Design and experimental study of the fast & high-intensity bunch merging on CSNS RCS

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on behalf of the bunch merging team of CSNS

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MuCol annual meeting 2025

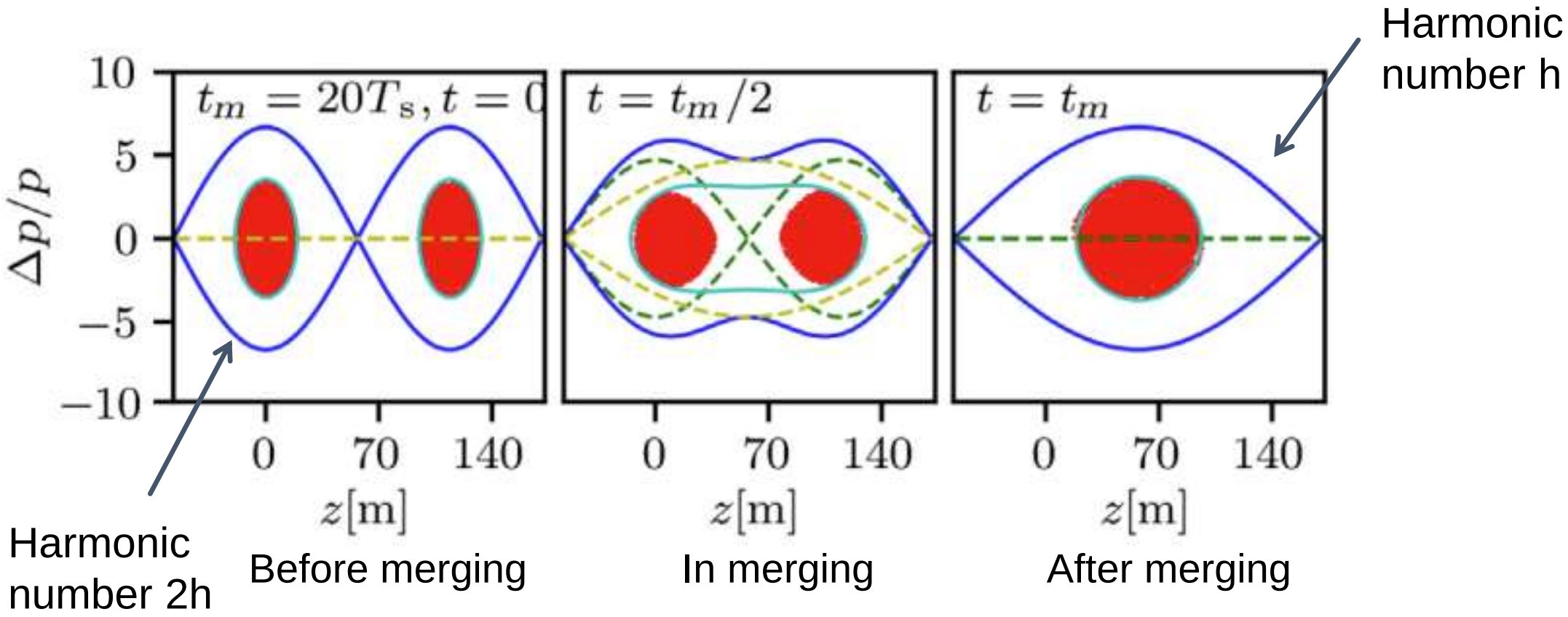
12th-16th May 2025 @ Hamburg.Germany

OUTLINE

1. Fundamentals of bunch merging
2. Design of high-intensity single-bunch mode operation
3. High-intensity effect in bunch merging
4. Experimental results of bunch merging on CSNS

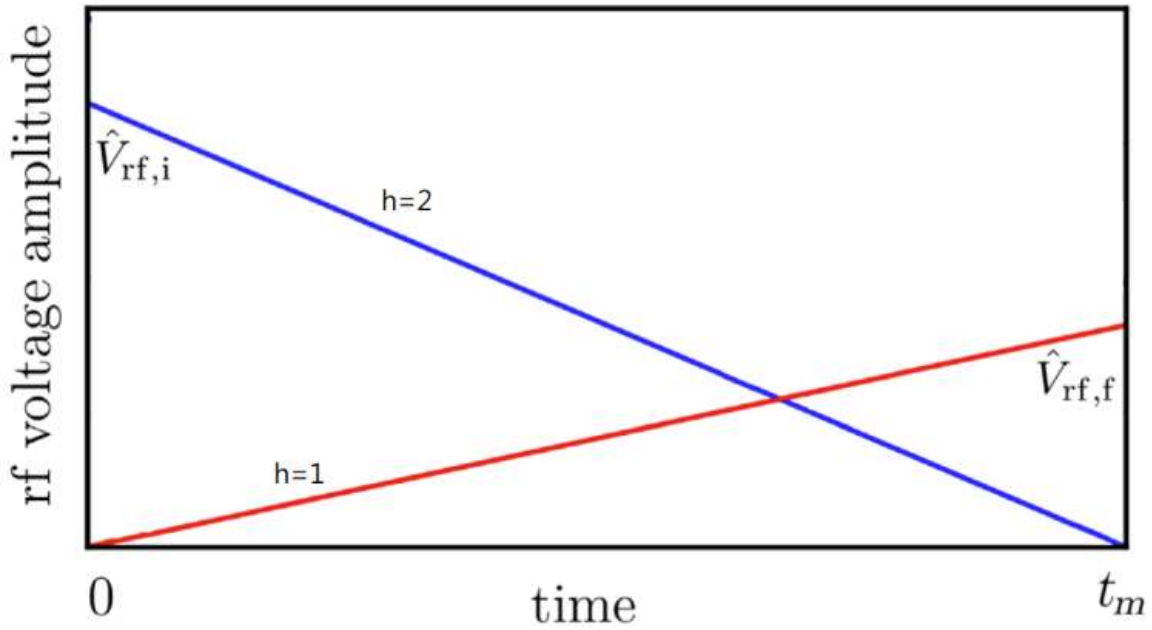
Fundamentals of bunch merging

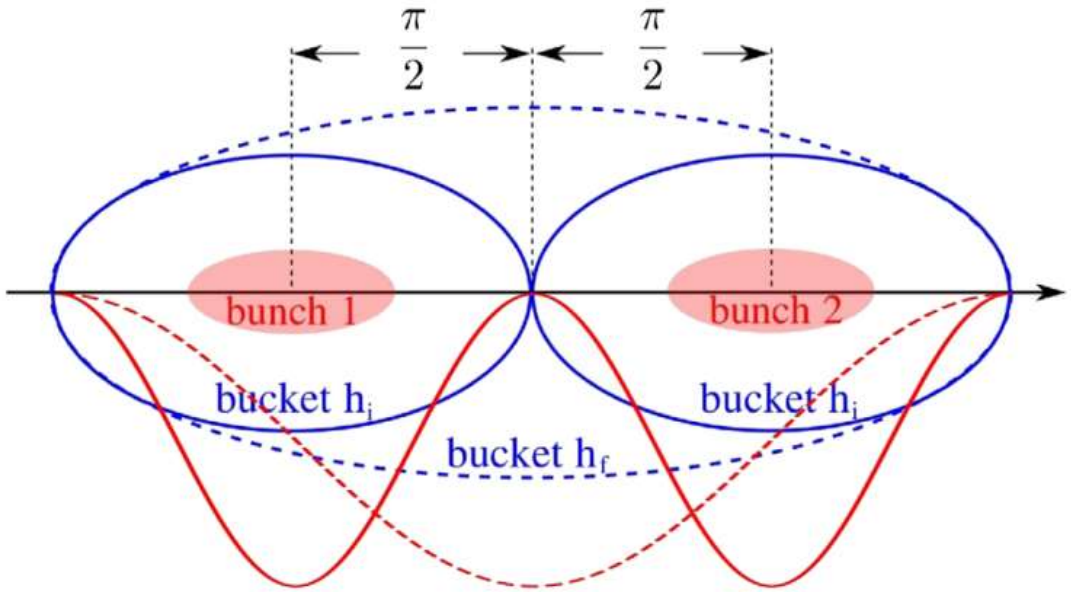
- Bunch merging: longitudinal merging of two bunches by adjusting rf voltages in a dual-harmonic rf system **to enhance the intensity**



Fundamentals of bunch merging

- Two key parameters: **rf voltage amplitude** and **phases**
  - Bunch merging is performed by increasing V_h, and decreasing V_{2h} to halve the bucket number for merging
  - Phase difference between the two harmonics is set to π/2





Fundamentals of bunch merging

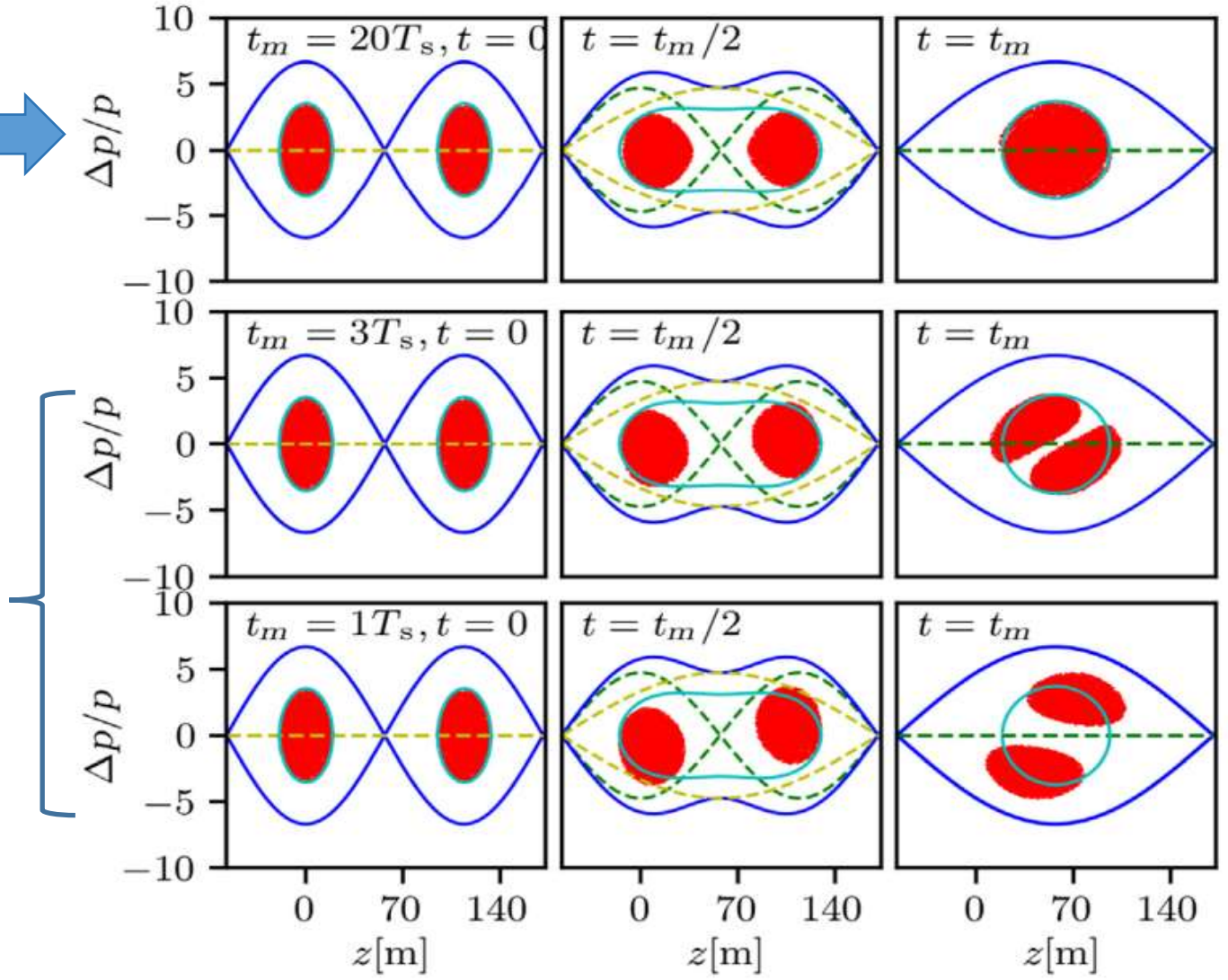
- An ideal bunch merging is adiabatic process without filamentation

