CHINESE PLANS FOR ADS AND CSNS

Shinian Fu, Hesheng Chen, Yunlong Chi, Shouxian Fang, Li Ma, Weimin Pan, Jingyu Tang, Chuang Zhang, IHEP, Beijing 100049, China

Yuan He, Hongwei Zhao, IMP, Lanzhou, China

Abstract

High intensity proton accelerator now has two major applications in China: one is Accelerator Driven Subcritical System for nuclear waste transmutation and another is spallation neutron source. ADS project launched in the first half of 2011 will build an ADS test setup with CW proton linac. China Spallation Neutron Source(CSNS) project will start construction in September 2011and it will operate at pulse mode at 25Hz repetition rate. This paper will briefly introduce these two projects, their accelerator design and the related technology development .

INTRODUCTION

High intensity proton accelerator is a new direction in China for its many important applications. Among them, Accelerator Driven Subcritical system (ADS) and spallation neutron source become major application field. A basic research program on ADS started in 2000 in China[1]. Recently a Chinese roadmap for long-term development of ADS was proposed by Chinese Academy of Sciences and the first budget of about \$260M has be approved for an ADS test setup construction. It includes a CW proton linac consisting of a room-temperature RFQ and superconducting spoke cavities. The ADS R&D program started in the first half of 2011. The same amount of budget has also been approved for the project of China Spallation Neutron Source(CSNS) and it is going to be launched in September 2011. CSNS accelerator consists of a room-temperature H^- linac and a rapid-cycling synchrotron with beam power of 100kW at 25 Hz repetition rate[2]. It will be upgraded to 500kW beam power in future by adding some superconducting cavities to the linac to raise the beam energy for reducing space-charge effect in the synchrotron when the beam current becomes 5-times higher.

In the following sections of the paper we will briefly introduce the two projects and outline its present status. The accelerator design and technology development will be presented in more details, especially on their superconducting linac part.

ADS PLAN AND PROTON LINAC

China, as a developing country with a great population and relatively less energy resources, is rapidly developing nuclear energy. The nuclear electricity is foreseen to reach 75GWe, and meanwhile 30GWe power will be under development in 2020, according to the recently revised plan of the Chinese government in April 2009. This plan has no change after the Fukushima nuclear crisis, but the safety issue is much more emphasised. To develop nuclear power in such a large scale, long-lived radioactive nuclear wastes have to be safely disposed to reduce the impact on the environment and to eliminate public fear of nuclear power. 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 disposal. A basic research program on ADS started in 2000 in China. Recently a Chinese roadmap for long-term development of ADS was proposed by Chinese Academy of Sciences. It outlines a three-step plan with a small test setup, an experimental facility and a demonstration facility in a period from 2011 to 2032 , as plotted in Figure 1.

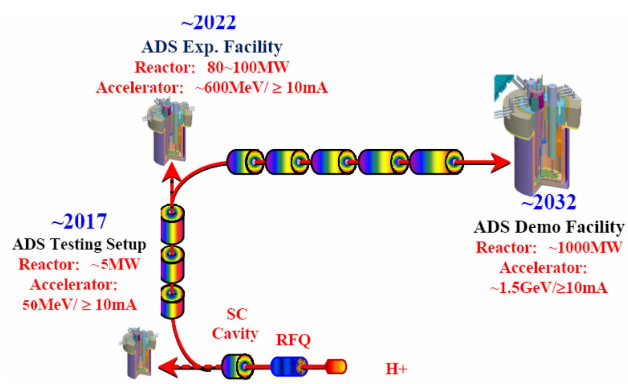

Figure 1: The road map of ADS development in China.

Step 1: From 2011 to 2017 we are going to construct an ADS test facility, called CIADS, which is the abbreviation of Chinese Initiative Accelerator Driven System. It is the first coupled system of an high intensity proton accelerator with subcritical reactor through a neutron production target. The thermal power of the reactor is designed at 5 MWth. Superconducting RF technology is one of the major subjects of this step, as it is still in the preliminary stage in China at present. CIADS project has been approved with a budget of \$260M for construction of an linac, a subcritical reactor, a target, as well as the related technology platforms, but without land cost and infrastructure which will be supported by the local government. It has been launched in the first half of 2011 and is expected to be completed in six years. The Inner Mongolia in north part of China is a most possible construction site.

Step 2: From 2017 to 2022, the same linac in the first step will be prolonged with more superconducting spoke cavities and medium-βsuperconducting elliptical cavities to increase the proton beam energy to about 600 MeV. It is coupled with a new subcritical assembly of 80-100 MW thermal power through a spallation neutron target of liquid metal. This is a medium scale ADS facility and we called it as ADS Experimental Facility. This facility will run for experiment of the waste transmutation and operation stability of the ADS system.

