China High-Intensity Accelerator Technology Developments for Neutron Sources and Accelerator Driven Systems

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Abstract. There have been aggressive developments in China on the technology of high intensity hadron accelerators for spallation neutron source, compact neutron source, accelerator driven sub-critical systems (ADS), and other related programs including hadron therapy. The primary challenge is to build a robust facility at a fraction of the "world standard" cost. Benefiting from a close collaboration with world leading institutes and facilities, tremendous efforts were made in China to develop domestic vendors to comprehend the technology for key systems of high intensity ion source, linear accelerators, and rapid cycling synchrotron. Goals of such facilities include spallation-neutron-based, muon-based, and proton-based platforms for multi-discipline science and industrial applications, fast-neutron-based platform for nuclear science and applications, and parasitic apparatus for medical therapy and ADS tests. This paper attempts to summarize the R&D efforts, key component prototyping and vendor development experience, and user development efforts during the past several years in China.

1. Introduction

Electron–accelerator driven radiation sources are relatively well developed in China. So far, four synchrotron radiation light sources in Hefei, Beijing, Taiwan, and Shanghai are in operation. The development of hadron-accelerator driven proton and neutron facilities, on the other hand, is rudimental at best; the China Spallation Neutron Source (CSNS) project still await construction to start in 2010. However, recognizing the importance of accelerator and nuclear research platforms to education, basic science and technological innovation, China with her presently growing interests in multi-disciplinary R&D areas is determined to expand the scope of proton-based accelerator applications to regional and university-based facilities.

During the recent years, several organizations and institutions in China including the Chinese Academy of Sciences (CAS), the China Institute of Atomic Energy (CIAE), the China Academy of Engineering Physics (CAEP), Tsighua University, and Beijing University, have significantly increased the efforts in their development of proton accelerator technology for multi-disciplinary applications. Approved programs and projects include the accelerator driven sub-critical systems (ADS) test front end participated by CIAE and the Institute of High Energy Physics of CAS, the China Spallation Neutron Source (CSNS) by CAS, the facility for neutron radiography by Beijing University, and the Compact Pulsed Hadron Source by Tsinghua University. In addition, several institutes are pursuing the R&D for proton and carbon beam therapy facilities.

Approved projects in China are usually awarded with a budget considerably lower than the corresponding one in the "world standard". This would make sense only if domestic production of major components can underprice foreign competitors with equivalent quality assurance. Therefore, it is crucial for the sponsoring institution to seek worldwide

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collaborations on instrumentation R&D in order to glean the knowledge and techniques. Eventually, the technologies are to transferred to the supporting domestic industry which would produce the final components with substantial saving by taking advantage of the relatively low labor cost in China. In the last several years we have benefited from a close networking with world leading institutes and facilities through advisory, training, and reviewing activities. As a result, major R&D and prototyping efforts were launched to comprehend the technology of high intensity ion source, linear accelerators, and rapid cycling synchrotrons.

This paper first introduces the design of several proton-accelerator-based programs and projects, and then summarizes the relevant R&D efforts and component prototyping and vendor development experience during the past several years in China.

2. High-intensity Proton-beam Based Programs

This section describes the major design aspects of the CSNS, CPHS, and ADS test programs.

2.1. China Spallation Neutron Source Project

The China Spallation Neutron Source (CSNS) project proposal was officially approved by the National Development and Reform Commission in September 2008 with a construction budget of 1.4 B CNY. The Guangdong provincial government and the Dongguan municipal government provide an auxiliary supporting fund of 0.5 B CNY and 0.67 km^2 of land. The project is co-sponsored by the Chinese Academy of Sciences and the Guangdong Province. Once the expected ground breaking in early 2010 at Dongguan, Guangdong, the construction is expected to be completed in 6.5 years.

As shown in Fig. 1, the CSNS complex consists of an H$^-$ linear accelerator, a rapid cycling synchrotron accelerating the beam to 1.6 GeV, a solid tungsten target station, and three instruments for neutron-scattering experimentation. The facility operates at 25 Hz repetition rate with an initial beam power of 120 kW and an upgradeable beam power of 500 kW.

