Operational Results of LHC Collimator Alignment using Machine Learning

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with contributions from:
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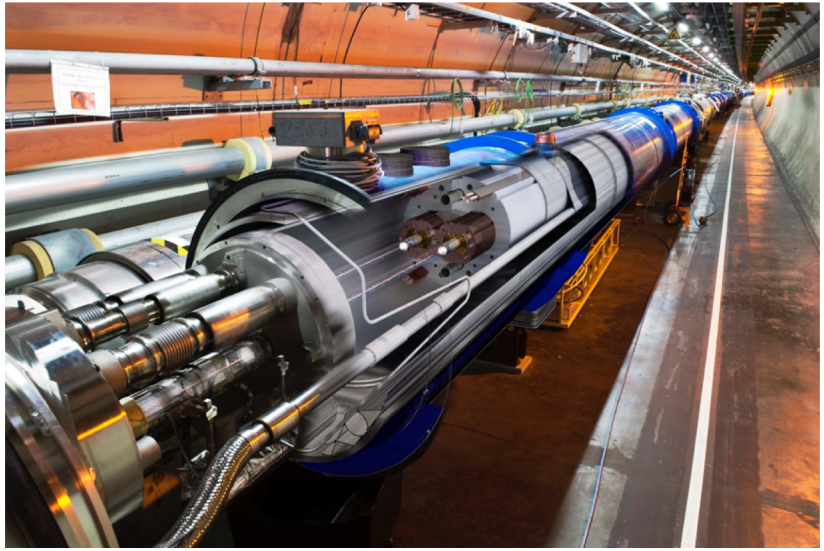
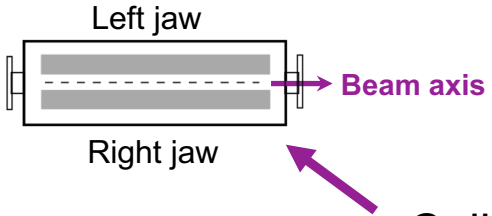
Introduction

Large Hadron Collider

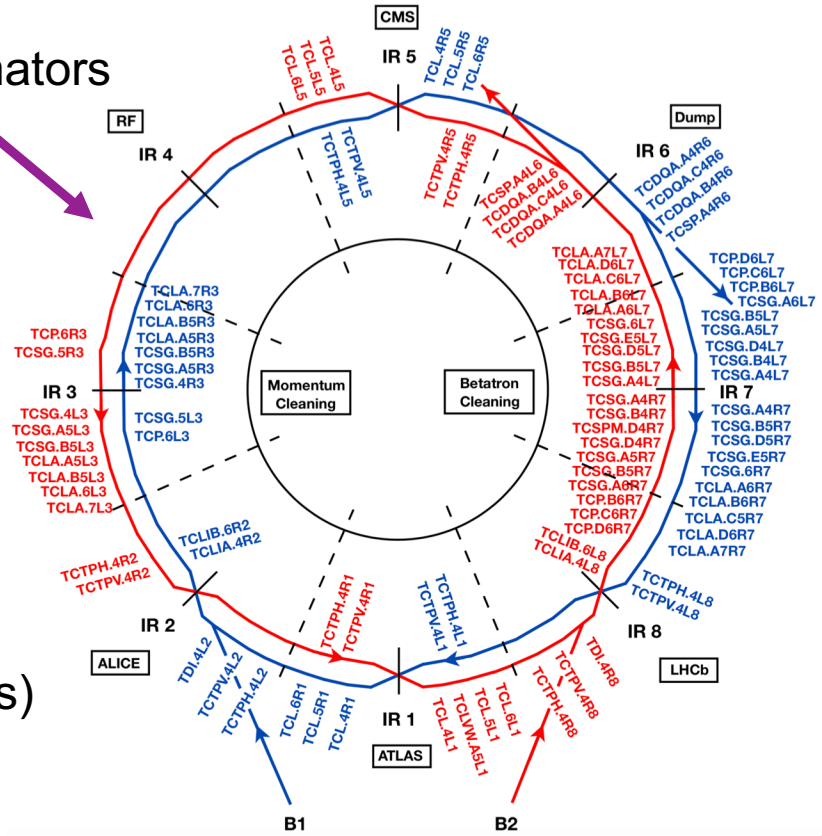


- 27 km with 1232 superconducting dipole magnets
- Accelerates and collides two counter-rotating beams at 6.5 TeV
- During Run II beam stored energies higher than 300 MJ
- The magnets and other sensitive equipment protected from quenching and any damage **=> Collimators**

The Collimation System

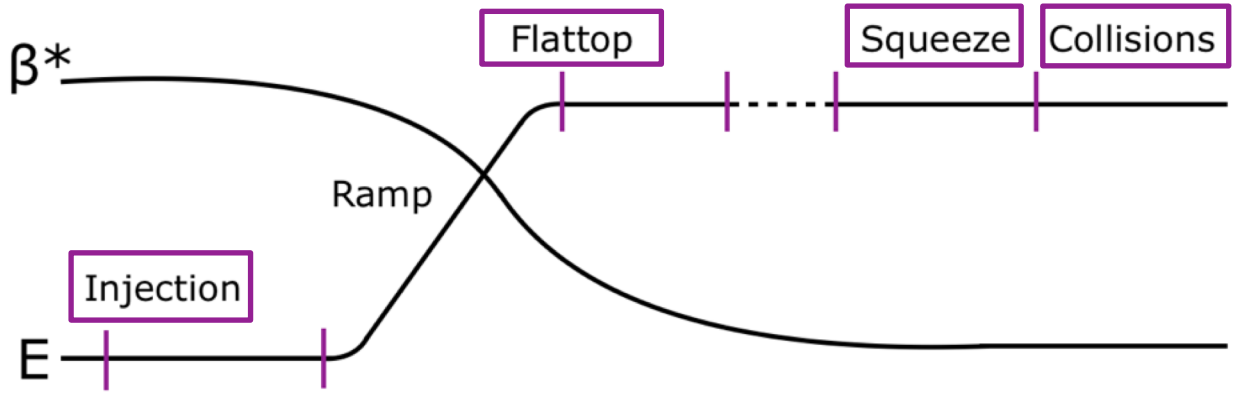


LHC Collimators



- 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)

