SURVEY OF BEAM OPTICS SOLUTIONS FOR THE MLS LATTICE

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Abstract

The Metrology Light Source (MLS) is an electron storage ring containing 24 quadrupole magnets which can be powered individually. Fully exploring the capabilities of the machine optics by tracking or experiment would be very time consuming. Therefore the quadrupoles were combined in five families and a numerical brute force approach was used to scan for areas of stable solutions in the scope of linear beam optics. In order to get information on the expected beam lifetimes for each generated optics, a model for the Touschek lifetime was implemented. Simulation results as well as experimental tests of selected optics will be presented.

INTRODUCTION

The Metrology Light Source owned by the Physikalisch-Technische Bundesanstalt (PTB) is used as a radiation source standard from the infrared to the soft X-ray regime [1, 2]. It is a ramped machine with an injection energy of 105 MeV and an operation energy of 630 MeV. The magnet lattice is characterized by a 4-fold symmetry. Long (LS) and short (SS) straight sections are separated by double bend achromat (DBA) segments in the setup: SS, DBA, LS, -DBA, SS, DBA, LS, -DBA. The standard operation of the machine is to power the quadrupoles in five different families as shown in Fig. 1. To study the overall optics capabilities in this setup, a database containing linearly stable solutions as well as corresponding performance parameters was generated.

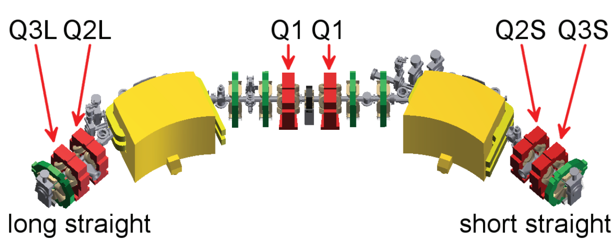

Figure 1: DBA segment of the MLS containing dipole (yellow), quadrupole (red), sextupole (green) magnets and an octupole magnet (black) in the center. [3].

ALGORITHM

Following the scheme of [4], as a first approach a Fortran algorithm was written to scan for solutions while independently varying the strengths of the five quadrupole families: Q1, Q2L, Q2S, Q3L, Q3S (Fig. 1). To save computation time the model was restricted to a vertically decoupled motion. A sketch of the algorithm with nested loops over all five quadrupole family strengths looks like:

1. check vertical transfer matrix for stability criterion
2. check horizontal transfer matrix for stability criterion
3. apply feasibility filters
   - maximum beta functions: $\beta_{x,y} < 20$ m
   - maximum dispersion: $|D| < 2$ m
4. calculate optics quantities of interest
5. calculate Touschek lifetime

In a first scan the quadrupole strengths were varied over the full design range including polarity reversal. A constant step size for all quadrupoles was used. A total number of 10^{12} combinations was checked generating a database of approximately $2 \cdot 10^6$ solutions. The runtime of the code on a 2.66 GHz single core was about 200 h. Figure 2 shows a histogram plot of the 5-dimensional scan into the plane defined by the transverse tunes. The color indicates the number of solutions in one bin normalized to the total number of solutions for the scan. The blue box in Fig. 2 corresponds to a region easily accessible from the standard working point (black cross). This area can be investigated while keeping the beam stored. Hence, there is no need to generate new injection states as well as new energy ramps. The database generated in the first scan was used to redefine scan ranges of the individual quadrupole family strengths. In a second run only ranges possibly yielding solutions in the blue region were regarded. As a consequence the step size could be decreased by a factor of four without an additional increase in runtime.

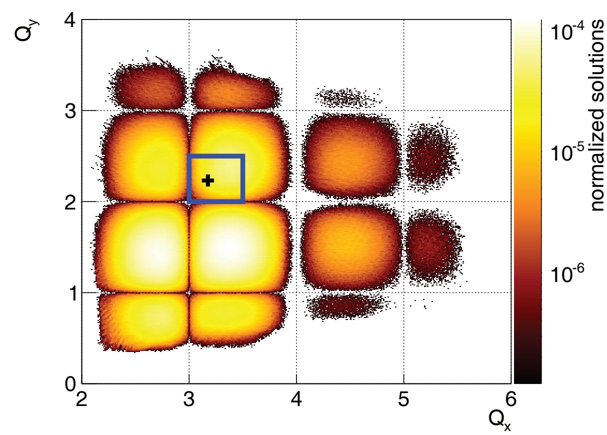

Figure 2: Regions of stability for the MLS lattice in the tune diagram [3]. The black cross marks the standard working point, whereas the area marked by the blue box is easily accessible and therefore preferred for operation.