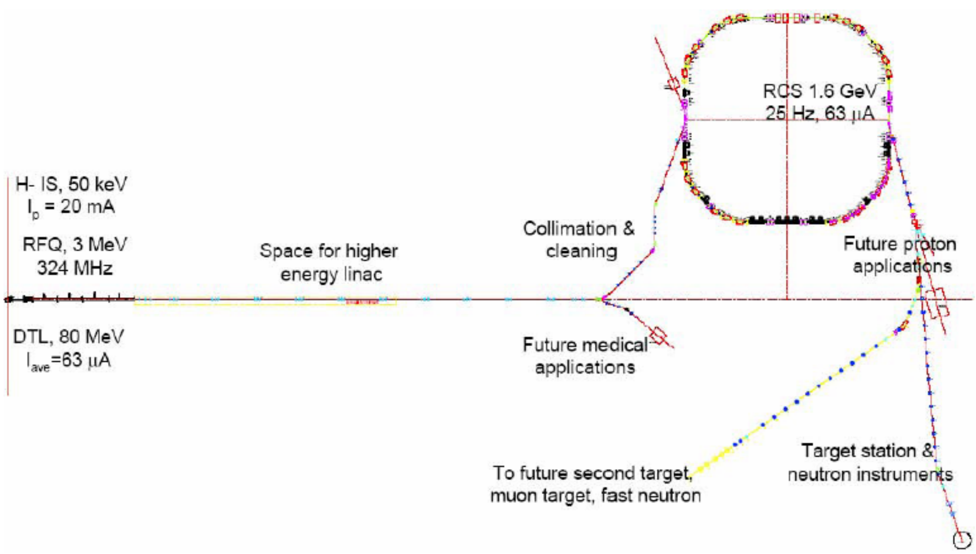

FIG. 1. Schematic layout of the China Spallation Neutron Source.

The design of the accelerator complex is based on the experiences at accelerator facilities including ISIS, PSR, SNS, J-PARC, the BNL AGS/Booster, BEPC, and project proposals including the AUSTRON and the ESS [3]. The ISIS-type Penning source was adopted, developed at IHEP with assistance from ISIS, and successfully tested at ISIS. A pre-chopper in the low-energy-beam-transport is designed to chop the beam macro-pulse at a 50% ratio at the ring injection revolution period. The linac RF frequency is 324 MHz, the same as that of J-PARC so that the same kind of klystrons can be used for the RFQ and DTL. Space is reserved in the medium-energy-beam-transport to house both the secondary chopper and beam halo scraper for phase II and beyond when the beam intensity is higher. Five sets of power sources of 2.5 MW peak power are used to power the RFQ and four DTL tanks. An ac-series resonance high-voltage power supply is developed for the klystrons avoiding step-up high voltage transformers and multiphase high-voltage rectifiers. The debuncher located at a distance from the end of linac reduces energy deviation and fluctuation. The 90^o bend facilitates momentum collimation of possible beam halo and tail in the longitudinal direction. Three sets of scrapers provide collimation in the transverse directions. The bend also provides outlets of the linac beam for future applications.

The RCS ring adopts a hybrid lattice with missing-dipole FODO arcs and doublet straights. The dispersion is suppressed by using two groups of three half-cells located on each side of a missing-dipole half-cell. The long dispersion-free straights facilitate injection, 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 allows efficient longitudinal collimation.

The neutron target is surrounded by a beryllium–iron reflector, three wing-moderators (decoupled water at the room temperature, coupled- and decoupled-poisoned hydrogen at 20K), bulk shields and neutron-scattering facilities. 18 ports with vertical steel shutters are designed in the iron-heavy-concrete shielding passing neutrons for the instruments. Under R&D evaluation is a surface-cooled target core rotating at the frequency of about 1 Hz. Such target may sustain the 500 kW design beam power with easier maintenance and lower cost. Furthermore, back-shine from the target travelling in the opposite direction of the incident proton beam may be conveniently utilized for fast-neutron applications. CSNS’ first target station accommodates at least 18 neutron scattering instruments. Three day-one instruments are supported: a high-intensity diffractometer, a broad Q-range small-angle diffractometer, and a multi-purpose reflectometer. Efforts are made to attract interested institutes and universities to invest in dedicated neutron instruments. Table 1 shows the primary parameters of the baseline and the upgrade phases.

