# AI: A Transformative Technology for Accelerators

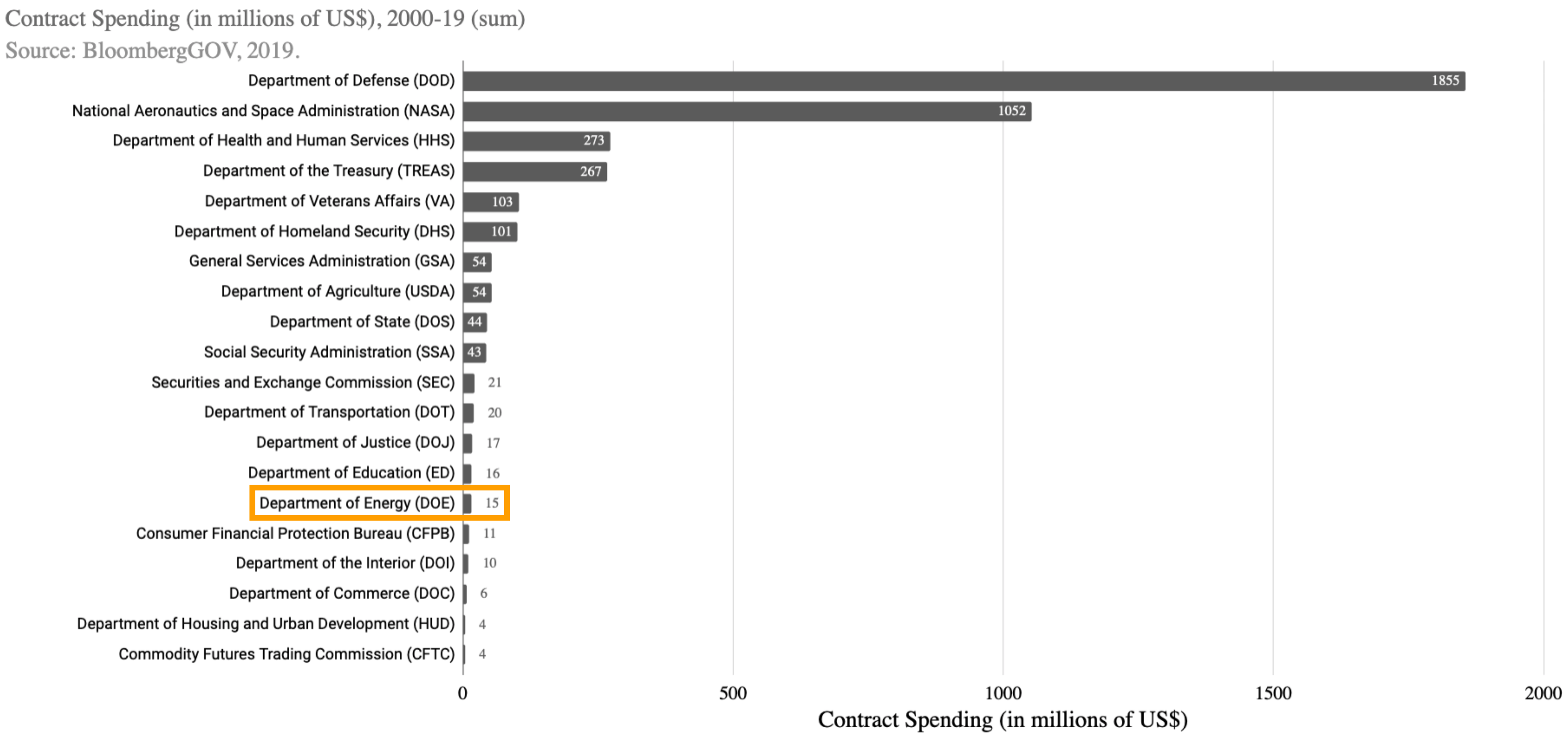
Resilient Infrastructure and Systems Engineering in Accelerator Construction and Operation

Chris Tennant

*February 12, 2020*

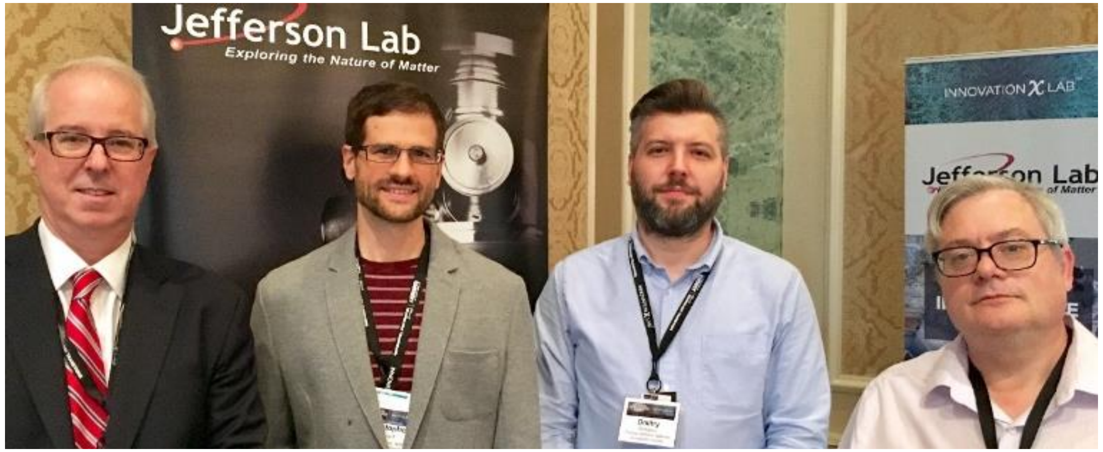
# AI/ML Trends: Government Spending

- government spending on AI projects




("The AI Index 2019 Annual Report")

