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China Spallation Neutron Source

Design and Beam Commissioning of Dual Harmonic RF System in CSNS RCS

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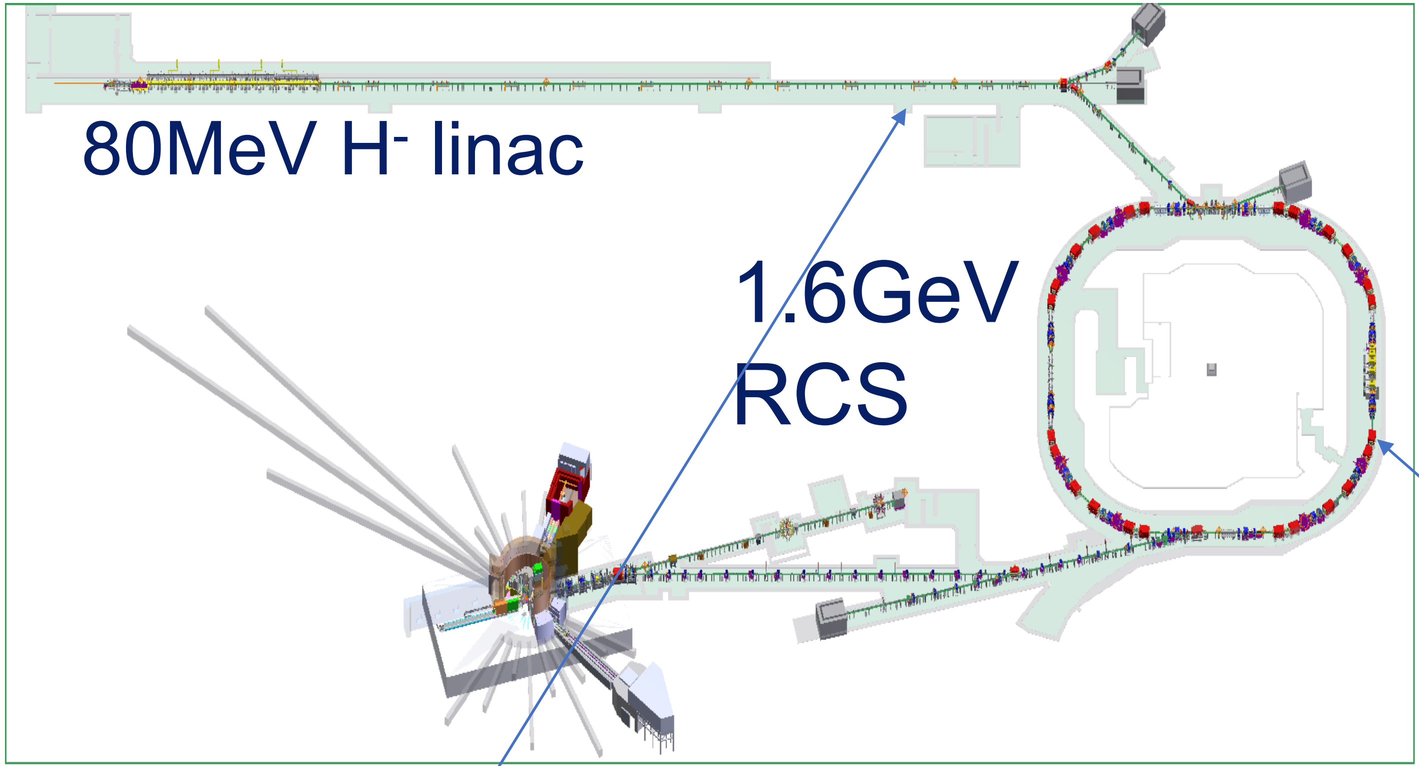
Main Content

- The dual harmonic RF system
- Beam measurement
- Next step

CSNS Layout



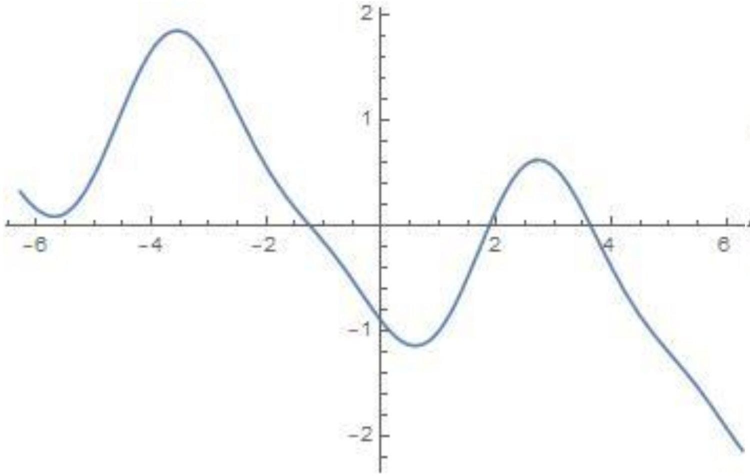
The RCS main parameters.

Parameter (unit)	Value
Circumference (m)	227.92
Protons	1.56e13
Inj./ext. kinetic energy (GeV)	0.08/1.6
Inj./ext. revolution time (μ s)	2/0.8
Inj./ext. RF frequency (MHz)	1.022~2.444
Harmonic number	2
Repetition rate (Hz)	25
Transition gamma	4.9
Inj. energy spread (%)	0.05–0.5
Momentum filling factor	0.81
Inj./ext. bunch length/ns	600/110

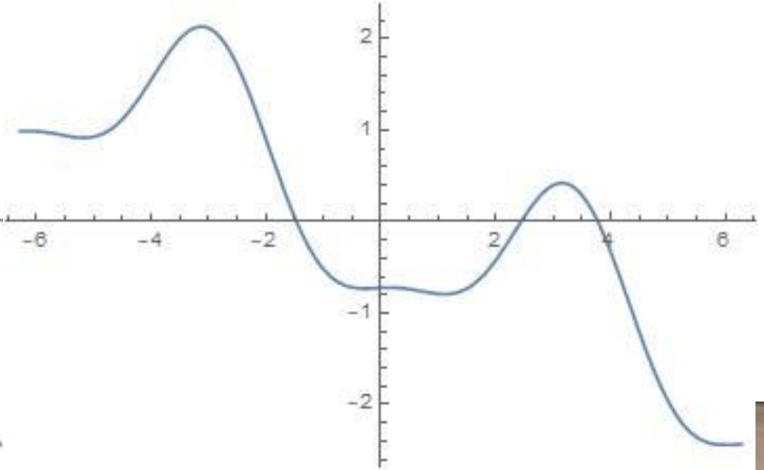
For CSNS-II, super conductive cavities will be added to increase the Linac energy from 80MeV to 300MeV

Three magnet alloy cavities will be added to RCS (2 already)

The Dual Harmonic RF System

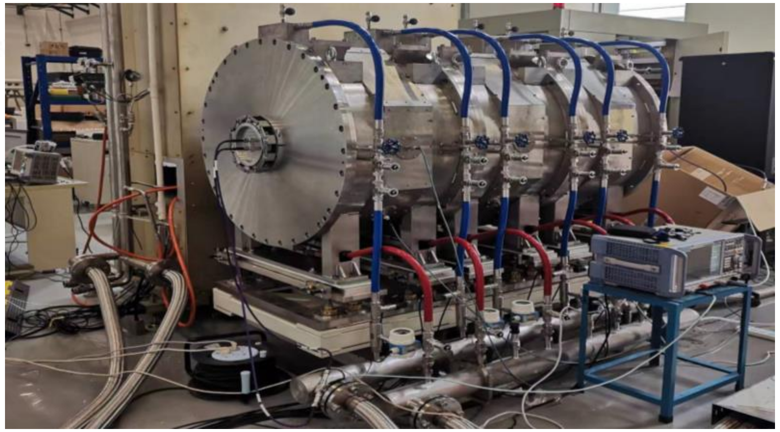


Single harmonic(r=0)



Dual harmonic(r>0.5)

Reduce the longitudinal peak current intensity, and thus reduce the beam loss caused by space charge effect.

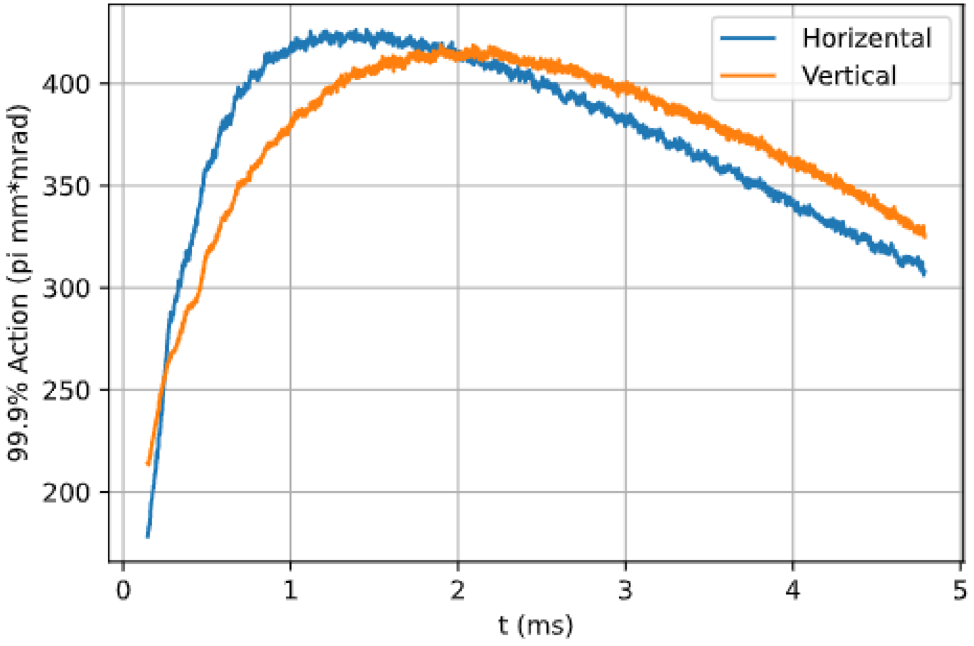


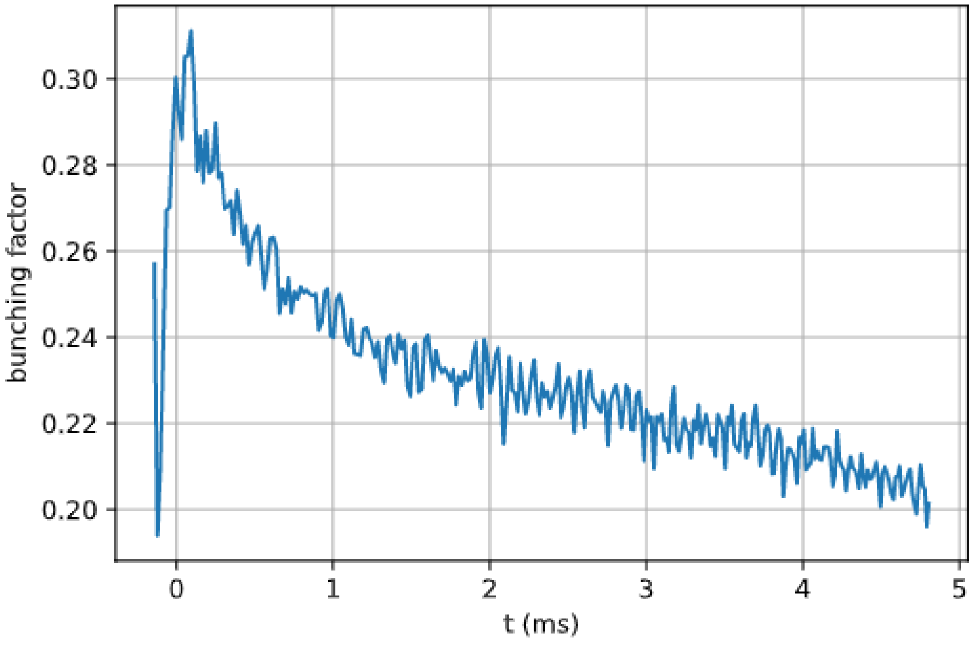
140kW has achieved

170kW (Two MA cavities added) → 200kW (Three MA cavities added，100kV) → 500kW (300MeV Linac energy) → ?

