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CSNS FRONT END AND LINAC COMMISSIONING

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Abstract

The China Spallation Neutron Source (CSNS) accelerator systems is designed to deliver a 1.6GeV, 100kW proton beam to a solid metal target for neutron scattering research. The accelerator consists of a front end, an 80MeV DTL linac, and a 1.6GeV Rapid Cycling Synchrotron (RCS). In August 2017 the first 1.6GeV proton beam hit on the tungsten target and production neutrons were monitored. This paper will report the major steps and results of the machine commissioning and beam commissioning of the CSNS front end and linac. In the first section, a brief introduction of the CSNS accelerator design and present status will be presented. Then, we will share our commissioning experience in the front end and the DTL linac in the following sections. Finally, a brief introduction to the linac energy upgrade design options are presented.

INTRODUCTION

After 6.5 years construction [1], the CSNS completed its project construction in March 2018. The bird view of the CSNS campus is shown in Fig. 1. In this photo, from right to left we can see the buildings of klystron gallery for the linac, target station and synchrotron hall.

Figure 1: CSNS site bird view.

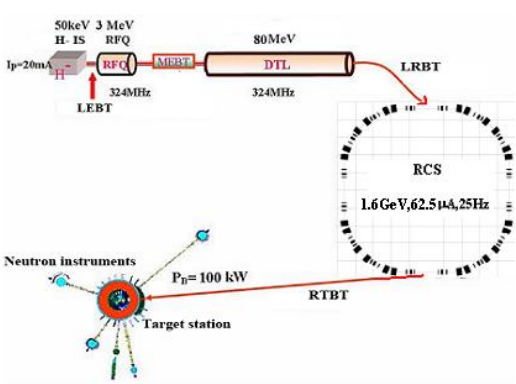

Figure 2: CSNS facility layout.

CSNS accelerator is designed with a beam power of 100kW in the phase-1 and reserved capability to upgrade the beam power to 500kW in Phase-2. The accelerator complex consists of an 80MeV H^- linac and a rapid cycling synchrotron of 1.6GeV at 25Hz repetition rate. CSNS facility layout is schematically plotted in Figure 2. Whole machine complex has been commissioned in the second half of 2017, with the first beam on the target in August 2017. Now the facility has been put into user operation at 20kW beam power. We are going to raise the power to 100kW within two years. This means the beam commissioning work will continue along with some user time about 7000 hours during the two years. As soon as we hit this target, phase-2 program for accelerator power upgrade to 500kW will be hopefully launched. For injecting 5-times more beam current into the RCS, it is necessary to raise linac beam energy to compensate for the space charge tune shift in the ring. The CSNS linac tunnel reserve a space of 80m long in the LRBT beam line for installing additional linac cavities for up to 300MeV output beam. Both RT and SC cavity are our present options for the linac section from 80MeV to 300MeV.

The present 80MeV linac consists of a Penning H^- ion source, a LEBT, a 3MeV RFQ powered by two tetrodes at 324MHz, a MEBT and a DTL linac with 4 tanks driven by 4 klystrons at 324MHz, as shown in Fig. 3.

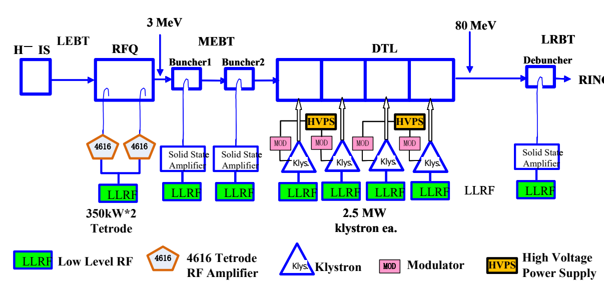

Figure3: Schematics of CSNS linac.

Beam chop at 50%-70% rate is performed by an electrostatic chopper at the end of the LEBT with space charge neutralization. There is no further chopping in the MEBT.

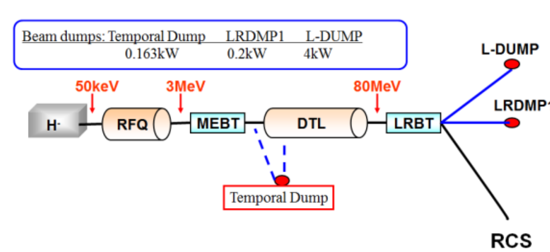

Figure 4: Linac beam dumps for beam commissioning.

