

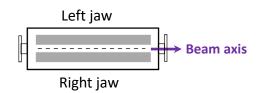
# LSTM Application for Automatic LHC Collimator Alignments

Gabriella Azzopardi

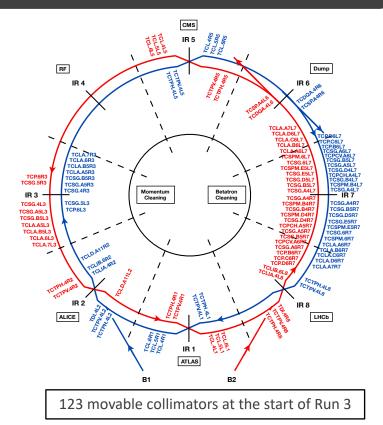
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#### Introduction



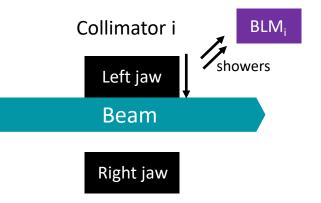
- The LHC relies on a collimation system for passive protection
- Step precision of 5 μm
- Concentrate beam losses into warm location
- Each year of operation begins with a commissioning phase to align all collimators.
  - Ensure the correct settings for nominal operation
- Alignments performed at all machine states:
  - Injection, Flat top, Squeeze, Collisions



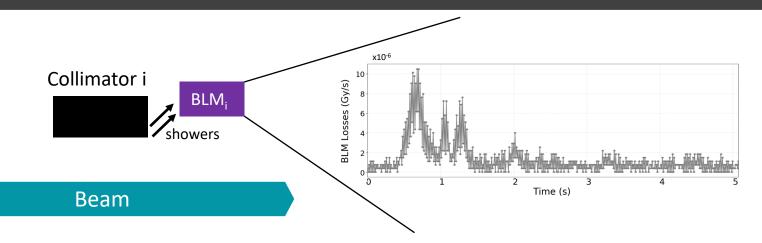
#### Beam Instrumentation

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





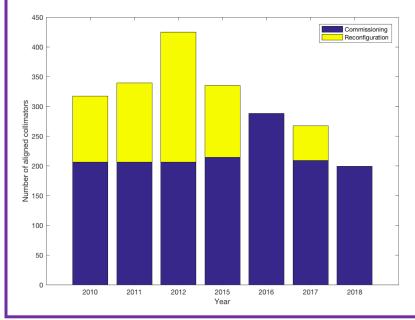
#### Beam-Based Alignment





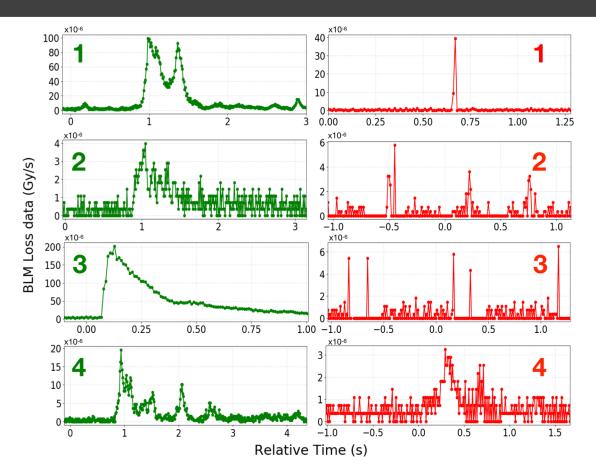
- Move jaw towards beam until loss spike detected in BLM signal.
- Wait for loss spike to decay between alignments.
- A complete alignment campaign can produce 1000+ observation spikes (1000+ alignments).

