STUDY OF GAS SCATTERING–INDUCED BEAM LOSSES AND COLLIMATION FOR THE SOLEIL II STORAGE RING

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Abstract

The SOLEIL II storage ring will be equipped with many in-vacuum undulators (IVUs) and superbends, which are vulnerable to gas scattering–induced beam losses due to their small vertical gaps. In this paper, gas scattering–induced beam losses in SOLEIL II are studied with tracking simulations. The results show that, without vertical scrapers, 53% of elastic scattering–induced losses happen at IVUs with 4 mm vertical gaps, posing a risk of damage to their magnets over 15 years of operation. Detailed tracking finds that most of these losses originate from scattering events in short range, e.g., within half a turn. This suggests that one vertical scraper located upstream of each IVU group could provide optimal collimation, protecting the IVUs while maintaining the beam lifetime. However, this scheme is not allowed due to space constraints. A second optimal vertical collimation scheme is proposed with 2 scrapers, which reduces the beam losses at IVUs by 40% while maintaining an elastic scattering lifetime of 40 hours. In contrast to elastic scattering, inelastic scattering leads to only minor beam losses and remains acceptable.

INTRODUCTION

The SOLEIL II project aims to upgrade the French 3rd-generation synchrotron light source to a 4th-generation machine [1, 2]. Operating at an energy of 2.75 GeV with a maximum beam current of 500 mA, the upgraded storage ring lattice is designed to be highly compact and achieve an ultra-low natural horizontal of 85 pm·rad [3]. The SOLEIL II storage ring will utilize numerous insertion devices, predominantly in-vacuum undulators (IVUs), and superbends. These IVUs have very small gaps, with a minimum vertical physical aperture of ±2 mm [4]. Consequently, electrons undergoing scattering with residual gas molecules have large betatron oscillation amplitudes and are eventually lost on the walls of vacuum chamber and IVUs [5]. The steady flux of the scattered electrons striking the narrow IVU gaps, mostly from elastic gas scattering, poses a serious risk, as the cumulative radiation damage can lead to the demagnetization of IVU magnets over the expected 15-year operation of the machine. To protect the IVUs, the spatial distributions of the losses of scattered electrons are evaluated and an optimized collimation scheme is designed, which is critical to the safe and continuous operation of the SOLEIL II storage ring.

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BEAM LOSSES WITHOUT COLLIMATION

To study the detailed distribution of lost electrons, tracking simulations were carried out using the code ELEGANT [6]. For elastic gas scattering, particles were tracked for 1026 turns with a grid of 24 in polar and 19 in azimuthal. The local dynamic acceptance in angle was set in the range of 0.0001 ~ 0.005 rad. Initial tracking was performed for the SOLEIL II storage ring lattice V3631 [2] with physical apertures and systematic multipole errors, but without other errors or vertical scrapers. An equivalent two-step gas pressure profile of N_2 was assumed to be 10^{-10} mbar in straight sections and 10^{-9} mbar in arc sections. The linear optics, vertical physical apertures, and distribution of electron loss rate from elastic gas scattering are shown in Fig. 1. The calculated lifetime for elastic gas scattering is 62.7 hours. As for inelastic (bremsstrahlung) gas scattering, simulation yields a lifetime of 123.4 hours. Since inelastic gas scattering induced beam losses are not significant and do not distribute on the vertical surfaces of IVUs in the uncoupled lattice, the remainder of this paper focuses only on elastic gas scattering.

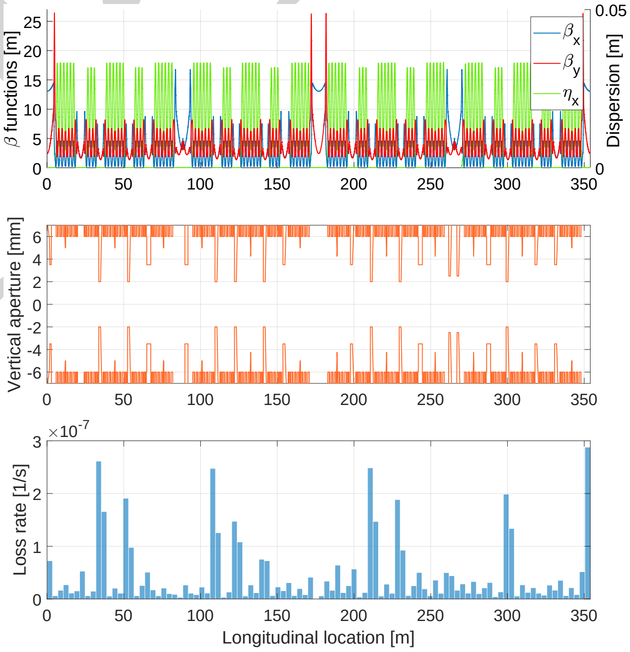

Figure 1: Linear optics (top), vertical physical apertures (middle), and distribution of electron loss rate from elastic gas scattering (bottom) of the SOLEIL II storage ring.

