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EMITTANCE REDUCTION WITH THE VARIABLE DIPOLE FOR THE ELETTRA 2.0 RING*

A. Poyet†, Y. Papaphilippou, CERN, Geneva, Switzerland
M. A. Dominguez, F. Toral, CIEMAT, Madrid, Spain
E. Karantzoulis, Elettra-Sincrotrone, Trieste, Italy
R. Geometrante, KYMA, Trieste, Italy

Abstract

Elettra is a 2/2.4 GeV third-generation electron storage ring, located near Trieste, Italy. In view of a substantial increase of the machine performance in terms of brilliance, the so-called Elettra 2.0 upgrade is currently on-going. This upgrade is based on a 6-bends achromat, four dipoles of which having a longitudinally variable field. So far, those dipoles are foreseen to provide a field with a two step profile. The VAriable Dipole for the Elettra Ring (VADER) task, driven by the I.FAST European project, aims at developing a new dipole design based on a trapezoidal shape of the bending radius, which would allow for a further reduction of the horizontal emittance. A prototype of this magnet should be designed by the CIEMAT laboratory and built by KYMA company. This paper discusses the new dipole field specification and describes the corresponding optics optimization that was performed in order to reduce at best the emittance of the Elettra ring.

INTRODUCTION AND MOTIVATIONS

The present Elettra machine is a third-generation Italian light source, located in Trieste. Operating at two different energies of 2 or 2.4 GeV, Elettra presently delivers electron beams with an emittance of 7-10 nm.rad [1]. The Elettra 2.0 upgrade [2] aims mainly at reducing the emittance by at least one order of magnitude, while keeping the geometrical structure almost identical. The current plan for the machine upgrade is based on an enhanced 6-bend achromat (S6BA-E), relying on the use of longitudinal gradient (LG) dipoles to reach a bare horizontal emittance of about 210 pm-rad at 2.4 GeV. The dipolar field of those magnets varies longitudinally in the form of two steps, to reach 1.43 T (at 2.4 GeV) at the center.

It has been shown that hyperbolic profiles for the longitudinal evolution of the magnetic field could bring better performances in terms of emittance reach [3]. In that respect, this paper describes the different steps taken in order to replace the present LG dipoles by the so-called VADER (Variable Dipoles for the Elettra Ring). In a first part, it is shown how the longitudinal profile has been designed and implemented in MAD-X [4]. Then we will demonstrate how the VADER were included in the Elettra 2.0 lattice and how the optics were tuned in order to reach the best possible performance. Finally, we will show the first tracking results obtained with a new single particle tracking code being developed at CERN. In all those studies, we assume a beam energy of 2.4 GeV.

DESIGN OF A TRAPEZOIDAL PROFILE

The design of the longitudinal profile is highly inspired by the work presented in [3], where a longitudinally variable dipole was designed for the damping rings of the CLIC study [5]. The maximum field is reached at the center where consequently the bending radius is minimum. We want to design a trapezoidal profile in bending radius. The length of the central constant part in field is denoted L_1, while the length of the varying part of the magnet is denoted L_2. Moreover, the minimum bending radius - reached at the center - is denoted by ρ_1, and the maximum - reached at the edge of the dipole is denoted ρ_2. We can therefore define two ratios in terms of length L_i and bending radius ρ_i as:

$$\lambda = \frac{L_1}{L_2} \qquad \tilde{\rho} = \frac{\rho_1}{\rho_2}. \tag{1}$$

The design of the longitudinal profile is then determined using those two parameters and the definition of the bending angle provided by such a profile, as given in Eq. (2):

$$\theta_{\text{trap}} = \frac{L(\lambda(\tilde{\rho}-1)+\tilde{\rho}\ln\tilde{\rho})}{\rho_1(\tilde{\rho}-1)(1+\lambda)}. \tag{2}$$

Since the peak field of the dipole (2.3 T at 2.4 GeV), the total length L (0.8 m) and the dipole bending angle are determined by the original lattice and the technological constraints, we can choose λ and $\tilde{\rho}$ in order to optimize the emittance reduction. To do so, one can compute the emittance given by a Theoretical Minimum Emittance (TME) cell with a uniform dipole, and the one obtained with a trapezoidal profile. The emittance reduction factor is then defined as:

$$F_{TME} = \frac{\varepsilon_{\text{TME, uni}}}{\varepsilon_{\text{TME, trap}}}, \tag{3}$$

and the full expression can be found in the Appendix C of [3]. One can then parameterize the emittance reduction factor with λ and $\tilde{\rho}$, for combinations which conserve the magnet bending angle, as shown in Figure 1.

