INVESTIGATION OF RADIATION DAMAGE OF INSERTION DEVICES AT PETRA III DUE TO PARTICLE LOSSES USING TRACKING RESULTS WITH SIXTRACK

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Abstract

PETRA III is a 3rd generation synchrotron light source dedicated to users at 14 beamlines with 30 instruments since 2009. The horizontal beam emittance is 1 nmrad while a coupling of 1% amounts to a vertical emittance of 10 pmrad. Some undulators and wiggler devices have accumulated total radiation doses of about 100 kGy. Doses measured regularly by Thermo Luminescent Dosimeters (TLDs) are monitored, which lead to inspect the magnetic field of all insertion devices in the PETRA tunnel. We are investigating particle losses with tracking simulation using SixTrack to gain a certain understanding of the radiation damage of the insertion devices. The goal is to develop a strategy to protect the insertion devices from further radiation damage.

INTRODUCTION

PETRA III [1, 2] is a 3rd generation synchrotron light source operating with electrons at beam energy of 6 GeV which is an upgrade of the previous machine PETRA II. The horizontal beam emittance of 1 nmrad is achieved using 20 damping wigglers each of 4 m length, while a coupling of 1% amounts to a vertical emittance of 10 pmrad. The machine is dedicated to users at 14 beamlines with 30 end-stations. Parts of PETRA III [3] have recently been rebuilt to accommodate 12 new beam lines including a super luminescence in near UV beamline providing bending magnet radiation. PETRA III operates with several filling modes, such as 40, 60, 240, 480 and 960 bunches with a beam current of 100 mA.

The insertion devices (IDs) and other accelerator components are expected to experience extreme radiation in synchrotron light sources especially where higher beam energies, beam currents and smaller gaps are in place. It is worth to mention that, permanent magnets operating under conditions of high radiation are especially susceptible to demagnetization [4] caused by direct and scattered radiation induced by electrons, positrons, high-energy photons and neutrons. Serious demagnetization has been observed in some of the operating light sources such as ESRF, where insertion devices experienced field losses of as much as 8% [5] and at the APS [6]. Here we report a partial demagnetization profiles which is not linear along the device [7, 8] in some of the IDs in PETRA III caused by radiation, similar loss patterns are also clearly seen in tracking results. To protect the IDs additional collimators have been installed at PETRA III.

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OBSERVATION OF RADIATION DAMAGE OF INSERTION DEVICES

Inspection of the magnetic structures and in-situ magnetic peak field measurements revealed a partial demagnetization of devices exhibiting performance losses. Some results of these measurements are summarized in Fig. 1 [7]. Devices located upstream in canted straight sections as PU02 and PU08 are damaged at the entrance end of the magnet structure while the downstream located device PU03 is damaged at the exit end (Fig. 1a). The measured decrease of the peak field is attributed to radiation damage and is most likely caused by particle losses.

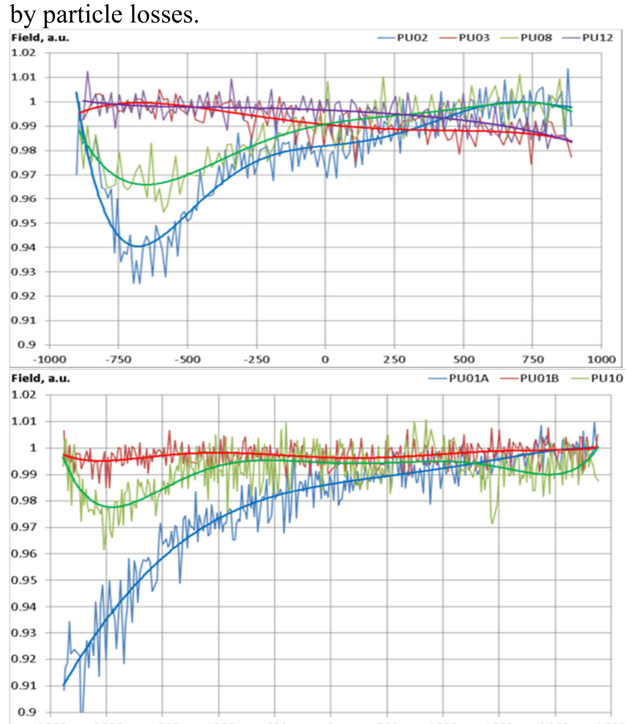

Figure 1: Recently measured longitudinal normalized peak field variation of (a) 2 m devices, (b) 5 m devices installed in PETRA III verses longitudinal position in mm.