It is seen in Fig. 1 that most of the beam losses due to gas scattering are distributed in the positions with small vertical apertures, corresponding to the narrow gaps of IVUs. Specifically, 72% of the scattered electrons are lost in the vertical direction and 53% are concentrated at the IVUs, with a few percents lost at the superbends. The peak loss occurs on the first IVU (IVU24 NdFeB), reaching a maximum lost rate of 3.885×10^{-7} 1/s. Figure 2 shows the scattering location of the electrons lost at IVU24 NdFeB and the transverse distribution of their loss rate. From the upper plot, it can be seen that the losses at IVU24 NdFeB originate from scattering events that occur in short range, mostly within one turn. From the lower plot, it is seen that the losses are mainly located at the vertical surfaces of the IVU in the transverse plane. At the nominal beam current of 500 mA, this corresponds to an energy loss power of 6.31×10^{-4} W deposited locally onto the IVU magnets. If unmitigated, this level of continuous radiation can represent a risk to the equipment in the long term operation.

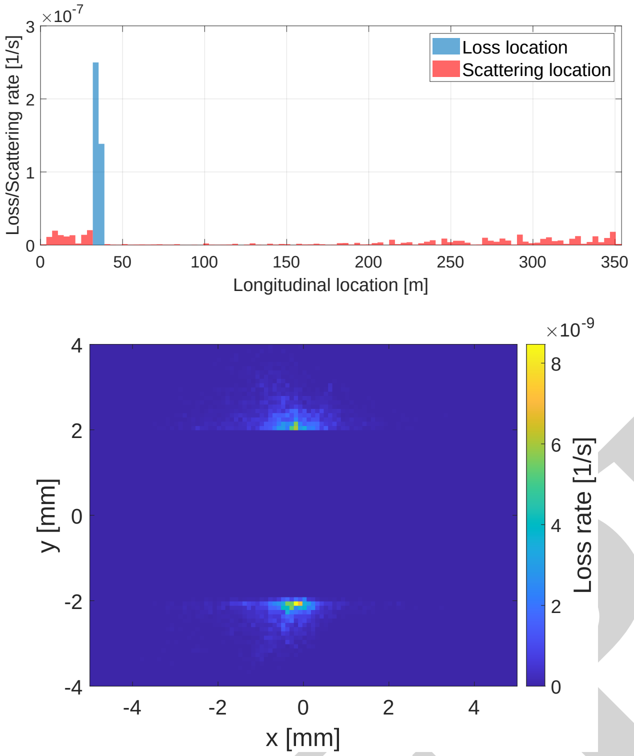

Figure 2: The longitudinal distribution of loss and scattering rates (upper) and transverse distribution of loss rate (lower) for the electrons lost at IVU24 NdFeB.

COLLIMATION STRATEGIES AND OPTIMIZATION

To alleviate the radiation on IVUs, the vertical scrapers must be introduced into the ring to collimate the concentrated losses on the IVU magnets. To efficiently collimate these scattered electrons while preserving the beam lifetime, the locations and gaps of the scrapers should be carefully chosen. First, because of the neutron flux that penetrates the blades, the scrapers cannot be located immediately upstream of the IVUs. It is preferable to place the scrapers some distance upstream to the IVUs, e.g., one cell upstream. Second, since the beam losses originate from scattering events in short range, the scrapers should ideally be located as close to the IVUs as possible. Considering the fully packed arc sections in the SOLEIL II lattice, the scrapers can be located in the upstream straight sections to the IVUs. Third, because the vertical betatron amplitude is proportional to $\sqrt{\beta_y}$, the gaps of the scrapers are also supposed to be scaled to $\sqrt{\beta_y(s)}$, where s is the longitudinal locations of the scrapers. Regarding the betatron phase, to efficiently collimate the scattering electrons at the betatron oscillation peaks, the vertical phase advances from the scrapers to the IVUs are preferably close to the multiples of π. However, the SOLEIL II lattice is quite compact considering the elements of all systems. There is only limited possible space for the scrapers, which cannot fully fulfill the conditions discussed above. Table **??** lists the possible locations for vertical scrapers. Figure 3 shows the vertical loss rate distributed at IVUs without collimation. It is seen that the peaks of loss rate at IVUs can be approximately divided into four groups. Within each group, the loss rate at IVUs is descent, which suggests that upstream IVUs naturally provide a shielding effect for subsequent downstream IVUs. From this point, one scraper upstream each IVU group can be optimal.

