STATUS AND CHALLENGES OF THE CHINA SPALLATION NEUTRON SOURCE

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Abstract

The accelerator complex of China Spallation Neutron Source (CSNS) mainly consists of an H- linac of 80 MeV and a rapid-cycling synchrotron of 1.6 GeV. It operates at 25 Hz repetition rate with an initial proton beam power of 100 kW and is upgradeable to 500kW. The project will start construction in September 2011 with a construction period of 6.5 years. The CSNS accelerator is the first large-scale, high-power accelerator project to be constructed in China and thus we are facing a lot of challenges. This paper presents the current status of CSNS project and summarizes the key technology development for the feasibility demonstration of the related technologies during the past several years.

INTRODUCTION

The China Spallation Neutron Source (CSNS)[1-3] provides a multidisciplinary platform for scientific research and technology development by scientific institutions, universities, and industries. The high-flux pulsed neutrons from CSNS will compliment for cw neutrons from the nuclear reactor CARR, which recently commissioned at China Institute of Atomic Energy and for x-ray from synchrotron radiation facilities, such as Shanghai Light Source. Strongly advocated by the users groups, the CSNS project was, approved by the Chinese central government in 2008 and is going to formally start construction in 2011.

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 The accelerator provides a beam power of 100 kW on the target in the first phase. It will be upgraded to 500kW beam power at the same repetition rate and same output energy in the second phase. Space is reserved in LRBT beam line in the present design to raise the linac beam energy for reducing space-charge effect in the synchrotron when the beam current becomes 5-times higher. A schematic layout of CSNS phase-1 complex is shown in Figure 1. In the phase one, an ion source produces a peak current of 25 mA H^- beam. RFQ linac bunches and accelerates it to 3 MeV. DTL linac raises the beam energy to 80 MeV. After H^- beam is converted to proton beam via a stripping foil, RCS accumulates and accelerates the proton beam to 1.6 GeV before extracting it to the target. 20 neutron channels is designed around the target, but only 3 spectrometers will be built in the first phase due to limited budget.

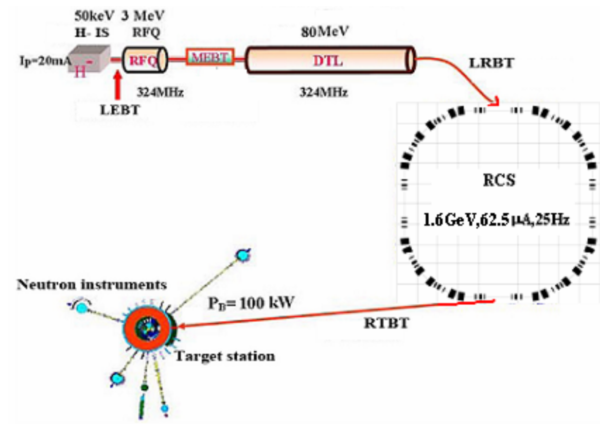

Figure 1: Schematics of the CSNS complex.

In the following sections, the paper will briefly introduce the present status of CSNS project, as well as its major challenges in the project construction and management. Then the accelerator design is outlined and finally the key technology development will be presented in more details.

CSNS PROJECT STATUS

The CSNS project was approved by the Chinese central government in 2008. It is going to start construction in September 2011 and complete the project in 6.5 years. The approved budget from the central government is increased to \$ 260 M from \$ 215 M in 2010. The local government will support additional \$ 77 M, free land and some infrastructure. CSNS will be located at Dong Guan in southern part of China, with a distance from Hong Kong about 100 km and from Beijing about 2000 km. IHEP will set up a new branch there for CSNS construction. Figure 2 is an artificial view of the campus.

