OAK RIDGE National Laboratory

Availability for Particle Accelerators

USPAS

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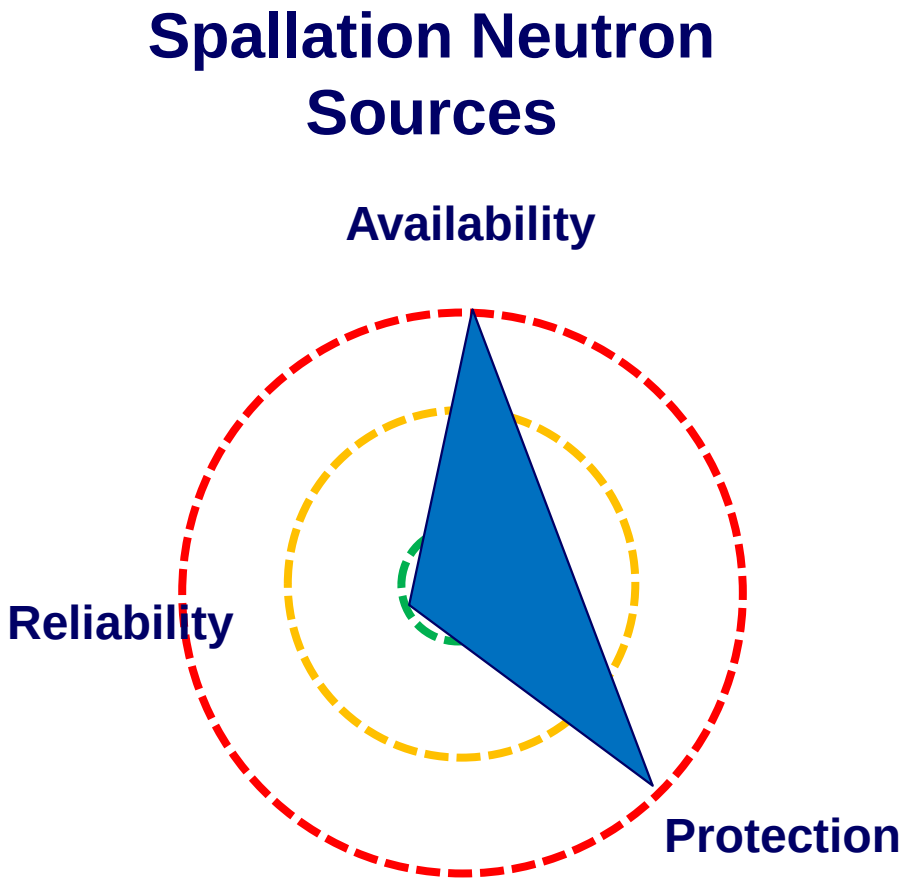
U.S. DEPARTMENT OF ENERGY

Acronyms

- SNS = Spallation Neutron Source
- MPS = Machine Protection System
- TPS = Target Protection System
- IS = Ion Source
- LEBT = Low Energy Beam Transport
- RFQ = Radio Frequency Quadrupole
- MEBT = Medium Energy Beam Transport
- Linac = Linear Accelerator
- DTL = Drift Tube Linac
- CCL = Coupled Cavity Linac
- SCL = Superconducting Cavity Linac
- SSA = Solid State Amplifier
- FCM = Field Control Module
- HPM = High-power rf Protection Module
- HEBT = High Energy Beam Transport
- RTBT = Ring to Target Beam Transport
- GeV = Giga Electron Volts
- MeV = Mega Electron Volts
- BCM = Beam Current Monitor
- BLM = Beam Loss Monitor
- BPM = Beam Position Monitor
- BSM = Beam Shape Monitor
- HVCM = High Voltage Converter Modulator
- PS = Power Supply
- RF = Radio Frequency
- CW = Continuous Wave
- DF = Duty Factor
- PPS = Personnel Protection System
- HPRF = High Power RF
- LLRF = Low-Level RF
- ADS = Accelerator Driven System
- DCM = Differential Current Monitor

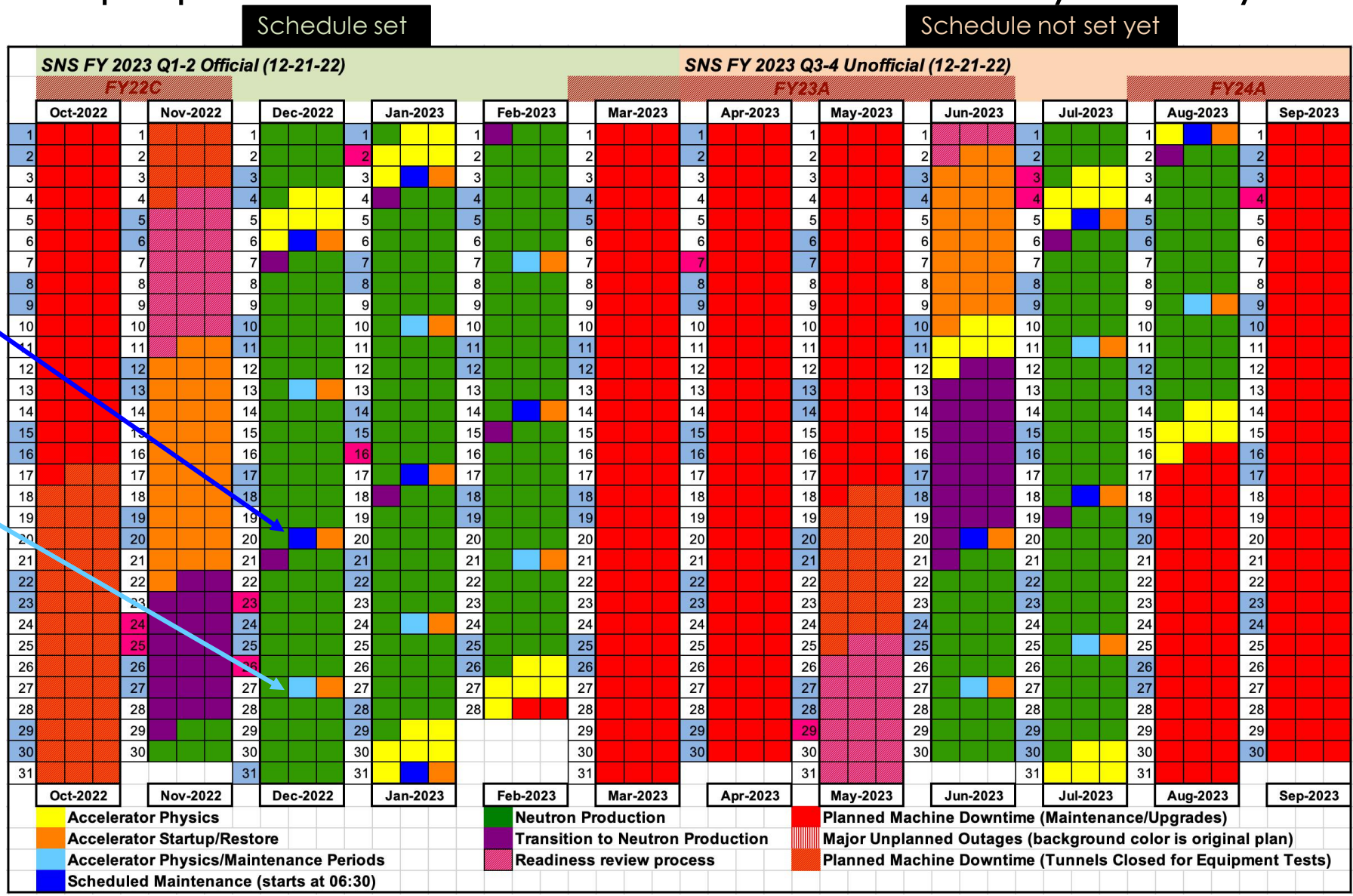
SNS focus is on high availability, minimizing beam trips, and maintaining low levels of residual activation

