AI at Jefferson Laboratory

Roundtable Meeting on AI/ML in NP Facilities

Chris Tennant

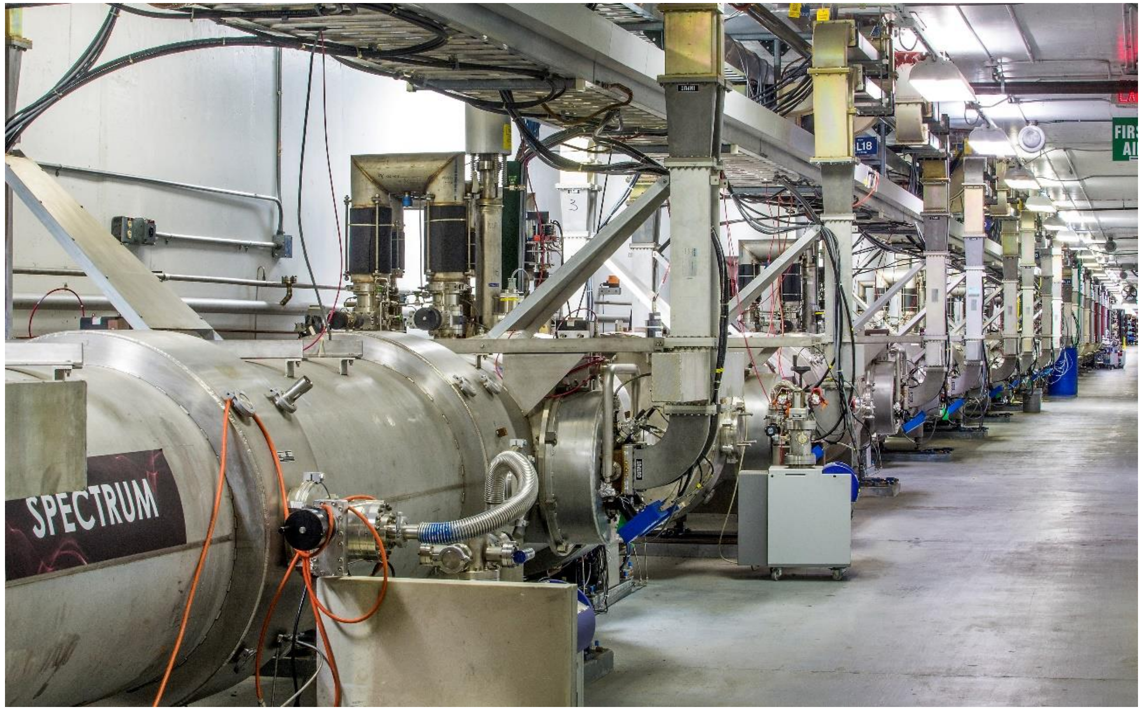
January 30, 2020

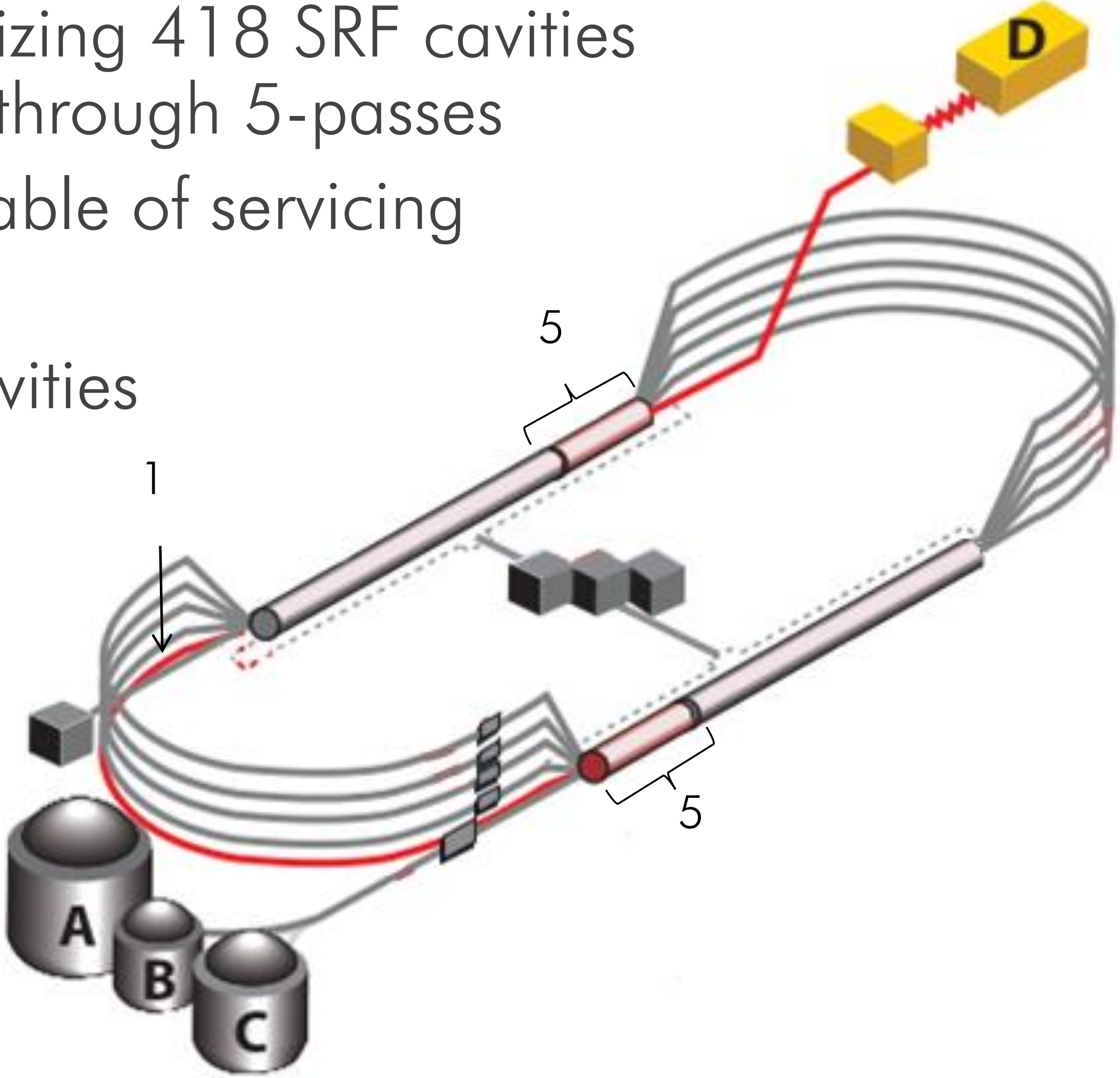
Outline

- ***CEBAF***
- ***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*
- ***Summary***

CEBAF

- CEBAF is a CW recirculating linac utilizing 418 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





