CHINA SPALLATION NEUTRON SOURCE ACCELERATORS: DESIGN, RESEARCH, AND DEVELOPMENT*

Jie Wei[†§], Shinian Fu[‡], and Shouxian Fang[‡]
for the China Spallation Neutron Source Accelerator Team
Institute of High Energy Physics, China[‡]; Brookhaven National Laboratory, USA[§]

Abstract

The China Spallation Neutron Source (CSNS) is a newly approved high-power accelerator project based on a H^- linear accelerator and a rapid cycling synchrotron. During the past year, several major revisions were made on the design including the type of the front end, the linac frequency, the transport layout, the ring lattice, and the type of ring components. Here, we discuss the rationale of design revisions, status of the R&D efforts, and upgrade considerations.

INTRODUCTION

The China Spallation Neutron Source (CSNS) provides a multidisciplinary platform for scientific research and applications by national institutions, universities, and industries [1, 2]. The high-flux pulsed neutrons from CSNS will compliment cw neutrons from nuclear reactors and synchrotron lights from synchrotron radiation facilities. Strongly advocated by the users groups, the CSNS project was approved by the Chinese central government in 2005.

The CSNS accelerator is the first large-scale, high-power accelerator project to be constructed in China. The CSNS is designed to accelerate proton beam pulses to 1.6 GeV kinetic energy at 25 Hz repetition rate, striking a solid metal target to produce spallation neutrons. As shown in Fig. 1 and Table 1, the accelerator complex is designed to deliver a beam power of 120 kW with the upgrade capability of up to 500 kW by raising the linac output energy and increasing the beam intensity.

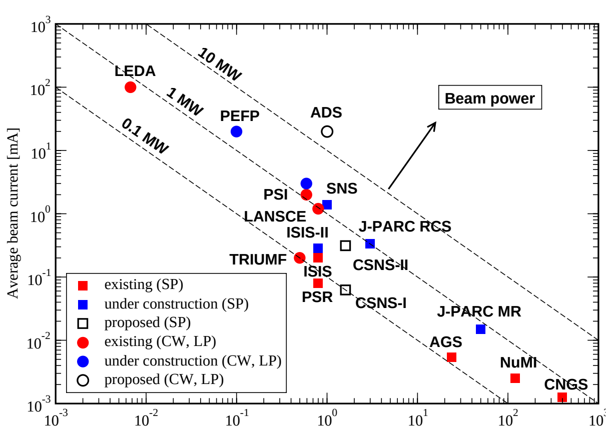

Figure 1: Accelerators at the power frontier (short pulse SP, long pulse LP, continuous wave CW).

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† weijie@ihep.ac.cn and jwei@bnl.gov

Table 1: CSNS accelerator primary parameters.

Project Phase	**I**	**II**	**II'**
Beam power on target [kW]	120	240	500
Proton energy on target [GeV]	1.6	1.6	1.6
Average beam current [μA]	76	151	315
Pulse repetition rate [Hz]	25	25	25
Proton per pulse on target [10^{13}]	1.9	3.8	7.8
Charge per pulse on target [μC]	3.0	6.0	12.5
Pulse length on target [ns]	<400	<400	<400
Front end length [m]	8.7	8.7	8.7
Linac output energy [MeV]	81	134	230
Linac length [m]	41.5	67.6	77.6
Linac type	DTL	DTL	DTL,SCL
Linac RF frequency [MHz]	324	324	324
Macropulse ave. current [mA]	15	30	40
Macropulse duty factor [%]	1.1	1.1	1.7
LRBT length [m]	142	116	106
Synchrotron circumference [m]	230.8	230.8	230.8
RTBT length [m]	76.3	76.3	76.3
Ring filling time [ms]	0.42	0.42	0.68
Ring RF frequency [MHz]	1.0-2.4	1.3-2.4	1.6-2.4
Number of injection turns	213	264	530
Max. uncontr. beam loss [W/m]	1	1	1
Target number	1	1	1 or 2
Target material	Tungsten		
Moderators	H_2O, CH_4, H_2		
Number of spectrometers	7	18	>18

Figure 2: Schematic layout of the CSNS complex (courtesy Institute of Physics, CAS).

The H^- beam is first produced from the ion source and transported, with pre-chopping option, through the Low Energy Beam Transport (LEBT). The beam is then bunched and accelerated through the Radio Frequency Quadrupole linac (RFQ) at a frequency of 324 MHz. The Medium Energy Beam Transport (MEBT) accepts the 3 MeV beam from the RFQ, further chops the beam to the ring RF period, and matches the beam to the Drift Tube Linac (DTL). At phase I, the DTL accelerates the beam to 81 MeV. The Linac to Ring Beam Transport (LRBT) contains empty drift spaces for future addition of linac modules (DTL or superconducting RF, SCL) for the linac energy and beam power upgrade. Upon collimation in both the transverse and longitudinal directions in the LRBT, the H^- beam is stripped of the electrons and injected by phase-space painting into the rapid-cycling synchrotron (RCS) ring. The ring accumulates and then accelerates the proton beam to 1.6 GeV. The beam pulse is extracted in a single turn and delivered to the target through the Ring to Target Beam Transport (RTBT) (Fig. 2, [1]).

