Drive laser system for the DC-SRF photoinjector at Peking University

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Abstract: Photoinjectors are widely used for linear accelerators as electron sources to generate high-brightness electron beam. Drive laser, which determines the timing structure and quality of the electron beam, is a crucial device of photoinjector. A new drive laser system has been designed and constructed for the upgraded 3.5-cell DC-SRF photoinjector at Peking University. The drive laser system consists of a 1064 nm laser oscillator, a four-stage amplifier, the second and fourth harmonic generators, the optical system to transfer the UV pulses to the photocathode, and the synchronization system. The drive laser system has been successfully applied in the stable operation of DC-SRF photoinjector and its performance meets the requirements. 266 nm laser with an average power close to 1W can be delivered to illuminate the Cs\(_2\)Te photocathode and the instability is less than 5% for long time operation. The design consideration for improving the UV laser quality, a detailed description of laser system, and its performance are presented in this paper.

Key words: drive laser, amplifier, harmonic generation, photoinjector

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1 Introduction

Photoinjectors are widely used for linear accelerators as electron sources to generate high-brightness electron beam after the development of more than two decades. Except determining the basic properties of the electron bunches, such as their time sequence, duration, and the amount of bunch charge, driver laser also affects the stability of the produced bunch and its synchronization accuracy to the accelerator RF field, as well as the emittance of the electron beam. As a crucial device of photoinjector, drive laser systems are generally developed by many laboratories themselves because there are few commercially available products which can meet the requirements of different applications. For example, for the ERL-FEL at JLab, a drive laser with the pulse repetition rate of 75 MHz, wavelength of 532 nm, and average power of 25 W has been developed [1]. For the FLASH at DESY Hamburg, a drive laser with the pulse repetition rate of 1 MHz or 3 MHz, wavelength of 262 nm, and pulse energy of 30 \(\mu\)J has been developed [2].

DC-SRF photoinjector, which combines a DC Pierce gun and a superconducting radiofrequency (SRF) cavity, was first proposed by Peking University in 2001 [3]. It is a potential candidate of SRF photoinjector to provide electron beam with medium average current, low emittance, and short bunch length. A prototype of this kind of injector with a 1.5-cell SRF cavity was designed and constructed in 2004 [4]. The preliminary experiment at 4 K demonstrated the feasibility of DC-SRF structure. An upgraded DC-SRF photoinjector with a 3.5-cell large-grain SRF cavity has been designed and constructed recently and the beam experiment was carried out. The results indicated that the drive laser system used for the 1.5-cell prototype is not stable enough to obtain high-quality electron beam. The main problems are low laser power at 1064 nm and instability of second harmonic generation (SHG) and fourth harmonic generation (FHG) induced by thermal effects. We have therefore designed and constructed a new drive laser system, which consists of a 1064-nm laser oscillator, a four-stage amplifier, harmonic generation system, laser beam transport optics, etc, to meet the requirements of the 3.5-cell DC-SRF photoinjector. In this paper, we introduce this new drive laser system and discuss its special features in detail.

2 Basic parameters and layout of the drive laser system

The main parameters of the DC-SRF photoinjector are shown in Table 1. Considering the stability and the less stringent requirement to vacuum environment, Cs\(_2\)Te photocathode is used even though it does not have a very high quantum efficiency and needs to be driven by...
ultraviolet (UV) laser with the wavelength around 260 - 270 nm.

Table 1. Main parameters of the DC-SRF photoinjector.

| Parameter          | Value | Unit |
|--------------------|-------|------|
| RF frequency       | 1300  | MHz  |
| Bunch charge       | > 12  | pC   |
| Average current    | > 1   | mA   |
| Normalized emittance | ~ 1.2 | µm   |
| Bunch length (FWHM)| ~ 3   | ps   |
| Beam energy        | 3−5   | MeV  |

The primary parameters of drive laser can be derived from the requirements of the DC-SRF photoinjector. The average current and bunch charge shown in Table 1 indicate that the drive laser does not need to have a repetition rate as high as 1.3 GHz. We have chosen a repetition rate of 81.25 MHz, the 16th harmonic of the RF frequency of the 3.5-cell SRF cavity. Since most commercially available laser oscillators work in infrared (IR) wavelength region, the laser oscillator with the wavelength of 1064 nm, which was used for the 1.5-cell DC-SRF photoinjector prototype, is still adopted for the new drive laser system. Nonlinear crystals will be used to convert the IR pulses to UV pulses with a wavelength of 266 nm.