Funded Activity

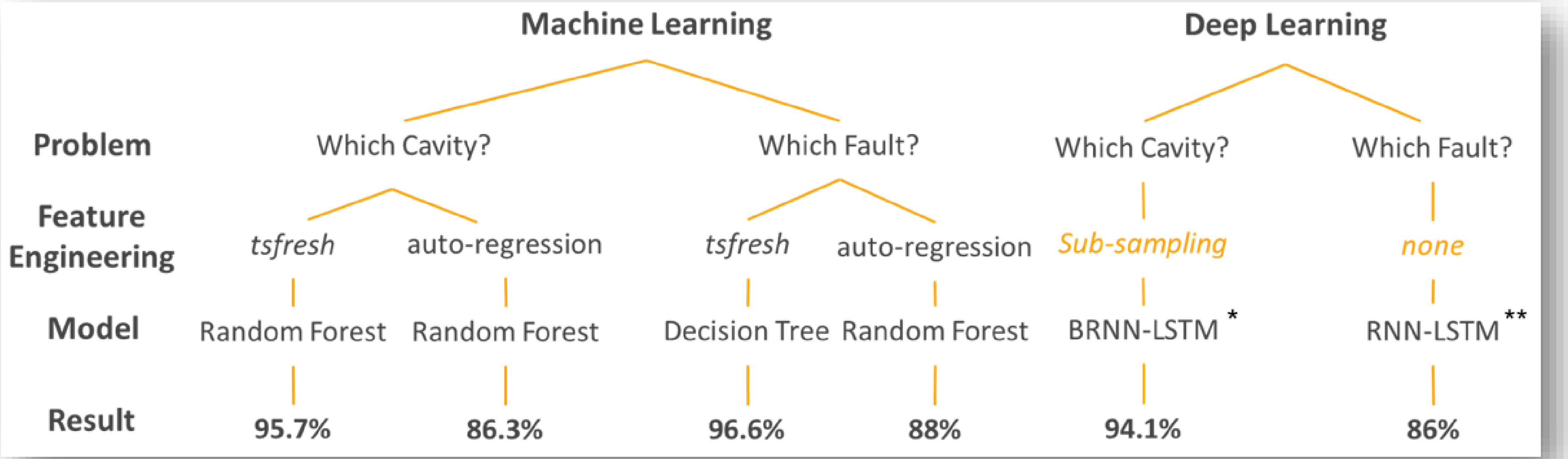
- Goal: *Superconducting RF Cavity Fault Classifier*
- Scope:

  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*)

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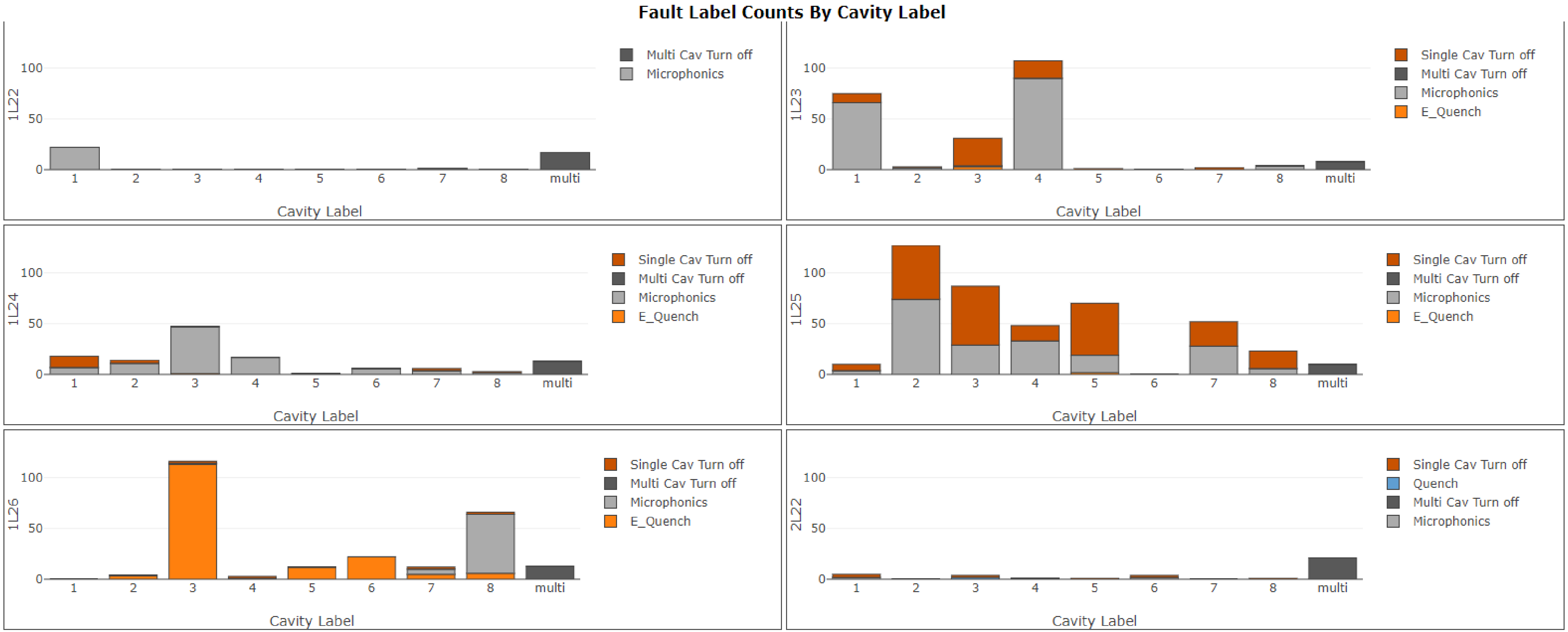
Funded Activity

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



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Data is the Fuel for AI/ML

- the SRF cavity fault classifier work is only possible because of a specially designed data acquisition system – which required the coordination of several different groups working together
- getting and then labeling (if necessary) data hard and expensive
- without data we can't leverage AI/ML
  - ✓need to be more proactive with machine measurements
  - ✓what kind of measurements should we be doing hourly/daily/weekly?

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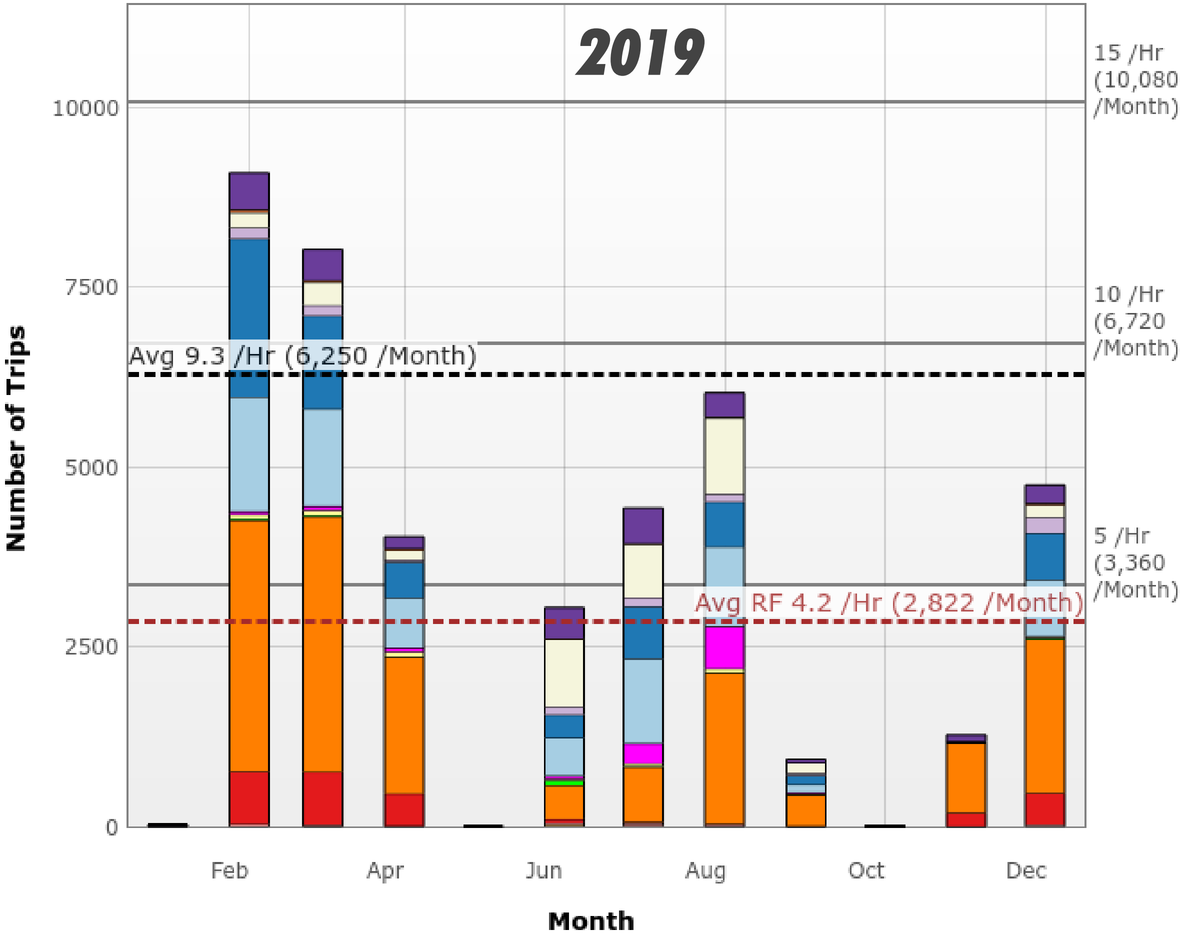
Improving CEBAF Availability

