Design studies on the ERL-FEL test facility at IHEP, Beijing

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Abstract: A proposed compact ERL test facility at IHEP, Beijing, is presented in this paper, and includes the design parameters, the essential lattice, and the key components features, such as the photocathode DC gun and the CW superconducting accelerating structures. Some important beam physics issues such as the space charge effect, the coherent synchrotron radiation (CSR) effect and the beam break-up (BBU) effect are briefly described with the simulation results.

Key words: ERL, test facility, DC gun, CW superconducting accelerating structure, CSR, BBU

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1 Introduction

The linac-based free electron laser (FEL), and the energy recovery linac (ERL)-based light source are the two major types of fourth-generation light source. FEL has higher brightness, a shorter pulse length and higher coherent features, but minor photon beam lines. ERL combines the good beam performance of the linac and the good operation efficiency of the storage ring machine. Its brightness and coherent degree are not as higher as FEL, but it has many (more than 30) photon beam lines. Therefore, both FEL and ERL cannot replace each other, we need both of them. Based on this point, IHEP has suggested "one machine for two purposes". Both FEL and ERL will share the same super-conducting (SC) linac to have high efficiency [1].

The design study on the ERL-FEL test facility (ERL-TF) was started at IHEP and is well in progress. A compact ERL test facility is proposed at IHEP, Beijing, and is aimed at studying ERL's key technologies, involving the photocathode high-voltage DC gun, the low emittance injector, the

merger system, the CW multi-cell SC cavity and some beam physics problems including CSR, BBU effects, and so on. The main parameters of the test facility are listed in Table 1. Fig. 1 shows the ERL-TF layout. A 500 keV photocathode DC gun followed by a 5 MeV injector provides an electron beam for the SC linac, with a bunch length of (2–4) ps and normalized emittance of (1–2) mm·mrad. Two 1.3 GHz 7-cell SC cavities accelerate the 10 mA beam to 35 MeV. The beam circulating loop consists of two TBA arc sections and two straight sections. As the beam passes through the first TBA, the bunch length may be compressed to 0.5 ps (as one of the options), and then gets into

Table 1. The main parameters of the test facility.

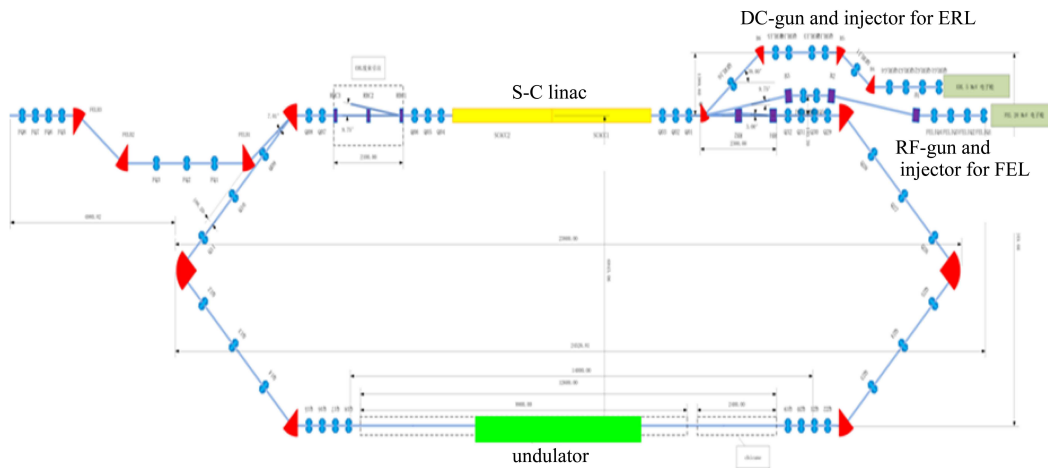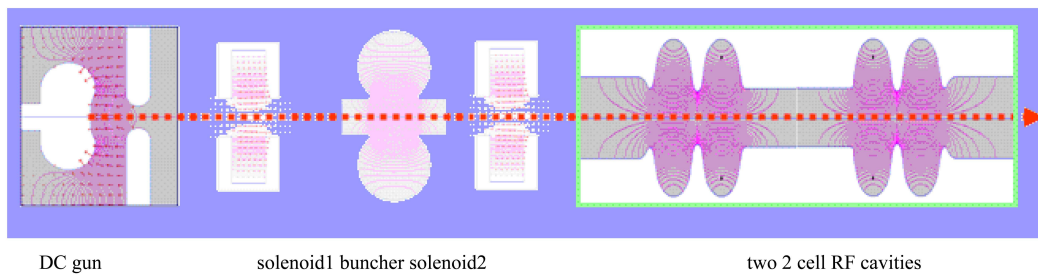|	
beam energy	35 MeV
beam current	10 mA
bunch charge	77 pC
normalized emittance	(1–2) mm·mrad
RMS energy spread	0.5%–1.0%
bunch length	(2–4) ps
bunch frequency	130 MHz
RF frequency	1300 MHz

Fig. 1. The layout of the test facility.

