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J. Wei

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Collider-Accelerator Department

Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

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CHINA SPALLATION NEUTRON SOURCE PROJECT: DESIGN ITERATIONS AND R&D STATUS*

J. Wei[†§], S.-X. Fang[‡], J.-S. Cao[‡], Y.-L. Chi[‡], C.-D. Deng[‡], H.-Y. Dong[‡], L. Dong[‡], S.-N. Fu[‡]
W. Kang[‡], J. Li[‡], Y.-C. Liu[‡], H.-F. Ouyang[‡], Q. Qin[‡], H.-M. Qu[‡], C.-T. Shi[‡], H. Sun[‡], J.-Y. Tang[‡]
C.-H. Wang[‡], L.-L. Wang[‡], Q.-B. Wang[‡], S. Wang[‡], T.-G. Xu[‡], Z.-X. Xu[‡], J. Zhang[‡], Z.-H. Zhang[‡]
for the China Spallation Neutron Source (CSNS) Accelerator teams
Institute of High Energy Physics, China[‡]; Brookhaven National Laboratory, USA[§]

Abstract

The China Spallation Neutron Source (CSNS) is an accelerator based high power project currently under preparation in China. The accelerator complex is based on an H^- linear accelerator and a rapid cycling proton synchrotron. During the past year, the design of most accelerator systems went through major iterations, and initial research and developments were started on the prototyping of several key components. This paper summarizes major activities of the past year.

OVERVIEW

There exist three classes of high-power proton accelerator facilities: [1, 2] continuous-wave (CW) facilities driven by high energy, high intensity cyclotrons or linacs (example: the operating Swiss Spallation Neutron Source (SINQ) isochronous-cyclotron at Paul Scherrer Institute (PSI) with a beam power of 1.2 MW at 590 MeV [3]); long-pulse (ms) facilities driven by high energy, high intensity linacs (example: the operated Los Alamos Meson Physics Facility (LAMPF) proton linac with a beam power of 1 MW at 800 MeV [4] and the Proton Engineering Frontier Project (PEFP) under construction in Korea with a high-duty 100 MeV linac [5]); and short (μs) pulse facilities driven by a combination of high intensity linacs and rings, as shown in Table 1 and Fig. 1 [4, 6, 7, 2]. Among the short-pulse facilities are two types of accelerator layout: a full-energy linac followed by an accumulator (example: the operating Los Alamos Neutron Science Center (LANSCE) linac and Proton Storage Ring (PSR) with a beam power of 80 kW at 800 MeV [4] and the Spallation Neutron Source (SNS) project just commissioned at Oak Ridge National Laboratory with a 1 GeV superconducting (SC) RF linac and an accumulator [8]) and a partial-energy linac followed by a rapid cycling synchrotron (RCS) (example: the operating ISIS facility at the Rutherford Appleton Laboratory (RAL) with a beam power of 160 kW from a 70 MeV linac and a 800 MeV synchrotron [9] and the Japan Proton Accelerator Research Complex (J-PARC) under construction in Japan with a 400 MeV linac and 3 GeV and 50 GeV synchrotrons [10]).

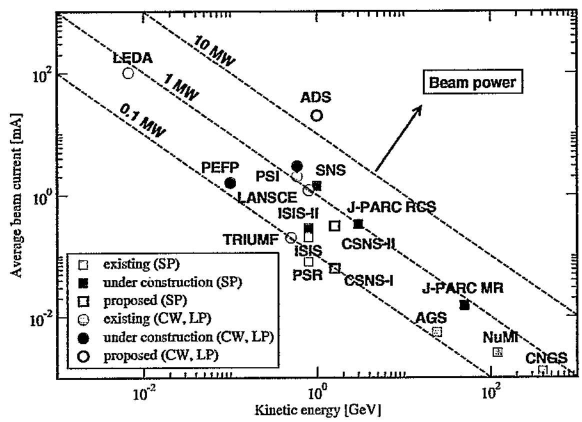

Figure 1: Accelerators at the power frontier (short pulse SP, long pulse LP, continuous wave CW).

