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Observation and study of space charge effect frequency shifts in high-intensity accelerators

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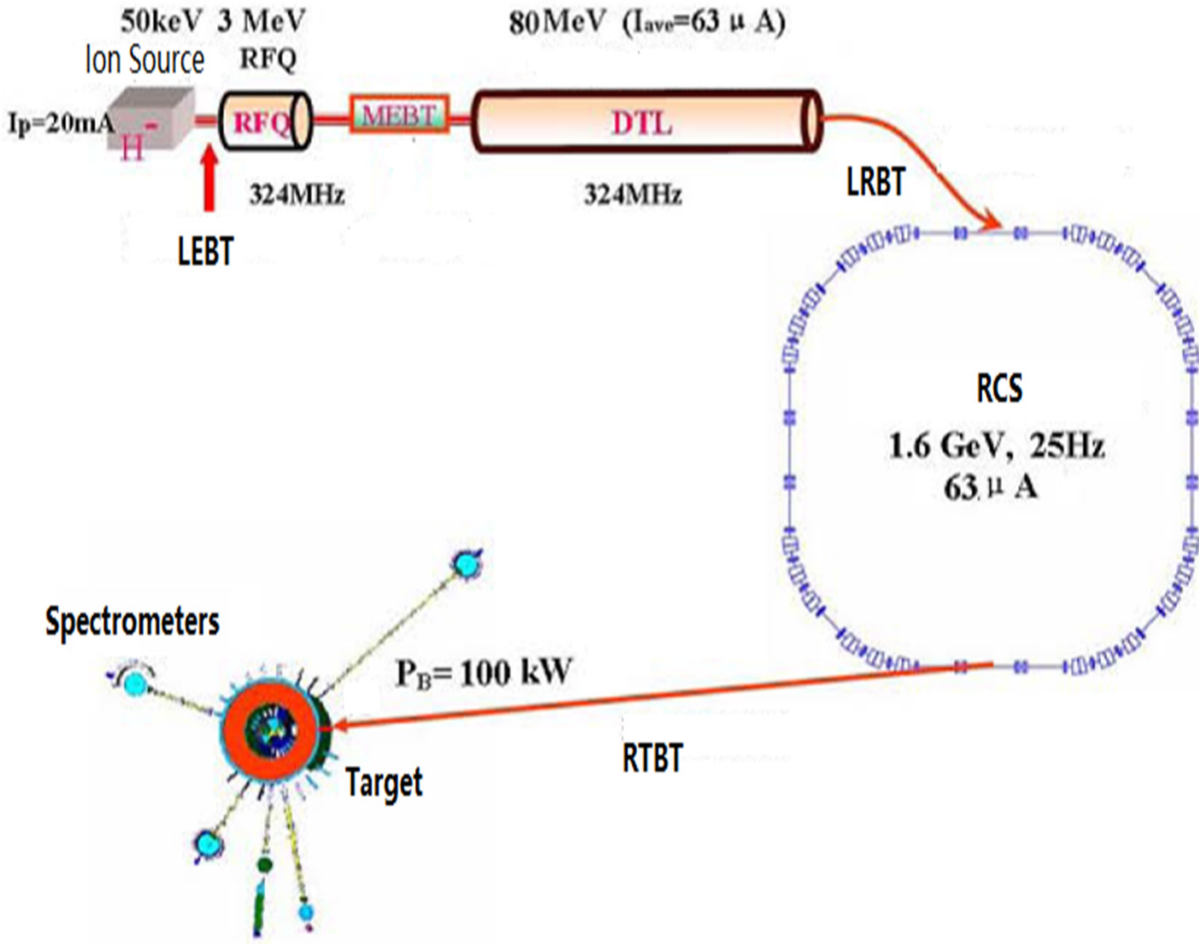
Outlines

- **Overview of CSNS**
- **A review of beam power upgrades for CSNS/RCS**
- **Space charge effects to CSNS/RCS**
  - **Experimental results**
- **Conclusion**

CSNS overview

- **The CSNS facility consists of an 80 MeV H⁻ linac, a 1.6 GeV rapid cycling synchrotron (RCS), beam transport lines, a target station, and several spectrometers.**

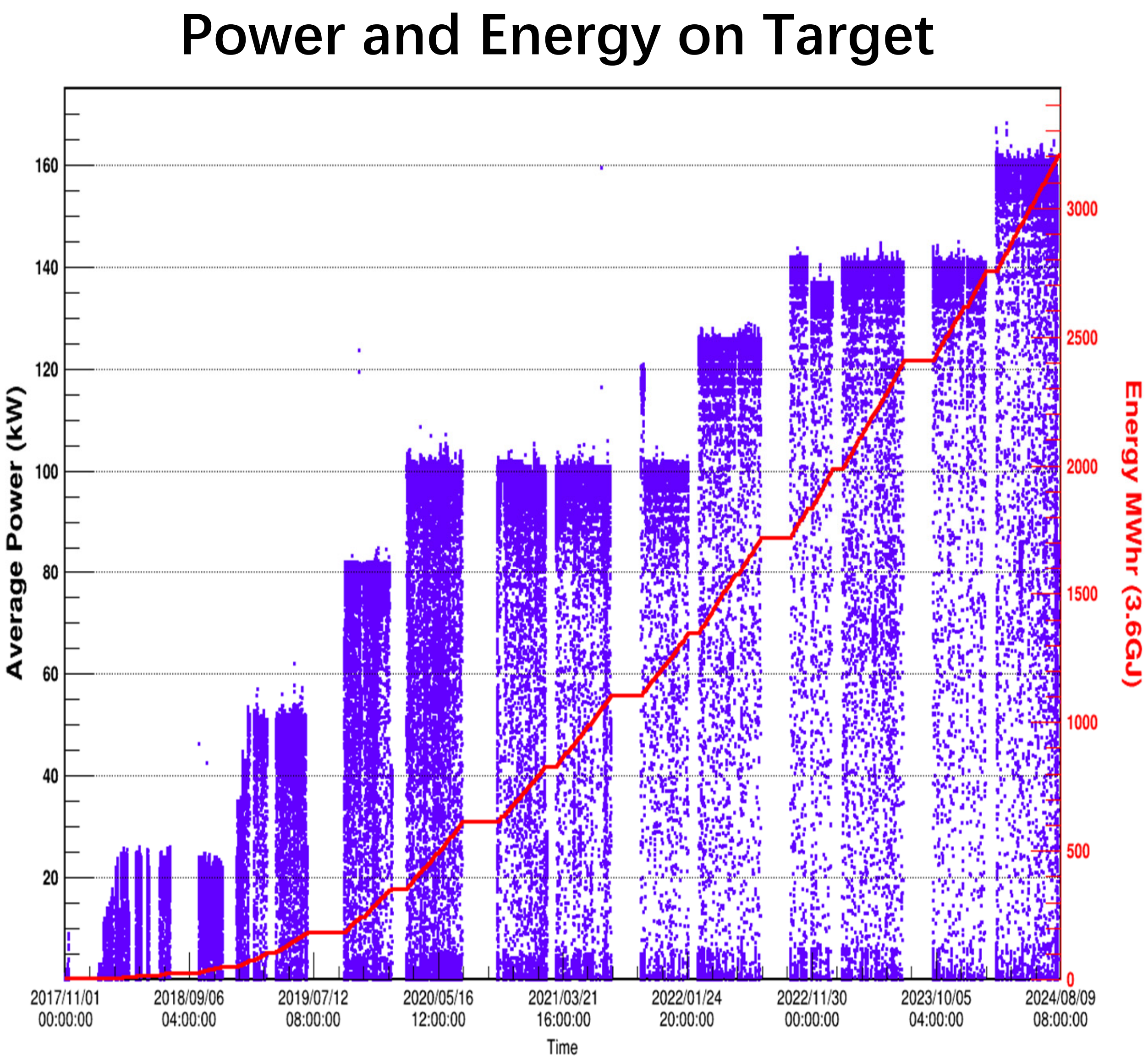
Project Phase	I	II	Now
Beam Power on target [kW]	100	500	160
Proton energy [GeV]	1.6		
Average beam current [μA]	62.5	312.5	100
Macropulse.ave current[mA]	15	40	15
Linac energy [MeV]	80	300	80
Linac type	DTL	Spoke+ Elliptical	DTL
Target	1	1	
Spectrometers	3	20	



A review of beam power upgrades for CSNS/RCS

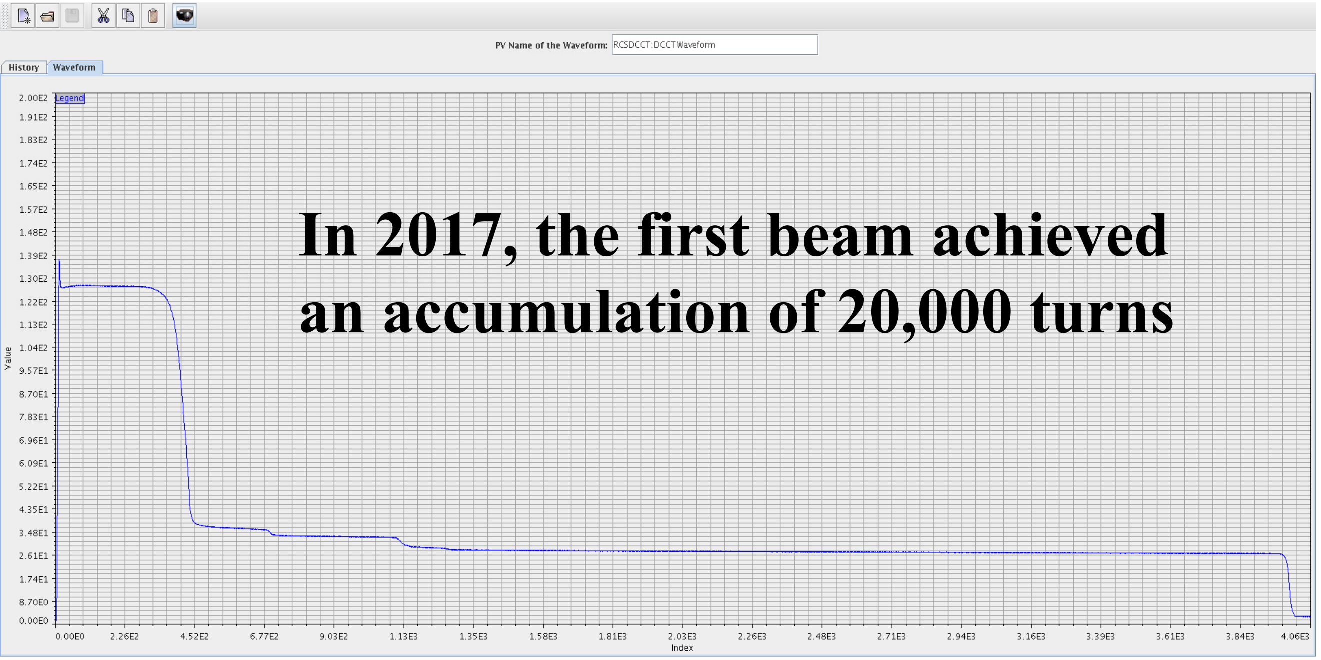
Timeline of Beam Power Achievements for CSNS/RCS

- 2017: Beam injection into the ring and stable acceleration achieved. |
- March 2018: Achieved 10 kW beam power, passing national acceptance.
- End of 2018: Supplied 50 kW beam power.
- End of 2019: Supplied 80 kW beam power.
- 2020: Achieved 100 kW beam power, reaching the CSNS I design goal and stable operation.
- 2022: Achieved 125 kW beam power.
- 2022: Achieved 140 kW beam power.
- 2024: Target to achieve 160 kW beam power.

