PROGRESS OF FEL BASED ON RF SUPERCONDUCTING ACCELERATOR AT PEKING UNIVERSITY*

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Abstract

A free electron laser (FEL for short) facility based on superconducting (SC for short) accelerator is under construction at Peking University (named PKU-FEL).This system is composed of a SC injector, a SC linac, undulators/wigglers and other subsystems.

In January 2003, the DC-SC photoinjector test facility was constructed, and after a year of commissioning and testing, we have accomplished the first successful step. The performance of this new injector is to be further improved. The main linac comprises two TESLA-type 1.3-GHz 9-cell cavities and a Rossendorf-type cryostat. The two 9-cell cavities will be fabricated by ACCEL and low-power cold test will be carried out at DESY. The undulator is developed jointly by the Institute of High Energy Physics and Peking University. Prototype of the undulator has been completed, validating the quality of the permanent magnets and the reliability of the construction. Meanwhile, the photocathode, the driving laser, and the beam diagnostic system have been tested and developed. PKU-FEL will run in THz and IR region. High average power FEL should be feasible, as the SC accelerator can run in CW mode.

R & D in the field of Radio Frequency (RF for short) superconductivity has been in progress all along at Peking University. Researches are going on to improve the performance of SC thin films prepared by sputtering technology. Design of a 2+1/2-cell Nb Cavity for injector has been accomplished; manufacturing has been carried out. Researches on SC accelerator based ERL (Energy Recovery Linac) light source are also in progress.

INTRODUCTION

Two aspects are involved in our researches on SC accelerators.

One is FEL. A FEL facility (PKU-FEL) based on SC accelerator will be constructed at Peking University, which will be used as a tool for experimental studies on nonlinear transient physical process, chemical kinetics, molecular biology, material science and so on. Based on PKU-SCAF [1], a SC accelerator facility, PKU-FEL has the characteristics of high stability and high average power.

PKU-FEL is an ideal experimental platform for universities. It will run in IR (5~10μm) and THz (100~3000μm) region. The facility can also provide high-quality electron beams for experimental studies in some relative fields such as nuclear physics experiments and so on.

The facility is composed of a DC-SC photoinjector, a 1.3-GHz 2×9-cell SC accelerator, a bunch compressor, undulator/wigglers and experimental terminals. A 200-W

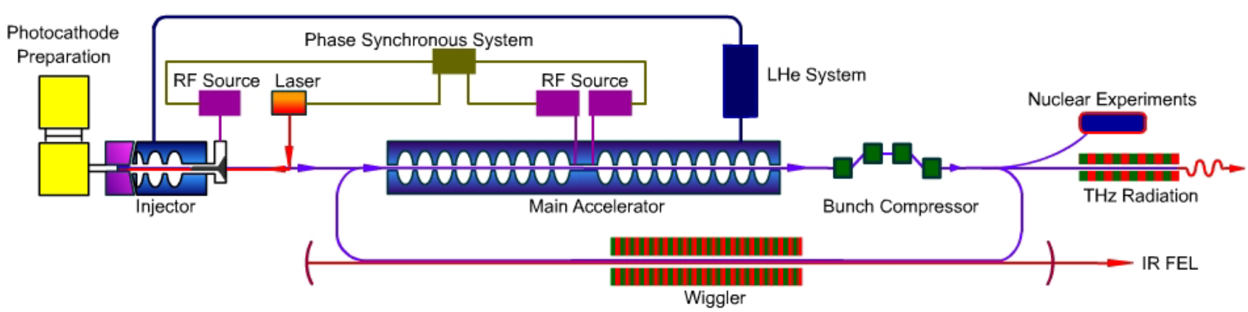

Figure 1: Schematic Layout of PKU-FEL facility

Table 1: Main Parameters of PKU-FEL

Electron Beam Parameters	Energy	30~40MeV	Bunch Length	1~2 ps
	RMS Energy Spread	80keV	Average Current	1mA (CW)
	Peak Current	>200 A (P)	RMS Emittance	5mm.mrad
THz Radiation	Wavelength	100~3000μm	Average Power	~1W
IR FEL	Wavelength	5.05~10.08μm	Average Power	100W
	Peak Power	600kW		

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LHe plant will furnish the SC injector and main accelerator with 2K environments. Figure 1 gives a schematic layout of PKU-FEL facility.