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A series of beam diagnostics are arranged in the MEBT and LRBT for beam commissioning of the front end and the DTL tanks. A temporal diagnostic plate (D-plate) with a beam dump was used for the beam commissioning of the front end and the DTL tank-1, and two fixed beam dumps (LRDMP1 and L-DUMP) are used for DTL tank-2 to tank-4, as shown in Fig. 4.

FRONT END COMMISSIONING [2]

The CSNS front end started beam commissioning first and finished step by step. Finally we achieved design specification, as listed in Table 1.

Table 1: Front End Beam Commissioning Results

	Design	Measured
Ion source current [mA]	20	31
MEBT peak current [mA]	15	17
RFQ beam energy [MeV]	3.0258	3.02±0.01
Chopping rat e [%]	50	50
Chopper rise time [ns]	20	10
Pulse width [μs]	420	500
Pulse repetition rate [Hz]	25	25
Emittance (π mm mrad)	0.22	0.27

Ion Source and LEBT

Thanks to the nice cooperation with ISIS, we developed an H^- Penning source. In Oct. 2014 the ion source, as the first CSNS facility, was moved into the linac tunnel after long-term beam commissioning in laboratory. It initially run at lower duty of 50μs at 1Hz and then gradually increase the duty to the design value of 500μs at 25Hz. The extracted H^- beam current can reach more than 30mA at the exit of LEBT, which is sufficient for our phase-1 operation. The real challenge is long-term stability, especially at low duty operation. Tightly controlling Cesium deposition on the extractor helps a lot for better stability. In addition to some other improvements including power supply, extractor and penning magnet, now the beam interruption duration becomes very short: about tens of ms for each spark, and the spark numbers are several times a day, satisfying user operation, as shown in Fig. 5.

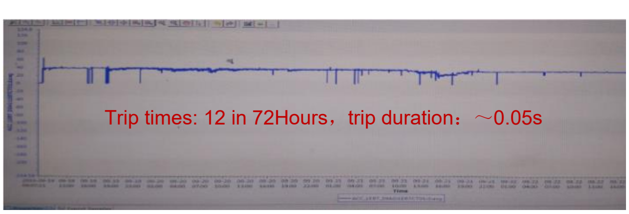

Figure 5: Record of the ion source trip rate in 72 Hours after improvement.

LEBT is a space-charge neutralized beam line for controlling beam emittance growth. Three solenoids focus the beam in two transversal directions to match the beam with the RFQ acceptance. And also a larger emittance (0.75-0.9πmm.mrad) from ion source is collimated to 0.2πmm.mrad for matching with RFQ acceptance. At the downstream end of the LEBT, there is a pair of electrostatic deflecting plates as a beam chopper. The chopper does not disturb the space-charge neutralization in the LEBT owing to the screening plate with a small beam hole. We require it must have fast rise time because there is no further chopping in the MEBT. The achieved rise time of the beam is about 10ns, as we can see from Figure 6. In this figure, one can see the rise time is about 3-4 periods of 324MHz and one period last about 3ns. The chopped beam is dumped on the entrance plate of RFQ and partially into RFQ cavity.

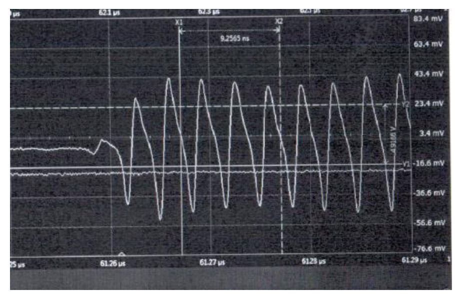

Figure 6: Measured beam rise time about 10ns after LEBT chopper.

RFQ and MEBT

RFQ cavity is a four-vane structure at 324MHz RF frequency. Two tetrodes powered the cavity through two power couplers with total power of 450kW pulse power. Due to the trouble of water leakage of the linac tunnel RFQ tunnel installation was delayed about one year. For catching up the schedule, we installed the RFQ and its RF power supply, as well as water cooling system in our laboratory and conducted high power conditioning. After 11 days conditioning with RF pulse length of 700μs at 25Hz, the RF power reached 480kW and the cavity gradually became almost no spark, as shown in Fig.7. Before this high power conditioning, the four sections of the RFQ cavity had been aligned and bead-pulling measurement had been conducted for field tuning. Two MEBT buncher cavities together with their solid-state power sources were also conducted high power conditioning.

