Update on the Linear and Nonlinear Optics of the ELETTRA Full Energy Booster Synchrotron

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Abstract

The present 1 GeV linac injector will be replaced by a 100 MeV electron linac and a 2.5 GeV booster synchrotron. The lattice is a two-fold symmetry structure composed of eighteen cells among which two are without bending magnets and four with one missing bending magnet[1]. Some magnets have been 3D mechanically designed[2] and accordingly, the linear and nonlinear optics have been checked and an optimization of some parameters has been performed, mainly to decrease the natural equilibrium emittance. Other changes concern the injection.

1 INTRODUCTION

The natural equilibrium emittance at 2.5 GeV was 244 nm.rad with a bending field of 1 T, a magnetic length of 1.86 m, and the working point (5.39, 3.42)[1]. Optics studies have been performed using bending magnets of a 1.431 m magnetic length and a bending magnetic field of 1.3 T[3]. The obtained emittance, keeping the same working point, was 306 nm.rad. For top up operation this emittance is not dramatically large considering our installed and foreseen insertion devices gaps. However, to get a relaxed top up, solutions are under study to decrease the equilibrium emittance by increasing the bending magnetic length to 2 m, keeping the same circumference, i.e., 118.8 m, and the same lattice, and also by increasing the horizontal phase advance/cell to slightly below 140º. The injection takes place along two long straight sections. The results of these investigations are summarized below.

2 BOOSTER LATTICE

The magnetic length of the bending magnets has been increased to 2 m, so that the magnetic field is 0.9356 T at the maximum energy 2.5 GeV, corresponding to a bending radius of 8.913 m. The maximum gradient in the quadrupoles, including 10% margin, is 18.5 T/m. With the working point (5.39, 3.42) the magnetic lengths for the defocusing and focusing quadrupoles (QD,QF) are 0.175 and 0.24 m respectively. For this optic, the natural equilibrium emittance becomes 226 nm.rad. The minimum emittance for our lattice is obtained with a horizontal betatron tune of 6.9. To avoid a too large increase of the maximum dispersion, the vertical betatron tune has been brought below 3. From the tune diagram, it is found that the best working point is (6.8, 2.85). To maintain the maximum gradient to 18.5 T/m, the magnetic length of the quadrupoles QF must be increased to 0.28 m. The arrangement of the bending magnets (red), the quadrupoles (red), the sextupoles (blue), the correctors (green) and the BPMs (**black**) are shown in figure 1. There are 12 focusing and 12 defocusing sextupoles (SF,SD), 10 horizontal and 12 vertical correctors. The lesser number of horizontal correctors is due to the symmetry of the lattice. There are 22 BPMs, 20 are in the arcs, the other two are at the QDs which are at the long straight sections. All are fixed to the nearby QFs or QDs. All are nearby the focusing or defocusing sextupoles, so that a well corrected orbit at the BPMs is a well corrected orbit at the sextupoles, too.

The optic functions for both working points are shown in Fig. 1 along half of the booster. The dispersion (dashdotted line) in the long straight sections stays within a few cm (< 3.5 cm) while it reaches a maximum value of 1.624 m in the arcs, for the working point (5.39,3.42). It increases to 0.3 m in the long straight sections and to 1.689 m in the quadrupole QFs which are at both sides of the arc center, for the tunes (6.8,2.85). Also, the betatron functions are larger for the latter working point.

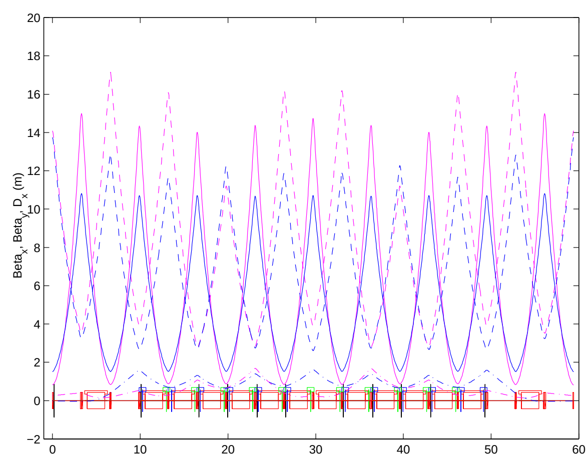

Figure 1: Optic functions along half the booster
Blue: twiss functions for the tunes (5.39, 3.42)
Magenta: twiss functions for the tunes (6.8, 2.85)
Solid line: horizontal betatron function, dashed line: vertical betatron function, dot-dashed line: dispersion

With the lower bending field, the energy loss per turn goes down to 388 keV. For a quantum lifetime of 1 second, the required effective RF voltages are 0.84 and

0.73 MV for the tunes (5.39, 3.42) and (6.8, 2.85), respectively. The booster main parameters for both optics are summarized in table 1.

