Optiks: An Optics Measurement and Correction Program for ELETTRA

Emmanuel Karantzoulis

Sincrotrone Trieste
Padriciano 99, I-34012 Trieste, Italy
e-mail: karantzoulis@elettra.trieste.it

Abstract

Optiks is a program that measures and corrects the optical functions (i.e. beta functions, phase advances, tunes, dispersion and chromaticity) in a circular accelerator. The methods involved and the performance of the program during the ELETTRA commissioning are presented and discussed.

1. INTRODUCTION

ELETTRA is the third generation synchrotron light source situated at Trieste (Italy), currently under commissioning [1] and at a variable beam energy from 1.0 to 2.3 GeV [2]. Operational aspects concerning the synchrotron can be found elsewhere [3], here we need only mention that the commissioning was greatly facilitated by the timely preparation of the various machine measuring programs [4].

Optiks belongs to that group of programs and it has been developed to meet the needs of a third generation light source. It is well known that such storage rings due to their many insertion devices will suffer from optical asymmetries. The situation can worsen if optical asymmetries already exist due to magnet misalignments. In parallel knowing and correcting the dispersion and chromaticity is of primary importance.

The program offers in a user friendly and compact manner almost all the needed information that the operator wishes to know about the machine optics as well as the means for correcting it. It is written in C, utilizes the UNIX operating system with Motif (Toolkit) widgets, it is installed in the ELETTRA control work stations and makes a wide use of the high level software data file structure [5] including the build-in twiss function that permits to calculate in a fast and easy way the nominal machine optics.

Optiks gets its data mainly from the ELETTRA beam position monitor (bpm) system. This consists of 96x4 button electrodes [6] positioned in an even and optically symmetric way around the 12 sections of the ring i.e. each of the i^{th} bpm (i=1...8) at each section sees-at least nominally-the same beta function and therefore can be grouped into one of eight families. The bpm system measures the closed orbit by averaging a great number of turns achieving thus an accuracy of <10μm rms. However no single turn storage capacity exists and therefore measurements of the machine optic functions that are based on the bpm system have to be extracted from closed orbit data.

Alternatively the quadrupole strength shifting technique can also be used to measure the beta function at the quadrupole locations.

For measuring beta functions both methods are installed into three main routines while there exist two main methods for correcting. Independently the user may also measure and correct the dispersion and chromaticity.

2. THE PROGRAM AND ITS MAIN PANEL

The program [7] consists of one main widget and six secondary, while there also exist a number of small auxiliary widgets. All panels are equipped with "help", "save" ,"plot" and plot "zooming" functions. There is also build in interactive help for guidance. In the following every widget is separately described.

From the main widget immediate information can be obtained about the machine status i.e. current, energy, RF frequency etc. and/or the status of the bpm system and of the correctors.To start anything Optiks needs the nominal machine optics and thus the user can choose either to load the machine file i.e. the file with all magnet settings currently used or to load the actual power supply currents. Either way the reading in is automatic and the nominal optics is calculated, however if as input the machine file has been used one may click "Check File<->Machine" button where the optic from the file as well as the optic from the actual power supplies readings are calculated and compared. This way eventual power supply malfunctions or drifts in current can be spotted. In the same window the global optic correction routine may be used to restore the nominal optics trying to eliminate the resulting asymmetry by using the most effective quadrupole families.

If the integer part of the tunes is not known or one would like to have a look at the actual orbit and its Fourier transform one clicks the button "FT". In this window one can also get the Fourier Transform of the corrector strengths. Since the routine does not need a closed orbit, it may be used for injection studies and it was particularly useful at the initial stages of the commissioning.

Once a closed orbit is established one can use it to get an average idea about the actual optics of the machine. This is achieved by obtaining a difference orbit for each transverse plane using an appropriate corrector to provide for the kick. The corrector may be chosen amongst 82 for each plane as well as the applied kick in current. The difference orbit can be analytically expressed as:

$$\Delta x_{cij} = \frac{\delta_j}{2\sin(\pi Q)} \sqrt{\beta_i \beta_j} \cos(\Delta\varphi_{ij} - \pi Q) \qquad (1)$$

where ΔX_{cij} is the beam displacement measured at the i^{th} monitor in a disturbed closed orbit due to the δ_j kick of the j^{th} corrector. Q is the tune, β is the beta function and φ is the phase advance between i and j. The measured difference orbit can be plotted and compared with the prediction given by eq. (1). Information like orbit rms, mean and peak to peak are also available. One may choose to plot all bpms or just a certain family (from 1 to 8) and therefore to get the bpms in groups of twelve. Then for a certain family one has:

$$\Delta x_q = \frac{\delta}{2\sin(\pi Q)} \sqrt{\beta_i \beta} \cos(2\pi \, i \, \Delta\mu + \Delta\varphi - \pi Q) \quad (2)$$

where i=0...11 is the i^{th} bpm of the family and $\Delta\mu$ is the nominally constant phase advance between the i^{th} and $i^{th}+1$ bpm.

