UNIVERSITY OF LIVERPOOL

Local Interaction Region Coupling Correction for the LHC

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A document submitted in fulfillment of the requirements for the degree of Doctor of Philosophy at the

University of Liverpool School of Physical Sciences

January 22, 2022

For/Dedicated to/To my…

UNIVERSITY OF LIVERPOOL

Abstract

CERN
School of Physical Sciences

Doctor of Philosophy

Local Interaction Region Coupling Correction for the LHC

by Felix SOUBELET

Lorem ipsum.

Acknowledgements

First and foremost,

"Just don't forget to eat and sleep."

Lee Robert Carver.

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List of Abbreviations

ABP	CERN's **A**ccelerators and **B**eam **P**hysics group
AD	**A**ntiproton **D**ecelerator
ALICE	**A** **L**arge **I**on **C**ollider **E**xperiment
ATLAS	**A** **T**oroidal **L**HC **A**pparatu**S**
AWAKE	**A**dvanced **WAK**efield **E**xperiment
BE	CERN's **BE**ams department
BPM	**B**eam **P**osition **M**onitor
CERN	**E**uropean **O**rganization for **N**uclear **R**esearch
CMS	**C**ompact **M**uon **S**olenoid
DA	**D**ynamic **A**perture
ELENA	**E**xtra **L**ow **EN**ergy **A**ntiproton ring
HERA	**H**adron-**E**lectron **R**ing **A**ccelerator
HiRadMat	**Hi**gh **Rad**iation to **Mat**erials
HL-LHC	**H**igh **L**uminosity **L**arge **H**adron **C**ollider
HSS	CERN's **H**adron **S**ynchrotron **S**ingle particle effects section
IP	**I**nteraction **P**oint
IR	**I**nteraction **R**egion
ISOLDE	**I**sotope **S**eparator **O**n **L**ine **DE**tector
LEIR	**L**ow **E**nergy **I**on **R**ing
LHC	**L**arge **H**adron **C**ollider
LHCb	**L**arge **H**adron **C**ollider **b**eauty
MAD	**M**ethodical **A**ccelerator **D**esign
n-TOF	**N**eutron **T**ime **Of** **F**light
OMC	**O**ptics **M**easurements and **C**orrections
PS	**P**roton **S**ynchrotron
PTC	**P**olymorphic **T**racking **C**ode
RDT	**R**esonance **D**riving **T**erm
SPS	**S**uper **P**roton **S**ynchrotron

Introduction

Some paragraph of text here. Figures to include:

FIGURE 1: The CERN Accelerator Complex as of 2020. This graphic indicates the first year of operation for each accelerator, as well as its circumference. Not to scale.

FIGURE 2: Cross-section of an LHC superconducting dipole magnet (see https://cds.cern.ch/record/40524).

FIGURE 3: The LHC ring with the purpose of the main sections. Not to scale.

As mentioned, each Insertion Region is separated from the previous one by an arc and has its own purpose:

1. IR1 houses the ATLAS experiment
2. IR2 houses the ALICE experiment and the injection of Beam1
3. IR3 houses the off-momentum collimation cleaning (ref https://accelconf.web.cern.ch/ipac2016/doi/ IPAC2016-WEPMW007.html)
4. IR4 houses the RF cavities to accelerate the beams
5. IR5 houses the CMS experiment
6. IR6 houses the beams extraction to the dumps (ref https://cds.cern.ch/record/1392619)
7. IR7 houses the betatronic collimation cleaning (ref https://cds.cern.ch/record/1056681)
8. IR8 houses the LHCb experiment and the injection of Beam2

FIGURE 4: Integrated luminosity in the four experiments of the LHC during the 2017-2018 LHC Run 2.

FIGURE 5: Beam positions around the two high luminosity Interaction Points during the 2018 LHC Run. The dipoles are represented by blue rectangles while the quadrupoles by red ones.