$$\varepsilon_f = 2\varepsilon_i$$

- Fast bunch merging (non-adiabatic)

$$\varepsilon_f > 2\varepsilon_i$$

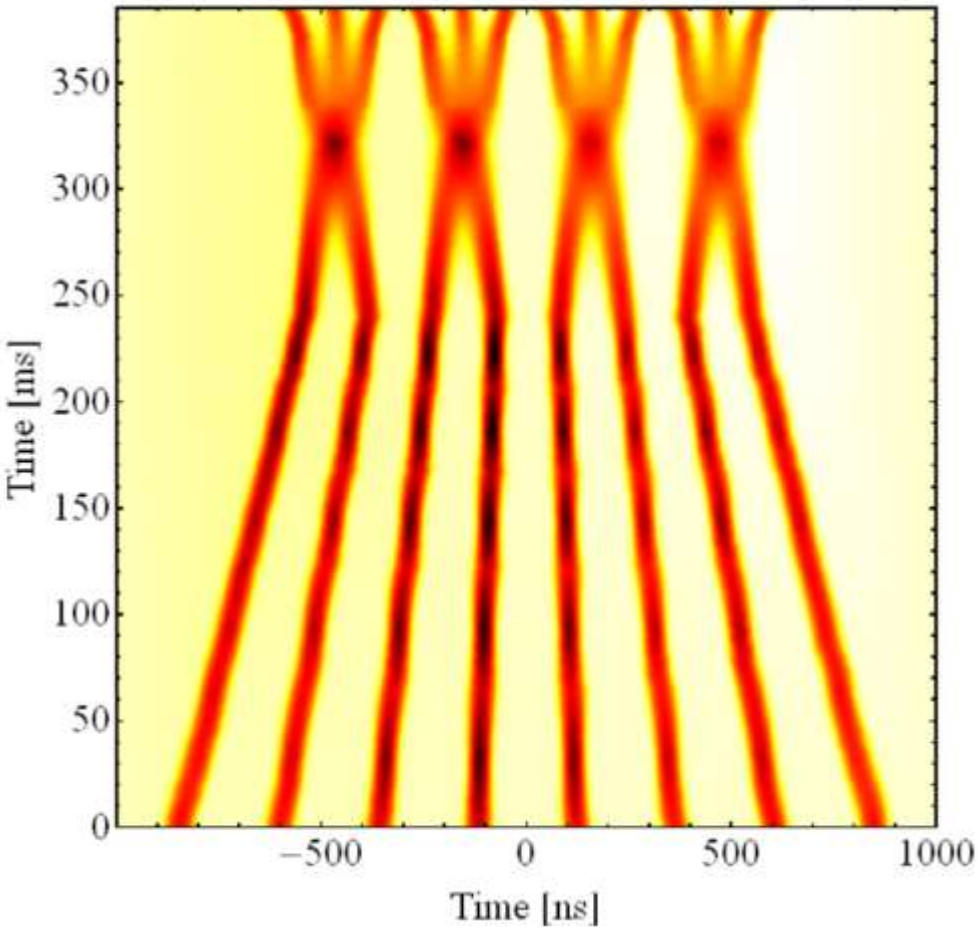
- A longer merging process can produce a better the merged bunch



Fundamentals of bunch merging

- Since initially proposed in 1983 by Bozsik, bunch merging has been successfully applied in CERN-PS, RHIC and so on.

- Example: Experimental measurement of the bunch merging on CERN-PS



Ref: [1] I. Bozsik et al., Numerical investigation of bunch-merging in a heavy-ion-synchrotron, in Computing in Accelerator Design and Operation (Springer, Berlin, Heidelberg, 1984).

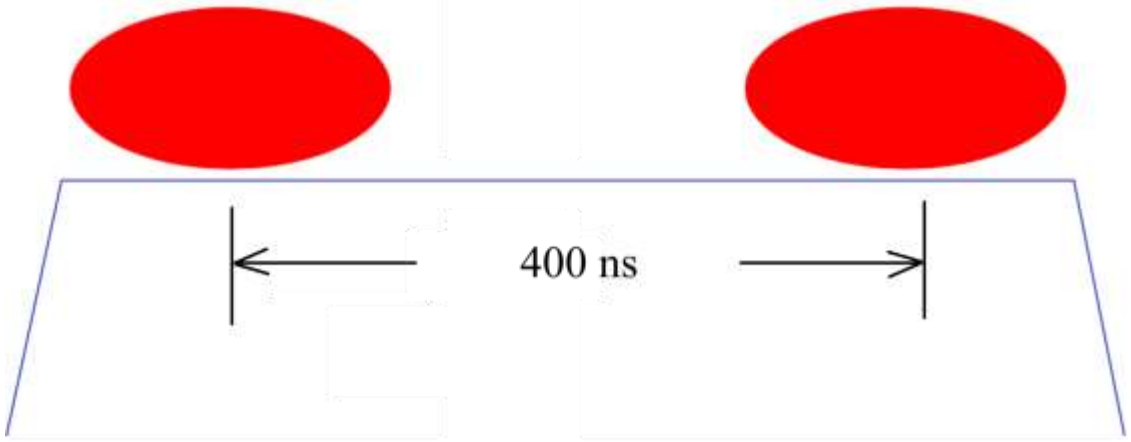
[2] Damerau, Heiko, et al. RF manipulations for higher brightness LHC-type beams. No. CERN-ACC-2013-0210. 2013

[3] R. Garoby et al. Status and plans for the upgrade of the LHC injectors, Report No. CERN-ATS-2013-059, 2013.

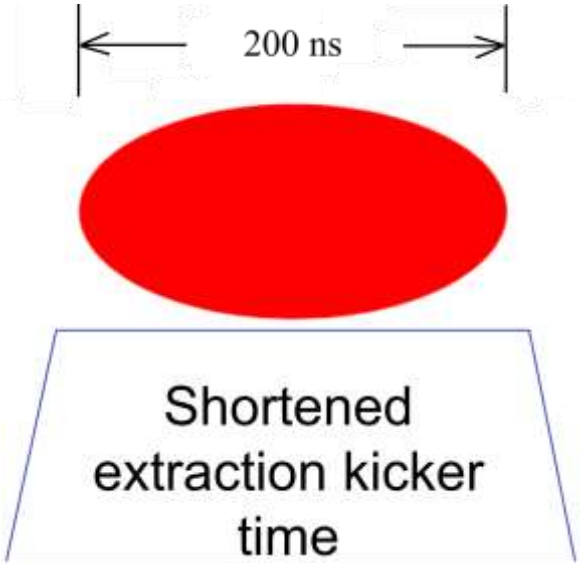
Importance of bunch merging for CSNS

1) For accelerator project / operation

- A single-bunch extraction can alleviate the workload of extraction kicker, **reducing extraction beam loss**



Double-bunch extraction

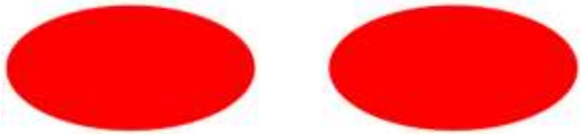


One-bunch extraction

Importance of bunch merging for CSNS

2) For users

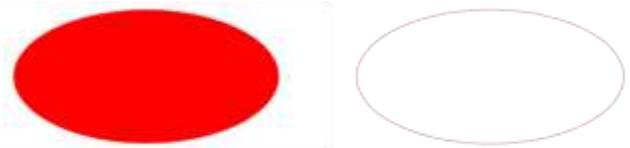
➢ At the moment, there are two operation modes:



Double-bunch operation

- bunch folding with the **reduced resolution** of the neutron measurements

95% operation time

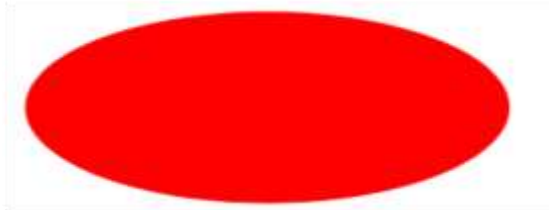


single-bunch operation

- **Reduced (halved) intensity**

5% operation time

➢ In the future, **high-intensity single-bunch mode operation**



- **High-intensity & high-resolution**
- Applied both for neutron user and **the muon experiment station of the CSNS (MELODY)**

100% operation time

Importance of bunch merging for CSNS

- Single-bunch operation is needed for

1) For the **future MELODY** (Muon station for sciEnce, technoLOgy, and inDustrY)