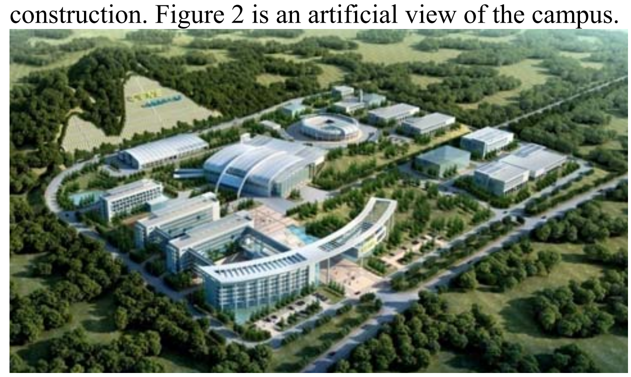

Figure 2: Artificial view of CSNS campus at Dong Guan.

Before the formal construction the land preparation and the 70m-high slop protection laid on the hillside have almost completed now, as show in Figure 3. And two dedicated 4-lane roads with a total length about 4 km long are under construction and will soon be connected with the high way. A new power transformer station of 50 MW will be built there late. The local government is in charge of these infrastructure projects and their investment.

Figure 3: Site preparation is almost completed.

The CSNS accelerator is the first large-scale, high-power accelerator project to be constructed in China. And it is also the first time for IHEP to build an accelerator facility outside of Beijing. So we are facing great challenges from technology, manpower, management, and, of course, tight budget. For these reasons, we launched two R&D programs to overcome the major technology difficulty in 2006 and 2008. More than 20 items in accelerator were identified as the key technology needed to be developed and prototyped in these two programs. At present almost all of them have been succeed. To reduce the cost, most of the equipments and apparatus will be procured from Chinese vendors. To organize the team, 400 new positions are open for the IHEP new branch at Dong Guan, and some key persons of IHEP, Beijing will also work at Dong Guan during construction period.

CSNS DESIGN

The major design parameters of the CSNS accelerator complex are listed in Table 1. The accelerator provides a beam power of 100 kW on the target in the first phase and then 500 kW in the second phase by adding superconducting spoke cavities to the linac to accelerate beam to 250MeV while increasing average beam intensity 5 times [4].

Table1: CSNS Design Parameters

Project Phase	**I**	**II**
Beam Power on target [kW]	100	500
Proton energy t [GeV]	1.6	1.6
Average beam current [μA]	62.5	312.5
Pulse repetition rate [Hz]	25	25
Linac energy [MeV]	80	250
Linac type	DTL	+Spoke
Linac RF frequency [MHz]	324	324
Macropulse. ave current [mA]	15	40
Macropulse duty factor	1.0	1.7
RCS circumference [m]	228	228
RCS harmonic number	2	2
RCS Acceptance [πmm-mrad]	540	540

The Linac Design

The H^- ion source provides 25 mA peak current, 0.5 ms long, 0.2πμm normalized emittance (rms) pulses at 50 kV and 25 Hz repetition rate for phase-I. The ISIS type Penning H^- surface source is chosen for CSNS, because it can well meet the specification of CSNS phase-I at a relatively low cost.

The LEBT is for matching and transporting the H^- beam from ion source to RFQ accelerator, and pre-chopping the beam according to the requested time structure by the RCS. Three-solenoid focusing structure is adopted for space charge neutralization. An electrostatic deflector is chosen as pre-chopper, positioned at the end of the LEBT. A prototype of the LEBT chopper reaches a fast rise time of 17 ns in beam test.

A four-vane type RFQ is adopted because we have built a similar RFQ with a duty factor up to 15% now in our ADS program. The total length of 3.62 m, composed of four segments. RFQ accelerates H^- beam from 50 keV to 3 MeV, with duty factor of 1.05%. The selection of 3 MeV output energy is a compromise between the fast-chopper design in MEBT and injection energy of the DTL.

The MEBT matches the H^- beam from the RFQ to the DTL in 6-dimentional phase space, and chops the beam with fast (~10 ns) rise time. The total length of MEBT is about 3 m, including 8 magnets, two bunchers and two J-PARC type RF choppers. Beam instruments for beam current, beam position and beam loss are also installed in the MEBT. As the LEBT chopper has already reach a rise/fall time less than 17ns, we will not install the RF chopper in the phase one.