Longitudinal dynamic for 200kW

- **backgrounds about beam upgraded**
  - Due to the edge focusing of injection magnets， the acceptance is decreased from **540πmm·mrad** to **480πmm·mrad.**
  - After the trim quadrupoles adopted, the acceptance can be recovered (RCS trans over 99%)

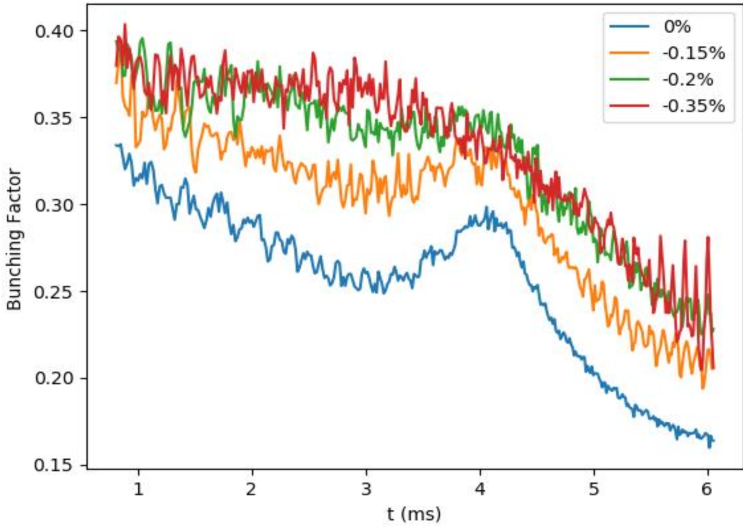


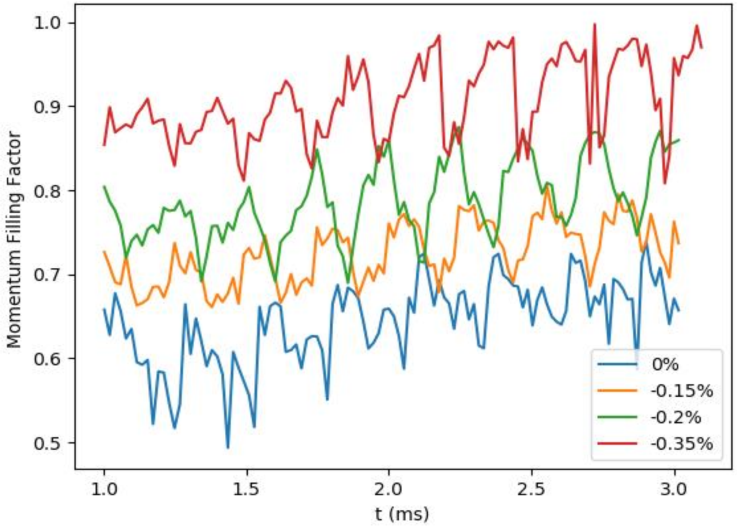


Maximum (99.9%) transverse emittance and bunching factor on 130kW

Longitudinal dynamic for 200kW

- Optimization of bunching factor





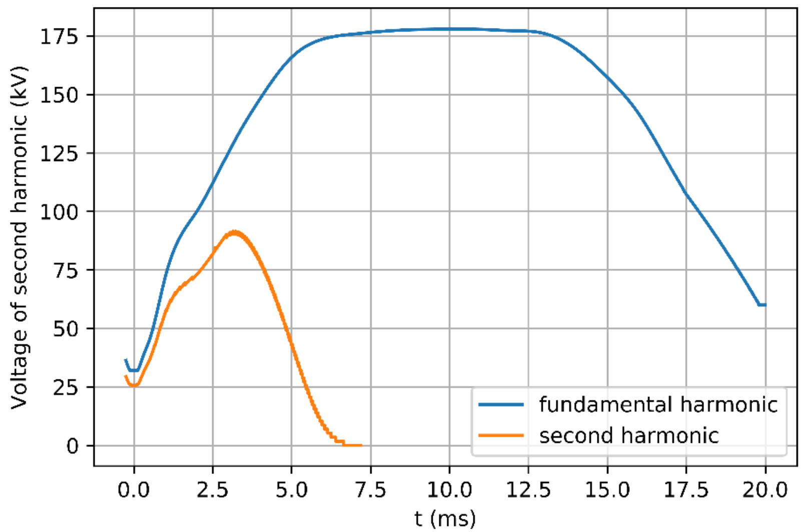
Since the upgrade project of 200kW doesn't include the momentum collimator at the first place， the momentum spread should be controlled under 1% to avoid that large beam loss occur in arc section， and the corresponding momentum filling factor is 0.8.

As a condition, r=0.8 and momentum offset is -0.2% during injection

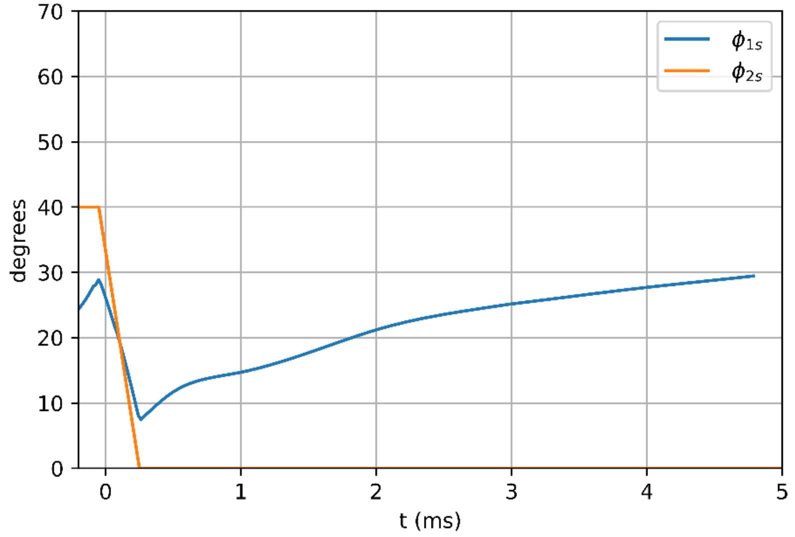
Circumference (m)	227.92
Energy range(GeV)	0.08-1.6
Harmonic Number	2 / 4
Inj/Ext rf frequency (MHz)	1.022~2.444
Inj/Ext rigidity (T·m)	1.320~7.867
RMS Energy spread (Inj) (%)	0.05
Repetition (Hz)	25
Transition energy - γ	4.89
RCS work tune (H/V)	4.80/4.87
Transverse painting range(mm)	30/20
β function of inject point (m)	6.72/5.58
99.9% emittance after painting without SC (π mm mrad)	170/155
Inject period (ms)	0.5
Chopper duty (%)	50
Total Injected particle number at 130 kW N_p	2.028×10^{13}
Total Injected particle number at 200 kW N_p	3.12×10^{13}

Longitudinal dynamic for 200kW

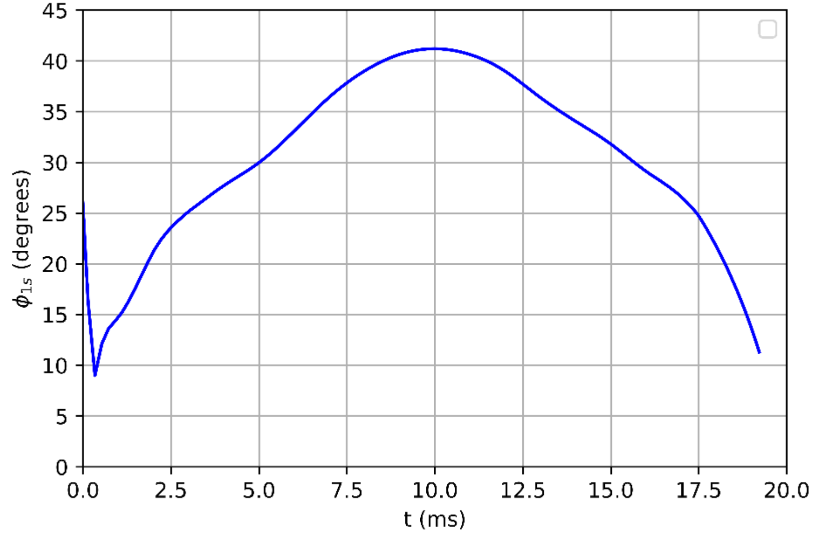
- **Optimized rf curves**



rf voltage curve in RCS



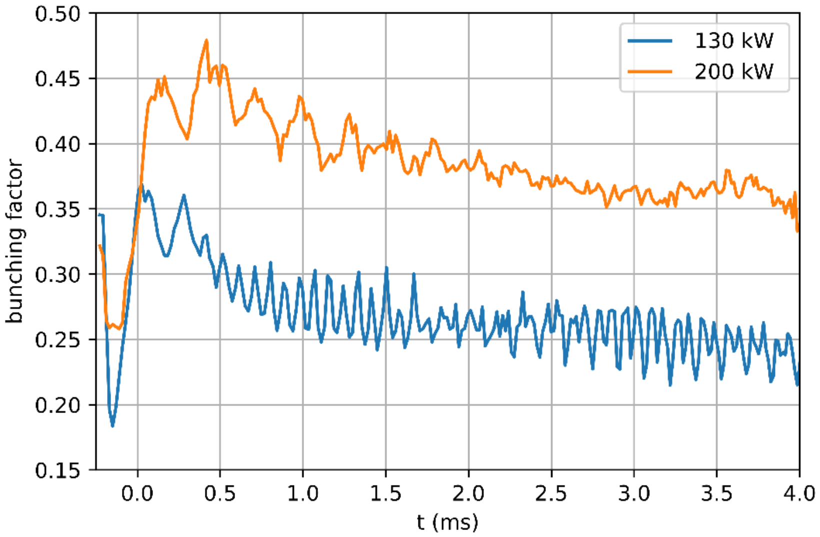
rf phase curve in the first 5ms



the design value of φ_{1s}

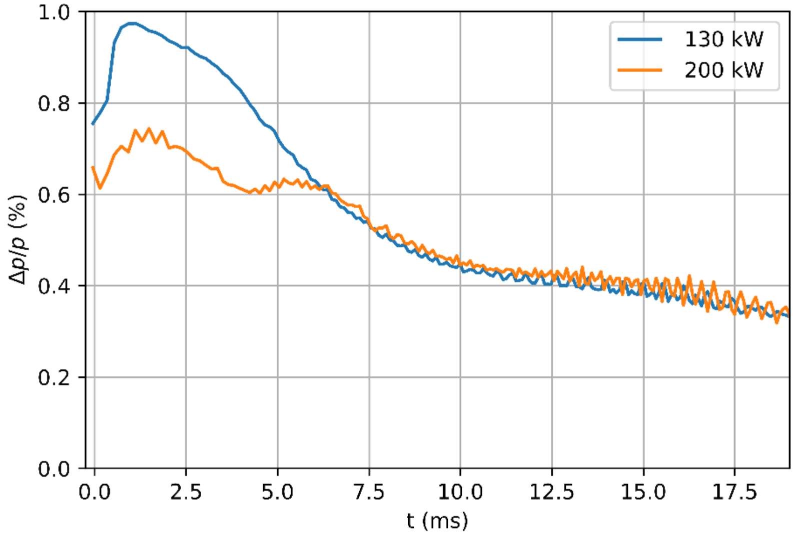
Longitudinal dynamic for 200kW

- 130kW vs 200kW



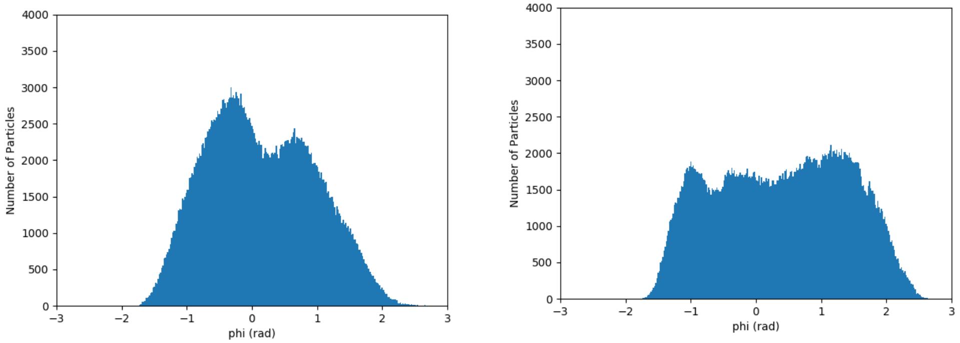
Comparison of bunching factor

Bunch length and momentum spread remain same after injection (even smaller), and the peak value of particle number has been decreased. Bunching factor increases because of the flatten longitudinal profile.

