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BEAM DYNAMICS STUDIES AND VACUUM DIAGNOSTICS IN THE SOLARIS STORAGE RING

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Abstract

Since 2015, the National Synchrotron Radiation Center SOLARIS has operated a light source supporting eight experimental beamlines. Following vacuum chamber replacements and beamline upgrades, the total beam lifetime at 400 mA has reached 13 hours in decay mode operation. Regular lifetime measurements are conducted to monitor vacuum quality, residual gas composition, and potential stability issues arising from machine aging. Beam dynamics studies involve measuring electron beam lifetimes at 400 mA, 300 mA, and low currents (as low as 10 mA) under both multi-bunch and single-bunch operating modes. A particular focus is placed on intra-beam electron interactions influencing the Touschek lifetime and the effects of residual gas on beam scattering. These investigations provide valuable insights into vacuum performance, electron bunch behavior, and overall storage ring dynamics.

INTRODUCTION

The NCPS Solaris facility at Jagiellonian University in Cracow operates a third-generation light source, consisting of an injector linac and a storage ring composed of 12 Double Bend Achromats. The linac injects a pre-bunched electron beam at 0.54 GeV into the storage ring, typically with a filling pattern of 32 bunches. After the beam is ramped to its nominal operating energy of 1.5 GeV, it is stored in the ring with a total lifetime of 12 hours at an intensity of 430 mA. The Radio Frequency (RF) system at Solaris includes two active cavities for beam ramping and energy loss compensation, as well as two passive third-harmonic Landau cavities for bunch lengthening. The details of the model and actual measured operation storage ring parameters are presented in Table 1.

Table 1: The Solaris Storage Ring Parameters

Observable	Model	Actual
Energy	1.5 GeV	1.51 GeV
Chromatycity	+1, +1	+1.5/+1.4
Tune Vx/Vy	11.22/3.15	11.236/3.154
Synchrotorn Tune	0.00239	0.0019
Master Oscilator frequency	99.933	99.934773
Landau frequency	300 Mhz	300 Mhz
Energy Loss Per Turn	114.1 keV	127.96 keV
Emitance X/Y	5.982/0.06 nm	8/0.07 nm
Momentum acceptance	4 %	3.4 %

Currently, seven experimental beamlines are available to users at SOLARIS, covering a spectral range from tender X-rays to infrared radiation. For online diagnostic systems, we utilize two parasitic optical lines for visible and X-ray light, 36 X/Y Beam Position Monitors (BPMs), and a boosted decision tree-based beam quality monitor. Synchrotron tune measurements are performed using the Bunch-by-Bunch Feedback (BBFB) system.

In addition to continuous pressure monitoring, we also analyze the components of the electron beam lifetime to detect potential beam scattering on residual gas, particularly after vacuum chamber replacements. Ongoing studies explore the feasibility of single-bunch operation, sparse filling patterns, beam excitation using 1 Hz horizontal and vertical magnets, and excitation via a stripline connected to the BBFB system.

The goal of these studies is to enhance diagnostic capabilities, improve understanding of intra-bunch dynamics, and investigate bunch-to-bunch interactions.

ELECTRON BEAM LIFE TIME

The beam lifetime in an electron storage ring is dominated by the following mechanisms:

1. **Touschek scattering** — intra-beam Coulomb scattering that leads to transverse momentum transfer between electrons. Formula for calculating Touschek lifetime in Eq.1:

$$\frac{1}{\tau_T} = \frac{r_e^2 cN}{8\pi\gamma^3\sigma_x\sigma_y\sigma_z\delta_{\mathrm{acc}}^3} \cdot F\left(\frac{\delta_{\mathrm{acc}}}{\sigma_\delta}\right) \tag{1}$$

   where:

   - r_e is the classical electron radius,
   - c is the speed of light,
   - N is the number of particles per bunch,
   - γ is the Lorentz factor,
   - $\sigma_{x,y,z}$ are the RMS beam sizes,
   - δ_{acc} is the energy acceptance of the ring,
   - σ_δ is the relative energy spread of the beam,
   - F is a form factor that depends on machine and beam parameters.

