BEAM LOSSES DUE TO INTRA-BEAM AND RESIDUAL GAS SCATTERING FOR CORNELL'S ENERGY RECOVERY LINAC*

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Abstract

Because of small beam emittance and high beam intensity, intra-beam scattering (IBS) in an energy recovery linac (ERL) can be a source of significant beam loss causing radiation doses. The doses should be carefully examined for adequate design of radiation protection. Additionally, the beam particle scattering on the residual gas nuclei (RGS), can cause significant irradiation and consequently can damage the insertion devices (IDs) with small vertical aperture.

In the study presented below we simulated IBS and RGS processes and estimated the beam loss distribution along the ERL beam line. IBS will cause $\sim 99.8\%$ of the total beam loss. Although RGS will contribute only $\sim 0.2\%$ of the beam loss, it can not be ignored because this process causes scattering in the vertical plane which results in irradiation of the insertion devices with small vertical aperture. For both, IBS and RGS processes, the highest beam loss occur at the very end of deceleration due adiabatic anti-damping causing the transverse betatron amplitudes to increase. However, since at this location the particle energy will be low, radiation doses will not be much higher than in another locations of the ERL beam line.

The beam particle loss rate at insertion devices allowes us to make estimation of their life time and suggest a radiation protection scheme.

MODEL

In simulation, we included elastic (Coulomb) and inelastic (Bremsstrahlung) scattering on the residual gas nuclei (RGS) as well as intra-beam scattering (IBS) processes. Basic formulas for their cross-sections can be found in [1]. For the average atomic mass parameter, we used $Z = 7.5$. This value was obtained in earlier experiments, see [2] and [3], from the measurement of the dependence of the beam life time on vertical aperture. Simulation was done for the "CERL Version 3.0" optics.

Optics Characteristic and Beam Parameters

Some of the model characteristics are depicted on Fig. 1. The slops in the beam energy dependence along the ERL, see Fig. 1a, indicate the beam acceleration/deceleration in the linacs. Plateaus seen at 2.5 and 5.0 GeV correspond to the 180^0 turn around between linacs (1); South transport line (2); CESR section (3) and North transport line (4). The minimum beam energy, E_{min}, at the end of deceleration is 10MeV. Horizontal dispersion along the ERL, see Fig. 1b, is zero in linacs and nonzero in the 180^0 turn around, South and North transport lines and in the CESR section.

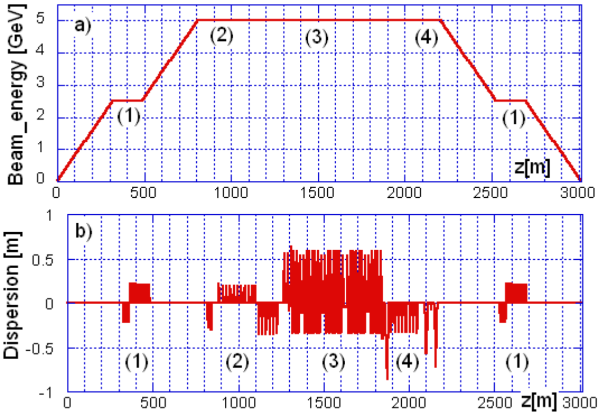

Figure 1: Beam energy (a) and horizontal dispersion (b) along the ERL.

In simulation we assumed 40mm diameter round aperture in linacs, 24.5mm diameter round pipe in transfer lines and 5mm × 80mm rectangular aperture in undulator magnets, as shown in Fig. 2.

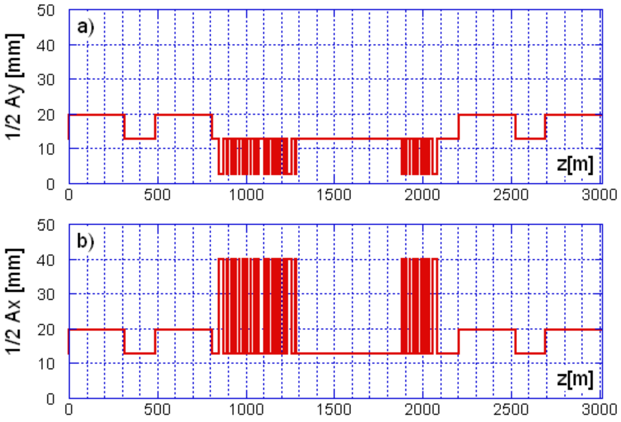

Figure 2: Vertical (a) and horizontal (b) beam line aperture along the ERL. The vertical aperture is reduced to ±2.5mm in IDs.

