PAUL SCHERRER INSTITUT

Sichen Li :: Scientific Computing, Theory and Data :: Paul Scherrer Institut

Novel Approaches for Forecasting of Beam Interruptions in Particle Accelerator

Sep.12 2022 at International Beam Instrumentation Conference

Outline

- Introduction and problem formulation
- Model 1: Recurrence Plot - Convolutional Neural Network model
- Model 2: Logistic Lasso regression model
- Model comparison in classification and real-time metrics
- Potential instrumentation
- Conclusion and outlook

Introduction - High Intensity Proton Accelerators

Injector cyclotron
72 MeV, 2.2 mA

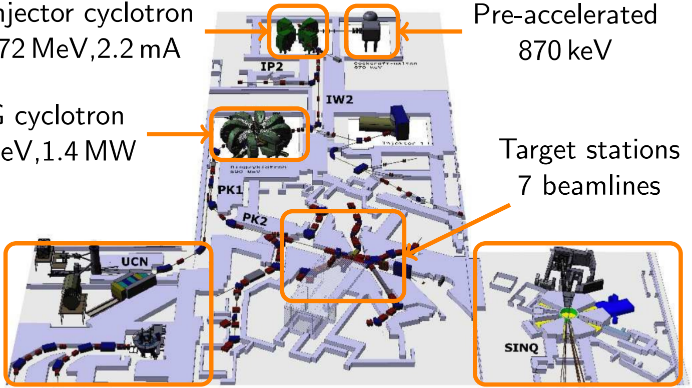
Pre-accelerated
870 keV

RING cyclotron
590 MeV, 1.4 MW

Target stations
7 beamlines

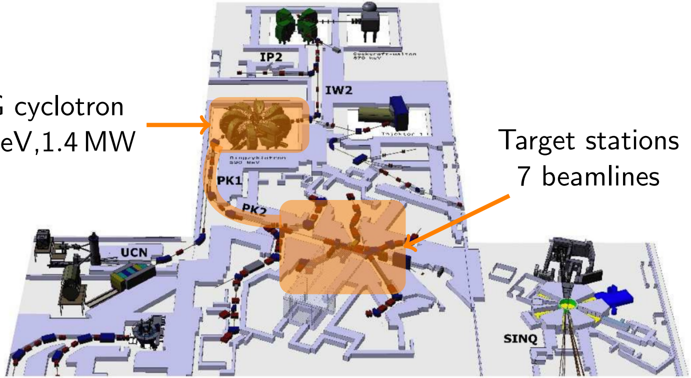
Ultra cold
neutron source

Spallation
neutron source



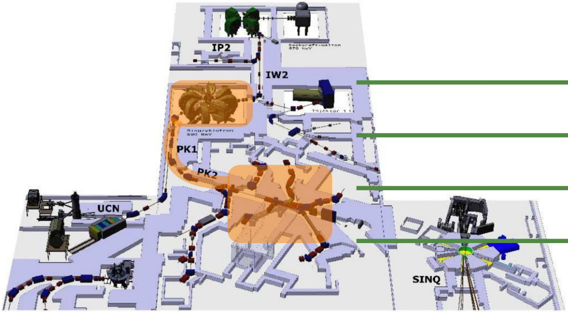
Introduction - Focus region

RING cyclotron
590 MeV,1.4 MW



Target stations
7 beamlines

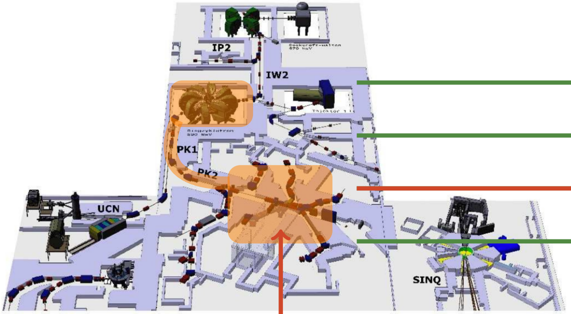
Introduction - Interlock system



- Temperature monitors
- Magnet currents
- Beam loss monitors
- Beam position monitors

