VERTICAL EMITTANCE REDUCTION AND PRESERVATION AT THE ESRF ELECTRON STORAGE RING

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Abstract

In 2010 a campaign for the reduction and preservation of low vertical emittance at the ESRF electron storage ring was undertaken: values between 20 and 30 pm have been dramatically reduced to 3.5 pm, even during beam delivery. This improvement is the result of an increased measurement precision provided by the recently upgraded beam position monitoring system, a new correction algorithm, a larger number of correctors and two independent schemes for the automatic compensation of coupling induced by a few insertion devices whenever their gaps are moved by users during beam delivery. This paper summarizes the campaign's milestones and the results updated to the first half of 2011.

INTRODUCTION

The benefit of corrected coupling and low vertical emittance is manifold in lepton circular accelerators, provided that the reduction of the Touscheck lifetime (induced by the reduced bunch volume) is tolerable. Colliders would benefit in terms of luminosity while third-generation light sources would increase their brilliance. During injections the horizontal oscillations of the incoming beamlets would not be transfered in the vertical plane, hence reducing the injection losses resulting from the limited vertical clearance. Ultra-low vertical emittances were already obtained and directly measured in Ref. [1]. Values as low as 1.3 pm have been recently reported in Ref. [2].

Because of synchrotron radiation in lepton machines, damping and diffusion reach within a few ms an equilibrium state that generates a non-zero horizontal emittance ($\mathscr{E}_x$) and energy spread (δ). An ideal machine with no coupling between the two transverse planes (betatron) and between the vertical and longitudinal planes (dispersion) would yield an almost zero vertical emittance, $\mathscr{E}_y \simeq 0$, ignoring collisional effects. Nonzero vertical dispersion generates a vertical emittance, which is measurable from beam profile monitors. In absence of coupling indeed $\mathscr{E}_y = \epsilon_y$, where

$$\epsilon_y = \sqrt{\sigma_y \sigma_{p_y} - \sigma_{yp_y}^2} = \frac{\sigma_y^2}{\beta_y} = \frac{< y^2 > -(\delta D_y)^2}{\beta_y} ,$$

where β_y is the Twiss parameter, D_y is the vertical dispersion, and σ denotes the second-order moments. As discussed in Ref. [3], in presence of betatron coupling the above relations no longer hold. Beam profile measurements in this case provide an *apparent* emittance $\mathbb{E}_y = \sigma_y^2/\beta_y$ which differs from the RMS *projected* emittance ϵ_y. Both vary along the ring and are always larger than the equilibrium emittance $\mathscr{E}_y$. In the same paper it is shown how and why the measurable *apparent* emittance $\mathbb{E}_y$ may largely underestimate or overestimate ϵ_y, in relative terms. Since neither ϵ_y nor $\mathscr{E}_y$ are directly measurable, as figure of merit the mean value of the $\mathbb{E}_y$ (averaged over the entire ring) is used, which is proved to be close to the mean value of ϵ_y,

$$\overline{\epsilon}_y = \frac{1}{C} \oint \epsilon_y(s) ds \simeq < \mathbb{E}_y > = \frac{1}{N} \sum_{n=1}^{n=N} \mathbb{E}_{y,n} , \qquad (1)$$

where N is the number of available beam profile monitors. The mean apparent emittance has also the advantage of being more consistent with the vertical emittance evaluated from measurements of the Touscheck lifetime. The larger N, the better the approximation. Throughout the paper, when referring generically to the vertical emittance it is intended to make use of the above definition, $\overline{\epsilon}_y$, where $\mathbb{E}_{y,n}$ are measured by 11 dipole radiation projection monitors placed rather uniformly along the ring. Two additional x-ray pinhole cameras are also available but not included in the sum of Eq. (1). $\overline{\epsilon}_y$ is reported together with the standard deviation $\delta\epsilon_y = \left(\sum_n (\mathbb{E}_{y,n} - < \mathbb{E}_y >)^2/N \right)^{1/2}$.