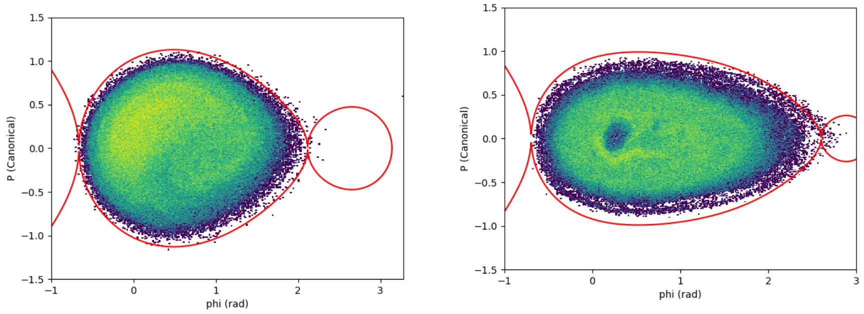


Comparison of maximum momentum spread

Only a few particle exceed the bucket, lower than 0.006% in simulation



Comparison of beam profile

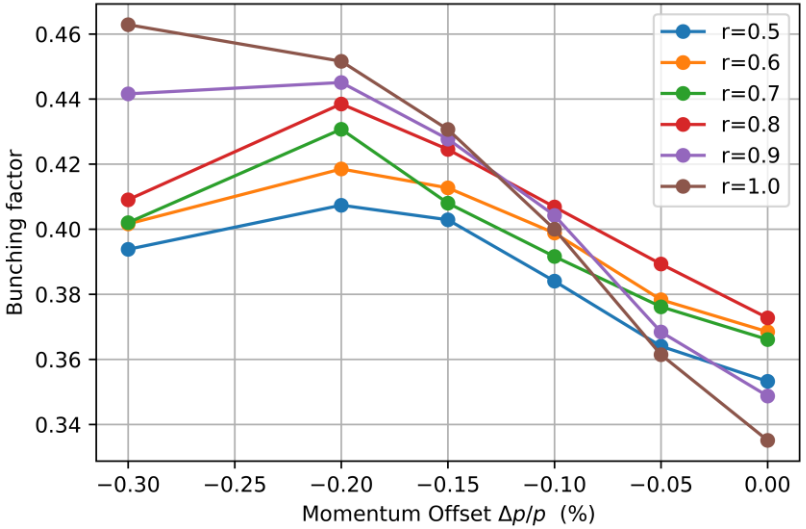


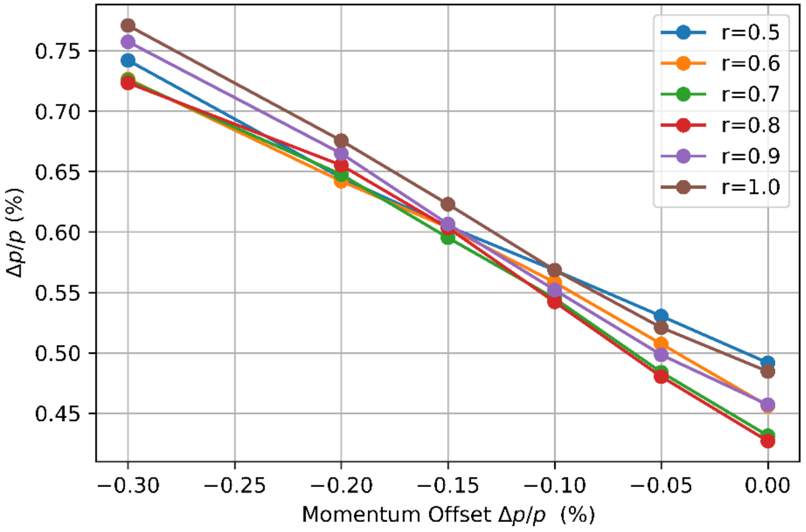
Comparison of phase space at the 5 ms

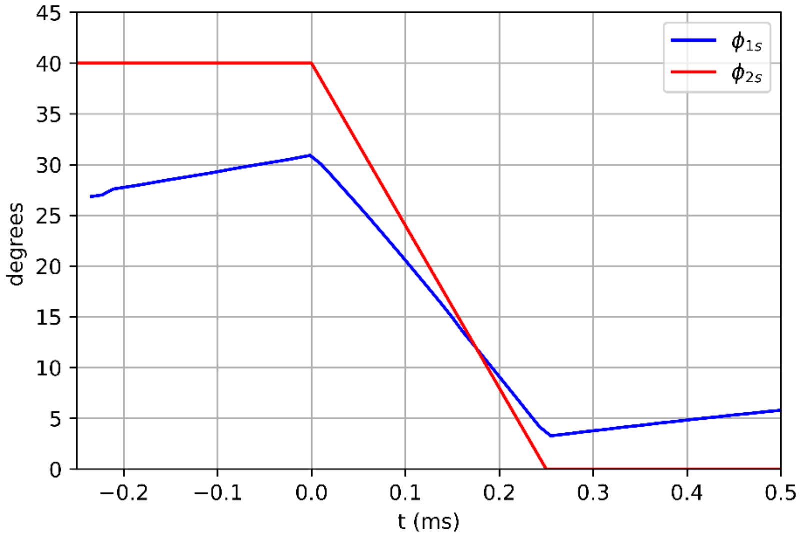
Longitudinal dynamic for CSNS-II

- ## Optimization of longitudinal parameters during injection

The inject energy of RCS is 300MeV， the longitudinal distribution of the injected beam is uniform, the momentum is Gaussian distributed, the rms momentum spread is 0.1%, and the slice rate is 50%. The simulation includes a multi-turn injection process, and the injection pulse width is 500 μs, which is equivalent to 430 turns. In order to ensure that there is enough bucket height after the energy increases, the initial cavity pressure is increased from 32 kV in the first stage to 60 kV.





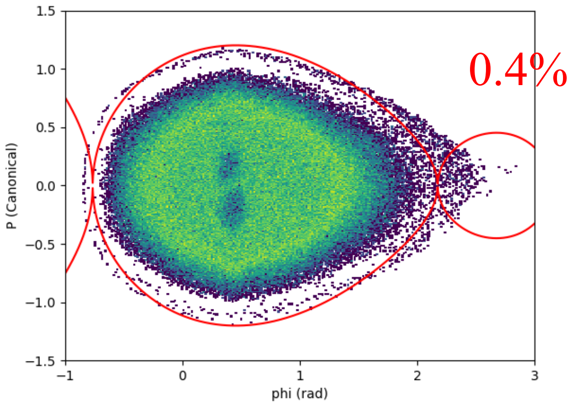


A combination of r=0.8 and momentum offset of -0.15% was used, that is, the longitudinal emittance after injection was 1.78 eVs. Second harmonic phase sweep was used during injection

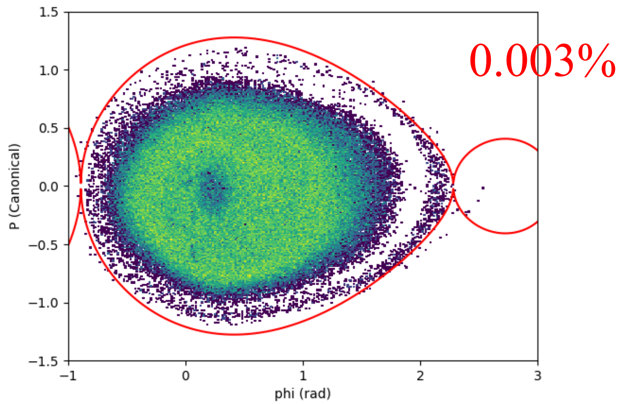
Longitudinal dynamic for CSNS-II

- Other optimizations

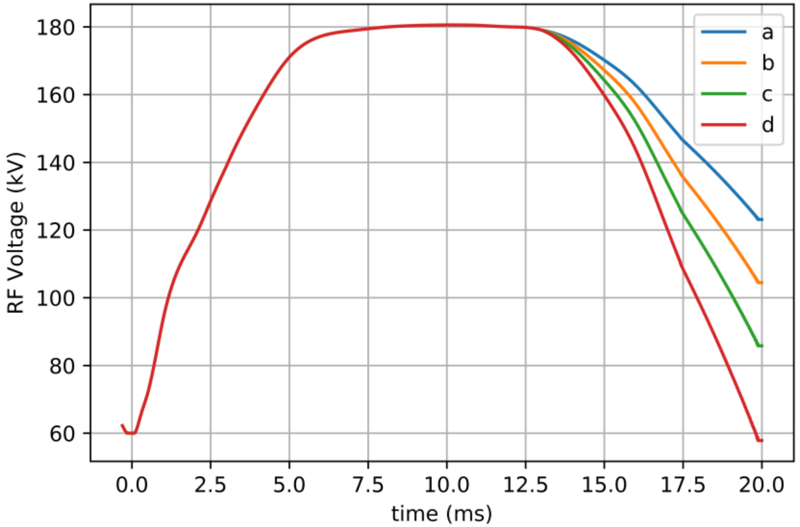
175kV
6ms

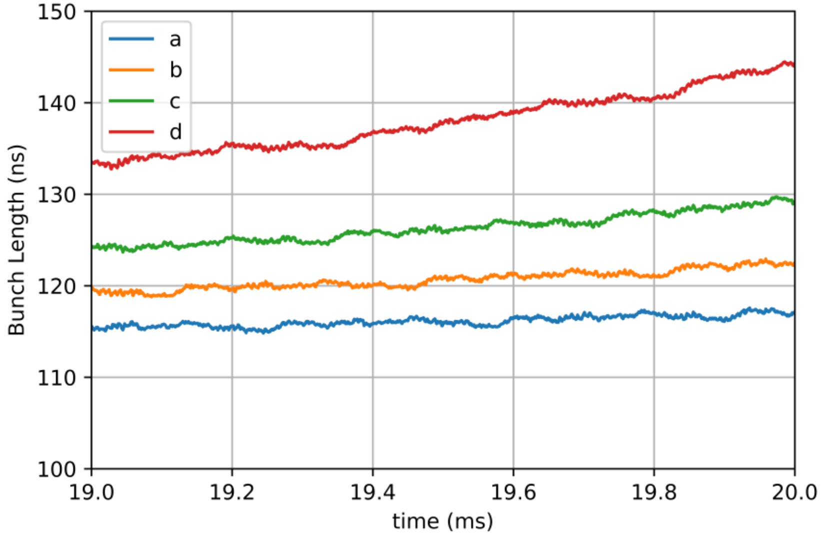


190kV
4ms



Optimization of longitudinal phase space distribution in the middle of acceleration period



