Tune Optimization for Alleviating Space Charge Effects and Suppressing Beam Instability in CSNS/RCS

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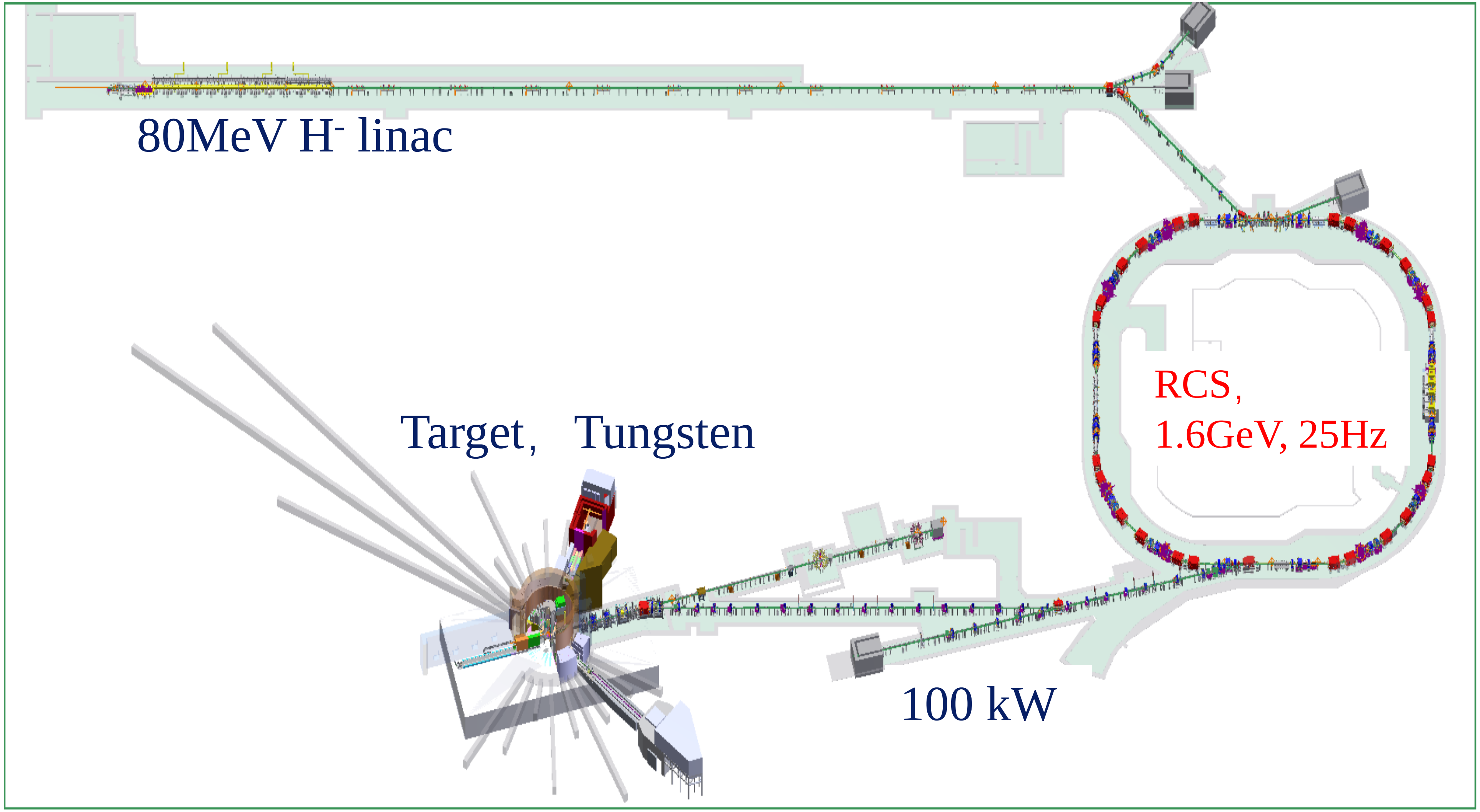
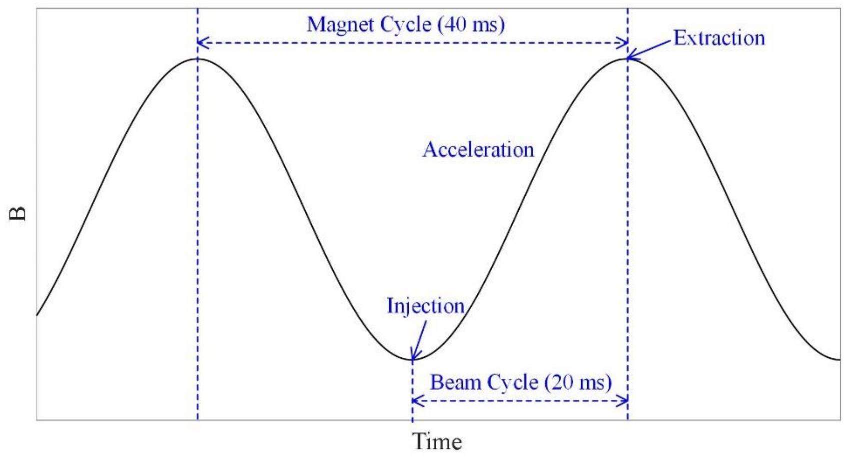
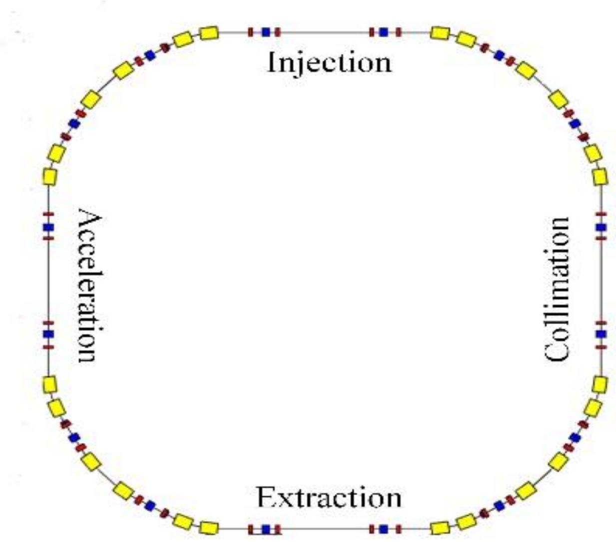
1: Introduction to CSNS/RCS



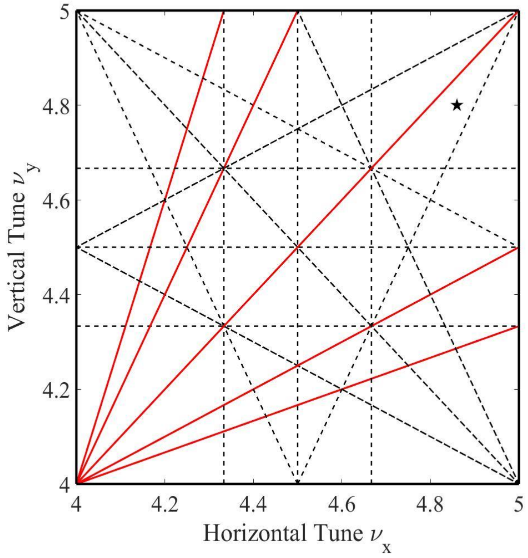
Output Beam Power [kW]	100
Injection Energy [MeV]	80
Extraction Energy [GeV]	1.6
Pulse repetition rate [Hz]	25
Ramping Pattern	Sinusoidal
Acceleration Time [ms]	20
Circumference [m]	227.92
Number of dipoles	24
Number of quadrupoles	48
Lattice Structure	Triplet
Nominal Betatron Tunes (H/V)	(4.86, 4.80)
Natural Chromaticity	-4.0/-8.2
Ring Acceptance [πmm-mrad]	540
Harmonic Number	2
Number of Particles per Pulse	1.56×10^{13}
Space-Chare Tune Shift	-0.28



