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DEVELOPMENT OF DC-SRF INJECTOR AT PEKING UNIVERSITY*

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Abstract

DC-SRF electron injector, which combines a DC Pierce gun and a 3.5-cell 1.3 GHz superconducting cavity in a cryomodule, has been developed at Peking University. Based on the improvements of beam line, LLRF system and 2K cryogenic system, stable operation of the DC-SRF injector has been carried out recently. Electron beams with 3.4 MeV energy and the currents of ~1mA in a macro-pulse mode was obtained. As the first application of this DC-SRF injector, THz radiation produced with a 10 period undulator was also detected. The description of the experiment process and results will be presented in this paper.

INTRODUCTION

To obtain electron beams with high average current and low emittance, superconducting radiofrequency (SRF) photocathode guns, which combine the high brightness of normal conducting RF photocathode guns with the advantage of CW operation of superconducting RF cavities, have been developed in many laboratories worldwide [1, 2]. For HZDR SRF photoinjector, the SRF cavity is a 3.5-cell TESLA type cavity and there is a center hole on the back wall of the half-cell for Cs_2Te photocathode installation, which is in normal conducting. An attached choke filter made of pure niobium was designed to protect RF power leak towards the cathode support system from a vacuum gap between the cavity and the photocathode [3]. This SRF injector has been in operation since 2008[4] and was used for FEL operation recently [5]. A 704 MHz half-cell cavity SRF gun with a double quarter wave choke joint cathode insert was constructed at BNL and K2CsSb was chosen as cathode material [6]. The RF conditioning has been carried out [7] and the beam test is underway.

DC-SRF injector was first proposed by Peking University in 2001 [8]. It combines a DC Pierce gun and a superconducting cavity. The feasibility of DC-SRF injector was demonstrated by the prototype injector with a 1.5-cell TESLA type superconducting cavity in 2004 [9]. An upgraded DC-SRF injector with a 3.5-cell large grain niobium cavity was then designed and constructed [10]. Conditioning of the DC-SRF photoinjector has been started since the 2K cryogenic system has been in operation in 2011 [11]. Based on a series of improvements on drive laser, photocathode, low level RF (LLRF) control system and beam diagnostic devices, electron beam with a current of mA level has been obtained at long-term stable operation. In this paper, the improvements, beam experiments and results of the DC-SRF photoinjector are described.

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DC-SRF INJECTOR

Figure 1 shows the schematic view of the upgraded DC-SRF photoinjector. The cryomodule consists of the DC pierce gun, 3.5-cell superconducting cavity, helium vessel, liquid nitrogen shield, input power coupler, tuner and auxiliary systems.

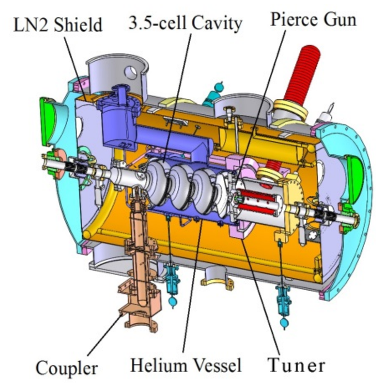

Figure 1: Schematic view of the DC-SRF photoinjector.

The designed DC voltage of Pierce gun is 90 kV. The surface electric field on the cathode is almost 5 MV/m and the peak electric field is lower than 13 MV/m. Simulations show that the electron beam experiences a focusing force when it leaves the cathode and is defocused around the anode [10]. The anode, which is also a part of the 3.5-cell cavity, is made of single crystal niobium in order to avoid the effect of the welding seam on the DC field distribution. The 3.5-cell large grain niobium superconducting cavity comprises three TESLA type cells and a special designed half-cell. The accelerating gradient of the cavity reaches 23.5 MV/m and the intrinsic quality factor Q_0 is higher than 1.2×10^{10} in vertical test [10]. The simulation shows that space charge effect of the electron beam is still remarkable due to the relatively low energy gained from the DC voltage. The gap between the Pierce gun and the 3.5-cell cavity should be as short as possible to prevent the beam from diverging too much due to space charge effect before it enters the high field area in the cavity. On the other hand, the RF field and DC static field infiltrating into each other should be suppressed. The length of connecting beam pipe between the DC anode and the half-cell of the cavity is 17 mm. The magnet field shielding of the DC-SRF injector is provided by the vacuum vessel, which is made of high pure iron plate with the thickness of 12 mm. The residual magnetic field in the

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cavity area is less than 20 milli-gauss. The input power coupler adopts compact capacitive coupling structure and consists of a ceramic cold window at liquid nitrogen temperature, a ceramic warm window and a coaxial-waveguide transition structure [12].