Fig. 2. The layout of the injector.

a wiggler at a south straight section to produce a co-herent THz wave with very high average power. The beam then passes through the second TBA and gets into the linac again to recover its beam energy to the structure at the deceleration RF phase. Then the 5 MeV beam gets into the beam dump.

2 Injector design

The injector for the ERL test facility includes one 500 keV DC gun with GaAs photocathode, two solenoids, one 1.3 GHz normal conducting RF buncher, and two 2-cell superconducting RF cavities as the energy booster. The layout is shown in Fig. 2.

2.1 The photocathode DC gun

To steadily support a 500 keV high voltage be-tween the cathode and the anode for the DC gun, be-sides employing an optimized ceramic insulator, pre-venting the emitted electrons from going towards the ceramic insulator is also very important. In our gun body design, the KEK/JAEA option is adopted [2], in which a segmented insulator structure with guard rings between every two adjacent segments is em-ployed to effectively stop the emitted electrons from moving towards the ceramic insulator, and therefore mitigating field emission, as shown in Fig. 3. The gun body and the guard rings are made of titanium alloy to minimize the gassing rate and to keep a very high vacuum in the gun. For a 500 kV high voltage, if the gap between the cathode and the anode is 12 cm, then the maximum field gradient on the cathode sur-face is 5.48 MV/m and the maximum gradient along the z axis is 6.45 MV/m [3].

Table 2. The main parameters of the DC gun.

high voltage	350–500 kV
cathode material	GaAs:Cs
quantum efficiency	5%–7%(initial), 1%
live time	20 h
driven laser	2.3 W, 530 nm
repetition rate	130 MHz, 1.3 GHz*
Nor. emittance	1–2 mm·mrad /77 pC/bunch; 0.1–0.2 mm·mrad /7.7 pC/bunch
bunch length	20 ps
bunch charge	77 pC
beam current	5–10 mA

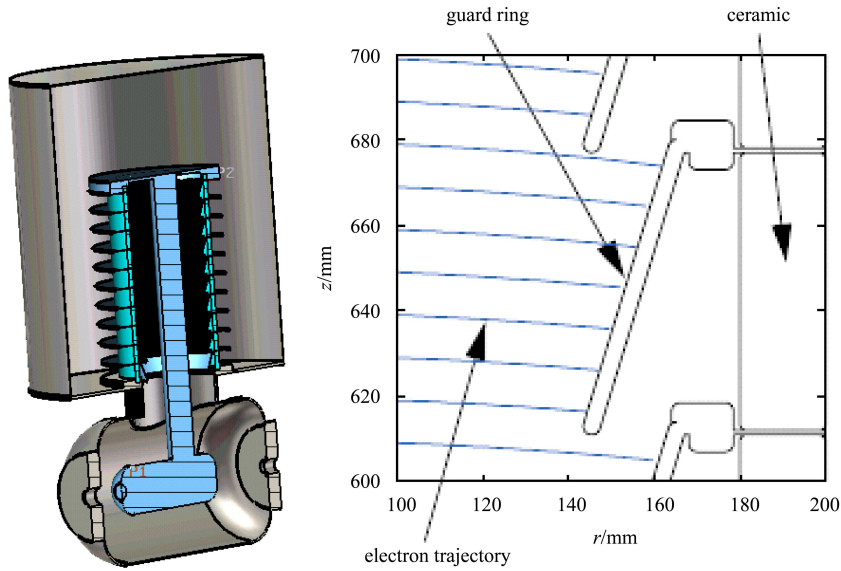∗ Two operation modes: (1) 130 MHz-10 mA-77 pC, (2) 1300 MHz-10 mA-7.7 pC.

Fig. 3. The DC gun with segmented insulators (left) and guard rings (right).

2.2 The 2-cell superconducting RF cavity

The 2-cell cavity's parameters are listed in Table 3. The electric field distribution is shown in Fig. 4.