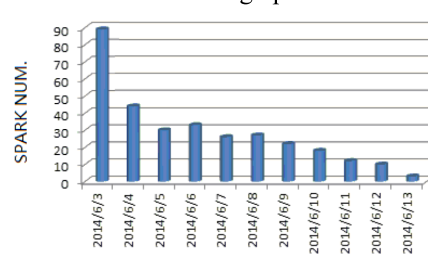

Figure 7: Spark number of RFQ cavity declined during high-power conditioning of 11 days.

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The RFQ was reinstalled in the linac tunnel in Feb. 2015. RFQ high-power conditioning was conducted again. This time it took only 5 days owing to the previous work. The first beam came then from the RFQ in April 2015 at low duty factor of 50μs pulse length at 1Hz for initial beam commissioning of the RFQ. Pulse length was doubled for beam chopping experiment. Then we returned to RFQ beam commissioning at high duty factor up to 500μs at 25Hz. Beam transmission rate was measured with a pair of CTs at the entrance and exit of the RFQ. Initially, the transmission rate was not so high as our expectation, around 75% - 85%. The reason is the beam emittance from the ion source is much larger than the acceptance of the RFQ. To deal with this issue, a collimator was added into LEBT and then the best transmission rate can reach up to 94%, as shown in Fig. 8. As a result the LEBT transmission rate becomes low.

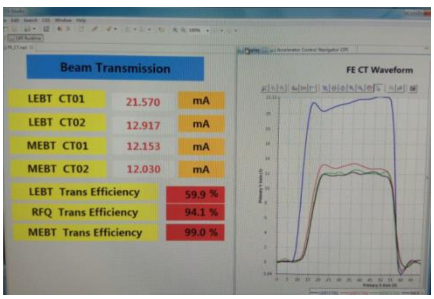

Figure 8: The best beam transmission rate of the RFQ.

After the initial independent beam commissioning, RFQ run a long period for beam commissioning of the following DTL tanks, RCS, as well as target and neutron spectrometers. It also serves for user operation since this year. After more than two years' operation, its performance gradually becomes worse in term of the stability, especially during the user operation with beam power of 20kW. Serious spark happened frequently and we had to conduct high power conditioning again and again. It seriously interrupted user operation. After excluding the vacuum problem, we realized that the chopped beam dumped onto the RFQ vane may be most susceptive issue. Even though the thermal damage is neglect according to calculation, the sputtering effect may make the roughness of the vane tip getting worse. Two measures have been taken: (1) turn the chopper 45 degree around beam axis so that the deflected beam can go through the gap between the vanes and then hit on the cavity wall surface, instead of the vane surface; (2) Add a smaller aperture in the entrance hole to limit beam into the cavity. After implement of these measures and improvement of high power conditioning strategy, the RFQ runs much more stable in recent.

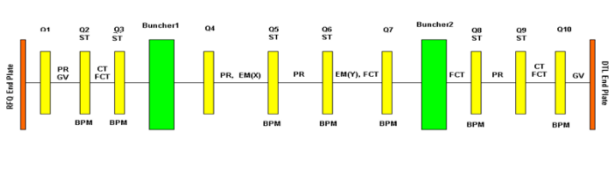

Figure 9: MEBT major elements.

The MEBT consist of 10 quadrupoles for transversal matching of the beam with DTL, two bunchers for longitudinal direction matching, 6 steering magnets for orbit correction and some beam diagnostics, such as BPM, PR, CT, FCT, EM and WS, as shown in Figure 9.

Four wire scanners are located along the MEBT to measure the Twiss parameters of the RFQ output beam. Table 2 shows the comparison of the design values (with PARMTEQM[3]) and the measured values. The Twiss parameters in the horizontal plane are agreed well with the simulated values, while those in the vertical plane are somewhat deviated from the simulated values. The emittance also agrees well in both directions. To confirm the measured results, we use PARMILA[4] code and the measured data in y-direction as input to simulate beam transmission to the location of the double-slit emittance monitor, as shown on the left of Fig.10. The measure emittance on the right of Fig.10 indicates a good agreement with the simulation.