- 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

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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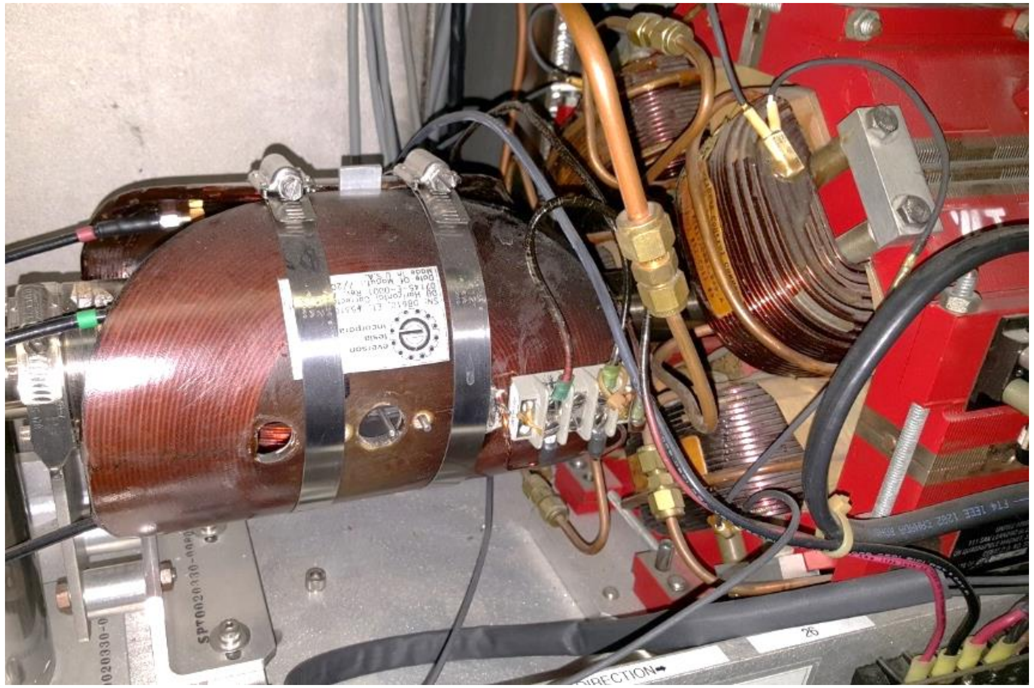
Future Projects

- 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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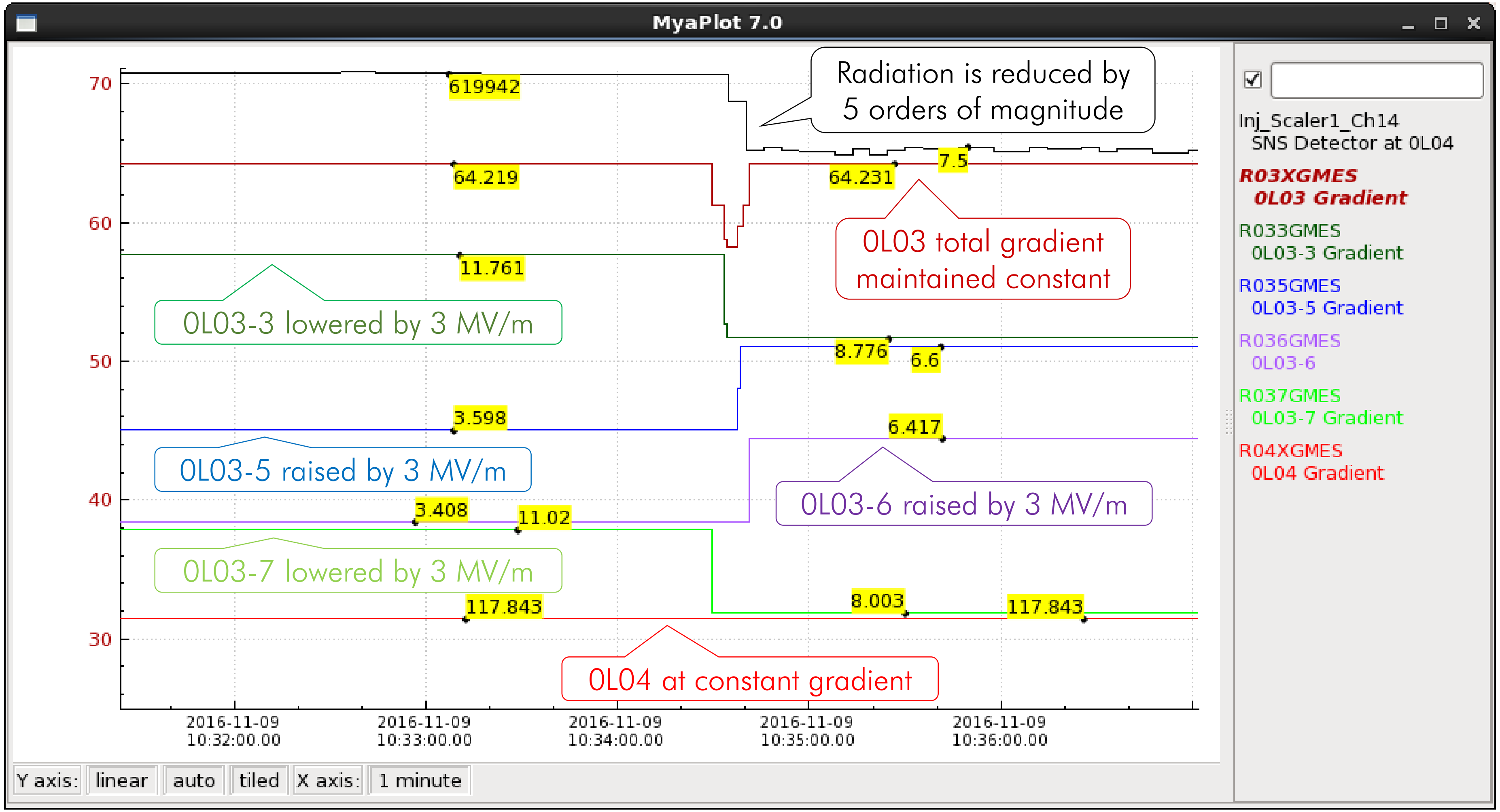
Future Projects

