



DUAL-HARMONIC ACCELERATION STUDIES AT CSNS RCS

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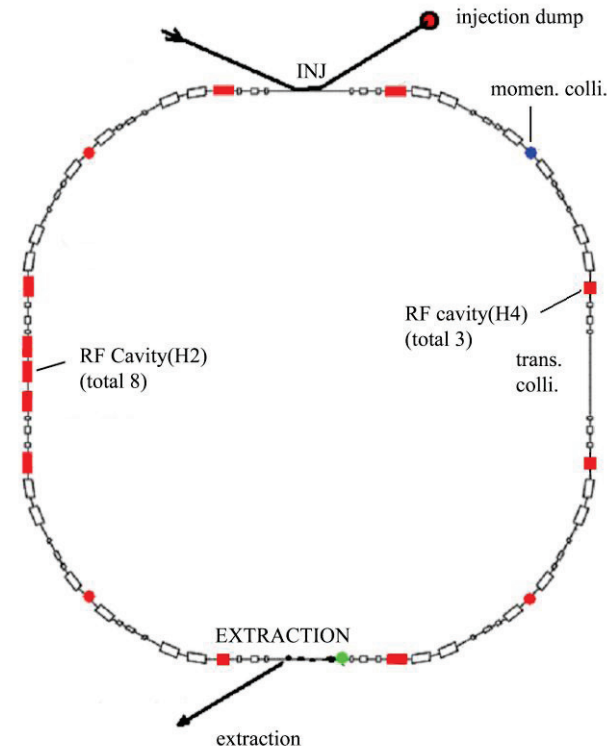
OUTLINE

- Basic parameters of CSNS/RCS
- Dual-harmonic acceleration scheme for CSNS-II
- Dual-harmonic acceleration scheme for CSNS-I
- Stationary-injection method
- 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



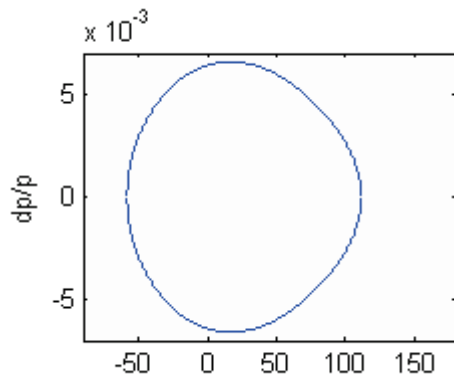
- At CSNS-II, the output energy of linac is enhanced from 80 MeV to 250 MeV and a dual-harmonic RF system in the RCS is applied.
- Spaces reserved for the 2nd harmonic cavities (H4) in the ring.

DUAL-HARMONIC ACCELERATION SCHEME FOR CSNS-II

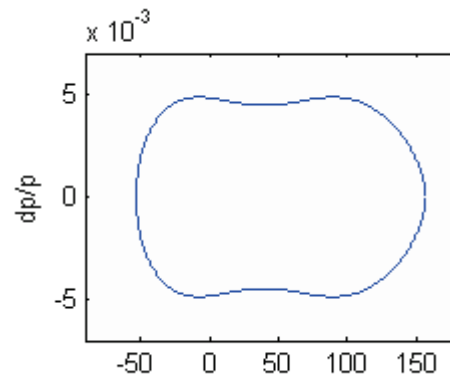
- Tune shift should be controlled more strictly at CSNS-II due to lower beam loss rate.
- Laslett tune shift (measure the space charge)

$$\Delta \nu = - \frac{\overset{\uparrow}{r_p} \overset{\uparrow}{n_t}}{\underset{\uparrow}{2\pi\beta^2} \underset{\uparrow}{\gamma^3} \epsilon B_f}$$

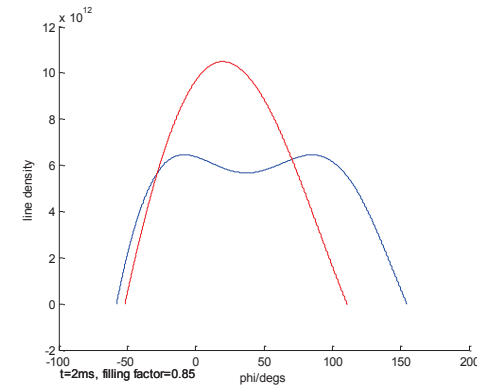
- Dual-harmonic acceleration method is used to increase bunching factor



Single-harmonic



Dual-harmonic



Line-densities
(red-SH, blue-DH)



