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THE COMPACT PULSED HADRON SOURCE PROJECT: A LONG-PULSE NEUTRON SOURCE AT TSINGHUA UNIVERSITY

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ABSTRACT

While the 21st century has witnessed outstanding progress in high-power spallation neutron-source projects, noticeably the realization of the SNS (US), J-PARC (Japan), ISIS upgrade (UK) and the ongoing progress of the ESS (EU), and CSNS (China), the development of compact, accelerator-based neutron sources is relatively tardy although their importance, especially in education, user training and R&D of neutronics and instrumentation, has long been recognized. Here, we report a new project of the Compact Pulsed Hadron Source (CPHS) led by the Department of Engineering Physics of Tsinghua University in Beijing, China. Initially, CPHS consists of a proton linac (13 MeV, 16kW, peak current 50 mA, 0.5 ms pulse width at 50 Hz), a neutron target station (a Be target, moderators and reflector), and a small-angle neutron scattering instrument, a neutron imaging/radiology station, and a proton irradiation station. An experimental platform for further proton applications and more neutron beamlines will be added at a later stage. Currently, fabrication of the accelerator components has begun while the neutron target station, beamlines and instruments are under design study. The initial phase of the CPHS construction is scheduled to complete in 2012.

1. Introduction

Since the discovery of neutrons by Chadwick nearly 80 years ago, both steady-state and pulsed-beam neutron sources were developed vigorously in the world. Steady-state sources range from radioactive isotope sources to large fission-reactor-based sources. Pulse sources range from electron-accelerator-driven photoproduction source and proton-accelerator-driven compact sources to large ion-accelerator-driven spallation sources.

The primary mission of large, high-power ion-accelerator-driven neutron sources such as the modern facilities in Asia, Europe, and North America is serving users in materials characterization; the instruments therein are built with adamant research interests in mind. This is contrary to the purposes of using neutrons for education, academic development of scattering methodology, and industrial applications. In the latter case, university-based, compact hadron-beam complexes and neutron sources with flexibility of the instrumental configuration are more suitable.

In China, electron-based accelerators and technologies are relatively well established. Hadron accelerators, on the other hand, are less developed, hence their applications, such as the proton-driven neutron sources, the China Spallation Neutron Source (CSNS) [1] and the 2-MeV deuteron-driven neutron imaging/radiography facility of Peking University [2], are still in an early stage of development. Responding to the increasing demand in China of accelerator-based neutron and proton experimental platforms for multidisciplinary basic research and technological developments, such as hadron therapy and radiography, beam optics and devices, accelerator-driven subcritical-system (ADS) facilities, etc., Tsinghua University has launched a project of realizing a Hadron Application and Technology Complex (HATC) which begins with the construction of a relatively small and moderate-power facility but later expandable to include new arenas and upgradable to high-power beam delivery. The initial phase of the HATC is called the Compact Pulsed Hadron Source (CPHS) [3].

CPHS is driven by a high-intensity proton source, a 3 MeV radiofrequency quadrupole linac (RFQ), and a 13 MeV drift-tube linac (DTL). The proton platform consists of multiple stations for biological, fuel-cell, and nano-materials applications, and space irradiation and detection. Neutrons generated from a beryllium target and moderated by solid methane and room-temperature water moderators are used by scattering instruments and imaging/radiology stations for education, research and instrumentation development. The design goals aim at the realization of an advanced, reliable, and cost-effective hadron-beam platform open to users from Tsinghua University and other academic and industrial institutions in China. Phase 1 of the project also includes a small-angle neutron scattering instrument (SANS) 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 nanotechnology) and additional neutron beam lines (e.g., for reflectometry, diffractometry, and neutron optical device evaluation). The construction of the Phase 1 facilities is to be completed in about 3 years. From the outset the CPHS design allows future upgrade and expansion beyond the Phase 2 scope. In the future CPHS may also serve as an injector to a ring accelerator of eventually producing a proton beam to up to 300 MeV for proton therapy and radiography [4]. During the construction and operation of CPHS and the subsequent expansion, we anticipate a gradual build-up of a staff of scientists and engineers and the accumulation of knowhow and experiences needed to pursue the aforementioned multidisciplinary R&D which the HATC is set out to achieve.

