COMMISSIONING AND OPERATION OF DC-SRF INJECTOR*

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Abstract

As a new and compact injector with medium beam current, the DC-SRF injector at Peking University has been upgraded recently. With a new 20 kW solid state RF power source, an improved LLRF control system and related diagnostic devices on the new beam line, a series of experiments have been carried out for stably operating the DC-SRF injector at 2 K temperature. The description of the system, experiment process and results will be presented.

INTRODUCTION

As a compact photocathode injector with medium beam current, DC-SRF injector, which combines a DC pierce gun and a superconducting cavity, was first proposed by Peking University in 2001 [1]. A prototype of this kind of injector with 1.5-cell superconducting cavity was designed and constructed in 2004 [2]. The preliminary experiment at 4.2 K demonstrated the feasibility of DC-SRF structure. An upgraded DC-SRF injector with a 3.5-cell large grain cavity has been designed, constructed and improved since 2007. The beam dynamics simulation, fabrication and vertical test of the 3.5-cell cavity, RF test of the system at 2 K were reported in the previous SRF conferences [3, 4]. To obtain stable electron beam, a series of improvements on 2 K cryogenic system, RF power supply, LLRF control and beam line have been carried out recently. The brief description of DC-SRF injector, recent improvements of the system and the beam experiments are presented in this paper.

DC-SRF INJECTOR

As shown in Fig. 1, the main components of the DC-SRF injector are a DC pierce gun, a 3.5-cell superconducting cavity, a cryostat and a RF power coupler.

The designed DC voltage is 90 kV. The distance between the anode and the cathode is 14 mm. 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 electron beam gets a focusing force when it leaves the cathode and defocuses around the anode. The anode is also a part of the 3.5-cell cavity. It is made of a single crystal niobium sheet with a diameter of 70 mm. This avoids the discharging at high surface field.

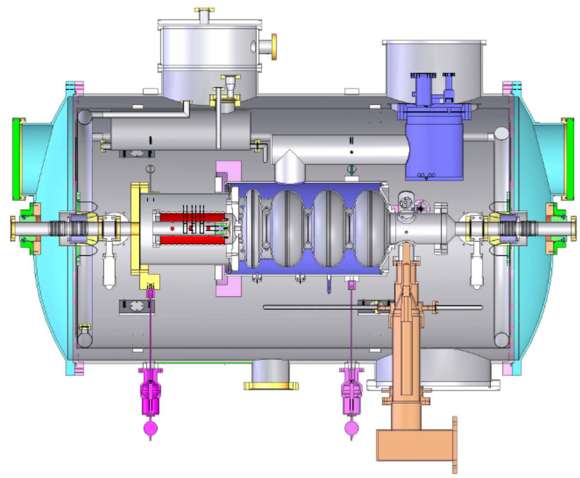

Fig. 1: Sectional view of the 3.5-cell DC-SRF injector.

After the DC pierce structure, the electron beam still has low energy and the space charge effect is remarkable. To maintain good emittance, the 3.5-cell superconducting cavity which focuses and accelerates the electron beam is as near as the pierce structure. To avoid the RF field and DC static field infiltrating into each other, the connecting beam pipe between the DC anode and the half cell of the cavity is designed as 17 mm long. The 3.5-cell cavity is made of large grain niobium and the gradient of the cavity reaches 23.5 MV/m, Q_0 value is higher than 1.2×10^{10} in vertical test at Jlab [3].

The cryostat of DC-SRF injector consists of liquid helium vessel, helium gas collector, liquid nitrogen shielding, tuner, vacuum vessel and etc. The magnet field shielding is produced by the vacuum vessel which is made of pure iron. The residual magnetic field in the cavity area is less than 20 milli-gauss.

The main coupler has a kind of compact capacitive couple structure, consists of a ceramic cold window at liquid nitrogen temperature, a ceramic warm window and a coaxial-waveguide transition structure (door knob). The cold window and warm window are separated and it is convenient for assembling and repairing.

EXPERIMENTAL FACILITIES

In order to produce high quality beam and to have stable operation of the DC-SRF injector, auxiliary facilities including 2 K cryogenic system, photocathode chamber, RF power supply, LLRF control system and beam line have been improved or maintained in a good condition.

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Cryogenic System

A closed-loop 2 K cryogenic system from Linde was installed in our SRF laboratory. The 2 K sub cooling system is in experimental hall together with DC-SRF injector and the helium liquefier system and pumping system is in a separate room.