The schematic diagram of the magnetic field waveform

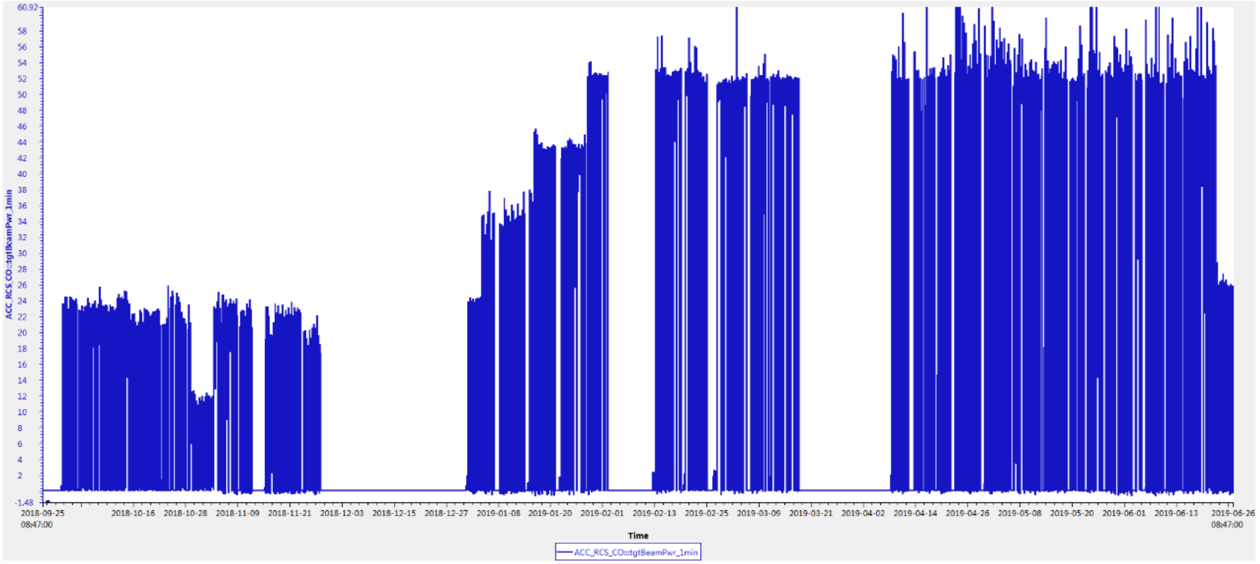


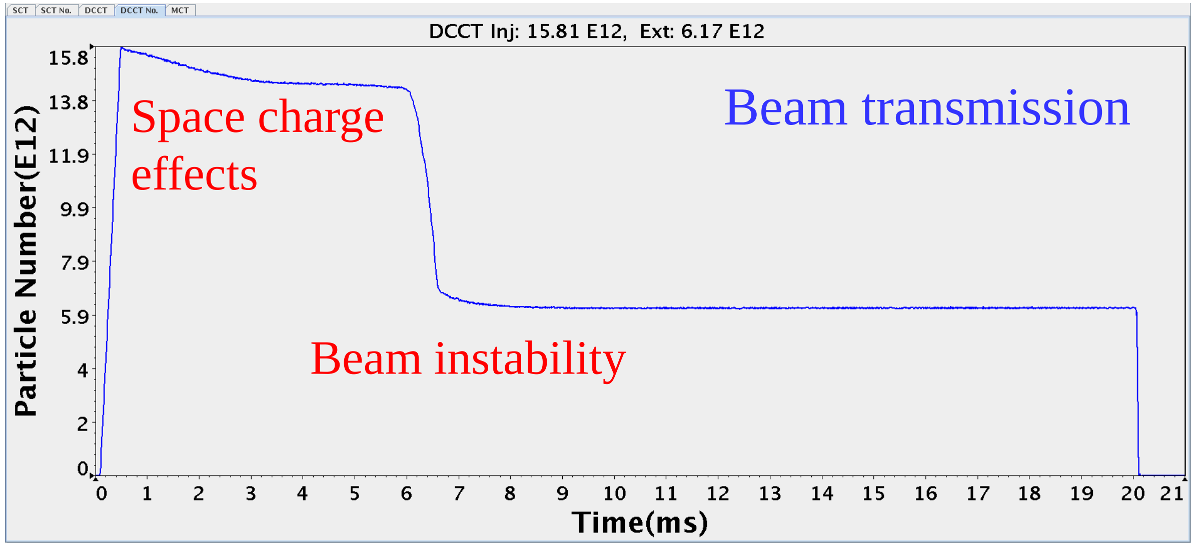
The schematic layout of the RCS

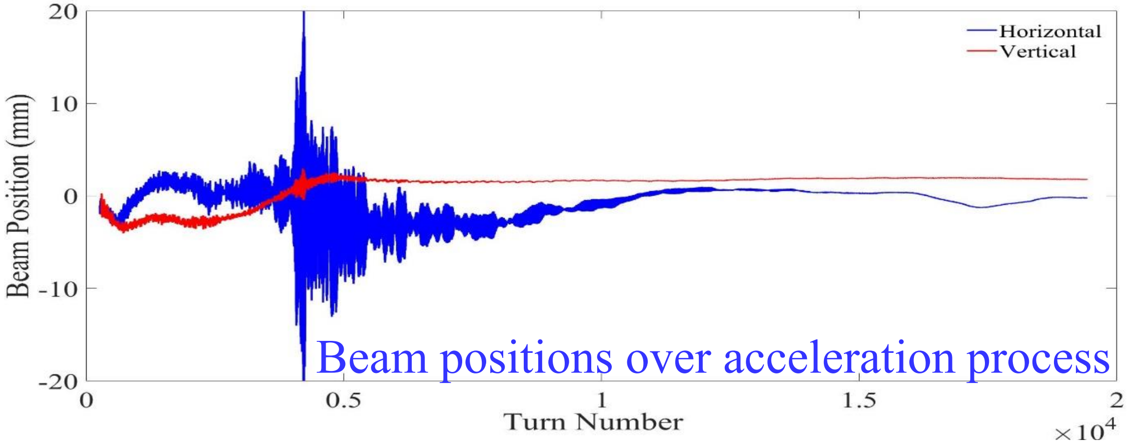


The design tune location in the resonance map

50kW

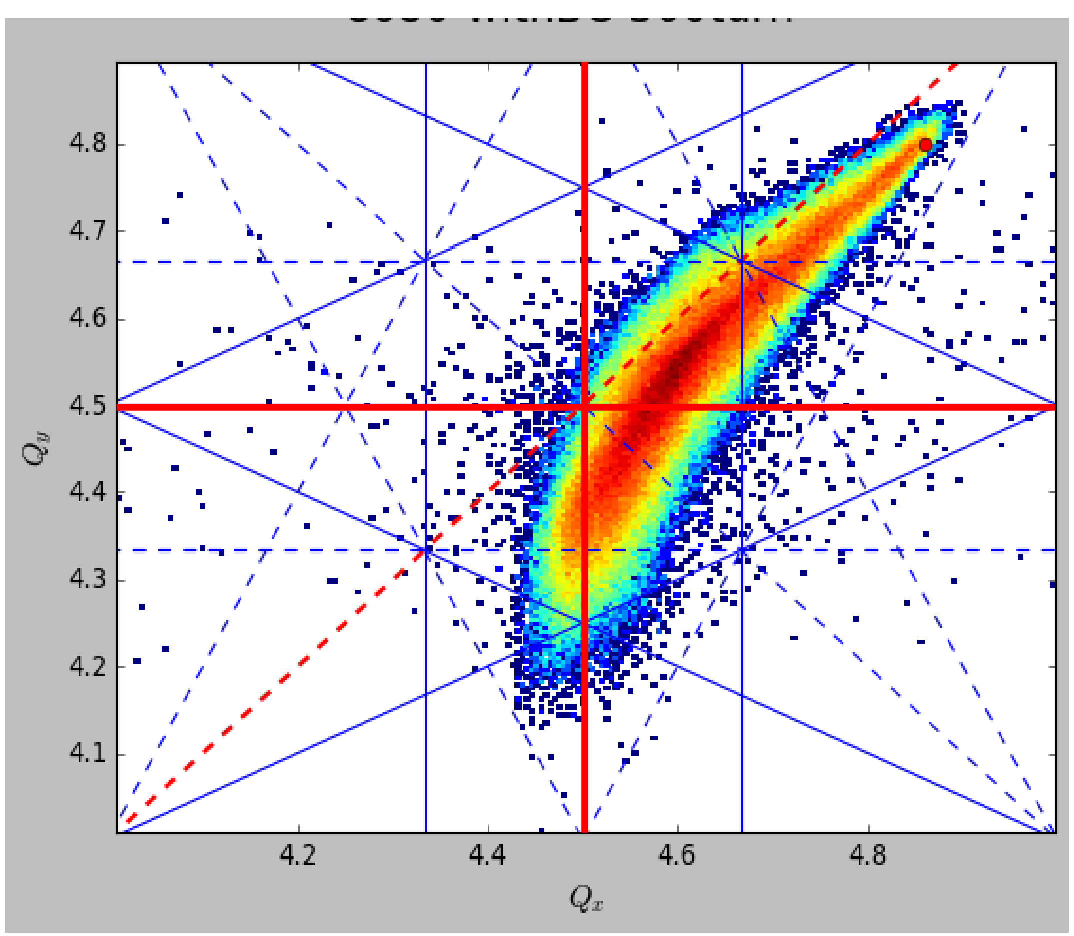




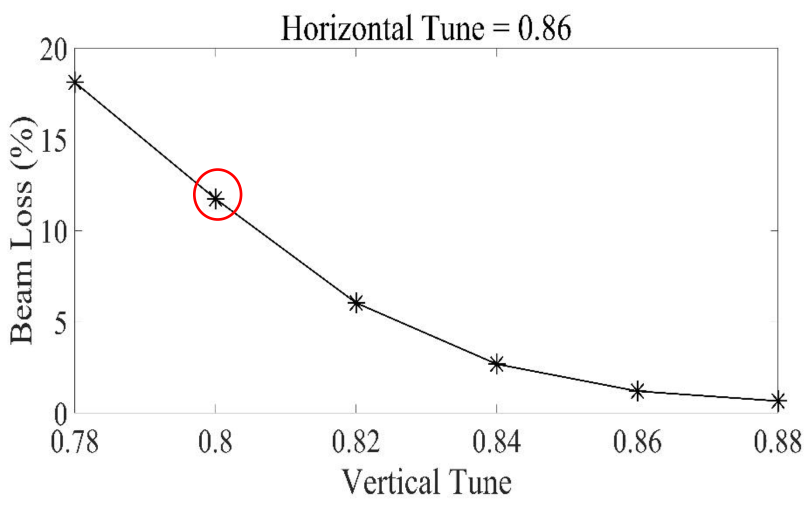


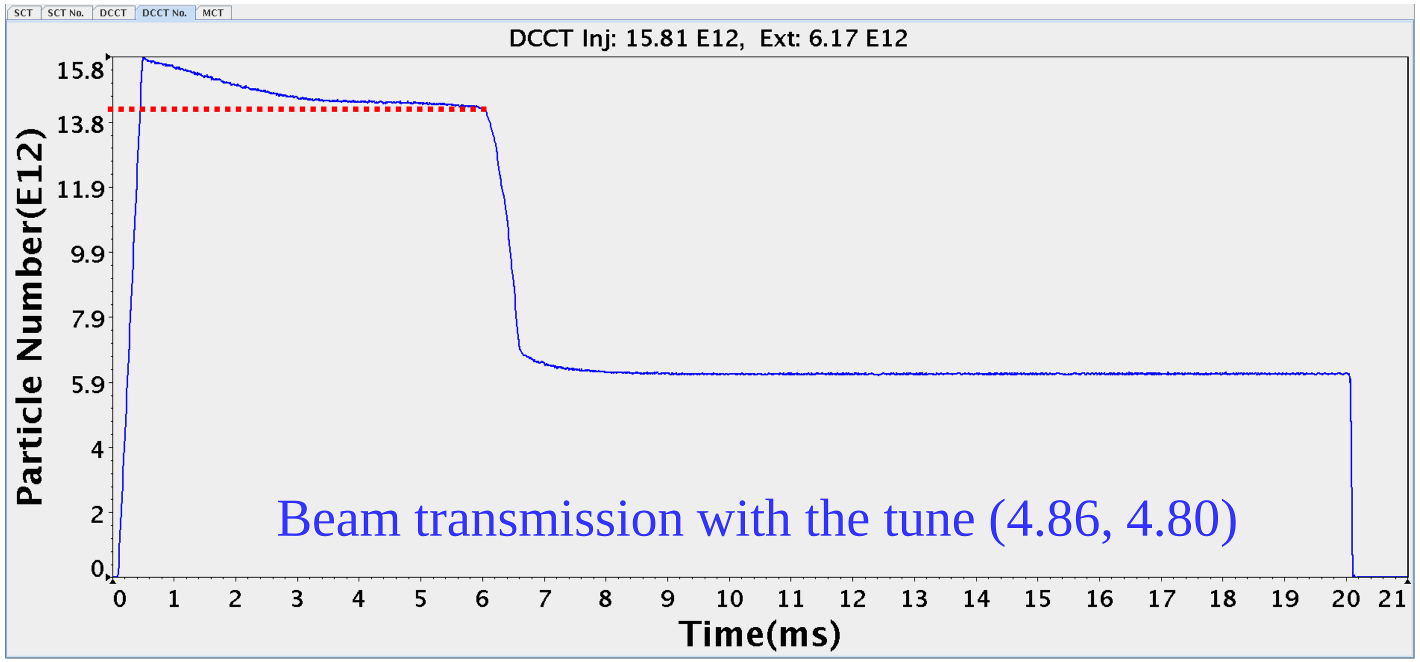
