AI Management of SRF Cavity Field Emission

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AI in the Accelerator

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Field Emission

Field emission is a notorious problem resulting in component damage, trips, activation, etc.

A single cavity produces field emitted electrons with a non-linear response to gradient above a threshold (FE onset). These may change over time due to various factors.

FE electrons can have complicated interactions with neighboring cavities/cryomodules and can be transported substantial distances up or downstream

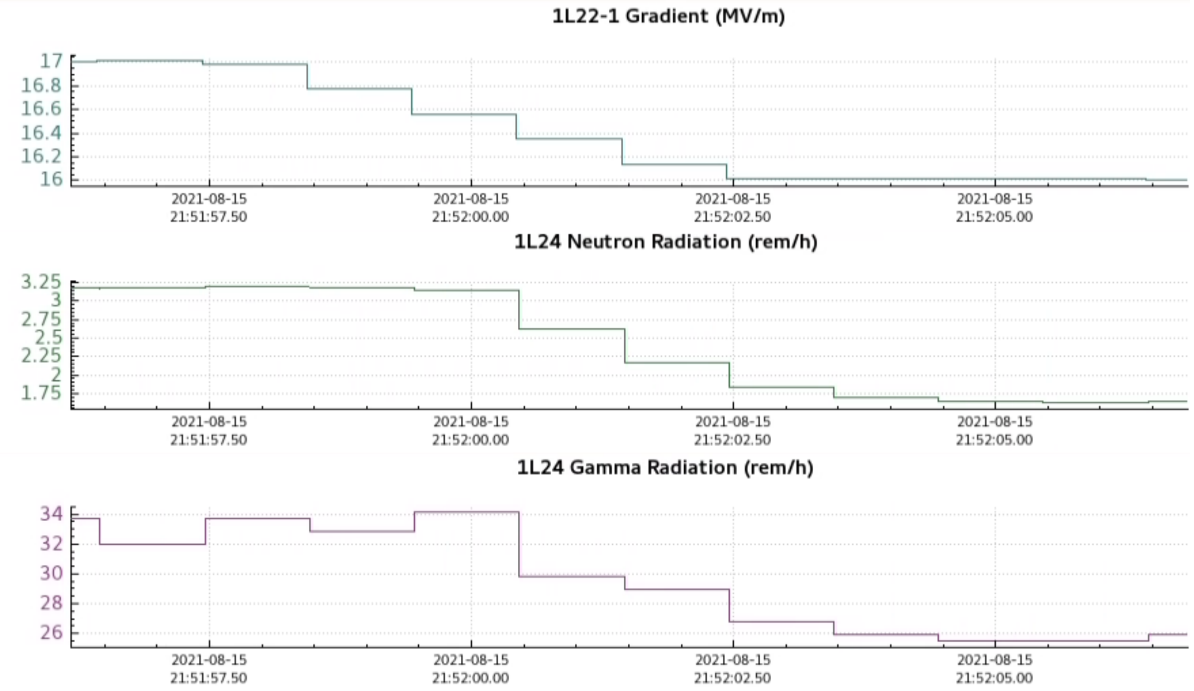
The C100 cryomodules present pronounced FE-related operational challenges.

We're trying to build machine learning models to help manage this radiation problem non-invasively. Namely,

1. *Given a machine configuration, can the cavities that are the leading contributors to FE-radiation be identified?*
2. *Can changes in existing field emitters be detected and localized?*
3. *Can the appearance or elimination of field emitters be detected and localized?*

Radiation hazards due to activation

Radiation damaged C100 valve



Large radiation response to smaller gradient change

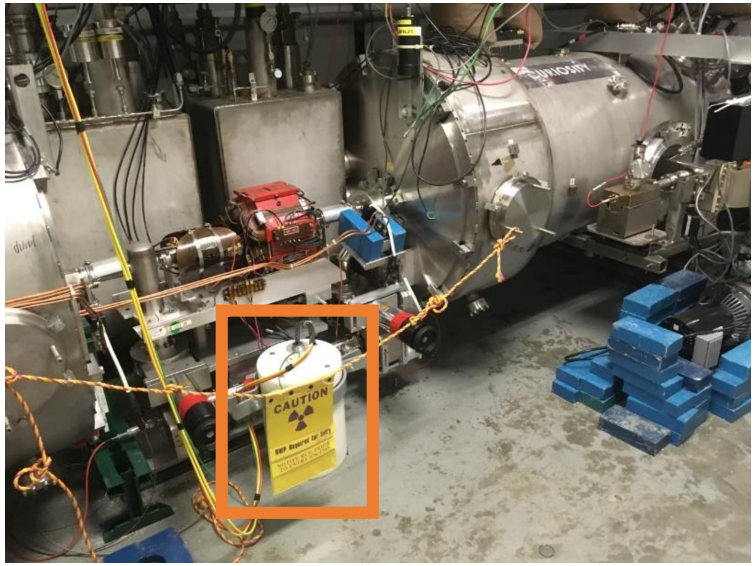
NDX Detector System

JLab designed, installed, and commissioned a new neutron and gamma radiation detection system focused on FE radiation. Operational as of August 2021.