- At a high-power neutron source most user samples are in the beam for a few hours, or days
- Typical user beam time is 4-14 days at a time
- Short duration beam trips have an impact, but the biggest impact is from beam trips lasting longer than 1 hour

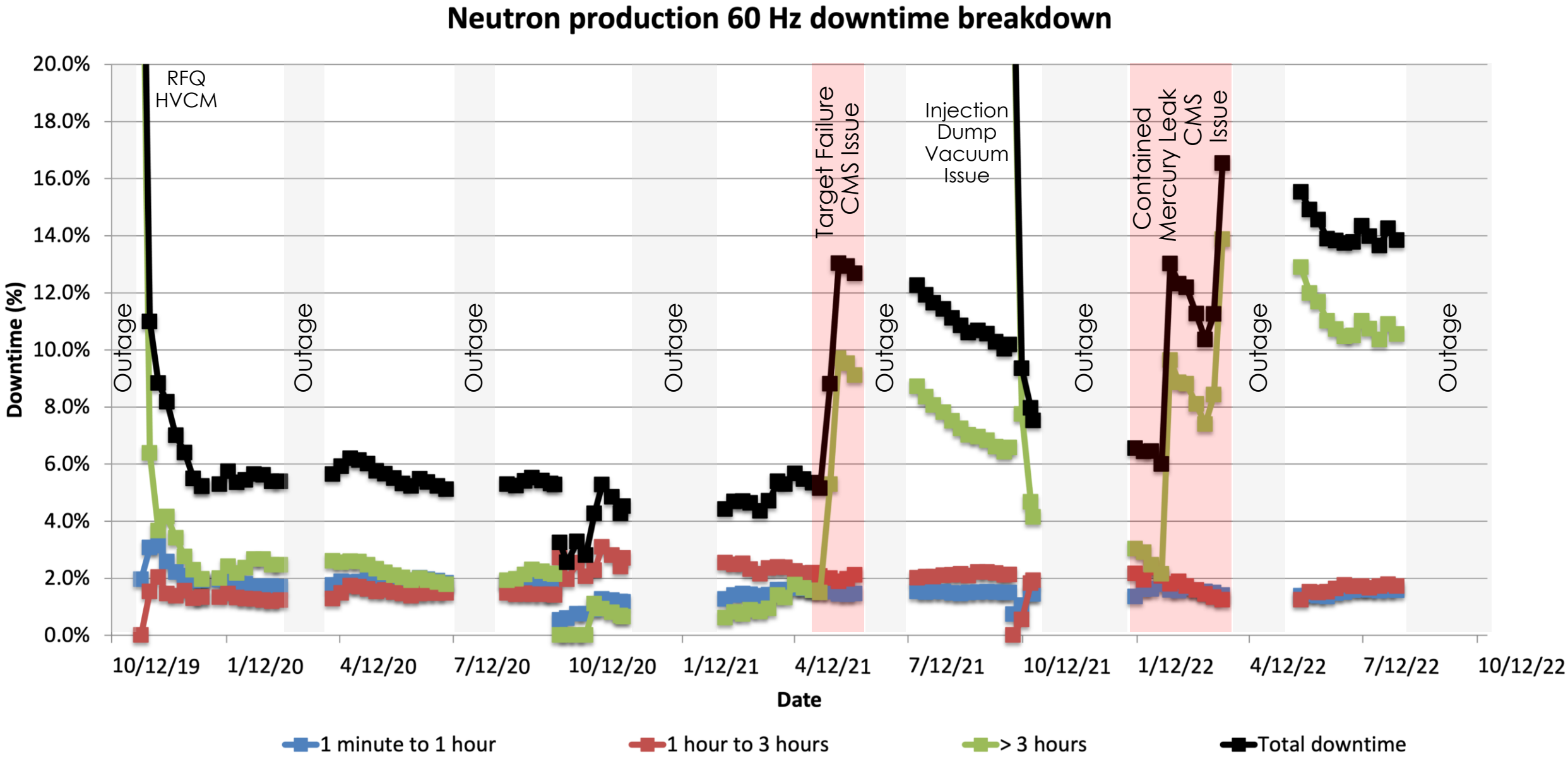


Schedule flexibility helps plan based on recent availability history

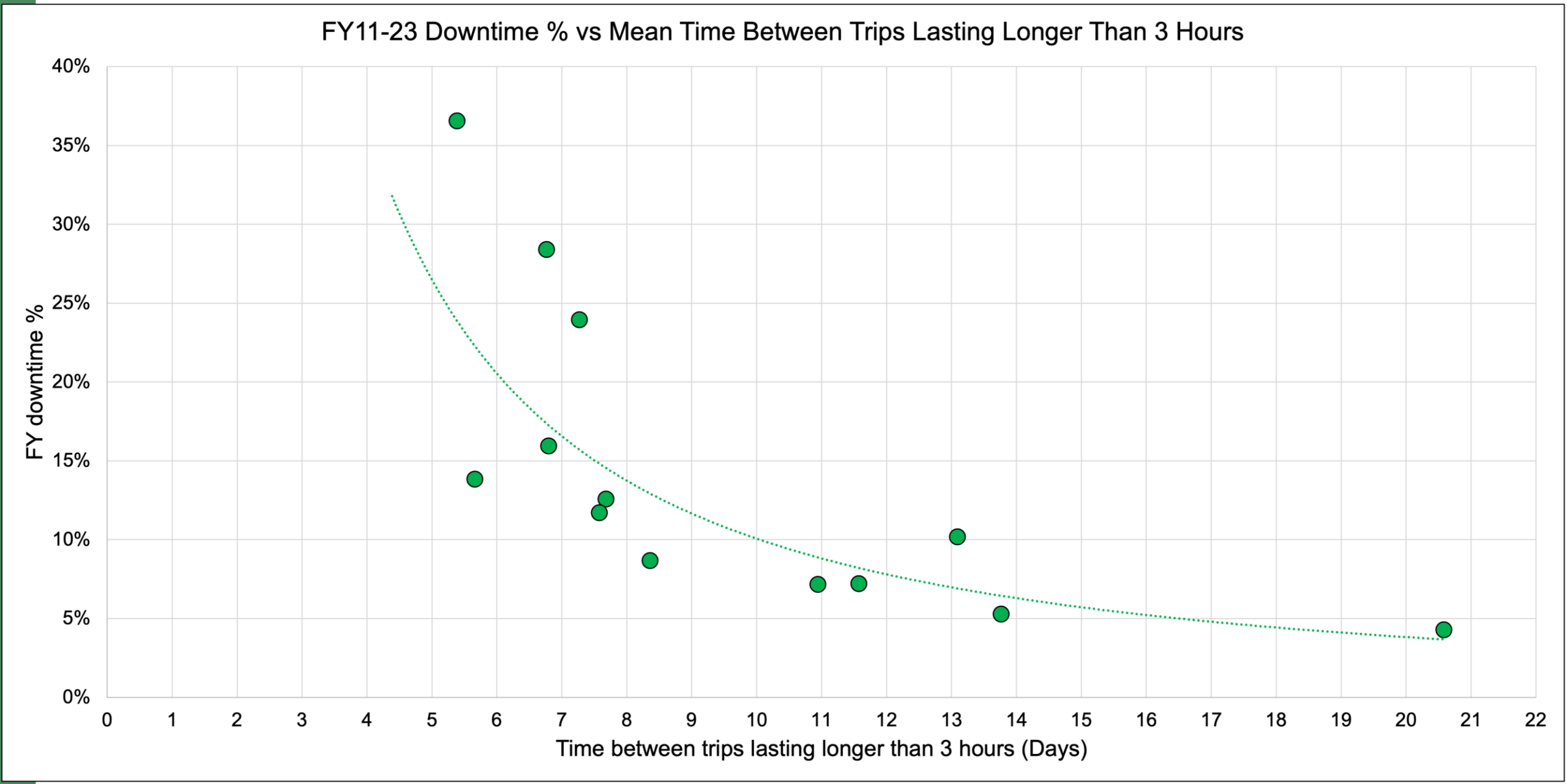
- Neutron production schedule is set by the fiscal year quarter
- Full maintenance days every other week
- Accelerator physics/optional maintenance days every other week
- Additional recovery time available following maintenance days



