PROTON ACCELERATOR DEVELOPMENT IN CHINA

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Abstract

The China Spallation Neutron Source (CSNS) and the Chinese Accelerator Driven Systems (C-ADS) projects are both underway in China. The CSNS includes a 100 kW RCS accelerator and first beam on target is planned for 2017. The C-ADS project includes a high power superconducting linac with a low energy (25-50 MeV) initial stage by 2015 and higher power deployment later. In addition to these intense-beam proton accelerators, some other proton accelerators for various applications are also under construction or planned. In this paper, the plans, R&D and construction activities of these projects will be discussed.

INTRODUCTION

Proton accelerator becomes a new direction in Chinese accelerator community for its many important applications. It will be used for neutron source for neutron scattering applications, Accelerator Driven Subcritical system (ADS) for nuclear waste transmutation, proton therapy for cancer treatment, as well as the space radiation effects research. China Spallation Neutron Source started construction in 2011[1]. Its accelerator provides a proton beam of 100 kW power onto the target in the first phase, and then will be upgraded to 500 kW beam power in the second phase. And meanwhile, a small neutron source is under construction in Tsinghua University[2]. In 2010 a Chinese roadmap for long-term development of ADS was proposed by Chinese Academy of Sciences[3] and the first budget of about $260M has be allocated for an ADS test setup construction. This year, Chinese central government has approved two proton accelerator-based big-science projects in its five-year plan: ADS program and space radiation effect research program. These proton accelerator-related projects, no matter big or small, give a great chance to Chinese accelerator community to develop the cutting-edge high-technology of proton accelerator in China. This paper will present an overview of these projects at different stage, including their design, key technology R&D, construction and future plan.

CHINA SPALLATION NEUTRON SOURCE

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. The accelerator provides a beam power of 100 kW on the target in the first phase. It will be upgraded to 500kW beam power at the same repetition rate and same output energy in the second phase. For this reason, the present design has reserved a long beam line in LRBT for superconducting spoke cavity installation for the linac energy upgrade in order to compensate for space-charge effect in the RCS when the beam current becomes 5-times higher. Table 1 lists the major parameters of the accelerator in the two phases.

Table1: CSNS Design Parameters

Project Phase	**I**	**II**
Beam Power on target [kW]	100	500
Proton energy [GeV]	1.6	1.6
Average beam current [μ A]	62.5	312.5
Pulse repetition rate [Hz]	25	25
Linac energy [MeV]	80	250
Linac type	DTL	+Spoke
Linac RF frequency [MHz]	324	324
Macropulse. ave current [mA]	15	40
Macropulse duty factor	1.0	1.7
RCS circumference [m]	228	228
RCS harmonic number	2	2
RCS Acceptance [πmm-mrad]	540	540
Target Material	Tungsten	Tungsten

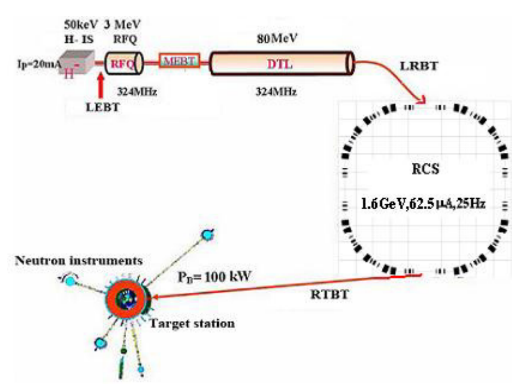

Figure 1: Schematics of the CSNS complex.

A schematic layout of CSNS phase-1 complex is shown in Figure 1. In the phase-1, an ion source produces a peak current of 25mA H^- beam. RFQ linac bunches and accelerates it to 3MeV. DTL linac raises the beam energy to 80MeV. After H^- beam is converted to proton beam via a stripping foil, RCS accumulates and accelerates the proton beam to 1.6GeV before extracting it to the target. 20 neutron channels are designed surrounding the target, but only 3 spectrometers will be built in the first phase due to limited budget.

The CSNS project started construction in September 2011 after the site land and the access road had been

ISBN 978-3-95450-138-0

prepared by the local government. The architectures for the linac tunnel has been completed and klystron gallery are under construction. We plan to start installation of the front end of linac in November, 2013. The civil construction status is shown in Figure 2.

Figure 2: Civil construction status of CSNS project.

