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Elettra 2.0 — The diffraction limited successor of Elettra

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A B S T R A C T

Elettra has been operating for users for 23 years; to stay competitive for world-class photon science in the future a massive upgrade of the storage ring is needed. An analysis of possible magnet lattice configurations has been performed with the aim of transforming Elettra into a diffraction limited storage ring. The optimum solution is based on certain design constraints and user requirements and their implications for beam dynamics and for practical considerations regarding certain accelerator components. The new proposed design will have a bare emittance of 250 pm-rad and coherent flux about two orders of magnitude higher than that of the present machine.

1. Introduction

Located on the outskirts of Trieste, Elettra has been operating for users since 1994 as the first third-generation, soft X-ray light source in Europe. During those 23 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 h/year of which 5000 are dedicated to the users on a 24/7 basis [1]. The storage ring has a double-bend achromat (DBA) lattice 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 space available for IDs. The IDs include 3 wigglers (1 superconducting, 1 permanent magnet and 1 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. Although the present Elettra configuration will continue serving the scientific community for several more years, the time has come to prepare for its successor.

The key parameters to perform synchrotron experiments with a given spatial, temporal, and energy resolution are the spectral brightness (radiation power in a small area) and the degree of coherence (uniformity of the radiation wave-front) of the X-rays. Recent developments in synchrotron technology and new concepts for generating synchrotron light have gained momentum during the past decade and have given birth to the next generation of synchrotron light sources. Although the times were not yet ripe, already in the 1990's people were speculating [2] about diffraction-limited light sources with their main characteristics being a substantial increase of the brilliance and the coherence fraction as compared to today's available third generation sources. The driving concept for such "ultimate" machines is a large reduction of the emittance (i.e. the transverse beam dimensions) of the stored electron beam, targeting emittance levels capable of providing a diffraction limited X-ray source also in the horizontal plane. (Such a limit had already been accomplished in third-generation machines for the vertical plane) For longitudinal coherence, ring-based light sources clearly could not compete with FELs with respect to the pulse length (tens of ps versus fs) at least at comparable intensities; however, some ideas have been developing for some time and mainly recently [3–6] that may reduce the pulse length below one ps, a very welcome perspective for storage ring time resolved experiments (spin dynamics, surface photo-voltage effect, electron–phonon coupling etc.)

One of the most important beam characteristics for synchrotron radiation users is the brilliance, defined as the ratio of photon 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:

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

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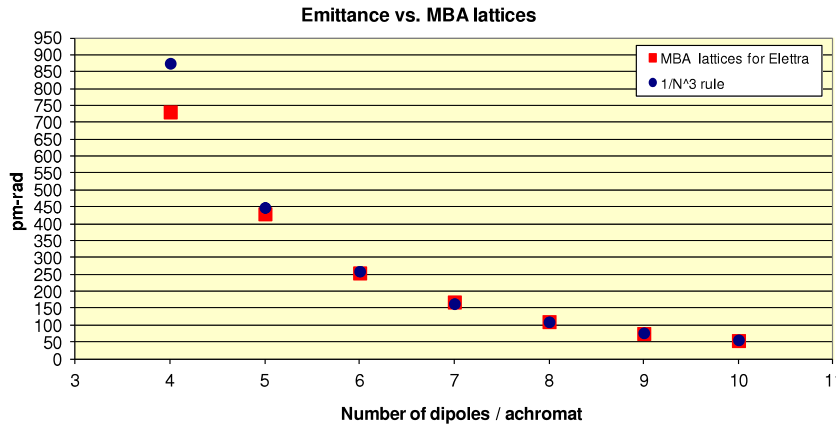

Fig. 1. Emittance versus number of dipoles per achromat for an Elettra size ring at 2 GeV.