0.1 The CERN Accelerator Complex and its Upgrade

0.1.1 An Overview of CERN History

0.1.2 The Large Hadron Collider and its Injectors

0.1.3 The Concept of Luminosity

0.1.4 The LHC Performance and the HL-LHC Upgrade

0.2 Optics Measurements and Corrections in the LHC

0.2.1 The need

0.2.2 The practice

0.2.3 ETC

Chapter 1

Theory of Single-Particle Beam Dynamics in the Large Hadron Collider

Beam dynamics is a field of accelerator science which is significant for the design, operation, performance, and protection of an accelerator. In this section an overview is given of the theories of beam dynamics which are relevant to the material presented in this thesis. The chapter begins with a description of the linear dynamics, then progresses to deal with aspects of the non-linear dynamics, concluding with a discussion of the luminosity.

1.1 Linear Beam Dynamics

Define concept: bend and focus particles to have them remain within the aperture tolerance of the machine. Bend with dipoles, focus with quadrupoles typically. Figure 1.1 illustrates the Frenet-Serret coordinate system traditionally used in linear beam dynamics.

FIGURE 1.1: Coordinate system for linear accelerator optics.

Coordinate system travels longitudinally with the particle, along a reference trajectory defined by an "ideal" / "reference" / "synchronous" particle. Define s as longitudinal / curvilinear coordinate. Define $\rho(s)$ local radius of curvature (depends on $\mathbf{B}$ and varies along ring). Define $(x, x\prime, y, y\prime)$, coordinates of transverse phase space: x and y are particle coordinates in the transverse planes (transverse displacement). $x^{'}$ and $y^{'}$ are "divergent angles" (says Ewen) in the x and y plane (differentiation with respect to s).

In linear regime, dipoles define ideal orbit for particle of *reference momentum* p_0. Ideal orbit goes through magnetic center of all elements and comes back on itself after a revolution, and is called a *closed orbit*. In practice dipolar errors (and more) will distort the real closed orbit from the ideal designed orbit. Particles within the beam are distributed in amplitude (the beam occupies a finite area in $(x, x\prime, y, y\prime)$ phase space). The closed orbit defines the path of a particle with zero amplitude within the beam. In practice particles oscillate around the closed orbit because of the focusing forces. In the LHC this focusing is provided predominantly by quadrupole magnets.

From Ewen: quadrupolar fields acting on charged particles displaced from the central axis provide a restoring (focusing) force proportional to the displacement in one transverse plane, while simultaneously providing a divergent (defocusing) force in the other. Tradition: a quadrupole focusing in the horizontal plane and defocusing in the vertical is referred to as a *focusing quadrupole*. A quadrupole defocusing in the horizontal plane but focusing in the vertical is referred to as a *defocusing quadrupole*. An alternating arrangement of focusing and defocusing quadrupoles, referred to as a FODO lattice, can create a net focusing in both planes [ref 18 ewen]. Figure 1.2 illustrates magnetic fields in an idealized dipole and quadrupole, together with the forces exerted on a positively charged particle travelling into the page.

FIGURE 1.2: Magnetic fields and forces in an idealized dipole (having a $cos(\phi)$ current distribution in the circular coil) and an idealized focusing quadrupole (having a $cos(2\phi)$ current distribution in the circular coil). Current in the dipole and quadrupole coils are indicated in colour. Forces exerted by the magnet on a positive charge travelling into the page are illustrated. Adapted from [19].

In circular machine focusing from quads is periodic in s with a period of max the circumference of the machine. Motion in the transverse plane is described by Hill's equation, Eq.(1.1), where $k(s)$ is a periodic coefficient describing the restoring force due to the distribution of focusing fields around the ring.

$$u'' \pm k(s)u = 0; \quad u = x, y; \quad u' = \frac{\mathrm{d}u}{\mathrm{d}s} \tag{1.1}$$

Solutions to Hill's equation take the form of Eq.(1.2),

$$\begin{aligned} x &= \sqrt{\beta_x(s)\epsilon_x}\cos\left(\phi_x(s) + \phi_{x_0}\right) \\ y &= \sqrt{\beta_y(s)\epsilon_y}\cos\left(\phi_y(s) + \phi_{y_0}\right) \end{aligned} \tag{1.2}$$

where ϵ is the emittance of a particle and is a constant of the motion at a given energy. $\beta(s)$ is called the *beta-function* and describes the variation of the oscillation envelope around the ring. In particle colliders such as the LHC, it is usual to denote the beta-functions at the Interaction Points (where the beams are made to collide) as β^*.

