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MULTI-BEND LATTICE ANALYSIS TOWARDS A DIFFRACTION LIMITED RING BASED LIGHT SOURCE

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Abstract

An analysis of lattice configurations up to 10 bend achromat is presented aiming towards diffraction limited ring based light source. The described analysis can apply to any type of a ring based light source however for practical reasons we consider Elettra that has been operating for users for 25 years; to stay competitive for world-class photon science in the future, a massive upgrade of the storage ring is needed. The optimum solution is based on certain design criteria, constraints regarding certain accelerator components and their implications on beam dynamics and user requirements. The space available for insertion devices as well as the impact of anti-bends on the design is also addressed. Two proposed realistic lattices are further discussed taking into account different criteria and user requirements. Those lattices reduce the emittance of the present machine by more than one order of magnitude but at the same time respect many other criteria such as realistic magnet gradients, magnets with magnetic length equal to the physical length, drift space enough for radiation extraction, large available space for insertion devices, minimal shift of the beam lines etc.

INTRODUCTION

Located on the outskirts of Trieste, Elettra operates for users since 1994 being the first third generation light source for soft X-rays in Europe. During those 25 years many improvements have been made to keep the machine competitive with the more modern light sources. At present the Elettra storage ring operates at 2.0 GeV (75% of the user time) and 2.4 GeV (25% of the user time) with beam currents of 310 mA and 160 mA, respectively. The total operating time is about 6400 hours/year of which 5000 are dedicated to the users on a 24/7 basis [1]. The storage ring lattice is a double-bend achromat (DBA) with an emittance of 7 nm-rad at 2 GeV and 10 nm-rad at 2.4 GeV. The ring has a twelve-fold symmetry with 12 long straight sections 11 of which host insertion devices (IDs) most occupying the 4.5 m per achromat pure space available for IDs.

The insertion devices (IDs) include 3 wigglers (one superconducting, one permanent magnet and one electromagnetic elliptical) and 8 undulators (3 sections host Apple-II type undulators). Another short undulator is installed in an additional 1.5 m short straight section in the arcs. Ten beam lines use the radiation from six bending magnets to yield the current total of 28 independently operating beam lines. Since 2010, Elettra has been operating in top-up mode, injecting 1 mA of current every 6 / 20 min at 2 GeV / 2.4 GeV, respectively

After 25 years of serving the user community with excellent results, a major upgrade towards what it is called the "ultimate" light source is planned to maintain its leadership for its energy range of synchrotron research and to enable new science and new technology developments to the general benefit.

Following the general trend of the rings for synchrotron light the new generation is generally characterized by a further increase of the brilliance and coherence of the photon source as compared to today's X-ray beams.

The brilliance of the source in general is given by:

$$B = \frac{flux}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \tag{1}$$

and the coherence fraction by:

$$\zeta = \frac{(\lambda / 4\pi)^2}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \tag{2}$$

while the brilliance of the nth harmonic of a well matched undulator for the corresponding λ_n photon wavelength is given by:

$$B_n = \frac{F_n}{4\pi^2 (\varepsilon_x + \lambda_n / 2\pi)(\varepsilon_y + \lambda_n / 2\pi)} \tag{3}$$

clearly those quantities become large by further reduction of the emittance of the stored electron beam at levels capable of providing a diffraction limited X-ray source also in the horizontal plane while such a limit has already been achieved at Elettra for the vertical plane. Elettra 2.0 thus, aims to provide intense beams in the range of VUV to X-rays for the analytical study of matter with very high spatial resolution.

Already in the 90's people were speculating on diffraction limited light sources [2] although the times were not yet ripe. Development in accelerator technologies during the last twenty years led to many important results featuring new magnet design, innovative vacuum and material technologies as well as important improvements in beam monitoring and feedback systems. Those new capabilities and technologies, which were not available or were at their infancy when the present Elettra storage ring was conceived, provide today a solid basis for the realization of the new machine.

Studies being carried out at Electra resulted in a new storage ring lattice design based on the multi-bend

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achromat concept and producing plausible versions of the new lattice [3-6].

