

APPROACH TO A START-TO-END SIMULATION OF 2-LOOP COMPACT ENERGY RECOVERY LINAC

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Abstract

Transport of an extreme low emittance electron beam is a critical issue in an energy recovery linac. In particular, the space charge effects on a low-energy electron bunch in an injector induce a large emittance growth. To apply the emittance compensation solenoid magnets, a nonlinear effect should be clarified by a six-dimensional tracking simulation. The tracking simulation, however, consumes an enormous time and is unsuitable for a double loop circulation because the simulation time depends on the transport length. Therefore the beam dynamics and optics are calculated by a Start-to-End (S2E) simulation, in which the simulation code is switched after acceleration. We used General Particle Tracer (GPT) for injector electron beam and 'elegant' for the circulator electron beam.

INTRODUCTION

High-brilliant X-ray light source based on a multi-GeV Energy Recovery Linac (ERL) is proposed as a successor to the Photon Factory in KEK [1]. In addition, XFEL-O is considered as an optional light source, which is operated by utilizing the ERL as a recirculating linac to accelerate an electron bunch twice. In both schemes, a transport of a low emittance electron beam is a critical issue. Therefore, we need to make R&D efforts of beam dynamics studies as well as other key components, such as a high-brilliant DC electron gun and superconducting cavities optimized for HOM damping.

A 200 MeV class ERL, named Compact ERL (cERL), is under construction in the KEK site as a R&D machine. A double loop scheme, which means accelerating and decelerating twice, is adopted for cERL to save the construction area and the running cost of the refrigerators. It makes an optics design complicated because four electron beams having different energies pass through the linac with a focusing field of the same quadrupole magnets. Therefore, iterations of optics design are necessary to transport and dump the electron beam with reasonable transverse beam sizes. For the optics design, we utilized a 6D tracking code 'elegant' [2], which induces a wake field due to Coherent Synchrotron Radiation (CSR wake) with a fast 1D transient model. However, it lacks Space Charge (SC) effects.

Another simulation code is necessary to evaluate the beam transport from the electron gun because the SC effects cause an emittance growth at non-relativistic energy region. Therefore, General Particle Tracer (GPT) [3] is utilized for a beam dynamics simulation to include

the SC effects. Although this approach can also be applied to the whole ERL to obtain detail information with the CSR and SC, it costs too much CPU time to optimize the optics from the electron gun to the dump. Therefore, we perform Start-to-End (S2E) simulation [4], in which multiple simulation codes are switched according to the electron energy.

MAIN PARAMETERS AND LAYOUT OF 2 LOOP cERL

Injector

The injector is composed of a 500 kV DC photo cathode electron gun, two solenoid magnets, a buncher cavity, three 2-cell superconducting cavities, five quadrepole magnets and a merger chicane. Figure 1 shows the layout of the injector. Two solenoids are installed to compensate for the emittance growth due to the SC effects. The bunch length is compressed at the buncher cavity down to 1-3 ps. The electron beam is accelerated by superconducting cavities up to 5 -10 MeV, and injected to the circulator loops at the merger chicane with an angle of 16 degree.

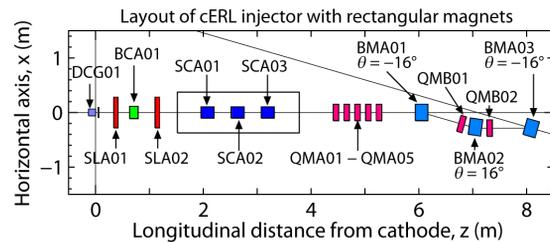


Figure 1: Layout of injector of ERL.

Double Loop Circulator

The layout of cERL is shown in Fig.2. An electron from the injector is accelerated by the main linac, which is composed of eight 9-cell superconducting cavities with an operation frequency of 1.3 GHz. The goals of the accelerating field and one pass energy gain are 15 MV/m and 120 MeV, respectively. 125 MeV electron beam is then led to the inner loop after the branch bending magnet. The electron beam is accelerated again after the circulation because the revolution frequency of inner loop is adjusted to an integer multiple of the 1.3 GHz. At the outer loop, the electron energy increase to 245 MeV. That of the outer loop is adjusted is a half-integer of 1.3 GHz,

so that the electron beam is decelerated after the circulation. Both accelerating and decelerating electron beams simultaneously are transported in the inner loop. After the second deceleration down to the injector energy, the electron beam is led to the dump at the extraction chicane. Previously mentioned, the four electron beams

with different energies pass through the main linac with a focusing field by the same quadrupole magnets. Both the inner and outer loops are designed to satisfy achromatic and isochronous conditions.