DESIGN PHILOSOPHY

Financially, the project must fit in China's present economical condition with a cost of near 1.5 B CNY. This limits the initial accelerator power to about 120 kW. On the other hand, we reserve the accelerator upgrade potential up to 500 kW. Since this is the first high-intensity proton machine in China, we intend to adopt mature technology as much as possible.

Among physical, technical, and management challenges [3] facing the project, the primary challenges are to complete the project at first quality with a fraction of the "world standard" cost, and to reserve upgrade potential for future developments. To meet these challenges, we must keep the final component fabrication domestic as much as possible and seek worldwide collaborations.

DESIGN, RESEARCH & DEVELOPMENT

The design of the accelerator complex is based on the experience at major high-power facilities including ISIS, PSR, SNS, J-PARC, and BNL AGS/Booster (Fig. 1).

Ion Source and Linac

The H^- ion source needs to provide 0.5 ms long, 15 mA peak current pulses at 25 Hz to 50 keV energy (phase I). The design transverse emittance (rms normalized) is $0.2\pi\mu$m. The design lifetime is 30 days. Two types of ion sources are considered: the ISIS-type Penning surface source, and the DESY/modified-SNS-type RF driven source with external antenna. A test stand for the ISIS-type source with a magnetic LEBT is under development.

The four-vane RFQ of CSNS is similar to the one previously developed at IHEP for the Accelerator Driven Subcritical reactor (ADS) program [4]. The main differences are that the frequency is chosen to be 324 MHz considering the available pulsed RF source, and the input energy is lowered to 50 keV to ease chopping.

The 324 MHz DTL is under prototyping. The DTL bore face angles are optimized, and electromagnetic quadrupoles made of Sakae coils are used. Both electroforming and explosive-forming methods are attempted for the DTL tank. We plan to power the DTL tanks with 2.5 MW peak power, 3% maximum duty klystrons from Toshiba and IGBT converter modulators under development domestically.

Synchrotron and Transport

A four-fold symmetry is chosen for the RCS to separate injection, collimation, and extraction to different straights (Fig. 3). The longitudinal and transverse collimation occupies a long section immediately downstream of the injection.

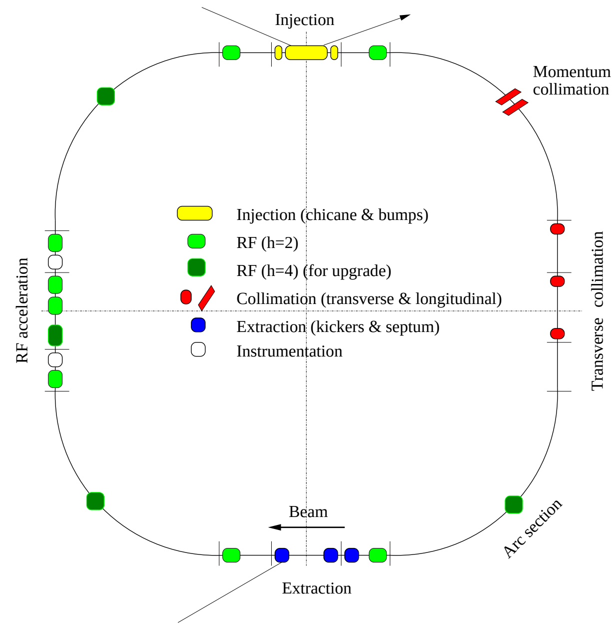

Figure 3: Schematic layout of the CSNS synchrotron.

The ring adopts a hybrid lattice with missing-dipole FODO arc and doublet straight [5, 6]. The long (one 9 m and two 6 m uninterrupted drifts per straight) straights facilitate injection [7], extraction, and transverse collimation. The FODO arcs allow easy lattice optics correction. The 4 m gap created by the missing dipole near the maximum dispersion location allow efficient longitudinal collimation.

The transverse acceptance is $350\pi\mu$m at the collimator and ring extraction channel, and $540\pi\mu$m elsewhere in the ring. The expected space-charge tune spread is near 0.3 for a beam of $320\pi\mu$m emittance. The momentum acceptance in $\Delta p/p$ is $\pm 1\%$ at the longitudinal collimator, and $\pm 1.5\%$ elsewhere for a beam of $320\pi\mu$m emittance.

Major ring systems under R&D include dipole and quadrupole magnets and their power supplies, ceramic vacuum ducts, RF cavity, and injection and extraction magnets. The ring contains 24 main dipoles, 48 quadrupoles, 16 sextupoles, 32 trim quadrupoles, 32 multi-coil correctors, and injection and extraction magnets. With a high field (maximum dipole field of 0.98 T) and large aperture (dipole gap height of 178 mm and quadrupole pole radius from 209 to 308 mm) main magnet prototyping is in progress starting with J-PARC-type braided aluminum wires fabricated by domestic vendors.