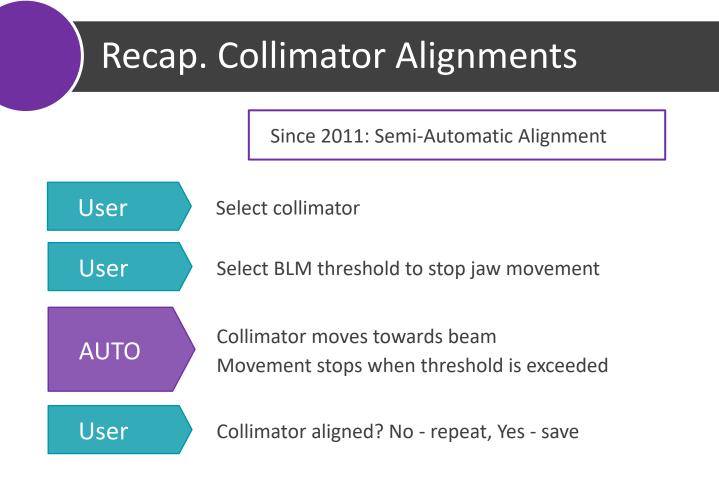
#### Beam-Based Alignment



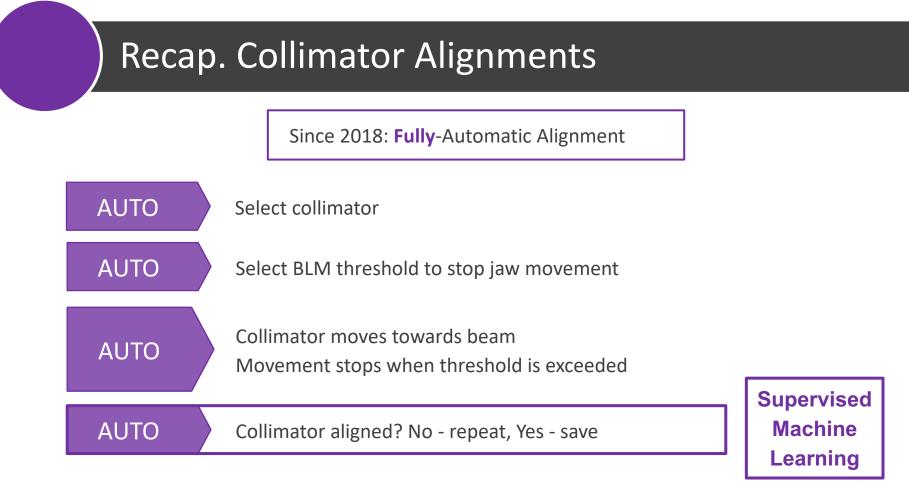
- All alignment campaigns for all machine states during commissioning and any reconfigurations throughout the years.
  - Excluding alignments required for dedicated setups for machine developments and operational measurements/tests.
  - Aligning each collimator with BLMs requires multiple alignments:
    - 2018: ~8 alignments / collimator
    - 2016-2017: ~25 alignments / collimator
    - 2010-2015: >25 alignments / collimator
- A complete alignment campaign can produce 1000+ observation spikes (1000+ alignments).

# **Beam-Based Alignment Observation Spikes**





BBA alignment of 40+ collimators require 4-5 collimation experts.

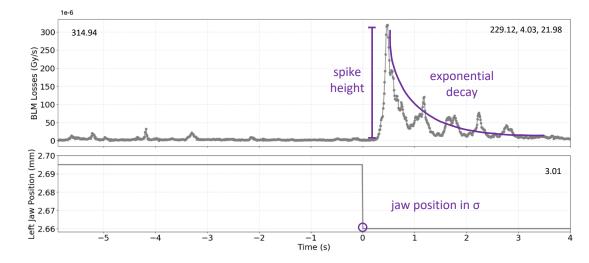


G. Azzopardi, et al., Software Architecture for Automatic LHC Collimator Alignment using Machine Learning, ICALEPCS'19

# Recap. Collimator Alignments ML

- Data sample taken when collimator stops moving:
  - 100 Hz BLM data
  - 1 Hz Jaw Position (mm)
- Fixed waiting time:
  - 4 s @ injection
  - 6 s @ flat top

