OPERATION OF ELETTRA WITH A LOWER EMITTANCE OPTICS

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Abstract

The paper describes application to ELETTRA of the so called distributed dispersion optics which further lowers the horizontal emittance with respect to the nominal value.

1. INTRODUCTION

Gaining a full experience as well as accomplishing an overall characterisation of the machine under the nominal optics of ELETTRA [1], with many of the performances surpassing the designed values, the machine operation is at the stage of exploring different optics modes. As being proposed and operated also elsewhere [2], an optics which breaks the dispersion free condition in the insertion device (ID) straight sections thereby lowering further the horizontal emittance is considered and operated in ELETTRA. We shall hereafter refer to this optics as Distributed Dispersion (DD) optics.

2. OPTICAL SOLUTIONS IN ELETTRA

(i) Linear Optics

The horizontal emittance ε_{x0} as defined by one standard deviation of the beam size of a beam performing a betatron motion, can be analytically expressed as [3]

$$\varepsilon_{x0} = \frac{C_q \gamma^2}{J_X} \frac{<H>}{\rho} \tag{1}$$

where $C_q = 3.83 \times 10^{-13}$ m, γ is the beam energy in mass units, J_x is the horizontal damping partition number, and ρ is the bending radius. H is familiarly given by $\gamma_x D^2 + 2\alpha_x DD' + \beta_x D'^2$ where $(\alpha_x, \beta_x, \gamma_x)$ are the betatron functions and (D,D') denote the horizontal dispersion and its derivative. The bracket signifies average over bending magnets. A marked feature in ELETTRA is the presence of combined function dipoles which focus the beam vertically at the same time lowering the emittance by nearly 25% through the function D which increases $J_x = 1 - D$ from unity to 1.32;

$$D = \rho \cdot < D(s) \cdot [\rho^{-2} + 2b_1(s)] > \tag{2}$$

where $b_1 \equiv e/p_0 \cdot \partial B_y / \partial x$ denotes the field gradient, and the symbol s is used to stress the position dependence. The emittance of 7 nm·rad at 2 GeV for the nominal optics of ELETTRA is thereby comparable to the minimum for the separated function case ($J_X < 1$), and is above the minimum for the combined function case only by a factor of 1.3.

The minimisation of ε_{x0} for the most general case without the achromatic condition which also takes account of D being different from zero is worked out in Ref. 4 with the result

$$(\varepsilon_{x0})_{\min} = \frac{C_q \gamma^2 \theta^3}{12\sqrt{15}} \cdot \left(1 - \frac{26}{210} k^2 \theta^2 + ...\right) \tag{3}$$

where θ is the bending angle and $k \equiv (1+n)^{1/2}$ with n being the field index, which is 13 for ELETTRA. While the first term in the above corresponds to the separated function case, the second term onwards represent the effect of a combined function, which for ELETTRA reduces the minimum from 2.27 to 2.06 nm·rad at 2 GeV. As can be inferred from the symmetry reason, the minimum occurs when both β_x and D are minimal at the centre of a dipole.

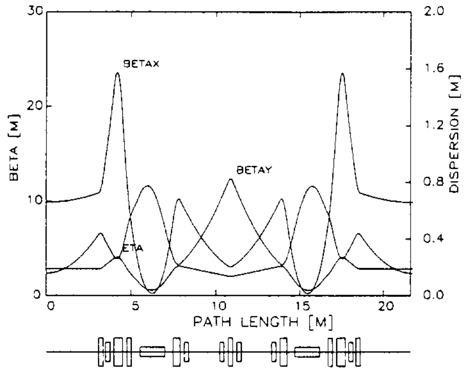

Fig. 1. Betatron and dispersion functions over a single cell of the DD optics considered in this work.

With respect to the expanded Chasman-Green (CG) structure of ELETTRA, it is found that only a slight shift in the balance between Q_F and Q_D, namely an increase in the strength of Q_F with respect to Q_D of less than 10% provides a wide range of solutions which approach the minimal emittance solution, without destroying the basic structure for the beta functions. Although we notice that the emittance can be further reduced by increasing the horizontal tune, a solution which keeps the tunes fixed to the nominal values had been searched (Fig. 1) for the sake of facility of operation, where the quadrupole triplet was used to finally adjust the tunes. The shown solution has ε_{x0} = 3.71 nm·rad, which is lower than the nominal emittance by a factor of 1.9, and is higher than the theoretical minimum by a factor of 1.8. There are no major changes in the magnitude of other beam parameters in the DD optics solutions with respect to the nominal values.

