THPV043

USING AI TO MANAGE FIELD EMISSION IN SRF LINACS

Jefferson Lab

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Field Emission (FE) in SRF cavities causes radiation, component activation, damage, machine trips, etc.

Cavity field emitters have an effective onset gradient, after which electrons are emitted with a non-linear response

FE electrons at CEBAF can be captured by the RF field and be accelerated upstream or downstream through many cryomodules

Figure 1: Radiation damaged valve from cryomodule

Data Collected on C100 style cryomodules in CEBAF's North Linac

Radiation Onset Scans

When does NDX first see radiation under operational conditions?

Gradient Scans

How does radiation respond to changes in gradient under operational conditions?

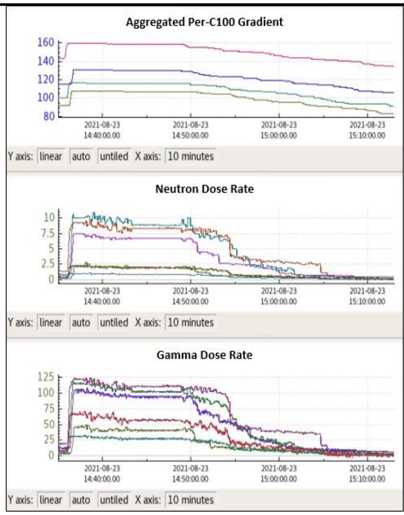

Figure 2: An example gradient scan

21 neutron and gamma detectors (NDX) recently designed, installed, and commissioned at CEBAF for monitoring FE radiation

Provides a new rich data source for training machine learning models

Figure 3: NDX detector (red box) between two C100 cryomodules

Preliminary machine learning (ML) model trained to predict radiation based on cavity gradients and radiation onsets

Future work to include modeling changes in existing field emitter behavior

Table 1: Model performance metrics

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

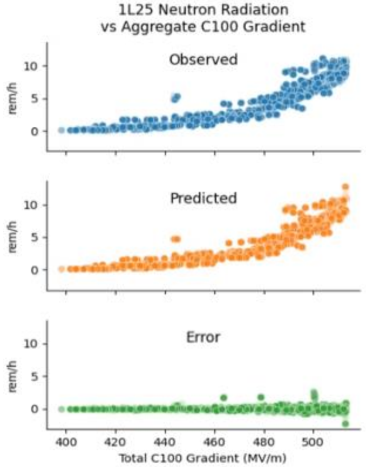

Figure 4: Test results for an individual detector at 1L25

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

Newer, high gradient 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?*

Figure 5: Radiation hazards due to activation

Figure 6: Radiation damaged C100 valve

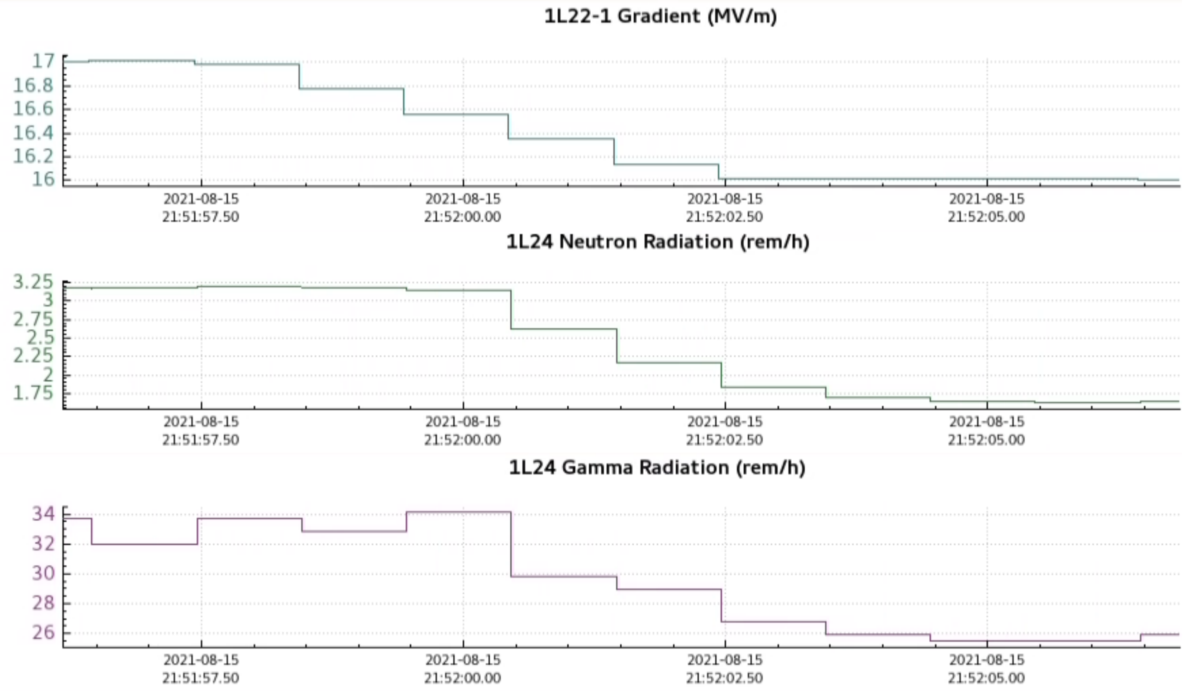

Figure 7: Large radiation response to smaller gradient change

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.