Downtimes longer than 3 hours dominate overall availability



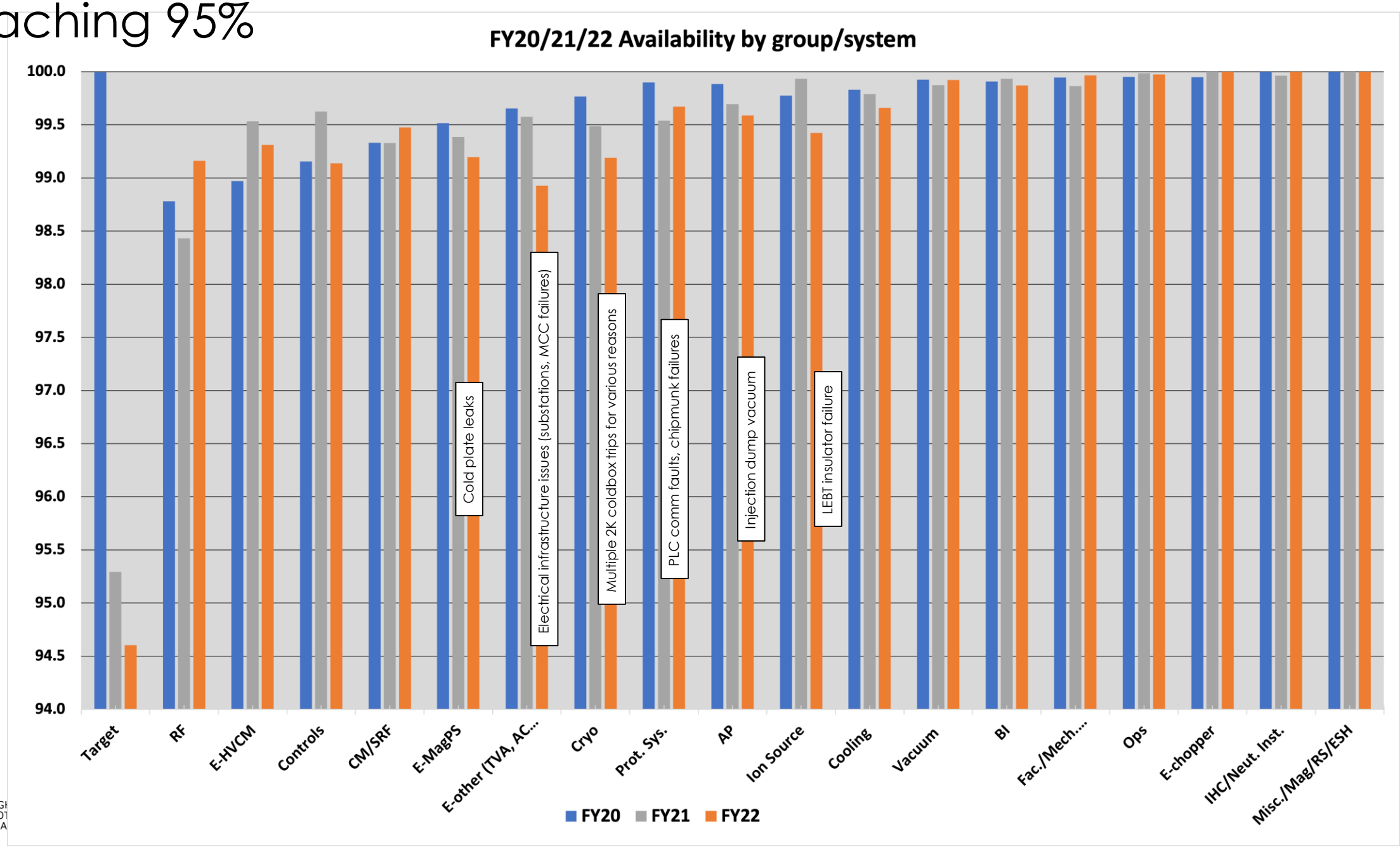
SNS availability limit ≈95%



Excluding downtimes from target systems the facility availability is approaching 95%