Front-end

Penning H^- surface source is chosen for CSNS. Based on prototype experience and some optimization in design, a new source for the project has been fabricated and set up at the laboratory of the Dongguan University of Technology for beam extraction test before the test hall is available, as shown in Figure 3.


Figure 3: CSNS H^- ion source in beam extraction test.

RFQ accelerates H^- beam from 50keV to 3MeV, with duty factor of 1.05%. A four-vane type RFQ at 324 MHz has total length of 3.62 m, composed of four technical modules. Two section cavities are resonantly coupled together with a coupling plate in between, as shown in Figure 4. The four module cavities are ready for assembly to form a whole cavity for field tuning. Two sets of 1000 *l*/s ion pumps and 500 *l*/s turbo-molecular pumps are designed for an order of 10^{-7} Torr dynamic vacuum pressure. Another set of backup pumps can be easily added. The RFQ cavity has been fabricated and is ready for assembly for field tuning measurement. Two sets of Burle 4616 Tetrode feed 530 kW total RF power to the RFQ through two coaxial power couplers. In the power test, each source reached 400 kW pulse power with pulse length of 700 μ s at 25 Hz, as shown in Figure 5.

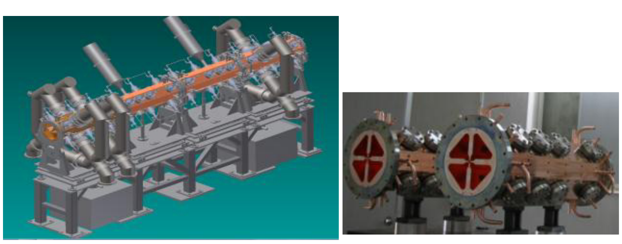
Figure 4: RFQ design and assembled cavity for field tuning.

Figure 5: RFQ power source and its output power in test.

The total length of MEBT is about 3 m, including 10 qaudrupole magnets, 2 bunchers, 12 steering magnets, as well as some beam diagnostics, including 8 BPM, 5 FCT, 4 BPrM, 3 BLM, 2 CT and EM. As the LEBT chopper has already reach a rise/fall time less than 17ns, we will not install the RF choppers in the MEBT in Phase-I, but leaves space for them for upgrade.

DTL Linac

The 324 MHz DTL accelerates the 3 MeV beam from the RFQ to 80 MeV. The DTL linac is composed of 4 tanks with a total length of 35 m. Each tank is about 9m long and assembled with three technical modules. Mass production of the tank and tube started in early 2012 and the first DTL tank has been fabricated. Figure 6 shows the fabricated tubes and tank. They will soon be assembled for field measurement and field tuning with slug tuners and coupling stems.


Figure 6: The fabricated drift tubes and tank.

The RF power source for DTL is 324 MHz klystron from CPI, with maximum output power of 3 MW. The adopted HVPS scheme is 400 Hz AC series resonance high voltage power supply. One power supply feeds the same voltage of 120 kV to two klystron cathodes through their m-anode modulators. We proposed such a new type of HVPS for klystron and demonstrated its feasibility with a 100 Hz prototype. Two sets of the power supply are under manufacture for CSNS DTL. Figure 7 shows the klystron and its HVPS under assembly.


Figure 7: 3MW klystron and its 120 kV HVPS under manufacture.

RCS

The RCS lattice consists of 48 quadrupoles and 24 dipole magnets, forming a four-fold ring with circumference of 227.92m. In the each super period, an 11m long drift space is left in a triplet cell. These four uninterrupted long straight sections are arranged with injection, extraction, RF acceleration and transverse collimation respectively. To reduce space charge effect, H^- beam from linac is stripped by a carbon foil and painted into a large phase space about 240 π mm-mrad in two transversal directions with 8 pulsed bump magnets. The maximum space charge tune shift is -0.28 in bunching stage. A two-stage collimator system with an acceptance of 350 π mm-mrad is utilized for removing halo particles.

The RCS AC dipole and quadrupole magnets is in mass production. The first dipole and quadrupole magnets in mass production have been produced(Figure 8). They have been continuously operated with full AC current of 877 A for 72 hours. The coils and cores of the magnets are robust enough, and no crack was found on their surfaces. The field of these two types of magnets has also been measured, and the results meet the specification. The magnet installation in the ring tunnel is foreseen in the middle of 2015 when the tunnel is available.