Dual-harmonic acceleration

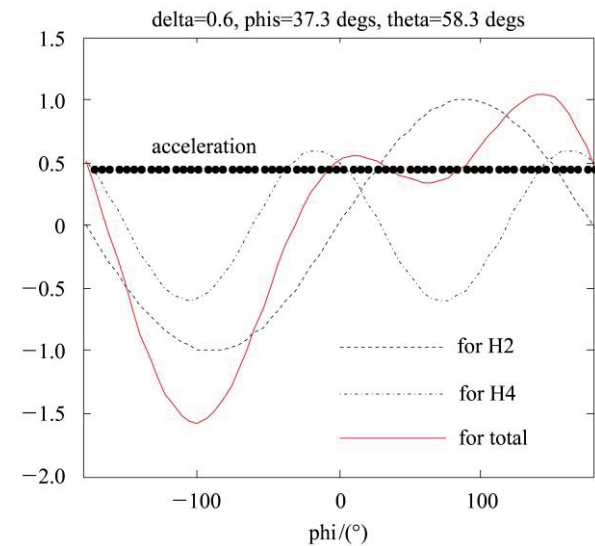
○ Dual-harmonic RF:

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

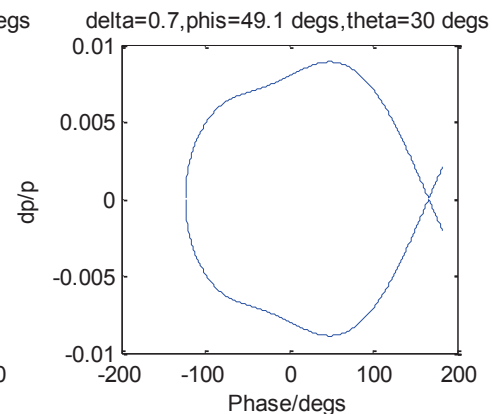
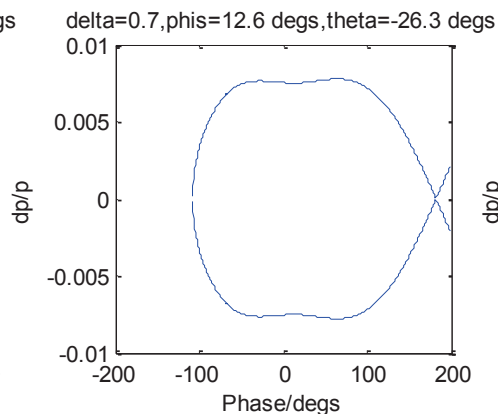
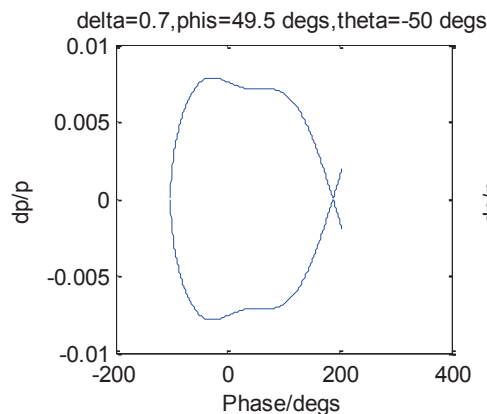
1st

2nd

- Bucket shapes decided by combinations of δ (V_2/V_1), ϕ_s and θ



Voltage waveforms for DH

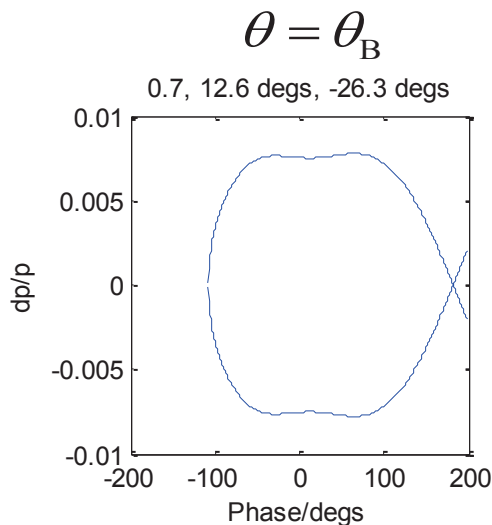


θ modes for CSNS-II

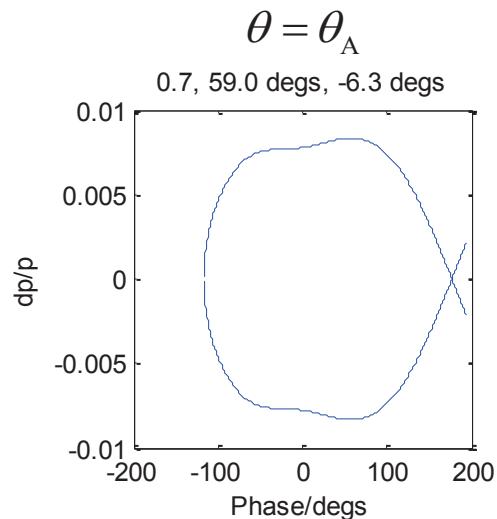
Two typical modes: $\theta = \theta_B$ (largest **b**unching factor)
 $\theta = \theta_A$ (largest bucket **a**rea)

Examples:

At 1ms, buckets

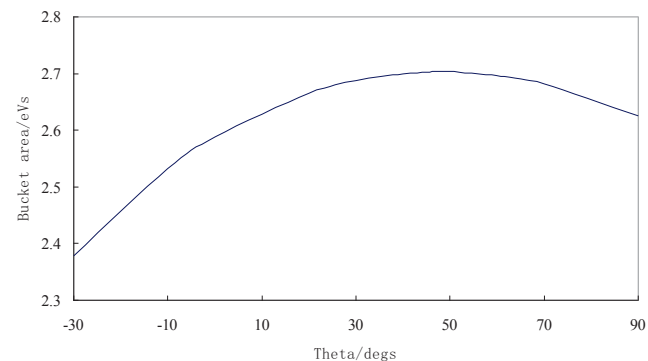


Area = 2.6 eVs
BF = 0.57



Area = 2.8 eVs
BF = 0.54

At 8ms



Bucket area reaches maximum
at a certain θ ($\sim 50^\circ$)

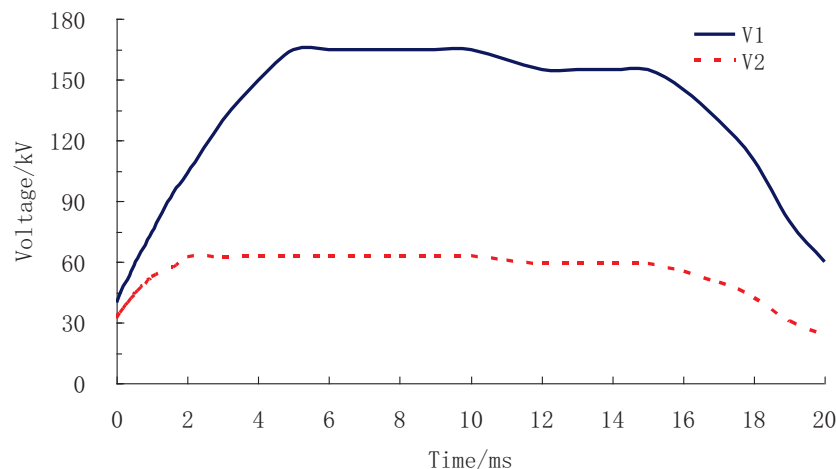


The RF pattern for CSNS-II (designed by self-made code — RAMADH)

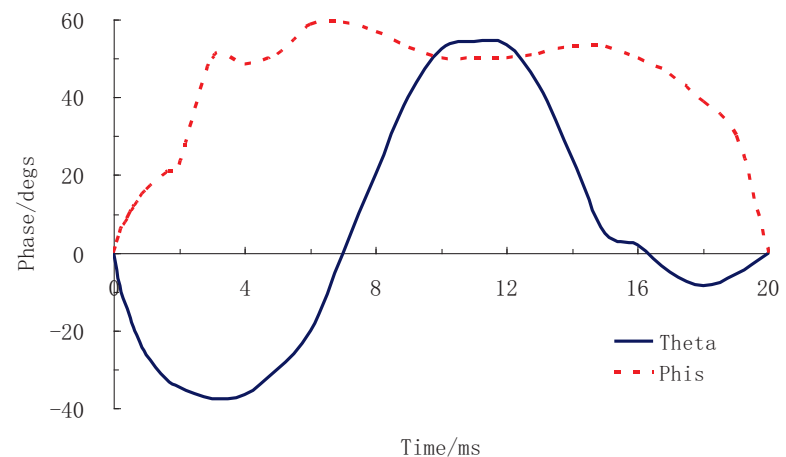
- At low energy stage, where the tune shifts are large, dual-harmonic RF is designed to supply the largest bunching factor
- At middle and high energy stage, where the space charge are no longer strong, dual-harmonic RF is designed to supply the largest bucket area.

Advantages:

- relieve the bucket shrink due to high accelerating rate at about 10 ms
- Reduce the RF voltages but keep the same bucket area at high energy stage



