Intense Beam Issues in CSNS Accelerator Beam Commissioning

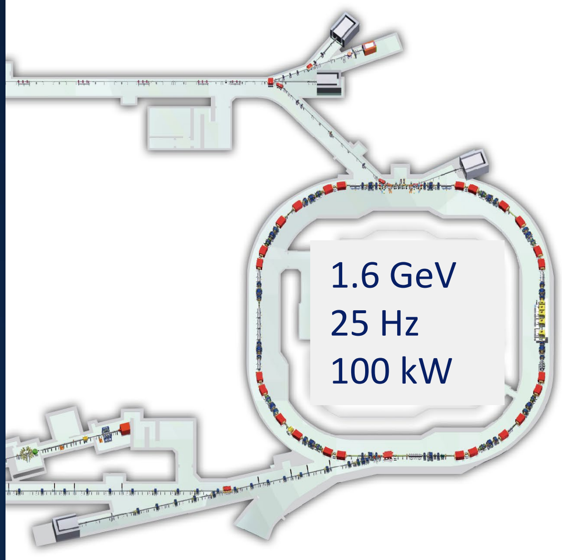
Sheng Wang

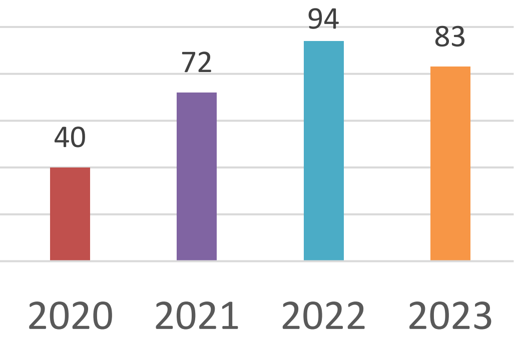
Institute of High Energy Physics, CAS, Oct. 9, 2023

Outline

I. The performance of CSNS
II. The beam commissioning
III. Intense beam issues in RCS
IV. The upgrade of CSNS (CSNS-II)
V. Summary

The Performance of CSNS

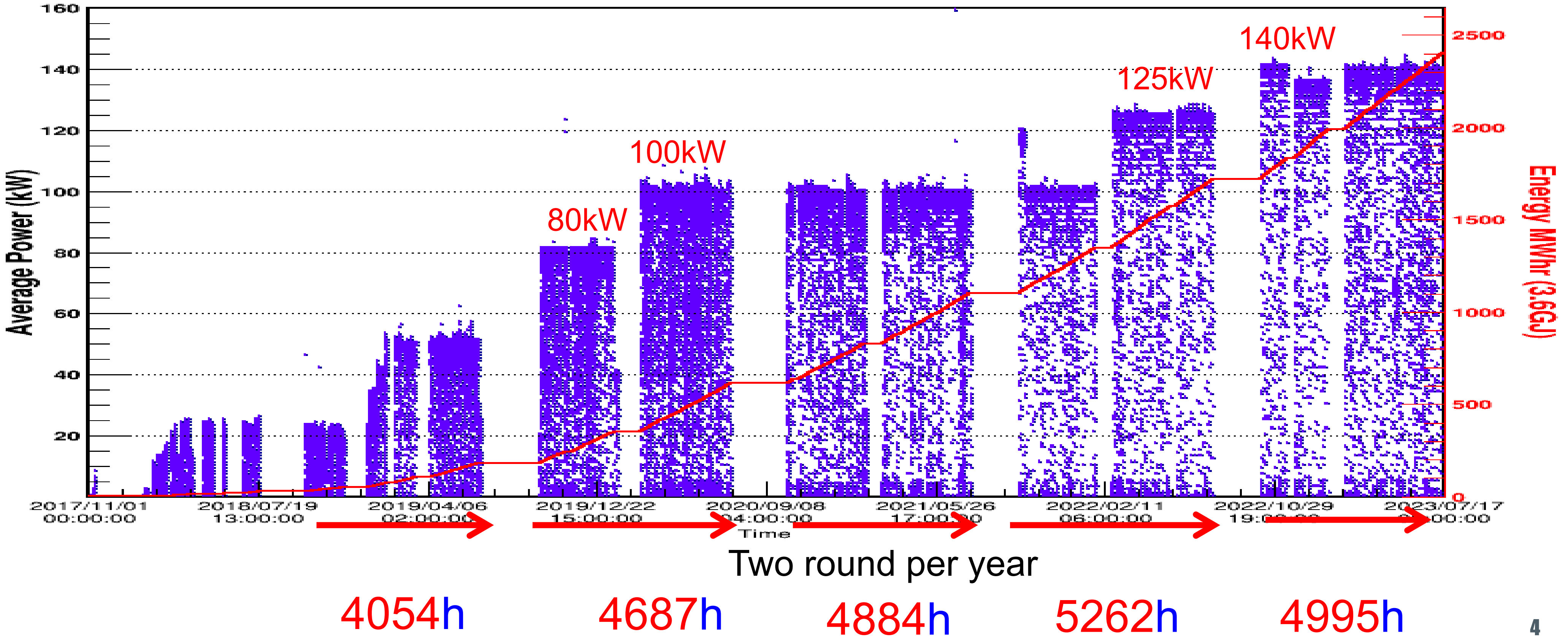




User publication

CSNS Beam History

The neutron beamtime 5262 hours and the availability of 97%

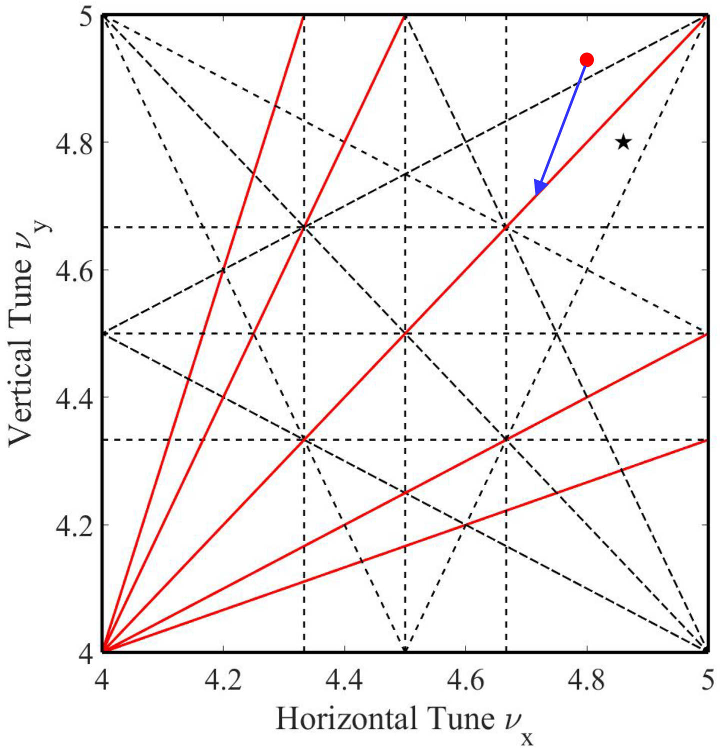


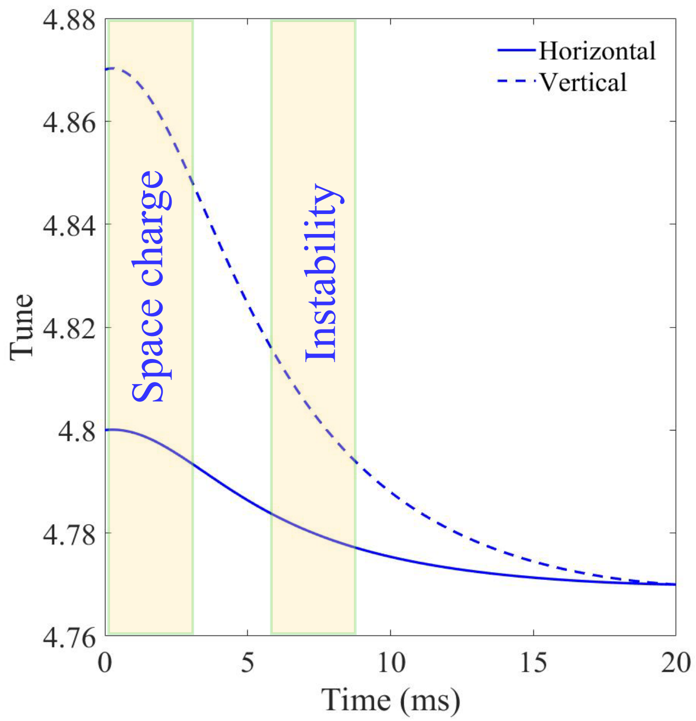
Intense beam effects in RCS commissioning

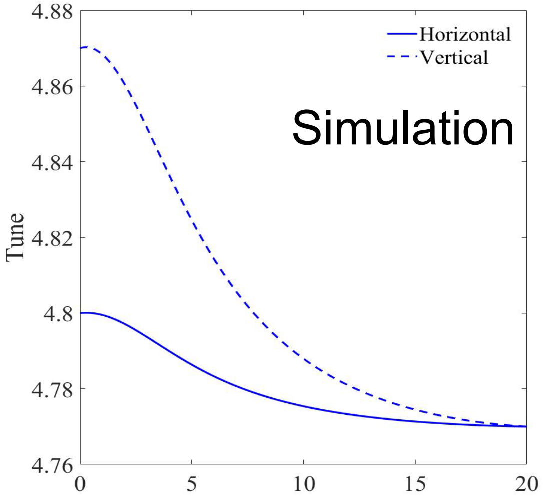
Beam power on target	Challenges	Solutions
50kW→80kW	Too large beam size after painting, non-uniform beam distribution, large transverse coupling	By using the correlated painting instead of the anti-correlated painting
80kW→100kW	Serious beam instability	Optimization of the tune and chromaticity
100kW→125kW	Emittance increase caused by broken four-fold symmetry of the RCS; Stranger beam instability	Slight modification of injection system; installation of AC trim quadrupoles and AC sextupoles
125kW→140kW	Strong space charge effects	Installation of a dual harmonic RF cavity