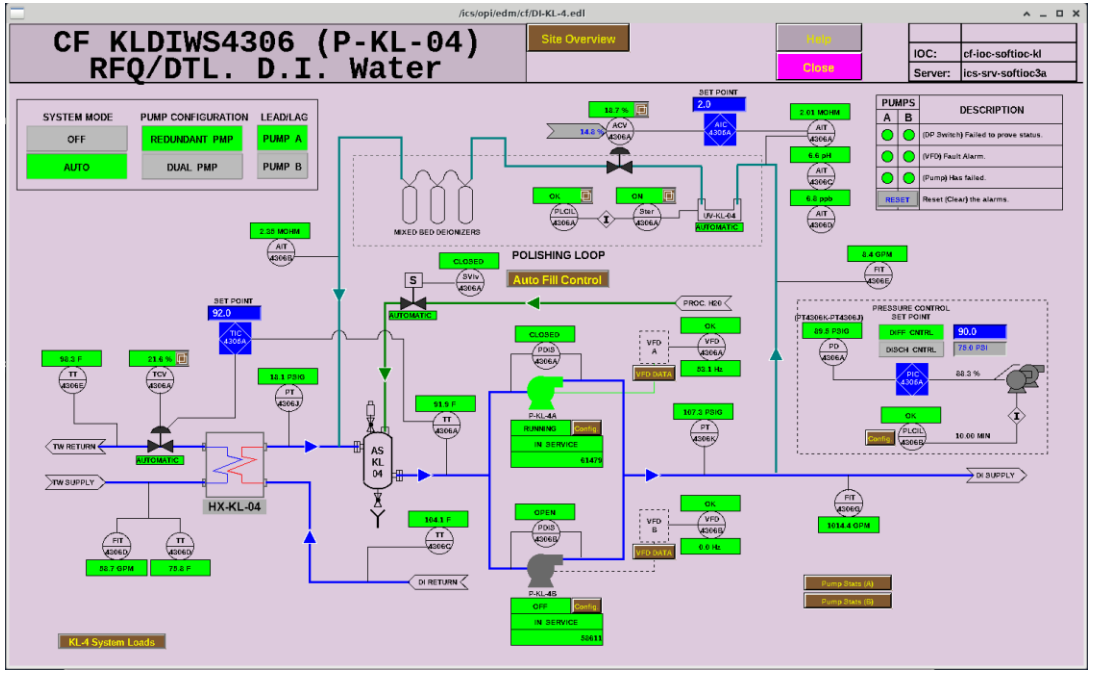
Exclude Target Systems

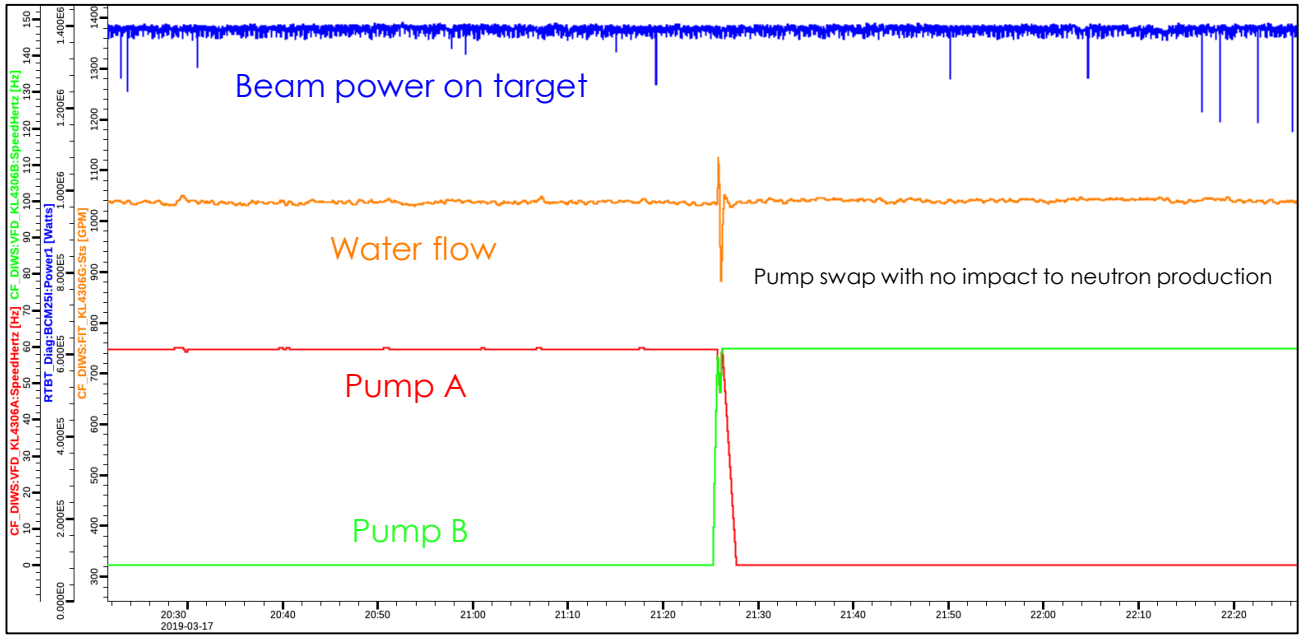
FY20 94.23%
FY21 93.94%
FY22 92.47%



Redundancy is important

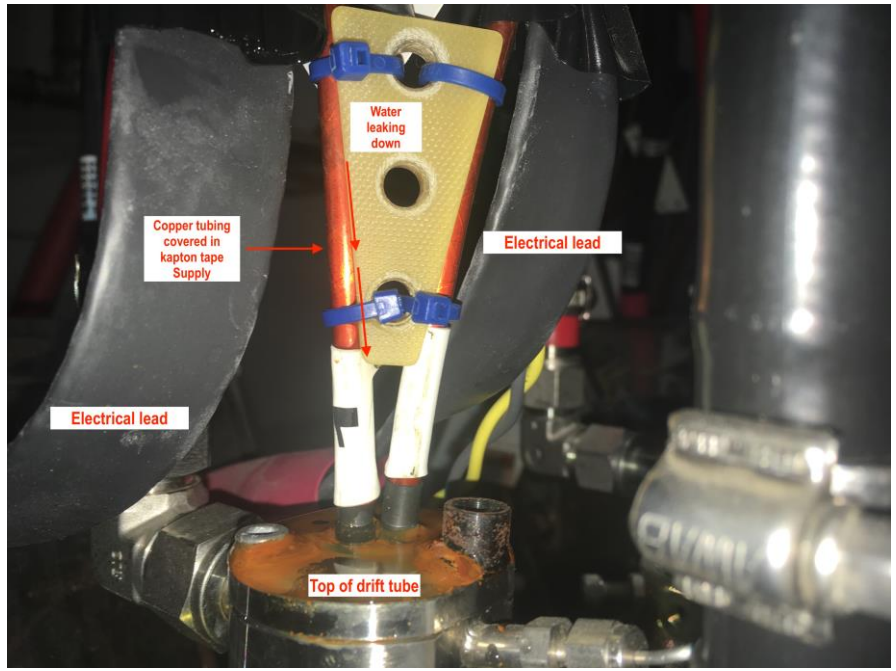
- Most systems are not repair in place
  - Some systems have redundancy
    - Cooling pumps
    - SCL cavities
  - Some systems have significant numbers and wide coverage
    - BLMs
    - Dipole correctors
    - MPS bypass system until maintenance can be completed
  - Most systems easily swapped to spare
    - Keep 10% spare inventory
- No redundancy no spare
  - DTL, CCL cavities





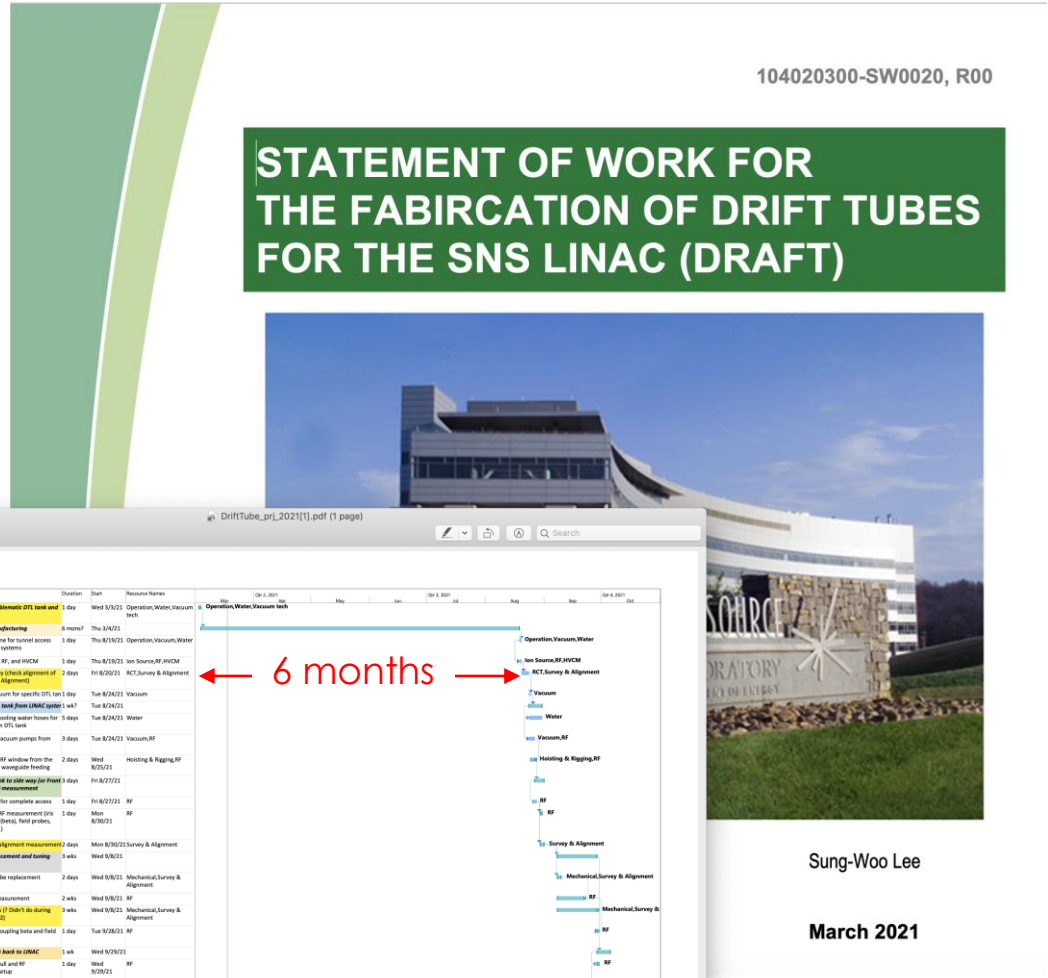
Vulnerability Example for DTL

- Each drift tube within the DTL cavities is unique
  - Drift tube failure is a vulnerability because too expensive to have spares for all
- Water leak developed inside a drift tube containing an electromagnet used to steer the beam (found by cooling group based on sensor trends)
- Water not leaking into vacuum so immediate repair not necessary
- Effect on beam minimal so repair may never be necessary
  - Study found beam loss impact was small
- Water isolated and electrical leads removed



