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OPERATION STATUS AND UPGRADE OF CSNS

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Abstract

China Spallation Neutron Source (CSNS) accelerator complex consists of a front end, an 80MeV DTL linac, and a 1.6GeV Rapid Cycling Synchrotron (RCS).It is designed with a beam power of 100kW in the first phase and reserves upgrade capability to 500kW in the second phase. It has completed initial beam commissioning and has started user operation in 2018. And meanwhile the beam power is quickly going up from the initially above 10kW to 50kW during the user operation, and we can foresee that the designed beam power of 100 kW can be reached in the next year. This paper gives the recent status of beam commissioning, beam power ramping, user operation, as well as future upgrade plan to increase the beam power up to 500 kW.

INTRODUCTION

The CSNS accelerator provides proton beam pulses of 1.6GeV kinetic energy at 25Hz repetition rate to a solid metal target to produce spallation neutrons for neutron scattering experiment [1]. A schematic layout of CSNS phase-1 complex is shown in Figure 1. In the phase one, an ion source produces a peak current of 25mA H- beam. RFQ linac bunches and accelerates it to 3MeV. DTL linac raises the beam energy to 80MeV. After H- beam is converted to proton beam via a stripping foil, the Rapid Cycling Synchrotron (RCS) accumulates and accelerates the proton beam to 1.6GeV before extracting it to the target. 20 neutron channels are designed surrounding the target, but only 3 spectrometers has been built in the first phase due to limited budget. The beam power is 100kW on the target in the first phase. The accelerator will be upgraded to 500kW beam power at the same repetition rate and the same output energy in the second phase by increasing the average beam current 5 times. Table 1 lists the major parameters in the two phases.

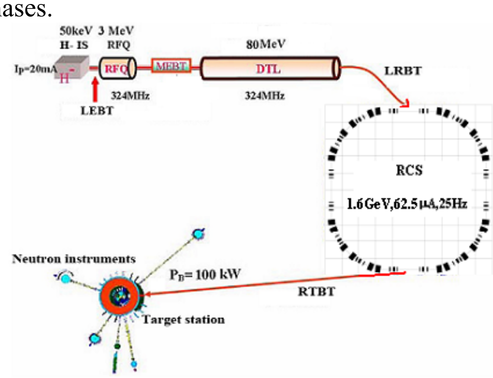

Figure 1: Schematics of the CSNS complex.

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Table1: CSNS Design Parameters

Project Phase	**I**	**II**
Beam Power on target [kW]	100	500
Proton energy [GeV]	1.6	1.6
Average beam current [μ A]	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	40
Macropulse duty factor	1.0	1.7
RCS circumference [m]	228	228
RCS harmonic number	2	2
RCS Acceptance [πmm-mrad]	540	540
Target Material	Tungsten	Tungsten

After 6.5 years construction [2], the CSNS completed its project construction in March 2018. The bird view of the CSNS campus is shown in Fig. 2. In this photo, from right to left we can see the buildings of klystron gallery for the linac, target station and synchrotron hall.

Figure 2: CSNS site bird view.

Whole machine complex has been commissioned in the second half of 2017, with the first beam on the target in August 2017. Since March 2018, the facility has been put into user operation while the beam power is increasing from initial 20kW to present 50kW. Accelerator beam availability is higher than 90%. We are going to raise the power to 100kW in the next year. After 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 85m long in the LRBT beam line for installing additional SC cavities for up to 300MeV output beam.

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In the following sections, we will firstly present a briefly recall of the accelerator commissioning. Then we will describe the status of the user operation and beam power growth. Finally we are going to foresee the beam power upgrade plan.

ACCELERATOR COMMISSIONING

We conducted CSNS accelerator beam commissioning in three major steps: first the frontend, then the DTL and LRBT, and finally the RCS and RTBT.

Frontend

The CSNS front end started beam commissioning first when the linac tunnel is useable. In Oct. 2014 the ion source, as the first CSNS facility, was moved into the linac tunnel. 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.