- ➢ The beam power was increased to 50 kW in January 2019.
- ➢ The beam loss caused by space charge effects and beam instability hinders the achievement of higher power levels.

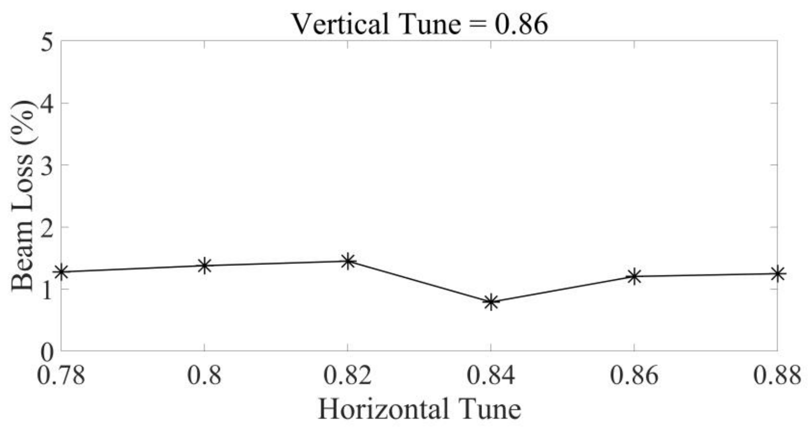
2: Space charge effects in CSNS/RCS



- With a tune below the integer value
- The incoherent RMS tune shift approaches -0.28
- Half integer resonance under space charge is a key beam loss mechanism



