Energy [GeV]	1.6
Pulse repetition rate [Hz]	25
Acceleration Time [ms]	20
Circumference [m]	227.92
Number of dipoles	24
Number of quadrupoles	48
Lattice Structure	Triplet
Nominal Betatron Tune (H/V)	(4.86, 4.78)
Natural Chromaticity	-4.0/-8.2
Ring Acceptance [π·mm·mrad]	540
Harmonic Number	2
Number of Particles per Pulse	1.56×10^{13}
Space-Chare Tune Shift	-0.28

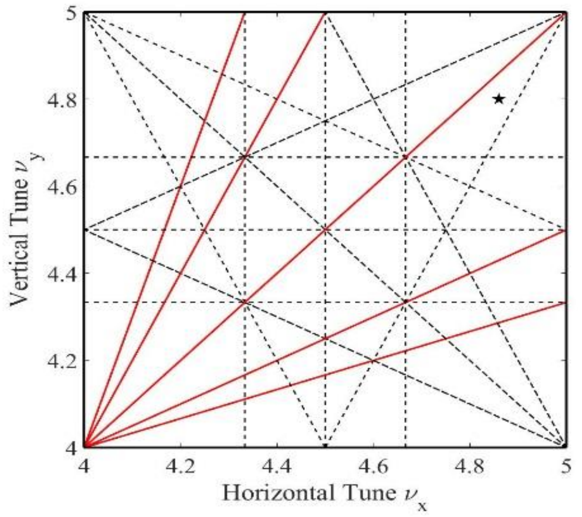


Layout of the RCS



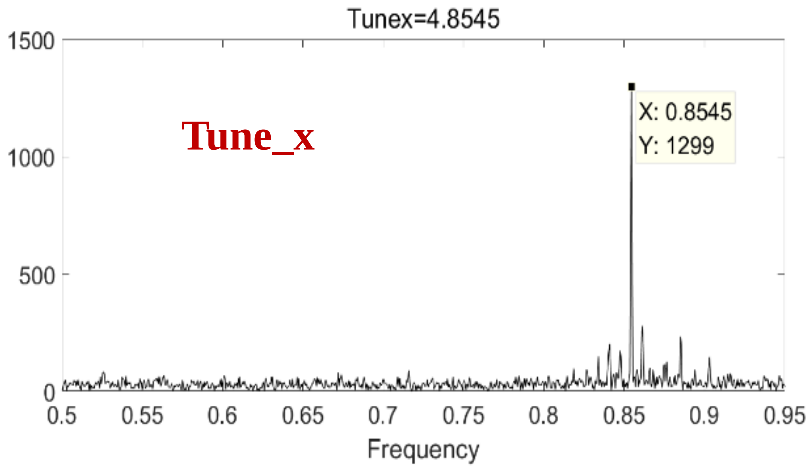
Optical parameters of a super-periodicity

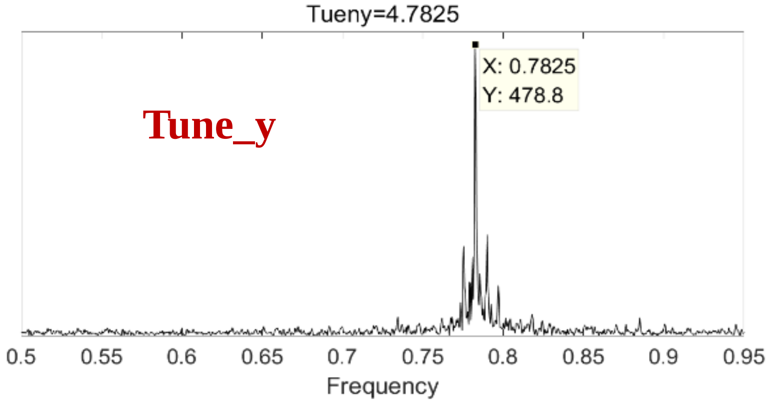


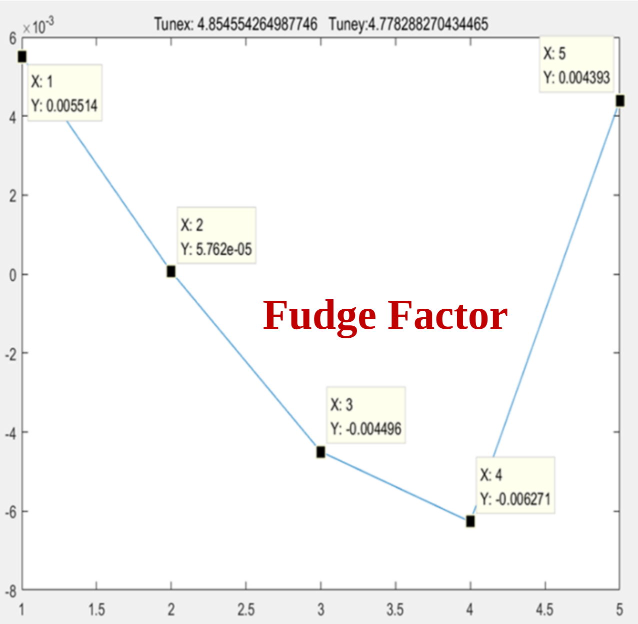


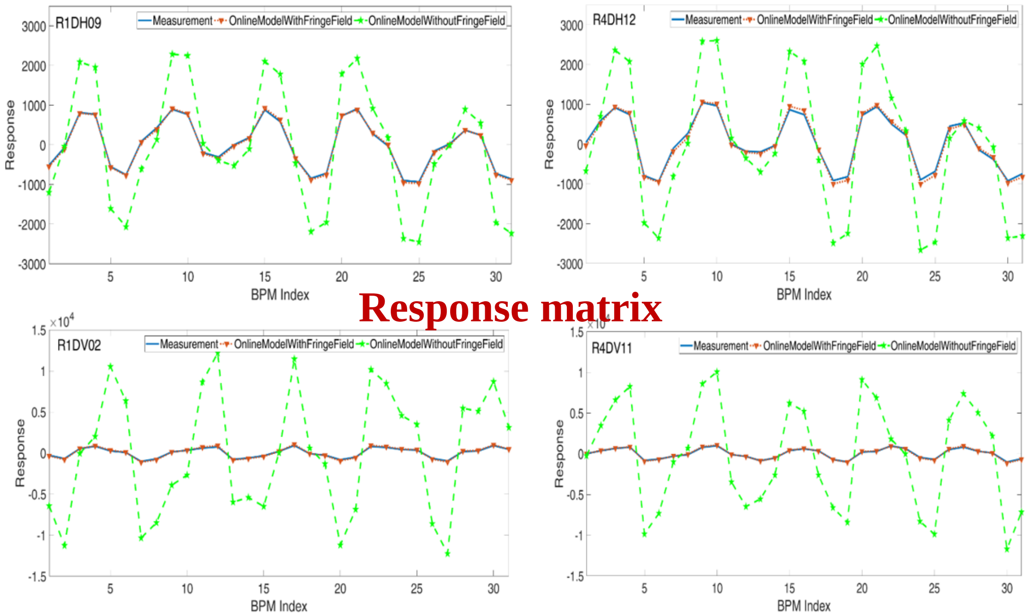
1. Low-intensity beam commissioning

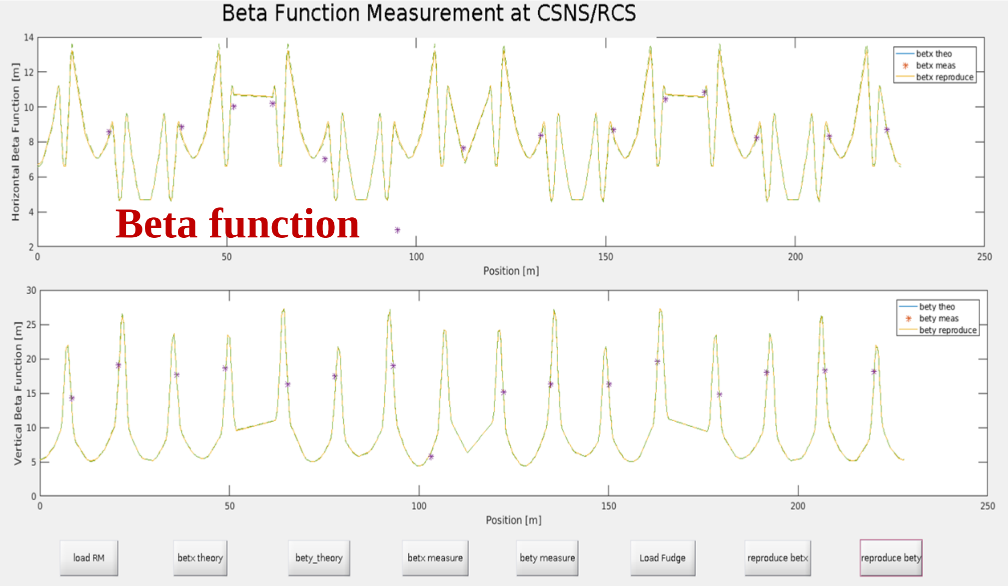
- The measured tunes were 4.855/4.783 in the DC mode, which were very close to the nominal value of 4.860/4.780







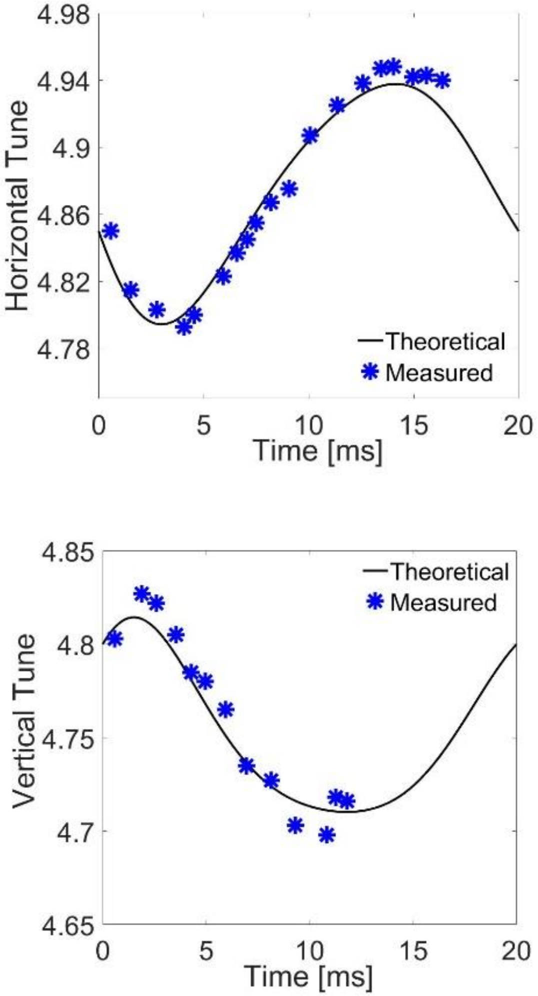




- It has been verified that the online model agrees with the theoretical design

- The theoretical design and magnetic field measurement results are good

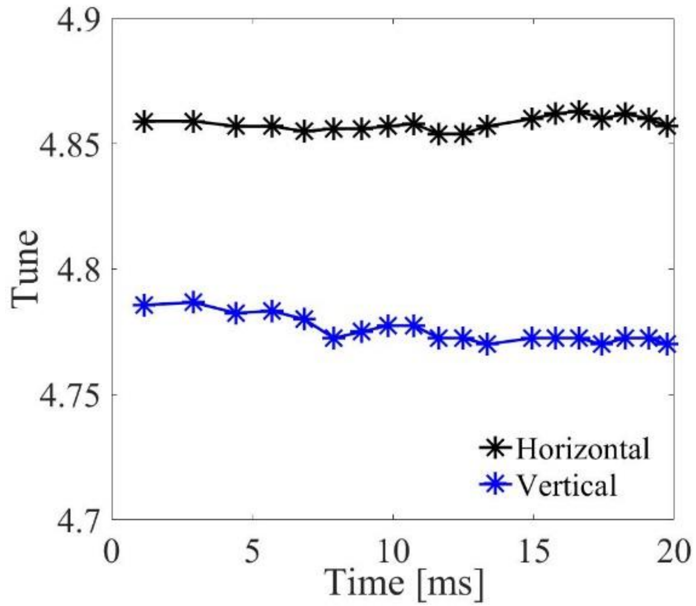
Control of the tune



Before harmonic compensation

Harmonic compensation

NIM-A, 897, 81, 2018



- Harmonic compensation on magnets was used for the tune optimization. The tune variation during the acceleration process was well controlled
- The design tune (4.86, 4.78) was adopted at low-intensity beam commissioning
- By using the theoretical design mode (tune, painting method, et al.), the beam power had successfully **reached 50 kW**

