# BEAM LOSS STUDIES FOR THE KEK COMPACT-ERL

O. A. Konstantinova#, N. Nakamura, M. Shimada, K. Harada, K. Umemori, H. Sakai, T. Furuya, KEK, Tsukuba, Ibaraki, Japan
E. Cenni, Soukendai, Tsukuba, Ibaraki, Japan

*Abstract*

Beam losses due to the Touschek effect, the residual gas scattering, the intra-beam scattering and due to field emission from the main cavity were studied for the KEK compact Energy Recovery Linac (cERL), which is now under commissioning. By studying the beam losses of cERL, we can better understand the loss mechanisms, estimate the beam loss rates, and localize potentially dangerous areas of the beam line for the future 3GeV ERL project. The goal is to achieve a safety low-emittance and high-current beam operation which can help contribute to the beam loss study under 3GeV ERL project. We used existing and modified ELEGANT routine to perform the simulations. We also developed a MATLAB data analysis algorithm to handle the large amount of information that is produced by the program. The data obtained then are compared with the theoretical estimation to verify the accuracy of the simulation.

## INTRODUCTION

We have been studying beam losses for the Compact Energy Recovery Linac (cERL) project [1], which is currently under commissioning. The cERL has been proposed as a test facility for the 3 GeV ERL (the next super-brilliant and ultra-short-pulse synchrotron light source).

Table 1: cERL Beam Parameters

| Beam parameters | Simulation | cERL |
|---|---|---|
| Maximum energy | 20 MeV | 20 MeV |
| Total beam current | 10 mA | 10 – 100 mA |
| Repetition | 1.3 GHz | 1.3 GHz |
| Charge per bunch | 7.7 pC | 7.7 – 77 pC |
| Norm. beam emittance | 1 mm·mrad | 0.1 – 1.0 mm·mrad |
| Rms momentum spread | $1\cdot10^{-3}$ | $< 3\cdot10^{-4}$ |
| Bunch length | 2 ps | 1 – 3 ps |

In order to answer design questions prior to the building of the 3 GeV ERL, more detailed loss studies are indispensable, taking into account study results in cERL [2]. We aim to understand the loss mechanisms, estimate the beam loss rates, and localize potentially dangerous areas of the beam line for the future 3 GeV ERL project.

Our goal is to achieve a safe low-emittance and high-current beam operation, which can help contribute to the beam loss studies in the 3 GeV ERL project. Four beam loss mechanisms were studied in details Touschek Effect with Intra-Beam Scattering (IBS), two cases of Residual Gas Scattering (RGS): elastic (RES) and inelastic (RIS)), and field emission (FE) from the main cavity.

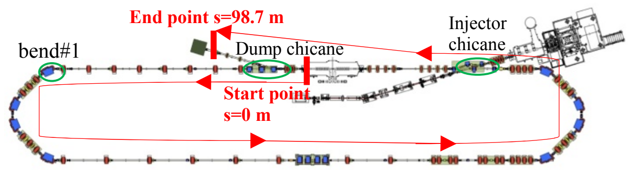


Figure 1: The cERL beam line used for tracking simulations.

## TOUSCHEK EFFECT

There are two types of Coulomb scattering within the beam: large-angle (Touschek scattering) and small-angle (Intra-Beam Scattering). Corresponding beam loss and emittance growth should be taken into account the high current operation modes of the cERL.

The Touschek effect (TS) is large angle Coulomb collisions in an electron bunch that lead to momentum transfers from the transverse into the longitudinal direction. The most general equation, which describes the scattering rate due to TS is Piwinski formula. For detailes see the work [3].

$$R\left[\frac{particles}{\sec}\right]=\frac{r_p^2 c\beta_x\beta_y\sigma_h N_p^2}{8\sqrt{\pi}\beta^2\gamma^4\sigma_{x\beta}^2\sigma_{y\beta}^2\sigma_s\sigma_p}\times F\left(\tau_m,B_1,B_2\right), \quad (1)$$

To perform the beam loss simulations due to this effect we used the particle tracking code ELEGANT [4] repairing a bug (described below) in the corresponding routine. The Touschek scattering routine [5] generates the particles distribution (Monte Carlo method, [6]) at each scattering element of the beam line (preliminary inserted). Then generated particles are tracked to the end of the beam line or to the point where they are lost (see Fig. 1), i.e. when the momentum deviation exceeds the transverse aperture. Particle interaction is described by the Moeller cross-section [7]

$$\frac{d\sigma}{d\Omega}=\frac{r_p^2}{4\gamma^2}\left\{\left(1+\frac{1}{\beta^2}\right)^2\left(\frac{4}{\sin^4\theta}-\frac{3}{\sin^2\theta}\right)+\frac{4}{\sin^2\theta}+1\right\}, \quad (2)$$

where $\theta$ is the angle between momenta before and after the collision, and $d\Omega=2\pi\sin\theta d\theta$ is the solid angle.

