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RESONANCE EXTRACTION RESEARCH BASED ON CHINA SPALLATION NEUTRON SOURCE

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Abstract

Resonance extraction from the RCS ring is a crucial element in beam applications. This article presents a novel design for resonance extraction in the CSNS-RCS ring. Through parameter adjustments, including the skew sextupole magnet, beam working point, RF-Kicker, and more, simulation results highlight the capability to efficiently extract a significant number of protons within a few revolutions. This innovative design offers new insights and approaches towards achieving high-performance proton beam extraction.

INTRODUCTION

The CSNS accelerator is made up of a linear accelerator (LINAC) and a rapid cycling synchrotron (RCS) [1, 2]. In 2020, it achieved stable operation at a power level of 100 kW. CSNSII is a significant upgrade to the accelerator, incorporating a superconducting radiofrequency system to increase the energy of the LINAC to 300 MeV. Additionally, the number of injected particles will be multiplied by five, allowing the accelerator to reach a target power of 500 kW. Table 1 shows the upgrades schemes of the CSNS.

Table 1: Upgrades Schemes of the CSNS

	CSNS I	CSNS II
Beam power	100	500
Repetition Rate [Hz]	25	25
Inj. Energy [MeV]	80	300
Ext. Energy [GeV]	1.6	1.6
Beam Intensity [$*10^{13}$]	1.56	7.8
Harmonic number	2	4

The increase in power of the neutron scattering source opens up more possibilities for its widespread applications. Proton radiography is one potential application of the neutron scattering source, which requires the extraction of beam bunches with strict specifications. For example, the time interval between adjacent beam bunches should be 410 ns, and each beam bunch should contain a high number of particles, such as exceeding 1E11 particles. In the case of CSNSII, the total number of particles in the extracted beam bunches is 7.8E13. If these particles can be extracted through resonant extraction, the requirements can be met.

The article is structured as follows: the second section discusses the design of the lattice, the third section presents the simulation of resonant extraction, the fourth section discusses the parameters of the skew sextupole, septa and RF Kicker, and the final section provides a summary.

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LATTICE DESIGN OF THE CSNSII

The lattice design of the CSNS-RCS is of utmost importance and has specific requirements to meet desired operational characteristics. One crucial requirement is the flexibility to adjust the working point of the optics. This adjustment allows for mitigating beam instability by varying the working point from 4.3/4.3 (horizontal/vertical) to 5.3/5.3 (horizontal/vertical), and it also enables easy adjustment of the working point to the third-order resonance for beam expansion and applications. Additionally, the magnets used in the lattice design should have relatively small apertures to reduce costs and provide longer straight sections. These straight sections are essential for accommodating high-frequency cavities, injection systems, collimators, and extraction devices.

Figure 1 provides a visualization of the twiss parameters for a single super-period in the RCS lattice. The CSNS-RCS lattice is constructed using a triplet cell configuration with a total circumference of 227.92 m. The linear lattice consists of 48 quadrupoles powered by five families of power supplies. Additionally, there are 24 dipoles powered by a single power supply.

Overall, the lattice design of the CSNS-RCS is carefully engineered to ensure flexibility in optics adjustment, cost-effectiveness, and the provision of suitable spaces for essential components and devices.

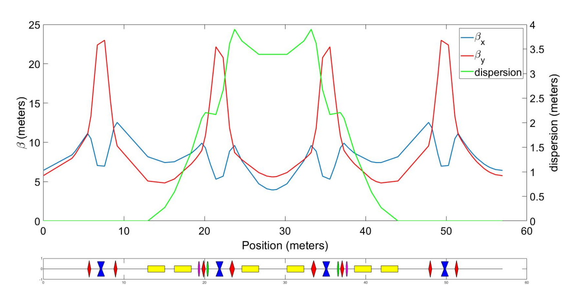

Figure 1: Twiss parameters of the RCS one super-period.

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SIMULATION OF THE RESONANT EXTRATION

Introduction of the Resonant Extraction

In the fast extraction mode of the CSNS-RCS, particles injected into the ring circulate for approximately 20,000 turns before being extracted. This extraction process involves the use of eight kicker magnets that induce a vertical deflection of about 20 mrad. The extracted particles then pass through Lambertson magnets and the RTBT (Ring to Target Beam Transport Line) to be delivered to the desired experimental area. To accommodate this fast extraction mode, the resonant extraction design incorporates skew sextupole magnets that can induce resonant oscillations in the vertical direction. The basic principle of resonant extraction with skew sextupole magnets is as follows [3–5]: Written in normalized coordinates of the phase space vector $\vec{Y} = (Y, Y')$ with

