Effects of Magnetic Field Tracking Errors and Space Charge on Beam Dynamics at CSNS/RCS

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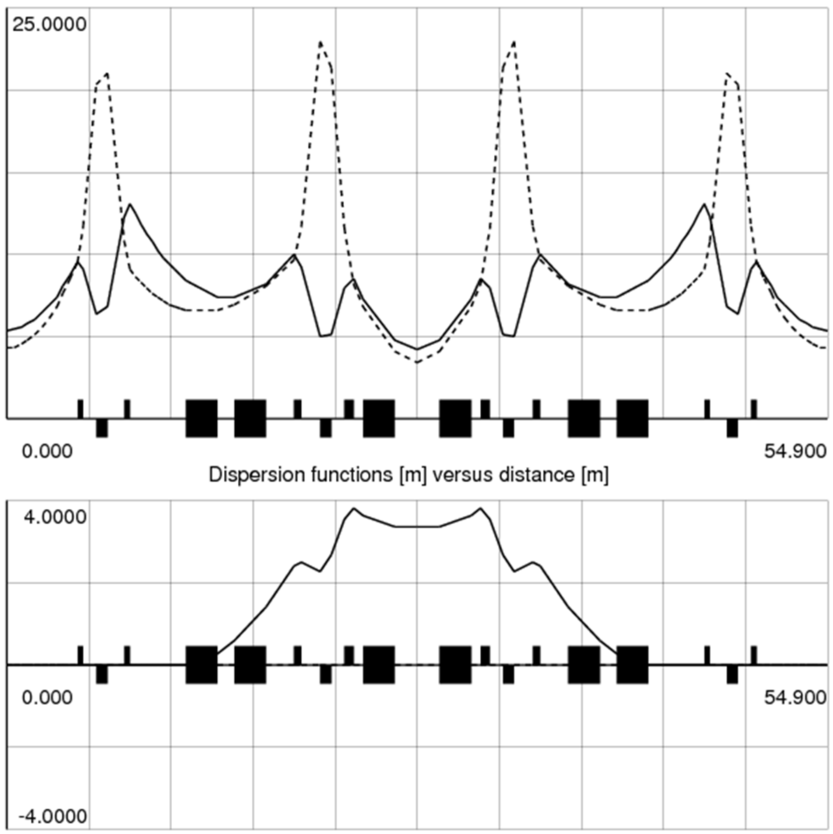
Outline

- Introduction of CSNS/RCS
- Effects of Chromaticity, Space Charge, Magnetic Field Tracking Errors
- Simulation Results