The best emittance reduction factor is found for $\lambda = 0.074$ and $\tilde{\rho} = 0.24$. Those parameters are then used to obtain the final longitudinal profile of the VADER dipole as displayed in Figure 2.

* Work supported by the I.FAST project
† axel.poyet@cern.ch

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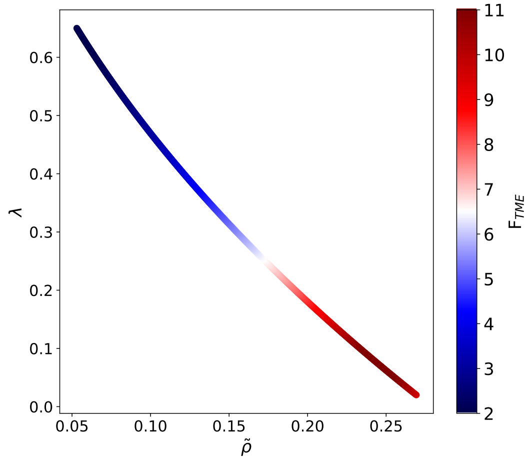

Figure 1: Emittance reduction factor as a function of the VADER profile parameters.

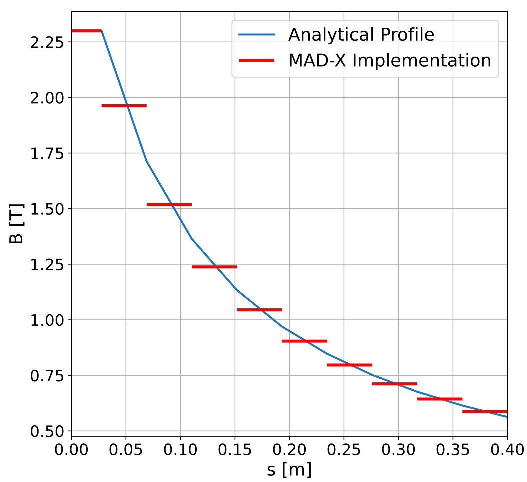

Figure 2: Proposal for the VADER longitudinal field. The blue line shows the analytical solution while the red steps show the implementation in MAD-X.

The MAD-X software does not allow the implementation of a continuous longitudinal profile for a dipole. For that reason, it has been chosen to split each half dipole in ten different slices. The varying part of the dipole is sliced in nine, all of the slices having the same length and a different bending angle. This is shown with the red lines in Figure 2.

Once this profile is designed and implemented in MAD-X, one can replace the LG dipoles installed in the original Elettra lattice by those. In the following, we assume that no Insertion Device is installed in the machine.

LATTICE DESIGN WITH VADER DIPOLES

In this study, we strictly keep the original geometrical linear lattice. Therefore, all dipolar and quadrupolar elements remain at their location. The LG dipoles are being replaced by VADER ones and the external dipoles are replaced by two steps dipoles (very similar bending angle) in order to control the dispersion in the long straight sections. The location of the sextupoles (presently considered thin) has been slightly changed in order to optimize the chromaticity correction. Moreover, the lattice is matched in order to meet the constraints of the Elettra ring. Namely, our main concern is to ensure the absence of dispersion in the long straight sections while keeping the optics functions at a reasonable level throughout the lattice so that no aperture limit is met. A possible lattice including VADER dipoles is shown in Figure 3 [6].