LHC Machine Cycle

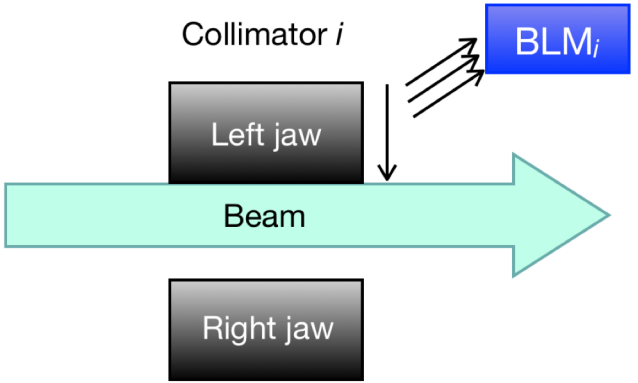


To prepare the machine cycle the collimators must be aligned at all machine states:

- 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

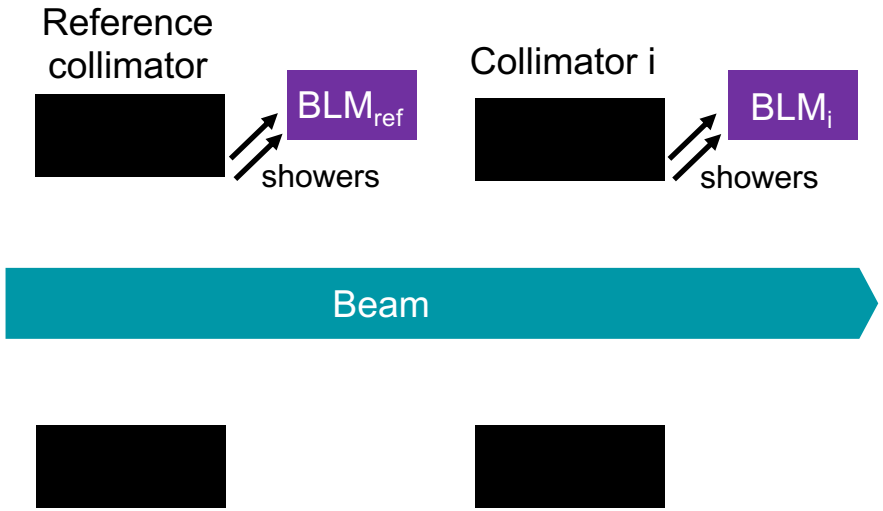
- Semi-Automatic Alignment
- Fully-Automatic using Machine Learning

Beam-Based Alignment

Four-stage alignment procedure:

4

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

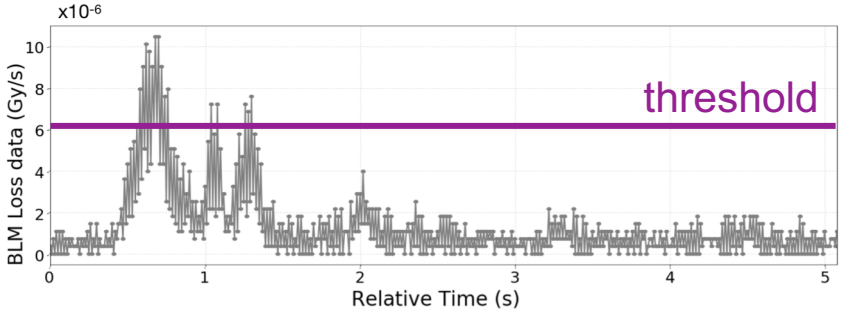
Since 2018: **Fully**-Automatic Alignment

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

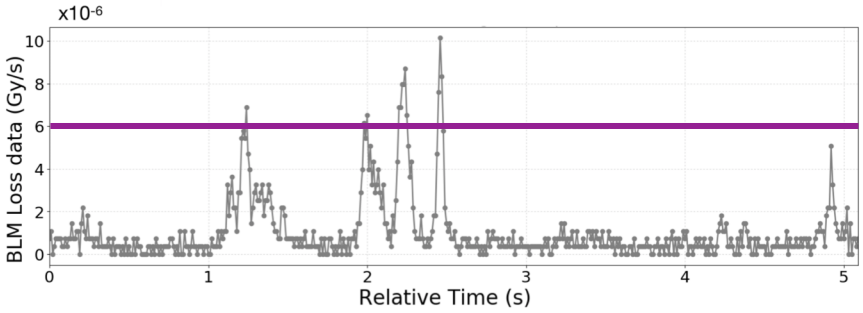
Machine Learning

Machine Learning

Alignment Spike



Non-Alignment Spike



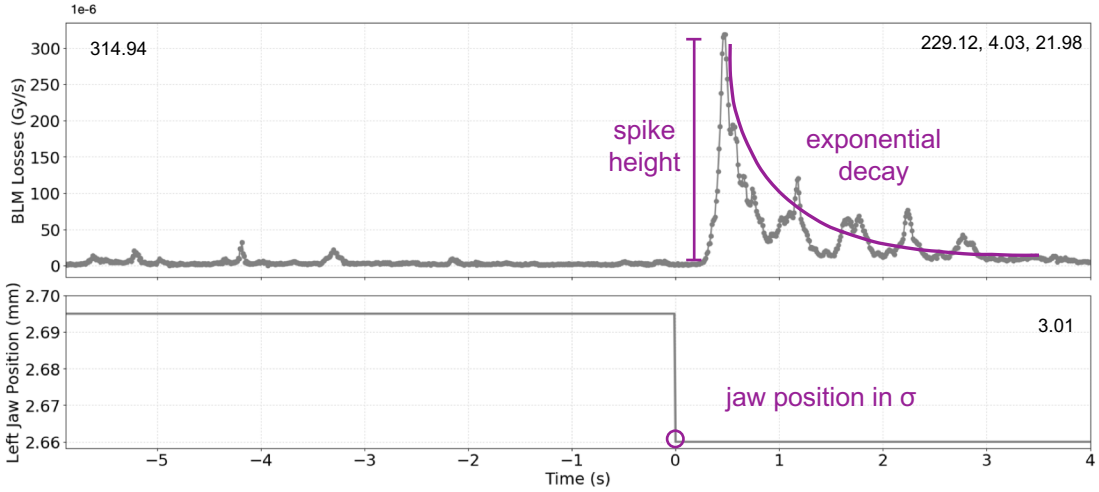
- Data set of 8706 samples from alignment campaigns in 2016 and 2018
- Six machine learning models for spike classification were compared