The output power is another important parameter of drive laser system. The photocurrent can be described with the formula

\[ I[\text{mA}] = \frac{\lambda[\text{nm}]}{124} \times P_{\text{laser}}[\text{W}] \times Q.E.[\%]. \]  

where \( \lambda \) is the wavelength of drive laser, \( Q.E. \) is the quantum efficiency of photocathode. The \( Q.E. \) of \( \text{Cs}_2\text{Te} \) photocathode has a maximum of around 10%, but it is very sensitive to vacuum environment. Considering a safety margin of 10, a UV laser with the average power of at least 0.5 W is needed to obtain an average electron beam current of more than 1 mA. The expected electron bunch length from DC-SRF photoinjector is around 3 ps (FWHM). According to the simulation of bunch compression by the RF field in the 3.5-cell SRF cavity \[8\], the drive laser is required to have a pulse length of less than 6 ps (FWHM).

An optical layout of the drive laser system is shown in Fig. 1 and a photo of the laser system can be seen in Fig. 2. The system consists of a 1064-nm laser oscillator, a four-stage amplifier, the harmonic generation system, the optical system to transfer the UV pulses to the photocathode, and the synchronization system. The laser oscillator produces seed pulses with a repetition rate of 81.25 MHz. These pulses are synchronized to the RF field in the linac cavities with sub-picosecond timing jitter. The 1064-nm seed laser pulse from the oscillator is amplified by about 8 times in power and then converted to 532-nm green laser and 266-nm UV laser by the harmonic generators. The UV pulses are finally transported onto the cathode of the DC-SRF photoinjector through proper imaging optics. The details of the design considerations and the performance of laser system will be described in the following sections.

![Fig. 1. Schematic layout of the drive laser system for the DC-SRF photoinjector.](image-url)
Fig. 2. A photo of the drive laser system for the DC-SRF photoinjector. The laser system is shielded in a box made of 3-mm thick aluminum plate.

3 Laser oscillator and amplifier

The 1064-nm laser is configured as a master oscillator power amplifier (MOPA). The master oscillator, Time-Bandwidth Products GE-100-XHP series, is a passively mode-locked, diode-pumped solid-state laser. The laser pulse from the oscillator has a repetition rate of 81.25 MHz and a nearly Gaussian temporal profile with a FWHM of 10 ps. The pulse forming process is started and stabilized by a semiconductor saturable absorber mirror (SESAM), which also forms one end of the laser cavity. It is mounted on a translation stage driven by a picomotor, through which the cavity length can be adjusted. The cavity can also be fine-tuned using a piezo. A photodiode with nanosecond-level response is applied to monitor the laser pulses. Its signal is phase-locked to the accelerator RF using Time-Bandwidth CLX-1100 timing stabilizer.

To obtain more stable UV laser pulses, we prefer to use shorter nonlinear crystals for wavelength conversion. To compensate the reduction of wavelength conversion efficiency, much higher 1064-nm laser power is demanded. A 1064-nm laser amplifier should therefore be applied. Nd-doped laser materials are widely used for amplifiers in many laboratories, such as FLASH, Daresbury, PITZ, FZD Rossendorf, Fermilab, SLAC, etc., due to its high efficiency, good reliability, relatively simply setup, and low maintenance costs. Moreover, low doping concentration Nd:YVO4 crystal has the advantage in reducing thermal loading density and achieving more uniform absorption under high intensity pumping. As a result, a-cut 0.3% Nd-ion concentration bulk Nd:YVO4 crystals (3 mm × 3 mm × 10 mm) are used for the amplifier. Both end faces of the Nd:YVO4 crystals are dichroic coated for high transmittance at 1064 nm and 808 nm. The crystals are wrapped with indium foil and placed in copper heat sinks with water cooling.