$$Y \equiv \frac{y}{\sqrt{\beta_y}}, Y' \equiv \sqrt{\beta_y y'} + \frac{\alpha_y}{\sqrt{\beta_y}} y, \tag{1}$$

see, e.g., [4], the UFPs have all the same absolute value

$$|\vec{Y}_{UFP}| = 8\pi |\frac{Q_r - Q_p}{S_v}| \tag{2}$$

where Q_r and Q_p are resonance tune and on-axis tune of the particles. The latter can be modified by chromaticity ξ_y and relative momentum deviation δ of the particles to

$$Q_p \equiv Q_m + \xi\delta. \tag{3}$$

S_v in Eq. (2) is the strength of a virtual sextupole and is given by

$$S_v e^{3i\psi_v} = \sum_n S_n e^{3i\psi_n}, \tag{4}$$

with the normalized strength of nth sextupole

$$S_n = \frac{1}{2}\beta_{x,n}^{3/2}(k_2 L)_n. \tag{5}$$

The resulting size of the stable phase space area is

$$A_{stable} = \frac{\sqrt{27}}{4}|\vec{Y}_{UFP}|. \tag{6}$$

The corresponding emittance is

$$\epsilon_{stable} = \frac{A_{stable}}{\pi}. \tag{7}$$

From Eq. (2), it can be seen that the efficiency induced by resonance extraction is inversely proportional to the strength of the sextupole magnet and directly proportional to the frequency distance between the particle and the resonance line.

Simulation of the Resonance Extracting

We need to study the necessity of septum magnets. There are two main considerations for the necessity of septum magnets. First, based on the characteristics of the RCS machine, which has a basic lattice structure of a triplet, it is difficult to design a suitable trajectory that achieves an emittance of 350 pi-mm-mr while maintaining an acceptance of 540 pi-mm-mr at the location of the Lambertson magnet. Second, the deflection angle of the Lambertson magnet is 20 mrad, and it is challenging to achieve such a large angle using resonance-induced sextupole magnets. Figure 2 illustrates the change in machine acceptance after incorporating the trajectory.

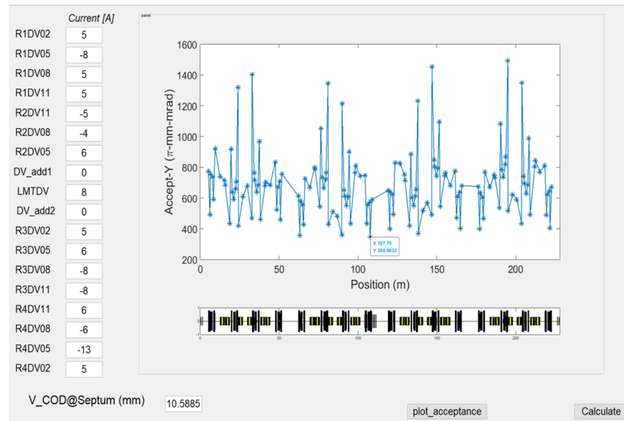

Figure 2: The acceptance shrink due to correctors.

Figure 3 displays the phase space obtained from different combinations and phases of the skew sextupole magnets.

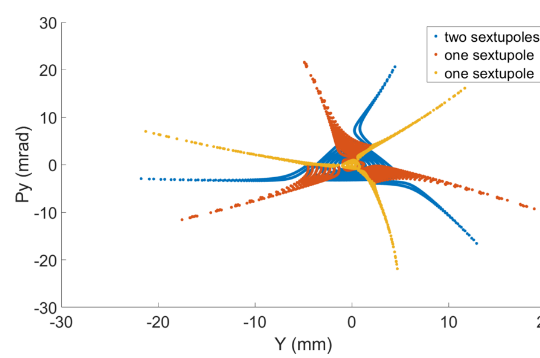

Figure 3: Resonance extraction due to skewsextupoles.

PARAMETERS OF THE SKEW SEXTUPOLE, SEPTA AND RF KICKER

Location of the Skew Sextupole, Septa and RF Kicker

Figure 4 shows the lattice structure of the extraction section. The red line represents the beam with an emittance of 350 pi·mm·mrad being extracted using 8 kicker magnets and directed towards the Lambertson magnet. The green line represents the acceptance of the circular beam pipe, which is 540 pi·mm·mrad. The white box represents the position of the septum. The skew sextupole magnet is located at the straight section of the RCS ring. The β_x/β_y values of the skew sextupole magnet are 6.83 m/5.24 m, indicating that the sextupole magnet has a relatively small aperture. The RF-kicker is in the region 4 of the RCS.