A similar situation is observed for the 5 m long devices (Fig. 1b). In sector 1, the upstream device PU01a is strongly damaged at the upstream end. The 5 m device PU10 also confirms the damage pattern observed at the 2 m devices installed in the canted straight sections. PU10 is installed in a standard (not canted) straight section. PU10 shows signs of demagnetization at the entrance and

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the exit of the device. Moreover, a comparison of data taken in 2012 and 2013 shows that in spite of the decreasing total dose measured with TLDs the damage seems to continue unabatedly (Fig. 2) and have accumulated total radiation doses of about ~100 kGy in some undulator devices [9].

Radiation damage of IDs follows a general pattern that devices located at the entrance of a straight section are damaged at the upstream end while devices installed at the exit of a straight section show signs of demagnetization at the downstream end. This seems to indicate that particle losses occur in the vertical plane at locations where the beta functions become large while the physical aperture limits are still very small. Particle tracking studies are made to find a way to mitigate these events.

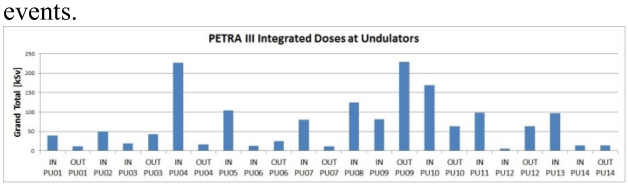

Figure 2: Integrated radiation dose accumulated at every insertion device from the first day of its installation as measured by TLDs.

SIMULATIONS

In order to gain more insight into the mechanism causing the radiation damage of the IDs, we did tracking studies using SixTrack [10]. This code tracks particles through complicated structures over large number of turns taking into account the full six-dimensional phase space including synchrotron oscillations in a simplistic manner. The studies include field errors and are performed for on energy as well as off-energy particles. This type of studies was of course already performed during the design and commissioning phase of PETRA III [2, 11]. In those studies however, only the resulting dynamic and momentum aperture were simulated. No investigation on the loss patterns has been done.

The tracking studies are based on the standard PETRA III optics used during user operation (p3_20wig) containing the damping wigglers modeled in terms of a numerical generating function [12]. The model of the accelerator is put together by constructing a sequence of blocks of linear elements, nonlinear elements, observation points and RF cavities. The linear magnetic elements (dipoles, quadrupoles) are split into two linear parts and thin nonlinear elements containing the measured multipole field errors are introduced at the center. Whereas sextupoles and correctors are split into two drift spaces and thin nonlinear elements containing the integrated strengths and/or multipole fields are introduced at the middle. Consecutive linear elements are blocked together for fast tracking using a single transfer matrix. The particle trajectories are recorded at 227 BPMs, sextupoles, absorbers, and collimators etc. The aperture limitations are imposed at those locations in horizontal and vertical plane by the physical aperture of the vacuum system. For example, the absorbers in west/north damping wiggler section are elliptic in size with half apertures of 30 mm in horizontal, 4.50/8.5 mm in vertical. The BPMs in undulator sections have an elliptic vacuum chamber with half apertures of 30 mm in horizontal, 5.25/3.5mm in vertical. The collimators and nonlinear elements such as sextupoles can be used for these purposes with half aperture of 40 mm in horizontal, 20 mm in vertical. During tracking if the tracked orbit exceeds the physical aperture then the particle is lost.

For the study of nonlinearities the choice of initial conditions is of crucial importance. The input structure for the initial conditions was therefore organized in such a way as to allow for maximum flexibility. SixTrack is optimized to reach the largest possible number of turns. Moreover, experience has shown that varying only the amplitude while keeping the phase constant is sufficient to understand the nonlinear dynamics, as a subsequent detailed post processing allows finding the dependence of the parameter of interest on these phases.

