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

- 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
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

- 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
  → Exponential Decay
  → Jaw Position in $\sigma$

Models achieved over 95% accuracy

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

Alignment FESA class

1) Collect 100Hz data
2) Align Collimator

Acquisition Property
25Hz BLM Data

Setting Properties
Start/Stop

LHCCollAlign

BLMs

UDP

GUI

Alignment GUI

1) Semi-automatic BBA

GUI

Software before 2018
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
Special reinforcement of 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?