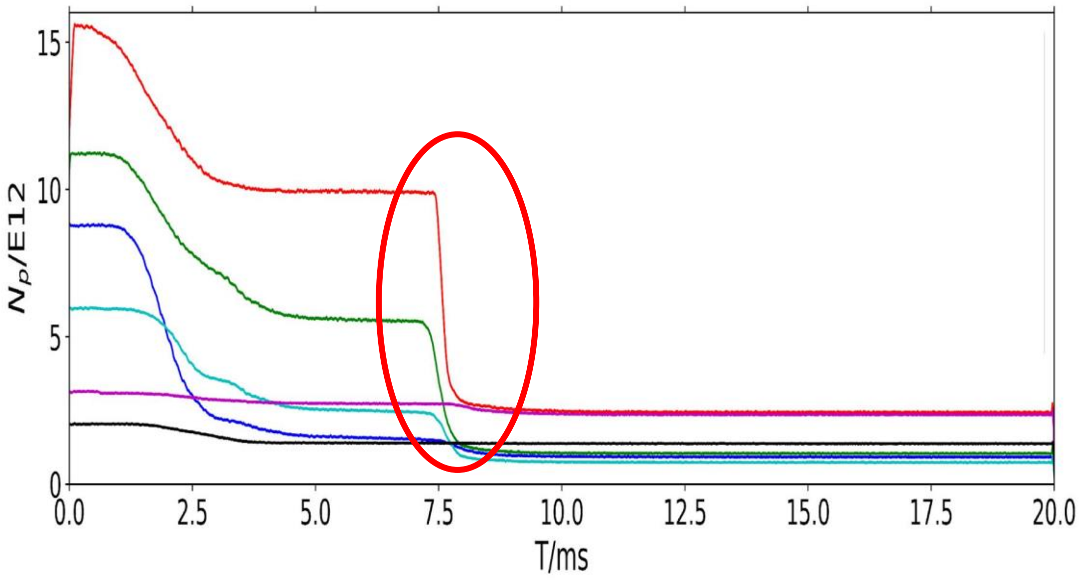




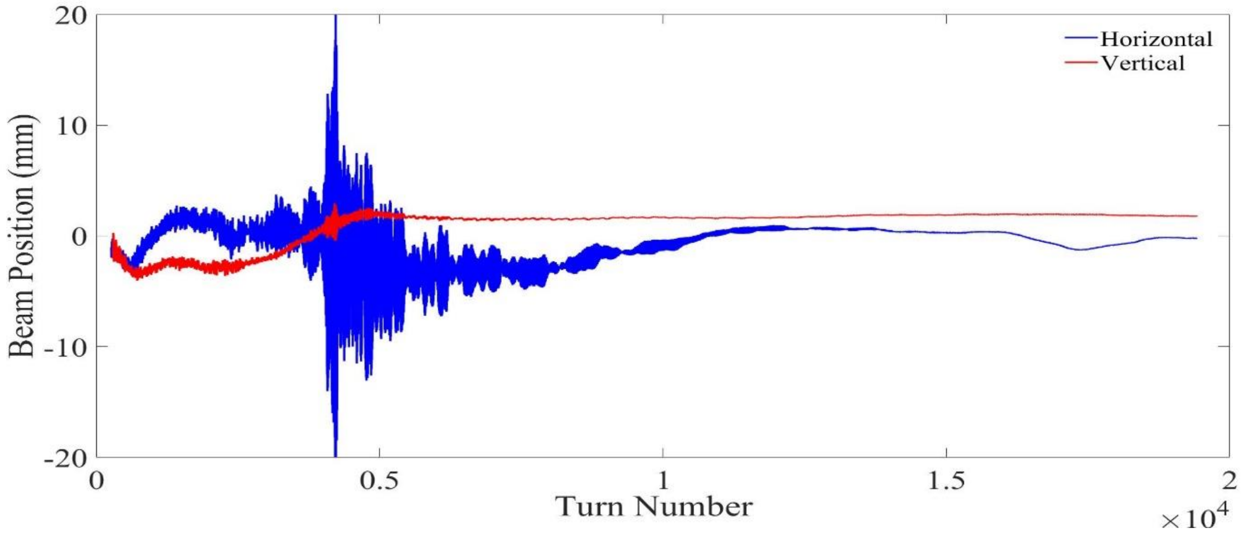
- Beam loss decreases as vertical tunes move up and away from half integer resonance lines.
- The horizontal tune has a minor impact on the transmission rate
  - Due to dispersion effects, space charge tune shift in horizontal plane is smaller.
  - The horizontal natural chromaticity is smaller.
  - A smaller horizontal tune spread induced by space charge and chromaticity

3: Beam instability in CSNS/RCS

- The greatest challenge we encountered in achieving higher intensity beam at CSNS/RCS was instability.
- Even at a beam power of 30kW, instability can be observed with the design tune (4.86, 4.80) and natural chromaticity.

