Union of Compact Accelerator-Driven Neutron Sources (UCANS) III & IV

Delivery of 3-MeV proton and neutron beams at CPHS: A status report on accelerator and neutron activities at Tsinghua University

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Abstract

The Compact Pulsed Hadron Source (CPHS) project that was launched in September 2009 at Tsinghua University has reached a first commissioning stage in conjunction with ongoing activities to fulfill the eventual design goal of a $\sim 10^{13}$ n/s epithermal-to-cold neutron yield for education, instrumentation development, and industrial applications. Here, we report the latest progress on the design, fabrication, engineering of the 13 MeV/16 kW proton accelerator system, the neutron target station and neutron beamlines, especially regarding the successful delivery of the first 3-MeV proton beam and the realization of the first neutron generation in 2013.

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1. Introduction

The Department of Engineering Physics (DEP) of Tsinghua University undertakes the Project of building the Compact Pulsed Hadron Source (CPHS), the first multi-purpose pulsed neutron source in China, to acquire the knowledge base and to realize the implementation of proton accelerators, neutron-producing target & moderators, and neutron-scattering & radiography instruments for materials characterization. The relatively low proton power and moderate neutron flux of CPHS allow employment of in-house designed and domestically produced compact instrumentation modules according to an expedient construction schedule. This approach presents several advantages: 1) The neutron imaging/radiography station (NIRS) and small-angle neutron scattering instrument (SANS) will form a basic experimental platform for neutron user training and rudimental research before China’s major neutron facilities, e.g., the China Spallation Neutron Source (CSNS), are open for operation; 2) The construction, commissioning and development of various accelerator and neutronic hardware complement DEP’s ongoing R&D program in nuclear instrumentation; and 3) CPHS will augment the Tsinghua Thomson X-ray (TTX) Source, a nearby DEP’s electron beam and hard x-rays research facility, as support structures for the Scientific Facility for Advanced Quantum Probes at Tsinghua University. To proceed with the Project which is funded entirely by Tsinghua University, DEP draws the workforce mainly from the departmental staff and seeks assistance from various external expert research and technical groups from national laboratories, universities and industry. Of equal importance is the networking with the international accelerator and neutron community for consultation and collaboration.

An overview of the CPHS, the design and operation parameters of the accelerator system, the neutron target station, experimental beamlines, controls and conventional facilities at the pilot stage of the Project were described in an earlier paper [1]. Here, we present a mid-term progress report of the Project, emphasizing the aforementioned game plan and numerous contributions that we received from collaborators. Details of the prototyping, test results, and expected performance of different systems can be found in cited references.

2. Progress in 2010-2012

Each system is led by a designated team that is in charge of the technical design, engineering evaluation, procurement and fabrication, installation and testing, and commissioning. Project management calls for various kinds of internal and external reviews, organizes focused workshops and taskforces for problem-solving, implements budget and work-breakdown controls, facilitates contract negotiation and procurement processes, and sets up interfacing between different organizations.

2.1. Accelerator system

The accelerator system consists of the ion source (IS), a 4-vane 3-MeV/50-mA radio frequency quadrupole (RFQ) proton accelerator, drift tube linac (DTL), RF power supply and distributor, and beam transport. The high-intensity, electron-cyclotron-resonance (ECR)-type IS and the low-energy beam transport (LEBT) were fabricated at the Institute of Modern Physics (IMP) of the Chinese Academy of Sciences (CAS). After delivery and installation, the system underwent tuning and testing and is deemed ready for commissioning. The RFQ team includes researchers from DEP (Q-Z Xing et al.), engineers from the NUCTECH Co Ltd. (J. Li et al.), and experts from the USA (J. Billen, J. Stovall, and L. Young). They supervise the manufacture of the RFQ and progressive benchmark tests at the Kelin Co. Ltd in Shanghai, undertake the installation of the completed product at CPHS and have obtained satisfactory results from a cold test of the RFQ accelerator [2]. The rectification of a material problem that caused
leakage in a RFQ flange during fabrication at Kelin and an erroneous specification in the RF power transmission system committed by the supplier, AFT in Germany, had impacted a 6-month delay in the accelerator installation, postponing the commissioning of the IS, LEBT, and proton RFQ for production of 3 MeV protons to 2013 (see Section 3 below). The fabrication of the DTL accelerator that will increase the proton energy to 13 MeV is ongoing at Tsinghua University. Fig. 1 shows the setup of the IS, LEBT, and RFQ segments.