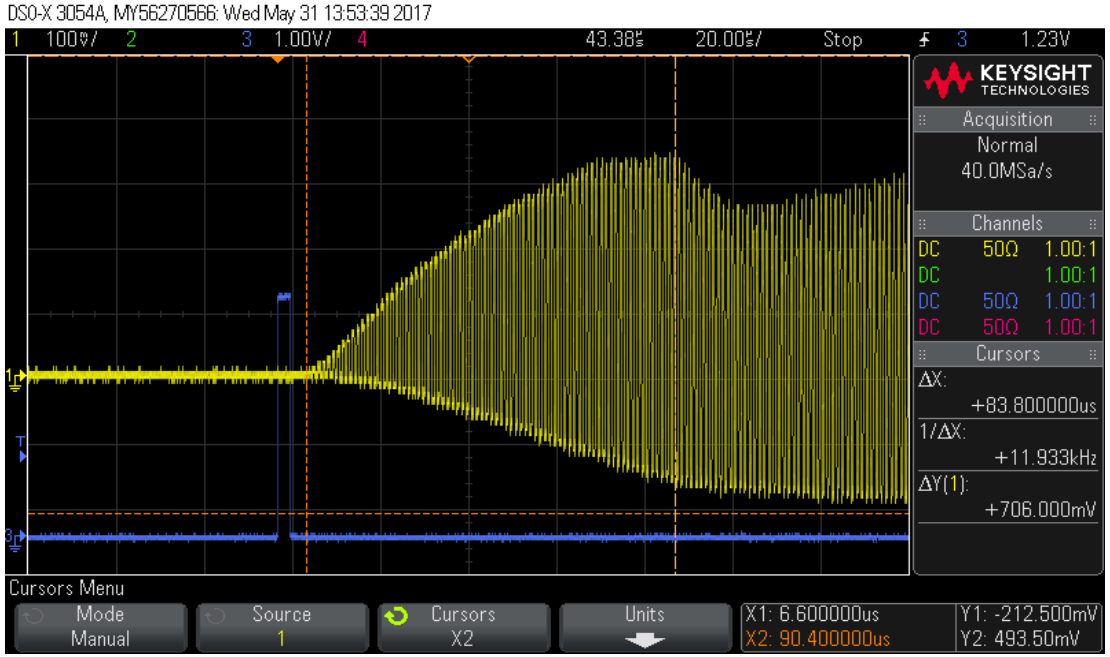


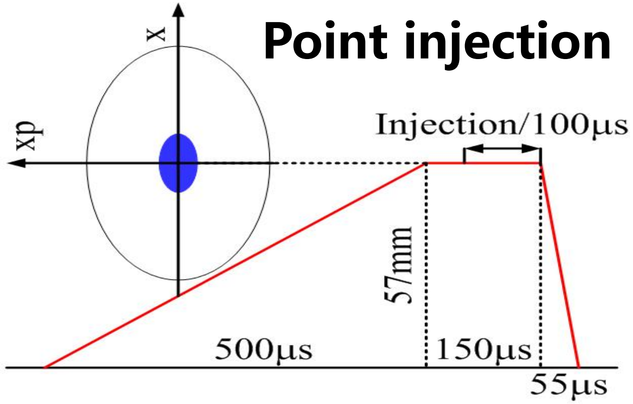
A review of beam power upgrades for CSNS/RCS

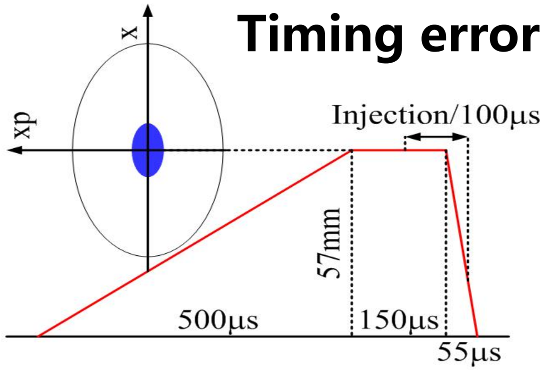
Weak beam tuning methods and hardware(≤50kW)

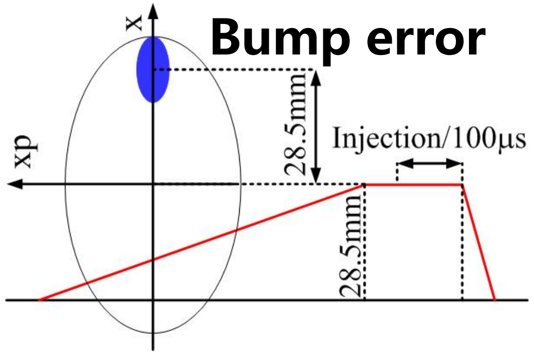


In 2017, the first beam achieved an accumulation of 20,000 turns







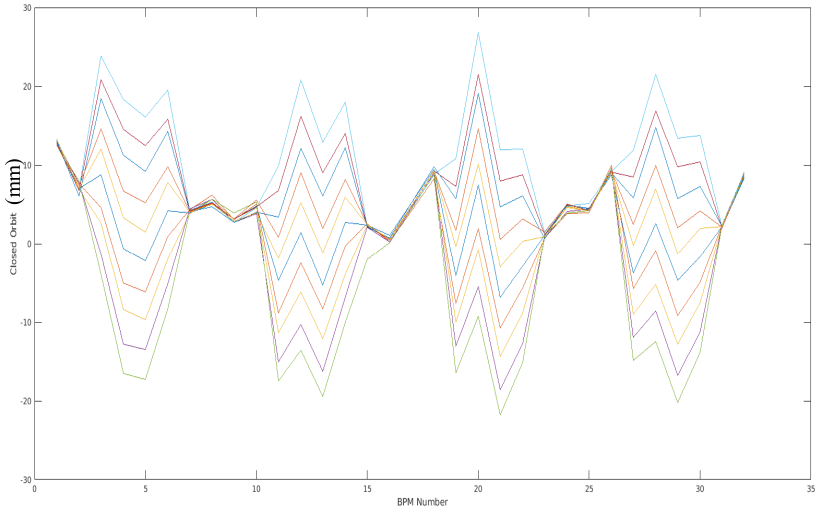


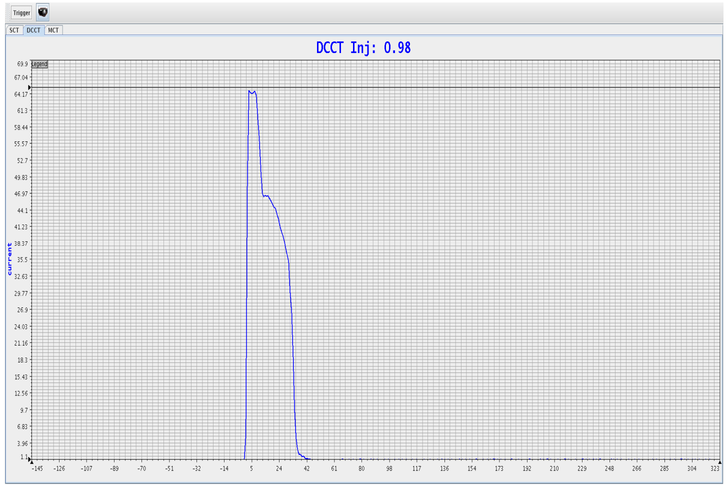
- **Achieving point injection**
- **by adjusting timing**
- **and orbit bump height**

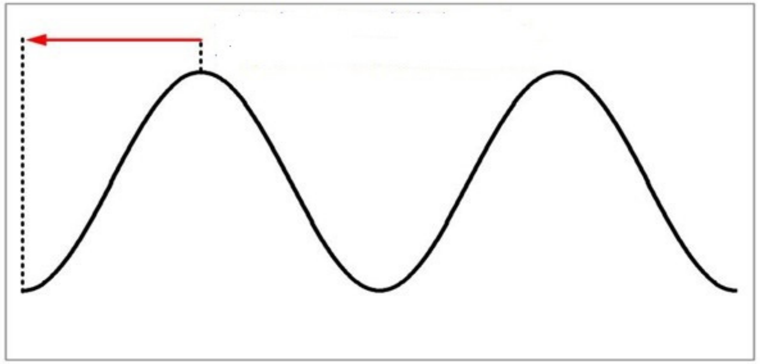
A review of beam power upgrades for CSNS/RCS

Weak beam tuning methods and hardware(≤50kW)

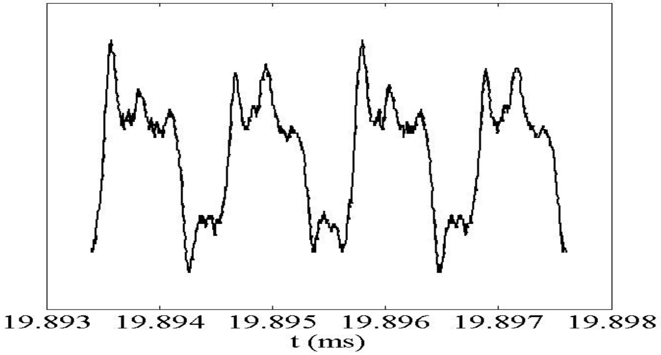
Matching injection beam energy and dipole strength by utilizing BPM in RCS



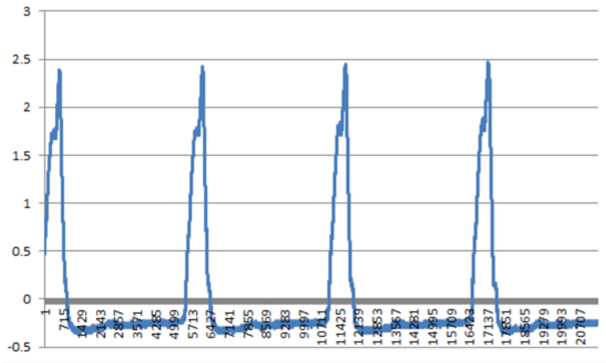




Using the peak current as the timing reference, shifting 20ms earlier would correspond to the current minimum.

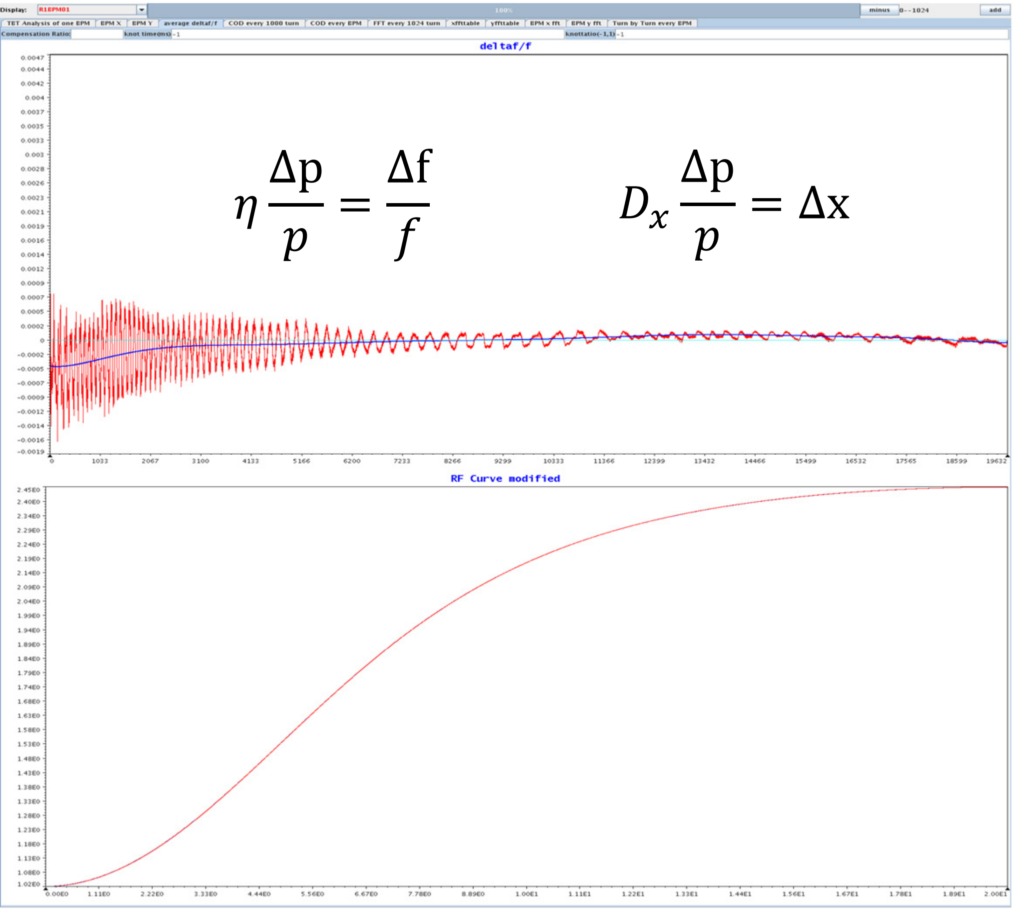


By adjusting the RF frequency from 902.5kHz to 903.2kHz, the overall longitudinal oscillation of the beam bunches were significantly reduced, resulting in improved bunching performance.



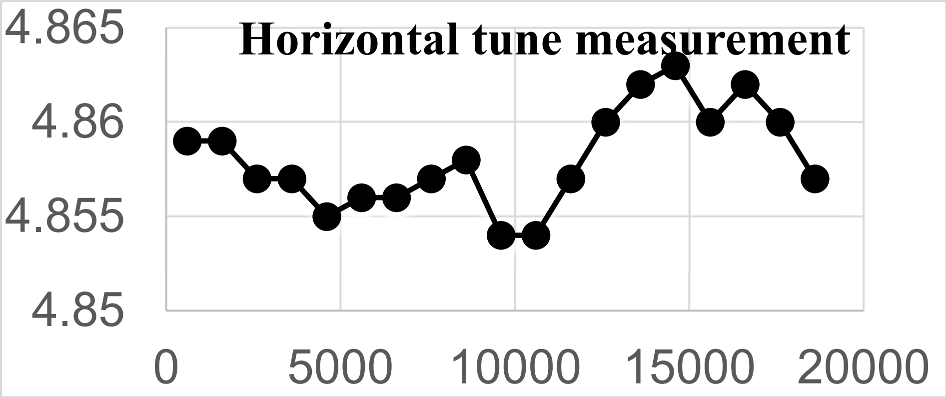
A review of beam power upgrades for CSNS/RCS

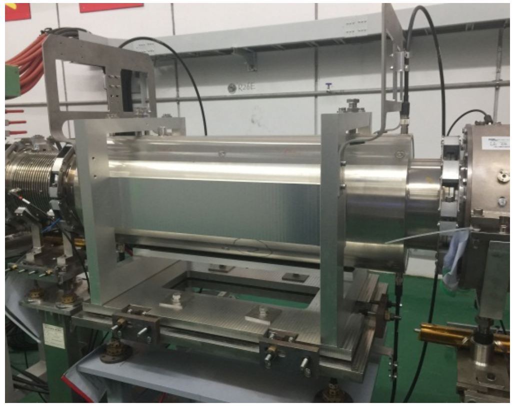
Weak beam tuning methods and hardware(≤50kW)