  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 σ *(x1 feature)*

Models achieved over 95% accuracy

G. Azzopardi, et al., *Automatic Spike Detection in Beam Loss Signals for LHC Collimator Alignment*, NIM-A, 2019

Alignment Evolution

- 8 Years of Collimator Alignments
- Fully-Automatic Alignment
  - ⇢ 2 Versions

Alignment Evolution

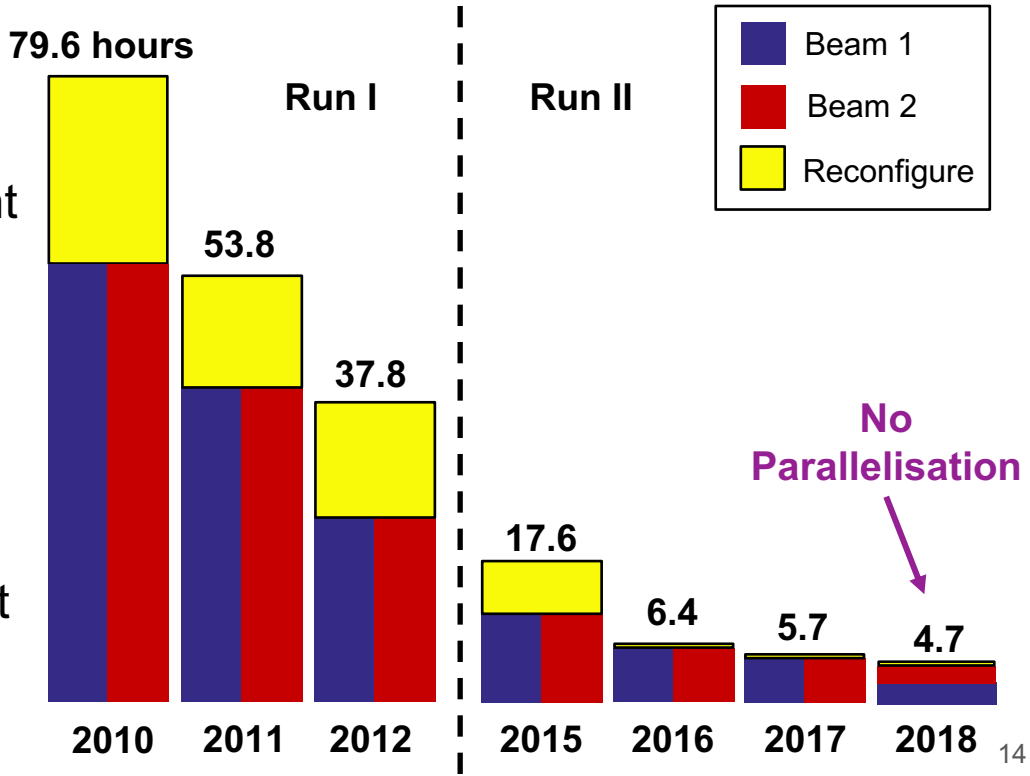
Collimators are aligned before each year of operation during commissioning at all machine states