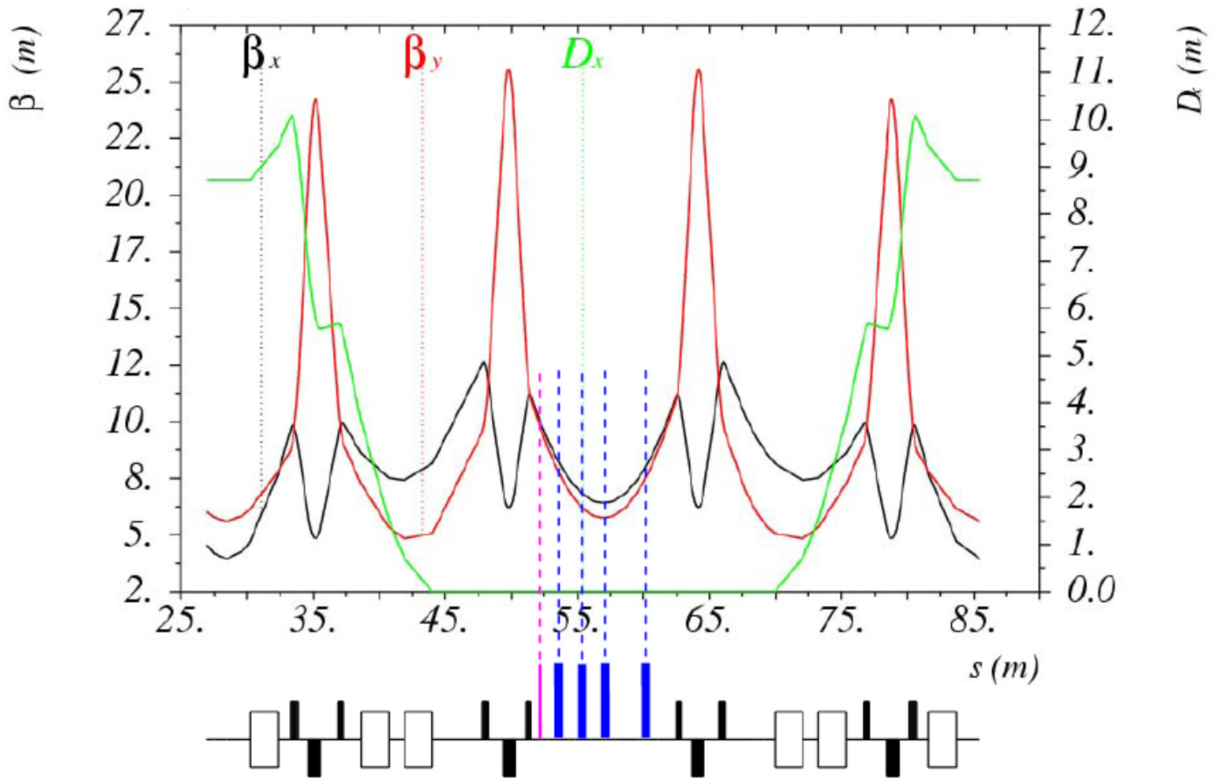
Introduction of CSNS/RCS

Circumference (m)	227.92
Superperiod	4
Number of dipoles	24
Number of long drift	12
Total Length of long drift (m)	75
Betatron tunes (h/v)	4.86/4.78
Natural Chromaticity (h/v)	-4.3/-8.2
Momentum compaction	0.041
RF harmonics	2
Injection energy (MeV)	80
Extraction energy (MeV)	1600
RF Freq. (MHz)	1.0241~2.444
Accumulated particles per pulse	1.56×10^{13}
Trans. acceptance (πμm.rad)	>540



Twiss Parameters of One Super-Period

Collimation System



The Layout of the Collimation System

(pink: primary collimator, blue: secondary collimators)

Acceptance of the Primary Collimators: 350 πμm.rad

Acceptance of the Secondary Collimators: 400 πμm.rad

Space Charge Effects

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

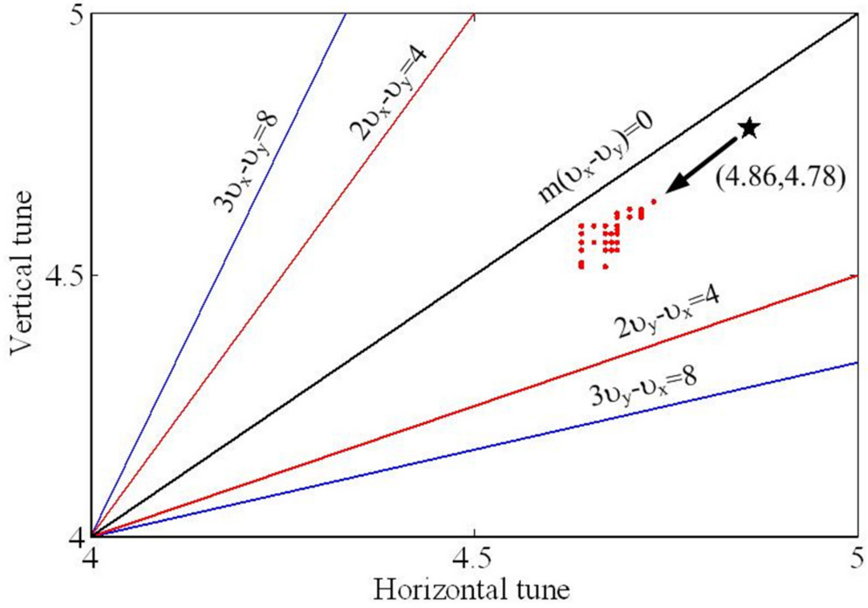
Incoherent Tune Shift for Uniform Distribution in Transverse Direction

