INJECTOR DESIGN FOR THE JAERI-FEL ENERGY-RECOVERY TRANSPORT

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Abstract

The energy-recovery experiments are planned at the JAERI-FEL facility for increasing lasing power. The main recirculating beam line consists of two 7.5 MV superconducting accelerators, an optical resonator of a 52 period hybrid planer undulator, and two sets of an 180° arc with three 60° bends. In this paper, we report on the design of injector for the above recirculating beam line. The transversal and longitudinal beam dynamics is studied with space charge included. The details of the simulated performance of the injector are presented.

1 INTRODUCTION

The JAERI free electron laser (FEL) facility has been constructed to produce a high power FEL at wavelength in far-infrared region (20-30μm). Recently, laser output power over 1.7 kW in average was achieved with 500 μs macro pulse duration at repetition rate of 10 MHz [1]. For further increasing the FEL power, energy recovery experiments are planned. In this scheme, the electron beam is reinjected to the same rf modules as used for the acceleration, but at the decelerating phase. The beam power can then be transferred to the rf cavities, and recycled for acceleration. Therefore, an electron beam with higher average current can be accelerated with minimum rf power supplement, which would enable a high power FEL operation. The conceptual design of the main recirculating beam line is discussed in ref. [2].

In this paper, we focus on discussing the injection system for the energy-recovery transport. In section 2, the major beam line elements and the design principles are described. Results of the beam dynamics simulation are presented in section 3.

2 DESIGN PRINCIPLES

The injector beam line can be separated into three parts. The first section (Fig. 1) consists of a 230 kV electron gun and an 83.3 MHz sub harmonic buncher (SHB) followed by two units of a 500 MHz superconducting rf one-cell cryomodule. The lattice geometry in this section is the same for the non-energy-recovery operation [1]. The electron gun is a grid structure type with a thermionic cathode. In order to prevent emittance growth due to space charge forces, a high voltage of 230 kV is applied, and the first solenoid is placed as close to the gun as possible. The electron gun parameters are listed in Table 1. The bunched beam is compressed by means of energy modulation of the SHB field. The path length between the SHB and the pre-accelerator is selected to optimize the longitudinal phase space parameters at the entrance to the first pre-accelerator. In the final of this section, the electrons gain energy up to 2.7 MeV at the two pre-accelerators with an electric field gradient of 4.5 MV/m.

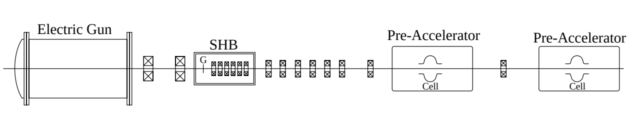

Figure 1: Schematic layout of the injection beam line from the electric gun to the pre-accelerators.

Table 1: Electron gun parameters

Accelerated voltage	230 kV
Charge per pulse	0.6 nC
RMS pulse width	0.34 ns
RMS beam radius	1.6 mm
Normalized RMS emittance	14 πmm-mrad

The second part of the injection system is a matching section (Fig. 2). The path length should be about 10 m long due to the building structure of the accelerating room. In this section, two quadrupole triplets and one quadrupole doublet are placed in nearly equal separation.

The remainder of the injector components is a magnetic buncher which is necessary to merge the injected and recirculated beams before the main cryomodule. For injecting high quality electron beam to the main cryomodule, the buncher should meet several requirements; (1)The magnetic lattice should be achromatic to avoid beam degradation at the exit; (2)The lattice geometry should be symmetric or anti-symmetric; (3)The bending angle should be small as possible. Satisfying the last two requirements would contribute to construct a compact achromatic array. After several types of achromatic buncher were investigated, we chose a staircase buncher with all the above requirements being fulfilled (Fig. 2). Following the buncher, the beam enters a quadrupole triplet lens for matching into the main cryomodule. Since the recirculated beam has about 7 times higher energy than the injected beam, the matching quadrupole triplet would little disturb the recirculated beam transport.

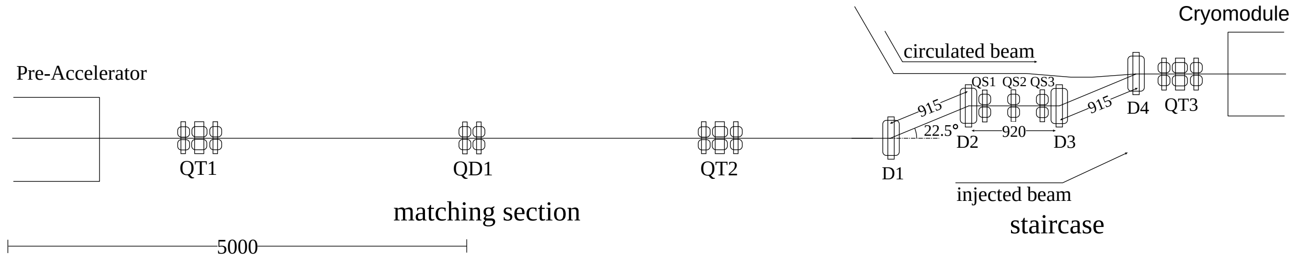

Figure 2: Schematic layout of the beam line from the pre-accelerator to the entrance of the main cryomodule, showing the matching section and the staircase buncher.

