DESIGN OF A BEAM TRANSPORT LINE FROM THE SACLA LINAC TO THE SPRING-8 STORAGE RING

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Abstract

A beam transport line from the SACLA linac to the SPring-8 storage ring was designed. The transport of low emittance and short bunch beam was studied for four candidates: a FODO lattice, a double bend achromat (DBA) lattice, a DBA lattice tuned to suppress the coherent synchrotron radiation (CSR) effect, and an isochronous triple bend achromat (TBA) lattice. The simple DBA lattice was selected for the arc section and the slope of the transport line.

INTRODUCTION

The SPring-8 Angstrom Compact Free Electron Laser (SACLA) linac was constructed at the SPring-8 site for XFEL [1]. The normalized emittance of the SACLA linac is less than 1 mm-mrad and the bunch length is shorter than 100 fs. If this high quality beam is injected into the SPring-8 storage ring, many interesting experiments can be done.

On the other hand, the upgrade of the SPring-8 storage ring is planning [2]. It is aimed to generate the diffraction-limited synchrotron radiation at the hard x-ray region. Since the emittance of the storage ring is very low and the dynamic aperture is very small [3], it is difficult to use the current injector to achieve high injection efficiency. If the SACLA linac is used as an injector for the upgraded SPring-8 storage ring, we can expect high injection efficiency.

With these two objectives, we determined to connect the SACLA linac to the SPring-8 storage ring via a new beam transport line XSBT (Fig. 1) [4]. In this paper, the lattice design of this transport line is described.

TRANSPORT LINE

Figure 1 shows the SACLA linac, the storage ring, and the injector linac and the synchrotron. As a beam transport line from the synchrotron to the storage ring (SSBT) already exists, we decided to connect the SACLA linac and the SSBT by constructing the XSBT. The total length of the XSBT is about 300 m and there is a 9 m height difference between the SACLA linac and the SSBT (Fig. 2). There is a 125-m-long arc section followed by a 60-m-long slope. After the slope there is a 115-m-long straight section.

LATTICE

It is important to construct a beam transport line inexpensively while at the same time maintaining the beam quality. We designed three types of transport lines to compare the beam quality and construction cost: a FODO based line, a double bend (DB) based line, and a triple bend (TB) based line. An achromat condition was imposed on the DB and TB lattices and an isochronous condition was imposed on the TB lattices. The FODO lattice was used in the design of the straight section.

Figure 1: The SACLA linac and the SPring-8 storage ring.

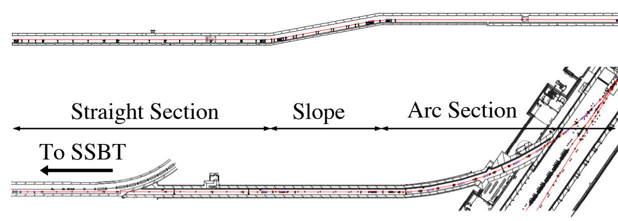


Figure 2: Beam transport line from the SACLA linac to the SSBT (XSBT).

The beam quality of SACLA is so high that strong CSR effects are expected. If the phase advance of the betatron oscillation of an electron beam is chosen to cancel the CSR kick, we can suppress the CSR effects [5]. For this purpose, we also designed CSR suppression lattices for the DBA based line.

The optics functions of the FODO based transport line are shown in Fig. 3. Lattice design is simple and the magnet strength in each region of the lattice is the same except in the matching section. However, the dispersion function is very large. In Fig. 4, the optics functions of the beam transport line consisting of the DBA lattices are shown. The dispersion function is small compared to the FODO based line. There are only five quadrupole magnets in this lattice, which required only three types of power supply.

The optics functions for DBA based beam transport line that was designed to suppress the CSR effects are shown in Fig. 5. The horizontal phase advance between the lattices in the arc section was set to $1.5\times2\pi$ and the vertical phase advance between the lattices in a slope was set to $1\times2\pi$. The horizontal phase advance of the original DBA lattice is $0.74\times2\pi$. To suppress the CSR, the phase must be set to $0.5\times2\pi$ or $1.5\times2\pi$. However, the phase advance between the bending magnets in each lattice is 0.58×2π. This means that it is difficult to set the phase advance to 0.5×2π without breaking the achromat condition. Therefore, we chose the 1.5×2π phase advance, which is about twice that of the original phase advance. In order to obtain the larger phase advance, we increased the number of the quadrupole magnets from five to fourteen per lattice.

The optics functions for the TBA based beam transport line are shown in Fig. 6. The dispersion function at the centre of the lattice is negative to maintain the isochronous condition. Eight quadrupole magnets are used per lattice.

