SUMMARY OF MACHINE TUNING SESSION*

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Abstract

This paper summarizes the work presented at the Machine Tuning session on the low emittance tuning for low emittance lattices and luminosity tuning at colliders.

SESSION TALKS

Optics correction is a key tool to achieve desired performances in an accelerator. It is very important to have a good lattice model so to be able to operate on the real machine in a reliable way. Unavoidable magnet errors, such as displacements, tilts or field errors, will affect the closed orbit, H-Y betatron coupling, H-V dispersion, H-V emittance. Their correction is crucial for reaching the design performances. Beam polarization is also heavily affected by errors, as shown in [1]. For the new generation of e^+e^- accelerators, where low emittance beams are needed to achieve the design luminosity, this is a very important topic to be addressed and solved.

Five talks have been presented on Optics correction (for LHC and SuperKEKB), Errors correction (for FCC-ee) and Luminosity tuning (for KEKB):

1. A. Langner (CERN), “Optics correction at large accelerators”,
2. Y. Ohnishi (KEK), “Optics correction and low emittance tuning at the Phase 1 commissioning of SuperKEKB”,
3. Y. Funakoshi (KEK), “Luminosity tuning at KEKB”,
4. S. Sinyatkin (BINP), “FCC lattice with errors and misalignment”,
5. S. Aumon (CERN), “Coupling and dispersion correction in FCC-ee”.

ERRORS SIMULATION

Errors simulations are needed in order to provide a model of what can be the *real* accelerator. The impact of different errors, such as magnet misalignments, magnet field errors, magnet tilts, BPM gain and position errors, have to be modelled to be able to perform corrections and prepare the online tools needed when running. Also, tolerances to these errors should be computed, in order to set up what are the requirements for the accelerator alignment and magnets quality. Most of the errors are impacting betatron coupling and vertical dispersion, which are particularly important to minimize since modern accelerators, both colliders and synchrotron light sources, aim to very low emittances in both planes.

For the FCC-ee project a study of the errors and misalignments at 175 GeV [2] showed that in the Arcs quadrupoles need to be aligned at 100 μ. Final Focus (FF) quadrupoles were studied separately, due to the high gradients and β-functions behaviour in the Interaction Region (IR). For these elements there is a strong vertical dispersion excitation due to errors. A tolerance of 25 μ to quadrupole misalignments has been found. This seems a very low value that must be checked with the alignment experts. The use of MADX code turned out not to be ideal for this study since is time consuming and in presence of errors it was difficult to find the closed orbit for a displacement of 100 μ in Arc quadrupoles. However, after closed orbit, betatron coupling and vertical dispersion correction the average ratio between the vertical and horizontal emittances was reduced from an initial 15% to a final 1.4%, as shown in Fig.1 below.

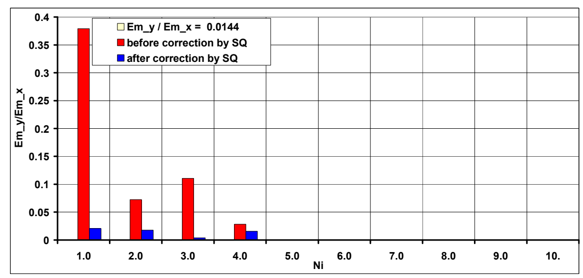

Figure 1: Emittance ratio as a function of optics correction iterations (in red before, in blue after correction).

Another study of betatron coupling and vertical dispersion correction for the FCC-ee 175 GeV [3] was presented. The energy losses in the Arcs at 175 GeV are so large (the so called saw-tooth effect) that a tapering of dipoles, quadrupoles and sextupoles fields is needed. However, this is an expensive requirement, so a study was performed to see if closed orbit correction was still possible by tapering dipoles only, so called “sector-wise” method. The lattice studied was a racetrack type with a “LEP-like IR” with sector-wise tapering. This scheme has shown to have some issues. A quadrupole misplacement tolerance of 20 μ in quadrupoles (here the FF quadrupoles are included in the simulation) has been found after a combination of dispersion free steering and Interaction Point (IP) betatron coupling correction. Fig. 2 shows the dependence of vertical emittance from quadrupole misalignments for this lattice. Future work will be needed to implement the real lattice and full magnets tapering.

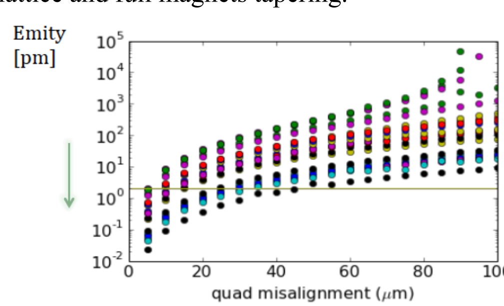

Figure 2: Vertical emittance vs quads misalignments.