2. Intense beam issues in the beam commissioning

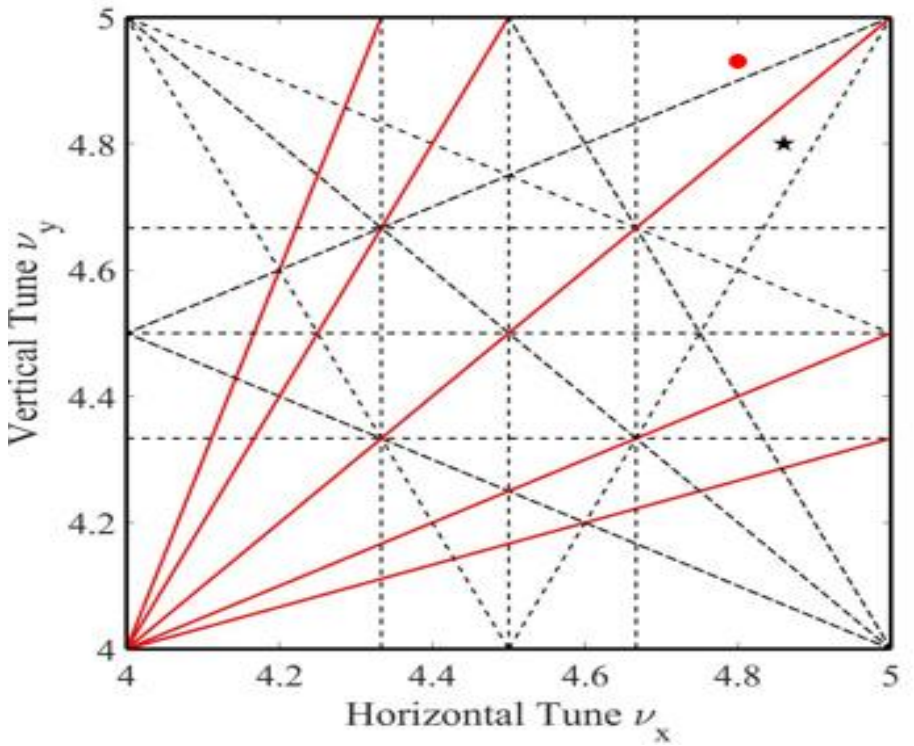
Beam power	Challenges
≤50 kW	Differences between the online model and theoretical design
>50 kW	Space charge effects and beam instability

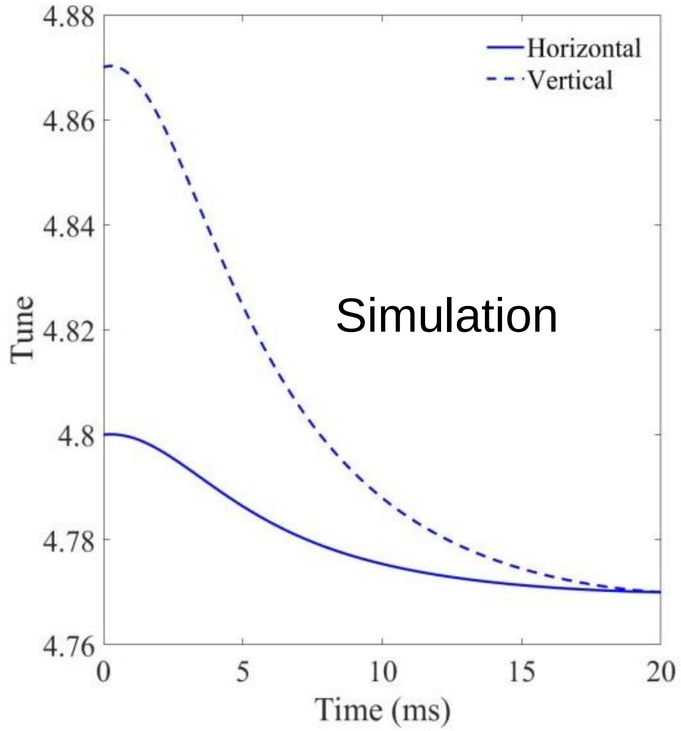
Intense beam effects

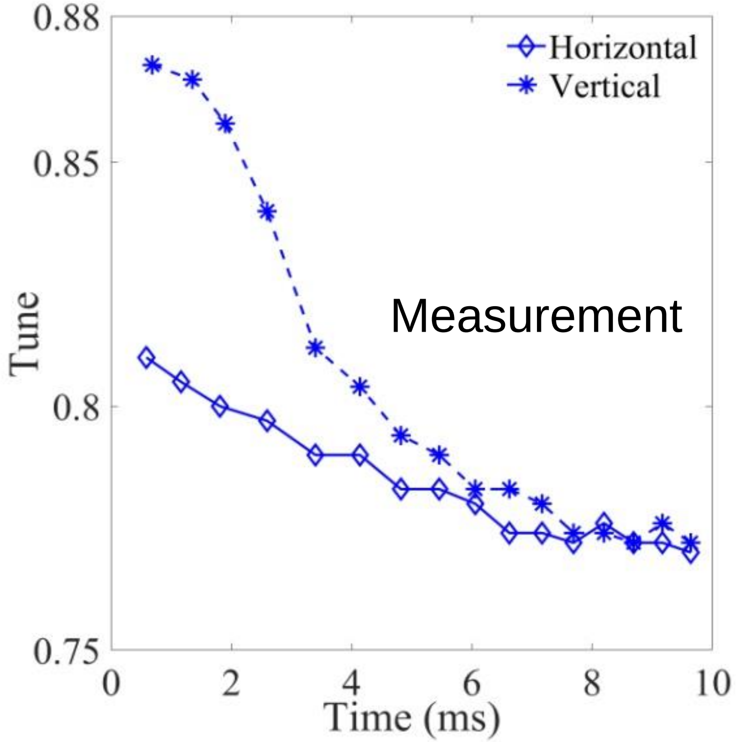
- **Space charge effects**
- **Beam instability**

2.1.1 Tune pattern optimization

- Tune pattern plays an import role in the control of the intense beam effects
- The tunes at injection were set at (4.81, 4.87) to reduce space charge effects induced beam loss (the tunes were moved downward to suppress the beam instability)



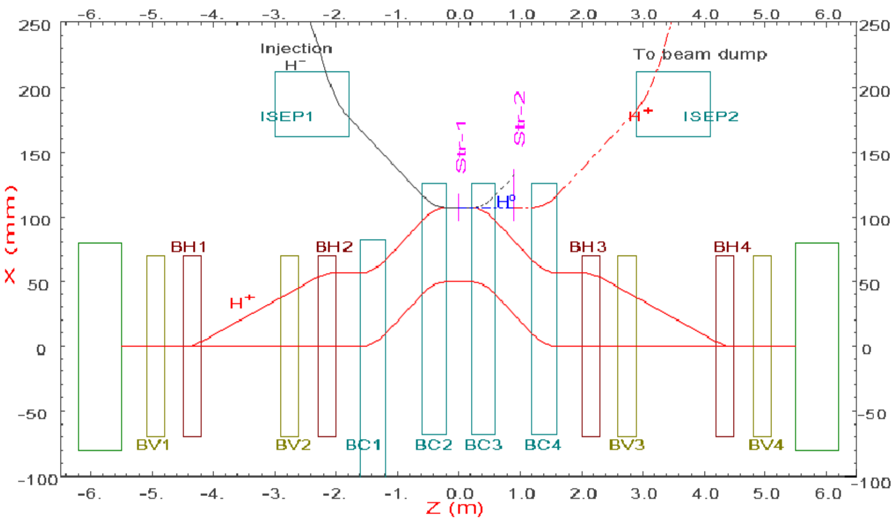


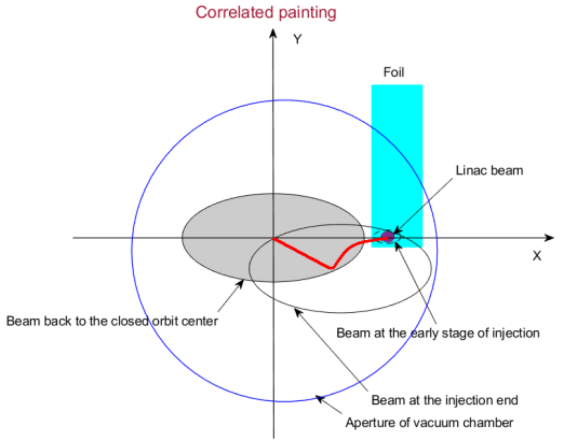


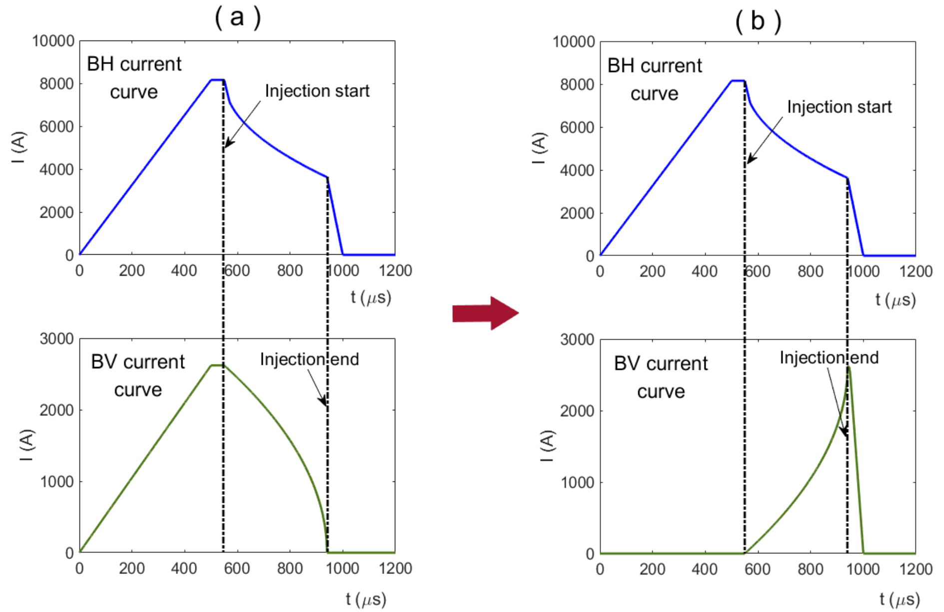
2.1.2 Method to achieve the correlated painting

- **Challenges:** too large beam size after painting, non-uniform beam distribution, large transverse coupling effects resulting in additional beam loss (>50 kW)
- **Reasons:** the actual vertical painting acceptance of the ceramic vacuum chamber is only about 70% of the design value; the transverse coupling effects on the beam distribution are very strong
- **Method:** Based on the mechanical structure of the anti-correlated painting, the rising curve of the pulse power supply current had been used for the vertical painting to achieve the correlated painting

PRAB, 25, 110401, 2022





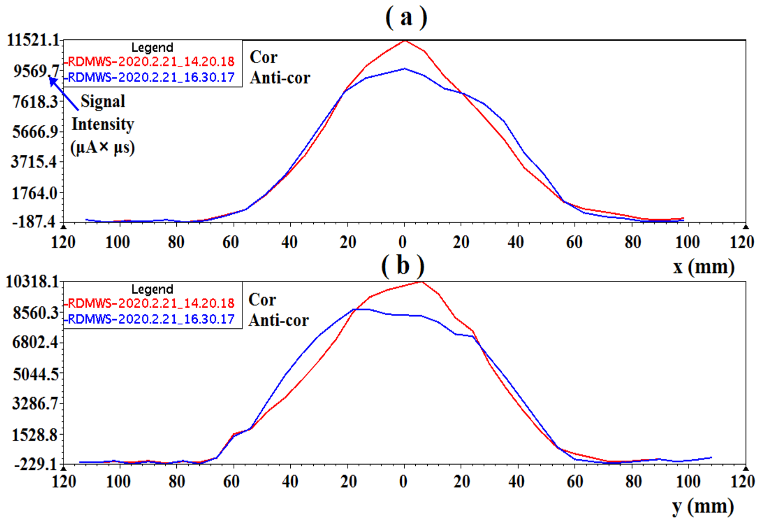


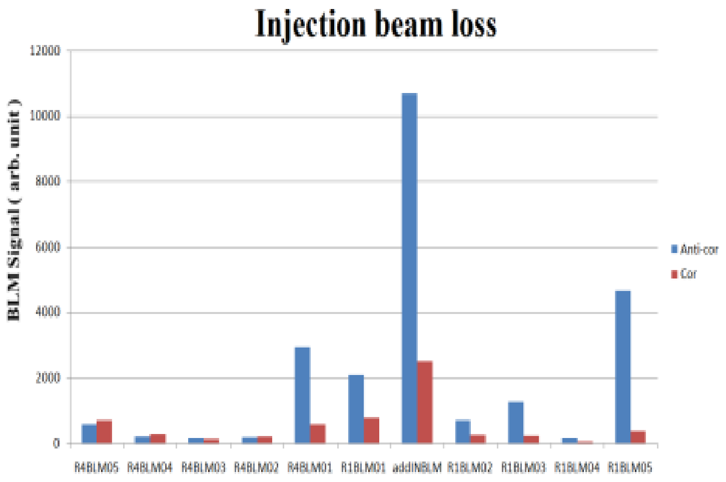
Beam commissioning results

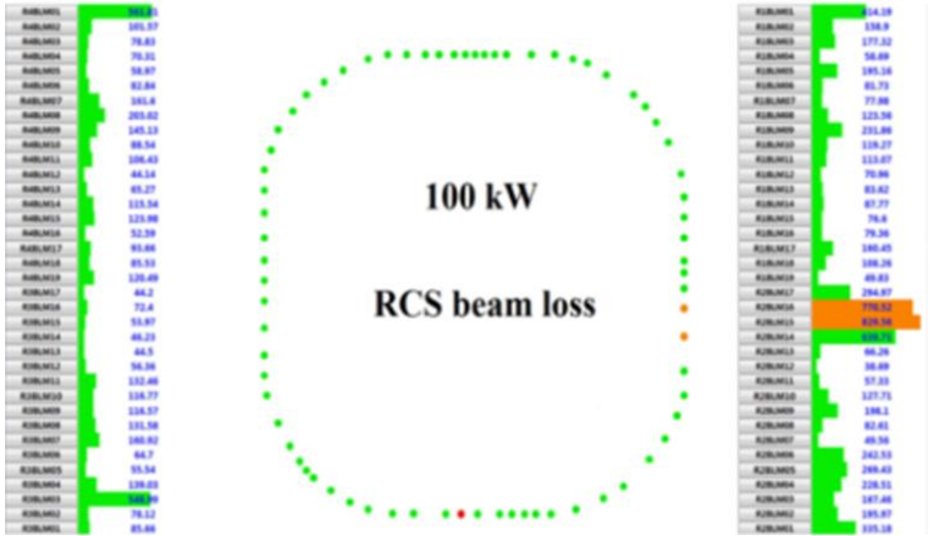
- By using the correlated painting:
  - ✓ **Beam loss was well controlled**
  - ✓ **Transverse beam size was largely reduced**
  - ✓ **Beam distribution was much better**
  - ✓ **Transverse coupling effects were improved**

