# STATUS OF A HIGH CURRENT LINEAR ACCELERATOR AT CSNS

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## *Abstract*

China Spallation Neutron Source (CSNS) consists of an $H^-$ linac as an injector of a rapid cycling synchrotron of 1.6 GeV. The 324 MHz rf linac is designed with beam energy of 81 MeV and a peak current of 30 mA. The linac design and R&D are in progress. A test stand of a Penning ion source is under construction. RFQ technology has been developed in ADS study, with beam energy of 3.5 MeV, a peak current of 46 mA at 7% duty factor and a beam transmission rate more than 93%. The first segment of the DTL tank is under fabrication. A full-scale prototype of resonant high-voltage pulse power supply for klystron has been successfully demonstrated. This paper will introduce the design and R&D status of the linac.

## INTRODUCTION

The CSNS accelerator is the first large-scale, high-power accelerator project to be constructed in China[1]. CSNS accelerator mainly consists of an H- linac and a proton rapid cycling synchrotron. It 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, as schematically shown in Figure 1. The accelerator is designed to deliver a beam power of 120 kW with the upgrade capability up to 500 kW by raising the linac output energy and increasing the beam intensity, as listed in Table 1[2].

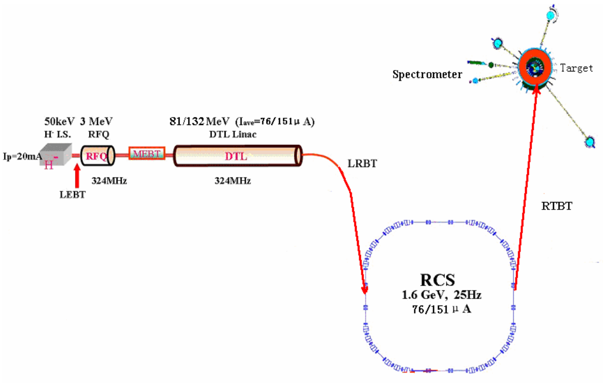

Figure 1: CSNS schematics.

This paper will introduce the design and R&D status of the linac. In the next section, physics design of the linac will be described. Then some R&D activities in the key technology, including ion source, RFQ, DTL and a new type of RF source power supply, will be briefly introduced.

Table 1: CSNS Primary Parameters in Baseline and Upgrade Phases

| Project phase | I | II | II’ |
|---|---|---|---|
| Beam ave. power, kW | 120 | 240 | 500 |
| Proton energy, GeV | 1.6 | | |
| Ave. current, $I$, μA | 76 | 151 | 315 |
| Repetition rate, Hz | 25 | | |
| Proton per pulse, $10^{13}$ | 1.88 | 3.76 | 7.83 |
| Pulse length, ns | <500 | | |
| Linac energy, MeV | 81 | 132 | 230 |
| Linac length, m | 50 | 76 | 86 |
| Linac rf freq. , MHz | 324 | | |
| Macro ave. $I$, mA | 15 | 30 | 40 |
| Macro duty factor, % | 1.1 | 1.1 | 1.7 |
| Ring circumference, m | 247 | 247 | 247 |
| Ring filling time, ms | 0.5 | 0.5 | 0.8 |
| Uncontroled loss, W/m | < 1 | | |

## CSNS LINAC PHYSICS DESIGN[3]

CSNS linac consists of an H- ion source, an LEBT, a 3MeV RFQ linac at 324MHz RF frequency, an MEBT and a 324MHz DTL linac. The output beam of the DTL linac is 81MeV with peak current of 15mA in the first phase. CSNS upgrade plan has been taken into the physics design. Beam pulse current will be increase to 30mA or even 40mA, while the beam energy will be increased to 132MeV or even 230MeV respectively so as to keep an acceptable space charge tune spread during the injection into the RCS. Some space in the linac-RCS beam line is now reserved for the additional accelerating structure for the upgraded CSNS linac.

