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UNIVERSITY OF APPLIED SCIENCES

CERN

Master’s Thesis

Anomaly Detection with Artificial Intelligence:

Post-mortem analysis of LHC ion beam losses during high-energy beam dumps

Presented by
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on
29 June 2023

Reference: [1]

Outline

1. **Introduction**
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   b. Beam loss monitors
   c. Post-Mortem analysis
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3. **Model creation**
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   c. Classification
4. **Result**
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   b. Polynomial model
   c. Comparison: proton model vs. ion model classification on ion beam dumps
5. **Conclusion**

Introduction

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The LHC

- Brief layout explanation
- Tasks of different systems

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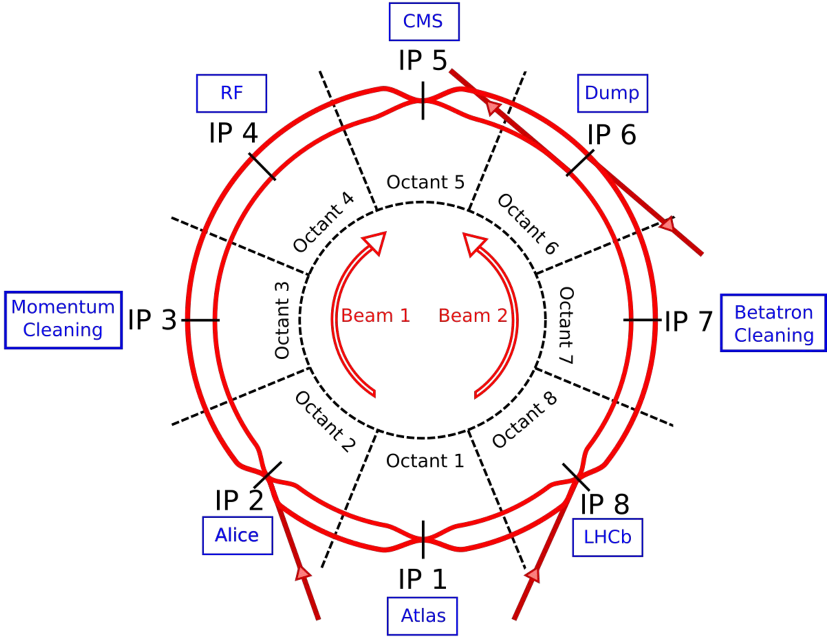
The Large Hadron Collider

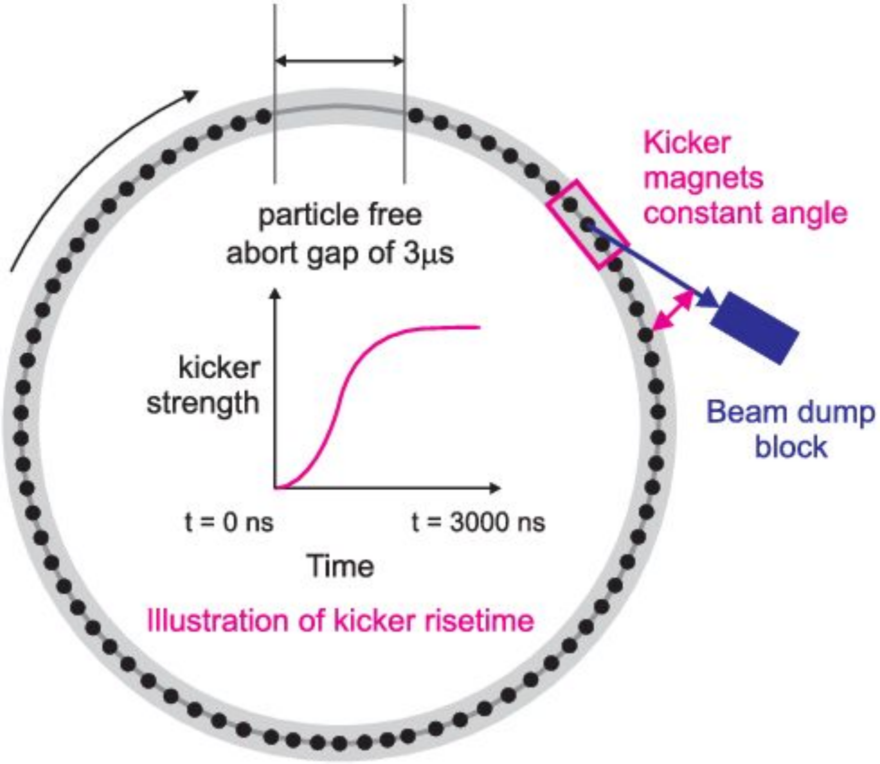
- Beam Injection in IP 2 and IP 8
  - Sum of particles in a beam => (beam) **intensity**
- Acceleration in IP 4
- Beam cleansing of …
  - particles that deviate from reference energy in IP 3
  - Particles that deviate from reference orbit in IP 7 (smallest aperture)
- Experiments (particle collision) in IP 1, IP 2, IP 5 and IP 8
  - (Instantaneous) **luminosity**
- Extraction of the beams in IP 6 (**beam dump**)
  - Triggered …
    - manually by operator (**Programmed dump**) e.g. end of experiments
    - automatically by protection system (**Protection dump**) e.g. high or unusual beam losses



Reference: [2] (adapted)

The beam dump

- Kicker magnets bend the beam in direction of the dump line
- Beam dump block at the end of a dump line absorbs the particles
- Full deflection field after 3 μs
  - Particles affected before are only partially deflected (losses in IP 6, IP 7 and dump line)
  - 3 μs particle-free gap needed (**abort gap**)
- Particle intensity in abort gap => **abort gap population** (AGP)



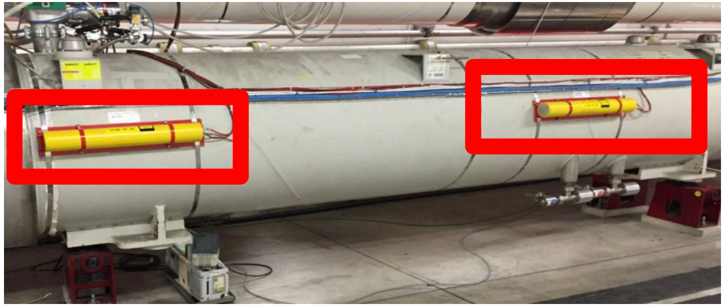
Reference: [3]

Beam loss monitors

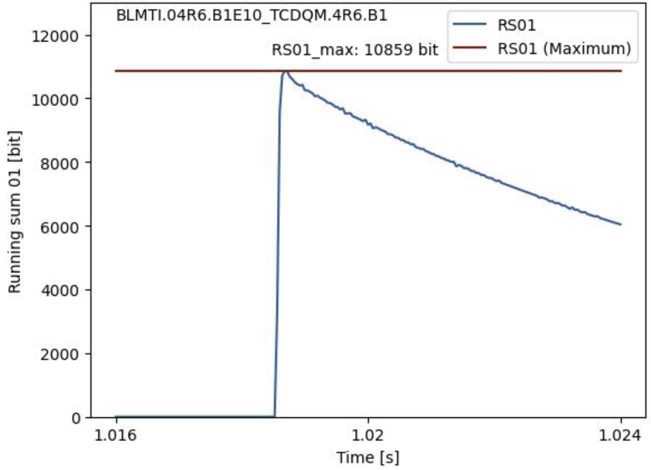
- Task of the BLMs
- Beam losses

Beam loss monitor (BLM)

- Approximately installed **4000** BLMs
- Supervise beam losses
- Beam loss data available in Post-Mortem system
  - Saved as times series
    - 1.024 s around the beam dump
    - Divided into 40 µs bins (**running sum 01** or **RS01**)
      - 25600 values per BLM
    - Analysis conducted with the maximum of the time series (**RS01 max**)
  - Saved in bit
    - Different types of BLMs have different conversion rates from bit to Gy/s



Reference: [4]



Post-Mortem analysis

- Analysis performed after each beam dump
  - Identify issues
  - Improve machine protection
- Manual analysis by experts
  - Time consuming task
  - Soon to be supported by automated anomaly detection

Goal

Goal

1. **Derive beam loss thresholds for the automated anomaly detection tool**
   - Specifically for Pb-ions
   - Based on previous work on proton beam dumps by P. Ziegler [5, 6] and F. Huelphers [7]

2. **Comparison of anomaly detection performance of high-energy ion beam dumps between**
   - Classification model derived from proton beam dumps by P. Ziegler [5, 6]
   - Classification model derived from ion beam dumps (this work)