Continuous-wave (CW) and long-pulse (LP, ms-long pulse) facilities have reached MW average beam power, as shown in Fig. 1. These facilities typically use high average-current proton sources with a high duty factor (8% or higher) accelerating to GeV beam energy level, so that to ease mechanical shock on the target, to reduce the energy deposition on the target window, and to maximize the yield of secondary beams (e.g. neutrons). Superconducting technology is considered advantageous to raise both the plug-in power efficiency and the facility reliability. LP and CW facilities, in particular those based on high-duty proton linac, are best candidates for applications including proton irradiation, nuclear waste transmutation, accelerator production of tritium, and accelerator driven sub-critical (ADS) reactor power generation.

Short-pulse (SP, μs-long pulse) applications include generation of pulsed, high-intensity secondary beams of neutrons, Kaons, neutrinos, muons for neutrinos, muons for muon collider, and radioactive isotope by isotope-separator-on-line (ISOL) method. Present facilities operate at 0.1 MW average beam power level (Fig. 1). Newly constructed and proposed facilities aim at MW beam power. These facilities typically use high peak-current H^- sources and a pulsed H^- linac combined with an accumulator ring

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† weijie@ihep.ac.cn and jwei@bnl.gov

Table 1: The China Spallation Neutron Source (CSNS) in comparison with a few existing and planned proton accelerator facilities in the world [3]-[12].

Name	Status	Accelerator type and energy	Ave. beam power (MW)	Repetition rate (Hz)	Protons per pulse (10^{13})	Pulse length at target (μs)
IPNS, ANL [4]	Operating since 1981	50 MeV linac and 500 MeV RCS	0.0075	30	0.3	0.1
ISIS, RAL [9]	Operating since 1985	70 MeV linac and 800 MeV RCS	0.16	50	2.5	0.45
SINQ, PSI [3]	Operating since 1996	590 MeV cyclotron	1.2	CW	-	-
LAMPF LANL [4]	Operating since 1977	800 MeV linac	1	120	6.5	1,200
LANSCE LANL [4]	Operating since 1988	800 MeV linac and accumulator	0.08	20	3	0.27
SNS, ORNL [8]	Construction	1 GeV linac and accumulator	1 (2)	60	10	0.7
J-PARC, Japan [10]	Construction	400 MeV linac and 3 GeV RCS	1	25	8.3	1
PEFP, Korea [5]	Construction	100 MeV linac	0.16	60	16.7	1,330
ESS Europe [11]	Planned	1.33 GeV linac and 2 accumulators	5	50	47 (2 rings)	1
CSNS, China [12]	Planned	80 MeV linac and 1.6 GeV RCS	0.1 (0.5)	25	1.6	0.8

or a rapid cycling synchrotron filled by multiturn injection and emptied by fast one-turn extraction. At the target, the proton beam duty factor is usually less than 10^{-4} providing high peak current and peak power.

CSNS INTRODUCTION

The China Spallation Neutron Source (CSNS) provides a multidisciplinary platform for scientific research and applications by national institutions, universities, and industries [12, 13]. 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 proton 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 2, 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. The CSNS complex is planned to be built at Dongguan, Guangdong province in southern China.

The H^- beam is first produced from the ion source, and then pre-chopped and transported through the Low Energy Beam Transport (LEBT). The beam is then bunched and accelerated through the Radio Frequency Quadrupole linac (RFQ) at a RF 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 (optional), and matches the beam to the Drift Tube Linac (DTL). At phase I of the project, 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) 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, [12]).

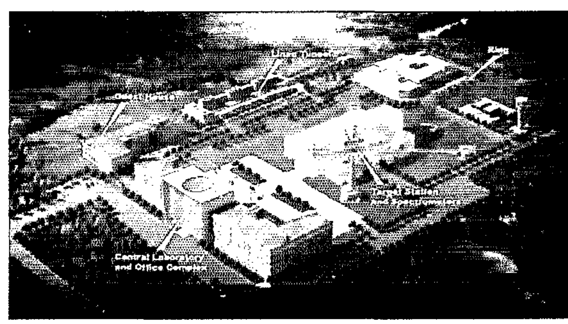

Figure 2: Artist's layout of the CSNS complex (courtesy Institute of Physics, CAS).