In the simulation we used electron beam parameters corresponding to the "High flux" mode of operation, see Ta-

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ble 1. Distribution of the residual gas density along the ERL was estimated [4] for the specified aperture and beam current and varied between approximately 1 and 20nTorr.

Table 1: ERL beam parameters

Parameter		Units
Total beam current	100	mA
Charge per bunch	77×10^{-12}	C
Normalized beam emittance	3×10^{-12}	$m \cdot rad$
Bunch length	0.6	mm
Momentum spread dp/p rms	0.0002	
Repetition rate	1300	MHz

Propagation of Trajectories

The scattered particle trajectories were propagated with liner transport matrices. In addition we take into account the following:

- Adiabatic anti-damping effect. It causes a betatron oscillation amplitude change $\propto \sqrt{E(z)/E_s}$, where E_s and $E(z)$ are the beam energies at the scattering and at tracking locations.
- The energy loss and gain from inelastic or intra-beam scattering. Note that the ration of this energy change to the beam energy strongly increases during deceleration.

Note that the first effect may result in a significant increase of the betatron-oscillation amplitude at the end of deceleration. Particles scattered at 5GeV at the end of deceleration will have a betatron amplitude that increased by $\sqrt{E_{max}/E_{min}} \simeq 22$. This causes much higher beam loss rates at the end of the linac compared to the average.

Simulation Technique

In the simulation we launched some number of particles (usually ~ 500) at each beam line element with a distribution corresponding to intra-beam scattering or scattering on residual gas nuclei. Then particle trajectories were propagated through the beam line untill they either reach the end of the beam line or cross vertical or horizontal aperture limits. The crossing location was considered as a particle loss location. To create the distribution of initial conditions, a Mote-Carlo type generator was used. For each tracked particle we calculated the corresponding number of the real particles scattered from the beam at a given element. This number was used to scale the simulated particle loss distribution to the actual beam loss.

All calculations were done with programs based on MatLab using a laptop IBM T42 (ThinkPad).

RESULT

This simulation yields the beam loss distribution along ERL beam line. It will be used for calculations of the radiation doses in surrounding areas and for the radiation protection design. Using the beam particle loss rate at IDs we estimated their life times.

Beam Loss and Radiation Power Distribution Along the ERL

Fig. 3a and Fig. 3b depict beam current loss induced by IBS and RGS. Horizontal axes shows coordinate along the ERL beam line. The data indicate that intra-beam scattering will be a major contributor. In the ”South transport line” area, where the first group of IDs is located, IBS will generate up to 1pA/m of beam current loss, which will generate up to ∼ 5 mW/m of radiation power, see Fig. 4. In the ”North transport line” area, few locations have beam loss density up to 10pA/m and radiation power of 50mW/m. At the end of deceleration, beam loss will be much higher, $\sim$ 100pA/m. This is the result of the discussed adiabatic anti-dumping. Despite of the high loss level, because particles at this location have low energy, radiation power here will not be much higher than the average.

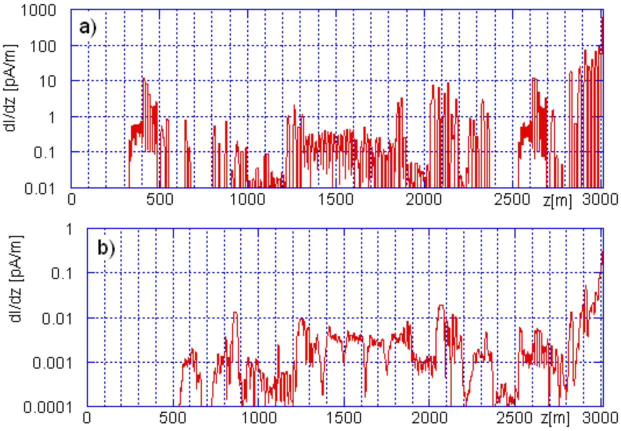

Figure 3: (a) - beam loss along ERL caused by IBS, (b) - beam loss due to RGS. The integrated beam loss caused by IBS $\sim 10nA$, by RGS $\sim 20pA$.