Performing a Fourier transform on eq. (2) the power spectrum is evaluated and plotted using the all poles method [8]. This way the full tune Q with an accuracy of about 0.02 - 0.03 is obtained and shown on the panel together with the nominal tunes. In parallel the found and theoretical amplitudes from eq. 2 are also shown. This routine has been particularly useful at the initial stages of the commissioning.

If one chooses to plot all bpms then at the same time a special window opens where tunes and amplitudes for each family found as well as the nominal ones are shown. Furthermore nominal beta functions may be plotted and compared with the β_i estimated from the measured amplitude in eq. (2) using the tunes found as input and setting the β nominal value at the corrector. It is obvious that this way one may inspect in a quick but albeit not very accurate way the optic.

The beta function is alternatively measured via the quadrupole sensitivities. In ELETTRA the quadrupoles are grouped in families and therefore only an average beta at the position of the magnets is possible. However since most quadrupoles are in groups of two - on either side of the straight sections - this method can be used especially there. To perform the measurement one has to click the button "Beta via Quadrupoles". A big panel opens where the user has to enter the initial tunes, the quadrupole family wished-via a scrolled window and the appropriate range of current change. Then for small relative current changes, the new tunes are measured and recorded and a line fit of tune changes versus current is performed. The slope of this line may be used to obtain the beta according to:

$$\beta = -4\pi C \frac{1}{LN} \frac{\Delta Q}{\Delta I} \quad (3)$$

where L is the magnetic length and N the number of magnets in the family. C = K/I the ratio between the magnetic strength and the applied current known from the calibration curves of the magnetic field measurements. Once the beta for a particular family is obtained one may continue with other families. Plots that can be updated at will show the nominal optic and the measured betas.

3. THE OPTICAL ASYMMETRY PANEL

This part of the program is used by clicking at the "optical asymmetries" button. A special panel appears where the difference between the orbit displacement measured by varying a certain steerer and via eq. (1) are shown. Scale buttons give the possibility to choose any other steerer and acquire all 96 bpms. Alternatively this can be done automatically via the "response matrix" button where the response matrix is obtained for a predetermined number of correctors, usually all of them.

When the 2x82x96 beam response matrix or a part of it is taken the program goes off line and tries to find an optic that minimizes the following figure of merit:

$$F = \sum_{i=1}^{M} \sum_{j=1}^{N} \left\{ \left(\Delta X_{mij} - \Delta X_{ij}\right)^2 + \left(\Delta Y_{mij} - \Delta Y_{ij}\right)^2 \right\} \quad (4)$$

where M in the number of acquired bpms, N the number of used steerers $\Delta X_m(Y)$ is the horizontal (vertical) closed orbit displacement at the bpm locations due to the steerer induced kick and $\Delta X(Y)$ are those given by eq. (1). The program minimizes F by modifying in a consistent manner a virtual optic. The method is based on the simplex multidimensional minimization [8] appropriately adapted to our needs. Here is enough to mention that the strengths of the individual quadrupoles are themselves the vertices of the simplex. Each quadrupole is allowed to change its strength individually i.e. power supply grouping is not respected since we are interested to find just the optic. On exit the minimization routine returns the quadrupole strengths that minimize F.

Once the closest optics is found one may use the "inspect optic" panel to inspect the resulting beta beat, beta functions, phase advance as well as the resulting tunes. Alternatively with the " inspect and correct " panel one has the possibility to also correct the optic to the nominal one. The correction is global and uses the beta beat relation:

$$\frac{\Delta\beta}{\beta}(s) = \sum_i \beta_i \frac{\cos(2\,|\,\varphi(s) - \varphi_i\,| - 2\pi Q)}{2\sin(2\pi Q)} (\Delta k\, L)_i \quad (5)$$

where $\Delta\beta$ is beta distorted minus beta nominal and the sum is over all quadrupoles of a family for which a Δk strength error exists. If we consider beta beats at the bpm locations the above eq. (5) may be alternatively written as:

$$\left.\frac{\Delta\beta}{\beta}\right|_i = \sum_j A_{ij} (\Delta k\, L)_j \quad (6)$$

where i refers to the bpms and j to the power supply families.