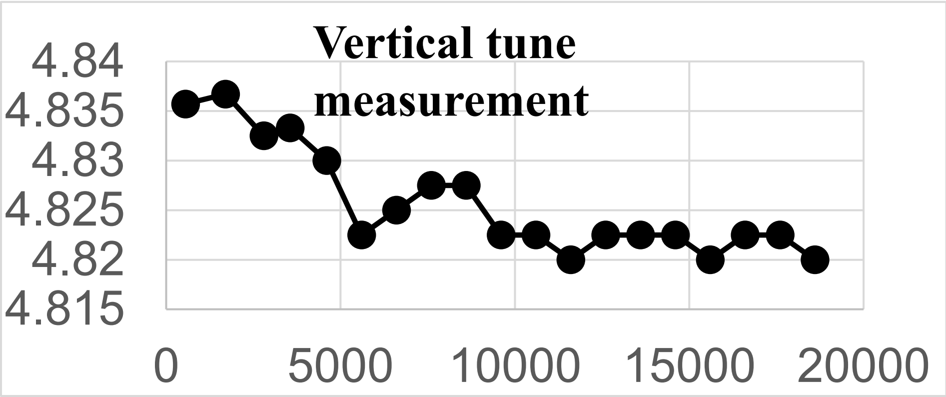


$$\eta \frac{\Delta p}{p} = \frac{\Delta f}{f}$$

$$D_x \frac{\Delta p}{p} = \Delta x$$





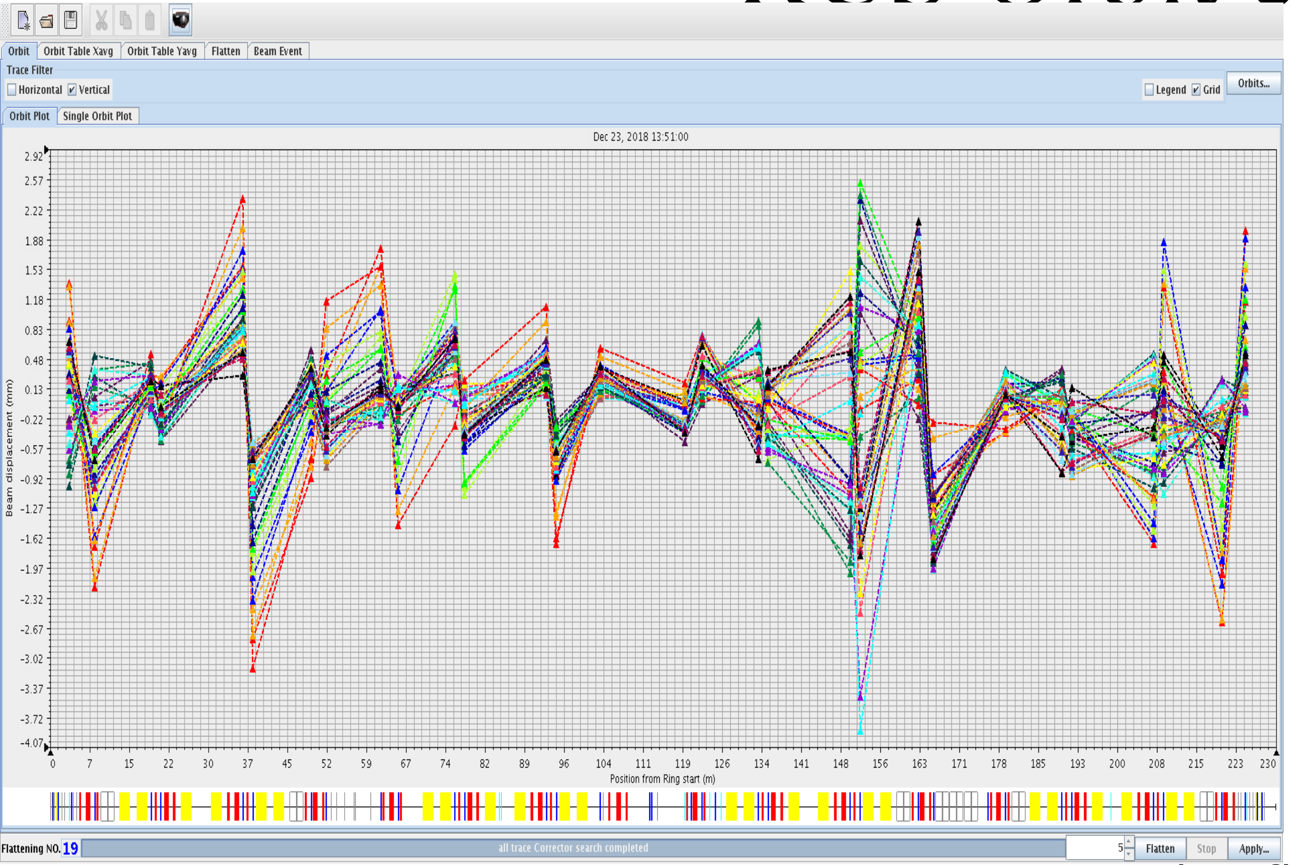


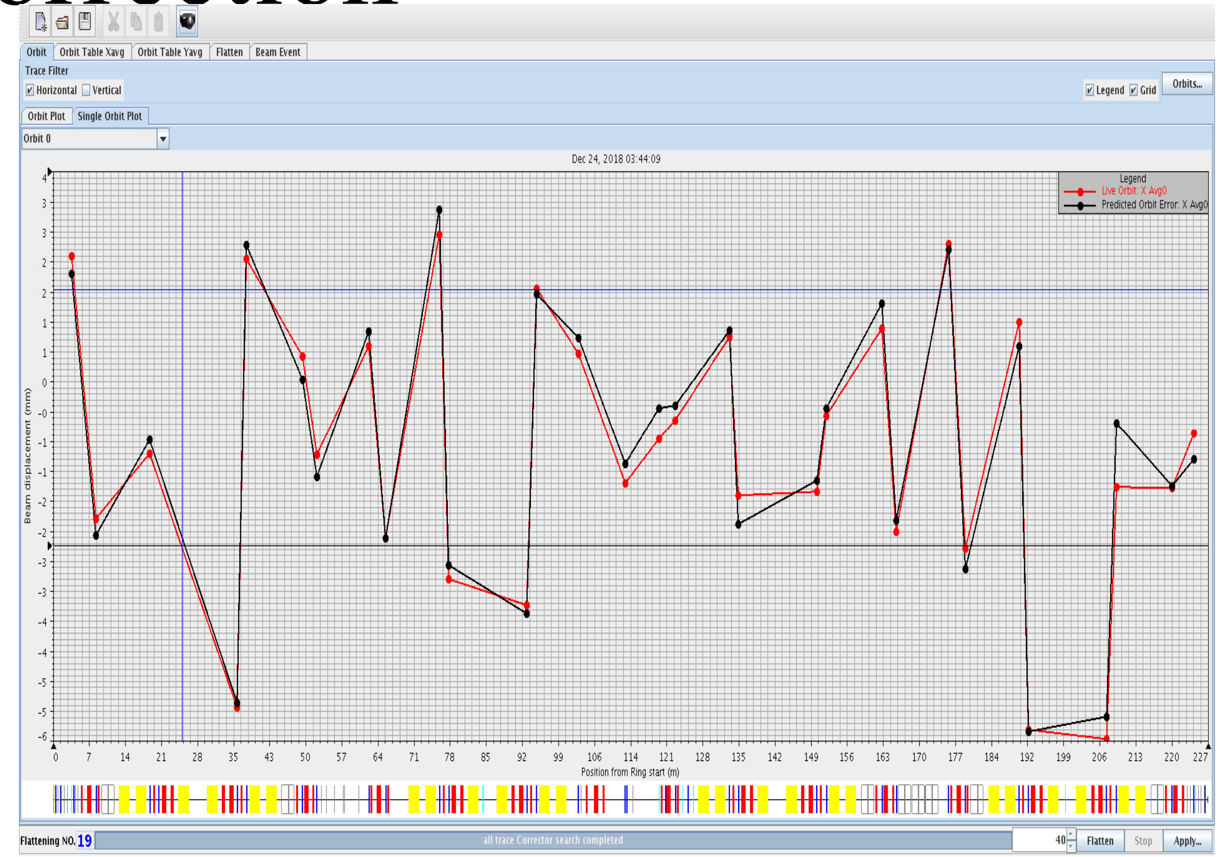
Four pairs of BPMs (*Dx* =1.7m; *phase advance = 0.98 π*) in the arc section were used to correct the matching between RF frequency and the dipole

By exciting white noise or sinusoidal waves using the tune kicker, the working point is obtained by performing FFT analysis on the BPM turn-by-turn data

50kW RCS commissioning

RCS Orbit correction



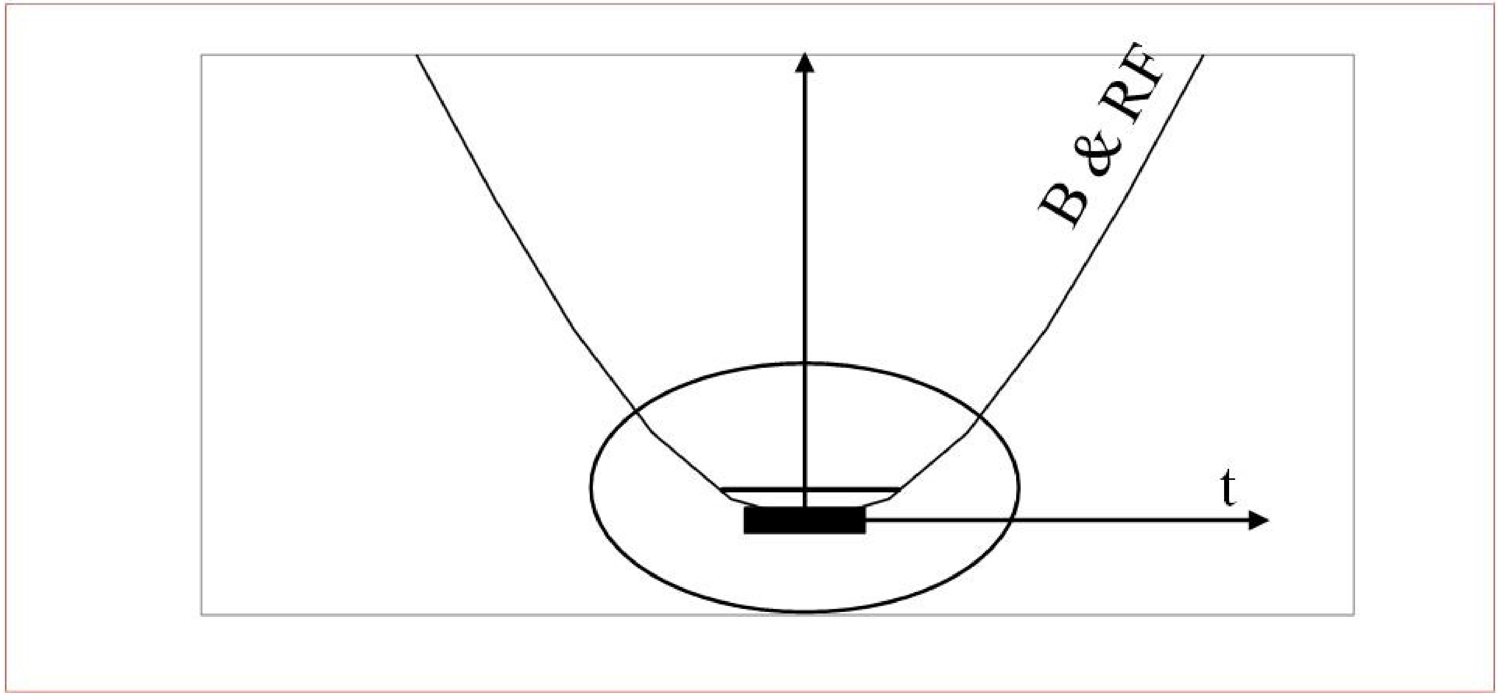


Vertical orbit corrected to ±3mm.

The first orbit in the horizontal direction is the most difficult to correct. After correction, most BPMs are within ±4mm, with three BPMs showing deviations of 5-6mm.

