Software Architecture for Automatic LHC Collimator Alignment using Machine Learning

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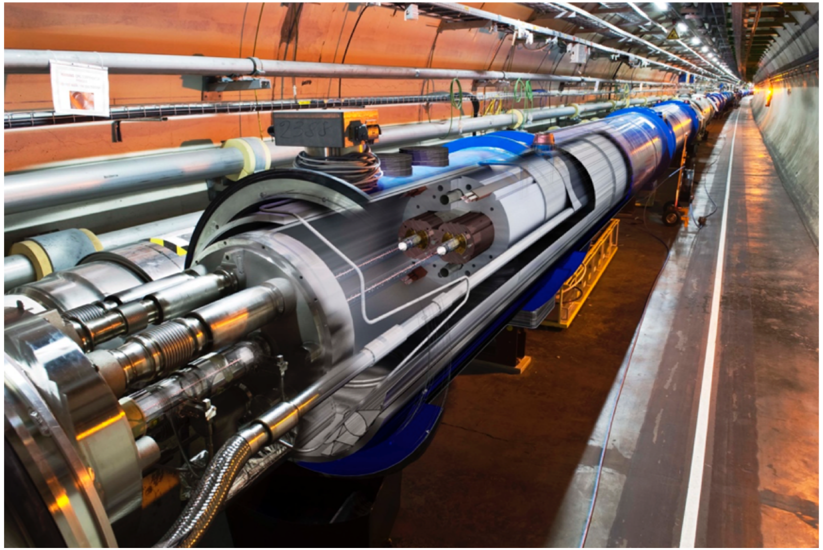
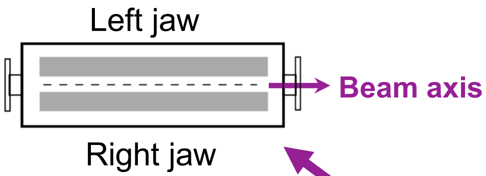
Introduction

Large Hadron Collider



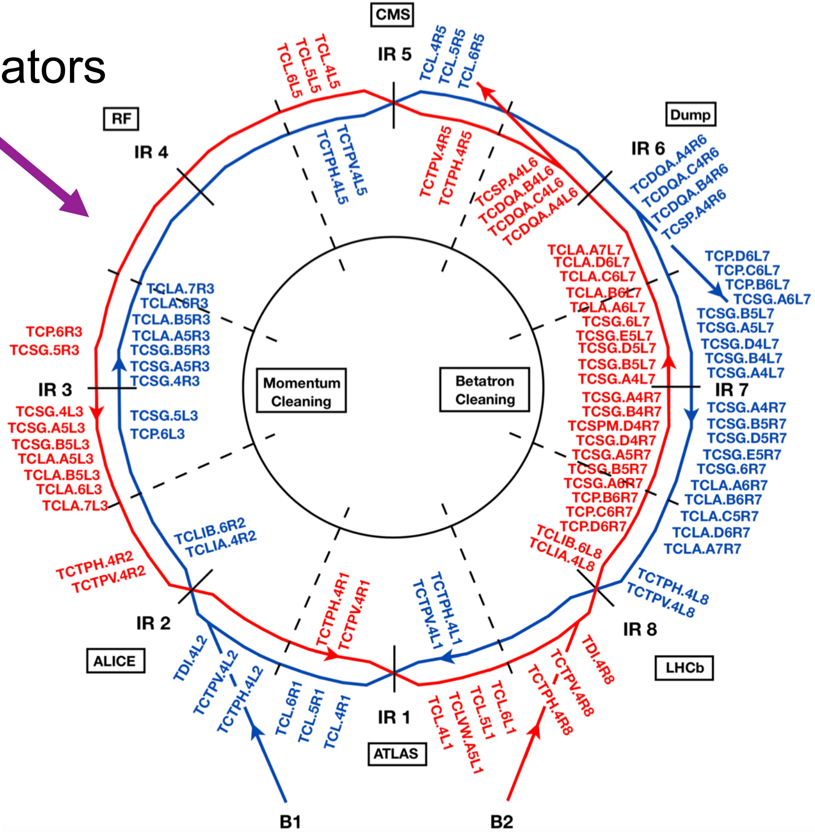
- 27 km with 1232 superconducting dipole magnets
- Accelerates and collides two counter-rotating beams at 6.5 TeV
- During Run II beam stored energies higher than 300 MJ
- The magnets and other sensitive equipment protected from quenching and any damage **=> Collimators**