Particle oscillate around ring, *betatron oscillations*, and the number of oscillations around the ring is the *tune*, $Q_{x,y}$. The tune is defined in Eq.(1.3), where $\Delta\phi_{x,y}$ is the total betatron phase advance undergone by a particle during one revolution around the accelerator ring.

$$Q_{x,y} = \frac{1}{2\pi}\Delta\phi_{x,y} = \frac{1}{2\pi}\oint\frac{\mathrm{d}s}{\beta_{x,y}(s)} \tag{1.3}$$

Figure 1.3 shows a tracking simulation of a particle undergoing such betatron oscillations in the LHC Arc12. Dipole errors were added which have distorted the closed orbit away from the ideal path.

FIGURE 1.3: Tracking simulation in LHC Arc12 of a particle undergoing betatron oscillations.

Define the *gamma-function* $\gamma(s)$ which describes the envelope of oscillations in $x\prime$ and $y\prime$. Both are related by the *alpha-function*:

$$\alpha_{x,y} = -\frac{1}{2}\frac{\mathrm{d}}{\mathrm{d}s}\beta_{x,y}(s) = \sqrt{\gamma_{x,y}(s)\beta_{x,y}(s) - 1} \tag{1.4}$$

In linear regime, trajectories are ellipses in phase space $(x, x\prime, y, y\prime)$. $\alpha(s)$, $\beta(s)$, $\gamma(s)$ and ϵ define the equation of the ellipse, Eq.(1.5). Figure 1.4 shows a schematic illustration of the phase space ellipse.

$$\gamma_u(s)u^2 + 2\alpha_u(s)uu' + \beta_u(s)z'^2 = \epsilon \quad \text{where } u = x, y \tag{1.5}$$

FIGURE 1.4: Phase space ellipse in the transverse z, $z\prime$ plane, where z represents either x or y.

Say emittance (ϵ) defines phase space ellipse area. Liouville's theorem: phase space volume (ellipse area) is constant in a closed system. In the LHC, protons, little synchrotron radiation [ref 20 ewen] we can consider emittance a constant (but at multi-TeV energy radiation emission may become non-negligible). Acceleration -> no more Liouville and *physical emittance* (ϵ) will reduce with increasing energy. One can construct *normalized emittance* (ϵ_γ) which is invariant with beam energy. See Eq.(1.6), where β_{rel} and γ_{rel} are the relativistic beta and gamma functions:

$$\epsilon_\gamma = (\beta_{\text{rel}}\gamma_{\text{rel}})\epsilon \tag{1.6}$$

For a specific particle we use *single particle emittance*. Different particles may have different ones. They will go through (undergo?) betatron oscillations of different amplitudes. We can define *beam emittance*: typically defined as the emittance corresponding 1σ amplitude in assumed Gaussian particle distribution.

The phase space trajectory of a particle depends on $\alpha(s)$, $\beta(s)$, and $\gamma(s)$. The transformation to *Courant-Snyder coordinates* [ref 21 ewen] (sometimes called *normalized Courant-Snyder coordinates*) removes this dependency, see Eq.(1.7),

$$\begin{pmatrix} \hat{u} \\ \hat{u}' \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{\beta_u(s)}} & \frac{\alpha_u(s)}{\sqrt{\beta_u(s)}} \\ 0 & \sqrt{\beta_u(s)} \end{pmatrix} \begin{pmatrix} u \\ u' \end{pmatrix} \quad \text{where } u = x, y \tag{1.7}$$

where the Courant-Snyder coordinates are denoted by ˆ. In this new system particles follow circular trajectories in phase space.

Say particles within the beam have a distribution in momentum, around designed momentum p_0. For a particle that doesn't have p_0 we define the *relative momentum deviation* δ, Eq.(1.8):

$$\delta = \frac{p - p_0}{p_0} \tag{1.8}$$

Define *magnetic rigidity*: relates magnetic flux $\mathbf{B}$ (perpendicular to motion) with local radius of curvature and particle momentum $\mathbf{P}$. See Eq.(1.9):

$$|\mathbf{B}\rho| = \frac{|\mathbf{P}|}{e} \tag{1.9}$$

Say difference to p_0 introduce *chromatic* errors into the beam dynamics. The most important one is *dispersion*. Different momenta(um?) -> different beam rigidity -> different local radius of curvature in dipoles -> different orbit.