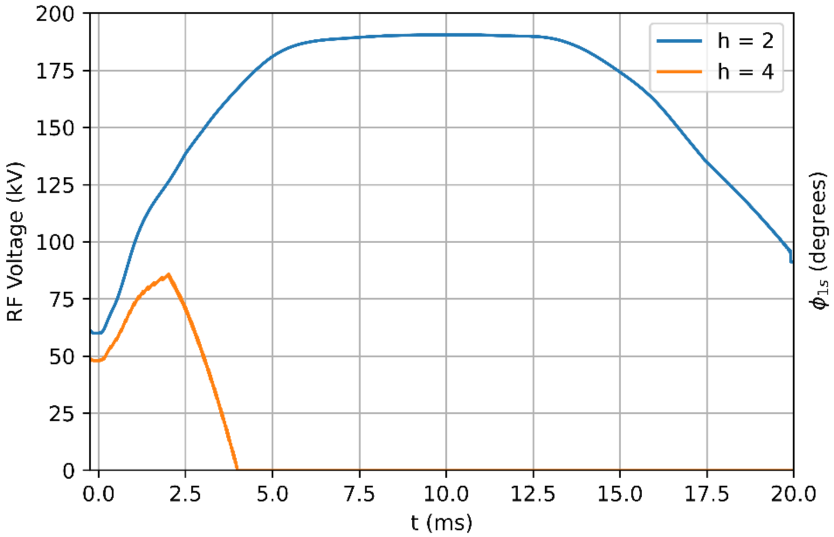


Optimization of rf voltage at extraction stage

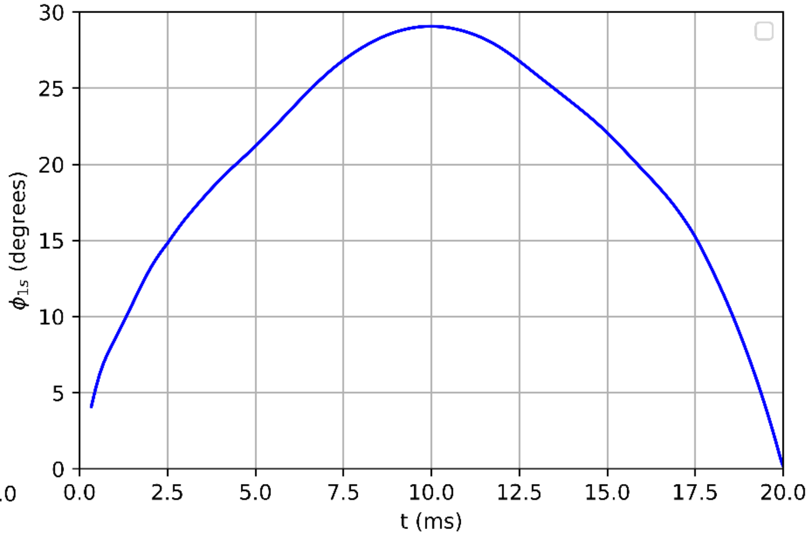
After optimization, the particles exceed bucket are relatively reduced. When the cavity voltage at the extraction stage is increased to above 90 kV, the bunch length can be compressed to below 130 ns

Longitudinal dynamic for CSNS-II

- Optimized rf curves and main parameters



rf voltage curve in CSNS-II RCS



The design value of φ_{1s}

Table 3 RCS main simulation parameters

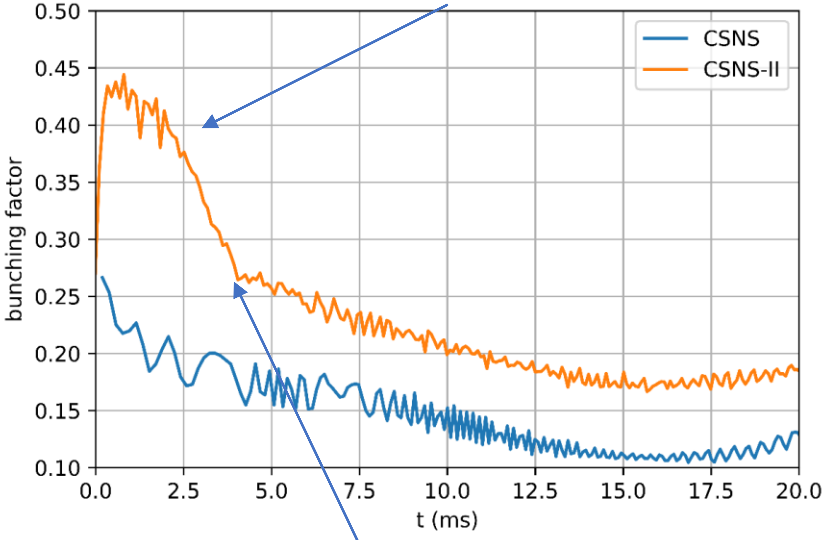
Parameters	CSNS	CSNS-II
RCS betatron tunes (H/V)	4.80/4.87	4.86/4.80
Transverse painting range (mm)	30/15	30/30
The beta function of injection point (m)	6.72/5.58	6.72/5.58
transition γ	4.89	4.89
Inj./ext. magnetic rigidity (T.m)	1.320–7.867	2.695–7.867
Chopper duty (%)	50%	50%
Injection period (μs)	400	500
Number of circulating particles (N_p)	1.56×10^{13}	7.8×10^{13}
Inj./Ext. Energy (GeV)	0.08/1.6	0.3/1.6
Inj. Energy Spread (%)	0.05–0.5	0.05–0.5
Fundamental harmonic RF Voltage (kV)	45–175	60–190

The results of CSNS and CSNS-II in the simulation will be compared in next slide.

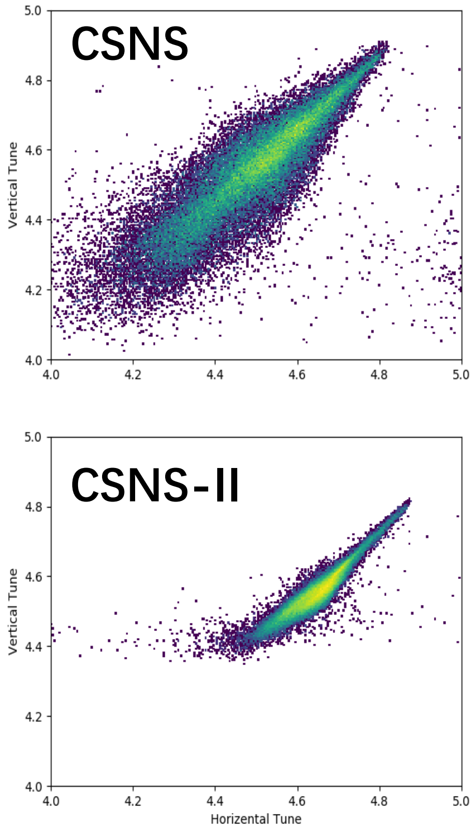
Longitudinal dynamic for CSNS-II

- **CSNS vs CSNS-II**

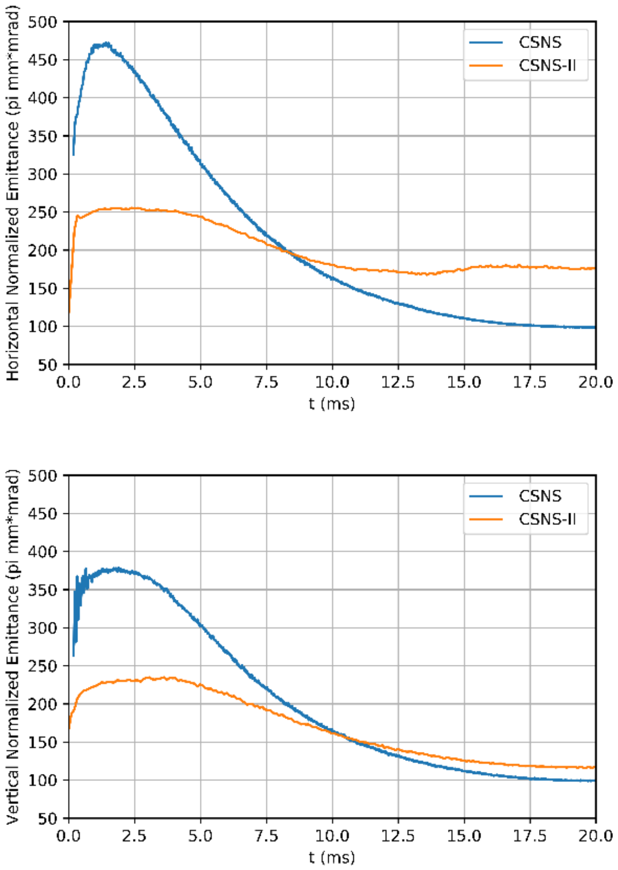
Keep above 0.4 in the first 2 ms



Since the energy increased ,space charge becomes weaker. Lower bunching factor is acceptable.



The tune spread at 500 kW is much smaller than at 100 kW.

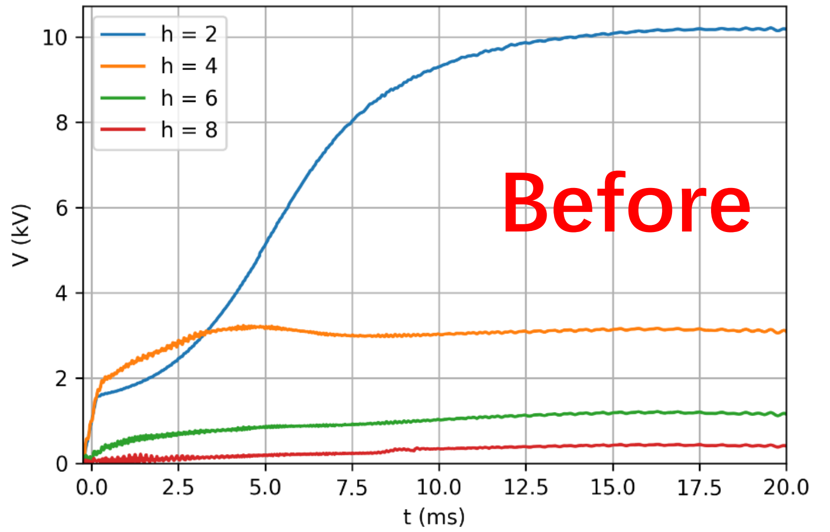


Transverse emittance

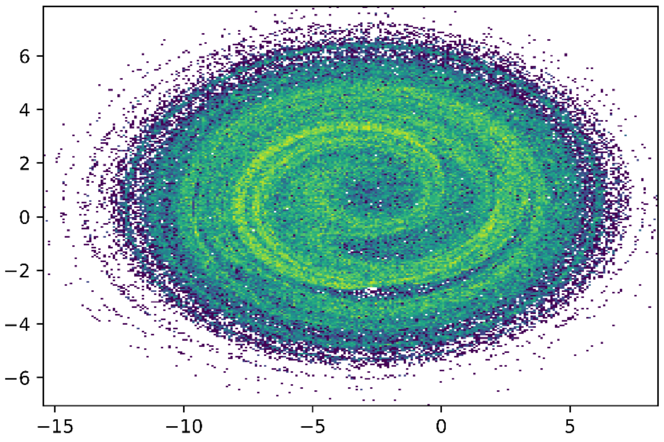
- The transverse emittance at 500 kW is much lower .
- Because of the energy ramp range shrined , the emittance decreases with increasing energy is correspondingly reduced
- However, it is still much smaller than the acceptance of the extraction transport line.

