DESIGN STUDIES ON THE ERL TEST FACILITY AT IHEP-BEIJING

S.H.Wang, J.Q.Wang, S.Y. Chen, Y.L.Chi, G.W. Wang, J.S. Cao, S.G. Liu, J.Gao, J.Y. Zhai, W.B.Liu, X.H.Cui, J.Q. Xu, Z.S. Zhou, X.P. Li, H.H. Lu, Q. Xiao
Institute of High Energy Physics, CAS, Beijing 100049, China

Abstract

A compact ERL test facility has been proposed at IHEP-Beijing. The design study is briefly presented, including the main parameters, essential lattice and the features of the key components, such as photo-cathode DC gun and CW superconducting accelerating structures. Some important beam physics issues such as space charge effects, coherent synchrotron radiation (CSR) effect and beam break-up (BBU) effects are described with the simulation results.

INTRODUCTION

The linac based Free Electron Laser (FEL), and the Energy Recovery Linac (ERL) based light source are the two major types of the 4th generation light source. FEL has higher brightness, shorter pulse length and higher coherent features, but with a minor photon beam lines. ERL combines the good beam performance of the linac and good operation efficiency of the storage ring machine, although its brightness and coherent degree not as higher as FEL, but with many (more than 30) photon beam lines. Hence, both FEL and ERL cannot be replaced each other, we really need both of them. Based on this point, IHEP has proposed a suggestion of “one machine two purposes”, both FEL and ERL will share a same super-conducting (SC) linac for having a high efficiency [1]. The design study on the ERL-FEL Test Facility (ERL-TF) has been started at IHEP and being well progressed.

A compact ERL Test Facility is proposed at IHEP-Beijing, aiming at studying the ERL’s key technology, such as photo-cathode high voltage DC gun, low emittance injector, merger system, 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. Figure 1 shows the ERL-TF layout. A 500 keV photo-cathode DC gun followed by a 5 MeV injector provide electron beam for the SC linac, with 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 beam passing through the 1st TBA, the bunch length may be compressed to 0.5 ps (as one of the options), and then get into a wiggler at south straight section to produce a coherent THz wave with very high average power. Then beam passes the 2nd 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. Table 1 shows the main parameters of the ERL-TF.

Table 1: 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
Beam energy	35 MeV

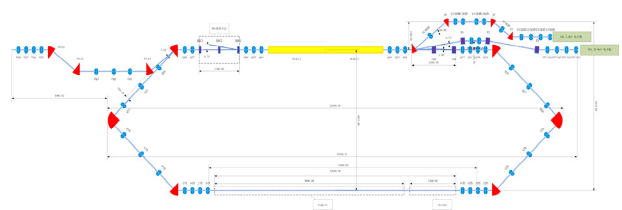

Figure 1: L Layout of the test facility.

INJECTOR DESIGN

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

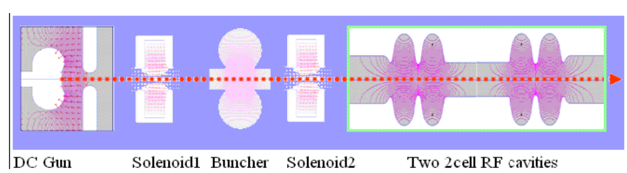

Figure 2: Injector Layout.

Photo-cathode DC Gun

To steady support a 500 keV high voltage between cathode and anode for the DC gun, besides employing an optimized ceramic insulator, avoiding the emitted electrons on 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 employed to effectively avoid the emitted electrons toward the ceramic insulator and hence to mitigate field emission, as shown in Figure 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 cathode and anode is 12 cm, then the maximum field gradient on the cathode surface is

ISBN 978-3-95450-145-8

5.48MV/m and the maximum gradient along z axis is 6.45MV/m [3]. Recently, IHEP has decided to fund this gun's construction.

Table 2: 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	2.3W, 530nm
Repetition rate	130MHz , 1.3GHz*
Nor. emittance	(1~2)mm.mrad@77pC/bunch; (0.1~0.2)mm.mrad@7.7pC/bunch
Bunch length	20ps
Bunch charge	77pC
Beam current	(5~10) mA
High voltage	350 ~ 500 kV

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

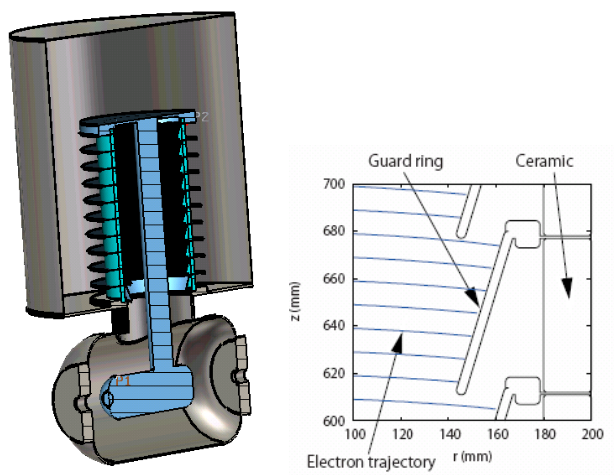

Figure 3: DC gun with segmented insulators (left) and guard rings(right).

