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EVOLUTION OF ELETTRA TOWARDS AN ULTIMATE LIGHT SOURCE

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Abstract

Considerations of possible lattices aiming to transform Elettra into an Ultimate Light Source (ULS), the best solution found and some considerations regarding the accelerator components are presented and discussed.

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 20 years many improvements were made in order to keep the machine updated and competitive with the other more recent and modern light sources. Although Elettra will continue serving the scientific community for many more years, machines do not last for ever and it was felt that the right time has come to start thinking of her successor.

After the 4th generation light sources came to operation, it became evident that free electron lasers (FEL) cannot replace storage rings (SR) (therefore the term 4th generation is not reflecting the reality since each generation replaces the previous one) but rather are complementary. There are many reasons for that such as the SR high repetition rate and the fact SRs can serve a very large number of experiments whereas FELs serve only a few (usually one).

SR light sources clearly cannot compete with FELs on the pulse length (ps against fs) at least at comparable intensities but there is a big margin of improvement on other beam characteristics, like emittances (coherent beams), flux and insertion devices. Already in the 90's people were speculating on diffraction limited light sources [1] although the times were not yet ripe.

One of the most important beam characteristics for synchrotron radiation users is the brilliance, defined as the ratio of flux divided by the electron and photon beam dimensions Σ (size and divergence) given by:

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

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

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

If additionally the electron beam emittance ε_x is equal or less to the photon emittance $\varepsilon_{ph}=\lambda/2\pi$ the light source is defined as diffraction limited. Thus for a wavelength $\lambda=1$ nm (1.3 keV) the electron beam emittance should be 0.16 nm-rad in order to be diffraction limited.

From eq. 2 one sees that as the electron emittance decreases the brilliance increases. One might naively think that reducing the electron emittance by a factor of 10 the brilliance increases by two orders of magnitude. However this is not always the case because it also depends on the photon emittance that dominates at low photon energies. For example for $\lambda=45$ nm (22.3eV) and a ring with 7 nm-rad emittance, by reducing the electron emittance by a factor of 10 the brilliance increases only 1.8 times. Thus emittance reduction does not always significantly increases the brilliance at lower photon energies whereas it gets more significant for higher photon energies. Other benefits from low emittances include smaller spot size and divergence, coherence and higher flux, beam properties highly desirable for many experiments.

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:

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

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. 3 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

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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 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 multibend achromats at 2 GeV keeping the same circumference and the same 12-fold symmetry, all optics up to 9-bend achromats were created, analyzed and plotted versus the number of dipoles per achromat (Fig. 1). In the same graph the $1/N_d^3$ rule is also plotted for comparison scaled from the actual Elettra emittance.

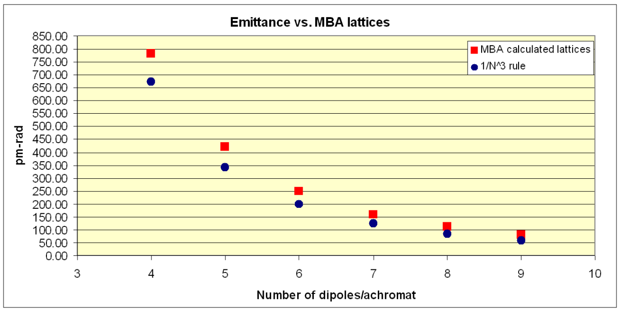

Figure 1: Emittance versus number of dipoles per achromat for an Elettra like ring at 2 GeV.

As can be seen from the above graph, one order of magnitude reduction of the actual emittance of Elettra occurs for a 5-bend achromat or higher.

Table 1: Emittances and beam sizes for various MBA lattices at 2 GeV for an Elettra size ring.

Number of dipoles /achromat	Emittance (nm-rad) @ 2 GeV	σ_x (μm) @ LS	σ_y (μm) @1% coupl @ LS
2	7	240	14
4	0.78	70	4.3
5	0.42	40	3
6	0.25	32	3.2
7	0.16	29	2.9
8	0.11	25	2.2
9	0.080	18	1.7

Another beam parameter is the beam size achieved. In the table 1 above the emittances and the corresponding beam sizes in the long straight sections (LS) are shown.

It is also important to examine the free space available (also for insertion devices). In the next Figure 2 the free space per achromat is shown for up to 9-bend structure.

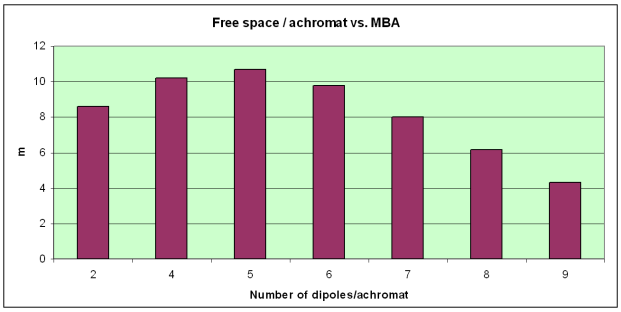

Figure 2: Free space per achromat for various MBA.

From the graph above it is observed that only the 4 to 6 bend achromats give more free space than 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.

REQUIREMENTS FOR THE NEW ELETTRA

In the above analysis emittances, beam sizes and free space for realistic lattices from 4 to 9 bend achromats were considered. In order to chose the best solution for the new Elettra some general requirements including also requirements from the users as expressed during a workshop on the Future of Elettra in April 2014 are presented below:

- Energy 2 GeV
- Same building, same ring circumference
- Maintain the existing ID beam lines, same position
- Maintain the existing bending magnet beam lines
- Emittance reduction by more than 1 order of magnitude
- Electron horizontal beam size less than 40 um
- Intensity 400 mA, maintain the filling patterns as before (hybrid, single bunch etc.)
- Free space available for IDs not less than that of Elettra
- Use the existing injectors i.e. off-axis injection
- 6+6 months downtime for installation and commissioning

Clearly then the best solution for the new Elettra is a 6-bend achromat.