Table 3. The ERL-TF 2-cell SC cavity parameters.

wave mode	standing wave
operation mode	TM010, π-mode
fundamental mode frequency	1300.000 MHz
accelerating gradient	15 MV/m
Q_0	1×10^{10}
effective length	0.2292 m
geometry factor (G)	274.5 Ω
R/Q	214.2 Ω
$G\cdot R/Q$	58776 Ω^2
$E_{\text{peak}}/E_{\text{acc}}$	2.02
$B_{\text{peak}}/E_{\text{acc}}$	4.2 mT/(MV/m)

Due to the high average beam current (10 mA), low accelerating gradient (5–15 MV/m) and small cell numbers, we firstly consider the HOM (higher order mode) suppression and lower the surface field in the structure, then lower the cryogenic loss of the fundamental mode (i.e. to increase the $G\cdot R/Q$). The shape of the cavity is based on the TESLA design but with one side beam pipe enlarged, so that most of the HOMs with frequencies higher than the cut-off frequency of the pipe (except a few quadrupole modes) can propagate to the HOM absorbers. The diameter of the beam pipe on the main coupler side is 78 mm (the same as the TESLA cavity), and on the other side the beam pipe is increased from 78 mm to 108 mm. The transition between the cavity and the large beam pipe is made with two arcs of R=6 mm and R=30 mm with multipacting free geometry [4]. To avoid a Q-value decrease in the fundamental mode by the HOM absorbers, the beam pipe length is relatively long (210 mm).
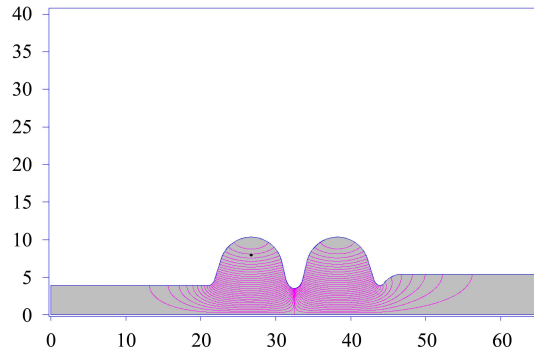

Fig. 4. The electric field distribution in the 2-cell cavity.

2.3 The injector beam simulation

The injector beam simulation aims at having small emittance, short bunch length, small energy spread and a compact structure. Because the field gradient in this gun is low, space charge is the dominant effect on the beam quality of a 77 pC bunch. The optimized simulation parameters are as follows. The laser RMS beam size is 1.2 mm with a longitudinal flat-top of 20 ps long, and the rise and down times are all 2 ps. In the photoemission process, the GaAs cathode is illumined by a 532 nm laser. Photoelectrons have an initial kinetic energy of 0.2 eV. The

thermal emittance due to the initial energy is taken into account in the simulation.

The two solenoids are used to have a reasonable transverse beam size in the buncher and in the energy booster. They can also have a slight emittance compensation effect. The bunching phase is chosen so that a good velocity modulation can be achieved for the original long bunch. The normal conducting RF cavity buncher can operate in CW mode with a water cooling system.

The two 2-cell SC RF cavities accelerate the beam from 0.713 MeV to 5 MeV. The maximum field gradient should be set to 20 MV/m. All the components of the injector are designed and optimized using the Superfish and Poisson codes, and the beam simulation along the injector is performed with the Astra code. The beam parameters at the exit of the injector are listed in Table 4 [3].

Table 4. The beam parameters at the injector exit.

beam energy	5 MeV
current	10 mA
normalized emittance	1.49 mm·mrad
RMS bunch length	0.67 mm (2.2 ps)
RMS energy spread	0.72%
total injector length (from cathode to the cryomodule exit)	3.2 m

3 Preliminary studies on ERL-TF beam physics

As shown in Fig. 1, two small emittance TBA arc sections, each composed of 45°-90°-45° three bends, are adopted to easily adjust the beam transport matrix elements of R56 and T556 to meet the right phase of the re-circulated beam at the linac entrance, and to easily adjust T166 and T266 to control beam emittance. The accelerating structures are placed in the north straight section and the insertion device is placed in the south straight section for high-power THz wave productions. The focusing strength of the quads in the acceleration area is optimized both for the accelerating and decelerating beams. A so-called "graded gradient" method [5] is used for this purpose, which makes the optics fully match the lower energy beam (due to its larger geometry emittance), and properly choose the beta function to control the beam envelope of the higher energy beam (due to its smaller geometry emittance).

To have a higher averaged power of the THz-FEL, the bunch length should be compressed before it arrives at the entrance of the insertion device. First we let the beam become accelerated at an RF phase of about 15° to increase the beam energy spread, then we use the first TBA to compress the bunch length from 2 ps to about 0.3 ps with a TBA R56 of 0.165, making the peak current increase by a factor of higher than six. The emittance growth caused by the bunch compression is about 35%. With a 1.5 m long wiggler, a THz coherent synchrotron radiation with a high average power of 270 W can be obtained, or a THz-FEL with an average power of 9 kW, using an optical oscillator cavity. The electron beam parameters, the insertion device parameter and the THz wave performance are listed in Table 5.