For a low beam loss during the injection to the RCS, injected beam needs to be chopped for pre-bunching in the ring RF bucket. The chopped beam pulse structure is illustrated in Figure 2. To realize such a macro-pulse of 468ns, a pre-chopper is designed in the LEBT. In the case that the chopping is not clear, another fast chopper may be added in the MEBT.

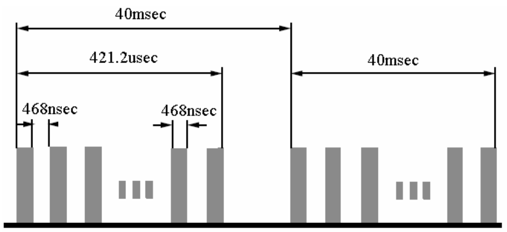

Figure 2: The linac beam pulse structure after chopping.

## $H^-$ Ion Source and LEBT

CSNS requires the ion source with a high reliability rather than a very high beam current for its first phase. Considering these factors as well as low cost, Penning surface source is preferred. The major design parameters are listed in Table 2. Beam dynamics in extraction was studied with PBGUN code.

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 |

The LEBT is mainly composed of three solenoids and an electrostatic chopper for beam matching and chopping, respectively, as shown in Figure 3.The beam from the extraction slit of the ion source is converted to a round beam at the entrance of the RFQ by the three solenoids. To reduce space charge effect, the LEBT is space charge neutralized except for the section of the electrostatic chopper after the last solenoid. Beam optics was studied with TRACE3-D code with 90% neutralization.

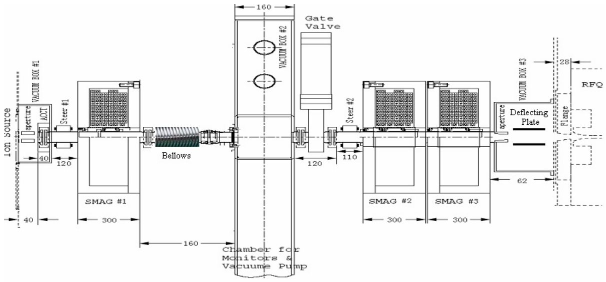

Figure 3: LEBT layout with three solenoids and an electrostatic chopper.

In our previous design, magnetic-alloy loaded induction cavity was design in the LEBT to decelerate the beam for chopping with the following RFQ longitudinal acceptance. Now we proposed to replace the induction cavity with an electrostatic deflector. Correspondingly, the chopper location shifts from the downstream of the first solenoid to the third solenoid, so that the space charge neutralization can be kept in the most space of the LEBT. The transversal acceptance of the RFQ will chop the deflected beam according to PARMTEQ simulation. In this figure, the beam at the RFQ entrance is deviated from the beam axis with x=2.65mm and x'=50mrad. At the exit of the RFQ, no particles emerged, which means the deflected beam is clearly chopped by the RFQ.

The deflector is designed with a length of 40mm and a gap of 30mm. The transit time through the deflector for a 50KeV beam is about 13ns. The applied voltage to generate the beam center deviation of x=2.65mm and x'=50mrad at the entrance of the RFQ is only 3.75kV. Dependence of the RFQ beam transmission on the applied deflecting voltage is plotted in Figure 5. During power source rise time and beam transit time, beam pulse will be partially deflected and thus, chopping becomes unclear. Increase of the deflecting voltage can alleviate this case. Voltage of 3.75kV is so low and so easy to get, and thus we are going to use a higher voltage power supply without much addition cost. In fact, the cost the electrostatic deflector system is much cheaper than our original induction cavity system that requires 150kW pulse power supply for the required decelerating voltage of 8.5kV, while the new deflector requires only 180W pulse power supply at the deflecting voltage of 4.5kV.