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TOUSCHEK IMPLEMENTATION

As measurements show, the lifetime at the MLS is Touschek limited [5]. To find optics with an increased Touschek lifetime a Touschek module was implemented into the Fortran code. The Touschek lifetime depends on the acceptance of the accelerator. Two major effects may limit the momentum acceptance δ_{acc}:

- RF-acceptance
- geometrical acceptance.

The RF-acceptance is calculated following [6]. The geometrical acceptance for the MLS can be calculated in a first order approximation as

$$\delta_{\text{acc}} \approx \min\left[\frac{a_x(s)}{2D_x(s)}\right] , \qquad (1)$$

with $a_x(s)$ being the horizontal aperture in each element and $D_x(s)$ the corresponding horizontal dispersion function. The maximum Touschek lifetime can be expected where RF-acceptance and geometrical acceptance are equal [5].

The Touschek lifetime is calculated according to the solution presented by [7], including horizontal dispersion:

$$\tau_{\text{T}} = \frac{8\pi\sigma_y\sigma_s\sqrt{\sigma_{x\beta}^2+\sigma_{xD}^2}\cdot\gamma^2\delta_{\text{acc}}^3}{D(\xi)Nr_e^2c} , \qquad (2)$$

with the vertical bunch size σ_y, the bunch length σ_s and the Lorentz factor γ. The horizontal bunch size has two contributions: $\sigma_{x\beta} = \sqrt{\beta_x\varepsilon_x}$ being the contribution due to emittance and $\sigma_{xD} = \sqrt{D_x{}^2\sigma_E{}^2}$ being the contribution due to dispersion. $D(\xi)$ is a function of acceptance δ_{acc}, the optical functions, their derivatives and the electron energy. N is the number of particles in the bunch (calculations for 1 mA at the MLS: $N = 1\cdot 10^9$) and r_e is the classical electron radius. For the vertical beam size, it was assumed that the ratio of vertical to horizontal emittance equals 1 %. Therefore, the vertical beam size was calculated as $\sigma_y = \sqrt{0.01\varepsilon_x\beta_y}$.

The algorithm calculating the Touschek lifetime looks like:

1. Find the minimum of $\delta_{\text{acc,geom}}$ following Eq. 1
   - → set geometrical acceptance = RF-acceptance to find optimum cavity voltage corresponding to maximum achievable acceptance
   - → calculate bunch length for the optimum cavity voltage
2. Calculate Touschek lifetime with maximum acceptance following Eq. 2 for each element
3. Calculate the total Touschek lifetime by weighting the single element Touschek lifetimes with the lengths of the elements

The calculated Touschek lifetimes have been checked for plausibility with the Touschek module offered by MADX. For the settings of the standard user operation in 2012 at the MLS the Touschek lifetime was calculated with the implemented Touschek module of the Fortran code: $\tau_{\text{T,mod}} = 12.64$ h for a cavity voltage of 408 kV; the Touschek module offered by MADX calculates a corresponding Touschek lifetime of $\tau_{\text{T,MADX}} = 12.47$ h.

RESULTS

Based on the results yielded by the scan, various optics have been investigated experimentally. Dynamic aperture was neglected in the first runs, as it is not usually a limiting parameter at the MLS. Conversion from calculated k-parameters to quadrupole currents to fit the predicted transverse tunes was better than 1%. Selected test optics in the blue region of Fig. 2 were set up by changing the quadrupole strengths while keeping the beam stored. Afterwards a LOCO characterization of the optics was conducted [8].

At first a low emittance (ε) optics was set up as shown in Fig. 3. The emittance in standard user operation is about 100 nm rad. A tuning of the optics while keeping the working point fixed promised an emittance reduction by a factor of 2.2, whereas allowing the working point to change within the blue area yielded a predicted emittance reduction by 3.7. We chose to try the latter concept.

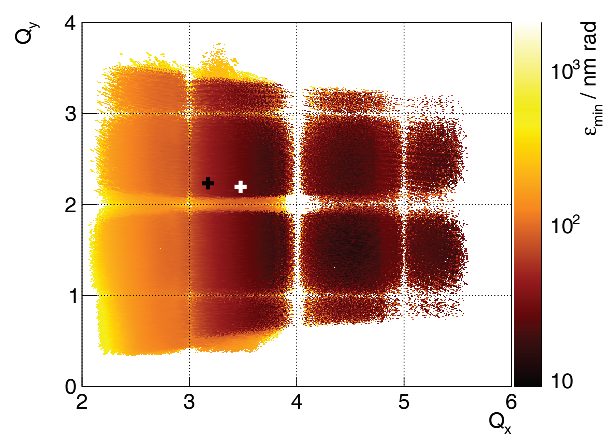

Figure 3: Minimum emittance of the MLS [3]. The black cross marks the standard working point. A recently established low-ε mode is marked by the white cross.

