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BEAM COMMISSIONING OF THE HEPS LINAC*

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Abstract

The High Energy Photon Source (HEPS) is an ultrahigh brightness synchrotron radiation source currently under construction in China. Its accelerator complex is composed of a 6 GeV storage ring, a full energy booster, a 500 MeV Linac, and three transfer lines. The Linac is an S-band normal conducting electron linear accelerator with available bunch charge from 0.5 nC up to approximately 7 nC. The Linac installation was completed in July 2022 and high-power RF conditioning was completed in September 2022. Physics quantity based high-level applications have been developed for the HEPS Linac using our own platform *Pyapas*. The beam commissioning of the Linac was started from March 9, 2023. Detailed beam commissioning experiences and results of the HEPS Linac will be presented in this paper.

INTRODUCTION

The High Energy Photon Source (HEPS) [1, 2] is the first fourth-generation synchrotron radiation source based on a 6 GeV diffraction-limited storage ring [3, 4] that is currently under construction in China. The accelerator complex of the HEPS comprises an injector and a storage ring. The injector consists of a 500-MeV Linac [5], a full-energy booster [6], a low energy transfer line connecting the Linac and booster and two high energy transfer lines that transport beams between the storage ring and booster [7].

Table 1: Main Parameters of The Linac

Parameter	Unit	Value
RF frequency	MHz	2998.8
Energy	MeV	500
Max. repetition frequency	Hz	50
Pulse charge	nC	0.5~7
Number of bunches per pulse	-	1 or 3
Energy spread (rms)	%	≤0.5
Emittance (rms)	nm-rad	70

The Linac is a normal conduction S-band linear accelerator and main parameters are shown in Table 1. The Linac is composed of three sub-systems: an electron gun, a bunching system [8] and the main accelerator. A thermal cathode electron gun is adopted, which can provide an electron beam of 10 nC per pulse. The bunching system 0 comprises two Sub-Harmonic Bunchers (SHB1 and SHB2), one Pre-BUNcher (PBUN), one BUNcher (BUN), one Accelerating Structure (AS) and twenty-two solenoids. In the main Linac, there are eight accelerating structures driven by four klystrons and five triplets. There are eight Beam

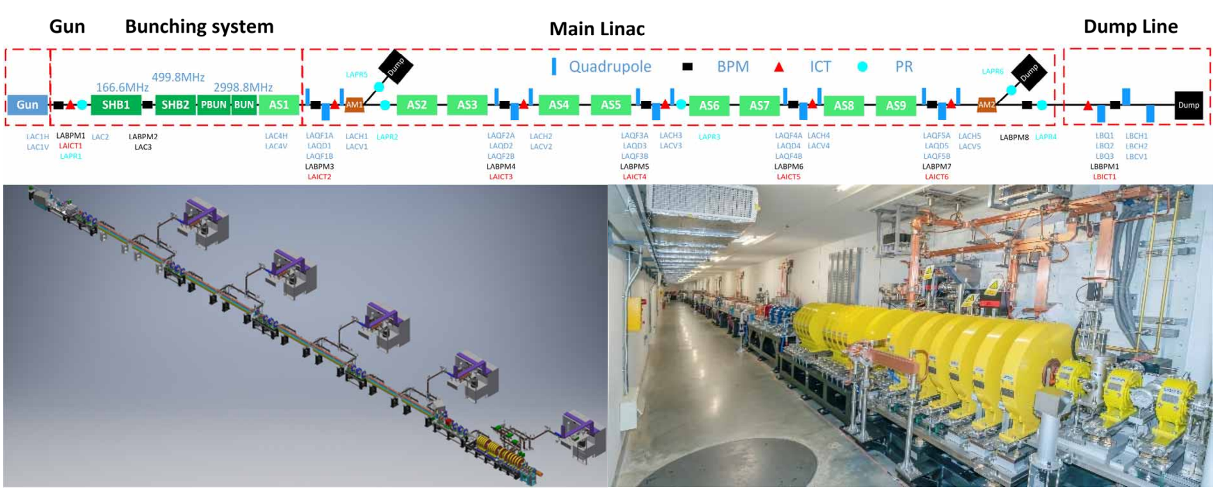

Figure 1: Layout (top), schematic diagram (bottom left) and tunnel (bottom right) of the HEPS Linac.

Position Monitors (BPMs), six Integrating Current Transformers (ICTs) and six PRofile monitors (PRs). Two of the PRs are used for measuring energy and energy spread at two energy analyzing station. Each PR have two screens, which are YAG monitor and OTR monitor. The layout,

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schematic diagram and tunnel of the Linac are shown in Fig. 1. In this paper, we introduce the brief construction process of the HEPS Linac, and present the latest results of beam commissioning.