The DTL accelerates the 3 MeV beam from the RFQ to 80 MeV. The DTL linac is composed of 4 tanks. To reach a high effective shunt impedance, the cell shape and size are tuned with β stepwise in the low β segment, while keeping the maximum surface field below 1.3 times the Kilpatrick limit. The FFDD focusing lattice is adopted in the dynamic design, and J-PARC type EM quadrupole is chosen. Equipartitioning scheme is applied in the lattice design to minimize the space charge coupling effect between transverse and longitudinal directions that may drive emittance growth. Table 2 summarises the major design parameters of the DTL. End-to-end multiparticle simulation of the linac with various errors was conducted to verify the beam loss is controlled within <1 W/m beam power.

Table 2: CSNS-DTL Design Parameters

Tank number	1	2	3	4
Output energy (MeV)	21.67	41.41	61.07	80.1
Length (m)	8.51	8.56	8.78	8.8
Number of cell	64	37	30	26
RF driving power (MW)	1.35	1.32	1.32	1.34
Total RF power (MW)	1.91	1.92	1.92	1.93
Accelerating field (MV/m)	2.86	2.96	2.96	3.0
Synchronous phase (degree)	-35 to -25	-25	-25	-25

The RCS Design

Due to the requirement of the beam collimation for beam loss control in a high intensity proton synchrotron, the lattice with four-fold structure is preferred so as to assign separated function to each long straight section, as shown in Figure 4 (upper). More ever the lattice superperiodicity of four is better for reducing the impact of low-order structure resonance than superperiodicity of three.

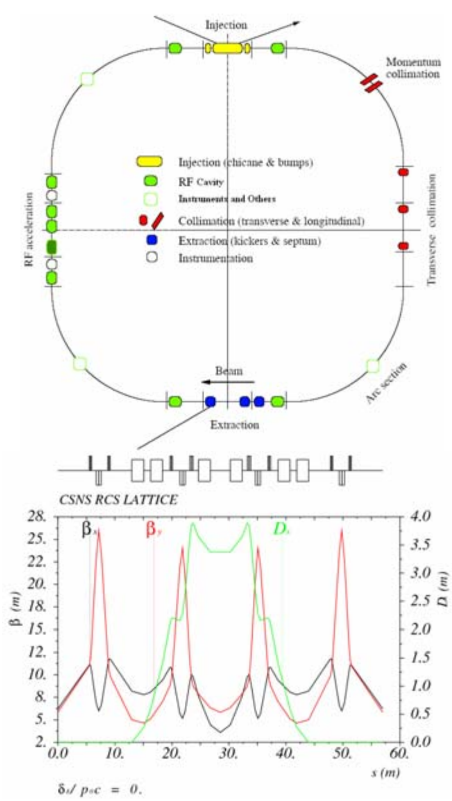

Figure 4: RCS function arrangement (upper) and twiss parameters of one super-period (lower).

The lattice is based on triplet cell, and the whole ring consists of 16 triplet cells, with circumference of 227.92m. In the each super period, an 11m long drift space is left in a triplet cell. These four uninterrupted long straight sections are very good for accommodation of injection, extraction, RF acceleration and transverse collimation system. Figure 4(lower) gives the twiss parameters of one super-period. The maximum beta function is less than 26 m, and the maximum dispersion function is less than 4 m. Especially in the middle of the arc, the dispersion is large and the horizontal beta function is small, and this is good for high efficiency momentum collimation.

The acceleration is performed by eight ferrite-loaded cavities which provide 165 kV RF voltage with harmonic number of two. The cavity resonant frequency shifts from 1.02 MHz to 2.44 MHz in 20 ms. An RF acceleration period consists of three stages: injection, capture and acceleration. The designed bunching factor at injection is less than 0.4 with space charge tune shift less than -0.3. With the increasing of RF voltage and beam energy, the bunching factor is decreased to 0.12, and meanwhile the space charge effect becomes weak due to beam energy increase.