◆ **Results**: The method unlocks the shackles that restrict the beam power increase of the CSNS accelerator. **The beam power had reached 80 kW and 100 kW (design goal) successively**

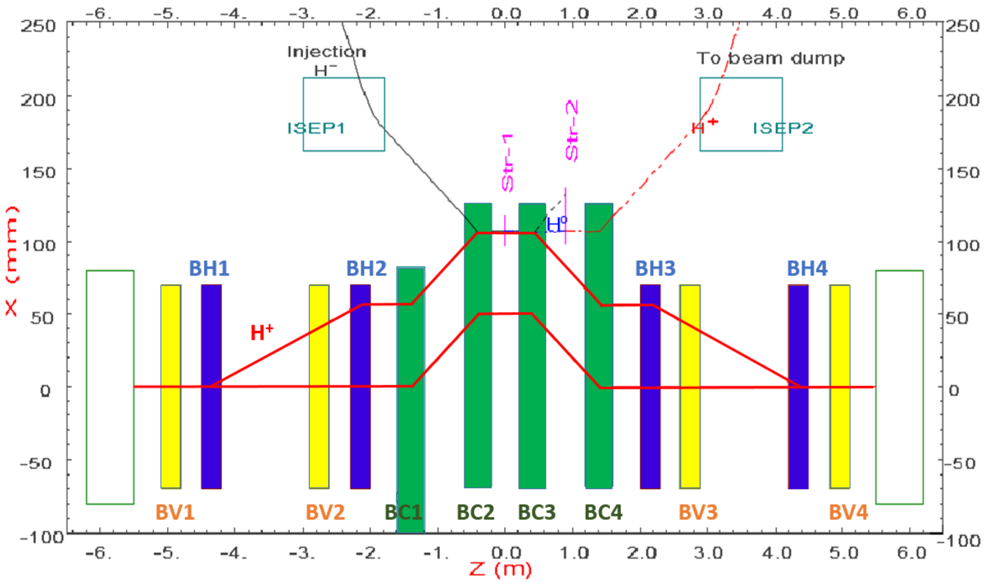
◆ **Experience and lessons**: **Both correlated and anti-correlated painting** need to be performed in the CSNS-II



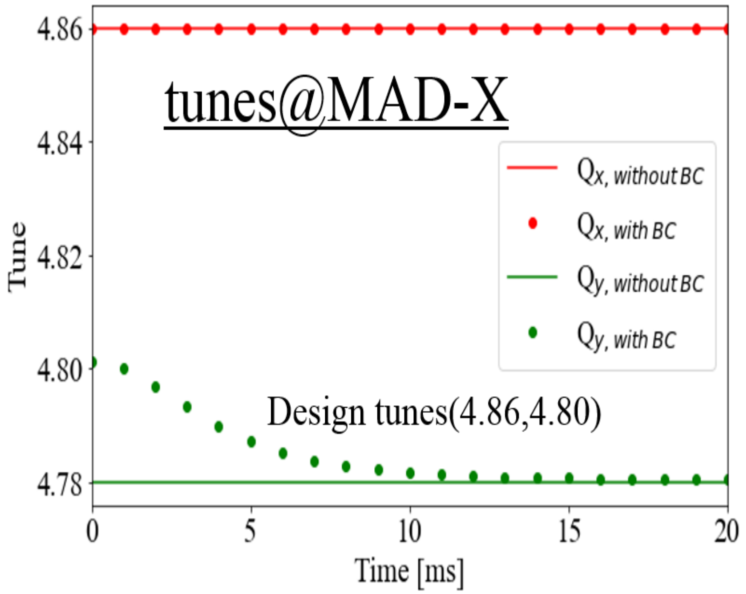


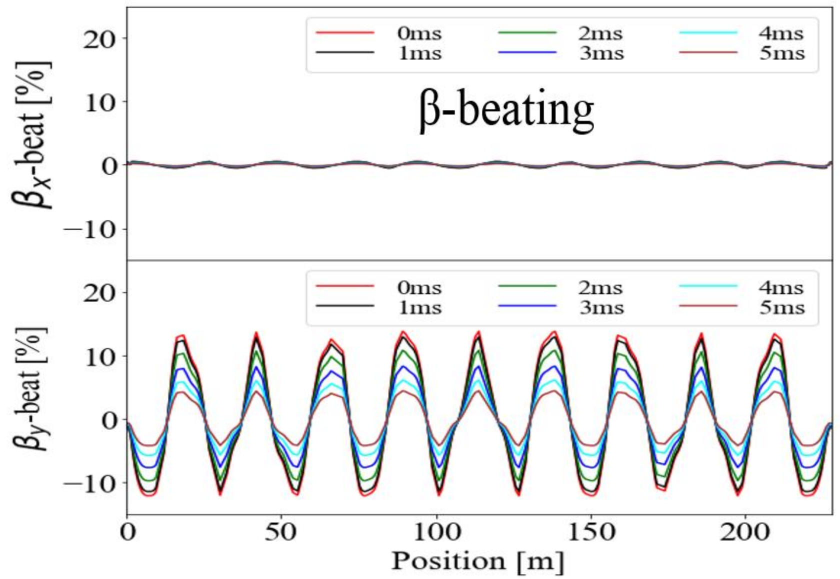


2.1.3 Edge focusing effects of chicane bump magnets

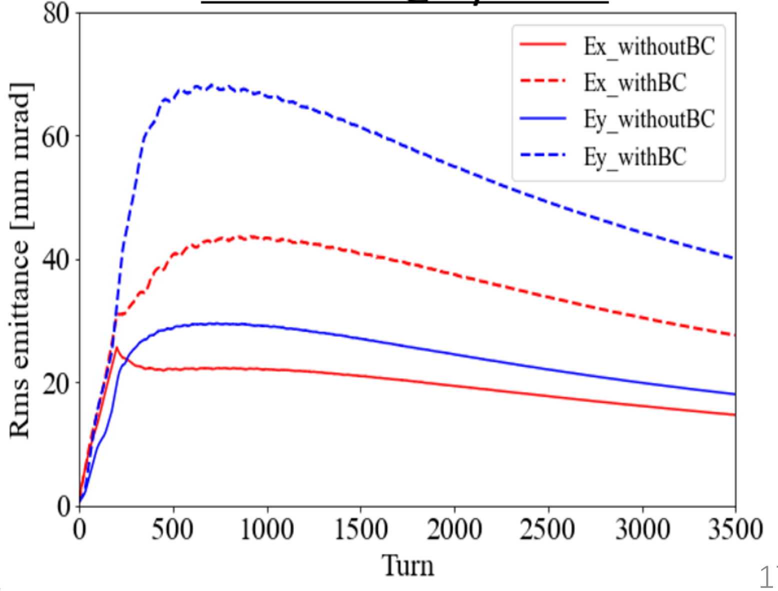


- **Broken four-fold symmetry :**
  - ✓ **Tune**
  - ✓ **Beta-Beating**
  - ✓ **Emittance**



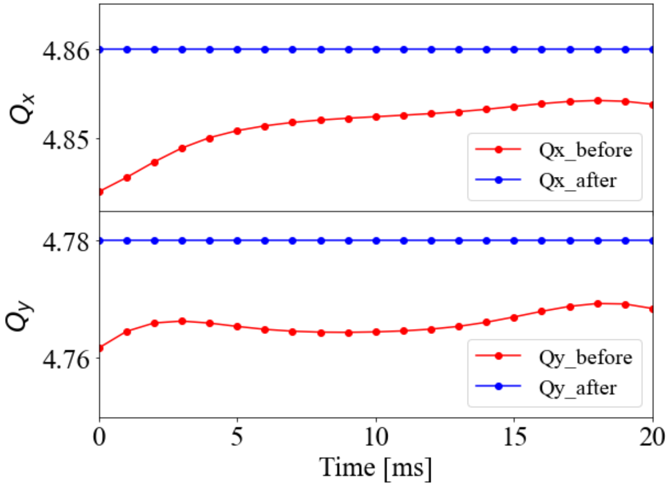


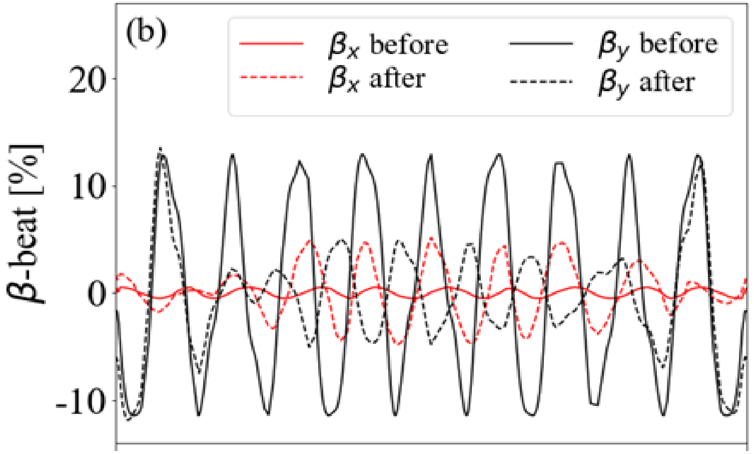
Emittance@PyORBIT



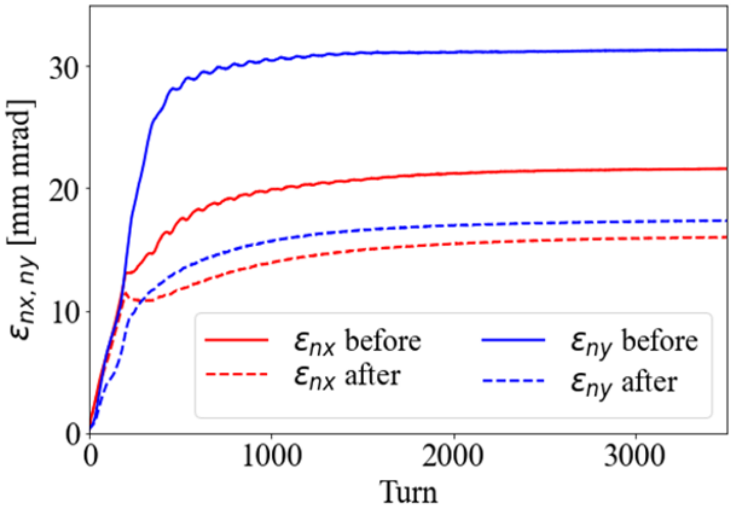
Super-periodicity restoration

- **Installation of AC trim quadrupoles :** correction of the tune and Beta-Beating; restoring the Lattice symmetry to reduce the emittance growth

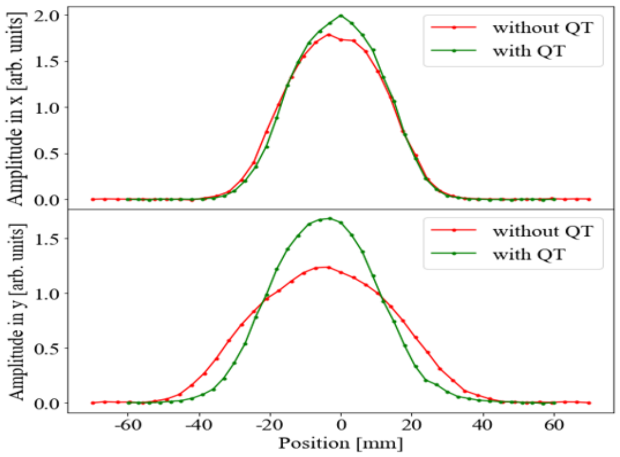


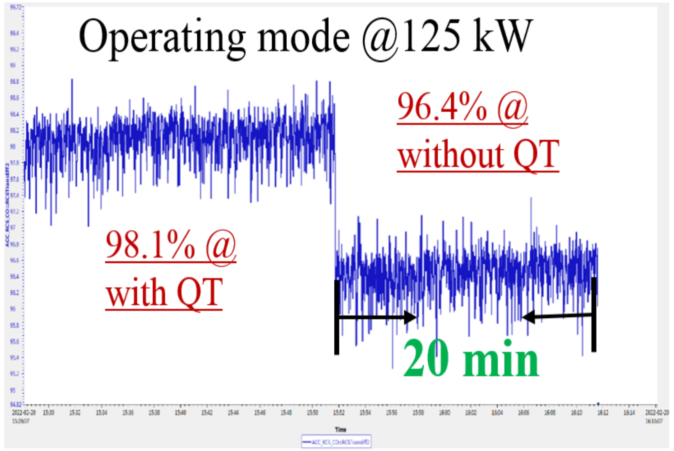


Emittance_QT@PyORBIT



Measured Beam Profile





PRAB, 26, 104201, 2023

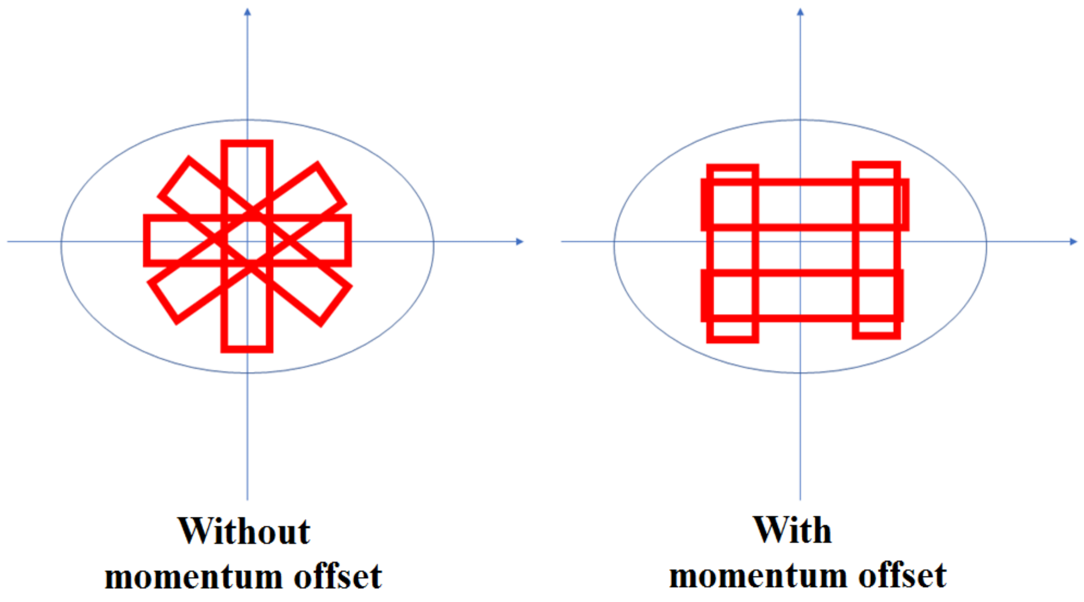
- **Solutions in the CSNS-II:**
  - ✓ **Power supplies of bump magnets will be changed from DC to AC**