The commissioning was carried out firstly by closing the 2 K Coldbox with two test caps. A gas heater was installed inside the 2 K Coldbox to simulate the heat load of the cryostats. The pressure stability of saturated pressure of 2.0 K helium was controlled within ±0.1 mbar around 30 mbar while the heating power was 58 W and the helium level was kept within ±1 liter in the 20 liter helium buffer inside the 2 K Coldbox. Then the 2 K cryogenic system was connected to the 1.3 GHz DC-SRF photocathode injector with liquid helium transfer line. A heater in the cryostat was adopted to simulate the constant heat loss of the superconducting cavities to help getting the proper running parameters. Successive approximation method was used to optimize the working parameters. The high and low limits of the control valves were preset and finely adjusted to avoid large fluctuation of the helium pressure and level. The fast change of the pressure was mainly controlled by the bypass valves of the pumping system and the slow change was adjusted by the variable frequency driver of the pumps. After optimization, the stability of the helium pressure in the cryostat can be controlled within ±0.1 mbar at 2.0 K and the helium level is within ±5%.

The cooling capacity at 2.0 K was also measured. The total static heat load at 2.0 K was about 20 W, which is obtained by calibrated helium gas flux measurement. It includes the static heat load of the 2 K Coldbox, the transfer line and the injector cryostat. Deducted the head load of 2 K Coldbox, the static heat load for the transfer line and the cryostat is about 15W. The dynamic cooling capacity was simulated with the heater in the cryostat. The 2 K cryogenic system can running stable at 2.0 K when the heating power was increased up to 50 W. Thus the total cooling capacity of the 2 K cryogenic system is more than 65 W at 2.0 K, which is larger than the designed value of 57.5W [5].

Photocathode Chamber

The vacuum deposition chamber for fabrication of Cs_2Te photocathode is improved to 10^{-7} Pa level with a sputtering ion pump (600 l/s). A SAES NEG pump (200 l/s) has been equipped recently. The plug is first transferred into the transfer chamber after fabrication, and then inserted to the injector. All the work is done in high vacuum with magnetic coupled actuator. The plug is made of stainless steel. Before being transferred into the deposition chamber, the plug should be polished mechanically, then rinsed in ethanol and acetone ultrasonically, and then is heated at 120-150 degree for more than 10 hours to remove the residual gas.

The driving laser system composes of a GE-100 XHP seed laser from the Timebandwidth Co., Switzerland and amplifier, SHG, FHG, lenses, control system and cooling system. The laser output power is 5 W for seed laser (1064 nm), 40 W after being amplified, 10 W for green light (532 nm) and around 1 W for UV light (266 nm). The repetition rate is 81.25 MHz.

The quantum efficiency (QE) of fresh Cs_2Te photocathode is around 8% and stabilized at 0.5% for months. The QE of the used photocathode could be rejuvated by being heated at 120 degree and laminated under the Hg lamp.

1.3 GHz Solid State RF Power Supply

The 1.3 GHz 5 kW solid-state RF power supply was replaced with a new 1.3 GHz 20 kW solid-state power source in 2011, which was designed and fabricated under the cooperation of BBEF and Peking University. The RF power source is composed of eight plates and each plate has one pre-amplifier and ten amplifiers. It can work in both pulse mode and CW mode. The output RF power can achieve 20 kW with matched load, and 16 kW with total reflection. The 3 dB bandwidth is more than 30 MHz. To keep the stability of the output power, a dedicated cooling water system, which provides cooling water with a temperature of within ±0.5 □, has been constructed for RF power supply.

LLRF Control

In order to stabilize the accelerating field in PKU 3.5-cell DC-SRF injector, a digital LLRF control system was designed. The designed digital LLRF control system has two feedback control loops for amplitude control and phase control. By comparing the pick-up signal with set point, the PI controller in FPGA can adjust output signal to compensate the deviation, thus make the system stable [6].

Recently a series of improvements have been carried out. A DC offset block was added in the FPGA to compensate the DC offset observed in the tests. To allow pulse operation, gate signal was added to the feedback path and the control algorithm was modified to handle Lorenz detuning. A hardware UDP core was implemented for high speed signal monitoring. The control UI was also re-written by Python. The new control UI offers many new features such as run-time plotting/modifying for many internal parameters. With those improvements, the LLRF control system has been used for the commissioning and operation of DC-SRF injector. Field stability is better than designed values of 0.5% for amplitude and 0.2 deg for phase. In recent experiments, long-time stability (>2 h), pulse mode operation and beam-loaded operation had been successfully tested.

