DARK CURRENT SUPPRESSION AT XFEL/SPRING-8 BY USING THE CHROMATIC ABERRATION

H. Tanaka#, K. Togawa, T. Hara, H. Kitamura and N. Kumagai, SPring-8/RIKEN, Hyogo, Japan

Abstract

The compact XFEL facility under construction in the SPring-8 campus is aiming at generation of SASE based XFEL at a wavelength of ~0.1 nm in 2011 [1]. From the viewpoint of reliable SASE XFEL operation, electron beam loss at an undulator section is strictly restricted to be less than 3 fC/pulse to avoid serious demagnetization of undulator permanent magnets. Shielding wall of the undulator hall was rationally designed assuming the electron beam loss is 1 pC/pulse, which is much higher than the requirement for protection against the permanent magnets demagnetization. This design beam loss, however, severely limits transmission of the dark current to the undulator hall. It is thus critically important to suppress the dark current in the accelerator tunnel toward smooth completion of the beam commissioning. We have investigated a removal scheme of the spatially diverged and energy deviated electrons forming the dark current by taking an earth magnetic field, focusing quadrupole and additionally installed sextupole magnets into account. The beam simulation showed that a small chicane at the beam energy of 3 GeV can efficiently remove the dark current emitted from the C-band acceleration structures. Here, we present the simulation results and the dark current suppression scheme designed for the compact XFEL facility at SPring-8.

DARK CURRENT SIMULATION MODEL

Schematic drawing of the XFEL accelerator system is shown in Fig. 1. Since our system has following features, a main source of dark current in the undulator hall is C-band accelerating structure after the third (final) bunch compressor BC3. (i) Our electron gun system [2] having an electro-magnetic deflector with a circular collimator [3] is almost dark current-free from the gun. (ii) Buncher system in the injector uses lower RF electric fields and barely emits dark current. (iii) Dark current from L-, S- and C-band accelerating structures generating an energy chirp over the electron bunch is removed at downstream magnetic chicanes for bunch compression, BC1~BC3.

Definition of Dark Current

We define dark current at the exit of each accelerating structure in our simulation model. Both energy and angular divergence of the dark current are therefore determined by a dark current emission-position in an accelerating structure as described later. The contribution ratio to the total charge of dark current is also determined by the emission-position taking a position-dependent angular acceptance into account.

Energy Distribution of Dark Current

The emission-positions are descritized by a periodic length of an acceleration cell. We simplify the model by introducing the condition that the dark emission timing always synchronizes to the accelerating beam. Energy of the dark current E_{dark} is then expressed by Eq. (1) with the energy gain per structure E_{acc}, the emission cell number n_{e} and the total cell number n_{T}. In the case of the C-band acceleration system where E_{acc} and n_{T} are equal to ~63 MeV and 91, respectively, energy resolution becomes ~0.7 MeV.

$$E_{dark} = \frac{n_T - n_e + 1}{n_T} \times E_{acc} \qquad (1)$$

Spatial Distribution of Dark Current

We assume that a spatial distribution of dark current is axial symmetric. The radius r has a Gaussian distribution truncated at 2σ by the exit beam hole with a radius of r_{e} and the angle θ around the longitudinal axis z has a uniform distribution. The angular divergence $r' = \mathrm{d}r/\mathrm{d}z$ is also a Gaussian distribution truncated at 2σ by the angular acceptance ϕ_{ne}, which is a function of n_{e} and expressed by Eq. (2) with the length of one accelerating structure L_{acc}.