LEBT is a space-charge neutralized beam line for controlling beam emittance growth. 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 3. 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.

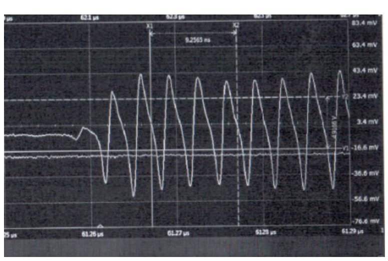

Figure 3: Measured beam rise time about 10ns after LEBT chopper.

The first beam came 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 as 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. 4. As a result the LEBT transmission rate becomes low.

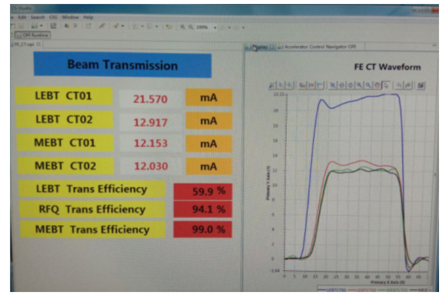

Figure 4: The best beam transmission rate of the RFQ.

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 emittance agrees well in both directions. The measure emittance on the right of Fig.5 indicates a good agreement with the simulation one on left. 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 have a nice matching with the following DTL.

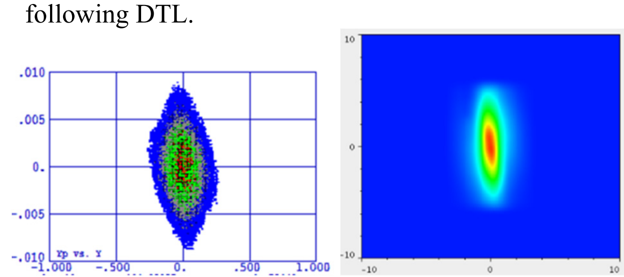

Figure 5: Simulated and measured emittance in y-direction in MEBT.

DTL Linac

Beam commissioning of the 80MeV DTL majorly took three steps. Firstly, 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.

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 [4].

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A software application called PASTA was applied for phase scan and analysis [5]. 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 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%. Four DTL tanks have a beam transmission rate nearly 100%.

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

RCS ring

The RCS beam commissioning preceded in three steps: firstly, commissioned in DC mode, and then AC mode at single shot, and finally AC mode at 25Hz [6].

In DC mode RCS functions like a storage ring without acceleration. Linac beam of 61MeV was firstly injected into the ring on 31st May 2017 and beam successfully accumulated on the same day with the accumulated particles of 1/3 design value with a lifetime longer than 40ms. Dipole magnets are tuned for matching with the injected beam energy of 61.07MeV by observing the COD at dispersion region. Beam painting curve at injection was optimized. RF bunching was also optimized by tuning the RF frequency and phase. Fig. 6 shows the measured bunch length changes before and after RF tuning. After parameters optimization, beam could pass the ring almost 100% transmission rate in one period time of 40ms. Tune was measured with (4.856,4.780), which has a good agreement with the nominal value (4.853,4.782).

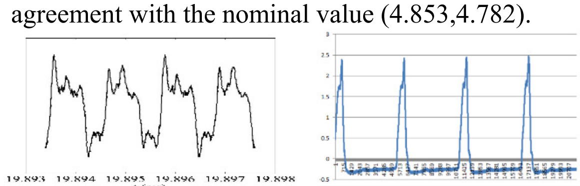

Figure 6: Bunching effect before(left) and after(right) RF optimization.

