RCDS OPTIMIZATIONS FOR THE ESRF STORAGE RING

S. M. Liuzzo, N. Carmignani, L. Farvacque, B. Nash,
T. Perron, P. Raimondi, R. Versteegen, S. M. White, ESRF, Grenoble, France

Abstract

The Robust Conjugate Direction Search (RCDS) [1] optimizer is applied for online optimizations of the ESRF accelerators. This paper presents the successful application of the algorithm in reducing vertical emittance, improving injection efficiency and increasing lifetime. A new set of sextupole settings to increase chromaticity has been obtained with lifetimes comparable to the existing one. This allows to run with double current in a single bunch, and unifies the optics for few bunch (except 4×10 bunches) and multi-bunch modes.

INTRODUCTION

The European Synchrotron Radiation Facility (ESRF) is running an accelerator complex based on a linac, a synchrotron booster and a 6 GeV Storage Ring (SR). The electron beam stored in the SR has 4 nmrad horizontal emittance, 5 pmrad vertical emittance and a beam lifetime between 10 and 60 hours depending on the filling mode. The storage ring magnets are powered with power supply families for the main quadrupoles (6 families) and sextupoles (7 families). There are also 96 orbit steerers, 64 skew quadrupole correctors, 32 quadrupole correctors and 12 sextupole correctors. Magnets in the transfer lines (TL) have independent power supplies. In this paper we present the application of the RCDS algorithm for the online optimization of vertical emittance, Touschek lifetime and injection efficiency, using the available knobs.

RCDS OPTIMIZATIONS

At ESRF, several attempts have been made in the past and are currently under consideration for offline optimizations of non linear dynamics [2]. In particular, genetic algorithms have been tested for the optimization of Touschek lifetime and dynamic aperture [3]. On the other hand, the online optimization of accelerator parameters has been tested in several laboratories, with different optimization methods, and allowed to achieve in some cases record performances [4]. The RCDS optimizer has been devised using Matlab [5] for online accelerator tuning at SPEAR3, SLAC. The use of this algorithm has proven to be very successful for SPEAR3 [1] and motivated the authors to pursue the use of online optimizations at ESRF, to search for improved running points, not previously found.

Vertical emittance

As a first test we verified that the RCDS optimizer could reduce coupling and thus vertical emittance, using skew quadrupole correctors. We assigned a subset of 32 skew quadrupoles and gave as objective function the vertical beam size measured at 13 in-air X-ray vertical beam size monitors distributed around the SR. We randomly distorted the skew quadrupole strengths to obtain a vertical emittance of about 10 pmrad. RCDS was used to achieve less than 5 pmrad after few iterations. This test was performed very rapidly thanks to the clear and user friendly implementation of the RCDS Matlab code. As we already have a reliable method available for coupling correction, we moved on to the more challenging topic of lifetime optimization.

Touschek Lifetime

With a vacuum lifetime of ~ 300 h, lifetime in the ESRF SR is dominated by the Touschek effect [3]. The various filling patterns have different lifetime due to different current per bunch and sextupole settings. The lifetime is influenced by the Insertion Device (ID) gap settings, and sextupole correctors are tuned during User Standard Mode (USM) to correct these effects. The tuning is usually done using sextupole resonance driving term knobs, the values of which are determined empirically [2].

The most used filling mode is the 7/8+1 (58% of USM), where 202 mA are stored in the SR: 7/8 of the buckets are uniformly filled with 196 mA, 4 mA are stored in a single (clean) bunch and 2 mA serve as markers in two bunches at the beginning and end of the train (see Fig. 1). The second most frequently used mode is the 16 bunch mode (24% of USM) where 92 mA are uniformly distributed in 16 evenly spaced bunches. Other less frequently used modes are: uniform 200 mA, 4 bunch of 10 mA, 24 trains of 8 bunches and a single bunch of 4 mA.