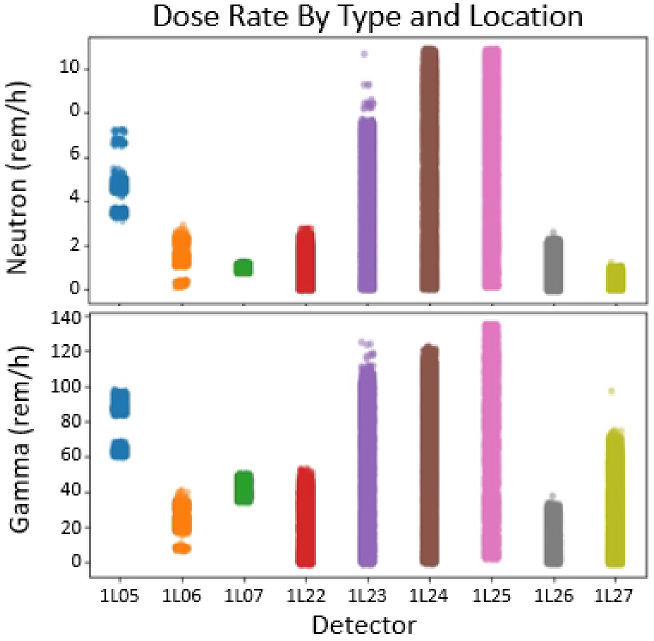
21 Detectors strategically placed around CEBAF

Mostly near high gradient cryomodules (C100s)

Primary focus is measurement of neutrons, with a secondary function of detecting gamma radiation.



NDX detector (red box) between two C100 cryomodules

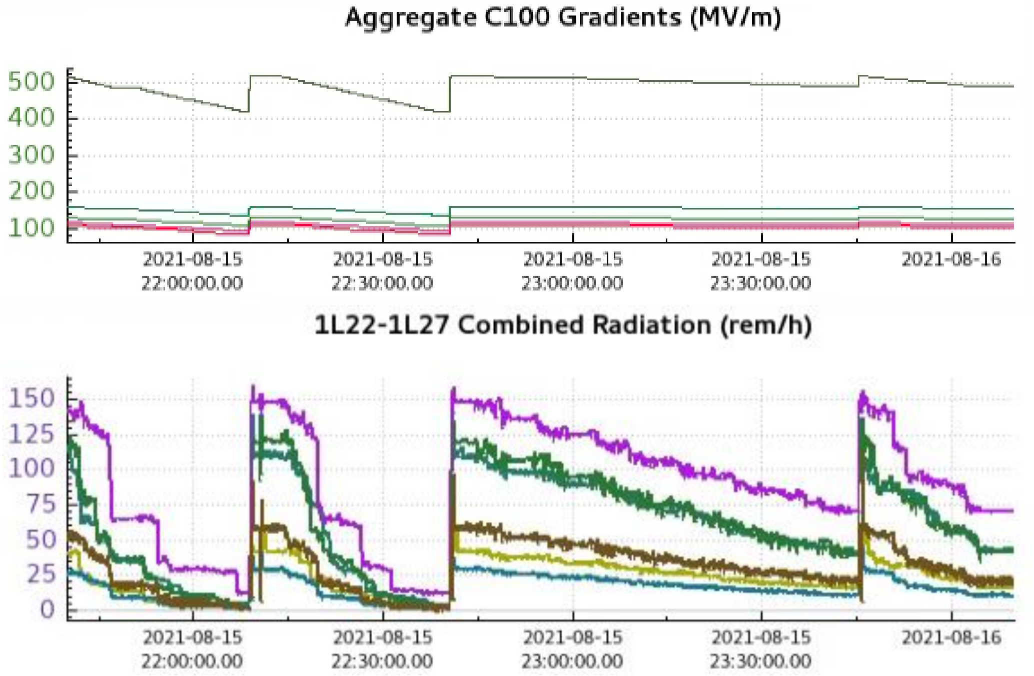


Radiation responses observed during gradient scans

Gradient Scans

Measured radiation signals via NDX as combination of North Linac (NL) C100 gradients were varied across a range of operational values

Collected 17,610 samples across 1,794 operationally relevant gradient combinations