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

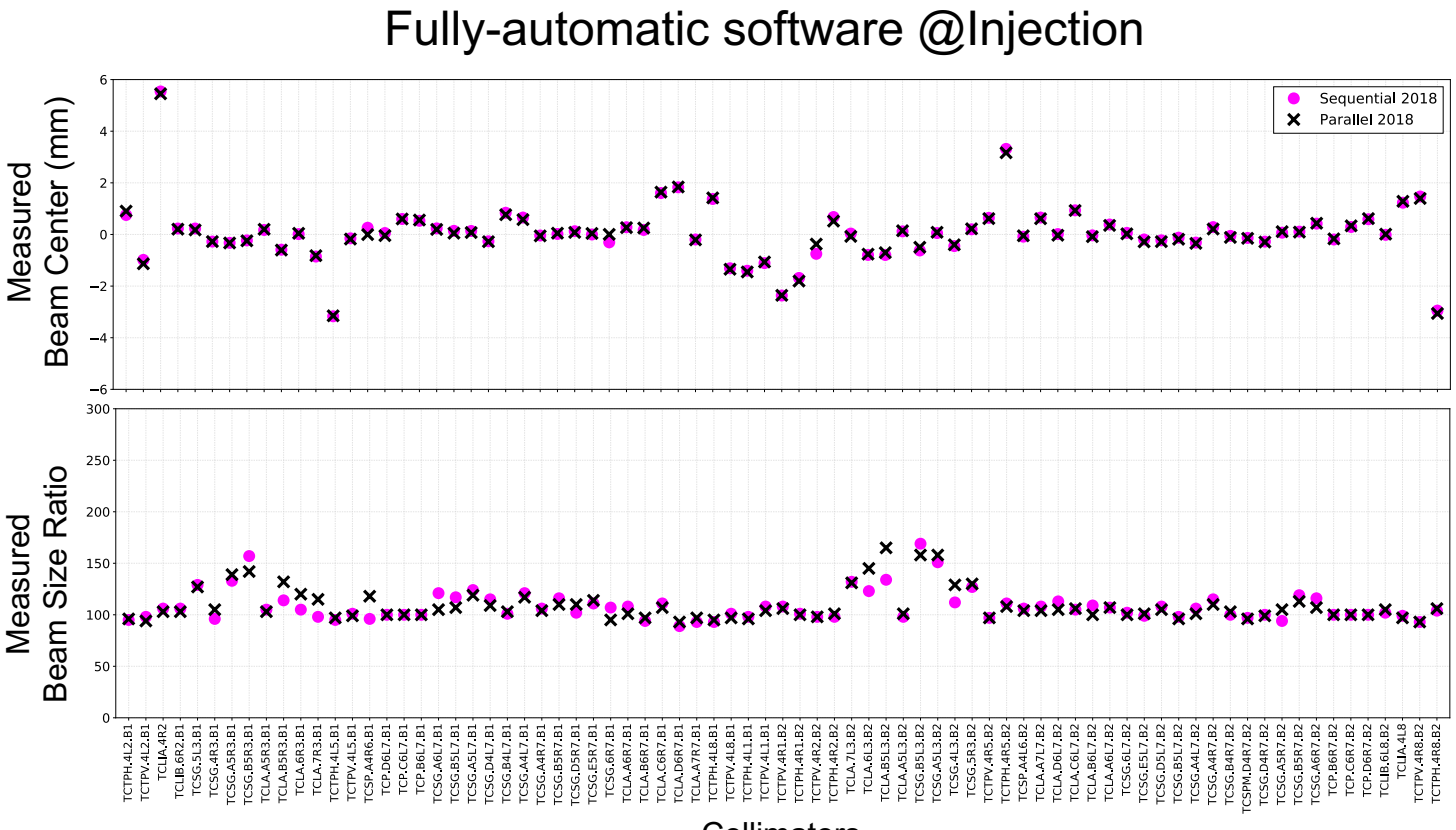


Fully-Automatic Alignment

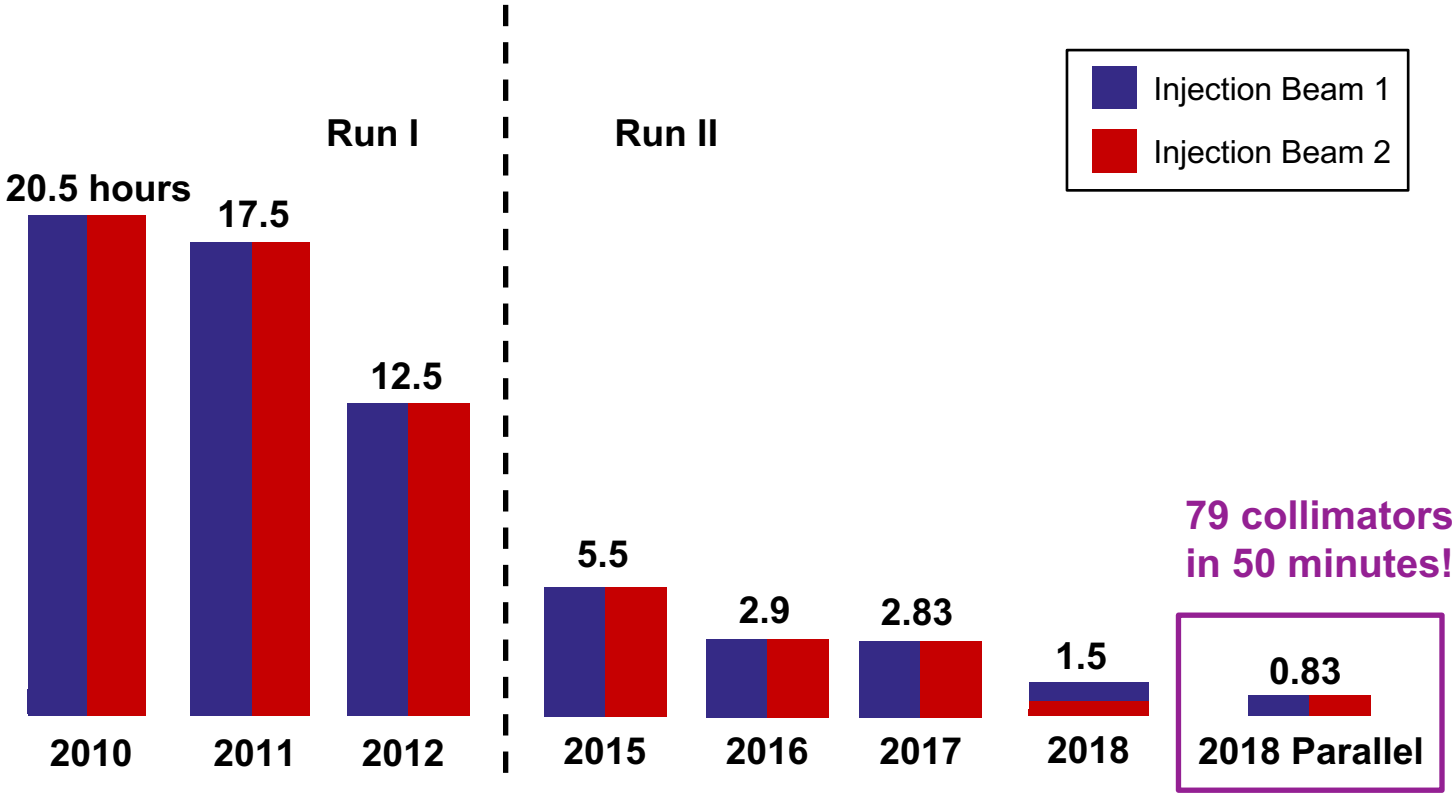
- The 1st version was used during commissioning 2018
  - ⇢ **Sequential** alignment of the collimators in the two beams
  - ⇢ Used at both **Injection** and **Flat top** commissioning
  - ⇢ The **beam centres** and **beam sizes** consistent with 2017 commissioning
  - ⇢ The settings were used during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

- The 2nd 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 Alignment Results



Conclusions

- Collimators are aligned each year using a beam-based alignment
  - ⇢ 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**)