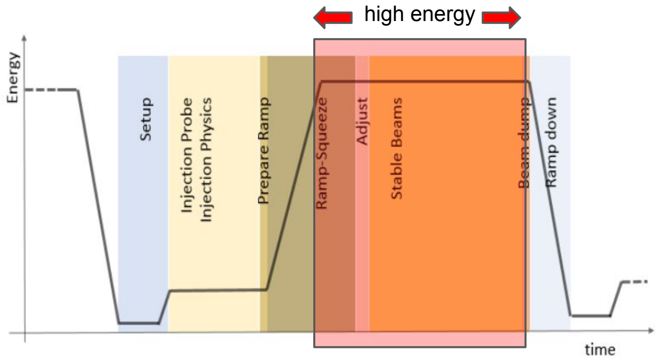
Model creation

Data

- Overview of the dataset
- Training and test data

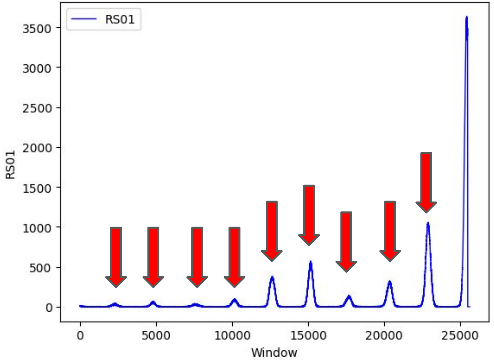
Data

- In total 195 ion beam dumps
    - Mainly from 2015 and 2018 (carried out for about a month in each year)
- **131 high-energy** ion beam dumps
    - 9 asynchronous beam dump tests
        - Tests that are intentionally carried out with a high number of particles in the abort gap
    - 6 “10 Hz” beam dumps
        - Horizontal oscillation of the beam in a frequency of 8-12 Hz



Reference: [8]

BLMTI.06L7.B1E10_TCP.B6L7.B1



In 40 µs

10 Hz pattern clearly visible

Timestamp:
21-NOV-2018
00.17.58.906000

Data

- Dataset was initially split into training and test dataset based on indicators (see table)
  - Labeled dataset not available in early stages
  - Labeling them manually by expert takes time
- After labeling the dataset by expert: confirmed that all dumps in the training set are labeled as “OK”
- Training and test split
  - 65 data samples used for training
    - Only OK samples
    - Used to create the classification models
  - 66 data samples used for testing
    - 48 could be clearly labeled as “OK” / “NOT OK” by expert
    - Used to verify the results

Feature Name	Feature Type	Feature values
Event Category	Categorical	PROGRAMMED_DUMP
Accelerator Mode	Categorical	ION_PHYSICS
Pm Machine Protection Result	Categorical	OK
Overall Result	Categorical	OK
Orbit Changes	Categorical	NO CONSIDERABLE ORBIT CHANGES
AGP Beam 1 (Maximum)	Continuous	$\leq 5 \times 10^9$ charges
AGP Beam 2 (Maximum)	Continuous	$\leq 5 \times 10^9$ charges
Years	Categorical	2015, 2018
Flag (Async. Dump)	Categorical	0
Flag (10Hz Dump)	Categorical	0
Flag (Xe-Ions)	Categorical	0

Training dataset parameters

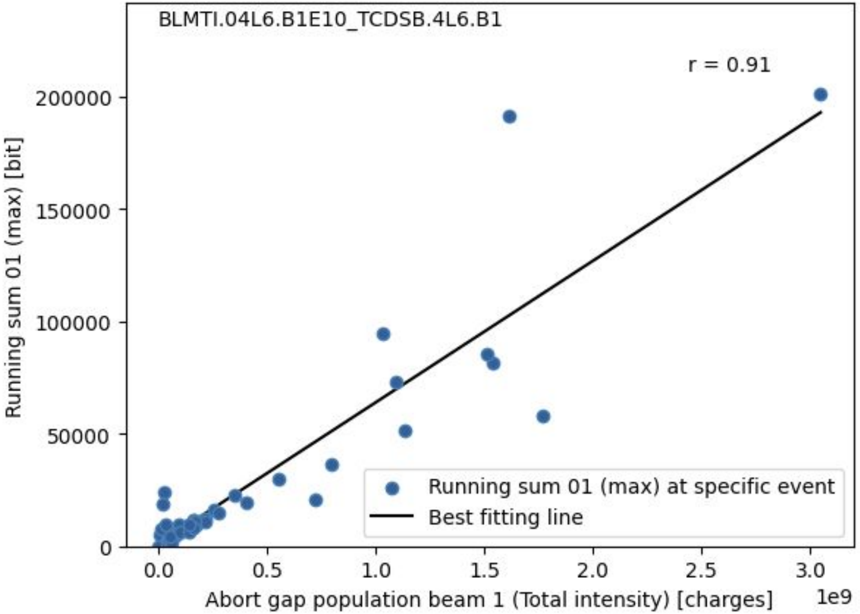
Model creation process

- Divide BLMs into classes and create model for each class
  - High-correlated BLMs
    - Correlations between beam losses and abort gap population, luminosity, beam intensity
  - Low-loss BLMs
    - Show no correlation
    - Usually record low beam losses
  - Remaining BLMs
    - Not considered in the analysis
- Derive beam loss thresholds to build classification model
  - Combination of high-correlated BLM and low-loss BLM

Divide BLMs into classes

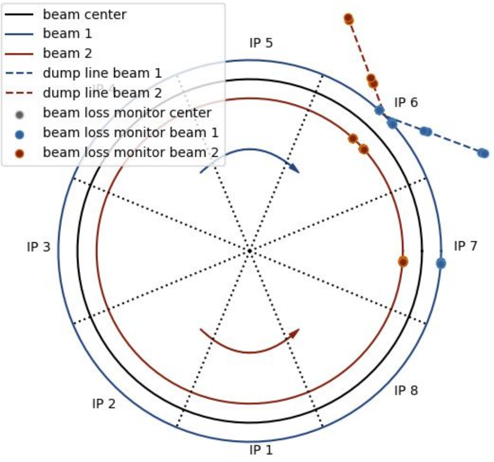
- <u>High-correlated BLMs</u>
  - Correlation analysis with **Pearson Correlation Coefficient** (PCC) per BLM
    - Between beam losses and features AGP, intensity and luminosity
    - At least 10 datapoints
    - Running sum > 120 bit (**noise limit**)
    - Running sum < 255,557 bit (**saturation limit**)
  - Selected one feature per BLM with highest correlation among all features
  - PCC >= 0.7

- <u>Low-loss BLMs</u>
    - At least 10 datapoints
    - 1-4 datapoints > 120 bit allowed
    - Remaining datapoints < 120 bit

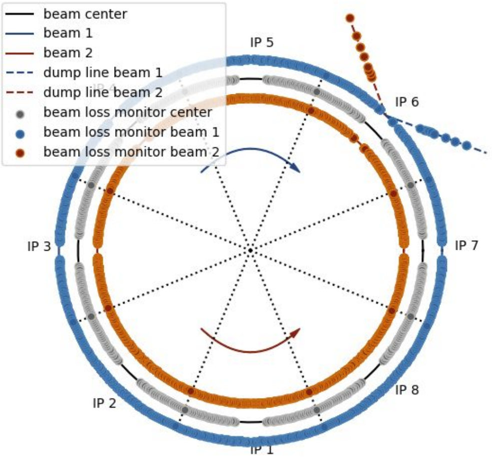


Divide BLMs into classes

- High-Correlated
  - 64 BLMs
    - 58 correlated with AGP in IP 6, IP 7 and at the beginning of the dump lines
    - 6 correlated with Intensity at the end of the dump lines



- Low-loss
  - 3828 BLMs distributed around the ring



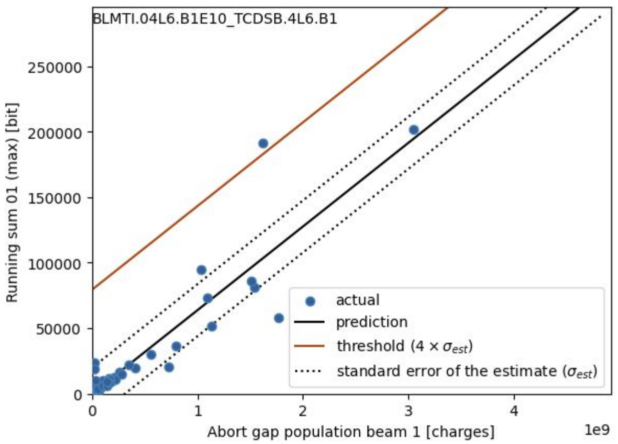
Classification models

- Estimation function:
  - High-correlated BLMs: $y_{est} = \sum_{i=1}^{o} (p_i \cdot x^i)$ { Linear: o = 1; Polynomial: o = 5 }
  - Low-loss BLMs: $y_{est} = \overline{m}$
- Calculation for high-correlated BLMs:
  - Ordinary Least Squares (OLS) regression
    - Find best fitting line
      - $\boldsymbol{p_i}$: coefficient of x_i
      - $\boldsymbol{\sigma_{est}}$: standard error of the estimate
    - If model is polynomial:
      - Calculate metrics for each order
        - Bayesian Information Criterion (BIC)
        - root mean squared error (RMSE)
        - R²-adjusted
      - Select the order for each metric with "best" value
    - Results in 4 functions per high-correlated BLM (linear, BIC, RMSE, R²-adjusted)
- Calculation for low-loss BLMs:
  - Calculate mean $\overline{\mathbf{m}}$ and standard deviation error of the mean $\boldsymbol{\sigma_{est}}$
- Deriving thresholds for classification:

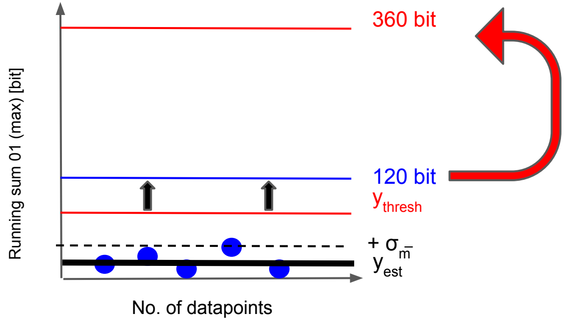
$$y_{thresh} = f \cdot \max(y_{est} + 4 \cdot \sigma_{est},\ 120)$$

{ High-correlated: f = 1; Low-loss: f = 3 }

High-correlated BLMs



Low-loss BLMs



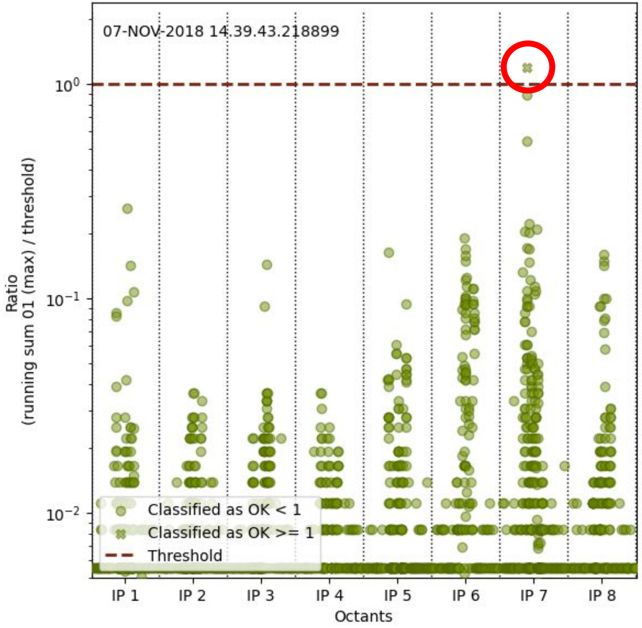
Classification

- Classification of beam dumps as OK / NOT OK

Classification

1. Classify individual BLMs as OK / NOT OK
   - beam loss > threshold => NOT OK
   - otherwise => OK

2. Classify beam dump
   - Beam dump NOT OK if:
     Number of NOT OK BLM classifications > 1



- One BLM above threshold
- Beam dump still OK

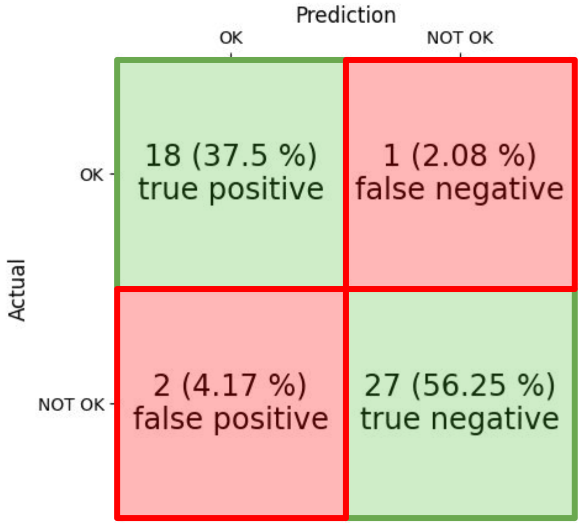
Results

Results

- Classification results of
  - Linear model
  - Polynomial models
- Comparison of proton model and linear ion model
  - Classification of ion dumps
  - Derived thresholds

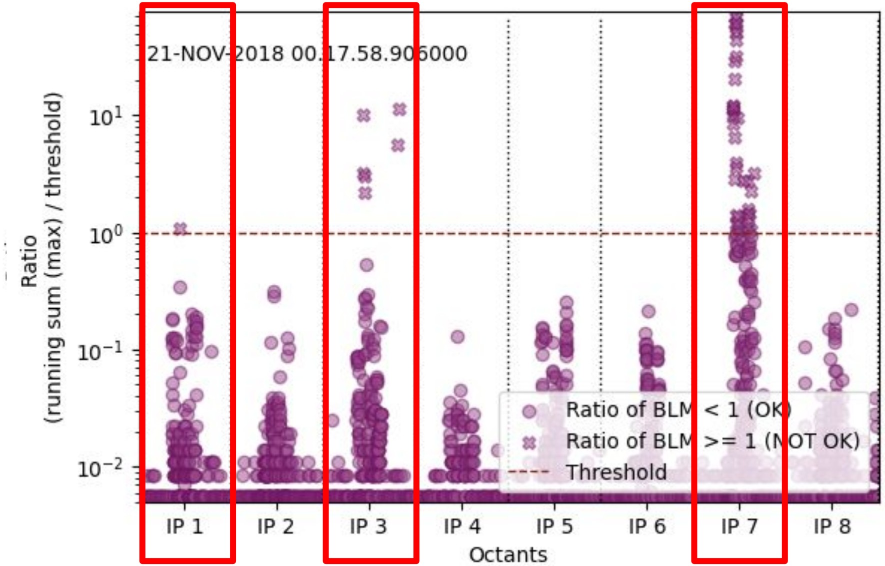
Linear model

- Classification
  - 45 of 48 beam dumps correctly classified
    - Accuracy: **94 %**
    - 8 / 9 asynchronous beam dump tests
    - 6 / 6 “10 Hz” beam dumps
  - 3 misclassifications



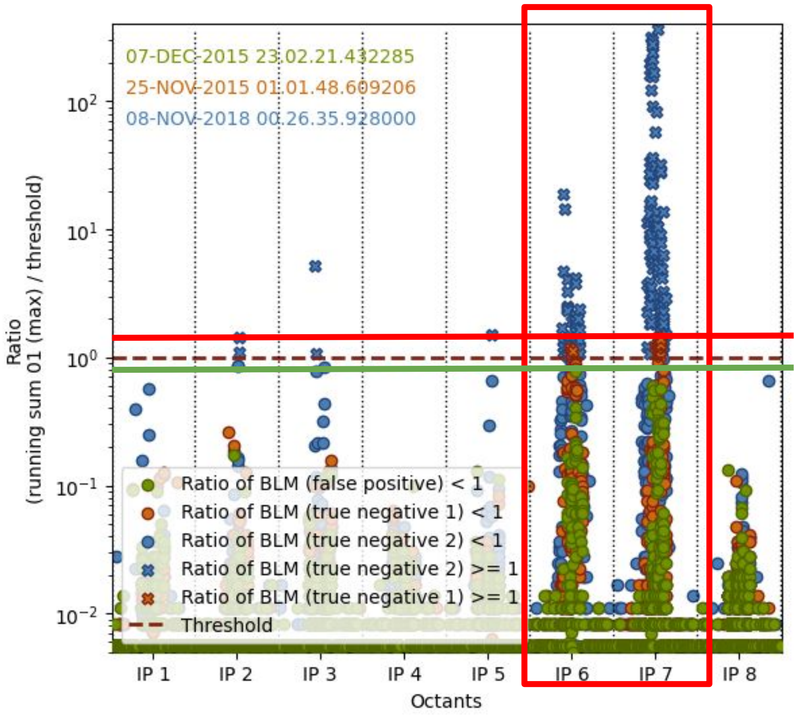
Linear model

- Correct classification example
  - True negative (“10 Hz” beam dump)
  - High losses expected in IP 3 and IP 7
    - mostly left of IP 7 (produced by beam 1)



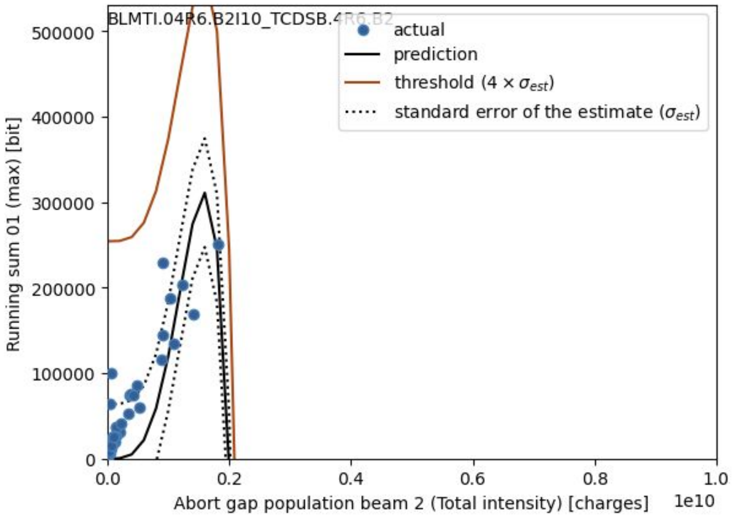
Linear model

- Misclassification example
  - 1 false positive misclassified asynchronous beam dump test:
    - AGP = 9.3 * 10^8 charges
      - Lowest AGP of all tests
      - Correctly identified as beam dump with low beam losses
  - Compared to 2 true negatives asynchronous beam dump tests:
    - AGP = 1.5 * 10^9 charges (1.6 times higher)
      - Next lowest AGP of all tests
    - AGP = 2.7 * 10^{11} charges (290 times higher)
      - Most tests in this range