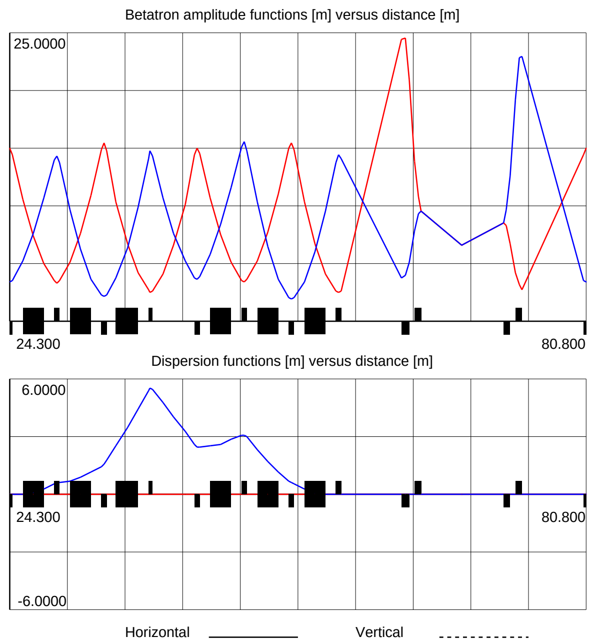

Figure 4: CSNS synchrotron lattice functions.

The ring main magnets are powered by a family of dipole and 8 families of quadrupole power supplies arranged in parallel with multimesh White circuits operating at 25 Hz resonance. The demand for stability and matching is high (THD $<0.02\%$, stability $<0.1\%$). The trim quadrupoles and correctors are expected to play important roles in orbit and tune controls during the ramp cycle. The sextupoles are dc powered for chromatic correction mainly at injection.

The ring RF system uses ferrite-loaded cavities to meet phase I ($h = 2$) requirements. The design gradient is about 10 kV/m. Test stands are set up to measure the ferrite properties under the dynamic ramp cycle. For phase II, second-harmonic ($h = 4$) cavities will be added to raise the bunching factor from 0.25 to about 0.4.

Ceramic ducts are chosen for the ring vacuum chambers under magnets to alleviate heating and magnetic field distortion caused by the eddy current, and to resist the impact of possible high-power beam loss. Both ISIS-type glass joint and J-PARC-type metallic brazing are considered to form long, large-bore ducts. Detachable, external metal-stripe wrappings are considered for the RF shielding, and all inner surfaces (ceramic, metal, and ferrite) are to be coated with TiN to reduce secondary electron emission yield [3].

The injection adopts SNS-type charge-exchange injection with phase-space painting using 4 shift dipoles and 8 painting bump magnets. For simplicity, we consider using dc shift dipoles instead of 25 Hz ac. The beam-dynamics impact of the closed bump with its amplitude reducing with energy ramping is expected to be small. Excessive foil hits are avoided by displacing the orbit immediately upon the injection completion using the painting bumps powered by IGBT-based programmable power supplies.

The extraction adopts SNS-type single-turn extraction with vertical kicking and horizontal bending. The kicker system consists of lumped, in-vacuum ferrite modules powered by dual PFN charging power supplies. The Lambertson-type septum avoids possible damage caused by a beam loss on the magnet coil.

For beam diagnostics we plan a suite of instruments similar to those of SNS, starting with allocating space and specifying accelerator-physics requirements. For accelerator controls, machine protection, and commissioning applications we build from the experience of BEPC/BEPCII and SNS projects (adopting EPICS, XAL, PSI/PSC control, static and dynamic databases, etc.).

FUTURE UPGRADES

Power upgrade depends crucially on maintaining a low uncontrolled beam-loss level. CSNS power upgrade beyond phase I will be mainly realized by raising the linac energy to allow a higher beam intensity under the same ring space-charge limit, and by adding the second harmonic RF to increase the bunching factor.

It is possible for CSNS to serve multiple purposes including serving as a test facility for the ADS (ADTF). Fig. 5 shows a possible layout with ADTF receiving test beams from the CSNS linac, CSNS ring, and a dedicated high-duty linac. Extension of the linac provides a higher power, while extension of the ring yields higher energies.

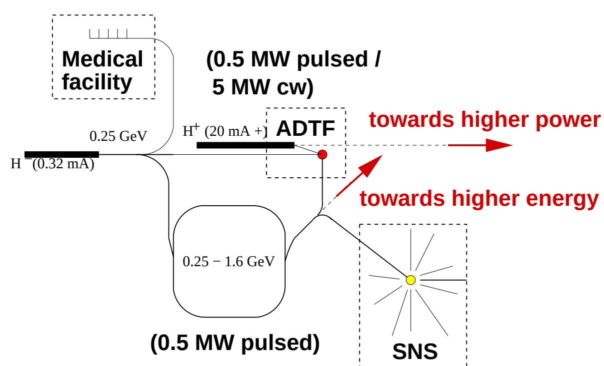

Figure 5: Possible CSNS upgrades towards higher power, higher energy, and multipurpose.

We thank colleagues and friends around the world for their generous help on the CSNS project.

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