# DOE's AI Initiative

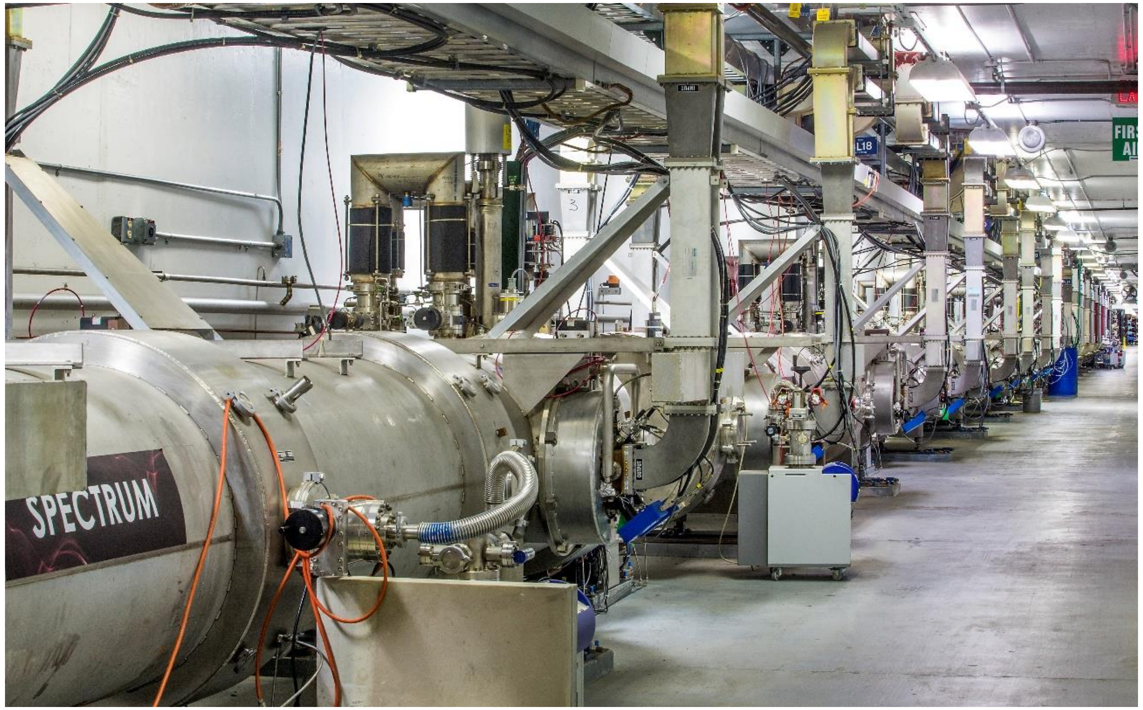



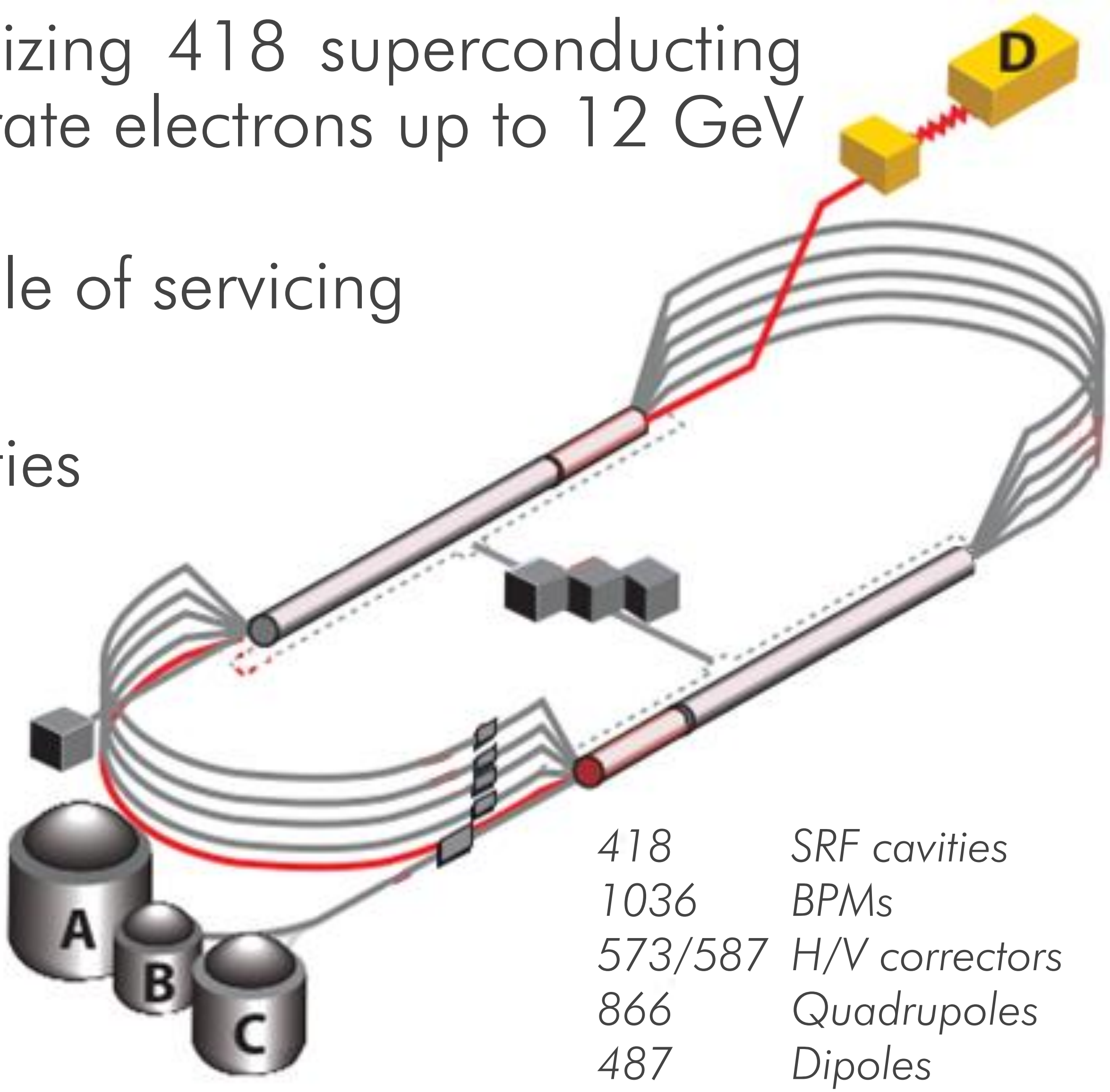


AI
FOR SCIENCE
TOWN HALL

# CEBAF

- CEBAF is a CW recirculating linac utilizing 418 superconducting radio-frequency (SRF) cavities to accelerate electrons up to 12 GeV through 5-passes
- it is a nuclear physics user-facility capable of servicing 4 experimental halls simultaneously
- the heart of the machine is the SRF cavities




| | |
|---|---|
| 418 | SRF cavities |
| 1036 | BPMs |
| 573/587 | H/V correctors |
| 866 | Quadrupoles |
| 487 | Dipoles |



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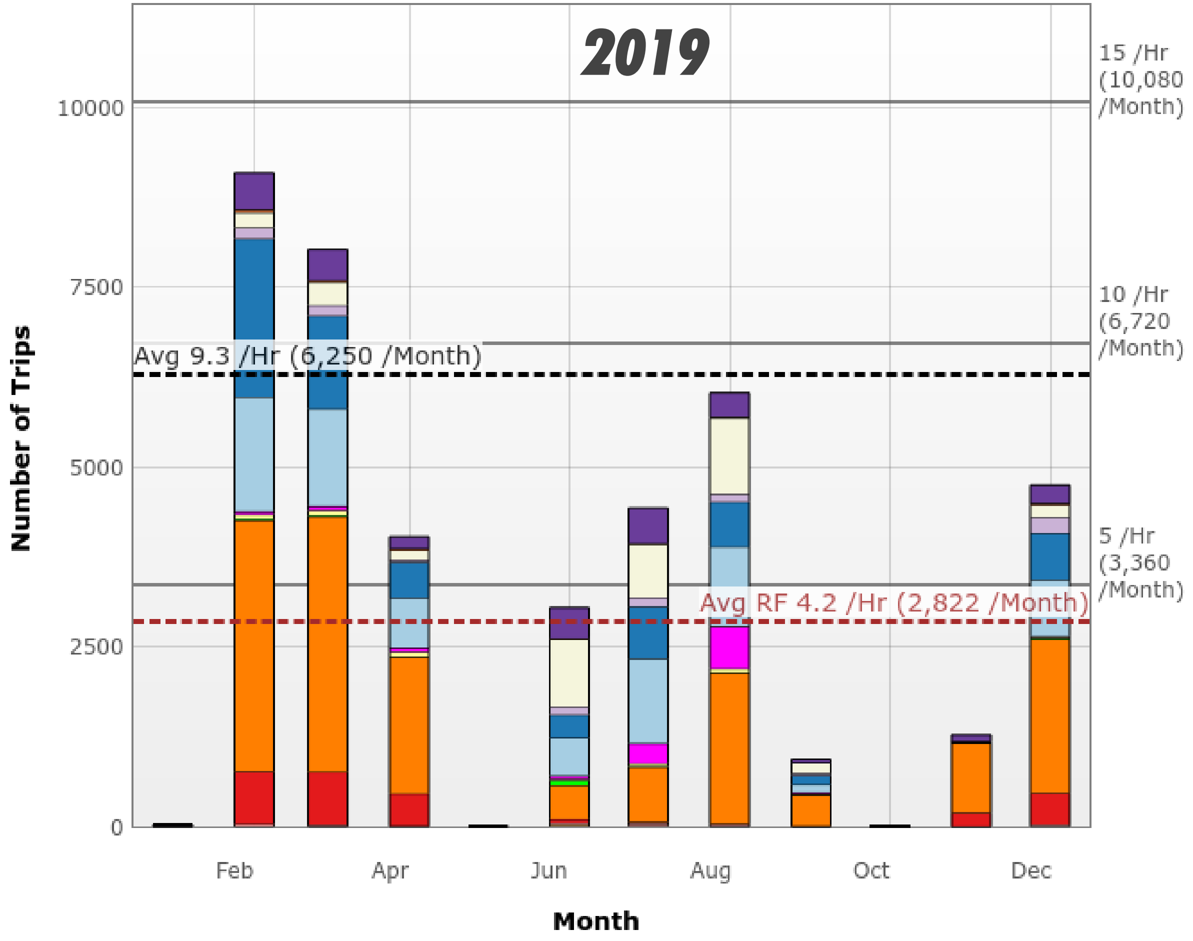
# Improving CEBAF Availability