2-cell Superconducting RF Cavity

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

Table 3: 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_{peak} / E_{acc}	2.02
B_{peak} / E_{acc}	4.2 mT / (MV / m)
Wave mode	Standing wave

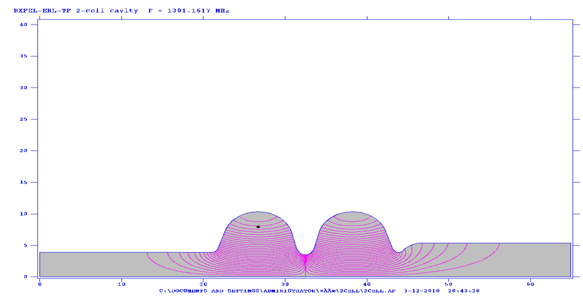

Figure 4: Electric field distribution in 2-cell cavity.

Due to the high average beam current (10 mA) , low accelerating gradient (5 ~ 15 MV/m) and small cell numbers, we firstly consider the HOMs (Higher Order Modes) suppression and to lower the surface field in the structure, then to lower the cryogenic loss of the fundamental mode (i.e. increase the G • R / Q). The cavity shape 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 (same as TESLA cavity), and in the other side the beam pipe is increased from 78 mm to 108 mm. The transition between the cavity and large beam pipe is made with two arcs of R = 6 mm and R = 30 mm with multi-pacting free geometry [4]. To avoid Q-value decrease of the fundamental mode by the HOM absorbers, the beam pipe length is relatively long (210 mm).

Injector Beam Simulation

The injector beam simulation aims at having small emittance, short bunch length, small energy spread and compact structure. Because the field gradient in this gun is low, the space charge is the dominated effect to the beam quality of a 77pC bunch. The optimised parameters for simulation are as following: Laser RMS beam size is 1.2mm with longitudinal flat-top of 20ps long, rise and down time are all 2ps. In the photoemission process, GaAs cathode is illumined by 532nm laser. Photoelectrons have initial kinetic energy of 0.2eV. 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. A little bit emittance compensation effect can be made by them also. The bunching phase is so 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 0.713MeV to 5MeV. The maximum field gradient should be set to 20MV/m. All components of the injector are designed and optimized with SUPERFISH and POISSION code. The beam simulation along the injector

ISBN 978-3-95450-145-8

is performed with ASTRA code. The beam parameters at the injector exit are listed in Table 4.

Table 4: 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

PRELIMINARY STUDIES ON THE ERL-TF BEAM PHYSICS

As shown in Figure 1 two small emittance TBA arc sections, each composed of 45o-90o-45o three bends, are adopted to easily adjust the beam transport matrix elements of R56 and T556 for meeting the right phase of the re-circulated beam at the linac entrance, and to easily adjust T166 and T266 to control the 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 are optimised both for accelerating and decelerating beams. A so called "Graded Gradient" method [5] is used for this purpose, which makes the optics fully matching to the lower energy beam (due to its larger geometry emittance), and properly chose 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 let the beam to be accelerated at the RF phase of about 15° to increase the beam energy spread as well, then using the 1st TBA to compress the bunch length from 2 ps to about 0.3 ps with a TBA's R56 of 0.165, making the peak current to be increased by a factor of higher than 6. The emittance growth caused by the bunch compression is about 35%. With a 1.5 m long wiggler, a THz coherent synchrotron radiation with high average power of 270 W can be obtained, or a THz-FEL with average power of 9 kW by using an optical oscillator cavity. The electron beam parameters, insertion device parameter and the THz wave performance are listed in Table 5.

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

Space Charge Effects

It plays 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 is boosted to 5 MeV by two 2-Cell SC cavities and with some focusing elements as well. The PARMELA simulation shows the bean emittance is increased from 1μm to about 1.5μm (with bunch length of 2 ps and bunch charge of 77 pC) due to the space charge effect. The further optimisation on this issue is under the way.

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 affects on the tail part of the bunch after a bending magnet and causes an emittance growth. Our simulation result with ELGENT code [6] shows that with beam parameters of 77pC-2ps - 1mm-mrad-10 mA the CSR effects in the TBA sections are not so important, and by properly optimising some optics parameters, the emittance growth can be controlled within about 2%. However, for the CSR mode operation the test facility, the bunch length should be suppressed to about 0.2ps. In this case, the CSR effect will cause emittance growth. The so called "envelop matching method [6]" is used. Detailed is described in [7]. The preliminary results show that the emittance growth is about 30% due to CSR with the orientation of the phase ellipse set parallel to the CSR kick by scanning the Twiss parameters at the arc exit.