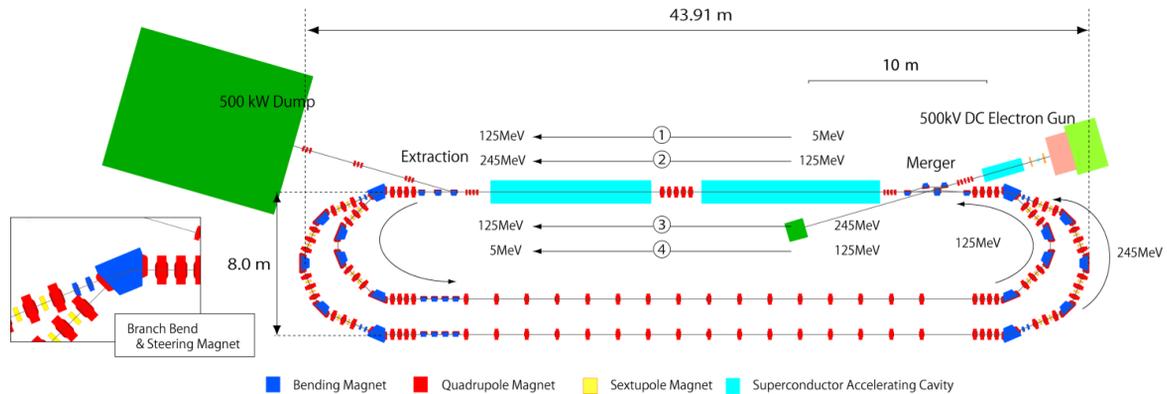


Figure 2: Layout of 2 Loop cERL at the KEK site. Steering Magnets nearby the branch bending magnets are used to control a central orbit of the outer loop, which depends on the ratio of electron energy between the inner and outer loop.

START-TO-END SIMULATION

Injector

In the non-relativistic energy range, SC effects induce the emittance growth and the distortion of the optical functions. To evaluate the SC effects, GPT is utilized with a 3D mesh based method. Optimization of the optics design with GPT is performed by genetic algorithm. To save the simulation time, the number of tracking particles are gradually increased, such as 2k, 5k, 10k and 100k.

The electron particle distribution derived from electron gun is assumed to be a beer-can shape. The longitudinal length is treated as a variable from 10 to 60 ps. The five quadrupoles before the merger chicane are used to compensate the emittance growth. Twiss parameter of the switching point is matched by the four quadrupoles after the merger chicane. The effect of CSR wake in merger section is ignored to save the CPU time.

Main Linac and Double Loop Circulator

It is important issue to optimize the optical functions of the four electron beams at main linac. In principle, the quadrupole magnets are optimized for the lowest electron beam. To simplify the optimization, both inner and outer loops are replaced the dummy loops, which are composed of eight quadrupole magnets and drift spaces. In addition, the optical functions of the accelerator and decelerator beams are designed to be approximately symmetric. It makes it easy to transport the electron beam to the dump with the reasonable optical functions.

The inner loop is composed of the four bending

magnets with satisfying the achromatic and isochronous conditions. The triplets between the bending magnets are set to DFD because it is easy to match the optical function with that of the main linac. The inner loop is also required to suppress the emittance growth due to CSR wake. It depends on the betatron function at the center of the arc as shown in Fig.3. The limits of the betatron function affect the optimization of the main linac.

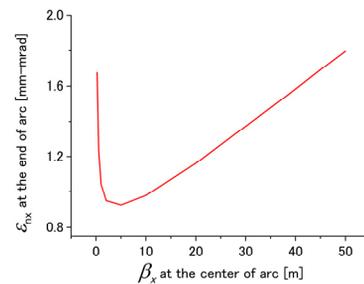


Figure 3: An example of emittance growth in the inner loop varied with the betatron function at the center of the arc.

Start-to-End (S2E) Simulation

For optimization of the optical function and the emittance growth, GPT is utilized at the injector and 'elegant' at main linac and the double loop circulator. The simulation code is switched just after accelerating up to 65 MeV although it is insufficient to neglect the emittance growth due to the SC effects [5]. The reason is that the quadrupole magnets QS2 shown in Fig 4 are most important variables for optimization of the main linac.

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As previously mentioned, the Twiss parameters at the switch point are limited to maintain the reasonable optical function or suppress the CSR wake effect. The acceptable ranges of the Twiss parameters are estimated by the iterated calculation of the double loop circulation. It limits the performance of the optimization at the injector. The 6D particle distribution is passed to ‘elegant’ by using the tool of ‘gdf2sdds’ for tracking the whole 2 loop cERL.