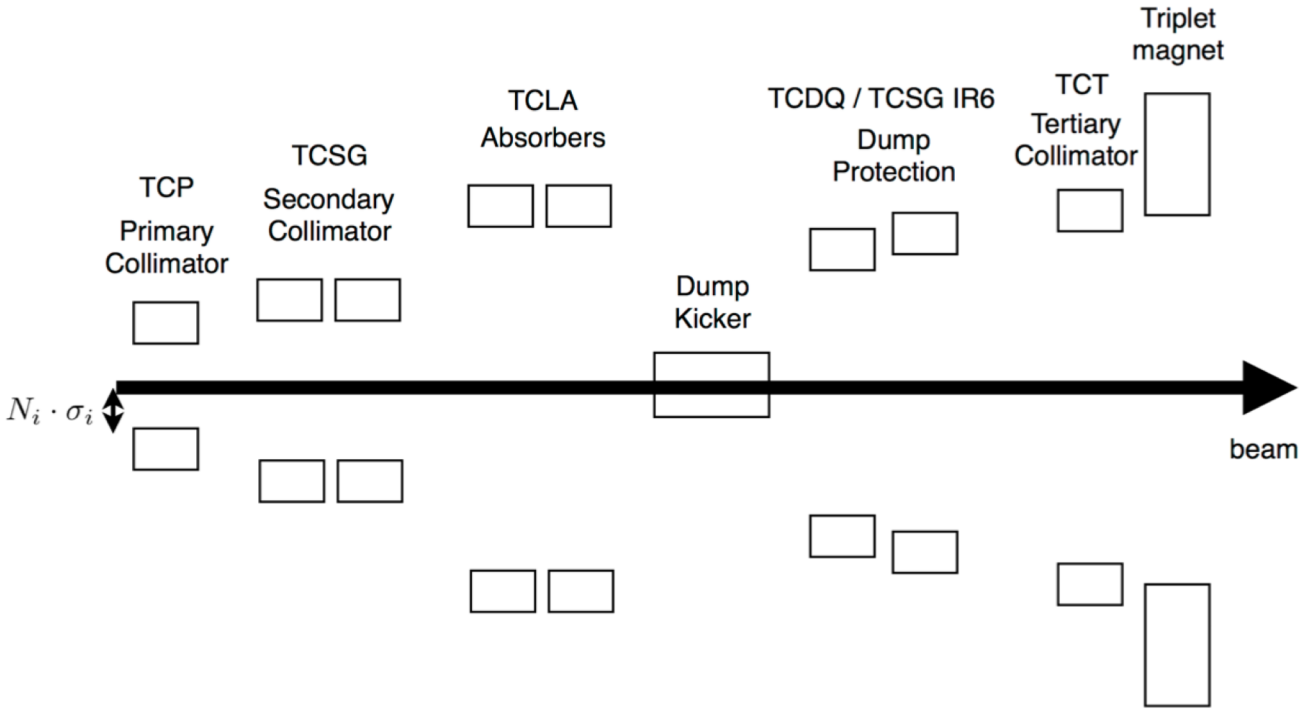
G. Azzopardi, et al., *Automatic Angular Alignment of LHC Collimators*, ICALEPCS'17

Thank you for your attention!

Questions?

Backup Slides

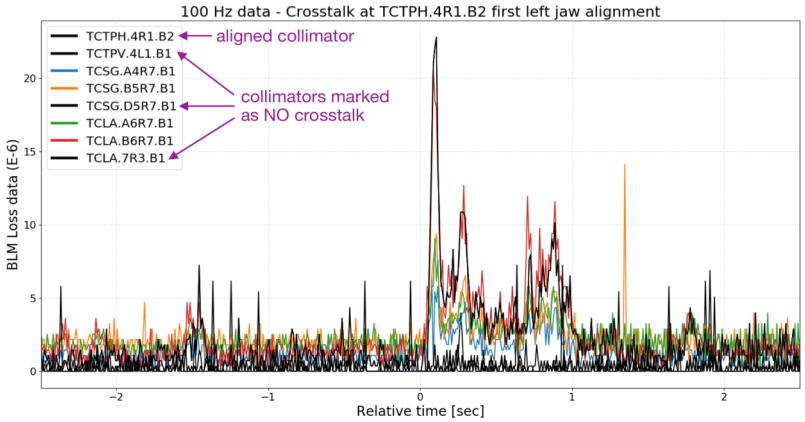
The Collimation Hierarchy



Fully-Automatic Alignment Implementation

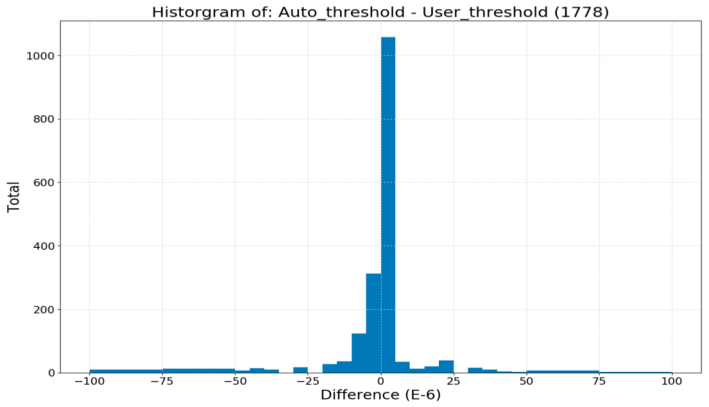
Crosstalk Analysis for Parallel Selection