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ERRORS CORRECTION

Errors correction on a running accelerator makes use of different tools and techniques in order to achieve desired performances. The knowledge of the *real* machine and a good model to reproduce the measurements are the fey points for successful running.

LHC

An example of how this was implemented at the LHC [4] was shown. The errors correction procedure was continuously improved during the running years. A new turn-by-turn phase advance measurement procedure for the derivation of the β-functions was used, which analyse the data not only at 3 adjacent BPMs, as usually done [5], but considers N number of BPMs in order to improve accuracy and precision. This technique was also used at ALBA and ESRF light sources [6]. Also, a segment-by-segment technique, based on local correction performed via comparison of measured phase advances and optics simulations, was implemented. The resulting β-beating was corrected to about 5%. A waist shift of the IP β-function was observed in 2015 and corrected including gradient modulation measurements in the local correction procedure. The results of errors correction and optics improvements during the running of the LHC are shown in Figs. 3 and 4 below. This shows how continuous work on optics and model understanding is very important to improve the collider performances.

	Beam 1		Beam 2		Year	Energy	β^*
	x	y	x	y		(TeV)	(cm)
peak	9 ± 1	9 ± 1	7.0 ± 0.6	6.7 ± 1.7	2012	4.0	60
$\frac{\Delta\beta}{\beta}$(%)	9.6 ± 1.6	5.0 ± 1.0	11.2 ± 1.1	6.8 ± 1.2	2015	6.5	40
	7.8 ± 0.7	4.5 ± 0.7	5.0 ± 0.4	4.2 ± 0.3	2016	6.5	40
rms	2.6	2.3	2.4	2.2	2012	4.0	60
$\frac{\Delta\beta}{\beta}$(%)	3.2	1.7	4.0	2.0	2015	6.5	40
	1.6	1.4	1.6	1.5	2016	6.5	40

Figure 3: β-beating correction results over the years.

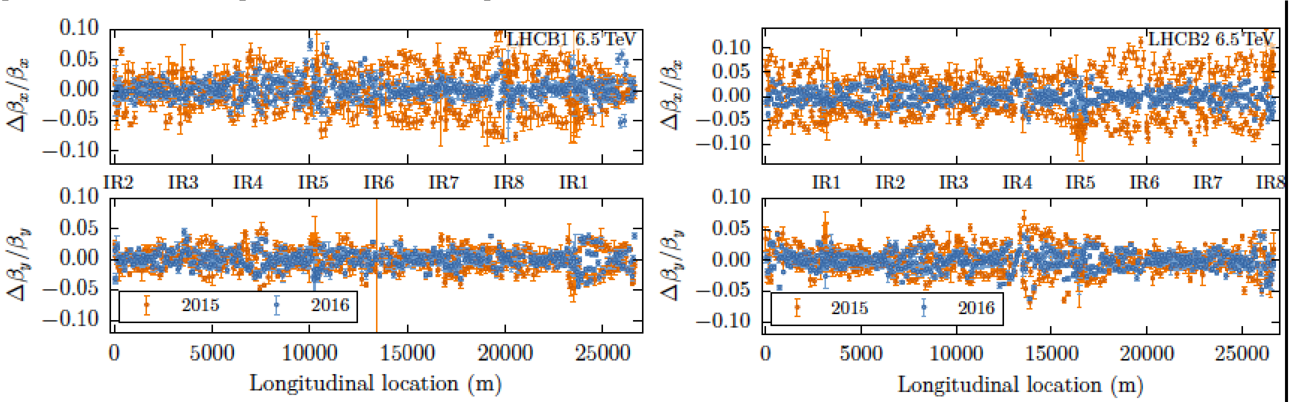

Figure 4: β-beating correction results for LHC Beam 1 (left) and Beam 2 (right).

SuperKEKB

The Phase-1 SuperKEKB accelerator was commissioned in the first 6 months of 2016. In this configuration the two beam did not collide, and beam pipe scrubbing and optics tuning was the main goal. Techniques and tools were the same developed for KEKB B-Factory.

After careful closed orbit and betatron coupling correction, a residual deviation was measured at the location of the Lambertson septum, used for the beam abort system. Leaking field from the septum was exciting residual X-Y coupling. Having spotted the problem, the installation of permanent skew quadrupoles at the septum location has allowed for a satisfactory coupling correction, see Fig. 5.