The fact that the emittance is lowered at the cost of releasing the dispersion in the ID straights urges one to examine the effective beam size $\sigma_x = [\varepsilon_{x0}\beta_x + (D\sigma_p)^2]^{1/2}$ where $\sigma_p = (\Delta p/p_0)_{rms}$ denotes rms energy spread. It turns

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out that with D = 0.19 m at the ID centre and the nominal value of $\sigma_{p0} = 7.8\times10^{-4}$, σ_x is calculated to be 0.24 mm, which is equal to the value in the nominal optics meaning that there is no net reduction. With a possible increase in σ_p due for example to a longitudinal multi-bunch instability, the effective beam size in reality could even be larger. However, following the discussion found in Ref. 5 which argues that what is actually inversely proportional to the brilliance of the photon beam should be the effective emittance defined by

$$(\varepsilon_x)_{eff}^2 \equiv \langle x^2\rangle\langle x'^2\rangle - \langle x\cdot x'\rangle^2, \qquad (4)$$

certain different aspects can be seen. In the above, x denotes the sum of the two oscillations, $x = x_\beta + D\cdot\Delta p/p_0$, and the average is taken over the particles. The effective emittance $(\varepsilon_x)_{eff}$ can be transcribed straightforwardly as

$$(\varepsilon_x)_{eff}^2 = \varepsilon_{x0}^2 + H(s)\cdot\varepsilon_{x0}\cdot\sigma_p^2. \qquad (5)$$

As $H(s)$ is an invariant where there is no curvature, $(\varepsilon_x)_{eff}$ is evaluated at three representative positions in a CG cell; i) ID straight, ii) Centre of the bending magnet, iii) In between the bending magnets, and compared between the two optics in Fig. 2 as a function of rms momentum spread σ_p.

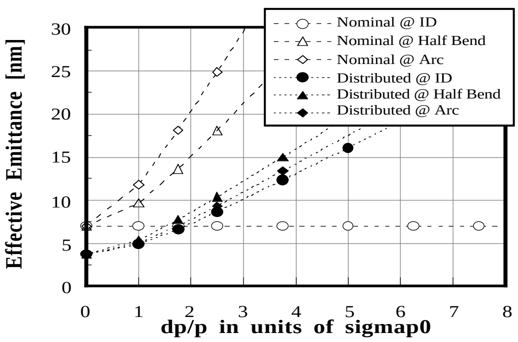

Fig. 2. Effective emittance versus rms momentum spread σ_p.

We notice first of all an interesting result that at one sigma, the effective emittance is lower for the DD optics than the nominal optics by 30% even in the ID straight, and that the reduction is further enhanced to 60% in between the dipoles. Those in the ID straight become comparable around two sigmas. Reflecting the larger magnitude of H(s), $(\varepsilon_x)_{eff}$ grows rapidly with σ_p in the nominal optics, which may render the DD optics particularly attractive for utilisation of light from the bending magnets.

(ii) Nonlinear Characteristics

As the dispersion is nonzero everywhere, the correction of chromatic and geometric aberrations with sextupoles apparently differs from the usual steps taken. The correction is made by using the program CATS [6] which performs the optimisation of geometric aberration under the constraint to keep the chromaticity to zero. In ELETTRA, there is one sextupole inside a quadrupole triplet besides SF and SD which are in between the dipoles. In the optimisation, coefficients of the lowest order amplitude dependent tune shifts as well as driving terms of the most influential resonances, Qx = 1 and 3Qx = 4 (Qx: horizontal tune) had been chosen to be minimised. The resultant dynamic aperture calculated is shown in Fig. 3 in comparison with residual limitations by resonances nQx = m, as indicated by [n,m], which are evaluated in the single resonance approximation [6].

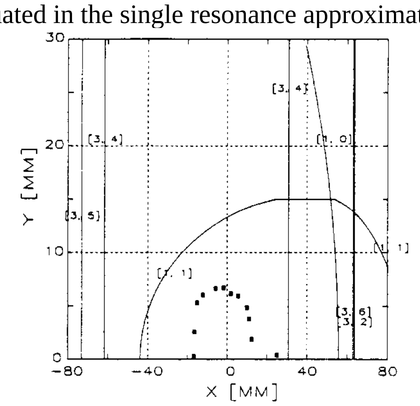

Fig. 3. Calculated dynamic aperture in comparison with limitations estimated in the single resonance approximation.

Although the alternating structure of the beta functions is still present and natural chromaticities are not much altered, as the dispersion at S_F and S_D is reduced by roughly 50% with respect to the nominal optics, it results in increasing the sextupole strength nearly by factor of two, which becomes the major reason for a large reduction of the dynamic aperture. However, as ramping is made in ELETTRA, the smallness of the dynamic aperture does not create a problem in injection. The above aperture still exceeds 50 sigmas of the transverse beam size. Calculated momentum dependence shows smooth variation of tunes of less than 0.05 over ±2% deviation, as well as of the dynamic aperture over the same range.

