CHINA SPALLATION NEUTRON SOURCE LINAC DESIGN

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Abstract

China Spallation Neutron Source has been approved in principle by the Chinese government. CSNS is designed to provide a beam power of 120kW on the target in the first phase, and then 240kW in the second phase. The accelerator complex of CSNS consists of an H- linac of 81MeV and a rapid cycling synchrotron of 1.6GeV at 25Hz repetition rate. In the second phase, the linac energy will be upgraded to 132MeV and the average current will be doubled. The linac has been designed, and some R&D studies have started under the support from Chinese Academy of Sciences. The linac comprises an H- ion source, an RFQ and a conventional DTL with EMQs. This paper presents major design results and progresses in the linac R&D.

INTRODUCTION

The China Spallation Neutron Source (CSNS)[1,2] provides a multidisciplinary platform for scientific research and applications by scientific institutions, universities, and industries. The high-flux pulsed neutrons from CSNS will compliment cw neutrons from nuclear reactors and synchrotron lights from synchrotron radiation facilities. Strongly advocated by the users groups, the CSNS project was, approved in principle by the Chinese central government in 2005. 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

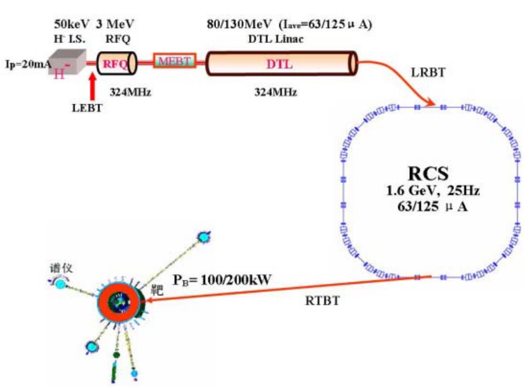

Figure 1: A schematic layout of CSNS.

target to produce spallation neutrons The accelerator provides a beam power of 100 kW on the target and then 200kW in the second phase by raising the linac output energy to 132MeV and doubles the beam intensity. A higher beam power of 500kW is also under consideration as an alternative option for the second phase. A schematic layout of CSNS complex is shown in Figure 1. In the accelerator design, some conservative redundancy has been taken into account. So the designed beam current and thus beam power is higher than the nominal value. The major design parameters of the CSNS accelerator complex are listed in Table 1. In the phase one, an H⁻ ion source (I.S.) produces a peak current of 20 mA H⁻ beam. RFQ linac bunches and accelerates it to 3 MeV. DTL linac raises the beam energy to 81 MeV in phase one and 132MeV in phase two. After H⁻ beam is converted to proton beam via a stripping foil, RCS accumulates and accelerates the proton beam to 1.6 GeV before extracting it to the target.

Table 1: CSNS Design Parameters

Project Phase	I	II	II'
Beam Power on target [kW]	120	240	500
Proton energy t [GeV]	1.6	1.6	1.6
Average beam current [μ A]	76	151	315
Pulse repetition rate [Hz]	25	25	25
Proton per pulse [10^{13}]	1.9	3.8	7.8
Linac energy [MeV]	81	132	230
Linac type	DTL	DTL	DTL,SCL
Linac RF frequency [MHz]	324	324	324
Macropulse. ave current [mA]	15	30	40
Macropulse duty factor	1.1	1.1	1.7
RCS circumference [m]	230.8	230.8	230.8
RCS filling time [ms]	0.42	0.42	0.68
RCS harmonic number	2	2	2
RCS RF frequency [MHz]	1-2.4	1.3-2.4	1.6-2.4

LINAC DESIGN

The linac is designed at a RF frequency of 324MHz, the same as J-Parc linac, so that the same klystron can be applied to the DTL as a high power pulsed RF source. And this frequency also gives a reasonable room for the EMQ inside the drift tube. As both the beam current and energy will be increased in the second phase, the linac is presently design for the high current in the second phase and the LRBT beam line leaves a length for some additional cavities. In present design we only consider the option of 132MeV energy upgrade, and thus some additional DTL cavities will follow to the 81MeV DTL linac in the second phase.

For this intense beam accelerator, beam loss is a major concern in the design. As an injector of a synchrotron, not only should the linac have a low beam loss, but also provide a high quality beam to the ring.