Just after the injection painting:

EK=80MeV

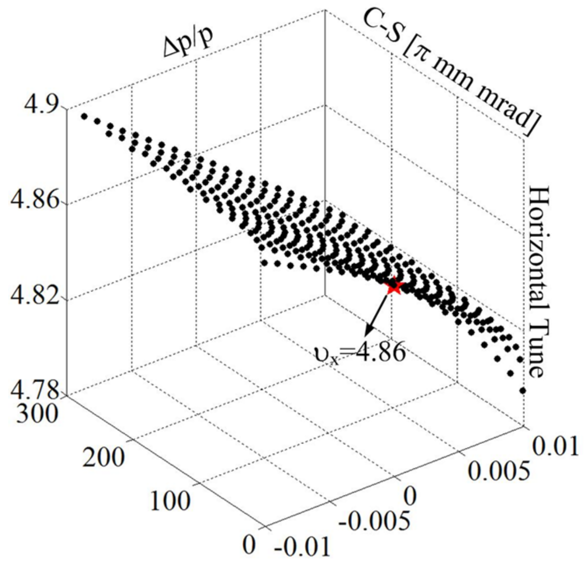
$\Delta\upsilon=0.2$

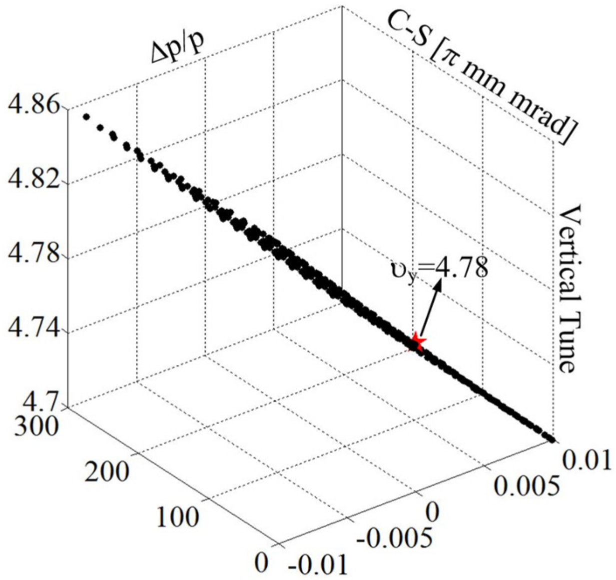
Simulations Results: $\Delta\upsilon_{max}=0.3$



