

EPS-AG SACHERER PRIZE: BEAM OPTICS DEVELOPMENTS FOR SPS, RHIC, LHC, CLIC AND ATF2

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Abstract

Highlights of linear and nonlinear optics studies are presented from various accelerators. At the LHC, optics correction is of critical importance to guarantee safe beam operation. Preparation for LHC optics measurements and corrections has been a major activity during the last decade. In particular, SPS and RHIC have served as excellent research and development machines to test new techniques and instrumentation, such as the measurement of resonance driving terms with and without AC dipoles. Together with a meticulous field quality specification, a careful installation strategy and an elaborate magnet model, these efforts have paid off in the LHC, where a record low beta-beating for hadron colliders below 10% has been achieved. Looking further into the future, the performance of the Final Focus System (FFS) is of critical importance for a future linear collider like CLIC, since it determines the IP beam spot sizes. The large chromatic aberrations required the development of novel non-linear optimization methods. Such techniques have successfully increased the CLIC design luminosity by 70% and an experimental test has been proposed for ATF2 to halve the design IP beam spot sizes.

SPS & RHIC: A JOURNEY TO THE RESONANCE DRIVING TERMS

In [1] Normal Form and Lie algebra techniques were used to describe the motion of a particle confined in an accelerator in presence of non-linearities. The particle position x_1 as function of the turn number N at a certain location (indexed by 1) was given the following form,

$$x_1(N) = \sqrt{\beta_{x1}} \Re \left\{ \sqrt{2I_x} e^{i(2\pi\nu_x N + \psi_{x1})} - 2i \sum_{jklm} j f_{jklm}^{(1)} (2I_x)^{\frac{i+k-1}{2}} (2I_y)^{\frac{l+m}{2}} \times e^{i[(1-j+k)(2\pi\nu_x N + \psi_{x1}) + (m-l)(2\pi\nu_y N + \psi_{y1})]} \right\} \quad (1)$$

where $I_{x,y}$ are the horizontal and vertical actions, $\nu_{x,y}$ are the tunes, $\psi_{x1,y1}$ are the initial phases and $f_{jklm}^{(1)}$ are the resonance driving terms (RDTs). First exploratory measurements of RDTs were carried out in [2, 3]. However the longitudinal variation of the RDTs was disregarded in these studies, probably due to the influence of Guignard's theory [4], where his harmonic terms h_{jklmq} have an invariant amplitude. The longitudinal variation of the RDTs was first described and exploited in [5]. These terms exhibit abrupt jumps at the location of the multipole sources. This property makes it even more interesting to measure RDTs as their longitudinal variation provides, in principle,

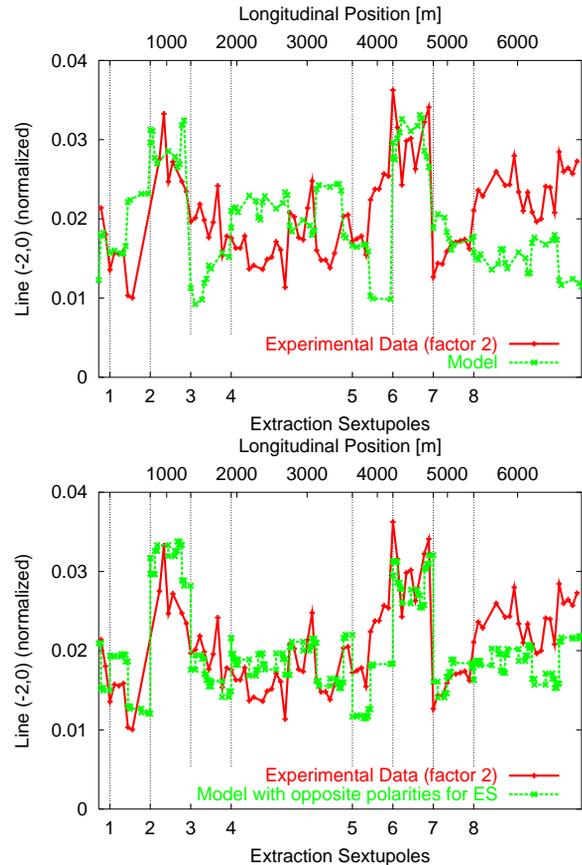


Figure 1: SPS longitudinal variation of the spectral line $(-2,0)$ from experiment and model with the nominal model (top) and with opposite sextupole polarities (bottom) at 120 GeV.

the full information of the multipolar components around the ring.

