HIGH-POWER ACCELERATORS IN CHINA: STATUS AND OUTLOOK*

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Abstract

Starting in 2000, high-power accelerator programs are actively pursued in China. Recent activities include the China Spallation Neutron Source (CSNS) and Accelerator Driven Subcritical (ADS) reactor research and development programs. In this paper, we give an overview with emphasis on the CSNS project status and future outlook.

INTRODUCTION

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 isochronous-cyclotron of 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 LAMPF proton linac at Los Alamos with a beam power of 1 MW at 800 MeV [4]); and short (μs) pulses driven by a combination of high intensity linacs and rings, as shown in Table 1 and Fig. 1 [4, 5, 6, 2]. Among the short-pulse facilities are two types of accelerator layout: a full-energy linac followed by an accumulator (example: the operating LANSCE at Los Alamos with a beam power of 80 kW at 800 MeV [4] and the SNS under construction at Oak Ridge [7]) and a partial-energy linac followed by a rapid cycling synchrotron (RCS) (example: the operating ISIS at the Rutherford Appleton Laboratory with a beam power of 160 kW at 800 MeV [8] and the J-PARC under construction in Japan [9]).

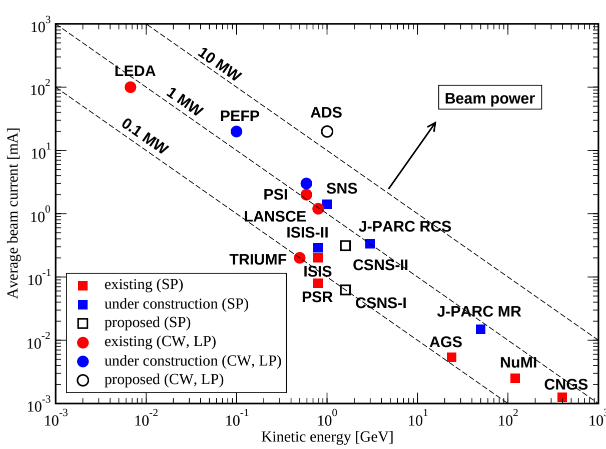

Figure 1: Accelerators at the power frontier (short pulse SP, long pulse LP, continuous wave CW).

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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 (10% 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 nuclear waste transmutation, accelerator production of tritium, and accelerator driven subcritical (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 (Fig. 1). Newly constructed and proposed facilities aim at MW beam power. These facilities typically uses high peak-current H^- sources and a pulsed H^- linac combined with an accumulator ring or a rapid cycling synchrotron filled by multi-turn 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.

High power accelerator programs in China mainly consists of the China Spallation Neutron Source (CSNS) project and ADS related research and developments [12]. In this paper, we present an overview with emphasis on the CSNS project status, R&D challenges, and future outlook.

CHINA SPALLATION NEUTRON SOURCE

The China Spallation Neutron Source (CSNS) provides a multidisciplinary platform for scientific research and applications by national institutions, universities, and industries [11, 12]. 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 2, the accelerator complex is designed to deliver a beam power of 120 kW with the upgrade capability of up

Table 1: The China Spallation Neutron Source (CSNS) in comparison with a few existing and planned proton accelerator facilities in the world [3]-[11].

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 [8]	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	-	1,200
LANSCE LANL [4]	Operating since 1988	800 MeV linac and accumulator	0.08	20	3	0.27
SNS, ORNL [7]	Construction	1 GeV linac and accumulator	1 (2)	60	10	0.7
J-PARC, Japan [9]	Construction	400 MeV linac and 3 GeV RCS	1	25	8.3	1
ESS Europe [10]	Planned	1.33 GeV linac and 2 accumulators	5	50	47 (2 rings)	1
CSNS, China [11]	Planned	80 MeV linac and 1.6 GeV RCS	0.1 (0.5)	25	1.6	0.8

to 500 kW by raising the linac output energy and increasing the beam intensity. The CSNS complex is planned to be built in the Guangdong province in southern China.

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

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, [11]).

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 [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 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 ADS program [13]. 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.

The ring adopts a hybrid lattice with missing-dipole FODO arc and doublet straight (Fig. 4 [14, 15]). The dispersion is suppressed by using two groups of 3 half-cells (90° horizontal cell phase-advance) located on each side of a missing-dipole half-cell, as shown in Fig. 5. The long (one 9 m and two 6 m uninterrupted drifts per

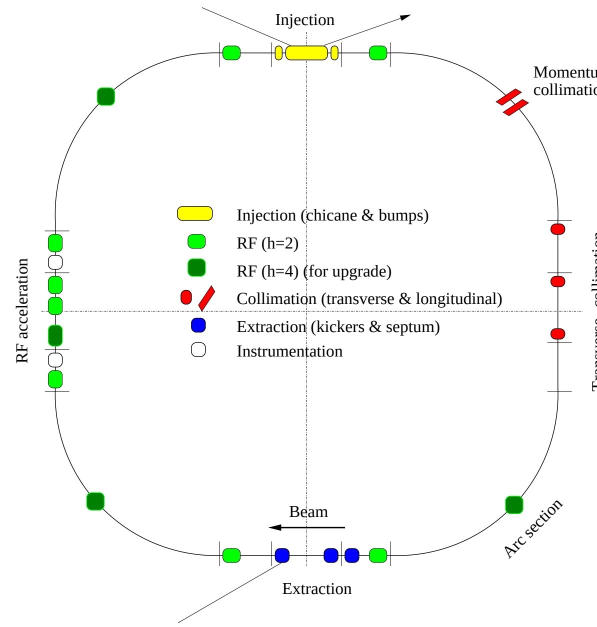

Figure 3: Schematic layout of the CSNS synchrotron.