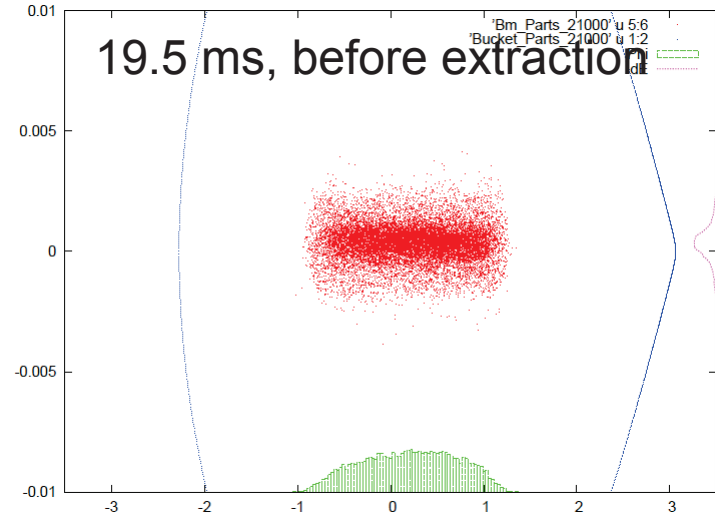
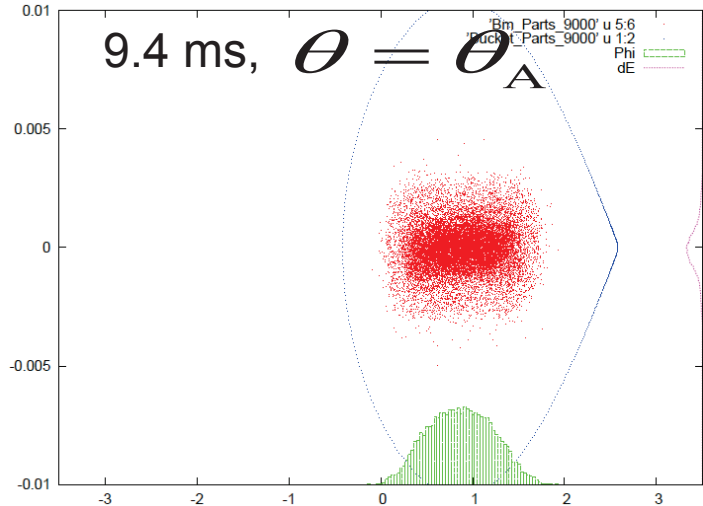
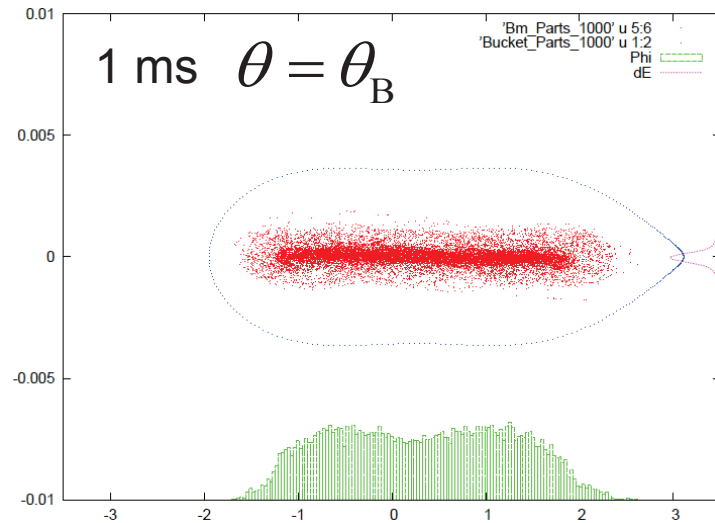
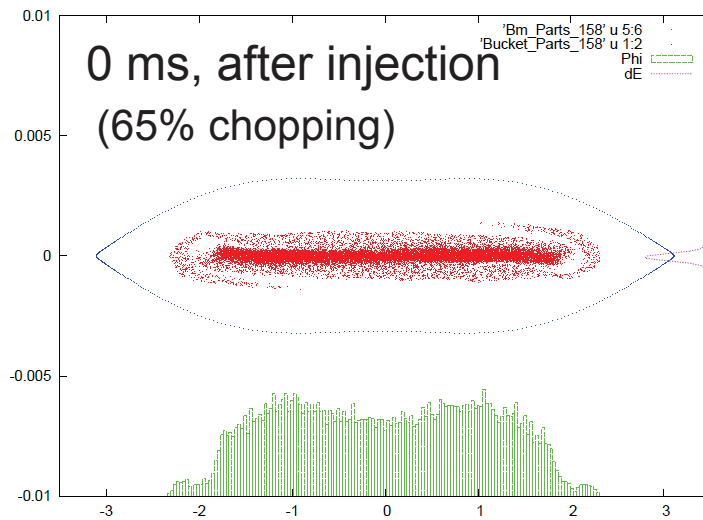
Voltages, 3 H4 cavities



0~4 ms, $\theta = \theta_B$
4~9 ms, transitional time
9~20 ms, $\theta = \theta_A$



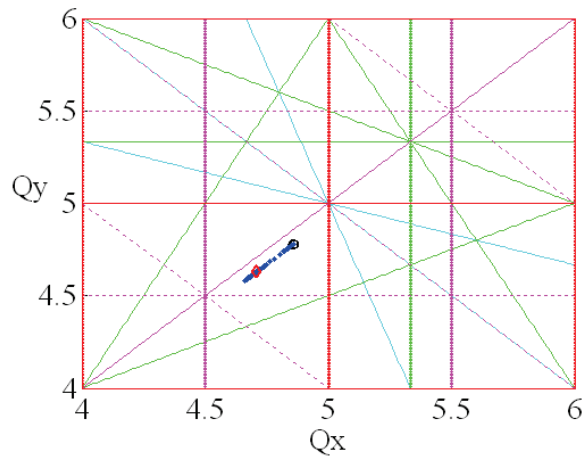
Simulation results by ORBIT



(No particle loss in longitudinal plane)