TABLE 1. CSNS PRIMARY PARAMETERS IN THE BASELINE AND THE UPGRADE PHASES.

Project phase	**I**	**II**	**II’**
Beam ave. power, kW	120	240	500
Proton energy, GeV	1.6		
Ave. current, I, µA	76	151	315
Repetition rate, Hz	25		
Proton per pulse, 1013	1.88	3.76	7.83
Pulse length, ns	<500		
Linac energy, MeV	81	134	250
Macro ave. I, mA	15	30	40
Uncontroled loss, W/m	~ 1		
Target material	Tungsten		
Moderators	H_2O, (2) H_2		
No. neutron instruments	3	18	>18

2.2. Compact Pulsed Hadron Source Project

The Compact Pulsed Hadron Source (CPHS) is a newly approved project led by the Department of Engineering Physics of the Tsinghua University, China. The compact facility is to be housed in the existing building previously and now no longer needed for cargo-inspecting accelerator systems. As shown in Fig. 2, the CPHS complex consists of a high-intensity proton linac (proton source, RFQ, and DTL) and a beryllium target station for neutron production. Phase 1 of the project also consists of a neutron small-angle-scattering instrument and a neutron imaging/radiography station. Phase 2 of the project consists of instruments for both proton (space irradiation and detection, bio-application, and fuel-cell and nano-applications) and neutron (engineering powder diffractometer, reflectometer, irradiation station, neutron therapy, and neutron R&D beam-line) beams. Phase 1 of the project is planned to be constructed in about 3 years.

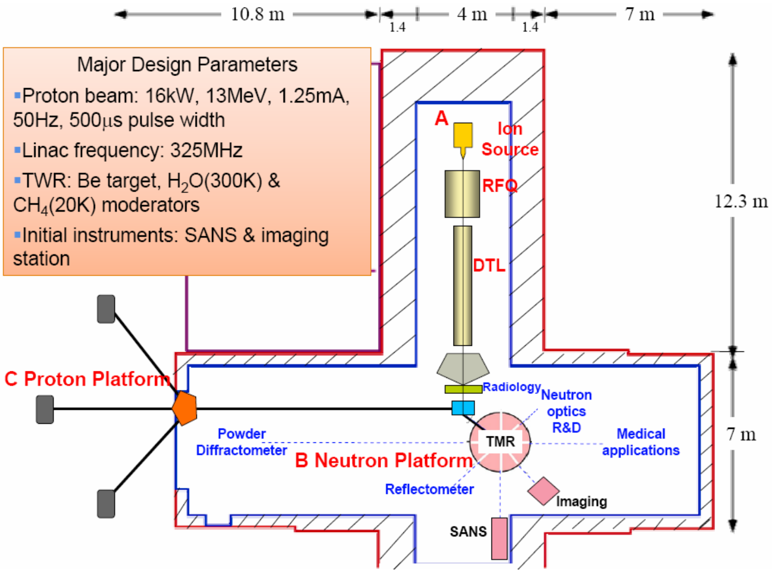

FIG. 2. Schematic layout of the Compact Pulsed Hadron Source.

Table 2 shows the primary parameters of the facility complex. The proton beam produced from the ECR source at 50 keV of energy is accelerated first by the RFQ to 3 MeV and then by the DTL to 13 MeV. Both RFQ and DTL linac are powered by a single klystron power supply. The lianc RF frequency of 325 MHz is chosen so that high-energy extension of the linac can operate at a frequency of 1.3 GHz shared by many R&D programs. Design experiences of the LENS facility of Indiana University are heavily referenced.

TABLE 2. CPHS PRIMARY PARAMETERS.