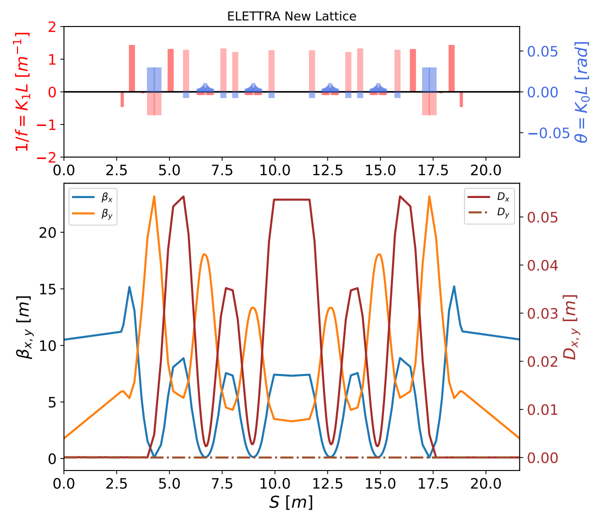

Figure 3: Lattice proposal for the ELETTRA 2.0 ring including VADER dipoles.

The proposed optics are very similar to the original ones in Elettra 2.0 (S6BA-E) in [2] and [1]. The dispersion is maintained to zero in the long straight sections, and the vertical β-function does not exceed 30 m in the lattice. We also kept the original so-called *anti-bends* since they turned out to be very useful to control the dispersion despite the operational constraint they bring. All the quadrupoles are assumed to be powered independently - as in Elettra 2.0 - so that all the knobs can be used for the emittance optimization. All the obtained gradients are well within the 60 T/m limit of the Elettra 2.0 upgrade.

The horizontal and vertical chromaticities are corrected to +1, as in the original lattice, using the lattice sextupoles (three focusing and five defocusing sextupoles are installed so far). The obtained betatron tunes are too close to the half integer resonance and are therefore modified to get the final value of 34.25 in the horizontal plane and 8.2 in the vertical plane. The original octupoles in the lattice are not considered for the time being.

Using this lattice, the equilibrium emittance is expected to be about 115 pm.rad. This gives a reduction of about 45 % in comparison with the S6BA-E lattice and a reduction factor of about 95 compared to the current Elettra ring. The beam size at the ID location is well within the Elettra 2.0 constraint since it is expected to be equal to about 35 µm. Some key parameters are summarized in Table 1.

[1] To be confirmed by tracking studies.

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Table 1: Comparison of Some Key Parameters Between the S6BA-E Lattice and the New VADER One

Parameter	S6BA-E	VADER
Hor. Emittance ε_x	212 pm.rad	115 pm.rad
Ver. Emittance ε_y	1 pm.rad	1 pm.rad [1]
Beam size @ ID $\sigma_{x,ID}$	60 µm	35 µm
$J_x/J_y/J_E$	1.52/1/1.48	1.49/1/1.51
Q_x / Q_y	33.25/9.2	34.25/8.2
Natural ξ_x/ξ_y	-76/-52	-123/-79
Corrected ξ_x/ξ_y	+1/+1	+1/+1
Compaction factor $\alpha_{c,0}$	1.2×10^{-4}	5.05×10^{-5}
Quadrupoles gradient	< 50 T/m	< 60 T/m

Among those parameters, one can notice a significant difference in the first order momentum compaction factor. This difference is due to the presence of strong dipoles (2.3 T peak field) in the cell. This could be a possible known issue in the future since this would also impact the second order momentum compaction factor and therefore the Touscheck lifetime.

FIRST TRACKING STUDIES

In order to validate this new lattice, we performed tracking studies using a new tool being developed at CERN, XSuite [7]. Tracking is done using a thin lenses lattice (all quadrupoles and dipoles are sliced in 11 parts). We generate a matched Gaussian distribution, assuming an initial horizontal emittance of 160 nm.rad as provided by the Elettra booster at 2.4 GeV [8], and a 2 % coupling. The initial bunch length is set to 75 ps. The particles are tracked for 30000 turns, which corresponds to the required time to reach the horizontal equilibrium emittance (about five times the horizontal damping time). We compute the emittances each turn so that we can obtain the evolution of the emittances as a function of the number of turns, as shown in Figure 4.