MEASURING AND CORRECTING COUPLING

The main sources of coupling in the ESRF storage ring are believed to be tilts of the main 256 focusing quadrupoles and vertical misalignments of the 224 sextupoles (and/or orbit distortion at their locations). Being the strongest chromatic sextupoles next to quadrupoles, *effective* quadrupole tilts that account for both sources are used. Quadrupole rotations are modelled by fitting the off-diagonal blocks of the orbit response matrix (ORM), i.e. the horizontal orbit response to vertical steerers and vice versa. The precision of the latter increased relative to the past, thanks to the recent beam position monitoring system upgrade [4]. For a more realistic error model, quadrupole focusing errors are also evaluated by fitting the two diagonal blocks. The residual vertical dispersion is attributed to transverse rolls of the 64 main dipole magnets.

Until the end of 2009 coupling correction was performed by minimizing along the ring either the vertical equilibrium emittance or the apparent one (as computed by the optics code Accelerator Toolbox (AT) [5] after loading the error model) via the Matlab function `fminsearch`. The dependence of the vertical emittances on the corrector strengths being quadratic, this resulted in a nonlinear multidimensional minimization over the number of corrector skew quadrupole, 32 at that time. The main drawbacks of this approach are CPU time (about 10 minutes for 500 iterations) and the risk of limited improvements whenever a local minimum (not necessarily the lowest) is found.

In Ref. [3] it has been shown how the use of coupling Resonance Driving Terms (RDT) of Ref. [6] facilitate enormously the task of correcting coupling. RDTs are indeed linear functions of the corrector skew quadrupole strengths, hence allowing their minimization after a simple SVD inversion. The advantage is rapidity and achievement of the lowest minimum. As reported in Ref. [3], the combined correction of coupling RDT and vertical dispersion (which has a linear dependence on the skew quadrupole gradients too) ensures the minimization of the vertical emittance along the entire ring.

This correction scheme was tested for the first time during the machine startup of January 2010 after the winter shutdown. The apparent emittance and RDTs measured with all correctors switched off (normal and skew quadrupoles) are shown in the top plots of Fig. 1, while results after correction are displayed in the bottom plots. The vertical emittance decreased from (237 ± 122) pm to (11.5 ± 4.3) pm. Further studies at open insertion devices (IDs) on June 22nd yielded (4.4 ± 0.7) pm.

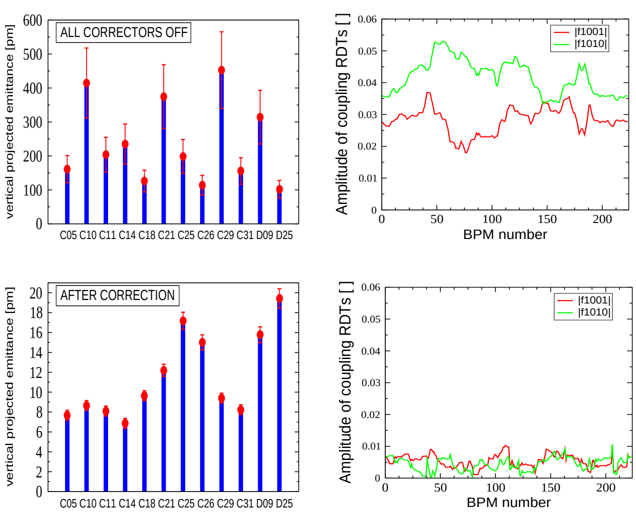

Figure 1: Vertical apparent emittances $\mathbb{E}_y$ measured on January 16 2010 along the ESRF storage ring (ten dipole radiation projection monitors and two pinhole cameras) and corresponding coupling RDTs with all correctors off (top) and after correction (bottom).

