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Eddy current effects in the SLS booster

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Abstract

It is a well know fact that the eddy currents generated in the vacuum chambers of the pulsed dipoles of the booster produce a heating of the vacuum chamber and a time dependent sextupolar field [1]. In this paper, we review the effect of this sextupolar field in the SLS booster, and estimate the strength of the sextupoles used to compensate the chromaticity, and review the differences between the SLS booster lattice and a more traditional one.

1 The SLS Booster

The SLS booster is composed of a FODO-like lattice, made mainly of two families of combined-function magnets [2]. The first one has horizontal-focusing and a low bending field (large bending radius). The second family has horizontal-defocusing with larger bending field (small bending radius). Each family has an integrated sextupole component on it, used to compensate the chromaticity near the desired values of (1,1). Additional families of quadrupoles and sextupoles are used to adjust the working point and to the fine adjustment of the chromaticity.

The repetition rate of the SLS booster is 3 Hz . It allows a reasonably fast filling of the SLS storage ring and gives the beam time to damp down to the equilibrium emittance, while allows a simple vacuum chamber design [3].

The existence of two different kind of bending magnets (with different bending radius) is one of the differences with respect to other machines, giving two different contributions to the sextupolar field generated by the eddy currents during ramping. The other difference with respect to conventional boosters is that the bending magnets have already a sextupolar component that brings the chromaticity to positive values.That would make the effect of the sextupolar field generated by eddy currents less important than in other more conventional boosters.

We are going to concentrate in the effect of the sextupole components generated in the bending magnets vacuum chamber. Other contributions, like eddy currents in the quadrupoles, or higher order multipolar terms in the dipoles are much smaller and can be safetely neglected. The other major effect of the eddy currents is a heating of the vacuum chamber. However, due to the low field, the small vacuum chamber with thin walls and the low repetition rate, the power dissipated is very small (about 0.1 W/m), and the heating of the vacuum chamber negligible.

The main parameters of the booster are summarized in Table 1 and the optical functions for 1/6th of the booster (half superperiod) are show in figure 1.

Circumference	270 m
Symmetry	3
Injection energy	0.1 MeV
Maximum energy	2.4 GeV
Tunes	
Q_x	12.41
Q_y	8.38
RF Frequency	500 MHz
Peak RF voltage	0.5 MV
Maximum current	12 mA
Maximum repetition rate	3 Hz
Values at extraction energy	
Equilibrium emittance	9 nm-rad
Radiation loss	233 keV/Turn
Energy spread (rms)	0.075 %
Partition numbers (x, y, ϵ)	(1.7, 1, 1.3)
Damping times (x, y, ϵ)	(11, 19, 14) ms

Table 1: Lattice parameters for the SLS booster.

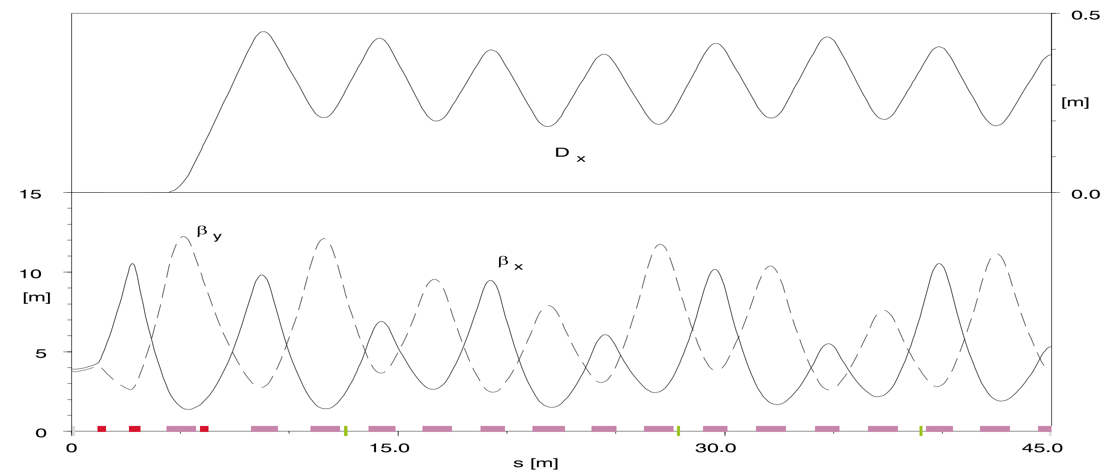

Figure 1: Optical functions for 1/6th of the booster.