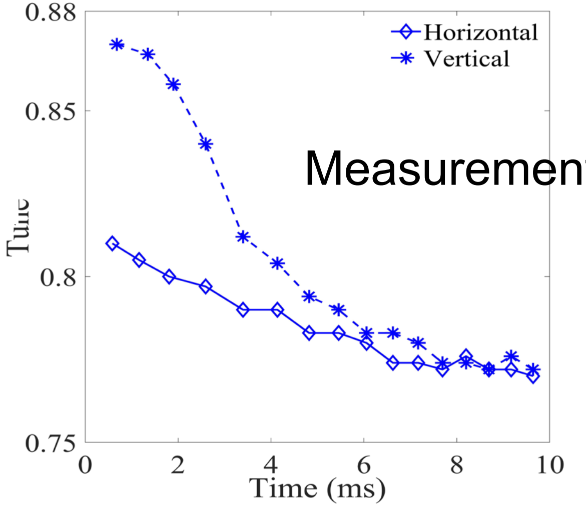
Tune Pattern Optimization

See Xu's report WEA2C1





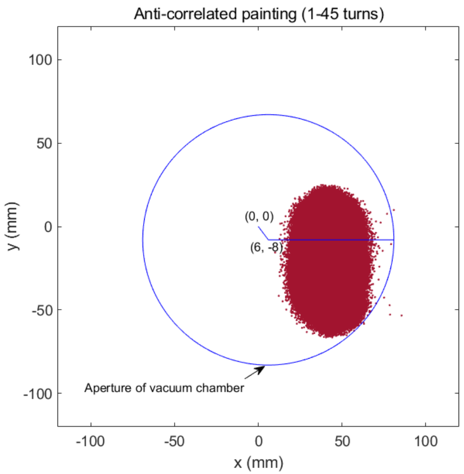


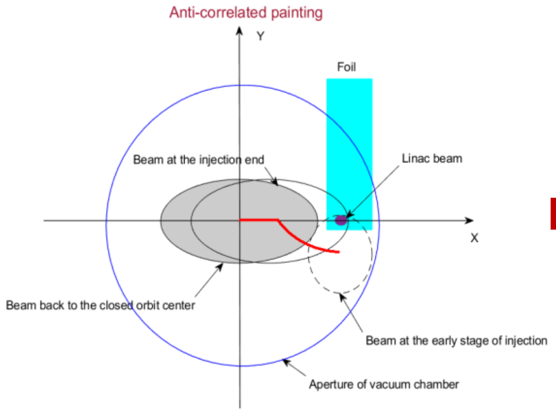


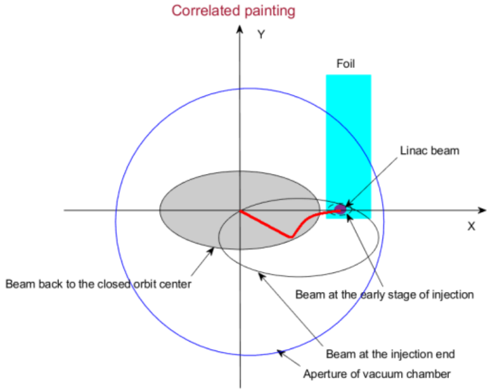
Tune pattern plays an import role in the control the intense beam effects