Newly approved by the University, the compact CPHS facility is housed in an existing building on the Tsinghua campus, previously built and used for testing the now completed cargo-inspecting accelerator system, as shown in Figure 1. The main facility occupies an area of about 400 m^2. The entire building housing the facility, the supporting systems, and the supporting laboratories occupies an area of about 1,000 m^2. The CPHS complex is immediately adjacent to the Tsinghua Thompson-backscattering light source current under development by the Department [5]. Table 1 shows the CPHS primary parameters which are similar to those of the Low Energy Neutron Source (LENS) facility [6] of the Indiana University, USA. The proton beam energy is chosen to be 13 MeV to maximize the neutron output without exceeding the threshold of tritium production. A linac is adopted over other types of accelerators for optimization of the pulsed proton yield and peak intensity. Our design efforts are benefited from the experiences of neutron applications at LENS [6] and the Hokkaido University neutron facility [7] in Japan, as well as the proton applications at the 20-MeV platform of the Proton Engineering Frontier Project (PEFP) [8] in Korea.

This paper summarizes the major technical design aspects of the CPHS and discusses its future perspectives. The CPHS complex consists of five major systems: accelerator (ion source, RFQ, DTL, RF power supply, beam transport), neutron target station, experimental beamlines (SANS, imaging/radiography), controls, and conventional facilities. Sections 2 and 3 discuss the physical design of these systems. Section 4 discusses related R&D efforts. Section 5 presents possible future extensions and applications.

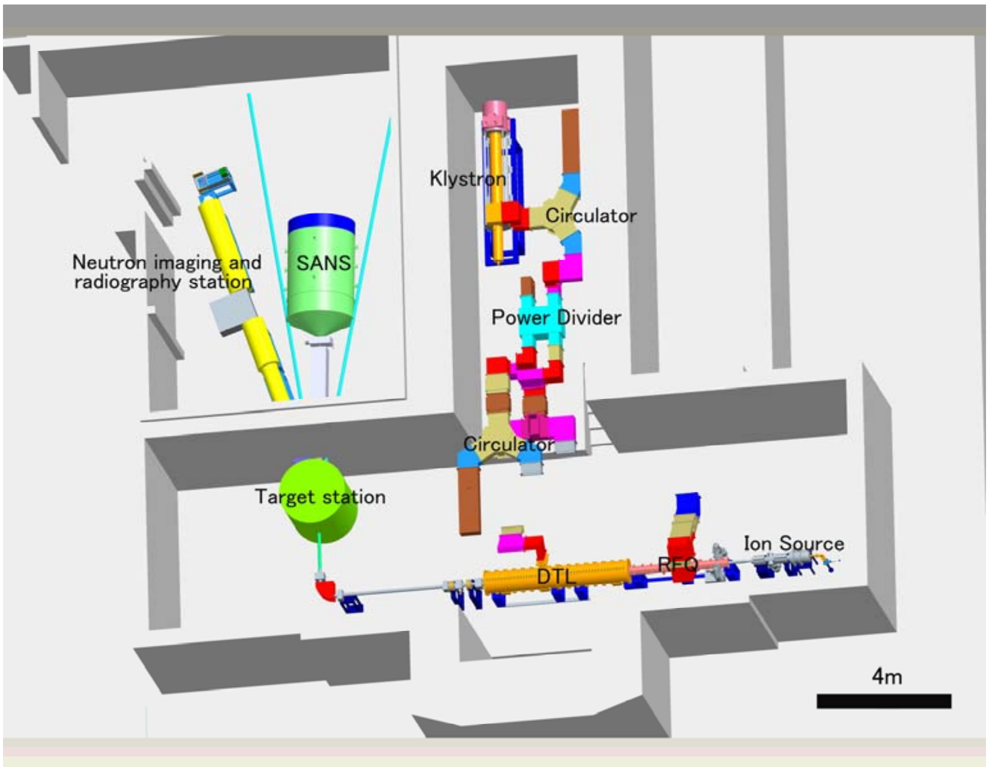

Figure 1. Schematic layout of the Compact Pulsed Hadron Source at Tsinghua University, China. The main facility, shown in this figure, occupies an area of about 400 m^2. The entire building housing the facility, the supporting systems, and the supporting laboratories occupies an area of about 1,000 m^2.