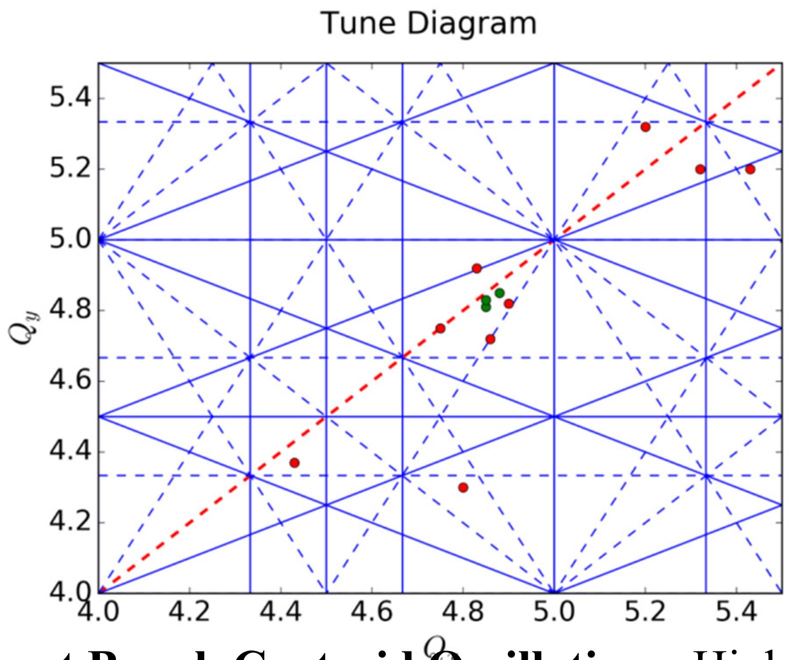
50kW RCS commissioning

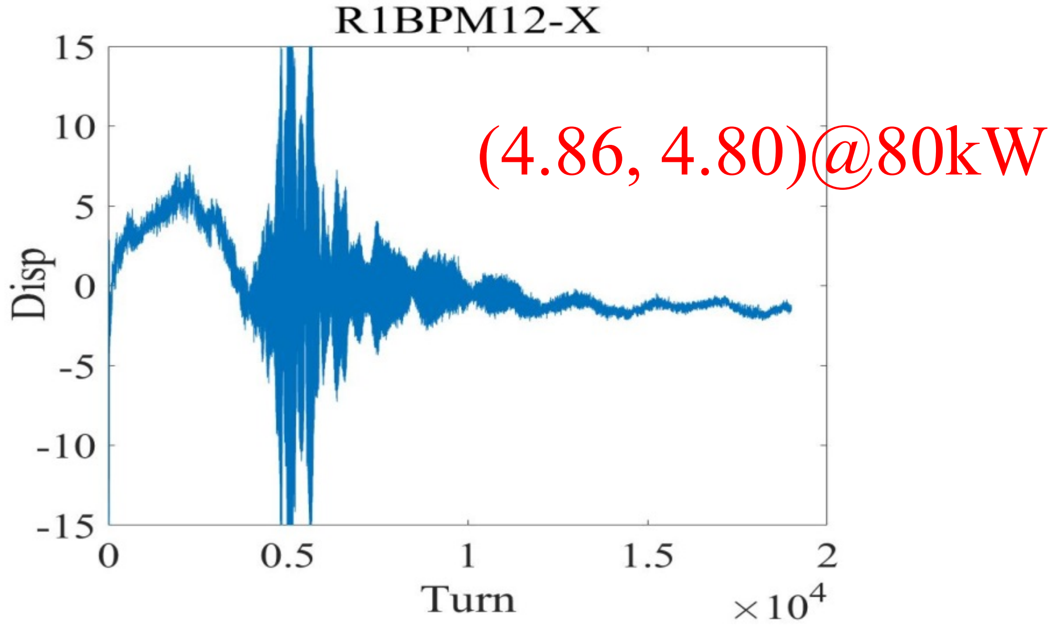
Longitudinal Dynamics Optimization for 50kW-Energy OFFSet



During the injection process, the RF frequency remains constant, and there is a fixed energy offset.

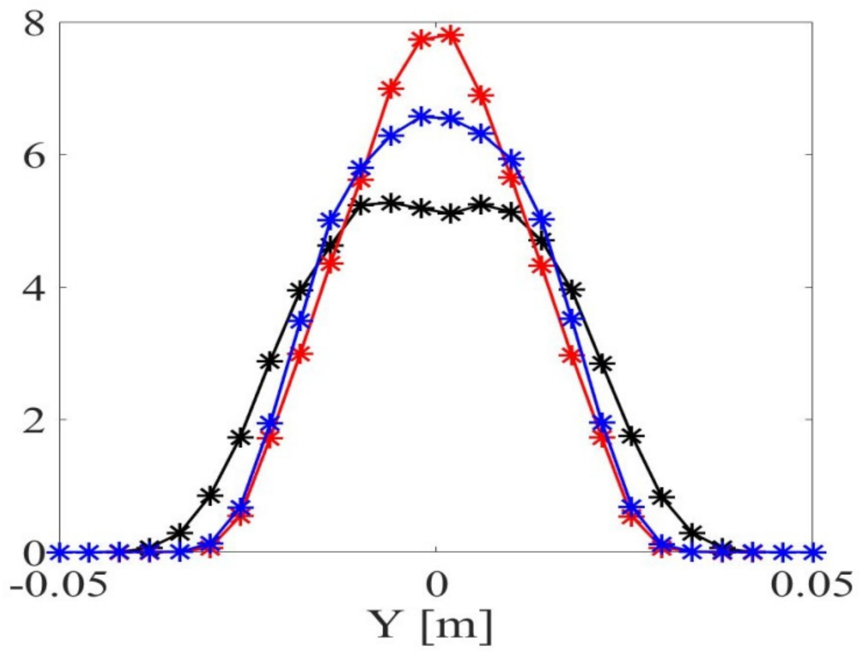
80kW RCS Commissioning – New Issues in 80kW





- **Significant Bunch Centroid Oscillations**: High-power machine studies have identified significant oscillations in the bunch centroid, which are suspected to be due to instabilities.
- **Dependence on Working Point**: These oscillations are dependent on the working point. No significant oscillations were observed for working points below the half-integer resonance. However, for working points greater than 0.85, severe centroid oscillations were noted.
- **Horizontal vs. Vertical**: The horizontal direction is more prone to these oscillations compared to the vertical direction.
- **Dependence on Beam Intensity**: The oscillations depend on beam intensity, although the relationship is not a simple linear increase with intensity.
- **Related Factors**: Bunch centroid oscillations are related to factors such as beam injection painting, bunching factor, and chromaticity.

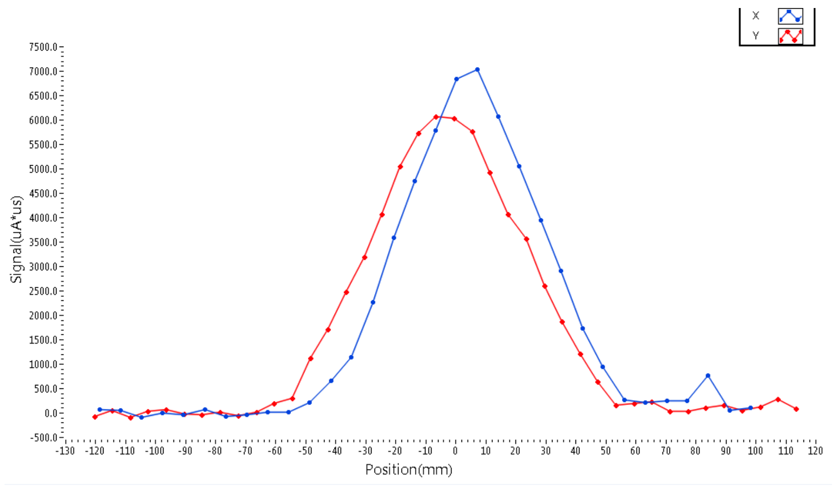
80kW RCS Commissioning – Measures to Reduce Beam Losses

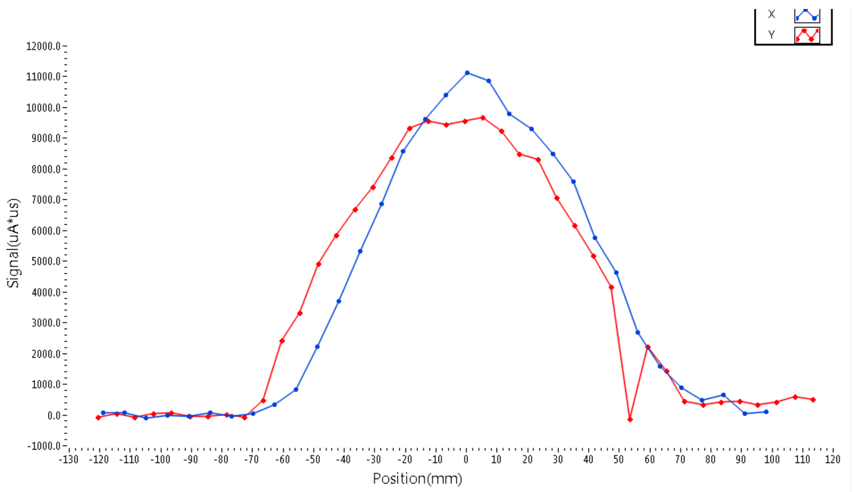


Optimization of Injection Painting Scheme:

Hollow Painting in Vertical Phase Space: Implement hollow painting in the vertical phase space to minimize the particle density at the center of the bunch. This technique helps in reducing space charge effects by spreading the particles more uniformly.

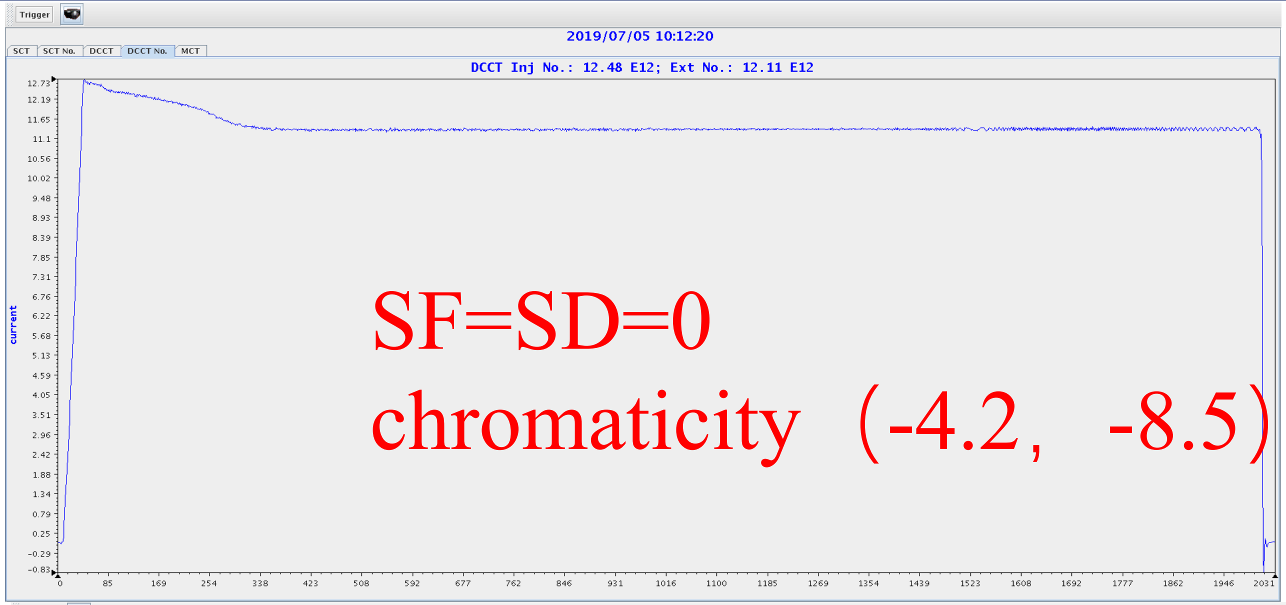
Comprehensive Horizontal and Vertical Optimization: Perform a comprehensive optimization of both horizontal and vertical painting schemes to achieve the best possible distribution of particles. This involves adjusting the painting parameters to ensure a uniform and stable beam profile, thereby reducing beam losses and enhancing overall beam stability.

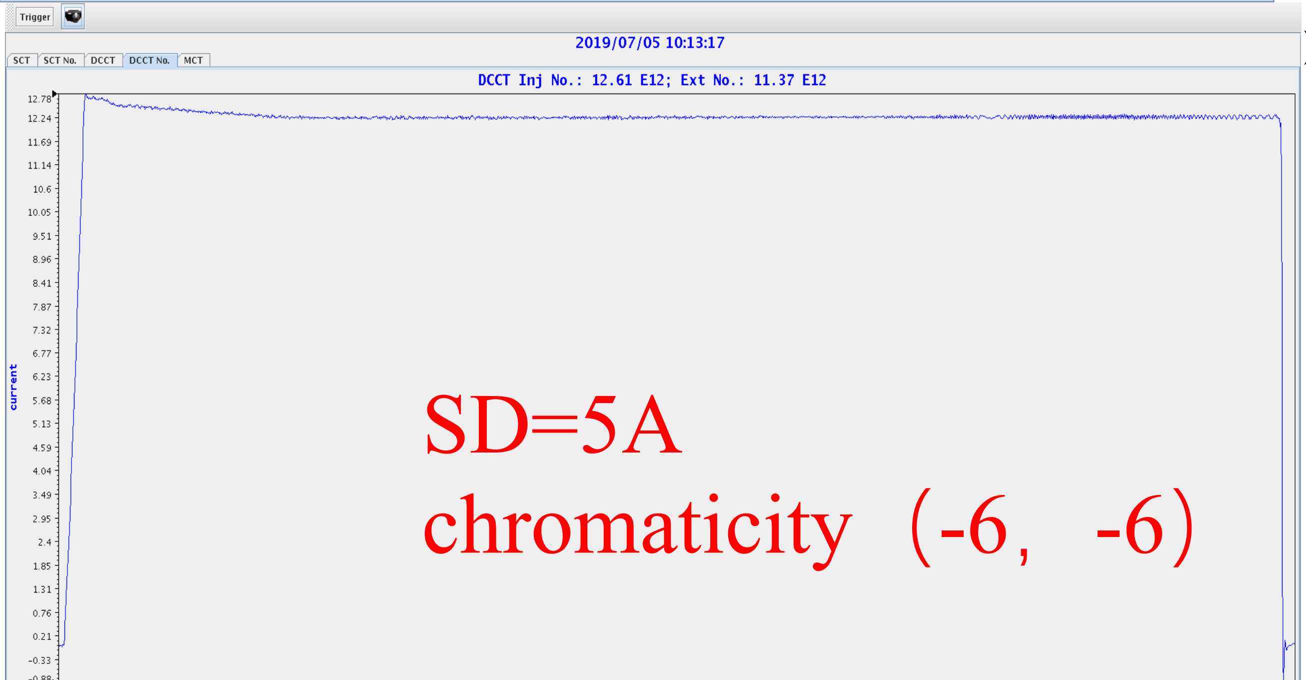




Horizontal and Vertical Coupling Effects

80kW RCS Commissioning - Measures to Reduce Beam Loss

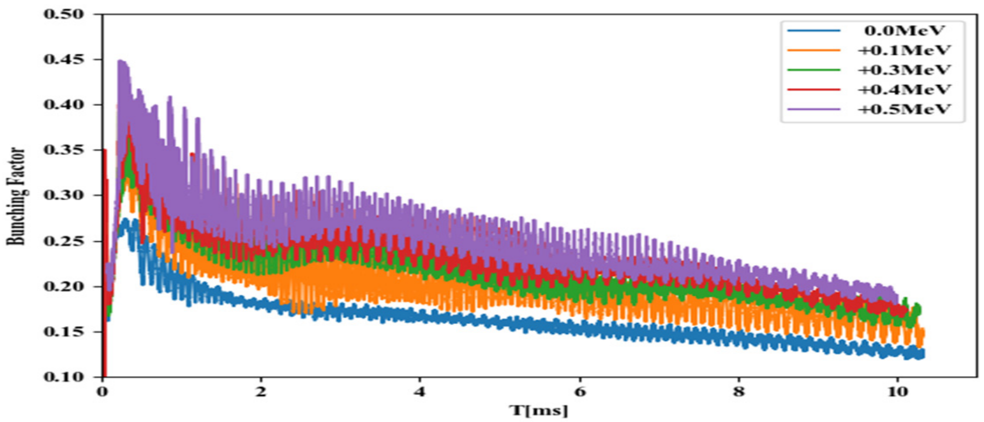




☐ Measures to Reduce Beam Loss

- **Reduce Vertical Chromaticity to Decrease tune spread**: Adjusting the vertical chromaticity to lower levels can help reduce tune spread, thereby minimizing beam loss due to chromatic effects.
- **Increase Horizontal Chromaticity to Suppress Instabilities**: Increasing the horizontal chromaticity can help suppress transverse beam instabilities, contributing to a more stable beam and reduced losses.