Interlock system

Introduction - Interlock system



Temperature monitors

Magnet currents

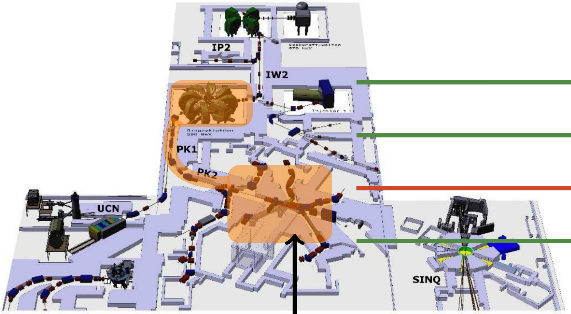
Beam loss monitors

Beam position monitors

Interlock system

Shut off the beam
Lose 25 s beam time

Introduction - Interlock system



Temperature monitors

Magnet currents

Beam loss monitors

Beam position monitors

Forecasting model

if interlock

Recover operation

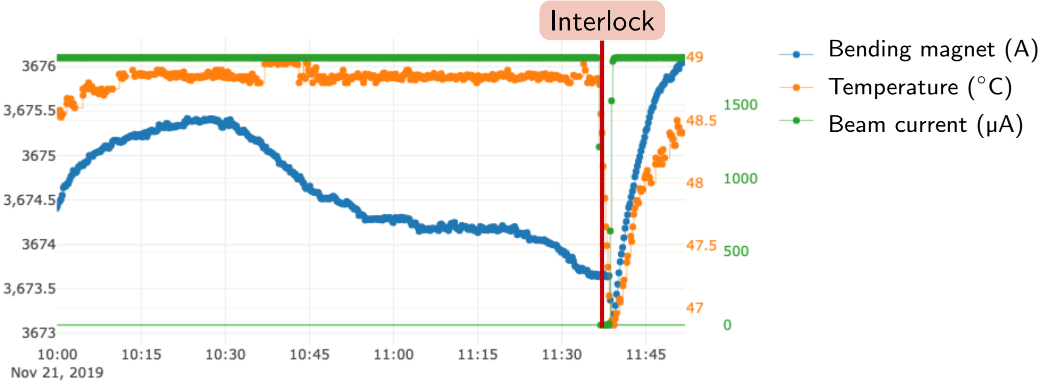
Shut off the beam

Lose 25 s beam time

Interlock system

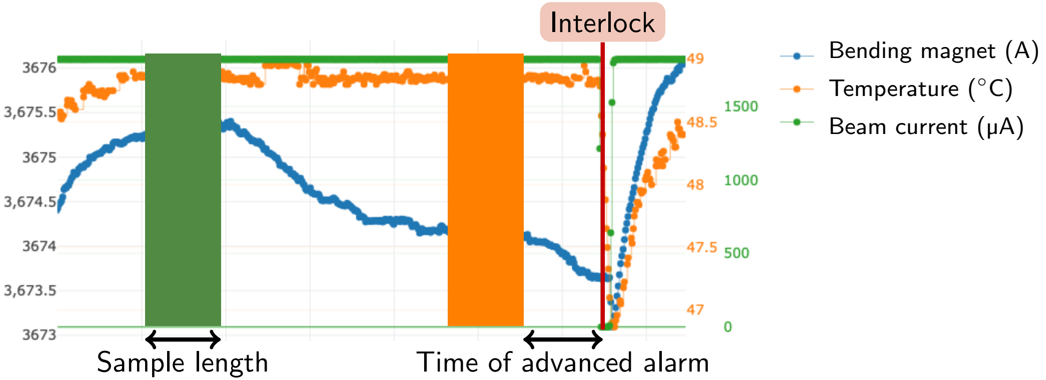
Introduction - Problem formulation

- Forecasting the interlocks in HIPA
- **Input**: *Channels* – signals of 5 Hz from all monitors of HIPA, total 376
- **Target**: *Interlocks* – beam interruptions of HIPA



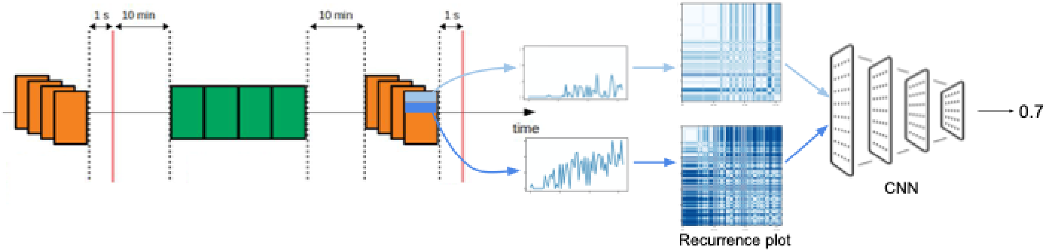
Introduction - Problem formulation

- Binary classification
- **Class Positive (1)**: interlock samples close to interlock
- **Class Negative (0)**: stable samples far from interlock