Table I. CPHS primary parameters.

Proton power on target	16	kW
Proton energy	13	MeV
Average beam current	1.25	mA
Pulse repetition rate	50	Hz
Protons per pulse	1.56x10^{14}	
Pulse length	0.5	ms
Peak beam current	50	mA
Target material	Be	
Moderator type	H_2O (300K), CH_4 (20K)	

2. Accelerator, controls, and conventional facilities

2.1. Ion source and low-energy-beam-transport

The electron cyclotron resonance (ECR) ion source is chosen for its compactness, low beam emittance, and easy matching with the RFQ. Without filament bombardment during the discharge process, the expected life of operation is prolonged. The source also has relatively higher discharge efficiency, lower discharge power, and less gas flow consumption along with a higher proton ratio. With an all-permanent-magnet design, the axial magnetic field of the source body is produced by NdFeB rings. The 2-kW microwave system consists of a pulsed 2.45 GHz microwave generator, a circulator, a directional coupler, an isolator, and a microwave window. A four-electrode extraction system consisting of the plasma electrode, mid-electrode, suppression electrode, and extraction electrode is used. The entire system is water-cooled in favor of the stable and reliable operation. With space-charge neutralization, the 50-keV proton beam extracted from the ion source passes through the low-energy beam transport that is optically matched the RFQ entrance.

2.2. Radio-frequency quadrupole linac (RFQ)

The RFQ accelerates protons from 50 keV to 3 MeV in a length of 3 m. The RF frequency of 325 MHz is chosen so that any future high-energy extension of the linac can be operated at the 4th harmonic frequency of 1.3 GHz which is common to many modern accelerator R&D programs. The RFQ system consists of a single four-vane resonant cavity, a power coupler, the RF power supply and its low-level control, vacuum, water cooling, resonance control, beam diagnostics, support and alignment systems. The objective of the physics design is to optimize the performance of the RFQ by tailoring the cavity and vane tip geometry as a function of longitudinal position while limiting the peak surface electric field to 1.8 Kilpatrick. The inter-vane voltage, the mean bore radius, and the vane-skirt width vary along the longitudinal axis of the RFQ. Simulations of the optimized design predict a beam transmission of 97.2% with a transverse emittance growth of 20%. To optimize the beam performance of the integrated linac there will be no medium-energy beam-transport line between the RFQ and DTL. The transverse and longitudinal focusing at the high energy end of the RFQ and the entrance of the DTL have been tailored to provide continuous restoring forces independent of the beam current. The RF field distribution will be established using 47 slug tuners and dipole-mode stabilizer rods.

2.3. Drift-tube-linac (DTL)

The DTL accelerates the beam from 3 MeV to 13 MeV in a length of 4.3 m. The DTL system consists of a single resonance cavity with 39 drift tubes each containing a magnetic quadrupole lens, post couplers, a power coupler, an RF power supply and low-level control system, water cooling, resonance control, vacuum, beam diagnostics, controls, support and alignment systems. The objective of the physics design is to optimize the performance of the DTL by tailoring the RF phase, accelerating field, quadrupole lens strengths and drift-tube geometry as a function of particle velocity while limiting the peak surface electric field to 1.8 Kilpatrick and avoiding sources of emittance growth and beam instabilities. We have adopted an FD lattice using permanent-magnet quadrupoles (PMQs) based on the successful experience of the US Spallation Neutron Source DTL. The shape of the cells is optimized by the SUPERFISH codes [9]. The RF field, which is linearly ramped from 2.2 to 3.8 MV/m, will be fine-tuned using 10 slug tuners and stabilized by 13 post couplers.

2.4. Radio-frequency (RF) power supply

Both RFQ and DTL share a single RF power source. The power source consists of signal generator of 325 MHz, amplifier, klystron, pulsed high-voltage power source, modulator, crow bar protection, RF transmission system, control and interlock system. The RF transmission system consists of circulator, power divider, attenuator, phase shifter, waveguides and couplers. The peak RF power needed by the RFQ and DTL are 0.6 and 1.4 MW, respectively. With a power divider, the RF power source supplies 0.8 MW of peak power to the RFQ through an attenuator, and 1.6 MW of peak power to the DTL.