Tune shifts contributed by longitudinal space charge



Working-point after injection

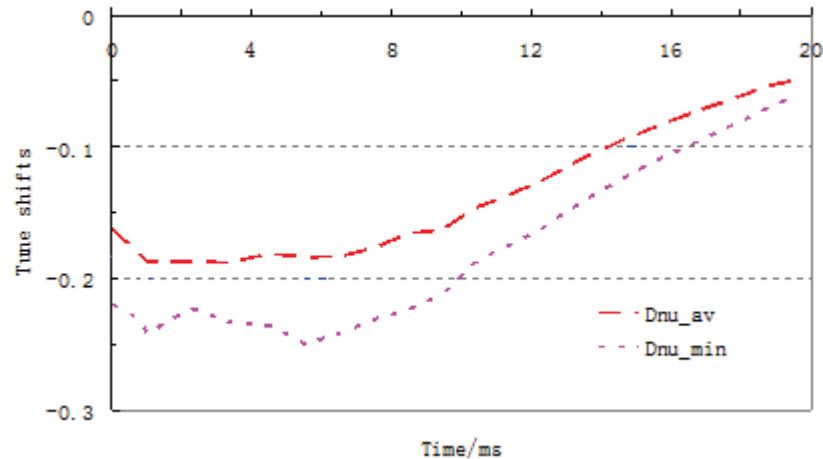
Naked working-point:

$Q_x/Q_y = 4.86/4.78$

Average shifted tunes:

$Q_{x_av} = 4.69$

$Q_{y_av} = 4.61$



Tune shifts in the whole acceleration period.

Red line: average tune shifts (all in -0.2)

Pink line: minimum tune shifts,

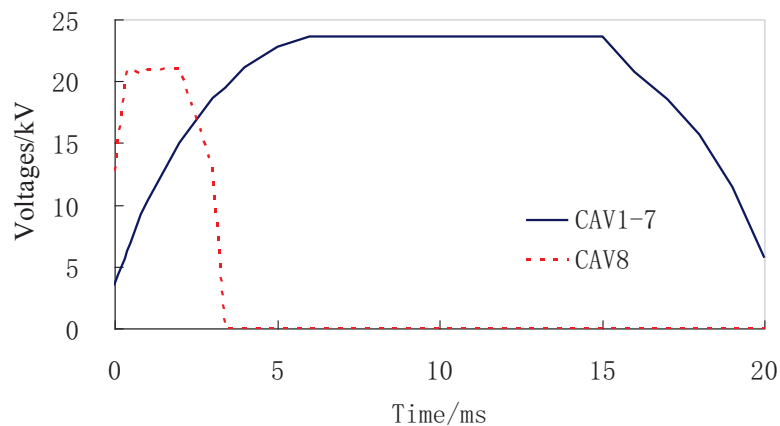
It is an analytical result. We cut the bunch into slices, and calculate the tune shift of each slice. From this, we can find the line density information along the bunch.

DUAL-HARMONIC ACCELERATION SCHEME FOR CSNS-I

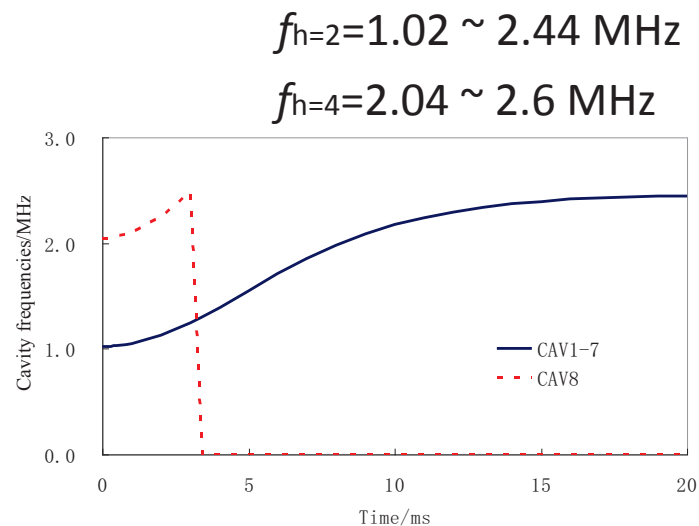
- At CSNS-I, 8 ferrite-loaded RF cavities ($h=2$) are installed in the RCS ring. However, 7 cavities has the ability to supply a maximum voltages of 165 kV already, and 1 spare cavity is reserved in case of single cavity failure.
- Therefore, we think, the spare cavity may be used as the second harmonic cavity before reaching its largest frequency limit. In the initial time, we can use a dual-harmonic RF system, which consists of the 7 fundamental cavities and the 1 spare cavity working on the 2nd harmonic, $h=4$.
- Although only one 2nd harmonic cavity used, study shows it can provide a considerable improvement in tune shift at low energy stage.