Vulnerability Example is a Development Project

- As soon as we realized the impact was not immediate the issue fell to the group level
- Develop the plan for possible drift tube replacement
  - Create/update drawings
  - Develop partnership with vendors
  - Cost estimate
  - Project schedule



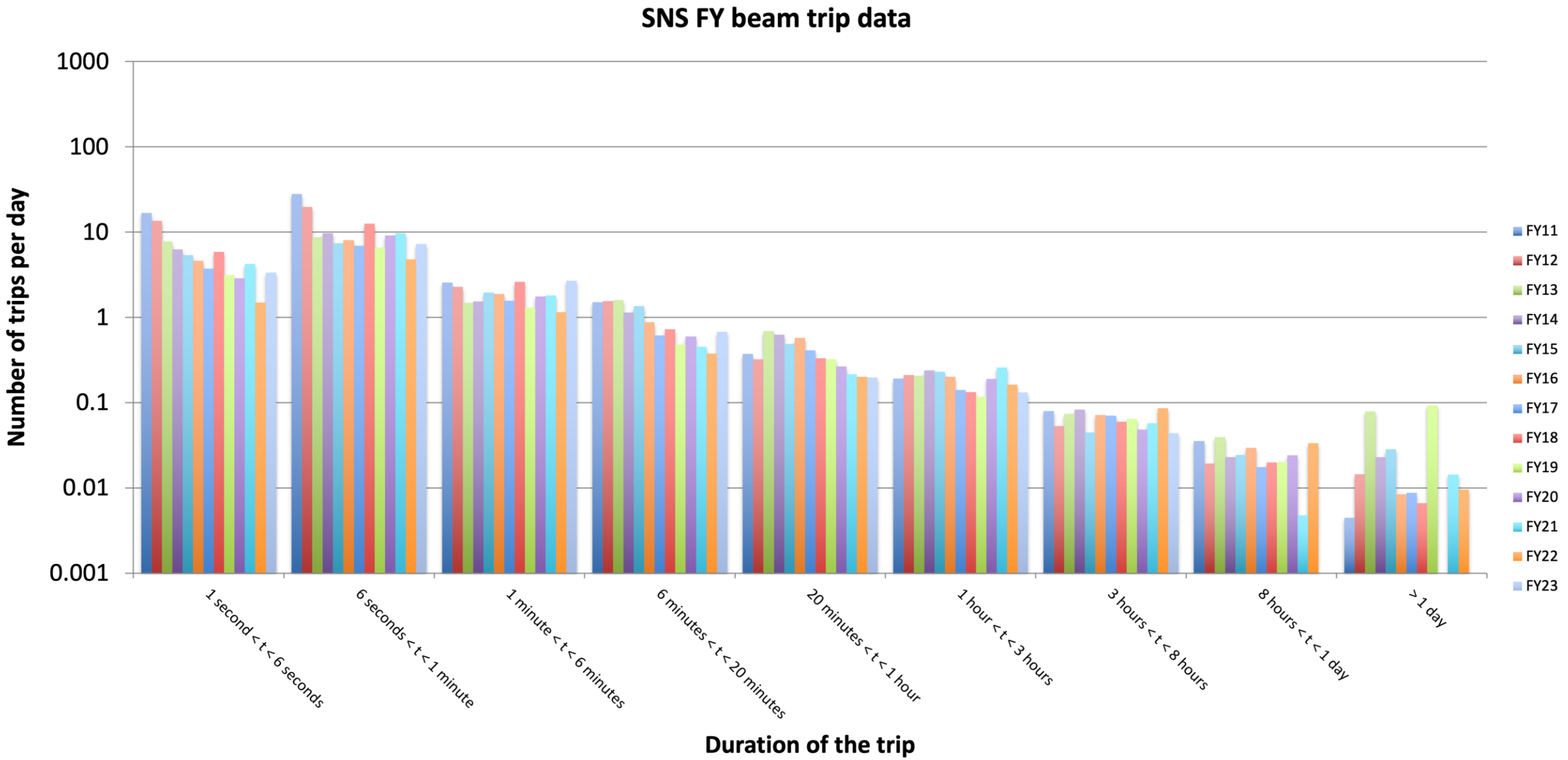
Do the best we can do to be prepared
Downtime is what it is for this vulnerability
Continue to monitor EPICS alarm and interlock data

Vulnerability Does Not Mean Long Downtime

- Failure of ion source filament will cause approximately 12 hours of downtime
- Have a lot of spare antennas and know how to change the source so the failure is not the vulnerability
- The vulnerability is the single vendor and the artist that paints the coating onto the copper tubing
- Need a plan for how to make sure the flow of quality antennas continues for the next 20 years