Emittance reduction was measured by two source point imaging systems yielding a factor of 3.9, which was reinforced by lifetime measurements. This optics is now operational up to 180 mA and was already applied in user operation.

In addition, the correlation between emittance and momentum compaction factor α has been investigated. As both quantities depend on the dispersion in the dipole magnets, arbitrary combinations of α and ε are not possible. In the low-α operation mode applied for users at the MLS an increased emittance is observed worsening the user conditions for users interested in short pulsed synchrotron radiation. On the other hand, users interested in coherent synchrotron radiation in the THz regime would benefit from larger emittances as it substantially increases lifetime without reducing the brilliance at these wavelengths. One

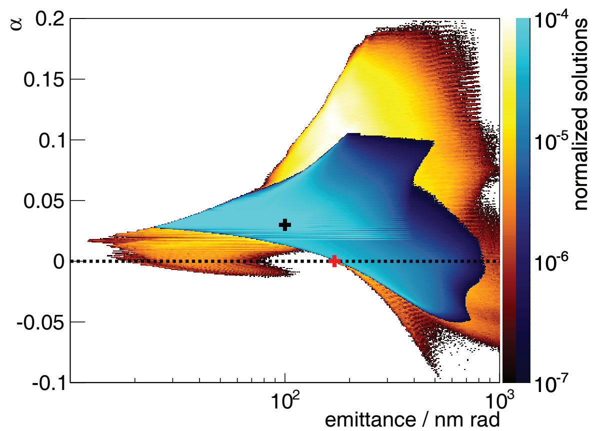

Figure 4: Momentum compaction - emittance correlation [3]. A global scan (yellow) as well as a subset of states within the currently used tune quadrant (blue) is shown. The black cross marks standard user operation, the red cross marks low-α operation.

finding of the brute force scan is, that there is no operational mode that delivers low-α at the design emittance of 100 nm rad as shown in Fig. 4 (blue). However, there are operational modes for low-α at lower emittances. These optics are all situated outside of the currently used tune quadrant. An optics setup featuring an increased emittance of 300 nm rad at low-α was experimentally verified but not yet tested in user operation.

Finding an optics that could provide a larger Touschek lifetime τ at the design emittance of the MLS was the main driving force to scan for new optics. An analysis of the Touschek lifetime regarding all states featuring an emittance smaller than 100 nm rad (Fig. 5) indicated a possible improvement of more than 60% at the standard working point and even about 300% when leaving the blue region. However, in the experiments investigating new Touschek-optimized optics inside the blue region, τ has shown an unexpectedly strong dependence on the dispersion at the septum magnet D_{sept}. Consequently tuning D_{sept} towards zero yielded an increase in lifetime of 40% [5]. However, this was done by splitting the family Q1 leaving the state space covered by the scan.

CONCLUSION

The optics scan has turned out to be a fruitful tool in generating new operational modes at the MLS. A user operational low-ε mode was set up close to the achievable minimum emittance in the tune quadrant currently used. Trying to increase the Touschek lifetime by changing the optics led to a better understanding of the limiting effects and in turn to an increase in lifetime by about 80%. Implementing more complex optics by breaking the symmetry of the storage ring generates the need to parallelize the code. Assessing the overall distribution of solutions as well as calculated Touschek lifetimes and emittances, it seems to be promising to explore other tune quadrants to generate new optics for standard user operation featuring a larger Touschek lifetime and/or smaller emittance.

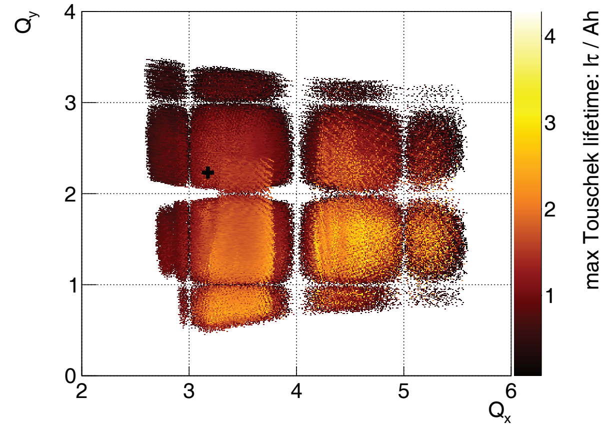

Figure 5: Maximum Touschek lifetime plotted for all solutions with $\varepsilon \leq 100$ nm rad [3]. The black cross marks standard user operation.

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