Polynomial models

- Classification
  - Polynomial orders of 3 to 5 lead to negative thresholds
    - drop of classification accuracy
      - BIC / RMSE: 88 %
      - R^2-adjusted: 90 %
  - Limiting orders to 1 and 2 better
    - But still slightly worse than the linear model
      - Accuracy: 92 %
      - (vs. 94 % of linear model)
  - No gain in adding higher orders
    - At least with an automated selection process



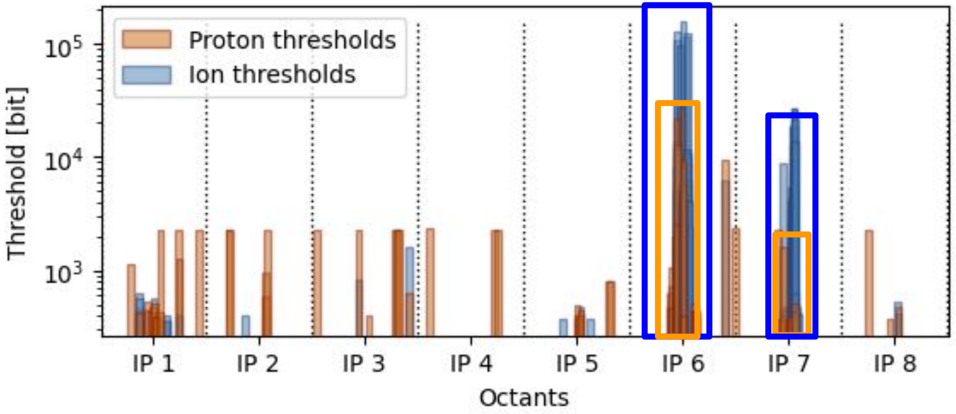
Comparison: proton model vs. ion model

- Classification performance
  - Proton model trained on proton beam dumps
  - Classification of ion beam dumps by both models
  - Same classification results for asynchronous beam dump tests and “10 Hz” beam dumps
  - Accuracy increased clearly from 79% to 94%
    - Confirms the need of thresholds specifically for ion beam dumps

Metric	**Models**	
	Proton	**Ion (linear)**
TP	15	18
FP	6	2
TN	23	27
FN	4	1
Recall	78.95 %	95.74 %
Specificity	79.31 %	93.10 %
Precision	71.43 %	90.00 %
Accuracy	79.17 %	93.75 %
F1-score	75.00 %	92.31 %

Comparison: proton model vs. ion model

- Comparison of thresholds done with same number of charges (AGP and intensity) for both models
- Ion thresholds are generally higher in high beam loss regions (IP 6, IP 7)
  - Areas marked for better comparison

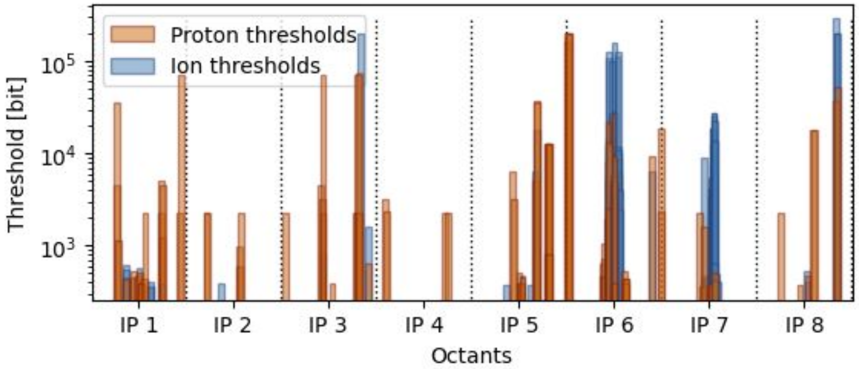


Parameters:

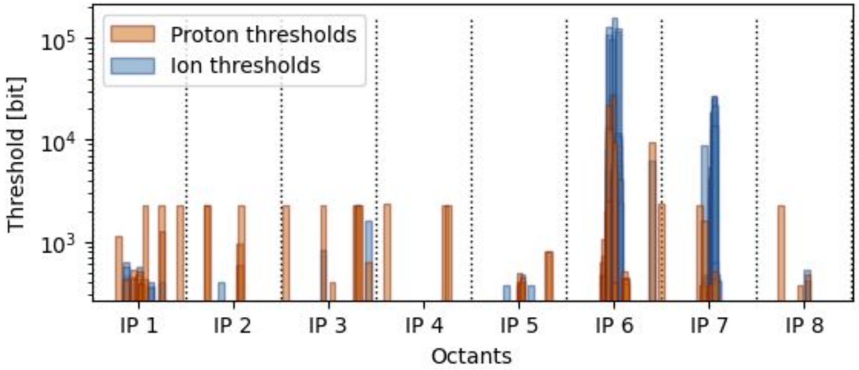
- Intensity: $1153 * 10^{10}$ charges
- AGP: $3 * 10^8$ charges

Comparison: proton model vs. ion model

- Discovered high, fake values of some BLMs
  - Due to corrupted memory cards
- Can lead to high thresholds in low-loss BLMs
  - Due to high standard deviation error of the mean
- Emphasizes the need for consistency check of (low-loss) BLMs
- Does not affect the classification results!



With fake values



Without fake values

Conclusion

Conclusion

- Confirmed differences in ion and proton model thresholds
- Ion specific thresholds are needed
  - Will be implemented in the automated beam loss analysis tool
- Polynomial models should be modeled only with expert knowledge
- Consistency check for (frequently) low-loss BLMs to identify fake values

References

[1] https://www.weltmaschine.de/sites/sites_custom/site_weltmaschine/content/e37820/e40691/e158693/e189177/e189185/20210-138LHC02.jpg [Online; accessed 26-June-2023]

[2] Cai, Y., Nosochkov, Y., Giovannozzi, M., Risselada, T., Todesco, E., Zhou, D. & Zimmermann, F. HE-LHC Optics Development. ICFA Beam Dyn. Newsl. 72, 141–151. https://cds.cern.ch/record/2315726 (2017)

[3] Koschik, A, Goddard, B, Höfle, W., Kotzian, G, Kramer, D. & Kramer, T. Abort Gap Cleaning using the Transverse Feedback System: Simulation and Measurements in the SPS for the LHC Beam Dump System. https://cds.cern.ch/record/1124316 (2008)

[4] Biłko, K. & Stein, O. Report on the Prompt Dose Distribution Along the LHC Based on BLM Data for proton-proton operation in Run 2. https://cds.cern.ch/record/2692574 (2019)

[5] Wiesner, C., Hernalsteens, C., Hülphers, F., Uythoven, J., Wollmann, D. & Ziegler, P. Automated evaluation of the LHC proton losses during highenergy beam dumps for the post-mortem system in 14th International Particle Accelerator Conference (IPAC 2023) (2023). https://cds.cern.ch/record/2858945

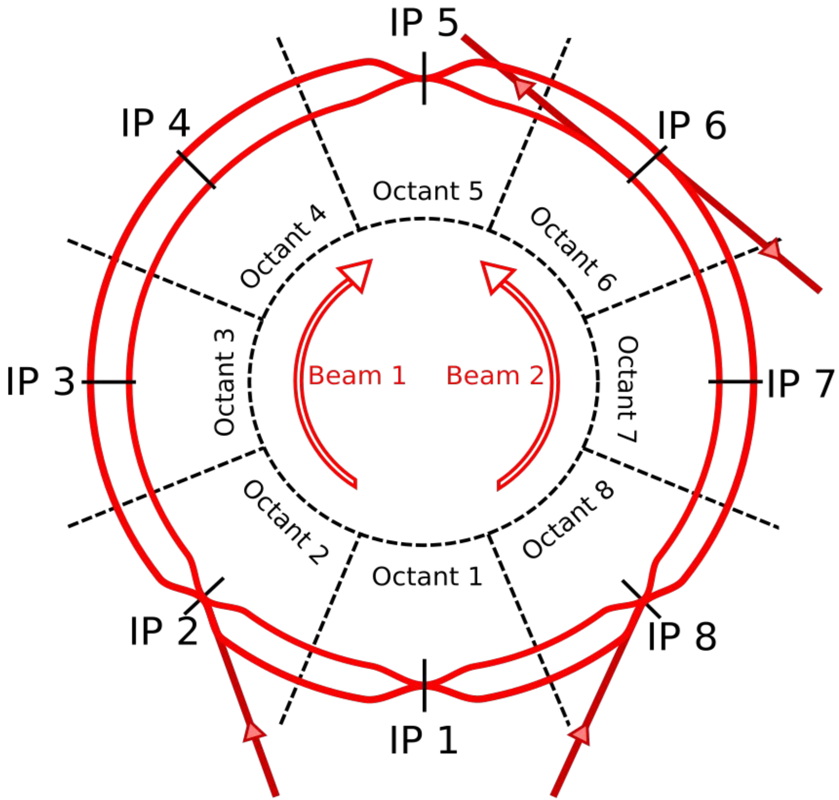
[6] Ziegler, P. Automated evaluation of beam losses during high energy proton beam dumps (to be presented). MA thesis (University of Regensburg, 2023).