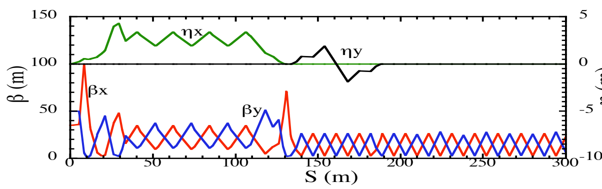


Figure 3: Optics functions of FODO based beam transport line.

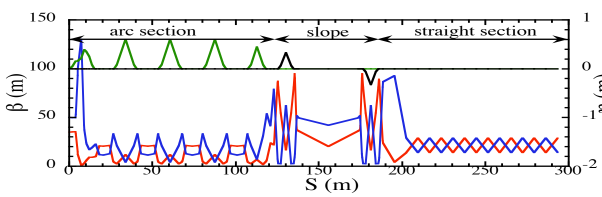


Figure 4: Optics functions of DBA based beam transport line.

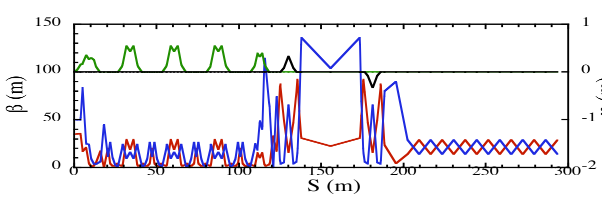


Figure 5: Optics functions of DBA based beam transport line. Phase advance is chosen to suppress the CSR effects.

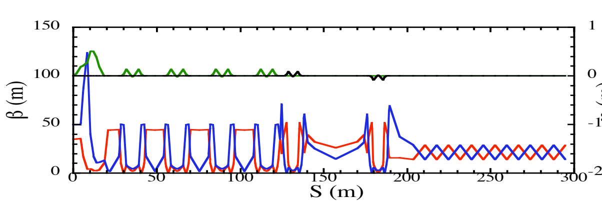


Figure 6: Optics functions of TBA based transport line.

BEAM QUALITY

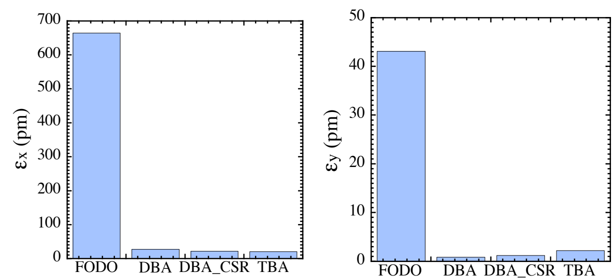
The beam quality of the SACLA linac is so high that the emittance growth by synchrotron radiation and the bunch lengthening due to dispersion in the bending magnets become problems. The emittance growth, the bunch lengthening and the energy spreading due to CSR are also serious problems. We evaluated these effects.

Emittance Growth by Synchrotron Radiation

Emittance growth by synchrotron radiation is expressed as [6],

$$\delta\langle a^2\rangle = \frac{3C_u}{4\pi}\frac{C_\gamma \hbar c}{(mc^2)^3}\frac{E^5}{\rho^3}\int H ds$$
$$H = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2$$
$$C_u = \frac{55}{24\sqrt{3}} \tag{1}$$
$$C_\gamma = \frac{4\pi}{3}\frac{r_e}{(mc^2)^3}.$$

Emittance growth was calculated for each beam transport line. The energy of the electron beam is 8 GeV and the bending magnet strength is 1.2 T. Figures 7 (a) and (b) show the horizontal emittance growth and the vertical emittance growth, respectively. The horizontal emittance growth of the FODO lattice is 660 pm-rad while the vertical growth is 43 pm. The emittance growth of the other lattice is less than 30 pm-rad in the horizontal direction and less than 3 pm-rad in the vertical direction.



(a) Horizontal (b) Vertical

Figure 7: Emittance growth by synchrotron radiation.

Bunch Lengthening by Dispersion Function

Bunch lengthening by dispersion function is expressed as,

$$\Delta L = R_{56}\,\Delta p/p$$
$$R_{56} = \int \eta/\rho ds. \tag{2}$$

The calculated results of R_{56} for each transport line are shown in Fig. 8. The transport line with the isochronous TBA lattice has a non-zero R_{56} value due to the first two bending magnets in the line (Fig. 6). The bunch lengthening for the 10^{-4} energy spread is 200 μm (~700 fs) for FODO, 4.5 μm (15 fs) for CG, and 0.9 μm (3 fs) for TBA.

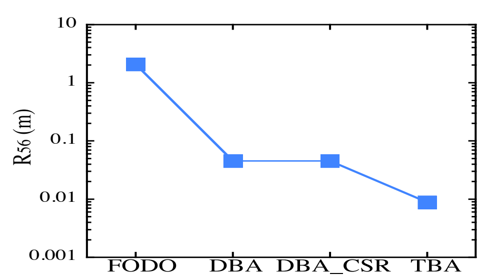


Figure 8: R_{56} for each transport line.