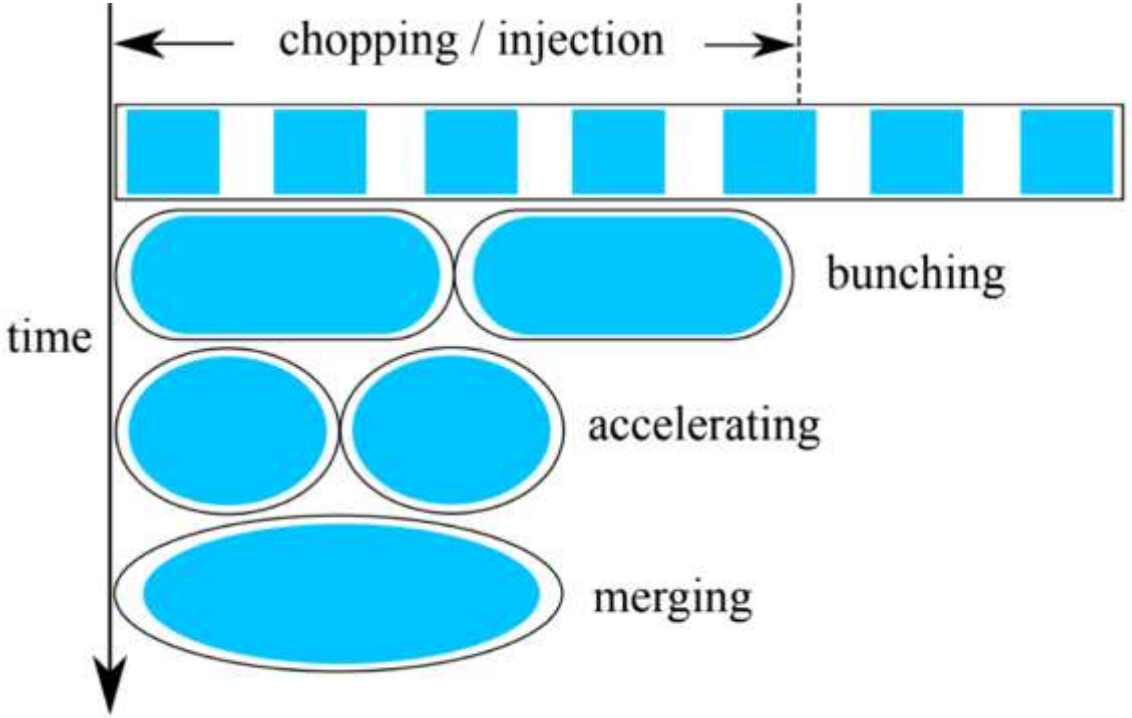
2) For the back-n white neutron source

- At present, single-bunch mode for 150 hours each year.
- Under the single-bunch operation, almost all the neutron scattering spectrometer are unable to function, causing a loss of roughly 1500 hours.

Ref: Jing-Yu Tang, Qi An, Jiang-Bo Bai et al. Back-n whiteneutron source at CSNS and its applications. NUCL SCITECH 32, 11 (2021).

Design of the fast bunch merging scheme in CSNS

- Recently-installed dual rf harmonic system in CSNS-II make it possible to conduct the bunch merging
- Based on bunch merging, a **high-intensity single-bunch operation mode** is proposed.



- Injected beams are longitudinal focused to 2 bunches with h=2
- Two bunches are accelerated with increasing rf voltage
- Two bunches are merged into one bunches with h=2 and h=1
- The merged single bunch is extracted to the target

Ref: Y. S. Yuan, G. Franchetti, H. Y. Liu and S. Wang, High-intensity effects on longitudinal bunch merging in hadron synchrotrons, PR-AB, 024201 **26** (2023)

Design of the fast bunch merging scheme in CSNS

➢ Bunch merging for CSNS is characterized as follows

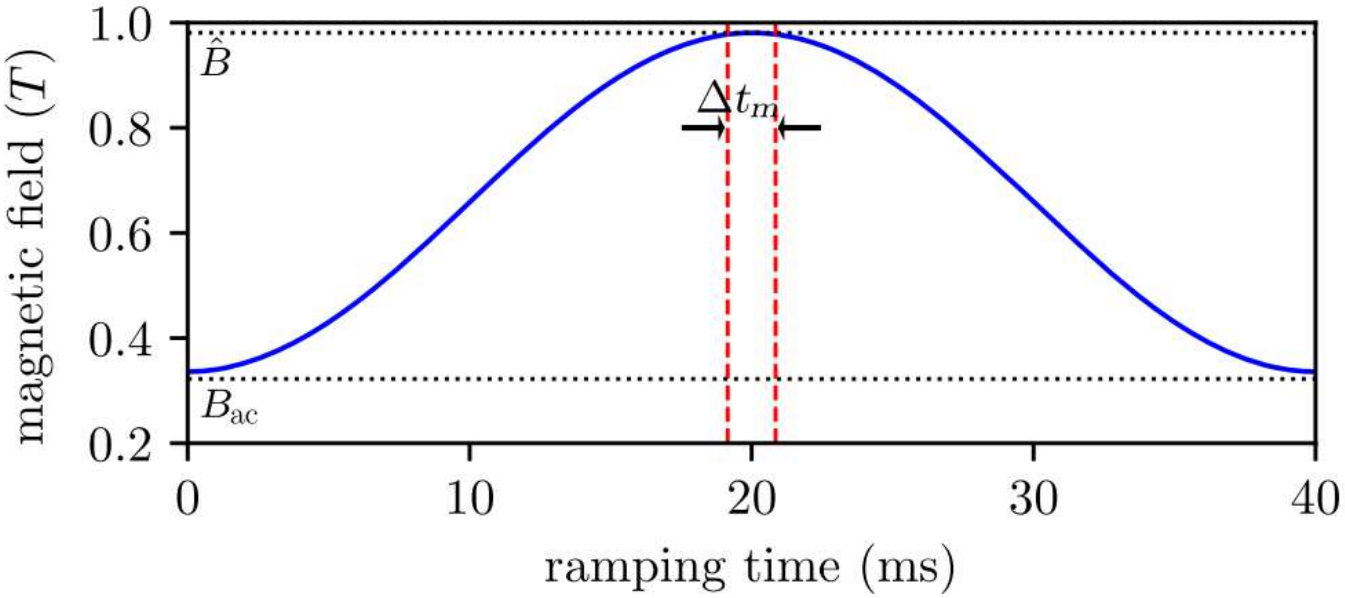
- **Fast** — During the 20-ms ramping period, the bunch merging should be fast and non-adiabatic
- **Asymmetry** — Since non-synchronous phase during ramping period, the two buckets not asymmetry
- **High-intensity** — Strong beam loading effect CSNS-II with the beam power 500kW

Design of the fast bunch merging scheme in CSNS-II

- Solution to "fast" and "asymmetry"

1) Increase of the merging time

- With the utilization of the "platform" from 20 ms -Δtm to 20 ms + Δtm to increase the merging time (where Φs≈ 0)
- Adjustment of the time difference between the dipole and the rf clock



Design of the fast bunch merging for CSNS-II

2) Recover of bucket symmetry

- Adoption of the "desynchronization" between the dipole and the rf systems to ensure a zero- Φs
- How large of the "desynchronization" can be done depends on the dispersion function

RCS dispersion

Momentum spread

Merging time

$$\Delta x = D_x \frac{\Delta p}{p} = 2\pi^2 D_x \frac{B_{ac}}{\hat{B}} \left(\frac{\Delta t}{T_0}\right)^2 .$$

Transverse deviation

Ref: Y. Zou, J. Tang, J. Chen, X. Li, and H. Sun, Short-bunch extraction in a rapid cycling synchrotron, Phys.Rev. Accel. Beams 17, 060101 (2014).

Design of the fast bunch merging scheme in CSNS-II

➢ Solution to “high-intensity” issues

1) Longitudinal space charge effect

- Defocusing， lengthen the bunch
- Lsc can be evaluated via the elliptical model

$$\hat{V}_{\mathrm{sc}} = \frac{3q\beta cX_s NR^2}{2hz_m^3}$$

- It is not a big issue for bunch merging, since
  - Beam at extraction (low space charge)
  - Interact between particles (no dipole oscillation)

Design of the fast bunch merging scheme in CSNS-II

- Solution to "high-intensity" issues

2) Cavity Beam loading effect

- Cavity impedance and BL voltage (Vbl) can be evaluated via RLC model

$$Z_n = \frac{R_{\mathrm{sh}}}{1 + iQ(h/n - n/h)}$$

$$V_{\mathrm{bl}}(z) = -\sum_{n=0}^{\infty} I_n Z_n e^{inz/R}$$

$\omega = n\omega_0$ Revolution frequency

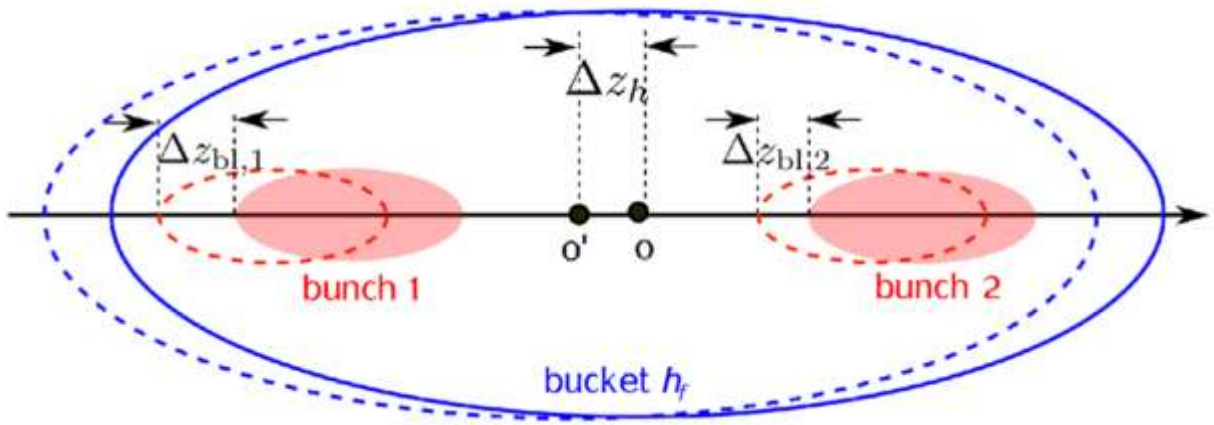
$\omega_r = h\omega_0$ Resonance frequency

- Beam loading can cause dipole oscillation and beam detoriation during bunch merging, and thus needs to be carefully treated