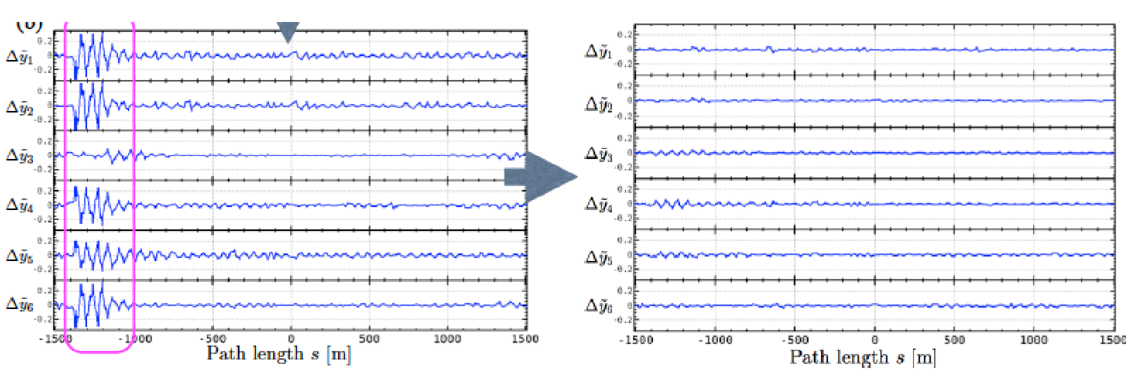

Figure 5: Example of X-Y coupling correction after installation of skew quadrupoles near the Lambertson septum.

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Optics correction has worked very well and a vertical emittance of 8 pm has been achieved in the LER after beam-based alignment, optics correction, installation of additional skew quadrupole coils at the focusing sextupoles, and of permanent skew quadrupoles at the Lambertson septum. The evolution of the emittance and dispersion tuning is shown in Fig. 6 below.

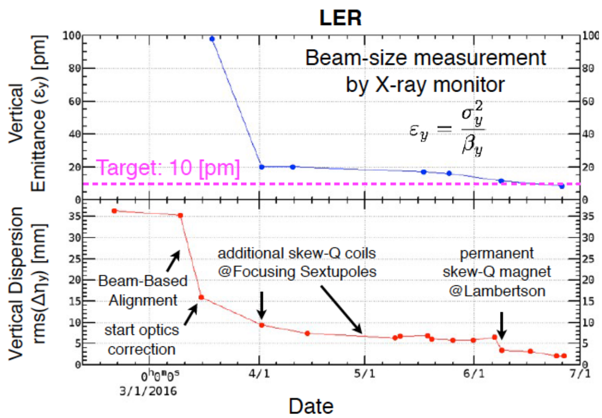

Figure 6: Vertical emittance and dispersion correction in LER.

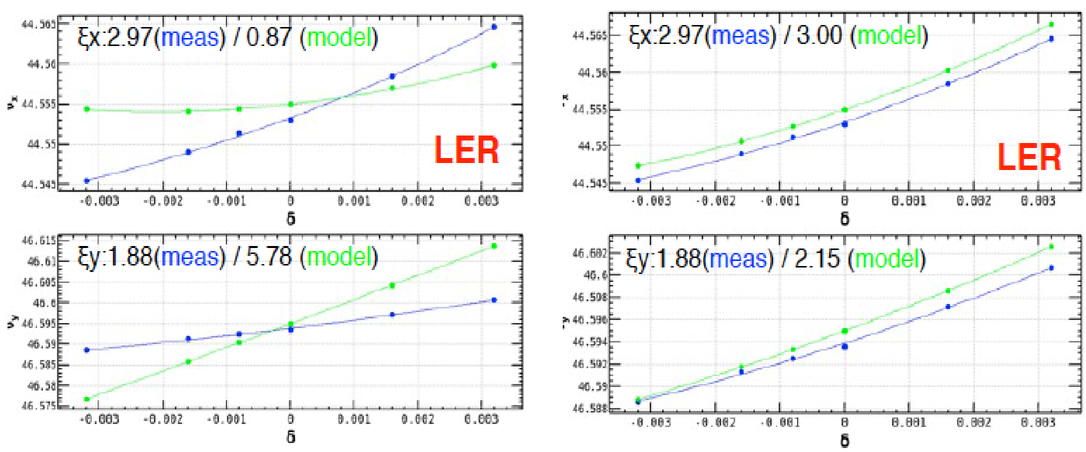

Figure 7: Chromaticity measurements compared to model before (left) and after (right) chromatic phase-advance correction in SuperKEKB LER.

The HER emittance measurement was affected by the performances of the synchrotron X-ray monitor and is far from the model value estimated from the β-function measurements, in spite of the goodness of orbit, dispersion and coupling correction. This problem is still to be addressed.

A large discrepancy was found when comparing chromaticity measurements with model for the LER (see Fig. 7, left plot), while for the HER the values were in good agreement. The problem was found to be due to the not well corrected off-momentum optics, a problem already observed and corrected in KEKB. The source of this off-momentum optics distortion is assumed to be a deviation in the sextupoles field. A few percent correction of the sextupoles settings, computed through an off-momentum phase-advance response matrix technique, was able to correct the discrepancy quite well (see Fig. 7, right plot). Understanding the off-momentum optics is very important and needed for the optimization of the dynamic aperture.