Due to the bug, tracking of scattered particles failed in the middle of the beam line. The bug was trivial (divide by zero), but we found the bug occurs in a particular condition when the loss probability is low such as in cERL. This is why the bug had not been discovered before. When it was fixed, we obtained the beam loss distribution and estimated the beam loss rate.

As the result we found a maximum loss rate peak of 21 pA/m which is observed at s = 93 m where dispersion is

#olga@post.kek.jp


ISBN 978-3-95450-132-8

large due to bending magnet and transverse aperture is small (2.5 cm x 2.5 cm collimator in the Lattice). Lost electrons originate at positions in the dispersive area of the arc sections.

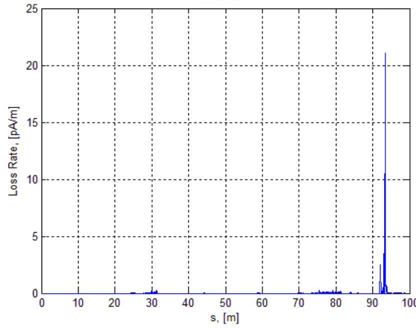


Figure 2: Beam loss due to Touschek effect (pA/m) as a function of the longitudinal position (m).

To judge the simulation result accuracy we performed a very rough estimation based on [8]

$$\frac{dN}{dt} = -\frac{\sqrt{\pi} r_0^2 N_b^2 C(\varepsilon)}{\gamma^3 V_b \sigma_x' \left(\Delta p/p\right)^2}, \qquad (3)$$

where $C(\varepsilon) \approx -\log(1.732\varepsilon) + 3/2$ . Comparison of the beam loss rates is given in Table 2 below.

## RESIDUAL GAS SCATTERING

The interactions between the beam particles and the residual gas atoms/molecules (RGS) may degrade the beam quality and can cause the beam losses. There are two principally different effects: elastic scattering and inelastic scattering [8] – [10]. In the elastic scattering, the bunch particles are transversally deflected and its betatron oscillation amplitudes are increased. If the amplitude is large enough to exceed the transverse aperture of the accelerator, the particles are lost. Elastic scattering is described by Rutherford cross-section. In the case of inelastic scattering energy of particles is reduced due to Bremsstrahlung on gas nuclei. It is when the electron is deflected by the residual gas nucleus and it emits a photon. Another way is excitation of a gas atom due to direct energy transfer from the electron to the residual gas atom. The beam particles are lost because the energy is beyond the acceptance of the beam line.

To examine the elastic and inelastic scatterings we implemented special routines into ELEGANT tracking code. The output of these routines consists of two parts; one is to estimate the total loss rate based on an integrated total cross section, and the other is to obtain beam loss distributions in the whole accelerator using a differential cross section by a Monte Carlo method.

The formula of the scattering rate can be written taking into account the assumption that the number of particles lost per unit of time is proportional to the cross section [11] (they are different for elastic and inelastic scattering), to the number of scattering nuclei ( $\rho_{target}$ ), to the number of incident particles ( $N_{beam}$ ), and to the relative velocity between the "beam" and the "target" ( $\upsilon$ ) as shown in Eq. (4). So, we use the same approach for both of elastic and inelastic scattering.

$$R = \frac{dN}{dt} = \sigma N_{beam} \rho_{target} \upsilon, \text{ where } \frac{dN}{dt} = \frac{c}{f}\frac{dN}{ds}. \qquad (4)$$

To calculate the lost number of electrons per second, and lost number of electrons per unit of longitudinal distance, we use Eq. (4), where $f$ is the repetition frequency [12].

For the Monte Carlo simulation for each beam electron, differential rate was used

$$w = \frac{dN}{dt \cdot d\Omega} = \frac{d\sigma}{d\Omega} N_{beam} \rho_{target} \upsilon = \frac{c}{f} \frac{dN}{ds \cdot d\Omega}. \qquad (5)$$

We applied Eq. (4) with the elastic and inelastic cross sections, and the beam velocity, and also replaced the beam acceptance to decide the beam loss.

Any kind of residual gas can be included by setting parameters such as the pressure and atomic components.

$$\rho_{target}^i = P^i \frac{P^i N_A}{P_{1atm} V_{std}}, \qquad (6)$$

For our simulation we assume residual gas to be the carbon monoxide ( $CO$ ). Gas pressure is from $10^{-6}$ Pa (for cERL) up to $10^{-8}$ Pa (for the light source) [13].