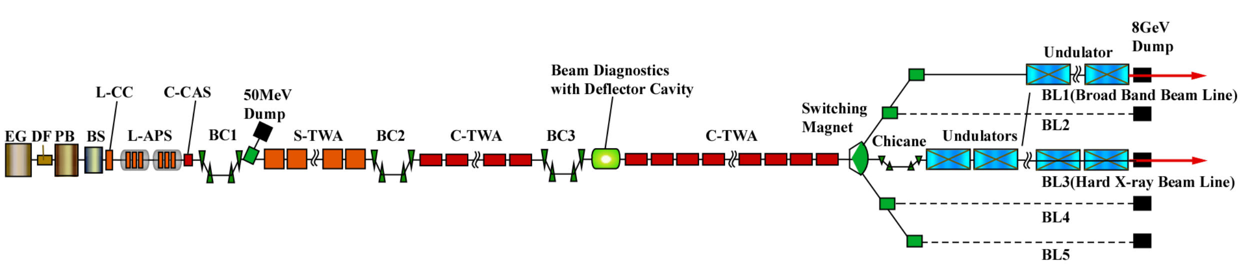

Figure 1: Schematic drawing of the XFEL accelerator system. EG, 500-kV electron gun; DF, deflector with collimator; PB, 238-MHz pre-buncher; BS, 476-MHz booster; L-CC, L-band correction cavity; L-APS, L-band alternating periodic structure; C-CAS, C-band correction accelerating structure; BC1~3, bunch compressor1~3; S(C)-TWA, S(C)-band travelling-wave structure; BL, beam line.

#tanaka@spring8.or.jp

$$\phi_{\mathrm{ne}} = \frac{r_e}{L_{acc}} \times \frac{n_T}{n_T - n_e + 1} \qquad (2)$$

Contribution from Each Emission Cell

We assume that the contribution of each emission cell to total charge of the dark current linearly depends on each angular acceptance ϕ_{ne}. The charge C_{ne} emitted from the emission cell n_{e} is expressed by Eq. (3) with the total charge of the dark current from one accelerating structure C_{t} and ϕ_{ne} for each acceleration cell. The total charge C_{t} measured at the SCSS test accelerator [4] is a few tens pC/pulse/C-band accelerating structure.

$$C_{\mathrm{ne}} = C_{\mathrm{t}} \times \frac{\phi_{ne}}{\sum_{i=1}^{n_T} \phi_i} \qquad (3)$$

Modelling of Earth Magnetic Field

We assume that an earth magnetic field (EMF) B_{e} is uniformly distributed over the accelerator with a constant acceleration gradient G and a length of L. The initial condition for a pseudo-periodic motion of an electron with an initial energy of E_0 is determined so as to cancel out the displacement due to EMF. This means that EMF is corrected on average by the steering magnets. When the EMF polarizes in the vertical plane, the necessary horizontal steering strength x_{st} giving the pseudo-periodic motion is expressed as

$$x_{st} \approx \frac{-\dfrac{0.6B_e}{E_0/c}\left\{\left(\dfrac{E_0}{eG} + L\right)\ln\left(1 + \dfrac{eGL}{E_0}\right) - L\right\}}{\ln\left(1 + \dfrac{eGL}{E_0}\right)}, \quad (4)$$

where e and c are the electron charge and speed of light, respectively. By applying Eq. (4) to our accelerator system, we can approximately estimate distribution of the steering magnet strengths along the accelerator for the pseudo-periodic motion. In the simulation with EMF, the estimated distribution is always considered; otherwise the dark current always loses under unrealistic condition.

Particle Tracking

In three-dimensional tracking program, all kinds of main magnets such as a bending, quadrupole and nonlinear multipole magnets are treated as thick elements without expanding a kinematics term involving canonical momenta. Steering magnets are only treated as kicks. Beam acceleration field in a travelling wave accelerator is simplified as only an acceleration mode. Accelerating structure is expressed by a series of the integrated electric fields, each of which was integrated over one acceleration-cell, with a separation of the cell length.

SIMULATION RESULTS

By using the above model, we have simulated the dark current decay due to the chromatic aberration. The quadrupole magnets, which are the main sources of the chromatic aberration, are installed with a periodic interval as shown in Fig. 2 to tailor FODO-like optics over the C-band main linac. The linac is composed of 13 C-band sections, each of which has 8 accelerating structures and can increase the beam energy by ~504 MeV. The main linac increases the beam energy E from 1.45 to 8.00 GeV as shown in Fig. 2.

