Proposal for muon and white neutron sources at CSNS*

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Abstract The China Spallation Neutron Source (CSNS) is a large scientific facility with the main purpose of serving multidisciplinary research on material characterization using neutron scattering techniques. The accelerator system is to provide a proton beam of 120 kW with a repetition rate of 25 Hz initially (CSNS-Ⅰ), progressively upgradeable to 240 kW (CSNS-Ⅱ) and 500 kW (CSNS-Ⅱ'). In addition to serving as a driving source for the spallation target, the proton beam can be exploited for serving additional functions both in fundamental and applied research. The expanded scientific application based on pulsed muons and fast neutrons is especially attractive in the overall consideration of CSNS upgrade options. A second target station that houses a muon-generating target and a fast-neutron-generating target in tandem, intercepting and removing a small part of the proton beam for the spallation target, is proposed. The muon and white neutron sources are operated principally in parasitic mode, leaving the main part of the beam directed to the spallation target. However, it is also possible to deliver the proton beam to the second target station in a dedicated mode for some special applications. Within the dual target configuration, the thin muon target placed upstream of the fast-neutron target will consume only about 5% of the beam traversed; the majority of the beam is used for fast-neutron production. A proton beam with a beam power of about 60 kW, an energy of 1.6 GeV and a repetition rate of 12.5 Hz will make the muon source and the white neutron source very attractive to multidisciplinary researchers.

Key words high power proton beam, pulsed muon source, white neutron source, muon science; nuclear data measurements

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1 Introduction

The China Spallation Neutron Source (CSNS) is a large scientific facility chiefly dedicated to multidisciplinary research on material characterization using neutron scattering techniques [1–2]. The core of the CSNS is a high beam power proton accelerator complex that consists of an H^- linac of 80 MeV, and a rapid cycling synchrotron (RCS) producing 1.6 GeV protons and beam transport lines. The accelerators can provide a proton beam of 120 kW with a repetition rate of 25 Hz, and can be upgraded to 240 kW (CSNS-Ⅱ) and 500 kW (CSNS-Ⅱ') by increasing the linac energy to 130 MeV and 250 MeV, respectively. Besides being a driving source for the spallation target, the proton beam can be exploited for additional usage, possibly for generation of muons and fast neutrons, hence offering fundamental and applied research over a wider area of nuclear and materials sciences. In order to satisfy the heavy demand for multidisciplinary research using muons and fast neutrons, we propose a second target station consisting of two targets in tandem to produce muons and fast neutrons. Fig. 1 shows the layout of the CSNS-Ⅱ that features muon and white-neutron sources.

The beam extracted from the RCS has the following properties: high energy, short pulse length, modest bunch length, and large beam emittance. In the upgrade phases, the beam power will be increased. Table 1 shows the main characteristics of the proton

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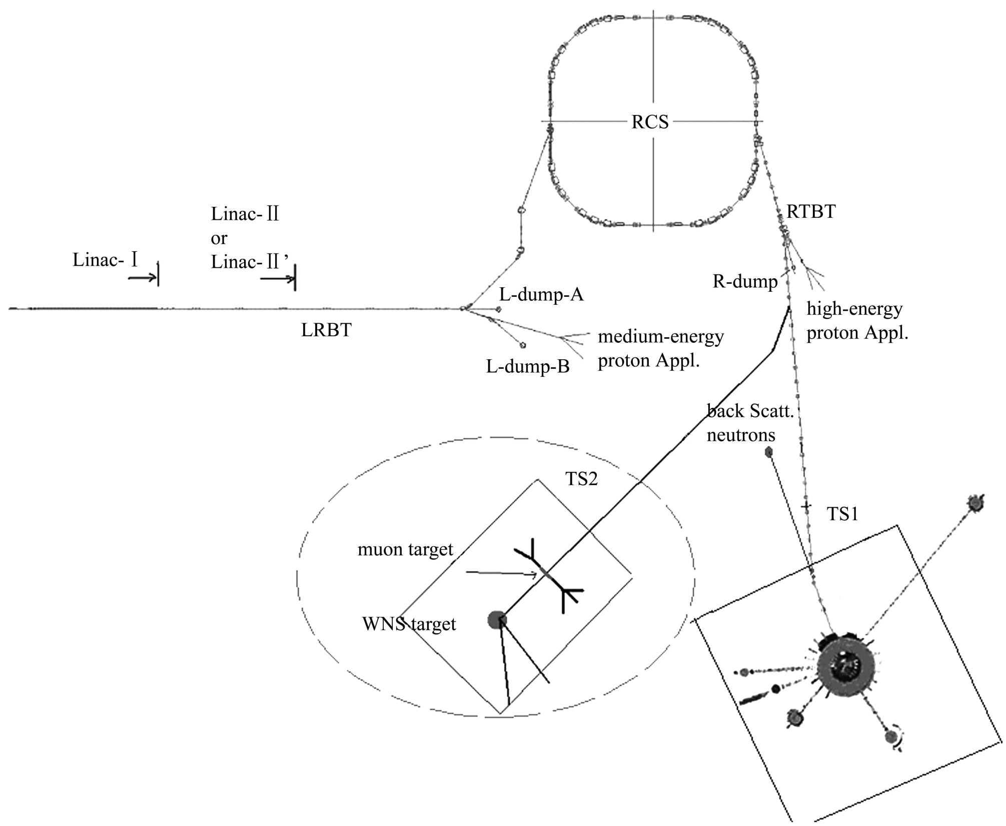