The case became more complex when we turned into single shot AC mode. July 2017 RCS AC mode beam commissioning started, but the first shot of beam survives only for 4ms， not reaching the final energy. We found the timing of the dipole magnet field is not coincident with RF field. After fine tuning, a nice synchronization between dipole field and RF field reached. Fig. 7 shows the beam current of the RCS before(upper) and after(lower) fine timing tuning. Even though, after timing tuning, the beam could be accelerated to 1.6GeV and extracted from the ring, there is still obvious beam loss (about 30%) during the acceleration, as we can see from the lower plot of Fig. 7. We identified the major reason for beam loss came from the mismatch between the dipole field pattern and RF parameter variation pattern, including RF magnitude, frequency and phase. The mismatch can be observed from the synchronous phase oscillation during acceleration. After solving these problems, we further fine tune the magnet field pattern to more close to a standard sinusoid curve. It was achieved by wave form compensation method developed by us for magnet power supply. In addition to these efforts, we also conducted many other optimizations, such as searching better working point, COD correction, injection painting scheme, and so on.

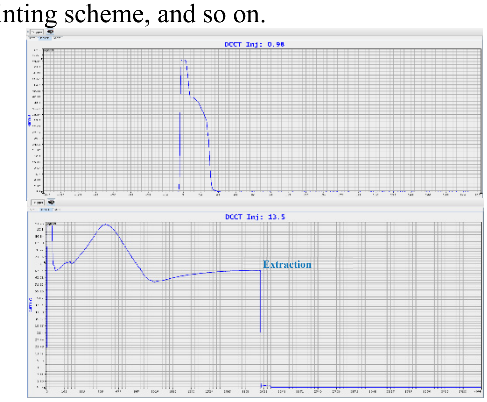

Figure 7: Beam current in RCS before(upper) and after (lower) timing tuning.

In July 2017 RCS reached 100% beam transmission, as shown in Fig.8 (upper) and in August 2017 the first proton beam hit on the target and produced spallation neutrons, as shown in Fig.8 (lower). After the final klystron was repaired and ready for the fourth tank of the DTL linac, we conducted the beam commissioning again at 81MeV beam injection to the RCS in January 2018.

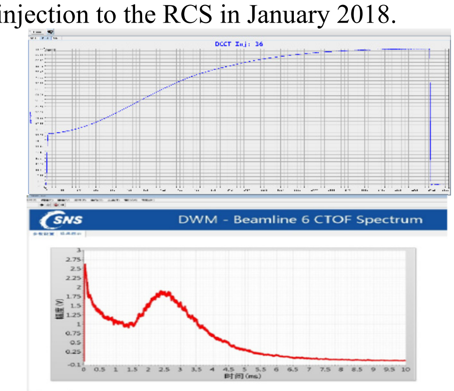

Figure 8: RCS beam transmission reached 100% (upper) and the first neutrons were generated on the target of CSNS(lower).

USER OPERATION

After successful beam commissioning, in March 2018 CSNS opens for user operation. Since then, we put many efforts both on the stable operation and beam power increase. In 2018 the total user beam time is about 2800 hours. We plan to provide user beam 3600 hours in 2019. Fig. 9 records the beam power history from beam commissioning

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up to now. Overview on this plot we can see that the beam power rise quickly from 20kW to 50kW for user, and the stability has been much more improved since the 2018 summer shut down for maintenance. The neutron beam availability is not so good if we record all period since the beginning of the user operation up to now. It is about 80%. But it rises to 91% if we record the period from the last summer shutdown up to now. The major contributor to the down time of the accelerator came from the RFQ, including RFQ cavity and its RF power source, as we can find in Fig. 10.

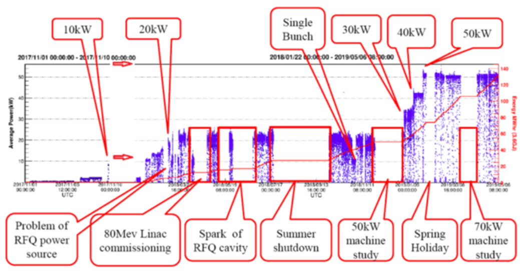

Figure 9: Overview of the beam power increase.