Radiation responses observed during gradient scans

Jefferson Lab

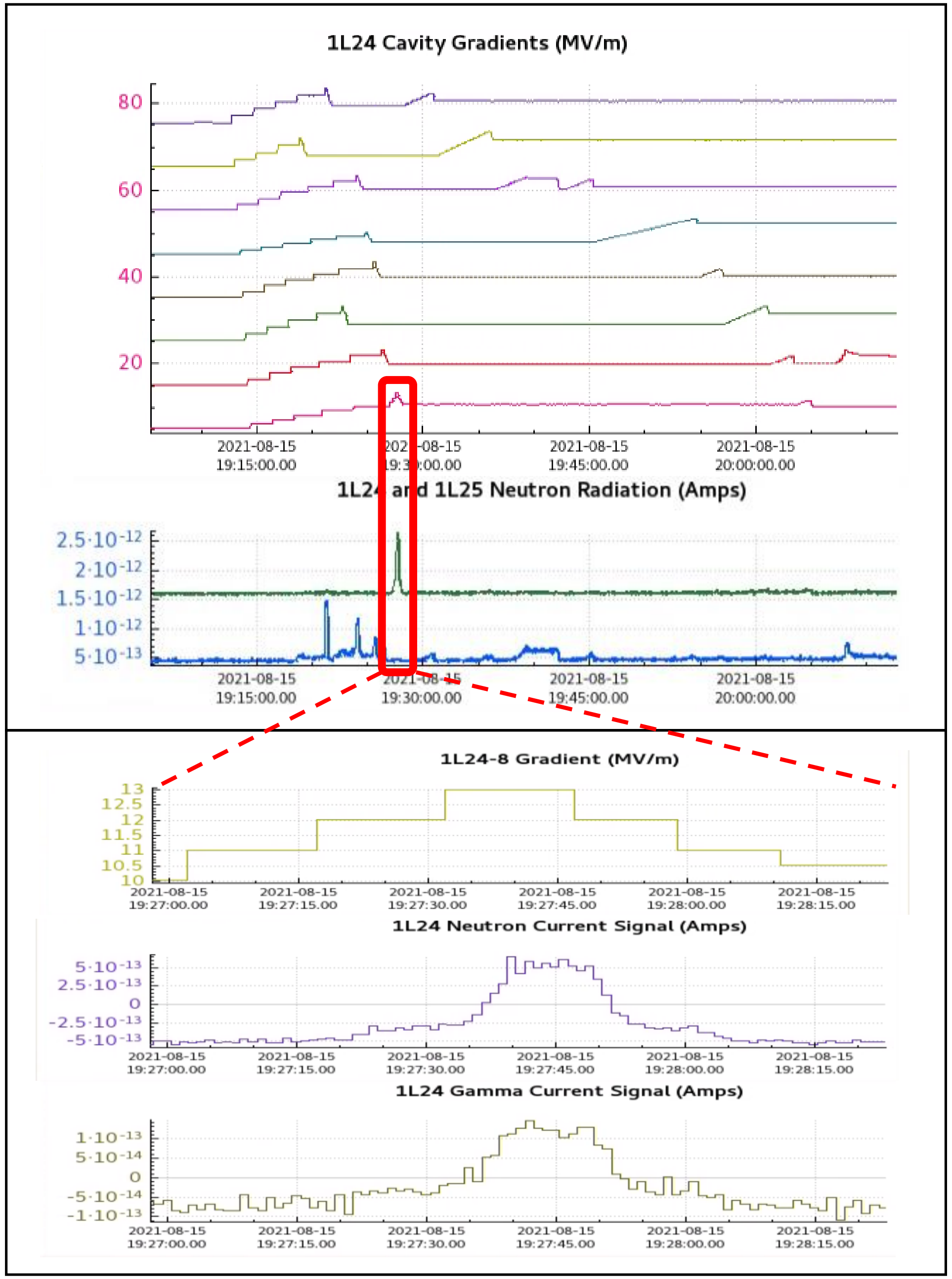
Radiation Onset Scans

Used NDX to identify radiation onset for every C100 cavity

- Radiation onset: highest gradient without radiation detected by NDX under operational conditions (phased, etc.)
- Closely related to FE onset

Measure one C100 at a time

- Turn off four zones up and down stream
- Establish a high, no radiation, baseline gradient within to amplify the radiation signal from each onset
- Walk each cavity up in 0.125 MV/m steps until a statistically significant increase in radiation is measured over a 10 sec interval



An example radiation onset scan with the procedure for a whole zone (top), and a zoomed in view (bottom) of an individual radiation detection (top red box).