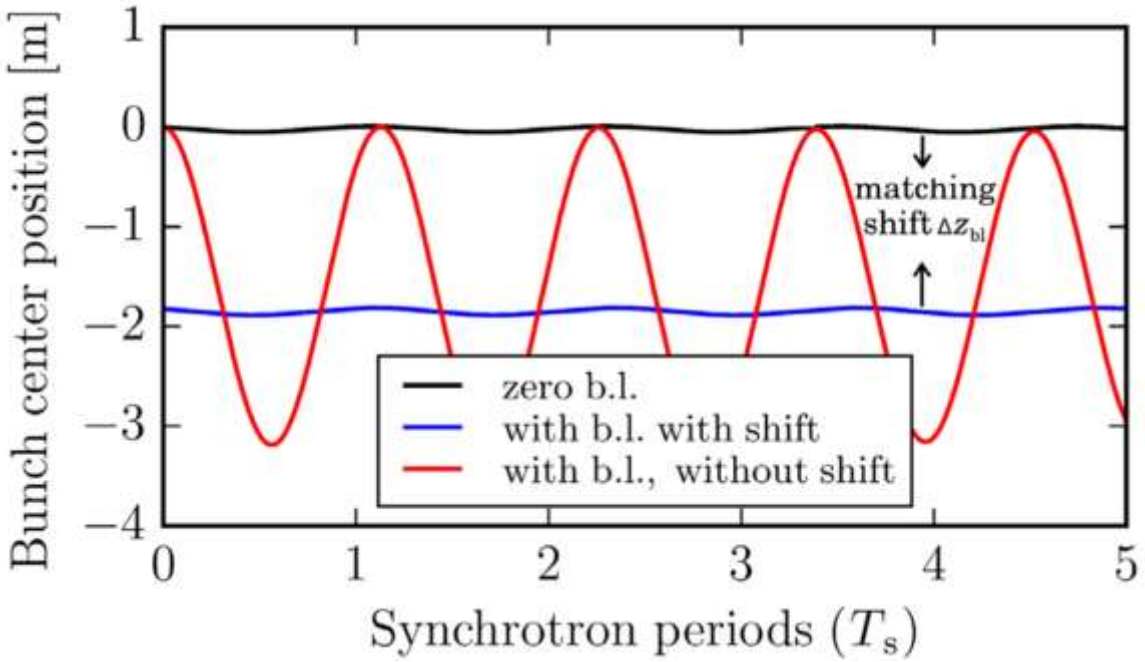
Design of the fast bunch merging scheme in CSNS-II

- Phase can be calculated for beam loading compensation via

$$\Sigma_{\mathrm{bl}} = \sin(\phi_{c,\mathrm{bl}}) = \left| \frac{V_{\mathrm{bl}}(z_{c,\mathrm{bl}})}{\hat{V}_{\mathrm{rf}}} \right|$$

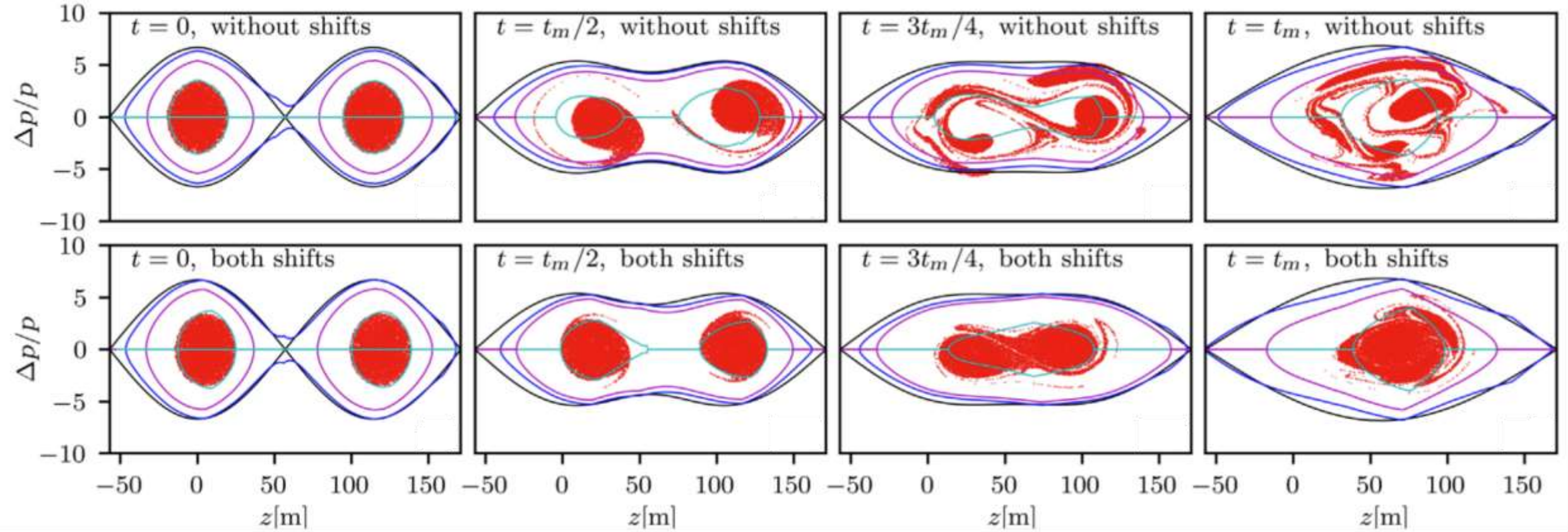


Schematic of the beam loading compensation via adjusting phases Φc,bl



Red：BL-induced dipole oscillation; Blue: after compensation（Black：no BL effect)

High-intensity effect in the bunch merging

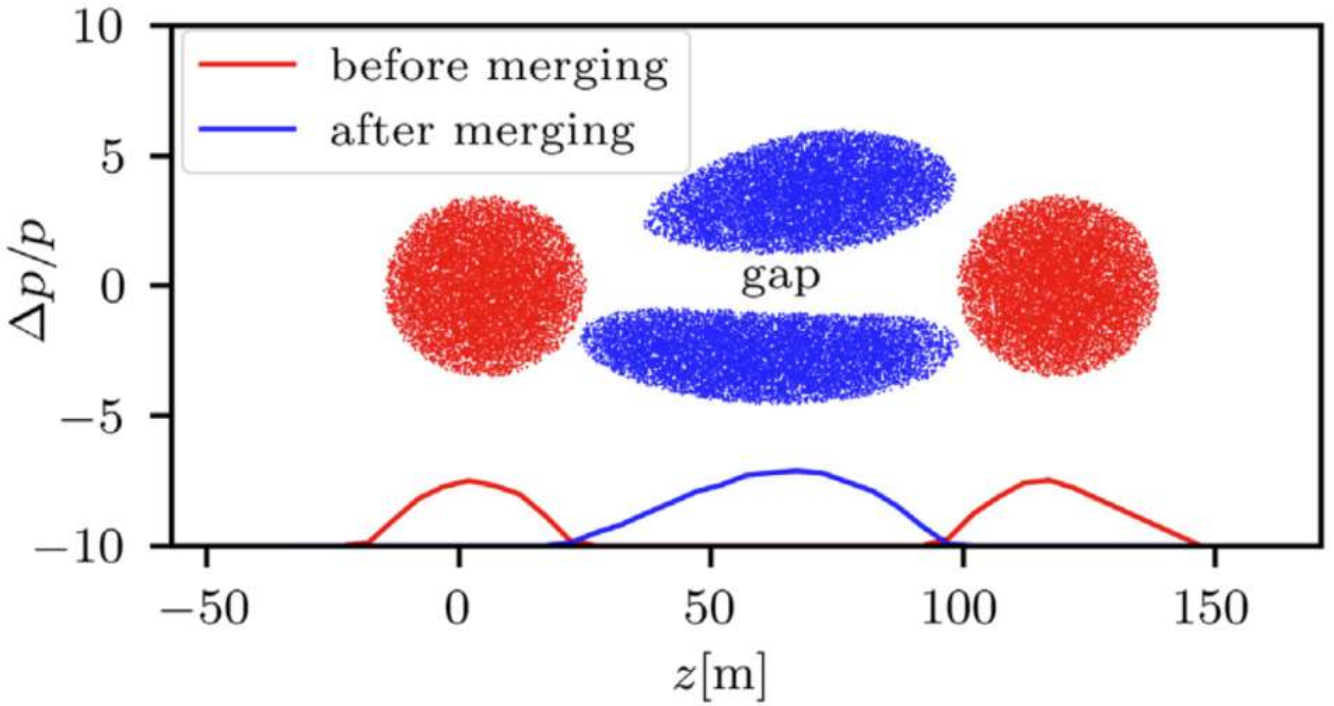


Simulation of bunch merging with beam loading effect
(Upper: without BL compensation; Lower: with BL compensation)

Ref: Y. S. Yuan, G. Franchetti, H. Y. Liu and S. Wang, High-intensity effects on longitudinal bunch merging in hadron synchrotrons, PR-AB, 024201 **26** (2023)

High-intensity effect in the bunch merging

Parameters (unit)	Symbol	Value
Atomic mass	A	1.0
Charge state	Z	1.0
Bunch intensity[a]	N	$7.8 \times 12^{12}(\times 5)$
Kinetic energy (GeV)	E_k	1.6
Circumference (m)	L	227.92
Slip factor	η	−0.095
Initial harmonic number	h_i	2
Final harmonic number	h_f	1
Initial rf voltage (kV)	$\hat{V}_{\mathrm{rf0,i}}$	29.2
Final rf voltage (kV)	$\hat{V}_{\mathrm{rf0,f}}$	14.6