2.1.4 Optimization of the bunching factor

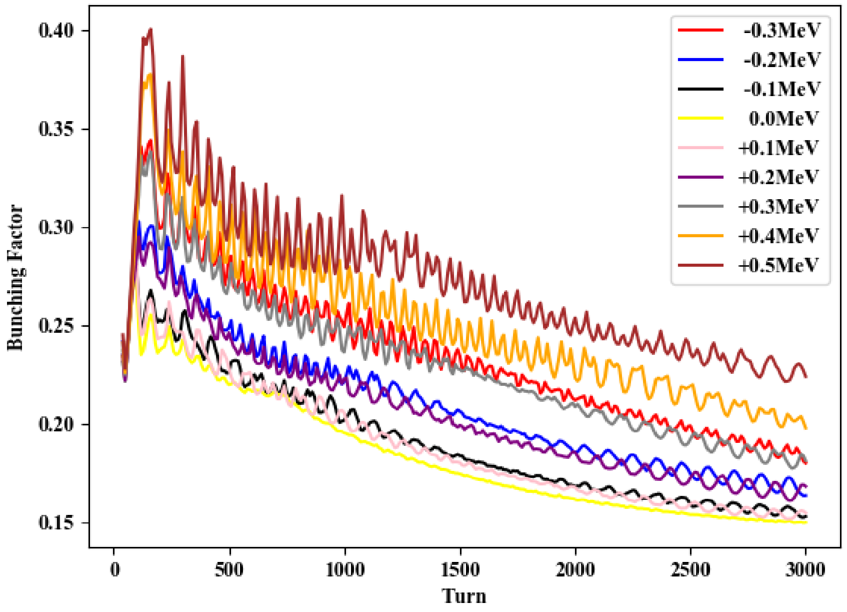
- Increase of the bunching factor can reduce space charge effects

- By adjusting the energy (momentum) offset during the injection, the bunching factor can be increased

PRAB, 27, 044201, 2024



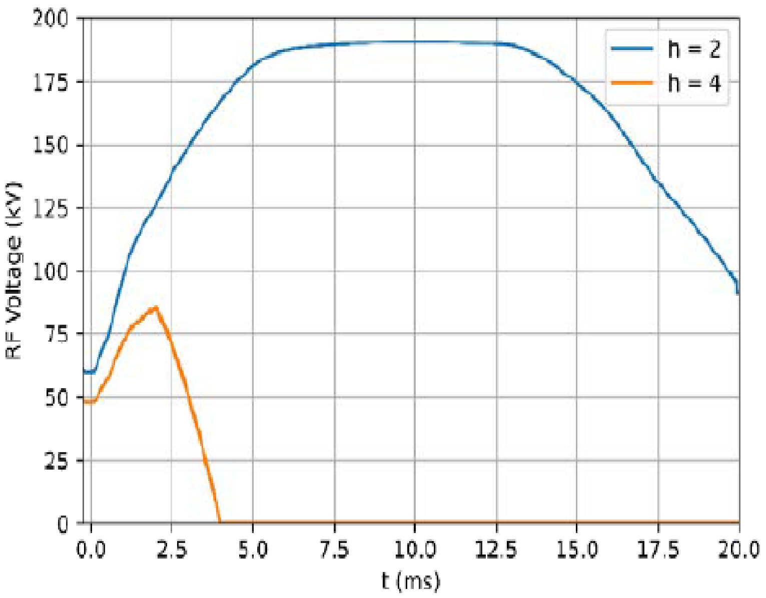
Longitudinal motion for the multi-turn injection process

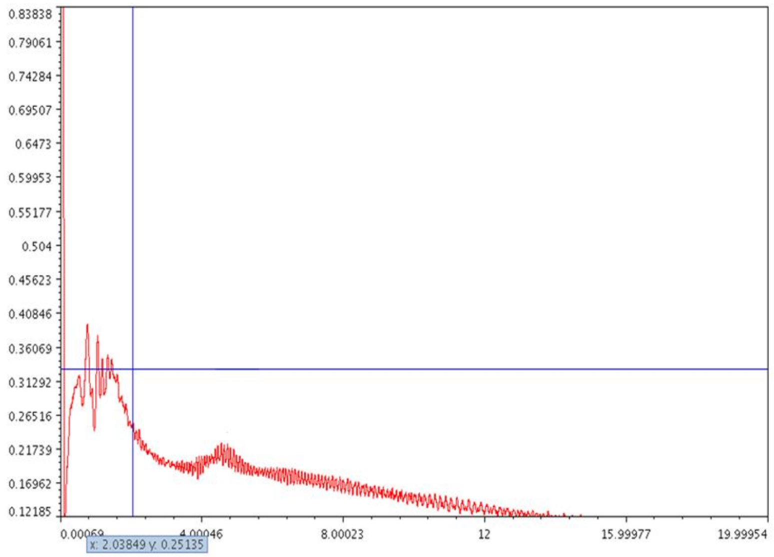


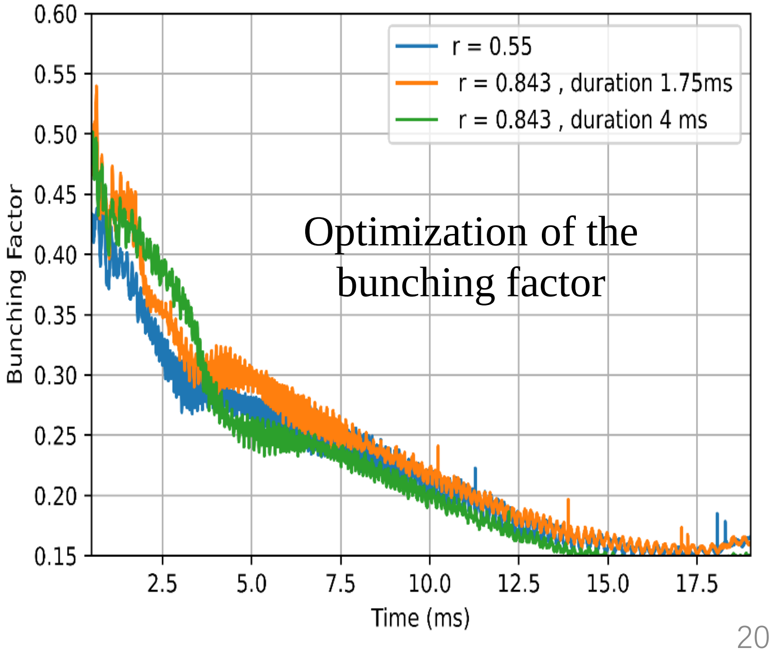
Measurement Results of Bunching Factor under Different Energy Offsets

Bunching factor optimization with dual harmonic RF cavity

- Using the dual harmonic RF cavity to reduce the space charge effects is one of the main methods of the beam power upgrade
- The bunching factor can be increased by optimizing the RF voltage waveform

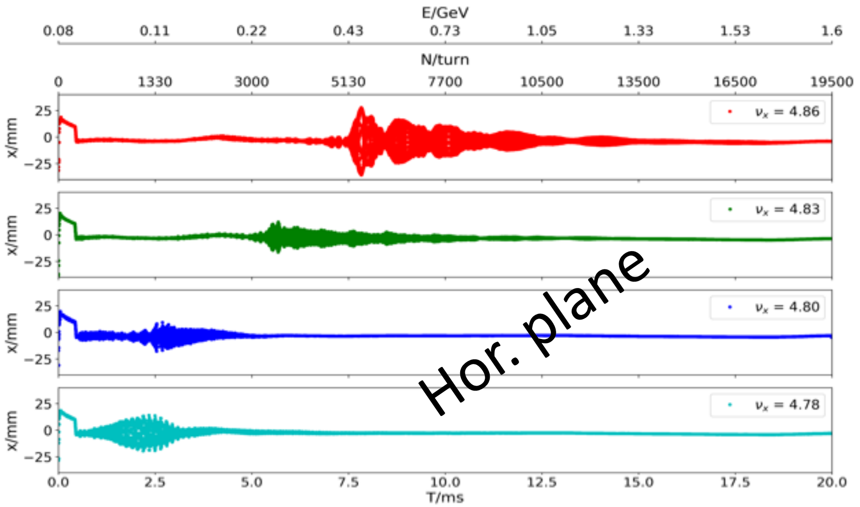


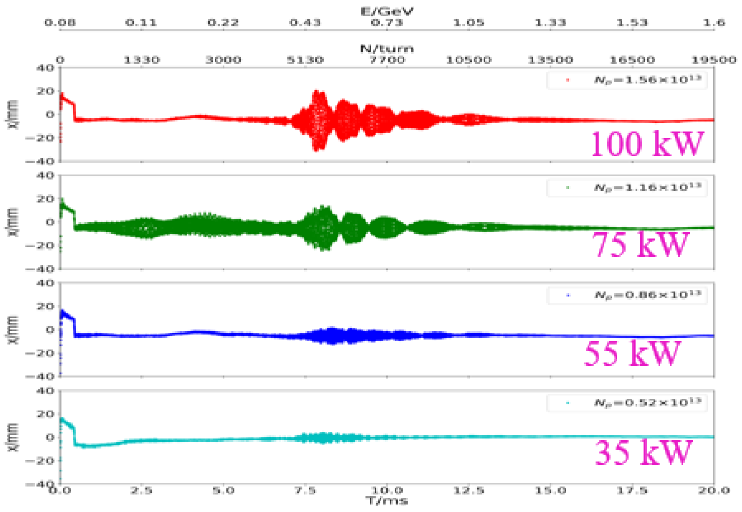


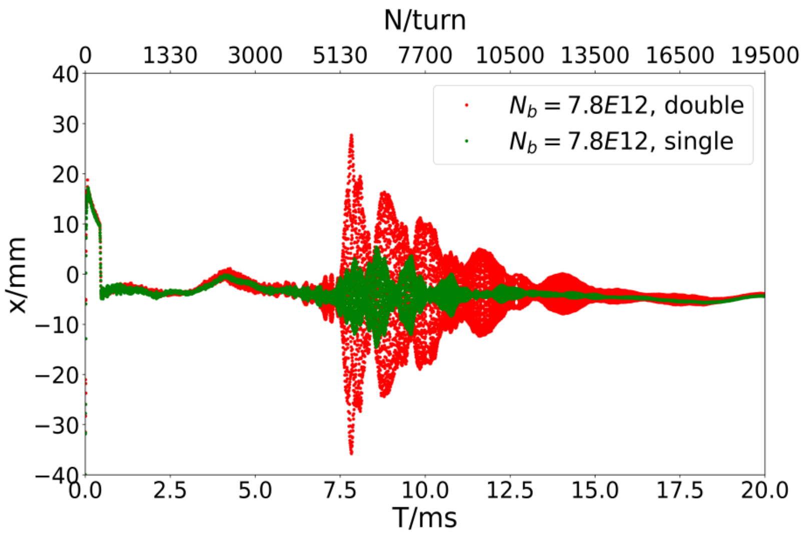


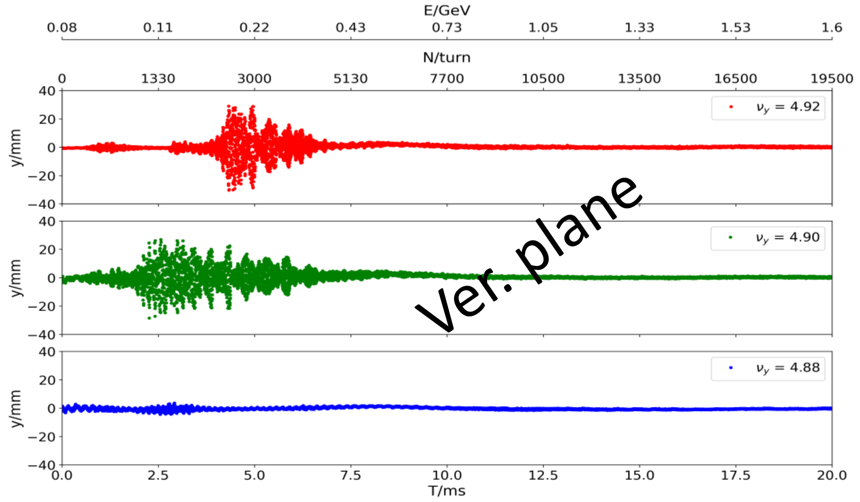
2.2 Beam instability

- With the nominal tune (4.86, 4.78) and nature chromaticity, beam instability was observed when beam power >50 kW
- The growth time is less than 1 ms for 100 kW
- The beam instability depends on the total particles number, double or single bunches, tune, horizontal and vertical, etc
- Base on the characteristic, it was given the name of "Head-tail coupling bunch instability"