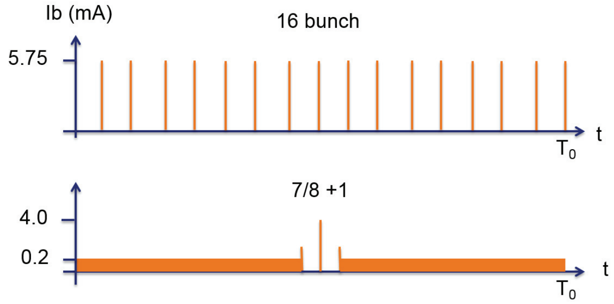

Figure 1: Most frequently used filling modes at ESRF.

Normalized lifetime τ_0 is the chosen *objective* for the RCDS optimization:

$$\tau_0 = \tau \frac{I}{I_0} \frac{BL(I_0)}{BL(I)} \frac{\sigma_{y,0}}{\sigma_y}$$

where I_0 and I are bunch currents (main train for 7/8+1 filling mode), BL is the theoretical bunch length at a given current (assuming an inductive impedance of 0.7 Ω) and σ_y

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and $\sigma_{y,0}$ are the vertical beam sizes averaged over 13 in air X-ray beam size monitors. The subscript 0 indicates the reference values, chosen according to the filling mode (ex: $I_0 = 5.75$ mA, $\sigma_0 = 5$ pmrad in 16 bunch mode), the values without subscript indicate measured quantities. The lifetime τ is measured by the BPM according to the procedure described in [6].

This normalization allows to optimize the beam lifetime independently of its current and bunch length. The normalization for the vertical beam size takes in account the modifications induced by vertical alignment errors in the sextupole correctors that may impact the beam size giving an improved lifetime due to a larger emittance.

All lifetime measurements were started after at least 30 minutes from the latest injection, to wait for beam polarization to stabilize (15% lifetime increase [7]).

Sextupole correctors 12 sextupole correction coils are available to correct lifetime degradation introduced by the IDs gap movements. These correctors have a beneficial effect on the beam lifetime if appropriately tuned, but are not strong enough to provoke a beam loss even if set to random values. This makes them very good candidates for RCDS lifetime optimizations, even during standard beam delivery. The sextupole correction coils are installed on the main sextupole magnets. When the correctors are powered orbit distortions are observed, due to misalignment of the main sextupoles, or hysteresis from those additional coils. Keeping the fast orbit feedback in operation during the optimization mitigates these effects.

The lifetime optimization results shown in Fig. 2 were obtained during a USM like shift in 7/8 + 1 mode, i.e. in the same conditions as standard delivery.

Initially all the sextupole correctors were set to zero leading to a measured lifetime of $\tau_0 = 47.5$ h. Then RCDS was started and ran for five iterations achieving a lifetime of $\tau_0 = 75.5$ h. The lifetime resulting by trimming the standard sextupolar resonance driving terms was instead $\tau_0 = 68.5$ h. The sextupole corrector strengths obtained by RCDS and by resonance trimming are shown in Fig. 3. The strengths obtained by RCDS have a lower rms compared to the set obtained by trimming resonance knobs, and led to a better lifetime. The optimization process required about 40 minutes using the 12 sextupole correctors.

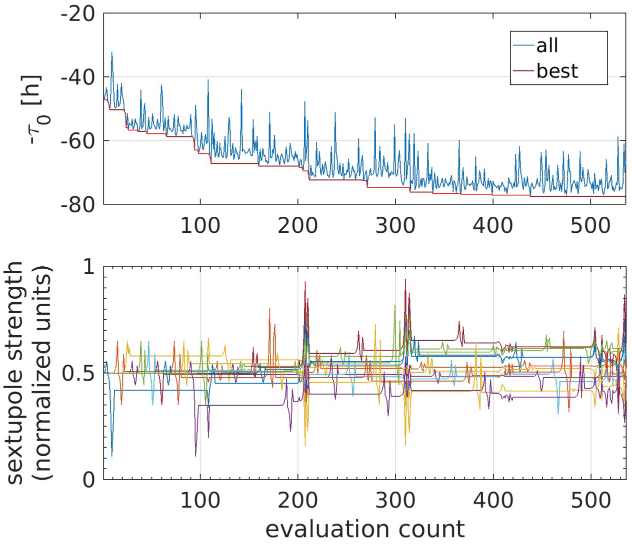

Figure 2: Optimization of lifetime using 12 sextupole correctors in 7/8+1 mode.