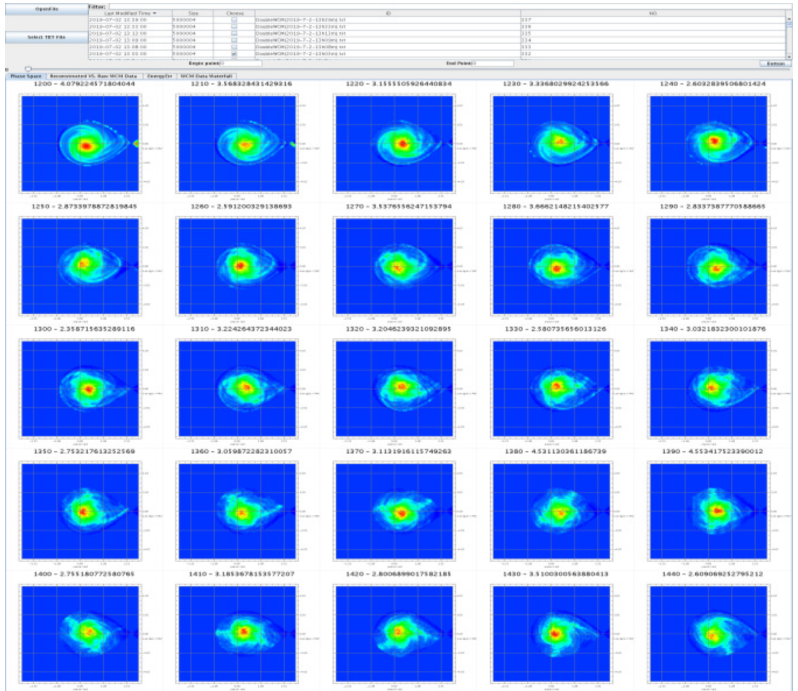
80kW RCS Commissioning - Measures to Reduce Beam Loss

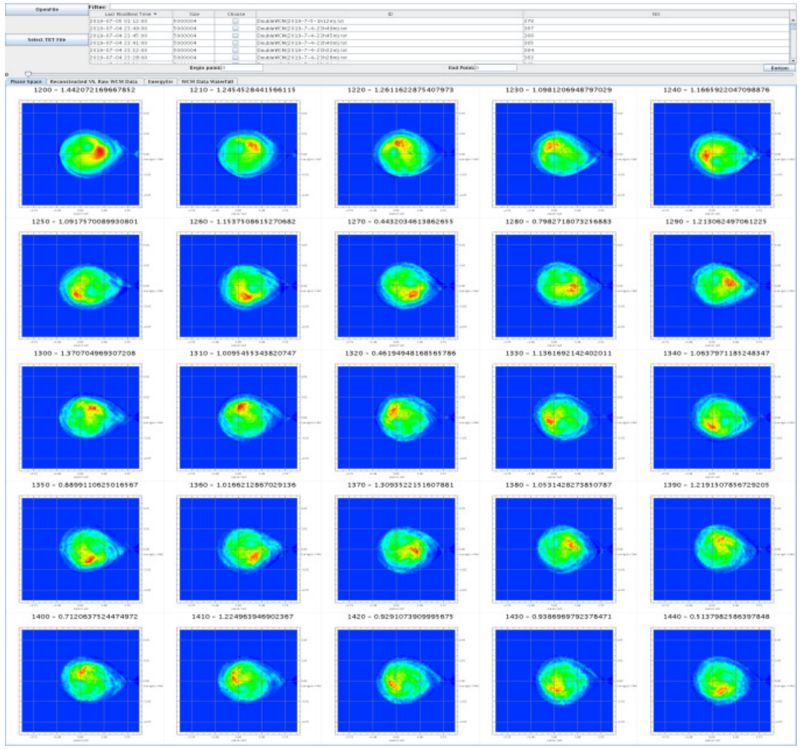


Bunching Factor Optimization

- Increase Bunching Factor to Reduce Space Charge Effects: By increasing the bunching factor, the space charge effects can be mitigated, leading to improved beam stability and reduced beam loss.

- Managing the maximum energy spread of the beam is crucial for minimizing beam losses in dispersion regions, thereby enhancing overall beam performance and efficiency.





Key Issues in High-Power Commissioning：

The RCS is experiencing beam instabilities, and it is crucial to optimize machine parameters to reduce beam losses caused by space charge effects while also mitigating instabilities.

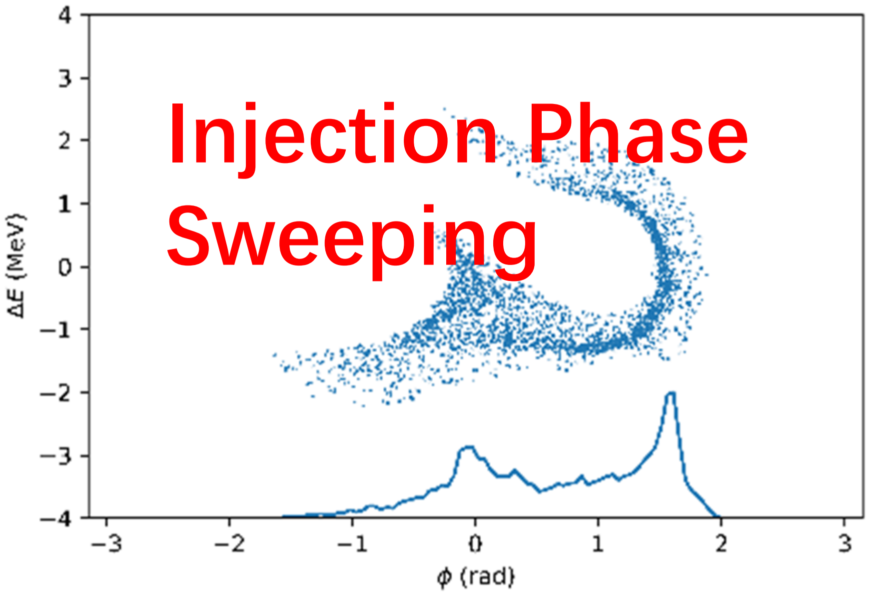
Injection Region Constraints: The aperture limitations in the injection region restrict the optimization of injection painting, which is critical for reducing space charge effects.

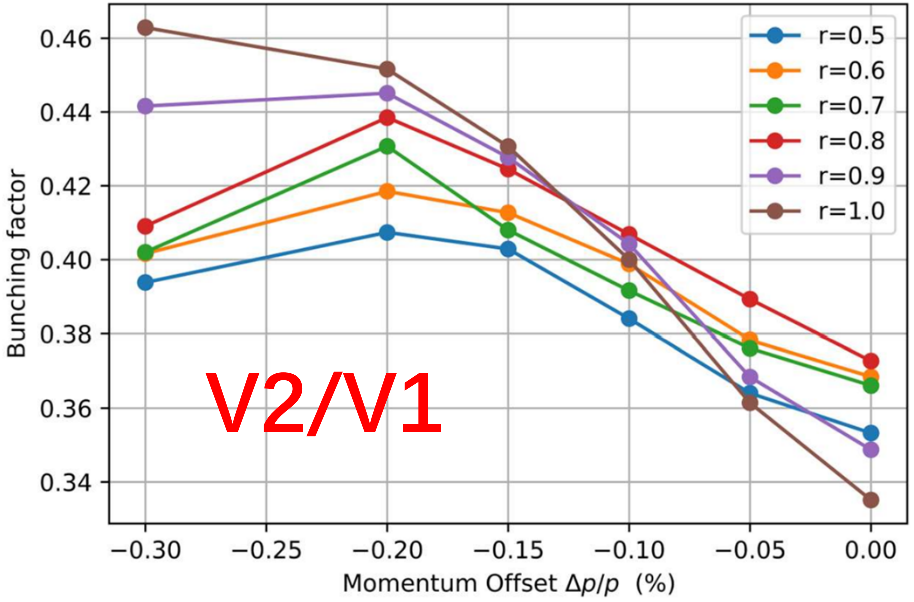
Mode Optimization:

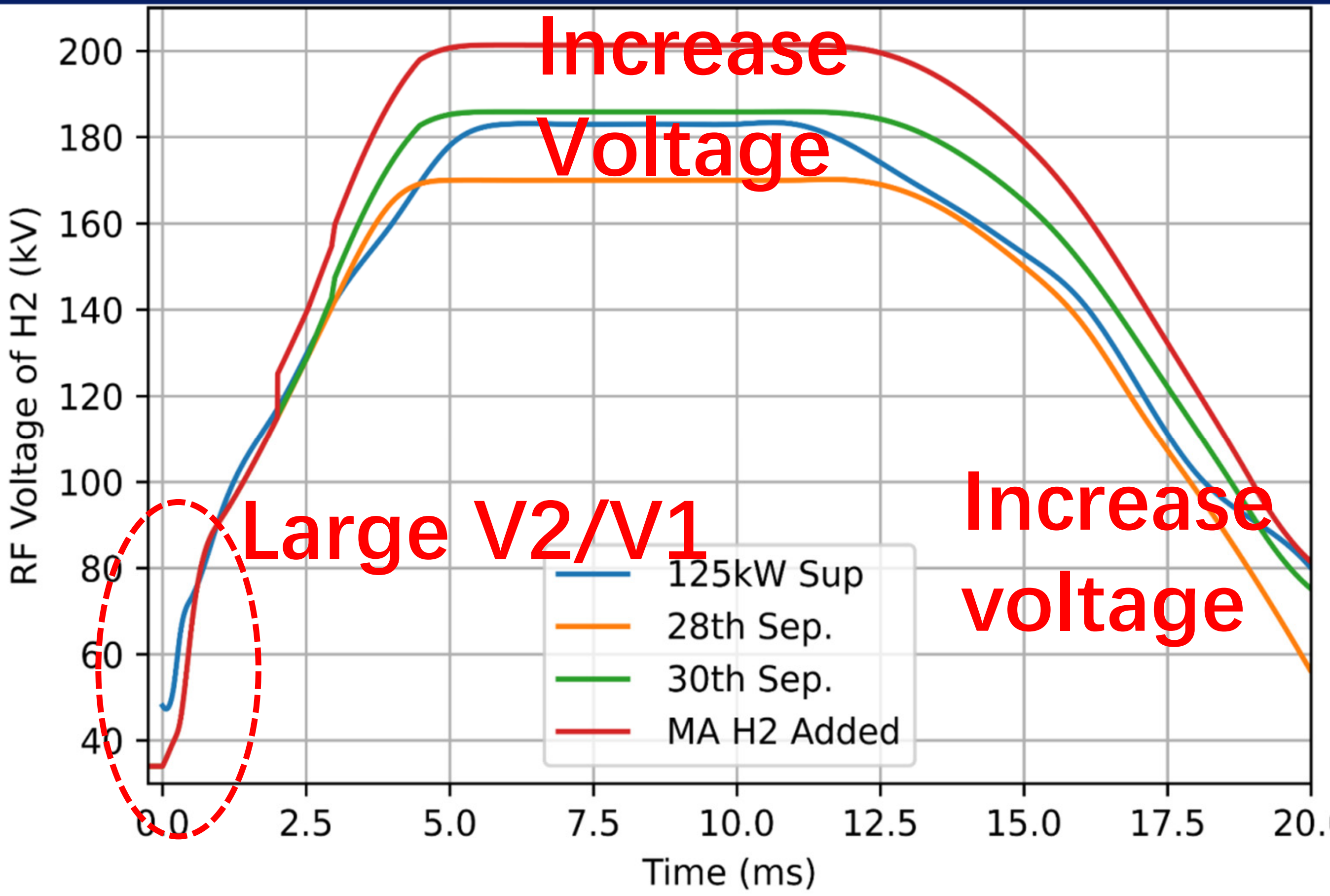
- **Working Point Adjustment**: The working point needs to be carefully chosen to balance the effects of space charge and beam instabilities. This involves finding an optimal tune that minimizes space charge-induced losses while avoiding resonance conditions that could lead to instabilities.
- **Acceptance Considerations**: The acceptance must be optimized to accommodate both the injection region and the Q272 section. This ensures that the beam is well-contained and reduces losses due to aperture limitations.