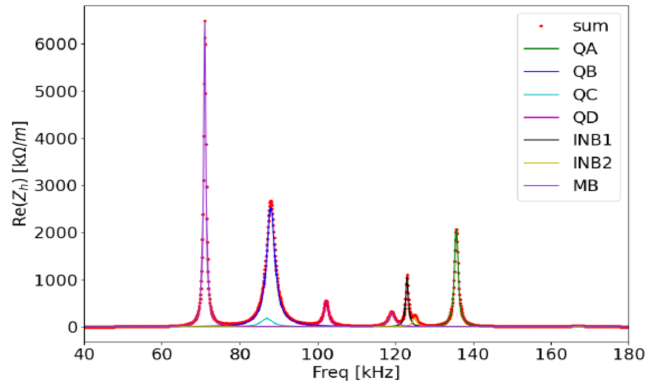


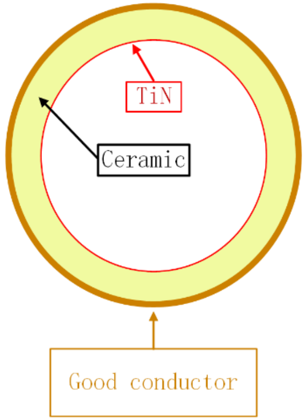
Impedance source of the CSNS RCS

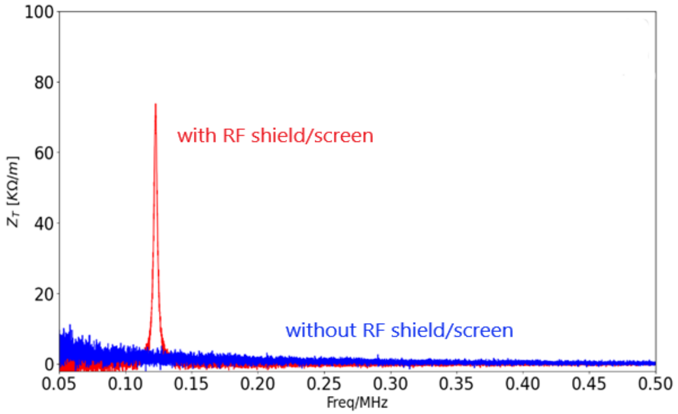
- Measurements have confirmed that the RF shield on the ceramic chambers is responsible for the instability. The beam behavior is perfectly consistent with the impedance
- The impedance of all the RCS ceramic chambers is much big. It is a “broadband” impedance

EPJ-P, 140, 71, 2025

- 9 types of ceramic vacuum chamber:
  - ✓ QKA is approximately (≈) QA; QKB ≈ QB; INB2 ≈ INB1
  - ✓ For the ceramic chamber of the diploes, the resonance in horizontal plane is different from that in vertical plane







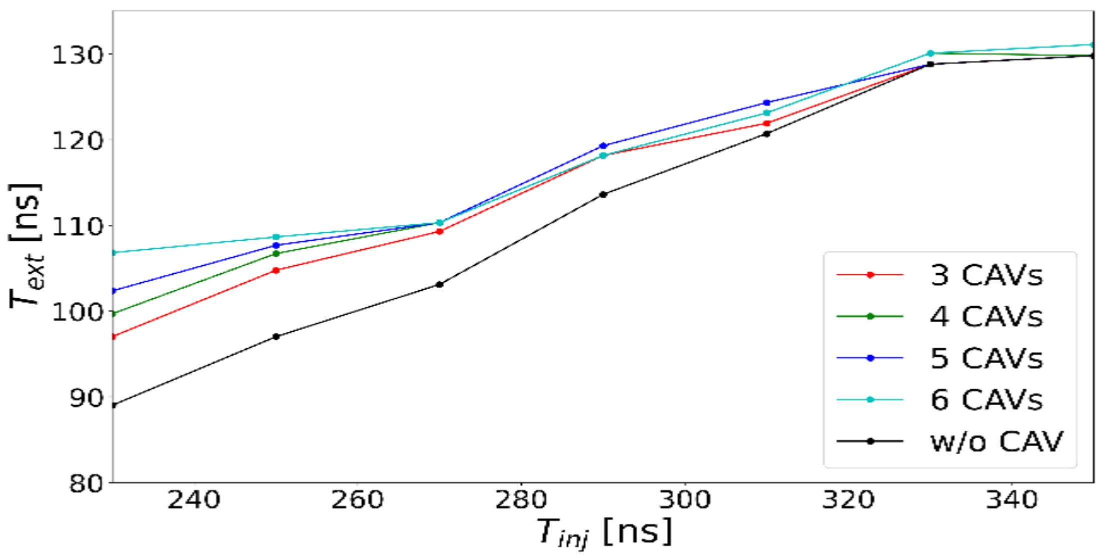
With RF shield/screen

Without RF shield/screen

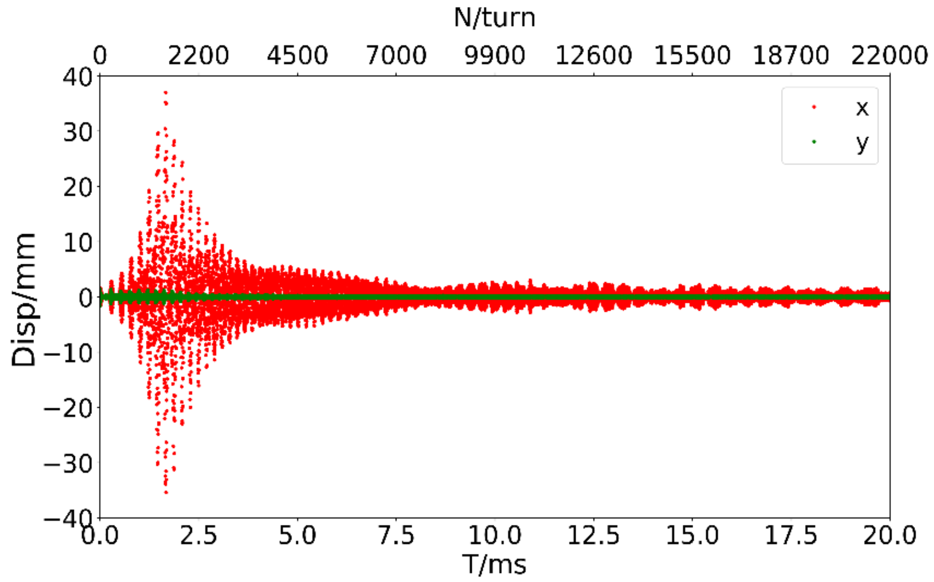
	Number	Fr [KHz]	Rs per one [kohm/m]	Q
MB, Elliptic/hor	24	71	350	150
MB, Elliptic/ver	24	79	150	40
QB, Circular #1	16	88	158	35
QD, Circular #2	8	102.2	66	70
QC, Circular #3	8	87	22	25
QA, Circular #4	16	135.7	128	120
INB, Circular #5	4	123	350	150

Beam instability in the CSNS-II RCS

- The new and replaced elements in the RCS have little effect on the change of the impedance
- Bunch lengthening driven by parasitic impedance of the MA cavity is very small
- The head-tail coupling bunch instability remains a key issue in the CSNS-II
  - ✓ The threshold of beam power is ~ 300 kW



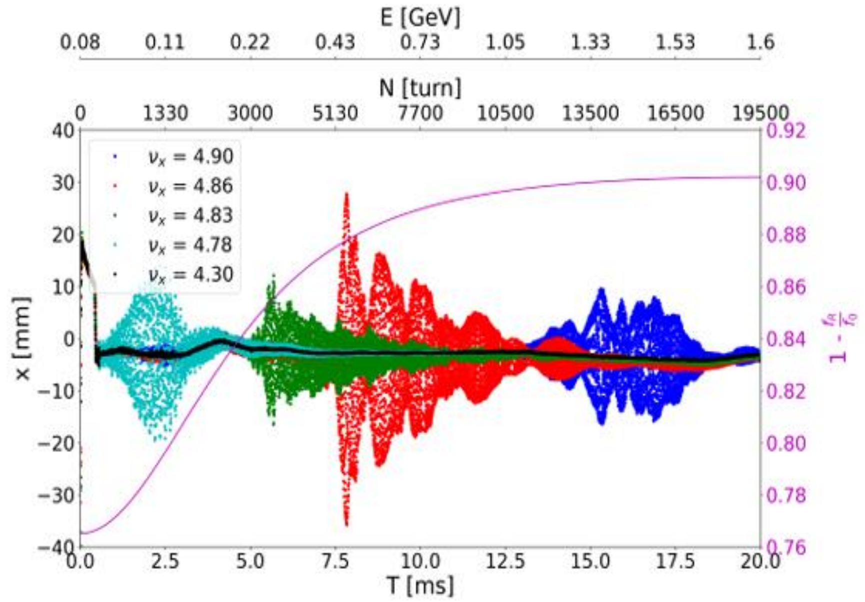
Bunch length with different number of the MA Cavity

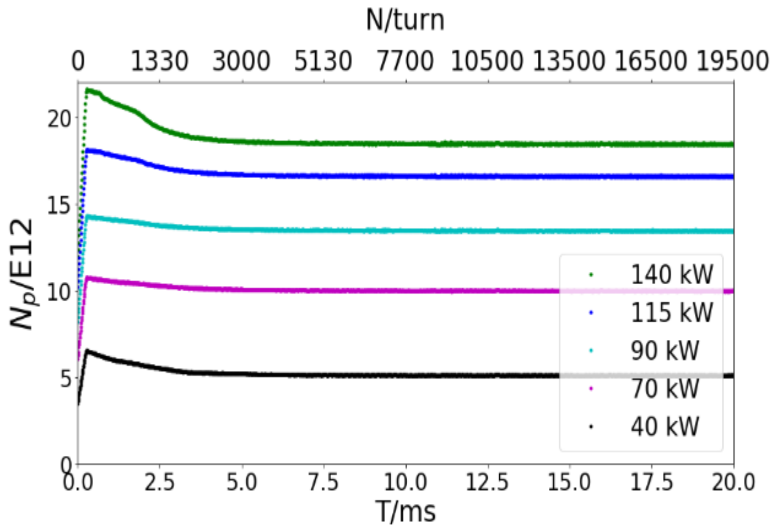


Prediction of the beam instability with 500 kW beam power in the CSNS-II

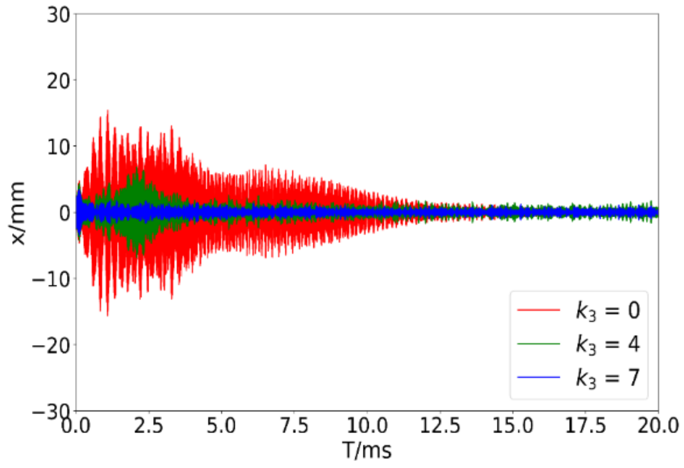
Mitigation of the beam instability in the CSNS-II

- Tune curve optimization
- Chromaticity optimization
- Tune below 0.5 — More detail: WEP4639
- Develop a low-impedance ceramic vacuum chamber
- Develop a feedback system





(4.3,5.3), w/o instability



Simulation study by using octupoles

Bandwidth	2.5 MHz
Shut impedance	3 kΩ
Voltage	5 kV
power	2.5 kW
Damp time	0.5 ms

III. Upgrade progress for the CSNS-II RCS

	CSNS	CSNS-II
Output beam power [kW]	100	500
Injection energy [MeV]	80	300
Extraction energy [GeV]	1.6	1.6
Pulse repetition rate [Hz]	25	25
Acceleration time [ms]	20	20
Extraction average current intensity (uA)	62.5	312.5
Circumference [m]	227.92	227.92
Number of dipoles	24	24
Number of quadrupoles	48	48
Number of trim quadrupoles	0	16
Lattice structure	Triplet	Triplet
Nominal betatron tune (H/V)	(4.86, 4.78)	(4.86, 4.78)
Ring acceptance [πmm-mrad]	540	540
Harmonic number	2	2
Number of particles per pulse	1.56×10^{13}	7.8×10^{13}
Space-charge tune shift	0.28	0.19

- **Space-charge induced tune shift**

Injection energy	**Beam power**	**ΔQ**	**Extraction energy**
80 MeV (CSNS)	100 kW	0.28	1.6 GeV (RCS)
300 MeV (CSNS-II)	500 kW	0.19	1.6 GeV (RCS)
400 MeV (J-PARC)	1 MW	0.12	3 GeV (RCS)
1 GeV (SNS)	1 MW	0.08	1 GeV (AR)
70 MeV (ISIS)	160 kW	0.4	800 MeV (RCS)

$$\Delta\upsilon = -\frac{Nr_0}{2\pi\varepsilon\beta^2\gamma^3 B_f}$$

- The highest beam intensity in the same kind of RCS for the CSNS-II

3.1 Challenges for the CSNS-II beam injection

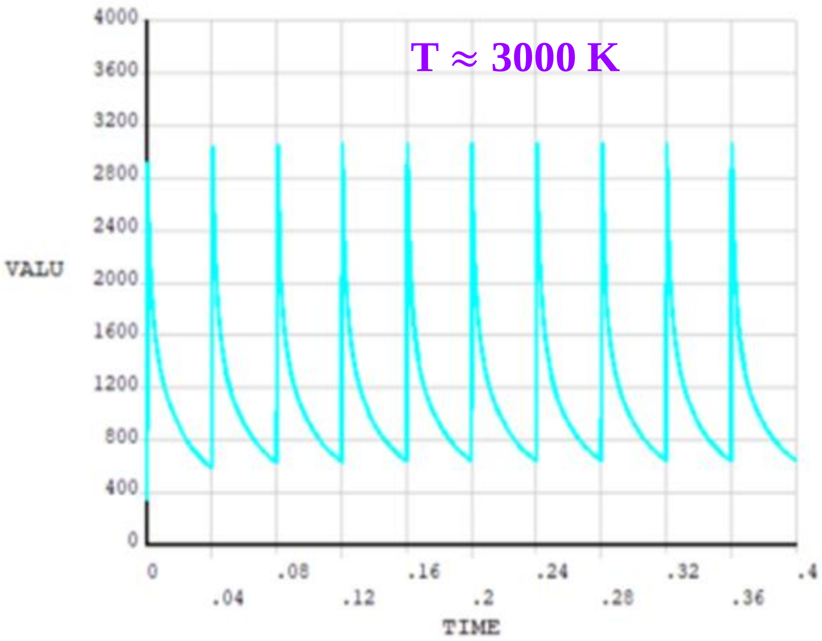
➢ **Key issues:** (1) The injection energy increases from 80MeV to 300MeV and beam intensity increases 5 times