Financially, the project must fit in China's present eco-

Table 2: 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

nomical condition with a cost of about 1.5 billion Chinese Yuan (1.5 B CNY, about US$0.2 B). This limits the initial accelerator power to about 120 kW. On the other hand, we strive to 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 managerial challenges [2] 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 taking advantage of the relatively low labor cost, and seek worldwide collaborations for advanced technology.

DESIGN ITERATIONS

The design of the accelerator complex is based on the experience at accelerator facilities including ISIS, PSR, SNS, J-PARC, the Brookhaven National Laboratory AGS/Booster (Fig. 1), and the Beijing Electron Positron Collider (BEPC) [14], and project proposals including the AUSTRON [15] and the European Spallation Source (ESS) [16]. In this Section, we discuss design iterations of major CSNS accelerator systems (Fig. 3).

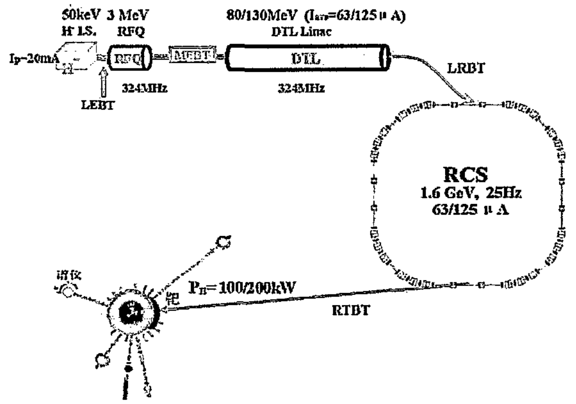

Figure 3: Schematic layout of the CSNS complex indicating the ion source, linac, ring, target, and instruments.

Ion Source and LEBT

The initial H^- ion source needs to provide 0.5 ms long, 25 mA peak current pulses at 25 Hz to 50 keV energy for phase I operation, and higher current and longer pulse length beyond phase I as shown in Table 3. Two types of ion sources are considered best candidates for their favorable cost and reliability performance: the ISIS-type Penning surface source [17], and the DESY/modified-SNS-type RF driven source with external antenna [18, 19].

Table 3: CSNS H^- ion source design parameters.

	Phase I	Phase II	Phase II'	Units
Ion species	H^-	H^-	H^-	
Rep. rate	25	25	25	Hz
Output energy	50	50	50	keV
Trans. emit., $\epsilon_{N,rms}$	0.2	0.2	0.2	$\pi\mu$m
Lifetime	30	30	30	days
Current	20	40	40	mA
Pulse length	500	500	900	μs

The LEBT matches the flat beam from the ion source slit to the RFQ aperture. A pre-chopper in the LEBT chops the beam macropulse at a 50% ratio at the ring injection revolution period. Space charge neutralization in the LEBT helps to reduce the emittance growth.

Linac

Originally, the RF frequency of the CSNS linac was 352 MHz based on available cw klystron and waveguide equipment assisted by CERN. However, the pulsed feature of the CSNS beam demands a linac RF source of higher peak power for efficiency. The RF frequency for the linac is thus changed to 324 MHz, the same as that of J-PARC so that the same klystron can be used for the RFQ and DTL as a high power pulsed RF source. This frequency also gives a reasonable room for the electro-magnetic quadrupole in-side the drift tube.

Tunnel space is reserved in the lianc section for future increase of linac output energy from 81 MeV of phase I to either 132 MeV using DTL or 230–250 MeV using a combination of DTL and SC RF linac.

RFQ The four-vane RFQ of CSNS is similar to the one previously developed at IHEP for the Accelerator Driven Sub-critical (ADS) program [20]. In comparison, the RF frequency is chosen to be 324 MHz, and the input energy is lowered to 50 keV to ease chopping. The cavity is divided into two resonantly coupled segments each consisting of two technological modules. Main RFQ parameters are listed in Table 4.

Table 4: CSNS RFQ design parameters.