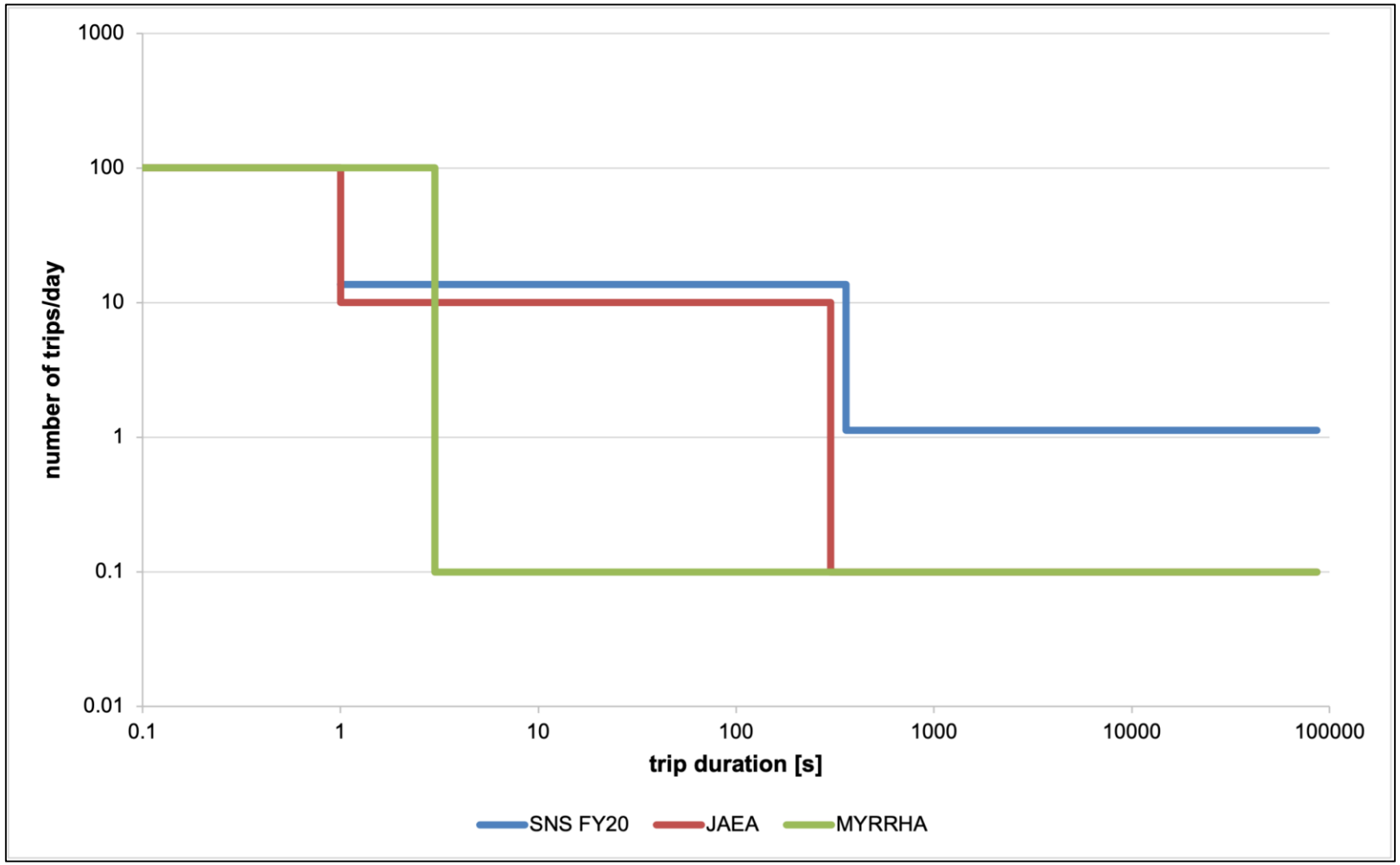
Try to think about the list from this perspective

Constant focus on minimizing trip bin frequencies



SNS beam trip data show still far from ADS needs

- SNS trip data show short trip frequencies are comparable to the expected ADS need but frequencies for downtimes lasting longer than 300 seconds are still an order of magnitude too high

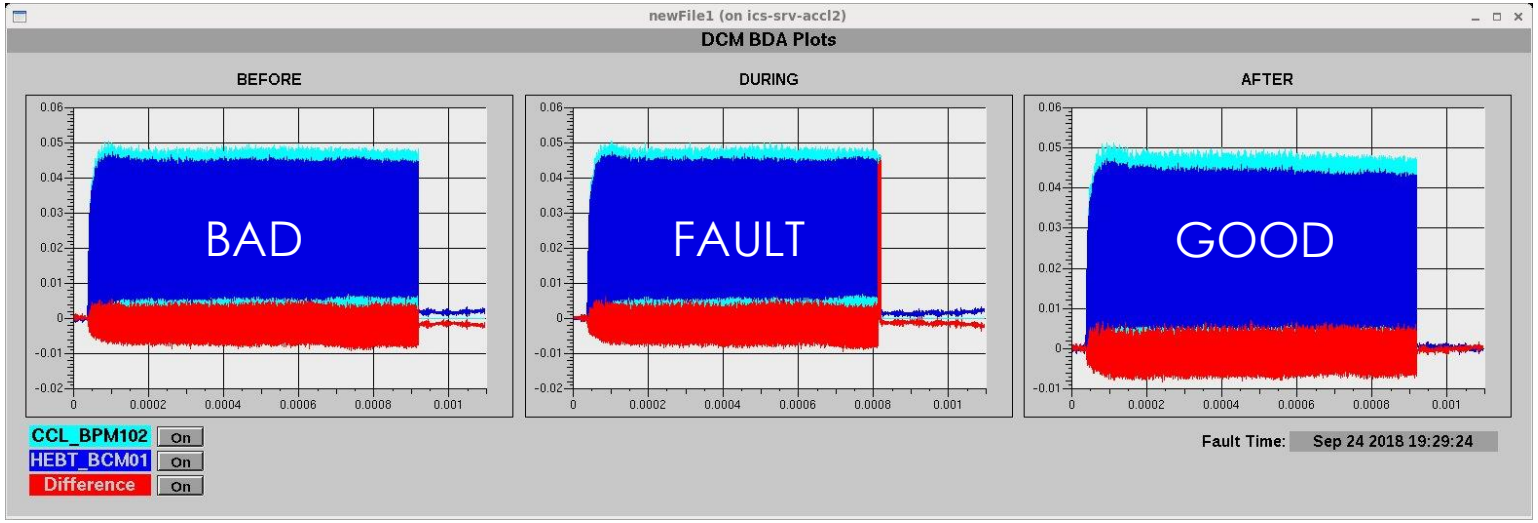


Advantage of accelerators is the large amount of streamed and archived sensor data

- SNS uses Experimental Physics and Industrial Control System (EPICS)
  - >100,000 sensor/analysis signals (Process Variables PVs)
  - Archived data using Oracle database
- Additional higher frequency data outside of EPICS utilized to look at pulse by pulse abnormalities
- Much more data than can be processed using a Computerized Maintenance Management System (CMMS) for asset management
  - CMMS useful for tracking labor and parts cost for budgeting

Use the beam to predict the instability

- The goal is to prevent the beam loss so when a fault is detected use the MPS to hold the beam off until the fault condition clears
  - Provide time to figure out the underlying cause without impact to the SCL
- Impractical to add machine learning algorithms to all equipment
- Add machine learning algorithm to monitor the beam
  - One thing that is impacted by all equipment
  - Have MPS and equipment diagnostics to find cause of fault
- The DCM was the logical starting point because it was already recording beam waveforms and tagging them



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Initial results looked promising

- Small group of accelerator personnel with graduate student with focus in machine learning
- Small dataset
- Implementation was to see if machine learning could predict bad beam pulses at least one pulse before the problematic pulse
- Initial results showed excellent prediction results
  - Up to 94% accuracy at detecting a bad pulse

Predicting particle accelerator failures using binary classifiers

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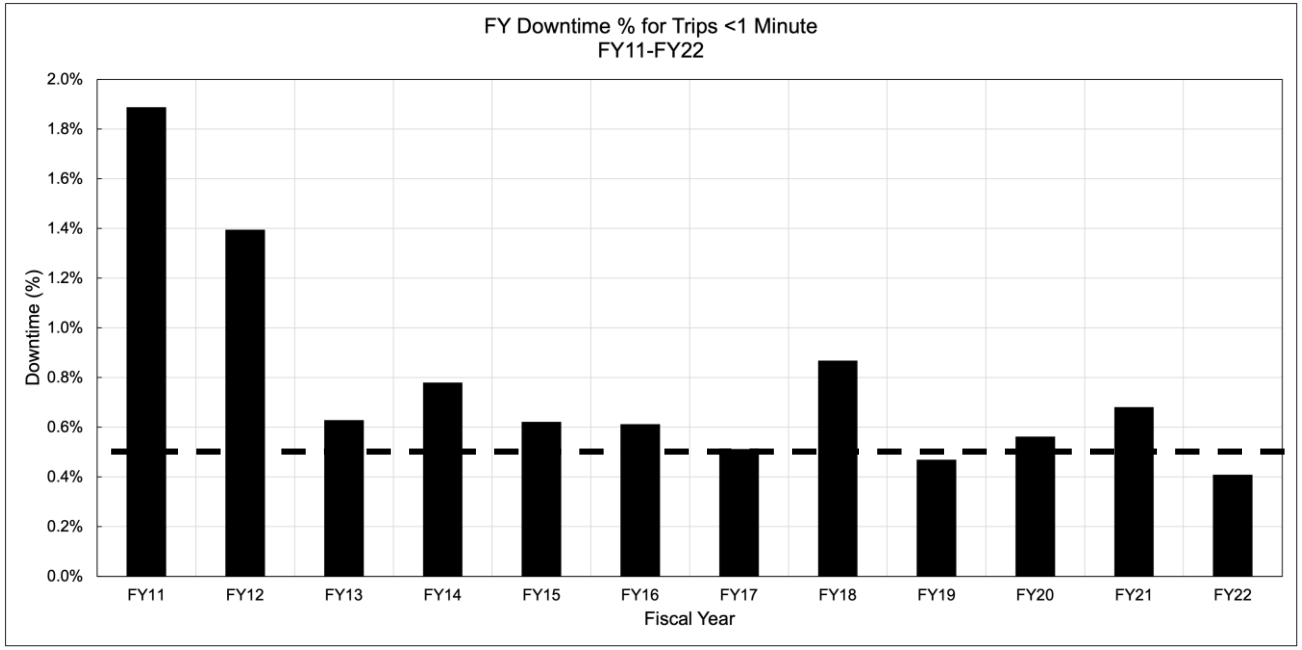
Abstract