The linac beam is injected to the RCS by using H^- painting method in both horizontal and vertical planes. The whole injection chain is arranged in an 11 m long straight section, consists of four horizontal painting magnets, four vertical painting magnets, and four fixed-field bumping magnets. The one-turn extraction from the RCS is achieved by using 7 vertical fast kickers followed by a Lambertson septum.

The Interface Design

There are two beam transport lines: LRBT and RTBT. The LRBT transports H^- beam to the ring, and transverse and momentum collimators are designed to scrape the halo particles. The debuncher is used in the LRBT to decrease momentum spread. The RTBT transports extracted proton beam from the RCS to the target. To generate a uniform footprint of beam onto the target, two octupole magnets are designed in the RTBT. The beam loss due to malfunction of one of the 7 kickers is minimized in the design. Collimation system is designed at the RTBT for protection of the target and shielding of back scattering neutrons.

KEY TECHNOLOGY R&D

Before we start construction of CSNS accelerator, a series of R&D on the key technology have been conducted since 2006 because we have little technology basis for such a high current proton accelerator. For the CSNS linac, prototypes of H^- ion source, pre-chopper, DTL, DTL quadrupole power supply, RF HV power supply, linac LLRF system, modulator, crowbar and beam diagnostics have been developed. For the CSNS RCS, main dipole and quadrupole magnets together with their measurement systems, White resonant power supplies for the two magnets, a ferrite-loaded cavity together with its RF power source and its biased power supply, RCS LLRF system, ceramic vacuum chambers for dipole and quadrupole magnets, an injection bump magnet and an extraction fast kicker together with their power supplies, some control apparatus and beam diagnostics are prototyped. With the success of the R&D activities, we become more confident in the aspects of the technology and cost control. In the following subsections, some of them will be outlined.

Linac Prototypes

There was no previous experience in high-current, low-emittance and long-lifetime H^- ion source in China. Owing to the collaboration with ISIS, an H^- Penning source test stand is built, as shown in Figure 5. The beam current reached 55 mA with a pulse length of 500 μ m at 50 Hz repetition rate. Its emittance measurement system has also been developed. The measurement result can be foreseen in recent.

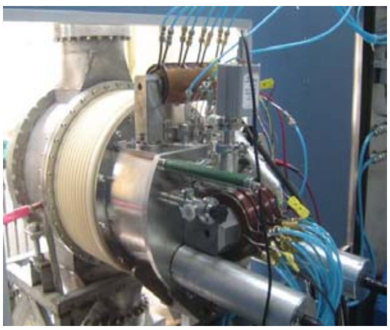

Figure 5: H- Penning ion source test stand at IHEP.

We omitted RFQ from this R&D plan, because we have already built a similar RFQ in an ADS program, as shown in Figure 6. Its duty factor was 7% with 1.43ms pulse length at 50Hz. An output beam current of 46mA was obtained with a beam transmission rate more than 93%. Recently its duty factor reached 15% and will rise further towards CW for ADS study. Commissioning of the ADS RFQ is encouraging for us to be optimism for the direct construction of CSNS RFQ without any more R&D.

Figure 6: A proton RFQ of 3.5MeV for ADS study has been built at IHEP with 46mA output beam at a transmission rate >93%.

R&D of DTL is emphasised in the linac R&D program, even though IHEP built a 35 MeV DTL at 201 MHz about 20 years ago. For the higher frequency and higher tudy factor DTL for CSNS, we are still facing some challenges and R&D is crucial. A prototype of the first section of the DTL-1 has been fabricated. The electro-magnetic (EM) quadrupole uses J-PARC-style coil with cooling channel made by periodical reverse electroform technology. Figure 7 shows the tank and the drift tube with Sakae coil quadrupole.

Figure 7: DTL prototype with Sakae coil

The RFQ and the DTL are to be powered by imported klystrons with domestically developed HV power supplies. An AC series resonance HV power supply was proposed and developed for the klystrons, avoiding step-up high-voltage transformers and multiphase high-voltage rectifiers. A digitalized low-level RF control system based on FPGA was realized in the ADS-RFQ operation. A prototype of modulator and a crowbar have also been developed.