Table 5: THz Performance and Beam Parameters

FEL Mode		CSR	Oscillator
Beam	Energy (MeV)	20	35
	Bunch length (ps)	0.5	4
	Emittance (μm)	2	2
	Energy spread (%)	0.5	0.5
	Peak current (A)	62	20
ID	Period length (mm)	60	60
	Gap (mm)	9-23	23-32
	Length (m)	1.5	1.5
FEL	Wave length (μm) Freq. (THz)	0.15-1 0.3-2	21-50
	Peak power (MW)	2	7
	Average power (kW)	0.27	9

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 well control the R/Q of the HOMs and well optimizes the beam optics. Our simulation results with a BBU-code for ERL [8] shows that with HOM's parameters of JLab 7-cell ERL SC cavities [9] and with our ERL-TF parameters the BBU current limitation could be higher than 200mA. For the BBU effects the simulation and experimental results can be well agreed with each other at JLab's ERL facility and many labs worldwide have done a lot of studies on above effects, and obtained their positive results to cure these effects [11-13].

Energy Compression with Return ARC

Downstream the undulator, the beam energy spread is enlarged. While decelerated through the Linac, relative energy spread is increasing. This energy spread can be

ISBN 978-3-95450-145-8

reduced by rotating the bunch in the longitudinal phase space, as so called Energy Compression [14]. In our ERL-TF, energy compression [7] is done by setting the return arc (2nd TBA arc) non-isochronous, and tuning the deceleration phase in the linac. To stretch the bunch length, R56 =-0.16 is set in the return arc, with RF phase around 193°, the energy spread could be controlled down to ~ 1.5%.

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) Lower the cryogenic loss with large G • R / Q; 2) Lower 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 to avoid HOM frequencies around the multiples of the fundamental mode; 3) small electromagnetic surface field; 4) Large bandwidth of dipole modes, to decrease the frequency error due to fabrication error; 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 optimised according to the beam dynamics requirements.

Table 6: 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)

* with bunch length 0.6 mm.

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, essential lattice and the features of the key components, such as photo-cathode DC gun and 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 Concept Design Report on the ERL-FEL Test Facility [15] and a 500 kV-DC Gun Preliminary Design Report [16] are prepared. They described all aspects of the test facility, such as beam physics, accelerating structure, RF power supply and LLRF, cryogenic system, magnet and power supply, vacuum system, beam instrumentation and control system, radiation protection and some utilities. These studies results established essential foundations to further promote the ERL-FEL studies at IHEP.

REFERENCES

[1] CHEN Senyu, ZHU Xiongwei and WANG Shuhong, “Towards one machine two purposes: using a common SC linac for XFEL and ERL simultaneously”, Chinese Physics C 34. 1, Jan., 2010.
[2] R. Nagai, et al, “High-Voltage Test of a 500-kV Photocathode DC Gun for the ERL Light Sources in Japan”, Proceedings of IPAC’10, Kyoto, Japan.
[3] LIU Shengguang and XU Jinqiang, Design Studies on a 500 kV DC gun photo-injector for the BXFEL test facility, Chinese Physics C 35. 1, Jan. 2011.
[4] S. Belomestnykh, V. Shemelin, Multipacting-free transitions between cavities and beam-pipes. Nuclear Instruments and Methods in Physics Research A 595 (2008) 293–298.
[5] Douglas D., Design Consideration for Recirculating and Energy Recovering Linac, JLAB-TN-00-027, November 2000.
[6] Borland M. "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," Advanced Photon Source LS-287, sept. 2008.
[7] R. Hajima, APAC2004.
[8] X.H. Cui, this workshop.
[9] JIAO Yi, A BBU code developed with C language implanted in Matlab environment, private communication.
[10] Mayes C.E. and Hoffstaetter G.H, Coherent Synchrotron Radiation Simulation for the Cornell ERL, Proceedings of IPAC 2010, TUPE-097, Kyoto, Japan.
[11] Merminga L.et al, High Average Current Effects In Energy Recovery Linacs, Proceedings 2001 Particle Accelerator Conference, Chicago, IL, 18-22 June 2001.
[12] Douglas D., “Operational” Beam Dynamics Issues, Talk to ERL-09, Cornell, 2009.
[13] Campisi I.E. et al, Beam Breakup Simulations for the Jefferson Lab FEL Upgrade, Proceedings of 1999 Particle Accelerator Conference,NY, USA 27 March-2 April 1999.
[14] P. Pilot, et al, Phys. Rev. ST Accel. Beams 6 (2003) 0.0702)
[15] Concept Design Report on the IHEP-ERL-FEL Test Facility (CDR-0, in Chinese), 2010.10.
[16] Preliminary Design Report on the IHEP-500kV-DC-Gun (in Chinese), 2011.2.

ISBN 978-3-95450-145-8