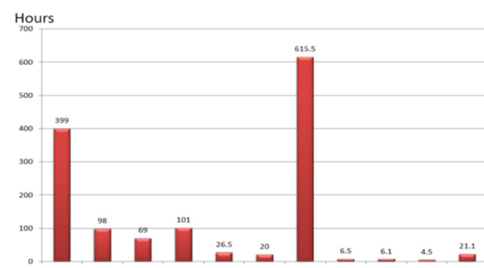

Figure 10: Statistic of the down time since Jan. 2018.

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 2018. 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 worse, as shown in Fig. 11. Two measures have been taken [7]: (1) turn the LEBT 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 size into the cavity. After implement of these measures and improvement of high power conditioning strategy, the RFQ runs much more stable.

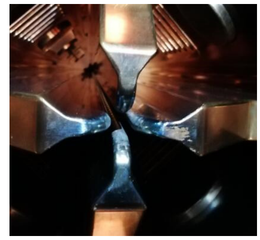

Figure 11: RFQ vane at the entrance before LEBT chopper rotation.

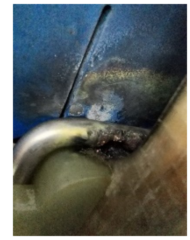

Figure 12: Discharge happened in a RCS quadrupole magnet.

In early of this year, we replaced the tetrode RF power source for RFQ with a decommissioned klystron from DTL as we bought two redundant klystrons. The retired klystron from DTL can sufficiently meet the power demand of the RFQ. Since then, RF power stability for RFQ get a lot of improvement. However, the RF power source for the linac now still remains the major contributor to the down time.

Except for the linac, RCS also had some troubles. For instance, high voltage discharge caused insulation failures of one RCS quadrupole magnet due to short distance between the magnet coil and its U-type fixture, as we can see from Fig. 12. To avoid the similar failure, all the U-type fixtures of the quadrupole magnets were replaced by the new ones with increased insulation distance.

With all efforts to improve the stability, the machine performance is getting better. Next we are going to replace the Panning H^- source with RF-driving ion source, expecting more stable, higher current and smaller emittance. We had started machine study with beam power of 70kW last month. We expect to increase the beam power to 80kW in 2019.

UPGRADE PLAN

Upgrade program in the CSNS accelerator is majorly related to the linac energy increase to compensate for space charge effect in RCS when beam current becomes 5 time higher, replacement of the present injection section with new one for higher injection energy, and additional 2nd harmonic cavities for better bunching factor, as indicated in Fig.13 in red-word parts.

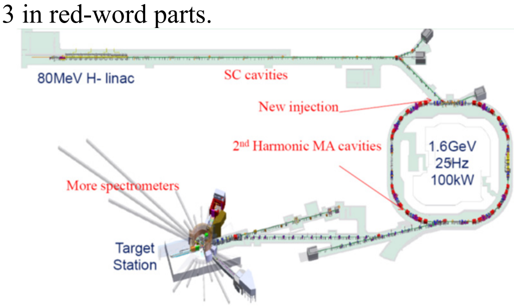

Figure 13: CSNS phase-2 major upgrade items (in red).

In the linac physics design we reserved the possibility for increase of the beam average current 5-times, and the linac tunnel also leaves a space of 85m long for installation

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of more cavities for beam energy up 300MeV in future. Superconducting cavity is decided to be used for raising the linac beam energy.

We have two options for the S.C. linac section. Full spoke cavity is a candidate or spoke plus elliptical cavity. Fig.14 plots the two schemes. For full spoke option, we are going to use double spoke with geometrical beta 0.5 at 324MHz. To reach 306 MeV beam energy, we will install 19 cryomodules in 83m tunnel. A similar cavity at 325MHz has been developed for ADS project at IHEP [8], as shown in Fig. 15. The vertical test has been conducted with promising performance. Only one type of cavity is utilized in the option and thus looks not so complex. But option-two uses only 61.5m long to reach 303 MeV beam energy, and thus leave more space for possibly more cavities as redundancy, or for higher energy. This medium beta elliptical cavity has also been developed at IHEP [8], as shown in Fig. 16.