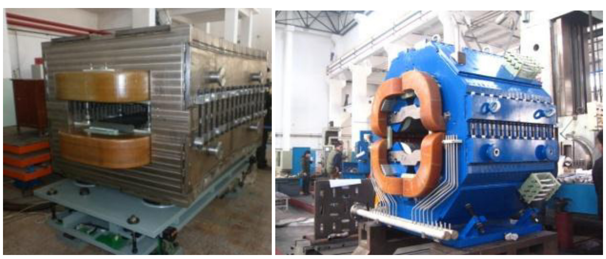

Figure 8: RCS dipole and quadrupole magnets in mass production.

The power supply for the magnets uses White resonant circuits to avoid the impact to the grid. Due to nonlinear feature of the magnet core, a pure sinusoid AC current from the power supply will result in a deformed sinusoid magnetic field with an unacceptable tracking error. To deal with this issue, high order harmonic current is injected into the power supply for compensating for the nonlinearity. The 24 dipole magnets are powered with one set of current supply and the 48 quadrupole magnets are powered with 5 sets of current supplies. All of these power supplies are under mass production.

The RCS has eight ferrite-loaded cavities for proton acceleration, of which seven cavities provide total 165 kV RF voltage with additional one as backup. The cavity resonant frequency shifts from 1.02 MHz to 2.44 MHz in 20 ms by a bias current supply. In the prototype RF system, the response bandwidth of the bias current supply has been improved up to 10 kHz by adding a small linear shunt modulator to the existing switching power supply. The resulted tracking error apparently reduced within the specification of ±0.2%. Based on the experience of high power operation of the RF system prototype, the design of the RF cavity structure has been optimized to ameliorate the cavity and RF transmitter performance. Manufacture of 8 sets of RF cavities and 500 kW transmitters has been in good progress. Figure 9 shows the fabricated cavity and its RF power source.

Figure 9: Ferrite-loaded RCS cavity and its RF power source in mass production.

Ceramic vacuum chambers are used in the RCS dipole and quadrupole magnets, injection bumps and extraction kickers to avoid the eddy current. The chamber size for dipole magnet is rather large with a length of 2.8 m and a cross-section of 135(V)×218(H) mm in inner diameter. All of these chambers have started mass production by a Germany vendor FRIATECH and domestic vendors. The inner surface of the chamber will be coated with TiN for low SEE. Figure 10 is the ceramic chamber for dipole magnet.

Figure 10: Ceramic chamber for dipole magnet.

The Beam Lines and Interface

The LRBT transports the H^- beam to the ring and it 47quadrupoles and 4 bending magnets. Some of the quadrupoles have been produced. A rebuncher is installed for reduction of the beam momentum spread. The injection stripping foil facility has been manufactured with 20 carbon foils on a rotating frame, as shown in Figure 11.

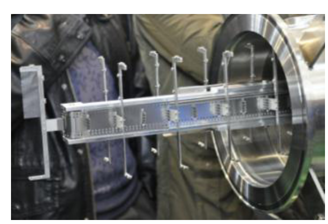

Figure 11: Stripping foil for H^- injection.

C-ADS CW PROTON LINAC

ADS in China is applied for nuclear waste transmutation, as a backup to the rapid nuclear power development. The accumulated waste is estimated to be more than 10k tons in 2020, and it will be doubled in 2030. ADS has been recognized as the best option for the nuclear waste final disposal. Roadmap of ADS development has been scheduled in four phases in China, as shown in Figure 12. In phase-I from 2011 to 2015, as R&D period, A 25-50 MeV linac will output a beam

ISBN 978-3-95450-138-0

current of 10 mA in CW; phase-II will take a few years to increase the beam energy up to 250 MeV with superconducting spoke cavities and the accelerator will be coupled with a subcritical reactor to form an ADS research system. In Phase-III, until 2022, the beam energy will further rise to 0.6-1 GeV to drive a subcritical system of 100 MW thermal power. In phase-IV, more superconducting elliptical cavities will be added to the linac to raise beam energy up to 1.2-1.5 GeV until 2032, serving for a full-scale ADS demonstration facility.