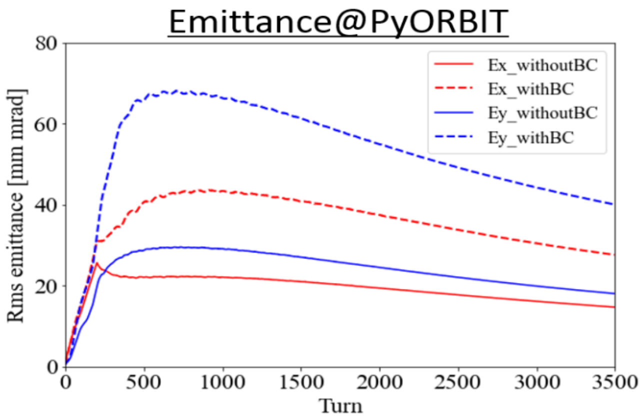
(2) The peak temperature of the stripping foil is too high (approaches or exceeds its melting point)

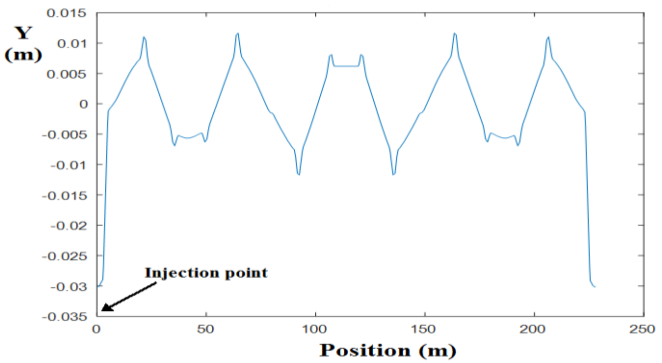
(3) The beam dynamics is greatly affected by the edge focusing effect of horizontal chicane bump

(4) The single fixed painting method may not be suitable for the future operational scenarios

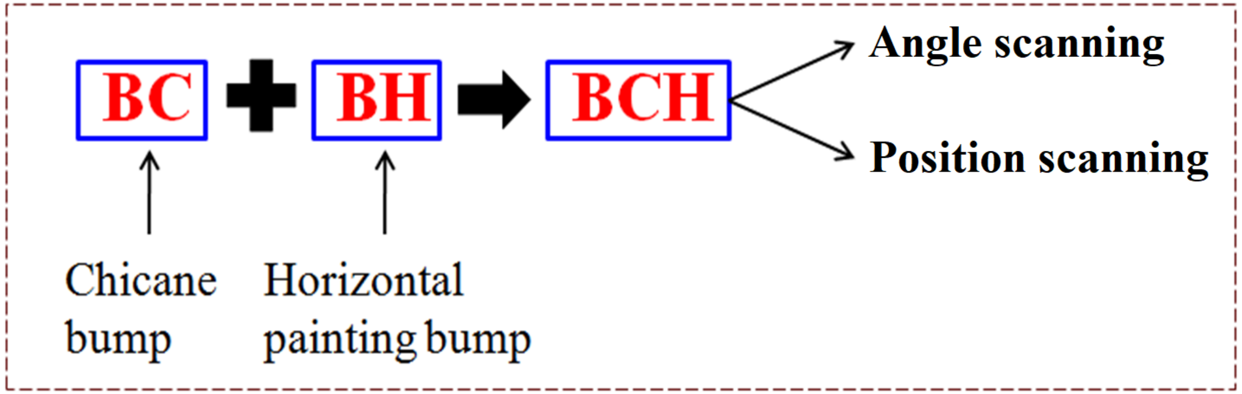
Injection parameters	CSNS	CSNS-II
Injection energy (MeV)	80	300
Average beam current (μA)	62.5	312.5
Proton number per pulse	1.56×10^{13}	7.8×10^{13}
Repetition frequency (Hz)	25	25
Injection beam power (kW)	5	94
Injection beam size（1σ）(mm)	1.0	1.5



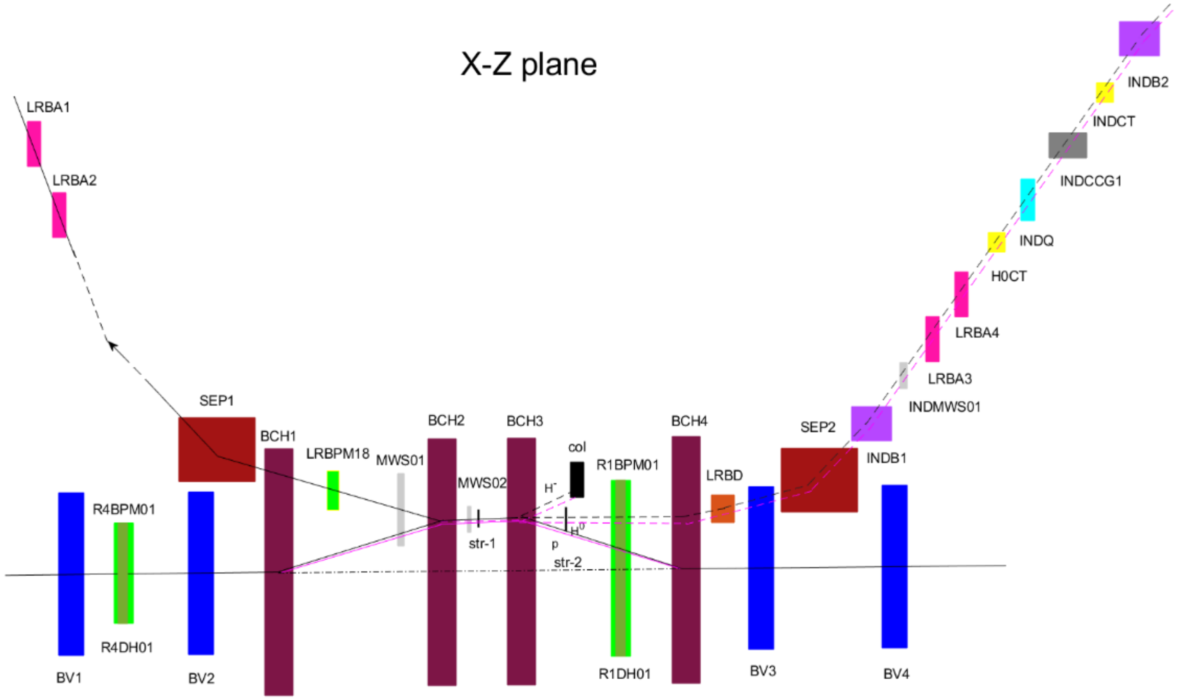




New painting injection method



- **Idea:** chicane bump and horizontal painting bump are combined into one bump which make the chicane bump "move“. The horizontal painting is performed by using the position and angle scanning at the same time



- **Advantages:**

✓ Foil peak temperature can be greatly reduced

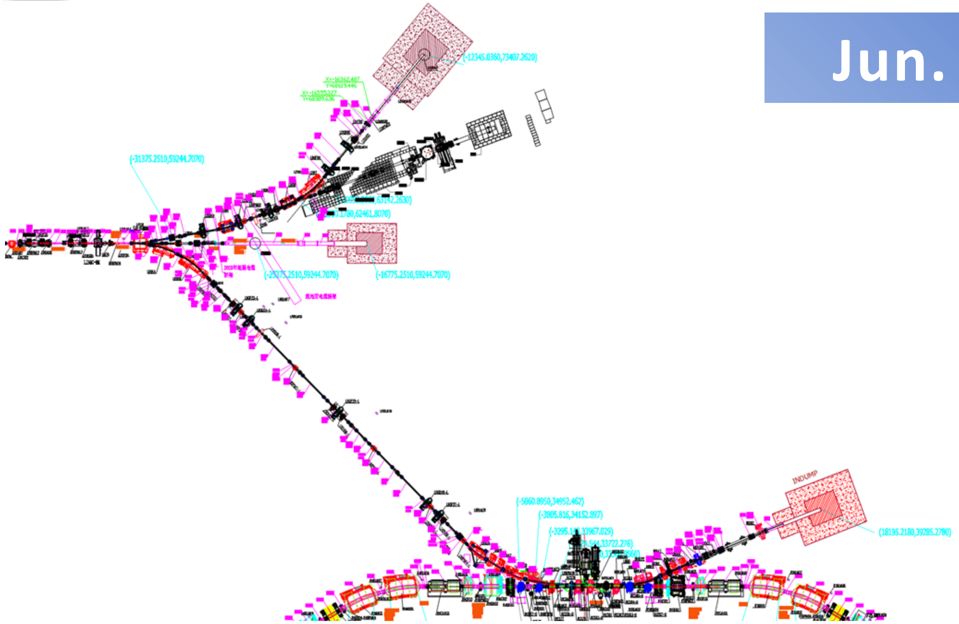
✓ Both correlated and anti-correlated painting can be performed

✓ The edge focusing effect of bump magnets is greatly reduced

✓ The difficulty of large aperture near the injection point required by angle scanning is solved

✓ It saves a set of bump magnets and is easier to optimize the layout of the injection system

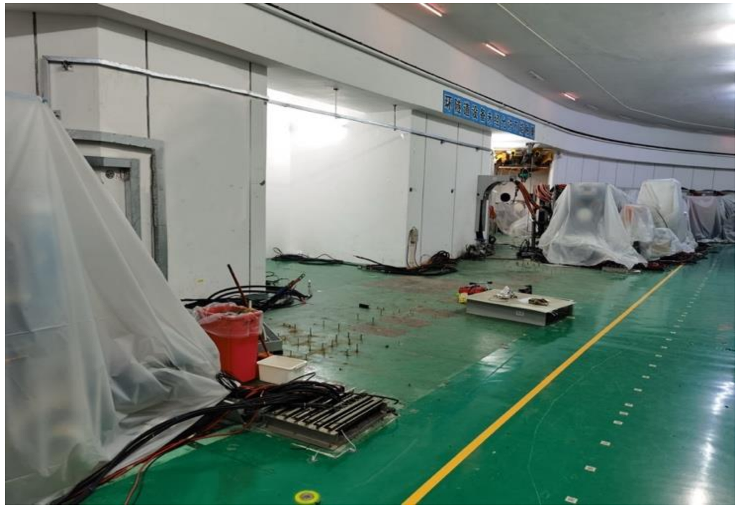
Upgrade of the injection system



Jun. 20- Aug.3， 2025

- Injection system upgrade
  - Physics
    - Design scheme
  - Magnet — V7
  - Power Supply — V7
  - Mechanical — V8
  - LRBT upgrade — V4
  - Beam diagnostics — V4
  - Vacuum — V4
  - Radiation — V4

CSNS Injection



Dismantling

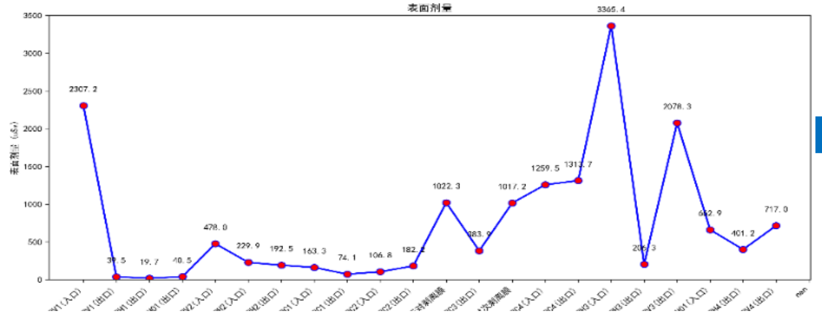
CSNS-II Injection

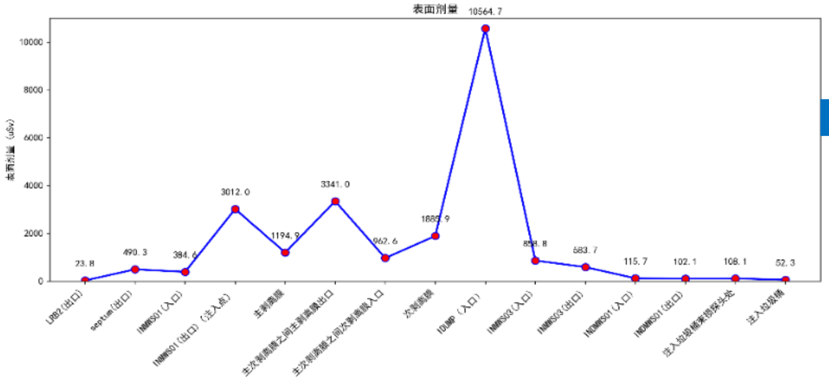
Beam commissioning results of new injection system