2 Theoretical background

The ramping cycle of the booster is determined by the time-dependent dipolar field of the bending magnets. These fields follows a biased-sine shape given by:

$$B_{F,D}(t) = B_{0\ F,D} * (\alpha_E - \cos(\omega * t)) \tag{1}$$

where α_E and $B_{0\ F,D}$ determine the minimum and maximum energy possible in the booster. In the SLS case, the beam is injected at the minimum energy of the ramping cycle, and extracted at the maximum. The energy ramp is:

$$E(t) = E_0 * (\alpha_E - \cos(\omega * t)) \tag{2}$$

And the parameters α_E, $B_{0\ F,D}$ and E_0 are given by::

$$\alpha_E = \frac{E_{extraction} + E_{injection}}{E_{extraction} - E_{injection}} \tag{3}$$

$$B_{0\ F,D} = \frac{B_{extraction\ F,D}}{\alpha_E + 1} \tag{4}$$

$$E_0 = \frac{E_{extraction}}{\alpha_E + 1} \tag{5}$$

The time dependent fields produce eddy currents in the vacuum chamber of the bending magnet. These currents create a distortion of the magnetic field inside the vacuum chamber. In the center of the pipe, the distortion of the dipolar magnetic field is a decrease of the field, given by:

$$\Delta B = \dot{B}\, \frac{\mu_0 \kappa D a^2}{h}\, \mathcal{J} \tag{6}$$

where $\dot{B}$ is the temporal derivative of the corresponding $B_{F,D}(t)$ field, κ the conductivity of the vacuum chamber, D its thickness and $2h$ the magnet gap. The parameters a and b are the horizontal and vertical half apertures of the vacuum chamber. $\mathcal{J}$ is a form factor given by:

$$\mathcal{J} = \int_0^{\pi/2} \left(\sin\varphi \sqrt{\cos^2\varphi + \left(\frac{b}{a}\right)^2 \sin^2\varphi} \right) d\varphi \tag{7}$$

For a round vacuum pipe ($a = b$), $\mathcal{J}$ is 1. in the SLS case, $b/a = 2/3$, and $\mathcal{J} \approx 0.8$.

The analysis of this field distortion shows[1] that it can be expressed as a sextupolar time-dependent component given by:

$$\begin{aligned} m &\equiv \frac{1}{2}\frac{1}{B\rho}\frac{d^2B}{dx^2} \\ &= \mathcal{J}\mu_0\kappa\frac{D}{h}\frac{\dot{B}}{B\rho} \end{aligned} \tag{8}$$

If we replace in equation 8 the values of the time-dependent magnetic field(equation 1) and its derivative, we obtain the following expression for the the sextupolar component:

$$m = \frac{\mu_0 \kappa D}{h}\frac{\omega}{\rho}\, \mathcal{J} \cdot F(t) \tag{9}$$

If we rearrange the terms in this last equation, we can write it as:

$$m = \tilde{m} \cdot F(t) \tag{10}$$

where $\tilde{m}$ is a constant, given by:

$$\tilde{m} = \frac{\mu_0 \kappa D}{h} \frac{\omega}{\rho} \mathcal{J} \tag{11}$$

and $F(t)$ contains the dependence in time:

$$F(t) = \frac{\sin \omega t}{\alpha_E - \cos \omega t} \tag{12}$$

The function $F(t)$ is plotted in figure 2. As show in the plot, the sextupolar contribution will be more important at the start of the ramping cycle (low energies).

