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STUDY ON EMITTANCE DILUTION IN THE JAERI-FEL ENERGY-RECOVERY TRANSPORT

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Abstract

An isochronous recirculating beam transport is under construction at the JAERI-FEL facility for energy-recovery experiments, where FEL output power over 2kW will be available. Since the FEL performance depends largely on the beam emittance, it is important to estimate emittance dilution along the recirculation. In the present paper, we study the emittance dilution in our recirculating transport, which is caused by higher-order aberrations, space charge force and coherent synchrotron radiation force.

1 INTRODUCTION

In the JAERI-FEL facility, a free-electron laser of high averaged power has been developed by using a superconducting linac, and the FEL output power over 2kW was recently demonstrated [1]. An energy-recovery system is under construction in our facility for the higher FEL power. The electron beam after the FEL interaction is reinjected to the accelerator tank at the decelerating phase and the beam power is converted into RF power. If the energy-recovery works as we expect, the beam current can be increased without any reinforcement of RF sources, and the FEL power will increase as well.

Basic configuration of the recirculating beam transport has been determined with consideration of critical issues for the energy-recovery : isochronicity, energy acceptance, second-order aberrations, RF instability [2]. The recirculating transport consists of several sub-lattices and matching quadrupoles between them as shown in Fig. 1. The sub-lattices are two 180-degree arcs, a half chicane before the undulator, injection and dump chicanes. The injection part with 2MeV beam is described in another paper [3].

2 EMITTANCE DILUTION

Since the performance of FEL depends much on the electron beam quality, emittance dilution through the beam transport must be studied. Although the recirculating lattice is achromatic in the 1st-order, emittance dilution occurs by several reasons: higher-order aberrations, space charge force, CSR force, magnetic field errors and so on. If all the emittance dilution is uncorrelated, total emittance growth can be calculated as

$$\varepsilon_{final}^2 = \varepsilon_{initial}^2 + \Delta\varepsilon_1^2 + \Delta\varepsilon_2^2 + \Delta\varepsilon_3^2 \dots \quad . \qquad (1)$$

We focus the present study on the emittance dilution appearing at the first half of the recirculation, from the main accelerator to the undulator. The beam dynamics after the undulator is primarily affected by large energy-spread arising from the FEL interaction, and the emittance dilution is not a critical issue there.

The JAERI-FEL injection system provides, in the daily operation now, electron bunches with parameters : charge of 0.6nC, pulse length of 5ps (FWHM), normalized emittance of 20 π mm-mrad. In the energy-recovery experiment, we consider that the longer bunch is preferable to prevent emittance growth in the injection staircase. We, therefore, assume injecting beam with pulse length from 5ps to 20ps in the present study.

2.1 Higher-Order Aberrations

Higher-order aberrations of the transport lattice may degrade the beam phase space. We have two families of sextupoles in the second arc to compensate second-order aberrations arising from large energy-spread after the FEL interaction. In the first half of the recirculation, however, we have no sextupoles for the correction of second-order terms, which is a source of emittance dilution.

The recirculation lattice has been determined by an accelerator design code DIMAD. Figure 2 shows betatron functions and horizontal dispersion from the accelerator to the undulator calculated by DIMAD.

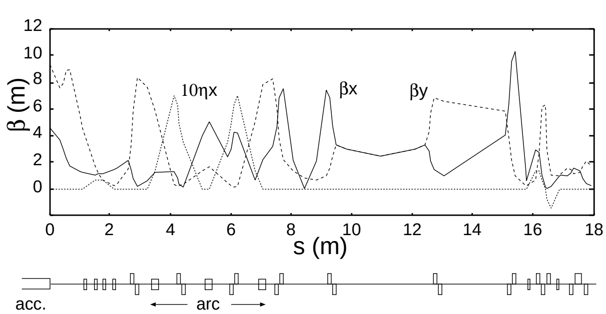


Figure 2: Betatron function and horizontal dispersion from the accelerator to the undulator calculated by **DIMAD**

The emittance dilution due to the higher-order aberrations is calculated by particle tracking with a second-order transfer map obtained by DIMAD. Since the space charge force is ignored in this calculation, initial pulse length of the bunch does not affect the final emittance. Figure 3 shows final emittance obtained as a function of initial energy spread of the bunch, where we assume initial normalized emittance of 20π mm-mrad for both horizontal and vertical plane. It can be seen that the emittance dilution due to the second-order terms depends on the initial energy-spread. From the design study of the injector, the