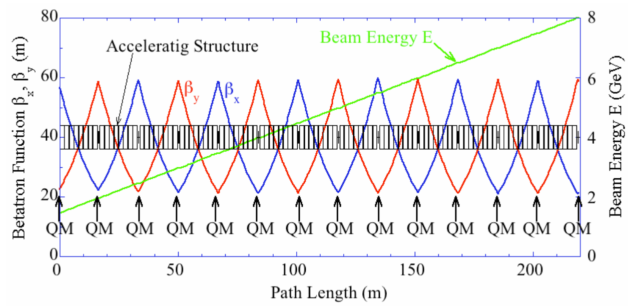

Figure 2: Beam envelope over the C-band main linac. The symbol QM represents a quadrupole magnet.

Dark Current Decay with EMF Shielded

Figure 3 shows dependence of the dark current decay on the dark current emission-point along the linac. It is clear that the dark current generated at the upstream of the linac is well transmitted to the undulator hall, due to smaller energy deviation from the acceleration beam. We have found that the dark current generated at the downstream of the 4th C-band section, which means that $\Delta E = E - E_{\mathrm{dark}} > 3$ GeV, is barely transmitted down to the undulator hall.

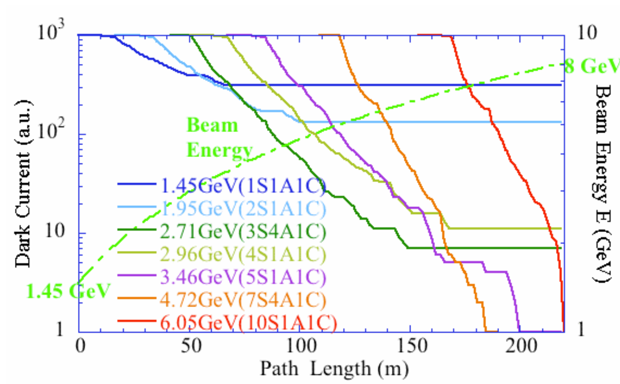

Figure 3: Dependence of the dark current decay on the emission-point along the linac. The seven different coloured lines represent the different emission-points along the linac. The words in the symbols, "GeV", "S", "A" and "C" denote the acceleration beam energy at the dark emission-point, the C-band section, the accelerating structure and acceleration cell, respectively. For example, 1S4A1C means the dark current generated at the 1st cell of the 4th accelerating structure in the 1st C-band section.

Dark Current Decay with EMF Shielded and Additional Sextupoles

We have investigated an effect of the sextupole magnets on enhancement of the chromatic aberration. The sextupole magnets are installed between the accelerating structures as shown in Fig. 4. The strength of each magnet is +30 m^{-3}, which is sufficiently weak and never degrades emittance of the acceleration beam. Figure 5 shows the obtained dark current decay. Although introduction of the sextupole magnets enhances the dark current decay, a few percent of the dark current generated in the 1st and 2nd sections can transmit down to the undulator hall.

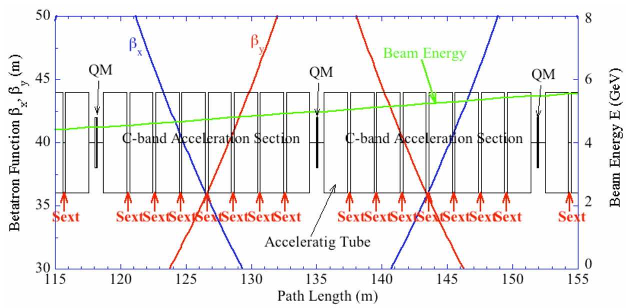

Figure 4: Sextupole magnet arrangement for enhancement of the dark current decay.