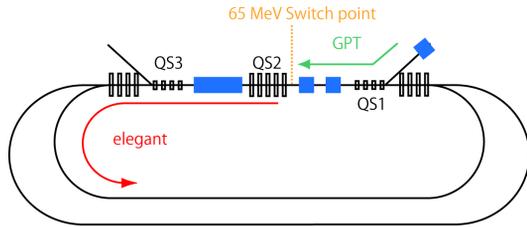


Figure 4: Start-to-End simulation scheme for 2 loop cERL.

SIMULATION RESULTS

The acceptable ranges of the switch point are set to $\beta < 100$ m and $-2 < \alpha < 2$ for both horizontal and vertical directions. The result obtained by GPT is $(\beta_x, \alpha_x, \beta_y, \alpha_y) = (16.7 \text{ m}, 0.82, 33 \text{ m}, -0.76)$. The normalized emittance is minimized down to 0.54 [H] and 0.89 [V] mm-mrad with the electron charge of 77 pC and the rms bunch length of 2 ps for the present.

Figure 5 shows the optical functions from the switch point the extraction chicane to the dump. The optical function is obtained by calculation of the transport matrix with the Twiss parameter at the switch point. The betatron functions are suppressed below 100 m in whole 2 loop circulator. The developments of the rms beam size and the emittance in Fig.6 are obtained from the 6D particle distribution. The figure indicates the horizontal emittance continues to increase by CSR wake at each arc and end up to be 10 mm-mrad at the extraction chicane. The longitudinal phase space is changed after the double loop circulator. You can see the electron energy is strongly modulated at the head of the electron bunch.

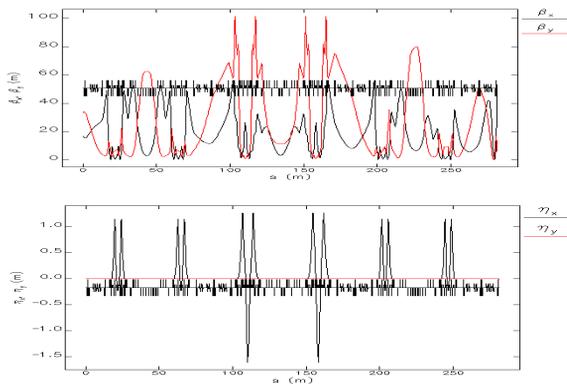


Figure 5: Betatron and dispersion functions of 2 loop cERL.

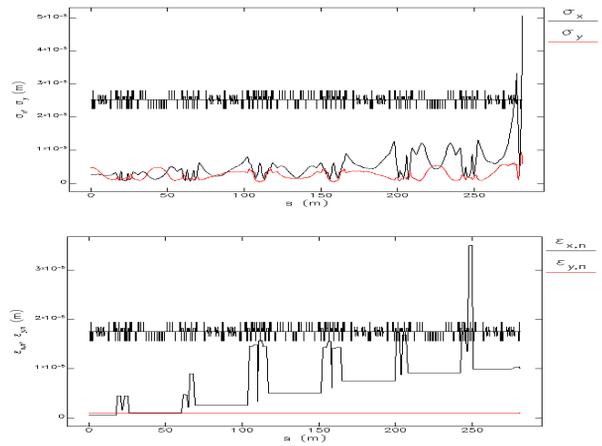


Figure 6: Transverse rms beam size in whole 2 loop cERL.

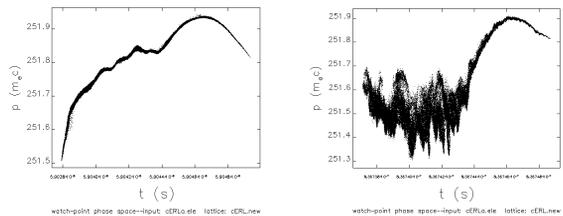


Figure 7: Longitudinal phase space (left) : just after the first acceleration from injector energy to 125 MeV, (right) : just before the second deceleration from 125 MeV to injector energy.

SUMMARY

The S2E simulation is performed to optimize the beam optics of a 200 MeV class double loop ERL with including the effects of SC and CSR wake. The optical function of the injector can match with that of the double loop circulator, and reduce the emittance less than 1 mm-mrad at the same time. Finally, we can find the optics to transport the electron bunch with the reasonable beam size and emittance from the DC gun to the dump.

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