The program uses the most effective quadrupole family to correct the optic in both planes, the method being iterative. Here the minimization figure of merit is:

$$F1 = \sum_i \left\{ \left(\frac{\Delta\beta}{\beta}\right)_{Hi}^2 + \left(\frac{\Delta\beta}{\beta}\right)_{Vi}^2 \right\} \quad (7)$$

where H and V refer to the horizontal and vertical plane respectively. The strength that minimizes F1 for each quadrupole family is then given by:

$$\Delta(kL)_j = -\sum_i \frac{\left(\frac{\Delta\beta}{\beta}\right)_{Hi} A_{Hij} + \left(\frac{\Delta\beta}{\beta}\right)_{Vi} A_{Vij}}{A_{Hij}^2 + A_{Vij}^2} \quad (8)$$

where here A_{Hij} and A_{Vij} are the horizontal and vertical matrix A_{ij} defined in eq. (6) via eq. (5). F1 is calculated for each family j and thus the most effective family whereby a local minimum in F1 is reached as well as the corresponding new strength are obtained. The fact that the planes are mixed can sometimes drastically reduce the convergence speed or indeed the convergence itself, however an average correction of a factor of two for both planes is easily achieved.

Although the measuring method is independent of the machine settings the correction is based on the assumption that the asymmetries are not very large. From simulations it has been found that asymmetries up to 25 % can be well corrected.

4. THE DISPERSION PANEL

By clicking the "dispersion" button on the main panel one starts the dispersion measuring window. The measurement is achieved by acquiring the orbit at three different frequencies namely at f_{rf} being the frequency at which the rf-system is tuned and two other frequencies f_1 and f_2. The program lets the user decide whether a "manual" or "auto" mode option will be used (manual mode is useful in case that the rf-frequency server is not functioning or for arbitrary f_1 and f_2). In "auto" the frequency changes by $f_{rf} \pm 2$ kHz. If X_{rf} (Y_{rf}) are the horizontal (vertical) readings of a bpm at the initial frequency and $X_{f1}(Y_{f1})$ and $X_{f2}(Y_{f2})$ the readings at the above mentioned other two frequencies then the dispersion at each bpm location for an orbit corresponding to a frequency distant δf from the f_{rf} frequency is given as:

$$\frac{D}{\alpha} = \frac{X_{f1}f_2 - X_{f2}f_1}{f_2 - f_1} - X_{rf} + \frac{X_{f2} - X_{f1}}{f_2 - f_1}\,\delta f \qquad (9)$$

where α is the momentum compaction.

The measurement is very fast and may be repeated many times. In this case the routine is equipped with an averaging procedure that updates at every measurement the mean and rms dispersion. The results are plotted together with the nominal dispersion for comparison. Nominal and found dispersion can be saved to file while the routine itself prints in a special text field the maximum and minimum dispersion measured. A dispersion correction scheme using the correctors also exists but has not been up to now used.

5. THE CHROMATICITY PANEL

By clicking the "chromaticity" button on the main panel one opens the chromaticity measuring and correction window. The measurement is achieved by acquiring the tunes at many different rf-frequencies. The program lets the user decide whether a "manual" or "auto" mode option will be used and in case of the auto mode the frequency is changing in steps of 500 Hz. The betatron frequencies versus rf frequency difference are plotted for both planes and the user has to decide whether a linear, 3rd-order or higher order fit will be performed. The chromaticity is obtained as the slope of the fit at the frequency that the rf-system was tuned according to the known formula $\xi = -ah\,(\Delta Q\, f_0)/\Delta f$, where h is the harmonic number, f_0 ($=f_{rf}/h$) is the revolution frequency and α the momentum compaction.

The chromaticity correction is on the same panel. There one has to set the machine chromaticity-if found with Optiks it is automatically set- as well as the wished one. Then the program solves the following system to obtain the new sextupole family strengths that can be applied to the machine:

$$\begin{aligned} \lambda_F \sum_F \left(D_h\,\beta_h + D_v\,\beta_h\right) + \lambda_D \sum_D \left(D_h\,\beta_h + D_v\,\beta_h\right) &= \frac{\bar{\xi}_h - \xi_h}{2} \\ \lambda_F \sum_F \left(D_h\,\beta_v + D_v\,\beta_v\right) + \lambda_D \sum_D \left(D_h\,\beta_v + D_v\,\beta_v\right) &= \frac{\bar{\xi}_v - \xi_v}{2} \end{aligned} \qquad (10)$$

where $\lambda_{F(D)}$ are the new strengths of the two sextupole families, D and β are the dispersion and beta functions at the sextupole magnet locations and for the nominal optic used, $\xi_{h(v)}$ are the chromaticities to be set while the barred chromaticities are the measured ones. As in all cases the results can be saved to a file.

6. DISCUSSIONS

The program is continuously used for measuring and setting the chromaticity. The measurement reproducibility is very good.

The dispersion is also currently measured using Optiks with an excellent reproducibility. The correction part has not been yet used. However, it will be used for fine tuning in the future.

The optical asymmetry routines were not much used since commissioning priorities were different up to now. However occasional measurements have shown asymmetries of the order of 10% to 15%. Those values were also verified using the quadrupole strength change technique. Measuring also the induced asymmetries due to insertion devices it was found in a very good agreement with theory [9].

Finally the harmonic analysis part of the program and its tune finder were very useful and mainly used at the beginning of the commissioning.

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