- The feasibility of new injection system design scheme has been verified
- The foil peak temperature is significantly reduced, and its lifetime is greatly increased
- The injection beam loss and radiation dose are significantly reduced

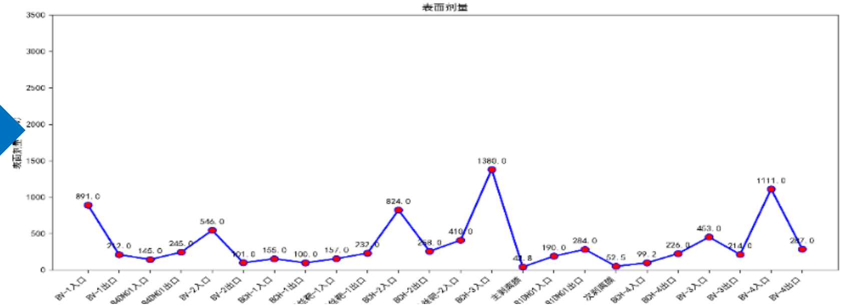
Stripping foil	Foil lifetime
Before upgrade	~ 3 weeks
After upgrade	**> 4 months**

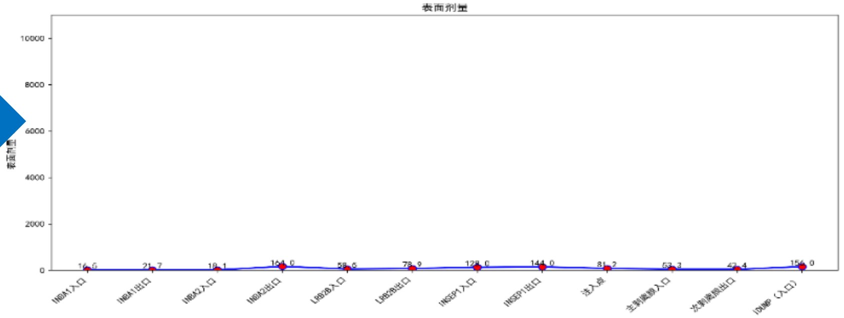
Before injection system upgrade

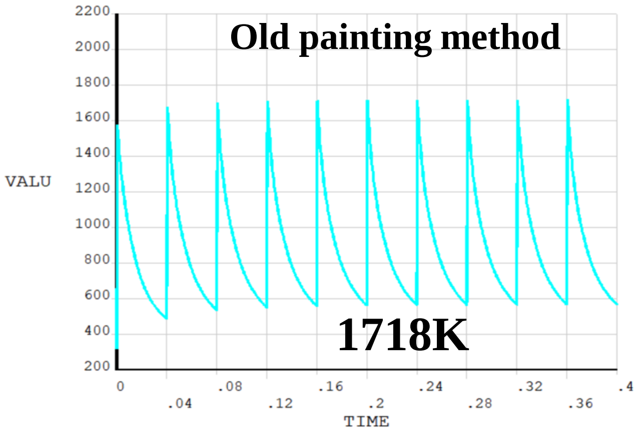


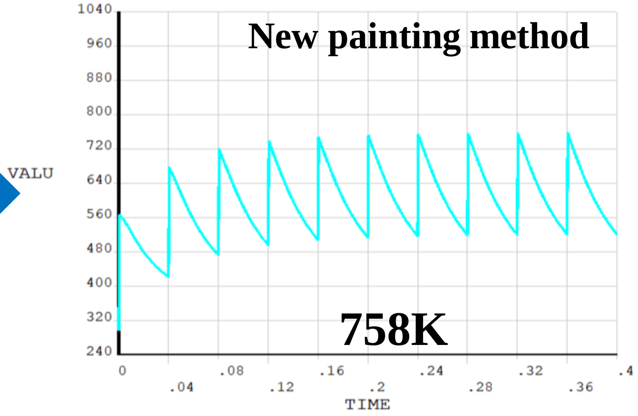


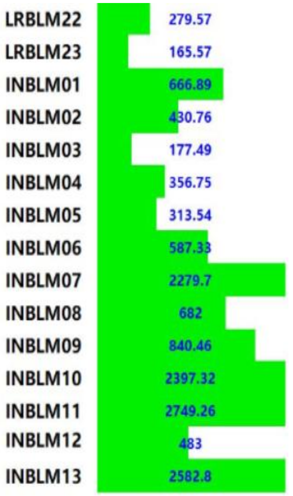
After injection system upgrade







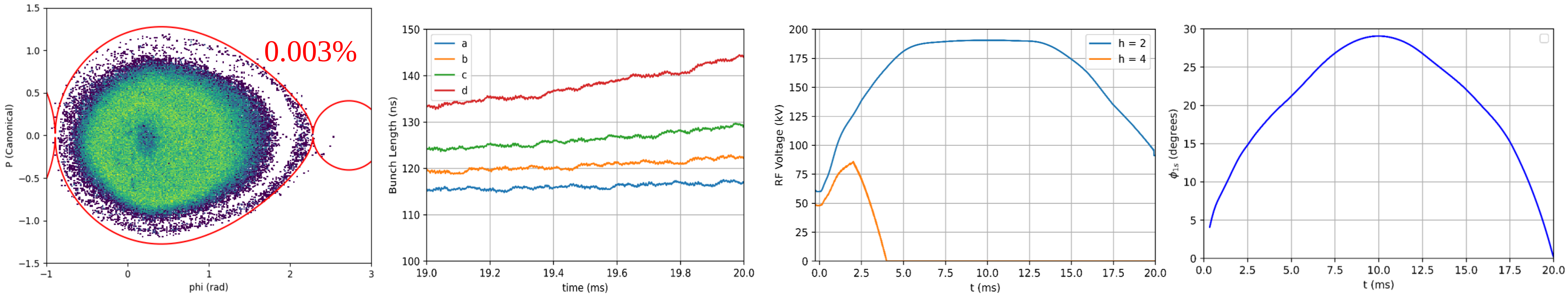




3.2 Longitudinal dynamics

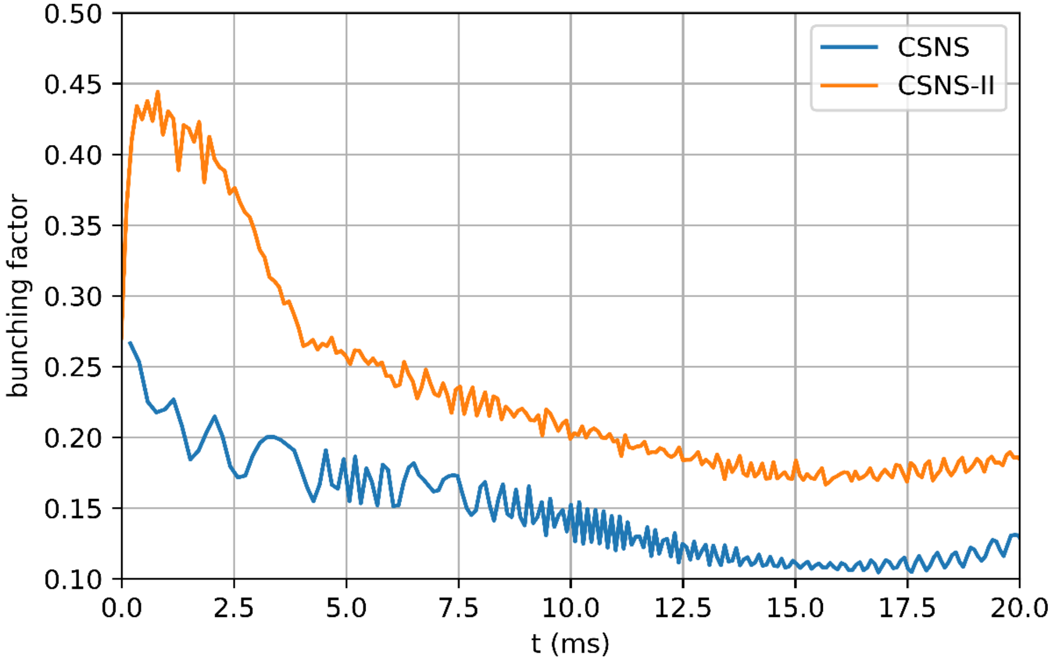
- When the injection energy increases from 80MeV to 300MeV and beam intensity increases 5 times, the longitudinal dynamics need to be optimized
  - ✓ Longitudinal parameter optimization during the beam injection
  - ✓ Optimization during the acceleration and extraction stages

- After optimization, most particles are within bucket and the bunch length can be compressed to below 130ns. The RF curves (voltage and phase) have been given below

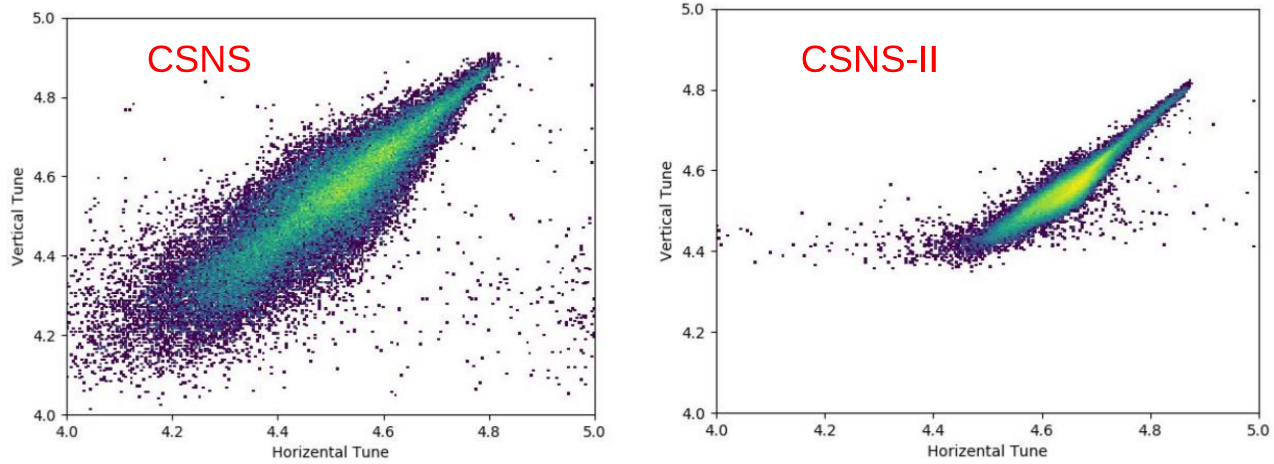


3.3 Simulation of 500kW beam power

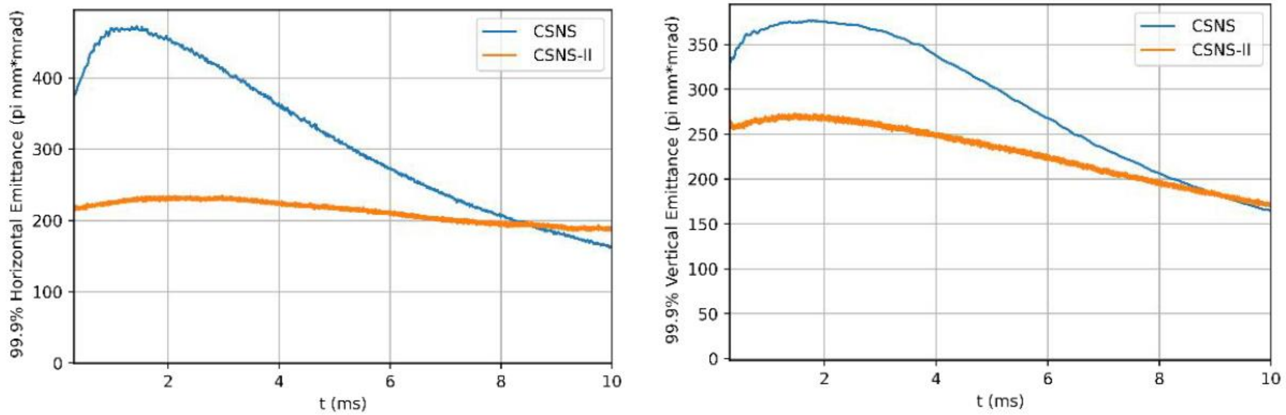
➤ Comparison of the simulation results between CSNS and CSNS-II



Comparison of the bunching factor between CSNS and CSNS-II



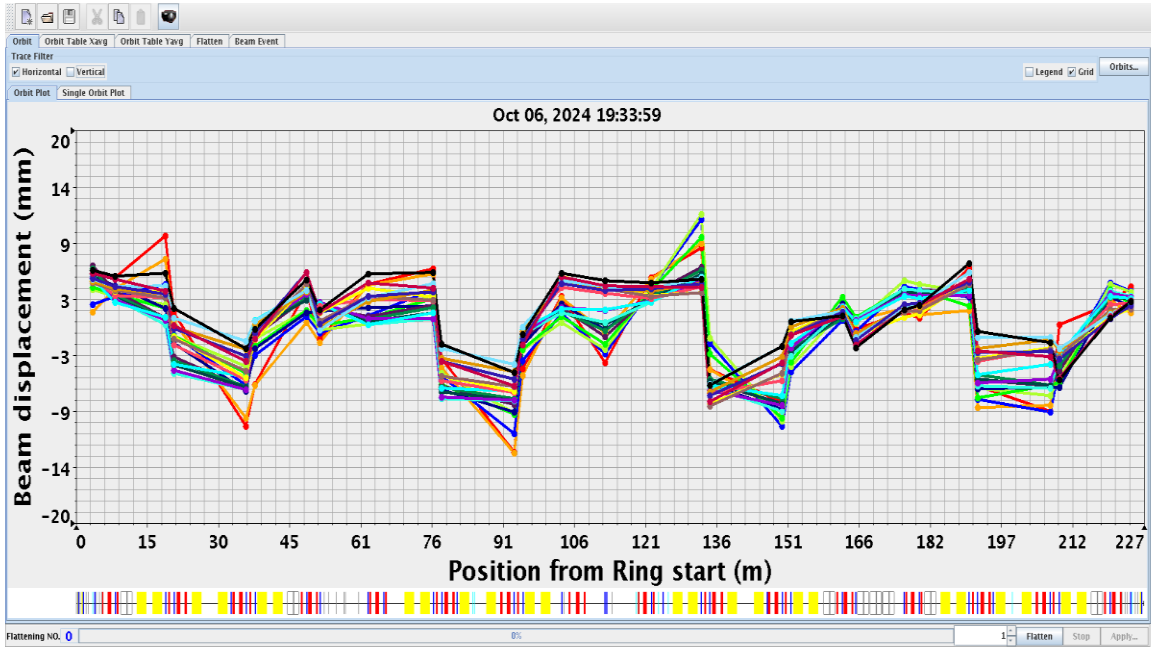
Tune spread of CSNS-II is far less than that of CSNS



