RADIATION SAFETY CHALLENGES ASSOCIATED WITH THE VERY LOW EMITTANCE STORAGE RING UPGRADE OF SYNCHROTRON SOLEIL

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Abstract

The SOLEIL II storage ring upgrade project aims at reducing the horizontal emittance of the electron beam from 4 nm.rad for the present ring down to less than 100 pm.rad for the SOLEIL II new 4th generation storage ring. It is based on the replacement of the present double bend achromat by a mixed multi-bend achromat, the so-called 7BA-4BA lattice and a general use of permanent magnets (PMs) for both dipoles and quadrupoles. The corresponding long shutdown is scheduled between October 2028 and October 2030, when user operation will resume. Compared to the present storage ring, SOLEIL II will operate with a slightly reduced beam lifetime and, consequently, with increased beam loss rates. This leads to many challenges in terms of Radiation Safety and Radiation Damage assessments. This paper will present the main characteristics of the SOLEIL II storage ring upgrade and the corresponding main challenges in Radiation Safety to maintain the Experimental Hall as a non-radiation area. A detailed shielding design study is required by the Authority for Nuclear Safety and Radiation Protection (ASNR) as a basis for the authorization request that SOLEIL will submit to recover the ASNR license before restarting the accelerators by the end of 2029. This paper also provides a status update on the shielding design study, mainly driven by extensive use of the FLUKA Monte Carlo code, the remaining radiation safety challenges to be addressed, and the foreseen effects of ionizing radiation exposure of the PMs.

INTRODUCTION

The compact 2.75-GeV, 354-m Storage Ring (SR) will ultimately reach a 50 pm round-beam emittance using an atypical 7BA–4BA lattice [1, 2], extensive use of PM technologies, nearly 100% NEG-coating, 12-mm diameter vacuum chambers, a new in-vacuum nonlinear kicker for transparent top-up operation, new 4th-harmonic cavities, and 10-µm magnet alignment [3]. From a radiation safety point of view, the challenge lies in ensuring that the present SR shielding is as effective as today for the new ring, considering that it will induce more continuous beam losses because of its reduced beam lifetime compared to SOLEIL's.

MATERIALS AND METHODS

To accurately model the behavior of lost beam particles, the loss distribution in the SR is derived from detailed pyAT [4] simulations provided by the Accelerator Physics Group. These calculations include spatial loss probability distributions and the 6D phase-space characteristics of lost electrons. Furthermore, the model accounts for horizontal and vertical physical apertures, including the minimum gaps of in-vacuum insertion devices (IDs), as well as the kinetic energy deviation of the lost beam. All these results are given for electron beam losses arising from the Touschek effect with the best possible error corrections, considering realistic magnetic field errors, alignment errors, and the ID portfolio foreseen ready at the restart of the ring for stage 1 [5]. The corresponding beam lifetime, without harmonic cavity induced bunch lengthening, is 3 hours for a 500-mA stored beam in a uniform-filling pattern. As a conservative assumption, this beam lifetime was retained for all radiation safety calculations and normalization factors. The evaluated gas-scattering beam lifetime being much higher (~60 hours), corresponding beam losses are considered as negligible compared to Touschek's. Except at the septum position in the injection area, beam losses are distributed relatively smoothly along the SR (see Fig. 1), the very narrow beam pipe acting as a distributed collimator. Upon closer examination of the distribution, a few 7BA-4BA cells appeared to accumulate a slightly larger part of the beam losses than the rest of the ring. Four zones were identified, and one was selected for radiation safety simulations as representative of the entire SR. The FLUKA code [6, 7] was chosen for the radiation safety calculations for its ability to simulate, as accurately as possible, high-energy particles transport and interactions in a detailed 3D geometric model that includes magnetic fields characteristics, bill of material, as well as its ability to sample complex beam losses and phase space distributions, thanks to dedicated user routines.

