Interpretation of Tracking Results with LIFETRAC for the Design and "Real" Optics

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Tracking with optical functions and helical orbits reconstructed by V.Lebedev from differential orbit measurements (with offsets at main IPs put to zero however) showed disastrous effect of the errors (optics asymmetry, crossing angle at main IPs). Here we undertake analytical study of the effect of these errors in order to explain the tracking results.

1. Comparison of tracking results obtained with different configurations.
2. Effect of the optics asymmetry on the phase-averaging of even-order resonances.
3. Excitation of odd-order resonances in head-on interactions in the presence of crossing angle and asymmetry.
4. Comparison of resonance driving terms (RDT) due to head-on (HO) and long-range (LR) interactions.
5. Tentative explanation of the "scallops" sometimes seen in the Tevatron.

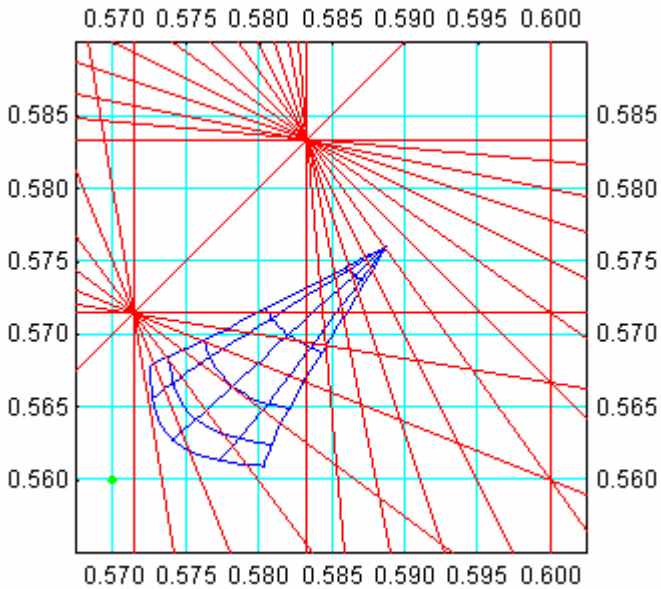


Figure 1. Bunch #6 footprint

The tracking was performed with the working point .57, .56. The pbar bunch #6 footprint calculated analytically with the "real" optics (without offsets at main IPs), N_p=202.5e9 (75% of the nominal value) and $\varepsilon_{95\%}=20\pi$ mm mrad is shown in Fig.1. The radial lines correspond to constant values of amplitude