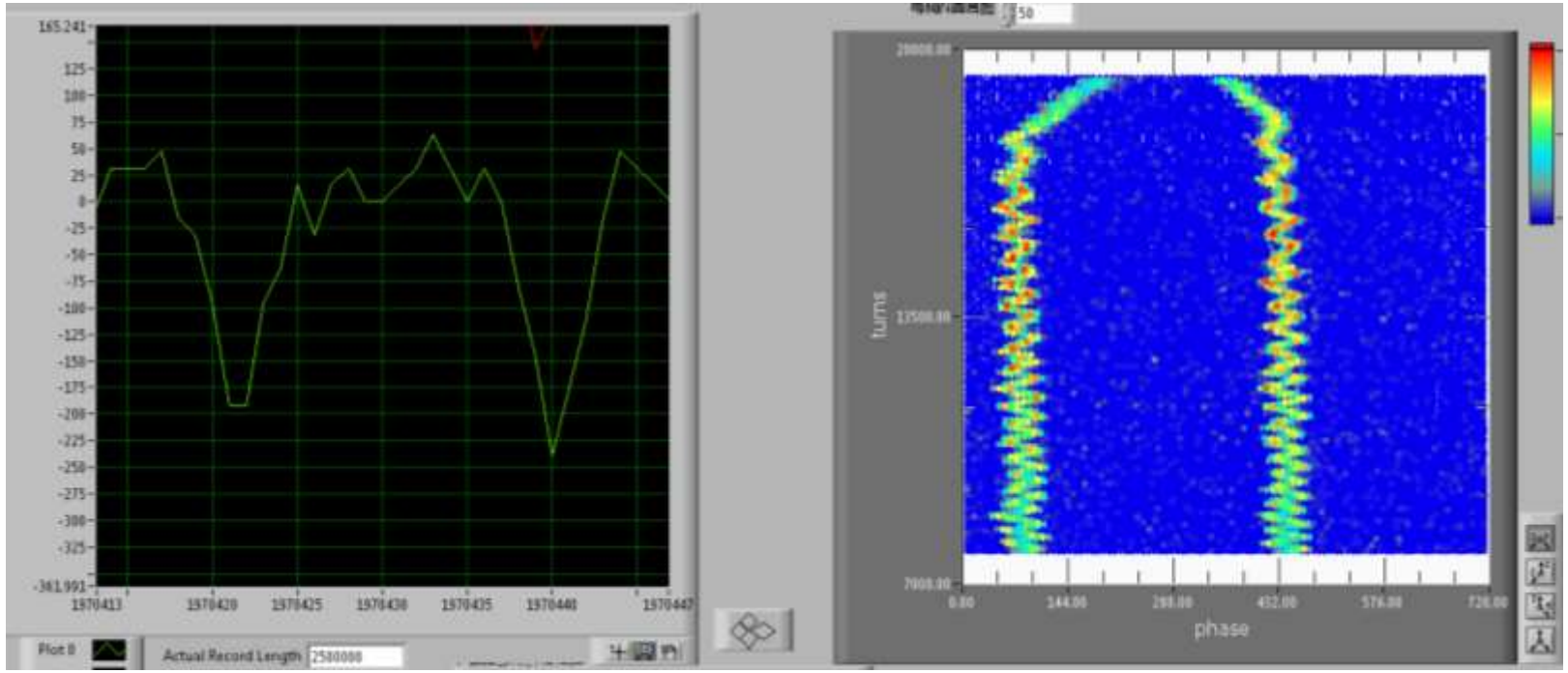


Simulation results of the fast & high-intensity bunch merging in CSNS RCS

Experiments of low-intensity bunch merging in CSNS

Starting time (ms)	Ending time (ms)	Merging time (ms)	Voltage for h=2 (kV)	Voltage for h=1(kV)	Merged bunch length (ns)
19.75	20.0	0.25	75	15	340

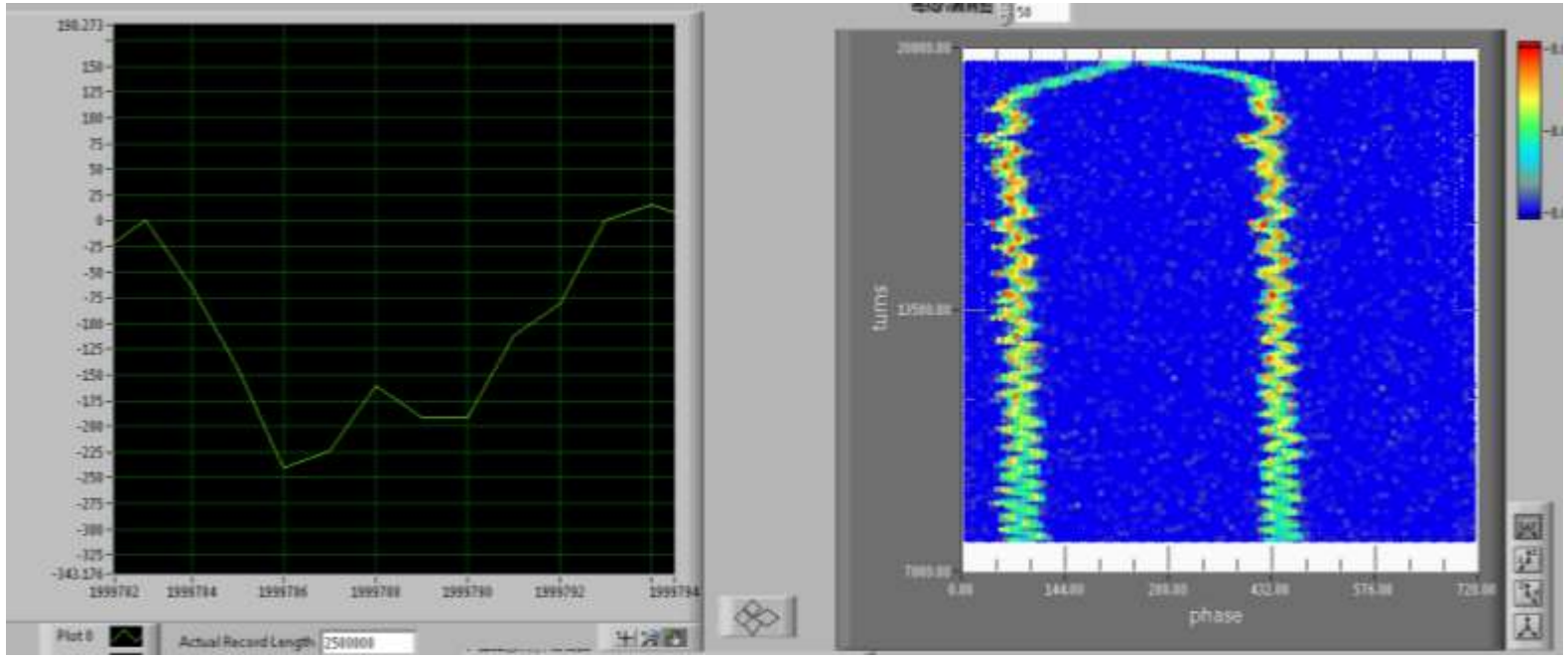
- Two "peaks" can be observed from WCM (wall current monitor)
- Two bunches are not fully merged



Experiments of low-intensity bunch merging in CSNS

Starting time (ms)	Ending time (ms)	Merging time (ms)	Voltage for h=2 (kV)	Voltage for h=1(kV)	Merged bunch length (ns)
19.75	20.0	0.25	75	15	340
19.75	20.9	**1.15**	75	15	120

- Only one peak can be observed via increase of merging time
- The experiments confirm the feasibility of fast bunch merging in CSNS RCS

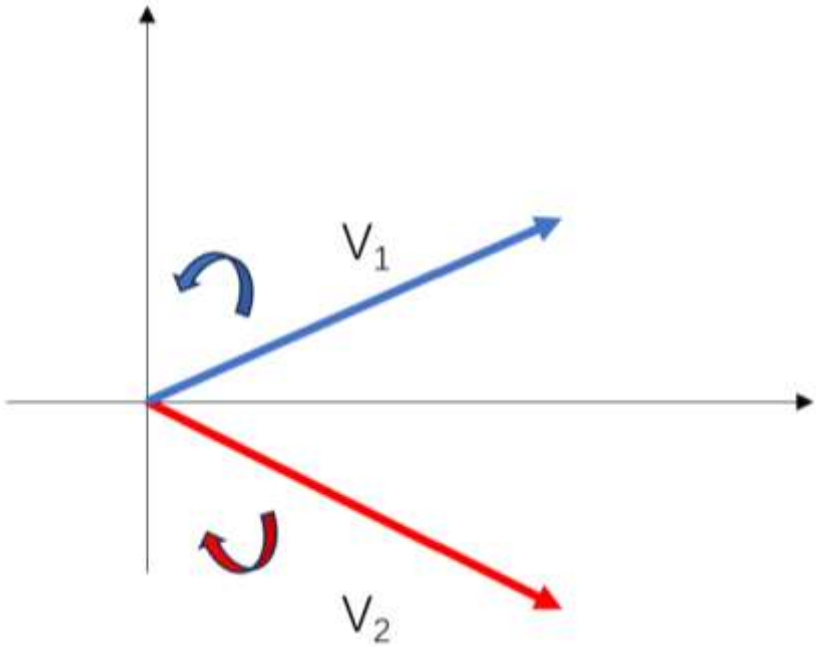


Experiments of high-intensity bunch merging in CSNS

- The beam loading effect increase as bunches get closed to each other during bunch merging

- Compared to the normal operation, it is more difficult to control the enhanced BL, since V(h=1) is approaching to 0 during merging

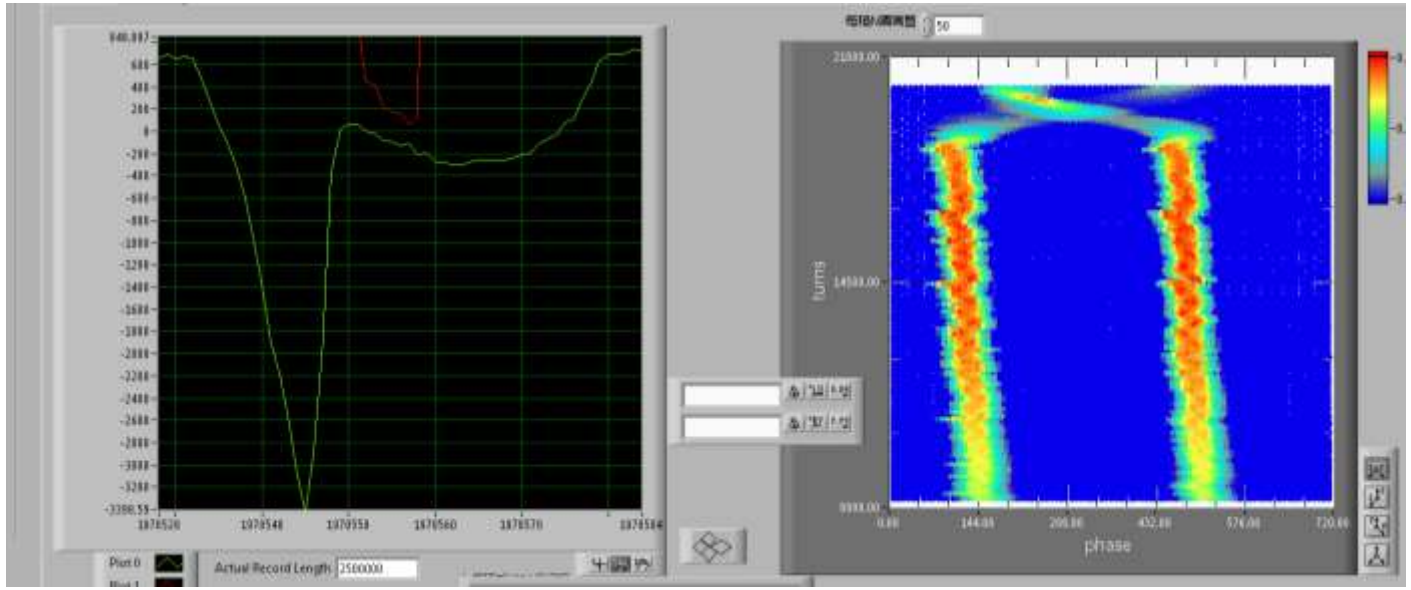
- To address this issue , we adjust the phases of the 4 of the 8 rf cavities to be use the opposite phases to other 4 rf cavities, to achieve a almost-zero V(h=1)



