

BUNCH COMPRESSION AND THE EMITTANCE GROWTH DUE TO CSR

M. Shimada, UVSOR, Institute for Molecular Science, National Institutes of Natural Sciences,
Myodaiji-cho, Okazaki, Aichi 444-8585, Japan

K. Harada, High Energy Accelerator Research Organization (KEK),
Oho, Tsukuba, Ibaraki 305-0801, Japan

R. Hajima, ERL Development Group, Japan Atomic Energy Agency (JAEA),
Tokai, Naka, Ibaraki 319-1195, Japan

Abstract

One of the notable features of the Energy Recovery Linacs (ERL), as compared to other types of accelerator, is the synchrotron radiation from the extremely short electron bunches. We have a plan to produce an extremely short electron bunch in a test ERL for the future ERL project in Japan. In the test ERL, wakes due to coherent synchrotron radiation (CSR), which is generated by short electron bunches in the arc section, are critical for keeping low beam emittance and short bunch length. In this paper, we describe a technique to suppress the emittance growth due to CSR and present the results of optimizations of the arc section for the test ERL.

INTRODUCTION

The ERL is expected as a new light source that can produce extremely low-emittance beams. Because such low emittances can be deteriorated by beam breakup instability (BBU), CSR wakes, space charge effect at low beam energy, and so on, careful countermeasures against these effects are very important. To study the above-mentioned effects on electron beams, we plan to construct a test ERL, which is an R&D facility for the future 5 GeV ERL project in Japan. The electron energy of the test ERL is planned to be 60-200 MeV, which is larger than the 17 MeV ERL at JAEA. One of the important R&D issues, to be conducted at the test ERL, is the preservation of low emittances under the influence of CSR wakes from the short electron bunches.

The test ERL is also expected as a unique user facility for limited users, that can provide intense terahertz coherent radiation or short X-ray pulses having pulse duration of sub-picoseconds. For both purposes, it is necessary to produce short electron bunches having lengths of sub-picoseconds.

In this paper, we present simulation results for two operation modes, a “low emittance and short bunch” mode and a “high charge and short bunch” mode. For the former mode, the optics of the arc section are optimized by using an envelope-matching technique for both cases with and without bunch compression. For the latter mode, we introduce two families of sextupole magnets in the arc section, and try to find the optimum optics by tracking simulations.

LAYOUT AND PARAMETERS OF THE TEST ERL

In the test ERL, an extremely short bunch is generated by the bunch compression system after full acceleration because it is unfeasible to preserve the extremely short bunch at the low electron energy. In this paper, the bunch compression is performed at the arc section. The layout of the test ERL from the merger to the insertion section and the schematic of the bunch compression scheme are shown in Fig. 1. The arc section is composed of triple bending achromat lattice, because R_{56} can be easily changed by controlling the quadrupole magnets. Furthermore, two families of sextupole magnets can be inserted between the quadrupole magnets. The main parameters of the test ERL are listed in Table 1.

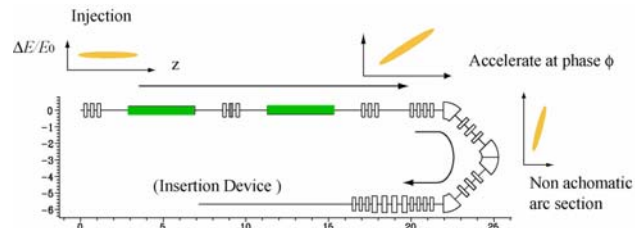


Figure 1: Layout of the test ERL in Japan from the merger section to the insertion section.

Table 1: Main parameters of the test ERL in Japan

| | |
|--------------------------------|------------|
| Injection energy | 5 MeV |
| Full energy | 165 MeV |
| Injection bunch length | 1 ps |
| Bunch length after compression | 0.1 ps |
| Initial normalized emittance | 100 nm rad |

PRINCIPLE OF BUNCH COMPRESSION AND CSR WAKE

Longitudinal energy correlation due to CSR wake and RF curvature

An accelerated electron bunch has longitudinal energy correlation due to the RF curvature. Besides, the CSR wake generated in the bending magnets induces distortion of the longitudinal phase space. The CSR wake potential for a Gaussian bunch is given by Derbenev's equation [1]. At the end of the arc section, the effects of both CSR

wake and RF curvature are accumulated. An example of the longitudinal energy correlation after the arc section is shown in Fig. 2. In this figure, the electron bunch is accelerated off-crest of the RF for bunch compression.

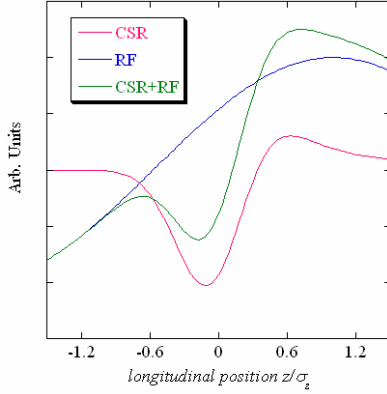


Figure 2: An example of the longitudinal energy correlation due to CSR wake and RF curvature. Here, the change in the longitudinal position is ignored.