Equation (1) describes the motion of a single particle while in real accelerators only the centroid of an ensemble of particles is accessible via the Beam Position Monitors (BPMs). In [5] it is shown how decoherence processes affect different spectral lines differently. In particular the spectral line with frequency $nQ_{x,y}$ is reduced by a factor $|n|$ in presence of decoherence.

Figure 1 shows the first application of the measurement of the sextupolar term f_{3000} , proportional to the line $(-2,0)$, in the SPS. Note that a decoherence factor of 2 is applied to properly compare to single particle tracking. The initial measurement-to-model discrepancy (Fig. 1 top) was resolved by changing the polarity of the extraction sextupoles (Fig. 1 bottom). This opposite polarity was confirmed with hardware checks.

Figure 2 shows the SPS measurement of the f_{3000} term

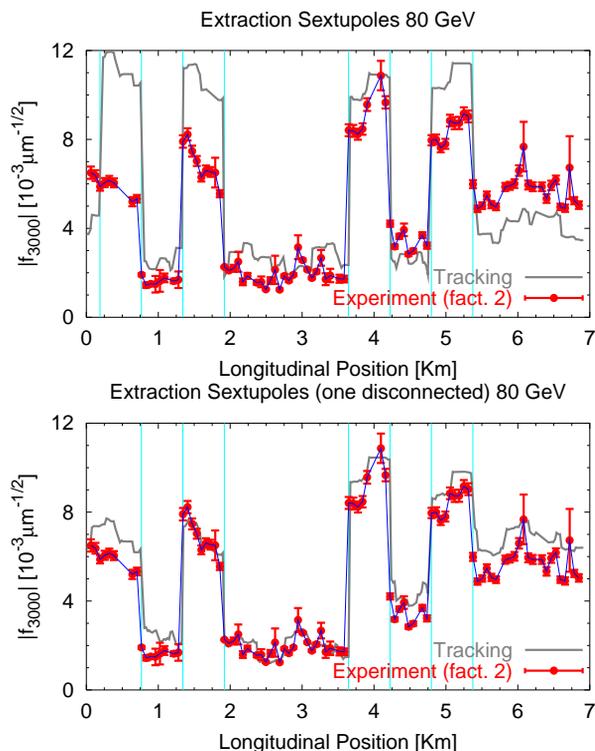


Figure 2: SPS resonance term f_{3000} versus longitudinal position from experiment and tracking at 80 GeV. The models include 8 and 7 extraction sextupoles in the top and bottom plots, respectively. The vertical lines denote the position of the extraction sextupoles.

at 80 GeV with extraction sextupoles. Accidentally the first extraction sextupole was disconnected, which was reflected by the measurement as the absence of an abrupt jump of $|f_{3000}|$ at its location.

AC dipoles can be used to force long-lasting and adiabatic betatron oscillations [6]. This instrument is ideal for the measurement of RDTs even though forced oscillations differ from the free betatron motion [7]. The first measurement of the sextupolar term f'_{3000} using an AC dipole in RHIC [8] is shown in Fig. 3. Note that the prime in f'_{3000} has been used to distinguish from the free RDT f_{3000} .

The measurement of sextupolar RDTs has allowed to perform successful corrections in the PSB [9, 10] and DIAMOND [11].