CONSTRUCTION

In terms of physical design, a complex bunching system was used to achieve a single bunch charge of up to 7 nC at the exit of the Linac. This is the highest bunch charge among linear (pre-)injectors for third and fourth generation light sources worldwide. In terms of technological innovation, a 3-meter-long S-band high-gradient accelerating structure has been developed, featuring arc cavity, internal water-cooling structure, and symmetric couplers. The structure had been tested to achieve a maximum acceleration gradient of 33 MV/m. An IGBT based solid-state modulator had been developed, which allows a pulse repetition stability better than 0.02%. A high-emission grid component had been developed, which can emit electron pulses with a charge of over 10 nC.

The physical design of the Linac was frozen in 2019. Then, each equipment entered the development stage. In order to carry out early testing of high-power components, we set up four testing platforms: an electron beam testing platform, a sub-harmonic buncher conditioning platform, a high-power testing platform for accelerating structure, and a high-power testing platform for power sources and microwave devices. We tested and conditioned all equipment for high power offline in advance [9], which guaranteed the successful installation and conditioning of the HEPS Linac.

Beam commissioning simulation of the Linac was completed in September 2021 [9]. In order to complete the development of the beam commissioning applications, a new platform, Python accelerator physics application set (*Pyapas*) [10] was developed. The *Pyapas* is designed based on physical quantities. All control variables are physical quantities, such as focusing strength K_1 for quadrupole, kick angle for corrector, energy for dipole, etc. This allows for more intuitive analysis of measurement parameters during the commissioning. We have developed high-level applications, which include measurement applications, control applications and monitoring applications. At the beginning of beam commissioning, it is crucial to ensure that the beam is properly accelerated through the Linac. These are the responsibility of control applications. In accordance with design requirements and commissioning needs, measurement and monitoring applications are also necessary to obtain beam information such as energy, energy spread, emittance, orbit, and bunch charge.

All magnetic field measurements of the Linac magnets were completed in February 2022. Equipment installation inside the tunnel started in March 8, 2022, and the full-line vacuum sealing was completed in May 2022. All equipment installation was finished in July 2022. Based on *Pyapas*, all the commissioning applications for the HEPS Linac were completed and deployed in July 2022. Afterwards, the entire Linac underwent high-power online conditioning which was completed in September 2022.

COMMISSIONING

There are two energy analyzing stations to measure beam energy and energy spread. Quadrupole scan method is used to measure beam emittance. Beam based alignment method is used to get the offset of BPM relative to the adjacent quadrupole. Feedback-based one-to-one correction method and global correction method are used to correct beam orbit.

In early March 2023, we obtained the radiation protection permit for the Linac beam commissioning, and beam commissioning started on March 9, 2023. On that day, the first electron beam was observed on the first profile monitor at 10:28 AM and the electron beam was successfully transferred to the end of the Linac at 12:15 AM with beam energy reaching 500 MeV [11]. Due to significant wakefield effects under high bunch charge, the requirement of orbit stability is very high. The target orbit is also very important. We measured the BPM offset continuously for 10 days and took the average as the final value.

At the first stage of the Linac beam commissioning, in order to reduce the difficulty, the SHBs were turned off. We finished the beam tuning and measured beam parameters. Each pulse has about five micro-bunches. Without using SHBs, we optimized the lattice and orbit under high bunch charge of 7.4 nC and obtained the emittances of below 70 nm.rad, which are shown in Fig. 2 and Table 2. In this case, only the bunch charge was changed to 3 nC, the measured emittance was larger. The lattice and orbit with bunch charge of 3 nC in the case of without SHBs needs to be further optimized.

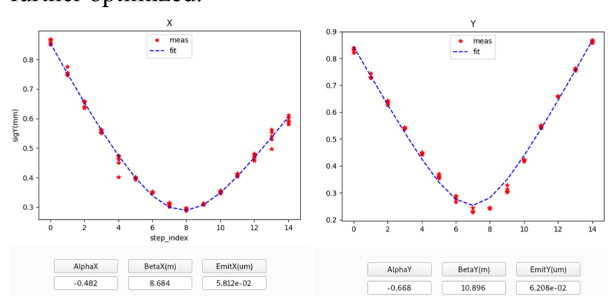

Figure 2: Measured beam emittance at exit of the ninth accelerating structure with beam energy of 500 MeV and bunch charge of 7.4 nC.