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

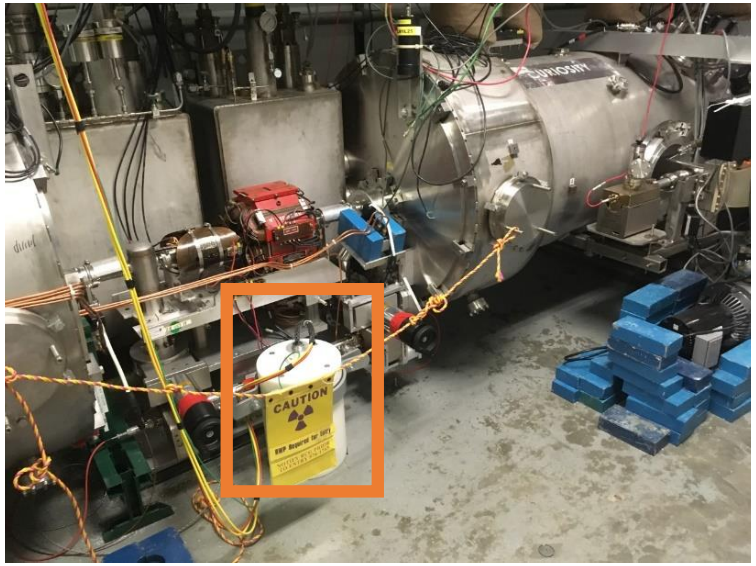

Figure 8: NDX detector (red box) between two C100 cryomodules

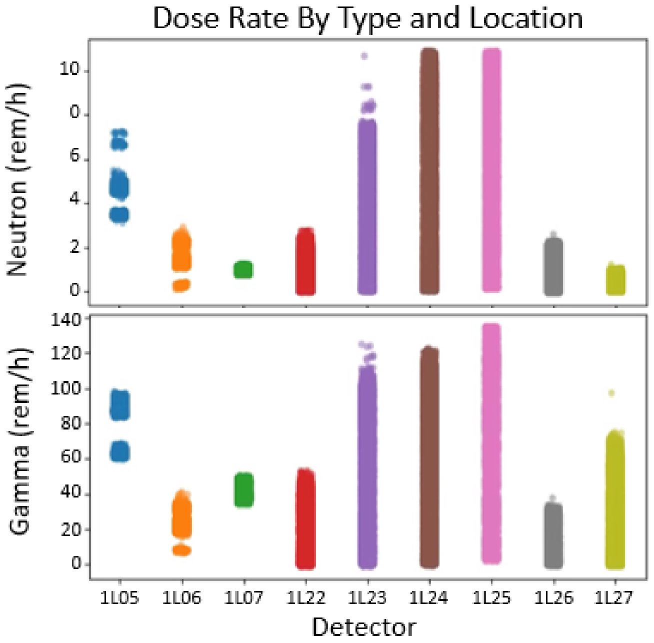

Figure 9: Radiation responses observed during gradient scans

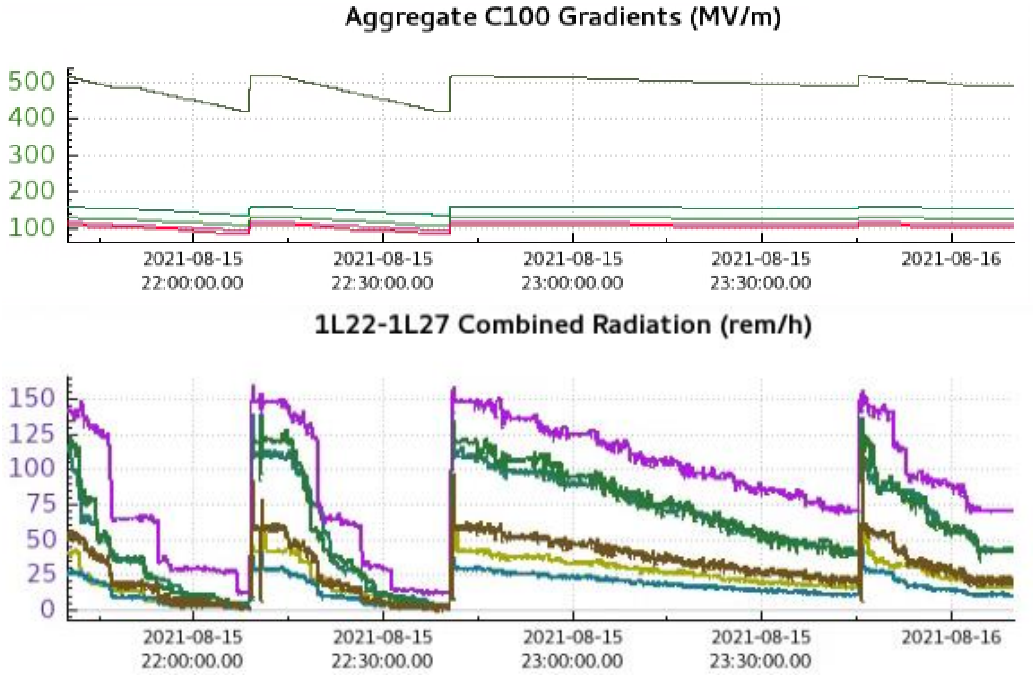

