

# FILO: A NEW APPLICATION TO CORRECT OPTICS IN THE ESRF-EBS STORAGE RING

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## Abstract

A new optics correction application (Fit and Improvement of Linear Optics, FILO) was designed and set in place for the ESRF-EBS storage ring. The widely used software LOCO is not available at ESRF and despite a few trials to set it in operation, it has been decided to write a new code. The application is flexible, may be used via the control system simulators and is adapted to a user friendly operation thanks to a wizard mode. Some features of LOCO are copied over, some others are yet to be implemented. The measurement of on and off-energy response matrices using slow or fast steerers is integrated in the same application. Results obtained with this application are presented together with an overview of the future developments.

## INTRODUCTION

Optics correction are necessary at synchrotron radiation storage rings (SR) to reach and maintain the user service mode (USM) properties in terms of beam equilibrium emittance, coupling and lifetime. The data necessary to perform optics corrections are either BPM turn by turn data [1] or orbit response matrix and dispersion [2]. We describe in this paper the matlab [3] application set up at ESRF to perform the second kind of measurements. Experimental results of ESRF-EBS optics correction and measurements can be found in [4, 5].

## OPTICS CORRECTIONS FOR EBS

The optics of the ESRF-EBS storage ring are corrected routinely upon each restart of the accelerators. These corrections are not necessary during user operation, but only after interventions on the magnets. Usually simply restoring orbit and tunes is sufficient to recover the expected operational performances in terms of beta-beating and coupling. Optics corrections are intended here as the adjustment of normal and skew quadrupole strengths based on the measurement of: 1) a partial orbit response matrix ( $ORM$  see Eq. (1) with  $x_{h,v}$  the orbit at the usable BPMs and  $\theta_{H,V}$  the steerers strengths) and 2) the response of beam in the horizontal and vertical plane to a shift of RF frequency (see Eq. (1)).

$$ORM_{(h,v),(H,V)} = \frac{\Delta x_{h,v}}{\Delta \theta_{H,V}}, \quad \eta_{h,v} = \frac{\Delta x_{h,v}}{\Delta f_{RF}} \quad (1)$$

The signals to be corrected to their theoretical values are described by the vectors  $D_{n,s}$  in Eq. (2) and (3) where the subscripts  $n$  and  $s$  refer to normal or skew, the weights  $w_\eta$

and  $w_t$  define a different scaling for the dispersion and tunes.

$$D_n = [ORM_{h,H}, ORM_{v,V}, w_\eta \eta_h, w_t \nu_h, w_t \nu_v] \quad (2)$$

$$D_s = [ORM_{h,V}, ORM_{v,H}, w_\eta \eta_v] \quad (3)$$

$J_{n,s}$  in Eq. (4) is the derivative of  $D_{n,s}$  for a given error.

$$J_{n,s} = \frac{\Delta D_{n,s}}{\Delta V_{n,s}} \quad (4)$$

The computation of  $J_{n,s}$  is performed numerically based on the lattice model. The quantities  $V_{n,s}$  refer to any variable that the user wants to use to fit the lattice model such to reproduce the measurements. This usually include the normal and skew quadrupole correctors gradients, beam position monitors scale and rotation errors, steerers gains and tilts. The fit is performed using an singular value decomposition pseudo-inversion in order to compute the values of  $V_{n,s}^{cor}$  that would yield a vector  $D_{n,s}$  as close as possible to the measured one  $D_{n,s}^{measured}$ .

$$V_{n,s}^{cor} = J_{n,s}^{-1} (D_{n,s}^{measured} - D_{n,s}^{model}) \quad (5)$$

The values of the fitted variables (sometimes assumed as measured lattice errors) are included in the optics model to create a *fitted optics* model. This model is then used to compute the skew and normal quadrupole corrections in two possible ways:

- applying the fitted normal and skew quadrupole errors to the lattice, or,
- in the general case of correction locations not strictly identical to the errors fit locations, computing the normal and skew quadrupole resonant driving terms (RDTs) and correcting them as described in [6].

## MEASUREMENT

The procedure to perform optics correction is the following:

1. measure initial emittances
2. measure an orbit response matrix with a given subset of steerers and BPMs
3. measure the frequency response at the same BPMs
4. select a series of variables to fit the measured quantities
5. prepare  $J_{n,s}$  (see later sections)
6. construct a fitted lattice model
7. compute normal and skew quadrupole corrections
8. plot expected results for inspection by the user
9. apply correction
10. measure the final emittances and dispersion