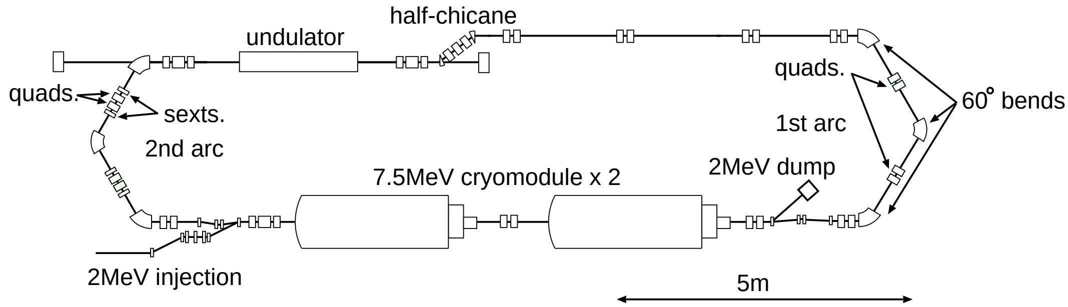


Figure 1: Recirculating beam transport for the energy-recovery experiment at JAERI-FEL

rms energy-spread at 17MeV is expected to be less than 0.1% [3], which is small enough to prevent the emittance dilution caused by aberrations.

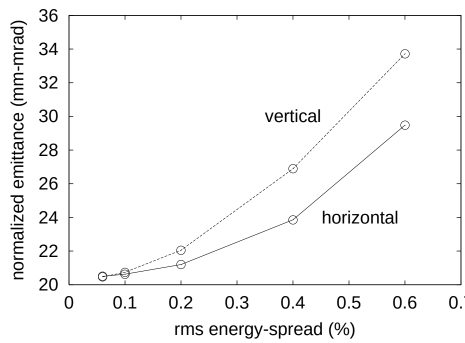


Figure 3: Emittance dilution caused by second-order aberrations as a function of initial energy-spread

2.2 Space Charge Force

Emittance growth due to the space charge force is usually negligible for an electron bunch of 17MeV and 0.6nC, if the bunch goes a straight path. In the energy-recovery recirculation, however, transverse emittance may degrade as the following reason. Achromatic sub-lattices in the recirculation, such as 180-degree arcs, have more than two bends separated by a straight section. Longitudinal space charge force during the straight section introduces redistribution of electron energy in a bunch and results in the error of bend angle at the next bend. Consequently the first-order achromaticity is broken and emittance dilution occurs [4].

The maximum energy change in an electron bunch caused by axial space-charge field after a drift length S is given by [5]

$$\Delta E = \frac{qeS}{4\pi\epsilon_0 r_0 \tau_b \gamma\beta c} F \, , \tag{2}$$

where q is bunch charge, r_0 is bunch radius, τ_b is pulse length and F is a form factor less than 1. The error of bend angle for this energy redistribution is calculated by

$$\Delta\alpha = \frac{\alpha_0 \Delta E}{E_0} \, , \tag{3}$$

where α_0 and E_0 is the nominal bend angle and electron energy, respectively. Since the emittance growth caused by this bend angle error is proportional to both the bend angle and the drift length between bends, it becomes significant only at the 180-degree arcs in our recirculation.

It should also be noted that the electron bunch alters its longitudinal size during the arcs as well as the transverse dimension, even if the arc is isochronous. For example, 5ps bunch injected to the arc becomes 15ps after the first bend due to the nonzero R_{51} and R_{52} terms at the bend. The bunch turns back to 5ps at the exit of arc. These variation of bunch size must be taken into account to estimate the emittance dilution.

We use a particle tracking code `PARMELA` to calculate the space charge effect including the variation of beam size in both transverse and longitudinal direction along the arc. Calculated emittance at the end of the first arc for different initial energy-spread is plotted in fig.4. The emittance growth is not large for an electron bunch between 5ps and 20ps.

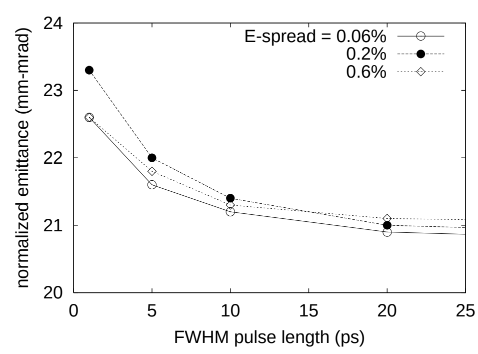


Figure 4: Initial bunch length and emittance dilution caused by space charge force in the first arc. The initial energy-spread is varied from 0.06% to 0.6% in rms value.