[7] Hulphers, F. Deep learning for anomaly detection in high-energy beam dump data from the Large Hadron Collider Presented 16 Sep 2022. MA thesis (Technical University of Munich, 2022). https://cds.cern.ch/record/2834608.

[8] Alemany Fernandez, R., Apollonio, A., Bartmann, W., Buffat, X., Niemi, A., Schulte, D., Solfaroli Camillocci, M. & Stoel, L. FCC-hh turn-around cycle tech. rep. (CERN, Geneva, 2016). https://cds.cern.ch/record/2239138

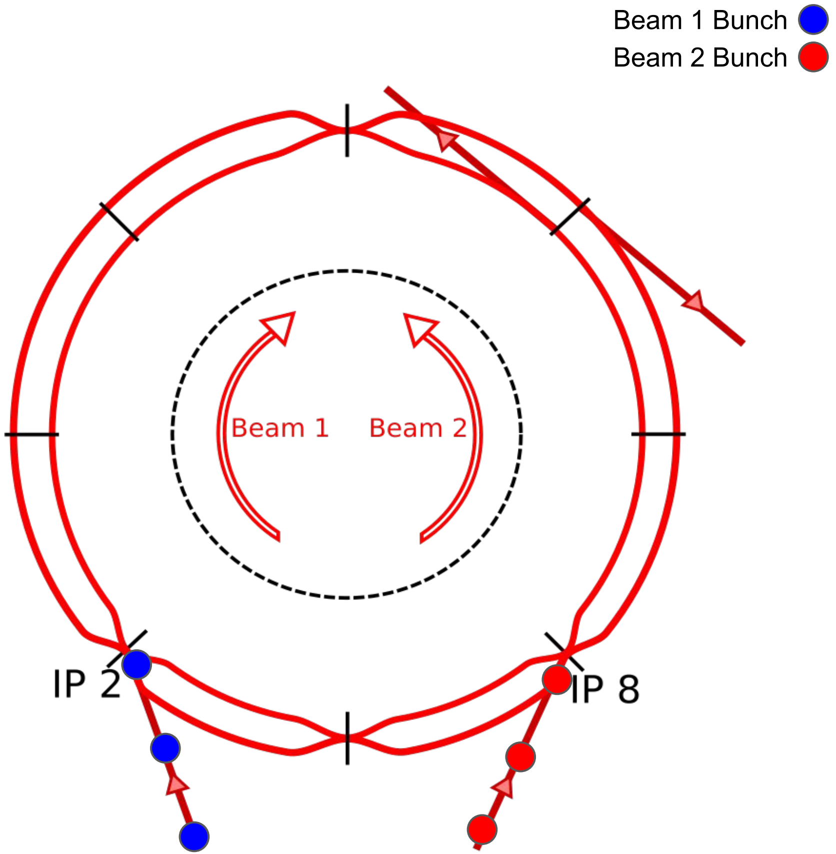
Layout and machine cycle of the LHC

- 8 octants
  - Center of octant is referred to as **interaction point** (IP)



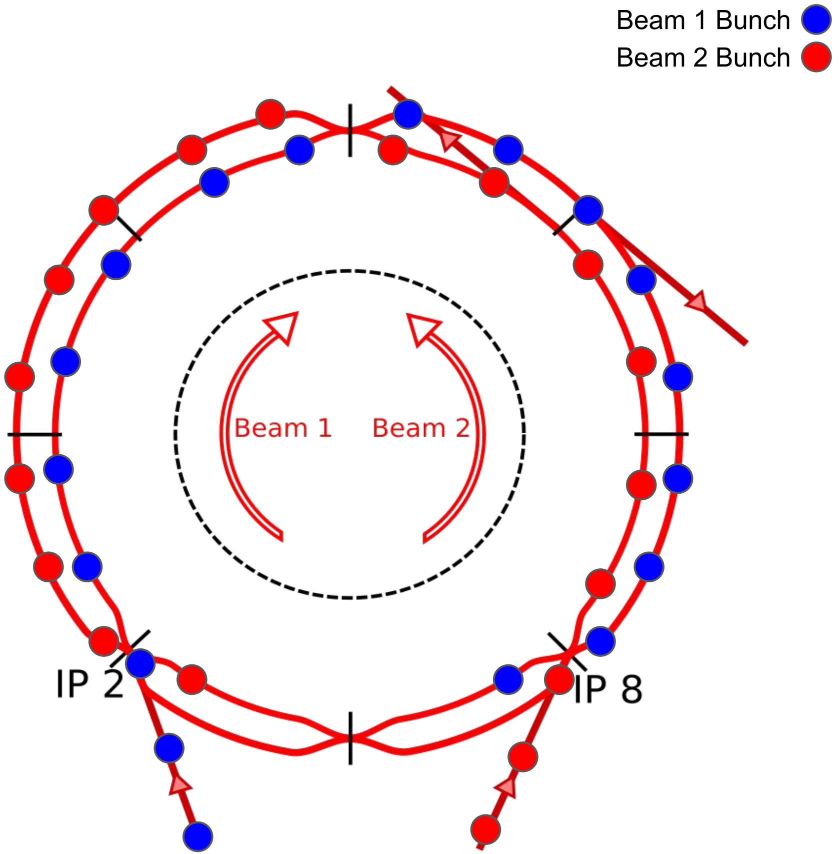
Layout and machine cycle of the LHC

- Beam injection
  - in **bunches** of particles



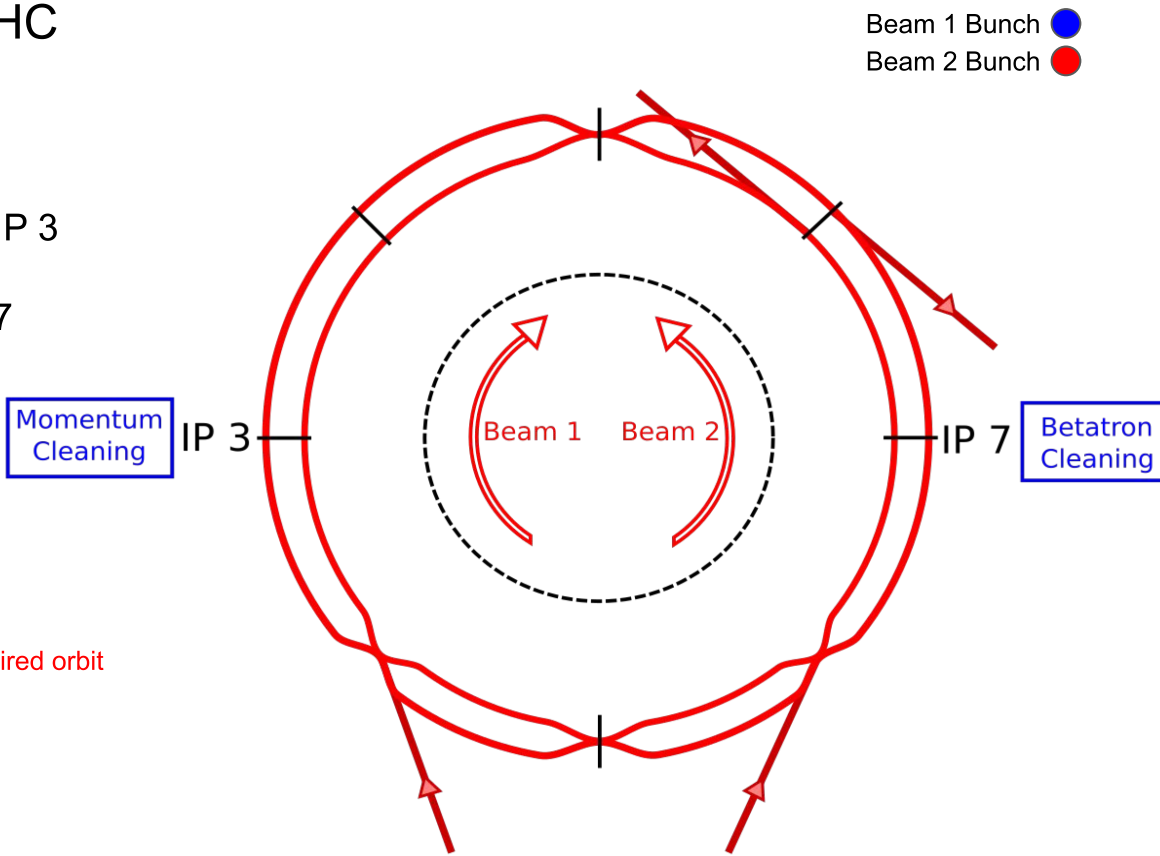
Layout and machine cycle of the LHC

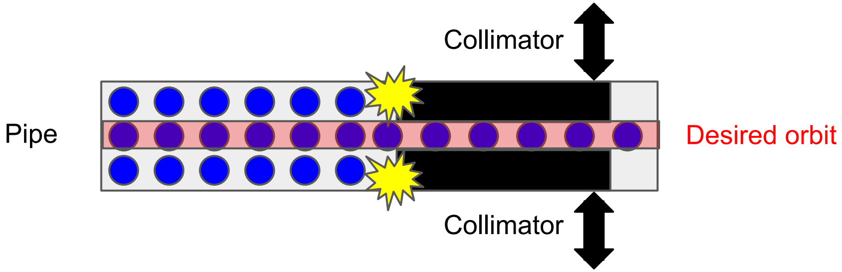
- Beam injection
  - Injection of bunches up to desired **intensity** (sum of all particles)



