

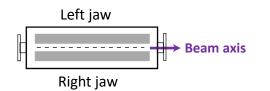
LSTM Application for Automatic LHC Collimator Alignments

Gabriella Azzopardi

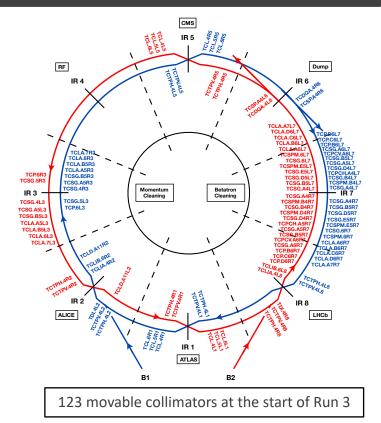
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Introduction



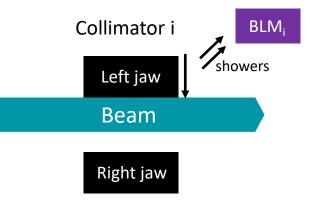
- The LHC relies on a collimation system for passive protection
- Step precision of 5 μm
- Concentrate beam losses into warm location
- Each year of operation begins with a commissioning phase to align all collimators
 - Ensure the correct settings for nominal operation
- Alignments performed at all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



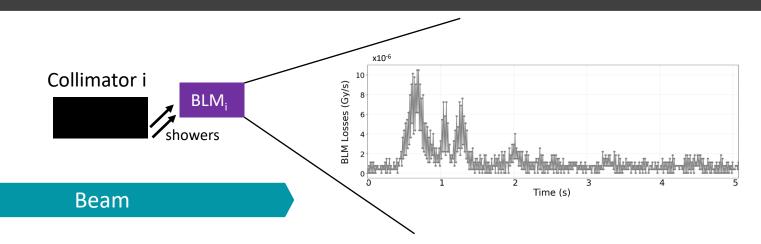
Beam Instrumentation

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





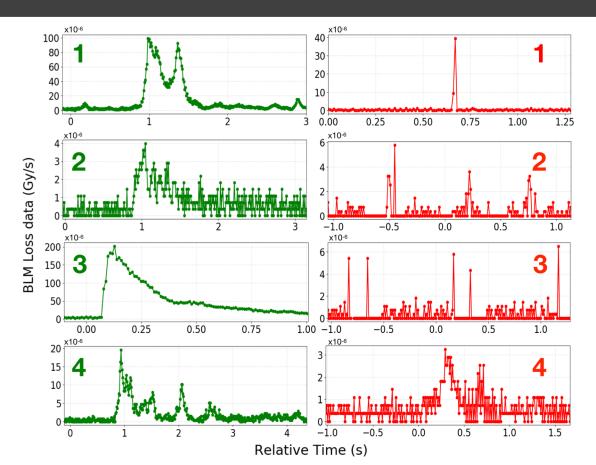
Beam-Based Alignment

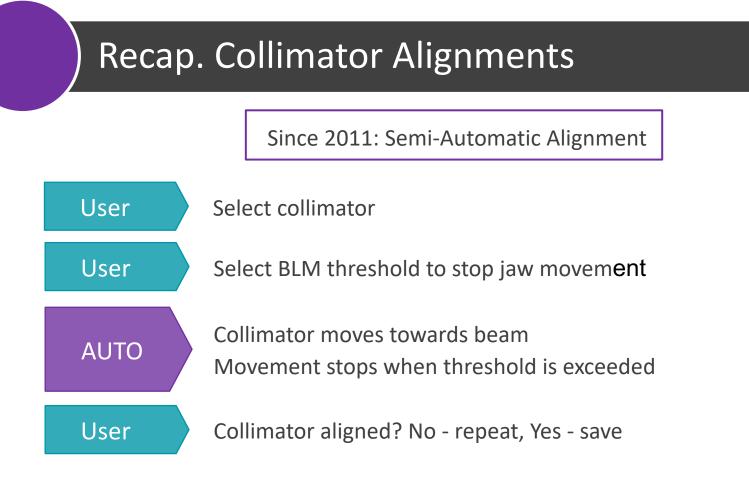




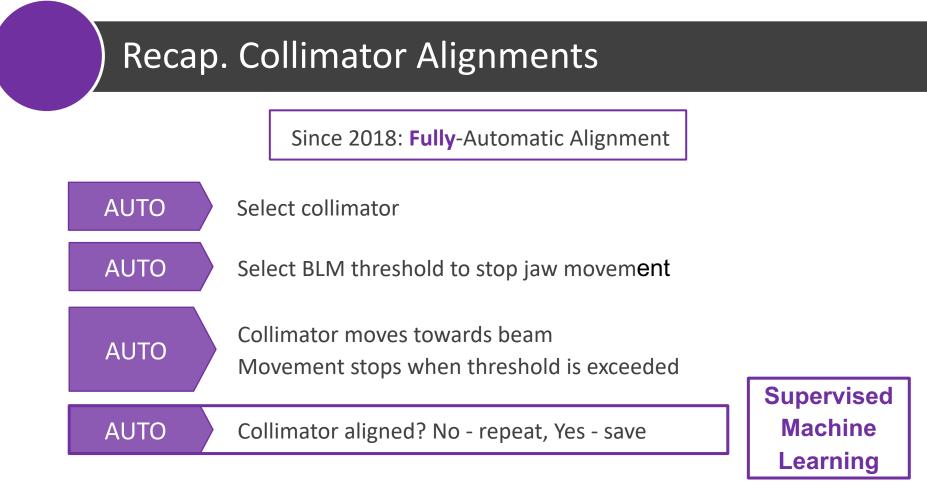
- Move jaw towards beam until loss spike detected in BLM signal.