H⁻ Ion Source and LEBT

In the 1st phase, the required specification for the ion source is moderate, as listed in Table 2. Various kinds of H- ion source can satisfy our demand. In the source type selection, we put more attention on cost and reliability. Penning source with Cesium used in ISIS becomes our first option. Beam pulse length should become longer than ISIS source. We started the collaboration with ISIS to develop this source in our lab.

Table 2: Major Parameters of the Ion Source

Ion	H^-
Extract energy (keV)	50
Extract current (mA)	>20
Emittance $\varepsilon_{n,rms}$ (π mm-mrad)	<0.20
Rep. frequency (Hz)	25
Beam duty factor (%)	1.3
Lifetime (month)	>1

Beam macropulse from the ion source will be pre-chopped at the ratio about 50% to form beam gaps for low-loss injection into the ring. A slow pre-chopper is designed in the LEBT. The magnetic alloy loaded cavity used in J-Parc linac is an option for the slow chopper, which decelerates the beam and then the beam losses in the following RFQ to form the beam gaps. Three solenoids in the LEBT will provide focusing to the flat beam extracted from the slit aperture of the ion source and match the beam with the RFQ acceptance, which is symmetric in the two horizontal directions. Space charge neutralization in the LEBT of about 1m long helps reducing the beam emittance growth. Figure 2 shows a schematic plot of the LEBT.

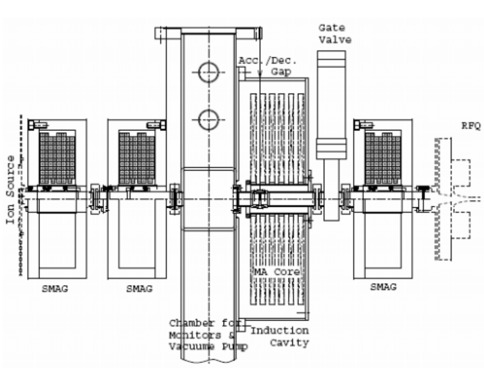

Figure 2: The LEBT with three solenoids and a magnet alloy loaded cavity for beam chopping.

RFQ Accelerator

We have built a 3.5 MeV RFQ accelerator in an ADS basic research program. Initial commission result with 92% transmission rate indicates this RFQ is successful. It has a higher pulse beam current and higher duty factor than CSNS RFQ. However, the RF frequency of the ADS RFQ is 352.2 MHz. We have to design and build another RFQ at 324 MHz and 3MeV. These changes make no significant difference, and thus we can follow the design of the ADS RFQ [3].

Beam dynamics design of the CSNS RFQ has been completed and RF structure design is going on. Table 3 lists the RFQ design parameters. PARMTEQM simulation indicates a beam transmission rate of more than 97% for 40mA beam. The transmission becomes zero if the injected beam energy is 10 keV lower than the designed value according to the simulation, as shown in Figure 3. This filter feature of the RFQ makes it possible to generate beam gaps in association with the pre-chopper in the LEBT. This four-vane type cavity is divided into two resonantly coupled segments, and each segment consists of two technological modules.

Table 3: The RFQ parameters

Input beam energy (keV)	50
Output beam energy (MeV)	3
Beam current (mA)	40
Beam duty factor (%)	1.05
Transmission (%)	97
RF frequency (MHz)	324
Structure RF power (kW) (1.4 time Superfish value)	390
Total RF power (kW)	510
Vane voltage (kV)	80
Maximum surface field (Kilpatrick)	1.78
Average bore radius (mm)	3.565
Total vane length (m)	3.62
Structure	4 vane
Segment	2

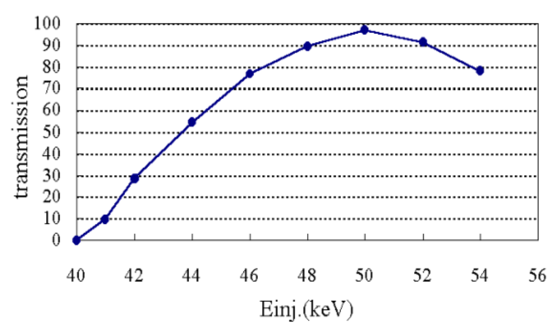

Figure3: RFQ transmission rate vs. injecting beam energy.