2.2. Neutron target station

The neutron target station consists of the target, moderator and reflector (TMR) assembly, shielding and four neutron beam ports. The design and prototyping of TMR constitute the PhD thesis projects of two graduate students, B. Zhong from DEP on the Be target and Q. X. Feng from Xi’an Jiaotong University on the cryogenic solid-methane moderator. The team receives generous and critical guidance from the Low Energy Neutron Source (LENS) of Indiana University, USA and engineering help from NUCTECH. Although the TMR design and shield-pile structure follow closely that of LENS, the team has to determine the proper supplier of materials and component parts, conduct mock-up tests of prototypes and transfer the methodology to vendors for scale-up fabrication or high-precision manufacturing. In the case of the TMR design, the neutronics was evaluated by Monte-Carlo simulations using the MCNP codes for optimization of cold-neutron fluxes and minimization of fast-neutron-induced background [3]. The cryogenic and gas-handling apparatuses were deemed feasible of making solid methane safely for the neutron energy moderation. Fig. 2a shows the TMR shield-pile and the entrance of proton-beam transport. The pile accommodates four neutron beam ports whose beam shutters, placed upstream of the biological shield barrier, are shown in Fig. 2b. The commissioning of the TMR system is a complicated business and the practice of mitigating problems such as cooling and proton-beam induced damage of the target are known and under control from the LENS experience. We plan to resolve these technical issues step-by-step, beginning with 3-MeV protons on a water-cooled, thin Be target with a room-temperature polyethylene moderator and gradually gain experiences for reliable operation and extend to higher proton energies and cold-neutron production.

Fig. 1. (Left) (a) The ECR ion source and the LEBT unit, (b) The naked RFQ, and (c) the RFQ with water cooling connected. The cold tests of the RFQ indicated a less than 2% error in the quadrupole field and the admixture of the two dipole modes with respect to the designed values.
2.3. Neutron beamlines [4]

Two neutron beams are to be built for imaging—the NIRS and small-angle scattering—the SANS. This corresponds to two PhD thesis projects, respectively, for S. F. Su of Sun Yat-Sen University and T.C. Huang of DEP who have received substantial help from faculty and staff of DEP. The SANS team also works closely with the instrument scientist and engineers from the Institute of High Energy Physics (IHEP), CAS who are building an SANS beamline for CSNS. The upstream beam tubes and collimation with shielding coverage have been designed and built. We expect to install the shielded hut that houses the sample positioning and translation unit, and the neutron camera and image-plate device in 2013, in parallel with the work of commissioning proton and neutron production. With regard to the SANS beamline, the design calls for a detector bank comprising about 80 He-3 linear position-sensitive detectors (LPSD) (each of 1000 mm in length and 12 mm in diameter). Although we successfully fabricated two He-3 LPSDs and developed the associated electronics, we are hesitant about the construction of the scattering chamber that is specifically designed for using He-3 LPSDs due to the uncertainty of worldwide He-3 gas supply. Currently we are weighing the options of detector types and the impact on SANS performance. Meanwhile we are actively pursuing development of neutron detectors based on non-He-3 technologies. Other peripheral apparatuses such as neutron bandwidth selecting choppers and low-efficiency beam monitors have been prototyped.