Quadrupole Magnet Power Supplies: With only five sets of quadrupole magnet power supplies available, the optimization of the magnetic lattice must be done efficiently to ensure proper focusing and beam stability

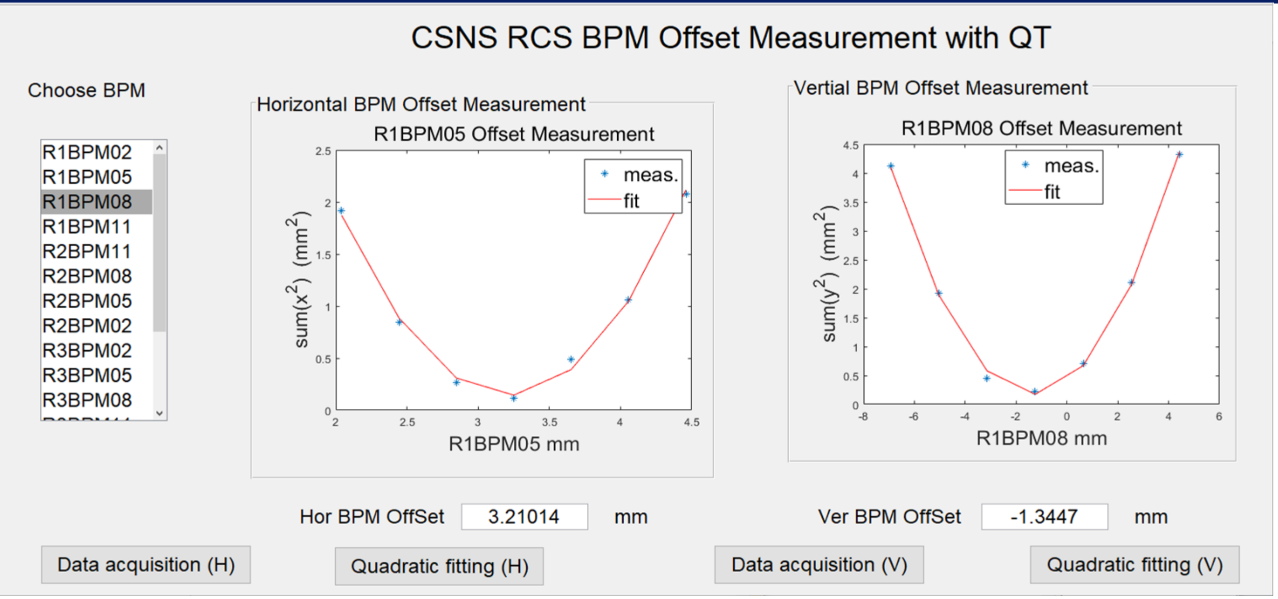
140kW RCS Commissioning – Magnetic Alloy