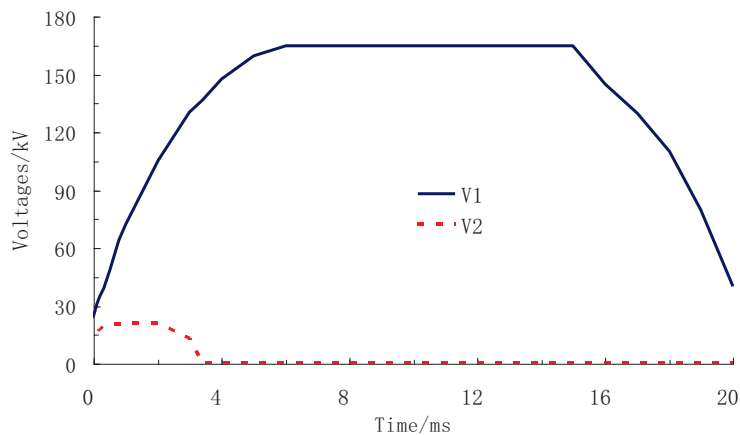
RF pattern for CSNS-I



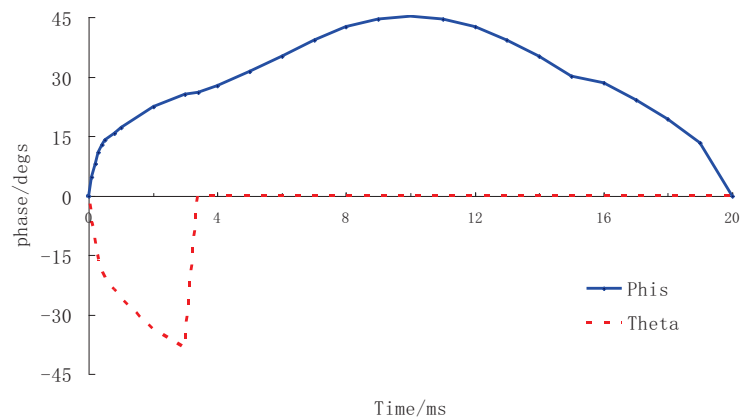
Voltage for each cavity



Frequency for each cavity



Total RF voltages

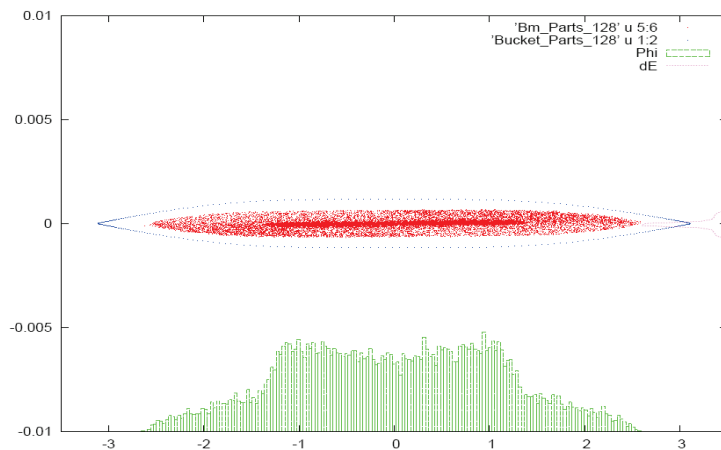
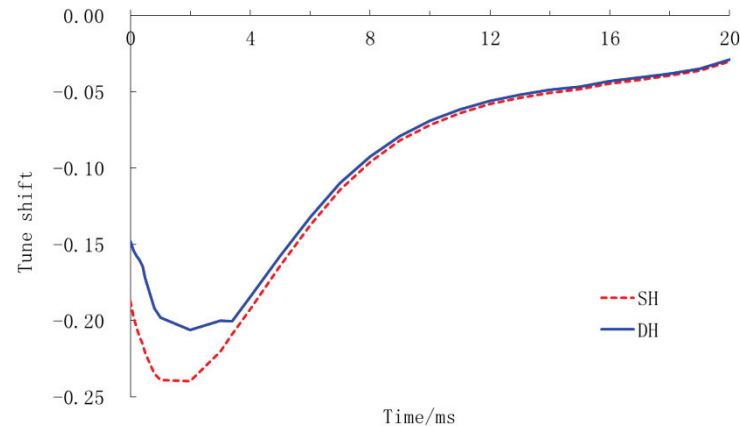