Fig. 1. Schematic of the CSNS-II layout.

beam in the different CSNS phases. In the normal operation mode, there are two bunches in a pulse. If high fluxes of muons and/or fast neutrons are needed for some special applications, one of the two bunches in a normal proton pulse can be diverted to the second target and be compressed to a shorter bunch length. Such beam characteristics are very suitable for driving a pulsed muon source and a fast neutron source.

Table 1. Main characteristics of the CSNS proton beam.

	CSNS-I	CSNS-II
beam energy/GeV	1.6	1.6
average beam current/μA	75	150
average beam power/kW	120	240
pulse repetition rate/Hz	25	25
peak beam current/A	6	12
pulse length/ns	~500	~500
bunch length/ns	~60	~70
bunches per pulse	2	2
particles per pulse/ppp	1.9×10^{13}	3.8×10^{13}
particles per second/pps	4.7×10^{14}	9.5×10^{14}
beam emittance/(rms, πmm·mrad)	~15	~17
beam emittance (99%, πmm·mrad)	~100	~110
energy spread (%)	$<\pm0.3$	$<\pm0.3$

2 The second target station of CSNS-II

From the outset of the deliberation of the CSNS project, the design team has adopted a policy of allowing an upgrade path of the facility to increase the proton power as well as to expand the breadth of the research and application realm in the future.

With the increased beam power, a second target station (TS2) is planned and new applications will be exploited at the CSNS. As neutron scattering will remain on the center stage of the CSNS' mission, the major portion of the beam power will be sent to the first target station (TS1). Fig. 2 shows the two new targets in the TS2, the spallation TS1 and the beam transport lines. For every pulse one of the two bunches will be diverted from the main RTBT line [3] via a transport line to the second target station by a group of six kickers and a septum magnet. The kickers are similar to those used for the beam extraction at the RCS. The septum is of a normal window-frame type. Two bending magnets together with 3 quadrupoles can make the horizontal bending section achromatic. The remaining downstream portion of the beam transport line is a long straight section.

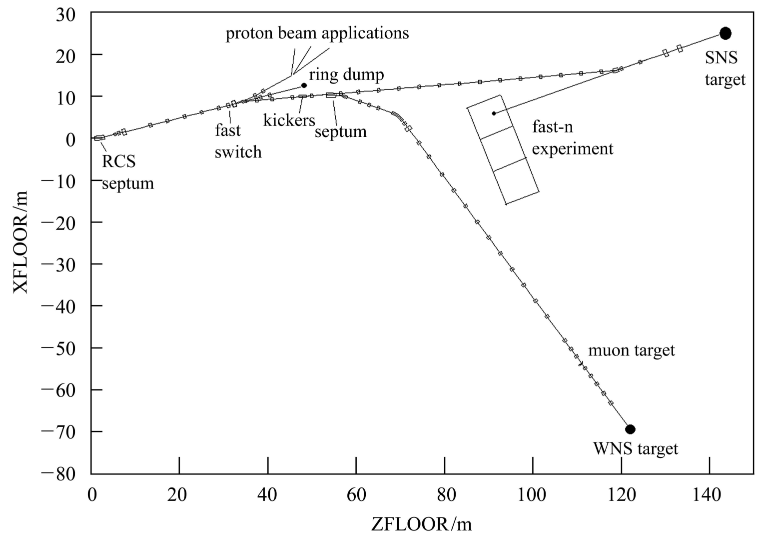

Fig. 2. Beam transport lines to the two target stations.