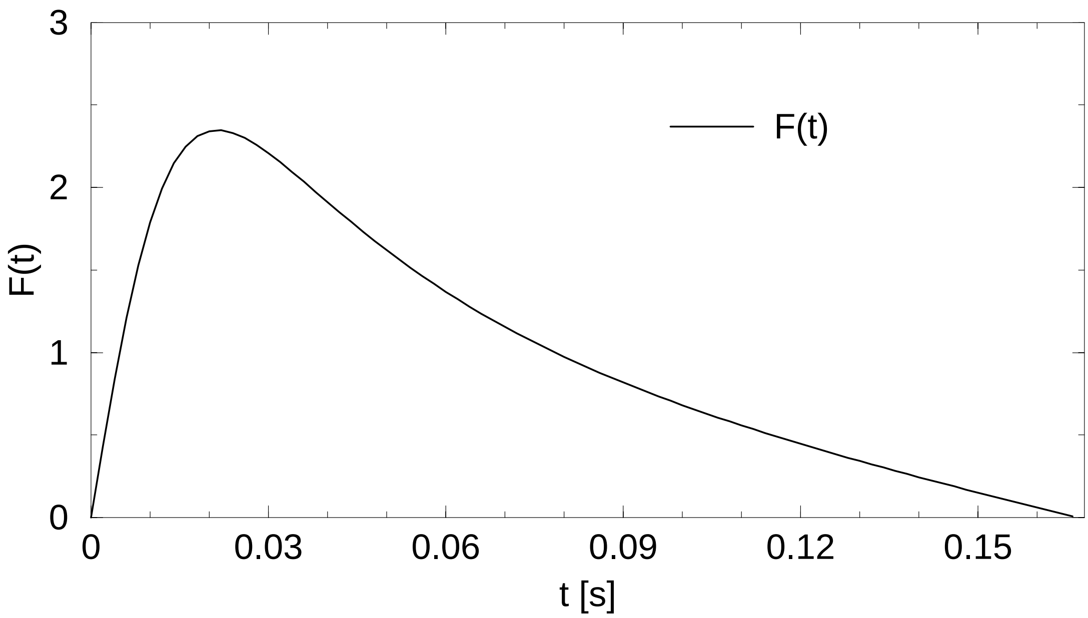

Figure 2: Plot of $F(t)$ for the SLS booster parameters (3 Hz repetition rate, E_{min}= 0.1 GeV and E_{max}= 2.4 GeV.)

3 Application to the SLS booster

The SLS booster differs from the boosters used in the majority of the light sources. The three peculiarities that concern us are:

- Large number of bending magnets with a relatively large bending radius.
- Two families of bending magnets with different bending radii.

- Sextupole component integrated in the bending magnet, through the pole profile, that brings the chromaticity to positive values. The sextupolar components are $m_{BD} = 1.22$ m^{-3} and $m_{BF} = 0.875$ m^{-3}

- Two families of sextupoles (S_F and S_D) are used to make adjustments in the chromaticity. The first family (S_F) consists of 6 magnets, and the second (S_D) of 12. All sextupoles are 0.2 meters long, have an aperture radius of 18 mm and can reach a maximum field of 0.063 T at the poletip.

The consequences of these facts can be summarized as:

- The large radius of the bending magnets will make the sextupolar component induced by the eddy currents smaller than in in a 'conventional' booster (the sextupolar component escalates with the inverse of ρ).

- There will be two different sextupolar contributions during the ramping, due to the two different bending radius.

- The changes in the strength of S_F and S_D required to compensate the effect of the eddy currents will be small, and the magnets will not be required to change polarities during the ramping, avoiding hysteresis problems.

In the following sections we will examine in more depth these facts.

3.1 Simulation

We have used **Tracy2** [4] to evaluate the chromaticity during the ramping. The model used is the 4th order symplectic integrator. This model allows us to do a good simulation of the integrated sextupole component of the dipoles. The sextupole component is treated in the same way than the dipolar and quadrupolar component. Table 2 shows the parameters for the booster vacuum chamber and magnets.

Vacuum chamber wall thickness	D	0.7	mm
Steel conductivity	κ	1.3×10^6	$\Omega\cdot$ m
Gap in D-magnets		23.3	mm
Gap in F-magnets		26.2	mm
Minimum Energy	$E_{injection}$	0.1	GeV
Maximum Energy	$E_{extraction}$	2.4	GeV
	α_E	1.0869	
Maximum B_D dipolar field	$B_{extraction D}$	0.714	T
bending radius at maximum field	ρ_D	11.22	m
Maximum B_F dipolar field	$B_{extraction F}$	0.158	T
bending radius at maximum field	ρ_F	50.72	m
Sextupole $S_{F,D}$ half-aperture		18	mm

Table 2: Parameters for the combined-function magnets.

