BEAM OPTICS STUDY FOR THE COMPACT ERL IN JAPAN

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Abstract

Beam optics of the compact ERL was studied with the simulation code "elegant" including CSR(Coherent Synchrotron Radiation) effects and optimized for each of three operation modes. In the optimized optics of HC(High Current) and LE(Low Emittance) modes, the normalized emittance was well preserved and excellent energy recovery was achieved. In the optimized optics of BC(Bunch Compression) mode, an ultra-short bunch of several tens picoseconds was achieved and the horizontal and vertical beam sizes were well suppressed by tuning the betatron functions and the decelerating RF phase to transport the beam to the beam dump without serious beam loss. In this paper, we present the results of the design study on the compact ERL optics.

OVERVIEW OF THE COMPACT ERL

A compact ERL(energy recovery linac) is planned to be constructed in Japan in order to demonstrate excellent ERL performances and to test key components such as low-emittance photocathode gun and superconducting RF cavity[1]. The layout of the compact ERL is shown in Fig. 1. The compact ERL consists of two TBA(triple bend achromat) arc sections, two long straight sections and injector and dump sections. The injector section generates the bunched beam and accelerates the beam to 5 MeV. Two main superconducting(SC) cavity modules in one long straight section accelerate the beam to 85-165 MeV for the acceleration field of 10-20 MV/m and also decelerate the accelerated beam down to the injection energy level for energy recovery. The other long straight section has a chicane system generating an orbit bump for tuning the orbit path length and hence the decelerating RF phases of the main SC cavity modules. It can also be used for insertion devices and SR user experiments. The two TBA arc sections can control the bunch length using their quadrupole and sextupole magnets. The compact ERL has three operation modes: HC(High Current), LE(Low Emittance) and BC(Bunch Compression) modes, which can realize a high current of 100 mA, a low normalized emittance of 0.1 mm·mrad and a ultra-short bunch of less than 100 fs, respectively. Table 1 lists the parameters of the compact ERL used for our beam optics study.

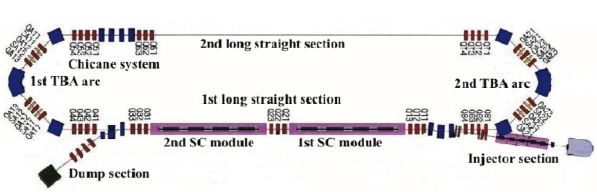

Figure 1: Layout of the compact ERL.

Table 1: Parameters of the compact ERL for three modes

Parameter	HC	LE	BC
RF frequency[GHz]	1.3		
Beam energy[MeV]	85-165		
Injection energy[MeV]	5 (10)*		
Injection rate [GHz]	1.3	1.3	≤ 0.001
Beam current[mA]	100	10	-
Bunch charge[pC]	77	7.7	≥ 77
Emittance**[mm·mrad]	1	0.1	-
Bunch length[ps]	1-3	1-3	< 0.1

*Increased up to 10 MeV, **Normalized emittance

DESIGN CONDITION AND STRATEGY

In the beam optics study of the compact ERL with elegant[2], the injector section including three bending magnets for injection was not considered and an initial beam with six-dimensional Gaussian distribution was given at the exit of the injector section. The initial horizontal and vertical betatron functions and their derivatives were assumed to be 20 m and zero. The bending magnets of the chicane system were normally turned off and effects of the bending magnets in the chicane and extraction systems on the optics were neglected.