CSR Effects

CSR effects were estimated by using Elegant [7]. Simulations were done for two DBA based transport lines: the one that suppressed the CSR effects and the one that did not. In the simulation, the electron beam energy is 8 GeV, the bunch charge is 300 pC, the initial emittance is 40 pm-rad in X and Y, the initial energy spread σ_E/E ($=\Delta p/p$) is 10^{-4}, and the initial bunch length σ_l is 30 μm (100 fs). The simulation results for the simple DBA based transport line in which CSR suppression is not taken into account are shown in Fig. 9. Due to the CSR, transverse emittance in a core part of the beam increases by about ten times. The bunch lengthening is not quite so dramatic, but the energy spread became very large. The simulation results for the CSR suppression transport line are shown in Fig. 10. The transverse emittance increases by a few times. The bunch length does not change. The energy spread increases but the increase is small compared with the simple lattice results.

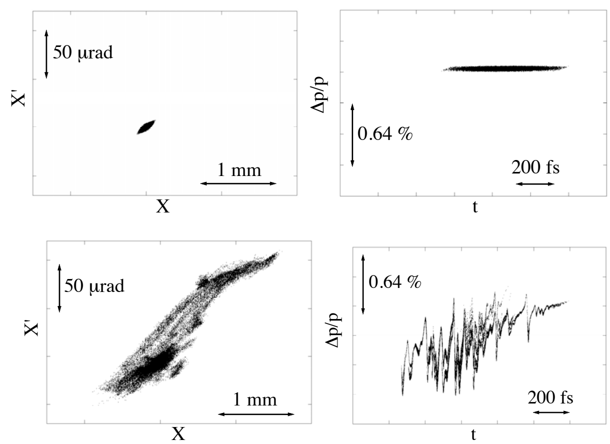


Figure 9: Transverse and longitudinal phase space distribution for simple DBA based beam transport line without CSR (upper) and with CSR (lower).

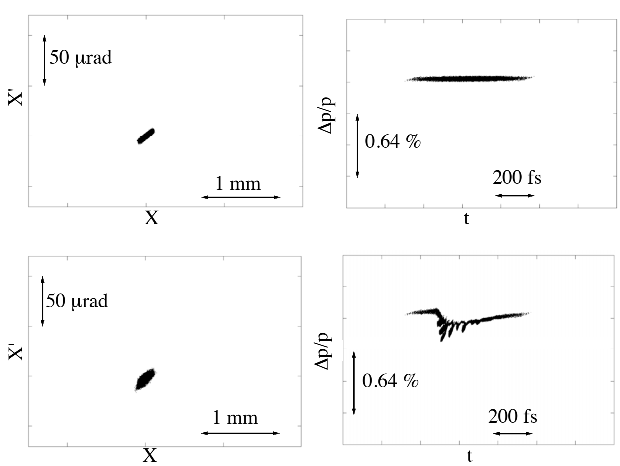


Figure 10: Transverse and longitudinal phase space distribution for CSR suppression DBA lattice without CSR (upper) and with CSR (lower).

DISCUSSION

Since the emittance growth and the bunch lengthening of the FODO based beam transport line is so large compared with the other lines, we excluded it from our candidate list for the transport line from the SACLA linac to the SSBT.

The emittance growth and bunch lengthening for the DBA and TBA based transport lines are small enough to be acceptable, and the CSR effects on both are considered to be the same order. The DBA lattice is both simpler and less expensive than the TBA lattice. On the basis of these results, we selected the DBA based transport line.

Although the emittance growth and energy spread deterioration due to CSR are large in the simple DBA lattice, they are still small for the injection to the upgrade storage ring. The CSR suppression DBA transport line fulfils both requirements for the injection to the upgrade storage ring and for the experiment with high quality beam but it requires the use of a large number of quadrupole magnets. If necessary, we can easily change the simple DBA lattice to the CSR suppression DBA lattice by increasing the number of quadrupole magnets. Thus we elected to use the simple DBA lattice for the beam transport line.

SUMMARY

The four beam transport lines from the SACLA linac to the SPring-8 storage ring were designed by adapting a FODO lattice, a simple DBA lattice, a DBA lattice tuned to suppress the CSR effect, and an isochronous TBA lattice, respectively. The emittance growth by synchrotron radiation, the bunch lengthening by the dispersion function, and the CSR effects were studied for these transport lines.

The FODO based line was rejected because its emittance growth by synchrotron radiation and its bunch lengthening are larger than those of the other lines. The DBA and TBA lattices have almost exactly the same ability to transport a high quality beam. The DBA lattice, which has a tuned betatron phase advance by adding the quadrupole magnets, is effective for suppressing the CSR effects. Since the simple DBA lattice can easily be changed into a CSR suppression DBA lattice by adding the quadrupole magnets, we selected the simple DBA lattice for use as the lattice of the transport line.

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