Step 3: From 2022 to 2032, a full-scale ADS demonstration facility will be built with thermal power of 1000 MW_{th}. More superconducting elliptical cavities will be added to the linac to raise beam energy up to 1.5 GeV with a beam power of 15MW. At this step, CAS will complete its mission on ADS research and technology development and industry will join the project and the technology will be transferred to industry from research institution.

Linac Design

The proton linac will operate in CW mode for a high average current. Superconducting cavity is the best option, except for the front-end. Instate of 352 MHz and 704 MHz RF frequency in the previous ADS linac design, the new design uses 325 MHz and 650 MHz RF frequency. The major consideration on the RF frequency choice is connected with ILC 1.3 GHz superconducting technology, as Project-X at Fermilab.

In our preliminary design the 1.5 GeV linac consists of two injectors, two spoke cavity sections and two elliptical cavity sections, as shown in Figure 2. 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 will take the approach of Injector-I and IMP will develop the Injector-II. 10 MeV proton beam from the injectors will be matched via an MEBT2 with the following linac and then accelerated with the superconducting linac to 1.5 GeV. The two spoke cavity sections use single-spoke structure at 325 MHz. The two elliptical cavity sections use 5-cell structure with RF frequency of 650 MHz. The major design parameters of linac with Injector-I are listed in Table 1.

Table 1: Linac Major Design Parameters

RFQ	
Injection energy	35 keV
Output energy	3.2 MeV
Pulsed beam current	15 mA
Inter-vane voltage	55 kV
Beam transmission	98.7%
Maximum surface field	28.9MV/m (1.62Kilp.)
Vane length	467.8 cm
Cavity Power	273 kW
Spoke Cavity 012	
Geometry β	0.12
E_p / E_{acc}	4.38
B_p / E_{ac}	7.76
Acc. Gradient	5.75 MV/m
Spoke Cavity 021	
Geometry β	0.21
E_p / E_{acc}	3.67
B_p / E_{ac}	6.59
Acc. Gradient	6.97 MV/m
Spoke Cavity 04	
Geometry β	0.4
E_p / E_{acc}	3.70
B_p / E_{ac}	7.22
Acc. Gradient	7.56 MV/m
Ellip. Cavity063	
Geometry β	0.63
E_p / E_{acc}	3.13
B_p / E_{ac}	4.57
Acc. Gradient	10.56MV/m
Ellip. Cavity 082	
Geometry β	0.82
E_p / E_{acc}	2.13
B_p / E_{ac}	4.30
Acc. Gradient	16.36 MV/m

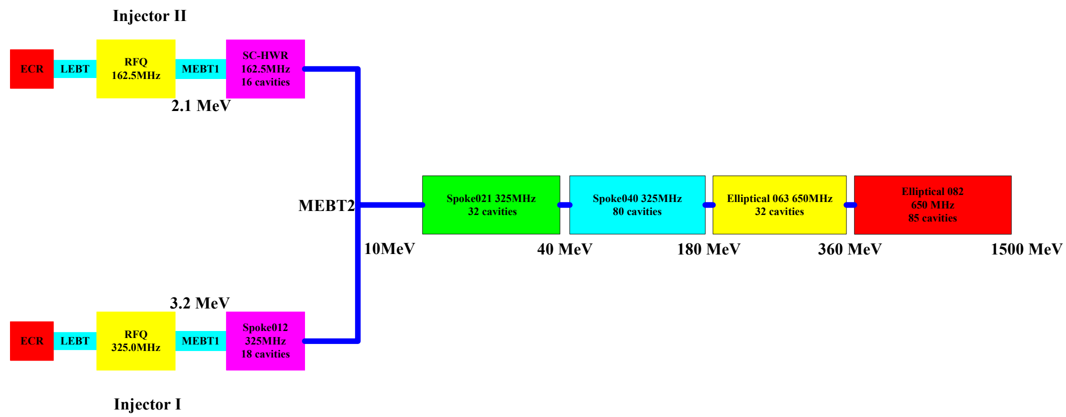

Figure 2: Sketch of the ADS 1.5GeV linac.

SC Technology Development

The technology of medium-β superconducting RF cavity has been studied since 2002. Three superconducting single elliptical cells of 1.3 GHz with geometricβ=0.45 were manufactured with assistance from KEK. It is the scaled-down prototype of 700 MHz cell, as shown in Figure 3. It reaches the surface field E_{sp}= 42.4 MV/m (Figure 4). Based on the successful experience of 1.3 GHz cell, 700 MHz cell is now under development.