Experiments of high-intensity bunch merging in CSNS

Strating time (ms)	Ending time (ms)	Merging time (ms)	Voltage for h=2 (kV)	Voltage for h=1(kV)	Beam power (kW)	Merged bunch length (ns)
19.25	20.9	1.65	75	20	128	560

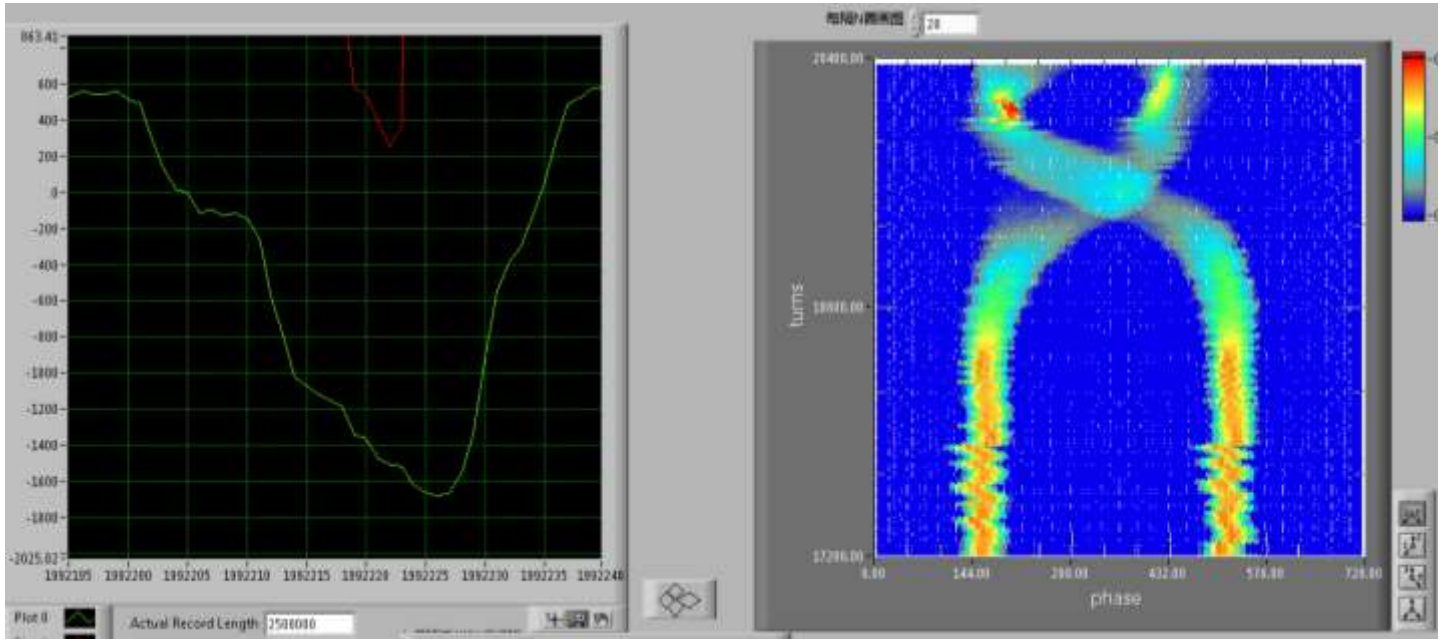
- Beam loading has been well-controlled
- No beam loss observed from DCCT



Experiments of high-intensity bunch merging in CSNS

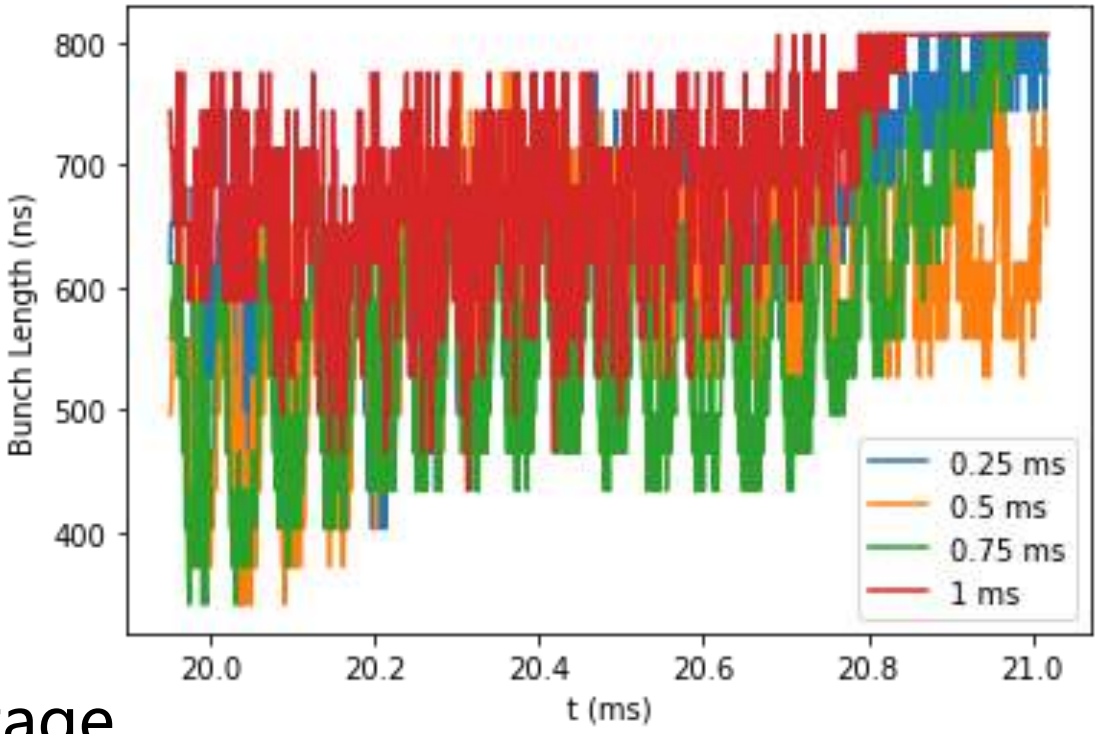
Strating time (ms)	Ending time (ms)	Merging time (ms)	Voltage for h=2 (kV)	Voltage for h=1(kV)	Beam power (kW)	Merged bunch length (ns)
19.25	20.9	1.65	75	20	128	560
19.25	20.9	1.65	75	**31**	128	350

- After the voltage (h=1) increased from 20 kV to 31 kV, the merged bunch length is further shortened



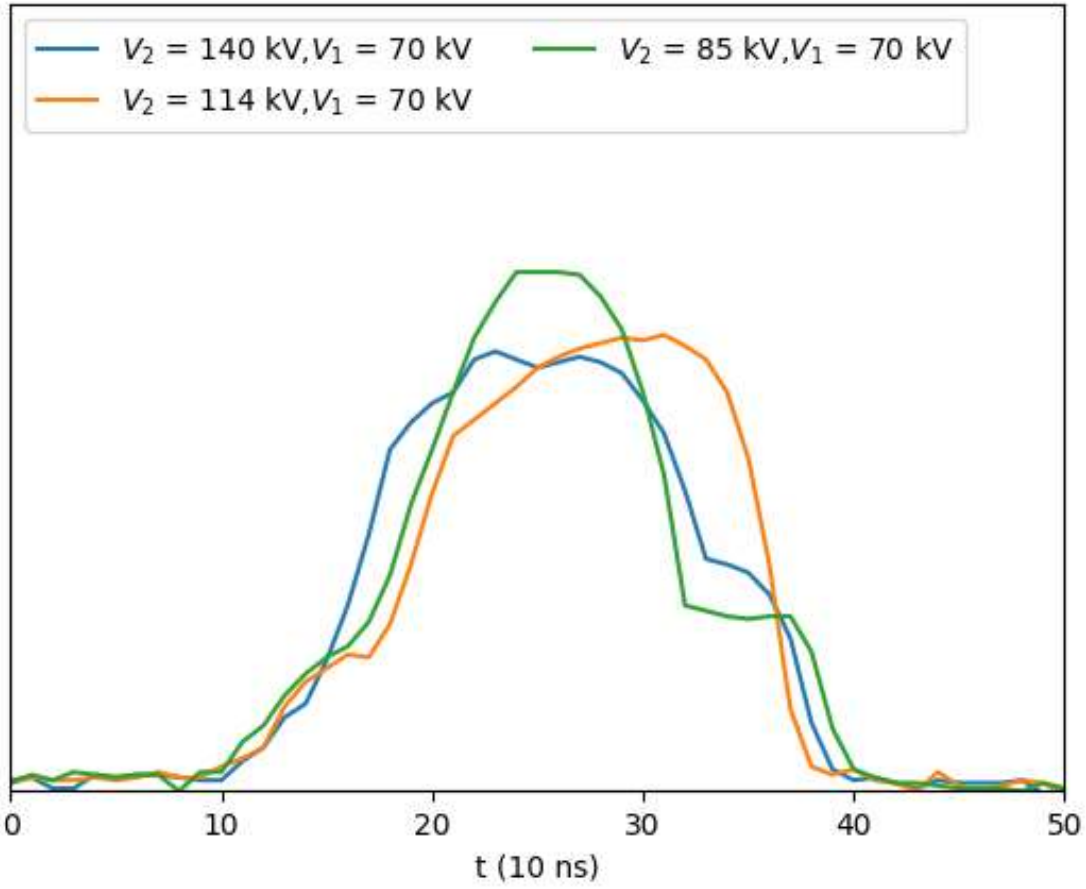
Experiments of high-intensity bunch merging in CSNS