2.5. Controls

The CPHS control system includes a timing distribution and event trigger subsystem, and an EPICS-based remote control subsystem integrated with person protect system (PPS) and machine protect system (MPS). The timing system is designed with 10 ns time resolution to distribute various event trigger signals in sequence to each sub-device via a master/receiver fiber link system. The EPICS control system is responsible for real-time status monitor and control of sub-devices including the ion source, LEBT, RF system, RFQ, DTL, neutron target station and experiment devices. An Ethernet-based distributed database is embedded in each local input/output controller (IOC), and users are able to trace the observed signals and communicate with hardware device in real-time through operator interface (OPI). The integrated MPS is capable of monitoring events and summoning quick responses so that the systems can shutdown or disable critical components for the protection of the instruments in the event of a serious anomaly. As a local controller for RF system, the low-level RF control system plays an important role in feedback and stabilization of the high power RF amplitude and phase.

2.6. Conventional facilities

The CPHS complex occupies a real estate of about 1,000 m^2 including an existed, ~400-m^2 shielded building that houses the accelerators and neutron target station, a ~600-m^2 experimental hall, and peripheral service buildings. The electrical capacity is 1 MVA, about one half of which is reserved for the linac klystron and modulator. The cooling water capacity is about 2000 l/min.

Radiation shielding and environmental protection consideration are based on expected beam loss during routine operation and in the event of fault scenarios [10].

Machine protection and personnel protection systems are designed to properly react to either rapid beam loss or tear-and-wear conditions by monitoring data at critical locations in the proximity of the ion source, linac, target station, and beamlines as well as in the perimeter of the entire compound. Radiation dosage is limited below 2.5μSv/h at the facility boundary so as to satisfy the 2.5-mSv/yr limit set by the government. Sky-shine and ground water impacts are evaluated accordingly. Presently, the attenuation lengths of the secondary particles produced by the proton beam loss are calculated by Monte Carlo codes like FLUKA [11] and MCNPX [12]. Whenever possible, local shielding will be employed first to contain the high radiation area only around the emission source such as the higher-energy section of the accelerator. Additional shielding, if necessary, will then be applied, including thickening the building's external wall and roof thickness and partitioning the accelerator and target-station areas.

3. Neutron target station and experimental systems

3.1. Neutron target station

The target station consists of the target, moderator, reflector, shielding and utilities (Figure 2) [13, 14]. The proton beam is defocused and re-directed toward the target station by bending and quadrupole magnets, striking a thin plate of beryllium without window along the way, so that fast neutrons generated from the target in the backward direction cannot enter the accelerator, as shown in Figure 1. The beryllium target is cooled by flowing deionized water on the rear surface. The moderator, parallel to and down-stream of the beryllium plate but translated vertically above the proton beam, in the so-called 'wing' configuration, prohibits fast neutrons generated along the proton-beam direction entering the neutron beamlines. Solid methane (CH_4) is chosen as the cold-moderator material, whose low temperature (~20K) is maintained by a close-cycle helium refrigerator (model PT415) using a high-purity aluminium arm to couple the cold stem and the moderator container for efficient thermal conduction. The target-moderator assembly is immerged in a light-water reflector. Surrounding the reflector assembly is the decouple used to absorb the escaped neutrons, thereby shortening the tail of the neutron pulse. The target-moderator-reflector assembly is covered by several layers of lead and lead-borated polyethylene composites, which function as the neutron and γ-ray shield.

Neutrons are produced by the Be (p, n) reaction, slowed to thermal and cold energies by the moderators/reflector, and delivered to the instruments via a number of neutron beam lines for neutron-scattering, imaging/radiography, and device-testing instruments. Since the proton pulse width is of the order of ~0.5 ms, the neutron pulses emitted from the moderators are expected to spread to a few ms wide with an asymmetric pulse shape, in sharp contrast to the very short (μs) pulse widths of spallation neutron sources. Sharpening of the incident neutron pulses is achieved by placing a bandwidth-limiting chopper in an upstream position of the neutron beamline.