A comprehensive 3D model of two cells of the SR was generated in FLUKA using an advanced version of the vacuum pipe design, permanent and electromagnetic magnets, girders, etc. This was done with the greatest possible accuracy to ensure consistency and to match the magnetic field position and strength that are input in FLUKA's dedicated magnetic field routine. The corresponding tunnel shielding was modeled as built with inner walls and roof blocks cast in ordinary concrete and the port-end and front-end outer walls in haematite heavy concrete. An additional 6-cm thick lead layer covers the entire surface of the front-end wall with an 8 cm thick lead reinforcement centered on the beam plan, +/− 20 cm in height.

NORMAL BEAM LOSSES

The Touschek Beam Losses are simulated for the two cells AN07 and AN08 because of their higher cumulated beam loss probability (12.8% of the total Touschek beam losses in the SR), as shown in Fig. 1. For each lost particle, the phase space characteristics provided by Accelerator Physics Group are implemented in the FLUKA user source routine. All the FLUKA calculations were performed by scoring several physical and radiation safety quantities, such as neutron and photon fluences, and photon, neutron, and total ambient equivalent dose rates, and Effective Dose (ED) rates. A general result is that all total ED rates are below the design criterion of 0.50 µSv/h but are quite close, so very little margin is available.

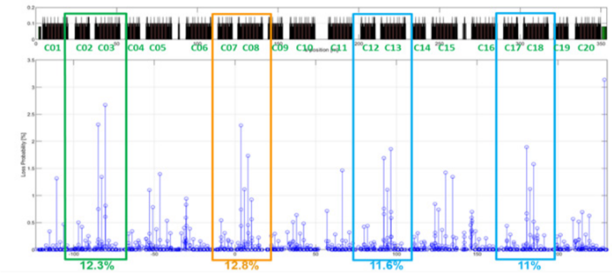

Figure 1: Touschek Beam losses distribution in terms of relative loss probability and selected region of interest.

A further general finding is that dose rates outside the tunnel shielding are predominantly driven by neutrons produced by photonuclear reactions. The shielding study results presented below (Fig. 2). show that the ED rate criteria is met almost everywhere along the inner walls, outer walls and roof, with dose rates at or below 0.10 µSv/h – most of them below 0.05 µSv/h – except at several critical points where dose rate values may reach 0.20 µSv/h

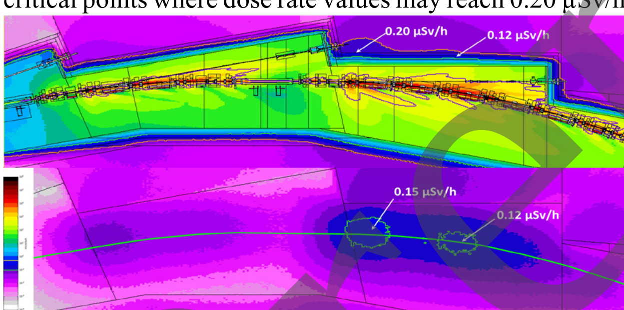

Figure 2: Total Effective Dose rates (γ+neutron) [8] due to normal beam losses for 500 mA operation. Beam plan level (top-view), and above the roof top level (bottom view).

LOCAL SHIELDING EVALUATION

An evaluation of local shielding options to reduce dose rates outside the tunnel has been carried out. Results show that relatively compact heavy-concrete local shielding can reduce the ED rates outside the tunnel by roughly a factor of two. Shielding dimensions and materials must be optimized with respect to available space, distance from beam loss positions, manufacturing cost, activation sensitivity, and dose-rate reduction efficiency. Because the radiation source term outside of the tunnel is dominated by photoneutrons – giant dipole resonance (~1 MeV) and high energy neutrons (few tens of MeV, mainly in the 60-80 MeV range at SOLEIL) – high-Z material may be preferred. Iron is known to be effective against high-energy neutrons with relatively thin thicknesses, but it can be significantly activated, the same applies to heavy-concrete. Therefore, combinations of the two may offer a practical solution. Several configurations were investigated, and Fig. 3 compares the results obtained. A local shield combining a heavy-concrete block with a cast-iron layer appears to be an efficient solution for reducing dose rates outside of the tunnel within a relatively compact volume.

