CHINESE ADS PROJECT AND PROTON ACCELERATOR DEVELOPMENT*

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Abstract

Significance of proton accelerator on the science and application has been widely recognized in the 21st century. The high-current proton accelerator can be utilized to drive the sub-critical nuclear reactor to build the clean nuclear power system. Moreover, it can serve in the field of high-energy physics, such as the neutrino factory and muon collider. For the spallation neutron source, the high-current proton accelerator provides the important platform for the multidisciplinary development of condensed matter physics, radiation physics, material science, aerospace science and life science. So proton accelerator is developing very fast in China nowadays. There're many proton accelerators under construction over China, which includes Accelerator Driven Sub-critical System (ADS), China Spallation Neutron Source (CSNS), Compact Pulsed Hadron Source (CPHS). These three projects will be introduced in this paper.

INTRODUCTION

ADS [1], CSNS [2] and CPHS have common ground, but are applied in different fields. They're all ongoing in China at present.

ADS ACCELERATOR

ADS project is a strategic plan to solve the nuclear waste problem and the resource problem for nuclear power plants in China [3]. It's supported financially by the central government and administrated by the Chinese Academy of sciences (CAS). With its long-term planning lasting until 2032, the project will be carried out in three major phases, see Figure 1.

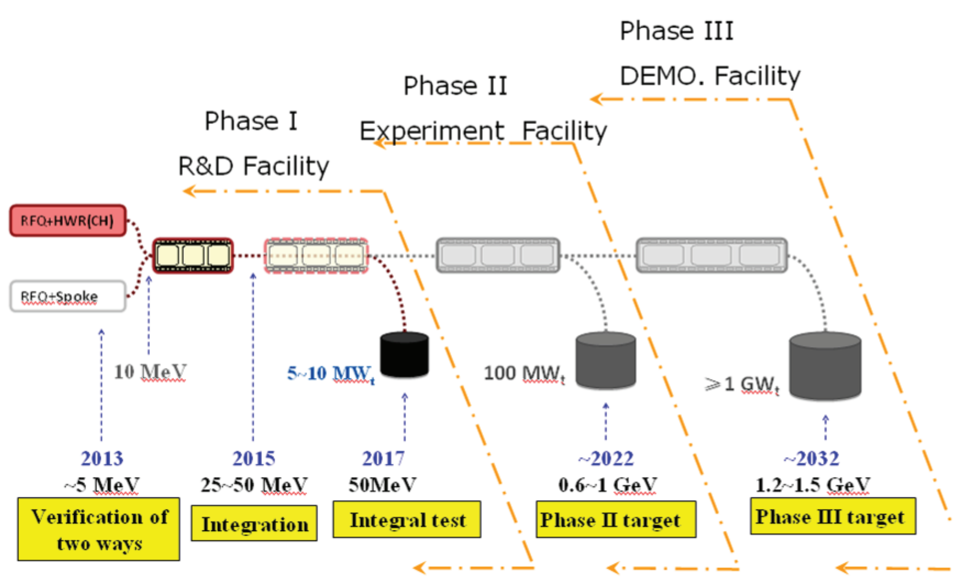

Figure 1: Road map of ADS

ADS accelerator will be built by two institutes of CAS: Institute of High Energy Physics (IHEP) and Institute of Modern Physics (IMP). It's a CW proton linac and uses superconducting acceleration structures except RFQ, the design specifications for the proton beam are shown in Table 1. For Phase I, the goal is to build a CW proton linac of 50 MeV and 10 mA by about 2015. Phase I will be executed progressively in several steps, with the 1st step to build two 5-MeV test stands of different front-end designs.

Table 1: ADS Proton Beam Specifications

Parameters	Value	Units
Energy	1.5	GeV
Current	10	mA
Beam power	15	MW
Frequency	162.5/325/650	MHz
Duty factor	100%	
Beam Loss	<1 (0.3)	W/m
Beam trips/year [4]	<25000 <2500 <25	1s<t<10s 10s<t<5m t>5m

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Design Philosophy

For the ADS accelerator, it has the characteristics of very high beam power and very high reliability which are not possessed by any of the existing proton linacs. However, several proposed CW proton/deuteron linac projects are good models for the physics and technical design, such Project-X, EFIT or MYRRHA, IFMIF and EURISOL. In addition, some pulsed high power proton linacs and some CW heavy ion linacs using superconducting cavities also serve as good examples. In general, there're several key points:

- It has been common understanding that superconducting proton linac is the best choice as an ADS driving accelerator, compared with other accelerator types which are still further away from the requirements as shown in Table 1. So hundreds of superconducting cavities (HWR, spoke, Elliptical) are widely used, as Figure 2 shows.
- High reliability is the most crucial for ADS. To achieve this goal, it's necessary to have enough redundancy for the entire accelerator. For the very low energy part, it's difficult to apply the local compensation as main linac, thus two parallel injectors are adopted. When one is on operation, the other is hot-spare and can be switched to the operation quickly. Figure 2 show that.
- Another key point of design is that beam losses should be kept as low as possible along the linac, with a usual acceptance of 1 W/m for all high-power proton accelerators. This is more difficult for the ADS, the beam power of which is 10 times higher. It also means a beam loss rate of 7e-8/m at the higher energy part, and requires very delicate error and beam loss studies.
- Beam emittance in the 3-D planes is very important. As the beam loss rate should be controlled at an extremely low level, all the measures should be considered to control the emittance growth along the linac, especially the halo emittance that is directly linked to the beam loss. Anyway, the total geometry emittance may increase during the acceleration due to all the errors and mismatches, so big physical aperture is adopted at higher energy section.

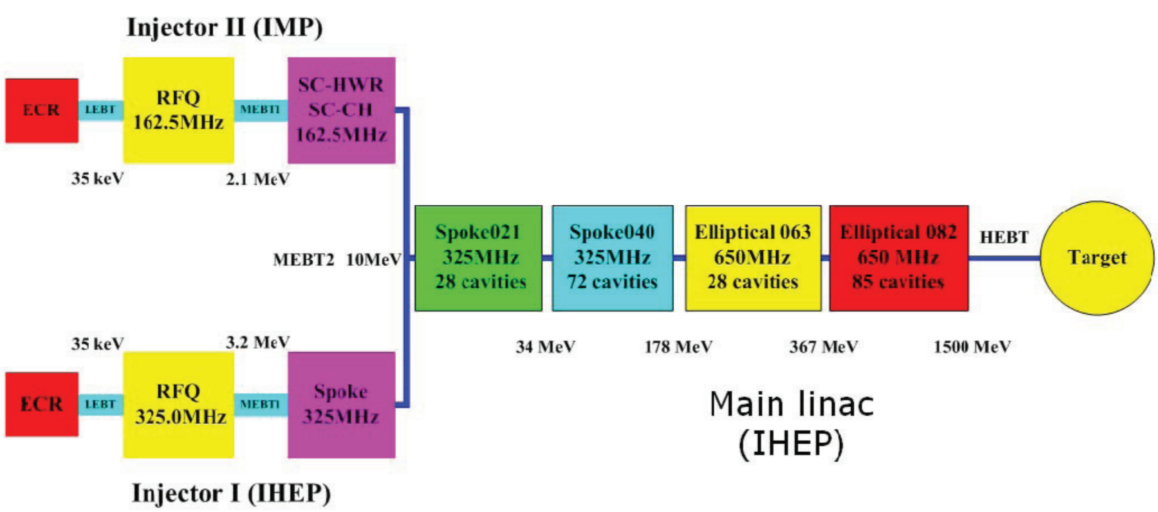

Figure 2: Layout of ADS accelerator

Injector I

Injector I will be built by IHEP, which Figure 2 demonstrates. The frequency of RFQ and Spoke cavity is 325 MHz, which is the same as Project-X. CW RFQ and low beta superconducting spoke cavity are the obstacles Injector I faces.

Currently, the design of RFQ has been determined, and the machining of prototype is ongoing now. Table 2 indicates main parameters of RFQ.

Table 2: Main RFQ Parameters

Parameters	Value	Units
Injection energy	35	keV
Output energy	3.2	MeV
Pulsed beam current	15	mA
Beam duty factor	100%	
Beam transmission	98.7%	
Total power	320.94	kW
Accelerator length	469.95	cm

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Although very low-beta single spoke cavity are considered very difficult to develop and lack of experience, it's straightforward for IHEP to adopt such a spoke cavity for the superconducting acceleration structure in the Injector I since the main linac uses the same type of cavities but with higher beta, which will reduce the time and cost in the cavity development. Main parameters are listed in Table 3.