On Momentum Tracking

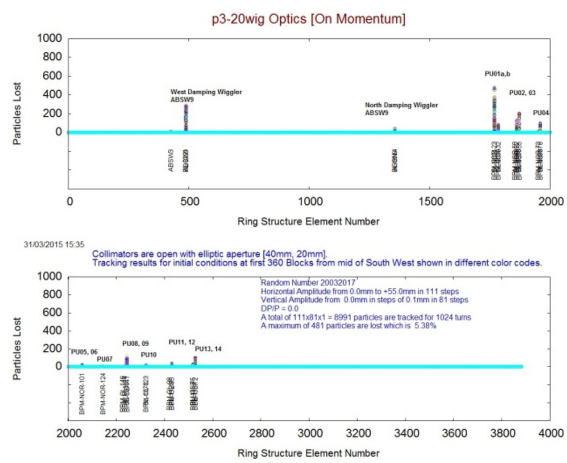

Figure 3: Tracking results for on momentum particles.

The on momentum tracking mainly aims at a better understanding of particle losses during injection. This is necessary to reduce the particle losses in the process of injection so that the radiation detectors (Pandoras) are at low rates to protect venerable locations against radiation. For the simulation 8991 particles are tracked for 1024 turns with $\Delta P/P = 0$. The results of these tracking are shown in Fig. 3. A maximum of 482 particles are lost out of 8991 near undulators PU01 which is 5.36%. The simulation shows that the losses are localized and independent of random errors, only the numbers of loss particles are changed. This means the loss of particles at PU01a is fixed as this is the first lowest vertical aperture (3.5mm) seen by the beam after the damping wiggler section (4.5mm).

Off Momentum Tracking

In many 3rd generations synchrotron light sources the beam lifetime is dominated by the Touschek effect [13, 14]. This is, in particular, also true for timing mode operation at PETRA III, where typically 100 mA are stored in 40 evenly spaced bunches. The beam lifetime in this mode is as low as 1.4 h. Typically, Top-Up leads to injections every 50 to 60 seconds when the beam current variation is limited to 1%. Since Touschek scattered particles suffer large longitudinal momentum deviations, off momentum tracking studies were performed to gain insight into the local distribution of the lost particles.

Before we go for the details of the tracking simulation, one can ask whether the inspection of the off momentum optics of PETRA III highlights preferred locations of particle loss. For this we studied optics of PETRA using the MAD-X [15] code, where the chromatic functions are defined in transverse plane as,

$$W_x = \sqrt{a_x^2 + b_x^2}, \qquad W_y = \sqrt{a_y^2 + b_y^2},$$

$$a_x = \frac{\partial \alpha_x}{\partial p_t} - \frac{\alpha_x}{\beta_x}\frac{\partial \beta_x}{\partial p_t}, \qquad a_y = \frac{\partial \alpha_y}{\partial p_t} - \frac{\alpha_y}{\beta_y}\frac{\partial \beta_y}{\partial p_t},$$

$$b_x = \frac{1}{\beta_x}\frac{\partial \beta_x}{\partial p_t}, \qquad b_y = \frac{1}{\beta_y}\frac{\partial \beta_y}{\partial p_t},$$

$$\phi_x = \frac{1}{2\pi}\tan^{-1}\left(\frac{a_x}{b_x}\right), \qquad \phi_y = \frac{1}{2\pi}\tan^{-1}\left(\frac{a_y}{b_y}\right),$$

$$b_x = W_x Cos(2\pi\phi_x), \quad a_x = W_x Sin(2\pi\phi_x), \quad b_y = W_y Cos(2\pi\phi_y), \quad a_y = W_y Sin(2\pi\phi_y).$$

Since the apertures are small in the vertical plane, we try to analyze a_y at undulator sections. The optical functions together with the chromatic functions a_y and b_y are shown in Fig. 4.