Beam Loading Effect-Compensation

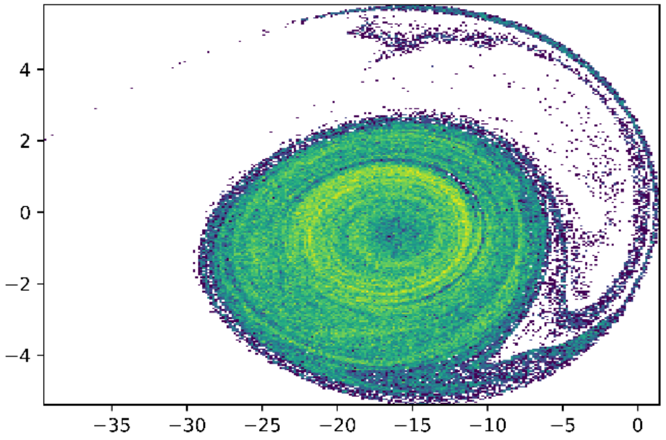
- The MA cavity has a higher accelerating voltage gradient compared to the ferrite cavity and also a wider bandwidth.
- The beam loading effect of MA cavities is very serious and should be considered carefully in high-intensity proton synchrotrons.
- To reduce the beam loading effects, a feedback system is used in the MA cavity for compensating the induced voltage.

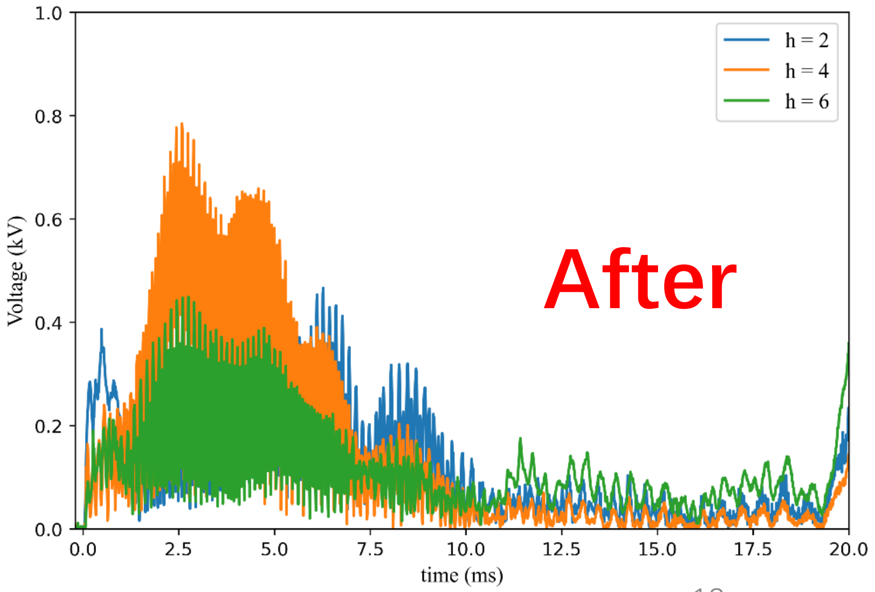


1 MA Cavities

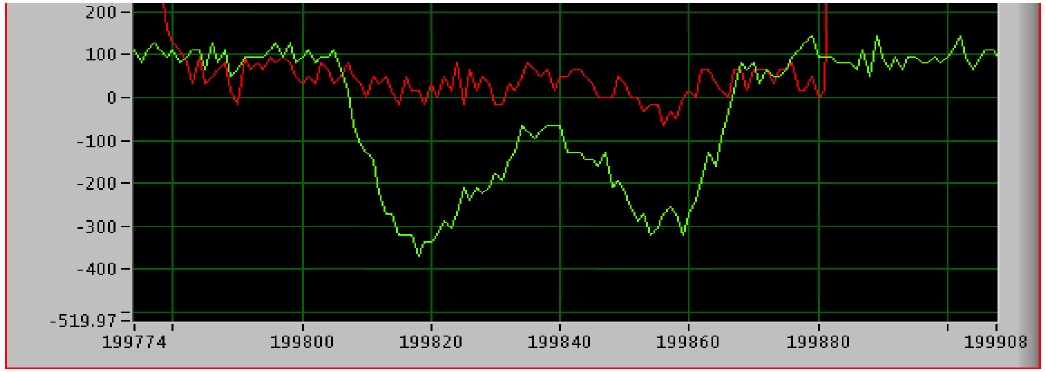


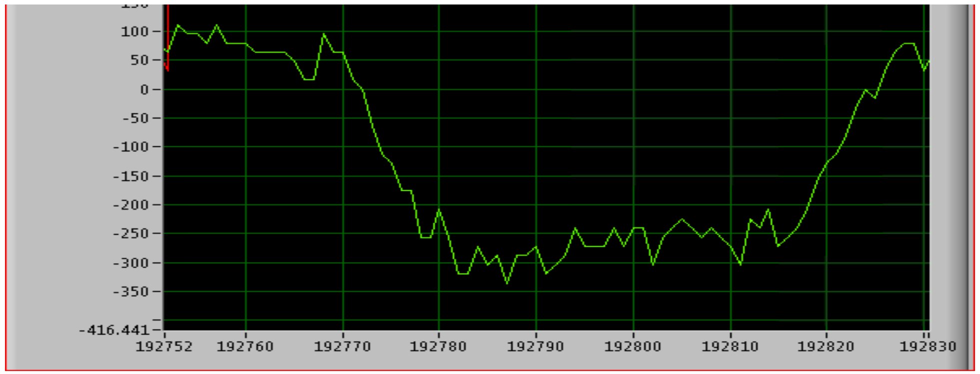
3 MA Cavities





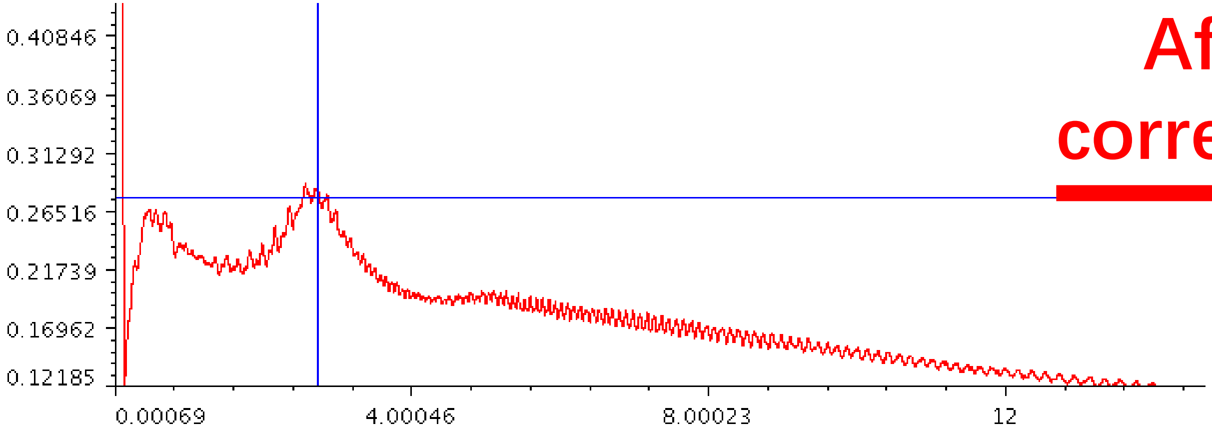
Beam measurement



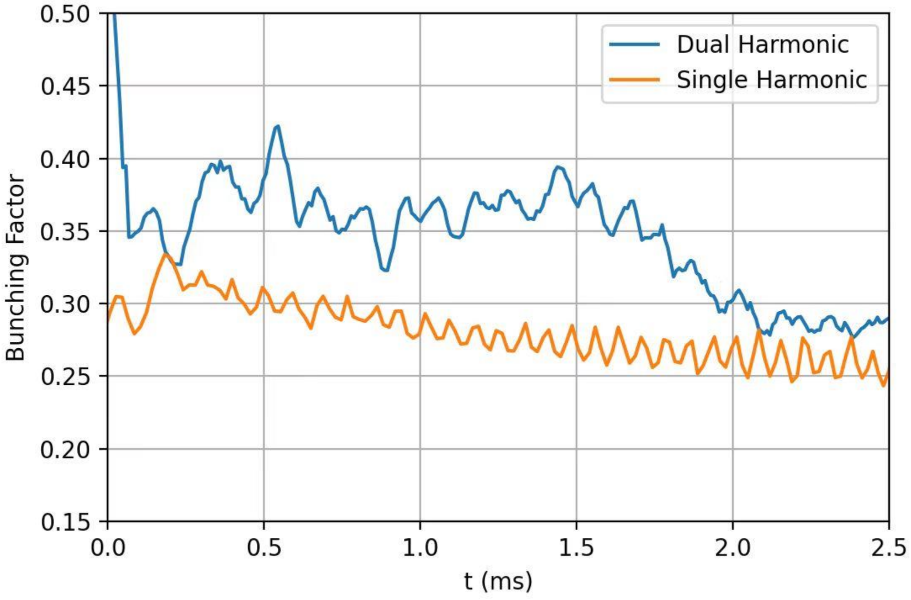


Add magnetic alloy cavity, r=0.8, adjust the second harmonic phase, ensure the peak height of both sides same(phase calibration)

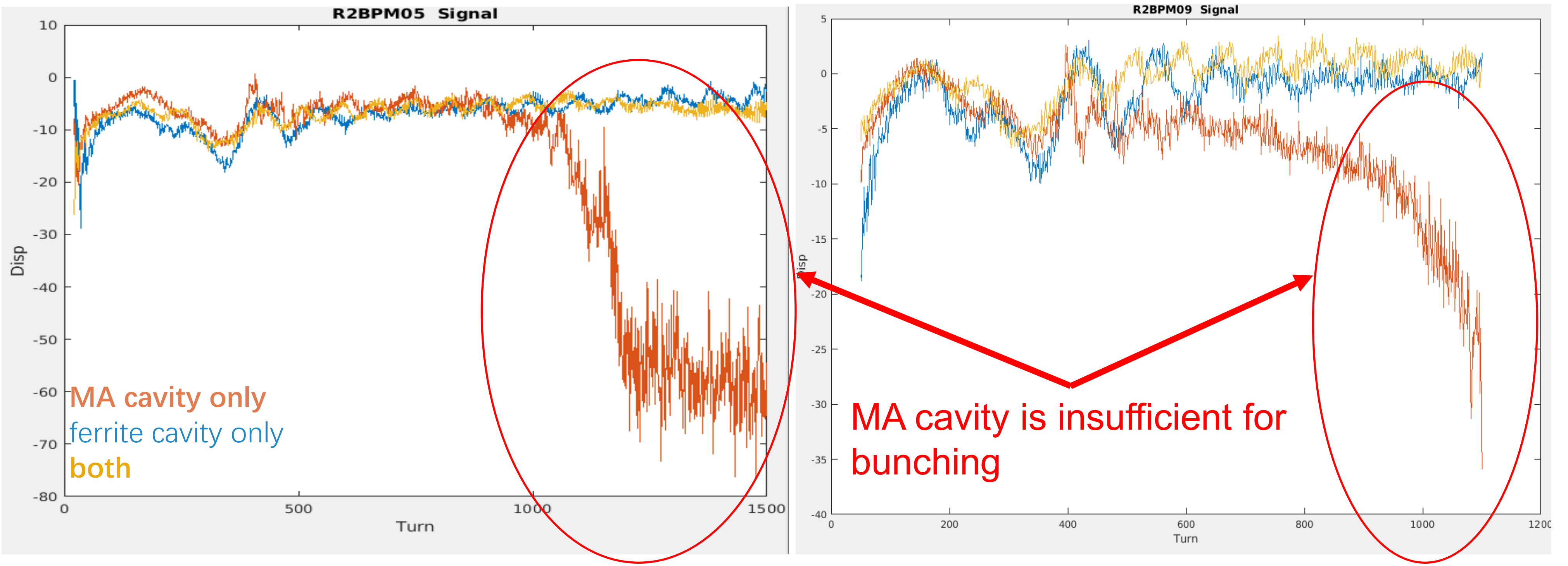
The nominal cavity RF is 16.6kV, the cavity pressure of ferrite is 32kV, r=0.5, which is consistent with the theoretical results (voltage calibration).