Painting scheme optimization

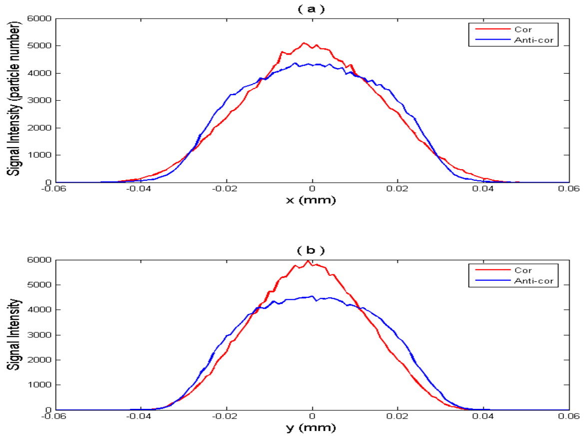
See Huang's report THA1I1

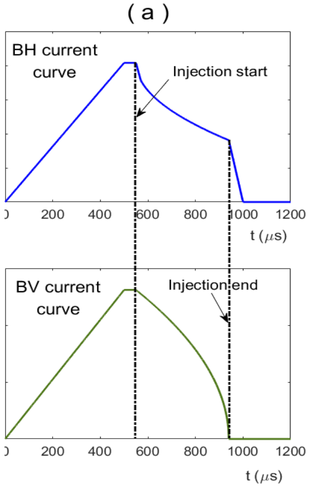


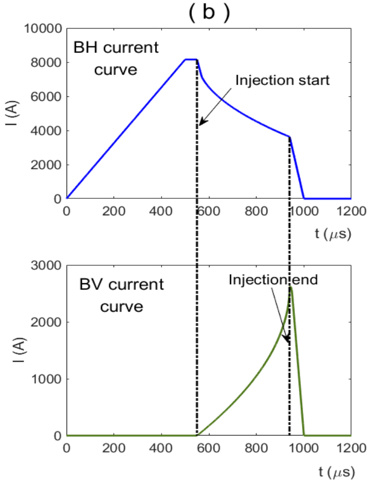




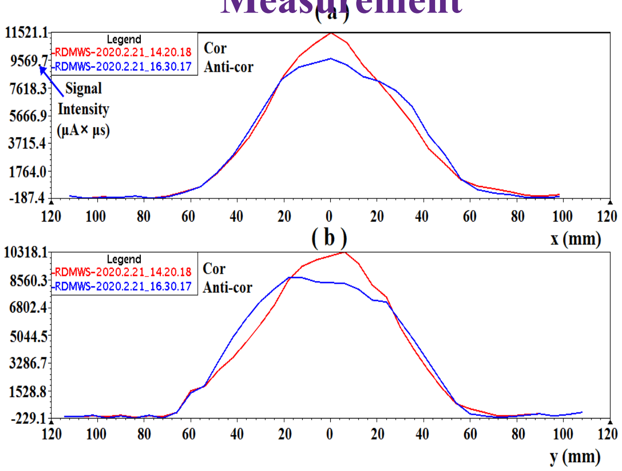
Simulation





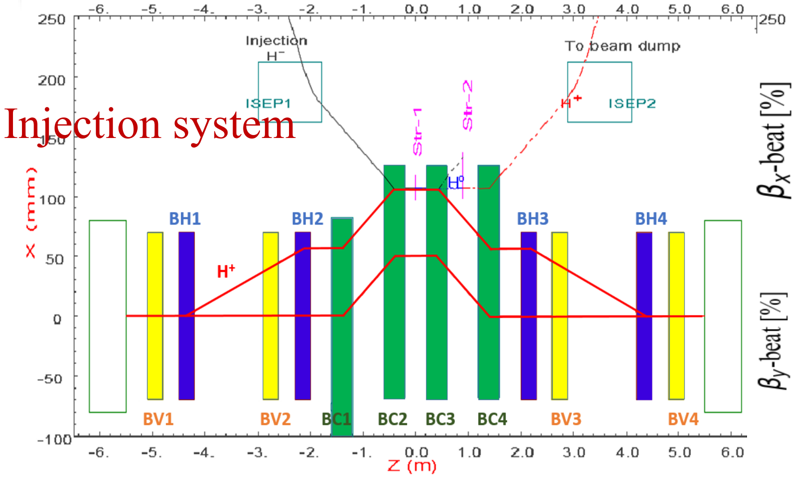


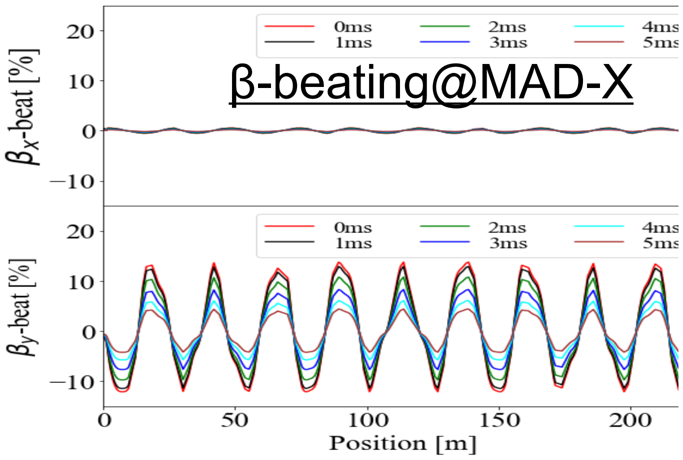
Measurement

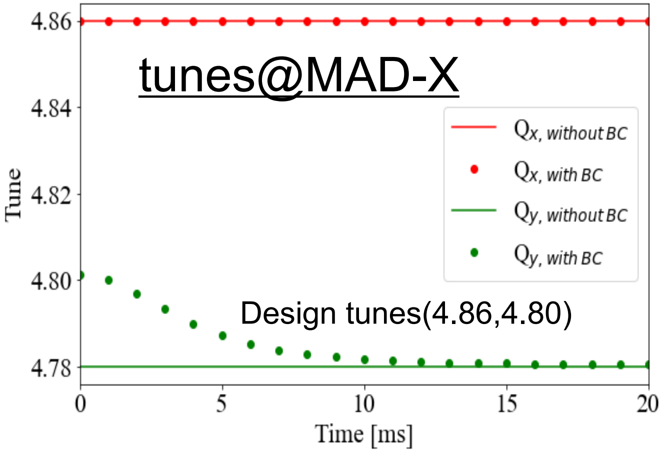


Super-periodicity restoration

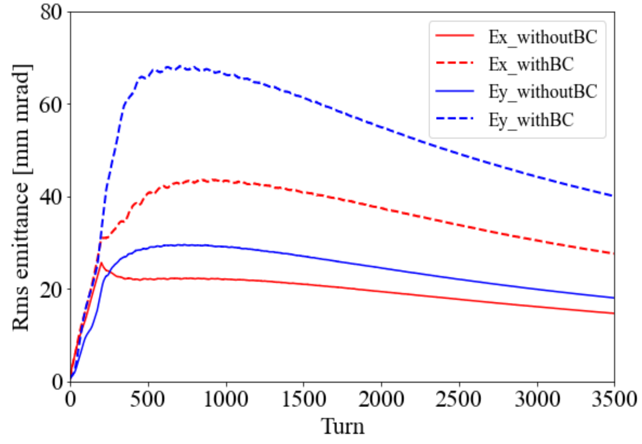
See Li's report TUA4C2



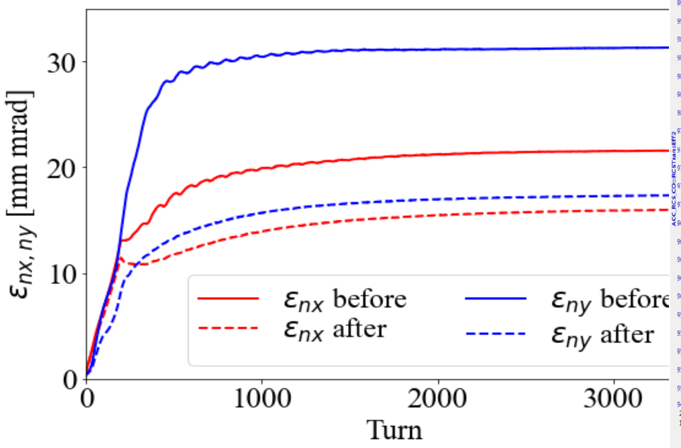




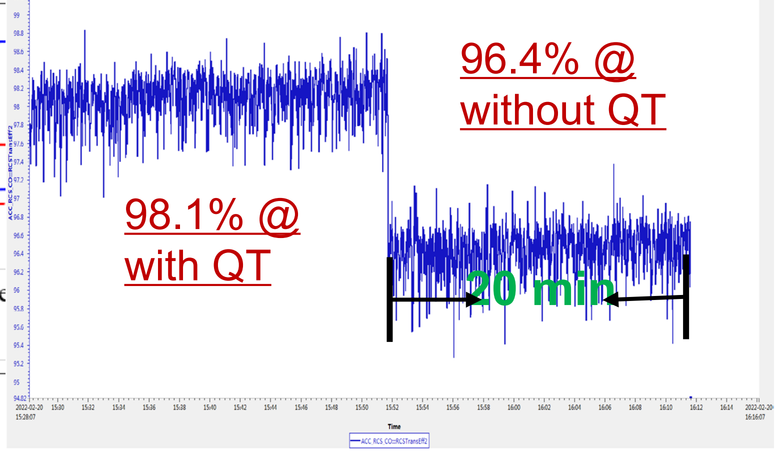
Emittance@PyORBIT



Emittance_QT@PyORBIT



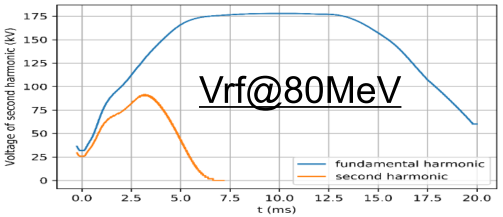
Operating mode @125 kW

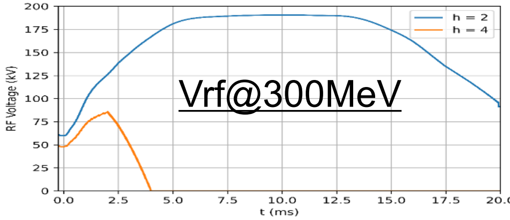


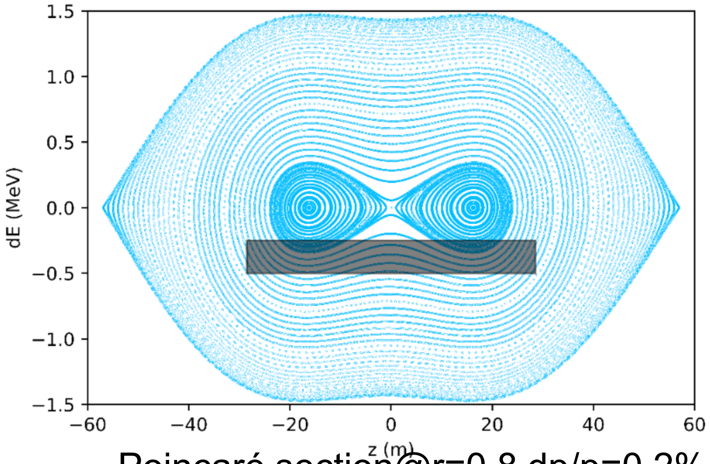
The duel harmonic RF system

See Liu's report FRA1I2

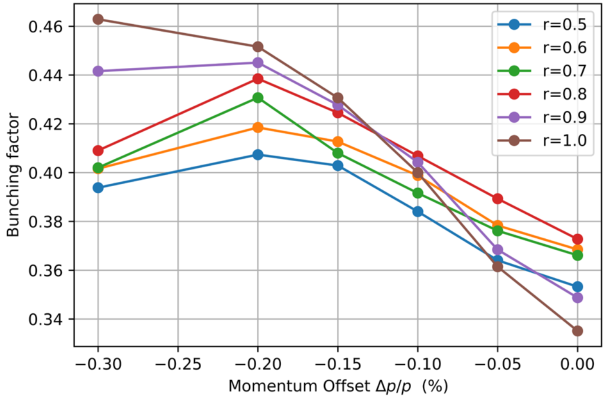
- The dual harmonic system is designed for ease the space charge effect in the upgrade of CSNS
- The prototype MA cavity was installed and operated online
- The initial use of dual harmonic system effectively reduces beam loss and increases beam power.