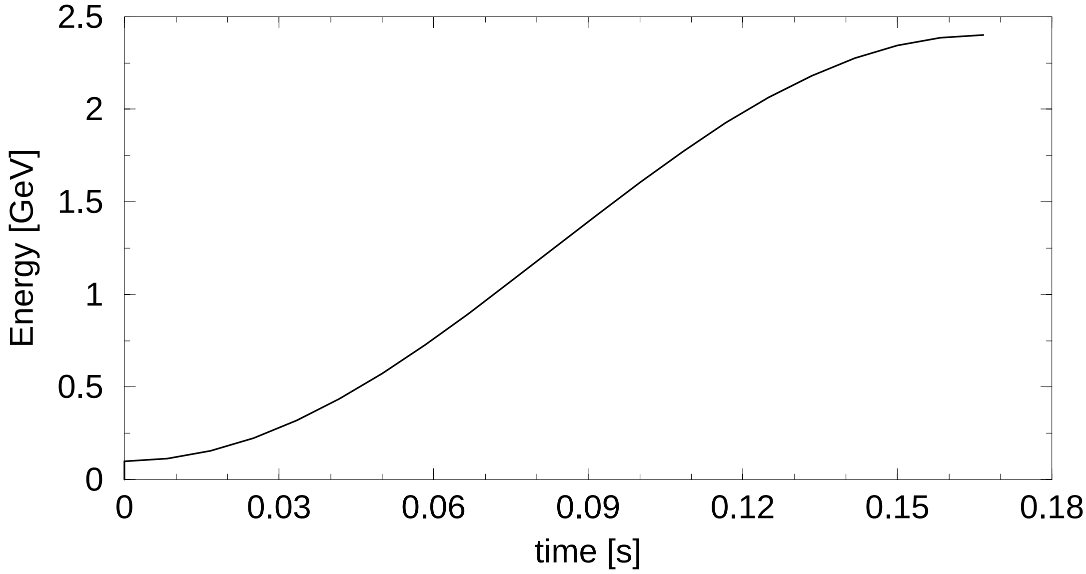

Figure 3: Energy ramping.

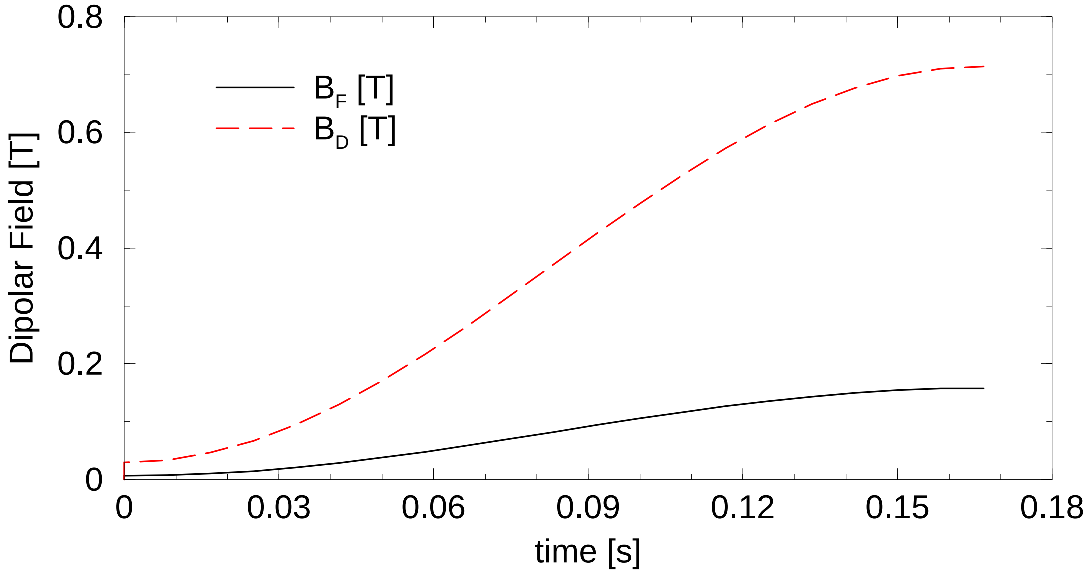

Figure 4: Dipolar fields ($B_{F,d}$) during ramping.

Figure 3 shows the energy ramping in function of time for the SLS booster. We assume that the injection takes place at the start of the ramping and extraction at the end. Figure 4 shows the required ramp for the dipolar field of the bending magnets.

The sextupolar component produced by eddy currents, during the ramping is shown in figure 5. As expected, the contribution is more important at low energies, with the maximum at 0.2 GeV (0.025 s after injection). Also, the contribution of the B_D magnets is much more important that the one from B_F magnets, due to the smaller bending radius in the B_D magnets. The chromaticity during the ramping cycle is shown in figure 6.