In the compact ERL, R_{56} of the 1st arc section was utilized for the bunch compression. This parameter is expressed by

$$R_{56} = \int_C \frac{\eta}{\rho} ds \quad , \qquad (1)$$

where η and ρ are the dispersion function and the bending radius in a section C. The deviation of the path length Δz or the time delay Δt is given by

$$\Delta z = c\beta\Delta t = R_{56}\frac{\Delta p}{p} + T_{566}\left(\frac{\Delta p}{p}\right)^2 + \ldots \quad . \qquad (2)$$

Here Δp is the momentum deviation from the reference momentum p and T_{566} is the 2nd order coefficient of the transfer matrix elements. In BC mode, the optimum R_{56} value of the 1st arc section for bunch compression is approximately expressed with the accelerating RF phase ϕ_{RF} and the RF wave number k_{RF} as follows:

$$R_{56} \cong \frac{1}{k_{RF}\, \sin \phi_{RF}} \quad . \qquad (3)$$

The detail of the R_{56} setting is shown in ref. [3]. R_{56} of the 2nd arc section is normally set to the same value with the opposite sign to recover the bunch length.

The design procedure for the compact ERL optics is as follows:

- R_{56}'s of the 1st and 2nd TBA arc sections are set to the optimum values for each operation mode. The dispersion function and its derivative are set to zero at the entrances and exits of the arc sections.

- Field strengths of the quadrupole magnets Q11–Q33 in the 1st long straight section are optimized to reduce the horizontal and vertical betatron functions. In this section, the beam passes them twice with different energies and the quadrupole magnets more affect the beam optics of the lower energy.
- Field strengths of the other quadrupole magnets in the compact ERL are also optimized to reduce the betatron functions.
- In BC mode, field strengths of the sextupole magnets (SA11 and SA12) in the 1st arc section and the accelerating phase of the 1st SC cavity module are decided at the same time to minimize the bunch length at its exit by cancelling the R_{56} and T_{566} terms in Eq. (2).
- Some of the quadrupole magnets are readjusted and the sextupole magnets of the 2nd arc section are used, if necessary, to avoid serious beam loss due to large beam sizes especially after the deceleration.

RESULTS

In the simulations, the acceleration field and the initial momentum spread were normally set to 15 MV/m and 2×10^{-3}. The energy of the accelerated beam with 15 MV/m was about $(15 \times 8 \times \cos\phi_{RF} + 5)$ MeV.

HC and LE Modes

Since bunch compression was not required in these modes, R_{56}'s of the arc sections were set to zero and all the sextupole magnets were turned off. Figure 2 shows the betatron and dispersion functions of the compact ERL in the two modes. The accelerating phase of the SC cavities were set to about -1.1 degrees, taking account of difference between the RF field and beam velocities, in order to minimize momentum dependence of the longitudinal position distribution.

The initial normalized emittance and the bunch charge were 1 mm·mrad and 77 pC in HC mode and 0.1 mm·mrad and 7.7 pC in LE mode. In both modes, the horizontal emittance at the exit of the 1st arc section was increased from the initial emittance by the CSR effects. It also increased with decreasing the initial bunch length, as shown in Fig. 3, because a shorter bunch caused stronger CSR effects in the arc section. In HC mode, since a 100-mA beam with a bunch length of 1 ps or less causes high parasitic loss in the SC cavities[4] as well as the large emittance growth due to the CSR effects, the initial bunch length of 2-3 ps is desired in HC mode. In LE mode, the emittance growth in the 1st arc section was less than 4 % for the initial bunch length of 2-3 ps.

Figure 4 shows the horizontal and vertical beam sizes along the longitudinal beam position for the initial bunch of 2 ps in HC mode. Since the maximum beam size is sufficiently small compared with a typical vacuum-duct half-aperture of 25 mm, serious beam loss can be avoided. The maximum beam size in LE mode was about 0.7 mm and smaller than that of HC mode. The energy recovery efficiencies of the SC cavity modules in HC and LE modes were evaluated to be higher than 99.96 % and 99.98 % by calculating difference between averaged beam energies after the acceleration and deceleration.