PRESERVING LOW VERTICAL EMITTANCE DURING BEAM DELIVERY

During beam delivery it was, however, difficult to preserve such low values because of continuous changes in the apertures of IDs performed by users. The residual magnetic imperfections in some IDs may indeed include gap-dependent skew quadrupole terms. This concerns mainly high-field wigglers installed more than ten years ago or small-gap devices such as in-vacuum undulators. For the time being ORM may not be measured during beam delivery. Hence, any automatic correction should be based on the knowledge of the amount of coupling introduced by IDs against the values of their gaps.

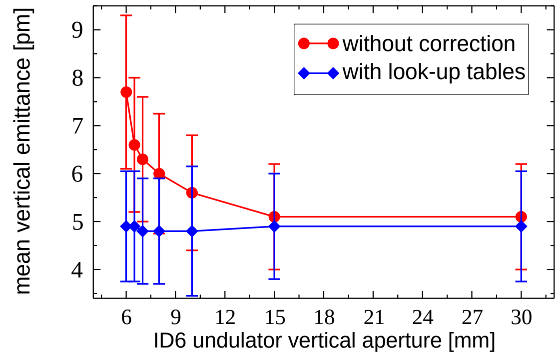

Figure 2: Mean vertical emittance $\bar{\epsilon}_y$ measured against the vertical aperture of the ID6 in-vacuum undulator without any correction (red circles) and with automatic coupling compensation (blue diamonds). Error bars corresponds to the spread $\delta\epsilon_y$.

Correction look-up tables may then be used to compensate for them (feed-forward). Dual-plane corrector steerers installed at both ends of each straight section can be configured as skew quadrupole correctors by modifying the electrical wiring between the coils. Thanks to the excellent coupling correction of the bare machine, any additional coupling induced by an individual ID may be easily quantified and corrected. A proof-of-principle test was carried out on May 5, 2010. The in-vacuum undulator ID6 was chosen as it was known to be one of the most important coupling sources at low gap values. The influence of this ID gap movements on the vertical emittance is represented by the red curve of Fig. 2: At its minimum aperture value, the vertical emittance is augmented by about 50%. At each step reported in the table, the setting of the two skew correctors that would bring back the vertical emittance to its initial value was empirically determined and stored in a look-up table. Intermediate values are determined via linear interpolation of the two neighbor measured points. The effectiveness of such a scheme may be evaluated by the (almost flat) blue curve of Fig. 2. After the successful test, the correction was left in operation during beam delivery and a programme for its extension to other IDs was launched.

A second independent automatic correction was conceived to trim the strengths of corrector skew quadrupoles to preserve $\bar{\epsilon}_y$, which is monitored at the frequency of 1 Hz. This coupling feedback loop varies the 32 skew quadrupole correctors so to generate a time-dependent coupling vector C_- [3]. After varying both amplitude and phase of C_- while monitoring the mean vertical emittance, the loop determines the minimum and sets the corresponding skew quadrupole trim currents. Until November 2010 operators would trim C_- via a software application by trials and errors. The coupling feedback loop was installed to perform the same action hourly. Figure 3 shows a comparison be-

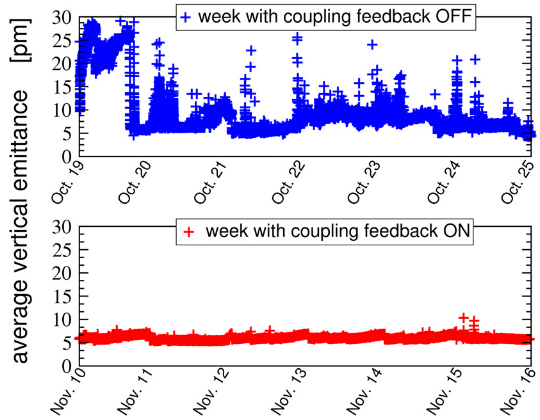

Figure 3: Comparison between the mean vertical apparent emittance $\bar{\epsilon}_y$ measured towards the end of 2010 during beam delivery without (top) and with (bottom) coupling feedback. Data acquired during refills are not displayed.

