Operational Results of LHC Collimator Alignment using Machine Learning

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Introduction
Large Hadron Collider

- 27 km with 1232 superconducting dipole magnets
- Accelerates and collides two counter-rotating beams at 6.5 TeV
- During Run II beam stored energies higher than 300 MJ
- The magnets and other sensitive equipment protected from quenching and any damage => Collimators
The Collimation System

- 100 collimators aligned
- Precision of less than 50 μm
- Concentrate beam losses in warm locations
- At tight gaps of 1.05 - 3 mm
- Provide 99.998% cleaning efficiency (protons)
To prepare the machine cycle the collimators must be aligned at all machine states:

- **Injection**: 75 collimators + 4 injection protection collimators
- **Flattop**: 75 collimators
- **Squeeze**: 16 tertiary collimators
- **Collisions**: 16 tertiary collimators + 12 physics debris collimators
Beam Instrumentation

- Beam Loss Monitors (BLMs) used to align collimators
- Record beam losses generated by collimators as they touch the beam
- Beam-based alignment (BBA)
Beam-Based Alignment

- Semi-Automatic Alignment
- Fully-Automatic using Machine Learning
Four-stage alignment procedure:

The reference collimator forms a reference cut in the beam halo.

**Beam centre** calculated from final collimator position.

**Beam size** calculated using reference collimator before and after.
Alignment Tasks

Since 2011: Semi-Automatic Alignment

User
Select collimator

User
Select BLM threshold to stop jaw movement

AUTO
Collimator moves towards beam
Movement stops when threshold is exceeded

User
Collimator aligned? No - repeat, Yes - save

BBA alignment of 40+ collimators require 4/5 collimation experts.
Alignment Tasks

Since 2018: **Fully-Automatic Alignment**

- **AUTO** Select collimator

- **AUTO** Select BLM threshold to stop jaw movement

- **AUTO** Collimator moves towards beam
  Movement stops when threshold is exceeded

- **AUTO** Collimator aligned? No - repeat, Yes - save

*Machine Learning*
The LHC

Alignment Spike

Non-Alignment Spike

Data set of 8706 samples from alignment campaigns in 2016 and 2018
Six machine learning models for spike classification were compared

Logistic Regression, Neural Network, SVM, Decision Tree, Random Forest, Gradient Boost

The models were pre-trained on 100 Hz data and are used in real-time for collimator alignments (in 2018 used majority vote)
Machine Learning Features

- Data sample taken when collimator stops moving
  - 100 Hz BLM data
  - 1 Hz Jaw Position (mm)

- 5 features extracted:
  - Spike Height (x1 feature)
  - Exponential Decay (x3 features)
  - Jaw Position in $\sigma$ (x1 feature)

Models achieved over 95% accuracy

Alignment Evolution

- 8 Years of Collimator Alignments
- Fully-Automatic Alignment
  - → 2 Versions
Collimators are aligned before each year of operation during commissioning at all machine states.

**Run I**
- 2011: Semi-Automatic Alignment
- 2012: 12 Hz data available

**Run II**
- 2015: BPMs Introduced
- 2016: 100 Hz data available
- 2018: Fully-Automatic Alignment

**NO Parallelisation**
Fully-Automatic Alignment

• The 1\textsuperscript{st} version was used during commissioning 2018
  → **Sequential** alignment of the collimators in the two beams
  → Used at both **Injection** and **Flat top** commissioning
  → The **beam centres** and **beam sizes** consistent with 2017 commissioning
  → The settings were used during LHC operation in 2018

• The 2\textsuperscript{nd} version was used later in 2018 at **Injection**
  → **Parallel** alignment of collimators restored using crosstalk analysis
  → The **beam centres** and **beam sizes** were compared to 2018 commissioning
Fully-Automatic Alignment Results

Fully-automatic software @Injection

Measured Beam Center (mm)

Measured Beam Size Ratio

Collimators
Fully-Automatic Alignment Results

- **Run I**
  - 2010: 20.5 hours
  - 2011: 17.5 hours
  - 2012: 12.5 hours

- **Run II**
  - 2015: 5.5
  - 2016: 2.9
  - 2017: 2.83
  - 2018: 1.5
  - 2018 Parallel: 0.83

- **Beam 1**
- **Beam 2**

- **2018 Parallel**

- **79 collimators in 50 minutes!**
Conclusions

• Collimators are aligned each year using a beam-based alignment
  \[\rightarrow\] 100 collimators with a precision of less than 50 µm
• In 2018 the beam-based alignment was Successfully Fully-Automated
• Demonstrated full automation does not need presence of (many) experts with the use of Machine Learning
• Successful Parallel Alignment of both beams by analysing crosstalk between collimators
• The full-automation will be used as the default alignment software for the start-up of the LHC in 2021
• This software with Machine Learning has also been used to align collimators with 4 degrees of freedom (Angular Alignment)

G. Azzopardi, et al., Automatic Angular Alignment of LHC Collimators, ICALEPCS’17
Thank you for your attention!

Questions?
Backup Slides
The Collimation Hierarchy
Fully-Automatic Alignment Implementation

Crosstalk Analysis for Parallel Selection

- Data set of 650 samples
- RMS smoothed BLM signals of all collimators >5E-6 Gy/s analysed
- Preliminary analysis -> Crosstalk if mean loss >5% of aligned collimator

Automatic Threshold Selection

- Data set of 1778 samples
- EWMA used to assign priority to the data and RMS to extract information
- >90% of auto selected thresholds show insignificant difference from users
Fully-Automatic Alignment Implementation

(FESA - Real-time control framework to develop LHC ring front-end equipment software)
Sequential Alignment Results

Fully-automatic software v1.0 @Injection (06/04/2018)
Version 1: Sequential Alignment

Fully-automatic software v1.0 @Injection (06/04/2018)

79 collimators in 74 minutes!
Version 1: Sequential Alignment

Fully-automatic software v1.0 @Flat top (08/04/2018)

79 collimators in 149 minutes!
Version 2: Parallel Alignment

Fully-automatic software v2.0 @Injection (13/09/2018)

79 collimators in 50 minutes!
Angular Alignment Implementation

• Collimators have always been aligned assuming no tilt angle w.r.t the beam

  → Angular alignment is key to tighten hierarchy

• Three novel angular alignments to find best angle:

  1. Using a reference collimator - Offset in tank
  2. At maximum angles - Quick centre calculation
  3. Using a jaw as reference - Asymmetries in collimator

• The algorithms were implemented using the fully-automatic alignment

G. Azzopardi, et al., *Automatic Angular Alignment of LHC Collimators*, ICALEPCS'17
Angular Alignment Results

1 collimator at 41 angles using 3 methods @Injection: 28 minutes

Relative timeseries chart for applied angular alignment methods

- BPM
- Method 1
- Method 2
- Method 3: left jaw
- right jaw
Ion Beams Alignment

-Aligned IR7 collimators with Ion beams in collisions
-Compared results to proton beam commissioning at flat top from 2018
-Consistent results for majority of collimators
  → Some indicate a difference between ±150 µrad and ±200 µrad

Fully-automatic software v1.0 @Collisions (06/11/2018)