## ORM Measurement

The measurement of the *ORM* requires particular care due to the specificity of the ESRF-EBS magnets. The correctors are of two kinds: stand alone and additional coils on sextupoles. There are 288 horizontal and vertical steerers  $\theta_{H,V}$ . Despite acting on the same yoke, all the steerers and correctors are mostly decoupled providing the required field (horizontal steerer, vertical steerer or skew quadrupole) without visible contributions to the other multipole components. However, all fields manifest hysteresis effects. In particular, when setting a steerer to a given value and returning it to its original setting the final orbit is different from the original one. The orbit residual is small ( $\sim 1 \mu\text{m}$ ), but over a whole partial *ORM* (64/288 steerers) measurement the errors are accumulated, making the orbit drift from its initial position and thus sampling different optics. For this reason the measurement sequence is the following for each steerer:

- measure the initial orbit  $x_{(h,v),ini}$
- set the given steerer to  $\theta = \theta_0 + \Delta\theta$
- measure the orbit
- set the given steerer to  $\theta = \theta_0 - \Delta\theta$
- measure the orbit
- set the given steerer to  $\theta = \theta_0$
- measure the final orbit  $x_{(h,v),fin}$
- correct the  $\Delta x_{(h,v)} = x_{(h,v),fin} - x_{(h,v),ini}$  orbit using the steerer concerned if  $std(\Delta x_{(h,v)})$  is above a given threshold ( $0.1 \mu\text{m}$ ).

When the measurements are started from an empty machine (no beam) correctors cycling is performed, powering all steerers to  $+2\Delta\theta_{H,V}$ , then  $-2\Delta\theta_{H,V}$  then to their operation point. This action may be done with beam only for small values of  $\Delta\theta_{H,V}$ . The *ORM* measurement may fail for unexpected reasons. The files that make the measurements are made such that (with a manual intervention) a large part of them may be recovered. The *ORM* measurement may be performed via the DC Power supplies or the fast AC power supplies used for the fast orbit feedback [7]. Both measurements are available via the FILO application with adequate modifications to the user input. For example, among others, the fast measurement may be performed at any stored current, while the slow one requires currents below 5 mA. It is worth to mention that also for the fast RM measurement, hysteresis issues make it necessary to correct the orbit after each steerer modulation.

**Off-energy Measurement** It is also possible to measure off-energy orbit response matrix. The software limits the RF frequency shift in this case to avoid loosing the beam (on a beam position interlock) at high current or too large energy shift. Such measurements are used in [8] to determine optimal sextupole settings. Also in this case the user input interface is modified for this specific measurement, for example, reminding the user to manually return the RF frequency to the initial setting.

## Jacobian Computation

The computation of the large matrices  $J_{n,s}$  may be specified and run within the application in three different ways:

- using the analytical formulas in [9] (still under test)
- using the matlab parallel computing toolbox [10]
- using the ESRF slurm cluster [11]

In all of the cases the computation is done using AT [12] based on the selected optics model and on the parameters (BPMs, correctors, errors  $V_{n,s}$ , ...) selected via the interface. The large matrices (up to several Gbytes) are usually computed off-line, ahead of the measurement and simply loaded when required. If parameters are changed a new computation is automatically triggered.

**Hardware** The application is developed in matlab2020b using AT [12] for optics calculations and appdesigner [13] for the interface. A specific machine with 64 CPUs and Ubuntu20.04 operating system has been installed to run the FILO application as fast as possible in control room. This machine is used for other purposes when not needed for operation. Due to the large size of the arrays involved in the computation, the feature of matlab to exploit the available cores for example for SVD is really appreciated. On the other hand when using the matlab parallel computing feature, the memory use is of the order of 1-2 Gbytes for each core required for parallel computation, sensibly reducing the reactivity of the interface.

## USER INTERFACE AND WIZARD MODE

The application allows to select most of the parameters relevant to the correction of optics and to save them for later use as a configuration file. The parameters that may be chosen are:

- steerers and BPMs to use for measurement (the non usable ones are excluded *a priori*)
- error types and locations: normal and skew quadrupole errors at sextupoles and quadrupoles, BPM and steerers gain and rotation
- the part of the arrays  $D_{n,s}$  to use
- the elements to use to compute the correction
- the parameters for the computation of the fitted model ( $w_\eta, w_t$ )
- plotting and display options

The standard non-expert user is not required to specify any of these parameters. She/He is instead prompted through a wizard mode to set up the accelerator and verify the progress of the measurement until the final correction. The user interface is depicted and explained in the following figures. The initial panel in Fig. 1 allows selection of the global parameters and gives the possibility to load/save the application settings. In this panel and always visible at the bottom of the window, is the presently used TANGOHOST. This allows to be able to verify immediately if the application is running in the real accelerator or in the control system

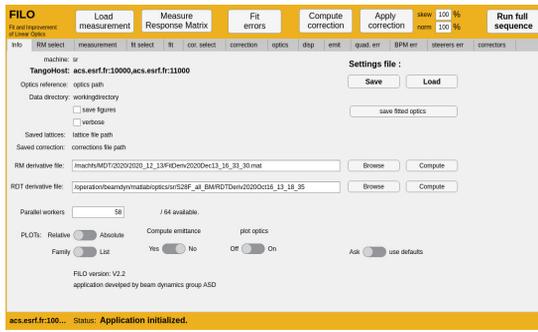


Figure 1: View of the FILO application initial panel with global settings.