Particle accelerator failures lead to unscheduled downtime and lower reliability. Although simple to mitigate while they are actually happening such failures are difficult to predict or identify beforehand. In this work we propose using machine learning approaches to predict machine failures via beam current measurements before they actual occur. To demonstrate this technique in this paper we examine beam pulses from the Oakridge Spallation Neutron Source (SNS). By evaluating a pulse against a set of common classification techniques we show that accelerator failure can be identified prior to actually failing with almost 80% accuracy. We also show that tuning classifier parameters and using pulse properties for refining datasets can further lead to almost 92% accuracy in classification of bad pulses. Most importantly, in the paper we establish there is information about the failure encoded in the pulses prior to it, so we also present a list of feasible next steps for increasing pulse classification accuracy.

Keywords: particle accelerator, accelerator reliability, machine learning, binary classifier, failure prediction

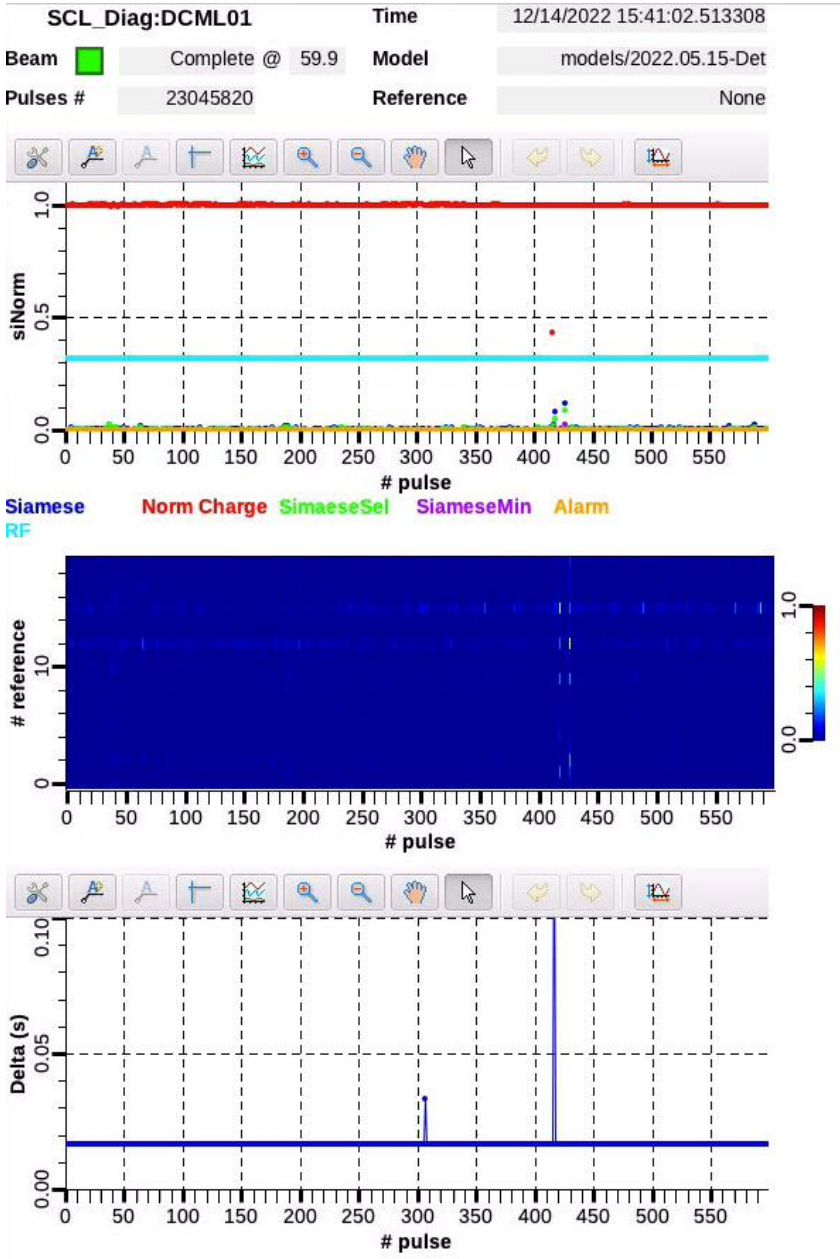
Focus is now on making an operational system

- Production vs a physics study
  - Operational machine learning system requirements
    - Dedicated machine learning expert
      - Need some understanding of operation of the accelerator
    - Properly filtered, labeled, and formatted data from BCMs, BPMs, MPS, and timing system
    - Data access for collaborators
    - Metrics for false positive rates
      - At SNS 0.5% allowable missed pulses though the goal is less
    - Significant time to take data for all types of beam shapes or rely on somewhat fixed accelerator settings