3 SIMULATED PERFORMANCE

3.1 Transport to Pre-Accelerators

The horizontal and vertical beam envelope functions are calculated with TRACE3D [3] as shown in Fig. 3a. Solenoid lenses are used for optimization of the transversal beam profiles. The beam is focused as a waist at the SHB gap and the pre-accelerator entrance to minimize emittance growth arising from time-dependent transversal rf fields. Since the space charge force causes a large emittance growth especially for low energy electrons, its effects to the transversal motion must be considered. In the linear space charge regime [4], the normalized rms emittance growth is estimated as $\Delta\epsilon^{\rm n}_{\rm rms} = 10 \sim 25\pi$ mm-mrad at the entrance to the first pre-accelerator, which is similar amount to the initial emittance at the exit of the electron gun. However, it is pointed out that the emittance growth by the linear space charge can be reduced by placing solenoid fields at the proper location [5]. Practically, the emittance compensation for the JAERI injector is done by parallel beam transport using a series of the solenoid lenses as shown in Fig. 3a. The transversal emittance calculated with PARMELA [6] is shown in Fig. 3b. While no emittance growth appears in the first 4-m section, an abrupt increase at the last solenoid position is due to the change in the beam radius. Because this emittance growth can be eliminated by placing the solenoid closely to the cavity, an installation of a solenoid lens at closer location to the first cavity is planned.

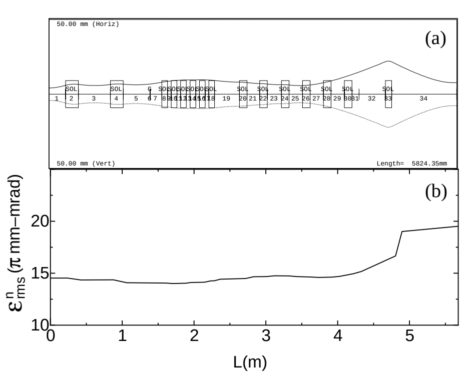

Figure 3: Horizontal and vertical beam envelope functions from the electric gun to the pre-accelerator are shown in upper panel(a). In lower panel(b), calculated emittance is shown.

The longitudinal motion with space charge included is also simulated using PARMELA. In Fig. 4, the axial phase space distributions at several different positions are shown. For optimal bunching, the applied voltage and the rf phase of the buncher is set as 75 kV and 10° off zero-crossing toward the decelerating direction. After the 4.5 m drifting space, the electron beam enters the first pre-accelerator (Fig. 4c). Since the velocity of the electrons is $0.71c$ and the rf phase velocity of the cavity is speed-of-light, both the longitudinal and transversal rf focusing effects suddenly change with the rf phase of the first pre-accelerator. For optimizing the longitudinal phase and minimizing the transversal emittances, the rf phase of the first cavity is chosen as 15° off the maximum beam loading phase toward the debunching direction (Fig. 4d). Furthermore, the

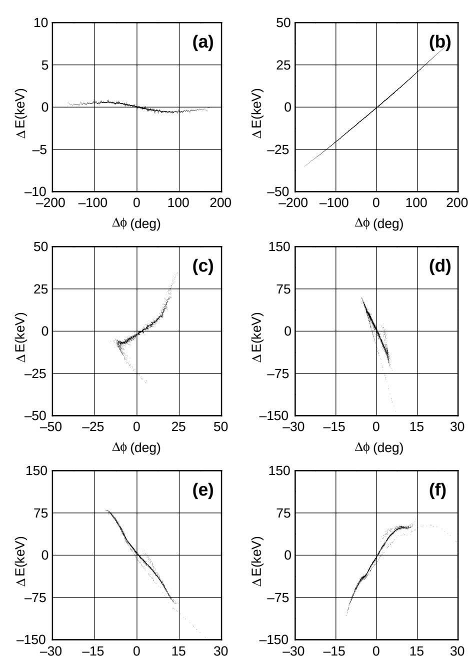

Figure 4: Longitudinal phase space distributions at (a) entrance to the SHB, (b) exit of the SHB, (c) entrance to the first cell, (d) exit of the first cell, (e) entrance to the second cell, (f) exit of the second cell.

best longitudinal phase space distribution for the entrance to the staircase buncher is accomplished with 32° off-crest phase toward the bunching direction for the second pre-accelerator.