Upgraded Beam Line

The preliminary beam test of 3.5-cell DC-SRF injector was carried out with the beam line which was used for the beam test of the 1.5-cell prototype injector. There were many problems when we tried to increase the beam current. Therefore a new beam line as shown in Fig. 2

was designed and constructed for recent experiments. Two solenoid lenses and 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 and the second one is put before the undulator (not installed yet). The dipole magnet is used to deflect the electron beam to a faraday cup with water cooling as dump. Before the faraday cup, a quadrupole magnet is used to defocus the beam. There are many beam diagnostic devices such as YAG or quartz screens, faraday cups and a beam emittance meter in the new beam line.

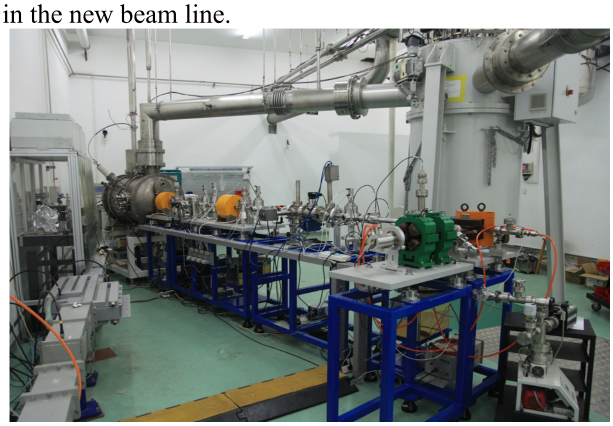

Fig. 2: New beam line for beam test of 3.5-cell DC-SRF injector.

EXPERIMENTS AND RESULTS

RF Conditioning and E_{acc} Measurements

Before the measurements of accelerating gradient, RF power coupler was conditioned at room temperature and low temperature from low RF power and low duty factor to high RF power and high duty factor. The temperature at several points inside the coupler was monitored by temperature sensors (see Fig. 3). The cavity was non-resonance during the conditioning. The highest power was 20 kW with duty factor of 40%.

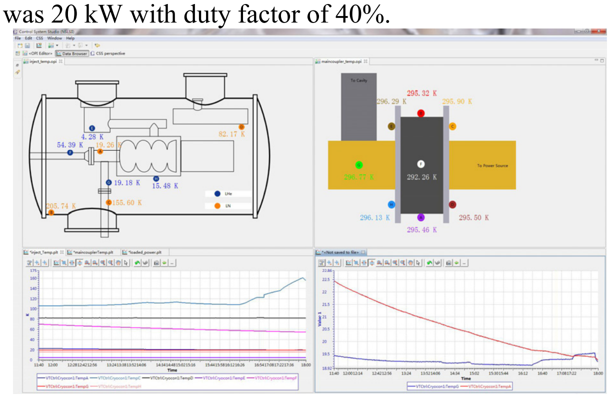

Fig. 3: Conditioning process of the main coupler.

The E_{acc} in different conditions have been investigated. The E_{acc} was increased up to 17.5 MV/m in pulsed mode with a duty factor of 10% and a repetition rate of 10 Hz. Higher E_{acc} was difficult to reach due to field emission. For CW mode, the E_{acc} reached 14.5 MV/m and the limitation was mainly the heat loss from the connection area of beam tube and main coupler. The above results were obtained in phase-lock mode. When we used the LLRF control system to stabilize the acceleration field, the E_{acc} was a little bit lower for safety operation of the solid-state RF power supply. The E_{acc} was 12.9 MV/m for a long-term test. Fig. 4 shows the amplitude (up) and phase (below) signals of 3.5-cell DC-SRF injector at 12.9 MV/m without beam load.

The microphonics effect has also been investigated. The frequency spectrum was measured as shown in Fig. 5. The vibrations at the frequency of 2 Hz and 14.5 Hz may affect the cavity. The investigation of the sources of these vibrations is underway.