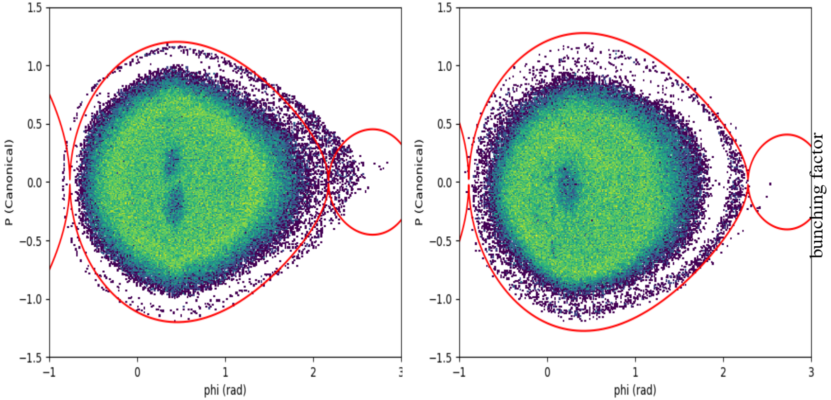




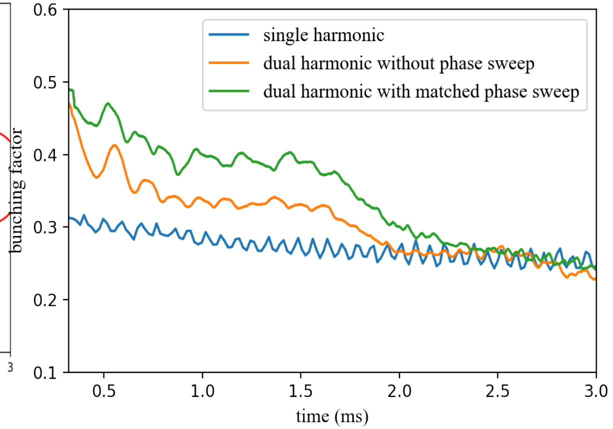
Poincaré section@r=0.8 dp/p=0.2%



Bunching factor with *r* and *dp/p*



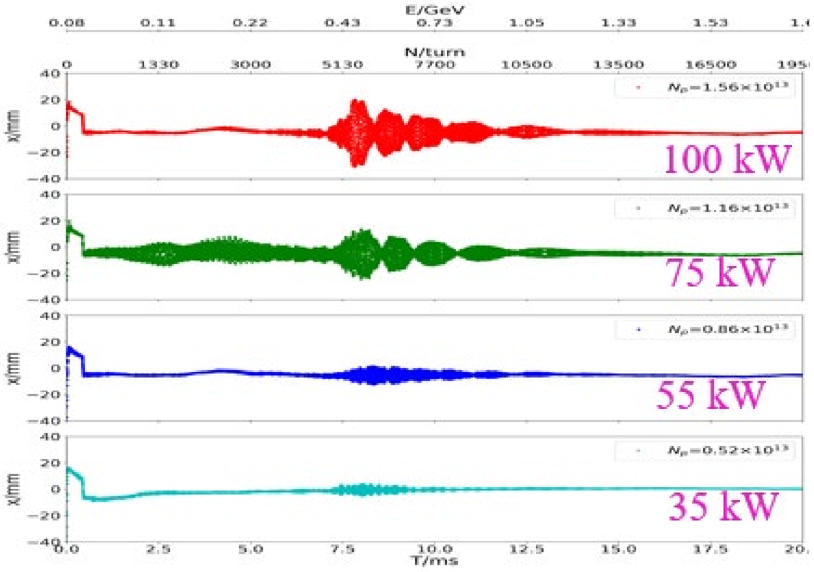
Optimization of Dual RF pattern

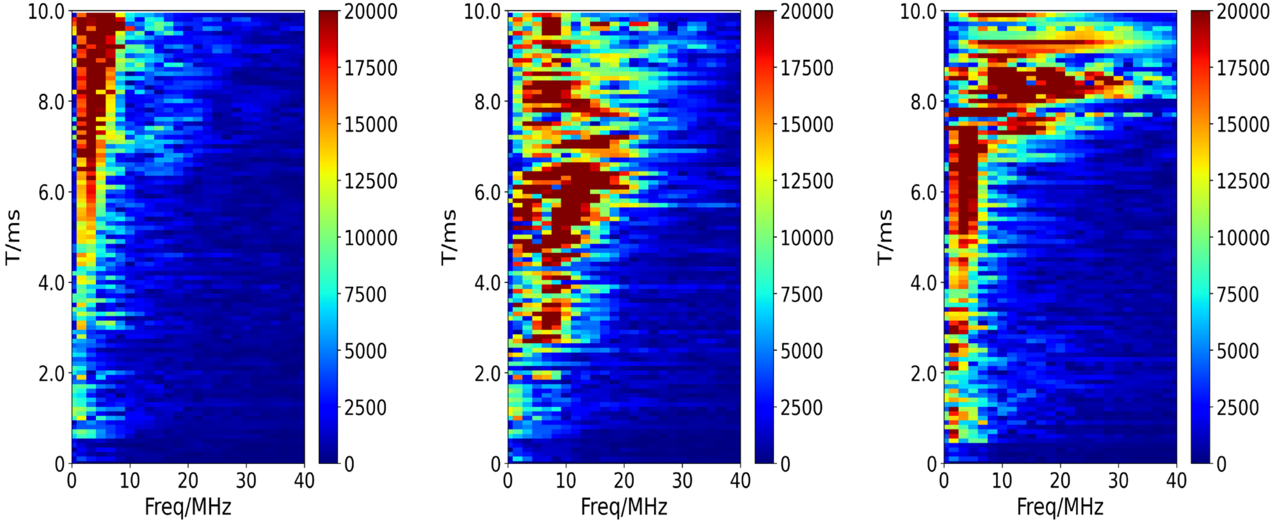


Measured Bunching factors

Collective instability in RCS

- With nominal tune (4.86/4.78) and nature chromaticity, coherent oscillations were observed when beam power >50 kW, with amplitude increasing as the intensity increases.
- The growth time is less than 1 ms for 100 kW
- The impedance is several handred kΩ/m
- It is a “broadband” impedance

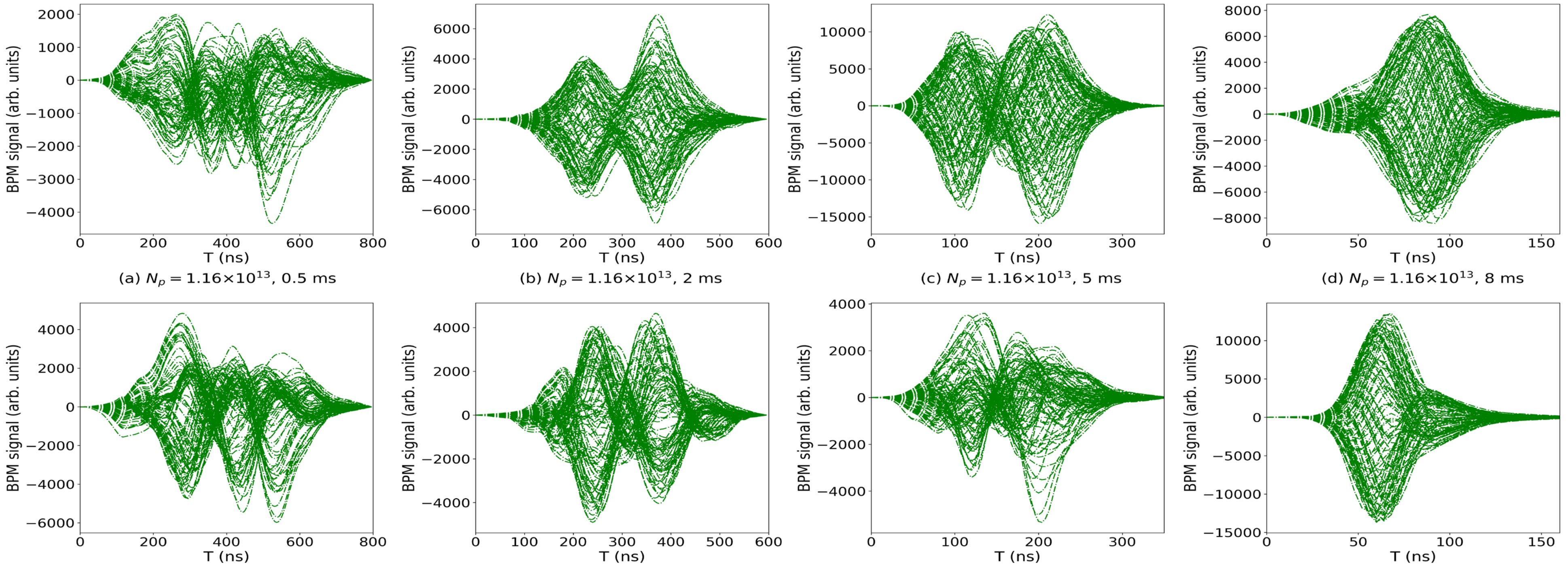




(a) $N_p = 0.52\times10^{13}$ (b) $N_p = 1.16\times10^{13}$ (c) $N_p = 1.56\times10^{13}$

Head-tail mode in a bunch

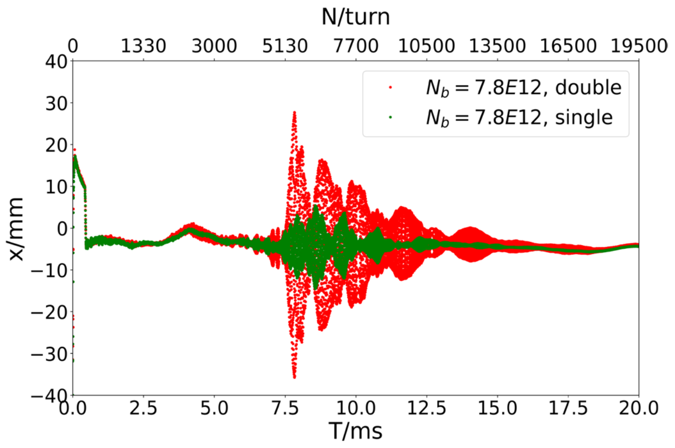
- Acquisition raw data from the BPM with sample frequency of 250 MHz, the head-tail mode can be observed
- The mode changes with the energy increase
- The mode changes with the beam intensity, compared between 75kW and 100kW

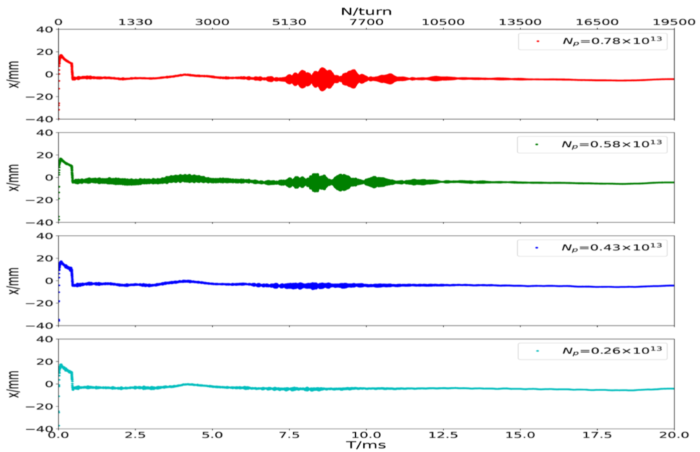


(a) $N_p = 1.16\times10^{13}$, 0.5 ms
(b) $N_p = 1.16\times10^{13}$, 2 ms
(c) $N_p = 1.16\times10^{13}$, 5 ms
(d) $N_p = 1.16\times10^{13}$, 8 ms
(e) $N_p = 1.56\times10^{13}$, 0.5 ms
(f) $N_p = 1.56\times10^{13}$, 2 ms
(g) $N_p = 1.56\times10^{13}$, 5 ms
(h) $N_p = 1.56\times10^{13}$, 8 ms