MEBT

MEBT consists of 10 quadrupoles, two re-bunchers in phase one, and additionally two fast choppers in phase two. As the beam current is not so high in the phase one, a fast chopper for cleaning up the beam gaps generated in the LEBT pre-chopper is not demanded. But their behaviour and installation space are considered in the present MEBT design. Figure 4 plots MEBT beam transport matched with the acceptance of the following DTL in three directions. The MEBT total length is about 3.2 meters.

RF chopper has advantages of compactness and stable operation. And the rise time can be less than 10ns. It has been successfully operated in the J-Parc MEBT. So we are going to use this type of chopper in the CSNS MBET in the second phase upgrade.

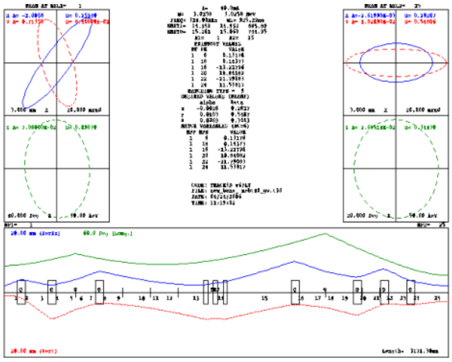

Figure 4: MEBT beam transport designed by TRACE3-D

DTL Linac

The conventional drift tube linac accelerates the 3MeV beam from the RFQ to 81MeV in phase one and to 132MeV in phase two. Phase one DTL is composed of four tanks, and additional three tanks will be followed in phase two. Each tank consumes almost the same amount of RF power so as to maximize the utilization efficiency of the RF power source. Table 4 lists the tank parameters of the DTL linac. To reach a high effective-shunt-impedance, the cell shape varies with beta in stepwise, while keeping the maximum surface electric field lower than 1.3 times Kilpatrick limit. In the first tank the average on-axis field gradient E_0 is increasing from the entrance end and then keeps constant. It is found the field variation pattern given by MDTFISH simulation using the cell data from PARMILA output becomes obviously different from the design value in the PARMILA input file, as shown in Figure 5. So tuning design of some cells is necessary to compensate for the difference. More details about the design can be found in reference[4].

Table 4: DTL Tank Parameters

Tank number	1	2	3	4	5	6	7	total
Output energy (MeV)	21.76	41.65	61.28	80.77	98.86	115.8	132.2	132.2
Length(m)	7.99	8.34	8.5	8.85	8.69	8.57	8.67	59.6
Number of cell	61	34	29	26	23	21	20	214
Cavity RF power (MW)	1.41	1.41	1.39	1.45	1.45	1.45	1.49	10.05
Total RF power (MW)	1.97	2.01	1.98	2.03	1.99	1.96	1.98	13.92
Accelerating field (MV/m)	2.2-3.1	3.1	3.1	3.1	3.1	3.1	3.1	
Synchronous phase	-30--25	-25	-25	-25	-25	-25	-25	

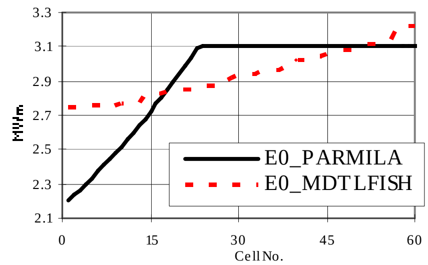

Figure 5: The solid curve shows the cavity design field input in PARMILA. The dashed curve shows the cavity field calculated by MDTFISH by using the cell data output from PARMILA.

FD lattice provides beam with a strong focusing and keep the beam transversal emittance almost no growth in PARMILA simulation. Beam rms radius is 4 to 13 times smaller than the DT bore radius and the maximum beam radius of the total particles is 2.5 to 5 times smaller than the bore radius, as shown in Figure 6. Because of the narrow space for EMQ magnet in the DTs of the first tank, the hollow conductor coil used in J-Park DTL is a good option for our design owing to its compactness and nice field distribution.

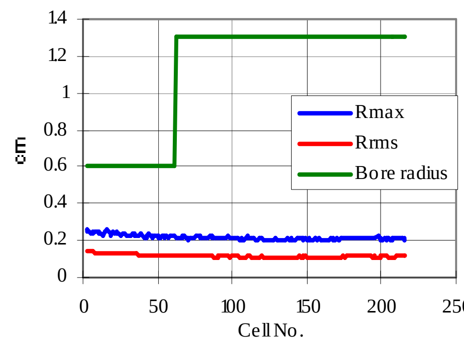

Figure 6: DT bore radius and rms/maximum beam radius along the DTL cell.