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



(doi:10.18429/JACoW-IBIC2017-TH1AB1)

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Future Projects

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

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

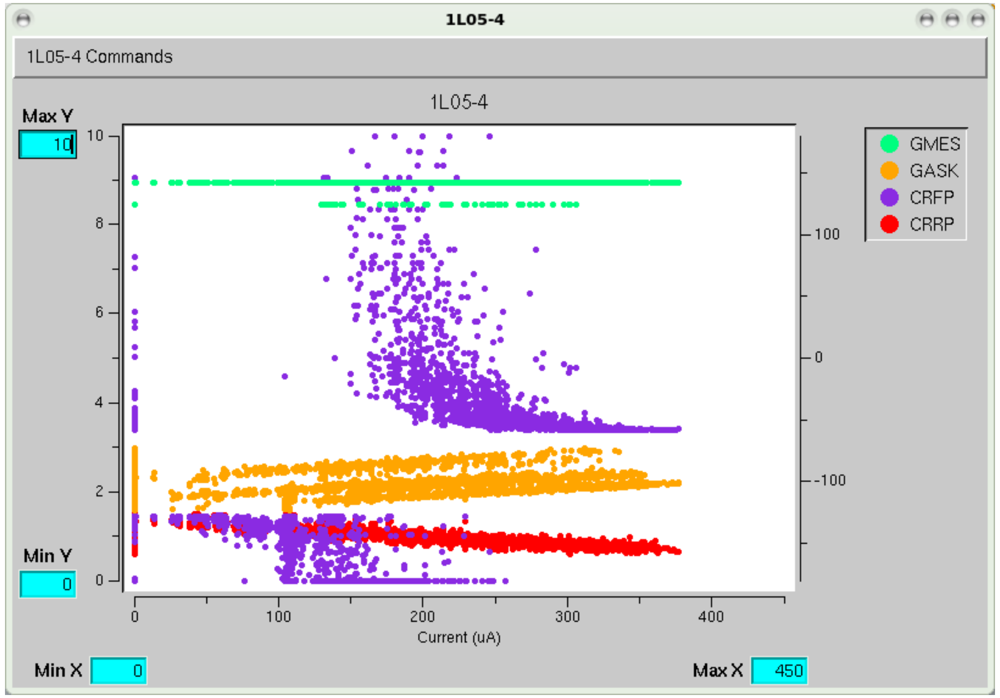
  Use the strength of machine learning's ability for pattern recognition (particularly in noisy data sets) to identify RF cavities that go unstable by analyzing recorded signals.
- Requirements:

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

Future Projects

- Goal: *SRF Cavity Instability Detection*

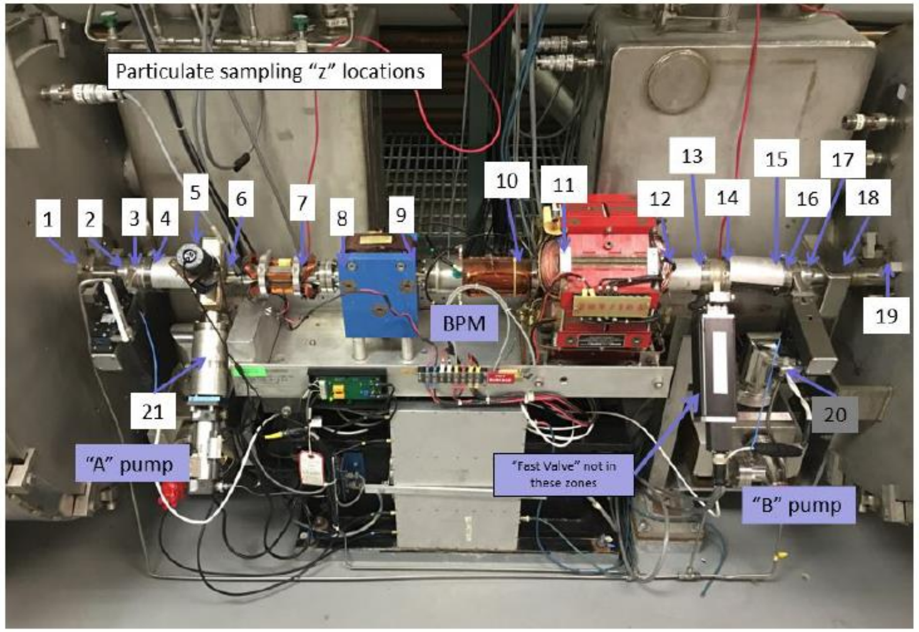
RF Analyzer Tool



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

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:

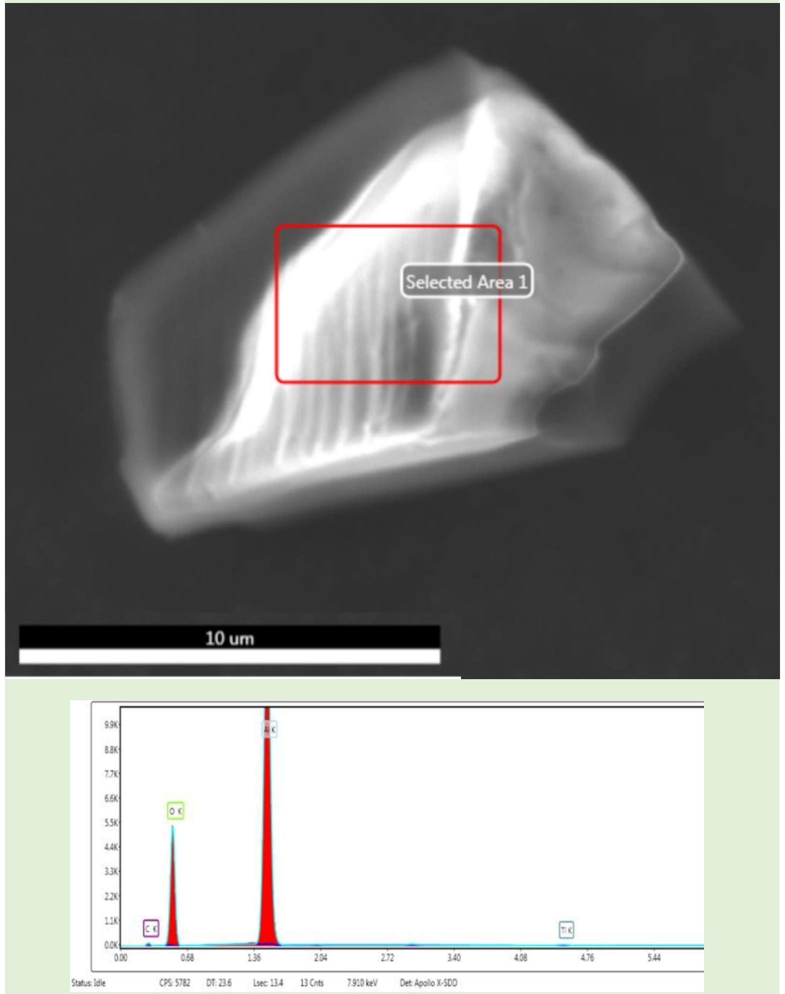
  Augment current (manufacturer's) software with AI to more accurately and efficiently analyze data.
- Requirements:

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

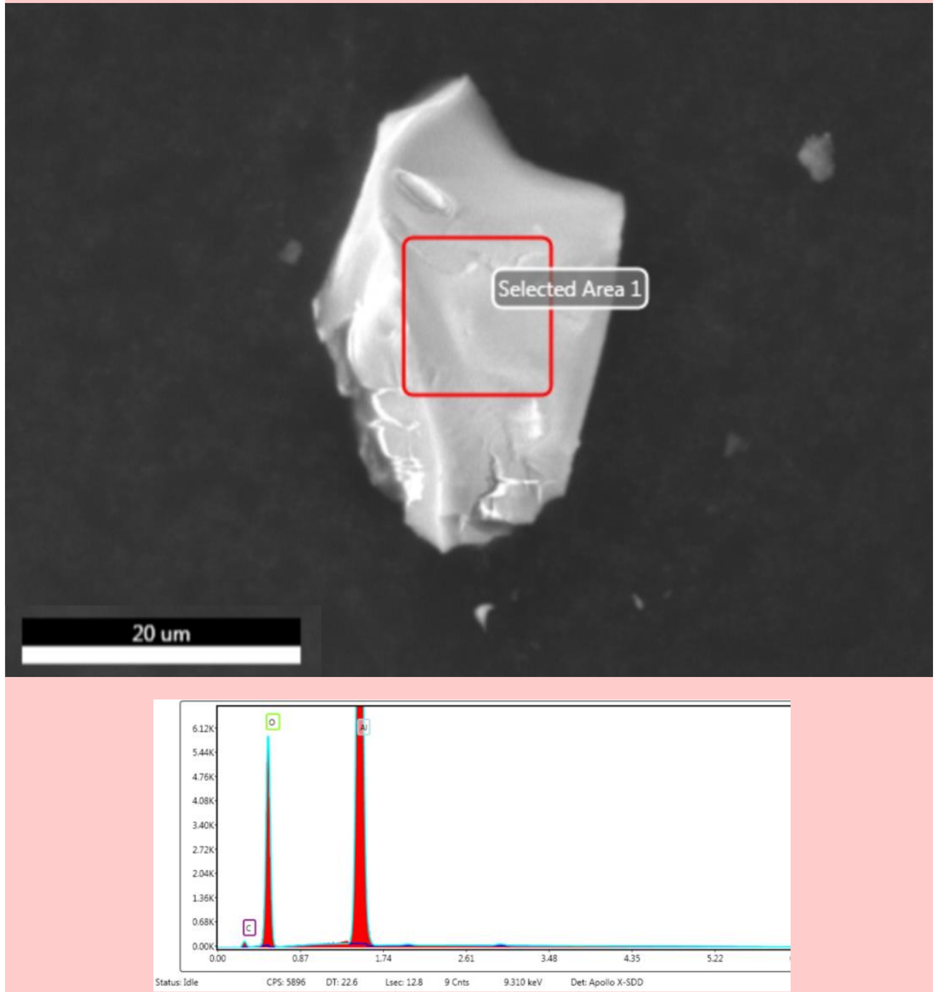
Future Projects

- Goal: *SRF Cavity Particulate Identification*

Alumina – AlO



Aluminum - Al

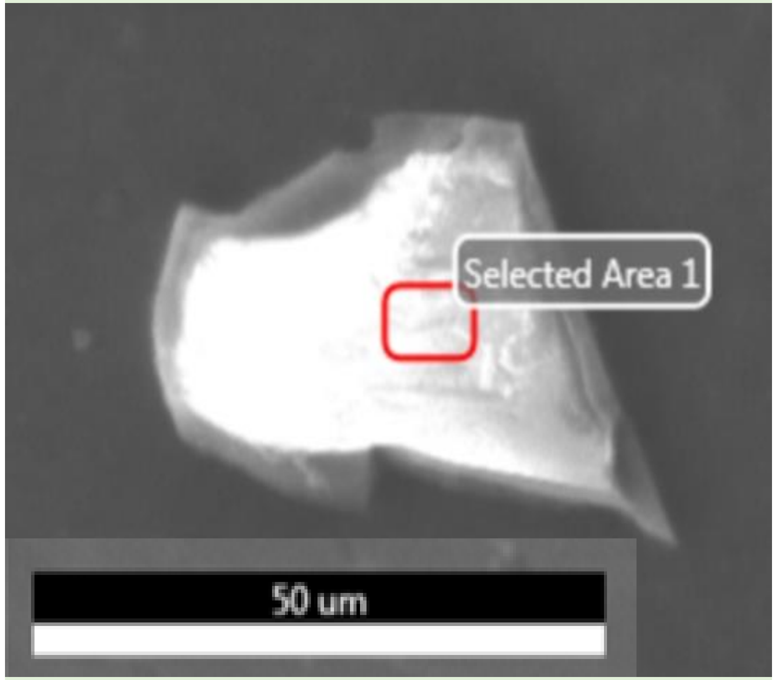


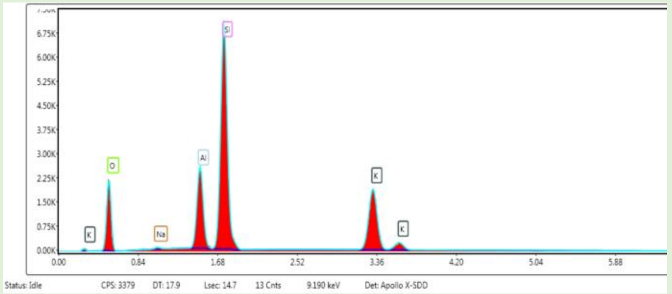
(courtesy J. Spradlin)

Future Projects

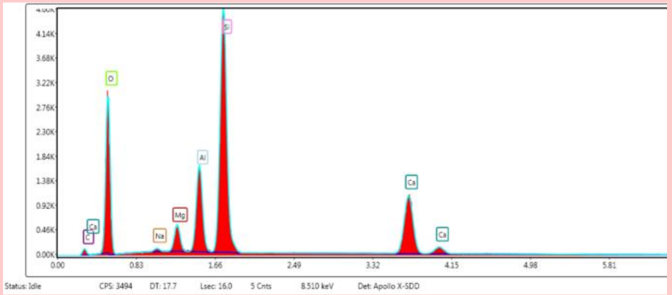
- Goal: *SRF Cavity Particulate Identification*

Aluminasilicate – AlSiO





Fiberglass



(courtesy J. Spradlin)

Future Projects

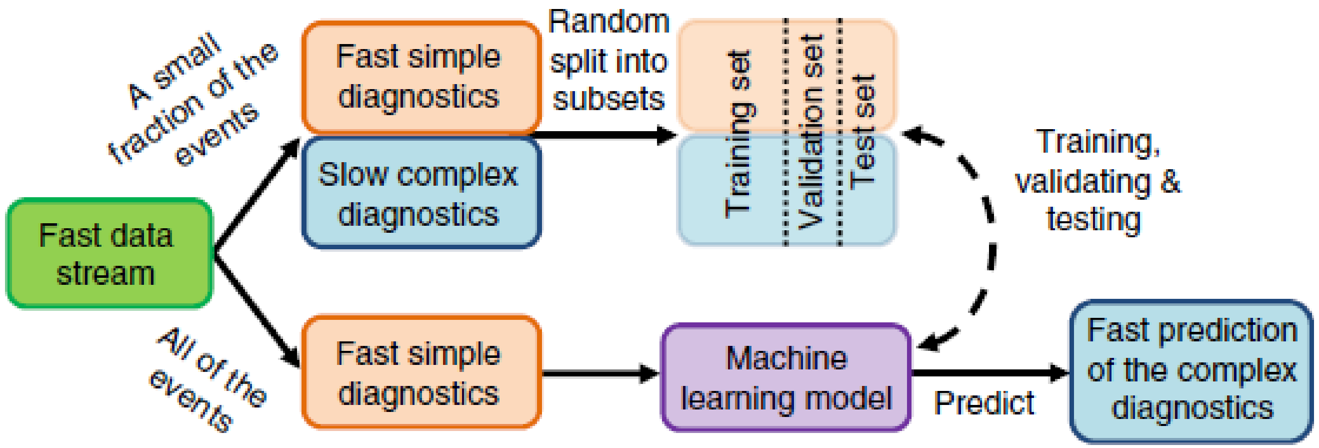
- Goal: *Passive Bunch Length Measurement*
- Impact:

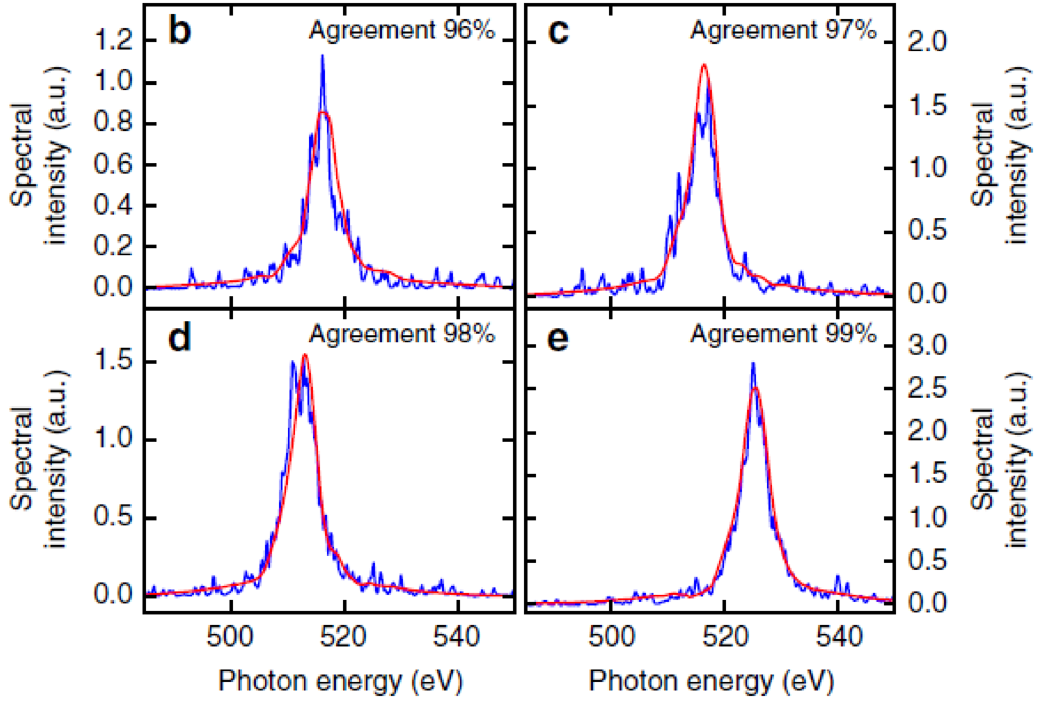
  Provide real-time bunch length information for non-invasive measurements and tuning.
- Description:

  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: *Passive Bunch Length Measurement*
- identify correlations between slowly-updating instruments (e.g. photon energy, spectral shape of X-ray pulses) and more abundant, quickly-updating outputs (e.g. readings from BPMs)
- extract information that is of interest to the users about each X-ray pulse quickly and with high fidelity





(*Nature Communications* **volume 8**, article number: 15461)

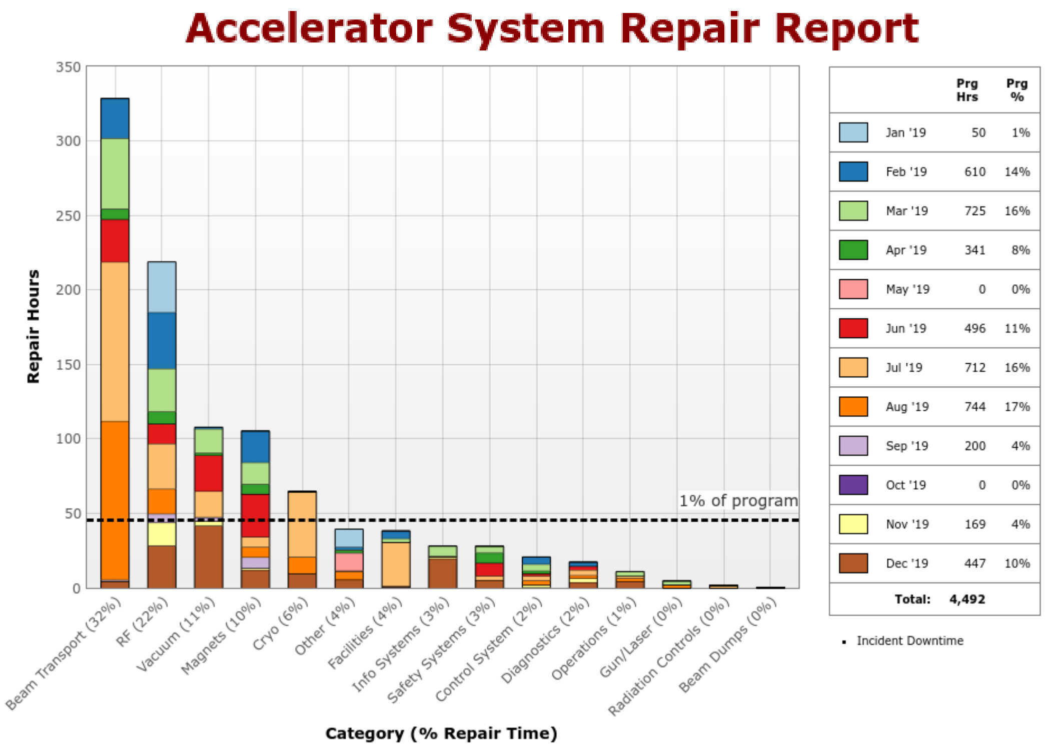
Future Projects

- Goal: *Computer Vision-aided Beam Tuning*
- Impact:

  Automate time consuming beam tuning tasks.
- Description:

  Utilize viewer-based beam diagnostics and leverage advances in computer vision for beam tuning tasks. Multiple synchrotron light monitors (SLMs) will be installed in CEBAF's Arc 7 in the near future and could be used for setup, tuning and monitoring.
- Requirements:

  Sufficient image database corresponding to a variety of machine conditions for training an AI model.



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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.