Figure 10: Radiation responses observed during gradient scans

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

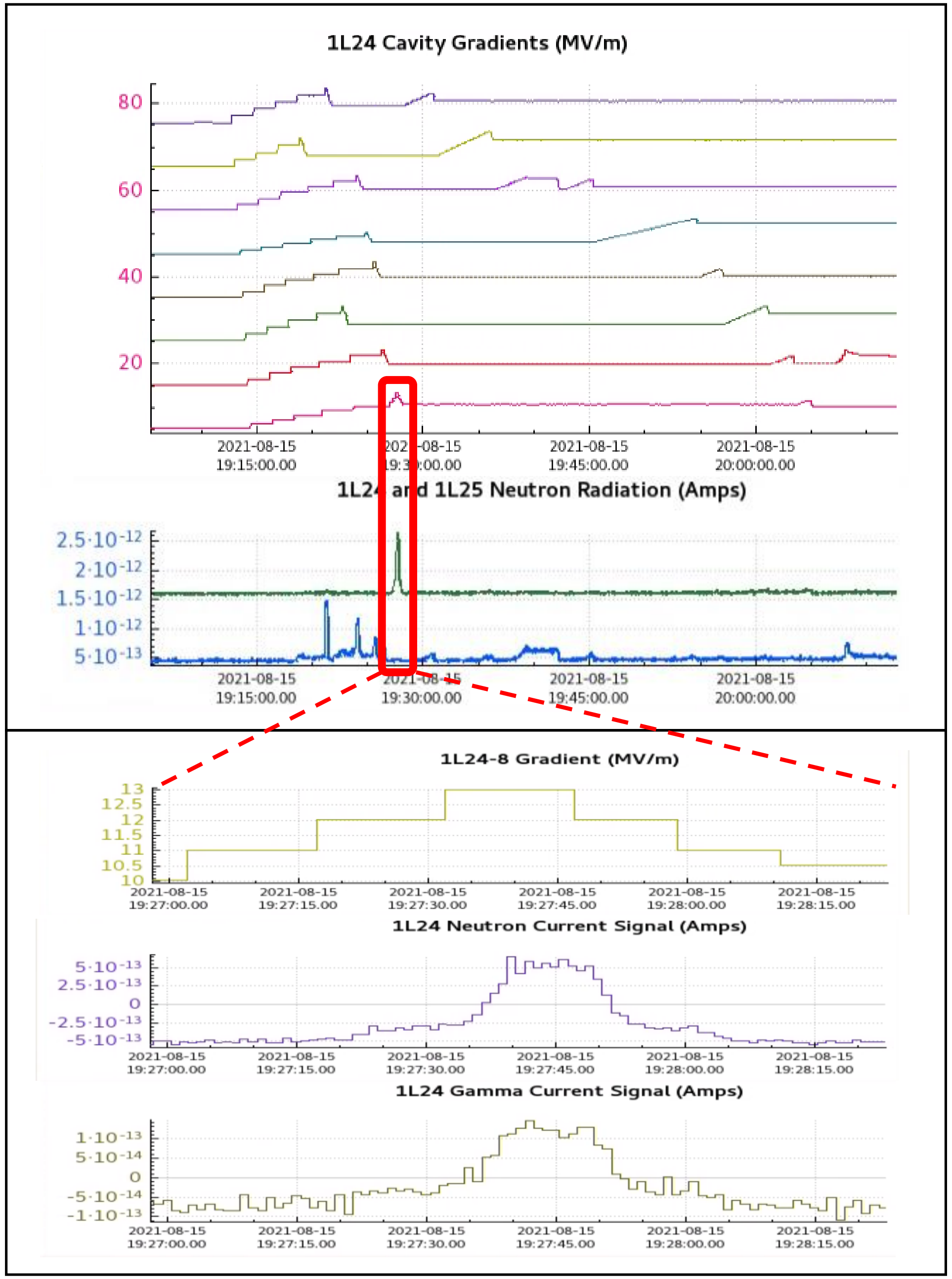

Figure 11: An example radiation onset scan with the procedure for a whole zone (top), and a zoomed in view (bottom) of an individual radiation detection (top red box).