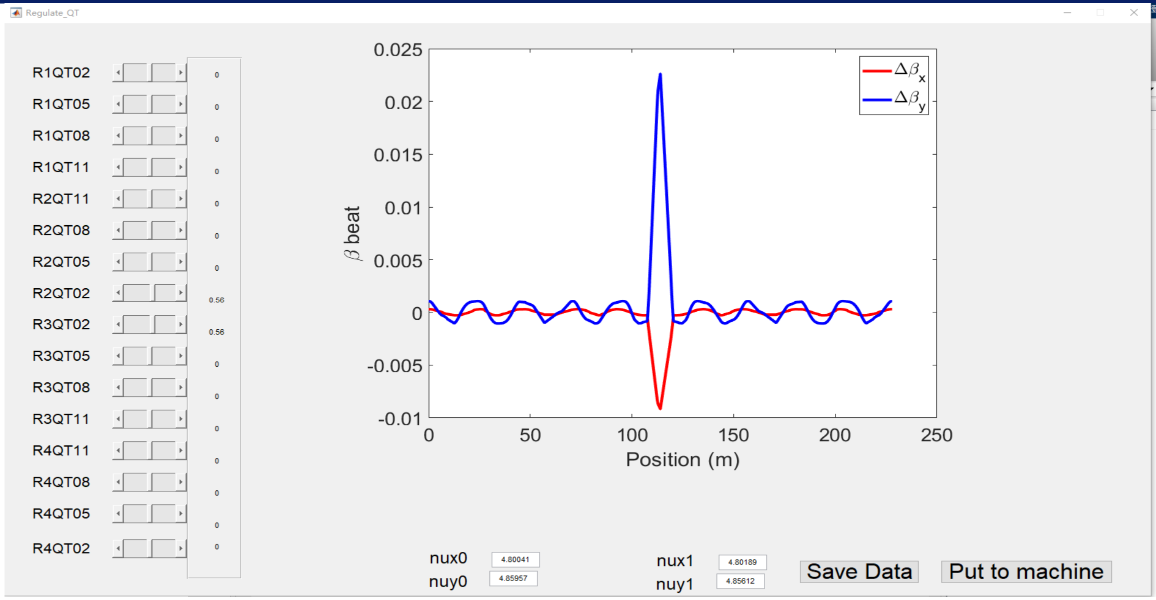


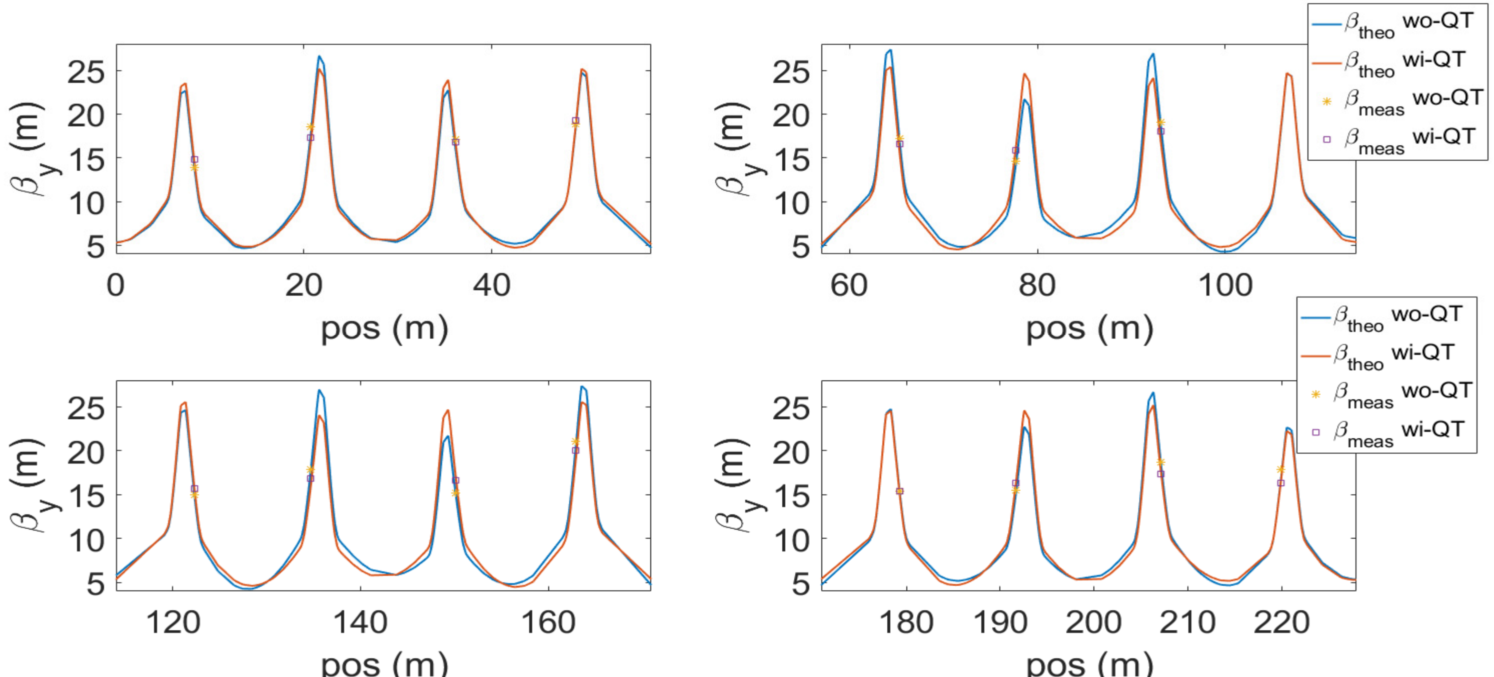




QT regulation







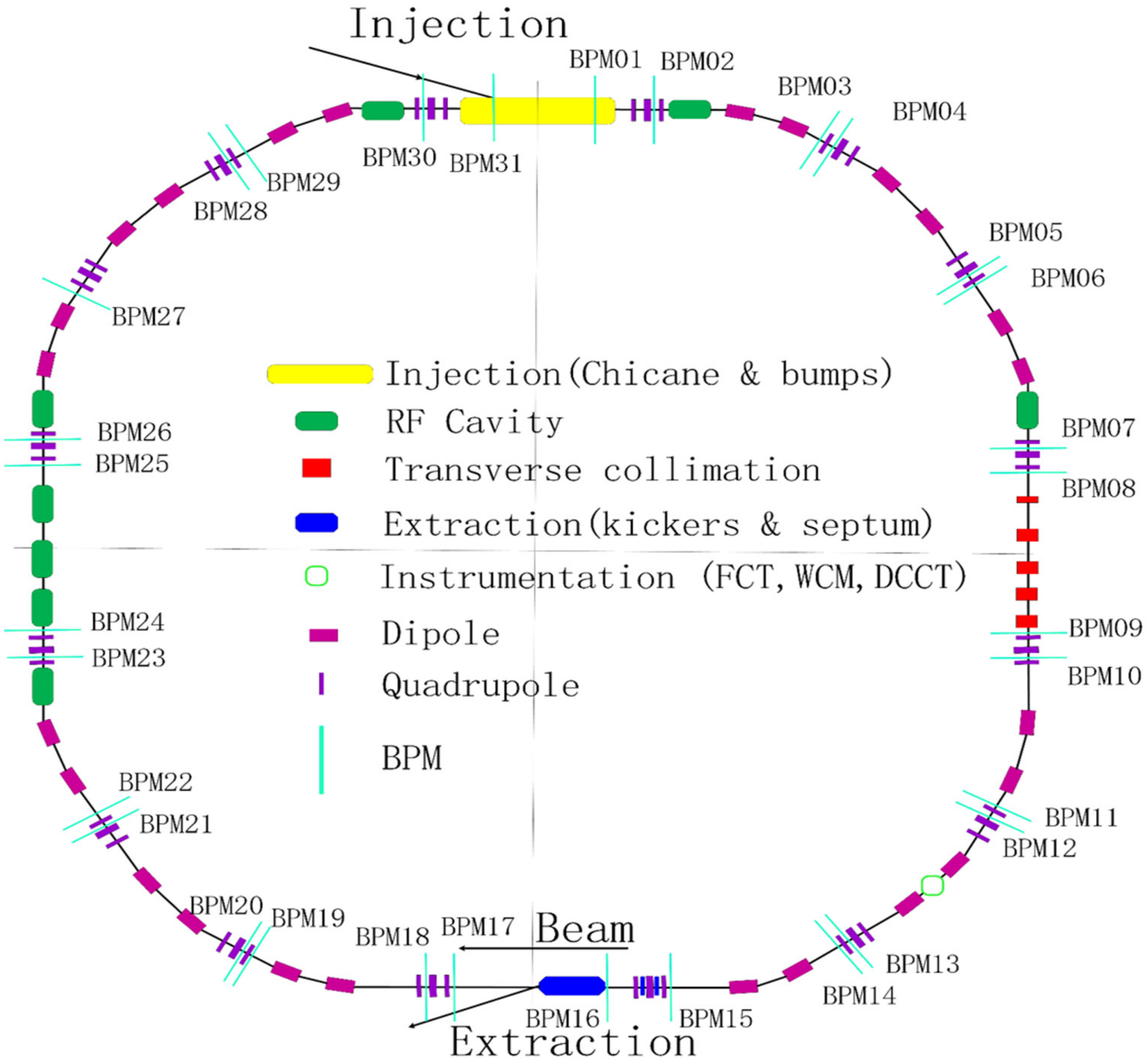
QT was installed in 2021

Measure BPM Offset

Measure fudge factor

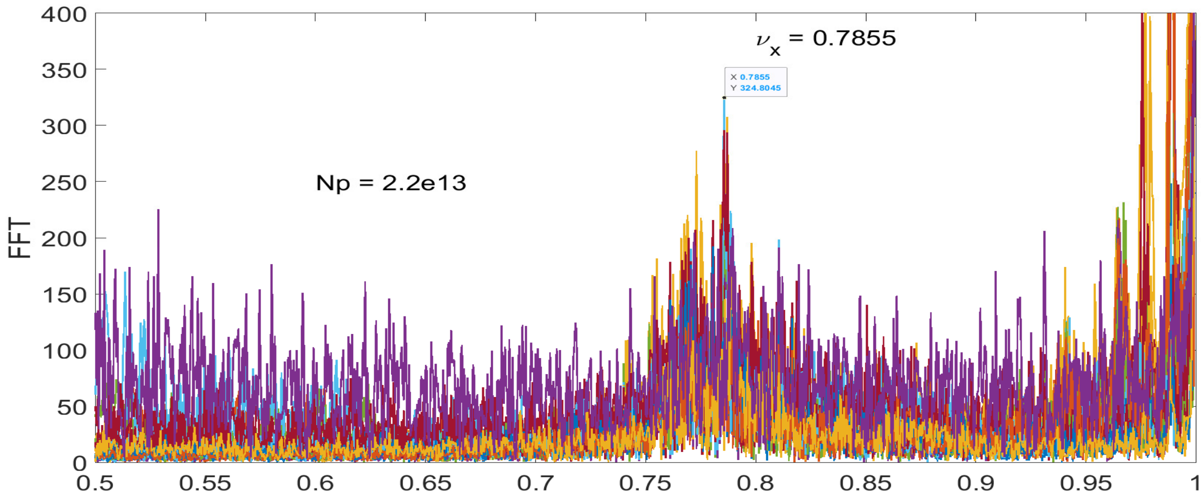
Compare beta beat wi&wo QT

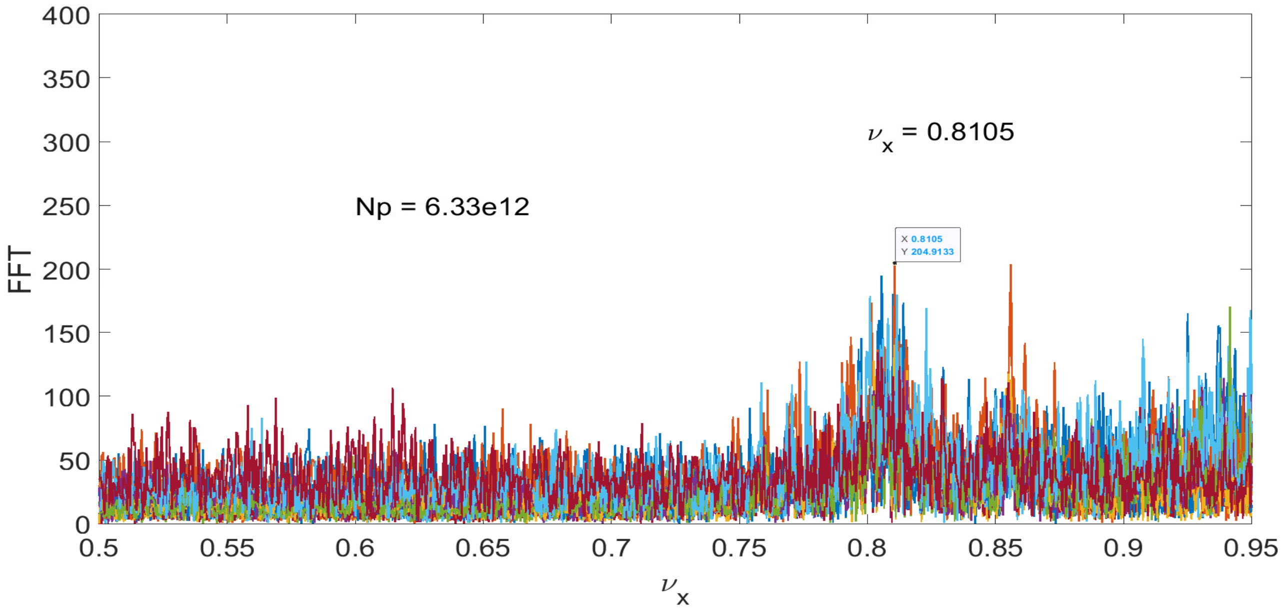
Observation of Beam Working Point Frequency Shift



- RCS Structure
  - Triplet Structure
  - 4 Superperiods
- Beam Position Monitors (BPMs)
  - Total of 32 BPMs
  - Bunch-by-Bunch Data
- BPM Naming Convention
  - Named According to Nearby Quadrupole Magnet (Q-Magnet)

Observation of Beam Working Point Frequency Shift

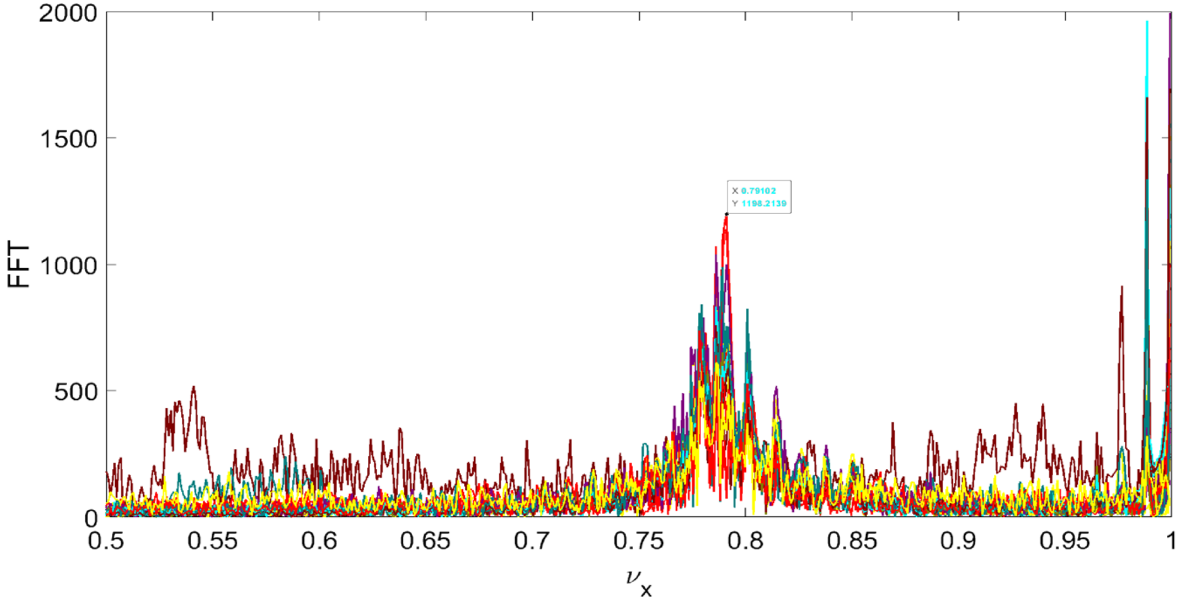


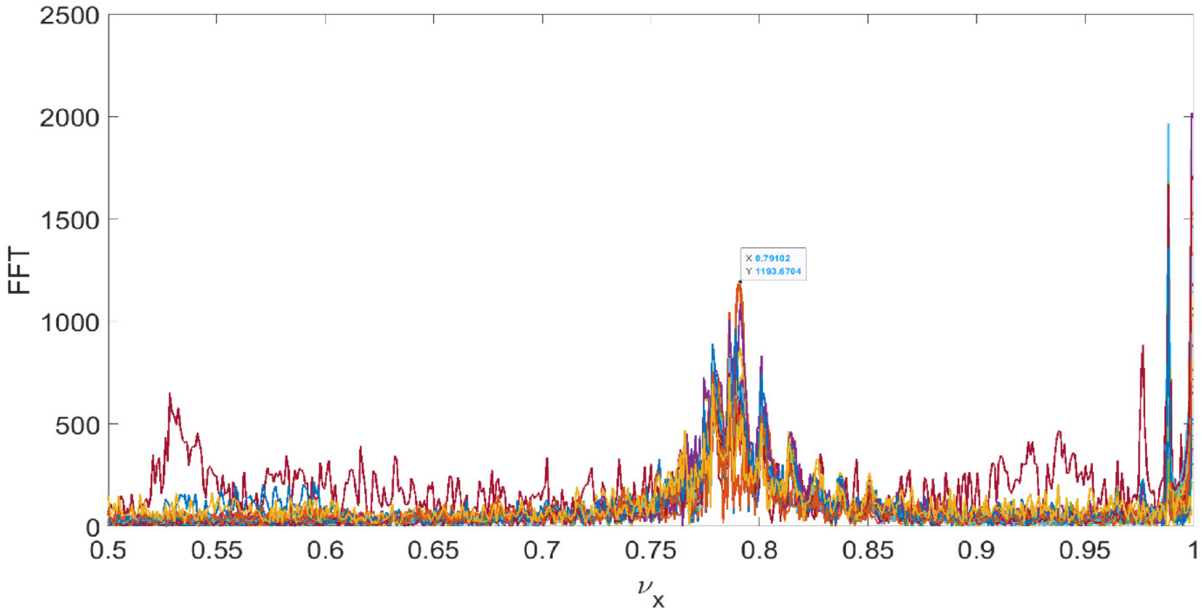


- The left graph corresponds to two comparative experiments conducted by us on the evening of December 17, 2023, at 02:26 and 02:42. The chopper duty for the first experiment was 42, and for the second experiment, it was 87. Due to the different chopper duties, the number of particles injected per pulse and the length of the injected pulse beam were different, resulting in different numbers of particles for the two experiments.

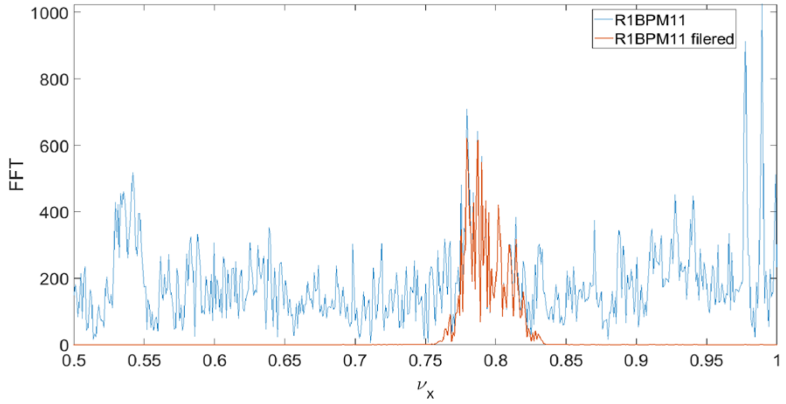
- The upper graph corresponds to a particle number of 2.2e13, and the lower graph corresponds to a particle number of 6.33e12. We performed Fast Fourier Transform (FFT) on the TBT data of the BPM and found that as the particle number decreased from 2.2e13 to 6.33e12, the horizontal working point increased from 0.7855 to 0.8105, an increase of 0.022.

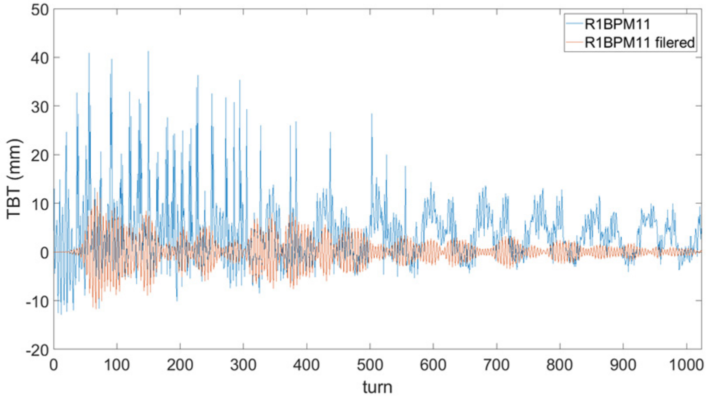
TBT data (from 1001 to 2024 turn) wo sext





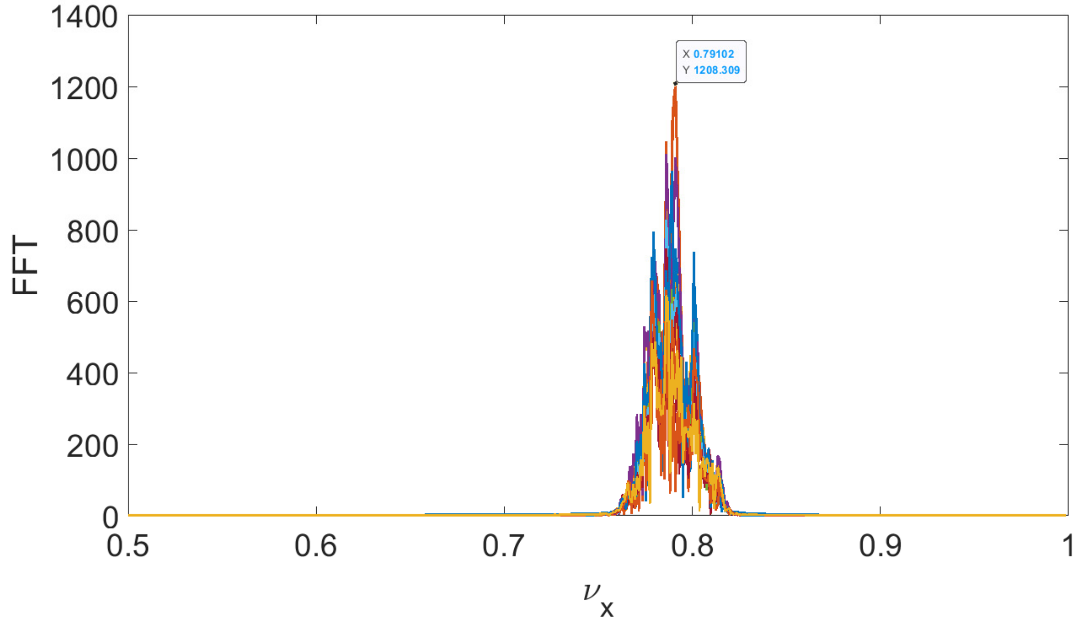
- ➢ TBT data preprocess
  - ➢ zero mean: subtracting the average values from the 1024-turn data.
  - ➢ narrow band filter