- largest contributor to short machine downtime trips (< 5 min.) are RF faults
- significant investment in energy reach program (cryomodule upgrades, plasma processing, re-furbished linac hard-ware)




| | Trips /Hr | Lost Hrs | Mins /Trip |
|---|---|---|---|
| Dump (Insert.) | 0.6 | 12.7 | 0.3 |
| Dump (Station.) | 0.0 | 0.0 | 0.3 |
| Gun/Laser | 0.0 | 1.5 | 0.5 |
| Hall | 0.8 | 17.7 | 0.3 |
| MPS (BCM/BLA) | 0.2 | 4.9 | 0.3 |
| MPS (BLM) | 1.4 | 35.9 | 0.3 |
| MPS (Multi/Other) | 1.6 | 39.7 | 0.3 |
| Magnets | 0.0 | 0.1 | 1.2 |
| Multiple/Other | 0.2 | 5.6 | 0.3 |
| Unknown/Missing | 0.1 | 2.3 | 0.4 |
| Vacuum | 0.0 | 1.9 | 0.8 |
| RF (C25/C50) | 3.5 | 109.2 | 0.4 |
| RF (C100) | 0.6 | 75.2 | 1.7 |
| RF (Multi/Other) | 0.0 | 3.0 | 1.0 |
| RF (Separator) | 0.0 | 1.1 | 1.3 |
| **Total:** | **9.3** | **310.7** | **0.4** |

- Max Trip Duration: 5 Minutes
- Rate from Program (4492.47 hrs)
- SAD Trips excluded



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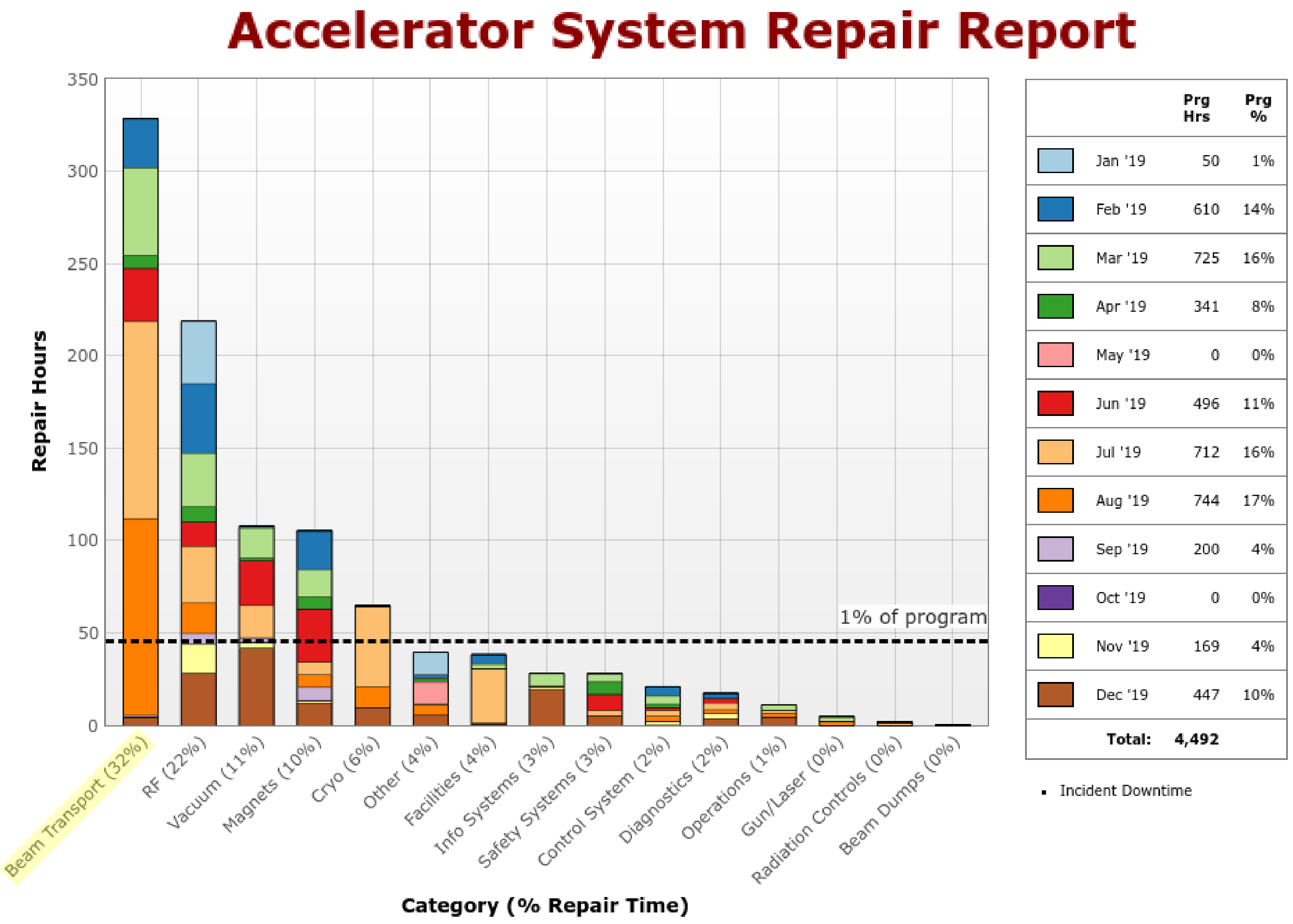
# Improving CEBAF Efficiency

- *“Beam Transport”* tasks represent the largest category of downtime
- investigate ways we can leverage AI to
  - ✓automate time-consuming tasks
  - ✓automate specialized tasks
  - ✓analyze data and provide results more quickly



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# AI Projects: Current and Proposed