OBTAINING A LOW EMITTANCE

The techniques in obtaining low emittances are well known and documented in the literature; a short description is presented here for the sake of completeness.

The emittance of a storage ring is given by:

$$\varepsilon_{x0}\left[mrad\right] = F_x(q_x, lattice)\frac{E^2(GeV)}{N_d^{\,3}} \qquad (4)$$

where N_d is the number of dipole magnets, E the ring energy and F_x a form factor depending on the H-function ($H=\gamma_x\eta_x^2+2\alpha_x\eta_x\eta'_x+\beta_x\eta'^2_x$) which is determined by the shape of the horizontal betatron and dispersion function in the dipoles and the horizontal damping partition number j_x (usually having values between 1 and 2). Low emittance can therefore be reached if betatron and dispersion functions have a minimum at the dipole locations. Such minimizing configuration can be achieved using unit cells consisting of one dipole and some quadrupoles. For space optimization unit cells of one dipole with a deflection angle ϕ and superimposed vertically focusing quadrupole component situated between two horizontally focusing quadrupoles are considered. From the above eq. 4 one sees that the more such unit cells the ring has, the smaller the emittance becomes since the dependence is one over the third power of the dipole number N_d. At the same time the more such unit cells are included in the lattice the less free space for insertion devices is available. It is important also to consider that the H-function minimisation of the unit cells leads to larger chromaticities which require stronger sextupoles, leading to problems with non linear dynamics and reduction of the dynamic aperture i.e. reduction of lifetime and difficulty with off-axis injection. It is then clear that a compromise should be found between the requested emittance, the free space needed for insertion devices and the accepted level of dynamic aperture and non linear effects. Furthermore in general it is preferable to have dispersion zero in the long straights where insertion devices are situated. This requires a matching of the Twiss functions to wished values in the straight section. Matching with minimised emittance is achieved when the outer dipoles of the arc have a magnetic length and deflection angle less than ϕ [2]. Those magnetic lattices are called multi-bend achromats (MBA).

ANALYSIS OF MBA LATTICES FOR THE NEW ELETTRA

The lattice of the actual Elettra is a double bend achromat. Its circumference is 259.2 m, twelve straight sections and 7 nm-rad emittance at 2 GeV. To see how the emitance is reduced assuming multi-bend achromats at 2 GeV keeping the same circumference and the same 12-fold symmetry, all optics up to 10-bend achromats were created, analyzed and plotted versus the number of dipoles per achromat (Fig. 1).

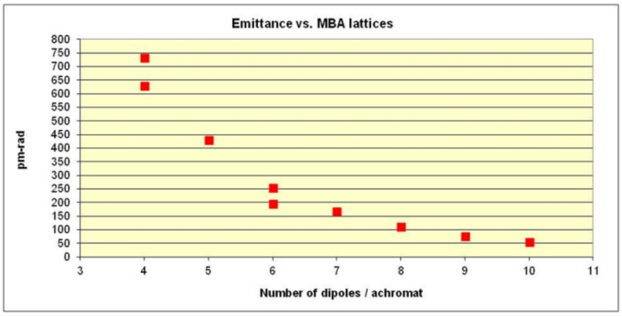

Figure 1: Emittance versus number of dipoles per achromat for an Elettra like ring at 2 GeV.

As can be seen from the above graph, one order of magnitude reduction of the actual emittance of Elettra occurs already for a 4-bend achromat or higher. For 4 and 6 BAs two solutions are shown. The solutins that show a reduction are achieved by using longitudinal gradient dipoles and anti-bends. Another beam parameter is the beam size achieved. In the table 1 below the emittances and the corresponding beam sizes in the long straight sections (LS) are shown.

Table 1: Emittance and beam size for various MBA lattices at 2 GeV for an Elettra size ring. The last column shows the brilliance increase factor compared to that of the actual machine for a certain undulator.