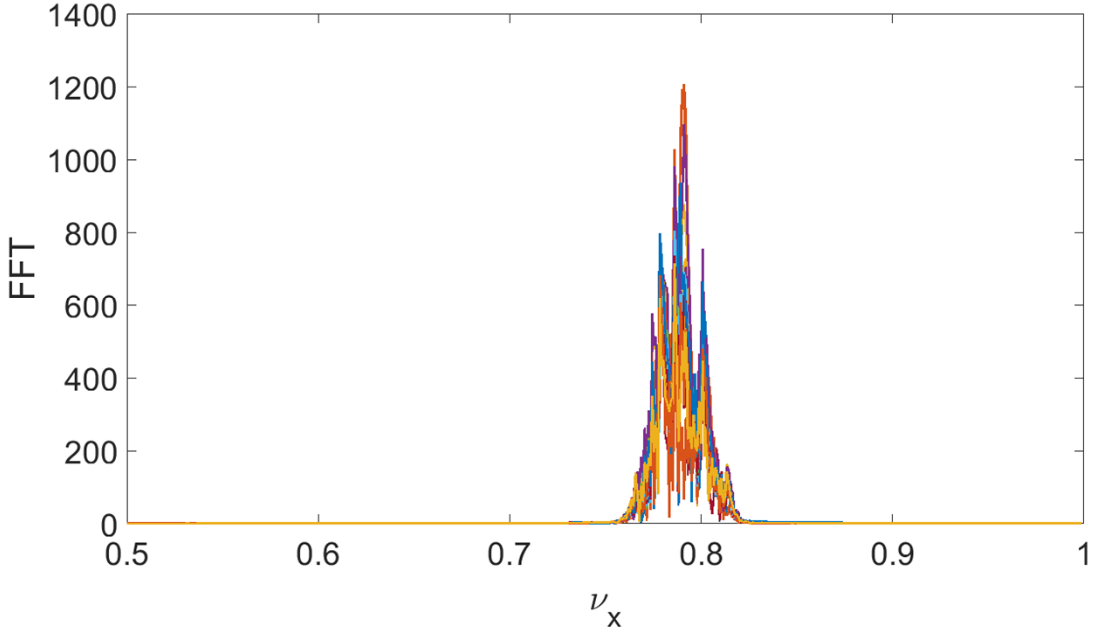




- ➢ A narrow band filter is designed
  - ➢ Sampling rate : 1024 Hz
  - ➢ Filter band: 184~235Hz
- ➢ After applying the narrowband filter, the R1BPM11 and the filtered data are shown in the left figure

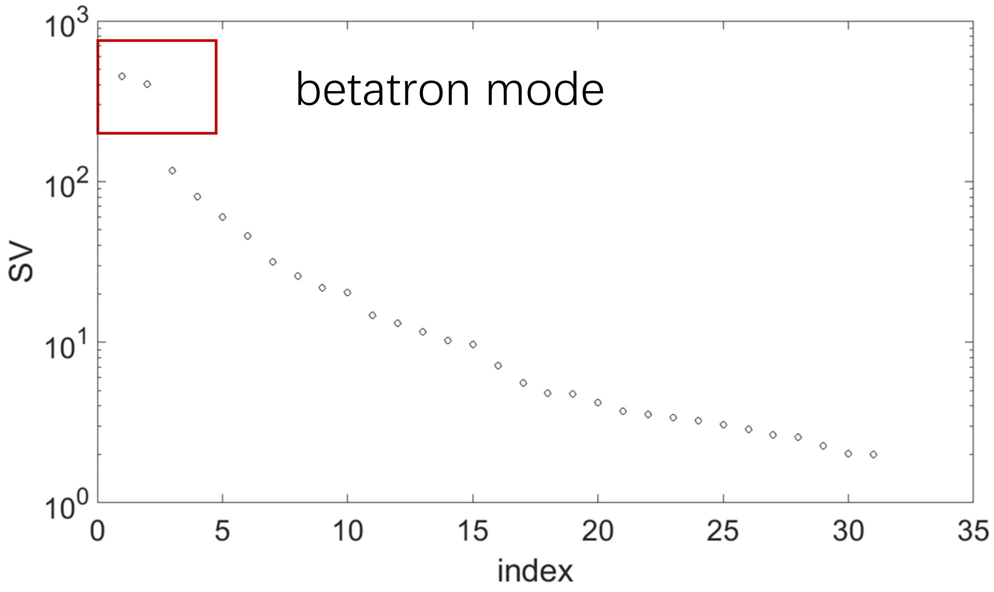
TBT data (from 1001 to 2024 turn) wo sext



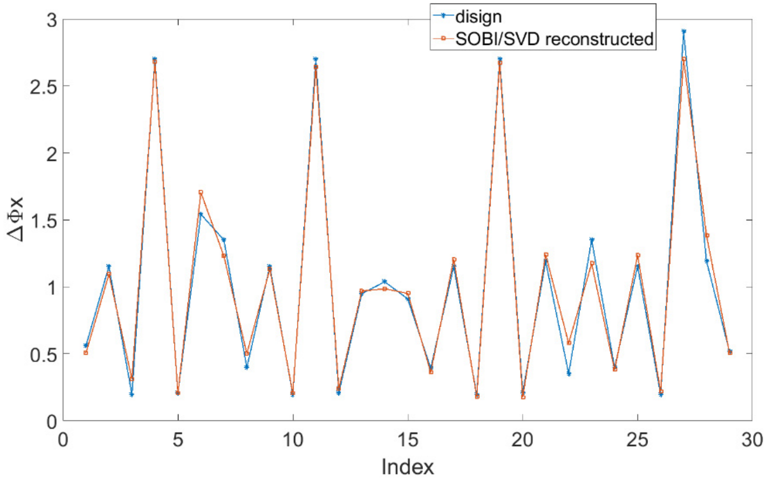


- In order to improve the recognition of betatron variations for certain machine learning algorithms, it is advisable to whiten the turn-by-turn (TBT) data. There are two algorithms used for data whitening.
  - zero mean : subtracting the average values from the 1024-turn data.
  - narrow band filter:
    - sampling rate: 1024
    - Filter band: 194~236Hz
- After applying the narrowband filter, the FFT of the 31 BPMs is shown in the upper figure

TBT data (from 1001 to 2024 turn) wo sext

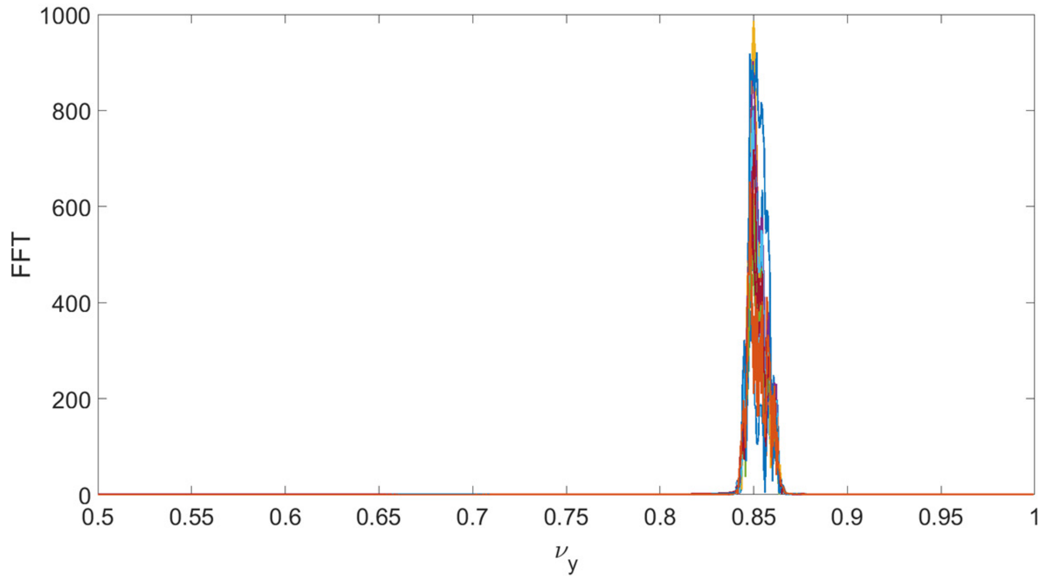


- ➢SOBI/SVD is applied to the filtered data
- ➢Two strong mode may be the betatron mode



- Phase beat of the horizontal mode
- The left figure represents the difference in phase advance between adjacent BPMs (R1BPM11 and R4BPM05 have been removed)
- The betatron mode is very sensitive to BPM TBT data;
- The difference in phase beat at some BPM locations is approximately 0.2, where 0.2 is close to 0.67*5-pi. For a double bunch data, if the data of the previous bunch is stored into the subsequent bunch, then the phase shift difference is 0.67; 0.67 = (1-0.785)*pi; 0.785 is the horizontal tune.

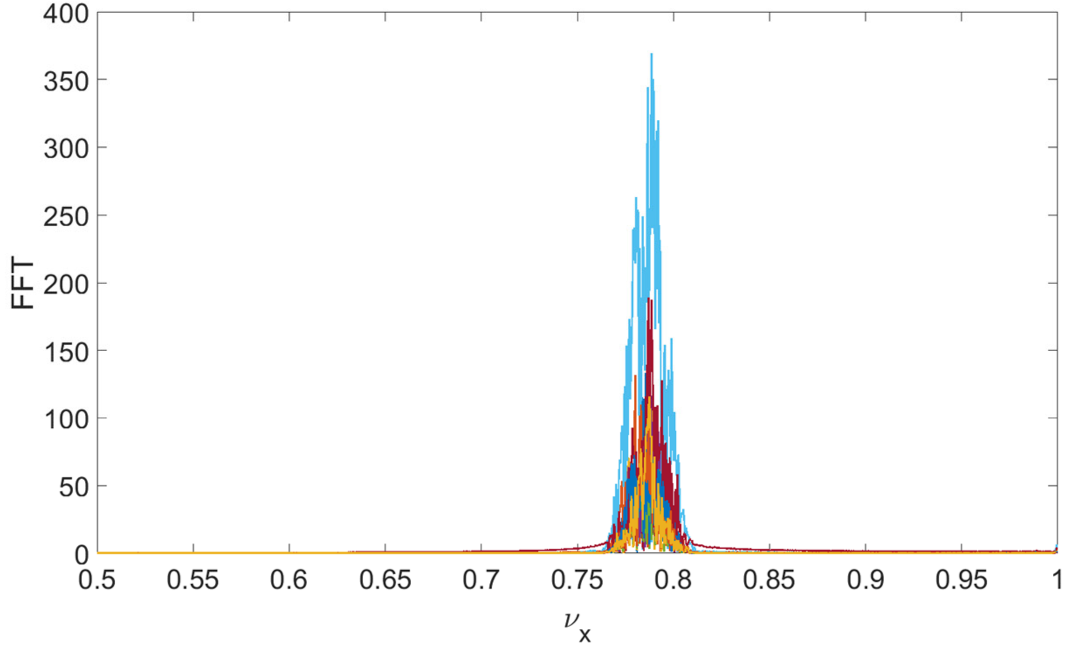
TBT data (from 1001 turn to 2024 turn) wo sext

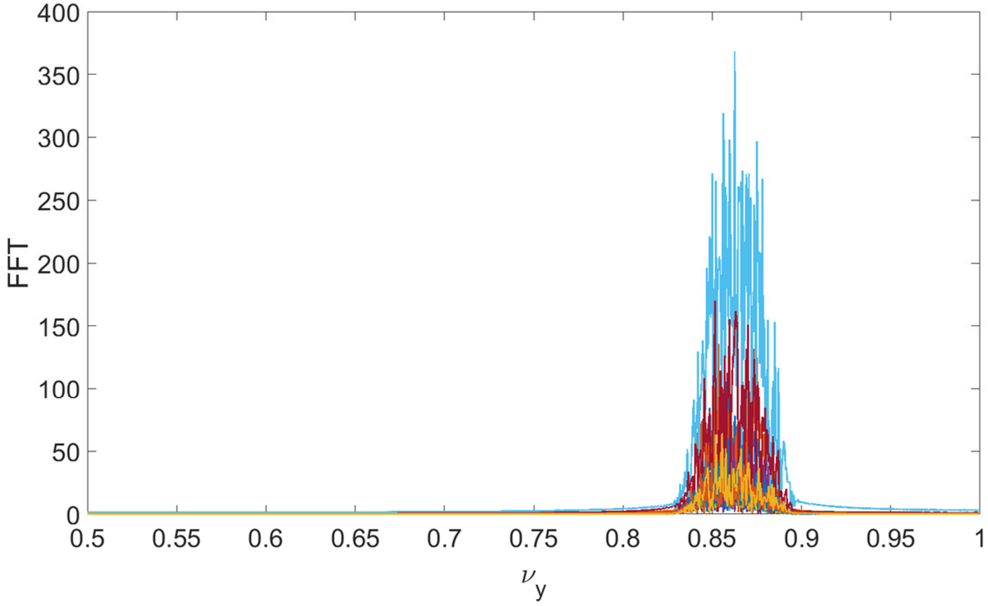


- We can use the same narrowband filtering method to process the vertical direction.
- The betatron mode is also very sensitive to BPM TBT data

TBT data (from 1001 turn to 2024 turn) wi sext

TBT data (from 1001 turn to 2024 turn) wi sext





- Beam oscillations are not significant at 140kW with sext.
- The narrowband filter can identify the horizontal and vertical working points, as shown in the figure. However, forcibly filtering out the noise appears somewhat unconvincing. Additionally, the peak of the vertical working point is quite broad.

Summary

- The commissioning of the CSNS beam is divided into two phases: low-intensity commissioning and high-intensity commissioning.
- - **Low-Intensity Commissioning**: Achieved through adjustments in timing, orbit correction, and optics correction. These steps ensure the basic functionality and stability of the beam at lower intensities.
- - **High-Intensity Commissioning**: Achieved by adjusting the working point, optimizing the painting scheme, and implementing phase sweeping. These measures are necessary to handle the challenges posed by higher beam intensities.
- During experiments, we varied the number of particles by changing the chop duty cycle and the peak current in the linear accelerator. Using narrow-band filters, we observed that the horizontal working point shifted by 0.02 under high-intensity conditions.

- These observations and adjustments are crucial for ensuring the stable and efficient operation of the CSNS at both low and high beam intensities.

Thanks For Your Attention!