Future Projects

- Goal: *Mobile Diagnostic with Collaborative Autonomy*
- Impact:

  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
- Description:
  - conduct a general radiation survey before personnel enter the enclosure
    - ✓ *lower potential personnel exposure and reduced survey time*
  - expand radiation monitoring to higher radiation areas (e.g. accelerator dumps)
  - improvement in first line response of in-tunnel system failures
    - ✓ *elimination of exploratory controlled access time*
- Requirements:

  Off-the-shelf hardware (e.g. robot platform, mechanical arm), software/control expertise

(R. Michaud, "Mobile Diagnostic – Drone Use in Accelerator Enclosures", *internal*)

Future Projects

- Goal: *Mobile Diagnostic with Collaborative Autonomy*

- (adjustable) collaborative autonomy
  - ✓ operators can inject information
  - ✓ operators can preempt behavior
- provides exactly the diagnostic needed for field emission studies
  - ✓ rather than many distributed monitors, have a single mobile diagnostic
- knowledge and experience is highly transferable to other accelerators

Southern Research to develop smart robots for next-gen nuclear reactors under DOE grant

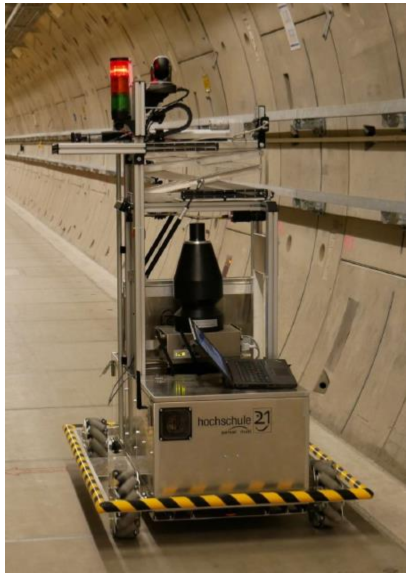
The U.S. Department of Energy (DOE) has awarded a team led by Southern Research a $2.8 million grant to develop smart maintenance robots that will work autonomously in the challenging conditions inside next-generation nuclear reactors.

(https://alabamanewscenter.com/2019/10/07/southern-research-to-develop-smart-robots-for-next-gen-nuclear-reactors-under-doe-grant/)

Future Projects

- Goal: *Mobile Diagnostic with Collaborative Autonomy*

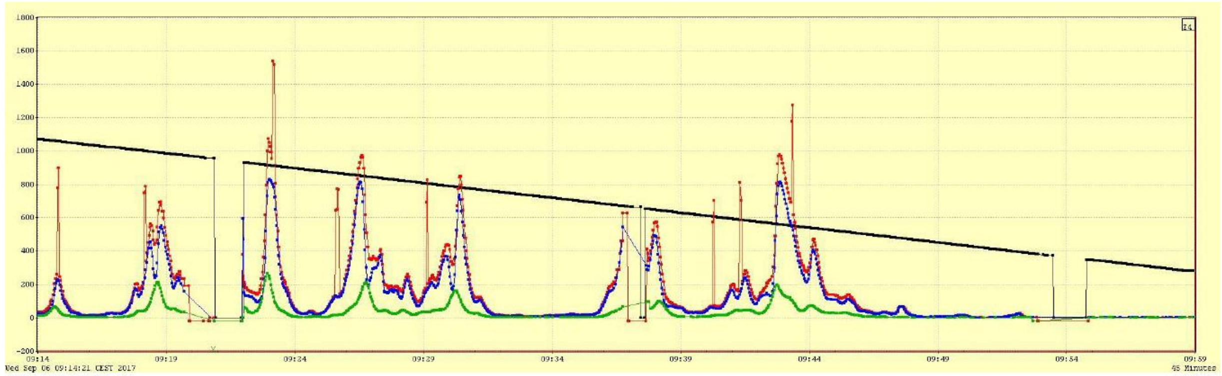
European XFEL uses a mobile autonomous robot platform for performing maintenance and inspection tasks



- collaboration with nearby university
- robotics expertise (DARPA challenge)

JOURNAL OF FIELD ROBOTICS

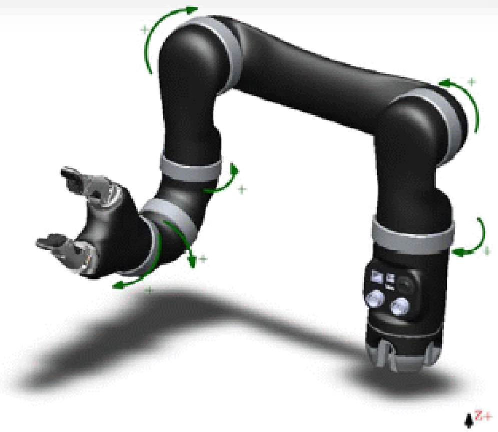
Collaborative Autonomy between High-level Behaviors and Human Operators for Remote Manipulation Tasks using Different Humanoid Robots



Radiation profile along XFEL accelerator

black: robot position [m]; red: dose rate [µSv/h]; blue: avg. gamma dose rate [µSv/h]; green: avg. neutron dose rate [µSv/h]; missing data: wireless data connection temporarily lost

(doi:10.18429/JACoW-ICALEPCS2017-MOCPL06)



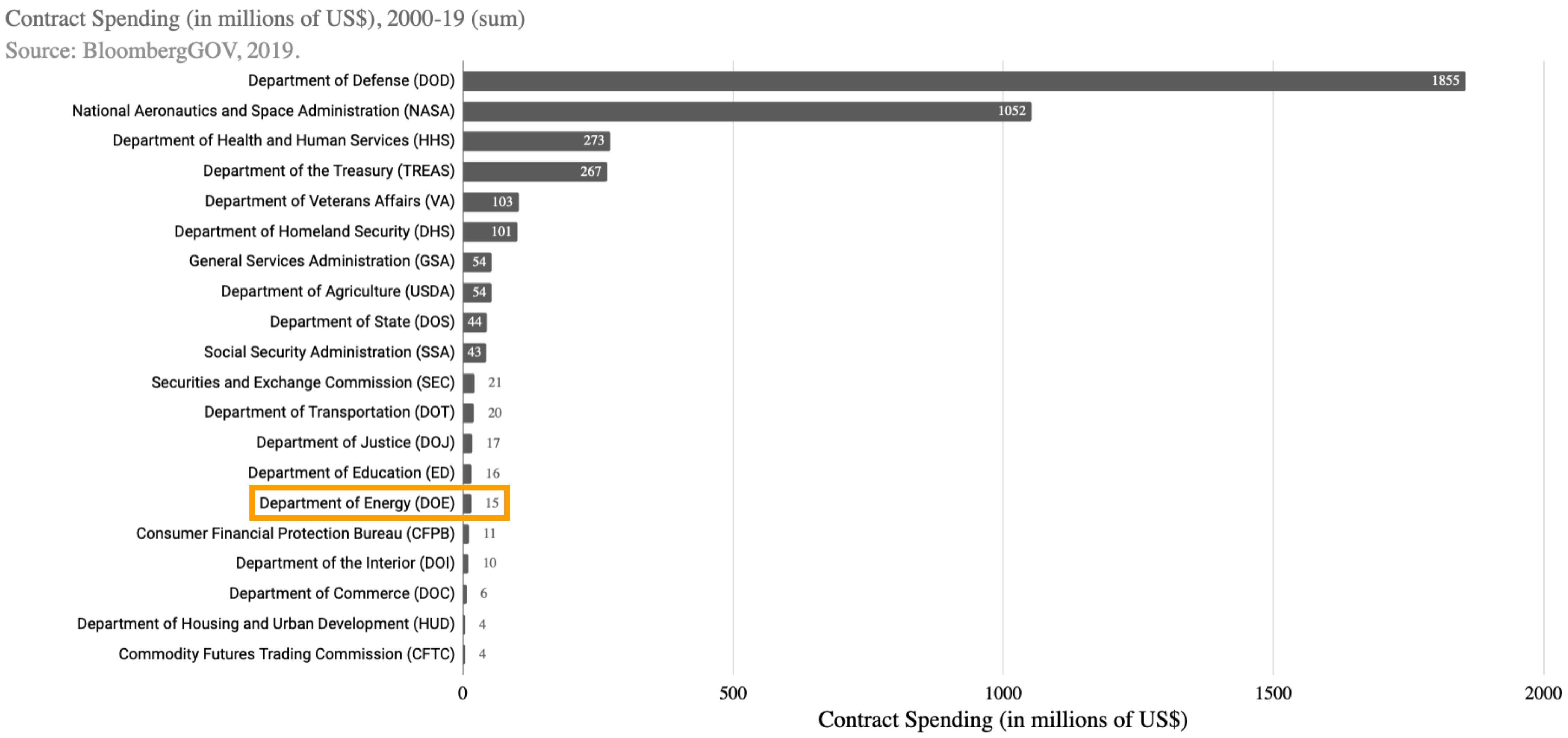
(courtesy D. Conner)

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
- with 25+ years of experience operating SRF systems, have expertise on the entire lifecycle of SRF cavities
  - ✓ provide unique insights for EIC and other SRF accelerators (LCLS-II, SNS)

AI/ML Trends: Government Spending

- government spending on AI projects



("The AI Index 2019 Annual Report")

Thank You.

