PERFORMANCE OF SOLARIS STORAGE RING

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Abstract

After one year of the Solaris storage ring commissioning excellent performance has been achieved. The optics was corrected close to the design values. However, some minor adjustments are still needed. The commissioning of the Solaris 1.5 GeV storage ring required a big effort in machine parameters optimization. Performance of position monitoring devices has proven essential for the successful optimization of beam parameters such as: closed orbit, tune, chromaticity, and dispersion. Now, the effort is focused on fine-tuning the machine by implementing the linear optics from orbit correction (LOCO) and reducing the disparity between model and measured results revealed by the phase advance analysis and dispersion measurement. Moreover, during daily operation the main task is to maintain long-term stability of the circulating electron beam allowing for beamlines commissioning. Within this presentation the current status of the Solaris facility and the commissioning results will be reported.

INTRODUCTION

Solaris – the first Polish synchrotron light source was installed in Krakow in spring 2015. The storage ring is a twin brother of MAXIV 1.5 GeV storage ring installed in Lund. The lattice is composed of double bend achromat (DBA) cells with zero-dispersion straights and exhibits 12-fold symmetry. With the circumference of 96 m and energy of 1.5 GeV, its strong focusing and ultra-compact lattice enables to reach the natural emittance of 5.98 nmrad [1]. It also provides twelve 3.5 m long straight sections and ten of them can host the insertion devices (IDs). The injection septum and diagnostics is located in the 1st straight section (SS) whereas the RF cavities occupy the 12th SS. In the 3rd SS the injection dipole kicker is installed, therefore in this location only short (up to maximum 1.6 m) ID can be installed.

The commissioning of the storage ring has started in May 2015 [2, 3] and was divided into three phases. Phase I took place between May and July 2015. During this period first electrons were injected into the storage ring at the energy of c.a. 400 MeV, first turns were observed and later the accumulation and stored beam of few mA was obtained. During this phase the main effort was put into matching the linac, transfer line and storage ring energy. However the working point of the SR differed from the design one. During summer shutdown the aluminium vacuum chamber and undulator in the 5th straight section was installed. After summer shutdown the phase II of the commissioning has started. The main achievements were to bring the tunes values to the design ones, correct the chromaticity to +1, improve the orbit correction, increase the stored current and ramp the beam to the final energy of 1.5 GeV. At the end of this phase the maximum current possible to store was 200 mA. The beam current*lifetime product at that time was about 0.5 Ah. During the long winter shutdown the 3rd harmonic cavities were installed and on spring 2016 the 3rd phase of storage ring commissioning has started. The goals of this phase were to improve the injection rate and ramping speed, make the beam based alignment, increase the lifetime by vacuum conditioning and Landau cavities tuning. Between April and December 2016 the time for the storage ring commissioning was shared with UARPES beamline commissioning. Now Solaris storage ring is in the post-commissioning phase. However, still some fine-tuning of the storage ring optics is required.

The magnet shunting was done at the early commissioning phase based on the magnetic measurements, but now after Linear Optics from Closed Orbit (LOCO) optimisation some additional changes in the shunting are needed.

INJECTION AND RAMPING

The linac delivers an electron beam with the energy of 525 MeV. The beam is injected to the storage ring with the repetition rate of 1 Hz. For the moment the chopper is not used and the 3 GHz bunches are injected as a long bunch train of 184 ns. Therefore during the injection to the storage ring buckets one can observe big losses. The injection of 200 mA can be done in 140 s.

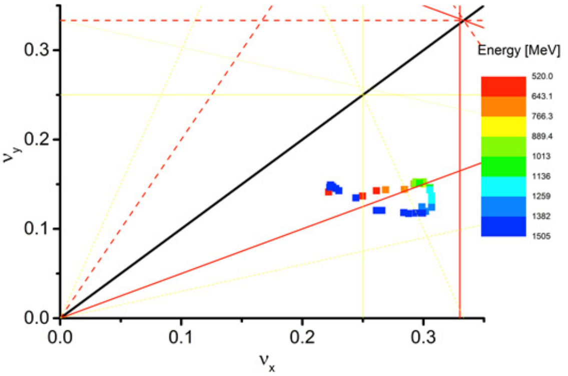

Figure 1: The working point footprint during the energy ramp at Solaris storage ring.