Due to the SC characteristics of the injector and main accelerator, PKU-SCAF has the abilities of supplying CW electron beams for PKU-FEL. However PKU-SCAF will run in long pulse mode according to requirements. The macro pulse length is of mm scale and macro repetition rate is 10 Hz. The micro pulse repetition frequency is determined by driving laser (81.25MHz). Table 1 lists the main parameters of PKU-FEL.

Another important aspect involved in our researches is R&D of RF superconductivity. Researches in this field have been in progress all along in SRF Lab. We have also developed close cooperation with Cornell University, DESY and Rossendorf.

Based on SC accelerators, ERL light source has captured more and more attention in recent years. Relative researches on SC injector, energy recovery technologies of SC linac and CSR will be carried out in Peking University.

Researches on SC QWR cavities have been in progress in our lab for many years. Now four Nb sputtered copper QWR cavities are developed for BRNBF (Beijing Radioactive Nuclear Beam Facility) of CIAE (China Institute of Atomic Energy). Based on our researches, we are investigating new approaches to improve the quality of Nb thin films. Experiments on a small-scale test facility have been carried out.

The feasibility of DC-SC photoinjector has been validated through experiments on the test facility. According to the requirements of PKU-FEL, we'll improve the core elements —DC gun and SC cavity. A 2+1/2-cell Nb cavity is under research; we have finished the design and optimization.

DC-SC PHOTOINJECTOR

PKU-FEL will employ a laser driving SC injector. As a result, a high brightness injector (named DC-SC photoinjector) test facility has been constructed at Peking University, which can supply CW electron beams. The injector start to run in 2003 and it is in commissioning and upgrading at present.

DC Pierce Gun and 1+1/2 Cell SC Cavity

The DC-SC photoinjector test facility is a compact system, integrating a DC Pierce gun with a SC 1+1/2-cell niobium cavity. Figure 2 gives an overview of the facility, including the cathode preparation chamber, the cryostat housing the DC gun and the SC cavity, the 100 kV high voltage source for the cathode of DC gun, the RF main coupler, the 4.5 kW solid-state power amplifier, the driving laser system, and the beam diagnostic system [3].

Core elements of this electron gun are the DC Pierce gun and the 1+1/2-cell SC cavity. The photocathode is placed at the cathode of the Pierce structure, and the anode makes up the bottom of the 1+1/2-cell cavity. A draft is shown in Figure 3.

Figure 2: Overview of the DC-SC photoinjector.

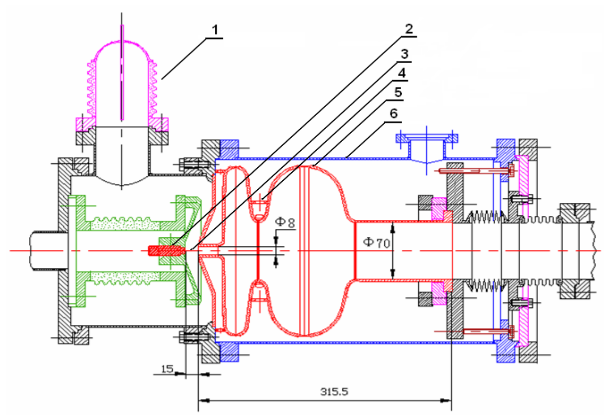

Figure 3: Draft of the 1+1/2 cell cavity.
(1) Ceramic insulation (2) Photocathode (3) Pierce DC gun (4) Stiffening ring (5) Niobium cavity (6) LHe tank

The structure of DC-SC injector has several advantages [2]:

- The effect of the photocathode on the SC cavity can be avoided because the photocathode is placed outside the SC cavity. The cathode plug with the photolayer can also be operated at low temperature, and the good vacuum conditions will increase the life span of the highly sensitive photocathode.
- The back wall of the half-cell has a conical geometry, which leads to an RF focusing of the electron beams.

Performances of the whole injector are listed in Table 2.