Model 1 - The RPCNN model

Recurrence Plot - Convolutional Neural Network [1]

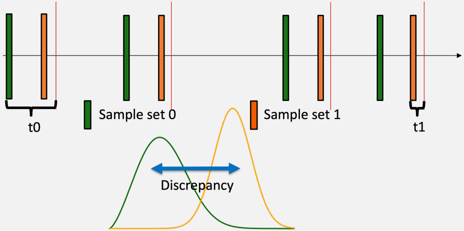


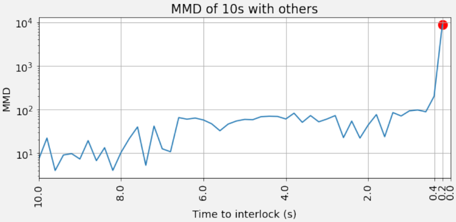
1. Take the two classes of samples, of size (376, sample length)
2. Transform each 1D time series into 2D *Recurrence Plot*
3. Train with *CNN* and get probability output $\in [0, 1]$

Complex model, yet high False Positive rate!

Problem - Interlocks are abrupt events

- **Two sample test** [2]: Statistically compare *Maximum Mean Discrepancy (MMD)* of samples taken at t_0 and t_1 before all interlocks
- 0.2 s is abruptly different, essentially no gradual change
- Positive class of RPCNN is taken before 1 s $\rightarrow$ fail to capture the difference





PAUL SCHERRER INSTITUT PSI

Model 2 - Logistic LASSO regression

Penalized regression with the Least Absolute Shrinkage and Selection Operator

1. **Class Positive (1)**: interlock samples, taken $t_1 = 0.2\text{s}$ before interlock

   Class Negative (0): stable samples, taken $t_0 = 10\text{s}$ before interlock

2. Input $\{\mathbf{x}_i \in \mathbb{R}^d\}_{i=1}^n$, label $\{y_i\}_{i=1}^n \in \{\pm 1\}$, fit weight $\omega \in \mathbb{R}^d$

   Minimize Loss

   $$\min_\omega L = \min_\omega \underbrace{\frac{1}{n}\sum_{i=1}^{n} \log\left[1 + \exp\left(-y_i \cdot \omega^T \mathbf{x}_i\right)\right]}_{\text{logistic loss for binary classification}} + \underbrace{\lambda\|\omega\|}_{\text{regularization}}$$

3. Also a probability output $\in [0, 1]$

> Simple linear sparse $\rightarrow$ interpretablity

Model comparison – classification metric

LASSO:
better
classification;
stable
performance

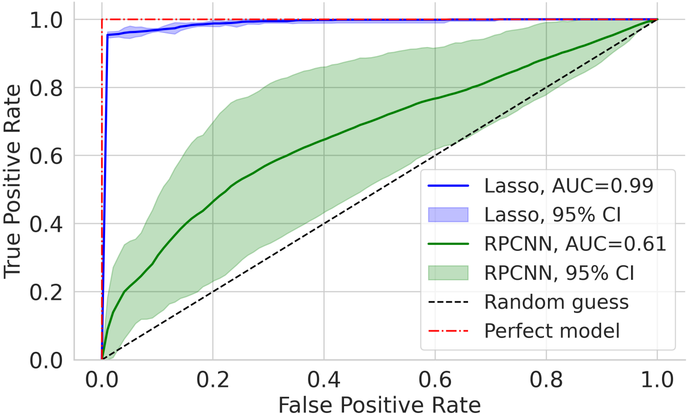


Figure: The Receiver Operating Characteristic (ROC) curves of both models.