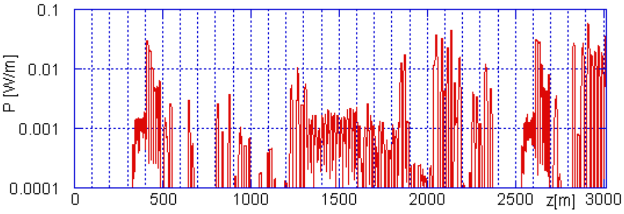

Figure 4: Total radiation power generated by the beam loss along ERL. $\sim 99.8\%$ of the radiation generated by IBS particles

RGS (scattering on the residual gas nuclei) generates $\sim$ 0.001 to 0.01 pA/m of beam loss, see Fig.3, i.e., $\sim 5 \times 10^{-3}$ to $5 \times 10^{-2} mW/m$ of radiation power which is two order magnitude less than for IBS.

As IDs have horizontal aperture larger than other elements, particles from IBS will be lost elsewhere and will not generate radiation at ID locations. However, elastic (Coloumb) scattering on residual gas nuclei may cause particle trajectory deviation in the vertical direction. If no special measure is taken, these particles will be lost at IDs which have small vertical aperture (we assuming 5mm vertical gap), causing their irradiation and demagnetization.

Insertion Devices Life Time and Their Protection

The insertion device life time caused by radiation damaging was estimated using experimental data obtained in ref. [5]. For 22mm period, NdFeB (grade 40SH) pure permanent magnet undulator at room temperature with 5mm gap the critical radiation dose causing 1% demagnetization was estimated as 0.9Mrad. Assuming that the 5GeV electrons lost at an undulator entrance will deposit all their energy into a volume of $\sim$ 40cm length and 2cm×1cm transfers dimensions[1] with 7.9 g/cm^3 density, one can find that 0.9Mrad of average radiation dose corresponds to 1.3×10^{13} electrons. Using this number and knowing the electron loss rate at ID, we estimated ID life times.

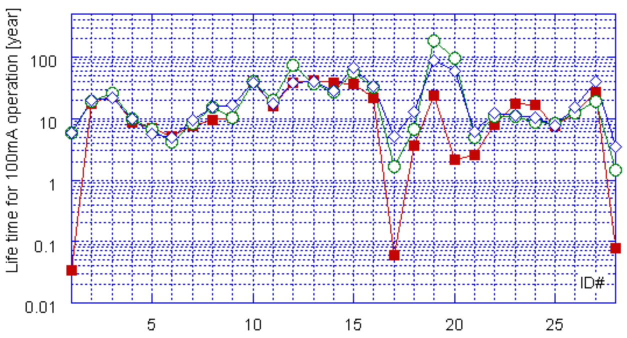

Figure 5: Undulator life time. Solid squares are for the model optics. Open circles indicate life time with added vertical collimators. Open diamonds are for optics with collimators and improved vacuum.

The data presented in Fig. 5 show estimated ID life time for continues 100mA operation: a) for the model described above, b) for optics with 8 collimators with ±2.5mm vertical aperture limits, c) for optics with colimators and lowered residual gas pressure of $1nT$ upstream of the 25m undulators.

Our simulation predicts that if no precautions are taken, all three 25m long undulators ("1","17" and "28") will be demagnetized in less than 0.1 year of operation! Eight collimators with small vertical aperture placed in locations with large vertical beta function will reduce the number of electrons lost at these IDs by a factor between 10 and 100. It will increase the undulator "1" life time to 8 years, and undulators "17" and "28" life time to ~ 1.5 years. Further improvement can be achieved by lowering the residual gas pressure. Lowering the pressure upstream of undulators "17" and "28" to 1nTorr gives another factor of 2, i.e., their life time will be increased to $\sim$ 3 years.

CONCLUSION

We developed a model allowing us to calculate beam loss along the ERL beam line. The model includes the intra-beam scattering process as well as elastic (Coloumb) and inelastic (Bremsstrahlung) scattering on the residual gas. Calculations were made for 100mA beam current operation, for the "CERL Version 3.0" optics and realistic residual gas pressure distribution. They indicate that $\sim 99.8\%$ of the total beam loss (~ 10nA) will be due to IBS, RSG will cause only $\sim 20pA$ or $\sim 0.2\%$ of the total loss. Although beam loss due to RGS is negligble compared with IBS, it can not be ignored because it will be responsible for undulator magnets' radiation damage. Most sensitive to radiation damage will be three long 25m undulators. If no precautions are taken, at 100mA operation their life time will be $\sim$ 1month. The life time can be improved to an acceptable level by collimators placed at locations with large vertical beta functions upstream of the magnets and by lowering the residual gas pressure.

ACKNOWLEDGE

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[1] The length was estimated using data from [6], 2cm×1cm are the permanent magnet block's transfer dimensions.