- Wait for loss spike to decay between alignments.
- A complete alignment campaign can produce more than 1000 observation spikes.

Beam-Based Alignment Observation Spikes





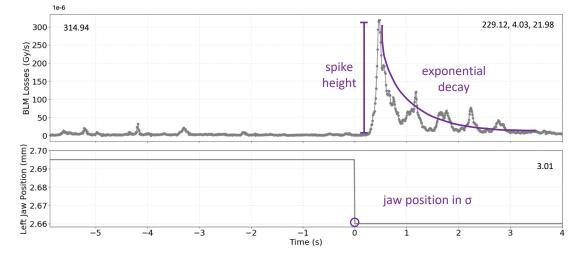
BBA alignment of 40+ collimators require 4-5 collimation experts.



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
 - Exponential Decay
 - Jaw Position in σ (x1 feature)

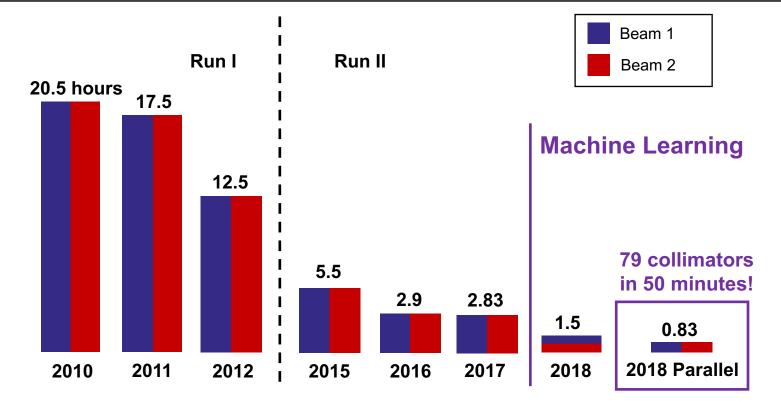
(x1 feature)

(x3 features)

G. Azzopardi, et al., Automatic Spike Detection in Beam Loss Signals for LHC Collimator Alignment, NIM-A, 2019 8

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Recap. Collimator Alignments Results



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

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

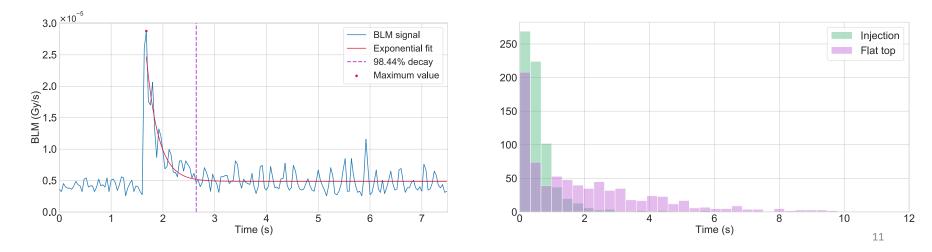
Decay Time Analysis

- 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.

