Studies on longitudinal dynamics at CSNS/RCS

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CSNS
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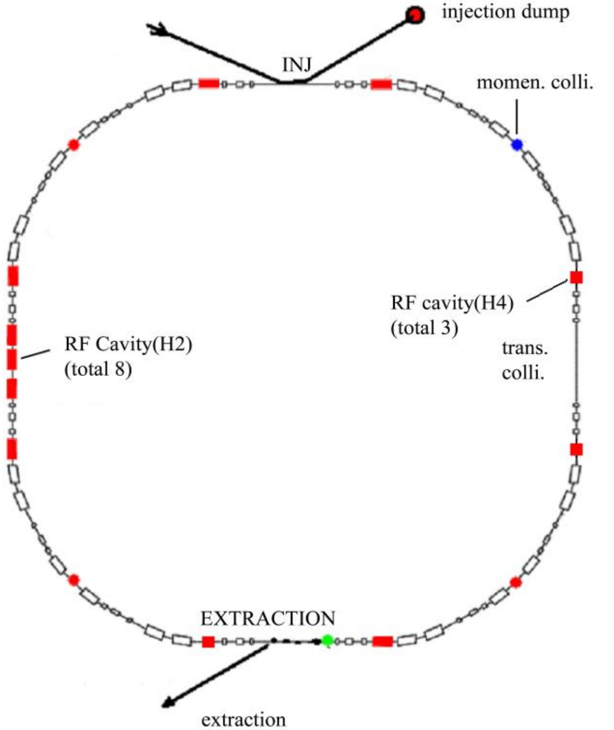
OUTLINE

- Basic parameters of CSNS/RCS
- Longitudinal space charge effect at CSNS/RCS
- Dual-harmonic acceleration for CSNS-II and CSNS-I
- Stationary-injection method
- Flat bucket and bunch formed by SH RF and SC
- Summary

BASIC PARAMETERS OF CSNS/RCS

Project phase	I	II
Beam power /kW	100	500
Ring circumference /m	228	228
Curvature of bending magnet /m	8.021	8.021
No. of RF cavities	8 (h=2)	8 (h=2) +3(h=4)
Injection energy/MeV	80	250
Extraction energy /GeV	1.60	1.60
Protons per pulse /10^{13}	1.56	7.8
Repetition rate /Hz	25	25



- At CSNS-II: 5 times upgrading in beam current
- Measures:
  1) Injection energy: 80 MeV →250 MeV
  2) With dual-harmonic RF system

Longitudinal space charge effects at CSNS/RCS

- Laslett tune shift (measure the space charge)

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

(Bf: Mean/peak current)

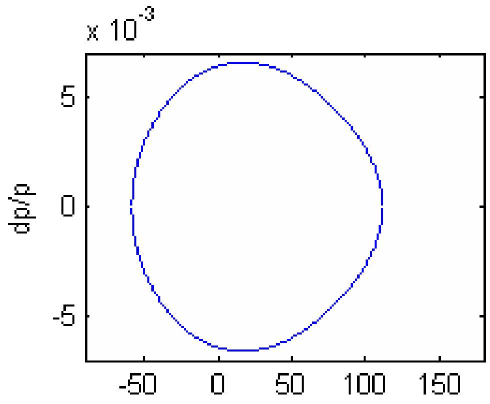
- The average tune shift and the tune spread or tune footprint may cause beam losses or significant emittance growth.

- More strictly for higher beam power synchrotrons

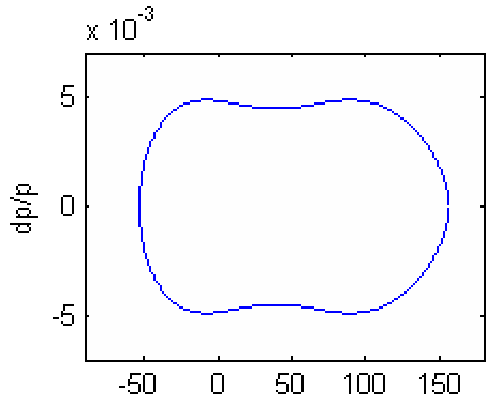
Hundreds kW: -0.30 or -0.40 may be permitted
~MW: >-0.20

- Therefore, with more accumulated particles at CSNS-II, tune shift should be controlled more strictly, from about -0.3 at CSNS-I to about -0.2: by higher injection energy and dual-harmonic RF

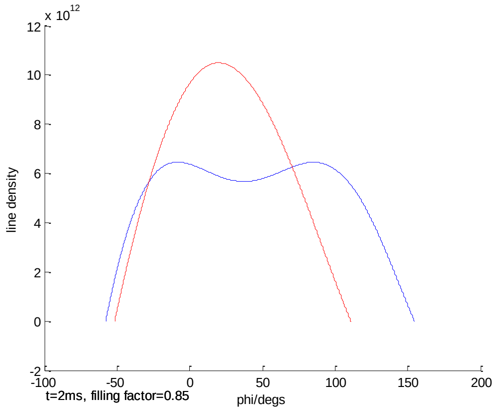
- Dual-harmonic acceleration method is used to increase Bf (bunching factor: mean/peak current)



Single-harmonic



Dual-harmonic



Line-densities (red–SH, blue-DH)