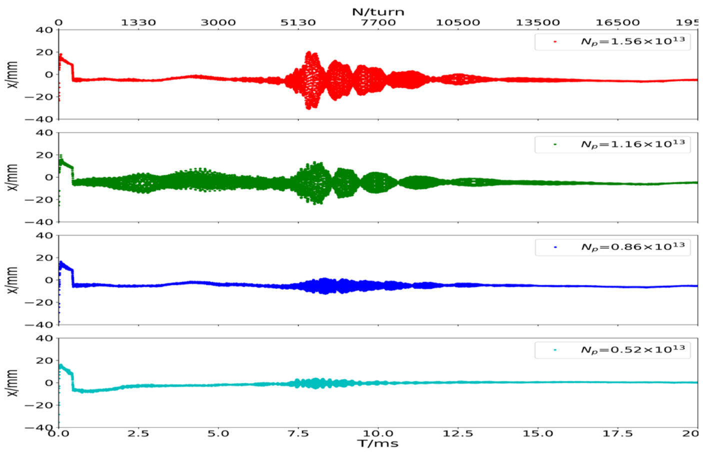
The dependence of oscillation on filling pattern

- When only one of two buckets is filled, the oscillation was also observed， but with much smaller amplitude
- It depends on the total number of particles, no matter they were filled into one or two buckets
- Base on the characteristic, given the name of “**Head-tail coupling bunch instability**”

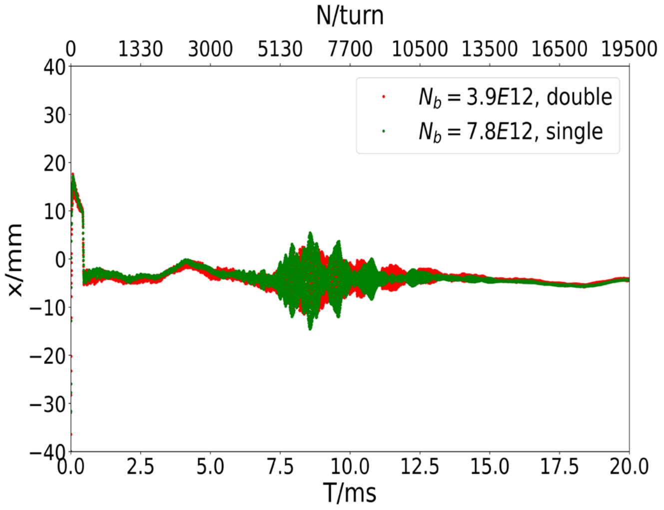




Single bunch

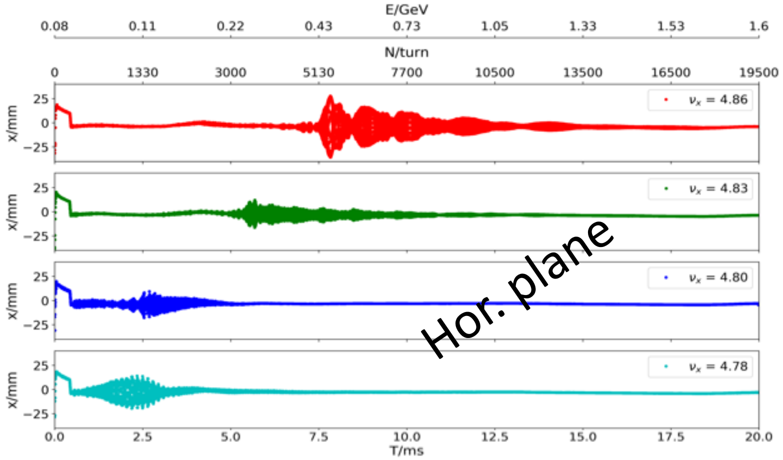


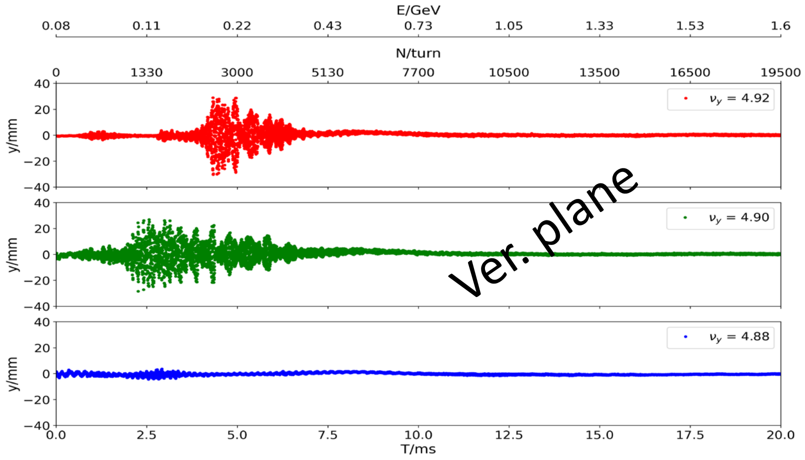
Two bunches



The dependence of oscillation on tune

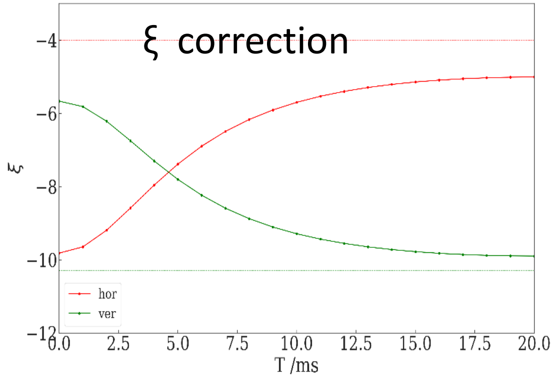
- Scan ν_x with $N_p = 1.56 \times 10^{13}$ of 100 kW.
  - ν_x from 4.78 to 4.86 with $\nu_y = 4.78$
- The oscillation amplitude increases rapidly as the tune moves toward 5.0, and the instability shows up later
- The instability has also been observed in vertical plane.
  - Scan ν_y with $N_p = 1.1 \times 10^{13}$ of 70 kW
  - ν_y from 4.88 to 4.92 with $\nu_x = 4.78$
  - Similar to that in horizontal plane

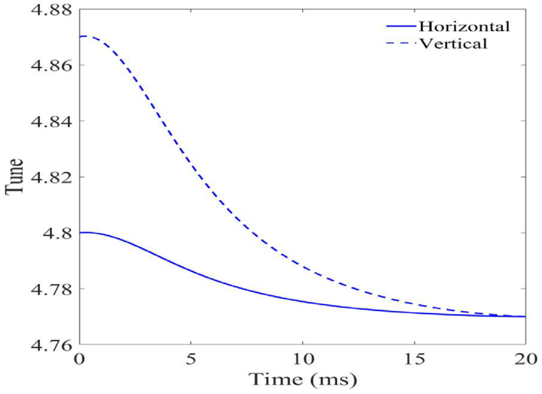


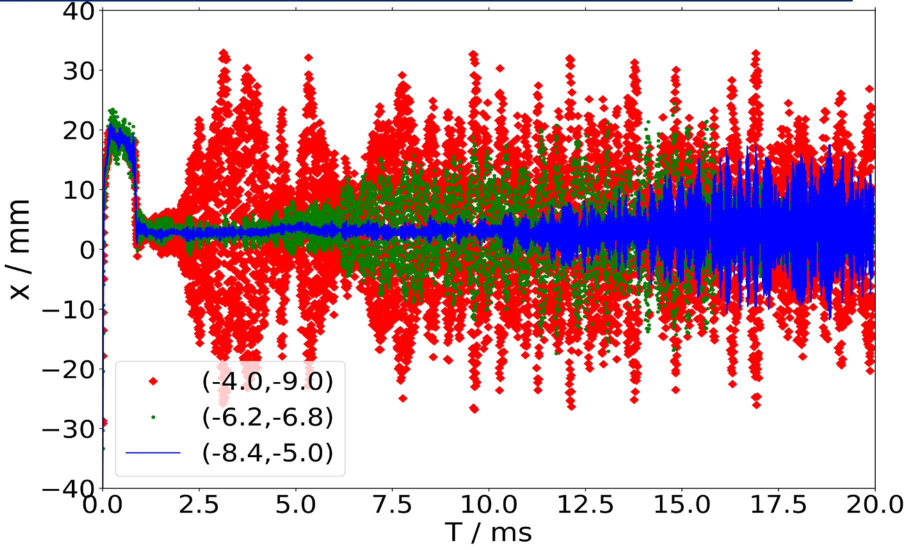


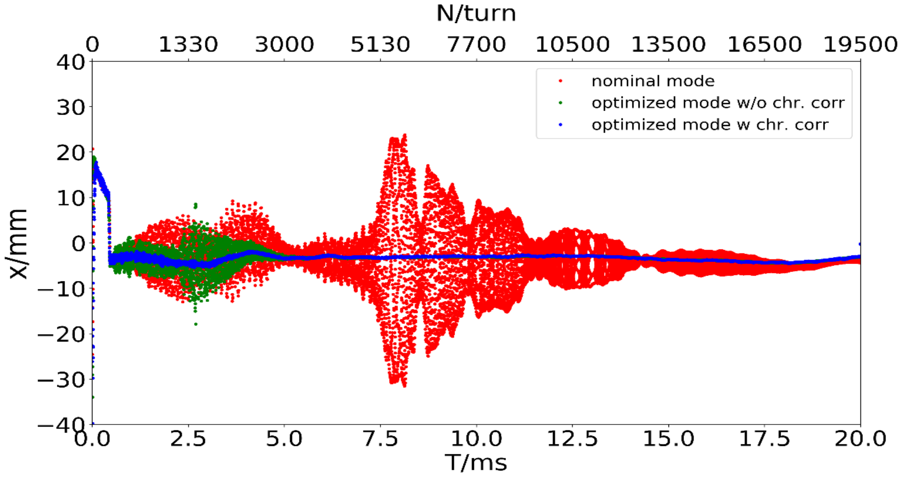
Mitigation of instability

- ➢ The coherent oscillation was damped by increasing chromaticity (DC sextupoles)
- ➢ Optimizing tune pattern to mitigate the coherent oscillation