Custom real-time metric

- True positive (TP), False positive (FP) according to 1min inspection window
- Beam time saved T_s in any given time: $T_s := 19 \cdot N_{TP} - 6 \cdot N_{FP}$

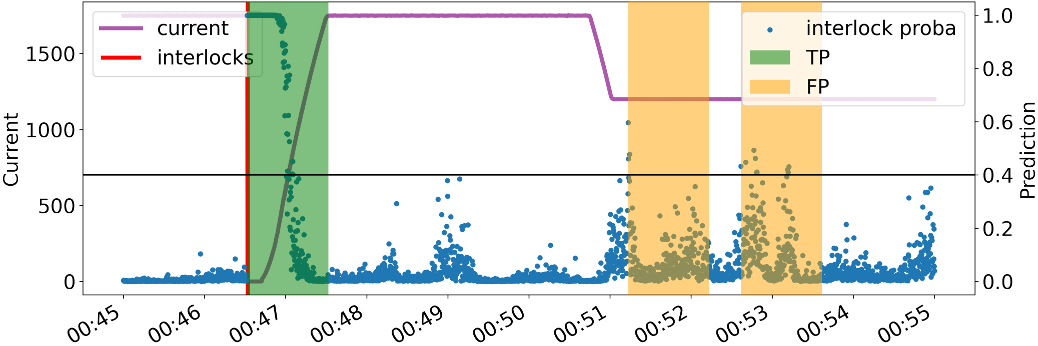
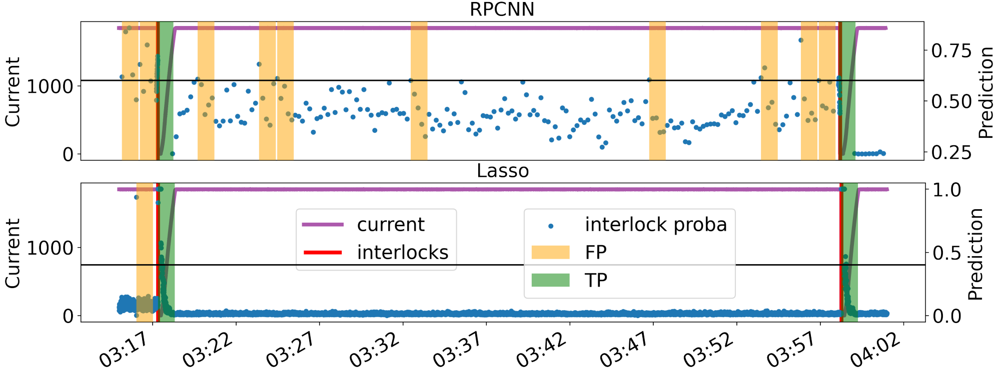


Figure: Examples of real-time TP and FP of the LASSO model.

Model comparison - Beam time saved

Model	N_{TP}	$N_{TP}/N_{int}(\%)$	N_{FP}	T_s (Min/day)
RPCNN	277	23.2	5408	-10.53
LASSO	1134	95.1	1214	5.63

Table: Real-time metrics of both models in 2 months with $N_{int} = 1192$.



Potential instrumentation for recover operation

- Need to reduce 0.2 mA (10% beam current) inside 200 ms time scale, according to the Lasso model

Instrumentation	Facility	Time scale (ms)	Comment
Kicker AVKI	HIPA	0.005	Used in interlock system
Kicker [3]	PROSCAN	0.05	Only response time
Deflector plates [4]	PROSCAN	0.2	Only response time
Beam blocker [3]	PROSCAN	60	Only response time
Collimator KIP2 [5]	HIPA	66.7/0.2mA	Response time ignored

Table: Potential instrumentation for fast adjustment of beam current.

Conclusion and outlook

- Formulate forecasting problem into binary classification
- RPCNN model transforms 1D time series into 2D images $\rightarrow$ complex, high false positive, improper input
- Two sample MMD test shows beam interruptions are more abrupt than gradual
- LASSO model outperforms RPCNN in both classification and real-time metrics
- Further experiments on real-time implementation, specific types of interlocks and recover operations are ongoing

References

S Li, M Zacharias, et al.
A novel approach for classification and forecasting of time series in particle accelerators.
Information, 12(3):121, 2021.

A Gretton et al.
A kernel two-sample test.
The Journal of Machine Learning Research, 13(1):723–773, 2012.

I Jirousek et al.
The concept of the proscan patient safety system.
Proc. ICALEPCS'9, pages 13–17, 2003.

P F Carmona et al.
Continuous beam scanning intensity control of a medical proton accelerator using a simulink generated FPGA gain scheduled controller.
Proc. PCaPAC'12, pages 242–247.

J Stetson et al.
The commissioning of PSI Injector 2 for high intensity, high quality beams.
Proc. Cyclotrons'13, pages 36–9, 1992.

Thanks to

- Mélissa Zacharias
- Dr. Jochem Snuverink
- Dr. Jaime Coello de Portugal
- Dr. Davide Reggiani
- Prof. Dr. Fernando Perez-Cruz
- Dr. Andreas Adelmann