Input energy	50	keV
Output energy	3	MeV
RF frequency	324	MHz
Peak current	40	mA
Beam duty factor	1.05	%
Transmission	97	%
Total Rf power	510	kW
Vane voltage	80	kV
Max. surface field	1.78	Kilp.
Total vane length	3.62	m
Ave. bore radius	3.6	mm
Structure	4-vane	

MEBT The Medium Energy Beam Transport (MEBT) consists of quadrupoles and re-buncher cavities to transport and march the beam from the RFQ to DTL. Space is reserved to house both the secondary chopper and beam halo scraper for phase II and beyond when the beam intensity is higher.

DTL The room temperature DTL is designed to accelerate the 3 MeV beam from the RFQ to 81 MeV, as shown in Table 5 ([21]). Each of the four tanks consumes about the same amount of RF power (cavity RF power of 1.5 MW, total RF power of 2.0 MW). To reach a high effective shunt impedance, we vary the cell shape with β stepwise while keeping the maximum surface electric field below 1.3 times the Kilpatrick limit. J-PARC type electromagnetic quadrupoles made of electroformed hollow coils are used [22].

Linac RF Power Supply Five sets of power sources are used to power the RFQ and four DTL tanks. At 324 MHz RF frequency and 2.5 MW peak power, the Toshiba E3740A klystron is one of the candidates [23].

The proposed high voltage power supply for the klystron is shown in Fig. 4. The 50 Hz, three phase 380 V power from the main is converted to 25 Hz, one phase 3.3 kV power to the LC resonance, ac charging circuit through an IGBT frequency converter. Voltage of 100 kV on the capacitor bank becomes negative half wave after the diode. Then, the modulator provides a dc pulse discharge to the klystron anode. The pulse flattop is optimized by properly selecting the modulator switching time so that pulse discharge decline is compensated by the rising sinusoidal waveform. This scheme avoids step-up high voltage transformers and multiphase high voltage rectifiers [24].

Table 5: CSNS DTL design parameters.

	Phase I	Phase II	Units
Output energy	80.8	132.2	MeV
Length	33.7	59.6	m
Structure	DTL	DTL	
No. DTL tanks	4	7	
RF frequency	324	324	MHz
Ave. syn. phase	−25	−25	deg.
Max. surface field	1.3	1.3	Kilp.
Bore radius	6 - 13	6 - 13	mm
Focusing structure	FD	FD	
Focusing period	2	2	$\beta\lambda$
No. quad	154	220	
Quad type	EM	EM	
Peak current	15	30	mA

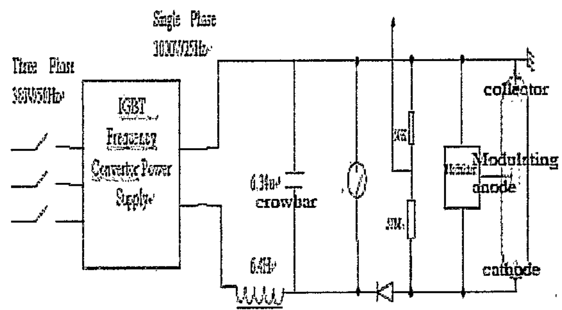

Figure 4: Proposed ac series resonance high-voltage power supply for the klystron.

LRBT line

The Linac to Ring Beam Transport (LRBT) serves several functions [25]. As shown in Fig. 5, the debuncher located at a distance from the end of linac reduces energy deviation and fluctuation. The 45° bend facilitates momentum collimation of possible beam halo and tail in the longitudinal direction. Three sets of scrapers provide collimation in the transverse directions. Finally, the beam is matched to design phase-space parameters for ring injection downstream of the 45° anti-bend.

The 45° bend sufficiently isolates the ring from the linac so that construction or maintenance may be performed on the ring while the beam is present in the linac. The bend also provides outlets of the linac beam for future applications (Fig. 5).

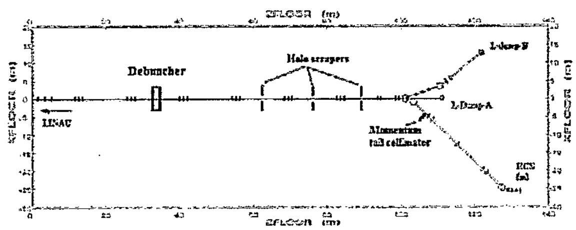

Figure 5: Schematic layout of the Linac Ring Beam Transport (LRBT).