Model Results

Model the NDX radiation measurements around NL C100 cryomodules using cavity functions of gradients (gmes) and radiation onsets (rad_onset) as input

Multi-output Random Forest Regressor

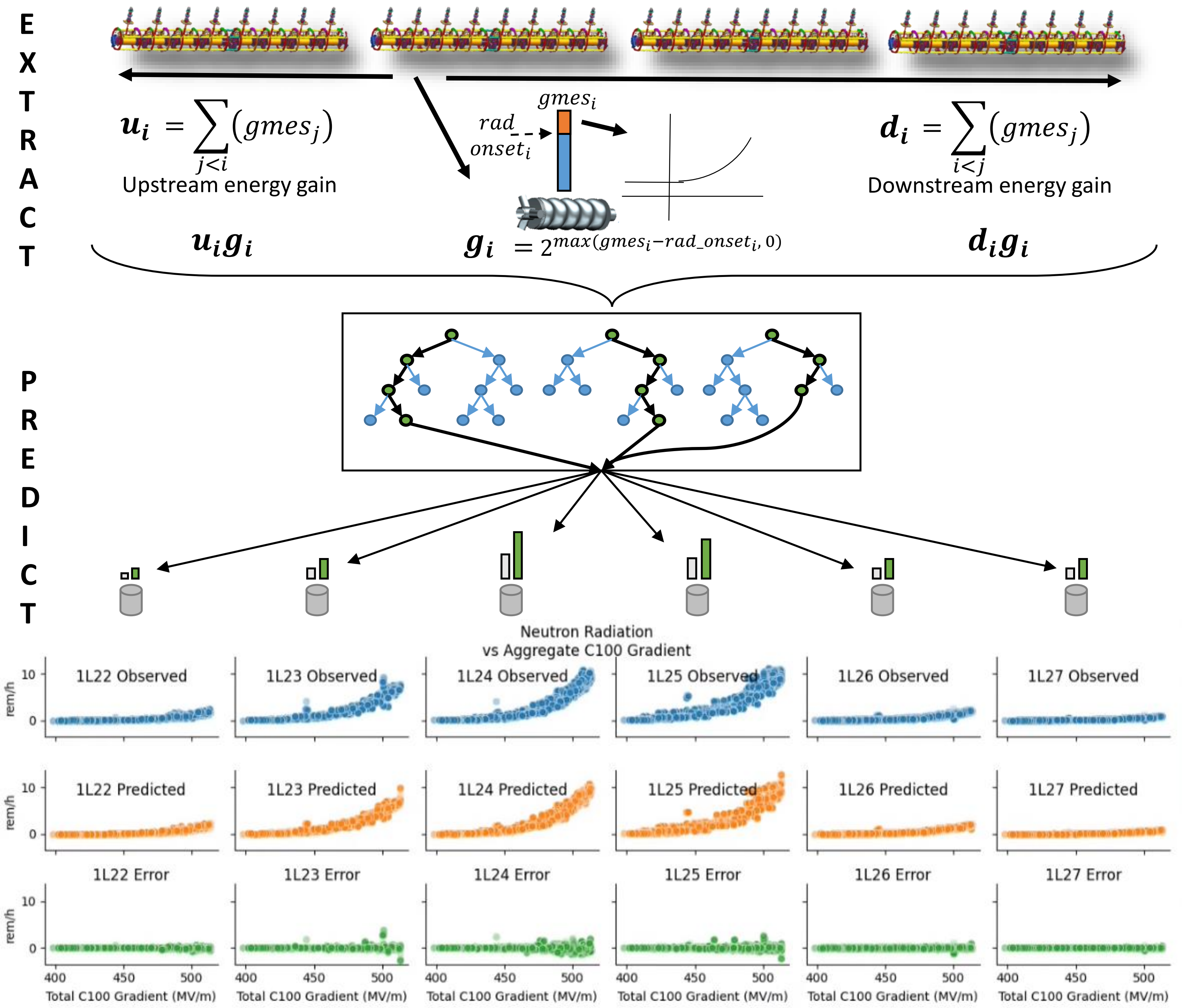
5 features per cavity, 8 cavities/CM, 4 CMs (160 features total)

Five per-cavity features

1. Surface FE: $g_i = 2^{max(gmes_i - rad\_onset_i,\, 0)}$
2. Upstream energy gain: $u_i = \sum_j (gmes_j)$ where cavity j is upstream of cavity i
3. Downstream energy gain: $d_i = \sum_j (gmes_j)$ where cavity j is downstream of cavity i
4. Upstream interactions: $u_i g_i$
5. Downstream interaction: $d_i g_i$

Model performance metrics

	Training	Testing
R-Squared	0.999	0.978
MSE	0.001	0.052
MAE	0.013	0.115



Machine learning workflow. The five features are extracted for each cavity (top), input to the random forest model with radiation levels predicted (middle). Test set observations, predictions, and errors are shown (bottom)

Onward!

Developing deep learning models that do not rely on feature engineering

- Getting similar performance as ML model

Create optimization software to suggest gradient distribution

- Genetic algorithm, etc.
- Investigate reinforcement learning as an alternative

Develop models goals 2) and 3) for changing field emitters, and (dis)appearance of emitters

- Model changes in radiation onset via MLP
- Anomaly detection via Autoencoder