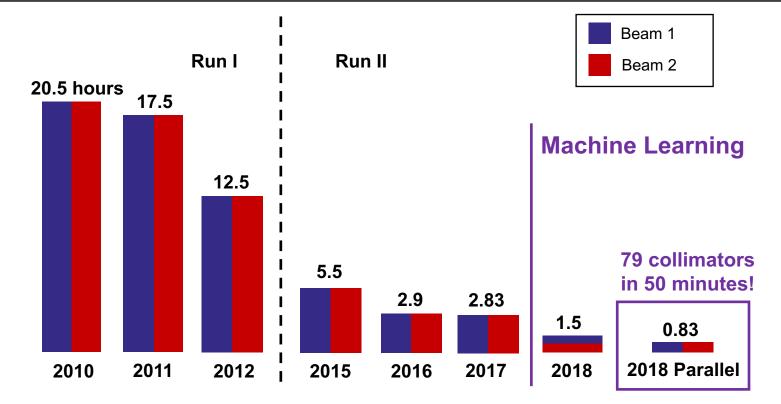
Precision > 95%



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

G. Azzopardi, et al., Automatic Spike Detection in Beam Loss Signals for LHC Collimator Alignment, NIM-A, 2019 9

# Recap. Collimator Alignments Results



G. Azzopardi, et al., Operational Results of LHC Collimator Alignment using Machine Learning, IPAC'19 10

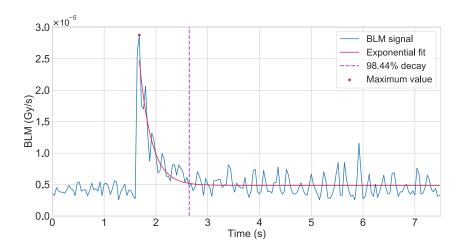
# Semi- Vs Fully- Automatic Alignment

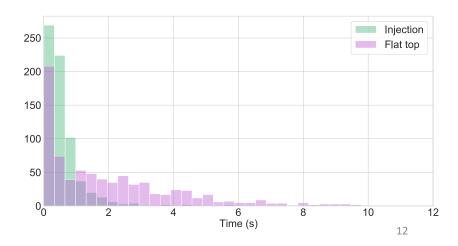
- Data collected using:
  - Semi-automation in 2016
  - Parallel fully-automation in 2018
- Can speed up the fully-automatic alignment by decreasing the time waiting for the signal to decay before extracting the features.

	Semi-Automatic	Fully-Automatic
Collimators	75	77
Total time	2h 31m 59s	49m 17s
Moving time	58m 13s	18m 14s
Total alignments	1903	637
Moving time	38.3 %	38.0 %
Alignments / Collimator	25.37	8.27

#### Decay Time Analysis

- **Analysis:** Actual time required for BLM signal to decay.
- Modelled the decay rate as an exponentially falling distribution, with optimal losses achieved after 6 half-lives.



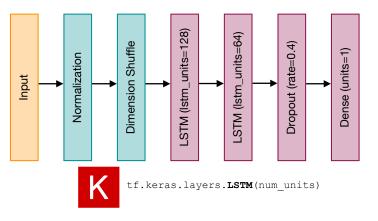


Mean decay time:

- 0.61 s at injection
- 2 s at flat top

# LSTM-RNN for Spike Classification

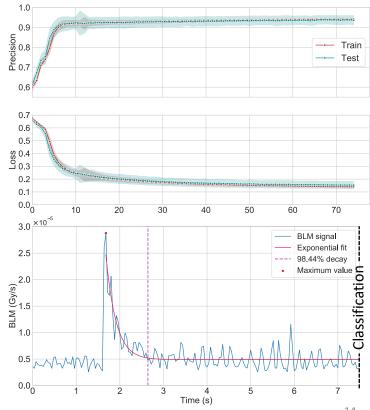
- **Proposed Solution:** Long Short-Term Memory (LSTM) Recurrent Neural Network (RNN):
  - Continuously classify spikes in real-time.
  - Automatically adjust to spike decay length.
- Dataset collected from alignments during 2016-2018:
  - 1550 alignment spikes
  - 1423 spurious spikes
- Input:
  - BLM signal scaled with the collimator position in sigma.
  - Z-Score used as the normalization technique to re-scale the features.



Courtesy of G. Ricci, Sapienza Università di Roma

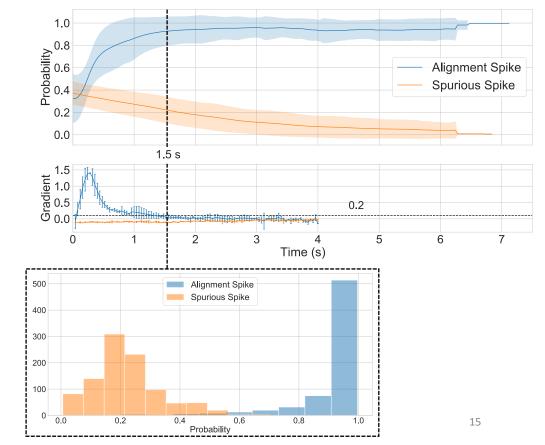
# LSTM-RNN for Spike Classification

- Results collected over a 10-fold cross-validation randomly stratified 30 times.
- Average of 94% precision on testing sets.
- Precision is used to avoid false positives:
  - False detection of an alignment spike is more grievous than not detecting an alignment spike.
- Precision calculated by evaluating the classification probability at the end of the available sample:
  - A classification score >50 % is classified as an alignment spike.
- Further analysis to determine the best moment to predict the spike class and the ideal probability threshold, to possibly improve the model's precision.



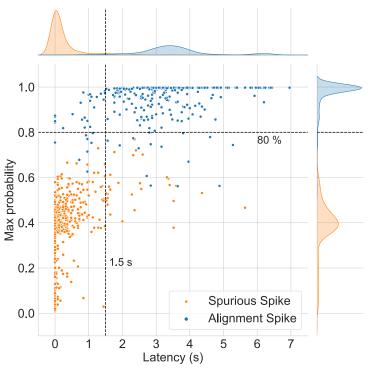
# Spike Classification Analysis

- Analysis: LSTM continuous classification of each sample at each time step.
  - Clear distinction between spike classes at 1.5 s.
  - Rate of change of classification probabilities for alignment spikes falls below 0.2.
  - No overlap at 80 % probability at a latency of 1.5 s.