The local resonance driving terms

For any segment of an accelerator containing 3 BPMs as shown in Fig. 4 a fully local quantity can be built as follows,

$$\chi(N) = \frac{\hat{x}_1(N)}{\cos \delta_1} + \hat{x}_2(N) (\tan \delta_1 + \tan \delta_2) + \frac{\hat{x}_3(N)}{\cos \delta_2}, \quad (2)$$

where $\hat{x}_i(N)$ are the i^{th} BPM turn-by-turn readings normalized with the oscillation amplitude $\sqrt{2I_x \beta_x}$, δ_i are defined in Fig. 4. In [8] it is demonstrated that $\chi(N)$ is a

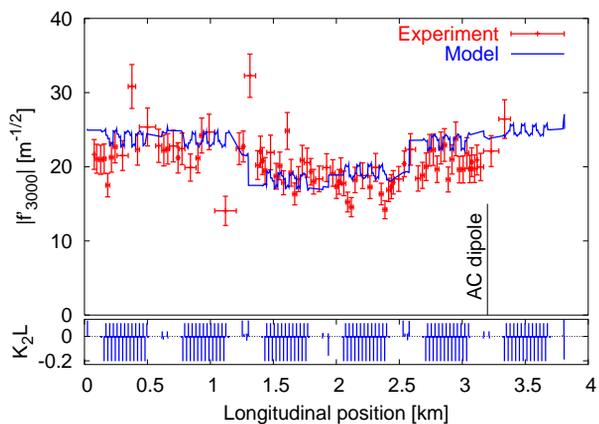


Figure 3: Measurement of $|f'_{3000}|$ with an AC dipole in RHIC. The bottom plot shows the sextupolar components.

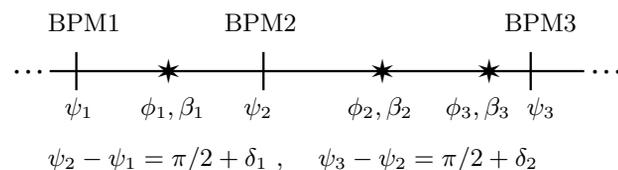


Figure 4: Segment of an accelerator lattice. BPMs and multipoles are shown with their relevant twiss parameters.

linear function of the strengths of the perturbative elements within the 3 BPMs. If the considered segment is free of non-linear elements $\chi(N) = 0$. In the general case $\chi(N)$ is expanded similarly to $x(N)$ in Eq. 1, allowing to connect every spectral line to a multipolar order. Figure 5 shows the first measurement of a sextupolar term of $\chi(N)$. This was carried out in RHIC at injection with single kicks.

The RDTs can also be directly used to infer sextupole strengths as shown in [12, 13]. A pair of BPM without perturbative elements in between is used at either side of the sextupole to provide two precise measurements of the sextupolar term, $f_{3000}^{(1)}$ and $f_{3000}^{(2)}$. The strength of the sextupole is given by

$$|k_2 L| = \frac{48}{\beta_x^{3/2}} \left| f_{3000}^{(2)} e^{-3i\Delta\phi_x^{1,2}} - f_{3000}^{(1)} \right| \quad (3)$$

Higher orders

Despite the successful applications of the measurement of sextupolar RDTs higher orders remain a challenge. Figure 6 shows an exploratory measurement of an octupolar term in the SPS with horizontal tune close to the fourth order. The agreement with simulation is limited and the dominant source of this octupolar RDT is the second order from sextupoles as can be concluded from the simulations with and without octupoles. Another exploratory measurement of octupolar terms was carried out in SOLEIL [14] but the non-linear BPM response was dominating the oc-