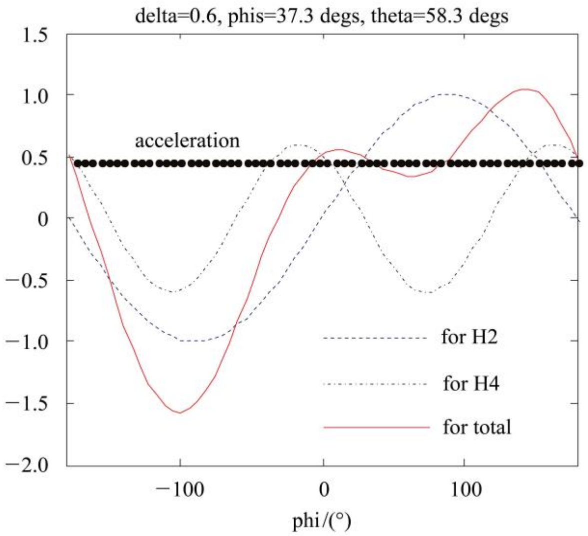
Dual-harmonic acceleration

- **Dual-harmonic RF:**

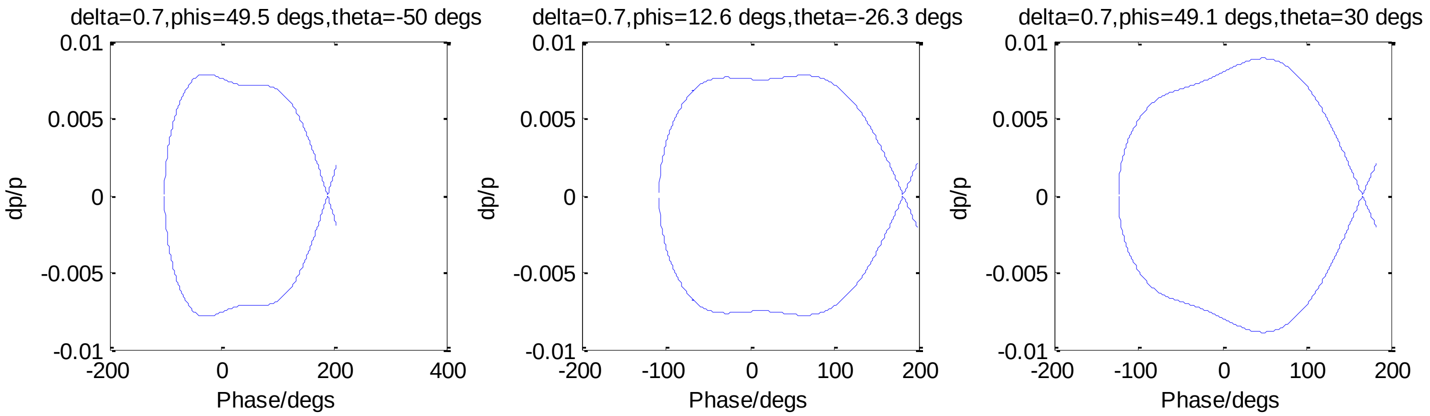
$$V_0 = 2\pi R\rho\dot{B} = V_1\left[\sin(\phi_s) - \delta\sin(2\phi_s + \theta)\right].$$

1st 2nd

- Bucket shapes decided by combinations of δ ($V2/V1$), Φs and θ



Voltage waveforms for DH



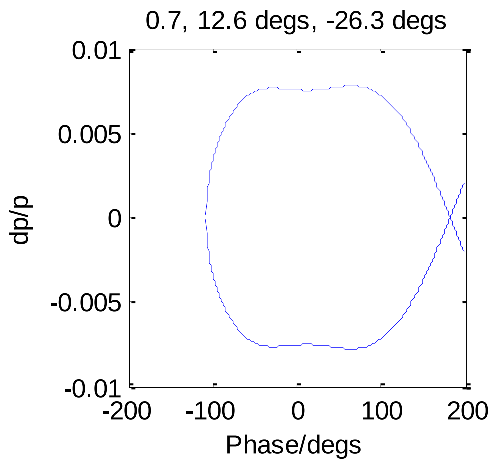
Acceleration schemes for CSNS-II

- 3 ferrite-loaded (or 2 MA-loaded) cavities are to be added to the existing 8 RF cavities (CSNS-I).
- **Special scheme:**
  - At low energy stage, where the tune shifts are large, dual-harmonic RF is designed to supply the **largest bunching factor**.
  - At middle and high energy stage, where the space charge are no longer strong, dual-harmonic RF is designed to supply **the largest bucket area.**

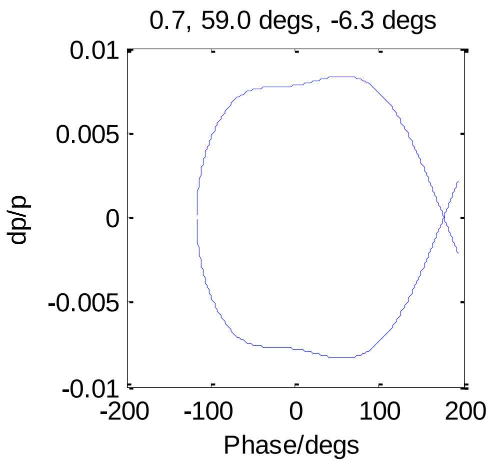
- **Advantages:**
  - **Relieve the bucket shrinking due to high accelerating rate at ~10 ms**
  - **Reduce the RF voltages but keep the same bucket area at high energy stage**