- ***Funded Projects***
  - ✓ *SRF Cavity Fault Classifier*
- ***Future Projects***
  - ✓ *Minimize Radiation Levels Due to Field Emission in an SRF Linac*
  - ✓ *SRF Cavity Instability Detection*
  - ✓ *SRF Particulate Inventory*
  - ✓ *Passive Bunch Length Measurement*
  - ✓ *Computer Vision-aided Beam Tuning*
  - ✓ *Accelerator "Smart Alarm"*
  - ✓ *Mobile Diagnostic with Collaborative Autonomy*

# Data is the Fuel for AI/ML

- without data we can't leverage AI/ML
  - ✓archiver records 350K+ channels
  - ✓need to be more proactive with machine measurements
    - what kind of measurements should we be doing hourly/daily/weekly?
- getting and labeling (if necessary) data hard and expensive




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# Future Projects

Project: *Mobile Diagnostic with Collaborative Autonomy*

- improve the efficiency, safety and automation of accelerator operations as well as providing a platform for *novel measurements and data acquisition with greater resolution than existing static sensors*

- provides exactly the diagnostic needed for field emission studies
  - ✓rather than many distributed monitors, have a single mobile diagnostic
- knowledge and experience is easily transferable to other accelerators

(courtesy D. Conner)



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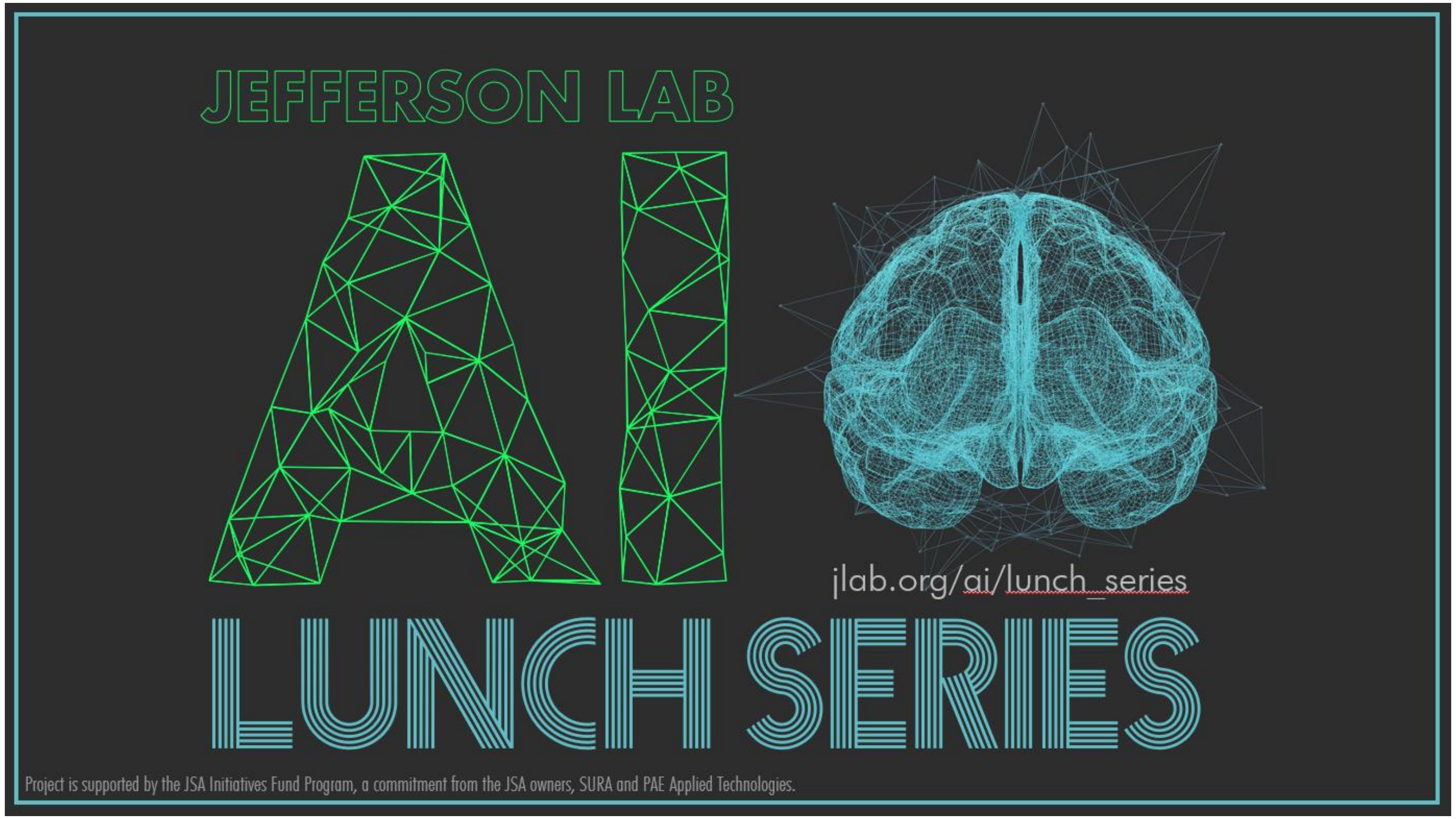
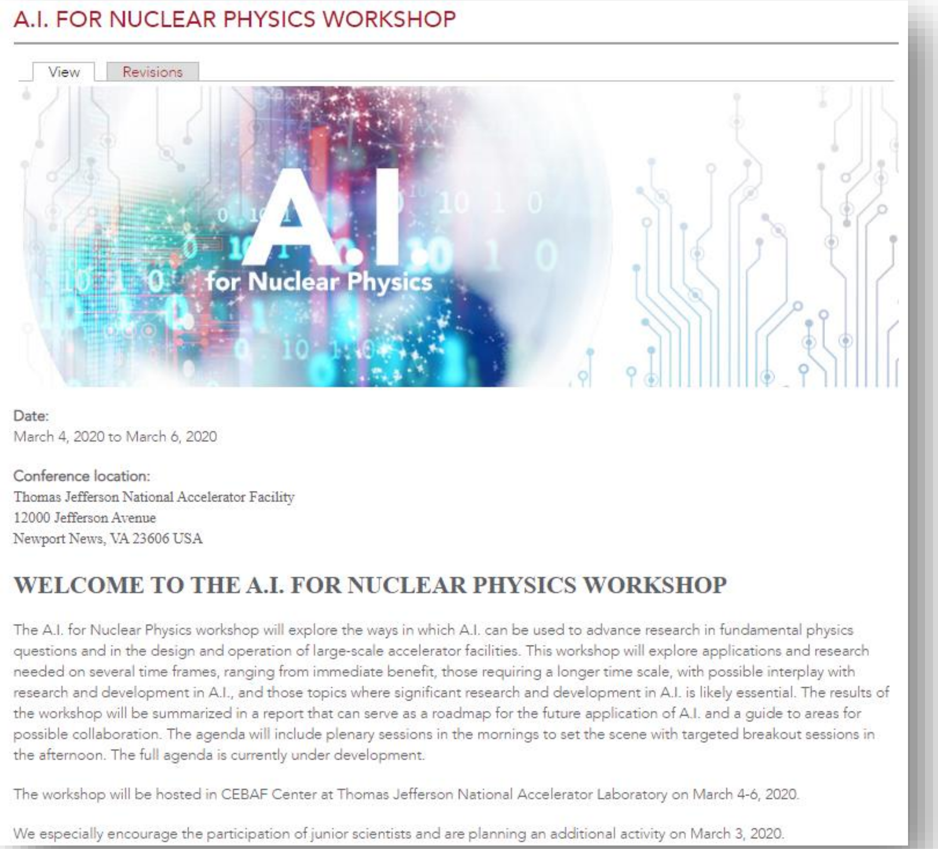
# Summary