Table 2: RFQ Output Twiss Parameters (I=10mA)

	α	β [mm/mrad]	Emittance rms, normalized [π mm mrad]
Horizontal			
Measured	*-1.716*	0.256	0.215
Simulated	*-1.773*	0.233	0.215
Vertical			
Measured	*1.944*	0.173	0.211
Simulated	*0.639*	0.074	0.212

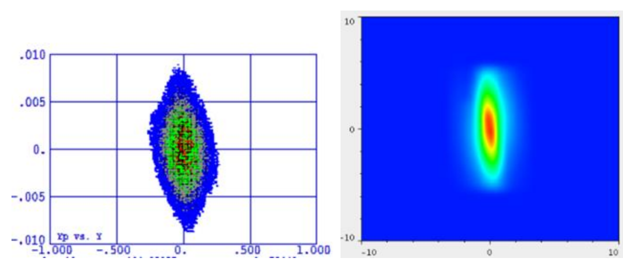

Figure 10: Simulated and measured emittance in y-direction in MEBT.

As the beam phase space in two directions is almost the same as the design values, we set all 10 quadrupoles in MEBT according to the design. The resulted beam transmission rate of the MEBT can easily reach 100% and a nice matching with the following DTL. During DTL beam commissioning, we majorly tune the orbit correctors and the two bunchers in the MEBT. The phase scan method is used for finding the RF set points of two bunchers. The beam phase is provided by Fast Current Transforms (FCTs) which are located at the downstream of the measured cavity. For three different RF amplitudes, three sets of measured phase differences vs. cavity phase were recorded, as shown in Fig. 11 with experimental data in solid curve and simulation results in circles. The red curve was taken at nominal RF amplitude, the blue one at 25% below nominal, and the black one at 25%

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above nominal. The buncher setting phase is located at the intersection of the three curves. At this point, the amplitude of the FCTs' signal was observed maximum.

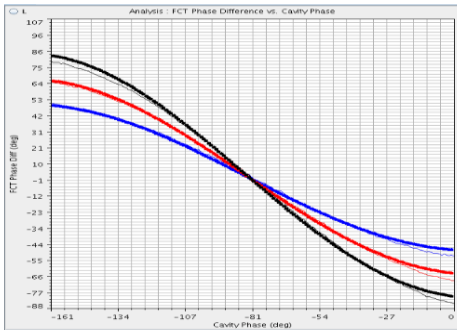

Figure 11: Measured phase differences (degrees) between two FCTs as functions of the buncher01 cavity phase.

DTL LINAC

The DTL consists of four tanks, and each tank is fed by a klystron power source. Beam commissioning of the 80MeV DTL majorly took three steps. Firstly, when the first tank had been installed together with its RF power source, the following three tanks were not ready for installation. So the first tank conducted beam commissioning with our reformed D-plate ever used for the front end. Secondly after we installed the rest three tanks beam commissioning was performed for the second and the third tanks. Through LRBT, the beam was initially sent to LRDMP1 for low duty factor beam and beam was measured with LRBT beam diagnostics. To catch up our schedule, we initiated RCS beam commissioning with 61MeV beam output from the third DTL tank and successfully obtained the first neutron beam from the target with 61MeV injection to the RCS. At this time, the fourth tank was only powered for quadrupoles in drift tubes, but no RF power at all, due to lack of klystron which was sent back to manufacture for repair. Finally in January 2018 we could start tank-4 beam commissioning and thus whole linac beam commissioning at 80MeV output beam energy.

The DTL transverse focusing was arranged in a FFDD lattice utilizing electromagnetic quadrupoles. Because no drift tube is empty, diagnostics have to be imbedded between tanks. After each tank, a FCT and a CT were installed to monitor beam phase and current. Between DTL 3 and DTL 4, a Beam Position Monitor (BPM) was added for monitoring beam orbit. A pair of FCTs were used for each tank, as shown in Fig.12, for phase difference measurement in RF phase scan.

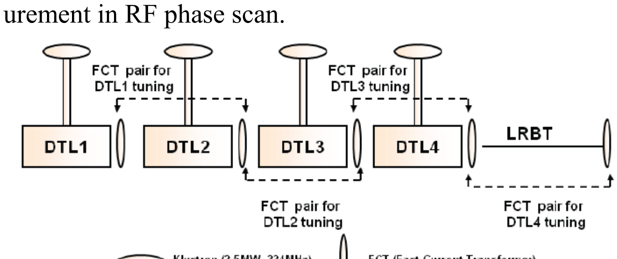

Figure 12: FCT pair for RF phase scan of each tank.