2.4. Detector development

In addition to the work on fabrication of He-3 gas proportional counters, we have carried out R&D of gadolinium-doped micro-channel plate (MCP) and boron-lined gaseous detectors. The effort has intensified recently by virtue of an independently funded program. Naturally, the detector team works in parallel with the CHPS Project and coordinates the results with the world community of neutron detector development. For example, the collaboration with the HUNS facility of Hokkaido University in personnel exchange and equipment testing has produced fruitful results. In both cases the neutron conversion efficiency, signal amplification, and spatial resolution depend on the thickness of the dopant or coating layers, which in turn dictate the methodology of fabrication and electronic read-out. First, the detector performance is assessed by simulations which point to a preferred structure and configuration. We then decide the method of fabrication and develop a prototype, followed by neutron testing. Chemical impregnation of Gd doping and electron beam evaporation techniques have been chosen for the MCP and natural B$_4$C-coated straw-tube-type detectors, respectively. Preliminary tests, which show promising results for the MCP detectors, are described elsewhere [5]. After neutron production is realized at CPHS,
we plan to make use of the spare beam ports and construct rudimental beamlines for neutron detector and
device development.

3. Delivery of 3-MeV proton and neutron beams in 2013

3.1. Delivery of 3-MeV proton beam

The first 3-MeV proton beam was produced on March 25, 2013 following the successful commissioning of the newly installed RFQ linac—the front-end proton linear accelerator for CPHS. The output peak current of the RFQ was 44 mA at a transmission efficiency of 88% while maintaining an input peak current of 50 mA at 50 μs (pulse duration) /50 Hz (repetition frequency) —accomplishing a performance near the design goal in the first week’s run. Eventually, the High-Energy Beam Transport (HEBT) segment already installed downstream of the RFQ together with the Drift-Tube Linac (DTL) currently under construction, will complete the designed goal of a high-intensity proton beam at 13 MeV.

Fig. 3. (a) The linac facility, (b) The RF power system, and (c) the RFQ output proton pulse profile (peak current 42 mA / pulse duration ~50 μs).
3.2. Delivery of neutron beam

In parallel with the HEBT assembling in 2013, the 3-MeV proton beam, being intentionally de-focused to reduce the power density, was incident on the water-cooled, thin beryllium neutron-generating target. The neutrons are thermalized by a room-temperature moderator made with polythene. The first neutron beam was generated on July 18, 2013 from the injection of 3-MeV proton beam at a peak current about 20 mA at 80 μs/50 Hz. For measurements of the neutronics performance the CPHS staff was assisted by researchers from the China Spallation Neutron Source (CSNS) Project of the Chinese Academy of Sciences (CAS). The flux of neutron below 1 eV was measured to be 403 n/cm²/s at the position 6.625 m away from the center of the target station, which agrees with the value simulated within ±15%.

Fig. 4. (a) The test beamline, (b) The wavelength spectra of the first neutron production.

3.3. Construction of the neutron imaging/radiography station

The next beamline to be completed at CPHS, besides the testing station with open sample geometry, is the imaging NIRS. The beam optics and the sample platform are currently under construction. We plan to use a neutron imaging-plate system (Fuji Photo Film Co, Japan) and a micro-channel plate detector (in-house development) as detectors.
4. Concluding remarks

The CPHS Project that started from scratch in late 2009 has made significant progress in the last two years. The ion source, RFQ accelerator, RF power-supply and beam-transport systems are now working to produce 3-MeV protons. The DTL segment for extending the proton energy to 13 MeV is underway. All the major components of the neutron target station, Be target housing and cooling system, the starting moderator and reflector, neutron beam shutters, and target-station and biological shielding are installed. The first neutrons were delivered in July of 2013. Our next task is to gain experience on running the proton accelerator and on prolonging the Be target life time for neutron production. Neutrons generated at this initial stage of CPHS’ operation will be used for instrumentation development such as testing detectors while the imaging NIRS is under construction, followed by the SANS instrument. The Project has been benefited from collaborations with neutron-source laboratories and universities, domestic and international. We shall continue to work with the neutron and accelerator communities with emphases on device development and scientific applications of using neutrons and protons.

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