I gratefully acknowledge contributions from:
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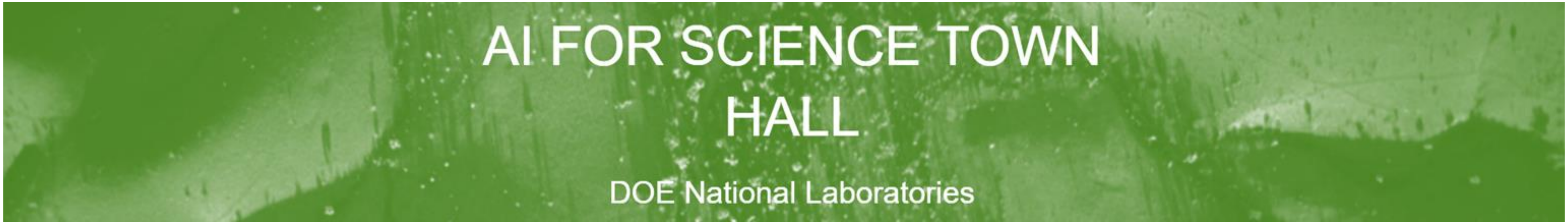
DOE "AI for Science" Town Hall Meetings



350

Chicago AI for Science Town Hall
Argonne National Laboratory
July 22-23, 2019

Oak Ridge AI for Science Town Hall
Oak Ridge National Laboratory
August 20-21, 2019

350

AI FOR SCIENCE TOWN HALL

400+

Berkeley AI for Science Town Hall
Lawrence Berkeley National Laboratory
September 11-12, 2019

Washington DC AI for Science Town Hall
October 22-23, 2019

400

Final report will include contributions from 1,000+ participants

Identifying Grand Challenges in Accelerator Science

Grand Challenge: Eliminate Unscheduled Downtime in Accelerators

- identify failure precursors
  - ✓ what accelerator sensor data is good and what data indicates an upcoming failure?
- high uptime (99%+) supports ADR (accelerator driven reactors)
- this is urgent as the end science user's experiments get preempted if the accelerator fails

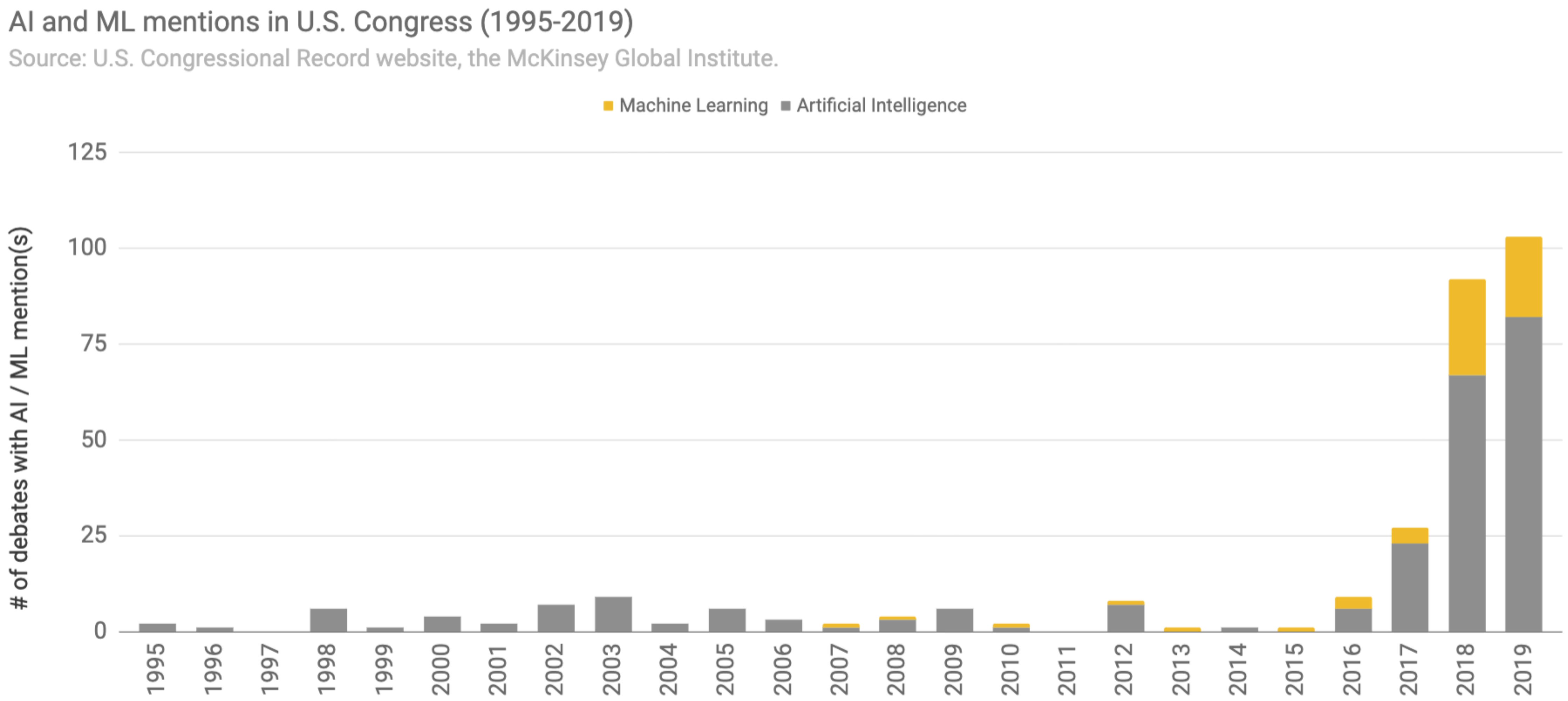
Current Data Available:

- beam properties, status of accelerator equipment,
- unspecified failure modes ("check engine light")
- maintenance inspection of the accelerator facility
  - ✓ human entered electronic logbook

(based on slide presented at DOE's "AI for Science" Town Hall Meeting at ORNL)

AI/ML Trends

- lots of metrics show to communicate the explosive growth of AI/ML



("The AI Index 2019 Annual Report")

AI/ML Trends: Education

- At the graduate level, AI has rapidly become the most popular specialization among computer science PhD students in North America, with over twice as many students as the second most popular specialization (security/information assurance). In 2018, over 21% of graduating Computer Science PhDs specialize in AI/ML.
- Industry has become, by far, the largest consumer of AI talent. In 2018, over 60% of AI PhD graduates went to industry, up from 20% in 2004. In 2018, over twice as many AI PhD graduates went to industry as took academic jobs in the US.
- In the US, AI faculty leaving academia for industry continues to accelerate, with over 40 departures in 2018, up from 15 in 2012 and none in 2004.

("The AI Index 2019 Annual Report")

AI Growth and Outreach at Jefferson Lab