Deviation to reference orbit is defined by the *Dispersion function*, $D(s)$ [ref 23 ewen]. In a region of non-zero dispersion the contribution to the orbit of a particle is described by Eq.(1.10):

$$\begin{aligned} \Delta x_{\text{dispersion}} &= D_x(s)\delta \\ \Delta y_{\text{dispersion}} &= D_y(s)\delta \end{aligned} \tag{1.10}$$

The orbit of any given particle is defined by Eq.(1.11):

$$u = u_{\text{betatronic}} + u_{\text{dispersion}} + u_{\text{closed orbit}}|_{\delta=0} \tag{1.11}$$

1.2 Non-Linear Magnetic Multipoles

1.3 Formalism of Non-Linear Beam Dynamics

1.4 Phenomenology of Non-Linear Beam Dynamics

1.4.1 Chromaticity

1.4.2 Detuning with Amplitude

1.4.3 Decoherence

1.4.4 Resonances and RDTs / CRDTs

1.4.5 Linear Betatron Coupling

1.5 Luminosity

Chapter 2

The LHC Accelerator

Some paragraph before the first section.

2.1 The LHC Lattice

2.1.1 The LHC Arcs

2.1.2 The LHC Insertion Regions

2.1.3 Error Estimates for the LHC Lattice

2.2 The LHC Experimental Interaction Regions (EIR)

2.2.1 Interaction Point

2.2.2 The LHC Triplet

2.2.3 Separation Dipoles

2.2.4 Matching Section

2.2.5 Dispersion Supressor

2.3 The Operational Cycle of the LHC

2.4 Beam Instrumentation in the LHC

Chapter 3

Interaction Region Local Coupling Correction in the LHC

Some paragraph before the first section.

3.1 Linear Coupling in the Interaction Regions

3.1.1 Overview of IR Difficulties (phase advances suck, DFFT of x -jpx, no instruments)

3.1.2 Twiss with Coupling and Ripken parameters

3.1.3 Equivalency of Ripken and Tracking when looking at beam size

3.1.4 Plan for Correction (or later?)

3.2 The Hunt for an Observable

3.2.1 Combined RDTs

Some theory here (see franchi's paper, see michael's paper), it can use DFFT of x/y only. Some studies that it's difficult to use directly (2021.8), maybe sbs?

3.2.2 SbS with combined RDTs and that it works better than with rdts?

3.2.3 Forced RDTs

Why am I looking into this again? Potentially if I have time we can see if using non-compensated stuff gives better corrections. Very optionnal at the moment.

3.2.4 Conclusioon that we might need to look at outside observables

3.3 Proof of Principle: Measurement and Correction of Local Coupling in the LHC Interaction Regions

3.3.1 Relating to outside observables

3.3.2 Beam-Based Study of IRs Local Coupling

3.3.3 Simulations of IRs Local Coupling

3.4 Impact of Local Linear Coupling Correction on Beam Lifetime/Quality?

3.4.1 Impact on Tune Footprint (hopefully minimal)?

3.4.2 Impact on Dynamic Aperture (hopefully none)?

3.4.3 Impact on Luminosity (hopefully yayyy)?

3.5 Operational Correction Procedure(s)

3.5.1 Full Procedure Steps

3.5.2 Developped Software

3.6 Containment Plan in Case of MQSX Failures

3.6.1 Lifetime Considerations of MQSX Elements

See F. Cerutti slides (slides 22, 23, and 12 to 16) at 2021 Evian Workshop (https://indico.cern.ch/event/107783

Explain that there is a real risk that some of our MQSX mqgnets die, especially the ones in IR1 (ATLAS). In this case, we will need a containment plan, as not only are they used for the but the local corrections they are a part of are a baseline for us to compute higher order terms corrections. This means in simple terms that MQSX dying will impact the LHC's operations, and potentielly shut the machine down.