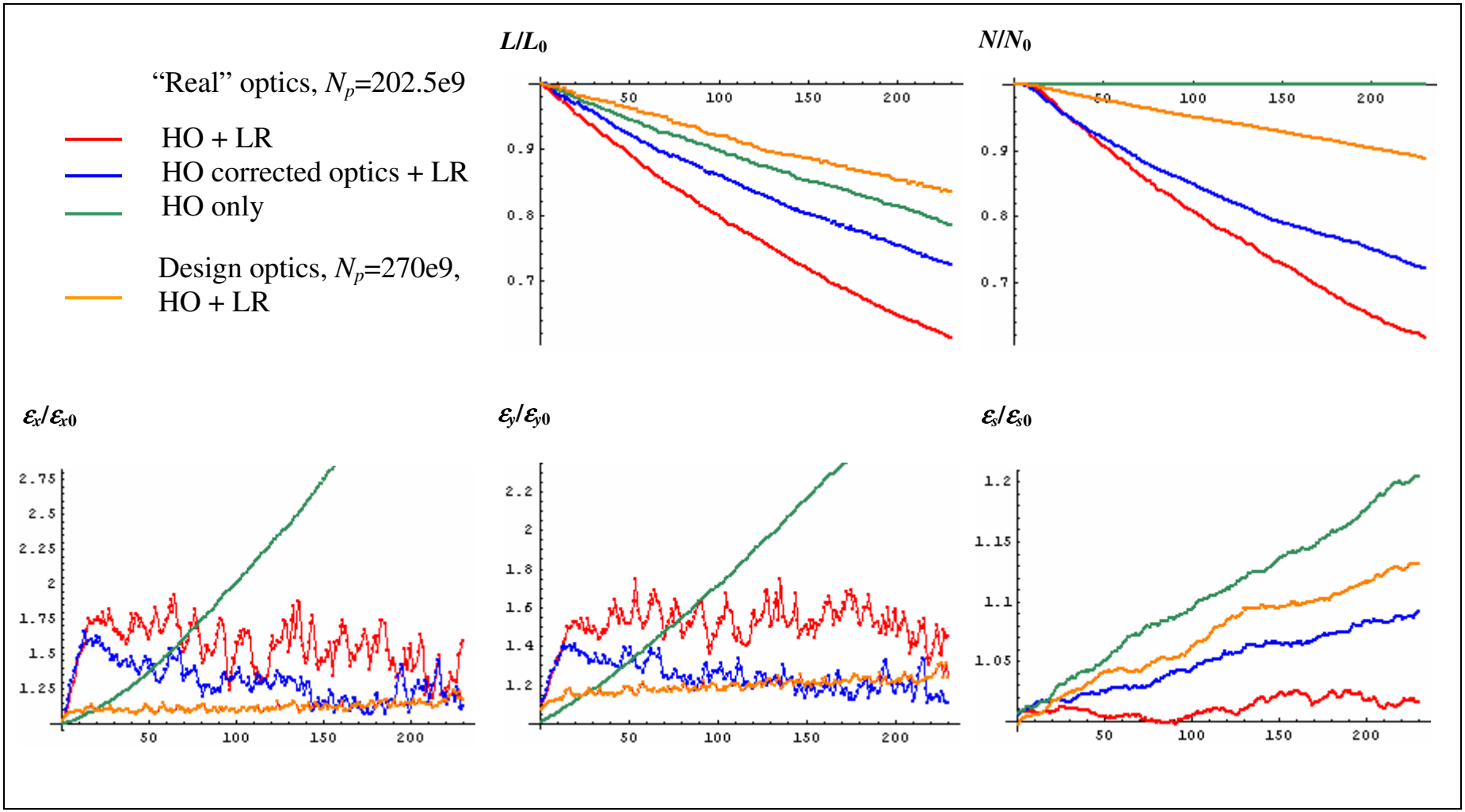
$$a=\sqrt{a_x^2+a_y^2}$$

with step 1σ.

The dynamics is dominated by 7th order resonances; however the 12th (and probably 14th) order resonances contribute as well.

The Surprise:

in the presence of IP errors (optics asymmetry, crossing angle) and only HO collisions the luminosity is decaying faster than with all 72 collisions (HO+LR) at nominal Np in the case of ideal optics, but there is no scraping!



Effects of the Optics Asymmetry on the Phase-Averaging:

Variation of the betatron phase over the interaction region with a long bunch leads to suppression of the resonance excitation (phase averaging); in the case of round beams the resonance driving terms can be factorized: $R_L = f_L R_S$, where R_S is RDT for short bunches and f_L is the suppression factor which describes the finite length effect of the strong bunch. Factor f_L depends on the longitudinal amplitude of the test particle, in this preliminary analysis we put it to 0.

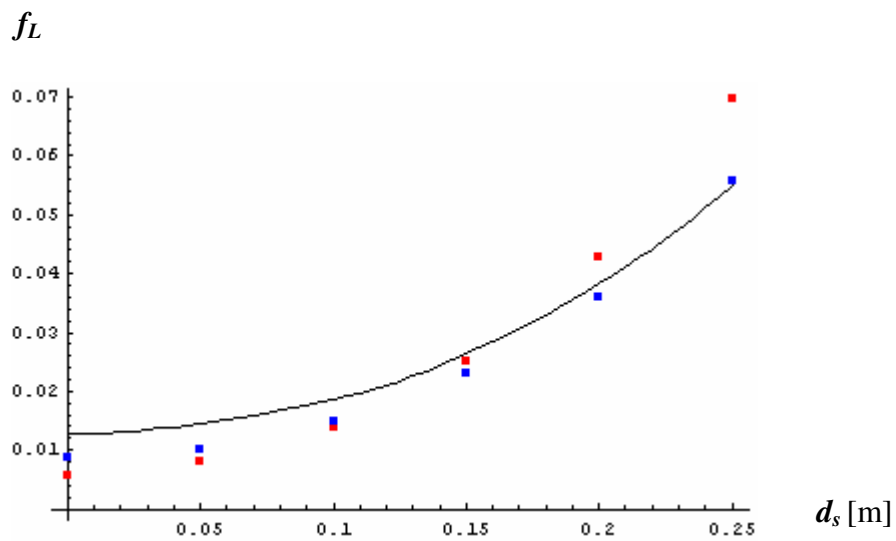


Figure 2.The12th order resonance suppression factor due to betatron phase averaging as function of the waist displacement at $\beta^* = 0.4$m, $\sigma_s = 0.5$m. Solid line – exact dependence, red squares – 11 slices, blue squares – 15 slices.

Particular values of factor f_L for 12th order resonances:

d_s	f_L
0	0.0130
0.1	0.0187
0.2	0.0384

1. The optics asymmetry enhances the 12th (and 14th) order resonances by a factor of 3-4.

2. With limited number of slices representing the strong bunch (12 in simulations, but I have no data for this number) the effect of the optics asymmetry is somewhat exaggerated; it would be better to increase it.