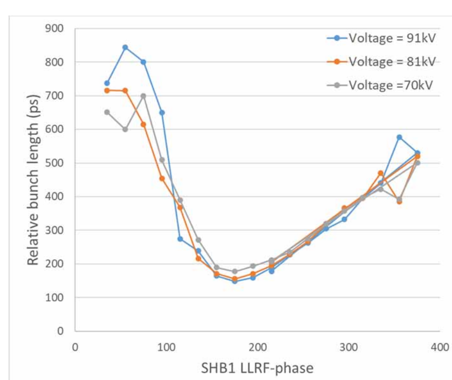

Figure 3: Relative bunch length measurement at BPM2.

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Table 2: Measured Parameters of The HEPS Linac

Parameter	Unit	Value	Measured results			
			W/O SHB		W/ SHB	
Energy	MeV	500	500	500	500	500
Pulse charge	nC	0.5~7	3.0	7.4	3.0	7.0
Number of bunches per pulse	-	1 or 3	5	5	1	1~2
Energy spread (rms)	%	0.5	0.4	0.4	0.34	0.4
Energy stability	%	±0.25	0.04 (rms)			
Emittance (H/V)	nm	70	72/94	58/62	64/59	82/94

With the accumulated experience, we turned on the SHB to further optimize the beam performance of the Linac. The significant impact of space charge effects caused by the high bunch charge had posed significant challenges to beam commissioning. The BPM2 is at the exit of SHB1 and was used to measure the relative bunch length, which is shown in Fig. 3. According to the measurement, we can calibrate the SHB1 phase when the shortest bunch length at BPM2 was achieved. Then, according to the simulation, we can adjust the SHB1 phase such to get the shortest bunch length at SHB2. After scanning the SHB2 phase we got the setting value of SHB2 phase. In this case, each pulse has one or two bunches after the bunching system, which is shown in Fig. 4.

Figure 4: BPM electrodes signal, indicate the presence of a bunch in the pulse.

In the high bunch charge case, the wakefield effect dominates the beam quality. Figure 5 shows two cases with pulse charge of 7 nC. Case one has three bunches and the orbit is not optimized. We can see that the effects of short-range and long-range wakefields are very significant. After carefully adjusting the bunching system settings, we suppress the wakefield effect by setting up a proper lattice and correcting the orbit. The beam distribution is shown in the right figure of Fig. 5. We measured the emittance at a beam bunch charge of 3 nC, with horizontal and vertical emittances of 64 nm and 59 nm, respectively. The beam energy and energy spread are shown in Fig. 6. The beam emittance increases at a beam bunch charge of 7nC, indicating a need for further optimization. The measured results at different cases are shown in Table 2.

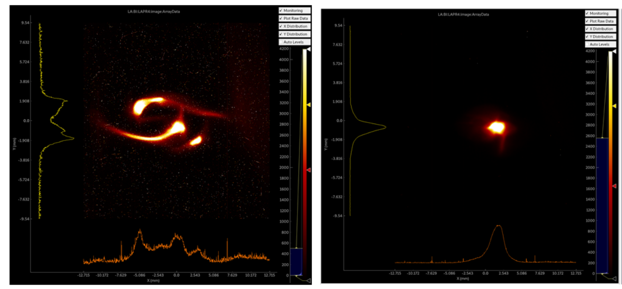

Figure 5: Beam distribution at the exit of the Linac with pulse charge of about 7 nC. Case one (left) have three bunch per pulse without optimization on the beam orbit, Case two (right) have one bunch per pulse with optimization on the beam orbit.

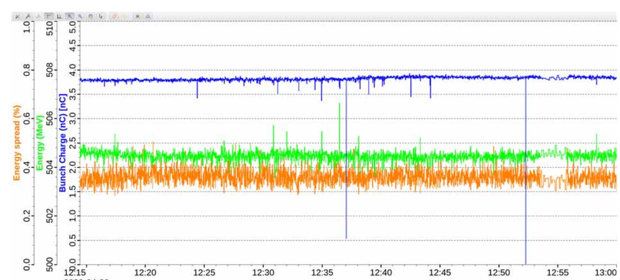

Figure 6: Beam energy and energy spread with bunch charge of about 3.8 nC.

CONCLUSION

HEPS linear accelerator is a high-bunch-charge S-band linear accelerator. Thanks to the thorough preparation work beforehand, the installation and conditioning progressed smoothly. The beam commissioning also proceeded smoothly, achieving full transmission of the Linac within two hours. However, due to the space charge and wakefield effects associated with the high bunch charge, beam commissioning posed significant challenges. Through appropriate lattice settings and orbit corrections, we completed the initial beam tuning task. We will further optimize the accelerator settings to improve the beam quality.

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