Layout and machine cycle of the LHC

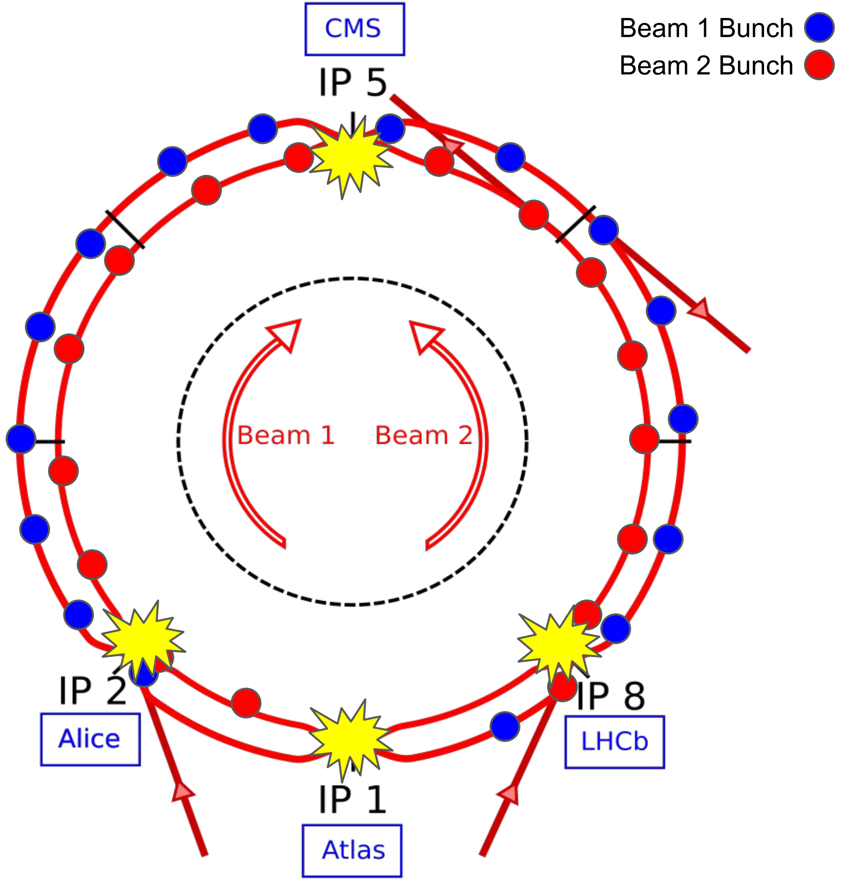
- Beam cleansing
  - Limit spread of particles
    - Momentum cleaning in IP 3 (energy deviations)
    - Betatron cleaning in IP 7
    - (orbit deviations)





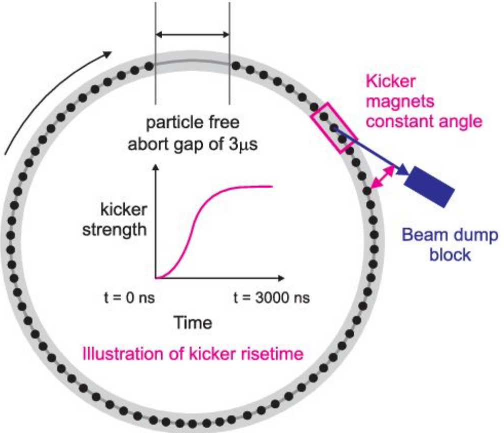
Layout and machine cycle of the LHC

- Collision of the beams
  - Measured in **luminosity**
  - Increased luminosity = increased probability of particle collisions

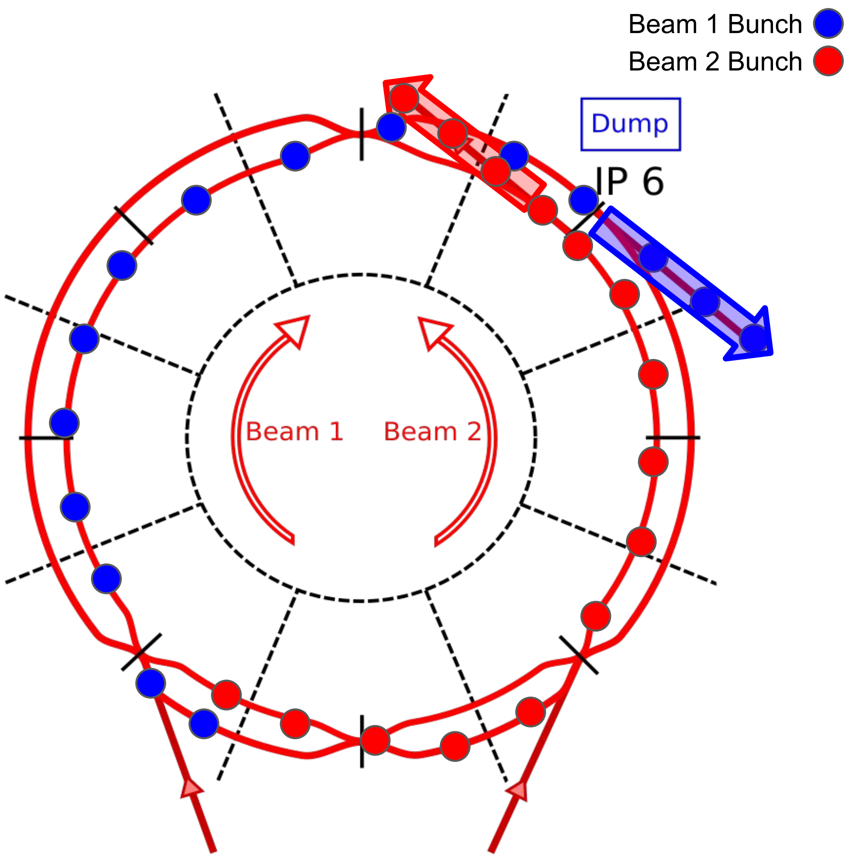


Layout and machine cycle of the LHC

- Beam extraction (**beam dump**)
  - 3 μs gap without particles needed (**abort gap**)

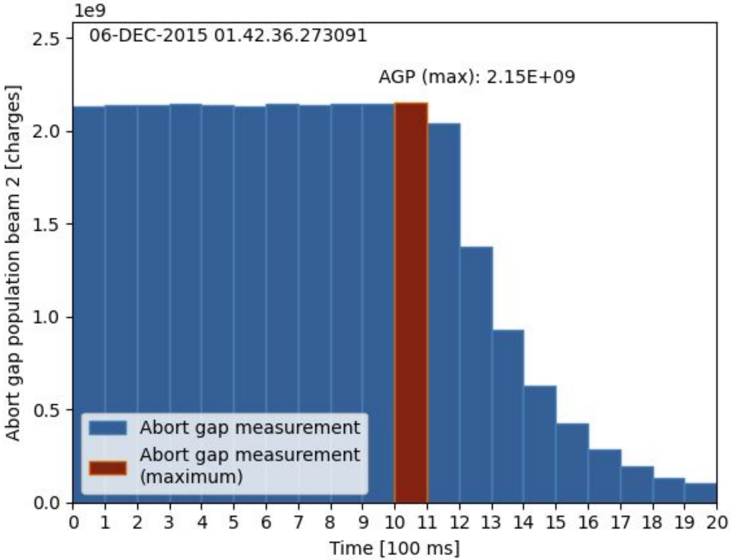


- **abort gap population** = intensity in abort gap

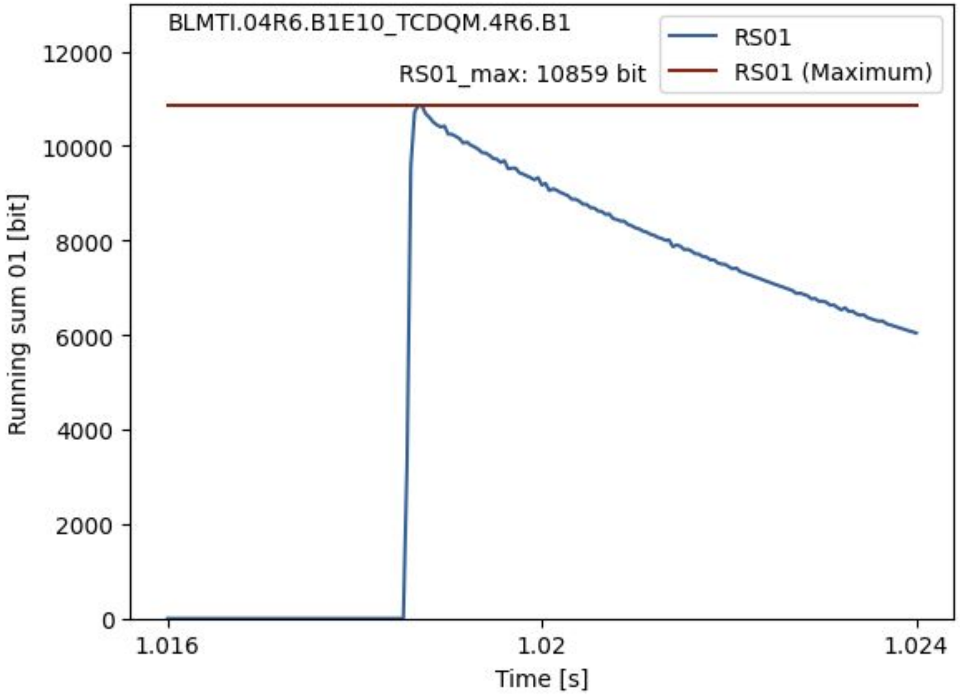


Abort gap population

- Measured in 100 ms intervals
- Maximum of all measurements if used for the analysis