Compensation of the emittance growth by the envelope optimization

The CSR wakes induces emittance growth even in an achromatic arc because the energy change by CSR wake results in dispersive motion of electrons. This energy change is a function of longitudinal position of electrons in the bunch and the emittance growth can be expressed as displacement of bunch slices in the transverse phase space (x, x') as shown in Figure. 3. With a linear approximation, the bunch slice displacement is characterized by CSR kick. If we define the direction of the CSR kick in the transverse phase space ζ_{CSR} , we can calculate ζ_{CSR} along a bending magnet as follows,

$$\tan \zeta_{CSR} = \frac{\sin \phi}{\rho(1 - \cos \phi)} \quad (1)$$

where ρ and ϕ are the bending radius and the angle.

Figure 3 shows the dilution of the transverse phase space at the end of the bending magnet for different orientation of the phase ellipse. It can be seen that the emittance growth can be suppressed when the direction of the phase ellipse matches the CSR kick. The direction of the phase ellipse ζ_{Phase} can be expressed by the Twiss parameters as follows,

$$\tan 2\zeta_{Phase} = \frac{2\alpha}{\beta - \gamma}. \quad (2)$$

We call this method an envelope optimization [2-3]. In this paper, we performed the envelope optimization at the end of only the last bending magnet, where the bunch length is smaller than at other bending magnets.

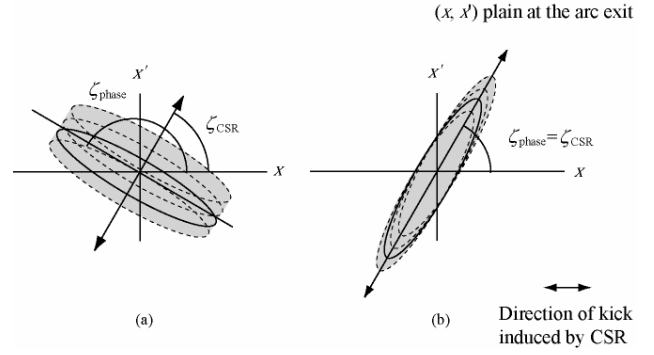


Figure 3: Schematics of the dilution of the transverse phase space in the two cases. The direction of phase ellipse is (a) : perpendicular to that of the CSR kick and (b) : the same as that of the CSR kick.

ENVELOPE OPTIMIZATION

Emittance preservation without bunch compression

In an isochronous beam transport, an electron bunch almost keeps its initial bunch length, 1 ps for our case, along the whole path, therefore we can neglect the effect of CSR wake. The emittance at the end of the 1st arc is found to be 0.14 mm-mrad even without the envelope optimization.

Emittance with bunch compression

In the calculations with bunch compression, R_{56} of the arc is varied from -0.1 to -0.35 m. RF phase is determined as $\phi_{RF} = -0.9c/2\pi f_{RF} R_{56}$ where f_{RF} is the frequency of the RF and the coefficient 0.9 is introduced to compress the bunch length down to 1/10 of the original bunch length. Figure 4 shows the r.m.s. bunch length at the end of the arc calculated by ERLTrack [4]. It seems difficult to compress the bunch length down to 0.1ps because of nonlinearities of the RF curvature and the optics. The efficiency of the bunch compression depends on R_{56} and its optimum value is between -0.15 m and -0.2 m. In the case of 77 pC the bunch length is diluted by CSR wake. In contrast, the bunch length for a 7.7 pC bunch is shorter than a 0.77 pC bunch. This can be explained by the fact that the longitudinal energy correlation of RF curvature is partially compensated by the CSR wake as shown in Fig. 1. Fig. 5 shows that a longitudinal phase plot for a 7.7 pC bunch has larger distortion by CSR wake compared with a 0.77 pC bunch.

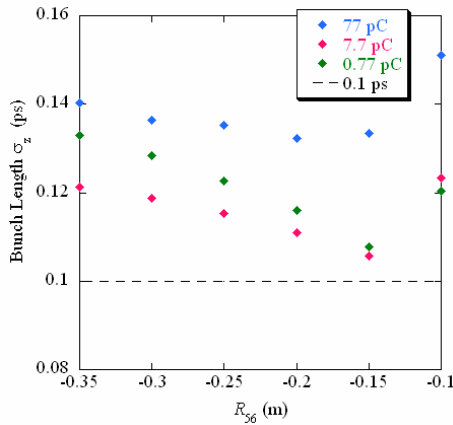


Figure 4: R.m.s. bunch length at the end of arc for various bunch charges.