- CEBAF is an operational, large-scale SRF, user-facility
- is a unique testbed to apply AI-driven solutions for a variety of challenges
  - ✓ University partners are eager to collaborate
  - ✓ Jefferson Lab is ready to enlarge efforts in AI/ML
- these AI applications have the potential to make CEBAF more efficient
  - ✓ automate time-consuming, manual tasks
  - ✓ automate specialized tasks so as to free up subject matter experts
  - ✓ analyze data and provide results more quickly
  - ✓ increase beam availability
  - ✓ minimize damage to beamline components

# AI Growth and Outreach at Jefferson Lab



A.I. FOR NUCLEAR PHYSICS WORKSHOP

View | Revisions

A.I for Nuclear Physics

Date:
March 4, 2020 to March 6, 2020

Conference location:
Thomas Jefferson National Accelerator Facility
12000 Jefferson Avenue
Newport News, VA 23606 USA

WELCOME TO THE A.I. FOR NUCLEAR PHYSICS WORKSHOP

The A.I. for Nuclear Physics workshop will explore the ways in which A.I. can be used to advance research in fundamental physics questions and in the design and operation of large-scale accelerator facilities. This workshop will explore applications and research needed on several time frames, ranging from immediate benefit, those requiring a longer time scale, with possible interplay with research and development in A.I., and those topics where significant research and development in A.I. is likely essential. The results of the workshop will be summarized in a report that can serve as a roadmap for the future application of A.I. and a guide to areas for possible collaboration. The agenda will include plenary sessions in the mornings to set the scene with targeted breakout sessions in the afternoon. The full agenda is currently under development.

The workshop will be hosted in CEBAF Center at Thomas Jefferson National Accelerator Laboratory on March 4-6, 2020.

We especially encourage the participation of junior scientists and are planning an additional activity on March 3, 2020.

# Thank You.

# Funded Activity

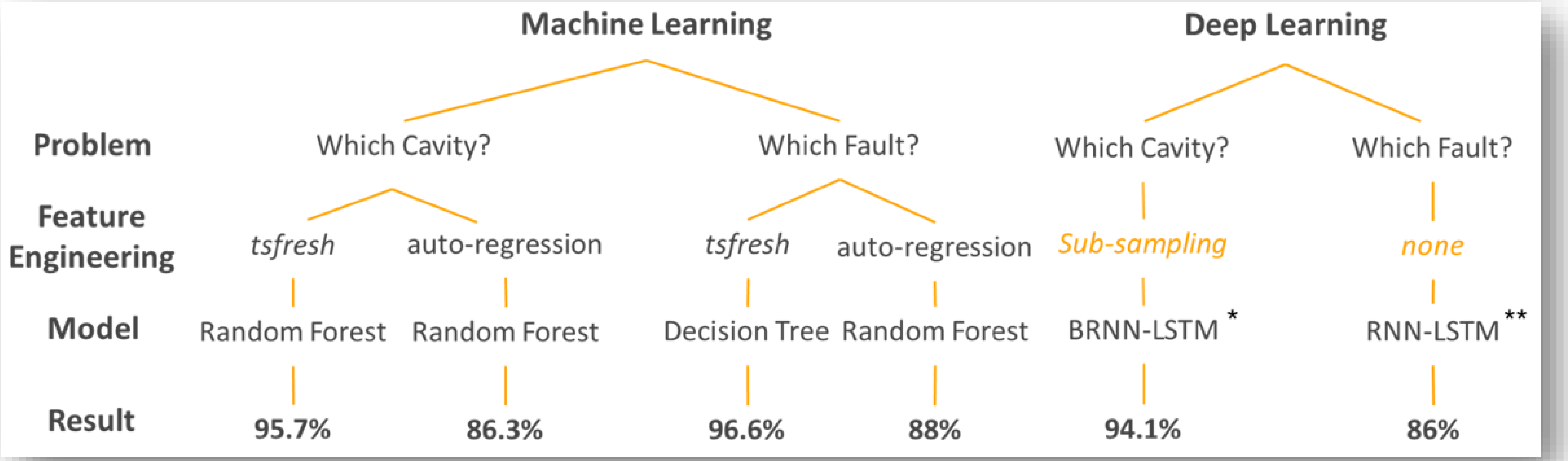
- Goal: *Superconducting RF Cavity Fault Classifier*
- Scope:

  Develop and deploy machine learning models to (1) identify cavity and (2) fault type in a control room application. Investigate models for fault prediction.
- Objective:

  Relaying information about which cavity and which type of fault caused a trip allows operators to retain gradient in other cavities, providing necessary overhead for meeting high energy goals.
- Source of Funding: Laboratory Directed R&D (LDRD)
- Duration: FY2020 *(FY2021 conditional)*

# Funded Activity

- Goal: *Superconducting RF Cavity Fault Classifier*
- using conventional machine learning tools as well as deep learning architectures, we have achieved encouraging results for predicting the cavity ID and type of cavity fault



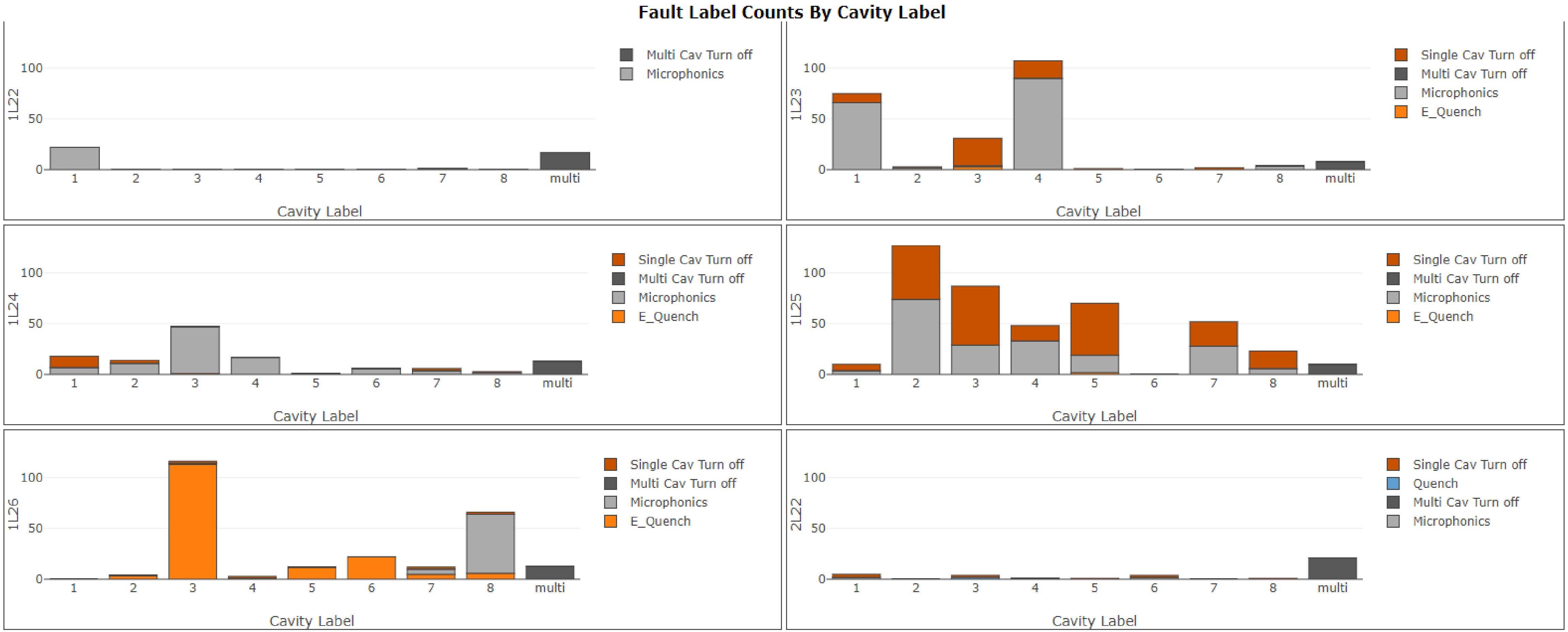

Deep Cellular Recurrent Network for Efficient Analysis of Time-Series Data with Spatial Information