- Optimization of the merging time
  - By scanning the merging time, we found the optimized merging time **0.75 ms**



- Optimization of rf voltage and phase
  - After some working on the rf voltage system, now we have V(h=1) ≈0.8 V(h=2)
  - The phase difference between the two harmonic system (h=1 and h=2) is optimized

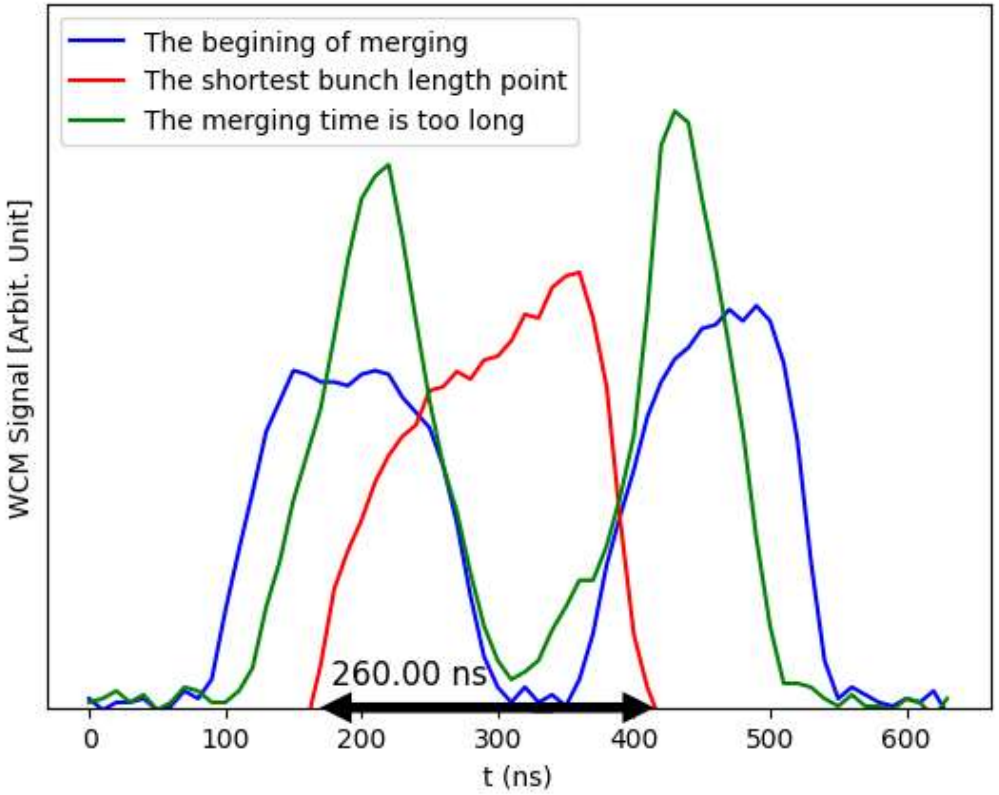
Experiments of high-intensity bunch merging in CSNS



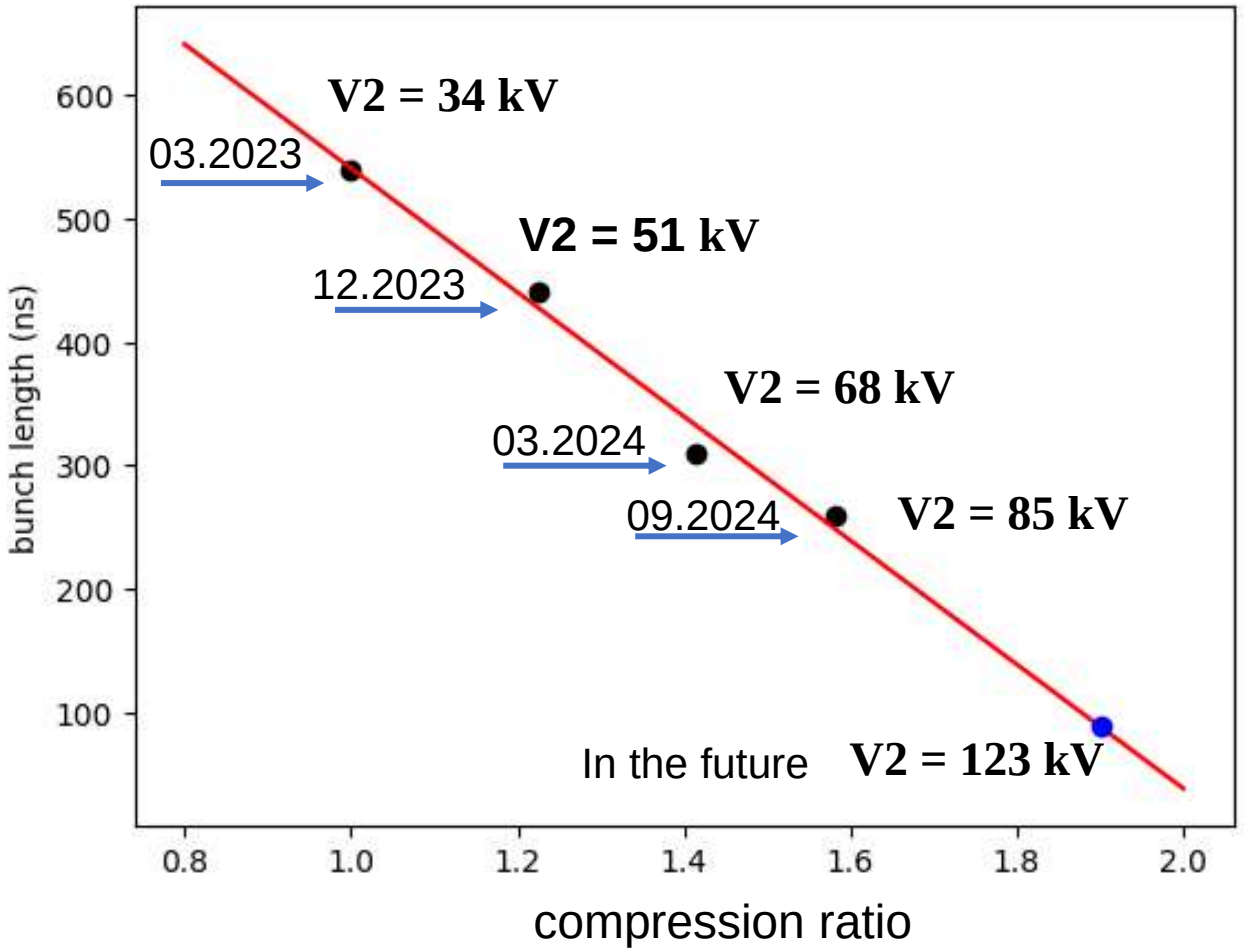
- Optimization of the voltage (h=2) is another key point
- A large V(h=2) can focus the bunches before merging
- However, too large V(h=2) can weaken the merging effect
- The optimized V(h=2) = 114 kV with a shortest bunch length (270 ns)

Experiments of high-intensity bunch merging in CSNS

- By optimized parameters including starting time, merging time, rf voltage and phases, the bunches are compressed to 260 ns

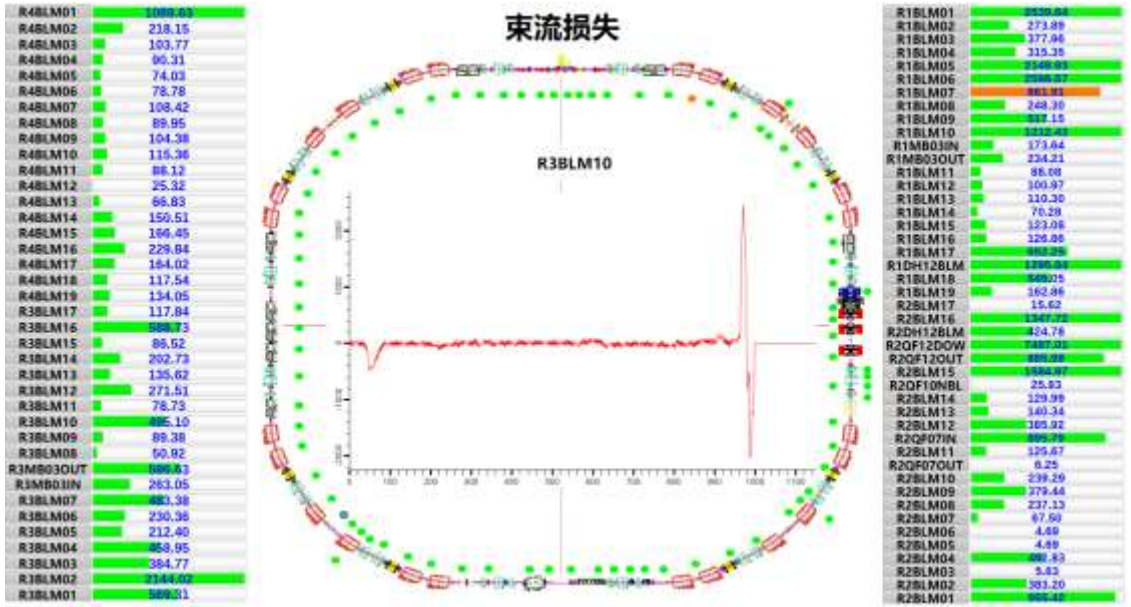


Experiments of high-intensity bunch merging in CSNS

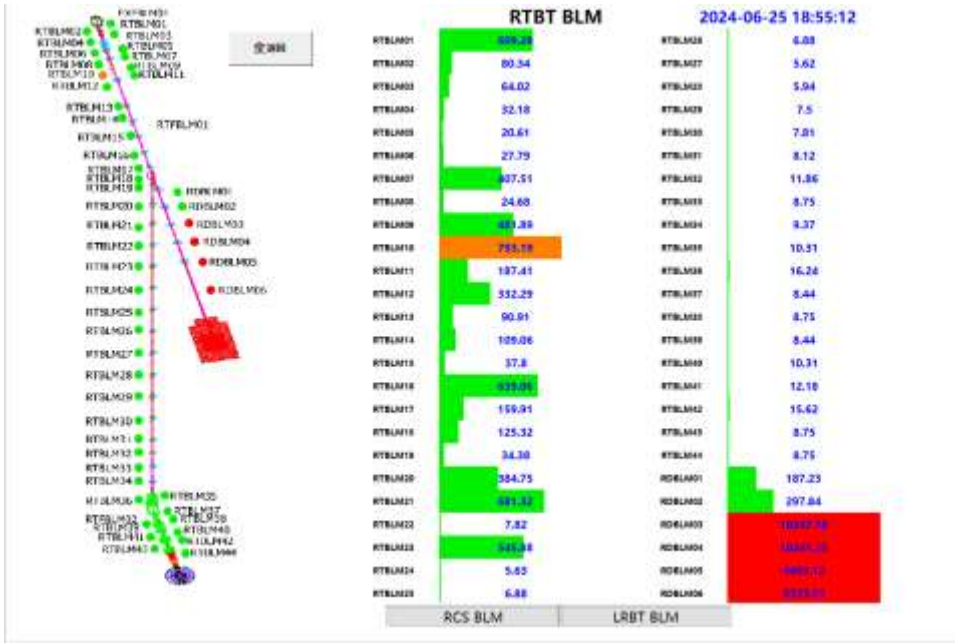


- A scaling is made based on measurement dates with different rf voltages;
- It is shown that the compressed bunch length depends on the voltage amplitude
- To achieve bunch merging with **100 ns** bunch **132 kV** rf voltage is required