Proton power on target	16	kW
Proton beam energy	13	MeV
Average beam current	1.25	mA
Pulse repetition rate	50	Hz
Protons per pulse	1.56×10^{14}	protons
Pulse length	0.5	ms
Peak beam current	50	mA
Linac RF duty factor	2.5	%
Linac RF frequency	325	MHz
Target material	Be	
Moderators	H_2O (300K), CH_4 (20K)	

2.3. Accelerator Driven Sub-critical Reactor Program

Accelerator Driven Subcritical system (ADS) is recognized as an attractive method of nuclear waste transmutation. Supported by the Ministry of Science and Technology of China, an R&D program was launched in 2000 to study key technologies of an intense beam proton linac, including construction of an ECR proton source and a pulsed RFQ linac. Chinese Academy of Sciences supported the research of linac superconducting RF cavity. Institute of High Energy Physics, China Institute of Atomic Energy, and Institute of Heavy Ion Physics of Peking University jointly conduct the research.

As shown in Fig. 3 and Table 3, the ECR source and the low energy beam transport (LEBT) were built by CIAE as the injector to the RFQ. Efforts were made on the reliability and stability of the source operation overcoming problems associated with the breakdown of the RF input ceramic window resulted from the electron back strike. 99.9% reliability was achieved during a 120-hour continuous operation.

FIG. 3 The ADS ECR proton source.

TABLE 3. ADS ECR SOURCE PARAMETERS.

Output energy	75 keV
Peak current	70 mA
RF frequency	2.45 GHz
RF power	1 kW
Emittance (norn., rms)	0.13 μm
Proton ratio	80%
Reliability	99%

For longitudinal field stability, the 3.5 MeV, 5 λ long RFQ is separated into two resonantly coupled segments each consisting of two technological modules of 1.2 m in length. Fig. 4 shows the RFQ together with the ECR ion source and the LEBT installed at IHEP. As shown in Table 4, the RFQ was designed with 100% duty for the cavity and RF power source. The RF duty factor was 6% during the initial commissioning and gradually rose to 15%.

TABLE 4: ADS RFQ PARAMETERS.

Output energy	3.5 MeV
Peak current	50 mA
Structure type	4 vane
Duty factor	6%-100%
RF frequency	352.2 MHz
Maximum E_s	33 MV/m
Beam power	170 kW
Structure power	420 kW
Total length	4.75 m

FIG.4 The ADS RFQ installed at IHEP.

Beam commission started at IHEP in 2006 with the RF system originally provided by CERN. The beam duty factor reached 7% with 1.43 ms pulse length at 50Hz. The 49 mA beam was transmitted with efficiency above 93%. Assisted by cooling water temperature control and a FPGA-based digital RF control system, the RF amplitude and phase stability reached ±1% and ±1^{o}, respectively (Fig. 5), during long pulse operation with heavy beam loading.

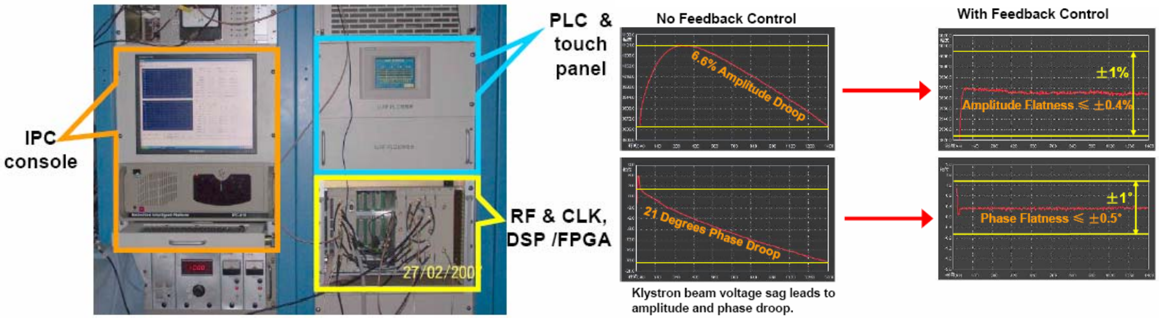

FIG.5. FPGA base digitalized LLRF system (left) and its effect on field control (right) .