Cs_2Te photocathode is used for DC-SRF injector. The photocathode preparation chamber is connected to the cryomodule. Cs_2Te photocathode with stainless steel substrate produced at the preparation chamber is transported into the transfer chamber, and then inserted into the injector. The whole process is completed with magnetic coupled actuators in high vacuum environment. The upgraded drive laser system composes of a Time-Bandwidth GE-100 XHP seed laser, amplifier, second harmonic generator, fourth harmonic generator and optical beam line to transport the UV pulses to the photocathode. The wavelength of the seed laser is 1064 nm. The repetition rate of laser pulses is 81.25 MHz. 45 W infrared laser is obtained after amplification. The harmonic generators convert the infrared pulses to UV pulses with a wavelength of 266 nm. The drive laser system can provide 1 W power in a train of 6 ps UV pulses with 5% power instability.

A 1.3 GHz 20 kW solid-state amplifier is set up. It can work in both pulse mode and CW mode. The 3 dB bandwidth is more than 30 MHz. In order to stabilize the accelerating field of the 3.5-cell SRF cavity, a digital LLRF control system was designed. By comparing the pick-up signal with the set point, the PI controller in FPGA can adjust output signal to compensate the deviation, thus maintain stable field in the cavity [13]. Recently a series of improvements have been carried out. To allow pulse operation, gate signal has been added to the feedback loop and the control algorithm has been modified to handle Lorentz force detuning. A hardware UDP core has been implemented for high speed signal monitoring. Also, the control user interface has been rewritten by Python. The new control user interface offers many new features such as run-time plotting/modifying for many internal parameters.

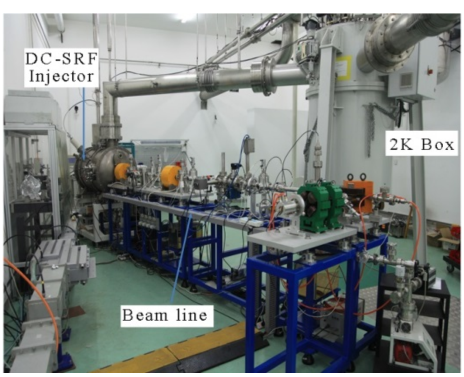

Figure 2: Beam line of the 3.5-cell DC-SRF injector.

A diagnostic beam line is designed and constructed, as shown in Fig. 2. Two solenoid lenses, a quadrupole magnet and a dipole magnet are adopted for beam focusing and deflecting. The first solenoid lens is installed as close as possible to the cryomodule for emittance compensation. The dipole magnet is used to deflect the electron beam to a Faraday cup with water cooling as dump. There are beam diagnostic devices including YAG screen, Faraday cups and a beam emittance meter in beam line.

BEAM EXPERIMENTS

QE of Photocathode

Four cathode substrates are polished mechanically and ultrasonic rinsed in ethanol and acetone before being placed into the preparation chamber. After cleaning, they are baked at 200°C for more than 10 hours to remove the residual gases. The deposition is accomplished in the vacuum of about 1.2×10^{-8} mbar. 7.0 nm tellurium film is deposited and then activated with cesium. The photocurrent is monitored during the preparation process by illuminating the surface of the photocathode with UV light.

A simple and effective method has been found to increase the QE and reduce the speed of degradation. The Cs_2Te cathode was activated again with cesium just before transferring it into the cryomodule. QE and life time of the cathode have been improved obviously after reactivation. Figure 3 gives the long term behaviour of a Cs_2Te cathode which was used for the beam experiments. The QE was more than 10% at the beginning and then stabilized at about 4% for more than 10 days. After one more week, the photocathode was illuminated again by drive laser and the QE was still 2% and lasted for a long time. QE of other cathodes had the same effect and all of them were stable with QE of 2% for long time. The possible reason for QE improvement is that the transferring of the cathode leads to a vacuum pressure raise for a short period and causes the oxidation of cesium in the cathode. Further activation introduces more cesium and reduces the influence of the oxidation.

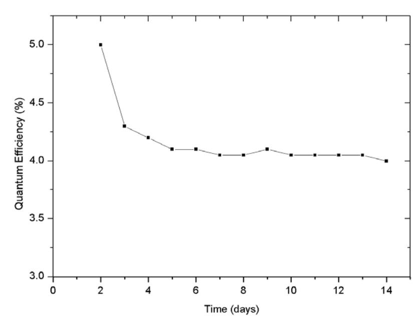

Figure 3: QE of Cs2Te cathode.

RF Experiments

The measurements of E_{acc} after assembling the cavity into the cryomodule have been carried out. The cavity was treated by light BCP and HPR before assembling in a class 100 clean room. Before the measurements of accelerating gradient, the input power coupler was tested up to 20 kW with duty factor of 40%. The temperature at several points outside of the coupler was monitored.