2.3 Coherent Synchrotron Radiation Force

Coherent synchrotron radiation (CSR) force is also a source of emittance dilution for an electron bunch traveling through a circular path [6]. The longitudinal collective force due to the CSR is calculated, for a Gaussian line-bunch with total charge of q, as

$$F_\theta(s) \simeq \frac{1}{4\pi\epsilon_0}\frac{2qe}{\sqrt{2\pi}(3\rho^2\sigma_s^4)^{\frac{1}{3}}} \int_0^\infty \frac{d\phi}{\phi^{1/3}}\frac{\partial}{\partial\phi}\exp\left[\frac{(s/\sigma_s-\phi)^2}{2}\right], \quad (4)$$

where s is axial position in the bunch, ρ is curvature radius and σ_s is rms bunch length. This force introduces nonuniform energy change in the bunch and results in bend angle error and emittance dilution similor to the space charge force discussed in the previous section.

It is also known that the CSR force is suppressed by conducting plates surrounding the electron beam. The shielding factor for two parallel plates separated by distance of h is calculated as

$$\eta = \sqrt{2/3}\,(\pi\rho/h)^{3/2}\,(\sigma_s/\rho) \quad (5)$$

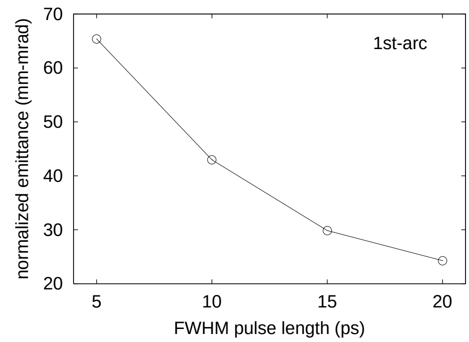
The CSR force has large effect in the 180-degree arcs and the half-chicane because of small curvature radius and large bend angle. The curvature radii and bend angles of the dipoles in the arc and the half-chicane are 0.24m, 60 degree and 0.4m, 45 degree, respectively. The CSR force is not dominant in the injection and the dump chicanes, which have curvature paths with relatively large radii and small bend angles.

For the estimation of emittance growth in a 60-degree bend of the 1st-arc for a bunch of 15ps(FWHM), we use eq.(4) with $\rho = 0.24$m, $\sigma_s = 2$mm, $q = 0.6$nC, and have $F_\theta^{max} \simeq 34$keV/m. The shielding parameter for the bend with $h = 38$mm becomes $\eta = 0.6$, which shields only 15% of the CSR power [6]. The shielding effect at the 60-degree bends is, therefore, small.

The lengthening of the electron bunch in the arc, again, must be considered to estimate the emittance dilution, because the CSR force depends on the longitudinal bunch profile as shown in eq.(4). The CSR force applied at the second bend of the arc is smaller than the first and the third bends because of the bunch lengthening.

For a quantitative analysis of the emittance dilution caused by CSR force including the bunch lengthening in the arc, we have made numerical simulations with `elegant` [7], which performs 6-D canonical tracking of particles with a calculation of the CSR force based on Saldin's model [8]. The usual space charge force is, however, not available in `elegant`. We must integrate numerical results obtained by `elegant` together with the space charge effect already discussed.

Emittance dilution in the first arc and the half chicane is calculated for bunch parameters similor to the previous section. Since the final emittance is found to be independent of the initial energy-spread between 0.06% and 0.6%, we plot only one line for each figure.



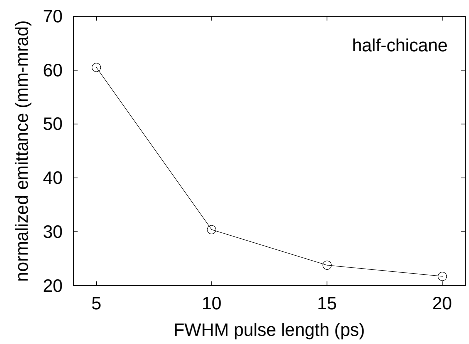


Figure 5: Initial bunch length and emittance dilution caused by CSR force in the first arc and the half-chicane calculated with **elegant**

3 CONCLUSIONS

It is found that the CSR force is the dominant source of emittance dilution in the horizontal plane, if we assume electron bunches from the accelerator with pulse length of 15ps(FWHM) and rms energy-spread less than 0.1%, which are parameters predicted in the design study [3]. Total emittance growth calculated by eq.(1) is $\Delta\varepsilon = 27\pi$ mm-mrad, that is, the initial emittance of 20πmm-mrad becomes 34πmm-mrad at the undulator. For the vertical emittance, the second-order aberrations degrade the initial emittance of 20πmm-mrad to the final value of 23πmm-mrad. It is considered that the emittance growth calculated is not critical for our FEL.

We also plan to measure the emittance growth after the completion of beam transport, because it is important to study emittance dilution in a circular path for the design of bunch compressors in future short wavelength FELs.

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