Table 1: Possible Location and Length for Vertical Scrapers

Straight Section Index	Longitudinal Location [m]	Longitudinal Length [mm]
Cell 1	1.6	350
Cell 5	68.0	287
Cell 6	84.9	309
Cell 10	153.8	210
Cell 11	181.2	322
Cell 12	200.9	210
Cell 15	245.0	287
Cell 17	289.4	287
Cell 20	334.0	350

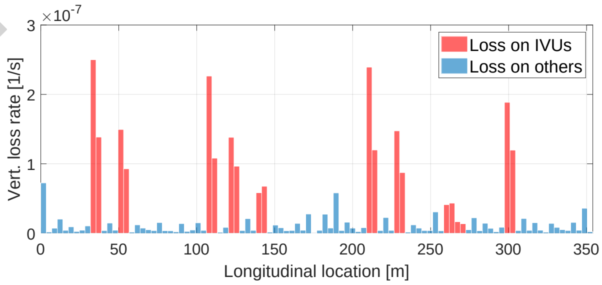

Figure 3: Vertical loss rate along the ring without collimation.

Ideal Four-Scraper Configuration

If spatial and budget constraints are allowed, the optimal protection scheme would be four scrapers in the straight sections upstream of each IVU group, which can be located in the straight sections of Cell 1, 6, 12 and 17 in Table 1. After optimization, the vertical half-gaps of these scrapers are 1.60 mm, 1.67 mm, 1.69 mm, and 1.53 mm, respectively, which are proportional to their local $\sqrt{\beta_y(s)}$. The distribution of beam loss rate due to elastic gas scattering for this four-scraper configuration is shown in the upper plot of Fig. 4. The loss rate at the IVUs drops from 2.35×10^{-6} 1/s to 1.06×10^{-6} 1/s, while the scrapers safely intercept 56% of the lost electrons. The maximum localized loss power on IVU24 NdFeB is subsequently reduced to 2.59×10^{-4} W for the 500 mA current. The elastic gas scattering lifetime is reduced to 41.7 hours, which is considered acceptable with the total beam lifetime reduced by around 10%. Further simulation shows that more scrapers do not significantly improve the protection for the IVUs.

Constrained Two-Scraper Configuration

Given the realistic constraints, a configuration utilizing only two vertical scrapers was evaluated. The optimal locations of the two scrapers are in the straight sections of Cell 1 and 10 in Table 1, with vertical half-gaps to be 1.60 mm and 1.48 mm, respectively. The distribution of beam loss rate due to elastic gas scattering for this two-scraper configuration is shown in the lower plot of Fig. 4.

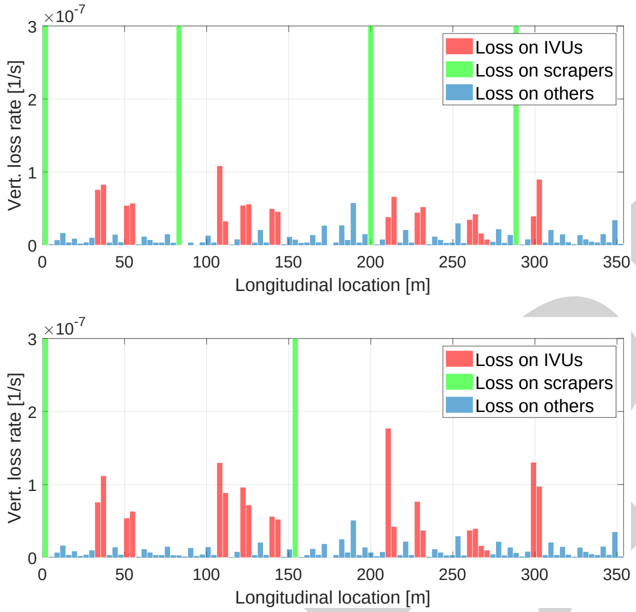

Figure 4: Longitudinal distribution of loss rate for two collimation schemes. Upper: the scheme with four vertical scrapers in the straight sections of Cell 1, 6, 12 and 17; Lower: the scheme with two scrapers in the straight sections of Cell 1 and 10.

The loss rate at the IVUs drops from 2.35×10^{-6} 1/s to 1.48×10^{-6} 1/s, while the scrapers safely intercept 50% of the lost electrons. The highest localized loss shifts to IVU20 SmCo, amounting to a deposited power of 3.71×10^{-4} W for the 500 mA current. The elastic scattering lifetime is 40.6 hours. Further simulation indicates that tightening the scraper gaps beyond these recommended values yields no significant improvement in IVU protection, but rather drastically degrades the elastic gas scattering lifetime.

CONCLUSION

A detailed tracking study showed that gas scattering–induced beam losses in the SOLEIL II storage ring predominantly occur over short ranges and are heavily localized at the IVUs, posing a long-term demagnetization risk to their permanent magnets. While placing four vertical scrapers upstream of each IVU group would offer ideal protection, it is not permitted by the spatial and budget constraints. A constrained configuration with two scrapers in the straight sections of Cell 1 and 10 is recommended as the optimal feasible solution. With vertical half-gaps of 1.60 mm and 1.48 mm respectively for the two scrapers, the elastic gas scattering lifetime is 40.6 hours while the loss rate at IVUs is reduced by 40%. Further work will be based on the final lattice version of the SOLEIL II storage ring with errors and corrections. A more realistic gas profile is needed and the gaps, and lengths of the vertical scrapers require careful numerical optimization considering the actual spatial conditions.

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