# Spike Classification Analysis

- **Analysis:** Latency required to obtain max. probability per spike class:
  - ~98% of spurious spikes obtain a max probability within 1.5 s.
  - 100% of spurious spikes constantly < 80 % classification probability.
- **Conclusion:** The LSTM can be used classify:
  - When the probability gradient < 0.2 (requires  $\sim$ 1-1.5 s @ Inj).
  - Classify spurious spike when probability <80 %, then the next alignment can begin.
  - Otherwise alignment spike, then fit an exponential function to determine when ~98.5 % of the BLM signal decays
    - On average already decayed (mean 0.61 s).



#### Classification Results

- Classifying the BLM signals as proposed by the presented analysis increases the classification precision on the dataset to 98 %.
- Analysis: The time taken to classify the BLM signals at the two machine states.

	Injection	Flat top
Start time	1 s	1.5 s
Mean	1.07 s	1.54 s
Stand. dev.	0.1 s	0.06 s
Maximum	1.72 s	2.04 s

•	Factor 4 speed-up compared to the
	present implementation with
	supervised ML.

# **Theoretical Improvement of Alignment Time**

The time required for automatic alignments using supervised machine learning.

Step	Action	Time (s)			
1	Move both jaws to 4 mm	~8			
2	Wait for losses to decay	х			
3	Classification delay	1			
4a	Align Left Jaw	2*(0.1 + <b>x</b> + 1)			
4b	Align Right Jaw	2*(0.1 + <b>x</b> + 1)			
5a	TCP before (Left Jaw)	0.1 + <b>x</b> + 1			
5b	TCP before (Right Jaw)	0.1 + <b>x</b> + 1			
6	TCP after (Left + Right )	2 * (0.1 + <b>x</b> + 1)			
Total	17.8 + 9x	@lnj x >= 4 @FT x >= 6			

- The proposed LSTM model is capable of dynamically classifying spikes of varying lengths in real-time.
- This will decrease the mean time waiting for the losses to decay:
  - x<sub>1</sub> = 1.07 s @ Inj, 2 s @ FT
  - x<sub>0</sub> = 1.07 s @ Inj, 1.54 s @ FT

(from slides 11, 16)

# **Theoretical Improvement of Alignment Time**

	~50% speed-up
Supervised ML	LSTM-RNN
53.8 s	27.43 s
69.1 s	33.94 s
70.84 mins	36.12 mins
90.98 mins	44.69 mins
71.8 s	35.8 s
93.1 s	43.72 s
94.53 mins	47.14 mins
122.58 mins	57.56 mins
	53.8 s 69.1 s 70.84 mins 90.98 mins 71.8 s 93.1 s 94.53 mins

- The average theoretical minimum time to sequentially align LHC collimators.
- Aligning the two beams in parallel, resulted in 79 collimators aligned in 50 minutes at injection.
  - The LSTM could theoretically align 79 collimators at injection in ~24.56 minutes.

1 spurious spike/align =  $3 * (0.1 + x_0 + 1)$ 



- 123 LHC collimators automatically aligned using supervised ML, using the software introduced in 2018.
- First-use performance analysis identified a bottleneck caused by the fixed observation window used by the ML model to classify the BLM loss signal.
- Trained an LSTM model to continuously classify BLM signals.
- Able to classify spikes within 1-2 s of a collimator stopping its movement, once the rate of change in classification probabilities is below 0.2.
  - Following each alignment spike classification, the suggestion is to fit an exponential function to the losses to determine whether the next alignment can begin.
- This work allows for classifying BLM signals independent of whether the losses decayed or not, decreasing the alignment time by ~50 %.
- The LSTM is readily available to be incorporated into the alignment software for testing during the LHC Run 3.

