

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





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





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



140kW has achieved







backgrounds about beam upgraded

- Due to the edge focusing of injection magnets, the acceptance is decreased from 540π mm·mrad to 480π mm·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





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
1	Transverse painting range(mm)	30/20
	β function of inject point (m)	6.72/5.58
J	99.9% emittance after painting	170/155
	without SC (π mm mrad)	
-	Inject period (ms)	0.5
	Chopper duty (%)	50
	Total Injected particle number at 130	$2.028 imes 10^{13}$
	kW N_p	
	Total Injected particle number at 200	3.12×10^{13}
	kW N_p	
		6

• Optimized rf curves



VS







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



Comparison of beam profile



Comparison of phase space at the 5 ms

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



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 μ s, 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





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

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



• Optimized rf curves and main parameters



 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 (μ s)	400	500
Number of circulating particles (N_p)	1.56×10^{13}	$7.8 imes 10^{13}$
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.

CSNS vs CSNS-II



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







time (ms)

13

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).



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.

SNS

The purpose of phase sweep





- In the presence of non-zero momentum ۲ 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





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

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

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



section

SNS

Beam measurement-Beam Status



LRBT BLM

RTBT BLM 19

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	LEBT CT02	3.14	mA	RDBT CT01	21.59	E12	R4BLM07 120.6 R4BLM08 1295.05	•••	R1BLM08 R1BLM09 R1BLM10	3
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	MEBT CT02	7.13	mA	RFQ Trans	226.1	%	R46LM12 33.14 R46LM13 107.75	•	R1BLM12 R1BLM13 R1BLM14	
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	LRBT CT02	7.18	mA	DTL Trans	100.93	%	R4BLM16 288.23 -43 R4BLM17 393.65 -43 R4BLM18 523.62 -43	• •	R1DH12BLM R1BLM18	_
	LRBT CT03	7.16	mA	LRBT Trans1	99.7	%	R48LM19 275.3 .513 R38LM127 14/26.25		R1BLM19 R2BLM17 R2BLM16	
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	DCCT-INJ	1921.51	mA	LDBT Trans	-	%	R35LM13 1225.0 R35LM13 1225.0 R35LM12 1421.28	• •	R2BLM15 R2QF10NBLM R2BLM14	
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	DCCT-EXT No	23.00	E12	RTBT Trans		%	R3MB03IN 8974 72	••••	R2BLM09 R2BLM08	
	RTBT CT01	23.43	E12	RDBT Trans	92.1	%	R3BLM06 S056.69	• •	R2BLM07 R2BLM06 R2BLM05	
	RTBT CT02	-0.13	E12	Beam Power	150.148) kW	R3BLM03 1101.8 R3BLM03 2.001.8	• •••• • •	R2BLM04 R2BLM03 R2BLM02	
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Next Step-Instability





transverse instability

200



- 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 !