The estimated injection efficiency is 30%. The ramping is executed in less than 4 min., therefore the whole injection process takes less than 10 min. The tunes were measured while the electron beam was ramped to the final energy. The footprint of the working point during the

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ramping process is presented in Fig.1. The nominal working point (0.22, 0.15) is obtained for the injection energy and the final energy of 1.5 GeV. During the ramping the tunes are changing crossing third and fourth integer resonances, however the beam losses are not observed during this process.

LINEAR OPTICS

The Solaris storage ring is equipped with three BPMs and three horizontal/vertical corrector pairs per DBA. The average phase advance between BPMs is 114 degree in the horizontal and 30 degree in the vertical plane. These phase advances are sufficient to sample betatron motion around the ring. BPM buttons are installed as close as possible to the dipole correctors in order to minimize the phase advance in between. The BPM/corrector pairs are located at both ends and at the centre of the DBA cells.

From the turn-by-turn mode of BPM data acquisition the phase for each BPM separately was computed. This allowed measuring the phase advance between consecutive BPMs along the storage ring. Comparison of measured and model phase advances in horizontal and vertical planes are presented in Fig. 2.

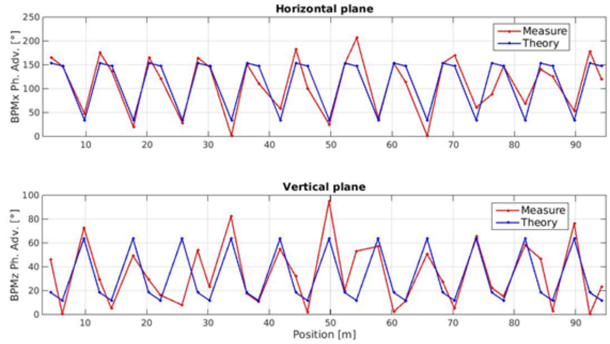

Figure 2: The measured (red) and simulated (blue) horizontal and vertical phase advance along the Solaris storage ring.

The measured phase advance values correspond quite well to the model. However, in sections 2, 3, 6, 7 some deviations from the model are observed. The origins of this difference are the misalignments and field errors. From the closed orbit measurements it seems that the major problem occurs in DBA no 2. To get the corrected orbit in this region, the correctors in the vicinity of this section are always set close to saturation. The reason of the discrepancy lays probably in the field strength errors between magnets from the same family. The DBA 2 is the prototype magnet that has quite high deviation (up to 0.5%) of magnetic strength. Therefore the magnets were shunted at some point to remove discrepancy between magnets from the same family. However, it seems that this procedure need to be revised. Regarding closed orbit and beam based calibration as it was previous reported in [3, 4] the rms values are below 100 µm.

The betatron functions around the Solaris storage ring were obtained by several methods [5]. One of these was analysing the measured response matrix using the Linear Optics from Closed Orbit (LOCO) calculation [6, 7]. The LOCO method allows calculating the differences between the measured and the model lattice by comparing the model and measured response matrices.

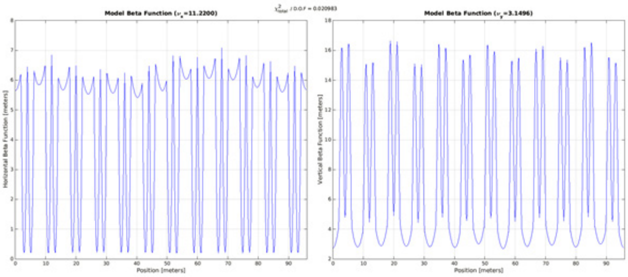

Figure 3: The horizontal and vertical betatron function obtained from the LOCO fitting.