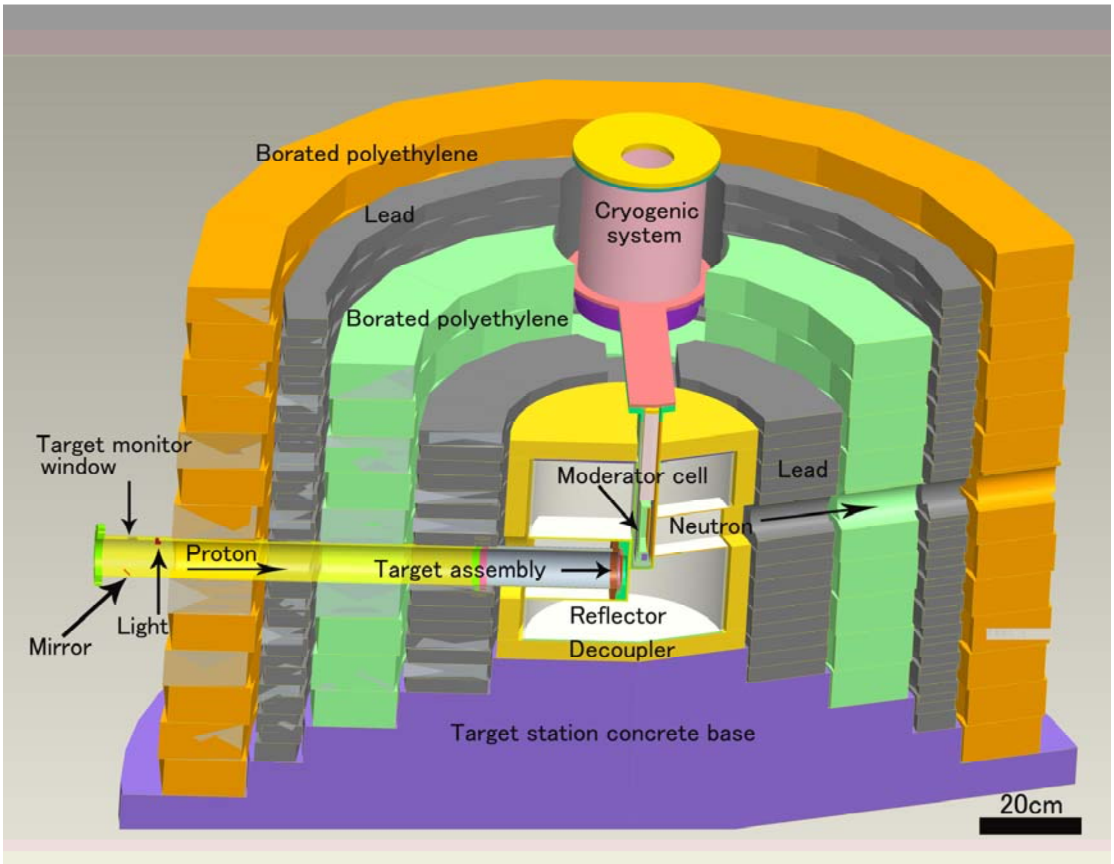

Figure 2. Schematic layout of the neutron target station of the Compact Pulsed Hadron Source. The proton beam strikes the beryllium target horizontally. The extracted neutron beam is vertically offset from the level of the incident proton beam to avoid direct-view of neutron beamlines to the target through the cold moderator reducing the fast-neutron background.

3.2. Small angle neutron scattering instrument

Small-angle neutron scattering offers a powerful means for the characterization of microstructures at a length scale of 1-100 nm in almost any kind of bulk condensed matter [15]. Examples of such structures are polymer solutions, lipids and membranes, microemulsion, inhomogeneity in alloys and composites, drug-delivery/release substances, batteries, magnetic impurities, porous minerals, and molecular sieves. We anticipate the SANS instrument of CPHS will serve many disciplines including soft matter, metals and ceramics, chemical engineering, biotechnology, and mineralogy. In the initial stage the SANS instrument strives to reach two objectives: its instrumental design, fabrication and optimization will help glean valuable scientific and engineering experiences; and its utilization will help initiate a fruitful domestic user program gradually expanding to different areas of research. Our design of the SANS instrument draws experiences from other TOF SANS instruments, particularly those of the LENS and IPNS (Argonne, USA) facilities. Considering the space constraint at CPHS and the user priorities in China, the design settles for a primary and secondary flight path of approximately 5 and 3m long, respectively. Because of the relatively high source repetition rate (50 Hz) and the limited space, a bandwidth-limiting chopper will be employed. Using a 2D-detector (100 cm x 100 cm), a Q-coverage of approximately 0.006 ~ 1 $Å^{-1}$ and a $\Delta Q/Q_{min} < 30\%$ can be achieved. Initially, the scattering geometry will conform to the conventional pin-hole configuration but the design permits future improvements of using optical devices such as focusing lenses, converging multiple-aperture collimators, and novel detectors to enhance experimental efficiency and scientific productivity.