#### Thank you for your attention!

# Questions?

LSTM for Automatic Alignment

#### Automatic Alignment Software

#### Collimation Controls for Run 3

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	G. Azzopardi*, CERN, Geneva, Switzerland, G. Ricci. Sabienza Università di Roma	ICALIFICS 2023		G. Azzopardi <sup>*</sup> , B. Salvachua Ferrando		nd,	ICALEPCE 2023			N, Geneva, Switzerland, G	<ol> <li>Valentino, University of M</li> </ol>	alta	ICALEPCE 2023
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letter.		lassification	Introduction	Beam-based Alignment (BBA) with BLMs	Software Architecture	Implementation	Multi-threading		· A collector is made up of two parallel	a Commissioning before math operational	<ul> <li>IPM solimators are algorid using a source/or assessimation describes.</li> </ul>	BM collinators are aligned by maxing	<ul> <li>Introduce the states in collimator laws.</li> </ul>
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The second secon	but International Final waiting time after the Proposed Solution: LSTM-RNN to continuously cla		<ul> <li>Collimation system protects LHC.</li> </ul>	<ul> <li>Reference collimator aligned with collimator to create reference halo.</li> </ul>	<ul> <li>à-tier structure (see Figure).</li> </ul>	<ul> <li>The fully-automatic alignment is implemented in a dedicated FESA days -</li> </ul>	<ul> <li>Only 2 calibrators can be aligned in garafiel. 1 per beam ishared reference</li> </ul>	A collection series while design of	<ul> <li>Each jow is controlled by two stepping maters is adjust the jay amilian/ande.</li> </ul>	machine states, to set up the him and y.	servicing the lanen orbit at up (denor- sionan science) the collimator lane function	Mashan IIM signal, jour problem.	<ul> <li>Allow for lighter sollimator settings</li> </ul>
	Loss takes that involution stopper meaning collimator stopp moving: real-time and automatically adjust to spike decay	regth.	<ul> <li>100+ collimators, each made of 2 jaws inside a vacuum tank.</li> </ul>	<ul> <li>The calimator jaws are moved towards the beam in steps of 5-30 µm whilst monitoring the BUM signal recorded in the colimator's respective BUM.</li> </ul>	· The hardware is abstracted and	coll/light/upervisor.	paratel, 1 per beam (shared reterence and cross-talk).	hears leaves, providing a cleaning	<ul> <li>The lightest settings (5 x / ~1 mm gaps);</li> </ul>	<ul> <li>Different setups needed for different machine parameters, and if orbit shifts.</li> </ul>	Markey III desirate base series	Inputs: The Ini of collimators to be algored. Procedure	<ul> <li>Correct tank misalgenents that could preparate upters performance.</li> </ul>
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<ul> <li>All collimators aligned before each year of operation, using beam-based</li> </ul>	Average of 65 % precision     Input: BLM signal scaled with the collimator posit	on in sigma.	the collimation hierarchy.	primary calimator, to establish the colimation hierarchy	· The control orders communicates	components:	run 2 instances of the suftware in	Raw 3 in 2022. Newly installed/replaced	<ul> <li>A spine of theshold functions is independent to here the law applicant.</li> </ul>	(BA) and in jew collimator Brain Pesition Munice (BB4)	time internal [1] hetaeren steps.	ignoring spurious IEM spikes, until a strue alignment spike. IM, used her	of 4 submater jan servers, a breaks fact and red andro (and of
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ij w	collimators aligned in 50 minutes at injection.	79 add #100 75.56 mms. 36.32 mms		change commutor)	features.	the alignment and re-added at a later stage.	efficiently with minimal effort.	ring ar in specific Bs.	Settings Check	<ul> <li>Impair Scient callmater to be tested.</li> </ul>	2 Continuously shift the jean by the amplefeed jay size size, unline the	optimal shareeling angle.	<ul> <li>Manilan Diplay for solimator settings is available to manilar the solimation</li> </ul>