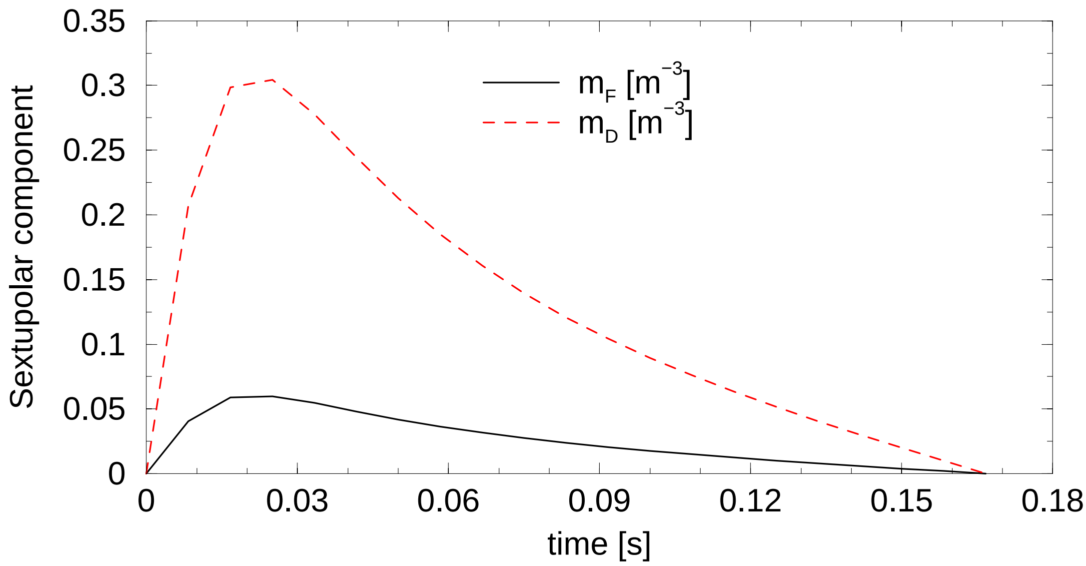

Figure 5: Sextupolar component generated by eddy currents in the vacuum chamber of the bending magnets.

The horizontal chromaticity remains positive during the process, but we need to compensate the vertical one, that goes very soon to negative values at the start of the ramping, with a maximum of $\approx$ -5 at 0.2 GeV, and remain negative up to $\approx$2 GeV. However, due to the integrated sextupole component in the bending magnets, the value of the vertical chromaticity remains relatively small and the compensation with the two sextupoles families S_F and S_D will be easy.

We contemplate two scenarios for running the booster:

1. Fixed chromaticity during the ramping of (1,1).

2. Fixed chromaticity during the ramping of (5,5).

3.2 Chromaticity (1,1)

Using **Tracy2**, we have used the two sextupoles families to keep the chromaticity during the ramping cycle fixed at a value of (1,1). Figure 7 shows the required integrated sextupole strength (the sextupoles are simulated as thin lenses). The figure 8 shows the magnetic field at the pole tip for the sextupoles, assuming a length of the sextupoles of 20 cm and a half-aperture of 18 mm. As can be seen, the required sextupole strength in the S_F magnet is almost constant and the