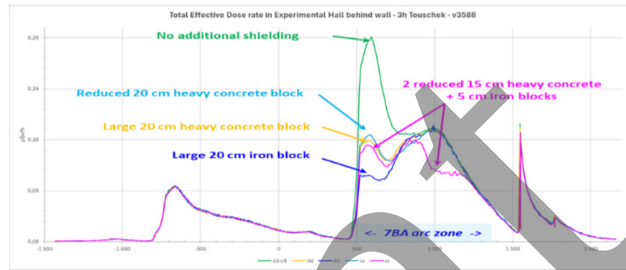

Figure 3: Comparison of different local shielding geometries and materials in terms of total Effective Dose rate reduction.

A similar evaluation was carried out by substituting 3 ordinary-concrete blocks of the first layer of the tunnel roof by heavy-concrete blocks. As shown on Fig. 4, almost a reduction by a factor of two may be expected.

Figure 4: Comparison of ED rate (µSv/h) above roof top along beam axis (see green line on Fig. 2) when 3 ordinary concrete blocks are substituted by heavy concrete blocks.

ACCIDENTAL BEAM LOSSES

To complete the radiation safety assessment of the new SR, several abnormal scenarios are evaluated for both total stored-beam and injected-beam losses. As a conservative case, the scenario in which the full beam strikes a closing vacuum valve upstream of an opened front-end is evaluated.

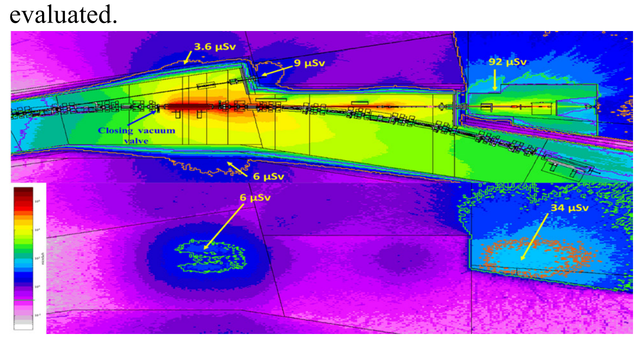

Figure 5: Total Effective Dose around tunnel for full beam accidental loss on closed vacuum valve, at beam plan level (top) and above roof top (bottom).

The movement of the valve is relatively slow compared to beam revolution frequency (few ms to close compared to 1.2 μs by turn). Consequently, the electron beam hits the valve only at Gaussian tail of the transverse spatial distribution, slightly off axis. At each turn, the Gaussian tail is repopulated, and the fraction intercepted by the valve is slightly larger than at the previous turn, until all electrons are finally lost. The thin part of the valve intercepting the beam was modeled and the ED outside the tunnel was evaluated for a 500-mA full beam loss on the valve. The corresponding ED ranges from a few μSv around the tunnel near the beam loss position to up to 90 μSv in the vicinity of the first optics hutch of the beamline downstream of the valve as shown in Fig. 5 above.