Table 2: Simulation results of the DC-SC injector

Electron bunch	Length	7.8 ps
	Energy spread, rms	1.16%
	Energy	2.61 MeV
	I_{ave}	1 mA
	Emittance, rms	3 mm-mrad
	Radius	2.8 mm
SC cavity	E_{acc}	15 MV/m

Choke point of this design is the narrow neck between the DC Pierce gun and the SC cavity. PARMELA simulation shows that when low energy (70 keV) electron beams pass through this neck, space-charge effect will lead to a rise in emittance. However, before the bunch charge increases to 100 pC, simulation results display good potential to meet our requirements. Moreover, the RMS emittance in Table 2 is as good as 3 mm-mrad at the end of the whole injector.

The whole procedure of preparing 1+1/2-cell cavity was carried out at Peking University. Cups are made of 2.5-mm-thick sheet niobium (RRR=250) by spinning, followed by trimming and electron beam welding. After heat treatment, the cavity undergoes mechanical polishing, electric etching, buffered chemical polishing (BCP), and DI water rinsing. The assembled cavity (Figure 4) is mechanically tuned to adjust the resonance frequency to the design value.

Figure 4: Image of the 1+1/2 cell niobium cavity.

The cavity was tested without cathode in it to evaluate the cavity and to prove the compatibility of the SC cavity and the RF input coupler. A resonant at 1300 MHz at 4.2K was achieved. The first test showed that the unloaded Q value of 1+1/2-cell was ~10^8 and the average gradient was about 4~5 MV/m, limited by field emission. A test on the DC gun has been performed, in which the current reached 400μA.

Drive Laser and Photocathode Preparation

The photocathode preparation chamber was designed and manufactured at Peking University. This chamber is bakeable, and the vacuum can reach ~10^{-6} Pa in the course of evaporation. Cs_2Te and Cs_3Sb are optionally fabricated. One layer of Cs_2Te on a stainless plug is excited by 266 nm UV laser, and its quantum efficiency is above 5% for several days. The “Yo-Yo” technique is used in the growth of Cs_3Sb, and the QE at 532 nm has reached 1%.

A schematic layout of the laser system currently in operation is shown in Figure 5. GE-100-XHP is a high-power mode-locked and diode-pumped Nd:YVO_4 picosecond laser. Its average output power is 10.4 W at 1064 nm. Using a timing stabilizer (CLX-1100) it can provide a full synchronization to the RF cavity with a time jitter less than 1 picosecond. The pulse duration is 10 ps. KTP is used as a frequency doubler, and a CLBO crystal, developed in China, is used to obtain 266 nm UV laser. After frequency doubling and quadrupling, it is able to generate 5 W at 532 nm or 1.2 W at 266 nm with the repetition rate of 81.25 MHz. The size of the RMS laser spot we measured was about 6 mm.

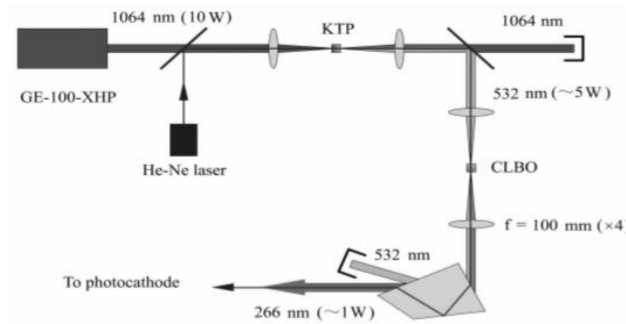

Figure 5: Optical scheme of the current drive laser.

Beam Tests

Tests of the injector are still in progress. Beam tests have been carried out step by step. As a primary step, experiments of DC Pierce gun were performed, including the preparation of photocathode, the transfers of photocathode, laser path adjustment, high voltage and beam diagnostics (Figure 6). After several tests, the DC gun can provide stable electron beams now. When the power of output laser went up to 100mW (266nm), the average beam current reached 400 μA.

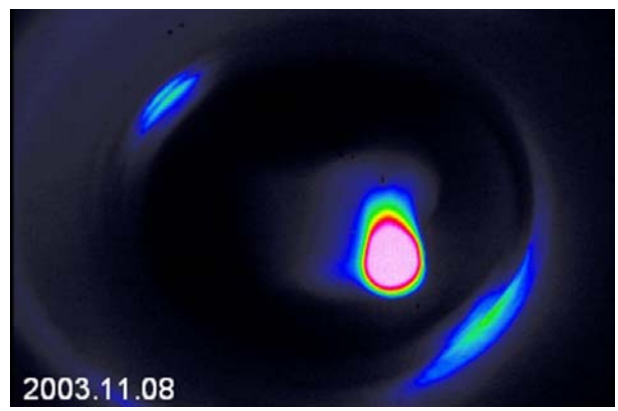

Figure 6: Beam spot at fluorescence, about 2 m apart from the photocathode.