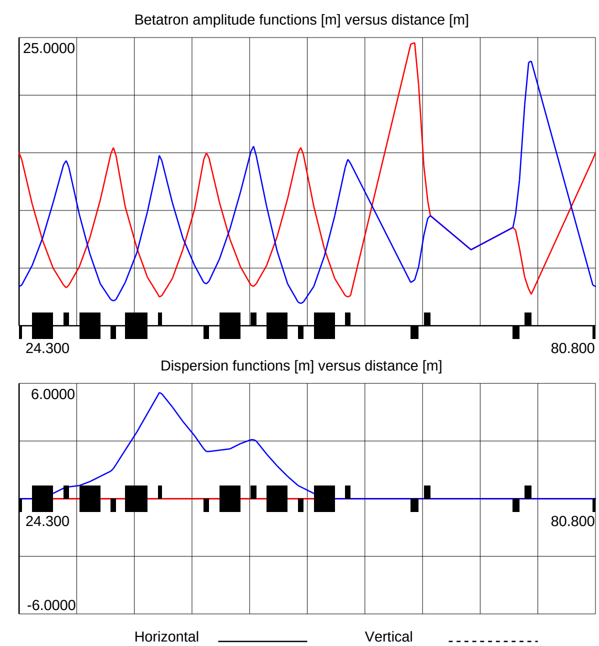

Figure 4: CSNS synchrotron lattice functions in one superperiod. The ring has a periodicity of 4.

straight) dispersion-free straights facilitate injection, extraction [16], 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 $\pm 1.5\%$

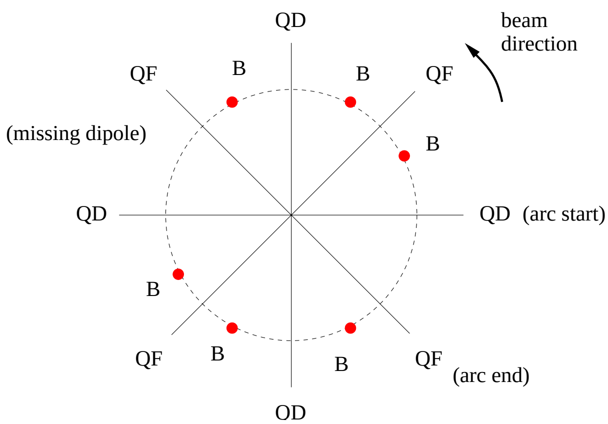

Figure 5: Dispersion suppression with a single missing dipole shown in the horizontal phase space.

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 (Fig. 6). Alternative designs of the magnet coil have been under evaluation considering the long-term operational reliability and fabrication robustness [17, 18, 19].

Figure 6: One of the first prototypes of the J-PARC type braided magnet coil fabricated by a vendor in China.

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 [20]. 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 [21]. 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, curved, large-bore ducts. Detachable, external metal-stripe wrappings are considered for the RF shielding [18], 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 [16, 22]. 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.

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.).

ADS RELATED R&D

The Strong economical growth in China demands a significant increase in the electrical power supply. In the next 15 years, 25 new nuclear power reactors are planned to be constructed in China. Accelerator driven subcritical (ADS) systems are recognized as one of the best solutions both for transmutation of the nuclear waste and for eventual fission-based nuclear power generation complimenting both fast-breeder reactors and pressure-water reactors [12].

An ADS basic research program was 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. 7 and Table 3, [13]). 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 [23]. 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 the 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. In July 2006, the first proton beam was injected from the ECR ion source and successfully extracted from the RFQ. Full beam commissioning is currently underway.

Figure 7: The ADS RFQ under commissioning at the Institute of High Energy Physics, China. The first proton beam was successfully extracted in July 2006.

Table 3: Major parameters of the ADS RFQ.

Input energy [keV]	75
Output energy [MeV]	3.5
Peak current [mA]	50
Structure type	4 vane
Beam pulse length [ms]	1.2
Duty factor [%]	≥6
RF frequency [MHz]	352.2
Maximum field E_s [MV/m]	33
Beam power [kW]	170
Structure power [kW]	420
Total power [kW]	590
Total structure length [m]	4.75

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 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 in the ring.

It is possible for CSNS to serve multiple purposes including serving as a test facility for the ADS (ADTF). Fig. 8 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.

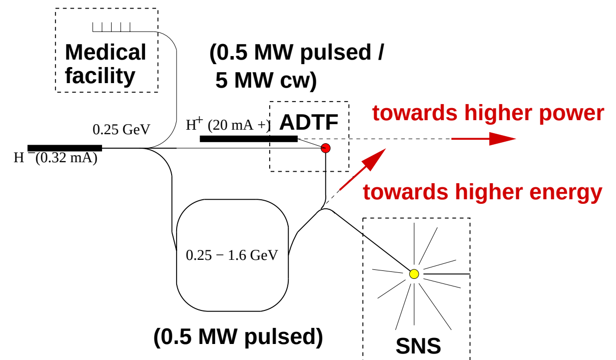

Figure 8: Possible CSNS upgrades towards higher power, higher energy, and multipurpose.

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