Excitation of Odd-Order Resonances in Head-On Interactions in the Presence of Crossing Angle and Asymmetry

1. Excitaion of odd-order resonances in head-on interactions in the absence of offsets is forbidden by the symmetry of the potential (no matter what the position of the waist is)

2. Due to crossing angle the test particle collides with the head and tail of the strong bunch at offsets of opposite sign, however due to variation of the betatron phase advance over the interaction region there is a non-zero net effect.

3. Optics asymmetry introduces disbalance in contributions from head and tail drastically enhancing the effect of the crossing angle.

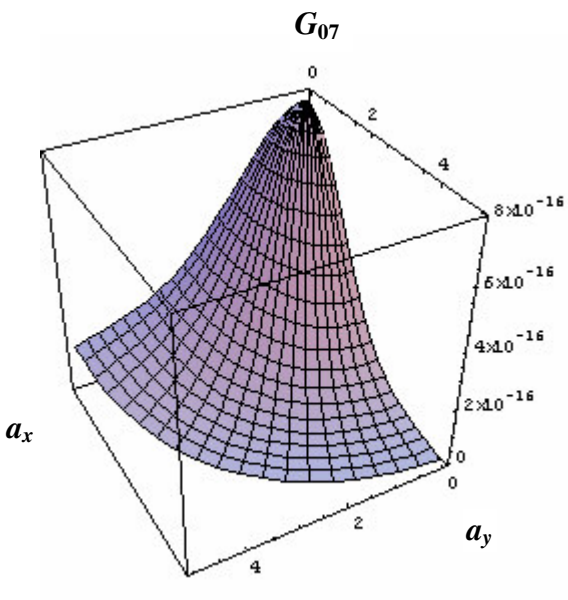
Example of $7Q_y$ RDT at $\sigma_s = 0.37$m, $\beta^* = 0.4$m and betatron amplitudes $a_x = 0$, $a_y = 2\sqrt{2}$

χ [mrad]	d_s [m]	R_{07} (arbitrary units)
0	–	0
0.03	0	$-i0.9\cdot10^{-5}$
0.03	0.2	$-(0.6+1.2i)\cdot10^{-4}$

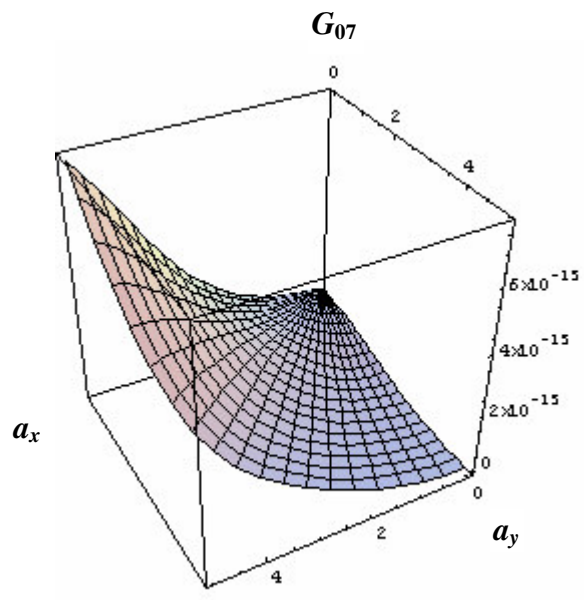
Results of computations for the “real” optics are presented below.

7Qy RDTs as Functions of the Betatron Amplitudes ("real" optics)

$$R_{m_x,m_y}(a_x,a_y,a_s) = 2^{(m_x+m_y)/2} a_x^{m_x} a_y^{m_y} G_{m_x,m_y}(a_x,a_y,a_s)$$