LUMINOSITY TUNING

Luminosity tuning at KEKB was described [6]. During the 20 years of operation the luminosity was increased by performing many and continuous parameter scans. These were routinely done by the operation team, even during physics run. In most of cases, these scans were not efficient, but sometimes an improvement in the luminosity was obtained, so it was very important to continue this luminosity tune-up. The introduction of a downhill simplex method speeded up the parameter search, however the achievable luminosity was not increased with this method. An enormous amount of effort was devoted to daily tuning to increase the beam-beam parameters, reaching the record values of $\xi_x = 0.09$ in HER and $\xi_y = 0.129$ in LER.

A number of tuning knobs were developed during the KEKB operation. Most of the luminosity tuning used the luminosity monitors and the beam size monitor (SR interferometer) as observables. The reliability of those monitors was important.

One of the reasons of high luminosity at KEKB was the short bunch length, which brought a lower β_y, thanks to the lattice flexibility that allowed for a lower momentum compaction. It was also found in operation that a horizontal tune closer to half-integer gave a higher luminosity, just like other factory colliders.

The continuous injection scheme (top-up injection) made the luminosity tuning easier since there were more stable beam conditions.

It was found that the chromaticity of X-Y coupling parameters (R-parameters) at the IP could degrade the luminosity, if the residual values, which depend on machine

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errors, are large. To control the chromaticity, skew sextupole magnets, 10 pairs for HER and 4 pairs for LER, were installed during the winter shutdown in 2009. It turned out that the skew sextuples are very effective to raise the luminosity. The knobs to control the R-chromaticity were introduced for beam operation on May 2009, and the gain in luminosity by these magnets was about 15~17%.

The continuous beam injection was needed in order to increase the integrated luminosity and keep peak luminosity stable, since the beam lifetimes were short. The gain in integrated luminosity was 30%.

A lot of effort was put in commissioning the crab cavities installed in order to compensate for the horizontal crossing angle at the IP (±11 mrad), which caused synchro-betatron resonances and decreased the tune space for luminosity optimization. It was expected that the beam-beam parameters and the luminosity would be doubled with the crab cavities. Actually the achieved luminosity gain with crab was about 30~ 40 % including the effect of the skew-sextupoles. The beam-beam parameters were also increased but not as much as expected by simulations. The discrepancy between the simulation and the experiment has not been understood yet. A plot of the luminosity tuning with and without crab cavities is shown in Fig. 8.

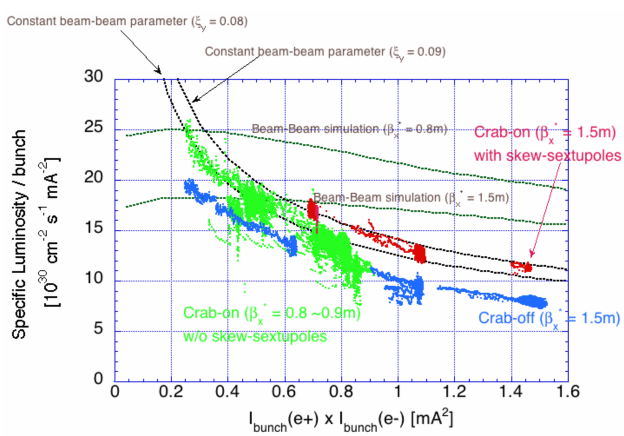

Figure 8: Tuning of luminosity with and without crab cavities.

CONCLUSION

The unavoidable errors in an accelerator (magnet misalignments, field errors, BPMs, …) must absolutely be corrected in order to achieve design performances such as low emittances and luminosity. Errors affect mostly vertical emittance which is zero in a "perfect" lattice and must be included in the Dynamic Aperture calculation. A number of different tools have been built, at LHC, KEKB and in modern synchrotron light sources, for optics correction on and off-momentum: it is very important the exchange of knowledge between the two communities.

The machine model, built by simulations, must be accurate in order to be able to reproduce the measurements and to perform needed corrections and tuning. Continuous work on optics and model understanding is very important to improve the performances. Turn-by-turn measurements are needed for optimum correction of closed orbit, coupling, vertical dispersion and β-beating.

Understanding the off-momentum optics is also very important and needed for the optimization of the dynamic aperture.

The impact of the high gradient FF quadrupoles has to be taken into account, both for the alignment tolerances, which may result in a particularly low value, and for their influence on the beam emittance growth.

Last but not least is the luminosity tuning is essential to reach and keep the design performances in colliders. The more the available knobs, the easier will be the tune-up.

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