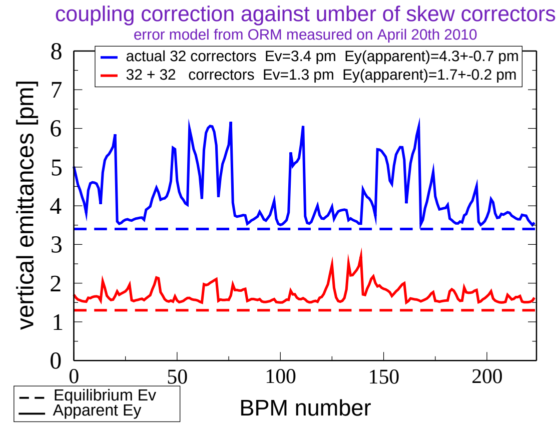

Figure 4: Simulation of vertical apparent and equilibrium emittance with the present coupling correction setting of 32 and its further reduction with 32 additional correctors.

tween the vertical emittance evolution during one week of beam delivery with and without coupling feedback towards the end of 2010. In the latter case, uncompensated ID gaps movements during the first day caused $\bar{\epsilon}_y$ to reach 30 pm (from the initial 6 pm). Low emittance is retrieved only after a manual regulation. When the automatic loop was activated a few weeks later, $\bar{\epsilon}_y$ remained stable between 6 and 7 pm.

TOWARDS ULTRA-LOW VERTICAL EMITTANCE

Following the successful campaign of 2010, a study was launched to assess whether a larger number of corrector skew quadrupoles would further reduce the vertical emittance. At the ESRF storage ring the correction of orbit distortion and lattice errors is performed by corrector coils mounted on the main 224 sextupoles. Until 2010, 52 sextupoles had unused corrector coils. Simulations based on a large set of measured ORMs indicated that 32 additional skew quadrupoles could provide a mean vertical emittance of about 2 pm (see Fig 4). During the 2010 winter shutdown those 32 new skew quadrupoles were put in operation. At fixed ID gaps the record low (for this machine) was achieved on April 5, 2011, with (2.8 ± 1.1) pm, while typical values during beam delivery and active coupling feedback range between 3.2 and 5 pm, with an average value over the week of 3.6 pm, as shown in Fig. 5. It is worthwhile noticing that at these low levels three issues are encountered. First, dipole radiation projection monitors are at the limit of their resolution. A programme for the installation of a new emittance monitor based on x-ray refractive lens imaging was launched with the aim of resolving vertical emittances below 2 pm [7]. Second, fast vertical beam motion, even if well compensated by the bunch-by-bunch orbit feedback, may still account for a fraction of the measured vertical beam size. Third, it is believed that the equilibrium emittance is dominated by vertical dispersion, whose RMS value remains at the level of 2 mm. Studies are under way to make use of the vertical steerers to compensate part of this dispersion while correcting the orbit, as done in Ref. [8].

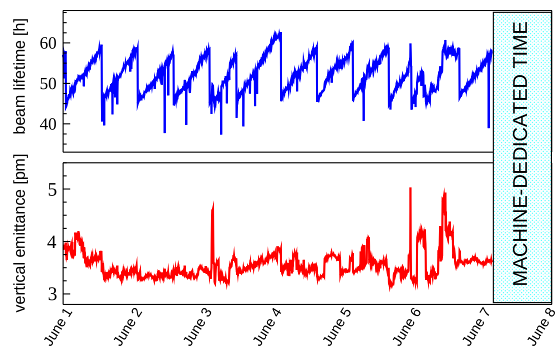

Figure 5: Beam lifetime (top) and mean vertical apparent emittance $\bar{\epsilon}_y$ (bottom) measured during a week of beam delivery (200mA with 7/8 filling mode) in June 2011. Data acquired during refills are not displayed.

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