3.3. Neutron imaging and radiography instrument

The decision of building a neutron imaging/radiography station is founded on the matching compatibility of this application with the CPHS source parameters and the demand for neutron imaging in China [16]. A neutron radiography station based on the pinhole optics will be built to perform neutron imaging for scientific and industrial applications. The field of view can be varied between 5x5 to 20x20 cm^2 by adjusting the distance between the sample and the moderator surface. The L/D ratio is tuned by varying the aperture size (D) given a chosen aperture-to-sample distance (L) to match different requirements of the spatial resolution.

Beyond the conventional neutron radiography, we are exploring advanced options, including Bragg-edge cutoff measurements and energy-selective imaging by TOF techniques. This will require the use of sophisticated pulse-shaping devices, high-resolution detectors/cameras, and novel beam optics. Base on the experience in x-ray applications, we plan to develop the neutron counterpart for an eventual x/n synergetic technology. The first extension beyond conventional imaging is a neutron computed-tomography (CT) instrument. We plan to apply the sample manipulation hardware and software currently available from the x-ray programs at the Department to realize CT function with neutron detectors [17]. The second extension is a grating-based phase-contrast radiography & CT instrument [18], where we explore the phase shifts of neutron waves caused by neutron-matter interactions in the sample. The third extension is conventional neutron-induced prompt γ-ray activation analysis (PGAA) and neutron-induced prompt γ-ray 3D emission CT (PGA-ECT) instruments. Especially, The PGA-ECT instrument would apply the CT technique for the reconstruction of the spatial images of the isotope(s) that caused γ-ray emissions in the object with the cold-to-epithermal neutrons at CPHS. The last extension is an energy-dependent imaging instrument using time-of-flight techniques, which can be used for the study of the microstructure and texture in engineering materials.

4. Research and developments

Major R&D efforts are currently directed to the linac, neutron target and moderator assembly, neutron choppers, and neutron detectors.

4.1. RFQ and DTL linac

As an effort to minimize the total length of the accelerator for compactness and to simplify the power supply systems, a physical redesign was launched on both the RFQ and the DTL to eliminate the medium-energy-beam-transport section between these two sections of linac, and to use permanent-magnet-quadrupole in the drift tubes replacing electromagnetic-quadrupoles so that power supplies are simplified. Fabrication of a 1-m long, full-cross-section prototype DTL is underway at the university workshop.

4.2. Neutron target station

Benefiting from a close collaboration with the LENS group at Indiana University, we optimize the target-moderator-reflector (TMR) layout and design through extensive

Monte-Carlo simulations and verification with LENS observations. Fabrication of the prototype components is underway on the TMR and the shielding components [13].

4.3. Neutron detectors

In the area of detector development, the design and fabrication of ^{3}He gas proportional counters and associated electronics, and the conversion of neutrons to charged particles using ^{10}B or ^{nat}Gd that are doped in or coated on micro-channel-plates in conjunction with a gas-electron-multiplier (GEM)-based detector system are currently underway [19].

Responding to the call of international collaboration on alternative techniques to ^{3}He-based detectors for neutron scattering applications, an R&D program was launched to fabricate and study 1-m long, 12-mm diameter tubes filled with ^{3}He and BF_3 gases, respectively. A second R&D program was launched on MCP and straw-tube based neutron converters. We have successfully plated 40nm of $^{nat}Ga_2O_3$ on the inner surface of 510-µm pores of MCP with a diameter of 12 µm. Also, the doping of MCP glass with 3.49mol% of $^{nat}Gd_2O_3$ was shown to be possible.