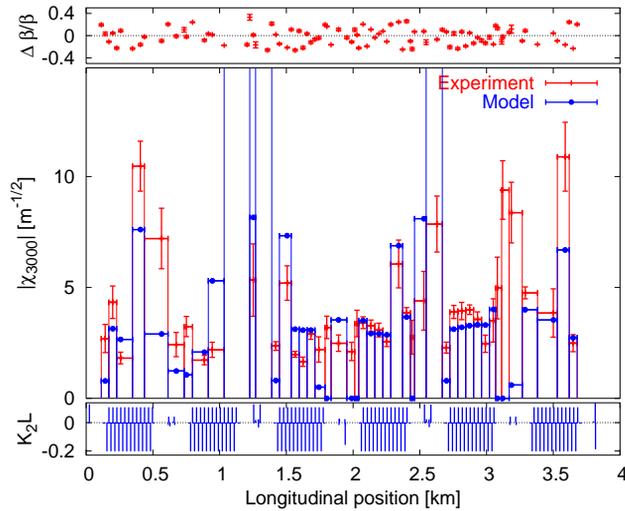


Figure 5: Measurement of $|\chi_{3000}|$ from kick data in RHIC. The top plot shows the beta beating. The middle plot shows $|\chi_{3000}|$ around the ring with a comparison to the model. The bottom plot shows the sextupolar components.

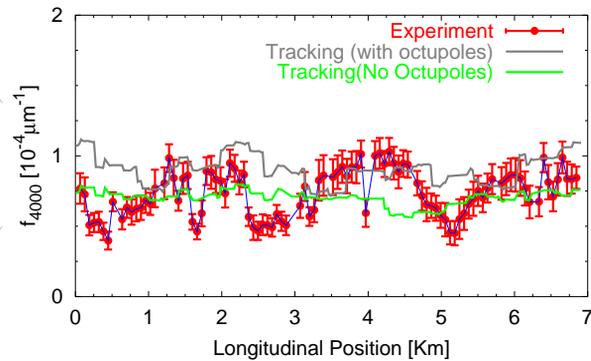


Figure 6: SPS generating function term f_{4000} versus longitudinal position from experiment and tracking model for SPS at 26 GeV close to the fourth order resonance.

tupolar spectral line. The measurement of pure octupolar and higher order RDTs will require more accurate techniques and instrumentation and a good control and modeling of the lower orders.

LHC: ACHIEVING $(\Delta\beta/\beta)_{\text{PEAK}}=10\%$

Most of the above mentioned developments were carried out with the LHC as main motivation. Initially the LHC optics challenge was to reach $(\Delta\beta/\beta)_{\text{peak}} < 20\%$ [15], however due to beam-beam arguments this was reduced to 10% [16, 17]. The first optics measurement in 2008 [18], with extremely constrained data, revealed a $(\Delta\beta/\beta)_{\text{peak}}=100\%$. This required the development of the Segment-By-Segment Technique (SBST) [18, 19] to identify local errors. The basic concept of the SBST relies on splitting the machine into various sections and therefore

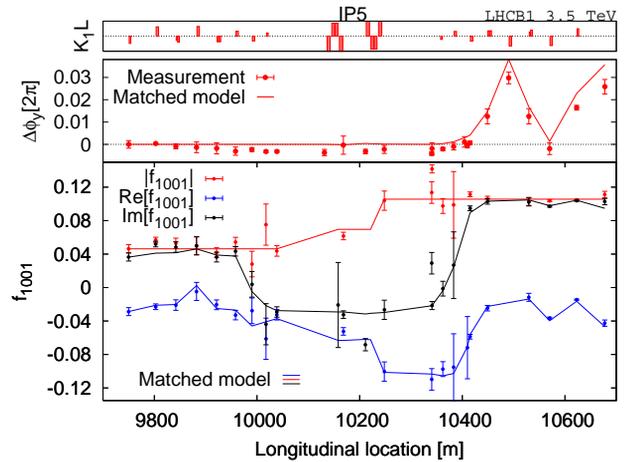


Figure 7: Example of the SBST applied to the correction of the IR5 normal and skew optics errors for Beam 1 at 3.5 TeV. The IR quadrupoles (top), the vertical phase advance error (middle plot) and the difference resonance term f_{1001} (bottom) are shown. The lines represent the matched model with normal and skew errors located in the triplets.