L. Vidyaratne, *Member, IEEE*, M. Alam, A. Glandon, A. Solopova, C. Tennant, and K. M. Iftekharuddin, Senior *Member, IEEE*

(submitted to *IEEE Transactions on Neural Networks and Learning Systems*)

# Funded Activity

- <u>Goal</u>: *Superconducting RF Cavity Fault Classifier*
- a prototype system is currently deployed online and operational



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# Future Projects

- Goal: *Minimize Radiation Levels Due to Field Emission in an SRF Linac*
- Impact:

  Improve reliability, availability, and maintainability, reduce personnel radiation dose and prevent damage to beamline components
- Description:

  Minimize field emission by re-distributing the gradients between cavities while keeping the overall gradient (energy) constant. The problem is complicated and depends on many factors; field emission can be accelerated downstream and upstream and gradients, field emission onsets and fault rates are always changing. Field emitted radiation and activation must be taken into account for gradient optimization.
- Requirements:

  A ML model takes as input: gradients and phases, field emission onset and RF fault rate, cryogenic loads, and radiation levels from newly developed photon and neutron dose rate meters.

(doi:10.18429/JACoW-IBIC2017-TH1AB1)



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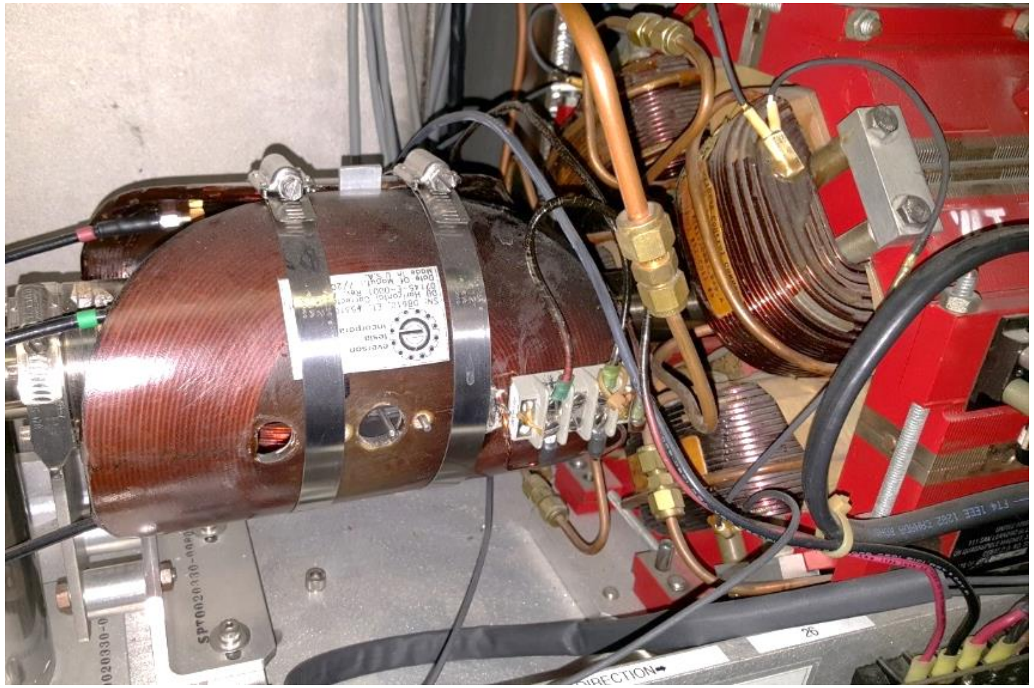
# Future Projects

- Goal: *Minimize Radiation Levels Due to Field Emission in an SRF Linac*


Radiation Area


damaged beamline valve



damaged magnet and cables



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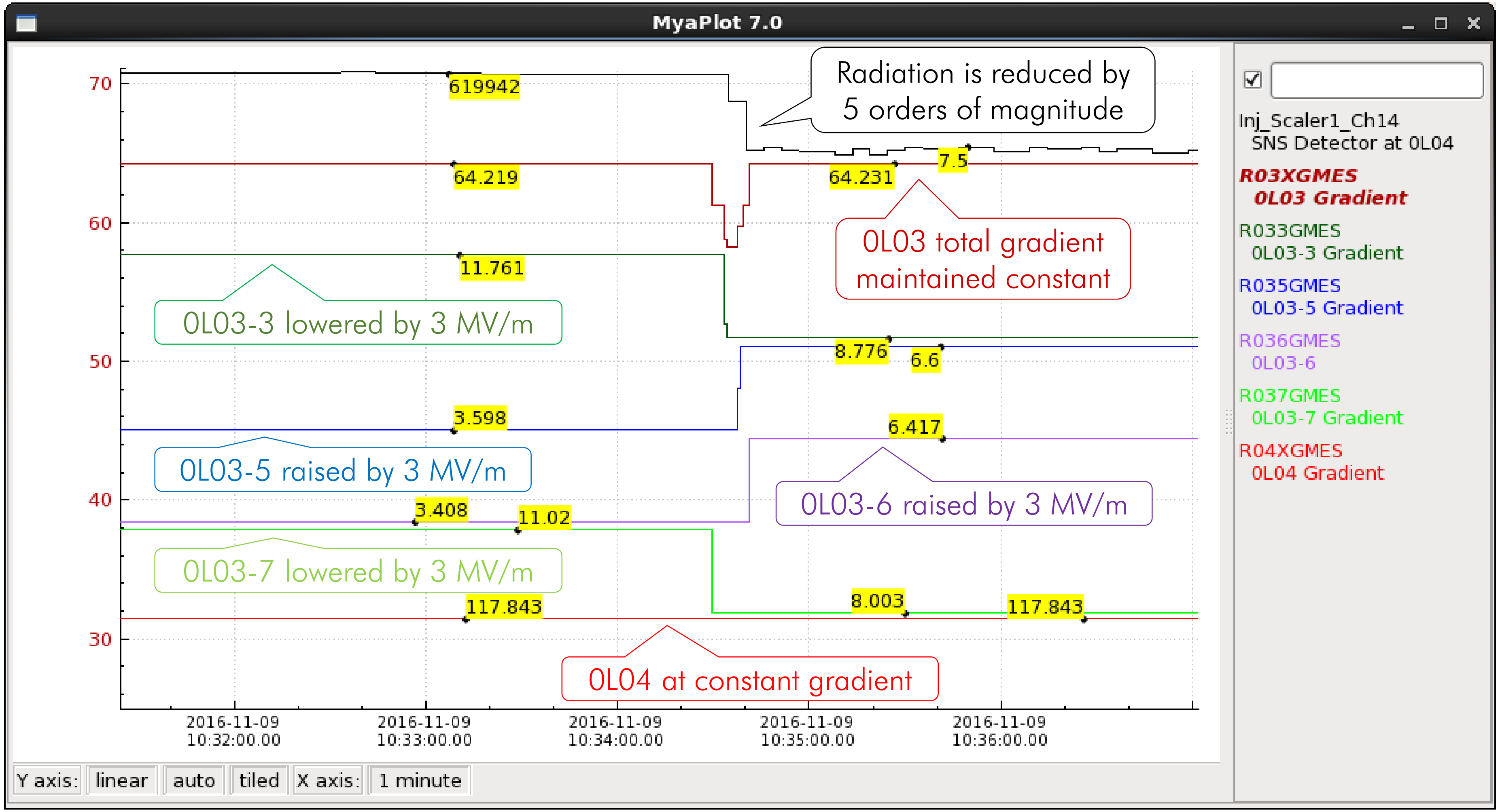
# Future Projects