   The Touschek effect is particularly significant in low-emittance, high-brightness rings where particle density is high.

2. **Beam-gas scattering** — interactions between beam electrons and residual gas molecules, which include:

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- *Elastic scattering*, where electrons are deflected but retain their energy,
- *Inelastic scattering*, where electrons lose energy and may fall outside the momentum acceptance of the ring;

3. **Aperture limitations** — constraints due to the physical size of the vacuum chamber or momentum acceptance, although this is typically negligible in well-designed storage rings.

Assuming the absence of beam instabilities and negligible aperture effects, the **total beam lifetime** τ is determined by the *harmonic sum* of the partial lifetimes:

$$\frac{1}{\tau} = \frac{1}{\tau_T} + \frac{1}{\tau_{\text{el}}} + \frac{1}{\tau_{\text{inel}}} \tag{2}$$

where:

- τ_T is the Touschek lifetime,
- τ_{el} is the elastic beam-gas scattering lifetime,
- τ_{inel} is the inelastic beam-gas scattering lifetime.

This relation (Eq. 2) assumes that each scattering process acts as an independent decay mechanism—an assumption commonly used in beam dynamics modeling.

Additionally, the quantum lifetime of electrons contributes to the overall beam lifetime. It represents the duration over which electrons remain confined within the beam phase space before being lost due to quantum effects, primarily as a result of stochastic synchrotron radiation emission. While the average energy loss per turn is compensated by the RF cavities, individual fluctuations can lead to particle loss, thus limiting the beam's quantum lifetime.

Electron beam Lifetime Measurement and Simulation

The lifetime measurement of the electron beam was performed by inserting a vertical scraper from the bottom of the vacuum chamber. Each measurement lasted 60 seconds per scraper position and was conducted using a DC current transformer (DCCT). Data were collected across various operational modes, including single-bunch operation, low-current operation, higher-current operation ranging from 50 mA to 250 mA, full filling patterns, sparse filling with six empty buckets between injected bunches, and operation with beam excitation using the Bunch-by-Bunch Feedback (BBFB) system [1]. Different filling patterns are presented below.

Figure 1 presents the distributions of the filling patterns used in this study. From the top: sparse filling pattern and single-bunch operation. The bunch length for the full filling pattern is 446 ps, for the sparse filling pattern it is 550 ps and for single bunch it is 262 ps.

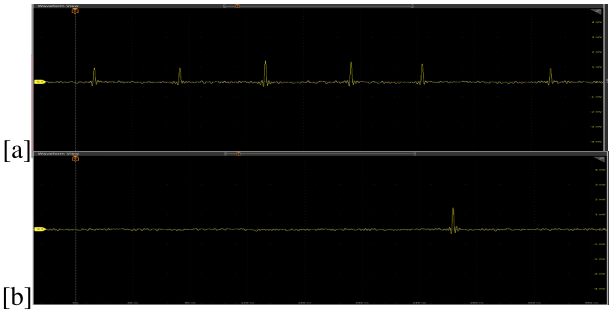

Figure 1: Filling pattern measured on the optical diagnostic line LUMOS [2]. Top canvas a) is the sparse filling pattern, bottom canvas b) is for single bunch operation.

The data set used to extract the components of the total beam lifetime is presented as a function of normalized lifetime with respect to beam intensity, plotted against the physical position of the scraper. These distributions are shown in Fig. 2, where the experimental data points are indicated by blue dots. The red solid line represents the fitted function obtained via least-squares minimization, while the uncertainty range from the Markov Chain Monte Carlo (MCMC) optimization is shown as a gray shaded region. The fitting model is based on the methodology described in [3].