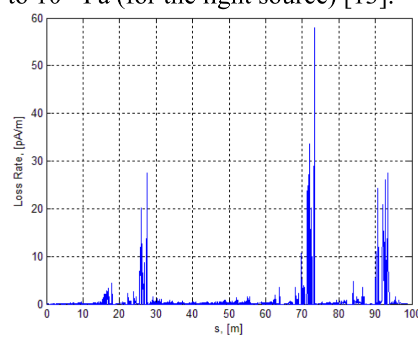


Figure 3: Loss distribution due to elastic scattering (pA/m).

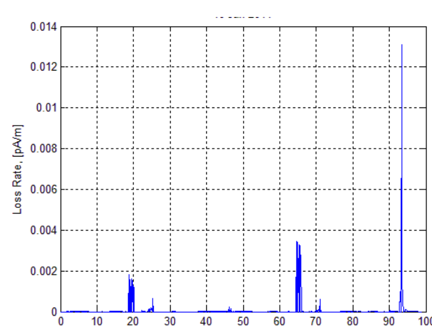


Figure 4: Loss distribution due to inelastic scattering (pA/m).

The simulation results are shown in Figs. 3 and 4. For elastic scattering circulating electrons are deflected by gas nuclei resulting in an increase of the betatron amplitudes. And for the case of inelastic scattering electrons with energy loss (dE/E) are lost at the transverse aperture limit where the dispersion or betatron function is high. Thus, we expect the peak loss current to be 58 pA/m for RES and $1.3\cdot10^{-2}$ pA/m for RIS; and the average beam loss current due to RES to be 0.76 pA/m and due to RIS to be $5.9\cdot10^{-5}$ pA/m.

To check validity of our simulation results, back-of-envelope calculations have been performed (Eq. 7). It is a collision cross-section that leads to a deflection angle greater than a maximum $\theta_{\max}$ =1 mrad defined by the acceptance of the beam line [10].

$$\sigma_{loss} = \frac{2\pi Z^2 r_p^2}{\gamma^2}\frac{1}{\theta_{\max}^2}, \quad (7)$$

Beam loss currents due to RGS are small; however, one should concern them as a possible source of irradiation because these processes typically occur in the vertical plane when the amplitude is increased by betatron oscillations.

## FIELD EMISSION FROM THE cERL MAIN CAVITY

Field emission (FE) is known to be the chief limitation associated with the emission of electrons from the regions of high electric field on the cavity surface [14]. Here we tried to estimate how FE impacts in the losses distribution along the beam line [15], i.e. treat it in terms of beam dynamics. Simulation workflow contains the result of the precise calculation inside the cavity using combination of several programs (Fishpact, Superfish, EGS5), and also experimental data, obtained during experiments, using rotating mapping system and cryomodule high power tests [16] – [18].

First the FE distribution on the cavity entrance/exit was created. The emission source is assumed to be located on an iris between 1st and 2nd cell with area of $10^{-13}$ $m^2$ and to have the enhancing factor of 100. These distributions at the exit and at the entrance are just the same due to the geometry of the FE. They contain spatial and angular coordinates, energy of emitted electrons, sampled at random moments of time in the interval ±3 ps. Then we track these particles until they are lost downstream (forward) and upstream (back) the recirculating loop using ELEGANT routine. For this purpose the lattice was modified to make use the elements involving symplectic integration (drift space, bending quadruple magnets) [20].

As the result we've got the loss distributions (see Fig. 5 and Fig. 6). Note, the $E_{accl}$=15 MV/cav.

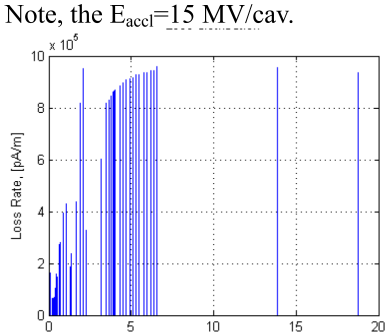


Figure 5: Loss distribution of the emitted electrons (pA/m) downstream the beam line.

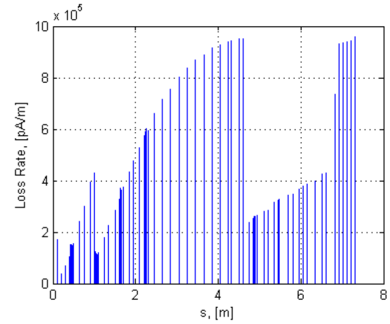


Figure 6: Loss distribution of the emitted electrons (pA/m) upstream the beam line.

It is easy to see, that for the FE propagating downstream the beam line (Fig. 1), most of the emitted electrons are lost around and before the dump chicane (2.5 m from the cavity exit). Those, who survived are travelling down the beam line until they are lost at the bending magnet #1 (18.7 m from the cavity exit). For the FE propagating in the opposite direction, all the electrons are lost around and before the injector chicane (7.1 m from the cavity entrance).