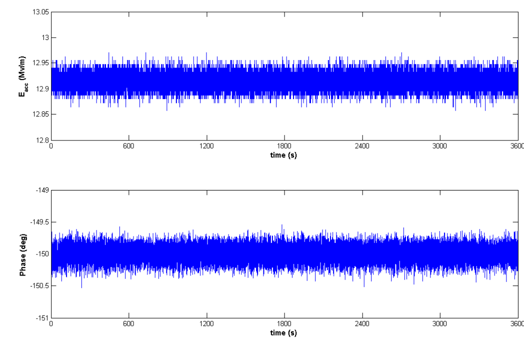

Fig. 4: Long-term test of LLRF control for DC-SRF injector.

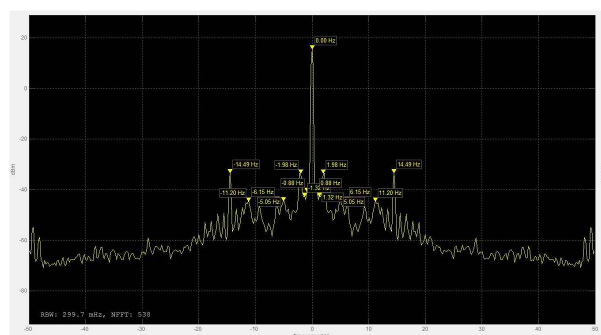

Fig. 5: Real-time measurement of cavity microphonics.

Beam Experiment

In order to avoid the electron beam bombarding the beam tube, beam tuning was carried out with a low beam current. This is realized by reducing the duty factor of laser rather than reducing laser power to keep the same bunch charge for different average current. When the duty factor of laser was 1% at 10Hz, the average beam current is about 2.5 μA. Under this beam current, the parameters of the elements in the beam line were optimized and the beam emittance was measured. Fig. 6 shows the reflected and pickup RF signals with pulsed beam load. When the beam tuning was finished, the duty factor was increased gradually to 100% and the average current increased to 250 μA at certain laser power. The beam current could be increased further by increasing laser power but the degassing of the dump faraday cup became serious.

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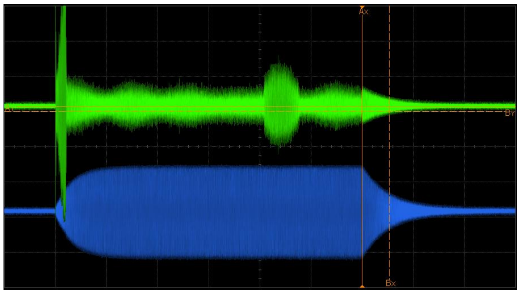

Fig. 6: The reflected (green) and pickup (blue) RF signals with pulsed beam load.

For stable operation, the E_{acc} was 8.0 MV/m during the beam test. The beam energy is about 3.3 MeV at this accelerating gradient. The energy of electron beam estimated with bending magnet and energy spectrum of radiation were 3.2 MeV and 3.1 MeV respectively, consistent with the calculation result from the gradient.

The beam emittances were measured at different DC voltages of 50 kV, 42 kV and 36.6 kV. Fig. 7 shows a picture of beam passing through multi-slits (left) and relative intensity (right).

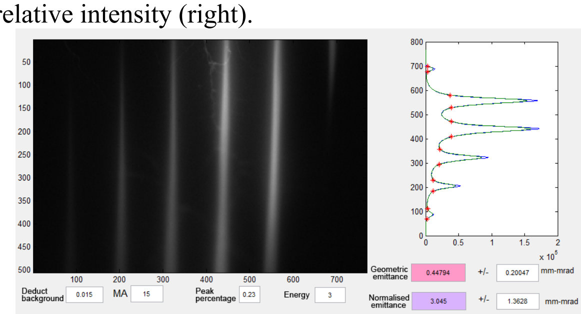

Fig. 7: Transverse emittance measurement by multi-slits method.

The normalized emittances are all around 3.0 mm·mrad. When the average beam current is 250 μA with repetition rate of 81.25 MHz, the space charge effect is very weak.

SUMMARY AND PROSPECT

Progress has been made on the 3.5-cell DC–SRF photocathode injector based on the improvements of RF power supply, photocathode preparation system and beam line. The beam experiments have been carried out and 0.25 mA CW electron beam has been obtained. The current limitation is mainly degassing of dump faraday cup. With a beryllium window before the dump, the beam current is expected to be about 1mA and the DC-SRF injector will be used for THz radiation production and then for ERL-FEL as the electron source.

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