Beam loading tests have been carried out, and we have succeeded in SC acceleration. Figure 7 gives the results of our latest test.

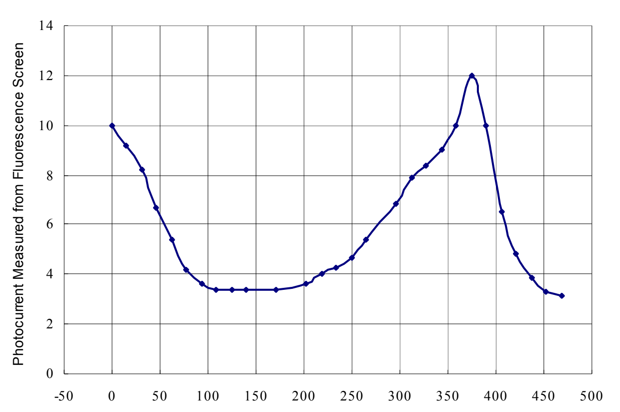

Figure 7: Electron beam current vs. phase difference between RF and laser.

2×9CELL 1.3GHZ SC ACCELERATOR

Two TESLA-type 1.3GHz cavities [4] are chosen for the main accelerator, which will be housed in a Rossendorf-type cryostat (figure 8). Parameters of the main accelerator are listed in Table 3.

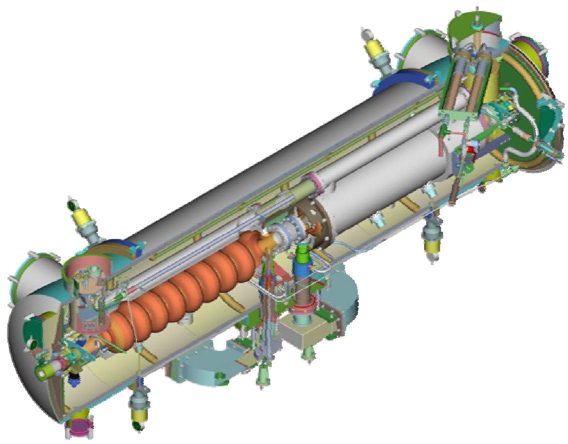

Figure 8: ELBE Module with two TESLA-type cavities in one cryostat

Table 3: Parameters of the main accelerator

RF frequency (cavity at 2.0 K)	1300 MHz
Accelerating voltage	17 MV/m guaranteed, Goal is≥ 20MV/m
Q0 @20 MV/m	1×10^{10}
Electron Beam Peak Current	20~50 A
Bunch Charge	About 20~50 pC
Electron Beam Ave. Current	1.625~4.0 mA
External Q of Power Coupler	2×10^6~1×10^7
Cryogenic losses (stand-by)	12W at 2K

ELBE Module can run in CW mode and provide electron beams with high average current. In order to minimize the scale of LHe machine, the main accelerator will operate in long pulse mode. At present, the macro pulse length is set to 1.5ms with a repetition rate of 10Hz.

UNDULATOR

Researches on wiggler/undulator for both oscillator FEL and SASE FEL have been carried out. A planar hybrid permanent magnet undulator combined with a superimposed periodic quadrupole lattice structure is adopted for our SASE FEL facility [5]. Through IR SASE FEL experiments, we'll investigate the physics and critical technical issues of SASE and also validate the quality of homemade permanents magnets and the reliability of the constructions.

To get an appropriate β function, we investigate different focusing structures.

- FODO focusing structure. According to our design, FODO period length is $8\lambda_w$, focusing field gradient is 17T/m and dispersing field gradient is 14T/m in x direction. With this FODO lattice and natural focusing of the planar undulator, average beta function of 26cm in both x and y direction are obtained, and the ratio β_{max}/β_{min} is about 2. GENESIS simulations show that the saturation length is about 3.6m; however, the position accuracy of focusing magnets should be better than 30um.
- FOFO focusing structure. To lower the position accuracy, it is necessary to decrease the focusing gradient. Considering the natural focusing of planar undulator in y direction, a FOFO focusing structure in x direction can be used. According to our design, focusing field gradient in x direction is 2T/m; focusing magnet length is $2\lambda_w$ and drift length is $10\lambda_w$, which lead to an elliptic transverse distribution of electron beams. GENESIS simulations show that the saturation length is about 4.3m.