After correction

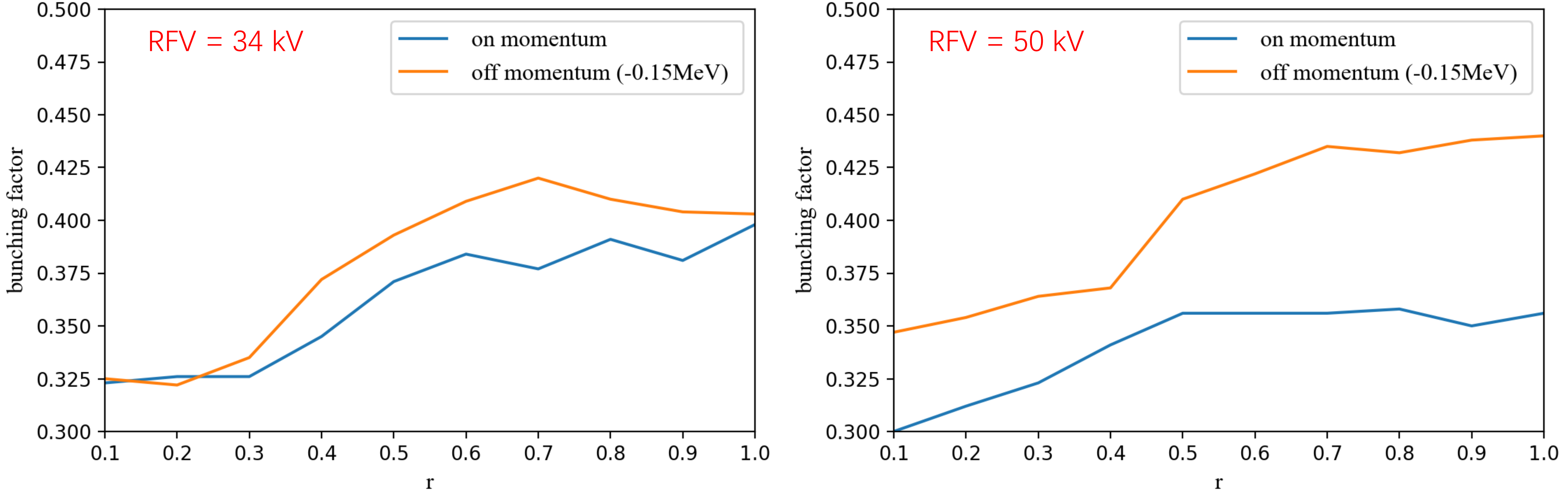


Beam measurement



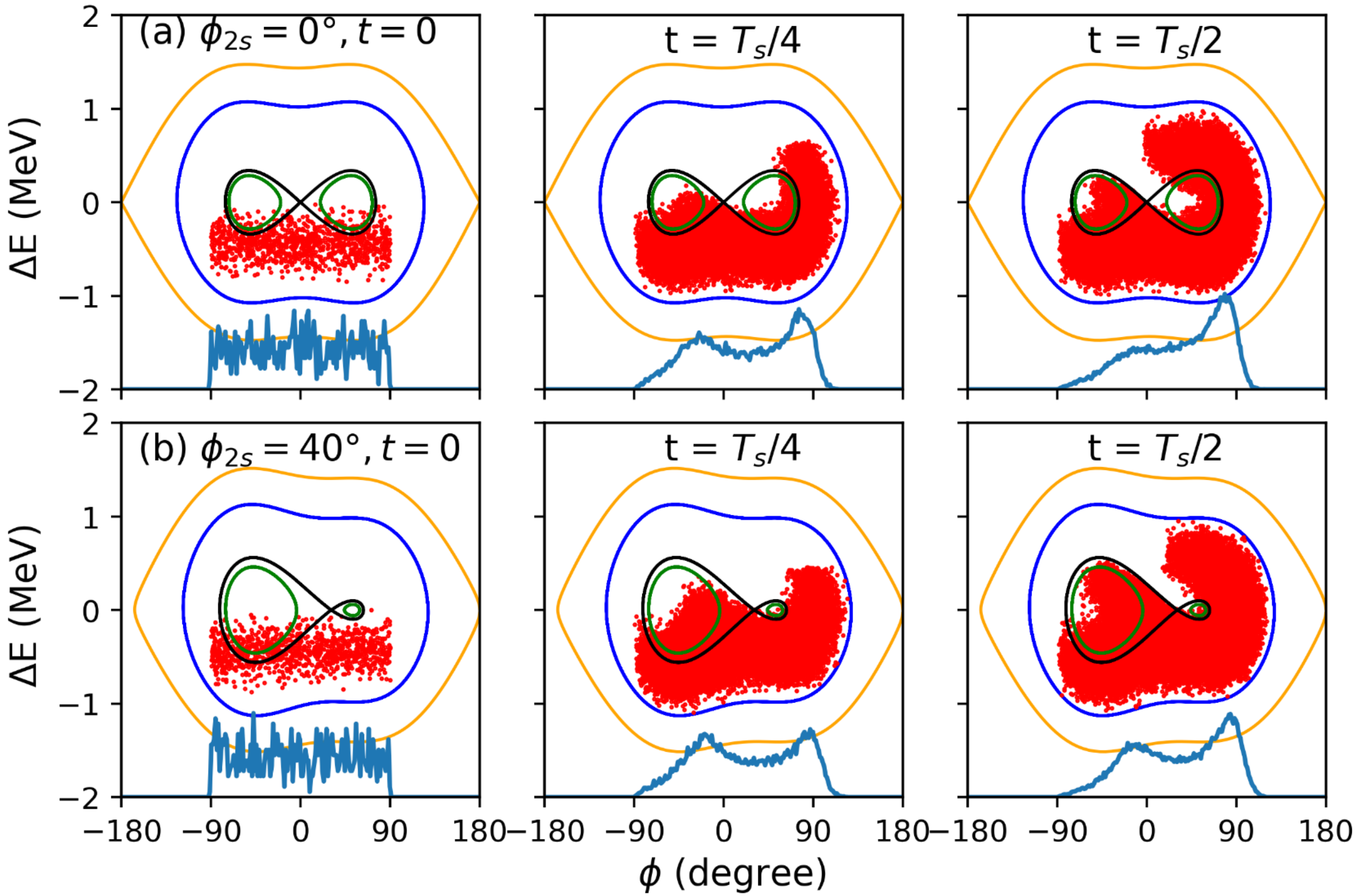
The orbit in the arc section is consistent,
which ensures the timing and frequency are consistent to a certain extent

Beam measurement-Optimizations



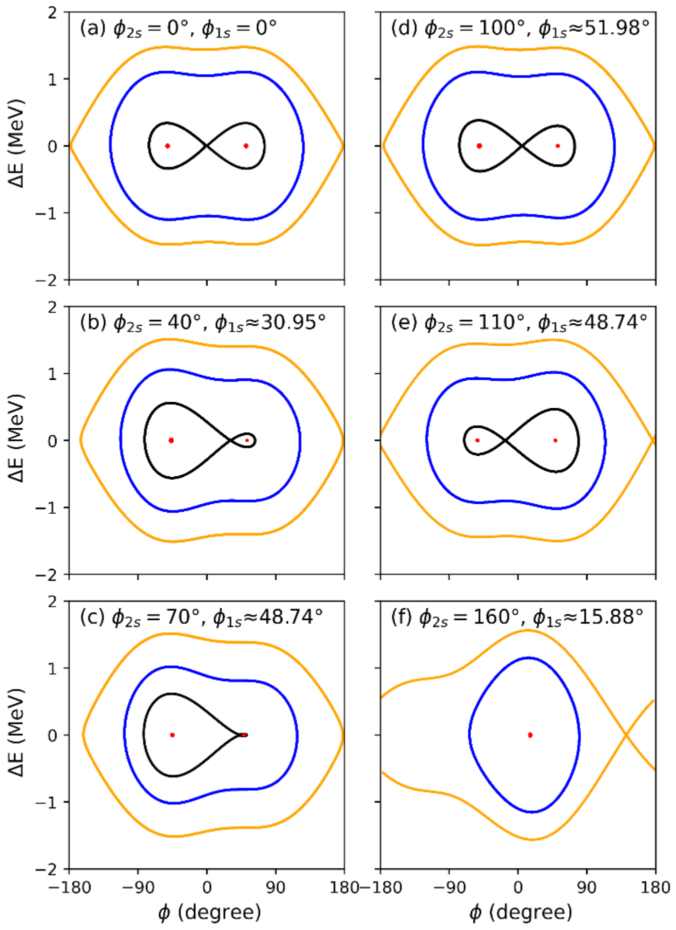
Combining injection momentum offset with a large second harmonic cavity voltage can better increase the bunching factor.

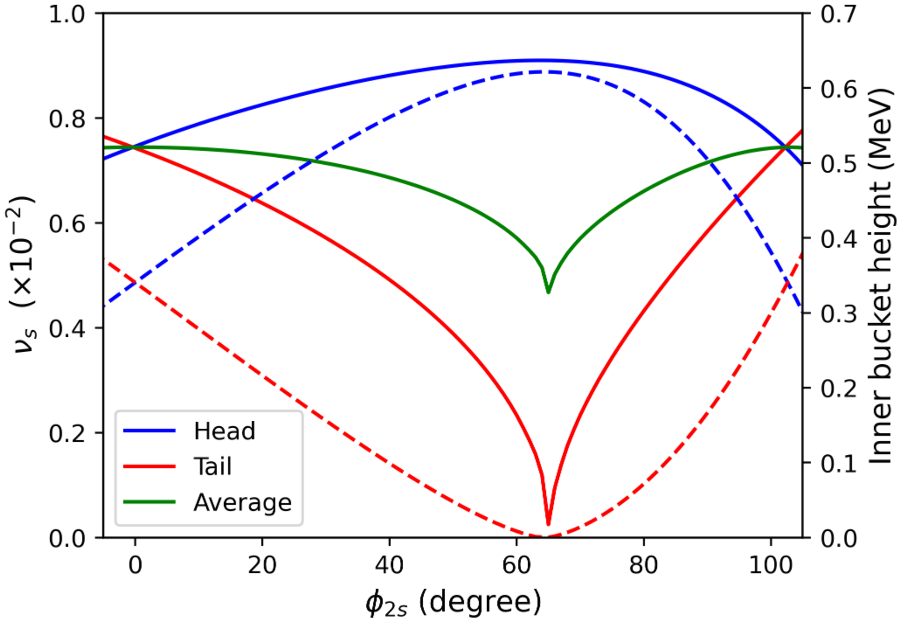
The purpose of phase sweep



- In the presence of non-zero momentum offset the bunching factor decreases in the first one quarter of the synchrotron oscillation period during beam injection.
- More particles are accumulated in one end of the rf bucket, increase the local peak beam current and the (transverse) space charge strength, consequently deteriorate beam quality.
- To address this issue, a phase sweep scheme was proposed by Yamamoto from J-PARC