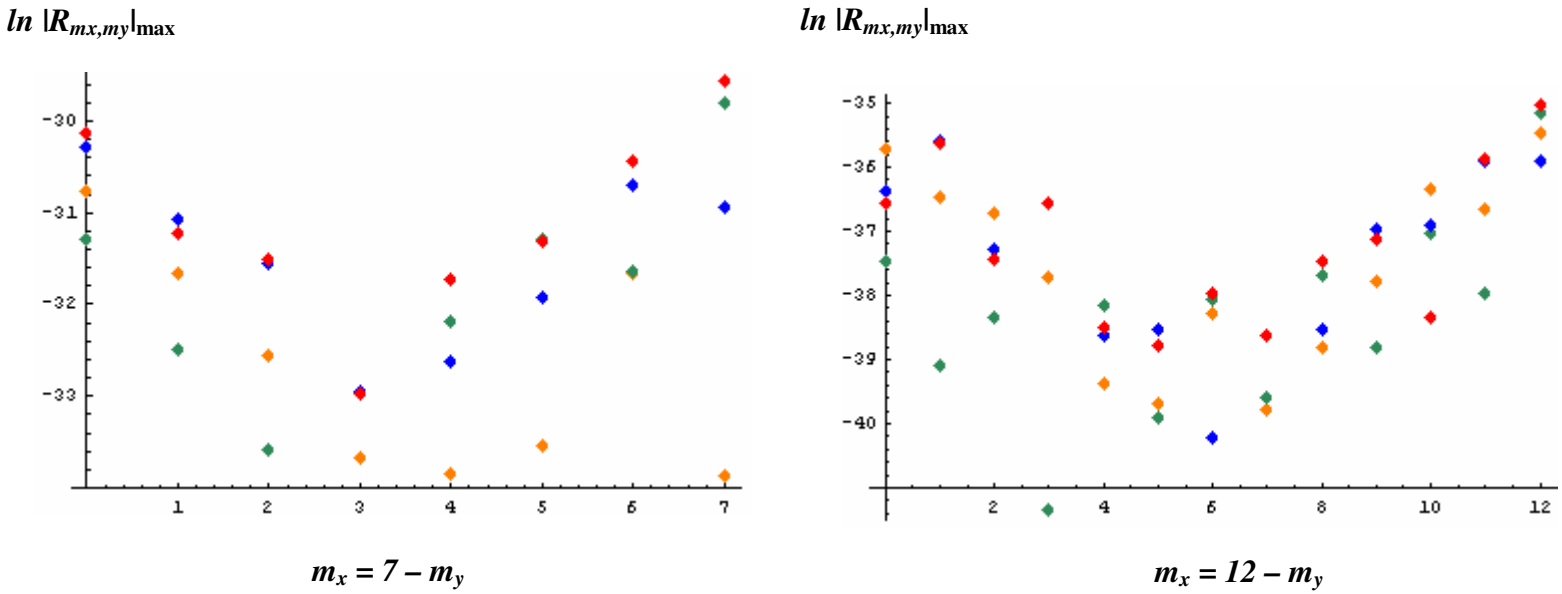
Head-On contribution



Long-Range contribution

1. Comparing these contributions one should realize that factor G for LR interactions is maximal at $a_y = 0$, after multiplication by a_y in power 7 the difference in RDTs is not that big.
2. The core particles are effected by both head-on and long-range interactions, whereas the tails suffer mostly from the long-range interactions.

Maximum values of the 7th and 12th order RDTs at $a = 3$



Maximum values of RDTs over

$$\phi = \arctan a_y / a_x$$

at fixed total amplitude

$$a = \sqrt{a_x^2 + a_y^2} = 3$$

"Real" optics, N_p=202.5e9

- HO + LR
- LR only
- HO only

Design optics, N_p=202.5e9,

- HO + LR

Tentative Explanation of the Puzzle:

1. The total (HO+LR) 7th order RDTs in the "real" case are significantly larger than in the ideal case – herefrom much faster losses in intensity and luminosity.
2. The head-on contribution to $7Q_y$ RDT in the "real" case is comparable with the total RDT in the ideal case (smaller by a factor of 1.7 at a=3, but larger at small a) – hence the comparable effect on luminosity.
3. The head-on contribution to $12Q_x$ RDT in the "real" case is larger the total RDT in the ideal case at $a \leq 3$, again this should lead to faster decay of luminosity in the case of HO with "real" optics.
4. At large amplitudes the HO contributions to RDTs are generally smaller than the LR contributions, so there should not be as strong "shaving" in the HO only case as in the cases with LR.
5. In the particular case of the design optics shown in Fig.2 the proton intensity was set to the nominal value, so the tuneshifts were higher than shown in Fig.1 and the 7th order resonances were encountered at larger amplitudes. In the result the core particles suffered less and the luminosity decayed more slowly.

Tentative Explanation of the "scallops":

1. In actual HEP stores the pbar vertical tune as reported by 1.7GHz Schottky is well above 0.58 so that the 12th order resonances are the major players.
2. From the last plot it follows that the resonances $12Q_y$, $Q_x + 11Q_y$, $2Q_x + 10Q_y$, $3Q_x + 9Q_y$, are excited mainly by LR interactions, almost completely by those downstream of the main IPs.
3. The first bunches in pbar trains do not collide at those IPs and do not suffer from these resonances despite lower vertical tune.
4. The last bunches in pbar trains have usually much smaller initial emittances than those in the middle of the trains and are less susceptible to high-order resonances.