The beta beating is in the range of 16.5% and 11.7% in the horizontal and vertical plane, respectively. Next step is to minimise the beating by adjusting the quadrupole strength of the individual magnets. The quadrupoles in Solaris storage ring are connected in series, therefore the local shunting of the magnets has to be done. So far the shunting was done based on the magnetic measurements done by the magnets supplier. By minimising the deviation between the model and the measured response matrices the rms gradient errors were obtained. In order to correct the beta beating and the dispersion function SQFO and SQFI gradients for individual magnets were fitted. For the SQFO family the quantities of shunting the supplying current is in range from 0.05 to 3.00 A, what corresponds to the shunt resistance change from 0.04 to 2.53 Ω. Similar quantities for SQFI families in range from 0.02 to 1.62 A for the supplying current and from 0.01 up to 0.73 Ω for the shunting resistance change are obtained.

LONGITUDINAL BEAM DYNAMICS

Solaris storage ring contains two 100 MHz main cavities and two 3rd harmonic passive cavities. The shunt impedance R_s of the main cavities is 3.5 ± 0.2 MΩ. Recently the cavities were calibrated. The calibration has been done by measuring the power forwarded P_{forw} and reflected P_{refl} on the directional coupler without the beam. The estimated error of those measurements is c.a. 10%. The power in the cavity was calculated according to the relation:

$$P_{forw} - P_{refl} = P_{cav} , \tag{1}$$

and the cavity voltage was obtained according to:

$$V_{RF} = \sqrt{P_{cav} R_s}. \tag{2}$$

Having done that, the measurement of the power with the stored beam current was carried out. The measurement was performed by decreasing the beam current in the storage ring while keeping the main RF voltage constant. The Landau cavities were detuned. The measured data are presented in Fig. 4. The beam loss per turn (U_0) as well as the cavities loses (P_{cav}) were obtained by fitting the following relation:

$$P_{forw} - P_{refl} = P_{cav} + \frac{IU_0}{e}, \tag{3}$$

where P_{forw}, P_{refl} are the power forwarded to and reflected from the cavity, respectively.
From the fit, the energy loss per turn of 103.7 ± 12.3 keV is calculated, whereas the cavity losses are in the range of 36 ± 1 kW.

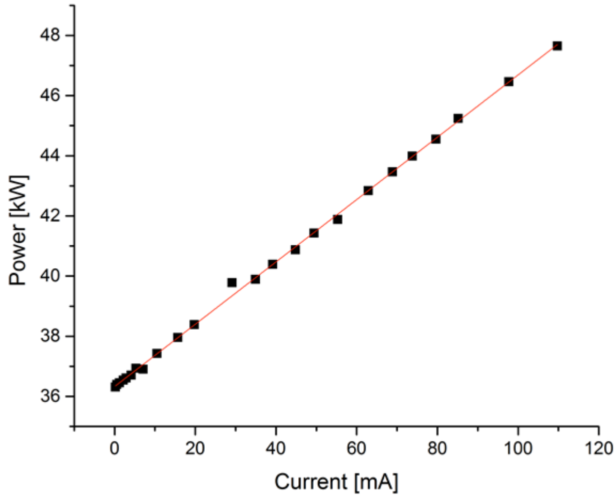

Figure 4: The power in the cavity versus stored current.

Additionally the synchronous phase $\phi_s = 167.4° \pm 2.7°$ was calculated by using the formula:

$$U_0 = eV_{RF} \sin \phi_s \,, \tag{4}$$

where V_{RF} is a total accelerating voltage.

Next, the measurement of the synchrotron tune with respect to the RF voltage was performed and the results are presented in the Fig. 5.