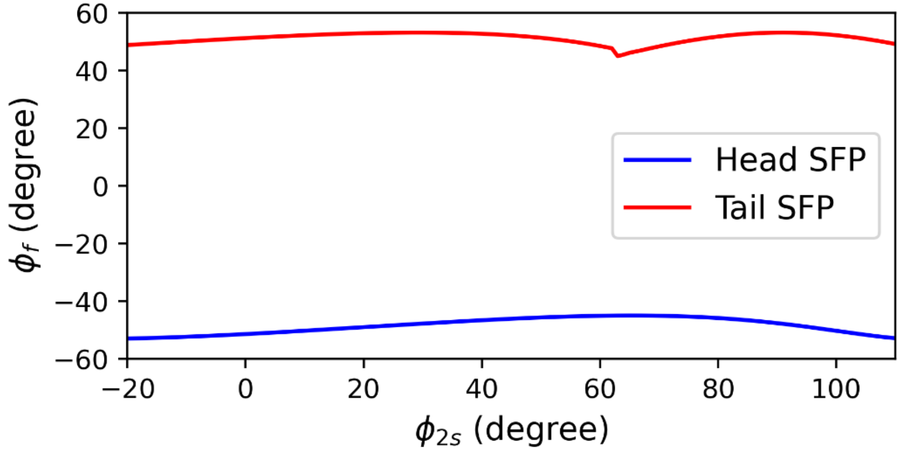
Calculation of phase sweep





$$\begin{cases} \dfrac{\partial \nu_s(\phi_{1s}, \phi_{2s}, \phi_f)}{\partial \phi_{2s}} = 0 \\ \sin\phi_{1s} = r\sin\phi_{2s} \\ \sin\phi_f = r\sin(h_r\phi_f - h_r\phi_{1s} + \phi_{2s}). \end{cases}$$

$$\nu_s = \sqrt{\frac{\eta h_1 e V_1}{2\pi\beta_s^2 E_s}[-\cos\phi_f + h_r r\cos(h_r\phi_f - h_r\phi_{1s} + \phi_{2s})]}.$$



The fixed point position is almost unchanged, but the longitudinal tune nearby fixed points changes dramatically.

Beam measurement-Optimizations

Two goals of "matched phase sweep" :

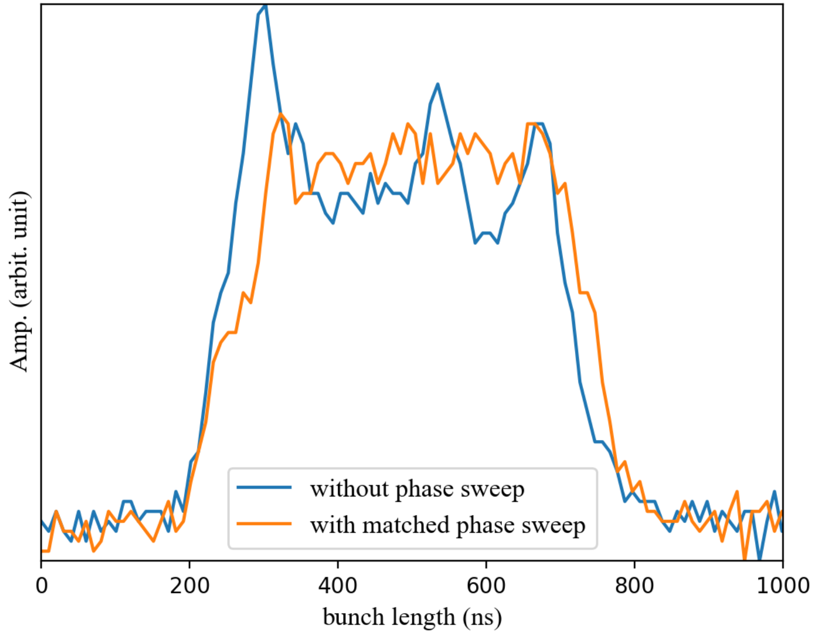
1、Increase the bunching factor during the injection

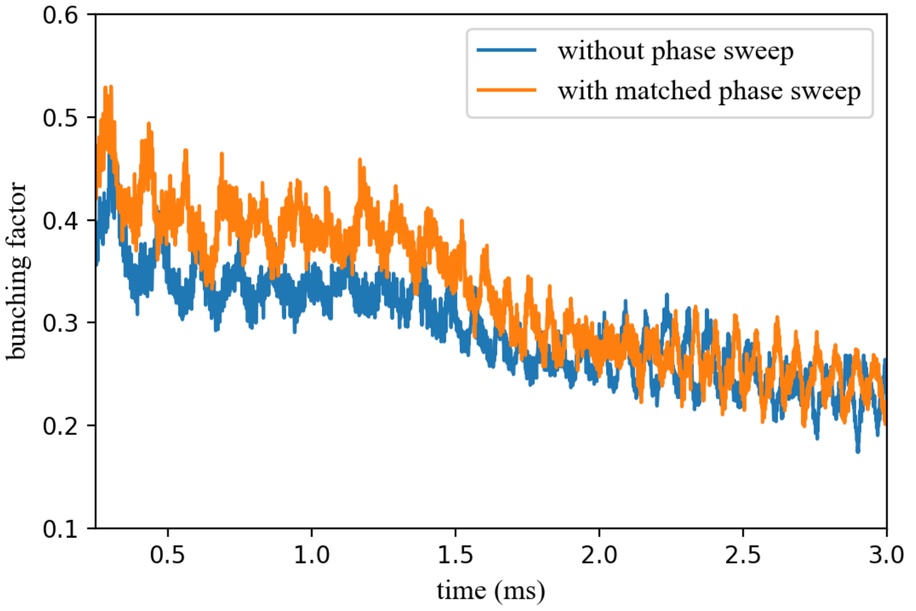
2、Match the Injected beam with the bucket

$$n_0 \nu_{s2,\max} + \int_{n_0}^{n_{inj}} \frac{1}{2}[\nu_{s1}(n) + \nu_{s2}(n)]dn = m$$

The maximum synchrotron oscillation frequency of the head fixed point remains unchanged at the early stage of injection,

and the second harmonic RF phase is slowly shifted to 0 before the end of injection (make the m be a integer)

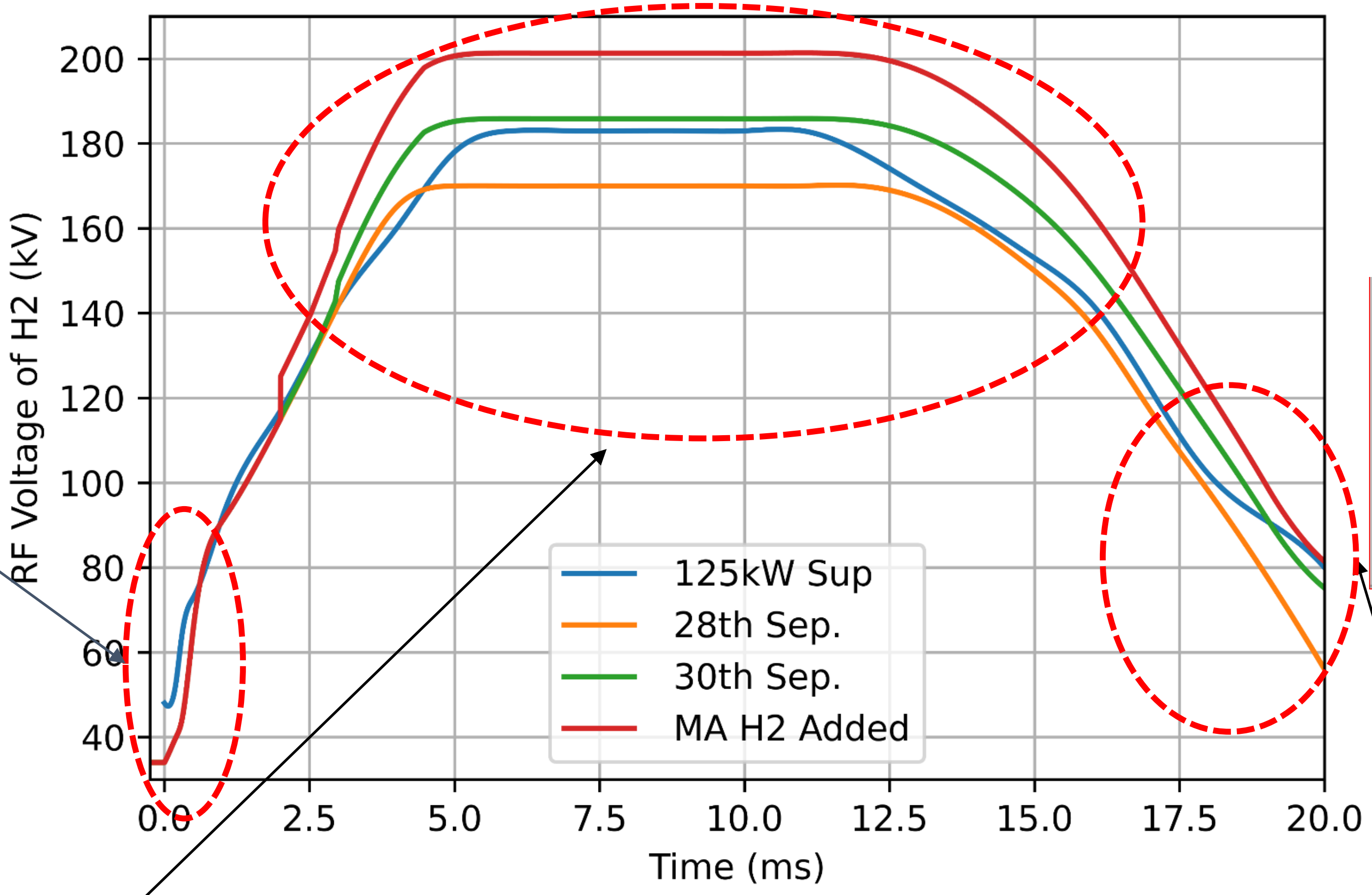


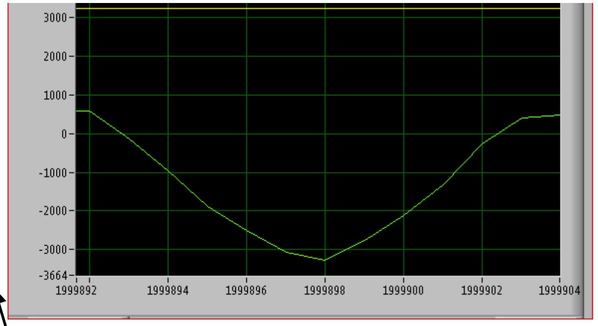


Bunching factor is higher with a matched phase sweep method. Additionally, the beam loss can also increase by approximately 3% with this method.

Beam measurement-Optimizations

Matching of synchronous oscillation period and injection turn.
Also increase the voltage ratio equivalently.