The E_{acc} in different conditions have been measured. During the measurements, the photocathode was inside the cryomodule. The E_{acc} reached 14.5 MV/m in CW

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mode and 17.5 MV/m in pulsed mode with a duty factor of 10% and a repetition rate of 10 Hz. The digital LLRF control system was used to stabilize the accelerating field. The amplitude (up) and phase (below) signals of 3.5-cell DC-SRF injector without beam load is shown in Fig. 4. The instability is less than 0.1% for amplitude and 0.1 degree for RF phase.

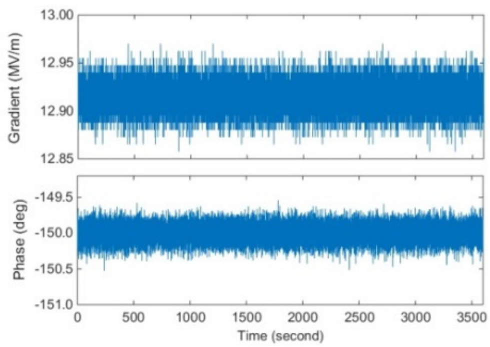

Figure 4: Long-term running of LLRF control system.

Beam Experiments

The beam experiments were carried out at an E_{acc} of 8.5 MV/m for stable operation. Commissioning of the DC-SRF injector with beam was carried out at a low average current in order to avoid electron beam bombarding the beam tube. We reduced the duty factor of drive laser instead of the laser pulse energy to keep the same bunch charge for different average current. The average beam current was about 2.5 μA when the duty factor of the drive laser was 1% at a repetition rate of 10 Hz. The parameters of the magnets in the beam line were optimized under this beam current. Figure 5 shows the screenshots of the electron beam after the first solenoid lens and before the deflecting magnet. The duty factor was then increased to 100% gradually and the average current increased to 250 μA at CW mode operation. The beam current was increased further by increasing laser power, but the degassing of the dump Faraday cup became serious. Pulsed mode was applied for long term beam test to protect the superconducting cavity. The duty factor of RF power was 7% with a repetition rate of 10 Hz. The average beam current in a macro pulse reached 1 mA and was kept at 0.55 mA for long term operation.

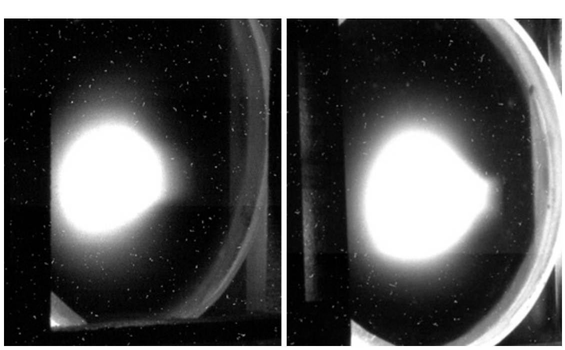

Figure 5: Screenshots of electron beam after the first solenoid (left) and before the deflecting magnet (right).

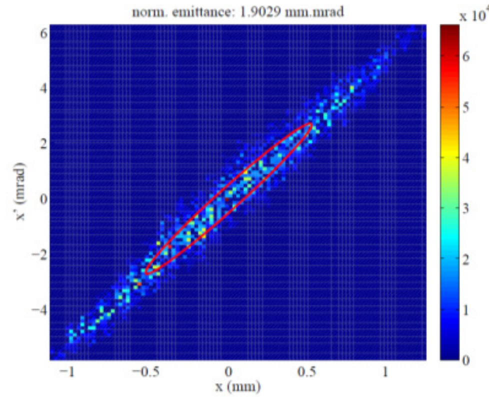

Figure 6: Measured emittance of electron beam.

The kinetic energy of electron beam was about 3.4 MeV, which was measured with the bending magnet. This was consistent with the value derived from the accelerating gradient. The measured normalized emittance was about 1.9 mm·mrad, see Fig. 6, which was larger than the simulated value [10]. The reason is under investigation.

CONCLUSION AND PROSPECT

Stable operation of the DC-SRF photoinjector has been realized based on a series of improvements of drive laser, photocathode preparation and LLRF control system. The average beam current in macro pulses reached 1 mA and was kept for long term operation at 0.55 mA with the RF duty factor of 7% and repetition rate of 10 Hz. The results are promising and confirm the design concept and its potential as a high average current electron source. Considering the current UV laser power and the QE of Cs_2Te photocathode, higher beam current is expected by simply improving the beam dump.

The DC-SRF injector will be used for THz radiation production in the next step. A superconducting cryomodule containing two 9-cell TESLA type cavities will be installed after the DC-SRF injector. The energy of the electron beam is expected to more than 25 MeV with this compact superconducting accelerator and more applications will be carried out.

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