The undulator is developed jointly by the Institute of High Energy Physics and Peking University. Prototype of the undulator has been completed; the quality of permanent magnets and the reliability of the construction have been validated.

R&D IN THE FIELD OF RF SC

Upgrade of DC-SC Photoinjector

As presented before, the DC-SC photoinjector test facility has been constructed at Peking University. Current tests indicate that the DC-SC injector is a good choice to provide moderate average current electron beams with low bunch charge and very high repetition rate.

Table 4: Parameters of the new photoinjector

2+1/2-cell cavity	
E_{acc}	15 MV/m
Drive laser	
Pulse length	10 ps
Spot radius	2 mm
Repetition rate	81.25 MHz
Electron bunch	
Charge/bunch	<60 pC
Energy	3.72 MeV
Energy spread (rms)	1.68%
Emittance (rms)	2.0 mm-mrad

To fulfil the requirements of PKU-FEL to the injector, it is necessary to upgrade the core elements of SC photoinjector-- DC gun and SC cavity. Voltage of the DC gun will rise to 150 keV, and accordingly, the structure of high voltage terminal will be improved which will lead to some changes in the structure of cryostat. A 2+1/2-cell cavity will be employed for the new injector. Design and optimization have been accomplished. Stamping technology and electron beam welding technology will be used to fabricate the new cavity. High-purity Nb plates (RRR>250, δ=2.8mm) from Ningxia of China will be chosen for the 2+1/2-cell cavity. Parameters of the new photoinjector are list in Table 4.

Quarter Wave Resonator (QWR) Cavities

Performance of Nb-sputtered copper SC cavities is determined by the quality of Nb films. With lots of effort, the performance of Nb films becomes almost the same with that of pure Nb under the condition of low gradient. However, the quality factor of cavity falls rapidly with the increase of gradient, which will greatly affect the applications of QWR cavity. We have been exploring new approaches to improve the SC performance. By inserting an NbN layer, we have changed the interface between Nb film and copper. Tests of samples indicate a change of the whole SC performance. Further studies on a 5 GHz module cavity are in progress.

CIAE is planning to insert an acceleration section after its tandem accelerator. 4 Nb-sputtered copper QWR SC cavities developed by our group will be employed. Now we are preparing for the fabrication of oxygen-free copper QWR cavities. First pressure forming will be adopted to reduce welding lines, and film forming technology will be improved to enhance purity and uniformity.

ERL

ERL light source is a rising star in the field of light source [6]. Peking University's Program 'SC Accelerator Based ERL Light Source' started in 2003. Our target is to provide multi-waveband FEL, which can be labeled 4th Generation Light Source. Researches on relative theory and experiments will be carried out accompanied with the construction of PKU-FEL.

For ERL, CSR effect arisen in bending magnets during electron beam recirculation is a dominating factor that affects the quality of electron beams, and it is also a critical factor that affects the operation of accelerator.

We'll mainly investigate the CSR effect arisen in bending magnets and its affect on energy spread of the electron beams. We'll also explore energy modulation, density modulation and what leads to micro bunch instability. Meanwhile, dispersion caused by bending magnets, coupling of electron beam transverse movements and longitudinal movements will bring on increase of transverse emittance. We'll analyze the trends of transverse emittance. We'll search for an approach to depress CSR effect; we'll optimize the bends of ERL facility; we'll control and keep the longitudinal momentum dispersion and transverse emittance of electron beams in admissible ranges; we'll also further investigate CSR effect. All of these play important roles in the lattice design of ERL facility, the design of bunch compressor and undulator/wiggler and the generation of THz radiation.

It is still a technical difficulty to generate and accelerate high average current (10~100mA) electron beams today. Fortunately, RF SC accelerating technologies have made it possible. Energy recovery technology based on SC accelerator is a critical approach to realize ERL light source. Experimental researches on energy recovery will be carried out in Peking University.

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