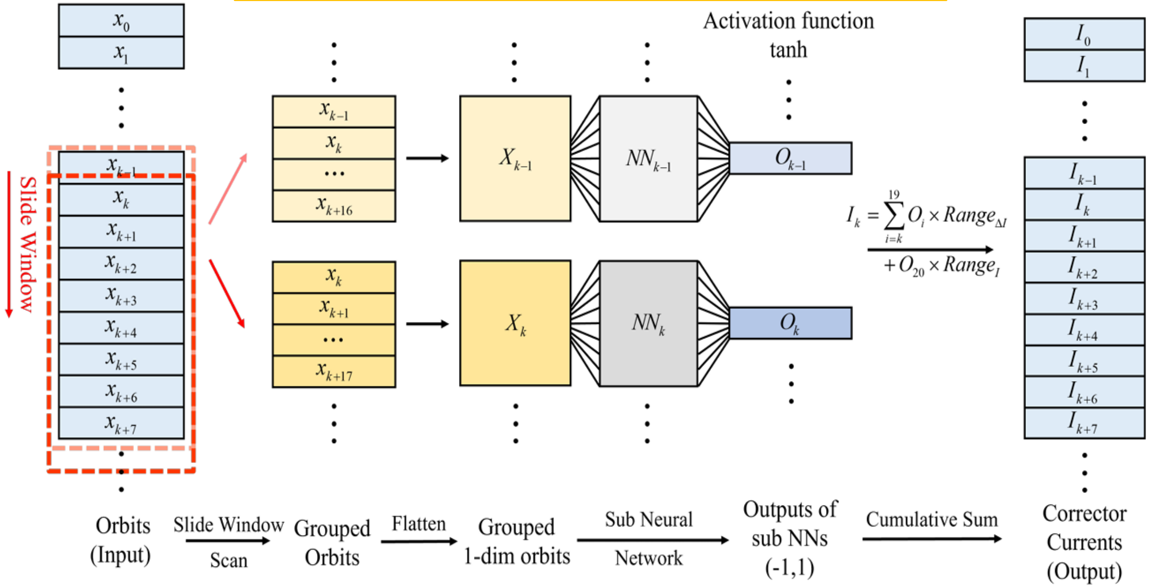
Transverse emittance of CSNS-II is much lower than that of CSNS

3.4 Closed orbit correction

- **Method: global closed orbit correction + local closed orbit correction**
- **The correction of horizontal orbit has always been a challenge for the RCS**
  - ✓ BPM offsets are difficult to measure
  - ✓ Energy mismatch makes orbit correction in the dispersion region difficult



Physics-constrained neural network



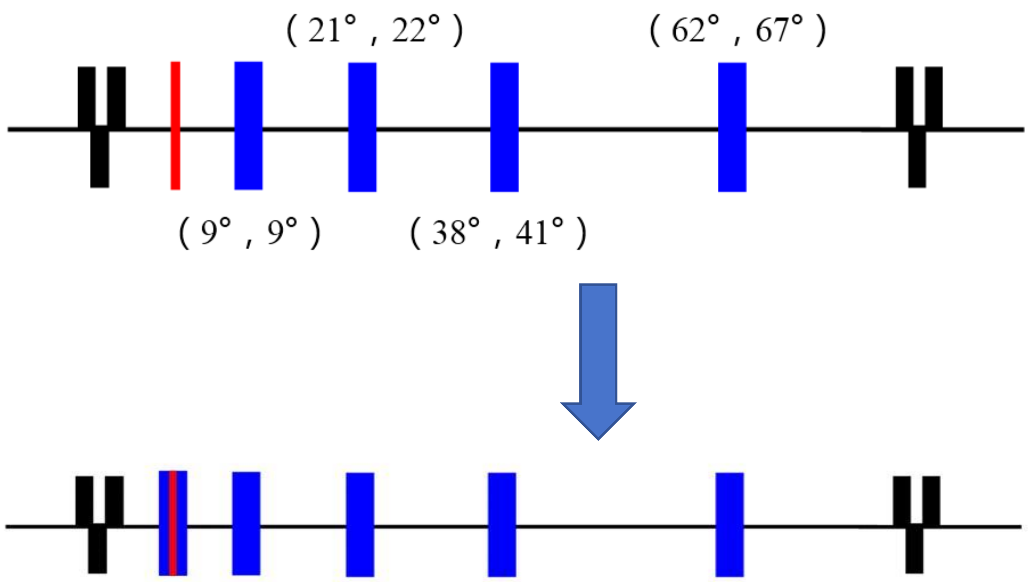
- A neural-network-based orbit correction scheme is being studied to search for improved correction solutions beyond conventional algorithms

More detail: MOP6603

3.5 Transverse and momentum collimators

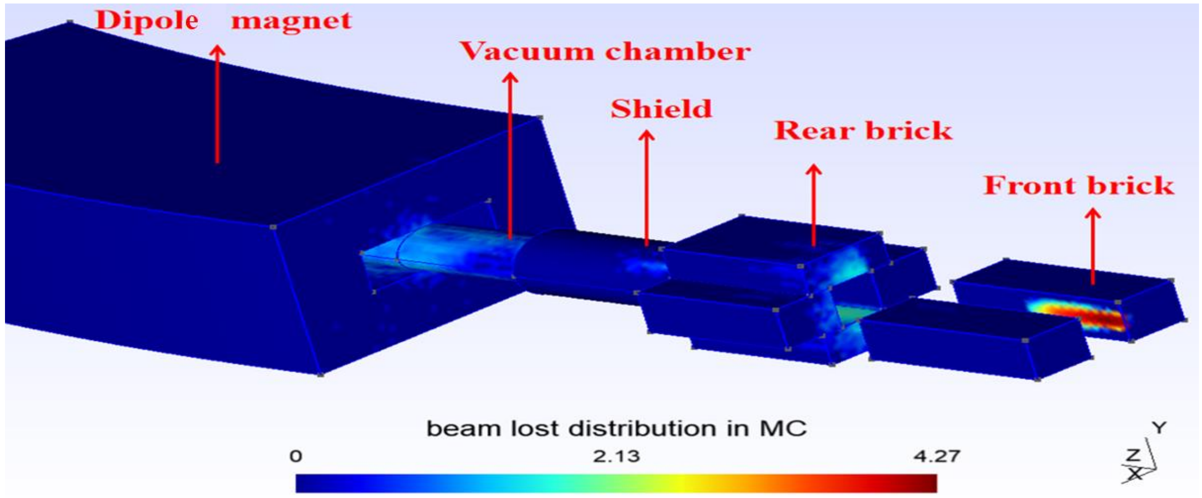
➢ Transverse collimator

- ✓ Complete the design of transverse collimator system that accommodates both single-stage and double-stage collimation schemes
- ✓ The simulated beam collimation efficiency reached 96%



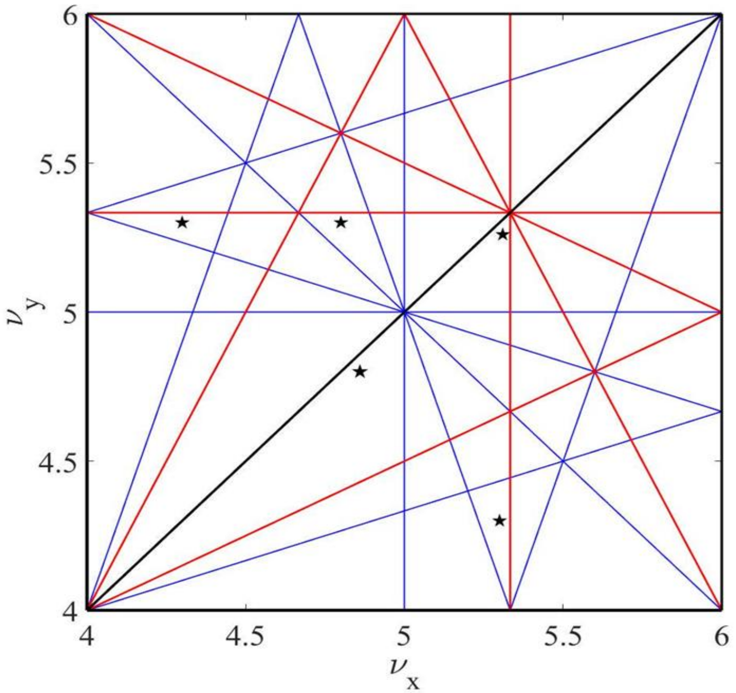
➢ Momentum collimator

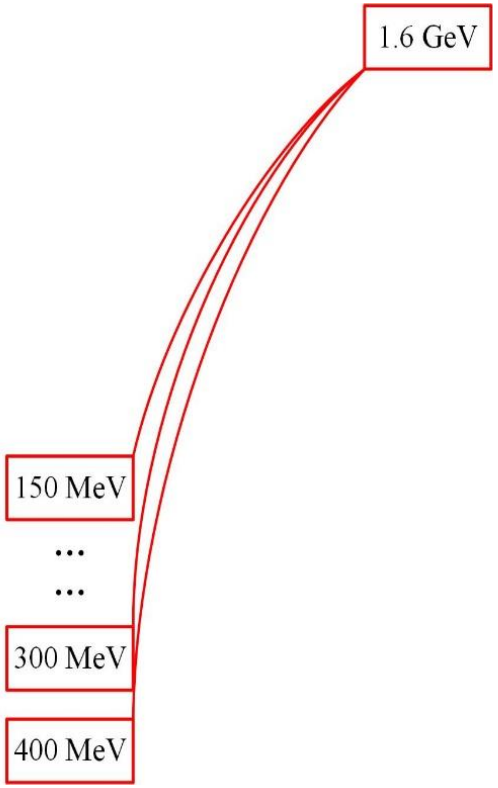
- ✓ The momentum collimator has been installed in the tunnel
- ✓ The physics design has been confirmed, and the beam loss in the arc section has been confined to the collimator area



3.6 Magnetic field measurement for main magnets

- Since the injection energy increase from 80 MeV to 300 MeV, the magnetic field measurement of main magnets need to be done
- A detailed and feasible magnet measurement plan has been developed
- All dipole magnets will be measured and sorted based on the measurement results to reduce the initial COD





3.7 Application software

- A simulation platform for beam dynamics was developed based on the PyORBIT
- OpenXAL and Pyapas are chosen as the beam commissioning tools

Simulation Platform

PyORBIT +

- **Geant4 Interface**
- **Time-varying elements**
- **Injection painting process**
- **Higher-order harmonics in RF cavities**
- **Eddy current effects in resonant power supplies**

Parameters	Simulation	Measurement
Beam transmission efficienfy	99.53%	99.4%~99.7%
Non-normalized RMS emittance measuredat 5ms（H/V）(πmm * mrad)	33.2/32.8	35.3/33.8
Beta function at extraction point measured at 5ms（H/V）（m）	6.57/5.72	6.72/5.81
Alpha at extraction point measured at 5ms（H/V）（（H/V）	0.0007/0.000 6	0.116/-0.014
Tune at the time of injection（H/V）	4.8/4.86	4.81/4.87

Beam commissioning tools

OpenXAL ⇒ SCORE, Wire Analysis, PASTA, Orbit Correction, TBT Analysis, RF Tuner, Injection Curve Set, ……………….

The beam commissioning software for CSNS will continue to be used!

Pyapas ⇒ The new requirements will be developed using new framework! Optimizer, Feedback, ………

IV. Summary

- The CSNS beam commissioning has been studied in detail and the beam power on the target has reached 185 kW
- Many intense beam issues have been studied in the beam commissioning
- The experience and lessons from the CSNS have laid an important foundation for the CSNS-II
- For the CSNS-II, the upgrade progress of the RCS have been studied in detail, including the new injection system, longitudinal dynamics, closed orbit correction, collimators, magnetic field measurement for main magnets, application software, etc.

Thank you for your attention!

Backup

BPM offset measurement

- **In the RCS, there are 32 BPMs in total**

✓ We can measure the offsets of 8 BPMs using the QT

✓ In principle, the offsets of another 10 BPMs could be measured through the quadrupoles sharing a common power supply

✓ However, the remaining 14 BPMs do not meet the conditions for offset measurement

✓ It is challenging to assess the impact of potential BPM offsets on orbit correction

BPM	Num	Quadrupoles Used for Measurement
R*BPM05/R*BPM08	8	R*QT05, R*QT08
R1BPM04	1	Series-Powered Quadrupole R1QF04
R1BPM11	1	Series-Powered Quadrupole R2QD02
R2BPM12	1	Series-Powered Quadrupole R3QF01
R2BPM09	1	Series-Powered Quadrupole R2QF04
R3BPM01	1	Series-Powered Quadrupole R3QF01
R3BPM04	1	Series-Powered Quadrupole R3QF04
R3BPM11	1	Series-Powered Quadrupole R3QD08
R4BPM12	1	Series-Powered Quadrupole R4QF01
R4BPM09	1	Series-Powered Quadrupole R4QF04
R4BPM02	1	Series-Powered Quadrupole R4QD02