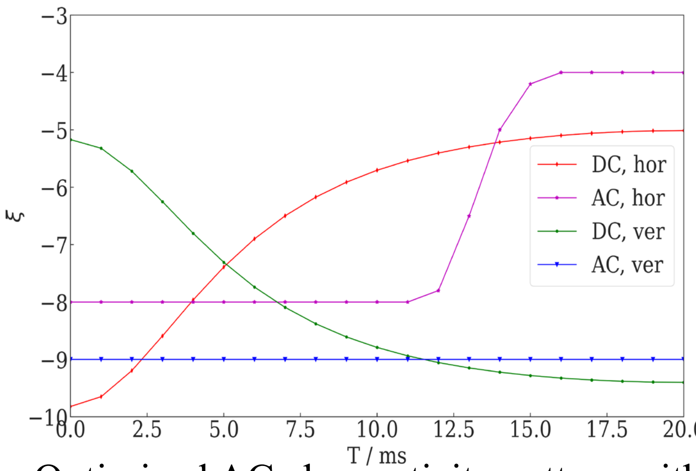




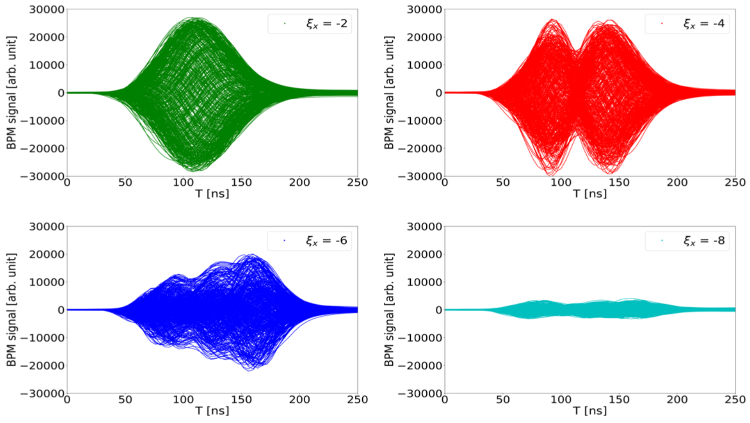
✓ With two mitigation methods, the beam power reached 100 kW successfully.

Upgrading sextupoles for high beam power

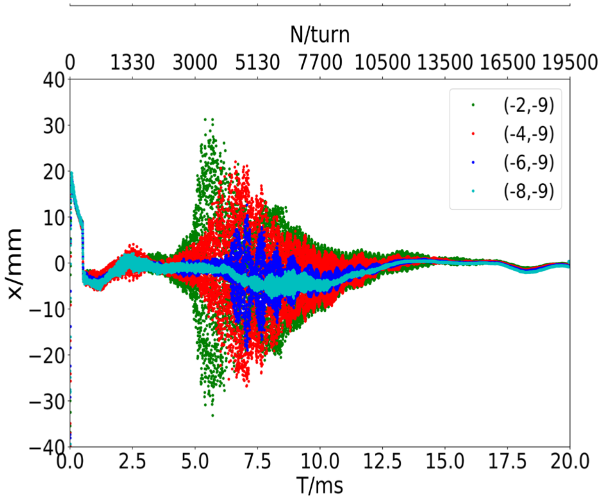
- DC sextupoles were replaced by AC after beam power reached 100kW (in 2021)
- With AC sextupoles, the chromaticity can be well controlled in an RCS cycle
- AC sextupole plays a crucial role in beam power of 100 kW+
- AC sextupoles made significant contribution from 100KW to 125 kW
- The instability can be completely suppressed with beam power of 140 kW



Optimized AC chromaticity pattern with DC and AC sextupole field.



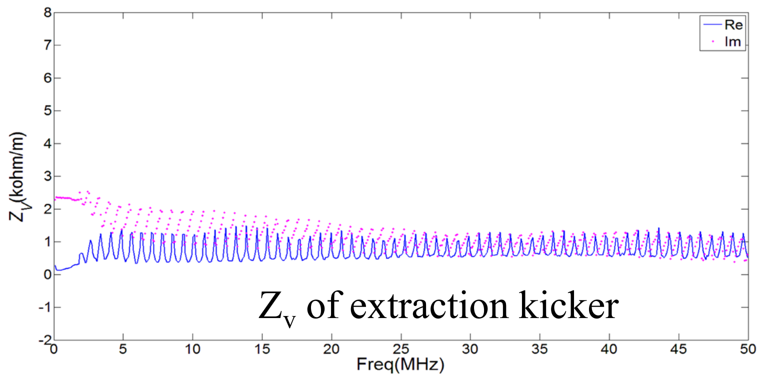
The head-tail mode with different chromaticities



Coherent oscillation well controlled in the commissioning

Possible source of impedance

- Many studies have been done on the collective instability in design stage, but this instability is unexpected.
- Key components—Vertical extraction kicker: good match between the kicker and PFN and small oscillation only in vertical plane
- Key components—Cavity: HOMs of the ferrite loaded cavity have been found, but small peak value
- By using the empirical formula, the estimated impedance of resistive wall from both stainless steal and ceramic chamber is small



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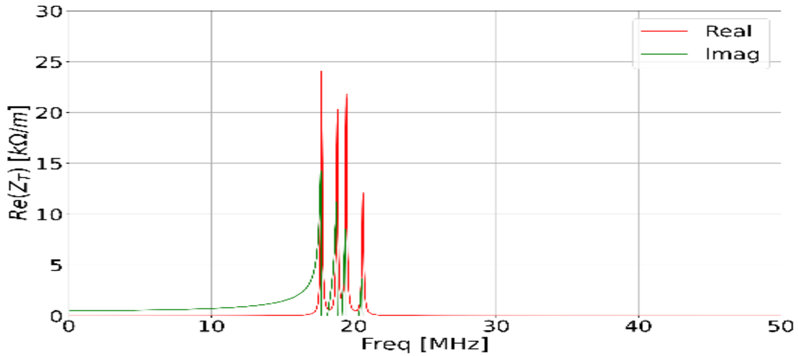
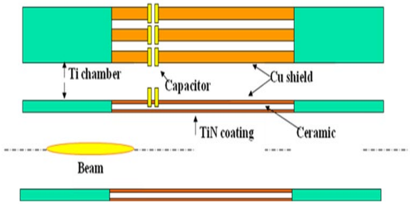


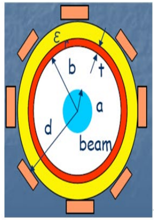
Measured impedance of eight ferrite cavities

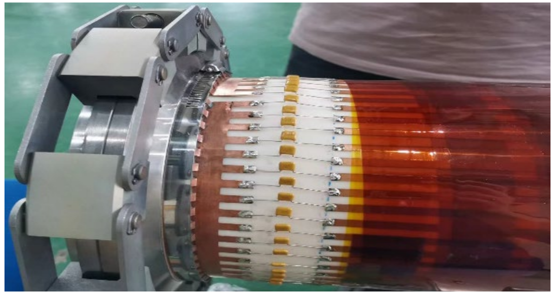
10.18429/JACoW-IPAC2021-TUPAB261; IPAC2023, WEPL162

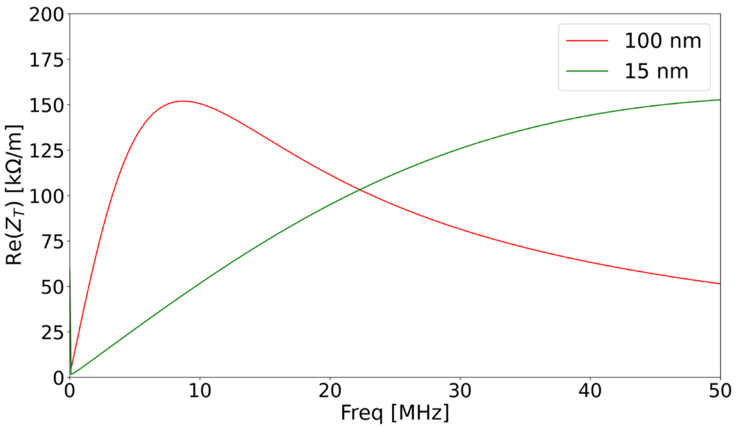
Possible source of impedance

- A very complicated structure of the ceramic chamber, 4 layers and 100 nm TiN
- Based on a simplified model, by using IW2D, the impedance and the impedance was estimated, and is much larger than the value based on the empirical formula.
- Although it is difficult to measure the impedance, we compared the impedance w. and w/o TiN coating.