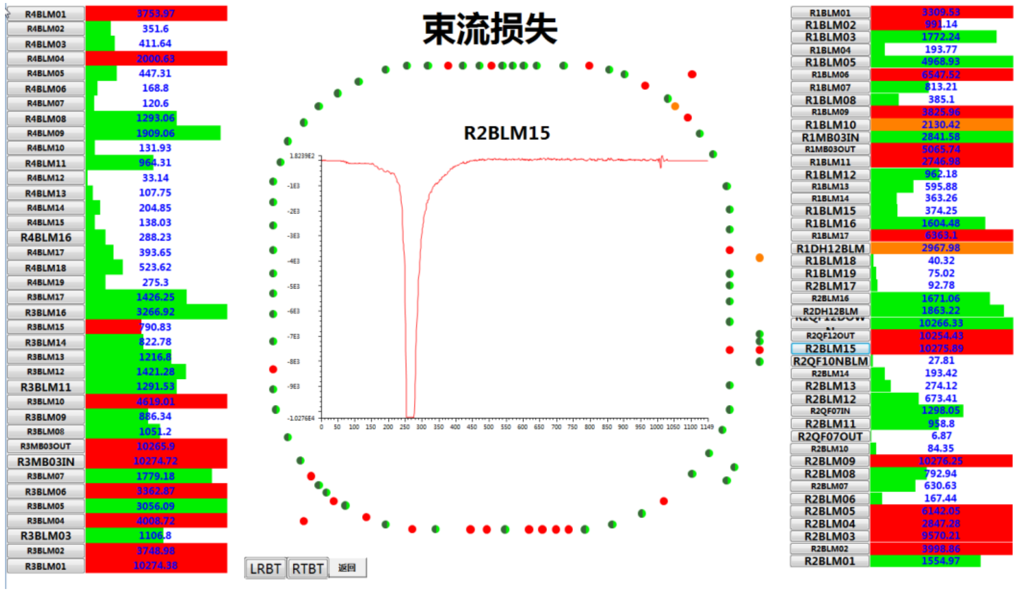
Extracted Bunch Length Compression (less than 120 ns)

Reduce the beam loss in the arc section

Beam measurement-Beam Status

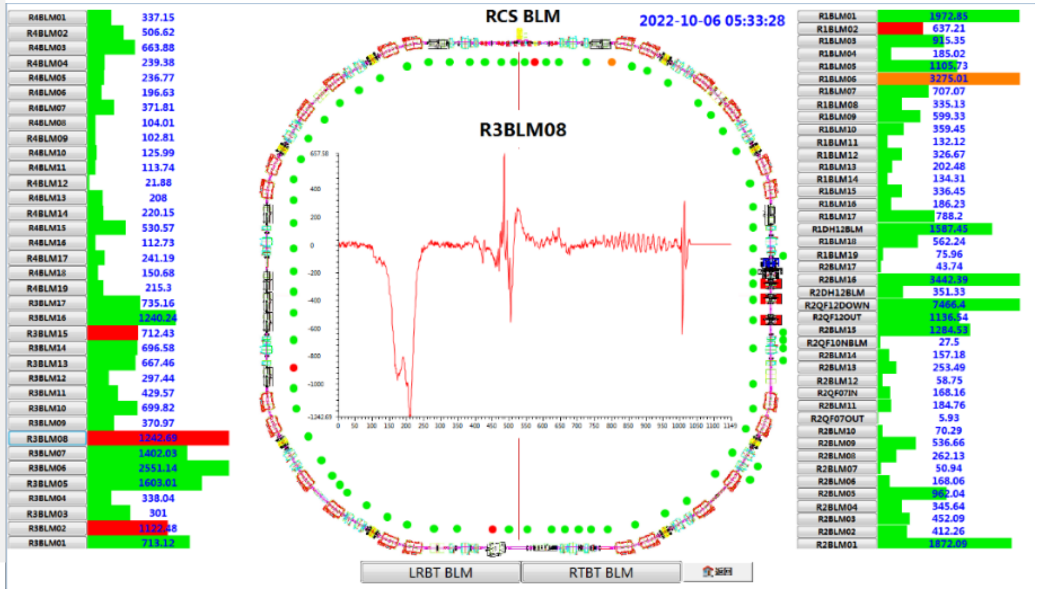
束流状态 2022-10-03 16:51:26

LEBT CT01	41.32	mA	RTBT CT03	-0.04	E12
LEBT CT02	3.14	mA	RDBT CT01	21.59	E12
MEBT CT01	7.11	mA	LEBT Trans	7.6	%
MEBT CT02	7.13	mA	RFQ Trans	226.1	%
LRBT CT01	7.20	mA	MEBT Trans	100.33	%
LRBT CT02	7.18	mA	DTL Trans	100.93	%
LRBT CT03	7.16	mA	LRBT Trans1	99.7	%
LDBT CT01	-0.00	mA	LRBT Trans2	99.8	%
DCCT-INJ	1921.51	mA	LDBT Trans	-	%
DCCT-EXT	4499.05	mA	EXT Trans	101.9	%
DCCT-INJ No	23.39	E12	RCS Trans	98.3	%
DCCT-EXT No	23.00	E12	RTBT Trans		%
RTBT CT01	23.43	E12	RDBT Trans	92.1	%
RTBT CT02	-0.13	E12	Beam Power	150.148	kW

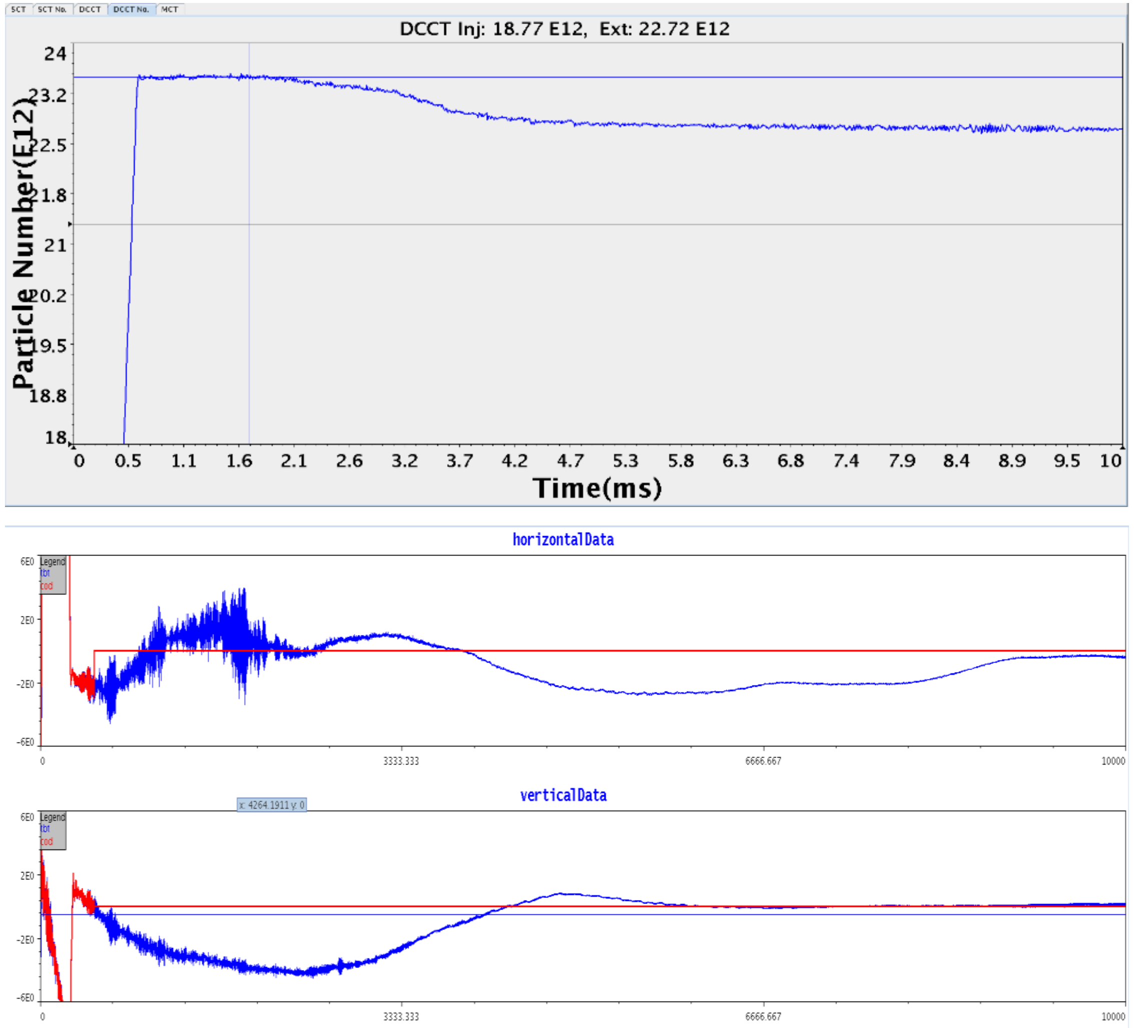


束流状态 2022-10-06 05:32:34

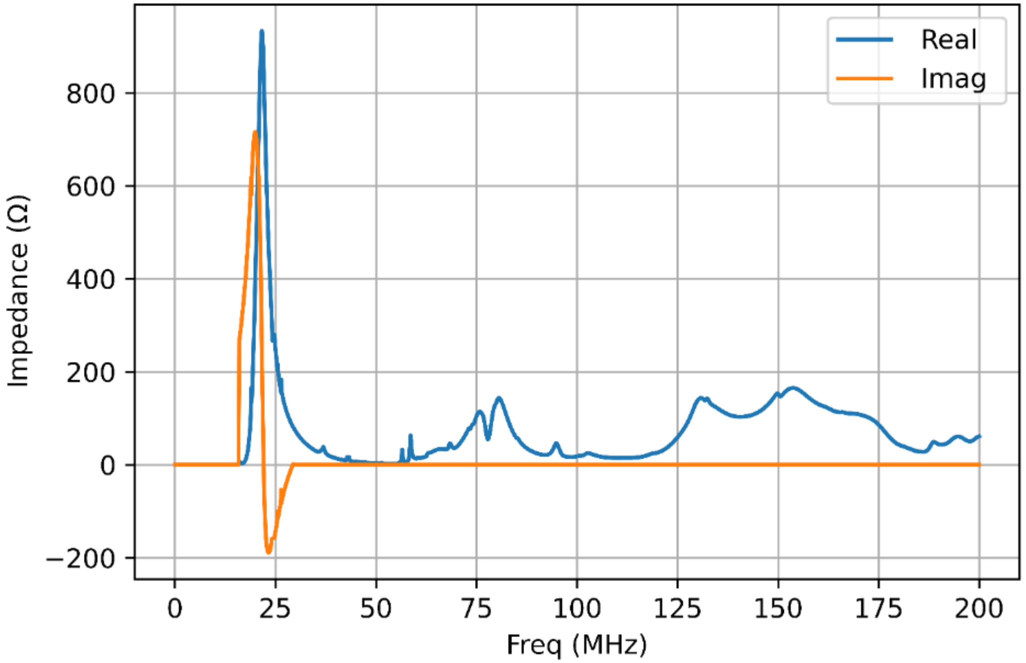
LEBT CT01	41.83	mA	RTBT CT03	-0.05	E12
LEBT CT02	3.10	mA	RDBT CT01	22.47	E12
MEBT CT01	6.75	mA	LEBT Trans	7.4	%
MEBT CT02	6.77	mA	RFQ Trans	218.1	%
LRBT CT01	6.82	mA	MEBT Trans	100.28	%
LRBT CT02	6.80	mA	DTL Trans	100.64	%
LRBT CT03	6.80	mA	LRBT Trans1	99.7	%
LDBT CT01	0.00	mA	LRBT Trans2	100.0	%
DCCT-INJ	1806.60	mA	LDBT Trans	-	%
DCCT-EXT	4223.55	mA	EXT Trans	102.2	%
DCCT-INJ No	22.00	E12	RCS Trans	98.2	%
DCCT-EXT No	21.59	E12	RTBT Trans	-	%
RTBT CT01	22.07	E12	RDBT Trans	101.8	%
RTBT CT02	-0.09	E12	Beam Power	141.444	kW



Next Step-Instability



transverse instability



longitudinal impedance of MA Cavity
(from power supply)

Summary & Outlook

1. The beam commissioning with the first MA cavity in CSNS RCS has been completed, and the beam power has achieved to 140 kW, which is 40% higher than the design.
2. One more MA cavity has been installed in this summer of 2023;
3. Momentum collimator has been designed (2024);
4. Octupoles have been installed to increase Landau damping;
5. Increase the beam power to 200kW with the linac energy of 80MeV

Thanks for your attention !