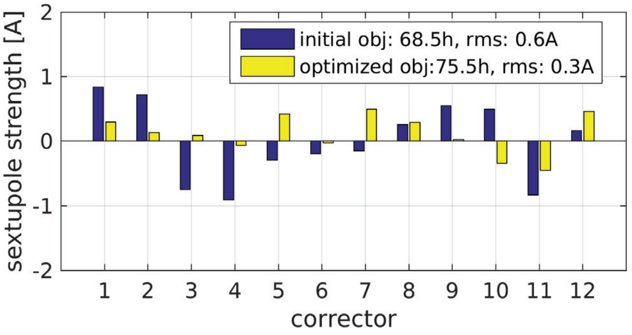

Figure 3: Sextupole correctors strengths tuning resonance knobs (blue) and obtained by RCDS optimization of Lifetime (yellow).

Sextupole families The two most frequently used filling modes (7/8+1 and 16 bunch) have identical linear optics but different chromaticities: ($\xi_x = 4, \xi_y = 6$) for the 7/8+1 filling mode, ($\xi_x = 10, \xi_y = 10$) for 16 bunch mode. Higher chromaticity is required at higher bunch current to stabilize the beam. The 4 mA single bunch in 7/8+1 mode is stabilized using a transverse feedback system. The high chromaticity optics has a substantially smaller momentum acceptance. We focused the RCDS optimization on the high chromaticity optics. In this respect, if the lifetime for the 7/8+1 filling mode with the optimized high chromaticity optics would be comparable or better with respect to the low chromaticity optics, the optimized optics could be used for both filling patterns. This would reduce the required setup time, namely: linear and non-linear optics corrections and injection bump tuning (sextupoles in the bump). Using the high chromaticity optics would also stabilize the high current single bunch of the 7/8+1 filling pattern, and allow storage of even higher currents in that particular bunch.

The RCDS optimization used as variables only the 5 out of 7 available sextupole families plus the sextupoles with independent power supplies present in the lattice, for a total of 10 variables. S19 and S20 families where used to keep the chromaticity constant. The chromaticity correction was computed using the measured AT [8] lattice model.

Figure 4 shows the change in sextupole strengths after optimization using RCDS.

The initial chromaticity was measured to be ($\xi_x = 9.5 \pm 0.5, \xi_y = 10.7 \pm 0.5$), while the final one was ($\xi_x = 7.7 \pm 0.5, \xi_y = 11.8 \pm 0.5$). The chromaticity correction did not work as expected, the reason for which is still under investigation. The initial lifetime in 16 bunch mode was $\tau_0 = 11$ h. After optimization we could achieve $\tau_0 = 17$ h.

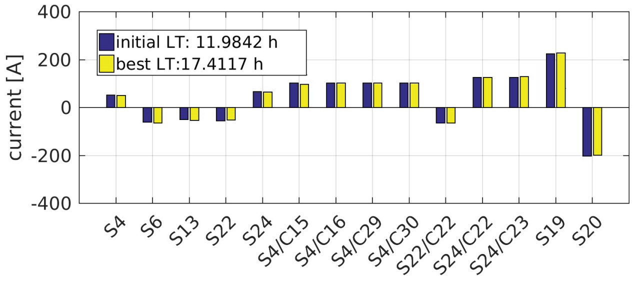

Figure 4: Sextupole families strengths before and after optimization of τ_0 using RCDS.