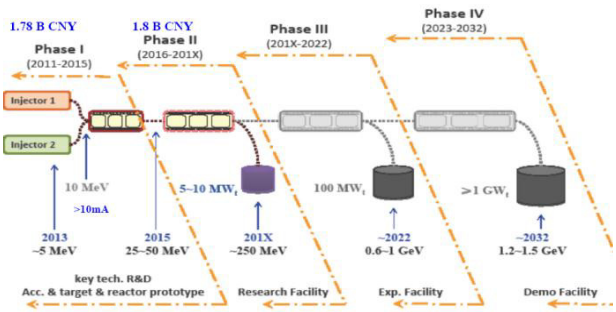

Figure 12: Roadmap for ADS development in China.

Linac Design

In the preliminary design a 1.5 GeV linac consists of two injectors, two spoke cavity sections and two elliptical cavity sections, as shown in Figure 13. In operation, only one injector runs and another is hot standby for a high reliability which is a key requirement for the target and reactor. To explore different technology at present, the two injectors have different design: the Injector-I is mainly composed with an ECR ion source, a 3.2 MeV room temperature RFQ at 325 MHz and superconducting spoke cavities at 325 MHz; while the Injector-II mainly consists of an ECR ion source, a 2.1 MeV room-temperature RFQ at 162.5 MHz and superconducting HWR cavities at 162.5 MHz. IHEP is in charge of the Injector-I, and IMP in charge of Injector-II.

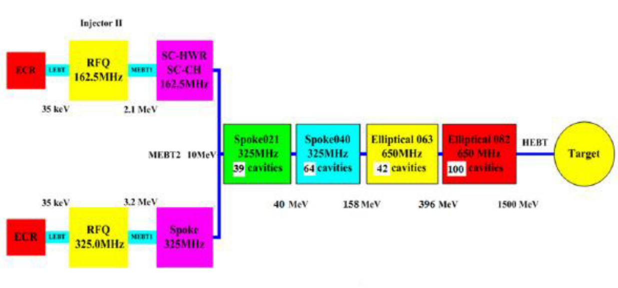

Figure 13: Layout of the C-ADS linac.

Key Technology R&D

Ion source An ECR ion source has been set up for beam extraction test at IMP, as shown in Figure 14(left). It can provide the RFQ with a CW proton beam of 25 mA at 35 KeV. This ion source together with LEBT will recently be installed in the tunnel at IHEP. At present the major work focus on the long-term operation stability of the ion source.

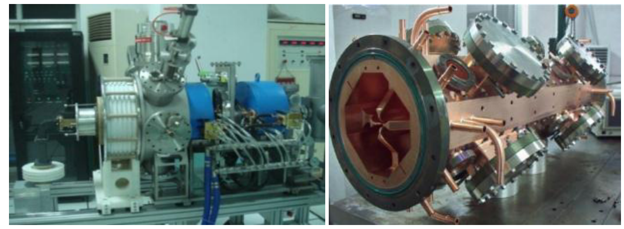

Figure 14: ECR ion source together with LEBT(left), and RFQ cavity(right) for Injector-I.

RFQ-I This four-vane type 325MHz RFQ will operate in CW mode at room temperature with RF power consumption about 273 kW. The full length of the vane is about 4.7m and maximum power density on the surface is 3.77 W/cm^2. Fabrication of the RFQ cavity is finished (Figure14) and RF measurement result shows that the design values have been achieved. Toshiba 600kW 325MHz CW klystron and 80 kV PSM power supply are adopted as the RF power source for the RFQ.

RFQ-II This four-vane type 162.5 MHz RFQ uses the PI-mode stabilizer for a wide mode separation between working quadrupole mode and the nearby modes. Fabrication of such a large cavity is not easy, and thus a short model cavity has been made for manufacture technology development, as shown in Figure 15.

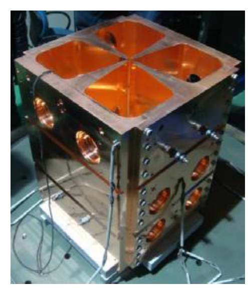

Figure 15：Short model cavity of 162.5 MHz RFQ for Injector-II.

Spoke012 This 325 MHz superconducting spoke cavity follows the 3.2 MeV RFQ-I. Two such low-β of 0. 12 cavities has been fabricated. The horizontal test has been completed at 4K and Q_0 value reaches 2.2x10^8 at E=6.5 MV/m, as shown in Figure 16.