THE NEW ELETTRA LATTICE

As seen before the 6-bend achromat emittance is 0.25 nm-rad. The corresponding beam size at the straight sections is 32 μm and the divergence 6 μrad. In the next Figure 3 the beta functions and the dispersion are shown using OPA [3]. The dipoles have now a field of 0.8 T (compared with 1.2 T at 2 GeV of Elettra) and their

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quadrupole component is 19 T/m (compared with 2.8 T/m in Elettra). The quadrupoles have a maximum gradient of 64 T/m (compared with 15 T/m in Elettra).

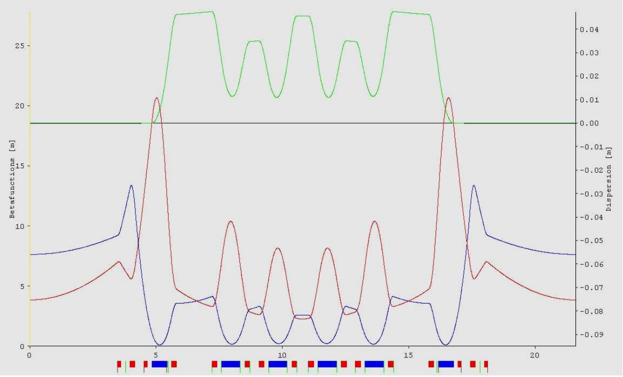

Figure 3: The New Elettra lattice.

The dispersion in the arcs is low (40 mm compared with 400 mm in Elettra) meaning that also the short straight sections (1.4 m long) situated in the arcs before the outer dipoles can be used for insertion devices. Preliminary studies show that the dynamic aperture is reduced as expected but still quite acceptable.

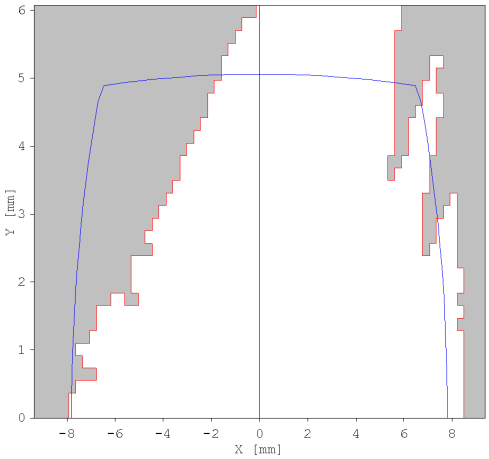

Figure 4: Dynamic aperture (not optimized).

Certainly it is challenging to inject off-axis to ±8 mm horizontal aperture (however not yet optimized) but this is not rendering the optics unfeasible because once the injected beam is stored the dynamic aperture still corresponds to 200 σ of the beam size (compared with 100 in Elettra).

The tunes are 33.3 horizontal and 8.2 vertical, natural chromaticities are about -60 the momentum compaction $3x10^{-4}$ while the natural energy spread stays as before $7x10^{-4}$. Furthermore the ring will be horizontally diffraction limited for photon energies up to 0.85 keV. The vertical beam dimension for 1% coupling is about 3 μm however higher coupling i.e. towards round beams to avoid resistive wall effects is preferable; for coupling control some families of skew quadrupoles are to be included. Touschek lifetime when using the actual Elettra rf-system is about 5 hours for 400 mA with the natural bunch length of 12 ps.

CHALLENGES AND DISCUSSION

Diffraction limited rings require very strong focusing i.e. magnets with high gradient which require high precision engineering, a very challenging task. Since the circumference available for the new Elettra is about 260 m, the magnets have to be longitudinally short. We opted for 0.20 m maximum magnetic length for the quadrupoles and 0.74 m maximum length for the dipoles. The maximum integrated field for the quadrupole with 64 T/m is 13 T. To achieve such a field the pole opening should be at about 26 mm meaning that the vacuum chambers should be at about 24 mm or less internally, a certain challenge for vacuum pumping. New materials such as cobalt-iron alloys can give a 40% higher field and possibly allow increasing the distance between the poles. Preliminary designs of the dipoles and quadrupoles [4] confirm their feasibility.

Fitting the new machine on the existing girders does not seem to be a big problem since the maximum radial shift of the new machine is only 400 mm [5] however passing a light exit chamber through the new quadruples needs further study. In order to preserve the “dipole” beam lines short wigglers of the phase shifter type will be installed in one of the short straight sections available, a small shift of the dipole beam lines position is inevitable.

Beam dynamics studies including intra-beam scattering and collective effect analysis are progress. The already existing third harmonic cavity will be used for the bunch lengthening required. In this aspect all possibly reusable hardware components will be considered.

CONCLUSIONS

The new Elettra will be a 2 GeV ULS in replacement of the old machine and therefore in the same building. The machine lattice shall most probably be a 6-bend achromat with an emittance of 250 pm-rad (28 times reduction from that of the actual machine) and very small spot size and divergence (< 40 μm , < 6 μrad). The photon source points remain the same meaning there is no need to move the existing insertion devices beam lines. The dipole beam lines will be served from short wigglers and a shift of their physical location of about 3 degrees shall be necessary. The new machine will be diffraction limited in the horizontal plane for $\lambda \geq 15$Å while in the vertical for 1% coupling for $\lambda \geq 0.15$Å.

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