With the aim of a high average beam power, some of the major key issues of the ERL-TF are studied and briefly described in the following sections.

Table 5. THz beam performance at ERL-TF.

modes	electron beam		insertion device		THz wave performance	
	energy	20 MeV			wave length	0.15–1mm
	bunch length	0.5 ps	period	60 mm	frequency	0.3–2 THz
CSR	Emittance	2 μm	gap	9–23 mm	peak power	2 MW
	energy spread	0.5%	length	1.5 m	average power	270 W
	peak current	62 A				
	energy	35 MeV				
	bunch length	4 ps	period	60 mm	wave length	21–50 μm
oscillator	emittance	2 μm	gap	23–32 mm	peak power	7 MW
	energy spread	0.5%	length	1.5 m	average power	9 kW
	peak current	20 A				

3.1 The space charge effect

The space charge effect play an important role in the low-energy injector system, in which the 500 keV beam from the gun is bunched with a single bunch cavity and boosted to 5 MeV by two 2-cell SC cavities and some focusing elements. The PARMELA simulation shows that the beam emittance is increased from 1 μm to about 1.5 μm (with a bunch length of 2 ps and a bunch charge of 77 pC) due to the space charge effect. Further optimization on this issue is currently underway.

3.2 The coherent synchrotron radiation (CSR) effect

A high current and short bunch beam could be affected by the CSR in the bending magnet, in which the CSR produced by the head part of the bunch may have an effect on the tail part of the bunch after the bending magnet, and causes emittance growth. Our simulation result with the Elgent code [6] shows that with beam parameters of 77 pC-2 ps -1 mm·mrad-10 mA, the CSR effects in the TBA sections are not so important, and by properly optimizing some of the optics parameters, the emittance growth can be controlled within about 2%.

3.3 The beam break-up (BBU) effect

In the high average current SC linac, the BBU effect caused by some HOMs in the SC cavity may be one of the most critical issues to limit the beam current. To suppress this effect, the most effective way is to control the R/Q of the HOMs and optimize the beam optics. Our simulation results with a BBU-code for ERL [7] show that with the HOM parameters of Cornell's 7-cell ERL SC cavities [8], and with our ERL-TF parameters, the BBU current limitation could be higher than 200 mA. For the BBU effects, the simulation and experimental results agree well with each other at JLab's ERL facility, and many labs worldwide have done a lot of studies on the above effects and obtained positive results to cure these effects [9–11].

4 Preliminary design studies on the ERL-TF 7-cell SC cavities

For the design of the SC cavities of the main linac, the following factors are considered: 1) lowering the cryogenic loss with large GR/Q; 2) lowering the HOM impedance (which is related to the cavity configuration and the location of the HOM absorber) about one order of magnitude than the ILC and XFEL cavities, and avoiding HOM frequencies around the multiples of the fundamental mode; 3) a small electromagnetic surface field; 4) a large bandwidth of dipole modes, to decrease the frequency error due to fabrication error; and 5) magnetic field shielding (less than 10 mG).

The preliminary parameters of the cavity are listed in Table 6. The cavity shape and HOM impedance will be further optimized according to the beam dynamics requirements.

Table 6. The ERL-TF 7-cell SC cavity parameters.

fundamental frequency f_0	1.3 GHz
cavity voltage V_c	15 MV
effective length L_{eff}	0.8 m
accelerating gradient E_{acc}	18.8 MV/m
Q_0	$> 10^{10}$
Q_L	2×10^7
bandwidth	65 Hz
R/Q	800 Ω
iris diameter	72 mm
large beam pipe diameter	110 mm
small beam pipe diameter	78 mm
geometry factor (G)	270 Ω
E_{peak}/E_{acc}	2.06
B_{peak}/E_{acc}	4.2 mT/(MV/m)
longitudinal loss factor*	13.1 V/pC
transverse loss factor*	13.7 V/pC/m

∗ with bunch length 0.6 mm.

5 Summary

In this paper, we briefly described the major issues of the design studies on the ERL-FEL test facility at IHEP, Beijing, including the design parameters, the essential lattice and the key components features, such as the photocathode DC gun and the CW superconducting accelerating structures. Some important beam physics issues, such as space charge effects, CSR and BBU effects are described with the simulation results. A conceptual design report on the ERL-FEL test facility [12] and a 500 kV DC gun preliminary design report [13] are prepared. They describe all aspects of the test facility, such as the beam physics, accelerating structure, RF power supply and LLRF, the cryogenic system, magnet and power supply, vacuum system, beam instrumentation and control system, radiation protection and some utilities. The results of these studies have established the essential foundations to further promote ERL-FEL studies at IHEP.

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