The Collimation System



Collimator

LHC Collimators

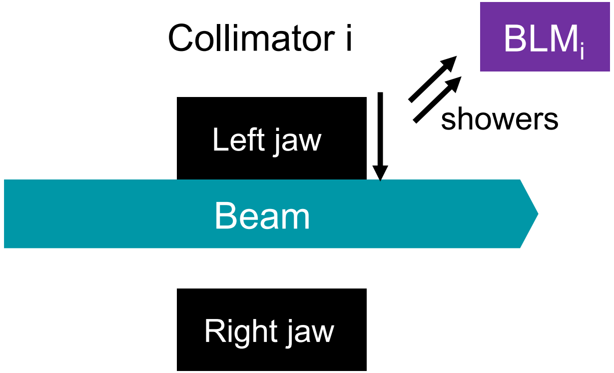


- 100 collimators aligned
- Step precision of 5 μm
- Concentrate beam losses in warm locations

- Alignments performed at all machine states:
  Injection, Flat top, Squeeze, Collisions

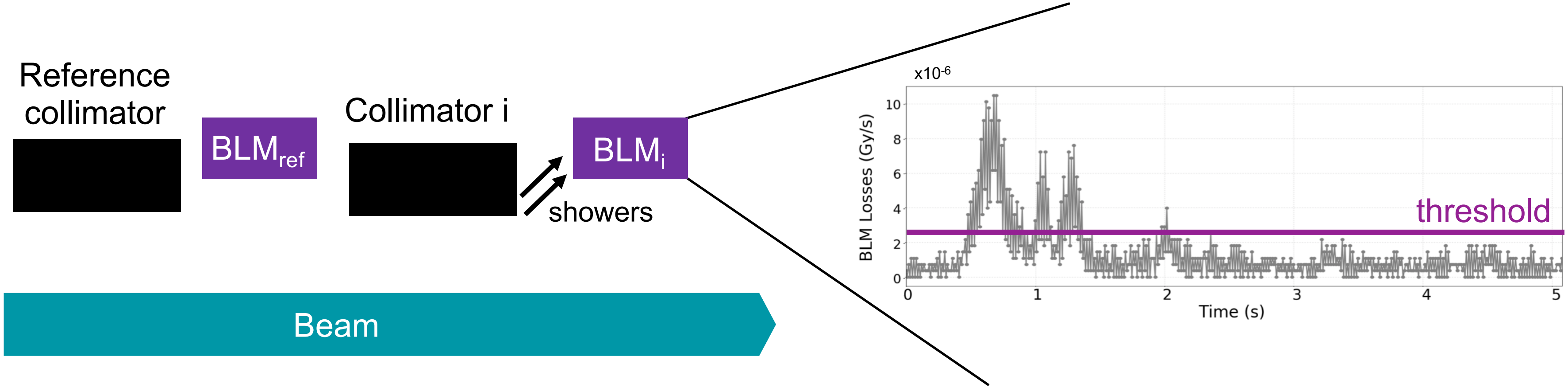
Beam Instrumentation

- 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

Beam-Based Alignment



Beam centre calculated from final collimator position.

Beam size calculated using reference collimator before and after.

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

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.