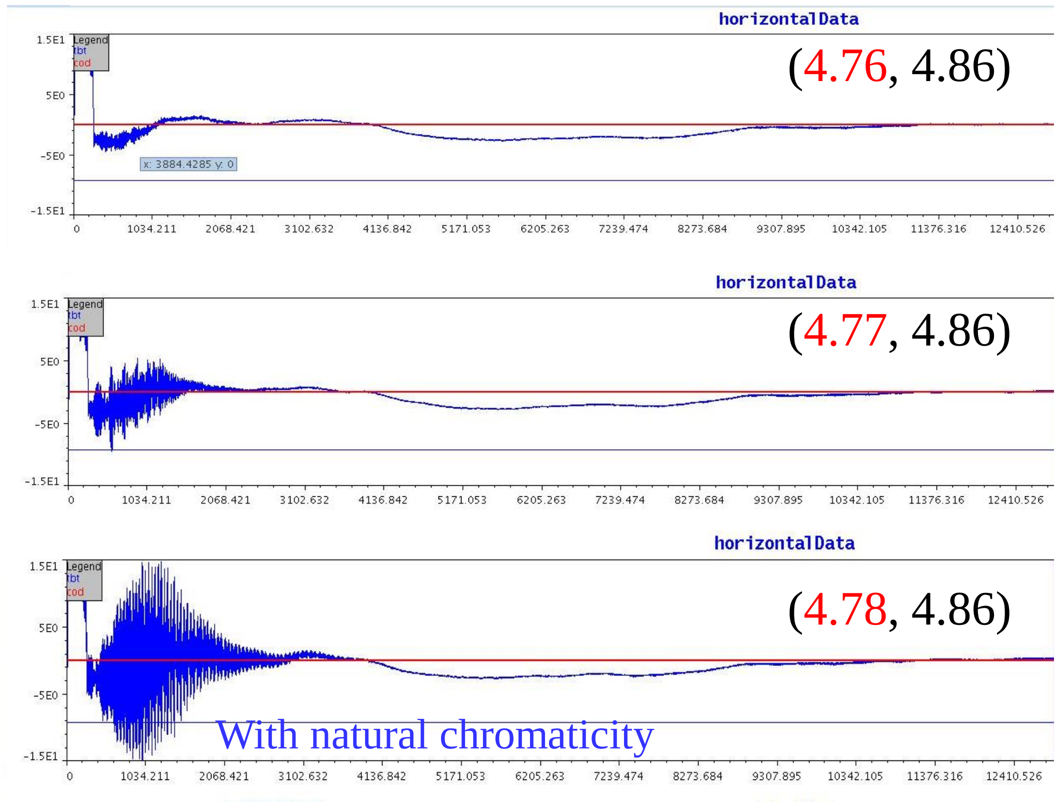


The correlation between beam instability and the number of stored particles

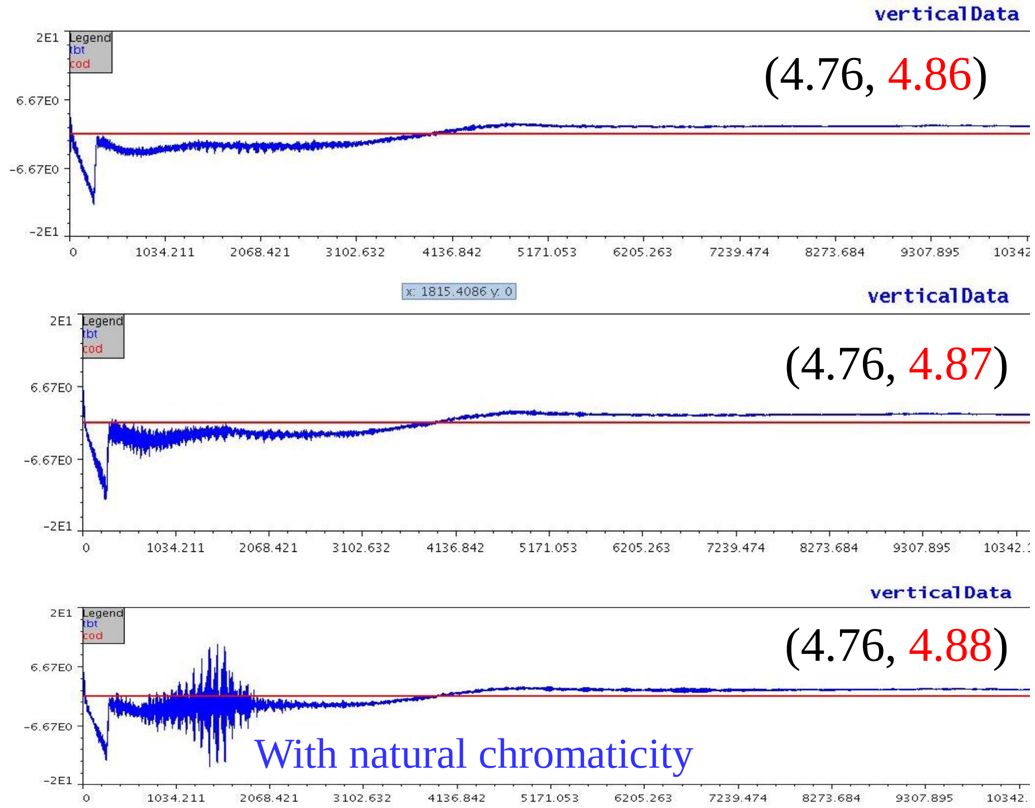


Beam positions for the beam power of 100kW

- The instability is strongly influenced by tune
- Instabilities arise when the tune approaches an integer from below

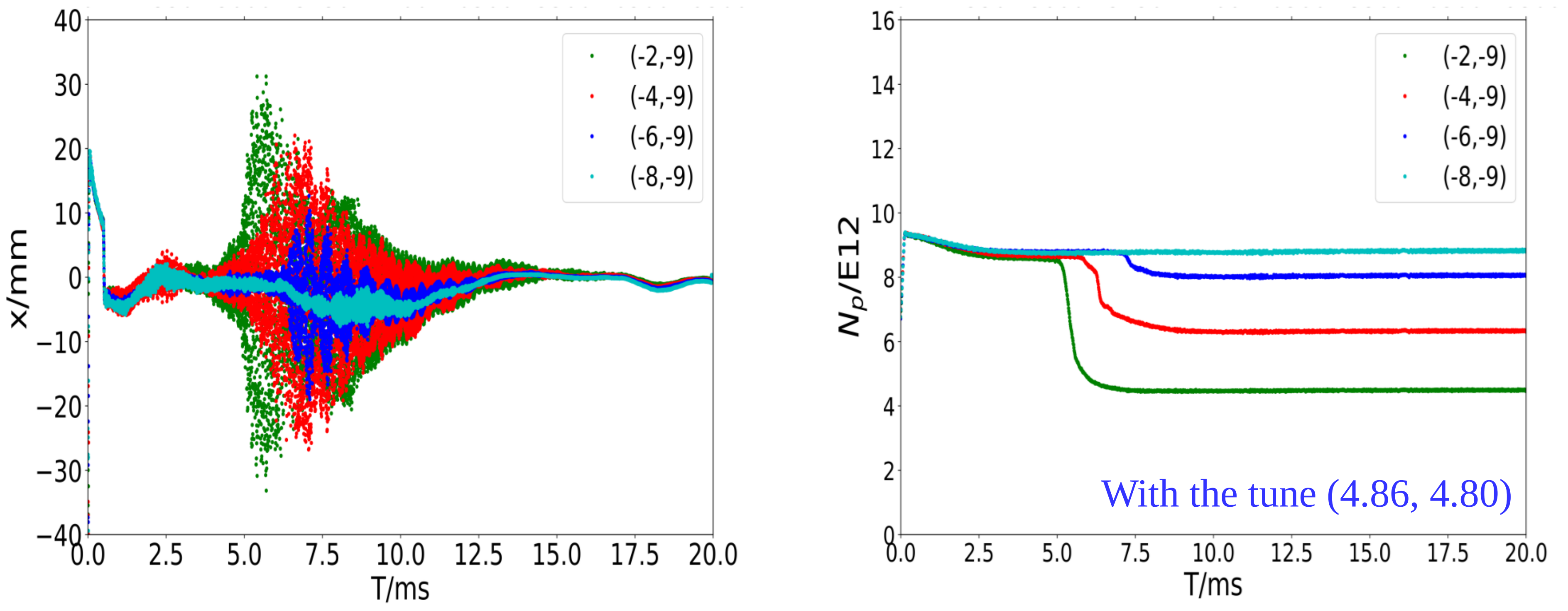


Beam positions in the horizontal plane with different tunes



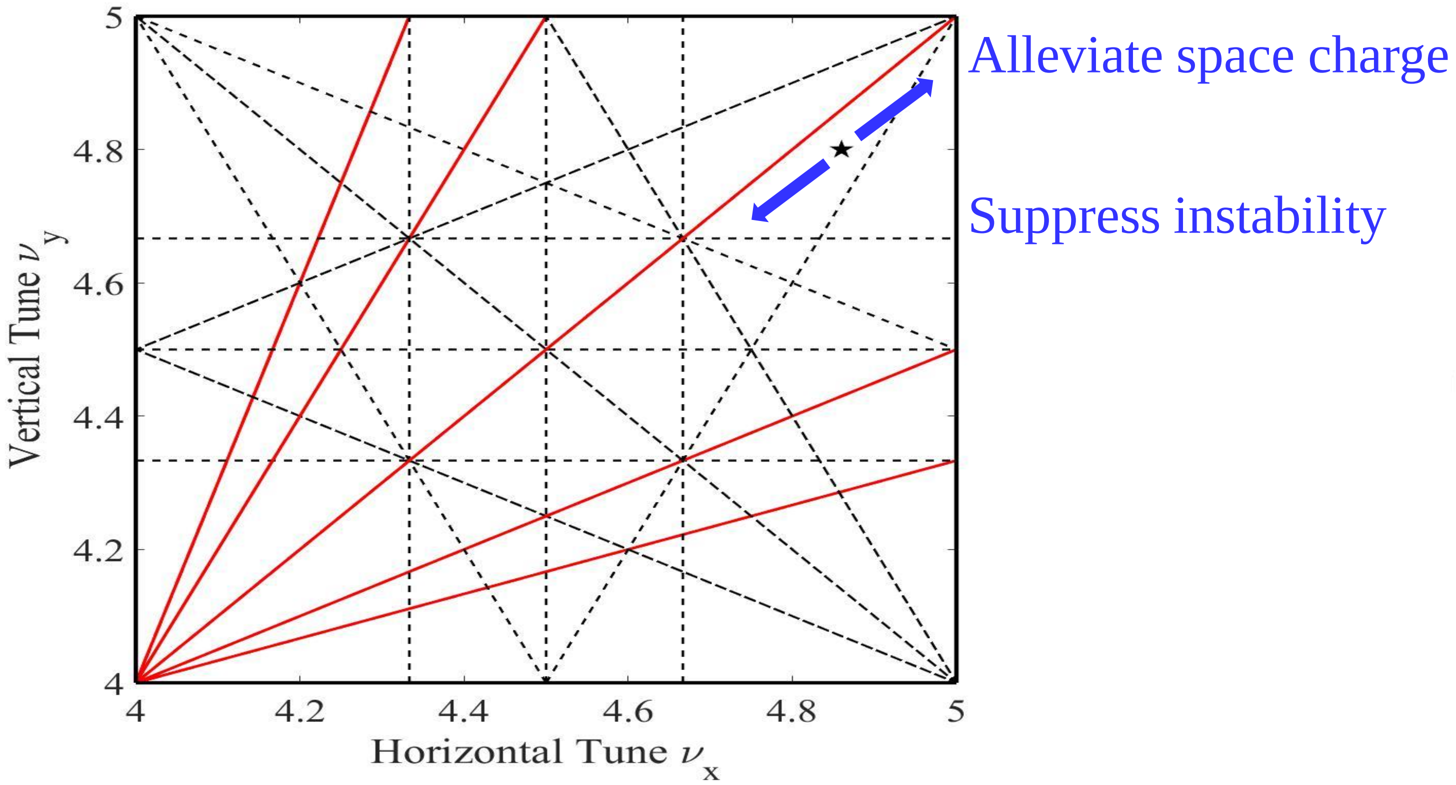
Beam positions in the vertical plane with different tunes