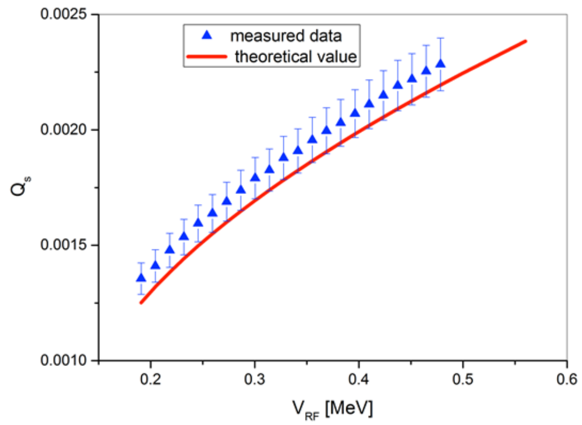

Figure 5: Synchrotron tune vs. total RF voltage. Blue triangles are the measured data whereas the red line is calculated according to the theoretical design values.

The synchrotron tune Q_s is following the formula:

$$Q_s^2 = \frac{\alpha_c h}{2\pi E}\sqrt{e^2 V_{RF}^2 - U_0^2}, \tag{5}$$

where α_c is momentum compaction factor, h the harmonic number, E energy of the electron in the ring. From the Eq. 3 the storage ring energy of 1.45 ± 0.29 GeV can be estimated. One can notice that the measured synchrotron tune values are approximately 5% higher than the theoretical values. This can be indication that the RF voltage calibration needs to be redone more carefully or/and the storage ring energy is lower than 1.5 GeV.
To investigate the maximum RF momentum acceptance the measurement of the total lifetime with the total RF voltage was done. The data presented in the Fig. 6 shows that the highest lifetime is obtained for the total RF voltage of 480±33 kV.

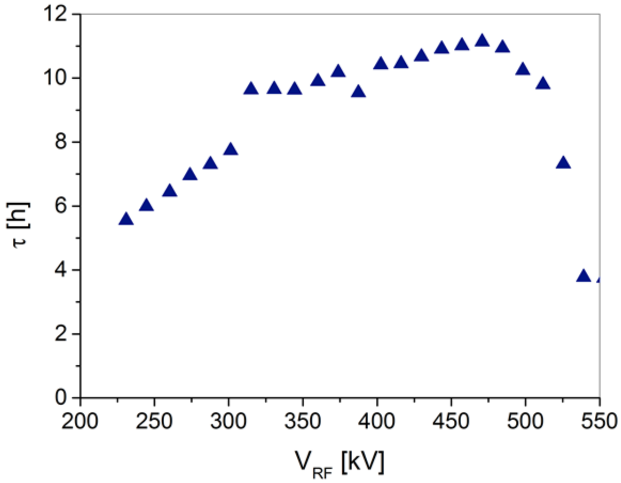

Figure 6: The lifetime measurement with respect to the total RF voltage.

The maximum RF acceptance $\delta_{acc,RF}$ calculated for Solaris storage ring according to the formula:

$$\delta_{acc,RF} \approx \frac{2Q_s}{h\alpha_c}\sqrt{1 + (\phi_s - \frac{\pi}{2})\tan(\phi_s)} \tag{6}$$

is around 3.7±0.4 %. It is a bit lower than the theoretical value of 4 %.

CURRENT AND LIFETIME

Since June 2015 up to now c.a. 390 Ah of the integrated current was accumulated in Solaris storage ring. The detailed information about the conditioning process is reported in [8, 9]. The average pressure in the storage ring with 250 mA of a stored current is $2.2 \cdot 10^{-9}$ mbar. The lifetime of the beam is still increasing with the accumulated beam dose. In Fig. 7 the beam current*lifetime (I*τ) product is presented. One can notice significant improvement of the beam lifetime since last year [3]. The storage ring is designed for maximum current of 500 mA and the total lifetime of 13 h. So far the maximum stored current at the energy of 1.5 GeV in

Solaris storage ring was 400 mA whereas the total lifetime was 8 h. This was obtained without the Landau cavities tuned.