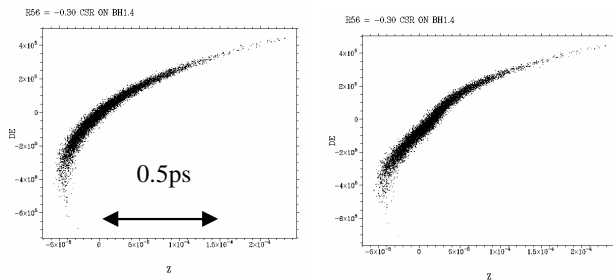


Figure 5: Longitudinal phase space at the end of arc section for the bunch charge 0.77 pC (right) and 7.7 pC (left).

Figure 6 shows the normalized emittance at the end of the arc. As we expected, the emittance growth for a bunch charge of 77 pC is a serious problem. On the other hand, the emittance growth can be suppressed to less than a few times of the initial value for 7.7 pC. The emittance growth also depends on the R_{56} of the arc as shown in Fig. 6. Fig. 7 shows an example of the envelope optimization. Normalized emittance of 0.192 mm-mrad for a bad-matching case (left) can be reduced down to 0.151 mm-mrad by envelope optimization (right).

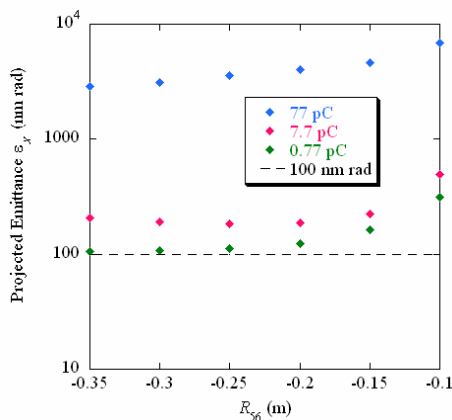


Figure 6: Normalized emittance at the end of arc section with various bunch charges.

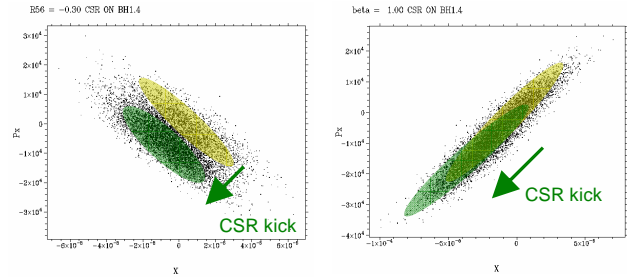


Figure 7: Transverse phase space at the end of arc without envelope optimization (left) and with the optimization (right). Bunch charge is 7.7 pC.

NUMERICAL COMPUTING OPTIMIZATION

Introducing some sextupole magnets

Higher-order correction of the longitudinal electron motion is necessary to compress an electron bunch down to 100 fs against the nonlinearities of the CSR wake and the RF curvature. To optimize second-order path difference of the arc, T_{566} , two families of sextupole magnets were installed. The longitudinal phase space with and without the T_{566} correction is calculated by elegant [5] and shown in Fig. 8. In the left figure, the direction of the second-order distortion of the longitudinal phase space is opposite to an accompanying paper [6] because the abscissa axis is different. In the right figure, the distortion by CSR wake is compensated by negative value of T_{566} after sextupole correction. As a result of numerical optimization of T_{566} and RF phase, the bunch length can be compressed down to 100 fs for bunch charge of 77 pC with relatively low emittance of 5.6 mm-mrad. Here, the optimum values of R_{56} , T_{566} and RF phase are -0.1 m, -0.970 m and 109.6 degrees respectively. We are able to compress a 154 pC electron bunch down to 100 fs in a simulation where the optimum values of R_{56} , T_{566} and RF phase are -0.1 m, -1.23 m and 108.5 degrees, which are different from the case of 77 pC.

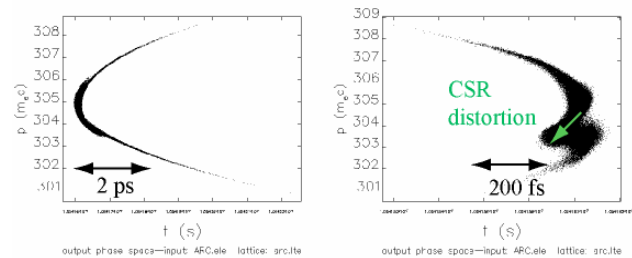


Figure 8: Longitudinal phase space at the end of arc with sextupole magnets (left) and without (right). Bunch charge is 77 pC.

SUMMARY

We present optimization and tracking simulations for “low emittance and short bunch” and “high charge and

short bunch” modes in the test ERL in Japan. In the former mode, the extremely low emittance (0.15 mm-mrad) can be preserved up to 7.7 pC by the envelope optimization. In the latter mode, the electron bunch with 156 pC charge can be compressed down to 100 fs with a correction of T_{566} .

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