- Goal: *Minimize Radiation Levels Due to Field Emission in an SRF Linac*




(doi:10.18429/JACoW-IBIC2017-TH1AB1)

# Future Projects

- Goal: *SRF Cavity Instability Detection*
- Impact:

  Improve beam availability by automating the process of identifying unstable RF cavities.
- Description:

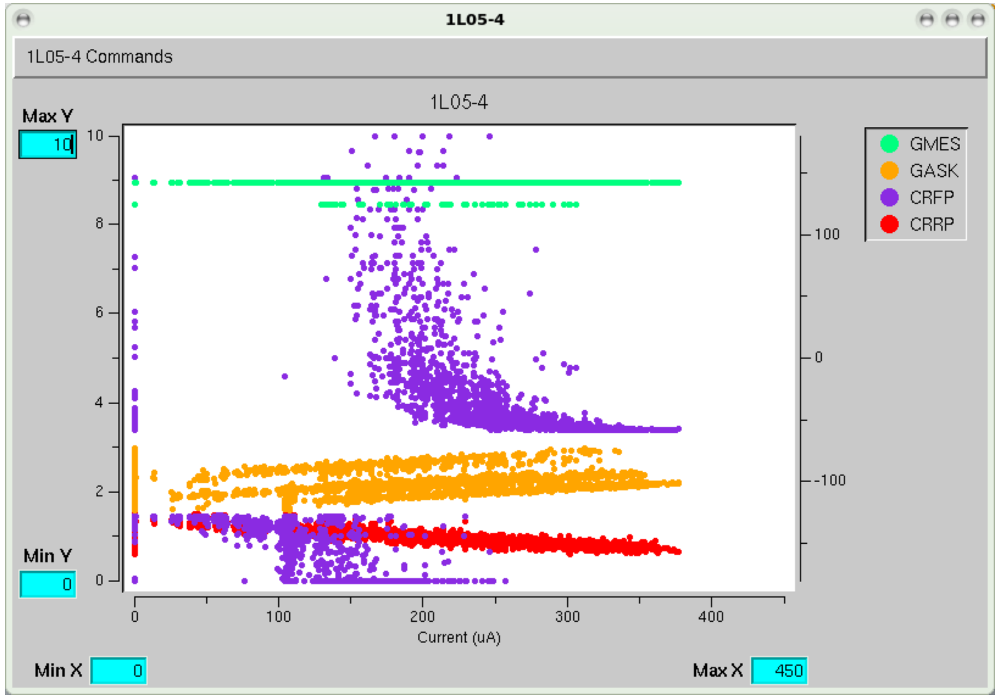
  Use the strength of machine learning's ability for pattern recognition (particularly in noisy data sets) to identify RF cavities that go unstable by analyzing recorded signals.
- Requirements:

  Faster sampling of RF cavity signals to discern unique signatures – currently use archived data sampled at $\sim$1 Hz.

# Future Projects

- <u>Goal</u>: *SRF Cavity Instability Detection*


**RF Analyzer Tool**




- note, this represents an obvious example
- not all instances are so easily detectable by an operator



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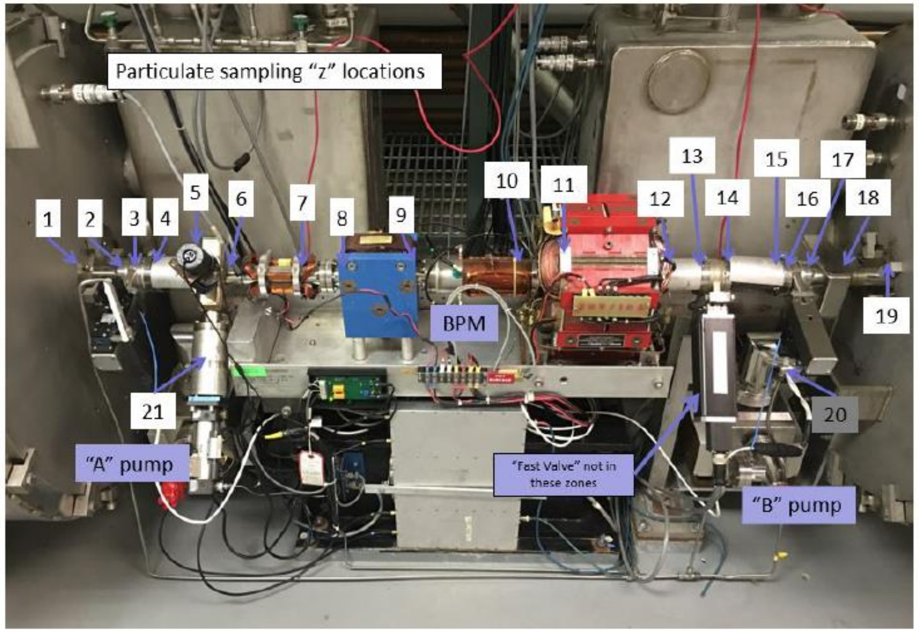
# Field Emission and Particulate Contamination

- root-cause analysis finds particulates are the dominate source of field emission → particulates on the inner surface of operational cavities are from *external sources* (e.g. ion pumps between modules)
- "…have developed a system for characterizing particulate contamination… conveniently analyzed in a scanning electron microscope (SEM)."
- particulate inventory: led to changes in procedures for tunnel installation




- hundreds of spindles collected, hundreds to thousands of particulates per spindle
- Big Data: a broad term for data sets so large or complex that traditional data processing applications are inadequate

(doi: 10.18429/JACoW-SRF2019-WEPRB097)

# Future Projects

- Goals: *SRF Cavity Particulate Identification*

  *SRF Cavity Particulate Counts*
- Impact:

  Insights into best practices for fabrication, installation and maintenance activities related to SRF cavities (note, these findings are not only relevant to CEBAF but to other SRF-based machines as well). Expected improvement in FE onset, yielding higher usable cavity gradients.
- Description:

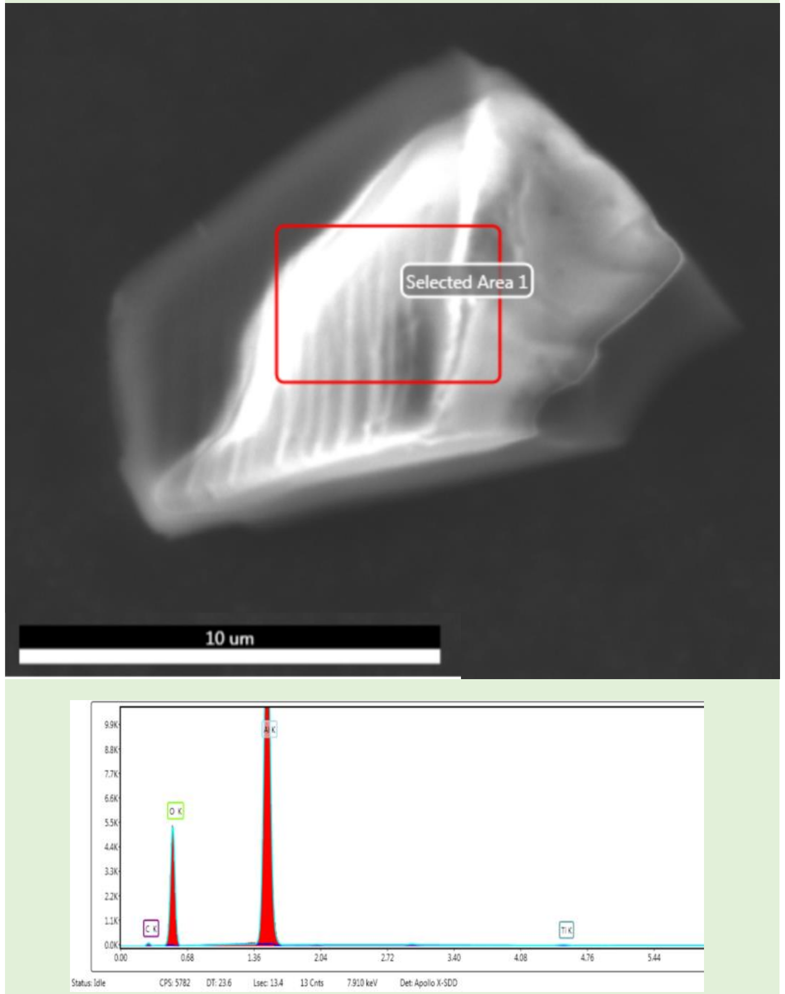
  Augment current (manufacturer's) software with AI to more accurately and efficiently analyze data.
- Requirements:

  Sufficiently large set of labeled x-ray intensity data and SEM images from collected spindles.

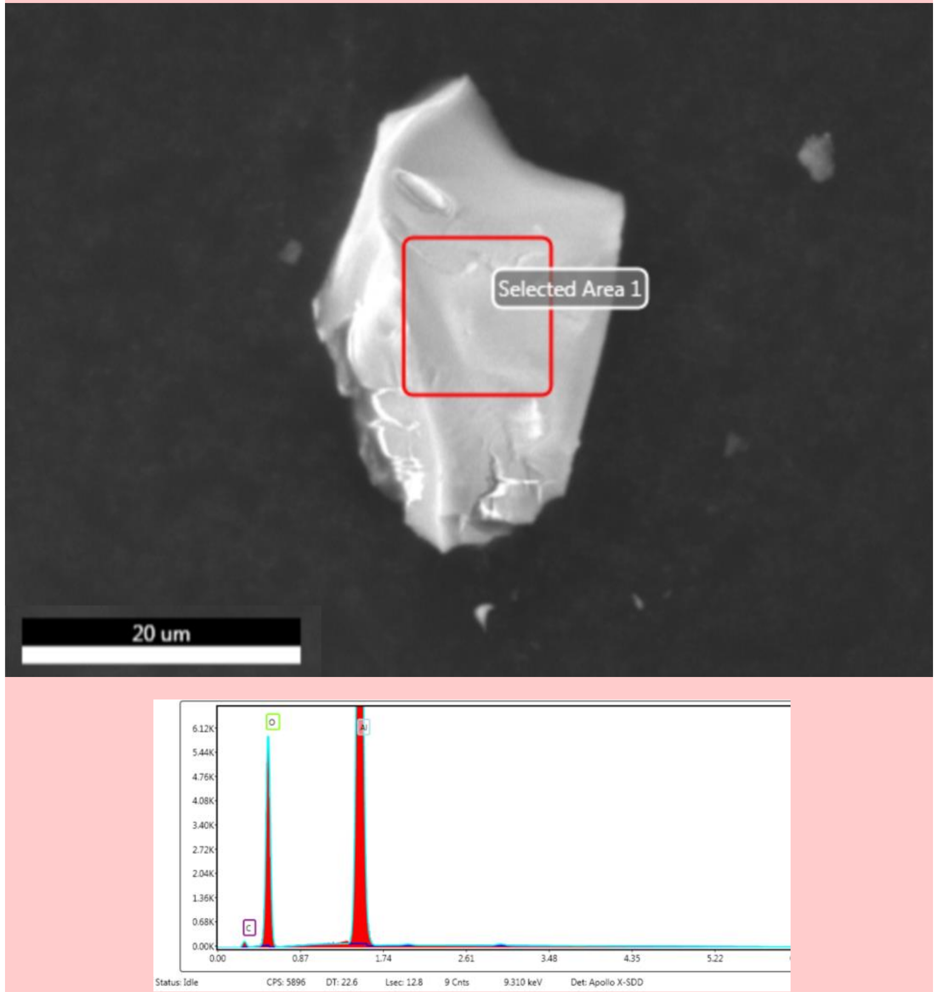
# Future Projects

- Goal: *SRF Cavity Particulate Identification*

Alumina – AlO




Aluminum - Al




(courtesy J. Spradlin)

# Future Projects

- Goal: *Passive Bunch Length Measurement*
- Impact:

  Provide real-time bunch length information for non-invasive measurements and tuning.
- Description:

  Create a so-called "virtual diagnostic" by using a trained AI model in conjunction with non-invasive beam measurements to provide accurate bunch length measurements (an otherwise invasive measurement).
- Requirements:
  - To get sufficient training data requires many invasive bunch length measurements (to correlate with non-invasive beam measurements).

# Future Projects

- Goal: *Accelerator "Smart Alarm"*
- Impact:

  Using readily measured data (BPMs, BLMs), identify root-causes for degradation in machine performance, thereby reducing the time required for beam tuning tasks.
- Description:

  Alarm systems are commonly used to indicate when specific machine parameters are drifting outside their normal tolerances. However, operators are still required to interpret these alarms in the context of many interacting systems and subsystems and take corrective action.
- Requirements:

  Generate training data by intentionally scanning setpoints that are known to change/drift (position of laser spot on cathode, cavity gradients and phases, etc.) and recording downstream responses.

# Accelerator Physics Use Cases

## I. *Optimization*

✓need a model that is (1) accurate and (2) fast

## II. *Prognostics (Anomaly Detection)*

✓identifying conditions that may negatively impact machine performance

## III. *Diagnostics*

✓provide an estimate of what an instrument would read when such a reading is unavailable (i.e. a non-invasive "measurement")

## IV. *Automation*

✓ the goal is to the maximize scientific output per operating dollar at a user facility

Example use cases include "analysis of large quantities of archived data, accurate and fast modeling of accelerator systems, detection of aberrant machine behavior, optimization of accelerator design, and active tuning and control" ("Opportunities in Machine Learning for Accelerator Physics", A. Edelen, C. Mayes, eds. arXiv:1811.03172)