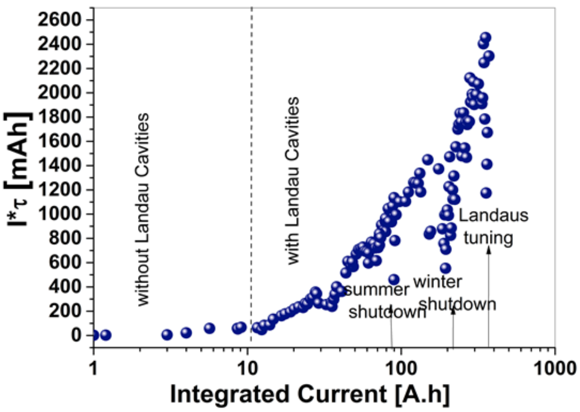

Figure 7: I*τ product vs. integrated current.

To estimate the different total lifetime contribution the lifetime measurements versus scraper position were carried out [10]. One set of measurements was performed with Landau cavities detuned high above 3rd harmonic and the total beam lifetime turned out to be mostly limited by 21 h of Touschek lifetime and 23 h of lifetime from elastic scattering on residual gases. Contribution from inelastic scattering on the gas is 38 h at these conditions. After tuning the Landau cavities close to the flat potential conditions, where most of longitudinal instabilities were damped, the Touschek lifetime has increased to the value of 69 h. An inelastic-scattering component of total beam lifetime of 44 h has been obtained, whereas elastic scattering has limited the total lifetime with 24 h contribution.

BEAM STABILITY AND REPRODUCIBILITY

The stability requirements of photon beam position and intensity at experimental stations are 10% or better of the photon beam size and divergence at photon source points for the Solaris storage ring. The beam orbit stability at the beam position monitors (BPM) near photon source points were monitored. Closed orbit without any corrections applied during the beam decay from 80 to 40 mA current at the energy of 1.5 GeV was registered over 25 h. Figure 8 presents the evolution of the vertical electron and photon beam position monitored by the BPM and XBPM, respectively. A drift of the electron beam in a vertical plane registered in the vicinity of the photon port is ±7.48 μm, whereas the photon beam drift is ±15.45 μm. The oscillations of the photon and electron beam are correlated with the temperature oscillations that are measured by the thermocouples mounted on the vacuum chamber (Fig. 9). In order to keep the beam stable over a long time the Slow Orbit Feedback (SOFB) is implemented in Matlab Middle Layer (MML). When the orbit correction is applied the oscillation of the photon beam are in the range of 2.67 μm and are linked to the thermal stability of the storage ring seen in the Fig. 9.

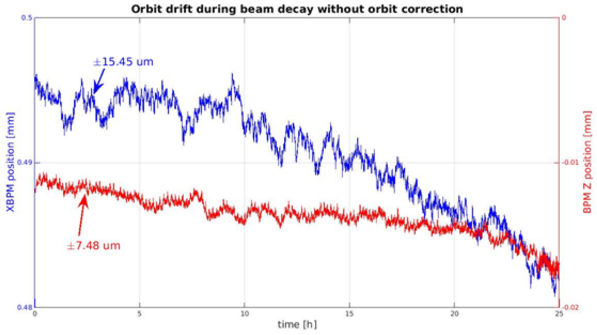

Figure 8: The vertical position drift of electron (red) and photon (blue) beam monitored over 25h without orbit correction.

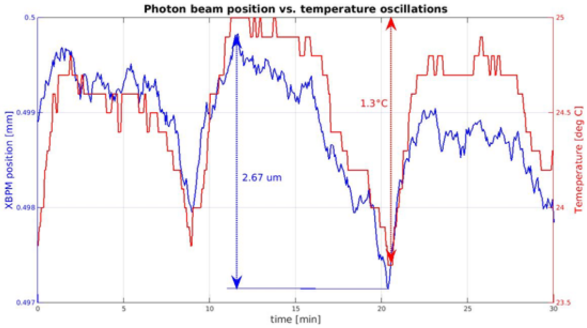

Figure 9: The temperature (red) and the photon beam oscillations monitored over 30 min with applied orbit correction.