- 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

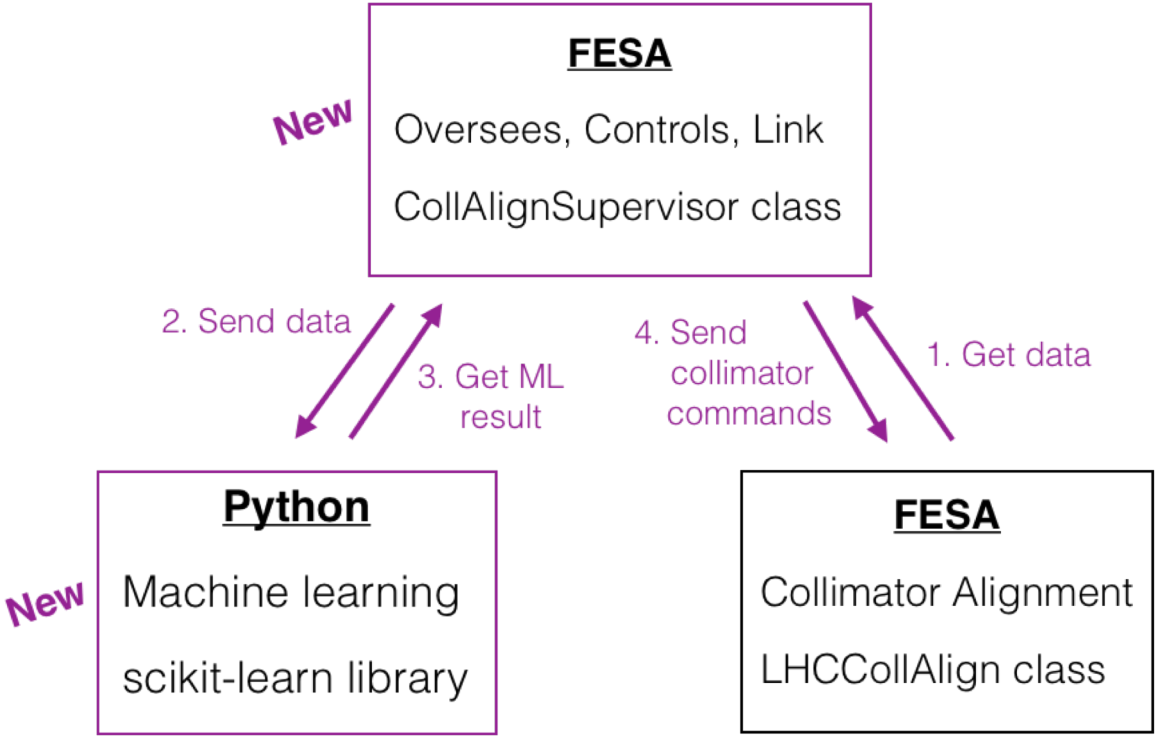


Automatic Threshold Selection

- 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



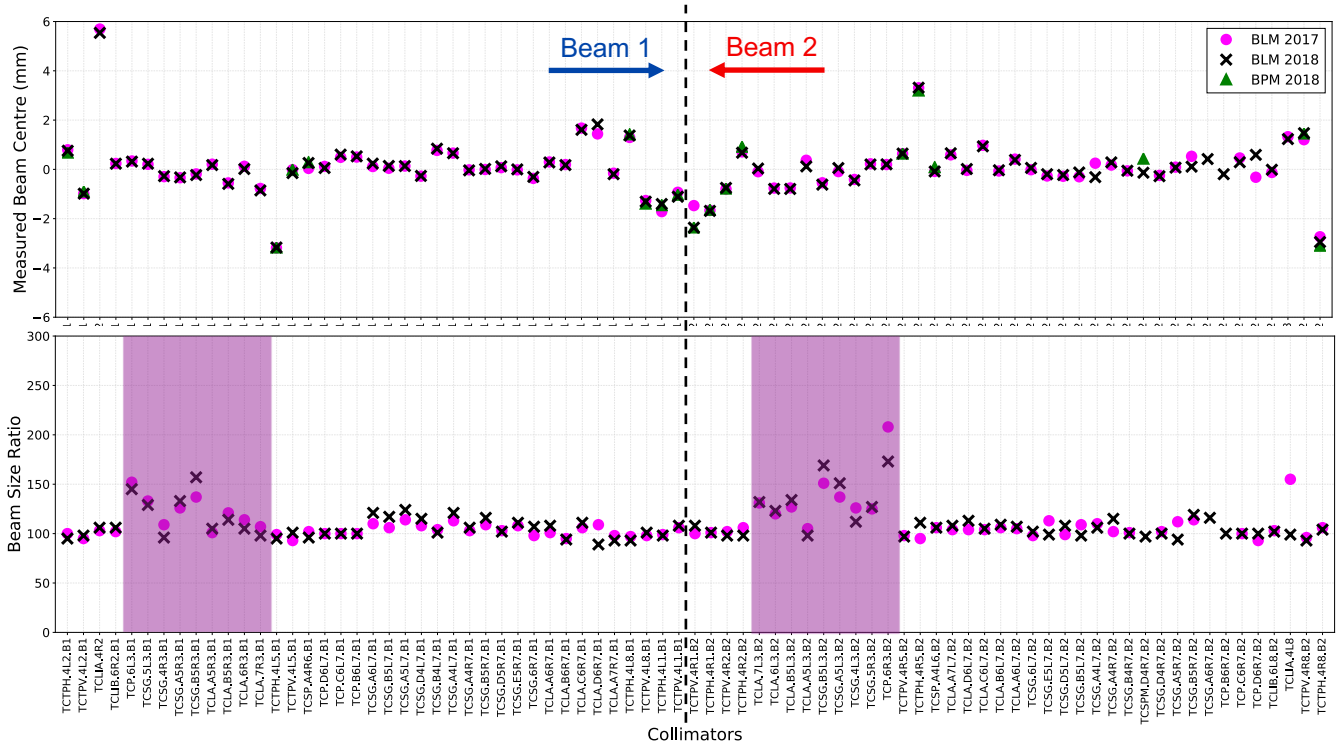
Fully-Automatic Alignment Implementation