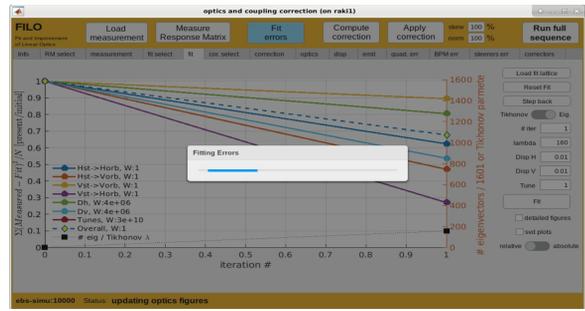


Figure 4: View of the FILO application during the definition of a fitted optics model.

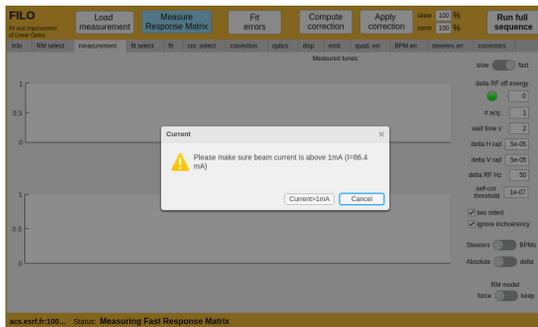


Figure 2: View of a FILO application wizard dialog box.

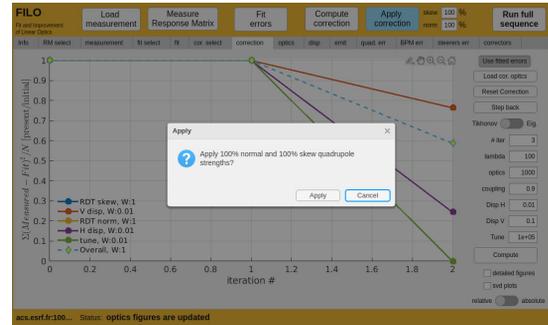


Figure 5: View of the FILO application final message before sending new strengths settings to correct optics coupling and dispersion.

simulator [14]. The user usually presses the button "Run full sequence". This triggers a wizard mode going from measurement to correction and eventually verification. Messages such as the ones in Fig. 2 are prompted to ask the user for non automated actions. In some cases, messages are given simply as acknowledgment. Figure 3 shows the progress of the measurement. The user is not allowed to interact with the application while actions are taking place. When the measurement is over the application immediately fits the data to the selected (or default) optics model. This action is visualized in a dedicated tab (Fig. 4). A similar tab is shown during the computation of correction. Finally the application asks the user (see Fig. 5) to apply or not a given fraction of the computed normal and skew quadrupole corrections. Setting this fraction to 0 later will remove the

correction from the SR if, for some unexpected reasons, it has to be removed. After the measurement it is possible to verify the fit quality by looking at the fitted and measured dispersion and beta-beating visualized in dedicated panels.

## CONCLUSIONS

The FILO application is presently operational and used for several studies such routine optics correction, ORM vs stored current and off-energy ORM. It is nevertheless cumbersome and should be integrated in the control system similarly to other applications. Namely this means a computational core made from a Tango Device Server (potentially in python [15]) and a separated user interface. The fluidity of the matlab user interface is in fact not at the same level of other JAVA control room applications (the FILO application freezes). The FILO application has been designed to allow flexible measurement and correction of the optics for the EBS storage ring. It is usable by non expert but has some graphical issues probably linked with the large files handled and the wish to exploit parallel computation within matlab. The FILO application is mostly used by the authors during machine development periods, thus not impacting user operation: It will stand as an upgrade to previous solutions until a more professional application is developed. The software is specific to EBS and it is not easy to migrate to other machines. Also, no complete automation is provided, to maintain awareness in the user concerning the actions conducted during the measurement and in all its different options.

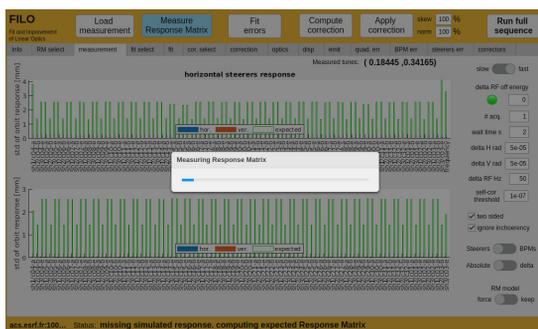


Figure 3: View of the FILO application when measuring an ORM.

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