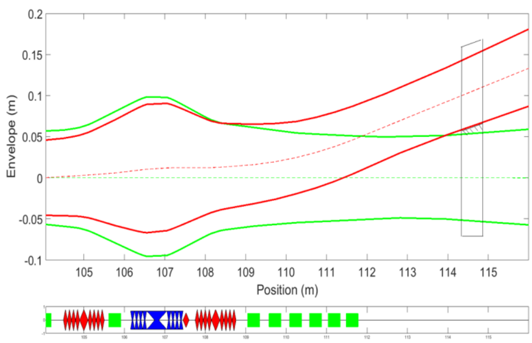

Figure 4: Envelope in the beam extraction area.

Parameters of the Skew Sextupole, Septa and RF Kicker

The RCS is accelerated to 1.6 GeV within 20 ms. During the extraction, we simulated resonant extraction under the conditions listed in Table 2. The beam passes through the skew sextupole magnet, causing the emittance to rapidly increase. It is then deflected by 20 mrad through the septum and enters the Lamberson magnet. During normal beam operation, the septum will be removed. However, for resonance extraction experiments, the septum will be reinstalled. Table 2 show the parameters of the skew sextupole, septum and RF kicker in our simulation.

Table 2: Parameters of the Skew Sextupole, Septa and RF Kicker

Devices	Parameters	Values
Skew sextupole	Length (m)	1
	Strength (T/m*m)	80
	Rate of change (T/(m*m*µs))	0.1
Septum	Central Field (T)	0.1
	Length(m)	1
	Thickness(mm)	1.5
	Gap(mm)	40
	Leak Field	<0.01
RF kicker	Max. kick angle (µrad)	4.0
	Freq. of RF kicker(MHz)	0.83

Simulation Results

From section II, it can be observed that the area of the stable region is mainly determined by the distance of the beam from the resonance line and the strength of the sextupole magnet. In our study, we first varied the strength of the sextupole magnet with a certain rate of change and found that the requirements for resonance extraction could be met. However, due to the high level of factors such as

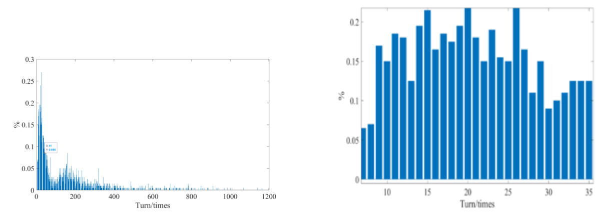

Figure 5: Beam instability occured without sextupoles.

power supply ripple at the operating point of 0.67, we considered changing the lattice through QT in the simulation. This approach helps to avoid the impact of ripple and beam stability. Fig. 5 shows the optimized beam extraction, and the results indicate that the beam extracted per revolution meets the requirements.

CONCLUSION

With the increasing power of spallation neutron sources, there is a growing demand for beam-based applications. Techniques such as proton radiography require accelerators to provide beam bunches with large pulse energies and short pulse intervals. In this paper, we investigate the feasibility of achieving this in the RCS ring through resonance extraction. By adjusting parameters such as the skew sextupole magnet, RF kicker, and septum, the simulation results meet the requirements of the users.

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REFERENCES

[1] S. Wang, S. X. Fang, Q. Qin, J. Y. Tang, and J. Wei, "Introduction to the overall physics design of CSNS accelerators", *Chin. Phys. C*, vol. 33, p. 1, 2009. doi:10.1088/1674-1137/33/s2/001

[2] J. Wei, S. N. Fu, J. Y. Tang, J. Z. Tao, D. S. Wang, F. W. Wang, and S. Wang, "China Spallation Neutron Source – an overview of application prospects", *Chin. Phys. C*, vol. 33, p. 1033, 2009. doi:10.1088/1674-1137/33/11/021

[3] T. Furukawa et al., "Global spill control in RF-knockout slow-extraction", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 522, pp. 196-204, 2004. doi:10.1016/j.nima.2003.11.395

[4] S. Sorge, P. Forck, R. Singh, "Spill ripple mitigationo by bunched beam extraction with high frequency synchrotron motion", *Phys. Rev. Spec. Top. Accel Beams*, vol. 26, p. 014402, 2023. doi:10.1103/PhysRevAccelBeams.26.014402

[5] L. Badano, M. Benedikt, P. J. Bryant, M. Crescenti, P. Holy, A. Maier, M. Pullia, and S. Rossi, "Proton-ion medical machine study (PIMMS) part I", CERN, Geneva, Switzerland, Rep. CERN/PS/99-010 (DI), 1999, https://cds.cern.ch/record/385378/files/ps-99-010.pdf/.