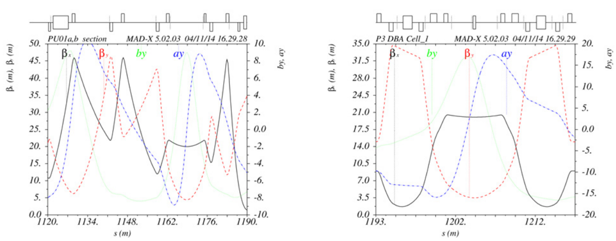

Figure 4: The computed values of a_y and b_y are plotted for the sections for sector (a) PU01 and (b) PU02. The a_y value is high at the upstream of PU01 and PU02; as well as downstream of PU01 and PU02.

High losses are foreseen at extreme values of a_y where particles are lost due to off momentum. The major contribution of a_y comes from b_y, which is nothing but higher beta beating with energy at very low physical aperture. So, one could say that the large beta beat at the limiting vertical apertures in these straight sections are consistent with primarily off-momentum particle loss in those regions, as Touschek scattered particles suffer large longitudinal momentum deviations.

A total of 5781 particles are tracked with synchrotron oscillations for 8192 turns with a maximum of $\Delta P/P = \pm 2\%$ for different random errors, where the collimators are open. The results of such tracking are shown in Fig. 5. A maximum of 606 particles are lost out of 5781 near PU01, which is 10.48%. The loss of particles at PU01 is fixed for any random errors, as this is the first lowest vertical aperture (3.5 mm) seen by the beam after the damping wiggler section (4.5 mm). It is quite noticeable from Fig. 5 that a comparable number of particles are lost at sextupoles locations. We have no beam loss monitoring system at this location. We have seen radiation damage at up and downstream of PU02 which is reproduced in tracking results. The tracking results show severity at PU04 as indicated in integrated TLD doses; unfortunately we do not have field measurement data of this undulator.

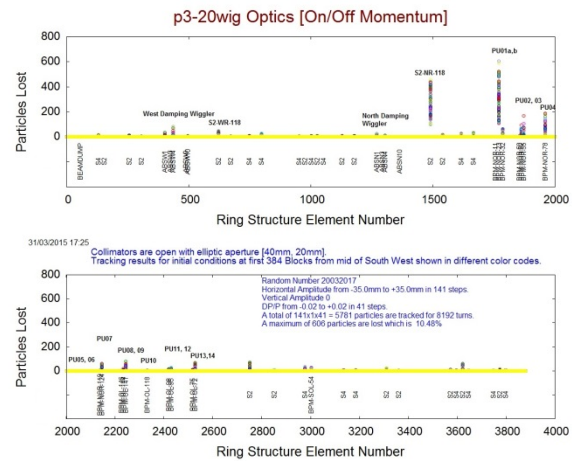

Figure 5: Tracking results for off momentum particles.

The tracking is carried out with vertical apertures of collimators COLL2 and COLL1 of 6.0 - 3.5 mm. As the vertical apertures becomes smaller and smaller (6 mm to 3.5 mm) the loss of particles increases at collimators from 12.35% to 24.72% due to obvious scrapping, as this become limiting vertical apertures prior to absorbers in the damping wiggler section and the undulator section. The loss rate is drastically reduced at the undulator locations except PU04 which is blind to these collimators. Tracking shows heavy loss at S2_NR_118 which is clearly seen in the measured radiation dose rates taken in the inner side of the ring on 22.01.2014 in the PETRA III tunnel.

CONCLUSIONS

Radiation damage of insertion devices is observed at several places of the PETRA III undulators. It follows a general pattern that devices located at the entrance of a straight section are damaged at the upstream end while undulators installed at the exit of a straight sections show signs of demagnetization at the downstream end. This seems to indicate that particle losses occur in the vertical plane at locations where the beta functions become large while the physical aperture limits are still very small. The tracking results showed the losses at the beamline positions where severe demagnetization had occurred confirming that this might have been avoided by proper collimation. The optics studies shows major contribution of a_y coming from b_y, which is nothing but higher beta beating with energy at very low physical aperture. So, one could say that the large beta beat at the limiting vertical apertures in these straight sections are consistent with primarily off-momentum particle loss in those regions, supported by the measured indication of losses in those areas as Touschek scattered particles suffer large longitudinal momentum deviations. To protect the IDs we have to put extra collimators at high β_y values with proper phase advances which we have incorporated in the PETRA III extension.

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