PERMANENT MAGNET DAMAGE ASSESSMENT

The new SOLEIL II SR lattice will use PMs for more than 35% of the magnets. Due to the sharp sensitivity of this specific lattice to magnet flux intensity and gradients in dipole and quadrupole magnets, even a very small variation of these critical parameters may dramatically affect the performance of the new ring. The risk that radiation exposure generated by accumulated beam losses may lead to partial demagnetization, even at a low rate, must be assessed in detail. Examining the available data in the literature, the results of demagnetization measurements correlated with neutron fluence exposure for different grades of PMs caught our attention. Neutron fluence is a physical quantity that can be easily computed with FLUKA for a primary assessment. Some PM grades, like Sm_2Co_{17} are known for being a bit more radiation resistant as it is confirmed in [9]. This is the grade selected for SOLEIL II lattice magnets owing to its specific magnetic properties. Small demagnetization rate for this grade may occur at neutron fluence level higher than 10^{14} n.cm^{-2}. $Nd_2Fe_{14}B$ grade will be used for the PMs of some IDs of SOLEIL II [5] and demagnetization of such a grade may occur just above 10^{12} n. cm^{-2} neutron fluence [9]. The FLUKA model of the SOLEIL II SR was used to quantify cumulated neutron fluence exposure of the lattice PMs, under conservative assumptions over the foreseen 25-year operation of SOLEIL II. A neutron fluence map was obtained for 25 years of operation, assuming a worst-case scenario of a 3-hour beam lifetime for the first 5 years and a 6-hour beam lifetime for the following 20 years. Considering more than 6 000 hours of operation per year this will result to a cumulative charge of about 37-mC on the SR. Highest neutron exposure is in the 7BA arc, mainly downstream the 1st and 3rd dipoles. Most exposed PMs show neutron fluence maximum values up to 6.10^{12} n.cm^{-2}. For these PMs a significant margin seems possible, given a demagnetization threshold for the Sm_2Co_{17} grade above 10^{14} n.cm^{-2}. Neutron fluence exposure was also evaluated in PMs of an in-vacuum ID installed in the AN07 straight section. The highest neutron fluences are at the first 20 magnet rows from the entrance of the ID vessel. The maximum neutron fluence accumulated locally into the PM reaches about 2.10^{12} n.cm^{-2}. This is very close to the apparent threshold for magnetic damage in $Nd_2Fe_{14}B$ grade PMs. These results may be mitigated by the fact that beam lifetime assumption, along with the whole operation duration of SOLEIL II is conservative and by the fact that stage 1 IDs will likely be replaced after the first ten years of operation with higher performance device. The use of two collimators may also be a possible mitigation measure. To confirm these results, experimental measurements were performed, using the capabilities of the CHARM Facility at CERN [10]. Some PM samples were irradiated at neutron fluence levels close to those calculated with FLUKA, as described above. Two sets of PMs were prepared for both Sm_2Co_{17} and $Nd_2Fe_{14}B$ grades with different magnet field axis alignments. All PM samples were characterized before and after irradiation session with a 2D Hall probe at SOLEIL's magnet laboratory to evaluate the level of demagnetization following the irradiation. The PM irradiation at CHARM was performed at a level of 1.9 10^{12} Si 1MeV neutron equivalent fluence as measured by dedicated detectors at sample position. Which corresponds, according to Infantino's note [11], to a PM sample neutron fluence exposure of 5.10^{12} n.cm^{-2}. The Sm_2Co_{17} PMs underwent a second irradiation session at 10^{13} n.cm^{-2}. No significant variation of the magnetic field was observed in the Sm_2Co_{17} PMs at both irradiation levels. For the $Nd_2Fe_{14}B$ PMs, the measured magnetic field has decreased by about 2% (confirmed twice). These results must be confirmed soon by complementary exposures and characterizations.

CONCLUSION

Detailed FLUKA simulations indicate that the planned 7BA-4BA lattice upgrade for SOLEIL II appears compatible with the existing SR tunnel shielding, allowing the experimental hall to remain a non-radiation worker area. Additional margin is expected from both the improvement in beam lifetime provided by the harmonic cavities and the potential use of local shielding optimally designed at the most critical points along the SR circumference. These two points will be mandatory in the argumentation to obtain ASNR authorization for the operation of the new SOLEIL II accelerator complex. Evaluation of PMs radiation damage has been performed. Results have been obtained for both calculated neutron fluence exposure and PMs irradiation exposure and corresponding demagnetization measurements. These results are promising for Sm_2Co_{17} grade PMs foreseen for SR lattice magnets with neutron fluence exposure more than 1 order of magnitude below the damage threshold and confirmed by the measurement of the irradiated samples at CHARM Facility. For $Nd_2Fe_{14}B$ grade PMs that will be used in IDs, the neutron fluence exposure evaluated by FLUKA calculation is very close to the damage threshold, and irradiated-sample measurements show a small but significant demagnetization of about 2%. Even though demagnetization risk for lattice PMs appears to be ruled out, further investigations will be carried out. A significant amount of work remains to be addressed for SOLEIL II radiation protection assessment, including injection losses, beam abort system, beam dumps, induced activity and corresponding residual dose rates.

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