Synchrotron

Fig. 6 shows the functional layout of the RCS ring. A four-fold symmetric lattice is favored over three-fold to separate injection, collimation, and extraction to different straights. For a high-power RCS, longitudinal collimation of beam halo and tail plays an important role [26]. The longitudinal and transverse collimation system occupies a long section immediately downstream of the injection.

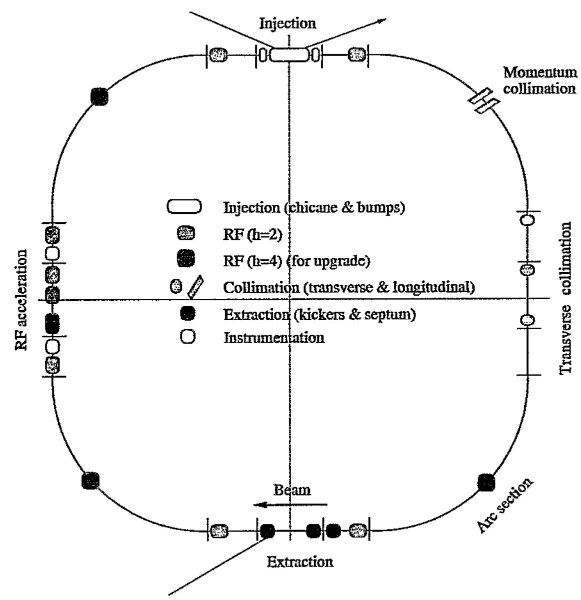

Figure 6: Schematic layout of the CSNS RCS ring.

Lattice The ring adopts a hybrid lattice with missing-dipole FODO arcs and doublet straights (Fig. 7 [27, 28]). The dispersion is suppressed by using two groups of 3 half-cells (with 90° horizontal phase advance per cell) located on each side of a missing-dipole half-cell, as shown in Fig. 8. The long (one 9 m and two 6 m uninterrupted drifts per straight) dispersion-free straights facilitate injection [29], extraction [30], 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 [28].

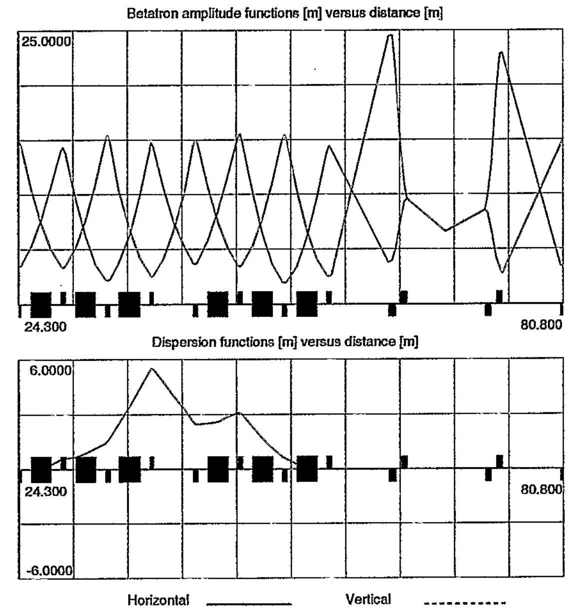

Figure 7: CSNS synchrotron lattice functions in one superperiod. The ring has a periodicity of 4.

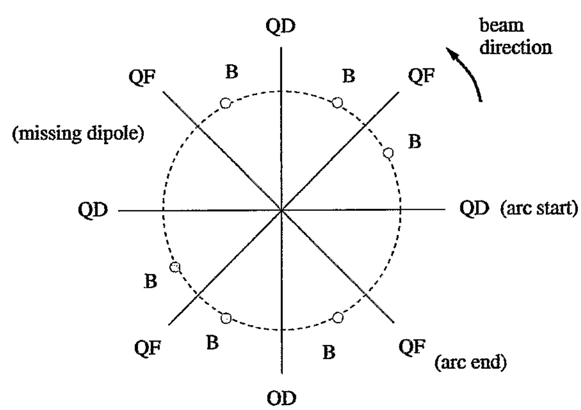

Figure 8: Dispersion suppression with a single missing dipole shown in the horizontal phase space.