RCS Prototypes

To reduce the eddy current of the dipole magnet coil, stranded aluminium coil with a stainless steel water-cooling channel was made in China, with which the prototype dipole magnet was also fabricated. The dipole magnet and its curved AC plus DC magnet measurement system are shown in Figure 8. Quadrupole magnet was also prototyped with split four-conductor copper coil. It has rather large bore radius of 154mm.

Figure 8: The prototype dipole magnet of stranded coil and the measurement system.

White resonant circuit was chosen as the magnet power supply for its merit in avoiding power impact to the grid. Its components, including power supply with DC plus AC sources, choke, and capacitor bank, were fabricated and installed at IHEP, as shown in Figure 9. The key feature of the power supply is a high tracking accuracy for the magnet field. Now the dipole magnet and its power supply system were assembled at IHEP. Initial magnet measurement is encouraging for the dipole magnet. However cracking in the epoxy resin related to the fabrication process and to vibrations at a 25-Hz repetition rate remains an unsolved problem. More prototype will be tested.

Figure 9: Choke and capacitor bank for White circuit of CSNS magnet power supply.

Ceramic vacuum chambers must be used in the RCS dipole and quadrupole magnets to avoid the eddy current. Fabrication of a prototype ceramic vacuum chamber followed two technical approaches: ISIS-type glass joining and J-PARC-type metallic brazing. Difficulties were experienced in meeting the strength and accuracy tolerance of the ducts and joints, and in stress-induced cracking and leakage. An 1-m long curved prototype of the ceramic chamber for dipole magnet was made by a Japanese vendor with 4 small sections connected by glass joining. Chinese vendors independently produced full-size prototype chambers for quadrupole magnet, as shown in Fig.10.

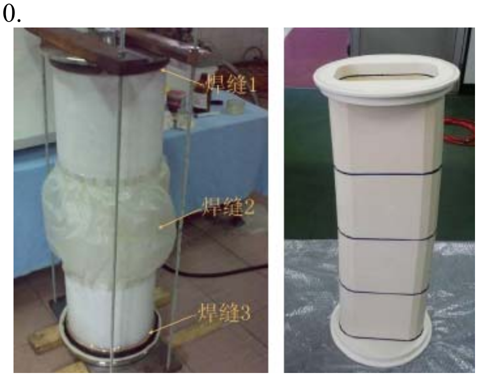

Figure 10: Prototype ceramic chambers for quadrupole (left) and an arc section for dipole (right).

A prototype of the ferrite loaded RF cavity with two accelerating gaps has been made in full-size. Between each ferrite plates is a copper plate with cooling water for heat release. A 500kW RF power source with a frequency swing from 0.9 to 2.5MHz has been developed for high power experiment together with the ferrite-loaded cavity, as shown in Figure 11. The gap voltage of the cavity has reached the design value of 12 kV in the frequency-sweeping test and a 24-hours test run preliminarily demonstrates its operation stability. The power source gave a pulsed output power of 500 kW on a dummy load in recent.

Figure 11: Prototype of RCS RF system.

Injection bump magnets are designed for H^- stripping injection into the ring. A prototype magnet was fabricated at IHEP with water-cooled windings of the copper plate. A pulsed power supply with 18,000 A output current in maximum during injection time of 500μs has also been developed and connected with the bump magnet together with some dummy loads for the magnet measurement, as shown in Figure 12.

Figure 12: Prototype of the injection bumper and its power supply.

Fast extraction kicker and its high voltage pulsed power supply are prototyped with a magnetic field of 520 Gauss and a rise time of 250 ns. The in-vacuum magnet uses a ferrite core for a high magnetic flux. The pulse power supply uses blumlein type pulse forming network to get a short pulse with a current of 5840 A and a flattop of better than ±1.5%.

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