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

Sequential Alignment Results

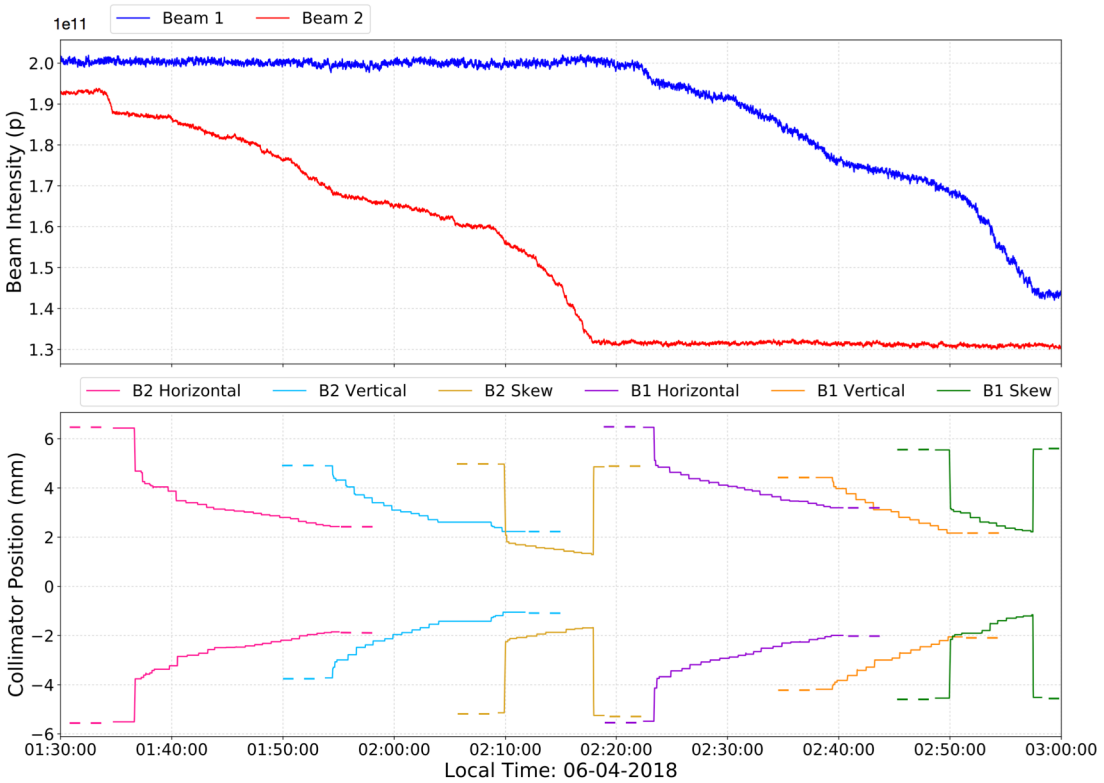
Fully-automatic software v1.0 @Injection (06/04/2018)



Version 1: Sequential Alignment

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

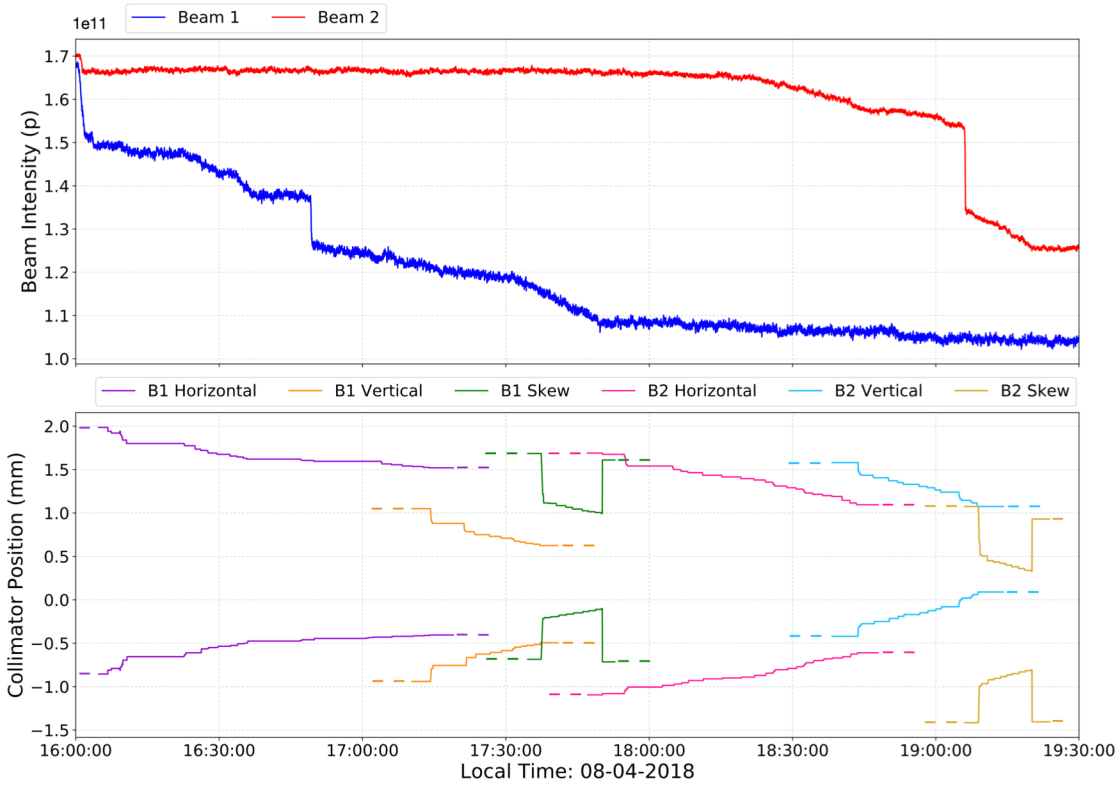
79 collimators in 74 minutes!