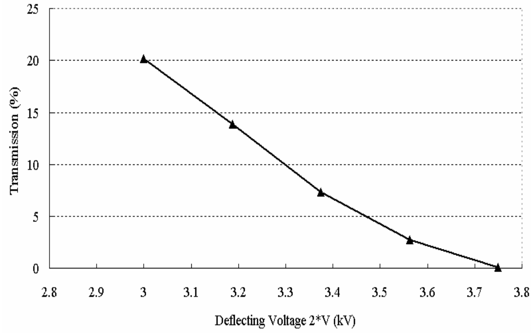

Figure 4: RFQ transmission rate versus deflector voltage.

Most of the deflected beam is lost at the entrance area of the RFQ without further acceleration. So the beam power dumped on the RFQ vanes is rather low, only 25W in average at 50% chopping rate.

## RFQ Design

Beam dynamics design with PARMTEQM code indicates a transmission rate higher than 97% for 40mA pulse current. The major design parameters are plotted in Figure 5.

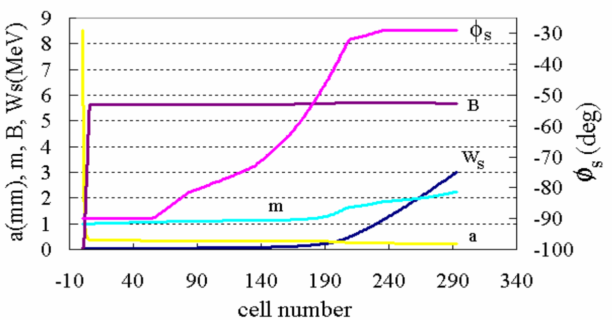

Figure 5: Major parameters along the RFQ.

Four-vane type structure is selected and the total vane length is 3.6m. The cavity is divided into two segments and then resonantly coupled together. Each segment consists two technological modules. Undercut and coupling cell have been carefully designed with 3D code. RF structure design study resulted an acceptable mode separation: the working quadrupole mode has a 3MHz gap from the nearest quadrupole mode and a 5.2MHz gap from the nearest dipole mode. For tuning of the resonant frequency and field distribution, 12 tuners are arranged in each quadrant, as shown in Figure 6. Structure thermal behavior has been studied and some cooling channels are design on the vanes and the cavity wall, as shown in Figure 6. The cooling water serves for two tasks: one for cavity cooling and another for frequency tuning during operation. Simulation indicates that the frequency shift sensitivity on the cooling water temperature is –5kHz/$^0$C.

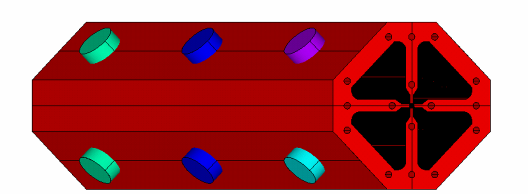

Figure 6: One technological module of the RFQ cavity.

## *MEBT Design*

The major tasks for MEBT are to chop the beam with a fast rise time for low beam loss and to match the beam from RFQ with DTL, again for low beam loss. However, meanwhile fulfilling these two tasks, some beam emittance growth and halo formation may be introduced, resulting in beam loss in the downstream beam transportation. In our case that the chopping task is not demanded in the MEBT in the first phase, we are going to leave a space for a RF chopper in the MEBT, and install it in the second phase for beam power upgrade. RF chopper is preferred so that we can share its successful experience in J-PARC linac.

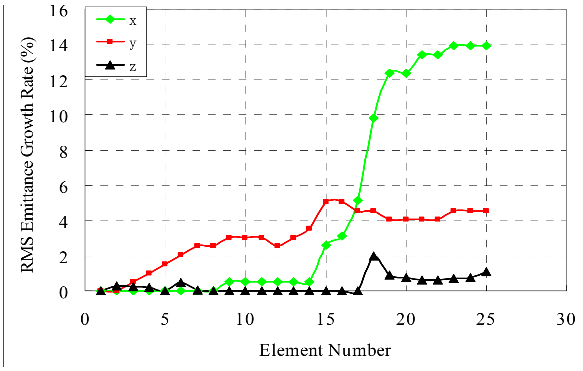

Figure 7: RMS emittance growth in three directions for 40mA beam in MEBT.

