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Local Interaction Region Coupling Correction for the LHC and High Luminosity LHC

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For/Dedicated to/To my…

UNIVERSITY OF LIVERPOOL

Abstract

CERN
School of Physical Sciences

Doctor of Philosophy

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by Felix SOUBELET

Lorem ipsum.

Acknowledgements

First and foremost,

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

Lee Robert Carver.

Contents

List of Figures

List of Tables

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 **O**f **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

Some paragraph before the first section.

1.1 Linear Beam Dynamics

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.

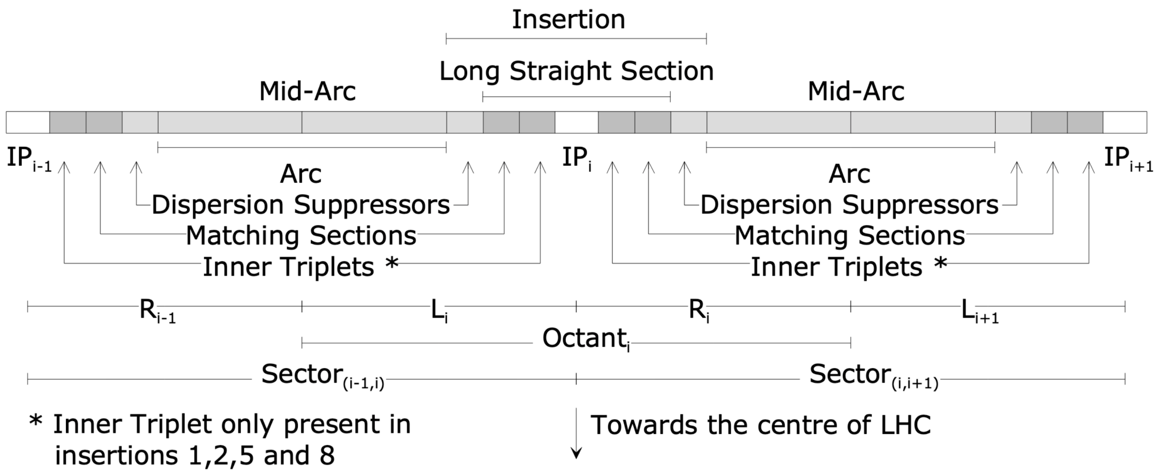

FIGURE A.1: In-depth view of the naming scheme in a segment of the LHC.

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

Appendix B Title

Some content.

Appendix C

Appendix C Title

Some content.