a	Tree ()  o LSTM cauld theoretically require -24.56 min Results: The LSTM cauld theoretically require -24.56 min		Parallel message	<ul> <li>Any message to display in first</li> </ul>	<ul> <li>Ensure the correct alignment.</li> </ul>	<ul> <li>Pre-set collimator subsets for</li> </ul>	<ul> <li>Subsets of collimators can be aligned more frequently</li> </ul>	18, staded for comparison	The generated settings must be substated.	<ul> <li>Presentate: The collimator is moved sensentially to reach of its limits to resource</li> </ul>	president jaw step size, waiting the requested time between maxements.	algorithm is not automated, requiring 10- 10 minutes, depending on machine state.	Normally income of incoment settings.
Retrieve 1	(de) When the probability product < 0.2 (requires = 1.1 C + 0.10). The LSTM is readily available to be incorporated into		TCP c286us -4, -3	i, -2, -0, 0, 1 before collimator: (not aligned), aligned), aligned before parallel, anone. Aligning, (before, after coll)	<ul> <li>The "unart" features include:</li> </ul>	alignments available.	during operation.	<ul> <li>Calculate the collimation hierarchy inefficiency/by analysing learners in DL.</li> </ul>	<ul> <li>Impulse LLX configuration, start/immittimes, Init of collimations to shock their settings.</li> </ul>	the interlasis are savenily inggrout.	<ol> <li>When the predefined limit is reached, many lass, lash to the starting axist</li> </ol>	<ul> <li>Refers on Bills this cross talk must be considered for seciled algorithms.</li> </ul>	BW selectors is bring developed to
Apres Apres	Sites all and the second	+1 guillous quite = 91.1 c = 21.72 c	Collimator estas	tame of collimator organig alignment.	<ul> <li>Equal priority for collimators from the two beams.</li> </ul>	<ul> <li>Closing the application is an automatic stop if any</li> </ul>	<ul> <li>Dedicated collinator configurations e.g. ion beams</li> </ul>		<ul> <li>Prevalues: Automatically compare settings:</li> <li>in the selected IAA configuration.</li> </ul>	<ul> <li>Performance: Typically takes less than 32 minutes per collimator.</li> </ul>	and reduce the jaw gap by the annihilate time into	Angular Parlamanan The Jargest angular	maniar they averall status. It will compare the collimator service and the
Laterary N	<ul> <li>All second sectors with the second sec</li></ul>	79 cals (#77 94.33 mms 47.34 mms *1 law law law 122.38 mms 37.38 mms	Jaw datus -	1, 0, 1, 2 Ignore, Aligning: (first jaw, second jaw, both jawt)	<ul> <li>Linit the overall waiting time.</li> </ul>	alignment is ongoing.	no longer bound to identical	and the second se	<ul> <li>Calculated based as the data in USA.</li> </ul>	<ul> <li>Parallel sequences can be started in for collimators not convented to the</li> </ul>	A Repeat until the minimum jaw gap is	san of 20 mail requires 2 1 hour.	loan serie measured by the EPMs in real-time.
Distribution of max, probabilities ashies have uptice cleases and the required to		The average theoretical minimum time for sequential alignments.	Spike class - 2	, -1, 0, 1 Agnare, Errar, No spile, Spile	<ul> <li>Reacting to user interrupts.</li> </ul>		setups as with protons.	Protocolar Stationary III Stationary 124 alore	<ul> <li>In MERIS legend during selected time.</li> <li>The real time collimator analism.</li> </ul>	same interlack units (typically are interlack unit per II).	reached. Save jow positions and IPM electrode signals for offline analysis.	inhibits determining the optimal sharenfing and/n in and analysis.	
								come and a finite radia of a physical state frame.					