- **EXAMPLE:** At 1ms，buckets

$$\theta = \theta_B$$



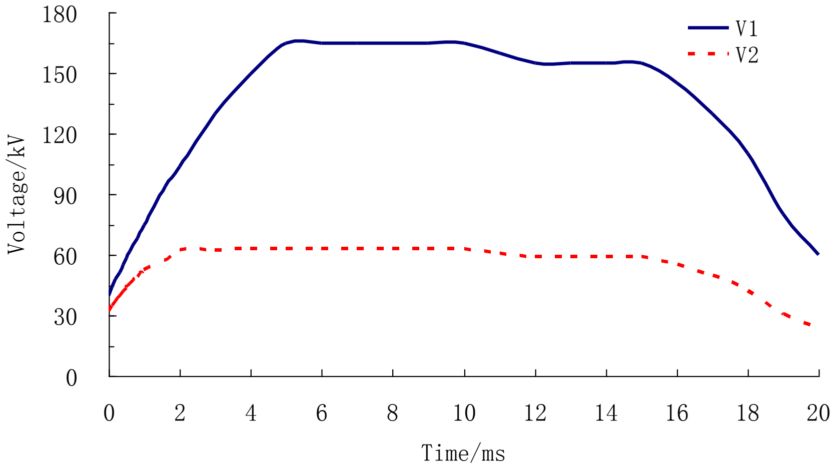
$$\theta = \theta_A$$



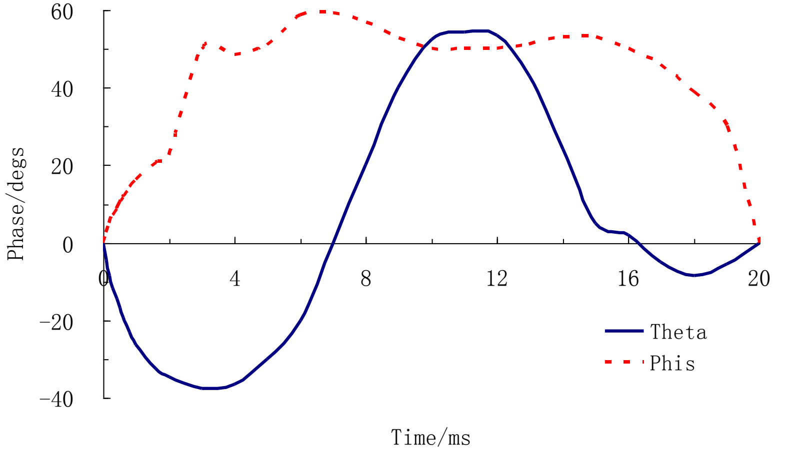
L: Area = 2.6 eVs
R: Area = 2.8 eVs

L: BF = 0.57
R: BF = 0.54

The RF pattern for CSNS-II



Voltages, 3 H4 cavities



0~4 ms, $\theta = \theta_B$

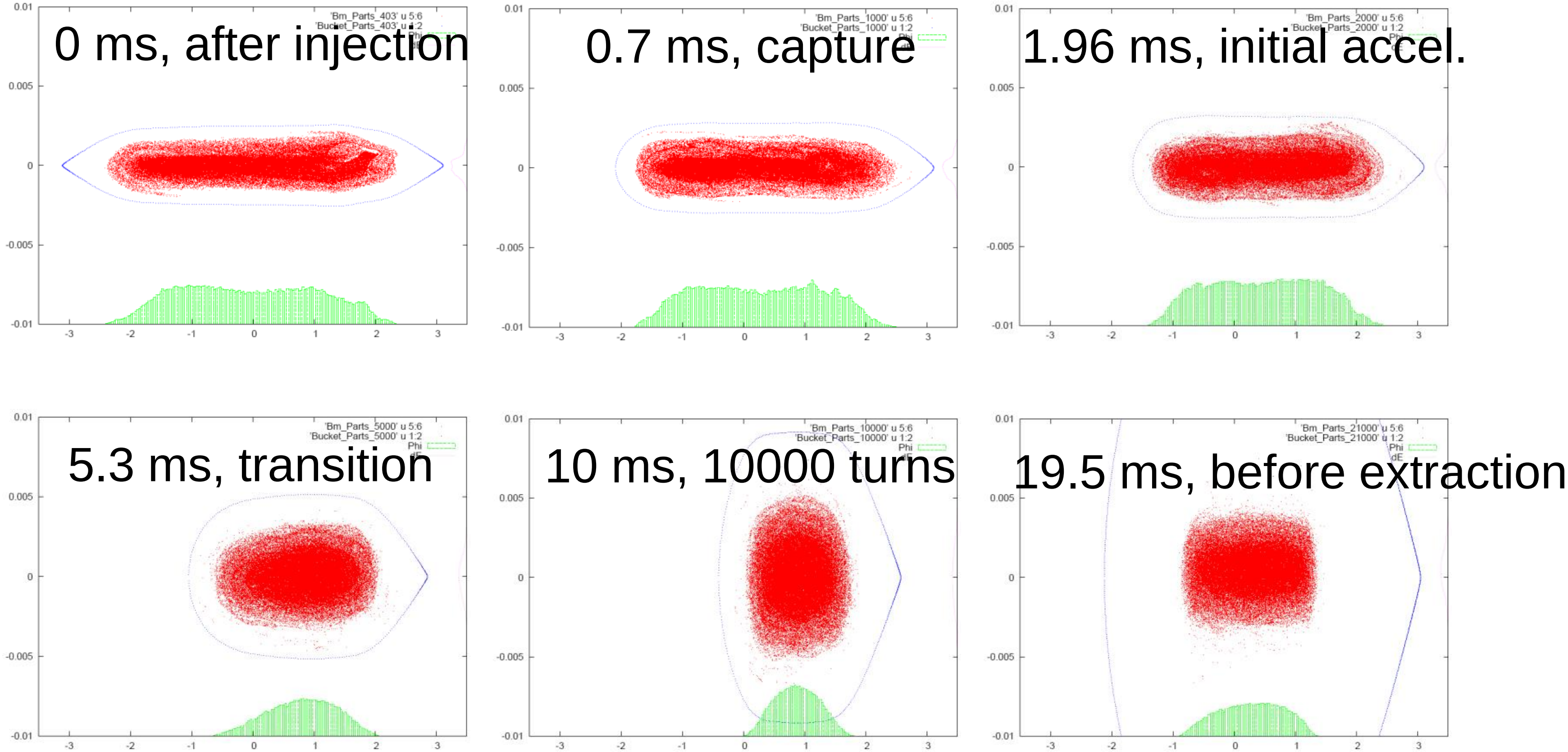
4~9 ms, transitional period

9~20 ms, $\theta = \theta_A$

Magnet-alloy loaded cavities are also considered as a choice of higher harmonic cavities. Acceleration schemes have also been studied, but will not be presented here.

Simulation results by ORBIT

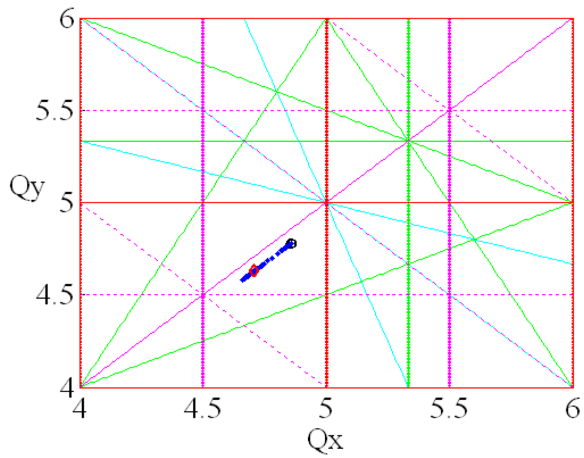
(65% chopping,0.1% off-m)



(No particle loss in longitudinal plane)

Tune shifts contributed by longitudinal space charge

Working-point after injection at CSNS-II



Naked working-point:

Qx/*Qy*= **4.86/4.78**

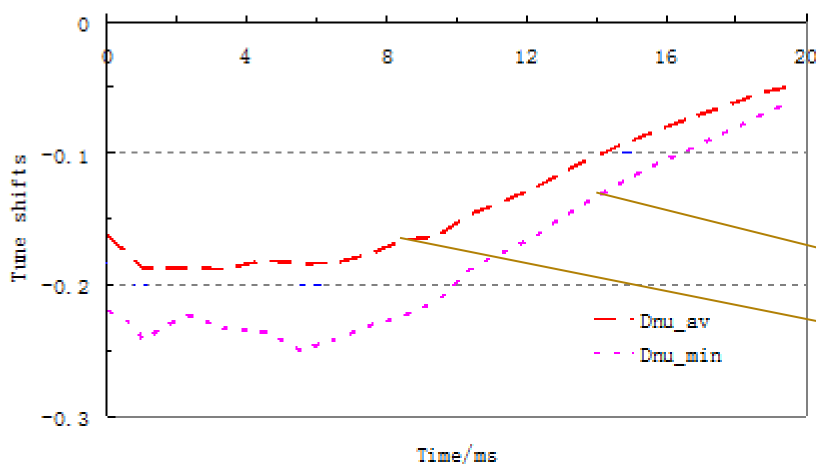
Average shifted tunes:

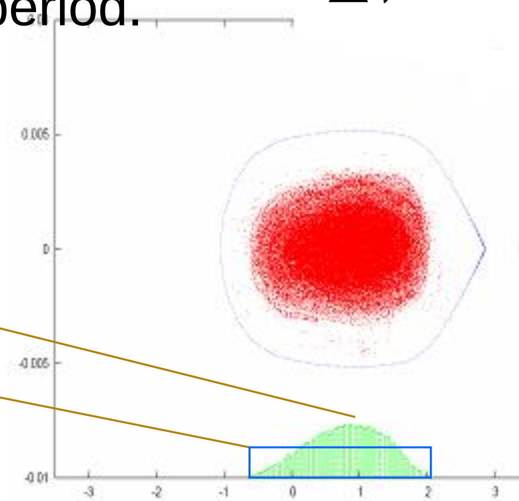
Qx_av = **4.69**

Qy_av = **4.61**

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

Tune shifts in the whole acceleration period.