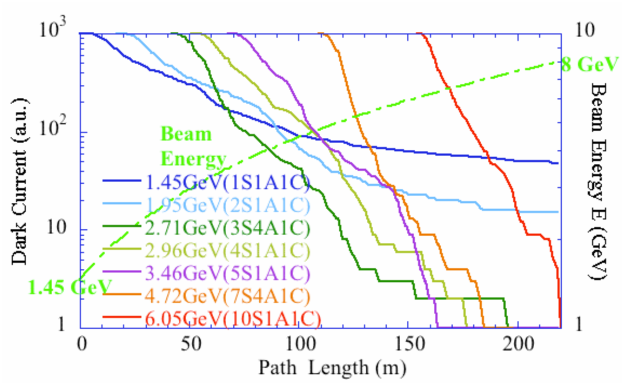

Figure 5: Dependence of the dark current decay on the emission-position along the linac with additional sextupoles. The seven different coloured lines represent the same conditions as in Fig. 3.

Dark Current Decay with EMF

We have investigated an effect of EMF on enhancement of the chromatic aberration. This means that EMF is not shielded and positively used to remove the dark current. However, the acceleration beam also suffers the EMF field effect. In order to transfer the acceleration beam through the axial near center, an adequate set of the steering strengths should be used as discussed in the previous section. Figure 6 shows the dark current decay patterns for three different conditions with EMF shielded, with EMF shielded and additional sextupoles, and with EMF of 0.4 Gauss. We have found that the decay enhancement by EMF is almost the same level as that of additional sextupole magnets.

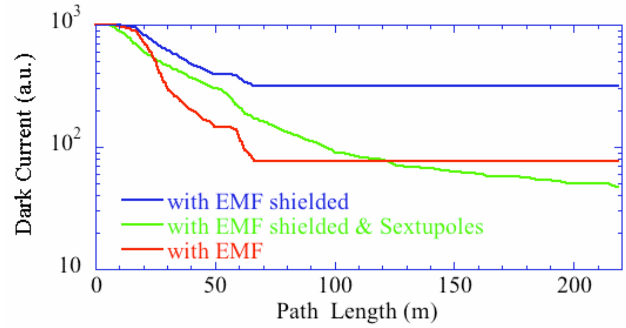

Figure 6: Dark current decay along the linac under three different conditions. The dark emission-point is the 1st cell of the 1st accelerating structure in the 1st C-band section.

ADOPTED SUPPRESSION SCHEME

On the basis of the simulation results, we have adopted a small chicane composed of identical four rectangular bending magnets with deflection angles of 0.17 deg. This chicane will be installed between the 3rd and 4th C-band sections. Since energy deviation of the dark current from the acceleration beam is significant, more than several tens percent, the dark current generated at the upstream of this chicane is completely removed. Figure 7 shows energy spectra of the dark current in the undulator hall obtained by the Monte Carlo simulations with and w/o EMF. The total charge C_t was assumed here to be 30 pC/pulse/C-band accelerating structure. The small chicane is expected to suppress the dark current less than 0.37 pC/pulse even with EMF shielded.

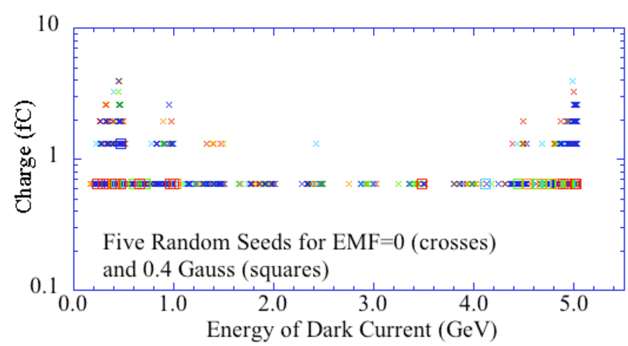

Figure 7: Energy spectra of dark currents in the undulator hall with and w/o EMF.

REFERENCES

[1] http://www.riken.jp/XFEL/index.html.

[2] K. Togawa et al., “CeB_6 Electron Gun for Low-emittance Injector”, Phys. Rev. ST Accel. Beams **10**, 020703 (2007).

[3] H. Tanaka et al., “Low Emittance Injector at SCSS”, FEL’06, Berlin, Aug. 2006, p. 769.

[4] T. Shintake et al., “A Compact Free-electron Laser for Generating Coherent Radiation in the Extreme Ultraviolet Region”, Nature Photonics **2** (2008) p. 55.