RMS emittance growth for 40mA beam is 14%, 4.5% and 1.1% in x, y and z directions respectively, as plotted in Figure 7. In this simulation, beam is chopped in x direction and beam envelope presents a large modulation. Emittance growth in x direction becomes half for half beam current of CSNS first phase linac. MEBT is recognized as most difficult section in the linac in terms of the control of emittance growth and halo formation, due to the combined function of beam chopping and beam matching in three directions.

## *DTL Design*

A conventional DTL was designed with four tanks for 81MeV Phase-I linac and additional three tanks for 132MeV Phase-II linac. Table 3 lists the major parameters of the seven tanks. 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. Cell tuning was hence applied in the tank design to restore the filed distribution back to the PARMILA input data[4] . One of our design goals is to make the RF power consumption in each tank almost the same so as to maximize the utilization efficiency of the RF power source.

Table 3: DTL Tank Parameters

| Tank number | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Output energy (MeV) | 21.76 | 41.65 | 61.28 | 80.77 | 98.86 | 115.8 | 132.2 |
| Length(m) | 7.99 | 8.34 | 8.5 | 8.85 | 8.69 | 8.57 | 8.67 |
| Number of cell | 61 | 34 | 29 | 26 | 23 | 21 | 20 |
| Cavity RF power (MW) | 1.41 | 1.41 | 1.39 | 1.45 | 1.45 | 1.45 | 1.49 |
| Total RF power (MW) | 1.97 | 2.01 | 1.98 | 2.03 | 1.99 | 1.96 | 1.98 |
| 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 |

FD lattice is chosen for strong focusing with a low envelope modulation, resulting in almost no emittance growth in multi-particle simulation. EMQ is preferred for convenient in beam commissioning. The physics design of the quadrupoles in the DTL drift tubes were conducted with POISSON code.

# KEY TECHNOLOGY DEVELOPMENT

R&D of the key technology in the CSNS linac was started three years ago with a small amount budget from Chinese Academy of Sciences and the site local government of Guangdong Province. It is crucial to make some prototypes for CSNS linac key technology because it has many challenges that we have never touched.

## *R&D of H Ion Source*

We have no experience to make such a high-current, low-emittance and long-lifetime H$^-$ ion source in China. Owing to the collaboration with ISIS, such an H$^-$ ion source is now under development. As a key part of the Penning source, a few source bodies, including discharge chamber and extractor, were fabricated and they were tested at ISIS ion source stand. The results are encouraging. We obtained a beam current of 55mA with beam pulse length of 500μm at 50Hz., as shown in Figure 8. The emittance measurement gave almost the same value as that of ISIS operating ion source. So we have reason to believe the source can meet for CSNS linac demand.

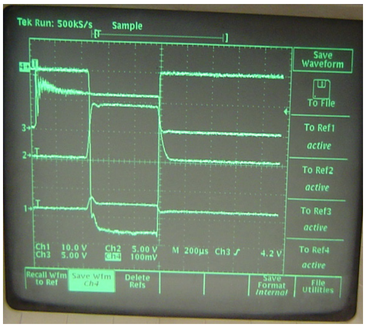

Figure 8: CSNS ion source body tested at ISIS with a beam current of 55mA.

An ion source test stand is now constructed at IHEP. Design of the source was completed (Figure 9) and all elements of the ion source have been fabricated. Assembly of the source is foreseen in recent. Various power sources, high voltage stand, vacuum system, water and gas cooling systems, as well as control system are all in progress.