**THPV040** 

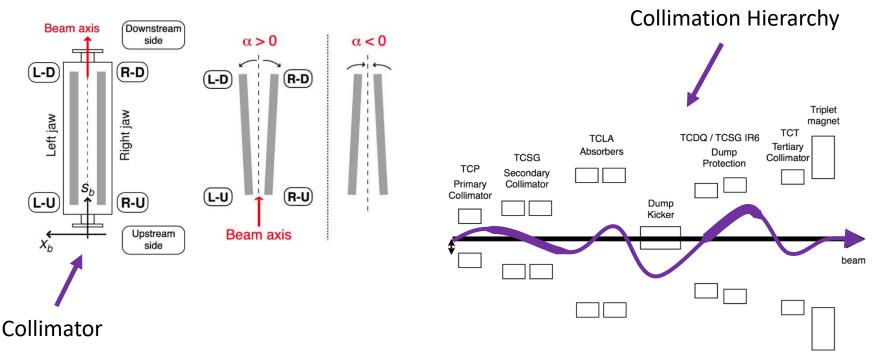




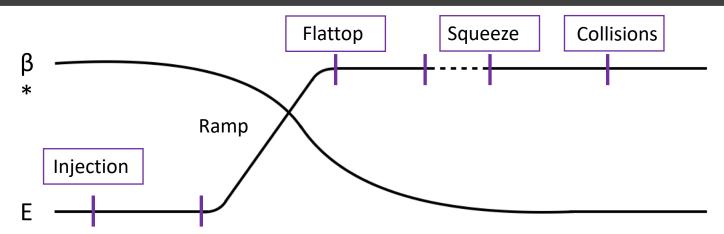
# Backup slides

#### The Collimation System

Collimators are positioned to clean in 3 planes: Horizontal, Vertical and Skew



### LHC Machine Commissioning

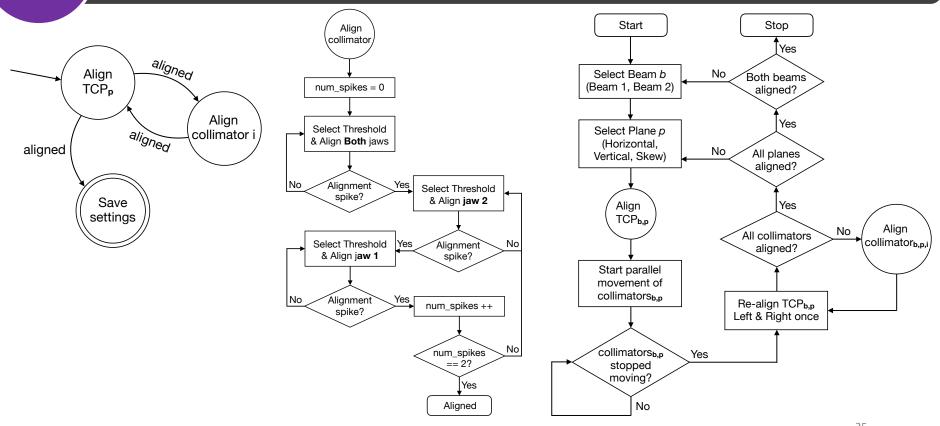


To prepare the machine cycle the collimators must be aligned at all machine states:

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

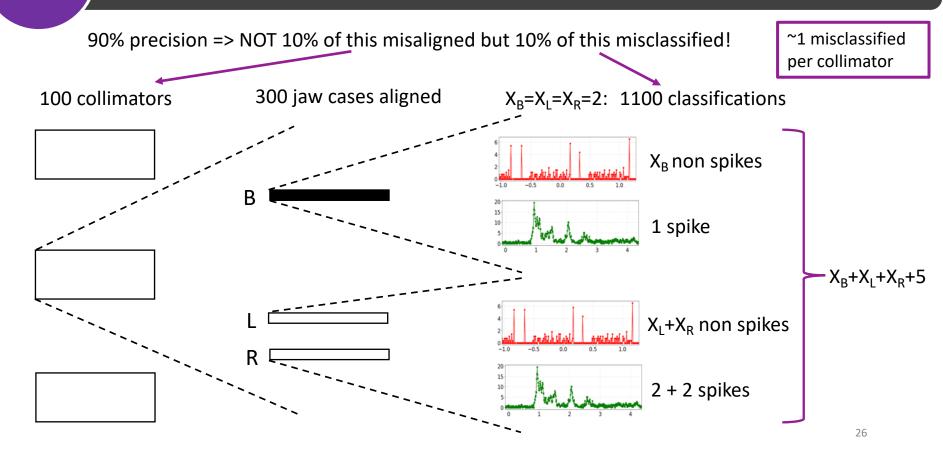


#### Collimator Alignment Procedure



G. Azzopardi, et al., The Automatic LHC Collimator Beam-based Alignment Software Package, ICALEPCS'21<sup>25</sup>

### Misclassification Rate Explained



### Long Short-Term Memory model

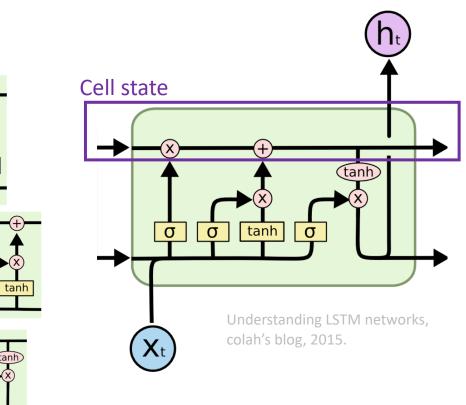
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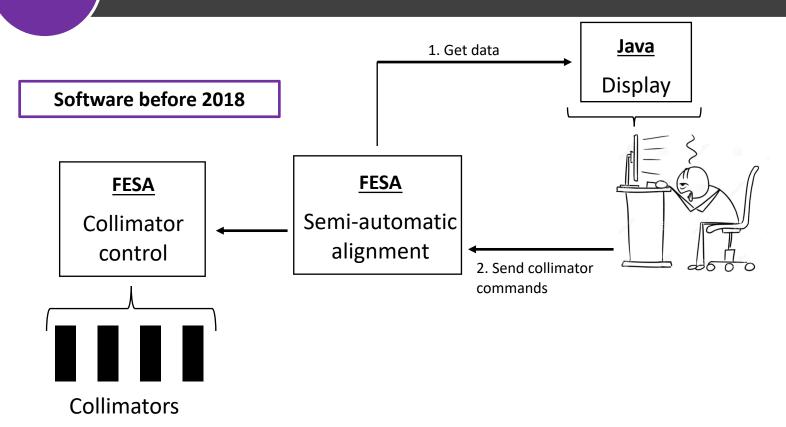
- LSTMs are a type of RNN that can learn long-term dependencies.
- 3 activations inside:
  - Forget gate layer: What information to keep from the cell state.

Input gate layer: Which values to be updated.

• Output layer: Decide what to output.