Experiments of high-intensity bunch merging in CSNS



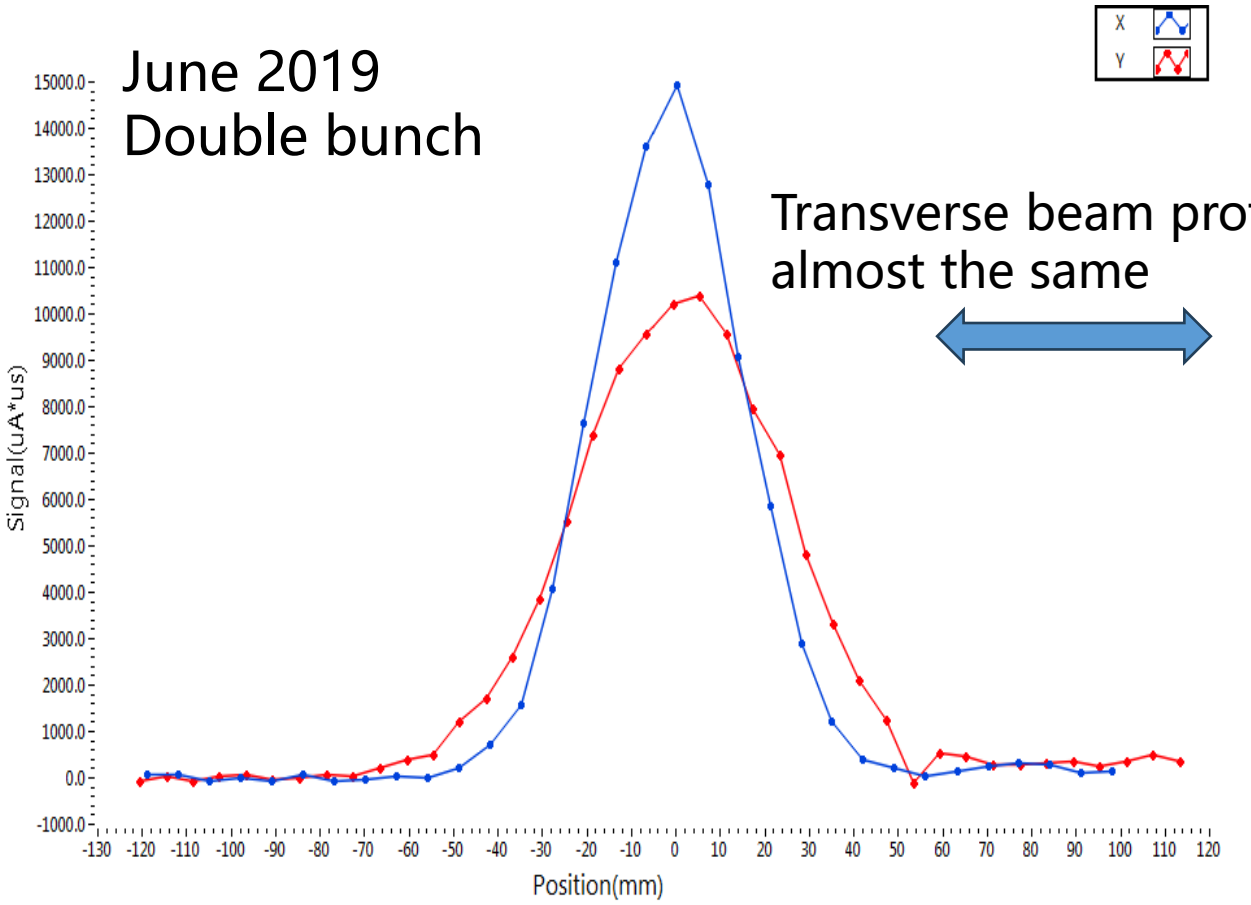
LEBT CT01	36.28	mA	RTBT CT03	-0.11	E12
LEBT CT02	0.66	mA	RDBT CT01	15.61	E12
MEBT CT01	4.73	mA	LEBT Trans	1.8	%
MEBT CT02	4.74	mA	RFQ Trans	721.4	%
LRBT CT01	4.72	mA	MEBT Trans	100.1	%
LRBT CT02	4.72	mA	DTL Trans	99.6	%
LRBT CT03	4.75	mA	LRBT Trans1	100.1	%
LDBT CT01	0.01	mA	LRBT Trans2	100.5	%
DCCT-INJ	1312.41	mA	LDBT Trans	0.3	%
DCCT-EXT	3054.64	mA	EXT Trans	99.7	%
DCCT-INJ No	16.00	E12	RCS Trans	97.6	%
DCCT-EXT No	15.62	E12	RTBT Trans	-	%
RTBT CT01	15.58	E12	RDBT Trans	100.2	%
RTBT CT02	-0.01	E12	Beam Power	###	kW



- No severe beam loss observed during bunch merging
- Beam loss can be further reduced by adjusting the rf clock in the extraction and the correctors

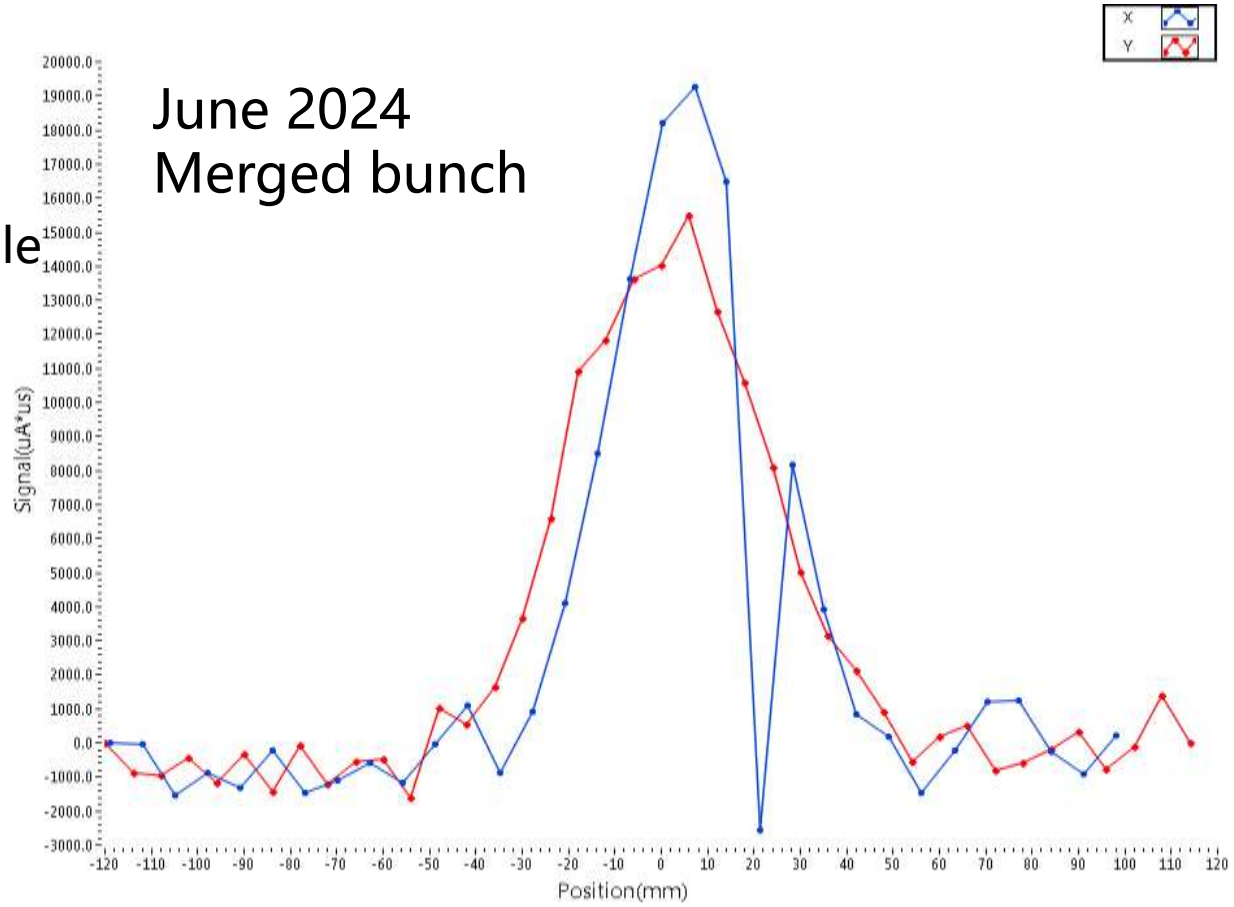
Experiments of high-intensity bunch merging in CSNS

June 2019
Double bunch



Transverse beam profile almost the same

June 2024
Merged bunch



- Longitudinal merging has not influenced the transverse beam size!

Conclusions

- Fast and high-intensity bunch merging for RCS is designed
- High-intensity single-bunch operation mode is proposed for CSNS-II
- High-intensity effects is investigated
- Fast and high-intensity bunch merging experiments is recently performed in CSNS
- With optimized parameters, bunches in 128 kW can be merged and compressed to 260 ns

Thank you!