At such a high frequency, one of the most difficult issues is the quadrupole in the drift tube. The first quadrupole in the first tank has been designed with POISSON. The major design parameters are listed in Table 5.

Table 5: Major parameters of the first quadrupole in the first DTL tank

Magnet aperture diameter (mm)	15
Yoke out diameter (mm)	118
Core length (mm)	35
Magnetic field gradient (Tesla/m)	75
Field Quality	7.5×10^{-4}
Good field Region (mm)	±6.5
Effective length (mm)	40.96
Core material	Silicon steel 470
Thickness of steel leaf (mm)	0.5
Number of turns per pole	3.5
Excitation current (A) (maximum)	530
Inductance of coil (μH)	31.66
Conductor area (mm^2)	16
Resistance of coil (mΩ) @80□	9.08

RF POWER SOURCE

RF power source of TOSHIBA E3740A can provide 2.5 MW peak power in operation while its maximum output power is 3MW. Each DTL tank consumes 2 MW power in our design (1.3 times SUPERFISH cavity dissipated power and at 30mA beam). Five sets of RF power source will be applied in phase one for the RFQ and four DTL tanks respectively.

A new type of klystron HV power supply was proposed for CSNS linac[5]. It is an LC alternating current series resonance HV power supply. Its principle is, in fact, an old idea, but never applied for klystron HV power supply. Figure 7 is a diagram of this circuit. The 50Hz three-phase 380V power from the mains is converted to 25Hz one-phase 3.3 kV power to the LC resonance AC charging circuit through an IGBT frequency converter. 100 kV voltage on the capacitor bank becomes negative half wave after the diode, and then modulator provides a DC pulse discharge to the klystron anode, pulsing the klystron operation. The pulse flattop can be optimised by properly choosing the modulator switching time at a little bit before the bottom of the sinusoid wave, so that the pulse discharge decline is compensated by the rise of sinusoid curve. For example, for a 1ms pulse at 25 Hz, the flattop is very nice according to the simulation, as shown in Figure 8. This new scheme has no step-up high voltage transformers and multi-phase high-voltage rectifiers. One of obvious advantages of this new type HV power supply over other traditional or new ones is its simplicity, leading to an easy maintenance and low trip rate during operation. Of course, there are still some key technologies need to be developed to realize this new proposal: high current IGBT frequency converter and synchronous phase lock control of the AC charge and pulse DC discharge. Code simulations and small-scale verification experiments have demonstrated this new HV power supply in principle. However, to avoid any risk in developing this novel facility, a backup scheme of the conventional HV power supply as used in J-Parc linac is also under consideration.

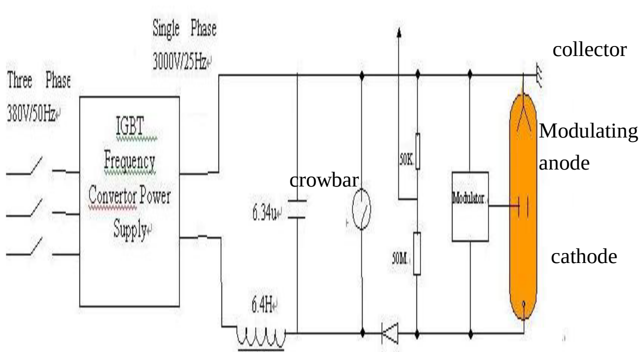

Figure 7: The proposed AC series resonance HV power supply for the klystron.

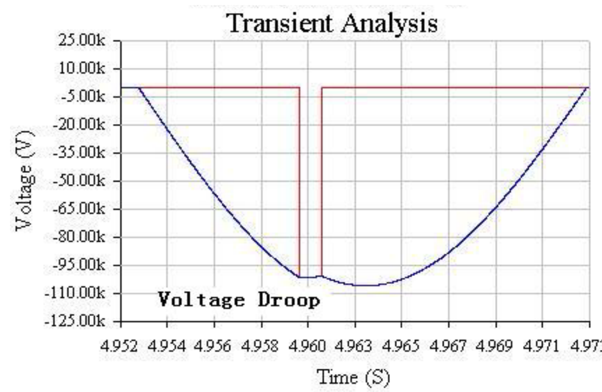

Figure 8: Flattop compensation by switching the DC pulse discharge at the moment a little before the bottom of sinusoid wave.