Table 1: Booster general parameters

Magnet lattice	2 fold symmetry
Maximum energy	2.5 GeV
Injection energy	100 MeV
RF frequency	499.654 MHz
Circumference	118.8 m
Revolution period	396 ns
Harmonic number	198
Equilib. emittance (2.5 GeV)	226 nm.rad 166 nm.rad
r.m.s. energy spread (2.5 GeV)	$7.18\ 10^{-4}$
Energy loss per turn (2.5 GeV)	388 keV
Damping times(h,v,l) (2.5 GeV)	5.1,5.1,2.6 ms
Betatron tunes Q_x , Q_y	5.39, 3.42 6.8 , 2.85
Natural chromaticity ξ_x, ξ_y	-6.6, -4.7 -11.1, -5.2
Momentum compaction factor	0.0433 0.0308
Maximum β_x, β_y, D_x	10.8,13.8,1.624 m 15.0,17.1,1.686 m
Peak effective RF voltage (τ_q~1 s)	0.84 MV 0.73 MV
Bending magnets: Number Bending angle Bending field (2.5 GeV) Bending field (100 MeV)	 18 12.857° 0.9356 T 37.4 mT
Quadrupoles: Number Magnetic length Max. gradient (+10% margin)	QF QD 18 18 0.28 m 0.175 m 18.5 T/m 18.5 T/m

3 CLOSED ORBIT

Closed orbit errors are mainly introduced by the transverse misalignments of the quadrupoles and by the errors on the magnetic integrated field, the longitudinal misalignment and rotation around the longitudinal axis of the bending magnets. The considered misalignments and the bending field errors are summarized in table 2. The integrated bending field error is a combination of a mechanical error in the gap assumed to be ±33 μm (2σ) and an error of the magnetic length assumed to be ±1 mm (2 σ). The maximum expected closed orbit distortions are around 8 mm h. and 6 mm v. for the working point (5.39, 3.42) and 18 mm H. and 15 mm V. for the working point (6.8, 2.85). The former tune has been, in fact chosen, near the half integer, to get a less sensitive lattice to the misalignments of the magnets. Closed orbit distortions have been simulated for 10 machines, each with a different set of random errors distributed according to Gaussians with the r.m.s. field and alignment errors listed in table 2, for both optics. The correction of the orbit has been performed via the Micado method of MAD. The largest closed orbit distortions before and after correction are listed in table 3. For all ten machines, the maximum corrector strength is below 0.6 mrad for the horizontal plane and 0.3 mrad in the vertical plane. In actual operation, it is foreseen to use the SVD method, so that the strengths will be much smaller. However, due to the saturation of the storage ring bending magnets, the RF frequency has to be set to 499.654, 499.652 and 499.647 MHz for the users requiring the operation at 1, 2 and 2.4 GeV, respectively. To compensate the path length in the booster, it is thought to use its horizontal correctors. The maximum strength is thus assumed to be 1 mrad for the horizontal correctors. The vertical correctors are the horizontal ones rotated by 90°.

Table 2: r.m.s. field and alignment errors

Bending magnets: $\Delta(BL)/(BL)_0$ Δs $\Delta\phi_s$	 5.5 10-4 0.5 mm 0.5 mrad
Quadrupoles: Δx Δy	 0.2 mm 0.2 mm

Table 3: largest of maximum and r.m.s. closed orbits

Largest of (mm)	Max_x	$r.m.s._x$	Max_y	$r.m.s._y$
Tune: (5.39,3.42)				
Before correction	6.4	2.4	3.6	1.3
After correction	3.5	0.9	2.3	0.8
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Tune: (6.8,2.85)				
Before correction	16.2	7.4	9.7	4.9
After correction	5.3	1.5	3.2	0.9

4 INJECTION AND EXTRACTION

The injection takes place at the opposite side of the extraction, along two long straight sections. Injection to the booster is performed on axis by means of a septum of 15° and a fast kicker of 4.6 mrad from the outside of the booster.

For the extraction, the beam is brought close to the extraction septum sheet by 3 slow bumpers which create a bump of 5 mm, then the beam is kicked out by a fast kicker. The kicked beam is then bent away by two septa, similar to the storage ring injection ones, of 6.5° total bending angle. For the working point (5.39, 3.42), the strength of the kicker is 1.8 mrad (including 10% margin), for the working point (6.8, 2.85), it is instead 1.9 mrad (including 10% margin). The highest kick requested for the slow bumpers is 0.8 and 1.6 mrad for the former and latter working points.