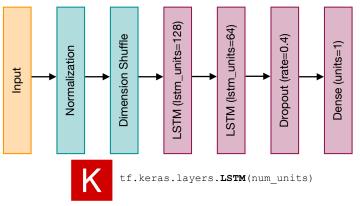


- 0.61 s at injection
- 2 s at flat top



LSTM-RNN for Spike Classification

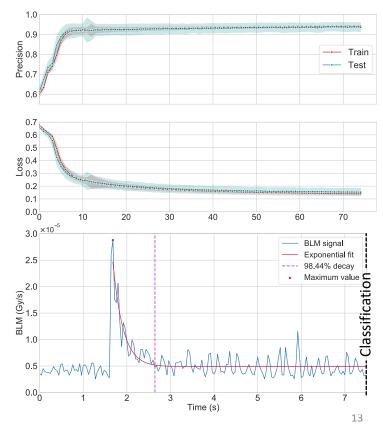
- **Proposed Solution:** Long Short-Term Memory (LSTM) Recurrent Neural Network (RNN):
 - Continuously classify spikes in real-time.
 - Automatically adjust to spike decay length.
- Dataset collected from alignments during 2016-2018:
 - 1550 alignment spikes
 - 1423 spurious spikes
- Input:
 - BLM signal 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

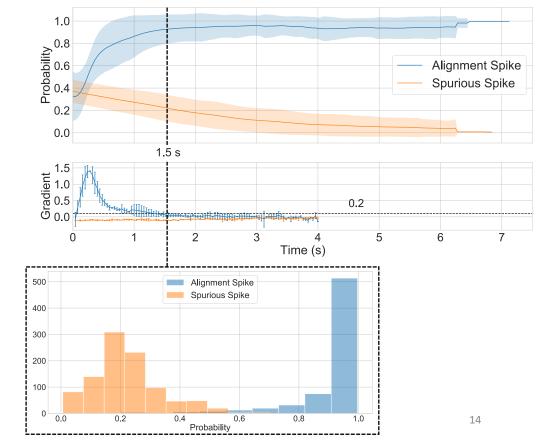
LSTM-RNN for Spike Classification

- 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.



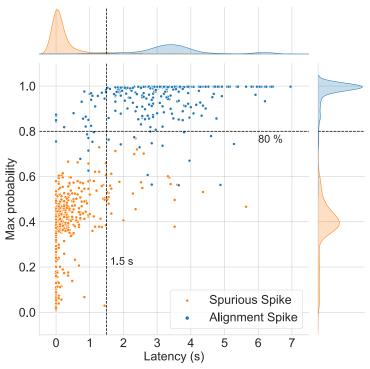
Spike Classification Analysis

- 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 + x + 1)
4b	Align Right Jaw	2*(0.1 + x + 1)
5a	TCP before (Left Jaw)	0.1 + x + 1
5b	TCP before (Right Jaw)	0.1 + x + 1
6	TCP after (Left + Right)	2 * (0.1 + x + 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:
 - x₁ = 1.07 s @ Inj, 2 s @ FT
 - x₀ = 1.07 s @ Inj, 1.54 s @ FT

(from slides 11, 16)

Theoretical Improvement of Alignment Time

		~50% speed-up
Case	Supervised ML	LSTM-RNN
1 coll @ Inj	53.8 s	27.43 s
+ 1 spurious spike/align	69.1 s	33.94 s
79 colls @ Inj	70.84 mins	36.12 mins
+1 spurious spike/align	90.98 mins	44.69 mins
1 coll @ FT	71.8 s	35.8 s
+1 spurious spike/align	93.1 s	43.72 s
79 colls @ FT	94.53 mins	47.14 mins
+1 spurious spike/align	122.58 mins	57.56 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