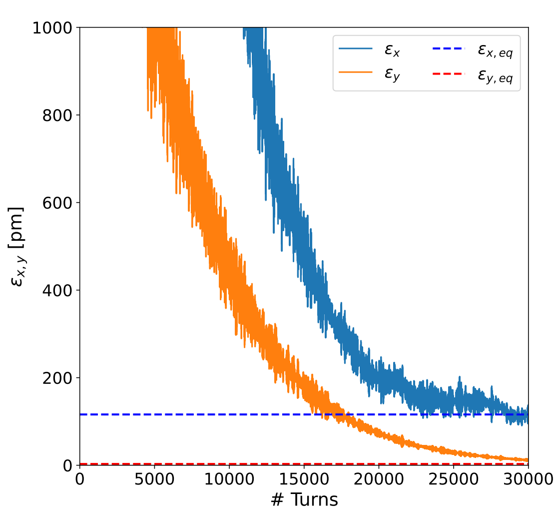

Figure 4: Horizontal and vertical emittances as a function of the turn number.

Those first tracking results seem to confirm the horizontal equilibrium emittance computed with MAD-X. However, the vertical equilibrium was not reached within the 30k turns, as it is usually reached after 7-8 damping times.

FUTURE CHALLENGES

Despite the demonstrated gain of emittances, several challenges are still to be tackled in case Elettra 2.0 should adopt permanent magnets in the future when it will operate only at 2.4 GeV. The first one concerns the chromaticity correction. As one can see in Table 1, the horizontal natural chromaticity is doubled, compared to the original S6BA-E lattice. This is due to the focusing strength of the quadrupoles which has been increased. However, the phasing of a single cell has been significantly modified and therefore the resonances correction is not as efficient anymore. One challenge consists therefore in implementing a new sextupole scheme, targeting the chromaticity correction without affecting the dynamic aperture. So far, new sextupoles were installed in locations where their efficiency is increased. However, one has now to tackle higher order corrections so that the energy acceptance and the dynamic aperture are preserved. One can also replace the 2-steps bends installed at the entrance and the exit of the cell by 3-steps (stair-like) dipoles, to reduce further the equilibrium horizontal emittance. Another challenge consists in removing the reverse bend magnets, since they might be more challenging to operate. They are in fact misaligned quadrupoles, requiring a very accurate control of the closed orbit. Finally, the lattice optics will be optimized further, and tracking studies will be performed in order to improve further the performance of the light source.

CONCLUSIONS

In this paper, we showed how a new longitudinally variable dipole could be implemented for the Elettra 2.0 ring. We proposed a longitudinal profile for the so-called VADER dipoles. This profile is trapezoidal in bending radius, as inspired by previous work done for the CLIC damping rings. Four out of the six dipoles of the achromat were replaced by VADER ones. Those dipoles reach a peak field of 2.3 T. The optics were re-matched in order to meet the original constraint of the Elettra 2.0 ring. With this new proposal, an emittance reduction of 45 % with respect to the S6BA-E lattice is expected, reaching an horizontal emittance of about 115 pm.rad. Once the design fully completed, magnetic specifications will be communicated to CIEMAT in view of a prototype. In parallel, other studies are also on-going in order to explore the possibility of replacing the present antibends by normal quadrupoles, as they are easier to operate. Finally, a non-linear optimization of the lattice remains to be done.

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REFERENCES

[1] E. Karantzoulis, A. Carniel, D. Castronovo, S. Di Mitri, B. Diviacco, and S. Krecic, "Elettra and Elettra 2.0", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 1474–1476. doi:10.18429/JACoW-IPAC2021-TUPAB051

[2] E. Karantzoulis and W. Barletta, "Aspects of the Elettra 2.0 design", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 927, pp. 70–80, 2019. doi:10.1016/j.nima.2019.01.044

[3] S. Papadopoulou, F. Antoniou and Y. Papaphilippou, "Emittance reduction with variable bending magnet strengths: Analytical optics considerations and application to the Compact Linear Collider damping ring design", *Phys. Rev. Accel. Beams*, vol. 22, p. 091601, 2019. doi:10.1103/PhysRevAccelBeams.22.091601

[4] https://mad.web.cern.ch/mad/.

[5] O. Brunner *et al.*, "The CLIC Project", Technical report, Mars 2022. https://cds.cern.ch/record/2806791/.

[6] F. Soubelet, fsoubelet/PyhDToolkit: Release 0.18.0. (Zenodo,2022,5), doi:10.5281/zenodo.6518967

[7] https://xsuite.readthedocs.io/en/latest/.

[8] A. Franciosi *et al.*, "ELETTRA 2.0 Technical Design Report", Trieste, Italy, Technical Report, 2021.