RF phases: ϕ_s, θ

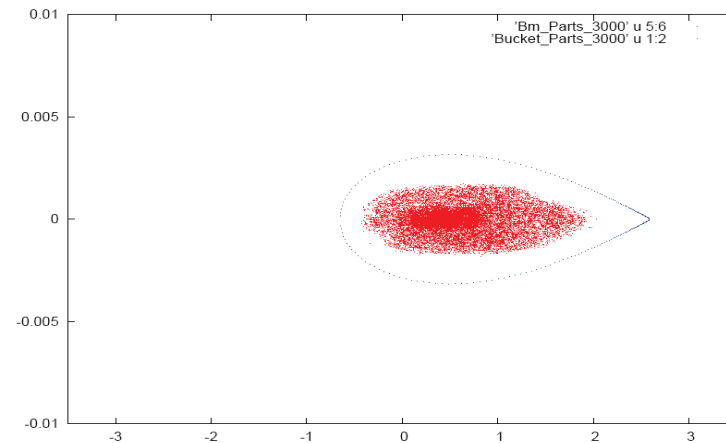


Tune shifts contributed by longitudinal space charge

- 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

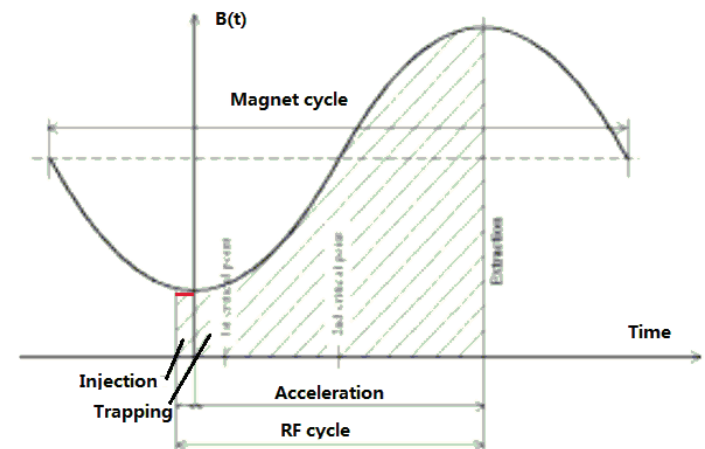


At 4.7 ms



STATIONARY-INJECTION METHOD

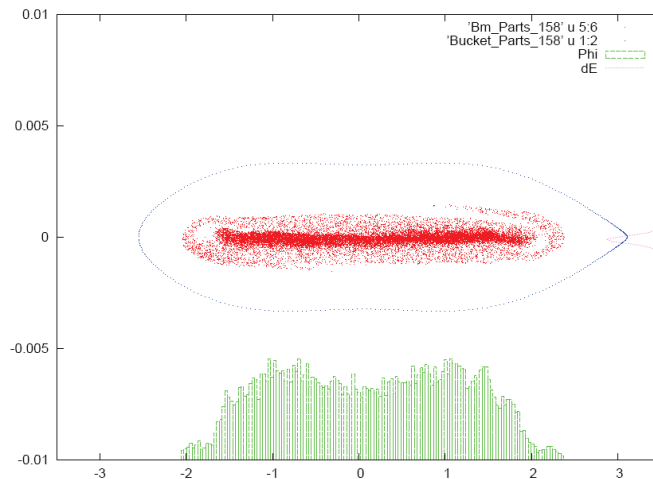
- In the RCS ring, a stable bunch shape is expected after injection. **Generally**, the RF frequency and phase are locked with the main magnet field to keep synchronous, which leads to bucket-shrink during the injection with the main magnet ramping. For this reason, the injected beam seems irregular in the bucket, especially with off-momentum injection.
- Here, a method called stationary-injection, which **unlocks the RF with main magnet field** during the injection time and locks them again after injection. (The bucket is stationary during the injection. It has been added in the ORBIT code, with a new parameter — **bindTime**.)
- Using this method, the simulation results show that a uniform and long bunch is obtained after injection.



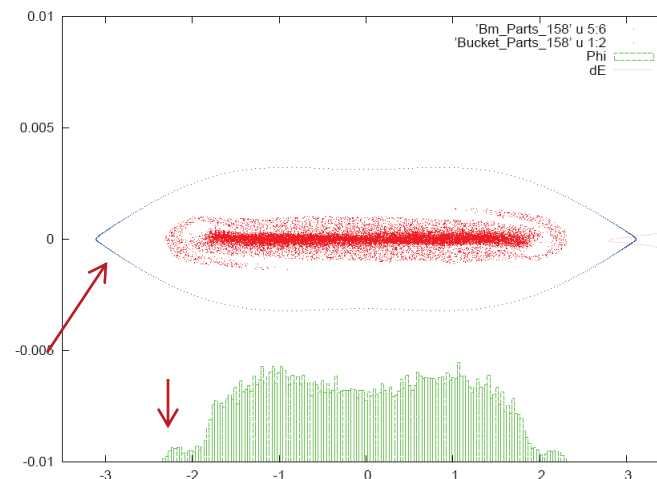
A case of using Stationary-injection method

- Beam distribution in longitudinal plane

Advantages: no bucket shrink, longer-flatter bunch



General injection



Stationary-injection

(Thanks for the use of ORBIT from SNS AP group.)



SUMMARY

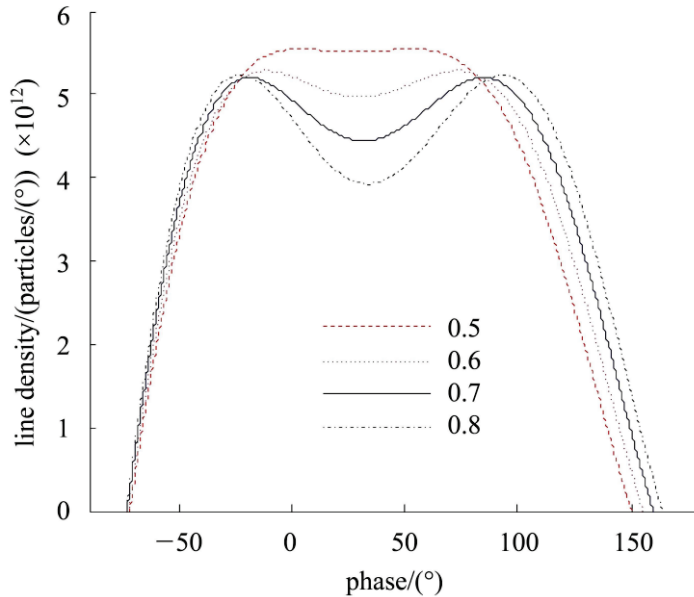
- Dual-harmonic acceleration schemes are designed for CSNS-II (500 kW) and CSNS-I (100 kW). Simulation results show that the tune shifts are improved considerably.
- A special ϑ pattern is designed for CSNS-II, which supply the largest bunching factor at low energy stage and the largest bucket area at middle and high energy stages.
- The stationary-injection method is found useful to obtain a good longitudinal painting after injection.