THPV040	NEW MACHINE LEARNING MODEL APPLICATION FOR THE	CERN V	WEPV016	THE AUTOMATIC LHC COLL		D	CERN CORN	THPV012			FOR RUN III OPERA		MA CENT
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	G. Azzopardi*, CERN, Geneva, Switzerland, G. Ricci. Sabienza Università di Roma	ICALIFICS 2023		G. Azzopardi*, B. Salvachua Ferrando		nd,	ICALIPCS 2023		Castro, CERI	, Geneva, Switzerland, G	 Valentino, University of M 	falta	ICALIFICS 2023
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0	supervised ML to classify spikes.	100 ortunat antidestare.	Colimation system protects LINC	Reference collinator aligned with collinator to create reference halo.		• The fully-automatic alignment is	-	mass energy of 14 TeV with 320 MJ of stored learn energy planned for Eur. 3.	alsorbing blocks, referred to as joan.	alignment comparigns required at all	 Parpase Find the jew position/angles, proteing the beam orbit at publicant 	angle m.r.t. the sollimator burne.	· Payme
Right pau	User International Sector Sect		 100+ collimators, each made of 2 jaws 	The collimator laws are moved towards the beam in check of 5-32 um whild monitoring	 3-tier structure (see Figure). 	implemented in a dedicated FESA class -	parallel, 5 per beam (shared reference	 A collection spine safely departs of 	maters in adjust the jaw position/argle.	machine slates, to set up the hierarchy. a Different setups needed for different	stream sides of the solimator (see Figure).	 Masshan Hild signal, jon protions. Jumps The lot of collimators to be alarent. 	Alson for tighter collector settings Convert lands minutes with sould
A collination system protects the LHC.	Calimator mamilowanis losam 0 4 5 0 10 6 5 0 FT • 2872 samples collected from alignments during 2016-2018.		inside a vacuum tank.	the BLM signal recarded in the collimator's respective BLM.	 The hardware is abstracted and controlled through FESA (Frant-End 	CollAlignSupervisor.	and cross-talk).	latare lasare, practiling a cleaning efficiency of 90.09882 of halo particles.	 The lightest settings (5 a / -1 mm gaps), remains -22 are sending assesses. 	machine parameters, and it orbit shifts.	 Manitan IPM storingten, losan position. Jepuise Min. and, pay (non), target align 	a Presentare	jespaniae spines primanae. • Maeilae: 10.11 stends, industrial annites.
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0 1 2 3 4 6 8		*1 gurdius gale 01.1 s 21.72 s 79 sals (§ 77 94.51 mms	Collimator status	tame of collinator orgoing alignment	 Equal priority for collimators from the two beams. 	 Closing the application is an automatic stop if any 	 Dedicated collinator configurations e.g. ion beams 		Procedure: Automatically compare settings in the unlexied ISA configuration.	 Personanan repeate set out out of minutes per collevator. Persite seturment can be stated in 	and reduce the jaw gap by the predefined gap step size.	 Angular Performance: The largest angular scanof 20 most requires > 1 hour. 	compare the collimate series and the basis porties are all the basis porties and the
Latenay (s) Distribution of max, probabilities ashiev	 Alignment spike >= 80 %, then fit exp. func. for =98.5 % decay. 	+1 lipuritous quite 122.58 mins 17.58 mins		I, 1, 2 Ignare, Aligning: (first jaw, second jaw, both jaws)	 Limit the overall waiting time. 	alignment is ongoing.	no longer bound to identical setups as with protons.		 Calculated based as the data in USA. In NEXUS based during selected time. 	 Parallel sequences can be started in for collimators not convexied to the same interlash units (twistally one 	 Repeat until the minimum jaw gap is reached. Same jaw positions and IPM. 	 Not sizer is parallel, as any orescials inhibits determining the patient. 	real time.
two uplies denses, and the required in	 On average already decayed (mean 0.61 s). 	The average these stical minimum time for sequential algoresris.	Spike class2,	 I. Barane, Erraci, No spike, Spike 	 Reacting to user interrupts. 		umages as wear protocili.	Putan full cirg late may () injection 824 place.	 The real time collimator protons. 	interlash anti-per II).	electroie signals for offline analysis.	inhials determining the optimal shareeling argin in past analysis.	