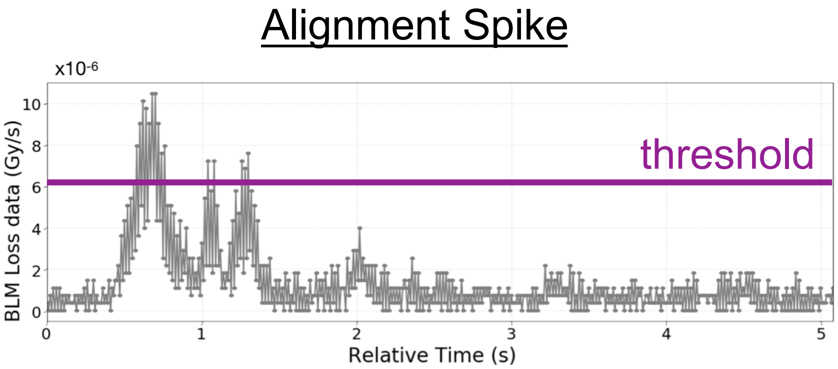
Alignment Tasks

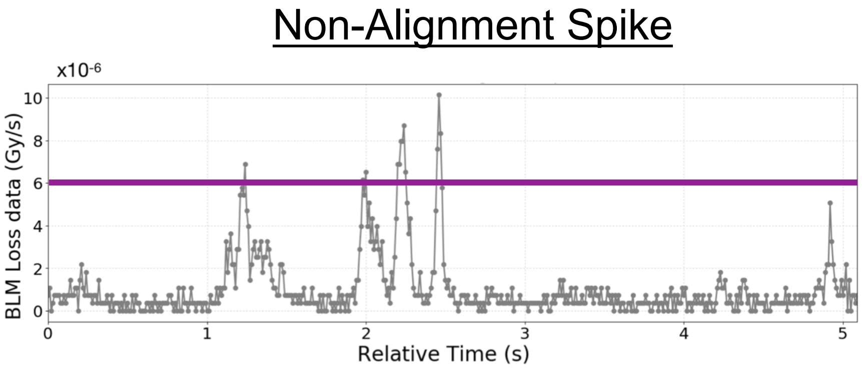
Since 2018: **Fully**-Automatic Alignment

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





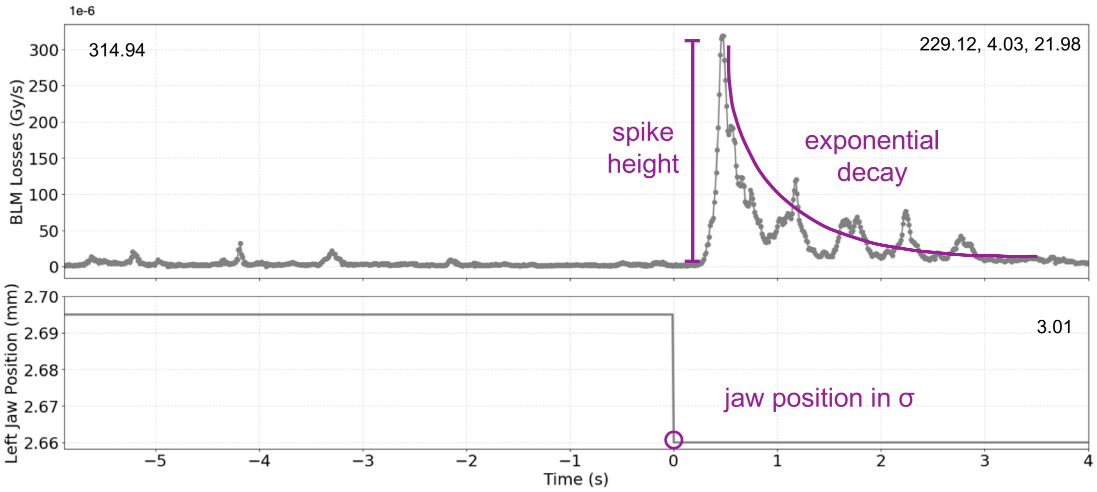
- Data set of 8706 samples from alignment campaigns in 2016 and 2018
- Six machine learning models for spike classification were compared

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

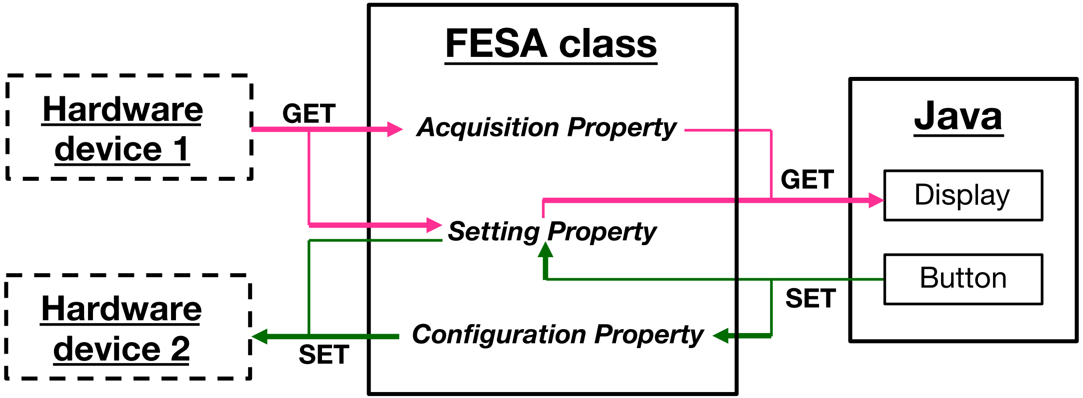
G. Azzopardi, et al., *Automatic Spike Detection in Beam Loss Signals for LHC Collimator Alignment*, NIM-A, 2019