Figure 3: 1.3 GHz single cell at β=0.45.

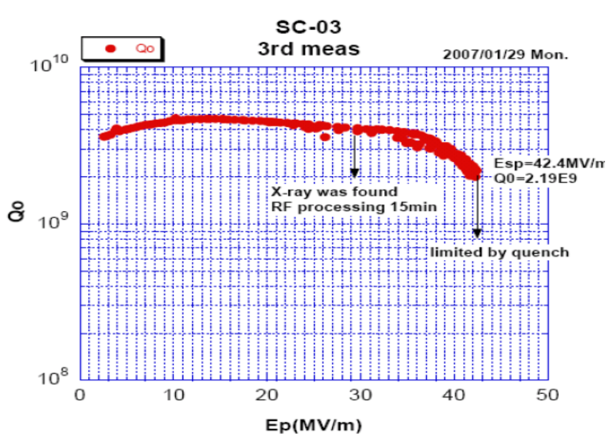

Figure 4: Measured Q_0 of the 1.3 GHz single cell.

In addition to the medium β cavity for proton linac, recently IHEP also developed superconducting cavities for electron accelerators, such BEPC-II and ILC. The second 500 MHz elliptical cavity has been manufactured in China for the BEPC-II, as shown in Figure 5. It reached voltage of 2.3 MV at 4.2 K with Q_0 =1.29E9, which is higher than the design values, as plotted in Figure 6.

For the development of superconducting RF technology at IHEP, an RF superconducting laboratory of 250 m^2 has been set up for the RF cell processing and measurement. A cryostat for 1.3 GHz cavity has been built for vertical measurement at the working temperature of 1.5~4.2 K. The lab is not only used for proton linac R&D, but also serve for the cavity development of ILC and photo cathode gun.

Figure 5: 500 MHz cavity for BEPC-II.

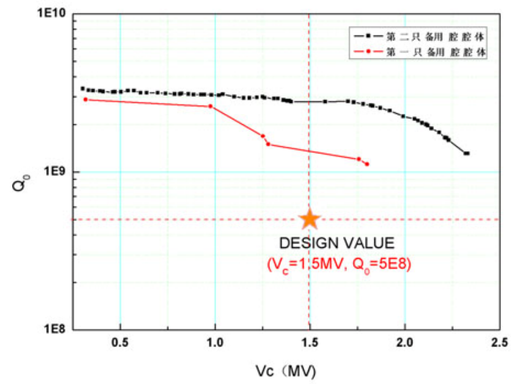

Figure 6: Measured Q_0 on 500 MHz BEPC-II cavity.

CSNS PROJECT

The CSNS project was approved by the Chinese central government in 2008. It is going to start construction in September 2011 and complete the project in 6.5 years. The CSNS accelerator is the first large-scale, high-power accelerator project to be constructed in China. 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 and then 500 kW in the second phase by increasing the average beam intensity 5 times while raising the linac output energy to 250 MeV. A schematic layout of CSNS phase-1 complex is shown in Figure 7. The major design parameters of the CSNS accelerator complex are listed in Table 2. In the phase one, an H^- ion source produces a peak current of 25 mA H^- beam. RFQ linac bunches and accelerates it to 3 MeV. DTL linac raises the beam energy to 80 MeV. After H^- beam is converted to proton beam via a stripping foil, the RCS accumulates and accelerates the proton beam to 1.6 GeV before extracting it to the target. Phase-I has a budget of $260 M for construction of the accelerator, the spallation neutron target and 3 neutron spectrometers. It is going to built at Dongguan, south part of China. The local government will support free land, additional budget of $57M, infrastructure, dedicated high-way and power transformer station.

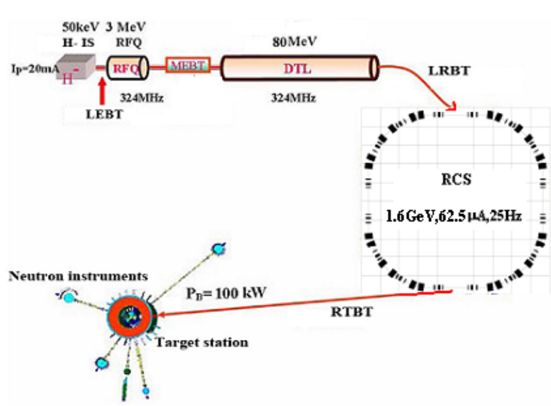

Figure 7: Schematics of the CSNS complex.