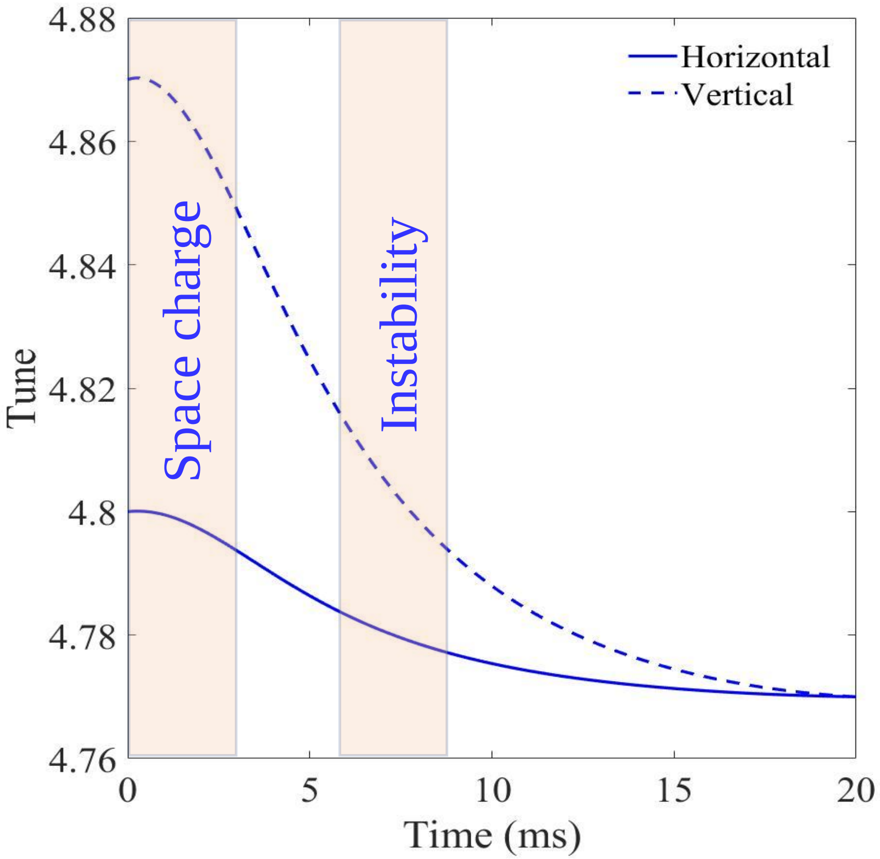
The influence of the chromaticity on the instability



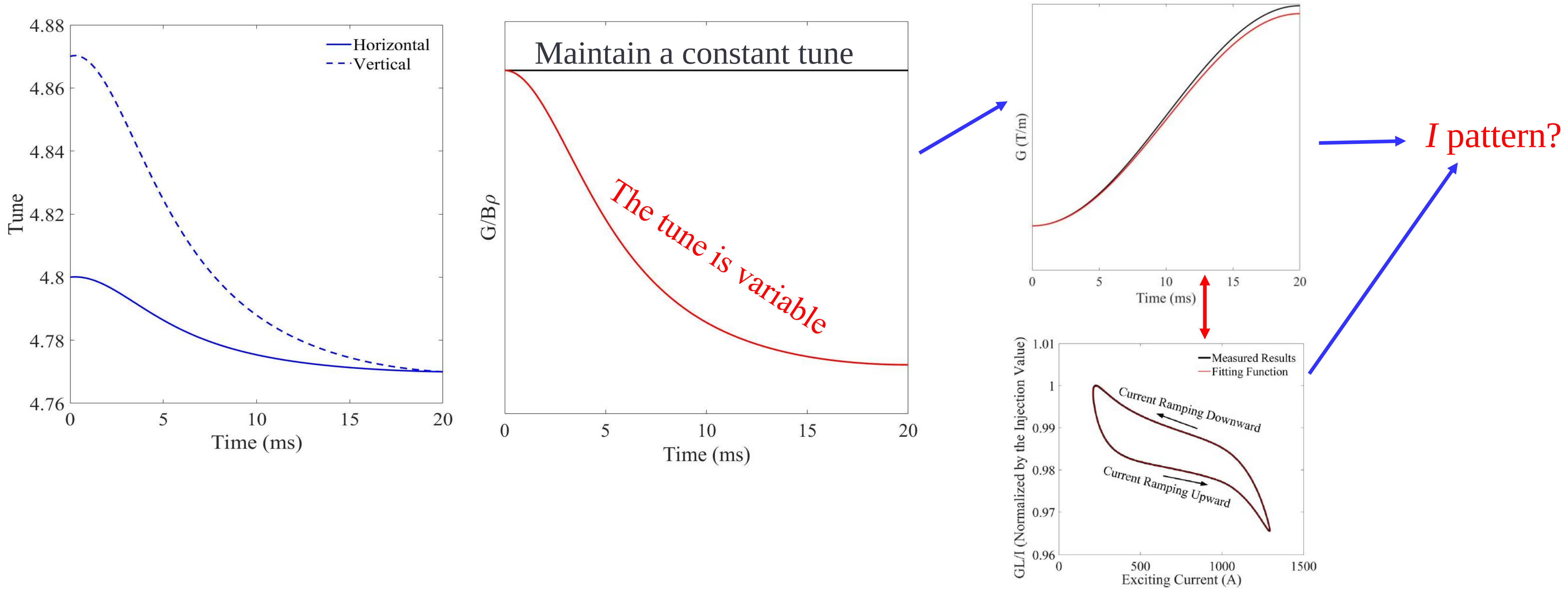
The instability is clearly changed with chromaticity.