Table 3: Main Parameters of Spoke Cavity

Parameters	Value	Units
Diameter	468	mm
length	180	mm
Beam aperture	35	mm
Beta	0.12	
R/Q	142	Ω
G	61	Ω
Epeak/Eacc	4.54	
Bpeak/Eacc	6.37	mT/(MV/m)

Now the prototype of spoke cavity is under machining now (Figure 3), which may finish in Oct, 2012. Then the vertical test may be done at the end of 2012.

Figure 3: Spoke bars after welding.

Injector II

IMP is in charge of Injector II [5], the frequency of which is 162.5 MHz, half of the frequency of main linac. It can reduce the power density of RFQ, thus the difficulty of cooling. Therefore, 162.5-MHz half wave resonator (HWR) is adopted. Furthermore, superconducting CH cavity is also a potential choice.

The physics design of RFQ, which is developed by collaboration with LBNL, has been completed. Table 4 shows main parameters. And the prototype is being fabricated now. The fabrication of HWR cavity is together with spoke cavity. It may finish in October of 2012, too.

Table 4: Main Parameters of RFQ

Parameters	Value	Units
Injection energy	35	keV
Output energy	2.1	MeV
Pulsed beam current	15	mA
Beam duty factor	100%	
Beam transmission	99.5%	
Total length	420.8	cm

Figure 4: Outer tube of HWR.

CSNS LINAC

CSNS is the first large-scale, high-power accelerator project to be built in China. It locates at Dongguan, Guangdong province. Through years of preparation, it has began the construction in Sep, 2011. The goal is that it will provide 100 kW proton beam (1.6GeV) on a target in 2018. The total budget of CSNS is $260,000,000, which includes an 80-MeV H- linac, a 1.6-GeV cycling synchrotron, the spallation neutron target and 3 neutron spectrometers, as Figure 5 shows.

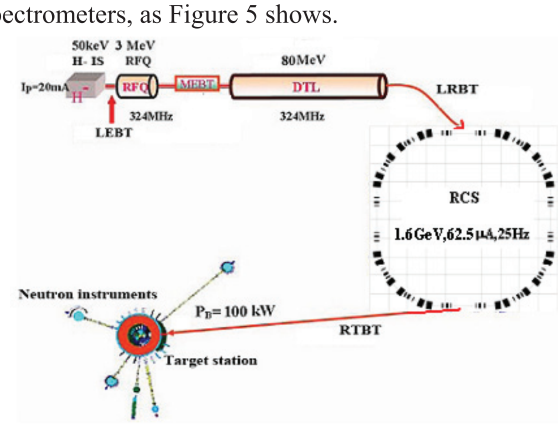

Figure 5: Schematics of CSNS.

Physics Design

CSNS accelerator [6] can produce proton beam of 1.6-GeV kinetic energy at 25 Hz repetition rate, striking a solid metal target to launch neutrons. Table 5 lists main parameters.

Table 5: CSNS Parameters

Project Phase	I	II
Beam Power on target [kW]	100	500
Proton energy t [GeV]	1.6	1.6
Average beam current [μA]	62.5	312.5
Linac energy [MeV]	80	250
Linac RF frequency [MHz]	324	324
Macropulse duty factor	1.0	1.7
RCS circumference [m]	228	228
RCS harmonic number	2	2
RCS Acceptance [πmm mrad]	540	540

The linac is made up of H- ion source, LEBT, RFQ, MEBT and DTL. But superconducting cavities (spoke or elliptical) will be applied in Phase II.

Present status

According to the plan, CSNS linac will start installation at the end of 2013 when the linac tunnel becomes available. Almost all the linac components have started fabrication or procurement at present.

CPHS PROJECT

CPHS in the Dept. Engineering Physics, Tsinghua University, is driven by one pulsed high-current proton linear accelerator. The accelerator consists of the Electron Cyclotron Resonance (ECR) ion source, Low Energy Beam Transport (LEBT) line, Radio Frequency Quadrupole (RFQ) accelerator, Drift Tube Linac (DTL) and High Energy Beam Transport (HEBT) line. The function of the whole accelerator system is to produce the proton beam, accelerate it to 13MeV, and deliver it to the target where one uniform round beam spot is obtained with the diameter of 5 cm. The whole performance of the CPHS facility relies critically on the accelerator system.