Number of dipoles / achromat	Emittance (nm-rad) @ 2 GeV	σ_x (μm) @ LS	σ_y (μm) @1% coupling @ LS	Brilliance increase factor at 1keV
2	7	240	14	
4	0.74 (0.63)	80	4.5	13 (15)
5	0.43	70	3	22
6	0.25 (0.19)	55	2.2	35 (43)
7	0.17	40	1.9	46
8	0.11	26	1.7	60
9	0.075	22	1.5	73
10	0.054	20	1.3	84

However many our users and partners are also interested in including super-bends, increasing the number of undulators, performing time resolved experiments and even consider the possibility to be able to go at a higher energy (2.4 GeV) as in the actual machine. This means that the available free space for insertion devices or other equipments is important.

In the next Figure 2 the free space per achromat is shown for up to 9-bend structure. The read colour indicates the pure free space for insertion devices in the long straights (dispersion free) whereas the green colour indicates free space for IDs or other equipment such as an Rf cavity in the arcs. From the graph below it is observed that only the 4 to 6 bend achromats give more or equal free space to that of the actual Elettra. This is due to the smaller magnet size, but then from 7 to 9 bend there is a reduction due to the increasing number of unit cells per achromat.

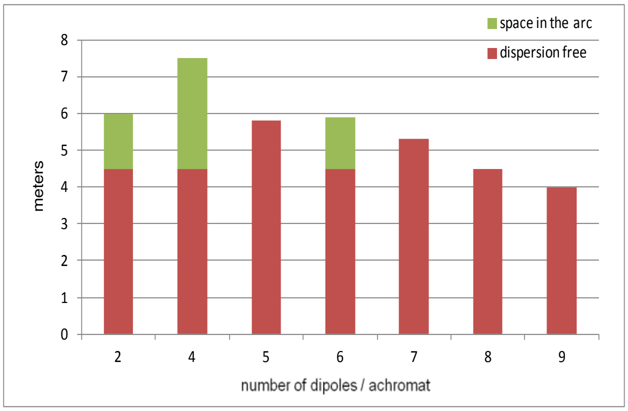

Figure 2: Free space per achromat for IDs or other equipment for various MBAs.

REQUIREMENTS FOR ELETTRA 2.0

The requirements for the new machine were defined in collaboration with some key users during a workshop back in 2014 as follows:

- Energy 2 GeV
- Emittance reduction by more than 1 order of magnitude
- Electron horizontal beam size less than 60 um
- Intensity 400 mA, maintain the filling patterns as before (hybrid, single bunch etc.)
- Use the same building and almost the same ring circumference (~260 m)
- Free space available for insertion devices (ID) not less than that of the actual Elettra
- Maintain the existing ID beam lines at the same position
- Maintain the existing bending magnet beam lines
- Use the existing injectors

From the above requirements and the analysis presented previously, the best candidate for Electra 2.0 is a 6BA lattice however also the 4BA lattice is quite attractive although its emittance reduction is not as high as in the case of 6BA (see table 1) and the horizontal beam size is larger than 60 microns (80 micron). However there is ample available free space and the lattice uses fewer and more relaxed magnets, it can thus work easily also at 2.4 GeV. Such a lattice may be a good candidate for a multivalent machine that needs to incorporate also the possibility of a variable bunch length. Since as mentioned before after the PHANGS workshop in December 2017 at ICTP Trieste, partners and users expressed interest in other aspects of the new machine, a trade between brilliance and the other aspects may be found. In the next we present a highly specialized version the so called S6BA lattice and a multivalent version the so called S4BA lattice. Note that the S6BA is the current official version that is also presented in the conceptual design report (CDR) already publicly available since 2017 [7].

THE S6BA LATTICE

The symmetric six bend achromat (S6BA) lattice consists of 6 quad-dipole-quad cells per achromat creating an invariant optic under relative position shifts between them. Thus relative long straight section can be created in the arcs without appreciable change of the optics functions increasing thus the space available for insertion devices.

The S6BA optics (basic version), shown in Figure 3 has an emittance of 0.25 nm-rad with working point (33.3, 9.2) and natural chromaticities (-75,-51).