(ε_{xy}=250 πmm.mrad)

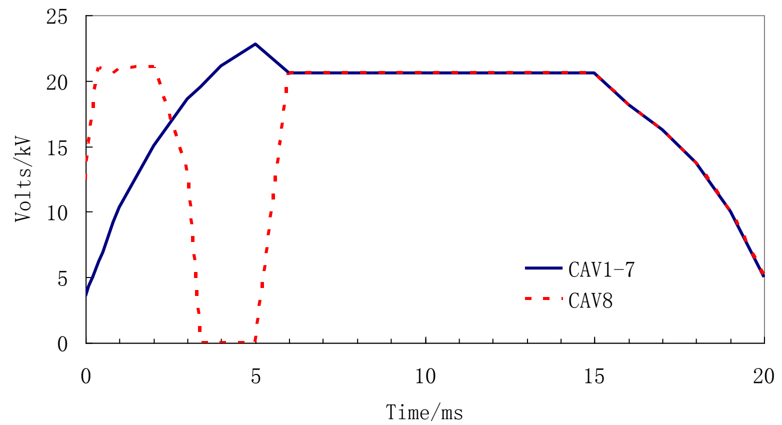
DUAL-HARMONIC ACCELERATION SCHEME FOR CSNS-I

- At CSNS-I/RCS, total 8 ferrite-loaded RF cavities (h=2): 7 cavities has the ability to supply a required maximum voltages of 165 kV already, and 1 spare cavity is reserved in case of single cavity failure.
- 1 spare cavity operated at h=4 before 3.4 ms (frequency limit), and tuned to h=2 after 5 ms.
- Although **only one 2nd harmonic cavity** used, study shows it can provide a considerable improvement in tune shift at low energy stage.

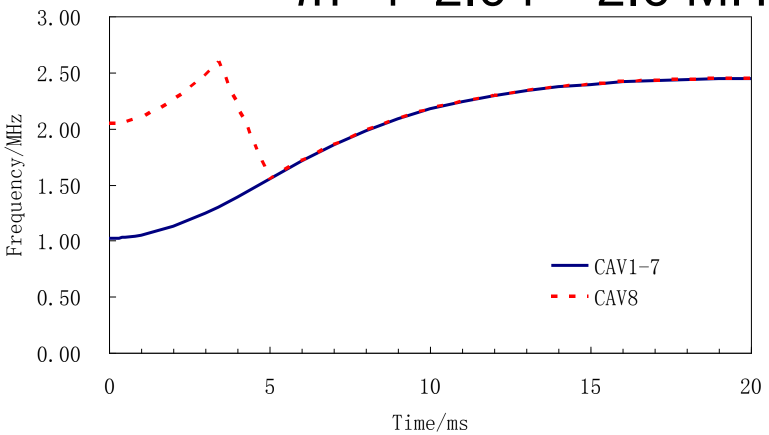
RF pattern for CSNS-I

*f*h=2=1.02 ~ 2.44 MHz

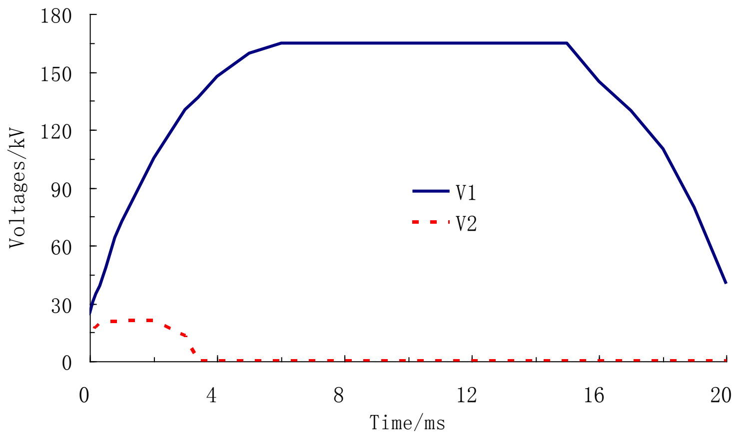
*f*h=4=2.04 ~ 2.6 MHz



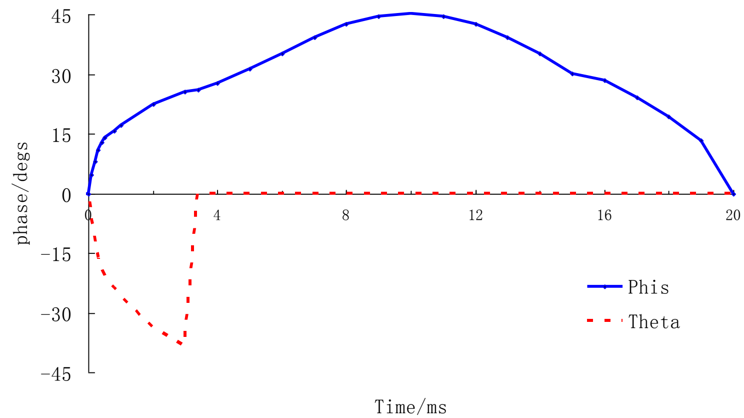
Voltage for each cavity



Frequency for each cavity



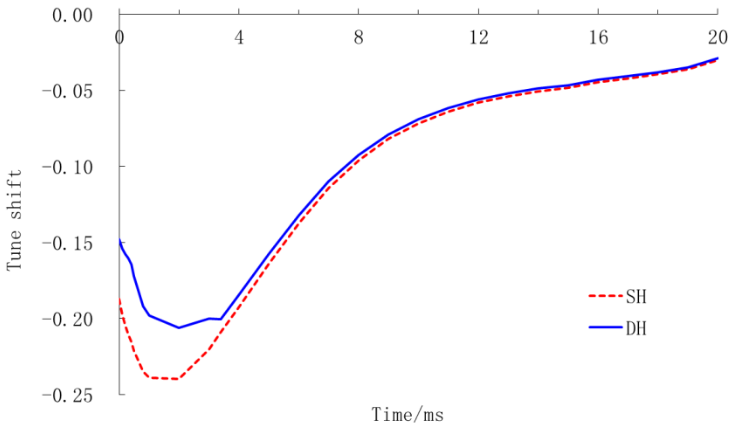
Total RF voltages

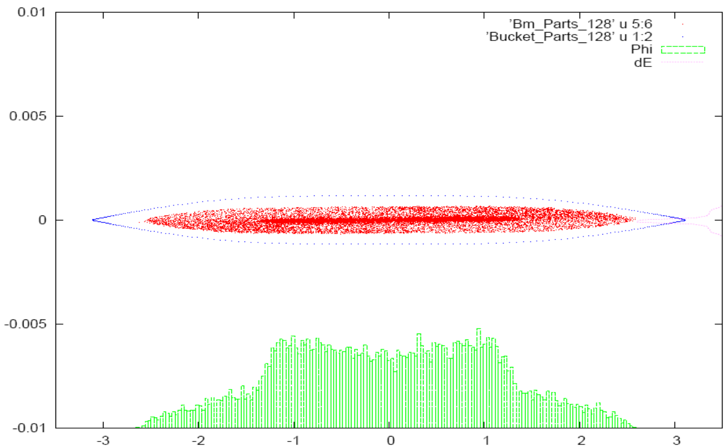


RF phases: $\Phi s, \theta$

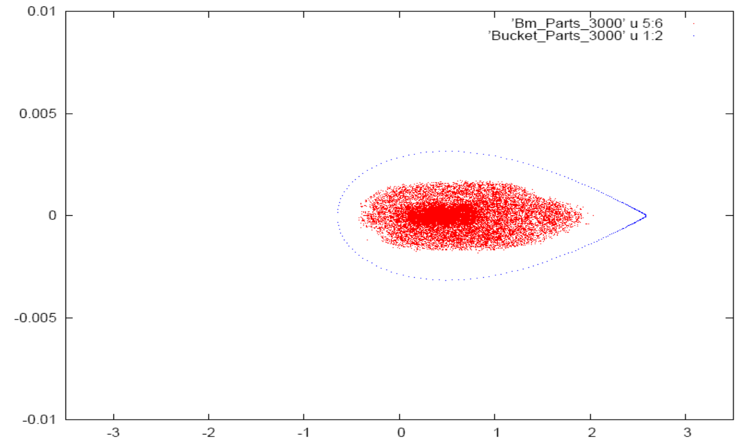
Tune shifts contributed by longitudinal space charge

- Tune shifts are improved after using this partial dual-harmonic acceleration (only before 3.4ms). The minimum tune shift is increased from -0.24 to -0.21.