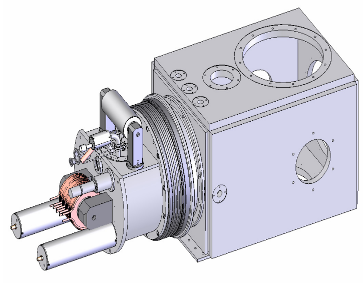

Figure 9: Design of the Penning $H^-$ source for CSNS.

## LEBT Chopper

To demonstrate the electrostatic chopper in the space charge neutralized LEBT, we are going to do some experiments on the existing RFQ developed for ADS study at IHEP. The LEBT of the RFQ linac has two solenoids and a beam collimator at the entrance of the RFQ. We will replace the collimator with an electrostatic chopper. It is found a couple of tapered electrostatic plates conforming the shape of the strongly focused beam at the entrance of the RFQ can provide more deflection to the beam at the same applied voltage. The pulse power source has been designed with two solid -state fast switches at the rise and fall ends of the pulse. The switch time is about 8ns at 6kV. A fast beam transformer will also added to the RFQ downstream beam line for beam diagnostics of the chopping effect. By this experiment we want to clarify our concerns: whether the RFQ vane will be damaged by the dumped beam, if spark occurs in the electrostatic chopper which is close to the space charge neutralized region, and if the chopping is fast enough for clear gaps. If it reaches a satisfactory result, we will consider the possibility to omit the MEBT so as to avoid beam degradation in it. In this case, a direct match design between the RFQ and DTL in CSNS linac will be considered.

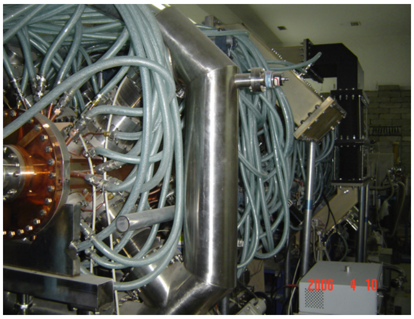

Figure 10. RFQ at 352 MHz for ADS Study.

## RFQ Developed for ADS Study

We have no R&D program for CSNS RFQ because we have built a high-current proton RFQ in our ADS research program. The ADS RFQ (Figure 10) has higher beam energy and beam current, and thus all the technology can be applied for CSNS RFQ. .

The major parameters of the ADS RFQ are listed in Table 4. This 3.5MeV RFQ is about 5 λ long. To address the longitudinal field stability, it is separated into two resonantly coupled segments. Each segment consists of two technological modules of nearly 1.2m in length. More detailed information about the design and development of the RFQ can be found in reference [5]. From Table 4 it noticed the duty factor is from 6% to 100%. It means the RFQ is designed with 100% duty in terms of the cavity and RF power source, but, as the first step, it was commissioned at 6% duty factor. In the end of this year, we are going to raise its duty factor to 15%. In fact, we have successfully finished high-power RF conditioning at this duty factor in recent. The initial commissioning result will be introduced in the following.

Table 4: RFQ Major Design Parameters

| | |
|---|---|
| Input Energy | 75keV |
| Output Energy | 3.5MeV |
| Peak Current | 50mA |
| Structure Type | 4 vane |
| Duty Factor | 6%-100% |
| RF Frequency | 352.2MHz |
| Maximum $E_s$ | 33MV/m |
| Beam Power | 170kW |
| Structure Power | 420kW |
| Total Power | 590kW |
| Total Length | 4.75 m |

In 2006 we started the beam commission at a low duty factor at IHEP. And gradually the duty factor reached 7% with 1.43ms pulse length at 50Hz. An output beam current of 46mA was obtained with an input beam current of 49mA, resulting in a beam transmission rate more than 93%, as shown in Figure 11. During the operation, the cooling water temperature was tightly controlled for fine tuning of the RFQ cavity resonant frequency. A digital RF control system based on FPGA was developed at IHEP and added to the RF system, which was provided by CERN by kind. With this new feedback system the operation stability became better in the case of long pulse and heavy beam loading. The RF amplitude and phase stability reached $\pm 1\%$ and $\pm 1^{0}$ respectively.