Tunes of 30 test particles with different C-S invariants

Effects of Chromaticity

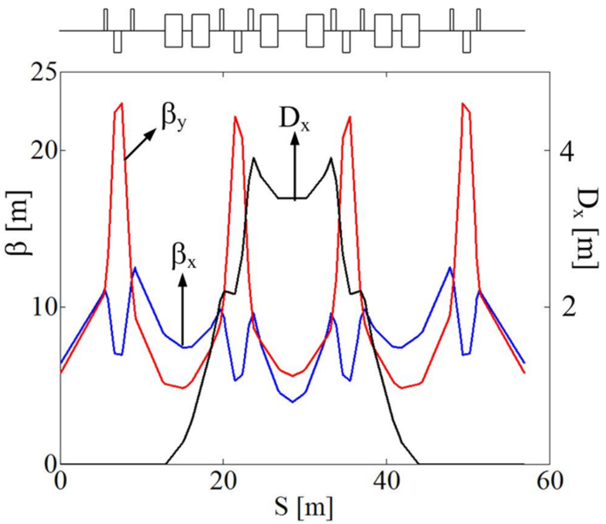


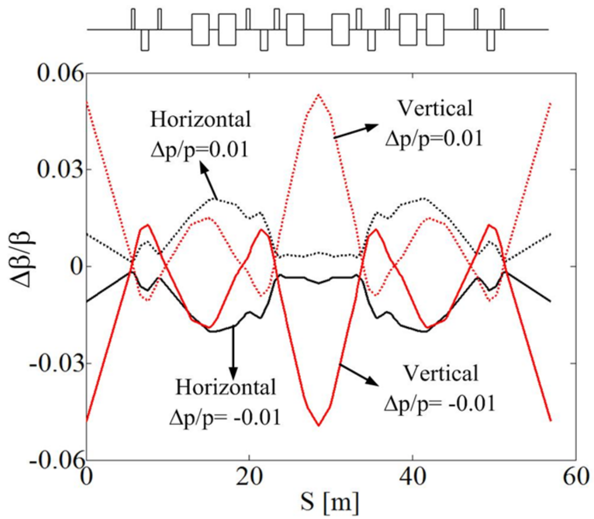


Natural Chromaticity: (-4.3/-8.2)

Tunes for particles with different momentum spreads and Courant-Snyder (C-S) invariants

Tune Shift: (0.04, 0.08) for Δp/p=0.01





$\Delta\beta_{x\text{-}max}$=0.17m

$\Delta\beta_{y\text{-}max}$=0.30m

The dependence of the Beta functions on the momentum spread without chromatic correction

Magnetic Field Tracking Errors

Magnetic field tracking errors betwen the quadrupoles and the dipoles for RCS.

	QuadrupoleGradient (T/m)	Saturations of the Fields
QA	0.80~6.60	<2%
QB	0.70~5.10	<1.5%
QC	0.70~5.00	<1.5%
QD	0.70~5.35	<1.5%

CSNS/RCS Design Value

In the measurements of the prototype quadrupole magnet of CSNS/RCS, the tracking errors can be adjusted within 0.1% by compensating by using higher frequency waves.

	50Hz/25Hz	75Hz/25Hz
No-Compensation	1.01%	1.85%
With-Compensation	1.13E-4	4.33E-5

The data is provided by X. Qi

Magnetic Field Tracking Errors

In the actual operations, 8 or 16 quadrupoles are powered by the same power supply.

There are differences between the quadrupoles powered by the same power supply.

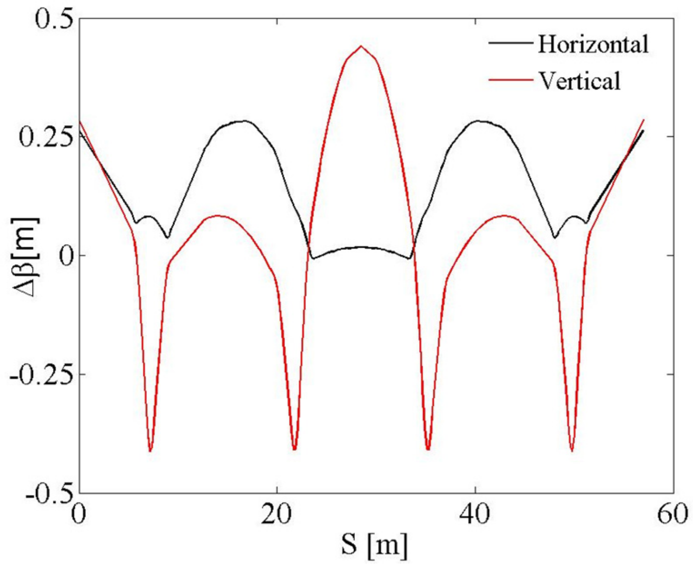
It is impossible to compensate the magnetic field tracking errors very well for all the quadrupoles, so the tracking errors $\Delta K/K_{QA}$= -2%， $\Delta K/K_{QB,QC,QD}$= -1.5% is considered for the worst case.