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 about 0.3 for a beam of $320\pi\mu$m emittance. The momentum acceptance in $\Delta p/p$ is $\pm1\%$ at the longitudinal collimator, and $\pm1.5\%$ elsewhere for a beam of $320\pi\mu$m emittance.

Acceleration Fig. 9 shows the injection and acceleration cycle of the RCS main magnetic field [31]. The acceleration is performed by 10 RF cavities with maximum total voltage of 165 kV per turn at harmonic $h = 2$. The main dipole field varies from 0.16 to 0.98 T. The bunching factor varies from 0.38 at injection to 0.12 at extraction. Chopping at 50% rate significantly reduces the expected beam loss occurring mostly during the initial stage of ramping.

Space is reserved to house the second harmonic ($h = 4$) RF cavities to increase the bunching factor allowing a higher total beam intensity (Fig. 6).

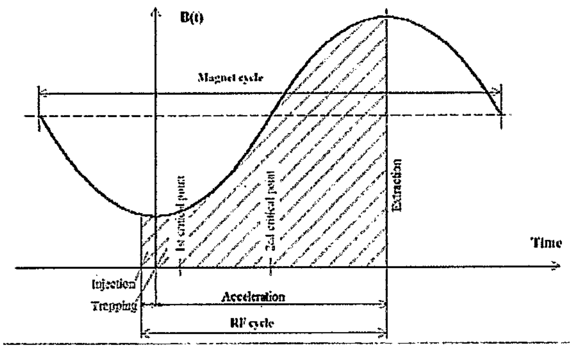

Figure 9: RCS main magnetic field variation showing the RCS injection and acceleration cycle.

Ring engineering systems 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 stranded aluminum wires fabricated by domestic vendors. Alternative designs of the magnet coil are under evaluation considering fabrication cost and robustness [32, 33, 34].

The ring main magnets are powered by a family of dipole and 8 families of quadrupole power supplies arranged in parallel groups with multimesh White circuits operating at 25 Hz resonance [35]. 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 [26]. 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 [36]. The design gradient is about 10 kV/m. Test stands are set up to measure the ferrite properties under the dynamic ramp cycle. Fig. 10 shows the cavity schematic design.

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 under study to form long, curved, large-bore ducts. Detachable, external metal-stripe wrappings are considered for the RF shielding [33], and all inner surfaces (ceramic, metal, and ferrite) are to be coated with TiN to reduce secondary electron emission yield [2].

The injection adopts SNS-type charge-exchange scheme with phase-space painting using 4 shift dipoles and 8 painting bump magnets [29, 37]. 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 from the corner-located foil immediately upon the injection completion using the painting bumps powered by IGBT-based programmable power supplies.

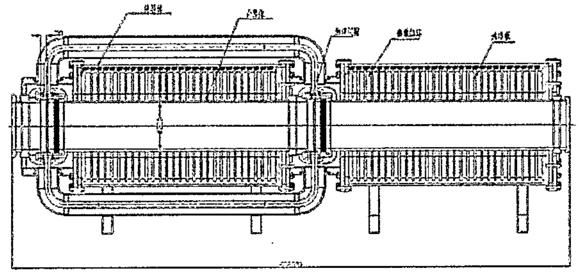

Figure 10: Preliminary drawing of the RCS ferrite loaded RF cavity.

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 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 [14] and SNS projects (adopting EPICS, XAL, PSI/PSC control, static and dynamic databases, etc.).

PROTOTYPE RESEARCH & DEVELOPMENT

Due to limited initial funding, prototype R&D on key accelerator components is staged in two periods. With the initial funds of about 20 million CNY (about US$2.5M) provided by the Chinese Academy of Sciences, we started period-I prototyping on five systems: a section of the DTL tank, two RCS magnets, a set of RCS dipole power supply, a RCS RF cavity, and RCS ceramic vacuum ducts. Items planned for period-II R&D include the H^- ion source, the linac HV power supply, the injection bump magnet and its power supply, the extraction kicker and its power supply, the RCS RF cavity power amplifier, and components for the controls, diagnostics, and radiation protection systems.

Ion source and the test stand

Owing to the kind support from the ISIS, we started to build an ISIS type H^- ion source and a test stand at IHEP. Mechanical design and fabrication of the Penning source body is in progress. J-PARC-like magnetic LEBT is also planned.