Four neutron beam lines are planned in the CPHS project at Tsinghua University, among which two lines are being constructed for the Small Angle Neutron Scattering (SANS) and neutron imaging. The neutron will be generated by the proton beam bombarding a Beryllium target.

Design

Main parameters of CPHS accelerator is listed in Table 6. Figure 6 is the layout of CPHS.

Table 6: Main Parameters

Parameters	Value	Units
Beam power	16	kW
Beam energy	13	MeV
Average current	1.25	mA
Pulse repetition rate	50	Hz
Protons per pulse	1.56×10^{14}	
Charges per pulse	2.5×10^{-5}	C
Pulse energy	0.325	kJ
Pulse length	500	μ s
Peak current	50	mA
Beam duty factor	2.5	%
RF frequency	325	z MH
Output energy of the ion source	50	keV
Output energy of the RFQ	3	MeV
Output energy of the DTL	13	MeV

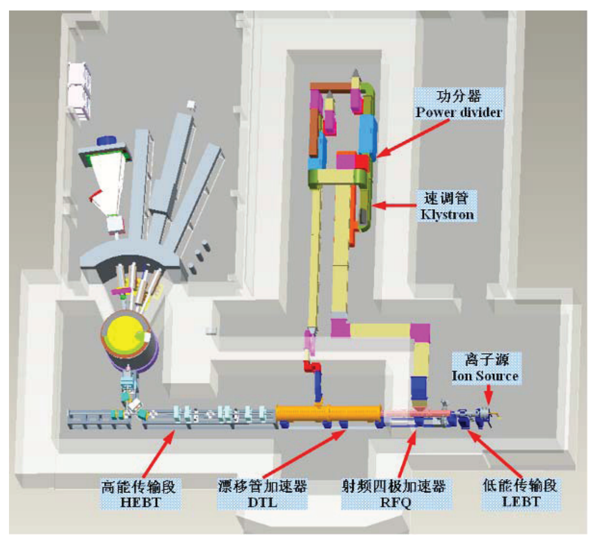

Figure 6: Layout of CPHS.

ECR Ion source and LEBT

The Electron Cyclotron Resonance (ECR) ion source is adopted to produce the proton beam. A three-electrode extraction system is to extract the 50keV proton beam from the plasma chamber. The LEBT matches the proton beam produced by the ion source to the RFQ accelerator. The 1.4m-long LEBT consists of two solenoid lens, two steering magnets, two diagnostic champers and one cone structure (the cone, ACCT and electronic trap).

The ECR proton source and LEBT are under conditioning now, and the maximum output proton beam has reached 60 mA, as Figure 7 shows.

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Figure 7: ECR and LEBT.

RFQ

Maintaining the good quality of the beam, Radio Frequency Quadrupole (RFQ) accelerator can bunch, focus and accelerate the low-energy CW proton beam from the ion source. The CPHS RFQ has a structure of four-vane 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 are not necessary for the 3 m-long RFQ. The RFQ are designed to be matched to the DTL directly without MEBT.

Machining, brazing and assembly of the RFQ (3MeV/50mA) have been finished, and the result of the cold test at THU is satisfactory, which Figure 8 shows.

Figure 8: RFQ.

DTL

Samarium-cobalt permanent magnets are adopted as the transverse focusing quadrupoles for the CPHS DTL . The field gradient is designed to be almost constant (84.6 T/m). The lattice structure is FDFD, which ensures small envelop of the beam. The DTL is matched directly with the RFQ accelerator. The average accelerating field increases almost linearly from 2.2MV/m to 3.8MV/m.

The construction of the DTL will be completed in 2013.

HEBT and Target

The CPHS HEBT (Figure 9) is to deliver the 13MeV proton beam accelerated by the DTL to the target station, with minimum beam loss, and obtain one uniform round beam spot with the diameter of 5 cm on the target. To decrease the influence of the recoil neutrons on the DTL, the proton beam is deflected before it bombards the target.

To carry out the proton irradiation experiment with the 13MeV proton beam directly bombarding the target, one straight beam line is designed simultaneously. Two sweeping magnets are designed to obtain the uniform beam spot of 10cm×10cm on the target.

Figure 9: HEBT and target station.

While the HEBT beam line is ready, the 3 MeV proton beam will be used to produce the neutron at the end of 2012.

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