For high power output and good beam quality, the amplifier is configured as four single-pass, single-end-pumped stages. Because of the high repetition rate of the laser pulses, CW laser diode modules need to be used as pump source to keep the laser power instability below 1%. Four sets of LIMO 808-nm off-board laser diode modules, with the output power of 37 W, are therefore chosen as the pump sources. The pump lasers, transported through 400 µm fibers, are coupled onto the end face of the Nd:YVO4 crystals using imaging optics. The pump source couplers are placed in holders which can realize four-dimensional translation and tilt adjustment. It is convenient for optimization and maintenance of the amplifier.

To direct the 1064-nm laser through the Nd:YVO4 crystals, four dichroic mirrors, anti-reflection (AR) coated at 808 nm and high-reflection (HR) coated at 1064 nm, are placed between the pump source couplers and crystals with the incident angle of 45° (see Fig. 1). Telescope optics are both used to match the 1064-nm laser beam into the Nd:YVO4 crystals and to expand the laser beam when necessary to avoid the damage of optical elements due to too high laser power density. To prevent the amplified laser beam from reflecting back into the master oscillator, the amplifier is isolated from the oscillator using a Faraday rotator.

Fig. 3. 1064-nm laser power after the four-stage amplifier during a long-term monitoring.

The 1064-nm laser power is 5 W before the first stage of the amplifier. In CW operation, at a pump current
of 45 A, 45 W stable output has been obtained from the MOPA system (see Fig. 3). The net power gain of the amplifier is 40 W. Compared to the total pump power of the four laser diode modules (148 W), the total optical-optical efficiency is about 27%. Fig. 3 shows the average laser power after the amplifier versus the current of the pump diode power supplies. It can be seen from the figure that the average laser power grows rapidly as the current increases above 25 A. The increase of the laser power slows down around 42 - 45 A. The operation pump current is therefore set at 45 A, which is still within the safe region.

4 Harmonic generation system

To obtain the UV laser pulses required by the Cs$_2$Te cathode in the DC-SRF photoinjector, a two-stage cascaded harmonic generation system has been designed. As the first stage, a LBO crystal is used for SHG. The 532-nm laser from LBO then traverses a BBO crystal for FHG. The LBO and BBO crystals are chosen for SHG and FHG because they are non-critically phase-matched and have high damage threshold and high conversion efficiency.

The LBO crystal has a length of 15 mm and a cross section of 4 mm × 4 mm and is cut at $\theta$ of 90° and $\varphi$ of 10.6°. Its end faces are AR coated for high transmittance ($T > 99.8\%$) at 1064 nm. The crystal is mounted in a thermostat, whose temperature can be remotely adjusted for optimized phase-matching angle. During the operation, the temperature is controlled at $45 \pm 0.1^\circ C$.

For FHG using BBO crystal, the large walk-off angle caused by BBO crystal’s large birefringence limits the conversion efficiency and makes the transverse profile of UV laser beam far from Gaussian distribution. This problem can be solved by using a walk-off compensation system, where two or more crystals having the same cut and length are arranged with the crystal optic axes in alternating directions (see Fig. 4). In our system, a pair of 2-mm long BBO crystals, which have a 4 mm × 4 mm cross section and are cut at $\theta$ of 47.7° and $\varphi$ of 0°, are used. The BBO crystals’ end faces are AR-coated for high transmittance at 532 nm ($T > 99.8\%$) and 266 nm ($T > 99.5\%$).

As shown in Fig. 4 demagnifying telescopes located before the LBO and BBO crystals are used to reduce the diameter of the beam to 10s µm for better wavelength conversion performance. After the LBO crystal, a set of lens and dichroic mirror is employed to collimate the SHG beam and eliminate the residual 1064 nm laser. After the BBO crystals, another set of lens and dichroic mirror is also employed to collimate the FHG beam and eliminate the residual 532 nm laser.