RFQ for ADS Program

The knowledge on RFQ benefited from the research program launched in 2000 under the support of the Ministry of Science and Technology, China. Under this program, a four-vane type RFQ accelerator was built (Fig. 11 and [20]). This 352.2 MHz RFQ has a length of about 5 times the wavelength $\beta\lambda$. To address the longitudinal field stability issue, we adopted the resonant coupling option proposed by L. Young [38]. The 4.8 m long accelerator is separated into two segments each consisting of two technological sections. On each section there are 16 tuners distributed in the four quadrants for frequency and field tuning. Dipole mode stabilizer rods are applied on both the end plates and the coupling plate. Since the duty factor is high (6% for phase I and 100% in future), water cooling is necessary for both the vane and wall to maintain thermal stability. We use two separated cooling water systems, one for the vane and the other for the wall, to tune the frequency during high-power conditioning.

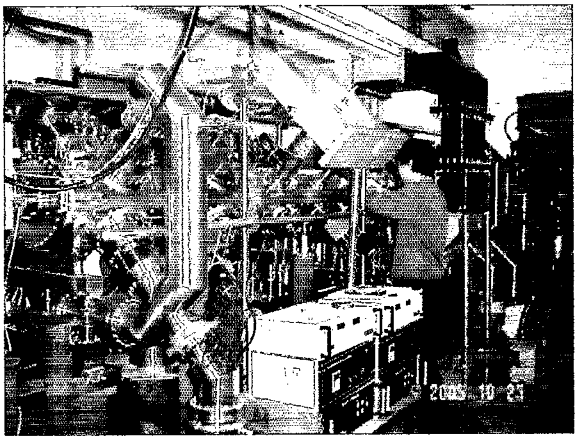

Figure 11: The ADS RFQ under commissioning at the Institute of High Energy Physics, China. The first proton beam was successfully extracted in July 2006.

In July 2006, the first proton beam was injected from the ECR ion source and successfully extracted from the RFQ. The initial transmission efficiency is 92% on a proton beam of 44 mA peak current. Recently, the beam duty factor reached 6% with beam of 1.2 ms pulse length running at 50 Hz (Table 6). Work is in progress to improve the cooling efficiency in the attempt to reach a higher duty factor.

DTL

Even though IHEP has built a 35 MeV DTL about 20 years ago operating at 201 MHz frequency, developing a DTL at 324 MHz in a short time presents challenge. Both electroforming and explosive-forming methods are attempted for the DTL tank. Fig. 12 shows a short section of the tank fabricated with explosive clad technology including all ports for vacuum grill, drift tube stem, stabilizer post, and tuner. To make the hollow conductor coil for the EMQ, a test plate with a cooling water duct is successfully fabricated with the periodic reverse electroforming method.

Table 6: Major parameters achieved with the ADS RFQ in summer 2006.

Input energy [keV]	75
Output energy [MeV]	3.5
Peak current [mA]	44
Beam pulse length [ms]	1.2
Repetition rate [Hz]	50
Duty factor [%]	6
RF frequency [MHz]	352.2
Transmission efficiency [%]	92

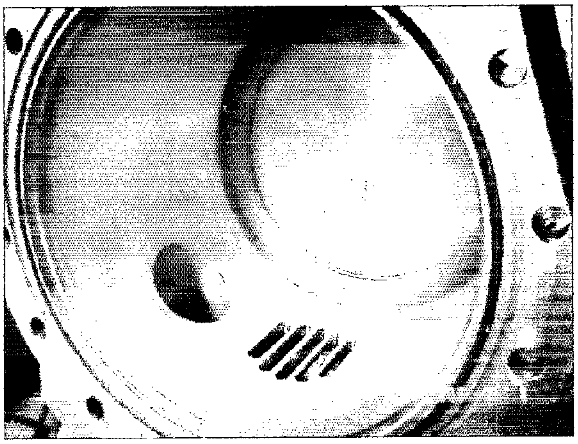

Figure 12: A steel-copper clad test tank with all type of ports made with explosive clad technology.