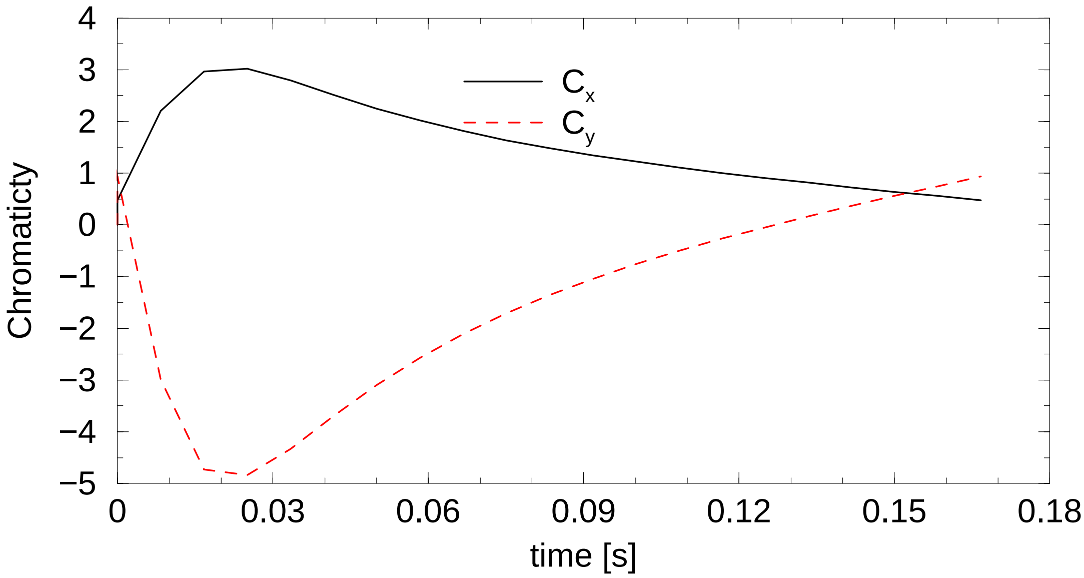

Figure 6: Chromaticity during the ramping, with pole shims and eddy current contributions.

magnetic field follows a curve equivalent to the energy (given by $F(t)$, equation 12) . The curve for S_D is more complex with a maximum at energy of ≈1.5 GeV, not at the extraction. The strengths required can be easily provided by the current design of the SLS booster sextupoles.

3.3 Chromaticity (5,5)

We have repeated the procedure of the previous section for chromaticity of (5,5) during the ramping. Now the contribution of the eddy currents is relatively less important, and both fields follow the curve dictated by the energy ($F(t)$). The required fields for the two families of the sextupoles are well within the maximum values specified in the SLS Handbook [2].

4 Dynamic aperture

The inclusion of new sextupolar fields (the ones due to eddy currents and the sextupole ones) will affect the dynamic aperture of the machine. The dynamic aperture for three cases is shown in figure 11. The first case is the 'standard' case (no eddy currents contributions, and the sextupoles for (1,1) chromaticity). The two other cases corresponds to the point in the ramping where the eddy current contribution is maximum ($E = 0.2$ GeV), and for the two chromaticities examined (the (1,1) case and the (5,5)).

The eddy current induced sextupolar components produce a small reduction of the dynamic aperture, but it is still much larger than the physical aperture, and more than enough for a safe operation of the booster, even in the case of the (5,5) chromaticity.

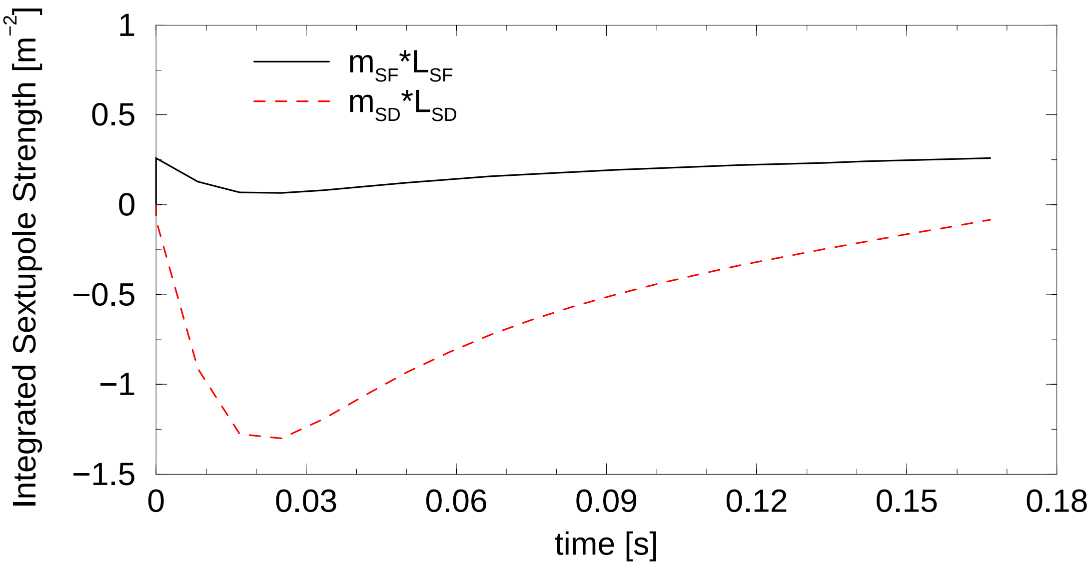

Figure 7: Integrated sextupole strength for (1,1) chromaticity.