## CONCLUSION

The impacts from all the examined beam loss mechanisms are summarized in the table below. We found the beam loss from the three scattering effects are still not so significant, namely, less than 1 nA.

Table 2: Results Summary

| | Peak [pA/m] | Aver. [pA/m] | Theor. [pA/m] |
|---|---|---|---|
| **TS** | 21 | 0.04 | 0.11 |
| **RES** | 58 | 0.76 | 0.44 |
| **RIS** | $1.3\cdot10^{-2}$ | $5.9\cdot10^{-5}$ | $1.4\cdot10^{-5}$ |
| **FE** | $95.7\cdot10^{4}$ | **Down.** $3.54\cdot10^{4}$ | **Up.** $1.66\cdot10^{4}$ |

All the beam loss studies with ELEGANT evaluate not only beam loss rates, but also the beam loss distributions, namely, the "source" point where interactions have occurred, and the lost point where irradiation has occurred. Increase of the beam current during the 3 GeV upgrade can essentially impact to the beam losses, so the simulations for new machine design should be performed.

Field emission from the main cavity is the dominant effect among all the loss mechanisms has been treated. However, up to now there is no worry about excessive emission in the area near the cryomodule because the accelerating gradient is kept sufficiently low. The state of arts could change during the upgrade, when a multiple cryomodules will be installed. This problem should be treated properly.

## ACKNOWLEDGMENT

The authors would like to thank Dr. Hiroyuki Sako (J-PARC) for the fruitful discussions on beam loss and ELEGANT.




ISBN 978-3-95450-132-8

## REFERENCES

[1] S. Sakanaka et al., "Progress in Construction of the 35MeV Compact Energy Recovery Linac at KEK", IPAC'13, Shanghai, May (2013).
[2] M. Shimada et al., in these proceedings.
[3] A. Piwinski, The Touschek Effect in Strong Focusing Storage Rings, DESY 98-179 (1998).
[4] M. Borland, "ELEGANT: A Flexible SDDS-Compliant Code for Accelerator Simulation", Advanced Photon Source LS-287, September (2000).
[5] A. Xiao and M. Borland, in Proceedings of the 2007 Particle Accelerator Conference, Albuquerque, New Mexico (IEEE, Albuquerque, New Mexico, 2007), p. 3453.
[6] S. Khan, "Simulation of the Touschek Effect for BESSY II: A Monte Carlo Appproach," Proc. of EPAC1994, 1192 (1994).
[7] Le Duff, "Single and Multiple Touschek Effects", in Proc. of the CERN Act. School, Berlin 1989, CERN 89-01, pp. 114-130.
[8] C. J. Bocchetta, Gas Scattering, CERN Accelerator School – "Synchrotron Radiation and Free Electron Lasers", Brunnen, Szittzerland, July (2003).
[9] G. H. Hoffstaetter et al.,. "Intra Beam Scattering in Linear Accelerators, Especially ERLs", Proceedings EPAC08, Genova, IT (2008).
[10] A. V. Fedotov, "Intra-Beam Scattering and its Application to ERL", Advanced Beam Dynamics Workshop, KEK, Tsukuba, Japan, October (2011).
[11] A. Wrulich, "Single-Beam Lifetime", CERN Accelerator School – " 5th General Accelerator Physics Course", Jyväskylä, Finland, Sep (1992), pp.409-435.
[12] A. Chao and M. Tigner, "Handbook of Accelerator Physics and Engineering", p. 601.
[13] N. Nakamura, "Beam Loss due to Residual Gas Scattering" (in Japanese), KEK, Beam Dynamics Working Group Meeting, August (2013).
[14] H. Padamsee et al., *RF Superconductivity for Accelerators*, (New York / Chichester / Weinheim / Brisbane / Singapore / Toronto: John Whiley & Sons, inc., 1998), 227.
[15] S.E. Mayes et al., "Dark Currents Simulations for the Cornell ERL", IPAC'11, San Sebastian, Spain, p.2214 (2011).
[16] E. Cenni et al., "Field Emission Measure during cERL Main Linac Cryomodule High Power Test in KEK", SRF2013, Paris, France, p.672(2013).
[17] E. Cenni et al., "Field emission simulation for KEK ERL 9cell superconducting cavity", IPAC'12, New Orleans, USA, May 2012, p.295 (2012).
[18] H. Sakai et al., "High power tests of KEK-ERL input coupler for main linac under liquid nitrogen condition", SRF'2011, Chicago, July, 2011, p.356 (2011).
[19] K. Umemori et al., "Vertical test results for ERL 9-cell cavities for compact ERL project", IPAC'12, New Orleans, USA, May 2012, p.2227 (2012).
[20] N. Nakamura, "Field Emission Simulation for the cERL" (in Japanese), KEK, Beam Dynamics Working Group Meeting, March (2013).