3. Accelerator Technology Developments

This section highlights technology developments pertaining to neutron source and ADS programs covering the front end, linac, and rapid cycling synchrotron (RCS).

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 is now under development. The discharge chamber and the extractor were fabricated in China and tested at the ISIS ion source stand. The beam current reached 55 mA with a pulse length of 500 μ m at 50 Hz repetition rate. Fig. 6 shows the test stand elements to be assembled at IHEP.

The prototype of the first section of the CSNS DTL is under fabrication. The electro-magnetic (EM) quadrupole uses J-PARC-style coil with cooling channel made by periodical reverse electroform technology. Fig.7 shows the tank and the drift tube with EM quadrupole.

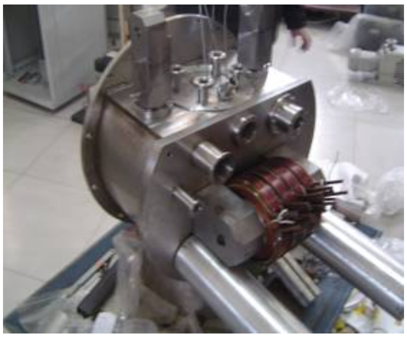

FIG. 6: A Penning source test stand is setting up at IHEP.

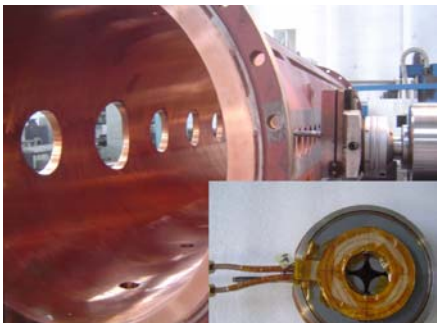

FIG.7. Prototype of the DTL tank and drift tube for CSNS.

Technology of superconducting RF cavity was studied for the medium energy section of a 1 GeV proton linac for ADS. A superconducting single ellipsoid cell of 1.3 GHz at β =0.45 was manufactured jointly with KEK. The cavities and the measured Q_0 are shown in Fig. 8.

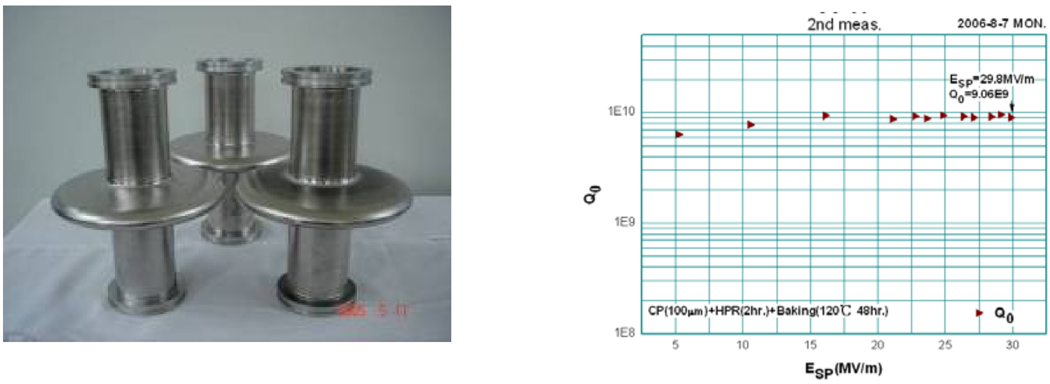

FIG. 8 β=0.45 SC cavities at 1.3 GHz with the measured Q_0>1×10^9.

A superconducting RF laboratory was established at IHEP for cell processing and measurement. A cryostat for 1.3 GHz cavities was built for vertical measurement at the working temperature of 1.5 to 4.2 K.

Developments on the RCS technology for the CSNS project focus on major components including the dipole and quadrupole magnets, magnet power supplies, ceramic vacuum chamber, ferrite loaded RF cavity, RF power source, inject and extraction magnets and their pulsed power supplies, beam diagnostics, and control system.