3. ACTUAL MACHINE OPERATION

Studies of the DD optics have been made at the operating energy of 2 GeV to which file ramping is performed from the injection energy of 1 GeV. The first attempt was actually made by file ramping from the nominal optics at 2 GeV keeping the correctors and sextupoles unchanged. As expected from similar phase advances and identical tunes, the orbit distortion was observed to be small. There was however a drastic reduction in lifetime, which was later understood by correcting the chromaticities to be due to a large chromatic effect. After improving the orbit, the horizontal dispersion which is the key quantity for lowering the emittance had been measured (Fig. 4). The rms of the difference to the model values ΔD_h came out to be $(\Delta D_h)_{rms}$ = 1.27 cm, while rms vertical spurious dispersion $(D_v)_{rms}$ was found to be 0.56 cm. To estimate the possible degradation of the emittance due to the distortion of the horizontal dispersion, a simulation had been made by generating machines with different rms values

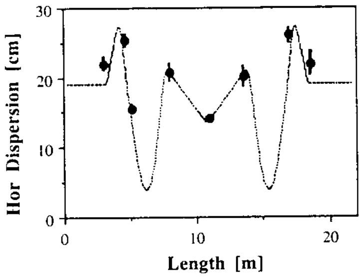

Fig. 4. Measured horizontal dispersion for the DDoptics. Circles: average over the same BPM family. Bars: one standard deviation.

of the distortion (Fig. 5). The obtained result indicates that the emittance degradation at $(\Delta D_h)_{rms}$ ~ 1 cm should be on the level of 10%.

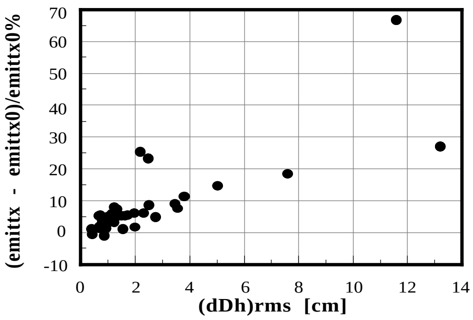

Fig. 5. Calculated emittance degradation versus different values of $(\Delta D_h)_{rms}$ over many simulated machines.

In the dispersion measurements, large offsets are often encountered in the average of ΔD_h, commonly to both optics, which are typically greater than 1 cm, if the designed value is assumed for the momentum compaction α_c. The empirically searched value of α_c at which ΔD_h oscillates around the zero axis turns out to be roughly 10% smaller than the designed values. A better agreement with the expectation is consistently found for the chromaticity if the empirical value is employed. The fact that measured synchrotron frequencies are usually lower than expected may be due to this discrepancy as well. This simple empirical search could be useful in estimating the actual momentum compaction.

Since the lifetime in ELETTRA is Touschek dominated [7], it implies that the lifetime is sensitive to the magnitude of the emittance. A series of lifetime measurements have therefore been performed with the DD optics and compared to those of the nominal optics under the same conditions. To eliminate the influence of the multi-bunch instabilities, measurements were performed in the single bunch mode. Two of such measurements are shown in Figs. 6 as examples. In Fig. 6a, the lifetime in the DD optics above ~1.5 MV is found to be limited by some other effect than the RF bucket

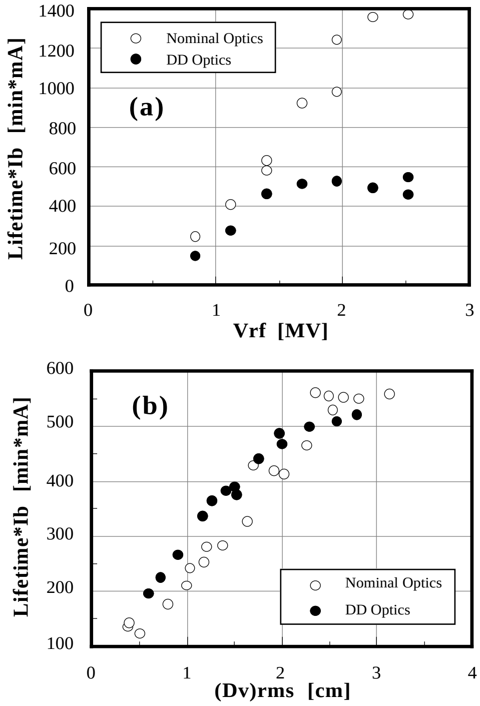

Fig. 6. Product of measured lifetime and average beam current versus (a) the RF voltage and (b) rms vertical dispersion $(D_v)_{rms}$ at Vrf = 1 MV, for the two optics, respectively.

size, while in Fig. 6b, the lifetime in the DD optics tends to be higher than in the nominal optics, which seems to be contradictory to the expectation. More careful and systematic investigation is yet to be carried out to understand these observations.

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