After injection

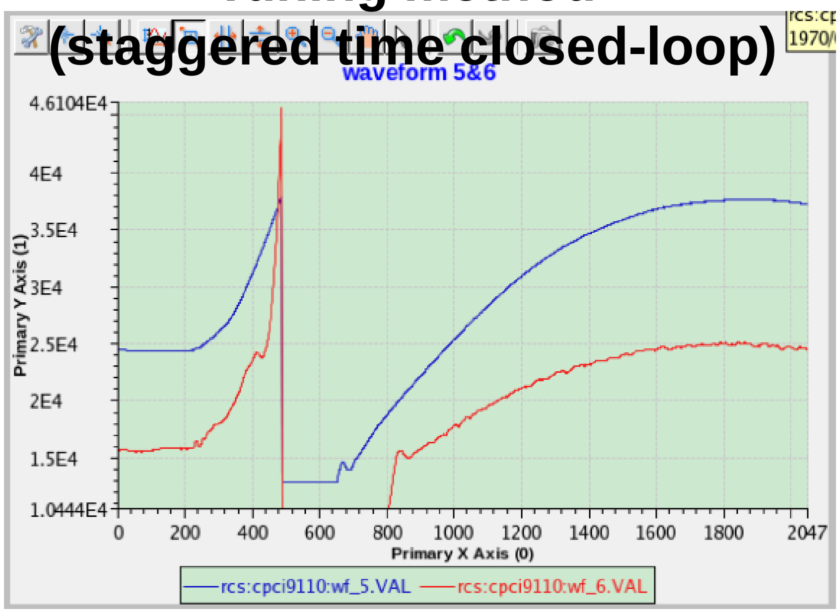


At 4.7 ms

- **Mode-change test** has been doing on the ferrite-cavity prototype for CSNS-I in IHEP. The primary results show that the tuning and voltages of CAV8 are transformed successfully after using staggered time of two steps tuning loop.

Ferrite-cavity prototype for CSNS-I

Tuning method (staggered time closed-loop)



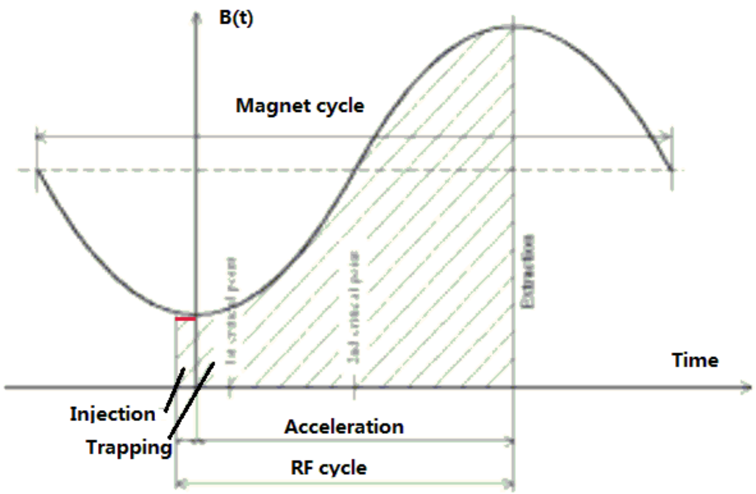
RF waveform

(Pictures offered by S.R. Shen)

STATIONARY-INJECTION METHOD

- **In the RCS ring, a stable bunch shape is expected after injection. Generally, the RF frequency and phase are bound with the main magnet field to keep synchronization, which leads to bucket changing during the injection with the main magnet ramping. For this reason, the injected beam seems irregular in the bucket, especially with off-momentum injection.**

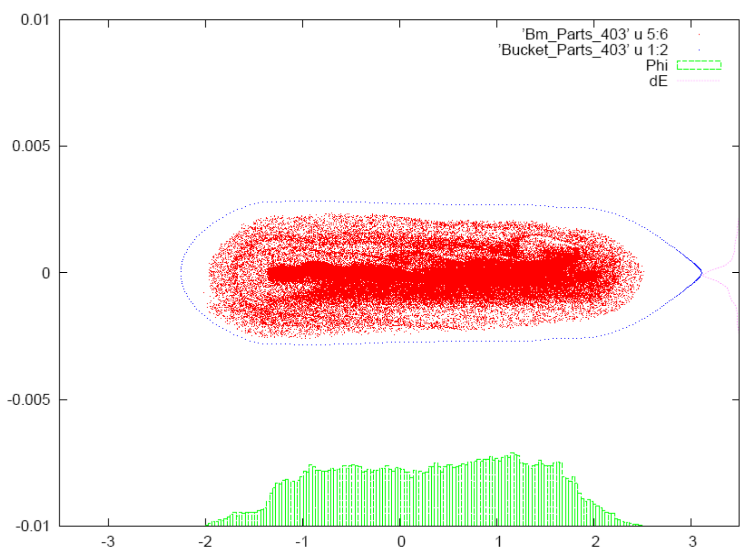
- Here, a method called stationary-injection, which desynchronizes the RF with main magnet field during the injection time and binds them again after injection. (The bucket is stationary during the injection. It has been added in the ORBIT code, with a new parameter — **bindTime**.)



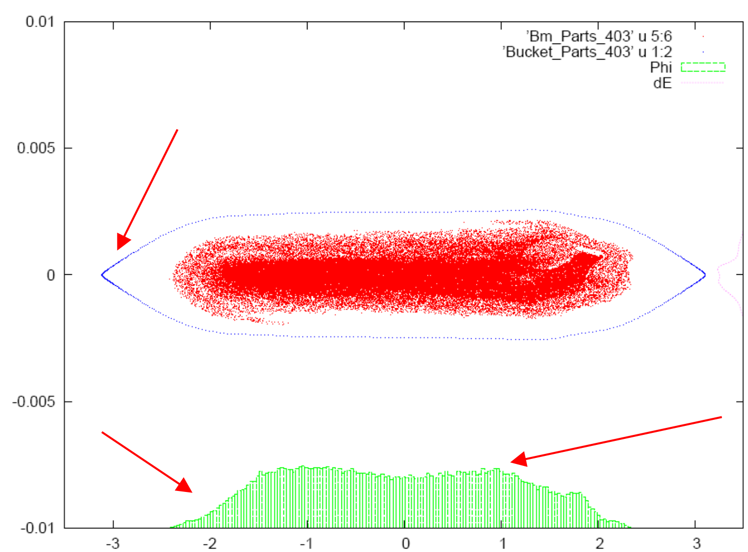
A case of using Stationary-injection method