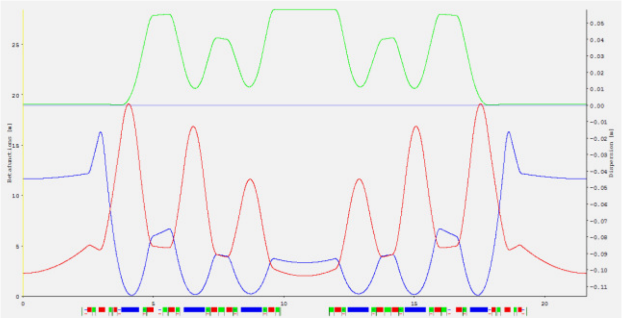

Figure 3: The S6BA lattice.

The corresponding horizontal beam size at the straight sections is 40 μm in the horizontal and 3 μm in the vertical at 1% coupling (however higher coupling i.e. towards round beams to avoid resistive wall effects is preferable) and the divergence is 6 μrad. The dipoles will be combined having a dipole field of 0.8 T (compared with 1.2 T at 2 GeV of the actual Elettra) and their maximum gradient is ≤15 T/m (compared with 2.8 T/m in Elettra). The quadrupoles have a maximum gradient of ≤50 T/m (compared with 15 T/m in Elettra).

The dispersion in the arcs is low (58 mm compared with 400 mm in the actual Elettra) meaning that also the short straight sections (1.8 m long) situated in the middle of the arc can be used for insertion devices or even, due to the very small and similar beam dimensions in both long and short straight sections, in-vacuum insertion devices with a 4.5 mm gap can be easily installed without additional optic elements.

Since the dipole fields of the lattice are now lower cannot be used for the dipole based beam lines but for the infrared beam line.

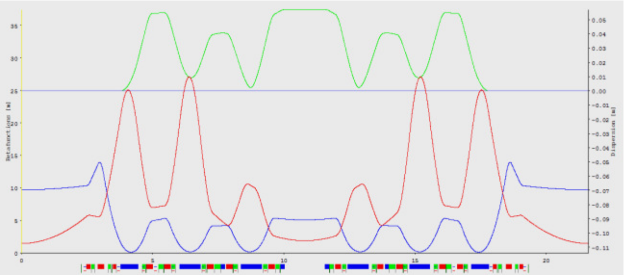

Figure 4: The S6BA lattice with anti-bends and two longitudinally focusing dipoles.

Two possible solutions were considered: either to install a short wiggler in the short straight section or to install a super-bend. Both solutions may contribute to an emittance increase of the bare lattice depending upon their field and number. Another solution however exists by using some longitudinal gradient dipoles and anti-bends. In that case (Fig. 4) the dipoles that will serve a beam line can have a peak field of 2.2 T and the emittance is reduced to 0.19 nm-rad but the available free space in the arc is reduced to 1.55 m, still acceptable. In this version of S6BA four anti-bends are used to reduce the dispersion on the 3rd and 4th bending magnet that now has the following profile (Fig. 5)

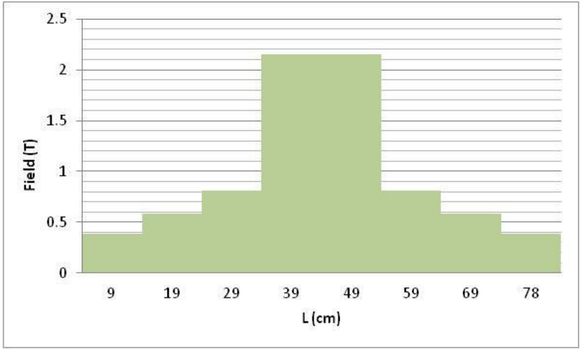

Figure 5: High field magnet profile.

The S6BA lattice basic version could also work at 2.4 GeV with a further reduction of the free space in the arc.