4: Tune Pattern Optimization

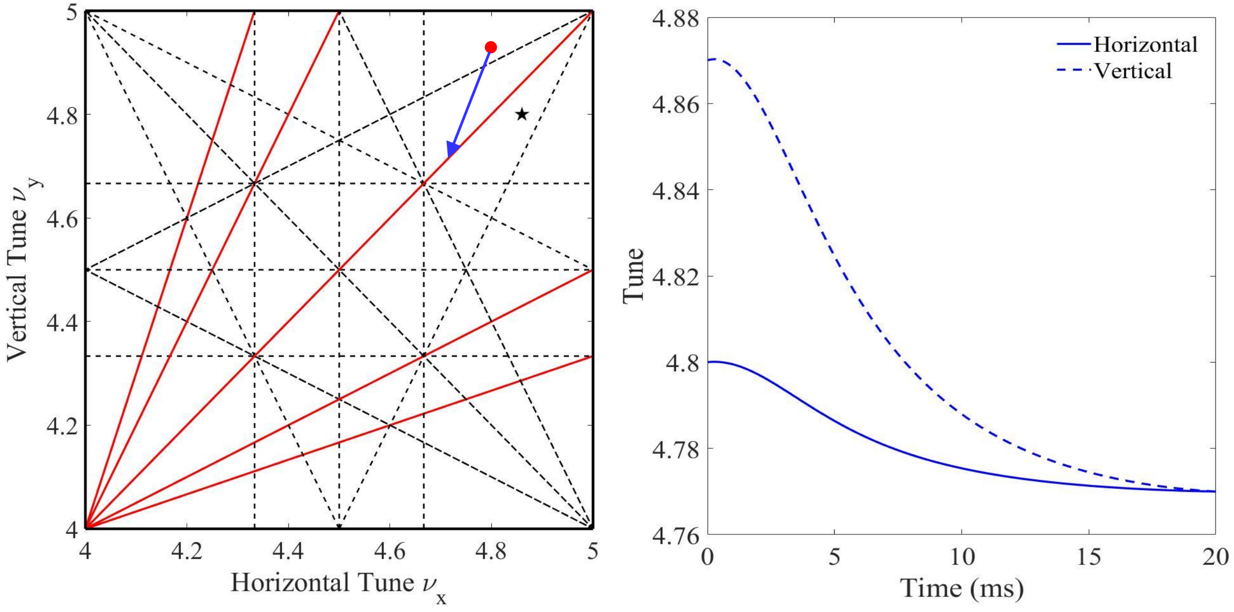


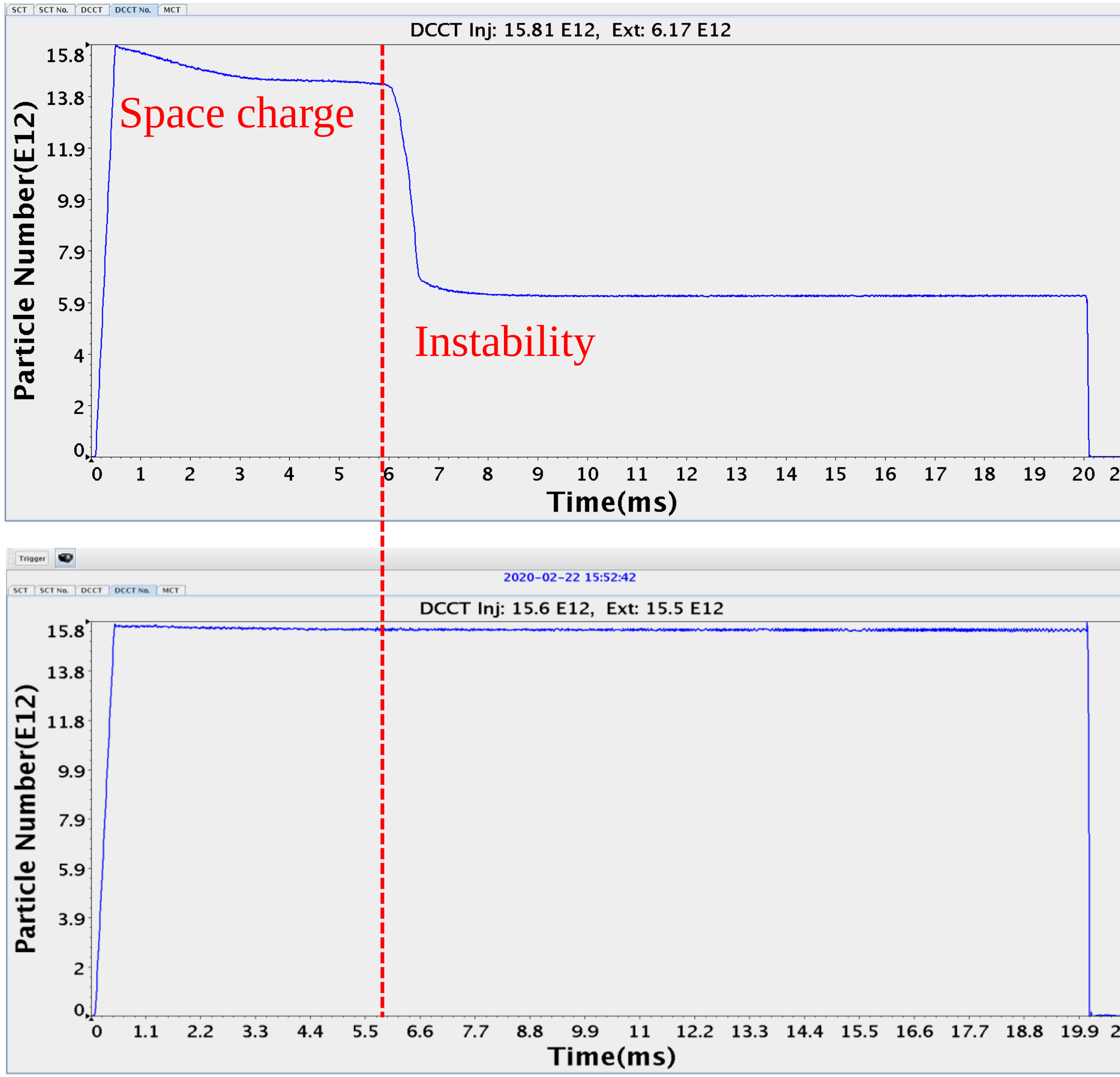


- Space charge induced beam loss decrease as tunes are moved up and away from half-integer resonance lines
- Instability growth rates increase rapidly as the tune approaches integer
- The tune requirements for reducing space charge induced beam loss and suppressing beam instability are different
- We propose a pattern of tune variation: the tune varies depending on space charge effects and instability

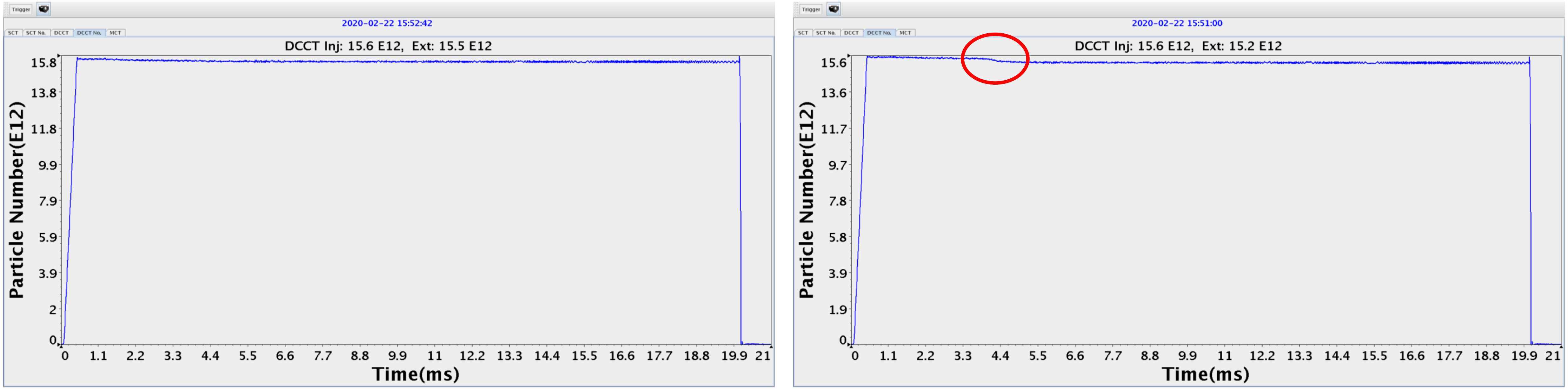


- The dipole magnetic field is ramped using a sinusoidal pattern, and the RF frequency is synchronized with the dipole magnetic field.
- The ramping process of the quadrupole magnetic field during the acceleration is modulated to produce a pattern of tune variation.