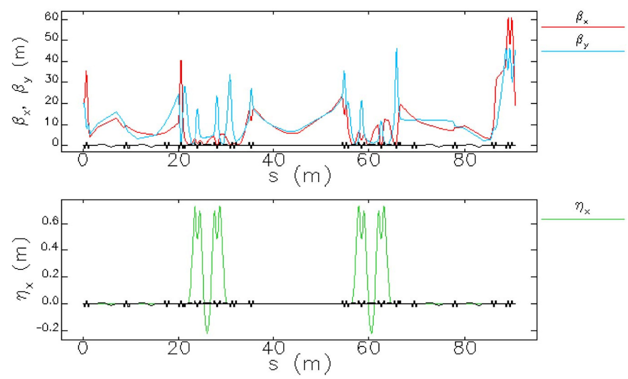

Figure 2: Betatron and dispersion functions of the compact ERL in HC mode.

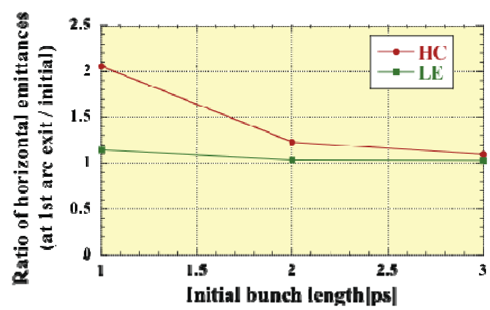

Figure 3: Dependence of normalized horizontal emittance on initial bunch length. The initial emittances are 1 and 0.1 mm·mrad for HC and LE modes, respectively.

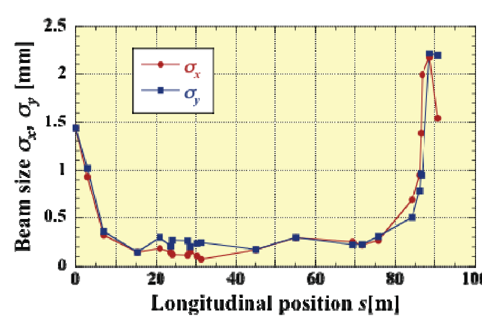

Figure 4: Horizontal and vertical beam sizes along longitudinal position for the initial bunch length of 2ps in HC mode.

BC Mode

The initial accelerating phases of the SC cavity modules were first set to 15 degrees for bunch compression. R_{56}'s of the 1st and 2nd arc sections were set to 0.131 m and -0.131 m, respectively. Figure 5 shows the betatron and dispersion functions in BC mode. In order to minimize the bunch length at the exit of the 1st arc section, the field strengths of the sextupole magnets were optimized and the accelerating phase of the 1st SC cavity module was finely adjusted. Figure 6 shows the optimized (t, p) distribution for the bunch of 77 pC. The bunch was compressed to about 56 fs for the initial bunch length of 1 ps and the initial emittance of 1 mm·mrad. As shown in Fig. 7, the maximum horizontal and vertical beam sizes were finally suppressed to about 4 mm by tuning the horizontal and vertical betatron functions with three additional quadrupole magnets in the 2nd long straight section and by shifting the decelerating RF phases by 2 degrees with the chicane system.

We also obtained dependence of the bunch length at the exit of the 1st arc section on initial bunch length, initial normalized emittance, initial momentum spread, beam energy and bunch charge. Figure 8 shows the dependence of the bunch length on these parameters. The normal values of the initial bunch length, initial normalized emittance and bunch charge were 1 ps, 1 mm·mrad and 77 pC, respectively. The bunch length was minimized for each parameter set by optimizing the accelerating RF phase and the sextupole magnet strengths. It is found in comparison with the CSR-off results that the minimum bunch length is significantly limited by CSR effects especially for the lower values of initial bunch length, initial momentum spread, initial normalized emittance and beam energy and the higher value of bunch charge.

SUMMARY

We optimized the compact ERL optics for the three operation modes. As a result, we succeeded in obtaining an ultra-short bunch of 56 fs for the bunch charge of 77 pC in BC mode and preserving the initial normalized emittance sufficiently for the initial bunch length of 2-3 ps in HC and LE modes. Furthermore we successfully guided the beam to the dump section without serious loss in all the modes and achieved efficient energy recovery in HC and LE modes. The parameter dependence of the bunch compression in BC mode was also obtained in order to understand mechanisms underlying them and to search the optimum parameter sets.