THE S4BA LATTICE

The symmetric four bend achromat (S4BA) lattice consists of 4 quad-dipole-quad cells per achromat (Fig. 6) creating an invariant optic under relative position shifts between them similar to those of the S6BA

The S4BA optics (basic version), shown in Fig. 6 has an emittance of 0.73 nm-rad with working point (24.3, 15.2) and natural chromaticities (-46,-58).

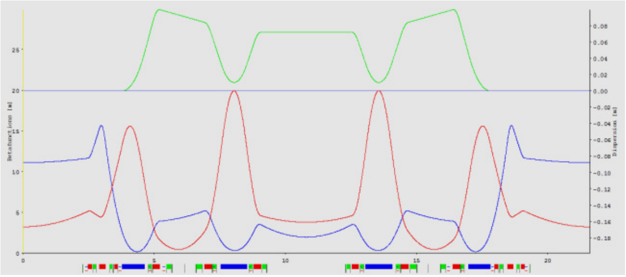

Figure 6: The S4BA lattice.

The corresponding horizontal beam size at the straight sections is 80 µm in the horizontal and 4.5 µm in the vertical at 1% coupling (however higher coupling i.e. towards round beams to avoid resistive wall effects is preferable) and the divergence is 11 µrad. The dipoles will be combined having a dipole field of 0.8 T (compared with 1.2 T at 2 GeV of the actual Elettra) and their maximum gradient is ≤12 T/m (compared with 2.8 T/m in Elettra). The quadrupoles have a maximum gradient of ≤36 T/m (compared with 15 T/m in Elettra).

The dispersion in the arcs is still low (76 mm compared with 400 mm in the actual Elettra) meaning that also the short straight sections (3.4 m long) situated in the middle of the arc can be used for insertion devices or even, due to the very small and similar beam dimensions in both long and short straight sections, in-vacuum insertion devices with a 4.5 mm gap can be easily installed without additional optic elements.

Similarly to the S6BA the longitudinal gradient version of the S4BA (Fig. 7) reduces further the emitance to 0.63 nm rad with the 2 and 3rd dipole having a field profile similar to the one in Fig. 5. As before, due to the anti-bends the free space in the arc is reduced to 2.8 m.

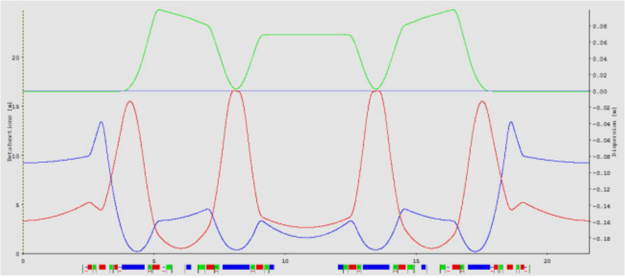

Figure 7: The S4BA lattice with anti-bends and two longitudinally focusing dipoles.

This lattice can without any change work also at 2.4 GeV although in that case the emittance increases to 0.9 nm-rad.

THE CURRENT ELETTRA 2.0 LATTICE

The S6BA at 2 GeV is considered the best possible lattice for Electra 2.0. It reduces the emittance by a factor 28 in a rather small circumference of about 260 m (12 achromats) while the requirement of the available free space to be at least as in the actual machine, results in having quite strong gradients in all magnets with an impact on the dynamic aperture. To investigate the DA, 6-dimensional (6-D) particle tracking was performed (2000 turns), including both betatron and synchrotron oscillations in the presence of classical synchrotron radiation emission and radiofrequency (RF) acceleration using Elegant [8,9] including alignment and field errors.

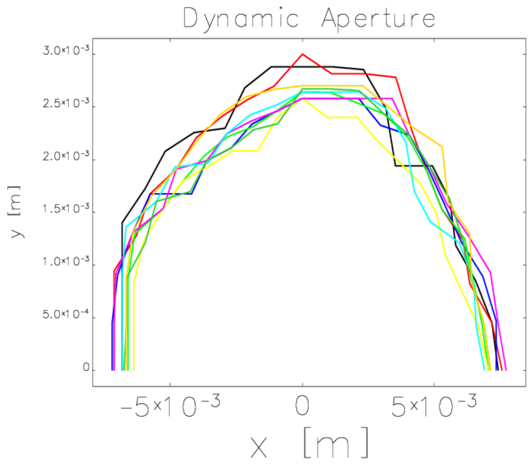

Figure 8: DA of the lattice with errors and all current insertion devices.