The measured conversion efficiencies of the SHG and FHG are 40% and 5.6%, respectively. The total conversion efficiency, from 1064 nm to 266 nm, is better than 2%. The 266-nm UV laser beam profile has been improved compared to our previous laser system using single-BBO (see Fig. 6). It can be further improved using transverse distribution shaping techniques. There is still enough room for increasing the conversion efficiency by different design of the harmonic generation system. Especially, an electro-optic (EO) modulator is being used to adjust the repetition rate of the 1064-nm laser pulses.
Using the EO modulator, the laser pulse repetition rate can be reduced as desired. This will benefit the harmonic generation system, since the laser pulse energy can be increased while the average power remains unchanged.

5 Stability improvement of the drive laser system

The laser system is installed in a class 1000 cleanroom, where the temperature is controlled at $20 \pm 0.5^\circ C$ and humidity less than 30%. Because of the air conditioning system, air flow exists in this cleanroom. To reduce the vibration caused by air flow, the main parts of the drive laser system is covered in a shielding box made of 3 mm thick aluminum plate (see Fig. 2).

In the previous drive laser system, the FHG system was installed in our SRF accelerator hall and the instabilities of both laser power and laser beam pointing became enlarged. In our new design, the FHG has been moved into the cleanroom. This makes the 266-nm laser transporting a longer distance (about 20 m) to the reflecting mirror installed in the vacuum chamber of electron beam line (see Fig. 4), and it is more difficult to project the laser beam to the photocathode. A motorized mirror mount has been designed and installed in the optical beam line for precise remote control of a 45’ mirror right before the in-vacuum reflecting mirror. The incident point of UV laser on the surface of the photocathode can therefore be precisely scanned using this motorized mirror mount. The optical beam line is shielded to prevent air turbulence caused by a temperature differential and air flow.

6 Performance of the drive laser

The performance of the drive laser system has been investigated, including the power instability, the beam pointing instability, and the synchronization with accelerator RF signal. The long-term instability of the 1064-nm and 266-nm lasers were monitored using a power meter integrated into our control system. Fig. 3 and Fig. 8 present the results of our latest monitoring of the 1064-nm laser and the 266-nm laser, respectively. During the measurements, the drive laser system was operated with the 1064-nm laser power of 45 W and the 266-nm laser power close to 1 W. The long-term instability of UV laser power is less than 5% after the warming up of the laser system. It is sufficient for the DC-SRF photoinjector beam experiments.

![Fig. 8. 266-nm laser power from warming up to stable operation.](image)

The pointing stability of the 266-nm laser beam was estimated by analyzing the laser beam on a virtual photocathode using a beam profiler. The pointing instability was estimated to be 10 $\mu$rad rms in both horizontal and vertical direction. It is remarkably improved compared to our previous drive laser system.

A phase detector, integrated with a fast photodiode, was used to monitor the phase difference between the 1064-nm laser pulses and accelerator RF field. The timing jitter, derived from the phase difference, was estimated to be less than 1 ps rms. The phase difference between the 266-nm laser pulses and accelerator RF field was measured by a UV phase detector. It is also less than 1 ps rms. This means that the UV laser beam is well isolated from environmental vibrations.

The new drive laser system has been applied in the beam test and stable operation of the DC-SRF photoinjector. With 0.5 W 266-nm laser power, a stable electron beam has been obtained with an energy of 3.4 MeV. The
average beam current reached 1 mA and was kept at 0.55 mA for long-term operation. The electron beam current is not limited by the drive laser system at present.

7 Conclusion

A new drive laser system has been designed and constructed for the upgraded 3.5-cell DC-SRF photoinjector at Peking University successfully. Double BBO crystals in the FHG are adopted to reduce the walk-off effect. Careful design makes the system more compact and isolated from interferences of surrounding environment. The 266 nm laser with the average power close to 1 W can be delivered to illuminate the Cs₂Te photocathode and the instability is less than 5% for long-term operation. The pointing instability was estimated to be 10 µ rad rms in both horizontal and vertical direction. The drive laser system has been applied in the DC-SRF photoinjector beam experiments and the performance meets the requirements. Recently, an EO modulator has been installed in our laser system. Using the EO modulator, the laser pulse repetition rate can be reduced as desired. The laser system, especially the harmonic generators, may be further developed to make the best use of this new capability.

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