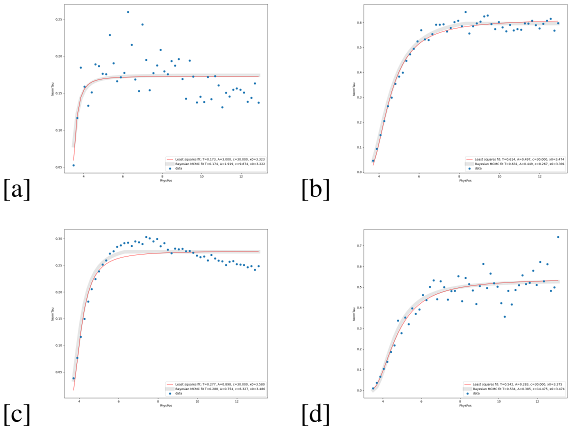

Figure 2: The distributions of normalized lifetime as a function of the scraper's physical position data for different operational modes: single-bunch operation (a), sparse filling pattern with the first and last bunch excited in the bunch train (b),sparse filling pattern (c), and full filling pattern with 32 bunches (d) at an intensity of 100 mA.

The fits to the data points enable the decomposition of components of the total electron beam life time, furthermore the Machine Learning optimization of the fit based one MCMC enhances the quality of the fit and in addition decreases linear correlation between the fit observable by a factor 1.5 up to 2. Thus statistically enhancing the precision of the method with correlation factors way below 25% between the four parameters. This study has been done for additional cases of the storage ring operation, the operation mode and the decomposed life time components are presented in the table below.

Table 2: Comparison of Life Time Components for non Excited Filling Patterns

Component	Single bunch	Full filling
Intensity [mA]	10	25
Elastic [h]	53	35
Rest [h]	0.4	2.2
P [Torr]	6e-9	9e-9
Inelastic [h]	104	69
Tuschek [h]	0.4	2.3
Total [h]	0.4	2.1

Table 3: Comparison of Life Time Components for Excited Filling Patterns with Static 1 Hz Magnets

Component	Horizontal	Vertical
Intensity [mA]	50	50
Elastic [h]	7	7
Rest [h]	0.5	0.5
P [Torr]	4e-9	4e-9
Inelastic [h]	14	14
Tuschek [h]	0.48	0.53
Total [h]	0.47	0.5

Table 4: Comparison of Life Time Components for BBFB Excitation Filling Pattern

Component	Full filling	Sparse
Intensity [mA]	50	50
Elastic [h]	9	5
Rest [h]	0.24	0.6
P [Torr]	4e-8	6e-8
Inelastic [h]	18	10
Tuschek [h]	0.24	0.7
Total [h]	0.23	0.6

Tables 2, 3, and 4 summarize the decomposition of the beam lifetime across different operational modes. Efforts were made to compare typical operation scenarios with sparse and beam-excited variants.

Furthermore, the existing SOLARIS storage ring infrastructure was implemented and simulated using the [4] package. The model was applied to simulate the Touschek lifetime component at 1.5 GeV with 300 mA injected current, yielding a simulated lifetime of 26 hours. For comparison, the measured lifetime under identical conditions at the ring was 23 hours.

RESULTS DISCUSSION AND FUTURE PLANS

The electron beam lifetime measurements conducted at SOLARIS in 2023 and 2025 indicate stable vacuum quality. Tests across different operational modes yielded promising results—particularly in single-bunch operation and in improving lifetime through high-frequency excitation of the beam using the Bunch-by-Bunch Feedback (BBFB) system.

Studying electron beam lifetime is not only important from the perspective of machine operation and diagnostics, but it also provides valuable insight into intra-bunch dynamics, electron–electron scattering processes, and the physics of bunch–bunch interactions within the filling pattern. A significant effect of bunch–bunch dynamics is evident in Table 4, which shows the difference in the Touschek lifetime component between sparse and full filling patterns. Similar conclusions can be also made from compering the results form Table 2. A striking difference in the Tuschek life time between single bunch and full filling pattern. Taking in to the account the bunch length ratio of multi to single bunch of 1.7 one can not describe the Tuschek life time difference. This hints the effect of bunch-bunch interaction on the inner dynamics such as transverse momentum transfer between electrons within the bunch.

The importance of modeling such effects is further illustrated in Fig. 2c, where the fitted function requires additional parameters to accurately capture the behavior of the data set, particularly in the plateau region. Similar trend may bee seen in Fig. 2a. Applying the excitation via BBFB on the first and last bunch in the train flattens the plateau region as in Fig. 2b. Improved understanding and modeling of these phenomena can contribute to enhancing the performance, stability, and brightness of third- and fourth-generation light sources.

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