If additionally the electron beam emittance ε_x is equal or less to the photon emittance $\varepsilon_{ph} = \lambda/4\pi$ the light source is defined to be diffraction-limited. Thus for a wavelength $\lambda = 1$ nm (1.2398 keV) the electron beam emittance should be 80 pm-rad 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 would increase the brilliance by two orders of magnitude. However, this is not always the case because the brilliance depends also on the photon emittance that dominates at low photon energies. For example for $\lambda = 45$ nm (22.3 eV) and a ring with 7 nm-rad emittance, reducing the electron emittance by a factor of 10 increases the brilliance by only 1.8 times. Thus emittance reduction does not always significantly increase the brilliance at lower photon energies, whereas it delivers a more significant gain for higher photon energies. Other benefits from low emittances include smaller spot size and divergence, higher coherence and higher flux, beam properties highly desirable for many (but not for all) experiments.

To be practical a diffraction-limited storage ring (DLSR) compared to the 3rd generation must have a much higher brilliance (at least one order of magnitude at low photon energies e.g. 1 keV), a larger coherence fraction given by [7]:

$$\zeta = \frac{(\lambda/4\pi)^2}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \tag{3}$$

in both planes and consequently a smaller spot size and divergence.

Certainly all those beam properties, highly desirable for many experiments, have a great impact on the design and operability of those machines. Reducing substantially the emittance may require higher gradients in the magnets which naturally will give rise to higher chromaticity, smaller dynamic aperture and stronger non-linear effects.

2. Emittance minimization

The techniques to obtain low emittances are well known and have been documented in the literature [2,8]; a short description is presented here for completeness. The emittance of a storage ring is given by:

$$\varepsilon_{x0}\,[mrad] = F_x(qx, lattice)\frac{E^2(GeV)}{N_d^3} \tag{4}$$

where N_d is the number of dipole magnets, E the ring energy and F_x a form factor depending on the H-function ($H = \gamma_x\eta_x{}^2 + 2\alpha_x\eta_x\eta'_x + \beta_x\eta'_x{}^2$) 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 that are included in the lattice, the less free space for insertion devices may be available. Moreover, the H-function minimization 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. Therefore, 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 the desired values in the straight section. Matching with minimized emittance is achieved when the outer dipoles of the arc have a magnetic length and deflection angle less than ϕ [9]. Such magnetic lattices are called multi-bend achromats (MBAs).

3. Analysis of MBA lattices for the new Elettra

Electra has a double-bend achromat (D-BA) lattice with twelve-fold symmetry and a circumference of 259.2 m. To choose the successor lattice an emittance analysis against MBAs was first performed [10]. The programs MAD, OPA and Elegant [11–13] were used for the linear and non-linear optics analysis, while for the optic graphics OPA was used. Assuming the same energy i.e. 2 GeV and keeping the same circumference and the same 12-fold symmetry, all optics up to 10-BA were created and studied. In Fig. 1 the resulting emittance is plotted against the number of dipoles per achromat. In the same graph the $1/N_d^3$ rule is also plotted for comparison scaled from the actual Elettra emittance of 7 nm-rad. Notice that the emittance value scaled by the $1/N_d^3$ rule agrees well with the emittance of the created lattices, whereas some optimization may further minimize the emittance as in the case of a 4-bend achromat. Fig. 1 shows that more than one order of magnitude reduction of the actual emittance of Elettra occurs for a 4-BA or higher.

Another important beam parameter is the resulting beam size. Table 1 below shows the emittances and the corresponding beam sizes in the long straight sections (LS). The lattices shown are realistic, and special care was taken to have dynamic apertures acceptable for nearly off-axis injection. Further optimization is possible.

In Fig. 2 the 4 to 7 BA optics are shown. In the structure the bending magnets are indicated in blue and the quadrupoles in red. Note that while producing the various optics care was taken to use “plausible” values for the magnetic gradients i.e <21 T/m for dipoles and <65 T/m for quadrupoles.

Finally, Fig. 3 shows the coherence fraction at 100 and 1000 eV versus emittance for an Electra size ring and a well-matched undulator.