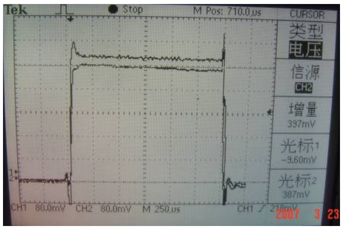

Figure 11: Input and output beam current of the RFQ.

### *R&D on DTL*

A prototype DTL tank was developed. It is the first module of the first tank. This module contains 28 drift tubes with a tank length of 2.9m. Before fabrication, several short tanks were tested to search for the feasible technology. Early attempts to fabricate DTL tank prototypes using the explosive-forming methods failed due to complications in fabrication of various ports on the tank. Periodic reverse electroforming method was successfully adopted by the domestic vendor in the tank fabrication. J-PARC type electromagnetic quadrupoles were fabricated with hollow conductor coils made with PR electroforming method. The drift tube is made of bulk copper and formed with electron-beam welding. Figure 12 shows the DTL tank under final machining of the drift tube holes, a hollow coil in drift tube and a bulk copper drift tube after EBW.

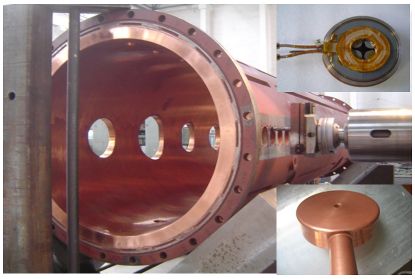

Figure 12: The DTL tank and quadrupole in drift tube of bulk copper.

For the magnetic measurement of the DTL quadrupole, various means, including Hall probe (HP), single stretched wire (SSW), rotating coil (RC), were adopted in order to verify the design specifications and fabrication technology. By carefully adjusting the DTL quadupole position relative to the harmonic coil in the rotating coil measurement, the dipole component can be controlled less than $6X10^{-4}$, and the magnetic center can be controlled within 0.003mm. More details can be found in a paper for this conference[6].

### *Prototype of Resonant HV Pulse Power Supply*

A new type AC series-resonant high-voltage pulse power supply was proposed by IHEP for the purpose to drive the klystron of the CSNS RF linac. The principle diagram is plotted in Figure 13. This new scheme has no step-up high voltage transformers and multi-phase high-voltage rectifiers. One of obvious advantages of this HV power supply over other types is its simplicity, leading to an easy maintenance and low trip rate during operation.

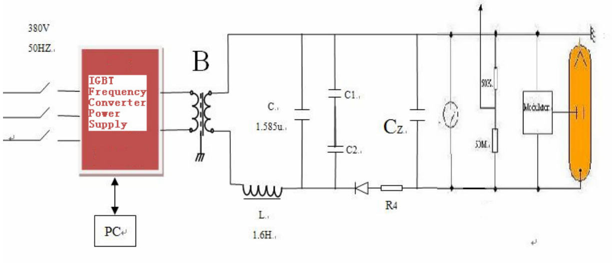

Figure 13: The proposed AC series resonance HV power supply for the klystron.

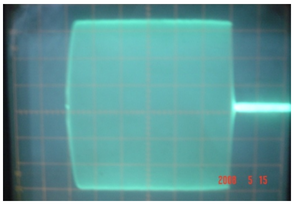

Figure 14: Klystron output pulse (1ms, 420kW) driven by the new prototype pulse power supply.

We have developed a full-scale prototype. Its highest output voltage reached 120 kV, with pulse discharging repetition frequency at 25 Hz or 50 Hz. We obtained an output power of 250 kW. Operation test together with the klystron of ADS RFQ was successful, with an AC-DC conversion efficiency up to 88%, a nice stability and flat-top, as shown in Figure 14. Consequently, the feasibility of the new power supply scheme was demonstrated. In the next step, we will strive for a more compact system.

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