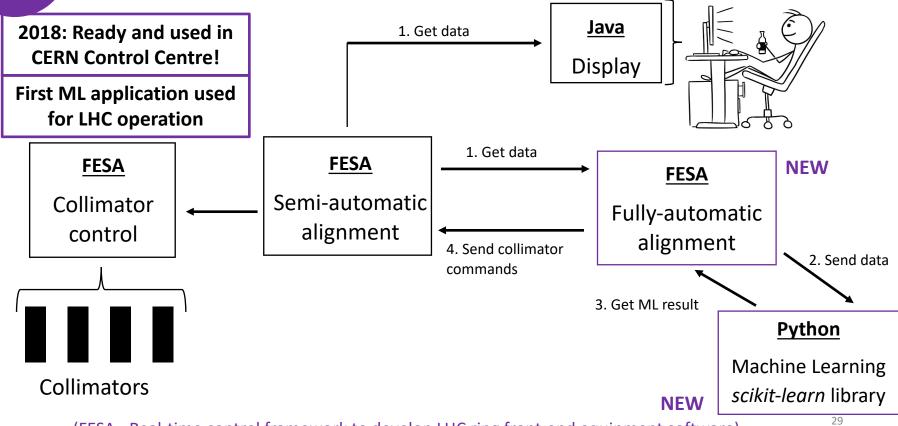


#### **Alignment Implementation**



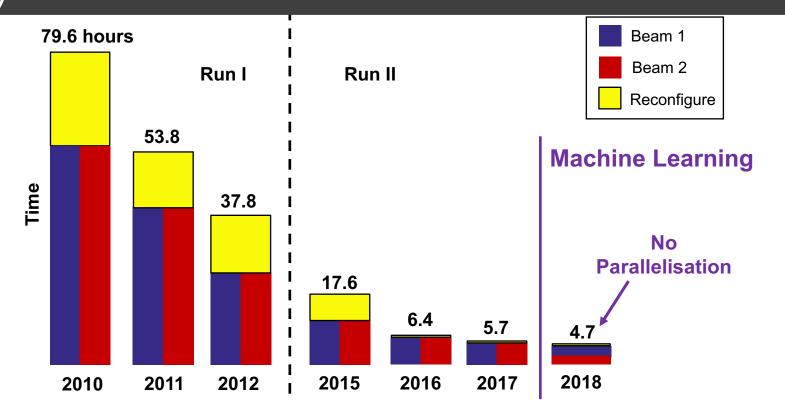
(FESA - Real-time control framework to develop LHC ring front-end equipment software)

## Alignment Implementation



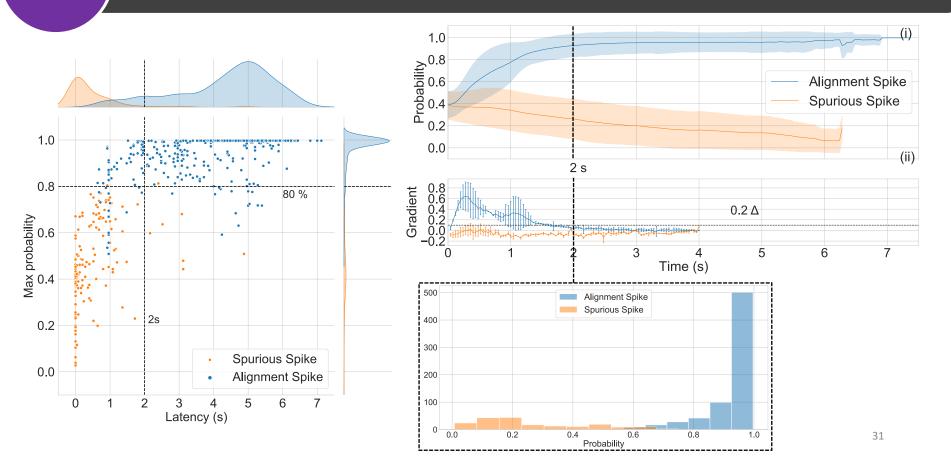
(FESA - Real-time control framework to develop LHC ring front-end equipment software)

#### Fully-Automatic Alignment Results



G. Azzopardi, et al., Operational Results of LHC Collimator Alignment using Machine Learning, IPAC'19 30

#### Spike Classification Analysis @ FT



# Spike Classification Analysis Results Overview

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	Prot	Ion beams		
	Injection	Flat top	Collisions	
Decay time	~0.61 s	~2 s	~1.08 s	
Classification probability threshold	80 %	80 %	80 %	
Classification probability gradient	0.2	0.2	0.2	
Classification latency	~1.07 s	~1.54 s	~2.08 s	
Classification precision		97 %		