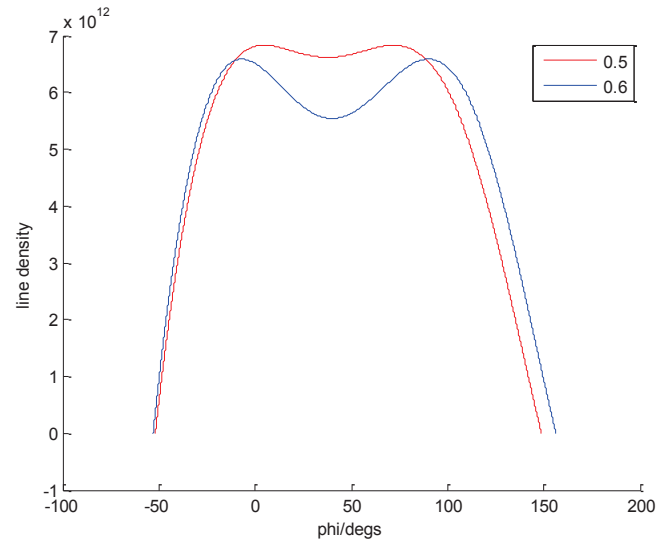
Thanks for your attention!



More figures



At 1 ms, different δ

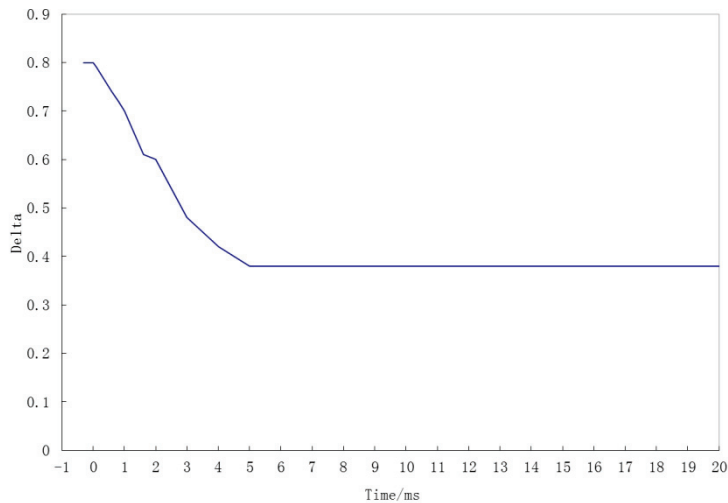


At 2 ms, different δ

Stages	Chopping factor	Off-momentum	Injection time (ms)
CSNS-II	65%	0	-0.2 ~ 0
CSNS-I	80%	0	-0.3 ~ 0

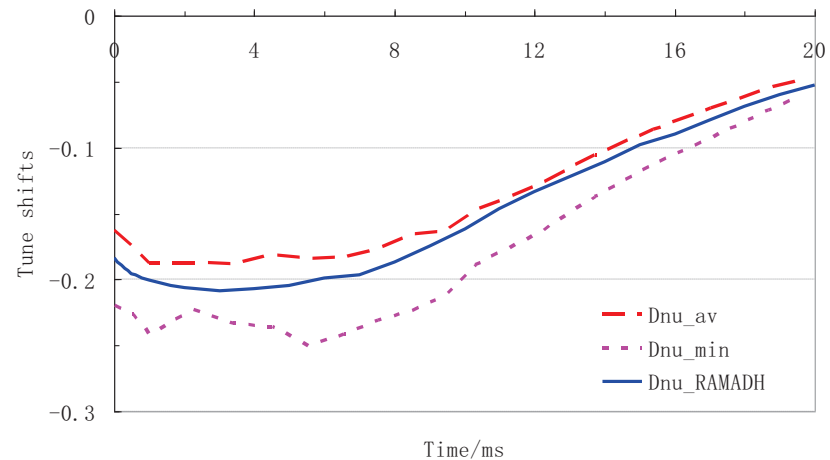
Injection parameters





V2/V1

CSNS-II



Red and pink lines are the average and minimum

tune shifts respectively, which present the line density along the bunch (from ORBIT).

It is an analytical result, which cuts bunch into slices.

Blue line is a theory result calculated by RAMADH;