treat them as independent beam lines. The measured optics parameters at the beginning of each section are used as initial optics conditions. Figure 7 illustrates the SBST applied to the IR5 betatron phase advance and coupling. In 2010 it was demonstrated that $(\Delta\beta/\beta)_{\text{peak}}=10\%$ was at reach by applying global corrections after having removed the local sources [20]. In 2011 the LHC has operated with $(\Delta\beta/\beta)_{\text{peak}}=10\%$ for both beams, see Fig. 8

The LHC is probably the first hadron collider achieving 10% peak β -beating with squeezed β^* . This owes to the meticulous magnetic field quality specification [15], a careful installation strategy [21] and an elaborate magnet model [22]. The optics measurements benefit from an excellent instrumentation with less than 1% BPM failure as shown by SVD and FFT analyzes [23]. The adiabaticity [24] of the LHC AC dipole [25] allows for multiple optics measurements throughout the LHC cycle using the same proton bunch. The spurious effects of the AC dipole on the optics measurements are removed according to [26, 27].

CLIC & ATF2: FOCUSING TO THE LOWEST BEAM SIZES

Linear colliders as CLIC [28] require the lowest possible beam sizes at the IP. Design and optimization of the Final Focus System (FFS) is therefore a critical aspect. The transfer map between the start of the FFS and the IP is expressed in the form

$$x_{IP} = \sum_{jklmn} X_{jklmn} x_0^j p_{x0}^k y_0^l p_{y0}^m \delta_0^n \quad (4)$$

the X_{jklmn} are the map coefficients of the corresponding final coordinate. The MAD-X [29] code together with

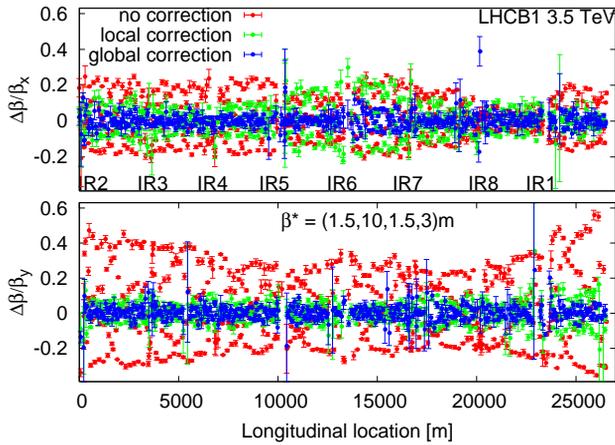


Figure 8: Horizontal (top) and vertical (bottom) LHC Beam 1 β -beating during the correction process with $\beta^* = 1.5$ m at IP1 and IP5, reaching $\Delta\beta/\beta=10\%$.

PTC [30] can provide X_{jklmn} up to the desired order. The typical approach for the optimization algorithms that take into account high-order aberrations consists in minimizing a collection of X_{jklmn} terms with appropriate weights [31, 32, 33]. This approach proved to be complicated and called for the development of better optimization algorithms [34]. Ideally one should optimize a physical quantity that would remove any arbitrariness from the choice of weights. In [35] it is shown that using the simplicity of the transfer map it is possible to express the rms beam sizes at the IP as function of the X_{jklmn} terms and the initial particle distributions,

$$\langle x_f^2 \rangle = \sum_{\substack{jklmn \\ j'k'l'm'n'}} X_{jklmn} X_{j'k'l'm'n'} \times \int x_0^{j+j'} p_{x0}^{k+k'} y_0^{l+l'} p_{y0}^{m+m'} \delta_0^{n+n'} \rho_0 dv_0 \quad (5)$$

The IP rms beam size is the natural quantity to be minimized. The code MAPCLASS [36] has been developed to compute and minimize the IP rms beam size using the X_{jklmn} terms from PTC. Figure 9 shows the application of MAPCLASS to the CLIC Final Focus System, yielding a 70% luminosity increase [35]. MAPCLASS was also successfully applied to the collimation system and to the LHC IR upgrade [37].