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: $d_i g_i$

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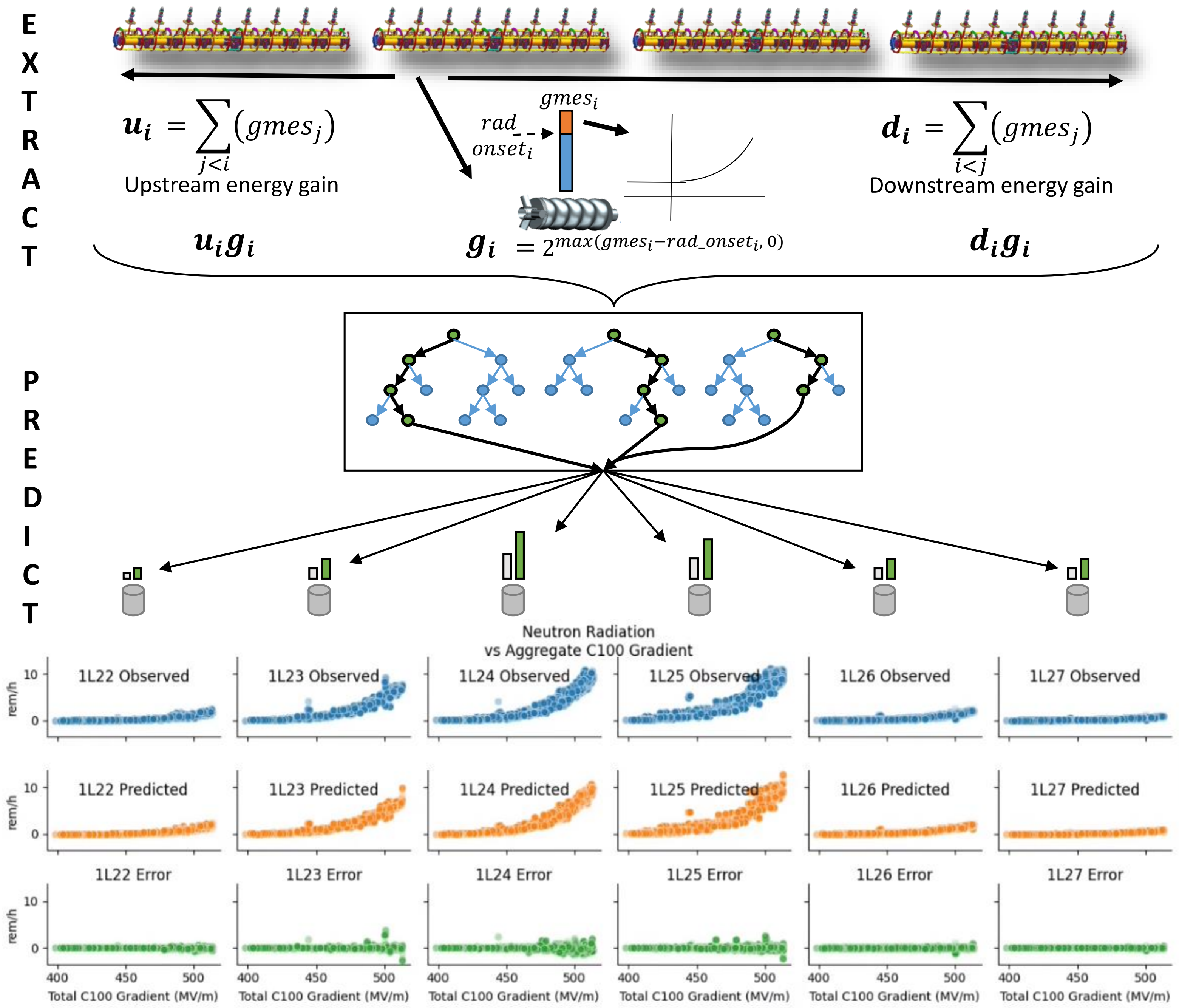

Figure 12: Machine learning workflow. The five features are extracted for each cavity (top), input to the random forest model with radiation levels predicted (middle). Test set observations, predictions, and errors are shown (bottom)