Effects of Magnetic Field Tracking Errors

The magnetic field tracking errors can induce beta function distortion and tune shift.

$$\Delta\upsilon = \frac{1}{4\pi}\oint_C \Delta K \cdot \beta(s) \cdot ds = -\frac{\Delta K}{K}\xi_{uncorrected}$$

$\Delta K/K_{QA}$=-2%， $\Delta K/K_{QB,QC,QD}$=-1.5%



Tune Shift

(4.86, 4.78) ⇒ (4.77, 4.68)

The effects of magnetic field tracking errors on Beta functions ($\Delta\beta=\beta_{with\text{-}error}-\beta_{no\text{-}error}$).

Combine Effects of Tracking Errors and Chromaticity

$$\Delta \upsilon = \frac{\Delta p}{p}\xi_{uncorrected}$$

$$\Delta \upsilon = -\frac{\Delta K}{K}\xi_{uncorrected}$$

$\Delta K/K_{QA}$= -2%， $\Delta K/K_{QB,QC,QD}$= -1.5%， $\Delta p/p$=0.01

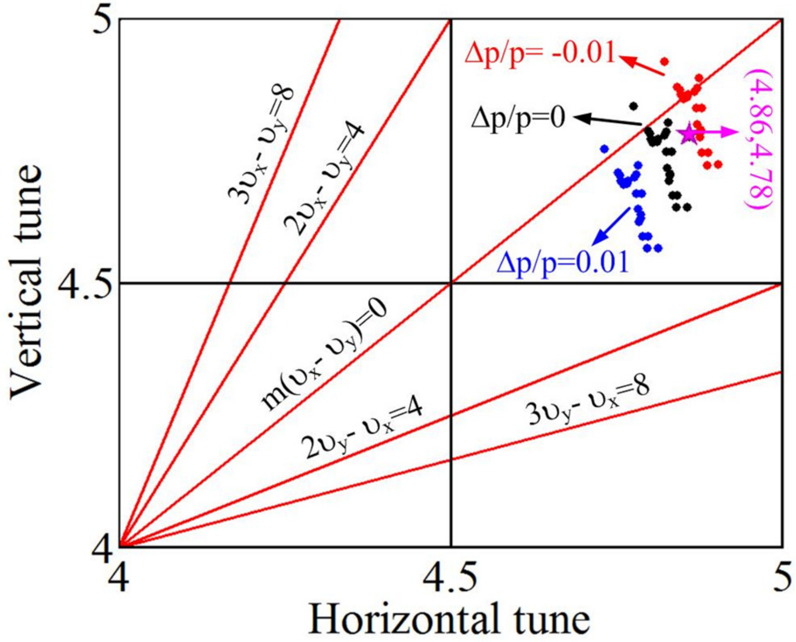
(4.86, 4.78) ⟹ (4.73, 4.61)

$\Delta\beta_{x\text{-}max}$=0.45m, $(\Delta\beta_x/\beta_x)_{max}$=6%

$\Delta\beta_{y\text{-}max}$=0.78m, $(\Delta\beta_y/\beta_y)_{max}$=14%

The combine effects of chromaticity and tracking errors on tunes

$-2\% < \Delta K/K_{QA} < 0$， $-1.5\% < \Delta K/K_{QB,QC,QD} < 0$



Effects of Magnetic Field Tracking Errors

	Tunes (H/V)	Physical Acceptance (H/V, πμm.rad)	Acceptance of the Primary Collimators (H/V, πμm.rad)	Acceptance of the Secondary Collimators (H/V, πμm.rad)	β_x/β_y at the Injection Point of RCS(m)
Case-1	4.86/4.78	542/556	350/350	400/400	6.425/5.757
Case-2	4.773/4.685	515/546	345/345	385/380	6.688/6.043
Case-3	4.775/4.834	515/555	346/354	389/406	6.622/5.525
Case-4	4.839/4.643	552/534	342/344	379/378	6.802/6.078