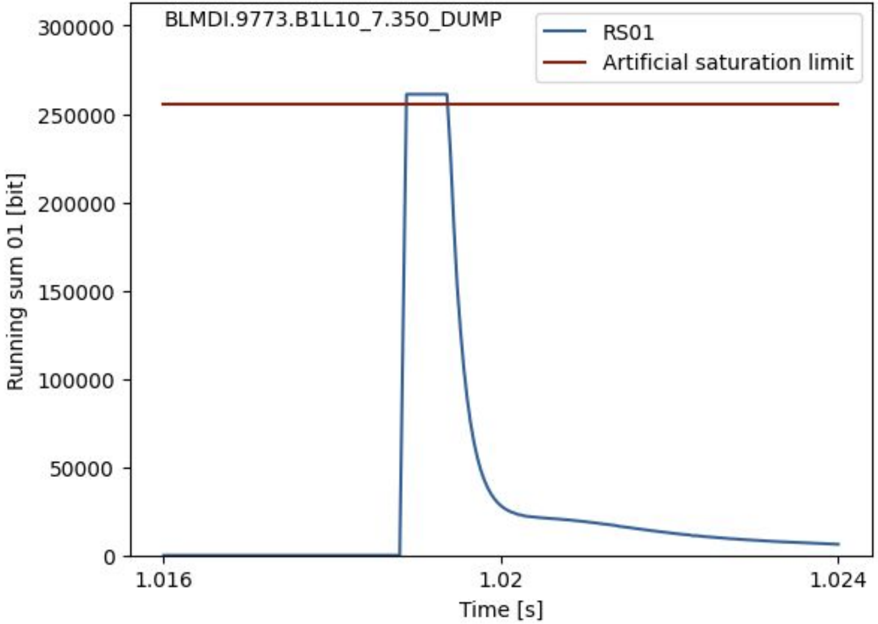


Running Sum 01 (max)



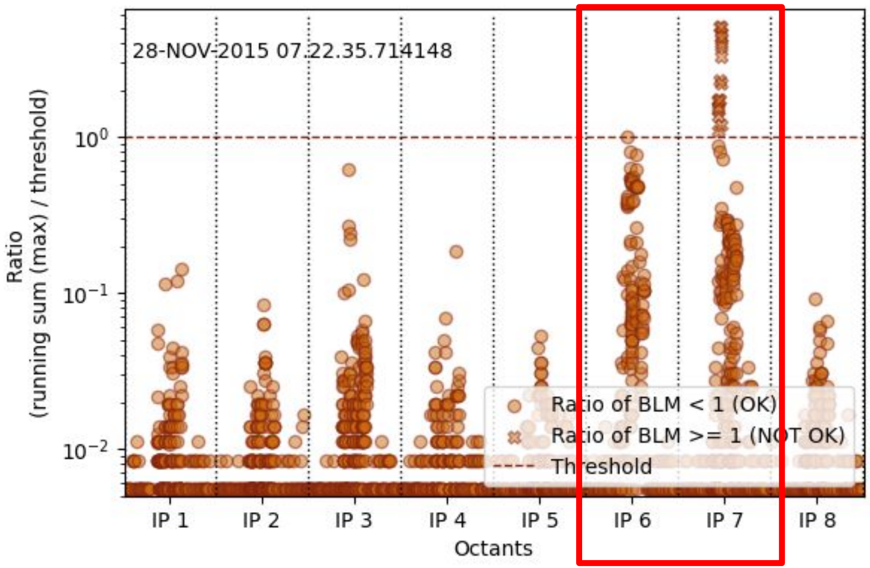
Saturation Limit

- (Artificial) saturation limit approx. 97.5% of real saturation limit



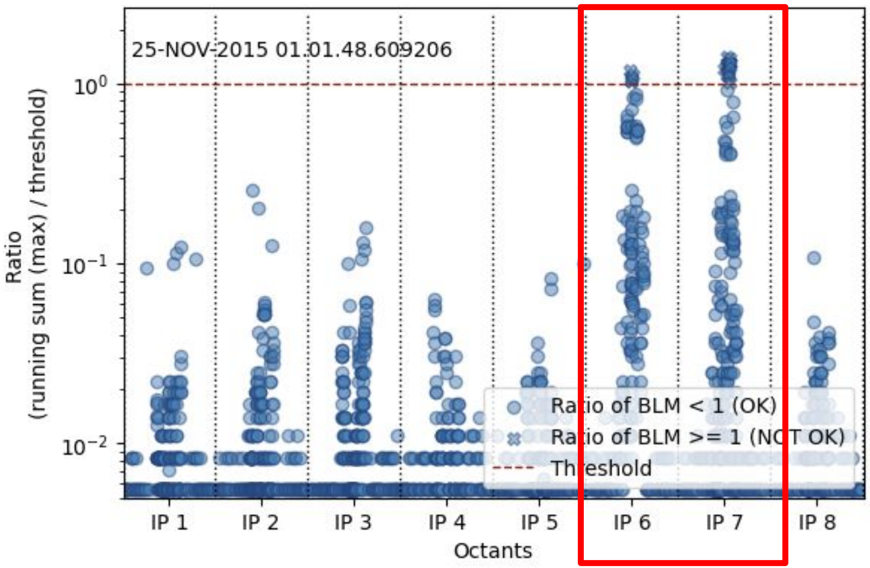
Linear model

- Correct classification example
  - True negative
  - Expert Comment:
    "**Losses** (…) **in IR7** (...). Clean dump (**losses in IR6** during the dump **relatively high** as usual with ions).
  -



Linear model

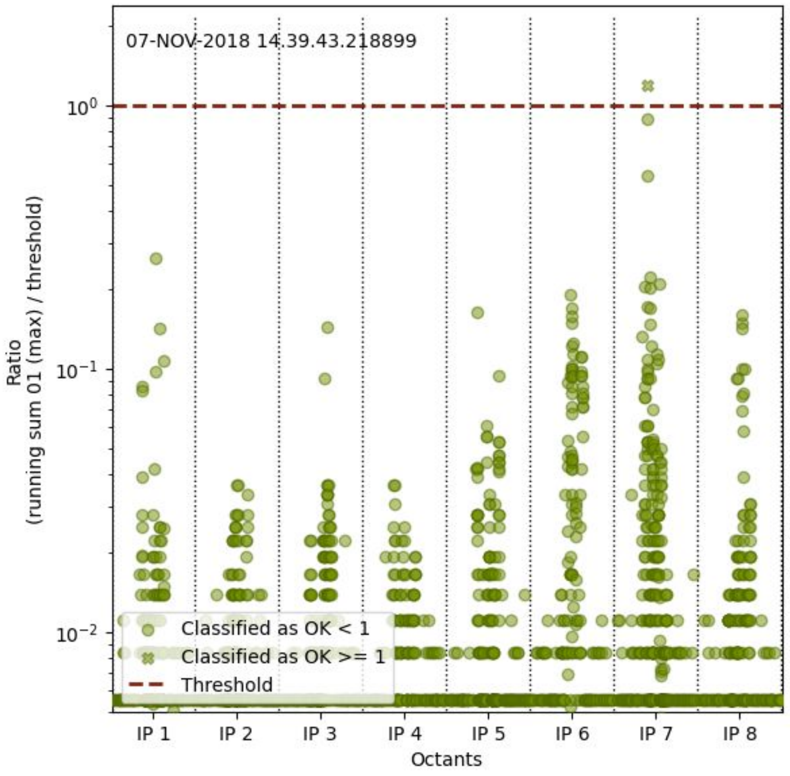
- Correct classification example
  - True negative (asynchronous beam dump test)
  - High losses expected in IP 6 and IP 7