- **Beam distribution in longitudinal plane**

Advantages: no bucket shrinking, longer-flatter bunch



Usual injection method



Stationary-injection method

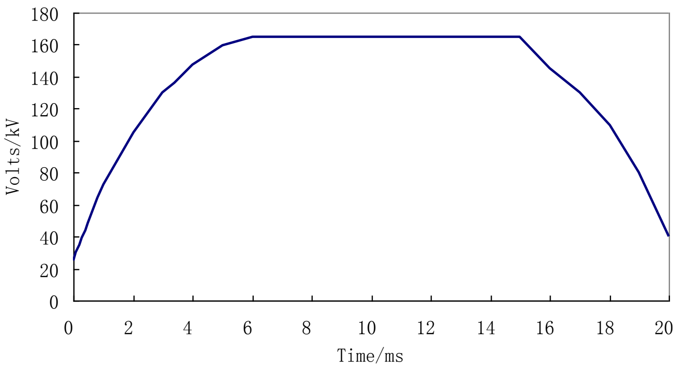
- **Using this method, the simulation results show that a more uniform and longer bunch can be obtained after injection.**

Flat bucket and bunch formed by SH RF and SC

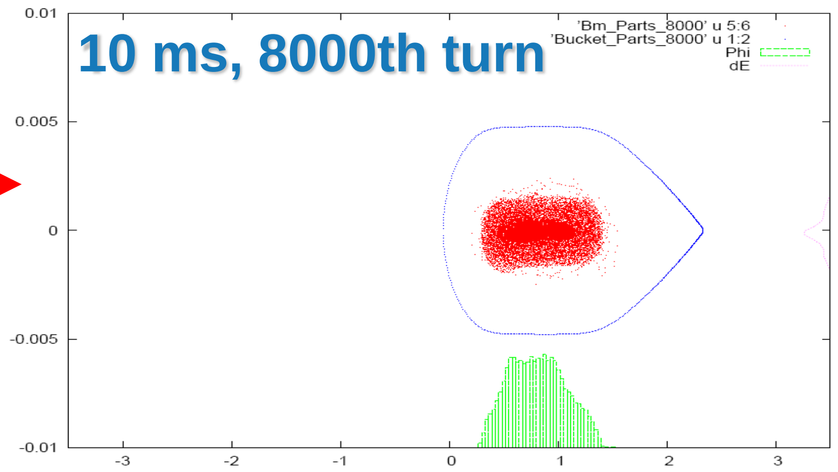
- **Phenomenon**

When longitudinal SC effect is strong, we find that a flat or quasi-flat bunch and bucket may be obtained with only single harmonic RF.

$$V(\phi) = V_1 \sin(\phi)$$



Single-harmonic RF



Flat bucket and bunch (CSNS-I, ORBIT simulation result)

Reasoning

- Defocusing effect of space charge will lower bucket height in longitudinal phase space.
- A model with 'Hofmann-Pedersen' elliptical distribution

Total voltage: $$V_t(\phi) = \begin{cases} V(\phi) - 2\pi h^2 I_b \operatorname{Im}\{Z_e/n\} \dfrac{V(\phi)-V_0}{u(\phi_1,\phi_2)}, \phi_1 < \phi < \phi_2 \\ V(\phi), elsewhere \end{cases}$$

Potential shape: $$U_t(\phi) = \begin{cases} \underline{(1 - I_b/I_{bm})} U(\phi), \phi_{p1} < \phi < \phi_{p2} \\ U(\phi), elsewhere \end{cases}$$

where $I_b = eN_b\omega_0 / 2\pi$ denotes average current of bunch

$$I_{bm} = \frac{u(\phi_{p1}, \phi_{p2})}{2\pi h^2 \operatorname{Im}\{Z_e/n\}}$$

Model case-1: convex

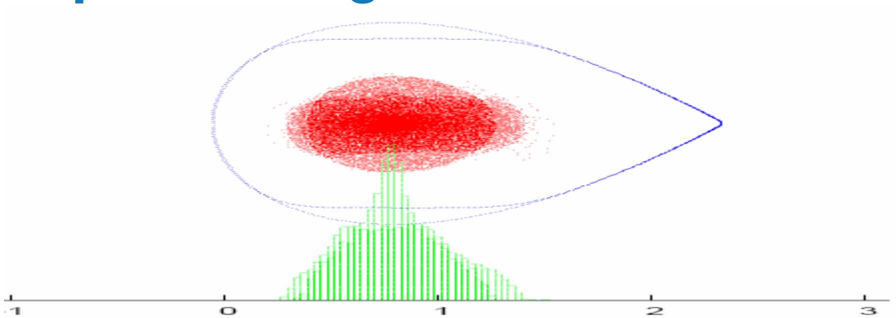
For CSNS-I:

Nb=0.78e+13

8000th turn, 10 ms

$$I_b / I_{bm} = 0.5103$$

Simulations with and without space charge



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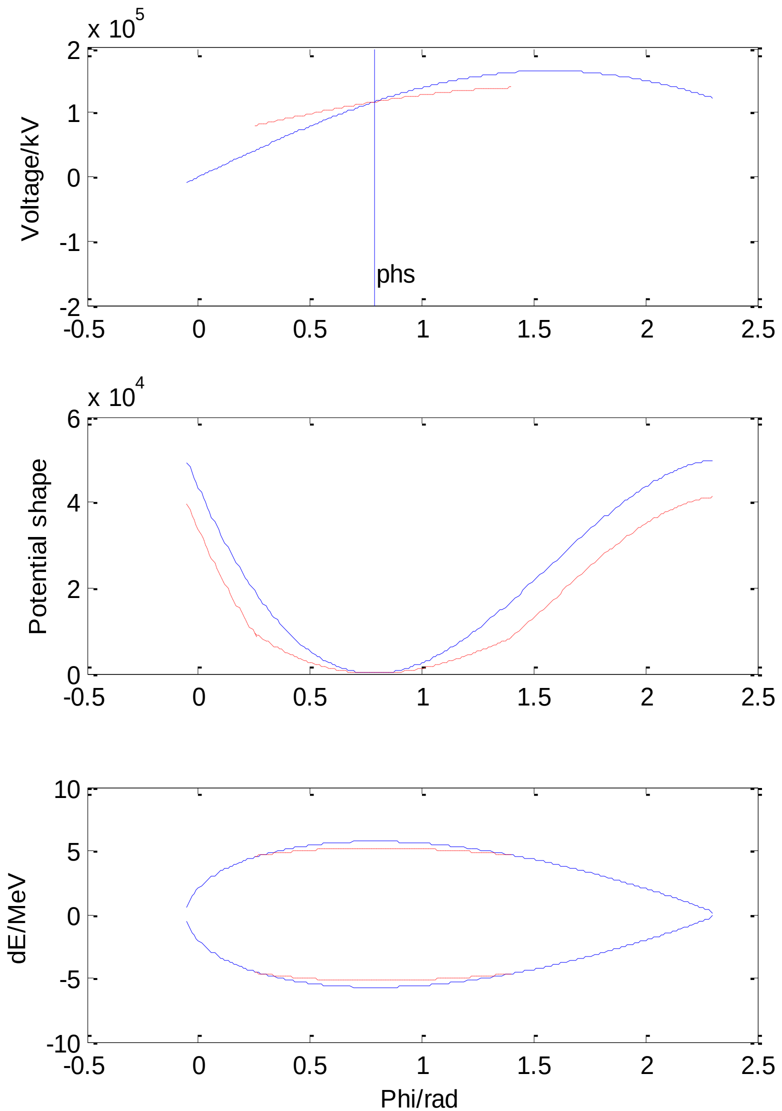