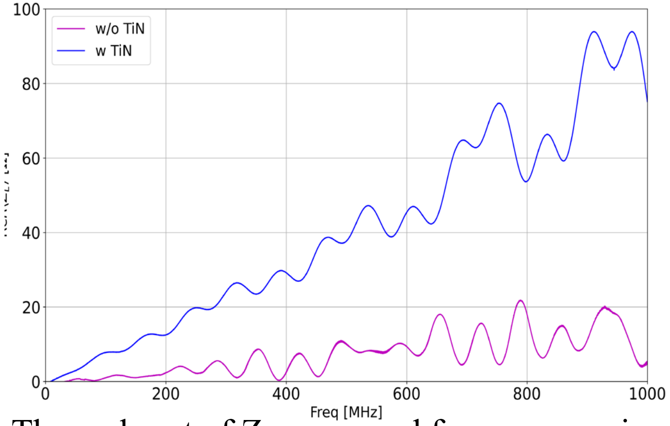






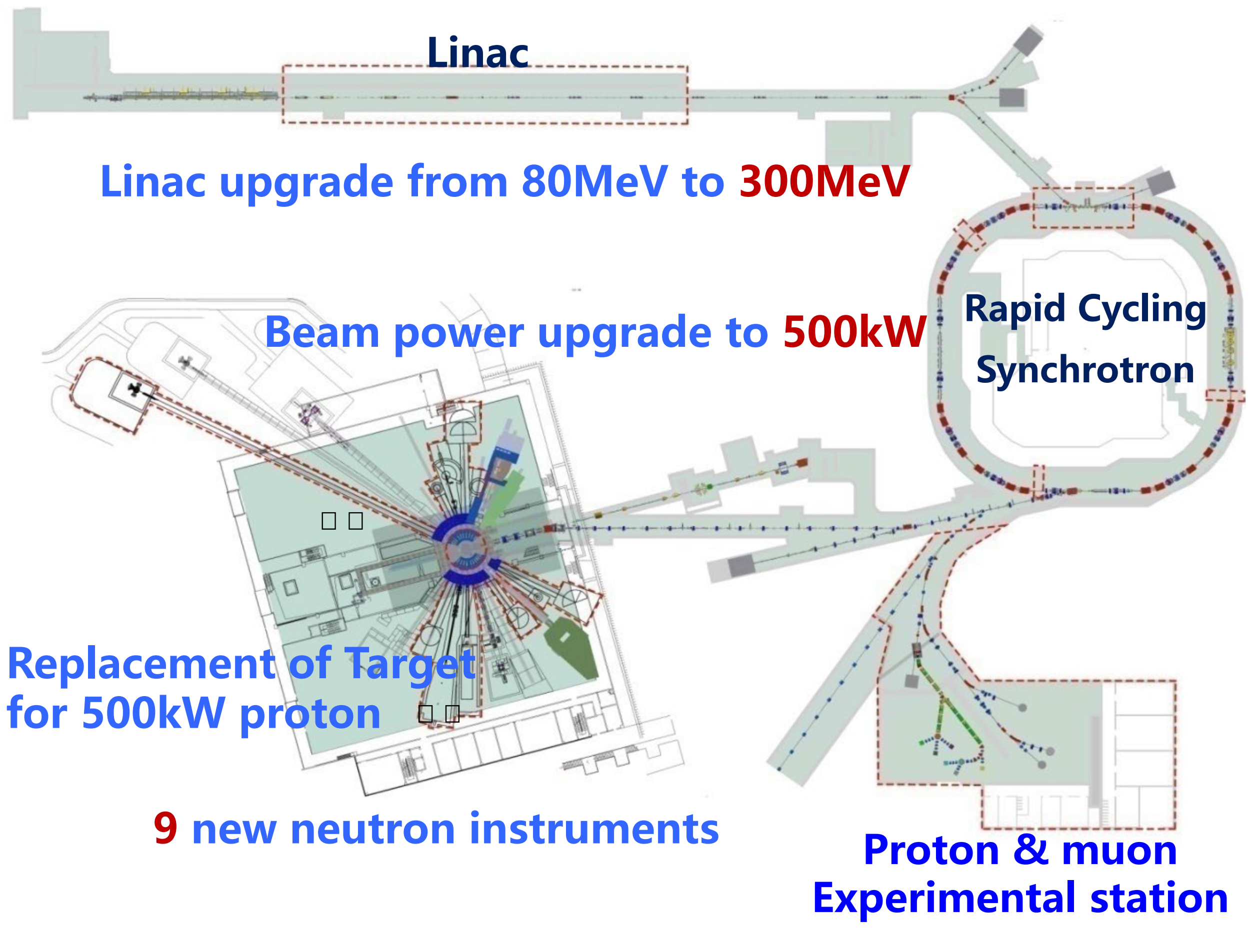


Simulated Z_T of RCS ceramic chamber



The real part of Z_L measured from a ceramic chamber with an inner radius of 80 mm and a length of 0.74 m

China Spallation Neutron Source-II



- Project Budget: 2.9 BCNY
- Funded by central and Guangdong local government
- Design and R&D completed
- Construction: 2023.11~2029.7 (5 years and 9 months)

Plans to maintain user operation almost unaffected during CSNS II construction

Challenge from Beam Dynamics

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

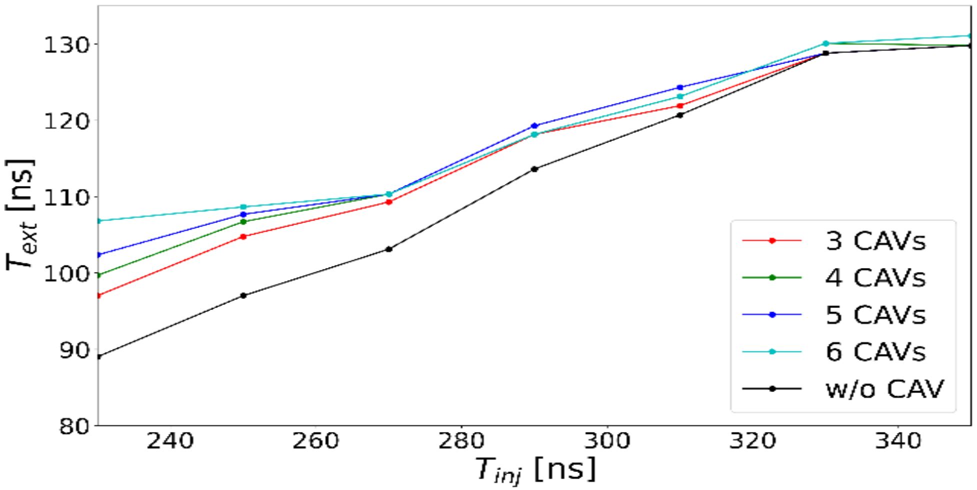
The highest beam intensity in the same kind of RCS for CSNS-II

Beam Power Upgrade （two-step）

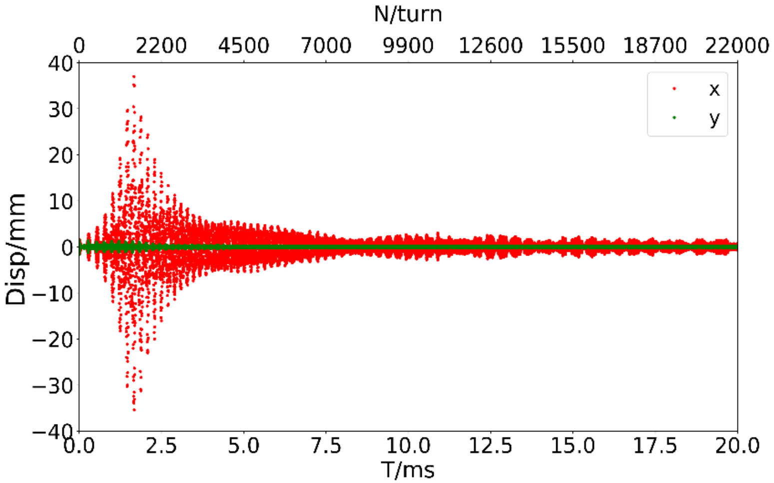
1. Linac（80MeV） + RCS upgrade 150~200kW (the first step)
   - ✓ New dual harmonic RF system
   - ✓ Adding AC trim quadrupoles, sextupoles and octupoles
2. Linac （300MeV+） + upgraded RCS 500kW(the second step)
   - ✓ SC linac to 300MeV
   - ✓ New injection region
   - ✓ Upgrade the power supplies for main magnets

Beam instability in RCS of CSNS-II

- **The new elements in RCS don't contribute a lot for impedance**
- **Bunch lengthening driven by parasitic impedance of MA CAV is very small**
- **The head-tail coupling bunch instability remains a key issue in CSNS-II**
  - The threshold of beam power is ~ 300 kW



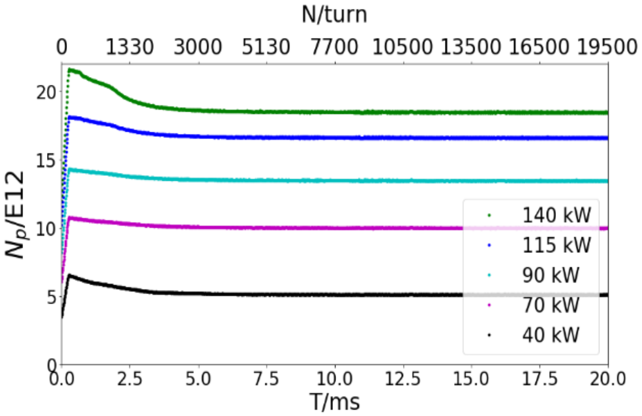
Bunch length with different number of MA CAV