Table 2: CSNS Design 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
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	30
Macropulse duty factor	1.0	2.5
RCS circumference [m]	228	228
RCS harmonic number	2	2
RCS Acceptance [πmm-mrad]	540	540

The Linac Design

The H^- ion source provides 25 mA peak current, 0.5 ms long, 0.2πμm normalized emittance (rms) pulses at 50 kV and 25 Hz repetition rate for phase-I. The ISIS type Penning H^- surface source is chosen for CSNS, because it can well meet the specification of CSNS phase-I.

The LEBT is for matching and transporting the H^- beam from ion source to RFQ accelerator, and pre-chopping the beam according to the requested time structure by the RCS. Three-solenoid focusing structure is adopted for space charge neutralization. An electrostatic deflector is chosen as pre-chopper, positioned at the end of the LEBT. A prototype of the LEBT chopper reaches a fast rise time of 17 ns.

A four-vane type RFQ is adopted, with total length of 3.62 m, composed of four segments. RFQ accelerates H^- beam from 50 keV to 3 MeV, with duty factor of 1 %. The selection of 3 MeV output energy is a compromise between the fast-chopper design in MEBT and injection energy of DTL.

The MEBT matches the H^- beam from RFQ to DTL in 6-dimentional phase space, and chops the beam with fast (~10 ns) rise time. The total length of MEBT is about 3 m, including 8 magnets, two bunchers and two J-PARC type RF choppers. Beam instruments for beam current, beam position and beam loss are also installed in the MEBT.

The DTL accelerates the 3 MeV beam from the RFQ to 80 MeV. To reach a high effective shunt impedance, the cell shape and size are tuned with β stepwise in the low β segment, and keeping the maximum surface field below 1.3 times the Kilpatrick limit. The FFDD focusing lattice is used in the dynamic design, and J-PARC type EM quadrupoles are adopted.

The RCS Design

Due to the requirement of the beam collimation for beam loss control in a high intensity proton synchrotron, the lattice with 4-fold structure is preferred for separated-function design, as shown in Figure 8(upper). Also the lattice superperiodicity of 4 is better for reducing the impact of low-order structure resonance than superperiodicity of 3.

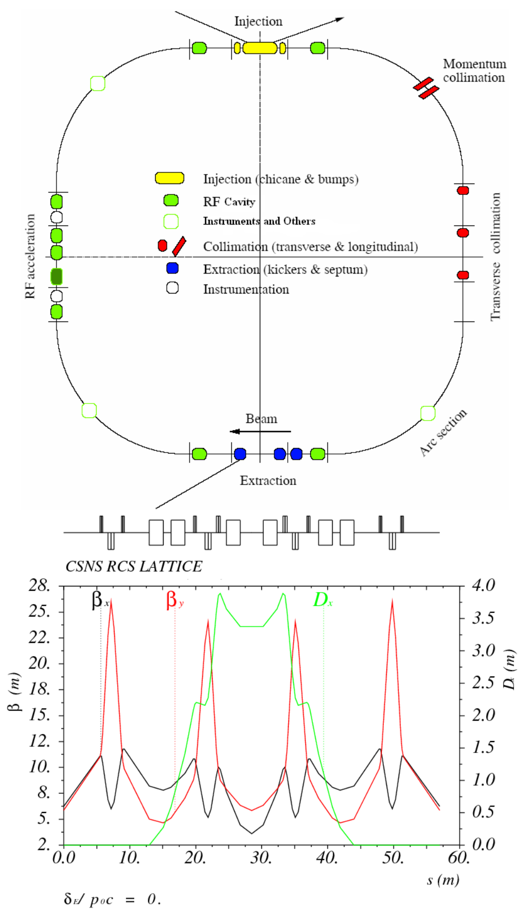

Figure 8: RCS function arrangement(upper) and twiss parameters of one super-period(lower).

The lattice is based on triplet cell, and the whole ring consists of 16 triplet cells, with circumference of 227.92m. In the each super period, an 11m long drift space is left in a triplet cell, and this uninterrupted long space is very good for accommodation of injection, extraction and transverse collimation system. Figure 8(lower) gives the twiss parameters of one super-period. The maximum beta function is less than 26m, and the maximum dispersion function is less than 4m. Especially in the middle of the arc, the dispersion is large and the horizontal beta function is small, and this is good for high efficiency momentum collimation.

The acceleration is performed by eight ferrite-loaded cavities which provide 165 kV RF voltage with harmonic number of two. An RF acceleration period consists of three stages: injection, capture and acceleration. The designed bunching factor in the beginning of the acceleration is about 0.4, and with the increasing of RF voltage, the bunching factor is decreased to 0.12.