(Model)

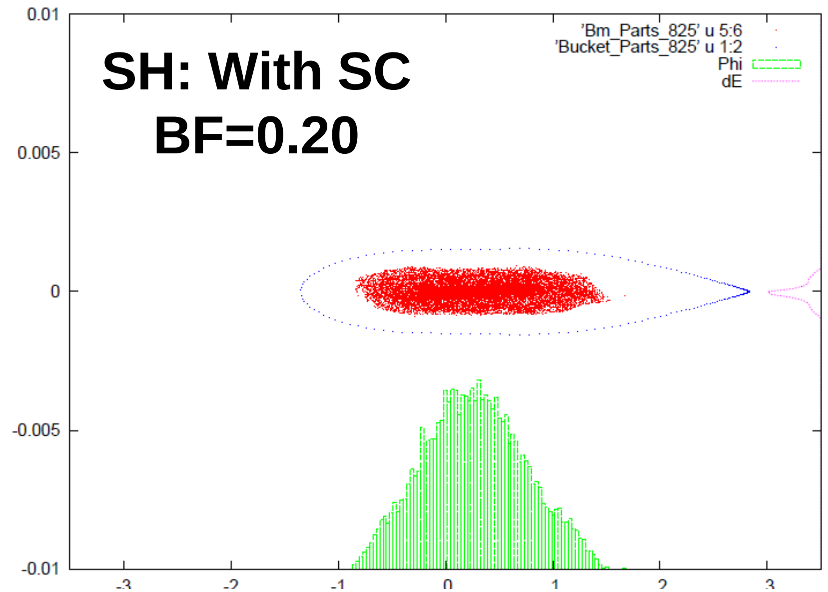
SC is helpful?

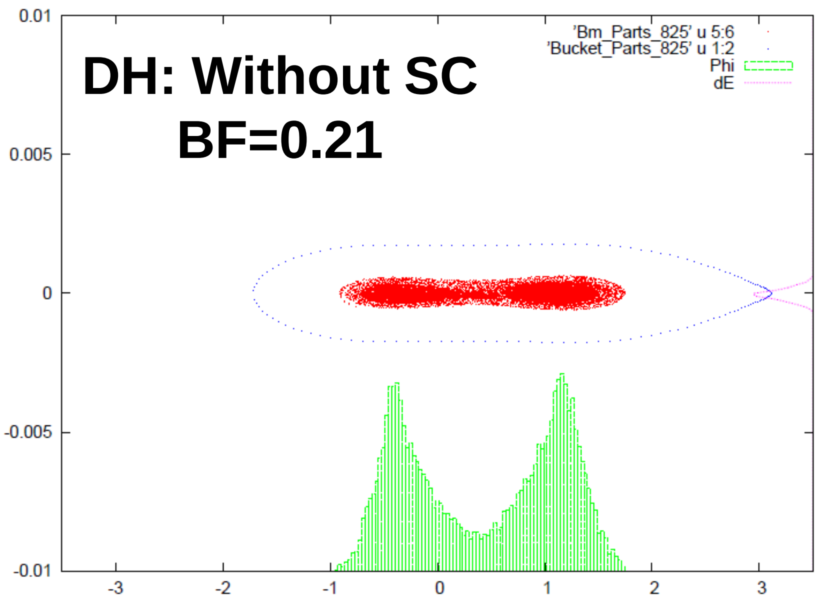
- **For CSNS-I, at low energy stage:**

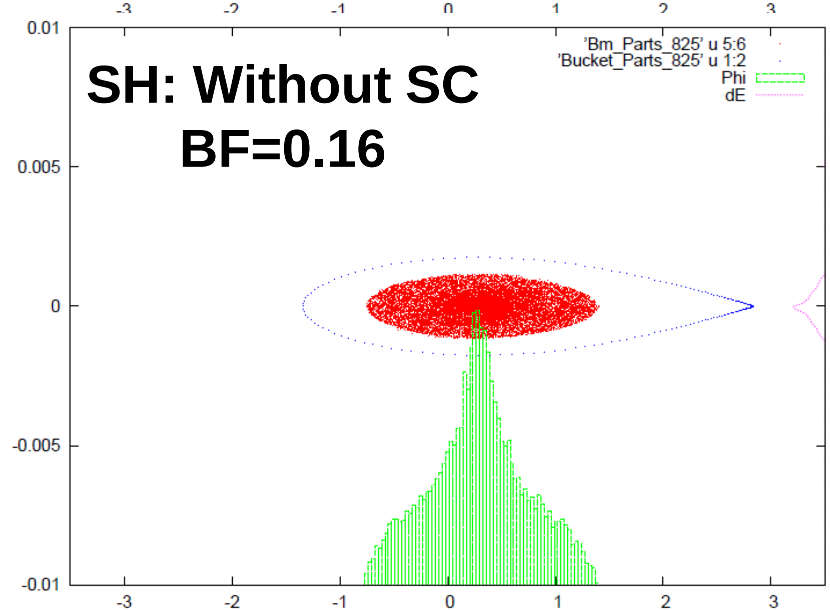
(Injection with 50% chopping)

Nb=0.78e+13

825th turn, 1.2 ms





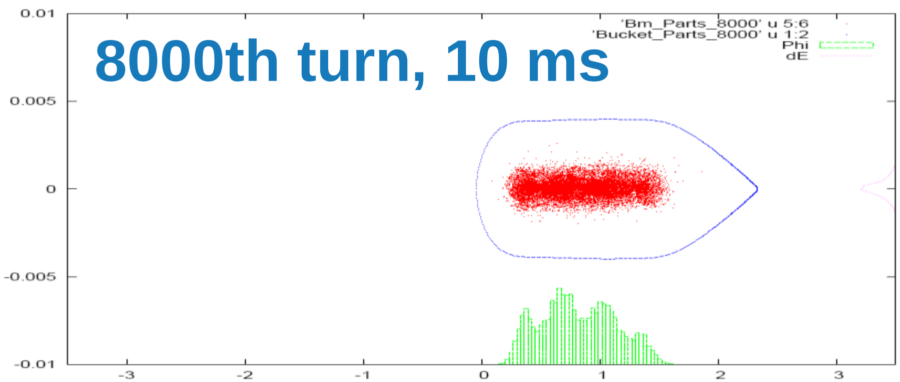


Model case-2: flat

- **Flat**

In CSNS-I, if Nb=1.64e+13;