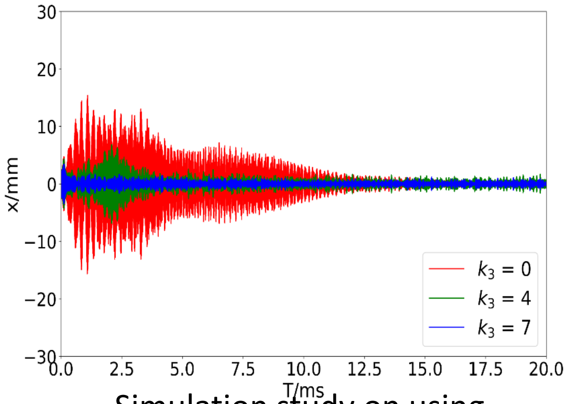
Prediction of the beam instability with 500 kW beam power in CSNS-II

Mitigation strategy for CSNS-II

- Many mitigation methods are being considered
- Tune below 0.5, such as (4.3,5.3), (5.29, 5.32)
  - Such as (4.3, 5.3) below, without instability observed until 140 kW
- Octupole magnet will be installed to increase Landau damping
- BxB feedback was being firstly developed, and further intra-bunch feedback



(4.3,5.3), w/o instability

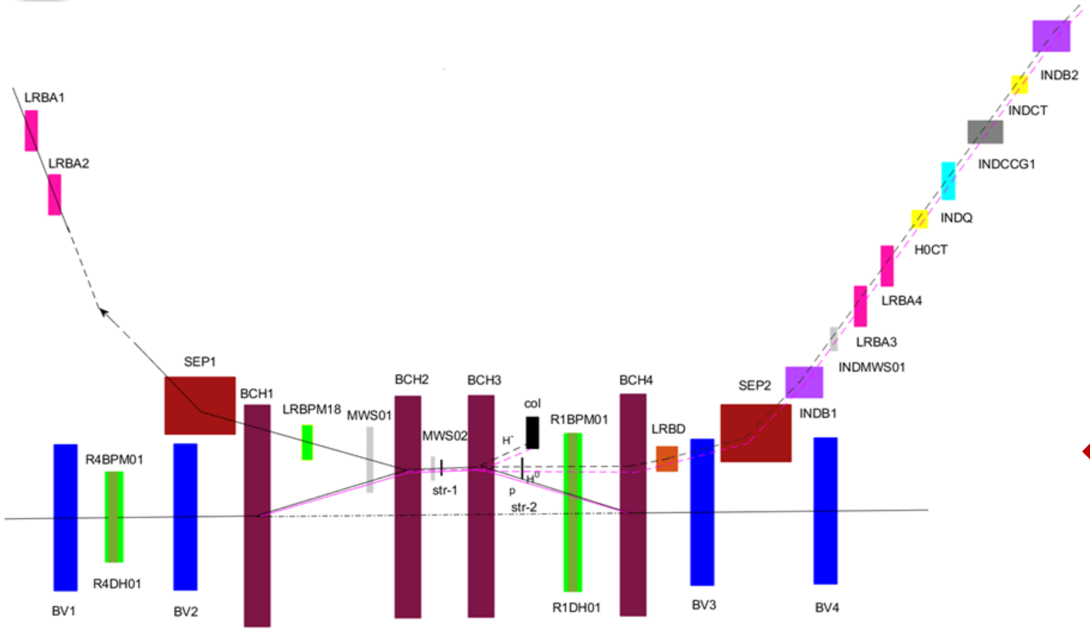


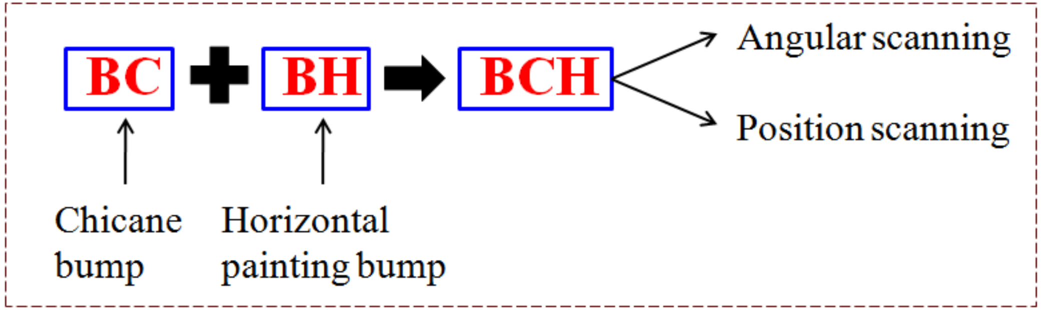
Simulation study on using octupole

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

A new injection painting scheme

See Huang's report THA1I1





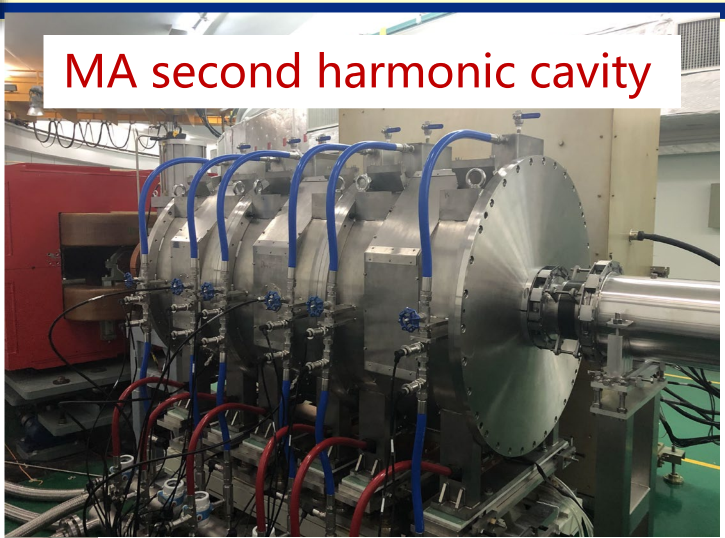
- New idea: chicane bump and horizontal painting bump are combined into one bump which make the chicane bump "move". The horizontal painting is performed by using the position and angle scanning at the same time.

◆ **Advantages:**

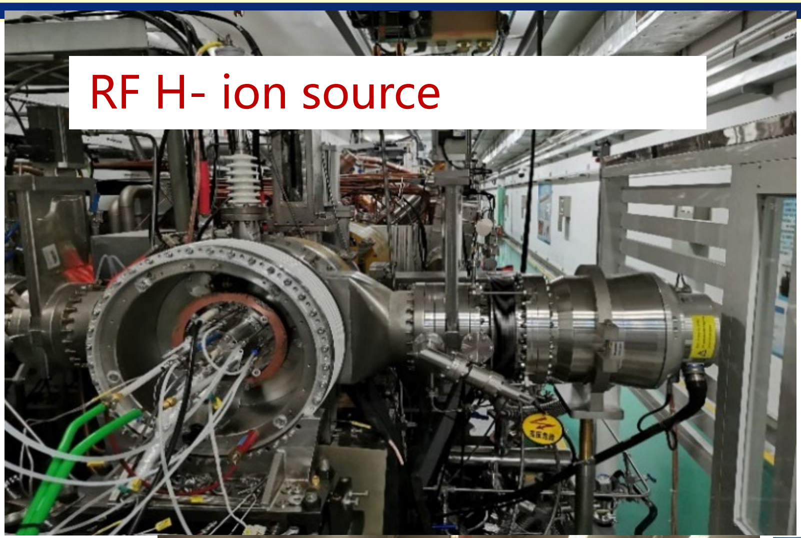
- ◆Peak temperature of the stripping foil can be greatly reduced.
- ◆Both correlated and anti-correlated painting can be performed.
- ◆The edge focusing effect of bump magnets is greatly reduced
- ◆The difficulty of large aperture of the injection port and transport line required by angular scanning is solved.
- ◆It saves a set of bump magnets and is easier to optimize the layout of the injection system.

R&D for CSNS-II Accelerator

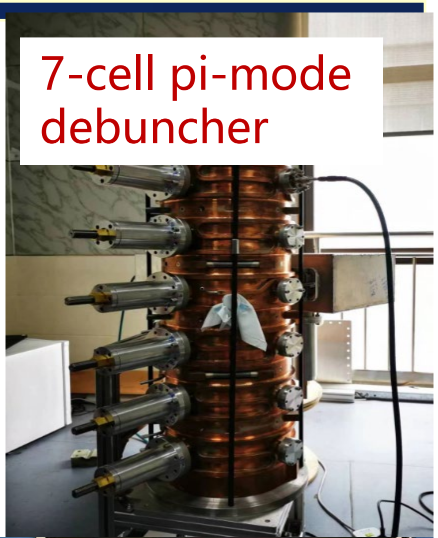
MA second harmonic cavity



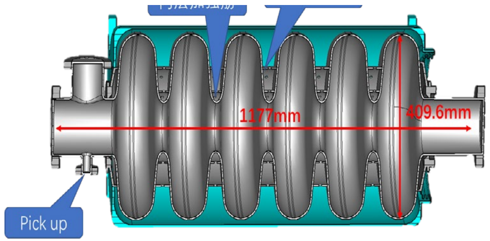
RF H- ion source



7-cell pi-mode debuncher



Prototype SC cavities: Double spoke & Ellipsoidal cavity



Long-pulse solid-state modulator

Low-level RF prototype

Summary

- ✓ **The CSNS beam commissioning has been successful, surpassing the 100 kW (design goal). Currently, CSNS operates steadily at 140 kW with high availability, reliability, and stability.**
- ✓ **Many intense beam related issues have been studied in the beam commissioning.**
- ✓ **CSNS-II, the upgrade project for CSNS, which will increase beam power to 500kW, will soon start the construction.**
- ✓ **The experience and lessons from CSNS have laid an important foundation for the CSNS-II.**

Thank you for your attention!