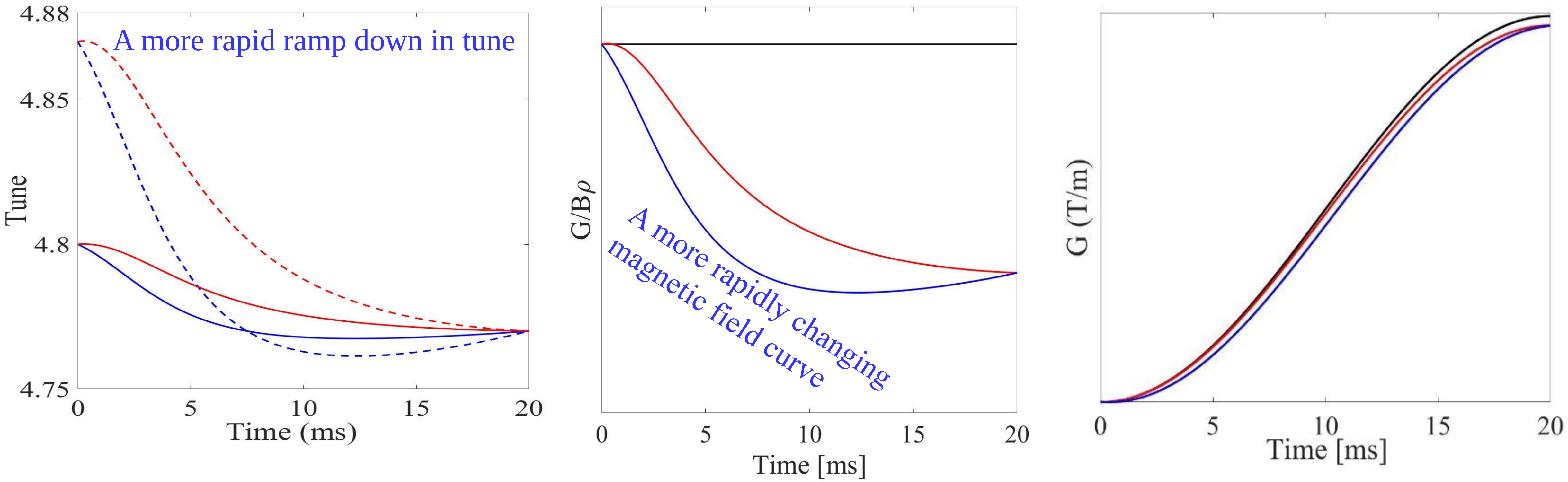




By utilizing optimized variable tune pattern, the beam transmission rate achieves a remarkable 99.5%.

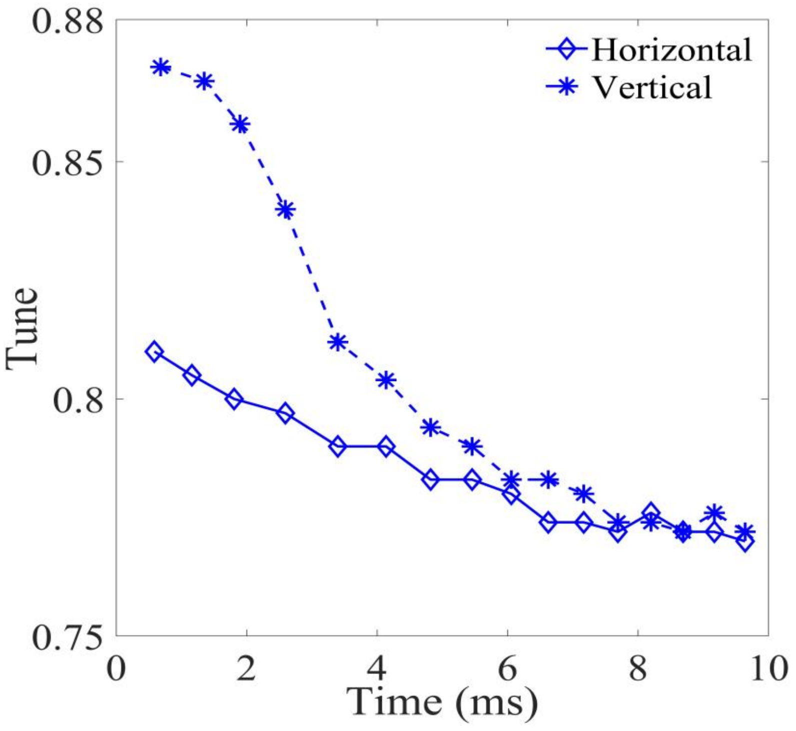


- By adopting the optimized tune pattern, the beam loss caused by the space charge effect and instability was effectively mitigated.
- However, occasional beam losses of 1-2% may occur, accompanied by beam instabilities.
- To reduce occasional beam losses, it is necessary to further suppress beam instability.

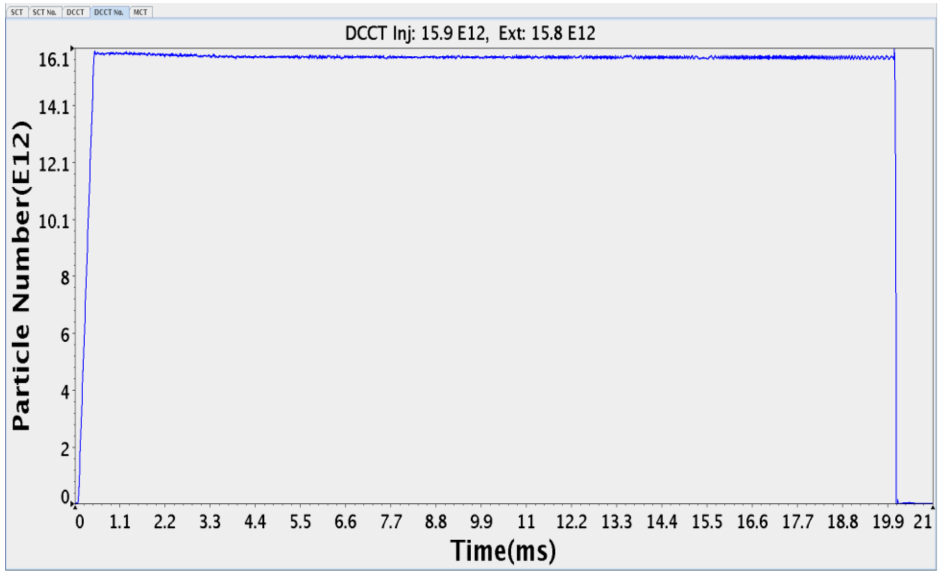


- To effectively suppress beam instability, it is necessary to more rapidly ramp down the tune.
- By shifting the timing of the quadrupole magnet, the magnetic field variation lags behind the RF frequency.
- The hysteresis change of the magnetic field can result in a rapid ramp down in tune.

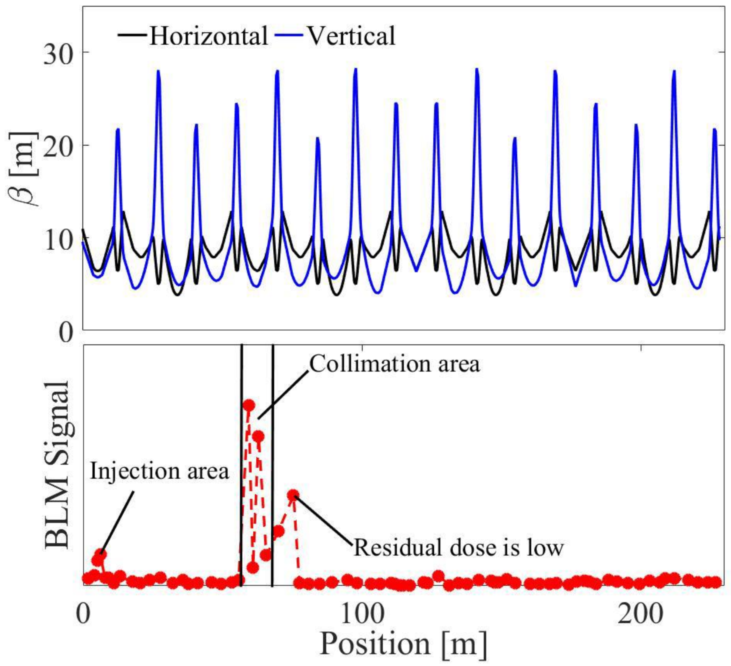
- After the tune optimization, beam loss caused by space charge and beam instability was successfully controlled.
- Occasional beam loss disappears, and beam operation is stable.



The measured tune variations after the tune optimization



Beam transmission with the optimized tune pattern



BLM signals along the RCS

THANK YOU !