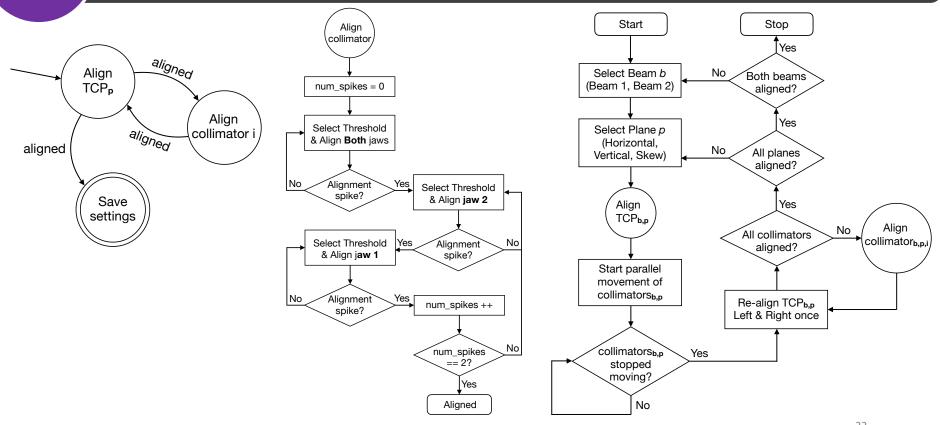
THPV040





Backup slides

Collimator Alignment Procedure



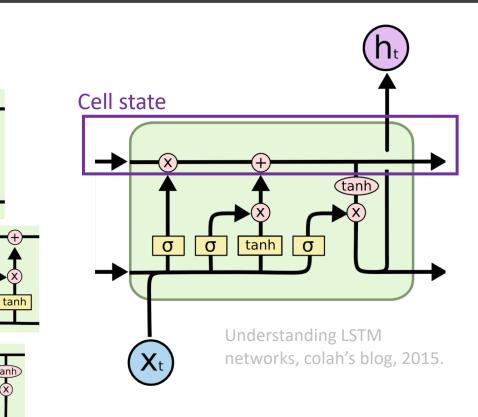
G. Azzopardi, et al., The Automatic LHC Collimator Beam-based Alignment Software Package, ICALEPCS'21²²

Long Short-Term Memory model

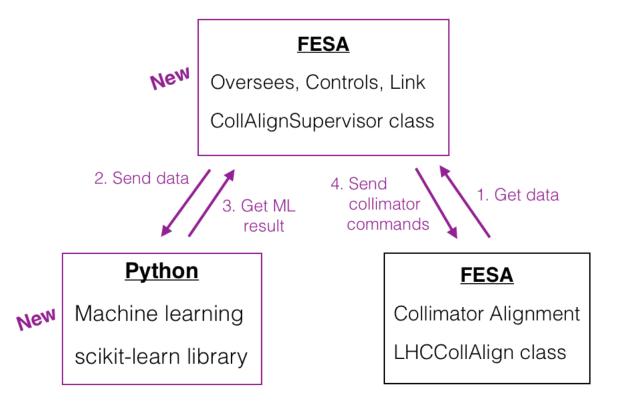
- LSTMs are a type of RNN that can learn longterm dependencies.
- 3 activations inside:
 - Forget gate layer: What information to keep from the cell state.

Input gate layer: Which values to be updated.

• Output layer: Decide what to output.

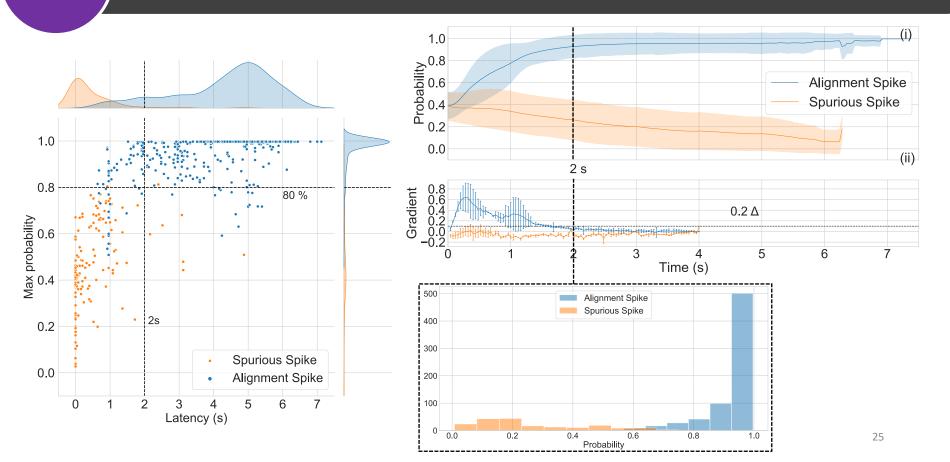


Fully-Automatic Alignment Implementation



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

Spike Classification Analysis @ FT



Spike Classification Analysis Results Overview

	Pro	oton beams	lon 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		98 %	97 %		