The linac beam is injected to the RCS by using H^- painting method in both horizontal and vertical planes. The whole injection chain is arranged in an 11 m long straight section, consists of four horizontal painting magnets, four vertical painting magnets, and four fixed-field bumping magnets. The one-turn extraction from the RCS is achieved by using 7 vertical fast kickers followed by a Lambertson septum.

The Interface Design

There are two beam transport lines: LRBT and RTBT. the LRBT transports H^- beam to the ring, and transverse and momentum collimators are designed to scrape the halo particles. The debuncher is used in the LRBT to decrease momentum spread. the RTBT transports extracted proton beam from the RCS to the target. The beam loss due to malfunction of kickers is minimized in the design. Collimation system is designed at the RTBT for protection of the target and shielding of back scattering neutrons.

SC Linac Design for Upgrade

In the LRBT design, a spare length of 85 m is reserved in the phase-I for the future upgrade of the beam power to 500 kW by adding a section of linac with output beam energy of 250 MeV. In our previous design, this section of linac would be composed by three DTL tanks of 324 MHz up to 132 MeV and some superconducting elliptical cavities with RF frequency of 972MHz. In a recent new design, one type of superconducting spoke cavity is adopted to cover the full energy range in upgrade program. It keeps the same RF frequency as the 80 MeV DTL, so that there is no RF frequency jump in whole CSNS linac, benefiting for controlling beam loss and emittance growth. In this new design we can take the technology advantage of the ADS program, in which a 325 MHz spoke cavity linac will have been built when we start CSNS upgrade program about 10 years late. The major difference from ADS linac is CSNS linac needs pulse-mode operation.

In the spoke cavity linac scenario, double spoke cavity with a geometry β_g = 0.488 will be used. The major cavity parameters are listed in Table 3.

Table 3: Double spoke cavity parameters

Cavity radius (mm)	242.0
Tube radius (mm)	35
Spoke base radius (mm)	85
Spoke center thickness (mm)	75
Spoke center width (mm)	180
Spoke center height (mm)	60
Iris to iris length (mm)	300
Tube length (mm)	150
Top cavity length (mm)	500
E_{acc}	5.59
E_p / E_{acc}	4.46
B_p / E_{acc}	7.1
Voltage gain @ 25MV/m (MV)	3.87
Magnetic field @ 25MV/m (mT)	39.83

Three cavities share a cryostat about 4 m long at 4.2K. Room temperature doublet quadrupole magnets in between the cryostats are designed for beam focusing. The total length of the superconducting section is about 78 m, which is shorter than the previous design scenario of DTL plus elliptical cavity. Its energy gain per meter is plotted in Figure 9. The preliminary beam dynamic simulation with beam envelopes in three directions is shown in Figure 10. It indicates the beam is well within in the bore radius of the cavity.

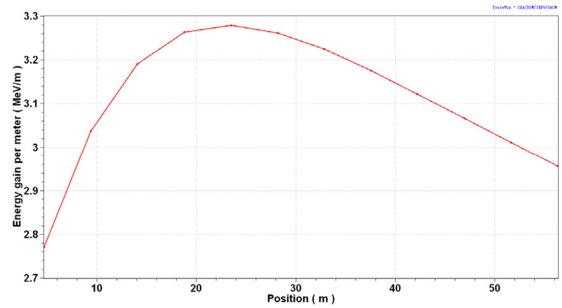

Figure 9: Energy gain of the spoke cavity.

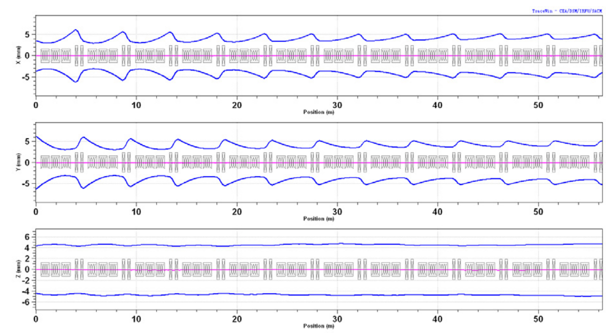

Figure 10: Beam envelopes in three directions simulated.

REFERENCES

[1] Shinian Fu, Shouxian Fang, et al., “Proton Linac for ADS Application in China”, LINAC’10, Tsukuba, Sept. 2010,TUP019, (2010).

[2] Shinian Fu, Hesheng Chen, et al, “Status of the China Spallation Neutron Source Project”, PAC'09, Vancouver, May 2009, TH1GRI02, (2009).