Software Architecture

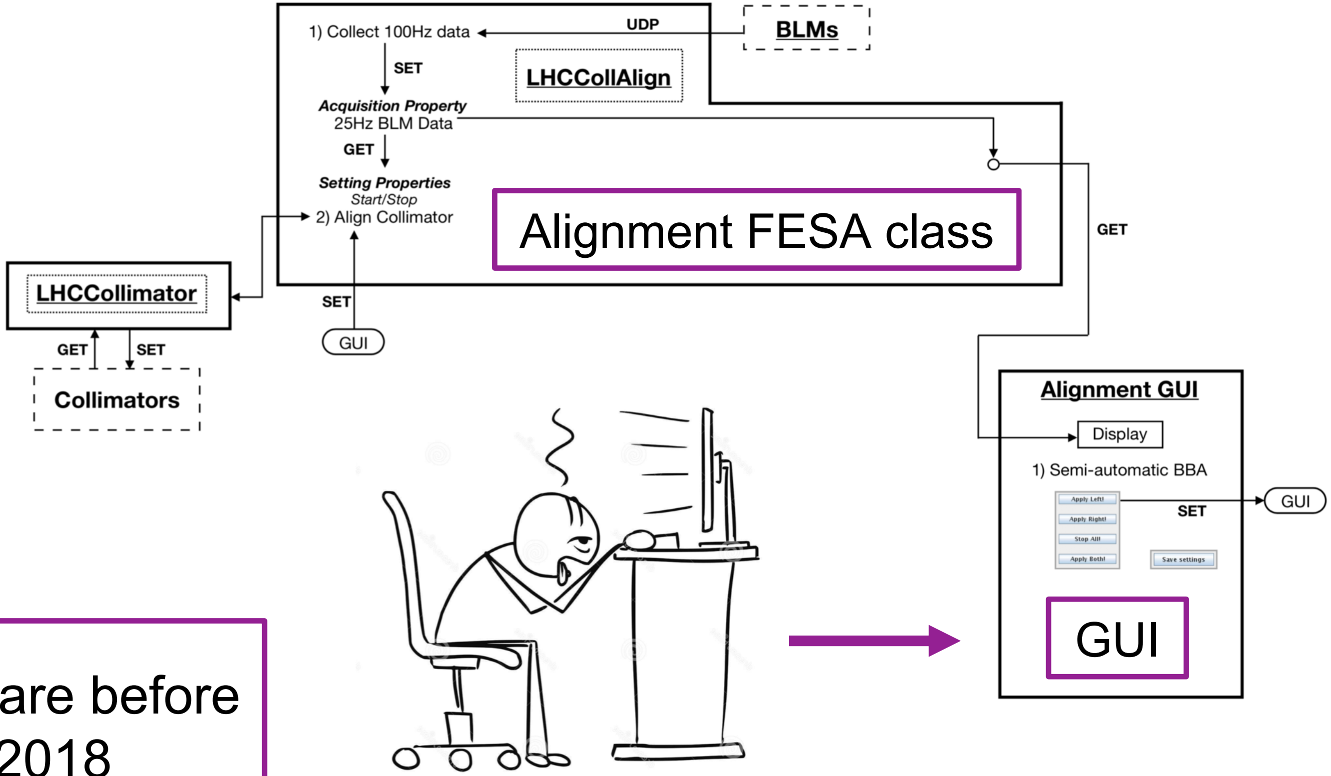
- Semi-Automatic Alignment
- Fully-Automatic Alignment

FESA Overview

- Front-End Software Architecture - Real-time C/C++ framework used to develop LHC ring front-end equipment software.
- Abstracts hardware devices by exposing a public interface of properties
- *FESA devices* are grouped into a *FESA class*
- JAVA GUI applications interact with directly with FESA