To examine the reproducibility of the closed orbit from injection to injection a set of measurements were taken over two days of the machine operation. Every injection and energy ramping were done using the same fixed magnet setpoints and correctors settings. Automatic orbit correction was launched after reaching the final energy. Figs. 10-12 include the sets of closed orbit in horizontal and vertical planes, respectively, at three stages – after injection at the energy of 525 MeV, after finishing the energy ramping procedure at 1.5 GeV and after final orbit corrections.

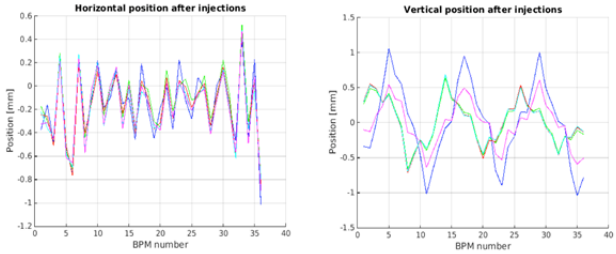

Figure 10: Sets of horizontal and vertical closed orbits after injection.

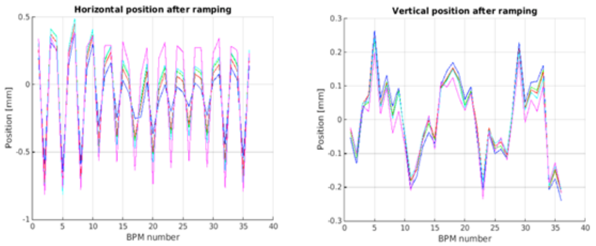

Figure 11: Sets of horizontal and vertical closed orbits after ramping.

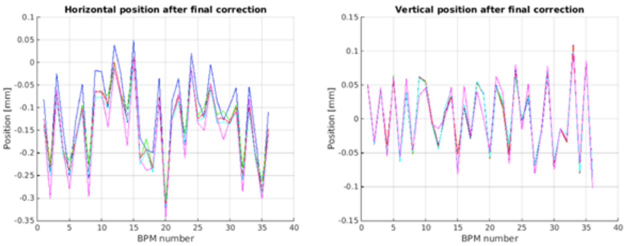

Figure 12: Sets of horizontal and vertical closed orbits after automatic orbit correction at final energy.

Based on those data the standard deviations of orbits on each BPM separately in each plane were measured. In the horizontal plane the standard deviations calculated from injection and ramping dataset are comparable reaching 200 µm and the deviation of final-corrected orbit is significantly lower (~30 µm). Comparable behaviour can be observed in the vertical plane, where most differences are observed for the injection orbits (up to 300 µm), less in the after-ramping dataset (up to 100 µm) and the lowest differences (below 10 µm) in corrected orbits at final energy. One can conclude that the automatic orbit correction is working properly and is repeatable.

CONCLUSION

During commissioning phases the good performance of the Solaris storage ring has been reached. The beam optics was brought close to the design one. However the studies of betatron function have revealed the beta beating in the range of several percent. This, in addition to closed orbit, phase advance and dispersion studies indicate that the shunting of individual magnets has to be revised. Recent studies of synchrotron tune have shown that Solaris storage ring is operating at c.a. 3.3% lower energy than expected. After c.a. 400Ah of beam cleaning the vacuum condition allows to store 400 mA of the beam current at the final energy with the total lifetime of 8 h. Some longitudinal instabilities that are present has been cured with the Landau cavities tuned to the 3rd harmonic resonance. Moreover once the Landau cavities are tuned the Touschek lifetime increases by the factor of 3. Since the commissioning of the experimental beamlines is ongoing, the beam stability and reproducibility is of great interest. These studies have shown that the electron orbit can be restored from injection to injection with tens of microns range when the orbit correction is applied. The main concern is the thermal stability of the storage ring, which for the moment oscillates in the range of 1.5°C having impact on the beam oscillations. Some changes in the cooling water system are planned in the near future to improve the thermal stability at Solaris.

ACKNOWLEDGEMENT

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