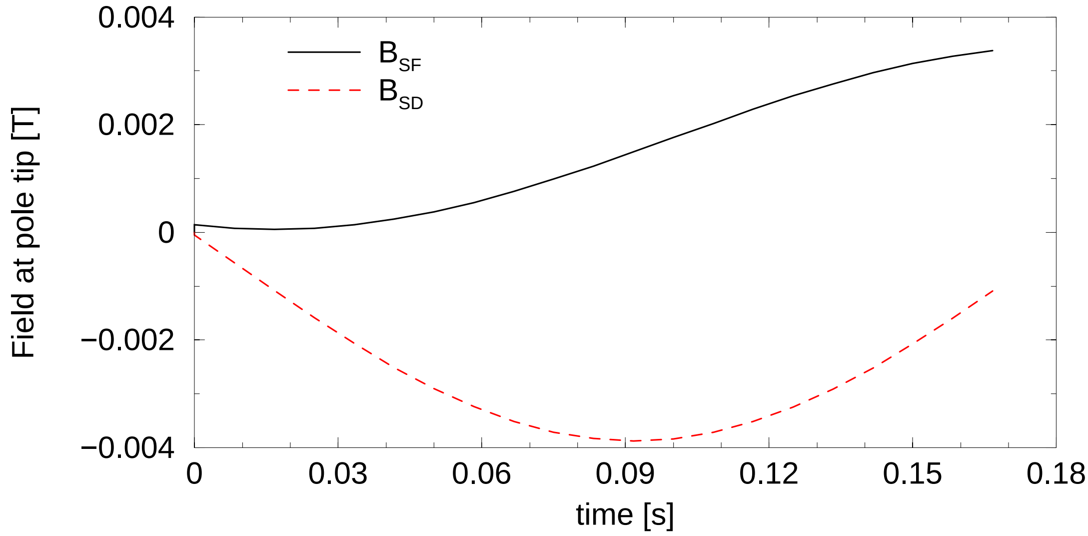

Figure 8: Magnetic field at sextupole pole tip for (1,1) chromaticity.

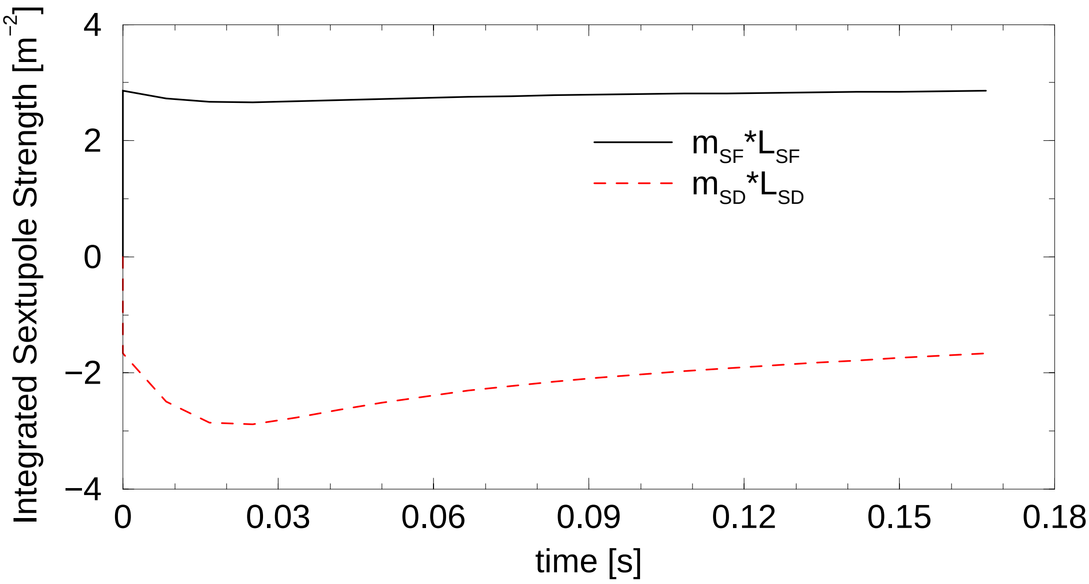

Figure 9: Integrated sextupole strength for (5,5) chromaticity.