4.4. Bandwidth-limiting neutron chopper

A bandwidth limiting neutron chopper contains a feedback controlled motor and a mass disk with an opening. The motor drives the disk running precisely related to the neutron beam to chop the beam into designed pulses. The undergoing project is aimed at the first prototype of bandwidth limiting neutron chopper, which is considered to be comparatively simpler in R&D (Figure 3 and Table II). Further improvement will lead to other types of choppers and possibly with active magnet bearings.

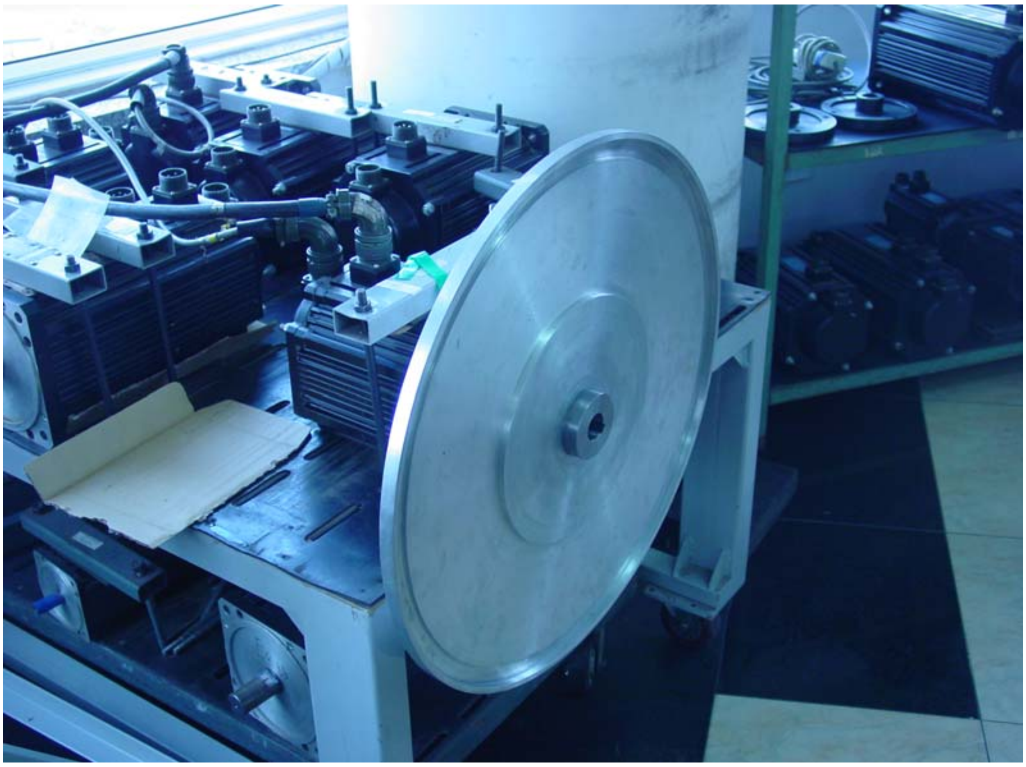

Figure 3. The prototype bandwidth-limiting chopper under development for the CPHS project.

Table II. Major parameters of the prototype bandwidth-limiting chopper under development for the CPHS project.

Rotating speed	50 Hz / 25 Hz	
Control rate of speed	4 Hz / min.	
Phase control accuracy	±10μs	
Dick radius	300 mm	
Cutout angle of the disk	90°	
Thickness of the disk	4 mm	At the edge
Neutron absorber type	B_4C	1 mm on each side
Window size	80 mm x 80 mm	
Window shell thickness	0.4 mm	
Dynamic balancing	National standard (rigid motor)	
Environment temperature	15 - 50° C	
Chamber vacuum	< 10 Pa	
Electric power	220 V / 380 V / 50 Hz	

We have chosen a suitable motor which can work well in vacuum environment. An encoder with 3600 lines in the motor is used as precise position detection. Tests were undertaken for the strength of boron carbide and resin composite, and its ability to attach firmly onto the aluminium alloy disk. Another type of rotor construction is suggested using glass fiber plus resin, where boron carbide can be incorporated into the disk easily.

Dynamic model for the disk bearing system was built. Natural frequencies of the system were calculated, which are important to avoid the system operates under serious vibration.