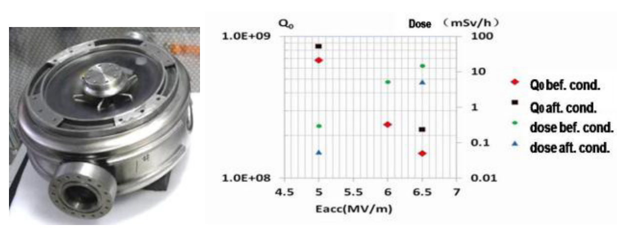

Figure 16: Spoke012 cavity and its horizontal test result for Injector-I.

HWR This 162.5 MHz superconducting cavity of β =0.1 follows 2.1 MeV RFQ-II. Two prototype cavities have been made (Figure 17）with measured Q_0=4.1x10^8 at 8.3 MV/m.

ISBN 978-3-95450-138-0

Figure 17: Prototype QWR cavity with β =0.1 for Injector-II.

Spoke021 and elliptic cavity In addition to the low energy section, superconducting cavities for medium and high energy sections are also under development. At present, two 325 MHz spoke cavities of β = 0.21 and some 650 MHz elliptical cavities of β =0.82 are under development, as shown in Figure 18.

Figure 18: Prototype development of 325 MHz spoke cavities with β = 0.21 and some 650 MHz elliptical cavities with β =0.82, for main linc.

OTHER PROTON ACCELERATORS

Except for the two high intensity proton accelerators for CSNS and C-ADS, some other proton accelerators are also under construction or in planning.

CPHS Accelerator

The Compact Pulsed Hadron Source (CPHS) in Tsinghua University, is driven by a pulsed high-current proton linac with a beam duty factor of 3%. The accelerator consists of an ECR ion source, a LEBT, an RFQ, a DTL and a HEBT beam line. The linac accelerates the proton beam to 13MeV, and delivers it to a Beryllium target. Four neutron beam lines are planned in the CPHS project, among which two lines are being constructed for the SANS and Neutron Imaging.

The 325 MHz RFQ has a four-vane structure and accelerates protons from 50keV to 3MeV. The inter-vane voltage increases with the beam energy. The total length of the RFQ is greatly shortened with a high transmission rate. The coupling plates become unnecessary for the 3m-long RFQ. The RFQ are designed to be matched to the DTL directly without MEBT. The 13MeV DTL adopts Samarium-cobalt permanent magnets with a field gradient almost constant (84.6T/m) in lattice structure of FDFD, which ensures small envelop of the beam.

At present, the 3MeV RFQ has been installed for beam tuning (Figure 18). In March 2013, its output peak current of 44 mA was achieved and the transmission efficiency was 88% while the input peak current was 50 mA with 50 µs pulse length at 50 Hz. The following DTL is under fabrication.

Figure 19: CPHS linac under beam tuning.

First neutron beam was obtained in July, 2013 by 22 mA proton beam with pulse length of 80 µs at 50 Hz. The total estimated neutron flux is about 2.8×10^{10} n/s.

APTron Accelerator

The Advanced Proton Therapy Facility (APTron) is proton therapy machine serving as a hospital-based facility [4]. It will be built at Jiading district of Shanghai with the technical support from Shanghai Institute of Applied Physics, CAS. The accelerator consists of a 7 MeV linac injector, a 24.6m circumference synchrotron capable of accelerating protons up to 250MeV, two horizontal fixed beam line and an isocentric gantry beam line in phase I, and can be upgraded to 3 gantry beam lines in total in phase II. The 7-MeV injector is composed of a RFQ and a short DTL tank. A proton beam is extracted from the synchrotron in an energy range of 70~250MeV with proton particles of 8×10^{10}p/spill at a repetition frequency of 0.1~0.67 Hz. This project has been funded by the local government.

Proton Accelerator for Space Radiation Test

Space radiation effect study calls for a proton accelerator with a weak beam current and micro-size beam spot on sample. This accelerator consists of a tandem with terminal voltage of 6 MV and a synchrotron with output energy range from 10-300 MeV. Beam from the tandem and the synchrotron will be sent to several test stands. A preliminary design of the accelerator has been proposed by IHEP. And this project has been approved in principle by the central government and it is foreseen the project will start construction in a couple of years.

ACKNOWLEDGEMENTS

The author thanks Prof. X.L Guan, Prof. D.M Li and Chinese proton accelerator community for their providing the necessary information for this paper.

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ISBN 978-3-95450-138-0