$$I_b / I_{bm} = 1.0$$



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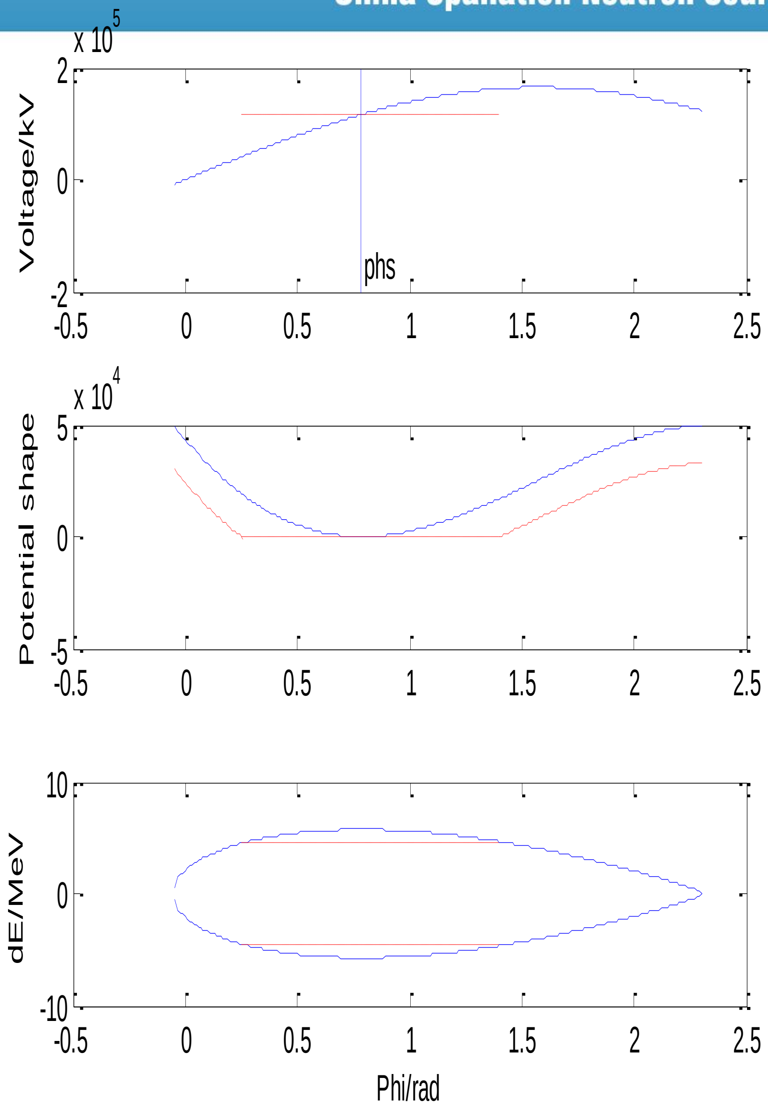


(Model)

SUMMARY

- **Longitudinal space charge (LSC) effect** is a key point in CSNS/RCS, especially in CSNS-II.
- **Dual-harmonic acceleration schemes** are designed for CSNS-II (500 kW) and CSNS-I (100 kW) to alleviate the LSC effect. Simulation results show that the tune shifts are reduced considerably.
- **The stationary-injection method** is found useful to obtain a good longitudinal painting during injection.
- **Flat bucket and bunch may be formed** by only single harmonic RF and the space charge. Whether it has some application?

Thank you for your attention!

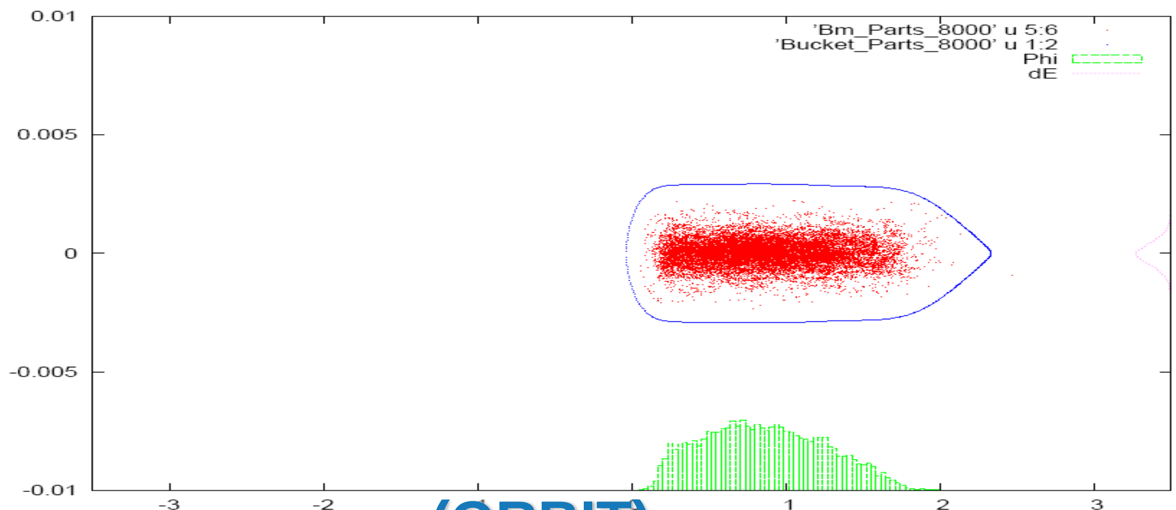
Model case-3: concave

- Concave

In CSNS-I , assume Nb= 2.84e+13;

at 8000th turn, 10 ms

$$I_b / I_{bm} = 1.7$$



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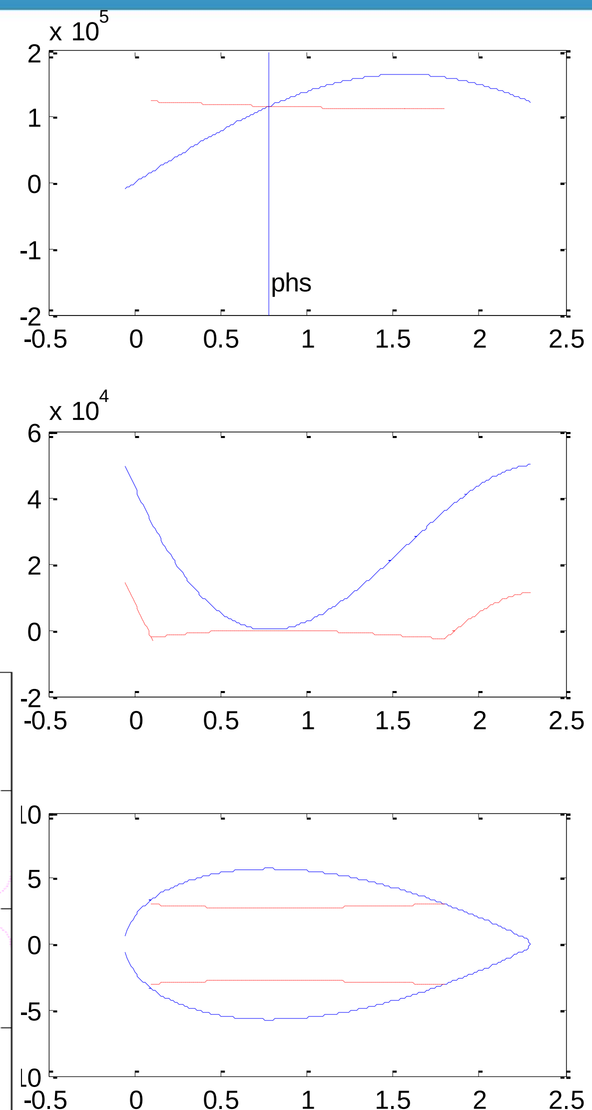

(Model)