Case-1: without tracking errors

Case-2: $\Delta K/K_{QA}$= -2%， $\Delta K/K_{QB,QC,QD}$= -1.5%

Case-3, 4: $-2\% < \Delta K/K_{QA} < 0$, $-1.5\% < \Delta K/K_{QB,QC,QD} < 0$

Simulaton Results

	Painted 99% Emittance (H/V, πμm.rad)	β_x/β_y at the Injection Point of RCS(m)
Case-1	185/195	6.425/5.757
Case-2	181/187	6.688/6.043
Case-3	181/207	6.622/5.525
Case-4	174/186	6.802/6.078

Without Space Charge Effects

$$\varepsilon = \frac{X_0^2}{\beta}$$

Painted Emittance

	Painted 99% Emittance (H/V, πμm.rad)	Beam Loss during Injection Painting
Case-1	229/241	0.19%
Case-2	218/250	0.25%
Case-3	202/302	6.2%
Case-4	191/293	2.8%

With Space Charge Effects

Simulaton Results

Without Space Charge Effects

	Painted 99% Emittance (H/V, πμm.rad)	Beam Loss During Injection Painting	Collimation Efficiency	Beam Loss During Acceleration (5000turns, 7.3ms)
Case-1	185/195	0.043%	72.1%	0
Case-2	181/187	0.038%	60.5%	0
Case-3	181/207	0.036%	69.4%	0
Case-4	174/186	0.036%	63.9%	0

Simulaton Results

With Space Charge Effects

	Physical Acceptance (H/V, πμm.rad)	Acceptance of the Primary Collimators (H/V, πμm.rad)	Acceptance of the Secondary Collimators (H/V, πμm.rad)
Case-1	542/556	350/350	400/400
Case-2	515/546	345/345	385/380
Case-3	515/555	346/354	389/406
Case-4	552/534	342/344	379/378

Serious Beam Losses for Case-3, Case-4

Larger Painted Emittance

Case4: decreased collimators acceptance

	Painted 99% Emittance (H/V, πμm.rad)	Beam Loss During Injection Painting	Collimation Efficiency	Beam Loss During acceleration	Collimation Efficiency
Case-1	229/241	0.19%	86.7%	0.53%	92.0%
Case-2	218/250	0.25%	88.1%	2.4%	92.2%
Case-3	202/302	6.2%	93.4%	1.6%	92.7%
Case-4	191/293	2.8%	93.7%	6.3%	92.7%

Simulaton Results

With Space Charge Effects

	Painted 99% Emittance (H/V, πμm.rad)	Beam Loss During Injection Painting	Collimation Efficiency	Beam Loss During acceleration	Collimation Efficiency
No-Error	229/241	0.19%	86.7%	0.53%	92.0%
0.1% Errors	228/249	0.21%	86.6%	0.79%	92.5%
0.3% Errors	204/249	0.29%	87.8%	0.62%	91.9%
0.5% Errors	222/223	0.16%	82.2%	1.15%	92.2%

Conclusion

1: The preferred working points of CSNS/RCS are (4.86, 4.78), which can avoid the major low-order structure resonances. But because of the chromatic tune shift, space-charge incoherent tune shift and the tune shift caused by magnetic field tracking errors, some structure resonances are unavoidable.

2: These three factors induce beta function distortion, and influence the physical acceptances, the acceptances of collimators and the painted emittances for the case that the collimator aperture and the painting scheme remain unchanged.

3: There are serious beam losses when the magnetic tracking errors are not compensated. Maybe, by the optimizations of painting, the beam losses can be decreased.

4: The tracking errors can be adjusted within 0.1% by compensating by using higher frequency waves for the prototype quadrupole magnet . The simulation results show that there is no serious beam loss for the tracking errors less than 0.3%.

Thank You for Your Attention!