ATF2 is under commissioning to demonstrate the feasibility of the FFS with local chromaticity correction using a scaled down version of the ILC FFS [38]. To demonstrate the CLIC FFS natural chromaticity it has been proposed to reduce the ATF2 β_y^* by a factor four [39]. This would allow to reach $\sigma_y^* \approx 20$ nm, see Fig. 10. The ATF2 magnetic field quality is an important obstacle to reach this ultra-low β_y^* . CERN is considering contributing a high accuracy quadrupole to ATF2.

09 Opening, Closing and Special Presentations

04 Prize Presentation

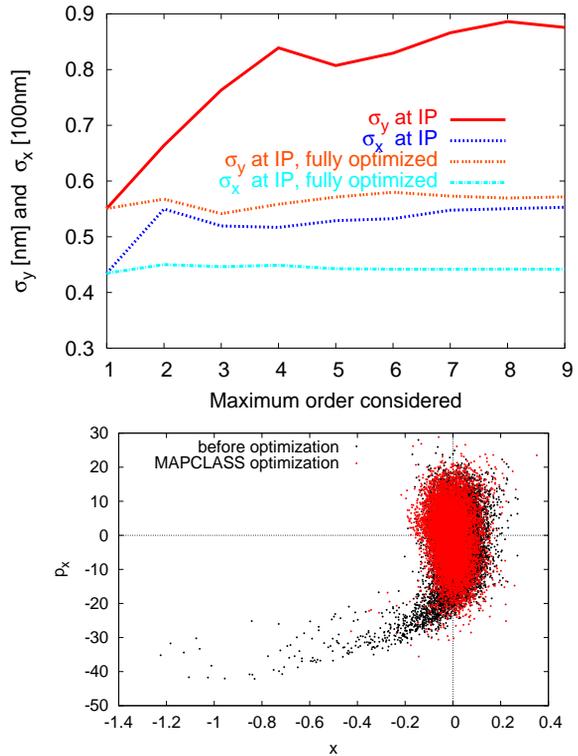


Figure 9: CLIC FFS optimization using MAPCLASS. Top: Horizontal and vertical rms beam sizes at the CLIC IP for the nominal BDS and the one fully optimized. Bottom: Horizontal phase-space before and after optimization.

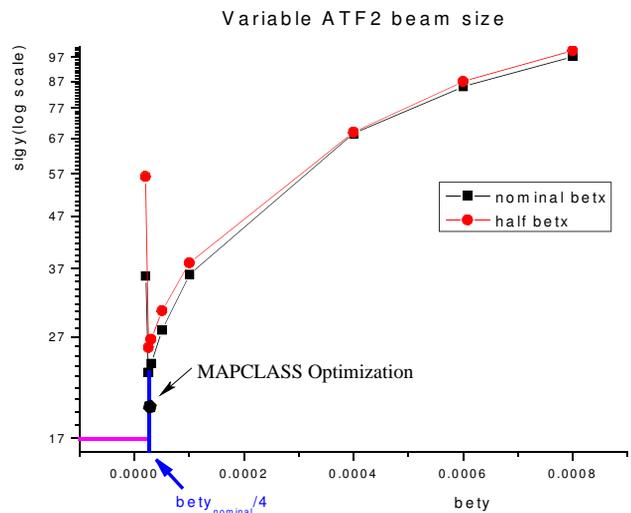


Figure 10: Vertical beam size (in [nm]) at the IP versus vertical beta function (in [m]) for two cases: nominal and half horizontal β^* . The quarter of β_y is marked on the plot.

ACKNOWLEDGMENTS

Heartfelt thanks to O. Brüning, J.P. Delahaye, A. Faus-Golfe, W. Fischer, M. Klein and F. Zimmermann for supporting my candidacy to the EPS-AG Sacherer prize and for their help with the outline of this paper. I am most grateful to my mentors in accelerators physics, A. Faus-Golfe and F. Schmidt. Great thanks to M. Aiba, R. Calaga, A. Franchi, R. Miyamoto, G. Rumolo and F. Zimmermann for the most enlightening discussions and codes. Thanks to A. Franchi and G. Vanbavinckhove for proofreading this paper.

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