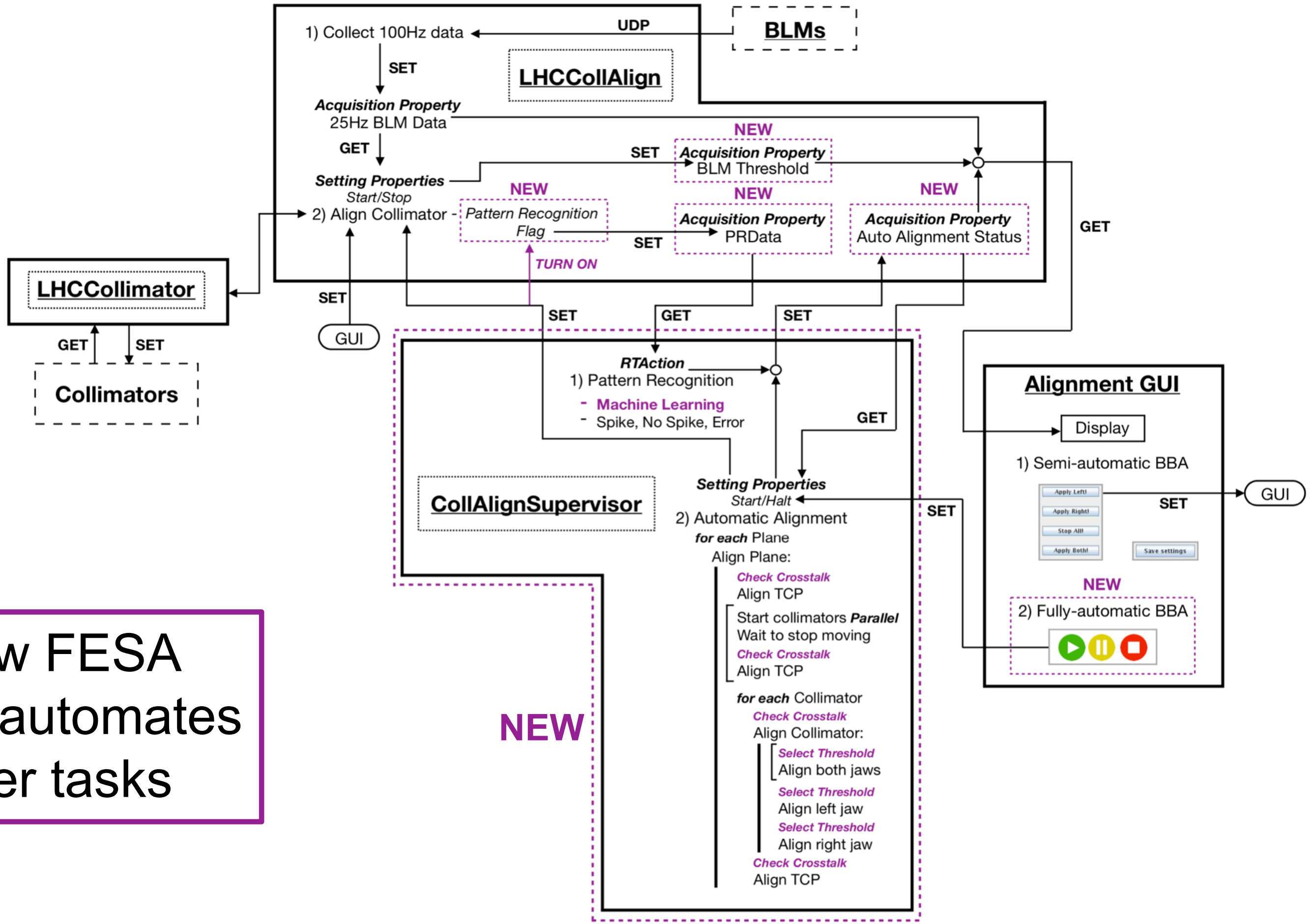


Software Architecture - Semi-Automatic Alignment



Software before 2018

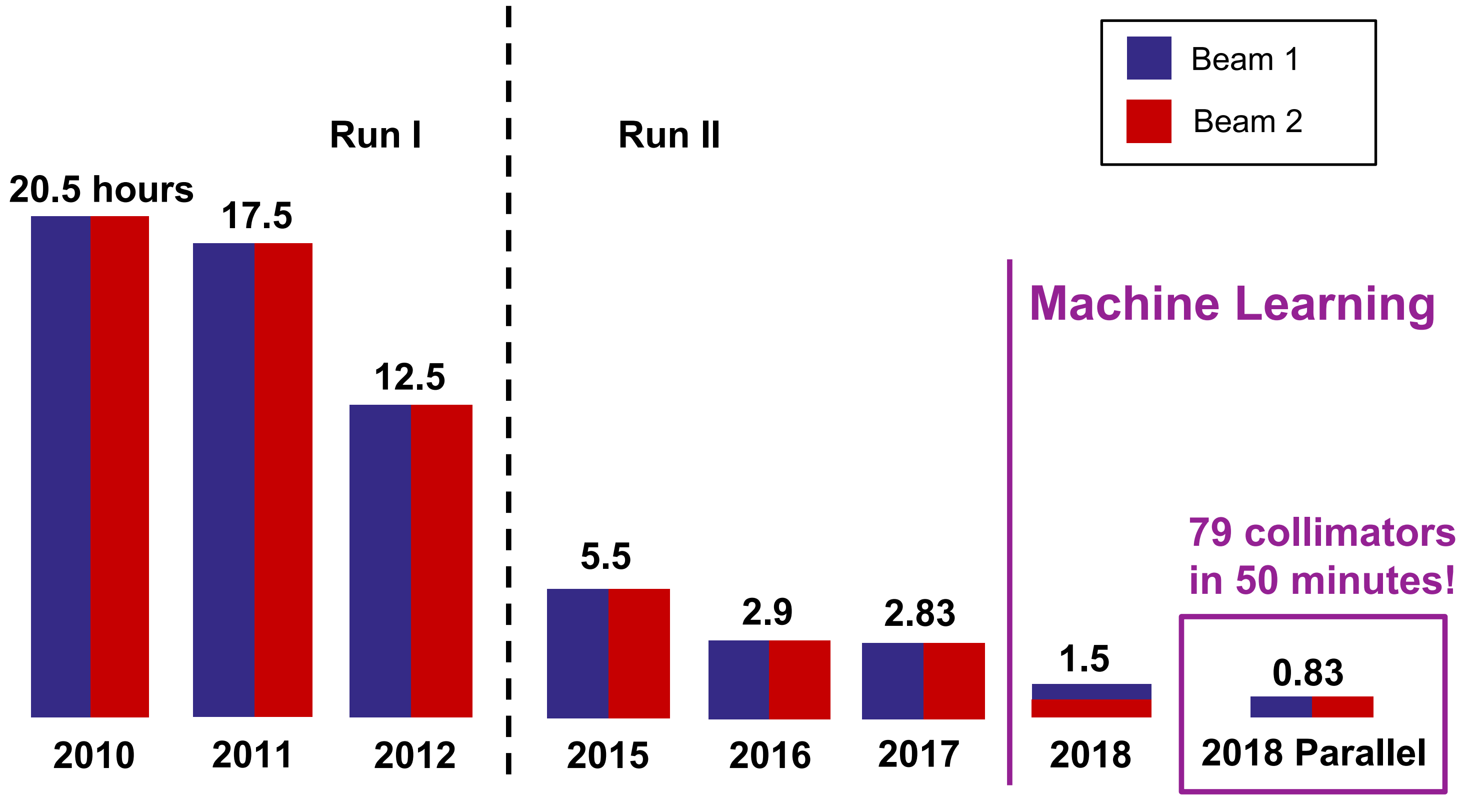
Software Architecture - **Fully**-Automatic Alignment



New FESA class automates user tasks

Results

Fully-Automatic Alignment Results



G. Azzopardi, et al., *Operational Results of LHC Collimator Alignment using Machine Learning*, IPAC'19

Summary

- Collimators are aligned each year using a **beam-based alignment**.
    - ⇢ 100 collimators with a precision of 5 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**.
- **New FESA class** implemented for full automation, allowing for both alignment tools to be available together and **maintaining backward-compatibility** with all previous functionality.
- The full-automation will be used as the **default alignment software** for the **start-up of the LHC in 2021**.

Thank you for your attention!

Questions?