3.2 Staircase Buncher

The staircase buncher consists of four rectangle dipoles with bending angle of 22.5°. Achromatic condition is kept by properly adjusting strength of two quadruple singlets (QS1, QS3) beside the second and third dipoles. One quadrupole singlet (QS2) at the center is used to optimize beam envelope functions at the buncher exit. The betatron and dispersion functions are shown in Fig. 5 calculated with TRANSPORT [7].

The buncher is achromatic without space charges. In this case the emittance growth is negligible to the first order. With space charges, both the electron beam energy and radial velocities are modified from magnet to magnet that cause a horizontal emittance growth [4]. However, this effect can be minimized when the beam enters with a waist to the buncher entrance in the bending plane. The normalized rms emittances are calculated with PARMELA including space charges as $\epsilon_{\rm x} = \epsilon_{\rm y} = 20\pi$ mm-mrad at the entrance and $\epsilon_{\rm x} = 26\pi$, $\epsilon_{\rm y} = 22\pi$ mm-mrad at the exit.

This staircase buncher is non-isochronous with $R_{56} = -0.34$ m. The axial bunching condition is satisfied by tuning the rf phase of the second pre-accelerator. Figure 6 shows the longitudinal phase space distributions at the entrance to the main cryomodule calculated with PARMELA. The axial beam parameters are obtained as rms bunch length $\sigma_{\rm t}$ =7 ps and rms energy spread $\Delta E/E =$ 0.4 % at 2.6 MeV. The optimized beam parameters at the entrance to the main cryomodule are summarized in Table 2.

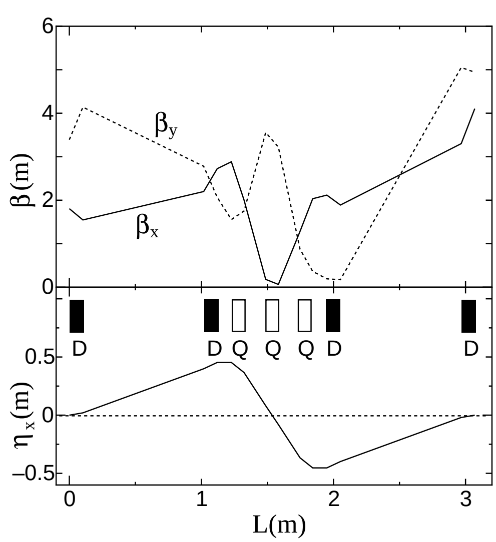

Figure 5: Horizontal and vertical betatron functions (upper panel) and horizontal dispersion function (lower panel) from the pre-accelerator to the main cryomodule through the staircase buncher.

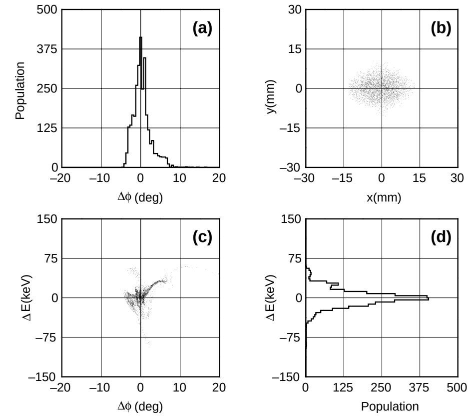

Figure 6: Various distributions of the longitudinal phase space at the entrance to the main cryomodule, with the optimized design performance.

Table 2: Optimized beam parameters at the entrance to the main cryomodule.

Beam energy	2.6 MeV
RMS energy spread	0.4 %
RMS pulse width	7 ps
Normalized RMS emittances H/V	$27\pi/24\pi$ mm-mrad

REFERENCES

[1] N. Nishimori et al., in these proceedings.

[2] R. Hajima et al., Nucl.Inst.Meth. **A**445 (2000) 384-388.

[3] K.R. Crandall and D.P. Rusthoi, LA-UR-97-886 (1997).

[4] B.E. Carlsten and T.O. Raubenheimer, Phys.Rev.E 51(1995)1453.

[5] B.E. Carlsten, Nucl.Inst.Meth. **A**285 (1989) 313-319.

[6] L.M. Young, private communication.

[7] D.C. Carey, K.L. Brown and F. Rothacker, FERMILAB-Pub-98/310.