5. Future perspectives

In addition to education and academic researches, one of the major goals of developing the Compact Pulsed Hadron Source is to grow the domestic technological expertise and to build-up the team to undertake future related projects and applications. Figure 4 shows possible extension of a CPHS-like front-end to a multi-purpose hadron accelerator complex, serving one or more application facilities including long-pulse neutron source, short-pulse neutron source, imaging and radiography, irradiation, ion-beam therapy, isotope production, ADS for nuclear-waste transmutation and new nuclear-energy (e.g. thorium) utilization, and rare-isotope research [3].

For example, CPHS-like front-end may serve as an injector to a synchrotron that subsequently accelerates the beam to up to 300 MeV for 3D stereo-tactic proton therapy and radiography. With increased RF duty, it may also be followed by a superconducting RF linac operating at 1.3 GHz frequency (4 times the frequency of the CPHS RF system) driving an ADS test facility and/or a rare-isotope-beam facility.

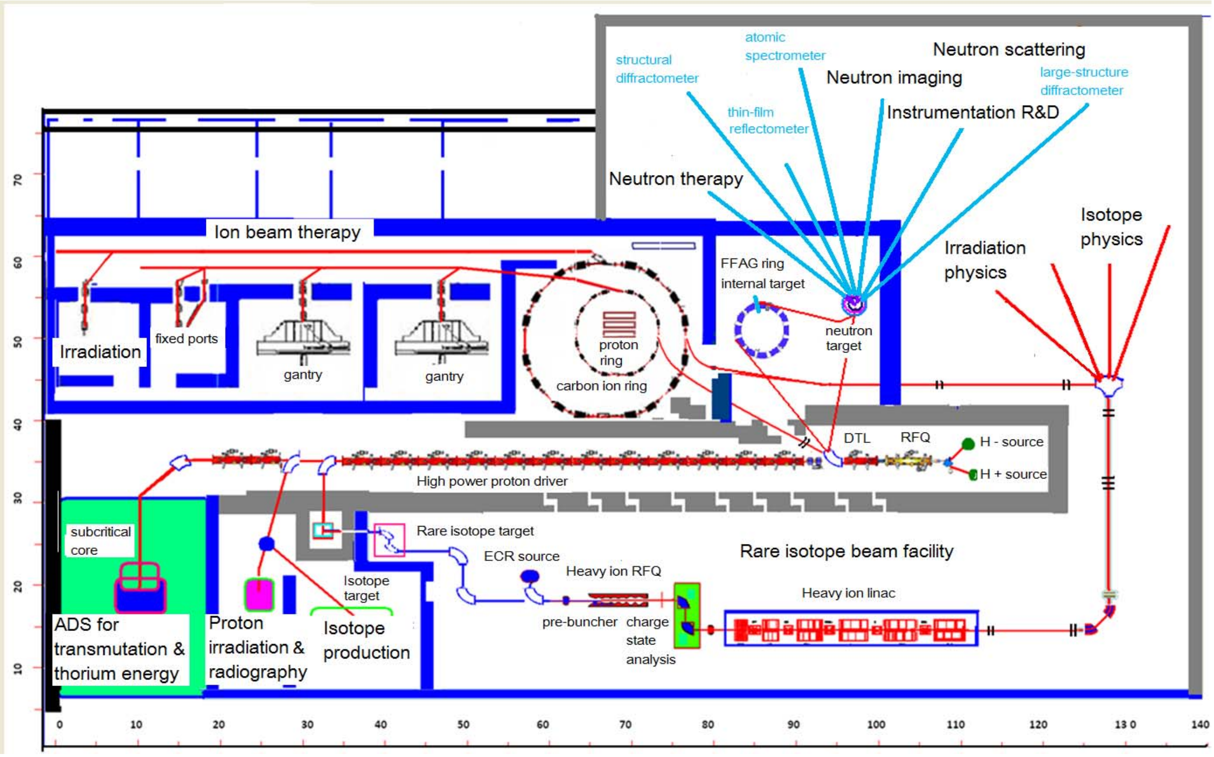

Figure 4. Schematic layout of possible extension of a CPHS-like front end serving one or more application facilities including long-pulse neutron source, short-pulse neutron source, imaging and radiography, irradiation, ion-beam therapy, isotope production, ADS for nuclear-waste transmutation and new nuclear-energy (e.g. thorium) utilization, and rare-isotope research. (The scales are in meters.)

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