In Figure 8 the dynamic aperture (that can be further optimised) is shown including all errors and also all current insertion devices. As position errors were taken, 20 µm between magnets in a girder, 100 µm between girders and 100 µrad in angle. Field errors were taken as 0.01%. Values refer to the standard deviation of a Gaussian distribution with 3-sigma cutoff. As can be seen from Figure 8 the dynamic aperture is ±7 mm horizontally and ±2.5 mm vertically. This aperture allows off-axis injection and the use of the injectors as in the present machine.

In Figure 9 the injection efficiency versus the horizontal bump is shown for the current injection scheme configuration. With an injection bump of about 7 mm the predicted efficiency is above 95%.

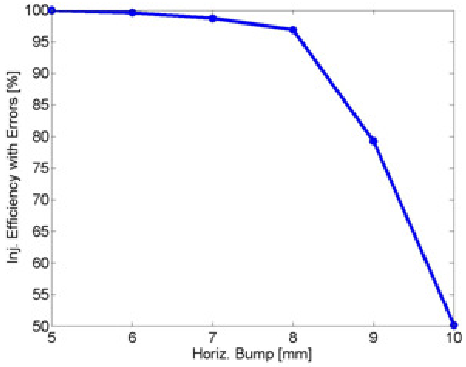

Figure 9: Injection efficiency versus the horizontal beam bump amplitude.

MAGNETS

Due to the demand for large free space available for IDs or other the magnets have to be longitudinally short and the distance between them is between 50-70 mm. Due to that the magnets are designed to have their magnetic length almost equal to their physical length [10].

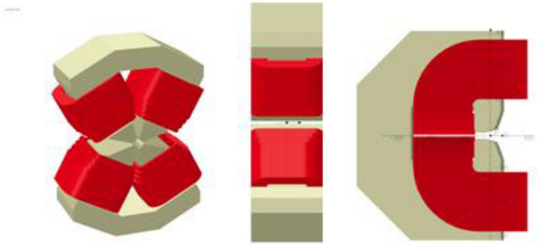

Figure 10: Quadrupole and dipole profiles.

The maximum length of the dipoles is 0.84 m and of the quadrupoles 0.22 m with bore radius at 28 mm. All magnets will be air-cooled. There will be 72 dipoles, 192 quadrupoles, 240 sextupoles of which 120 will be combined for providing dipole (correctors) and skew quadrupole field. Additionally 72 pure correctors are foreseen.

In Figure 10 a quadrupole and its profile are shown. One can readily check that coils do not hang out the yoke. All magnets including correctors are designed and a quadrupole prototype is under construction.

LIFETIME ISSUES

In general we opt for a cylindrical vacuum chamber of 23 mm internal diameter (except for light exits and the low gap chambers) with some parts made out of stainless steel or copper and other parts of aluminium with NEG. Such configuration can give vacuum similar to the existing machine i.e. 4 nTorr of N_2 dynamic pressure. Assuming 1% coupling, 400 mA stored intensity and 2.4 MV effective RF voltage, the Touschek lifetime is 19 hours and including elastic (1021 h) and inelastic scattering (27 h) the total linear lifetime becomes 11 hours taken the “zero” current bunch length of 1.73 mm. However when performing 4-D tracking using OPA [11] whereby particles start on axis but with momentum deviation $\Delta p/p$, the total lifetime is reduced to 6.5 hours indicating also a momentum acceptance of 7%. The above investigation suggests that the new machine will be also Touschek dominated and using the third harmonic cavity (3HC) one expects a threefold increase in lifetime.

Due to small emittance intra-beam scattering becomes important. For the “zero” current bunch length (3HC off) a 92 % emittance increase at 400 mA is estimated whereas in the case of bunch lengthening (3HC on) the emittance increase is 46% as seen in figure 6. Hence, the already existing third harmonic cavity (3HC) should also be used for Elettra 2.0.