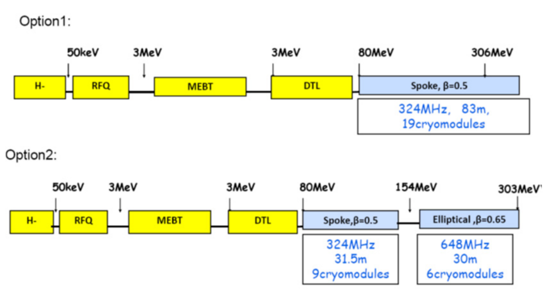

Figure 14 : Two options of the S.C. linac.

Figure 15 : S.C. Spoke cavities developed at IHEP.

Figure 16 : S.C. elliptical cavity developed at IHEP.

In the RCS, presently we use ferrite-loaded cavity with RF voltage of 27 kV in a cavity of 2.7m long. Due to limit space, we can only add 2nd harmonic cavity with RF voltage higher than 36 kV in a length 1.8m. In this case ferrite is not userable and we must adopt Magnetic Alloy (MA) as the loaded metterial for the new cavity. Even though MA has successfully applied in J-PARC RCS, we have to develop the MA strip due to export ban from Japan. Fig. 17 shows the measurement(left) and its results(right) of the domestically developed MA strips [9]. It indicates a good property very close to HITACH products FT3M. High power test will be conducted in recent.

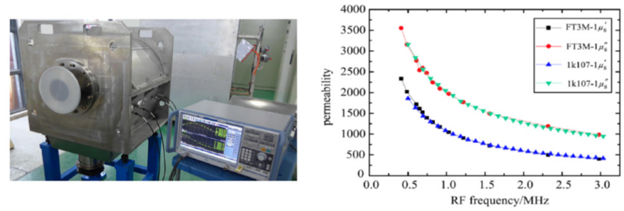

Figure 17 : Measurement(upper) of the domestically developed MA strip and its results(lower) in comparison with HITACHI products FT3M.

CONCLUSIONS

The CSNS accelerator complex has been successfully commissioned. The peak current and beam energy have achieved the design goal. Now the CSNS construction project has been completed. Machine is put into user operation at beam power of more than 50kW. 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.

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REFERENCES

[1] Shinian Fu, Hesheng Chen, *et al.*, Status of CSNS Project, IPAC2013, Shanghai, 2013.

[2] S. Wang, S. Fu, J. Zhang, Construction and Beam Commissioning of CSNS Accelerators, *Proc. of IPAC2016*, Bushan, May 2016, p.47

[3] K.R.Crandall et al., "RFQ Design Codes", LA-UR-96-1836.

[4] T.L Owens *et al.*, "Phase Scan Signature Matching for Linac Tuning", *Particle Accelerators*, 1994, Vol98, p.169.

[5] J.Galambos et al., "PASTA-An RF Phase Scan and Tuning Application", *Proceedings of PAC2005*, Knoxville, Tennessee.

[6] S. Y. Xu, *et al.*, "Beam Commissioning Experience of CSNS/RCS", presented at the Int. Particle Accelerator Conf. (IPAC19), Melbourne, Australia, May 2019, paper MOPTS068, this conference.

[7] H.F.Ouyang, *et al.*, "The Operation Status of CSNS Frontend", presented at the Int. Particle Accelerator Conf. (IPAC19), Melbourne, Australia, May 2019, paper TUPTS038, this conference.

[8] Zhongquan Li,Weimin Pan, Yunlong Chi *et.al.*, Development of spoke cavity for main Linac of China ADS, in Proceedings of SRF2017, Lanzhou, China, 2017.

[9] B. Wu, *et al.*, "MA RF Cavity Design and Simulation for CSNS/RCS Upgrade Project", presented at the Int. Particle Accelerator Conf. (IPAC19), Melbourne, Australia, May 2019, paper WEPRB051, this conference.