ACKNOWLDGEMENTS

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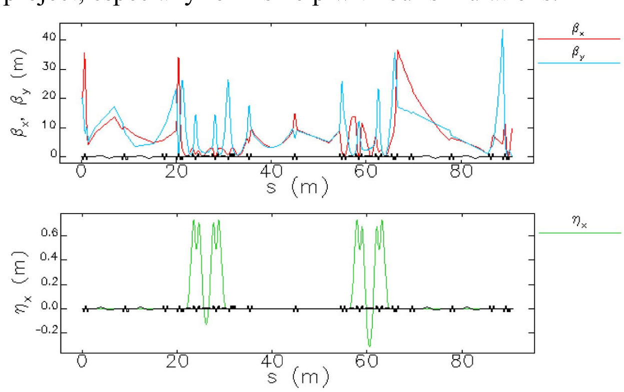

Figure 5: Betatron and dispersion functions of the compact ERL in BC mode.

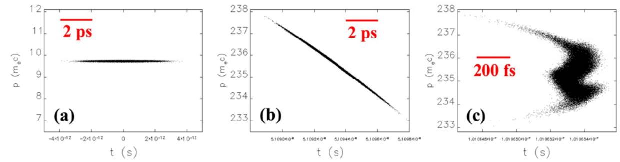

Figure 6: (t, p) distribution of bunch (a) at initial position, (b) after accelerating RF cavity modules and (c) at exit of 1st arc section. Momentum p is expressed in unit of m_ec.

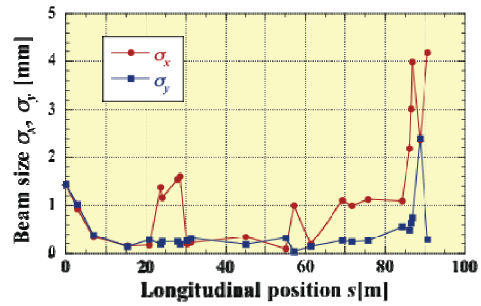

Figure 7: Horizontal and vertical beam sizes along longitudinal position in BC mode.

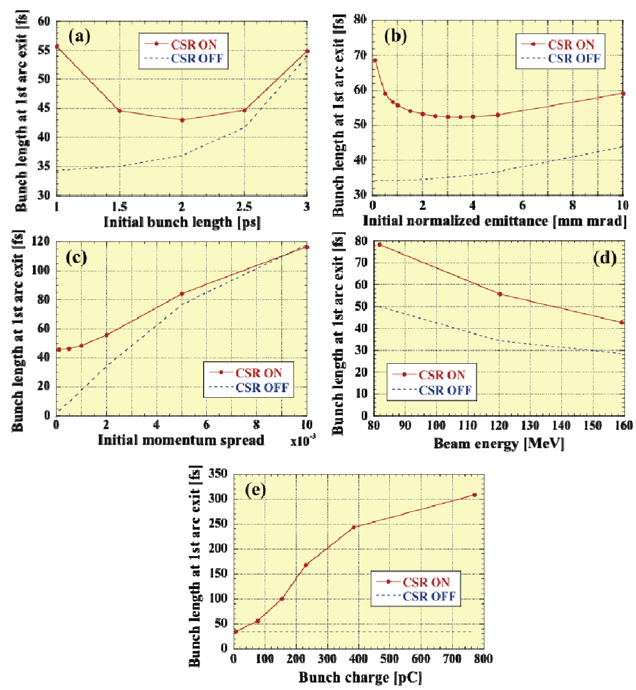

Figure 8: Dependence of bunch length at exit of the 1st arc section on (a) initial bunch length, (b) initial normalized emittance, (c) initial momentum spread, (d) beam energy and (e) bunch charge in BC mode.

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