To reduce the eddy current of the dipole magnet coil, stranded aluminium coil with a steel cooling channel was made in China with which the prototype dipole magnet was fabricated. The magnet measurement is underway, as shown in Fig. 9. Fig. 10 shows the choke, capacitor bank, and power supply of the White circuit.

FIG. 9. The prototype RCS dipole magnet of stranded coil and the measurement system.

FIG. 10 The prototype power supply for the dipole magnet (choke, capacitor bank, and supply).

The prototype quadrupole magnet uses split four-conductor copper coil. Fig. 11 shows the prototype quadrupole magnet made in China. Ceramic vacuum chambers were in the RCS dipole and quadrupole magnets. A 1-m long curved prototype of the dipole ceramic chamber was made by a Japanese vendor with 4 small sections connected by glass joining. Chinese vendors independently produced the full- size prototype quadrupole chamber, as shown in Fig.12.

FIG. 11. The prototype RCS quadrupole magnet.

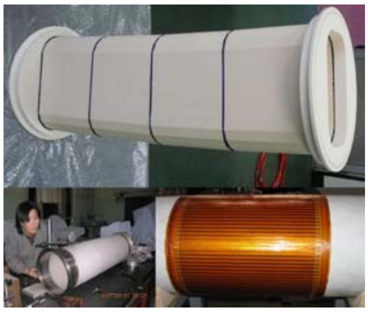

FIG. 12. The short prototype of the dipole ceramic chamber (upper) and two full-size quadrupole ceramic chambers (lower) .

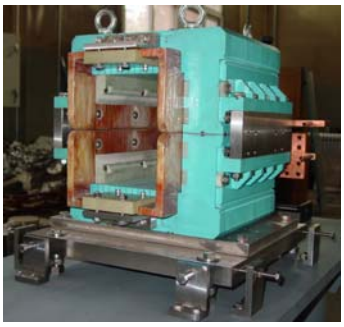

FIG. 13. The prototype injection magnet for the CSNS RCS.

FIG. 14. The prototype extraction kicker (insert) and its pulse forming network for the CSNS RCS .

Fig. 13 shows the prototype injection magnet for the CSNS RCS. Fig. 14 shows the prototype extraction kicker magnet and its pulse forming network. A prototype of the ferrite loaded RF cavity with two accelerating gas is assembled for vacuum leakage check in recent, as shown in Fig. 15. Many designs follow the practise of the Brookhaven National Laboratory for the SNS project in USA. A mock-up assembly of a rotating neutron target was fabricated to test the long-term reliability, as shown in Fig.16.

Fig. 15 The prototype ferrite-loaded RF cavity for the CSNS RCS

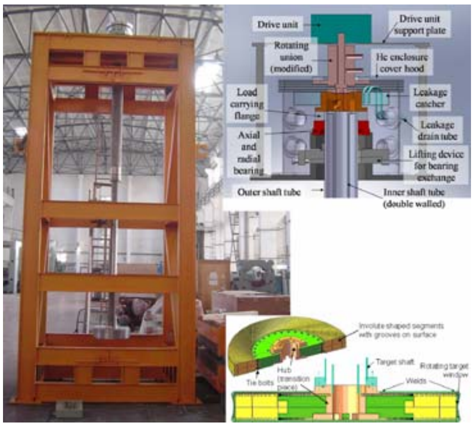

Fig.16: The mock-up CSNS rotating neutron target.

4. Summary and Discussions

This paper summarizes the technological development during the past several years in the field of high intensity proton accelerators. With ever increasing interests in compact hadron sources, hadron therapy facilities, spallation neutron sources, and ADS programs, hadron accelerator programs are flourishing in China. With years of intense R&D and the growth of domestic industry on accelerator components in China, these facilities may be built at a budget much lower than the "world standard" cost. Similar to the popularity of electron-based accelerators ranging from table top X-ray machines to synchrotron light sources, hadron-based accelerators may one day become indispensable parts of mankind's life.

5. Acknowledgements

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