Version 1: Sequential Alignment

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

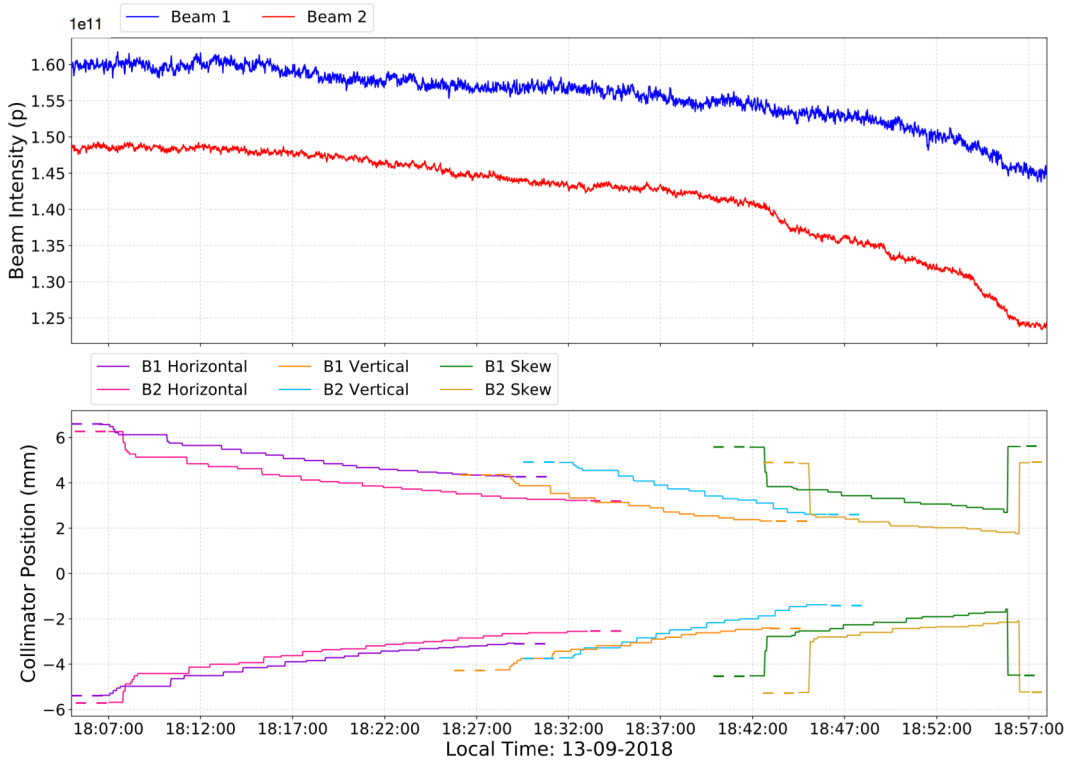
79 collimators in 149 minutes!



Version 2: Parallel Alignment

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

79 collimators in 50 minutes!



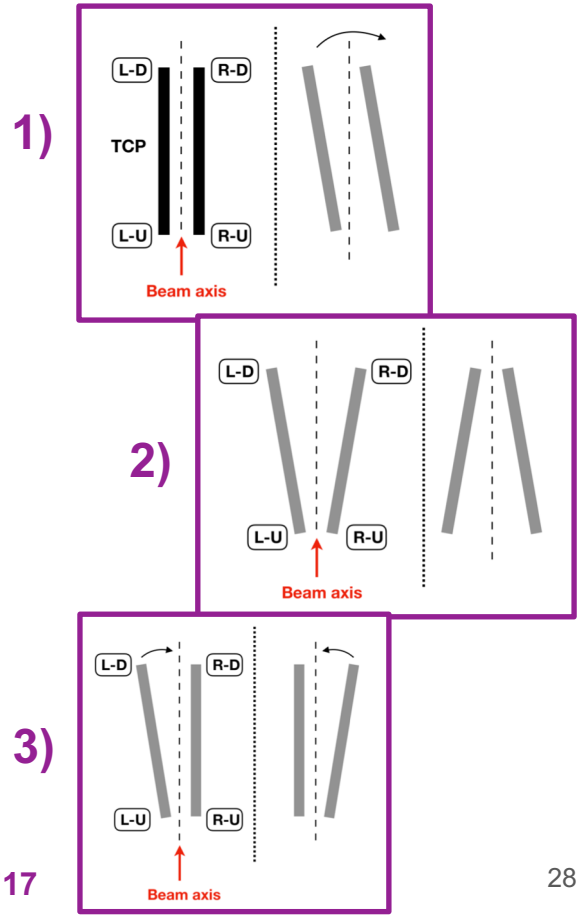
Angular Alignment Implementation

- 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

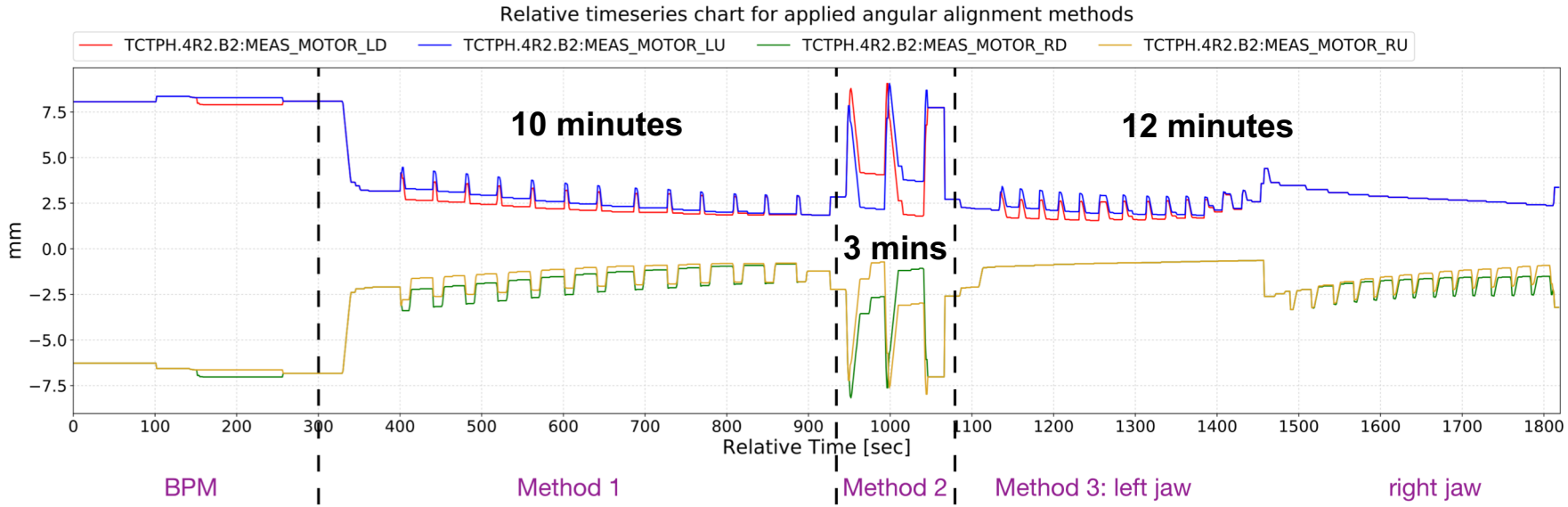
- The algorithms were implemented using the fully-automatic alignment



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



Ion Beams Alignment

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

- 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