Within the TS2, the arrangement of the two targets is similar to the muon source at ISIS [4] and J-PARC [5]. One muon-generating target and one fast-neutron-generating target (also called the White Neutron Source target or WNS target) are configured in tandem, with the muon target upstream. Compared with the instruments in the TS1 and WNS, the muon beamlines are simple and will be housed within the TS2 building while we anticipate that a few of the fast-neutron beamlines will be extended/tunneled outside the building to special housing of individual experimental end-stations. To minimize particle loss between the two targets due to the emittance blow-up induced by the Coulomb scattering process, the beam spot at the muon target is made very small. This is also helpful to reduce the muon beam emittance. The two-waist focus of a spot to a diameter of 20 mm is accomplished by three strong quadrupoles; another set of 3-quadrupole plus 2-quadrupole units is used to control the beam size needed for the WNS target. The water-cooling system and remote handling system, etc. are similar to those for the spallation neutron target, but the shielding for the WNS target is considerably simpler and its design can follow those of the CERN n-TOF target [6] and the LANSCE WNS target [7].

3 Muon beam and muon science at the CSNS-Ⅱ

The demand for high-intensity, pulsed muon beams is on the rise on account of the works pioneered at KEK [8] and ISIS [4, 9]. Using a quarter of the proton beam power of the CSNS-Ⅱ, the muon intensity can reach a competitive level with that of the pulsed muon source of ISIS—currently of the highest flux in the world, but is expected be substantially lower than the one at J-PARC. Nevertheless, this first muon source in China, also being one of three pulsed muon sources in the world, will certainly provide an impetus for research using muon beams in China in the 21st century. Table 2 shows a comparison between the three pulsed muon sources. Although the proton beam power of CSNS is lower than that of ISIS, the muon yield is comparable owing to the higher proton energy and thicker target dimension at the CSNS. The proton energy of 1.6 GeV is almost the optimized one if we take into account the production of negative muons [10]. This implies that research using negative muons at the CSNS will be superior to ISIS provided that a decay channel will be built at a later stage.

Muons are produced in a graphite target with a thickness of 10–20 mm via an intermediate process of pion production. Collisions between the incoming protons and the hadrons in the target will produce pions through different reaction processes, and very short life-time pions will decay into muons in either a surface channel or a superconducting decay channel. The muons after velocity selection will then be guided to different experiment ports. Because the repetition rate of the muon beam is as low as 12.5 Hz and there is only one bunch in a beam pulse, we propose that electrostatic deflectors be used as in a CW muon source to split the beam into different instruments. This is different from the other pulsed muon sources. This method compared with fast kickers has the advantage of offering a smaller muon spot size at the sample positions. On the other hand, fast kickers can also be considered for the beam dispatch as a backup option.

Instrumentation for muon-beam applications at the CSNS will be developed in stages. Like to the design philosophy of the AUSTRON project [11], only the target suite (target, collimators and shielding, etc.) together with a surface channel source will be built in the initial phase. With an energy of 4.1 MeV, the intensity of a positive muon beam can reach about 1.2×10^6, as estimated from a simple scaling, which is almost twice that of the corresponding muon surface source at ISIS. In a later phase, a decay channel will be added. Both positive and negative muon beams are obtainable over an energy range of 10–100 MeV; the negative muon beam intensity is about one order of magnitude higher than that at ISIS, made possible by the higher proton beam energy. End-stations of each muon channel can be added at any time along with the expanding muon applications. It is important that the design consideration is to apply to the entire target and muon-channel system so as to realize consecutive upgrades in the future.

Table 2. Comparison between three pulsed muon sources.