Linear model

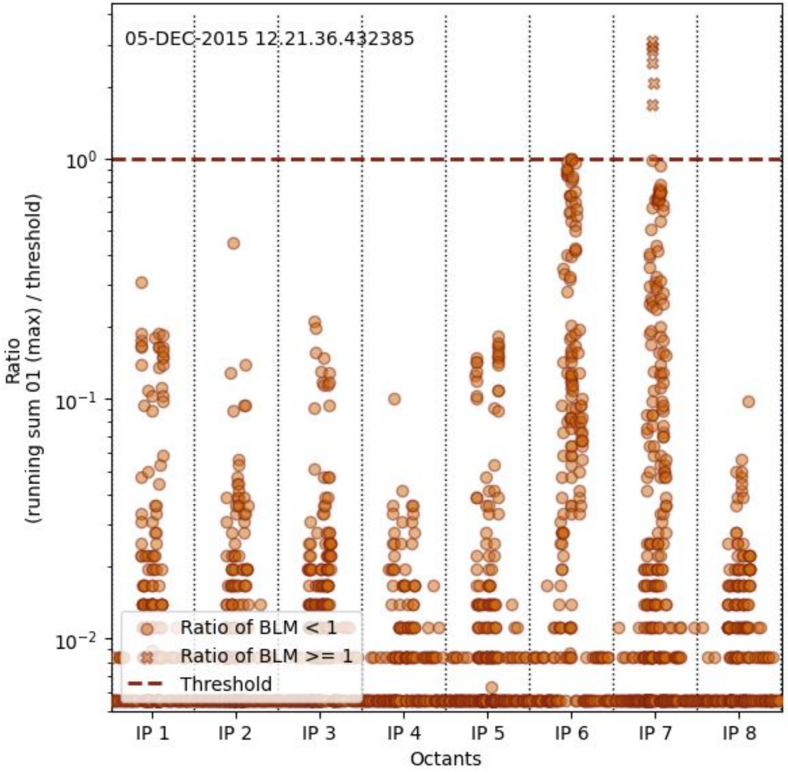
- Misclassification example
  - False positive
  - Protection dump
  - Operator comment:

    ***beam losses at IP7** during collimator alignment in collision*
  - Very low intensity beam dump



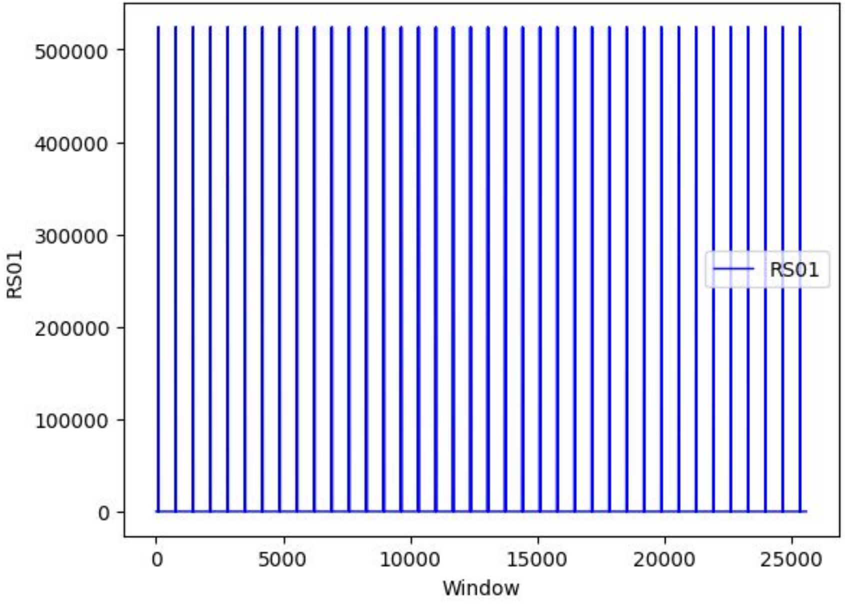
Linear model

- Misclassifications
  - False negative
  - Higher losses than usual in IP 7
    - Root cause not determined yet



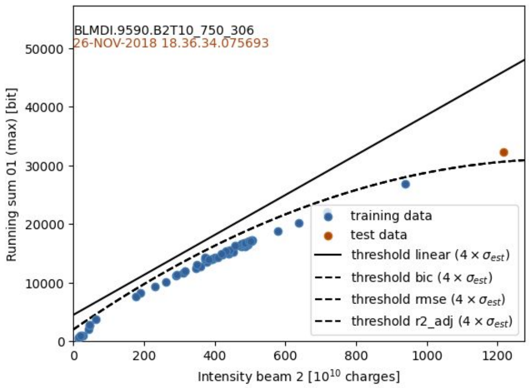
Corrupted component / BLM

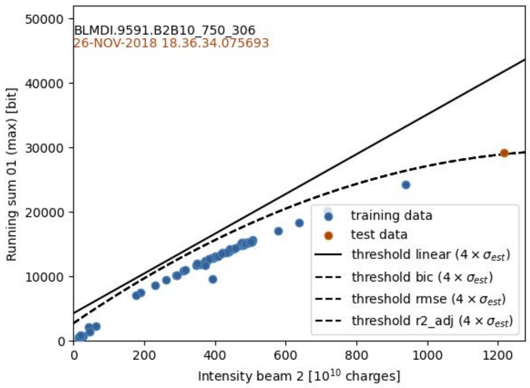
BLMBI.08R7.B0T10_MBA-MBB_07R7

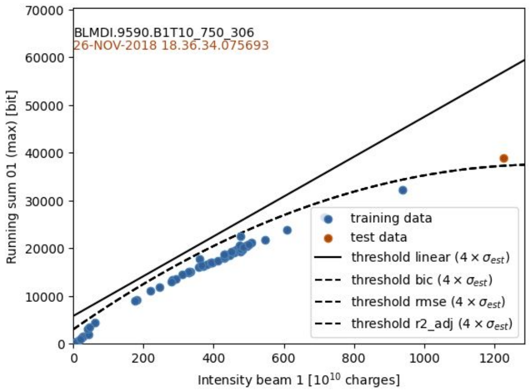


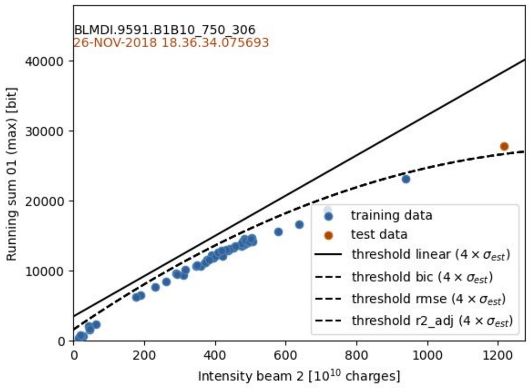
in 40 µs

Timestamp:
19-NOV-2022
16.17.44.047000


BLMDI.9590.B2T10_750_306
26-NOV-2018 18.36.34.075693
Running sum 01 (max) [bit]
Intensity beam 2 [10^{10} charges]
training data
test data
threshold linear ($4 \times \sigma_{est}$)
threshold bic ($4 \times \sigma_{est}$)
threshold rmse ($4 \times \sigma_{est}$)
threshold r2_adj ($4 \times \sigma_{est}$)


BLMDI.9591.B2B10_750_306
26-NOV-2018 18.36.34.075693
Running sum 01 (max) [bit]
Intensity beam 2 [10^{10} charges]
training data
test data
threshold linear ($4 \times \sigma_{est}$)
threshold bic ($4 \times \sigma_{est}$)
threshold rmse ($4 \times \sigma_{est}$)
threshold r2_adj ($4 \times \sigma_{est}$)


BLMDI.9590.B1T10_750_306
26-NOV-2018 18.36.34.075693
Running sum 01 (max) [bit]
Intensity beam 1 [10^{10} charges]
training data
test data
threshold linear ($4 \times \sigma_{est}$)
threshold bic ($4 \times \sigma_{est}$)
threshold rmse ($4 \times \sigma_{est}$)
threshold r2_adj ($4 \times \sigma_{est}$)


BLMDI.9591.B1B10_750_306
26-NOV-2018 18.36.34.075693
Running sum 01 (max) [bit]
Intensity beam 2 [10^{10} charges]
training data
test data
threshold linear ($4 \times \sigma_{est}$)
threshold bic ($4 \times \sigma_{est}$)
threshold rmse ($4 \times \sigma_{est}$)
threshold r2_adj ($4 \times \sigma_{est}$)

NOT OK beam dump (sub)set	No. of NOT OK beam dumps	No. of distinct high-correlated BLMs contributing to NOT OK classifications	
		total	exclusive
Total	27	45	-
Asynchronous dump tests	8 (29.63 %)	43 (95.55 %)	37 (82.22 %)
10 Hz dumps	6 (22.22 %)	0 (0 %)	0 (0 %)
Other	13 (48.15 %)	8 (17.77 %)	2 (4.44 %)

NOT OK beam dump (sub)set	No. of NOT OK beam dumps	No. of distinct low-loss BLMs contributing to NOT OK classifications	
		total	exclusive
Total	27	173	-
Asynchronous dump tests	8 (29.63 %)	155 (89.59 %)	73 (42.20 %)
10 Hz dumps	6 (22.22 %)	54 (31.21 %)	3 (1.73 %)
Other	13 (48.15 %)	96 (55.49 %)	11 (6.36 %)

BLM naming convention