R&D ACTIVITIES

The key technologies in the CSNS linac need to be developed before the linac construction. H⁻ ion source, DTL and HV power supply are recognized as the major R&D items. Chinese Academy of Sciences provided a small budget for the R&D of CSNS key technology in the linac, RCS ring, target and scattering instruments, before CSNS project is formally launched.

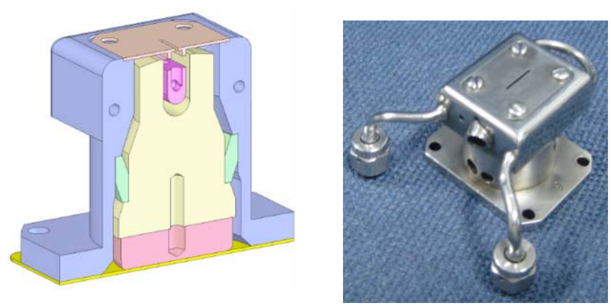

Figure 9: H^- Pinning source body.

We plan to build an H- ion source test stand at IHEP, as a research bench for the source technology development. Owing to the kind support from ISIS, we obtained a lot of knowledge about the Penning source used at ISIS. The same source will be set up in the test stand. The mechanic design and fabrication of the source body is under preparation. Figure 9 shows the design plot of the source body and a used one from ISIS.

We omitted RFQ from this R&D plan, because we have already built a similar RFQ in an ADS program[6], as shown in Figure 10. Initial commissioning of the ADS RFQ is encouraging for us to be optimism for the direct construction of CSNS RFQ without any R&D.

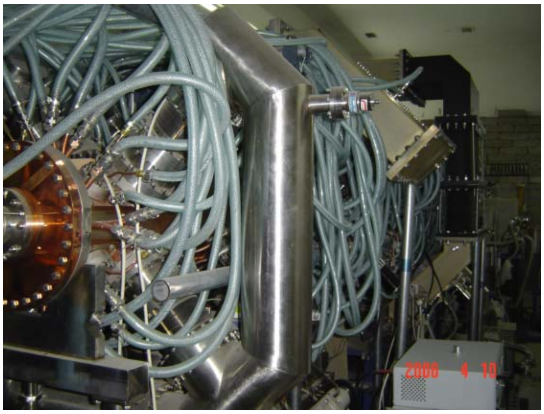

Figure 10: The ADS RFQ with a high-duty factor has been constructed at IHEP.

R&D of DTL is emphasised in the linac R&D program, even though IHEP built a 35 MeV DTL about 20 years ago, which was operated at 201 MHz. For the higher frequency DTL for CSNS, we are still facing some challenges and some R&D is demanded. A short tank made with explosive clad technology has been fabricated. On this test tank, all ports for vacuum grill, drift tube stem, stabilizer post and tuner are made, as shown in Figure 11. Laser welding of the drift tube has been tested with a good vacuum seal. To make the hollow conductor coil for EMQ, a test plate with a cooling water duct manufactured by periodic reverse electroforming technology has been successfully made.

Figure 11: A steel-copper clad short test tank with all type of ports made with explosive clad technology.

To develop the novel type of HV power supply, a small-scale circuit has been set up for demonstration of the principle. In this LC alternating current series resonance HV power supply, as shown in Figure 12, we have achieved 14 kV high voltage and 14A pulse current. By an adequate choice of the pulse trigger time, a very nice flattop has been obtained, as shown in Figure 13. Encouraged by this preliminary result, we are going to make a full-scale prototype in next step.

Figure 12: Small-scale demonstration apparatuses of the novel type of HV power supply.

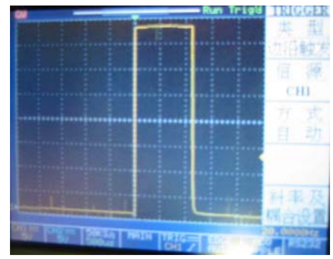

Figure 13: A nice flattop of the pulse generated by the small-scale LC alternating current series resonance HV power supply.

SUMMARY

CSNS linac has been designed for two phases with a final energy of 132MeV. For the 500kW beam power option, superconducting spoke cavity may be a good candidate for the energy range from 81 MeV to 230 MeV. We plan to start spoke cavity development after the optimisation of the DTL design is completed. One third of the first DTL tank will be manufactured in the R&D program by the end of 2007. A prototype of the novel HV power supply for the klystron will also be worked out.

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