CONCLUSIONS

Electra 2.0 will operate at 2 GeV replacing the actual machine in the same tunnel. The lattice will be the symmetric 6-bend achromat (S6BA) with an emittance of 250 pm-rad and very small spot size and divergence (< 60 µm horizontal, 3 µm vertical, < 6 µrad). The photon source points from the insertion devices will remain unchanged. For the dipole beam lines various options are offered: either to be served from a LG dipole of 2.2 T or by a short 2 T wigglers or by installing super-bends. In all those cases the dipole beam lines have to be shifted accordingly. Functioning at 2.4 GeV is possible by reducing the free space in the arcs or the diameter of the vacuum chamber. Short pulses are possible if a dedicated straight section will be available.

The new machine will be diffraction limited in the horizontal plane for $\lambda \geq 15$Å while in the vertical at 1% coupling for $\lambda \geq 0.15$Å whereas its coherent fraction at 1keV will be 38%.

REFERENCES

[1] E. Karantzoulis, A. Carniel, M. Cautero, B. Diviacco, S. Krecic, R. Visintini, “Elettra status, present upgrades and plans”, in *Proc. 8th Int. Particle Accelerator Conf. (IPAC’17)*, Copenhagen, Denmark, May 2017, pp. 2657-2659 (2017);

[2] D. Einfeld, M. Plesko, “A modified QBA optics for low emittance storage rings”, *Nucl. Inst. Meth. in Phys. Res. A* 336 (1993) p. 402.

[3] E. Karantzoulis, “Evolution of Elettra towards an ultimate light source”, in *Proc. 5th Int. Particle Accelerator Conf. (IPAC’14)*, Dresden, Germany, June 2014, paper MOPRO075, pp. 258-260.

[4] E. Karantzoulis, “Electra 2.0 - The next machine ”, in *Proc. 6th Int. Particle Accelerator Conf. (IPAC’15),* Richmond, VA, USA, May 2015, paper TUPWA052, pp. 1532-1534.

[5] E. Karantzoulis, “The diffraction limited light source Electra 2.0”, in ***Proc. 8th Int. Particle Accelerator*** *Conf. (IPAC’17),* Copenhagen, Denmark, May 2017, pp 2660-2662, (2017)

[6] E. Karantzoulis, "Elettra 2.0 - The diffraction limited successor of Elettra", *Nuclear Inst. and Methods in Physics Research,* A 880 (2018) 158–165

[7] E. Karantzoulis, S. Bassanese, D. Baron, A. Bianco, F. Bille, R. Borges, P. Borsi, A. Buonnano, E. Busetto, A. Carniel, D. Castronovo, K. Casarin, M. Cautero, V. Chenda, S. Cleva, I. Cudin, S. Di Mitri, R. De Monte, B. Diviacco, A. Fabris, R. Fabris, P. Furlan, G. Gaio, F. Giacuzzo, G. Kourousias, S. Krecic, G. Loda, M. Lonza, A. Martinolli, E. Mazzucco, M. Miculin, D. Morelli, L. Novinec, C. Pasotti, R. Passuello, L. Pivetta, R. Pugliese, L. Rebuffi, L. Rumiz, L. Sturari, C. Scafuri, G. Stopar, P. Tosolini, G. Tromba, R. Visintini, A. Vascotto, M. Zaccaria, D. Zangrando “Elettra 2.0 Technical Conceptual Design Report”, ST/M-17/01, Elettra–Sincrotrone Trieste, internal document (2017)

[8] M. Borland, “Elegant”, version 31.0.0, APS, (2016).

[9] S. Di Mitri, contribution to ST/M-17/01, Elettra - Sincrotrone Trieste, internal document (2017)

[10] D. Castronovo, contribution to ST/M-17/01, Elettra - Sincrotrone Trieste, internal document (2017)

[11] A. Streun, “OPA version 3.39”, PSI, (2014).