5 DYNAMIC APERTURES

The dynamic aperture has been evaluated at injection and before extraction. The nonlinear components considered are the systematic multipole components of the main field obtained from the 3D mechanical design of the bending and quadrupole magnets[2], and at lower energies, adding the sextupole component induced in the metallic vacuum chamber by the time variation of the magnetic field. To get a small eddy current induced sextupole, the ramping should start with the bending field set to the value required at injection energy, that is 37.4 mT at 100 MeV. The previous total horizontal physical aperture 34 mm is increased to 48 mm to increase the safety margin. To get an acceptable stress on the vacuum chamber, its thickness has been increased to 1 mm. For simplicity, it is intended to built a unique vacuum chamber for the whole booster, an elliptical 48*26 mm total. With a repetition frequency of 3 Hz and the above aperture and thickness of the vacuum chamber, the maximum induced sextupolar component, obtained at 200 MeV, is 0.79 m^{-3} . At 100 MeV, it is zero. For both optics, the dynamic aperture, for $\Delta p/p$= [-1%,+1%] in steps of 0.1%, has been simulated at injection, i.e., only the systematic multipoles obtained for 60 mT in the dipoles and 0.53 T/m in the quadrupoles[2], and at 200 MeV, including the eddy current sextupole. For both optics, there is no need of the chromaticity correction at injection, even assuming multipoles with twice their values obtained from the 3D mechanical design[2]. At 200 MeV, instead we do need a chromaticity correction. The strengths required, are SF=+0.1 and -0.1 m^{-2} and SD=+1.2 and +1.55 m^{-2} for the tunes (5.39,3.42) and (6.8,2.85). Assuming multipoles with twice their values obtained from the 3D mechanical design, the strengths required become SF=0 and -0.2 m^{-2} and SD=+1.0 and +1.3 m^{-2} for the tunes (5.39,3.42) and (6.8,2.85). The dynamic apertures and tunes, for both optics, are shown in the figures 2 and 3, respectively, assuming multipoles with twice their values obtained from the 3D mechanical design.

At extraction, the eddy current sexupole is zero, and the assumed systematic multipoles of the main field are the ones obtained for 1.35 T in the dipoles and 19 T/m in the quadrupoles[2]. The energy spread range is [-0.36%, +0.36%], that is a longitudinal quantum lifetime of about 1 second, in steps of 0.1%. For both optics, the dynamic apertures are well outside the physical aperture, even assuming multipoles which are three times and twice the designed values for the quadrupoles QF and QDs, respectively.

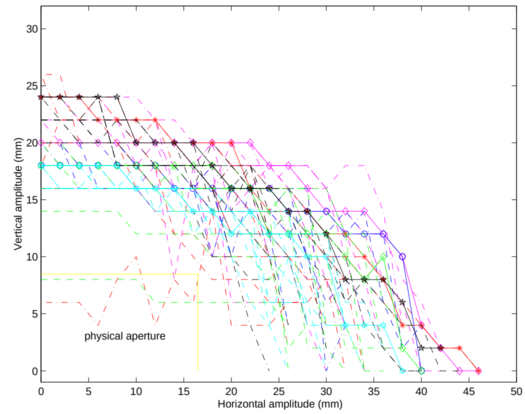

Figure 2: Dynamic aperture at 100 and 200 MeV. Working point (5.39, 3.42): magenta at 100 MeV, red at 200 MeV *without chromaticity* correction and **black** with *compensated chromaticity*. Working point (6.8, 2.85): blue at 100 MeV, green at 200 MeV*without chromaticity* correction and cyan with *compensated chromaticity*. Yellow: physical aperture. Solid line: $\Delta p/p = 0$, dashed line: $\Delta p/p < 0$, dotdashed line: $\Delta p/p > 0$

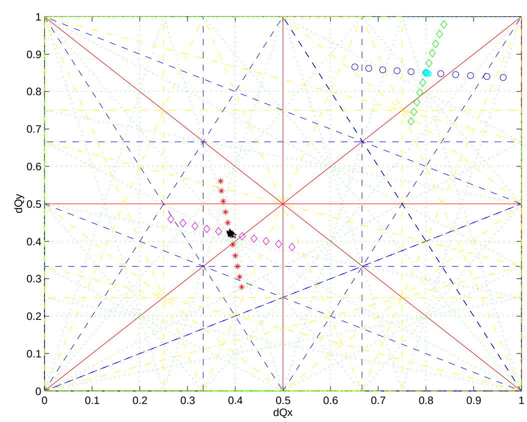

Figure 3: Betatron tunes vs momentum spread at 100 and 200 MeV. Working point (5.39, 3.42): magenta at 100 MeV, red at 200 MeV *without chromaticity* correction and **black** with *compensated chromaticity*. Working point (6.8, 2.85): blue at 100 MeV, green at 200 MeV*without chromaticity* correction and cyan with *compensated chromaticity*.

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