3.6.2 Containment Concept: Tilt of Triplet Elements

Talk about what we want to do (tilt Q3 or Q2) to induce a skew component + simulation results. Found settings of the Q3 or Q2 that would negate the MQSX one determined in beam test / commissioning. The idea is if we

Also show we have a very minimal beta-beating from this. Show we have had a look at different optics (30cm and 1m betastar) and it works for both.

3.6.3 Operational Constraints

The LHC systems are not meant for this, but for vertical alignment of these magnets! System relies on bellows: 2 pieds IP side and 1 pied other side for Q2 for instance. This means that inducing rotation is not only not the design purpose, but also imperfect (on move les 2 pieds pour essayer de mimer une rotation mais c'est pas parfait). Would be very good to have a plot of the assemblies here to show what I mean. Ask MP people? See in the LHC design report?

It is considered by MP people to be quite dangerous to do this unless forced to (read an MQSX dies), especially in cold mass, as if we damage the belows then we're in for 1 year of shutdown to repair it. Say that for these reasons we decided not to test this concept in the machine, unfortunately.

3.7 Conclusions

Chapter 4

Machine Learning for Interaction Region Local Coupling

Some paragraph before the first section.

4.1 Relevant Theory of Machine Learning

4.2 Identification of Sources with Machine Learning

Which magnets are tilted, eventually how tilted are they?

4.3 Prediction of Corrections for Local Coupling

Should start here with a simple approach: linear behavior, simple errors only in the region and a Regression model. Show results. However move on to add that we need realistic scenario for the training data and that includes nonlinear errors, so maybe another type of model would be better suited. Explain additions to simulations for training data, changes to model approach. Show results, do a comparison and highlight improvements.

4.4 Reinforcement Learning for Segment by Segment

Currently the SbS needs manual input, should be a good ground for a RL model to find its way. Forget about Jaime's automatic matching, never got it to work anyway.

4.5 Conclusions

Chapter 5

Experimental Measurement and Correction of Interaction Region Local Coupling in the LHC Run III

Some paragraph before the first section.

5.1 Dedicated Measurement and Correction of Local Coupling in IR1 and IR5

5.1.1 Measurement of Local Coupling in the IRs at $\beta^*_{IP} = 0.3m$

5.1.2 Correction of Local Coupling in the IRs at $\beta^*_{IP} = 0.3m$

5.1.3 Application of Machine Learning for Correction at $\beta^*_{IP} = 0.3m$

5.2 LHC Run III Commissioning Experience

5.3 Conclusions

Conclusions

Talk about stuff.

Bibliography

Appendix A

Element Naming Conventions in the LHC

As element names occur often in this document, it is worth spending an appendix detailing the element naming convention in the LHC and HL-LHC. Figure A.1 below shows the established scheme for a segment of the LHC.

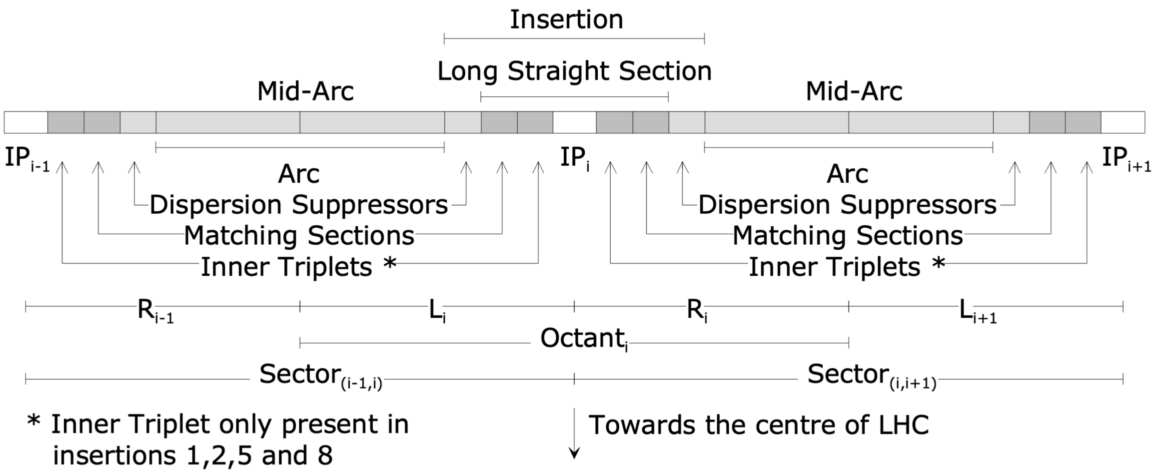

FIGURE A.1: In-depth view of the naming scheme in a segment of the LHC.