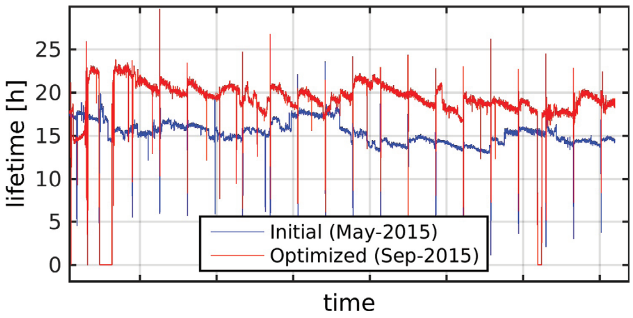

Figure 5: Measured lifetimes in 16 bunch mode in May 2015 (before RCDS optimization) and in September 2015 (using the RCDS sextupole settings). Spikes are due to injection transients.

Injecting the 7/8+1 filling pattern in the high chromaticity optimized optics, the measured lifetime was $\tau = 50$ h for the main train and $\tau_{single} = 8$ h for the single bunch, which is comparable to the lifetimes observed for low chromaticity optics. An additional advantage is that the higher chromaticity allows the SR to work without transverse feedback for the single bunch and to inject up to 8 mA in the single bunch: twice the current stored in this bunch for the low chromaticity optics.

Those optics were also tested for currents 10% above nominal values, for radiation safety issues, and the bunch cleaning procedure was validated in both filling modes. The optimized high chromaticity optic is now used in daily operation since July 2015 for 7/8+1 and 16 bunch filling patterns. Figure 5 shows the recorded lifetime over one run in 16 bunch mode before the RCDS optimization and after. The lifetime varies due to the different gaps settings and sextupole correctors, but is on average higher.

Injection efficiency

Using the magnets of the transfer line from the booster to the storage ring (TL2), it is possible to optimize the transport and the injection efficiency. To measure the injection efficiency in a fast and reproducible way, we inject the beam and kill it after ~ 4000 turns using a vertical kicker, delayed by about 11 ms with respect to the injection kickers. During this time, turn by turn data are recorded. At each turn, the sum signal of the BPMs is proportional to the stored current. Normalizing this quantity with the extracted current from the booster gives a parameter proportional to the injection efficiency and reproducible over a long time. For one injection efficiency measurement 10 such data sets are averaged. An alternative could be to inject very slowly and use the current transformers to measure the injection efficiency, however this method proved to be slow and not sufficiently precise for our purpose. Figure 6 shows the normalized current at each turn before and after a successful RCDS optimization of the two SR injection septa and the two last vertical correctors in TL2. The injection efficiency that was intentionally deteriorated to test the optimization process is completely recovered after the optimization.

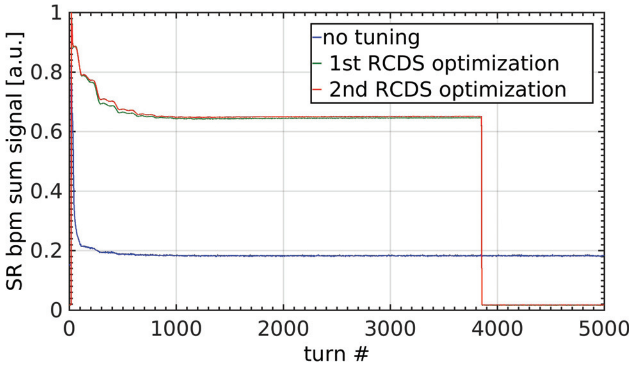

Figure 6: Measured sum of all BPM buttons vs turn number optimized using RCDS.

CONCLUSION

The measurements presented show the application of the RCDS online optimizer to improve several key performance parameters in the ESRF acceleration chain. Thanks to this online procedure for optimization we can now take advantage of:

- automated tuning of the sextupole correctors to improve lifetime (not fast enough to be a feedback yet),
- unified high chromaticity sextupole setting for 16 bunch and multibunch modes,
- double the current in the single bunch,
- improved lifetime in 16 bunch mode,
- automated optimization of transfer line septa steering for injection efficiency.

The RCDS algorithm is now a tool used at ESRF in many applications, constantly improving the accelerator performance.

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