For DTL tanks, it is essential to find the correct tank RF field amplitude and phase to minimize energy spread and mismatch, which are highly required by the following RCS. A method called "phase scan signature matching" was adopted for determining the RF set points of DTL tanks [5]. The method involves varying an RF cavity amplitude and phase settings over a fairly large range and comparing the measured downstream beam phase response "signatures" to model predictions. A software application called PASTA was applied for phase scan and analysis [6]. The RF amplitude, relative phase of beam and the input energy were used as variables in model fitting.

Time of flight measurement was also performed. For each tank, three FCTs were used to form two short pairs and a long pair. The two short pairs were used to determine the number of integer periods and the long pair was used to calculate beam energy. The beam energy calculated with TOF and phase scan are summarized in Table 3. The deviation of measured beam energy from the design value is less than 1%.

Table 3: Beam Energy From Two Methods

	TOF [MeV]	Phase scan [MeV]	Design [MeV]
DTL1	21.73±0.01	21.67	21.67
DTL2	41.54±0.01	41.45	41.41
DTL3	61.36±0.02	61.05	61.07
DTL4	80.34±0.01	80.17	80.09

During DTL commissioning a great challenge came from water leakage of the quadrupole coil in a drift tube into the cavity of the first tank. A new drift tube was manufactured for replacing the failure one, however we realized it would be very difficult to do so with both time risk and quality risk. The commissioning schedule as well as the project schedule would certainly be affected seriously. Another way is to cut-off magnet power supply and the coil cooling water, and seal the inlet of the coil cooling water. In this way the focusing lattice is seriously perturbed and beam simulations indicated an obvious beam loss. To deal with this issue, we modified the focusing lattice so as to compensate for the lost function of the quadrupole. More details can be found in this proceedings [7]. After the change of the cable connections, a new lattice is formed. Linac beam commissioning resumed and beam transmission rate keeps nearly 100%, confirming the new lattice can fully compensate for the cut-off quadrupole, the same as the simulation expectation.

LINAC UPGRADE OPTIONS

In the linac physics design we leave the possibility for increase of the beam average current 5-times, and the linac tunnel also leaves a space of 85m long for installation of more cavities for beam energy up 300MeV in future. Under this space limitation, we find both room temperature cavity and superconducting cavity can accelerate beam to 300MeV from the present 80MeV.

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In our present design, room temperature cavity will use PI-mode structure which has successfully operated in LINAC-4 of LHC upgrade program [8]. PIMS cavity keeps the same RF frequency as the DTL.

Spoke cavity is a candidate for superconducting structure. Double spoke with geometrical beta 0.5 at 324MHz is designed. A similar cavity at 325MHz has been developed for ADS project at IHEP [9]. The vertical test has been conducted with promising performance. Table 4 lists the major design parameters for RT and SC structures respectively for CSNS linac energy upgrade.

Table 4: Major Design Parameters of RT Structure and SC Structure for CSNS Linac Energy Upgrade

Parameters	RT PIMS	SC Spoke
Frequency/MHz	324	324
Energy range/MeV	80-306	80-306
Length/m	83	82.9
Cavity number	40	57
Module number	20	19
Cells per cavity	7	3
Energy gain /cavity/MeV	4.3~6.65	3.7
Quad. number	42	41
Lattice structure	FD	R^3FD
Aperture/mm	40	60
Cavity length/mm	1273~2119	710
Fill factor	0.8	0.5
Cavity diameter/mm	610	512
E0/MV/m	3.7 – 4.0 (<1.8Kilp)	5.2
Voltage/MV (E_{peak}=30MV/m)		3.9
B_{peak} /mT (E_{peak}=30MV/m)		73

CONCLUSION

The CSNS front end and DTL linac have been successfully commissioned. The peak current and beam energy have achieved the design goal. The rise time of the LEBT chopper is about 10ns. Beam transmission rate of the RFQ is around 92%. DTL has a higher beam transmission rate about 98%. Linac beam was sent to RCS ring for RCS, target, neutron spectrometer commissioning. Now the CSNS construction project has been completed. Machine is put into user operation at beam power of more than 20kW. Meanwhile, we will raise beam power to 100kW, the design specification of the first phase of CSNS project. For the second phase, beam power will rise to 500kW. For this target, CSNS linac will increase its beam energy up to 300MeV. Now we designed both RT and SC structure for linac upgrade.

ACKNOWLEDGEMENT

Thanks to the great efforts of all the members of CSNS Accelerator Division the beam commissioning of CSNS front end and DTL has achieved a full success.

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