Linac RF supply

A small-scale circuit (Fig. 13) was set up to demonstrate the principle of the CSNS type linac HV power supply. In this LC ac series resonance supply, we achieved 14 kV voltage and 14 A pulse current. A satisfactory flattop was obtained by optimizing the pulse trigger timing [24, 21].

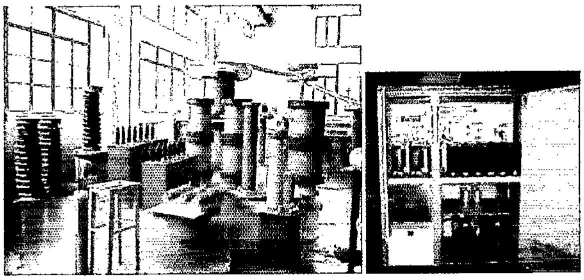

Figure 13: Small-scale demonstration apparatus of the CSNS type linac HV power supply.

Ring magnet

So far, three domestic vendors have successfully fabricated dipole magnet coils made of stranded aluminum wires (Fig. 14). This type of coil will be used for the prototype dipole magnet. For the quadrupole magnet, we pursue in parallel designs with stranded aluminum wires and with four-piece hollow-conductor copper wires. A comparison will be made to determine the most robust and cost effective quadrupole magnet.

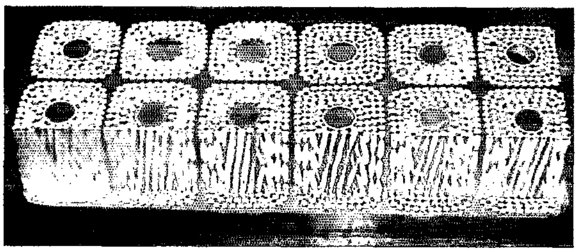

Figure 14: One of the first prototypes of the J-PARC type stranded magnet coil fabricated by a vendor in China.

Ring magnet power supply

A small-scale resonance circuit (Fig. 15) (about 0.1% of dipole stored energy) was set up to test the performance of different working modes of the White circuit. Actual-scale prototyping is in progress to power the prototype ring dipole magnet. For the prototype White circuit, we plan to use multi-gap type choke and normal single-phase capacitor with low dielectric losses and a long lifetime.

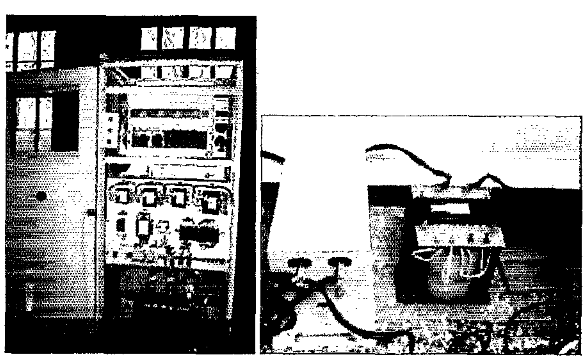

Figure 15: Small-scale demonstration apparatus of the CSNS ring magnet resonance White circuit.

FUTURE OUTLOOK

The CSNS accelerator is designed to provide beam power up to 500 kW in phased stages capable of supporting one or more target stations. Power upgrade depends crucially on maintaining low uncontrolled beam loss. 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 in the ring.

It is possible for CSNS to serve multiple purposes including serving as a test facility for the ADS (ADTF). Fig. 16 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 higher power, while extension of the ring yields higher energies.

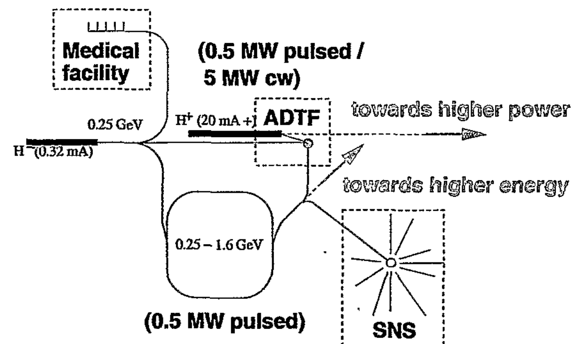

Figure 16: Possible CSNS upgrades towards higher power, higher energy, and multipurpose.

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