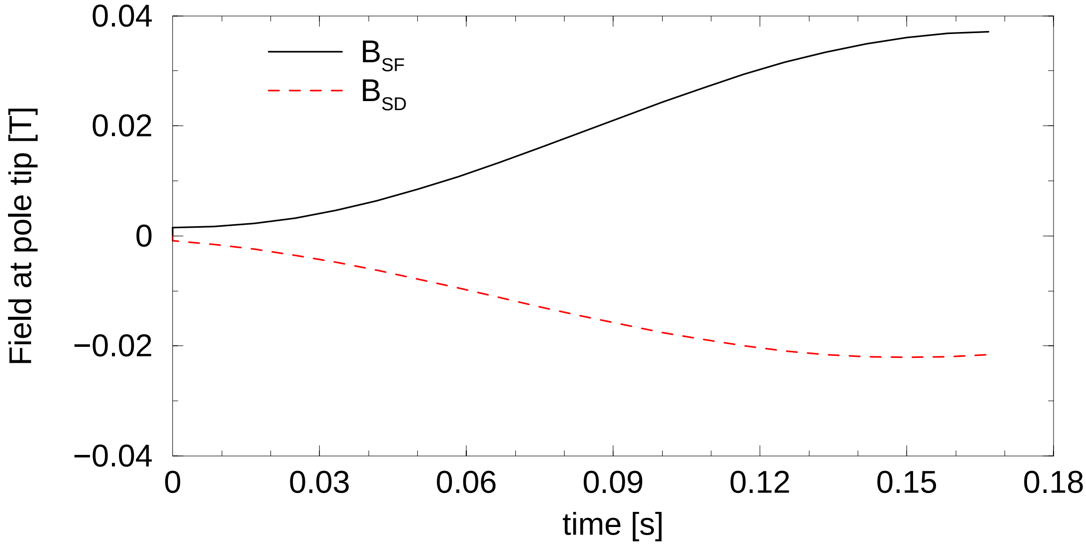

Figure 10: Magnetic field at sextupole pole tip for (5,5) chromaticity.

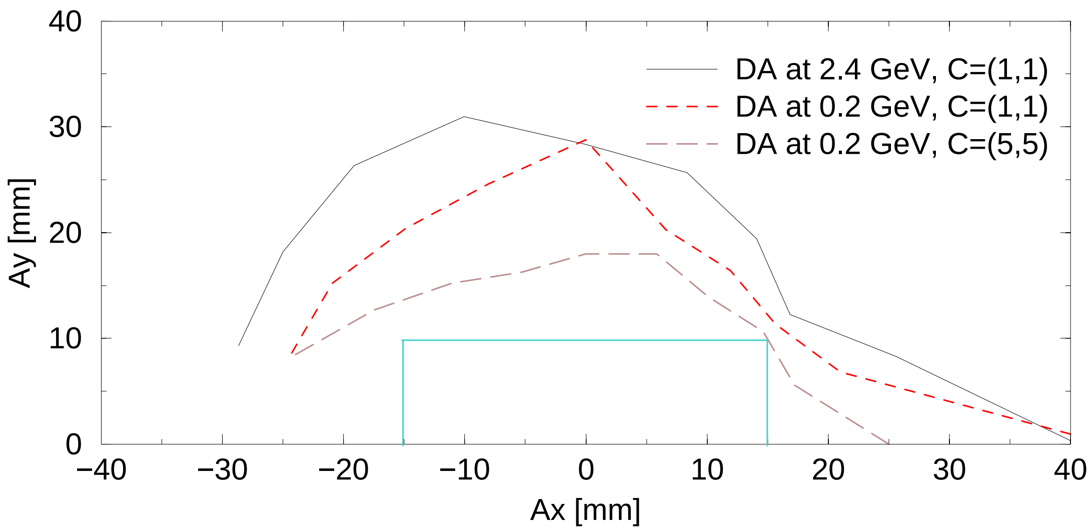

Figure 11: Dynamic aperture for 512 turns, for three cases: lattice at extraction settigs(no eddy current contributions, chromaticity (1,1)), and at the energy where the eddy current contribution is maximum for two different chromaticities. The vacuum chamber dimensions are also shown

5 Conclusion

The effect of the eddy current in the SLS booster is relatively small. Due to the combination of large bending radius and integrated sextupole field in the bending dipoles, the sextupolar component arising from the eddy currents are small and its effects is easily compensated. The chromaticity can be kept at the desired (1,1) value during the ramping, while keeping a large dynamic aperture. The case of a chromaticity (5,5) during ramping is also feasible.

References

[1] G. Hemmie, J. Rossbach; *Eddy currents effects in the DESY-II dipole vacuum chamber*; DESY M-84-05, April 1984.

[2] *The SLS Handbook*.

[3] G. Mülhaupt and L. Schulz; *Design considerations for the SLS Booster vacuum system*; SLS Note 15/97.

[4] *The Tracy2 program*