The general structure goes as follows:

1. Each octant is divided into two *half-arcs* surrounding an *insertion*.
2. Each octant is divided into a left side and a right side.
3. The center point of some octants is the *Interaction Point* or IP, with their surrounding region sometimes also referred to as *Interaction Region* (IR).

From the perspective of lattice definitions, there are eight IPs, but this is only for notational ease. An interaction point in the strict sense is a point where the two beams collide, which is only a feature of octant 1, 2, 5 and 8 where experiments are run. When an IP or IR is referred to in this document, it is taken for granted that it applies to one of these octants. What all octants nevertheless have in common is that they all have a long straight section in the middle as part of the insertion. The arc can be perceived to be roughly uniform across LHC whereas the long sections differ from octant to octant.

As the base pattern is a FODO lattice, the machine can be broken up into half-cells containing one quadrupole each. In doing so, each half-cell is given a number, where the i^{th} quadrupole away from the center of its octant is associated with the i^{th} half-cell. With this in mind, the general naming convention can be summarized as follows:

- TYPE: Entry specifying the type of element. See Table A.1 for examples.
- SPECIAL: Optional entry which can be used to sub-type an element, e.g. H or V to signify if a corrector is acting on the horizontal or vertical plane.
- EXTRA: Optional entry used to separate between otherwise identically named elements. E.g. A, B, C to separate between three bending magnets in the same half-cell
- LR: Entry specifying which side of the closest IP the element is on. Assumes either L (*left*) or R (*right*).
- OCTANT: Entry specifying the octant the element is a part of. Valid entries are integers from 1 to 8.
- 12: Entry specifying which beam the element is part of. Either 1 or 2, unless the element is shared between the two beams in which case the element name ends with the OCTANT entry.

Element Type	**Prefix**
Bending Magnet	MB
Quadrupole	MQ
Orbit Corrector	MCB
BPM	BPM
Crab Cavity	ACFCA
Drift	DRIFT

TABLE A.1: Example prefixes for different LHC element types.

For instance, the element MQ.25L5.B1 is a quadrupole on the left side of IP5, in the 25^{th} half-cell and for beam 1. The special identifier can be used in multiple ways, for example MQML.10R1.B1 is a different type of quadrupole in half-cell 10, on the right side of IP1 for beam 1. Here the special identifier describes the type of quadrupole. For MCBH.21R5.B1, the special identifier H signifies that it is a horizontal orbit corrector. In the triplet quadrupoles one can notice for instance elements MQXB.A2L1 and MQXB.B2L1. In this case the elements share type MQXB (middle, single aperture inner triplet quadrupole), octant, side of IP and half-cell, which is why they make use of the extra specifiers A and B to tell them apart.

Note that these elements skip the appendage of $.B < 12 >$. These correspond to elements common to both beams, which can only happen in the IR. This is due to the fact that when two beams are brought to collision they pass through the same equipment close to the point of collision.

Appendix B

List of LHC Fills Used for Measurements

One can find in this Appendix the fully detailed list of LHC fills considered for the experimental campaign. Table B.1 reports this list together with the dates, beams intensities and energies, the ??? (IR details), the reason for the following beam dump and some eventual comments.

Fill #	Date	N_b (B1) [p]	N_b (B2) [p]	Energy [GeV]	Dump	Comments
6000	15/04/2022	$5.5 \cdot 10^{12}$	$3.5 \cdot 10^{11}$	450	Normal	None
6000	15/04/2022	$5.5 \cdot 10^{12}$	$3.5 \cdot 10^{11}$	450	Normal	None
6000	15/04/2022	$5.5 \cdot 10^{12}$	$3.5 \cdot 10^{11}$	450	Normal	None

TABLE B.1: List of the LHC fills considered for the experimental campaign.

Appendix C

Appendix C Title

Some content.