	ISIS	J-PARC	CSNS-Ⅱ
proton energy/MeV	0.8	3.0	1.6
current/μA	200	315	38
repetition rate/Hz	50	25	12.5
proton beam power/kW	160	900	60
bunches per pulse	2	2	1
carbon target thickness/mm	10	20	20
muon line acceptance/msr	30	40	40
surface muon intensity/(μ^+ per second)	6×10^5	3×10^7	1.2×10^6
decay muon intensity/(μ^- per second)	10^{4-5}	10^{6-7}	10^{5-6}

Note: CSNS μ^+ intensities are scaled from the ISIS parameters with a gain factor of 4 comparing 1.6 GeV to 0.8 GeV according to Ref. [10], a factor of 2.67 due to the acceptance and target thickness.

The CSNS muon source, the first in China, will provide an excellent platform and a suite of powerful tools such as μSR (muon Spin Rotation, Relaxation and Resonance) techniques for Chinese researchers in the fields of materials and bio-medical sciences, muon catalyzed fusion (μCF) in energy technology, and fundamental muon physics.

4 The white neutron source and applications

Neutrons of energies ranging from a few eV to tens of MeV are indispensable for measurements of neutron-nuclei cross-sections in nuclear technology, astrophysics, and fundamental physics. Accurate measurements of some reaction cross-sections using high-flux fast and high-energy neutrons are very important in the transmutation of nuclear waste, thorium cycling, and the accelerator-driven subcritical system (ADS). These include the cross-sections of neutron capture, neutron-induced fission and inelastic neutron scattering of certain isotopes. In astrophysics, nucleosynthesis by neutron capture in stellar evolution and supernova explosions is an important process. High-flux neutron sources can play a key role in the realization of measurements of events of very small cross-sections and/or overcome the limit of very small sample sizes.

Table 3. Main parameters of CSNS-WNS.

	dedicated mode	parasitic mode
proton energy/GeV	1.6	1.6
proton beam power/kW	<60	56
Max. protons per pulse (10^{13})	<0.9	1.7
pulses per second	25	12.5
Min. bunch length/(ns, rms)	<3	14
neutron yield/(10^{15} n/s)	<9	~8

The CSNS high-power proton beam is well suited to the production of fast neutrons based on the designed WNS, which is similar to the CERN n-TOF facility [12, 13]. Using the beam parameters of CSNS-Ⅱ, the main parameters of the CSNS WNS are given in Table 3. Due to much higher proton beam power, the available neutron flux should be much higher for the CSNS WNS. Moreover, the relatively modest repetition rate and proton energy of the CSNS are advantageous to the effective utilization of high flux neutrons in conjunction with easing the requirement of the target shielding. Only about 5% of beam loss occurs due to transmission through the muon target and 95% of the beam (25% of the RCS beam under the parasitic mode of operation) can be used for fast neutron production at the WNS. By virtue of the time-of-fight (TOF) technique, a short bunch length is critical to achieve high resolution. In the dedicated mode, the bunch length can be reduced significantly by using special accelerator settings at the sacrifice of beam intensity to some extent. In this case, only one of the two RF buckets in the RCS is filled. Due to modest beam power (maximum 60 kW), lead will probably be a suitable target material for WNS; as is the case for CERN n-TOF, water will serve dual functions as coolant for the target and moderator of the neutron spectrum. Neutron beamlines with a length of 50–150 m will be designed for various research purposes. Typically, a long beamline is for total cross-section measurements, and a short one for measurements of (n, γ), (n, f) and (n, charged particle) reaction cross-sections. High-flux fast neutrons are also useful for neutron radiography, complementing those using thermal or cold neutrons at the spallation neutron source.

5 Summary

A second target station consisting of a muon target and a fast neutron target in tandem is proposed as an expansion option for the CSNS facility in a future upgrade. According to the plan, the CSNS muon source will be a world-class facility capable of providing a unique platform for domestic and international users in muon science. The CSNS-WNS will be one of the leading fast-neutron sources in the world for neutron physics, nuclear technology and astrophysics as well as for neutron radiography. A preliminary assessment of the performance of the CSNS muon source and WNS has been carried out. More detailed considerations are underway.

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