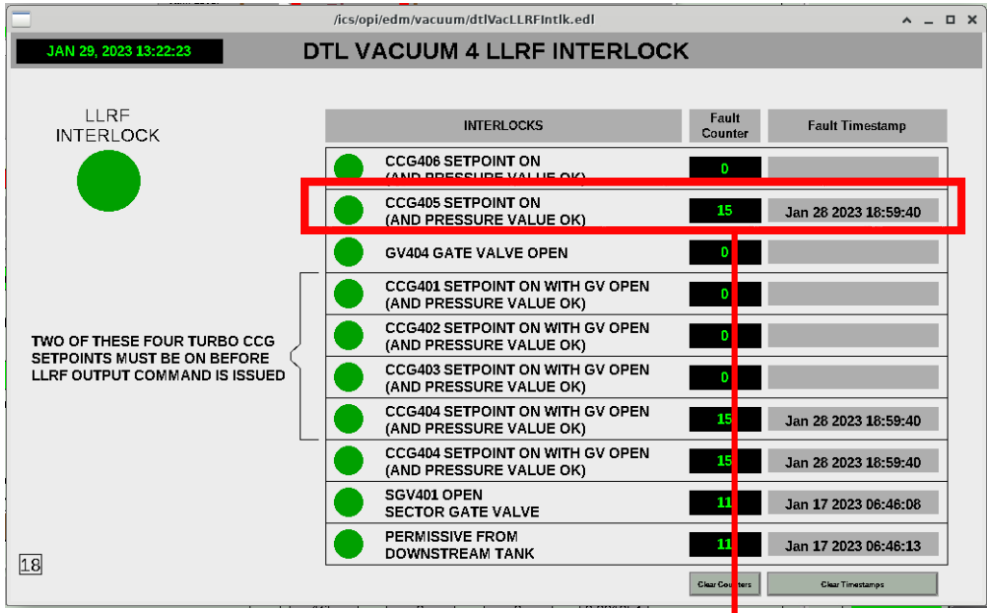
Online system is under development

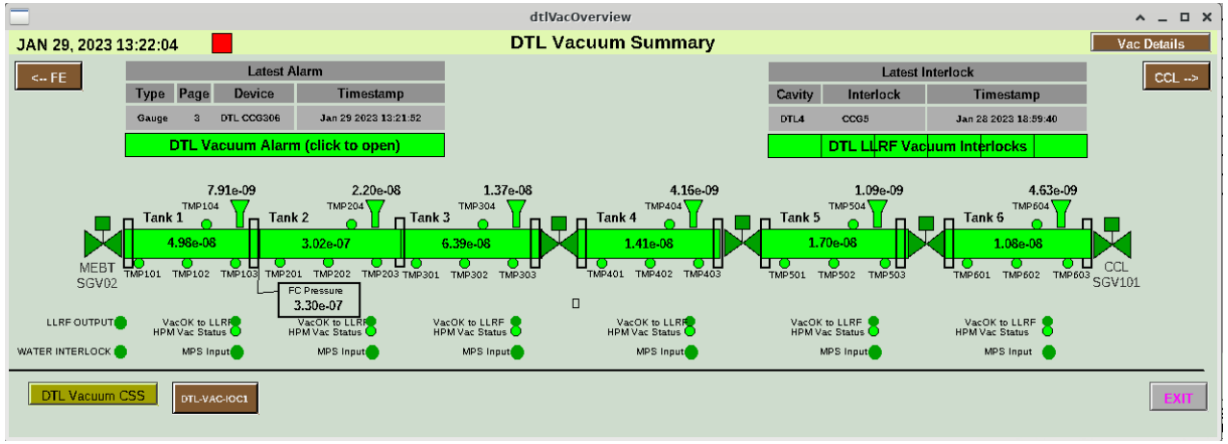
- Upcoming pulse type decision (good or bad) must be made between pulses (≈15 milliseconds)
- Machine learning on an FPGA
  - Developed by collaborators at ORNL
- System feeds data for machine learning training while the original DCM still protects the machine
- Multiple algorithms being tested to find best performers
- Need similar system for BPMs

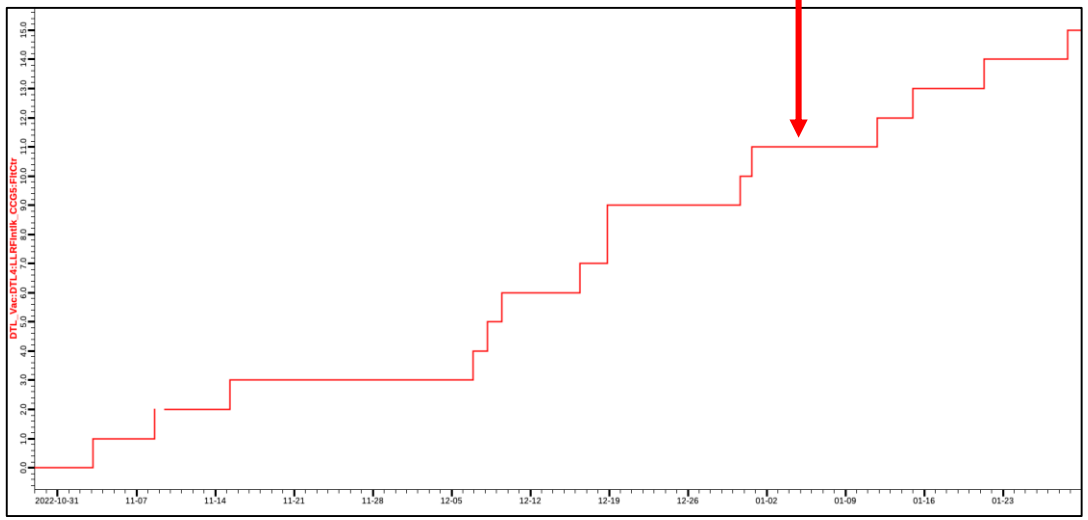


Alarm and interlock trends guide maintenance

- Accelerator predictive maintenance is utilizing alarm and interlock trends to plan future maintenance
  - Automatically log trips with cause and beam off duration
    - MPS provides this information (see MPS and Operation)
  - Machine Health Report (MHR)

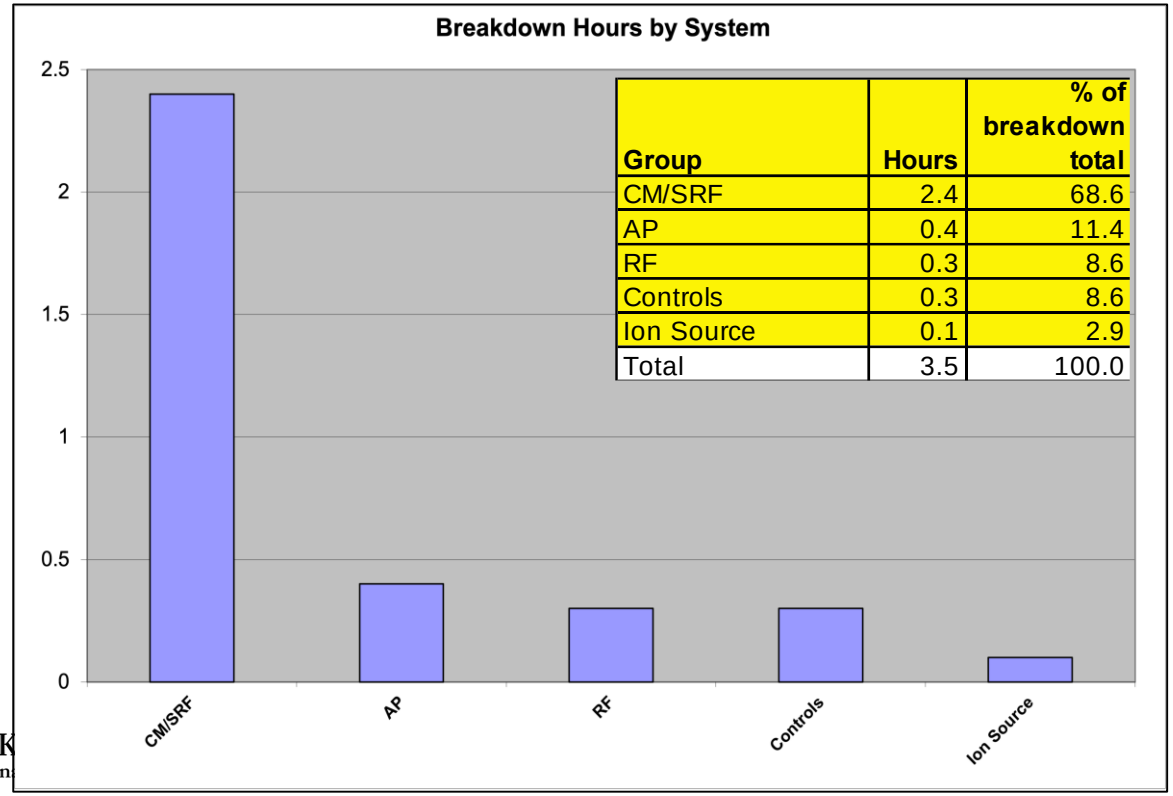




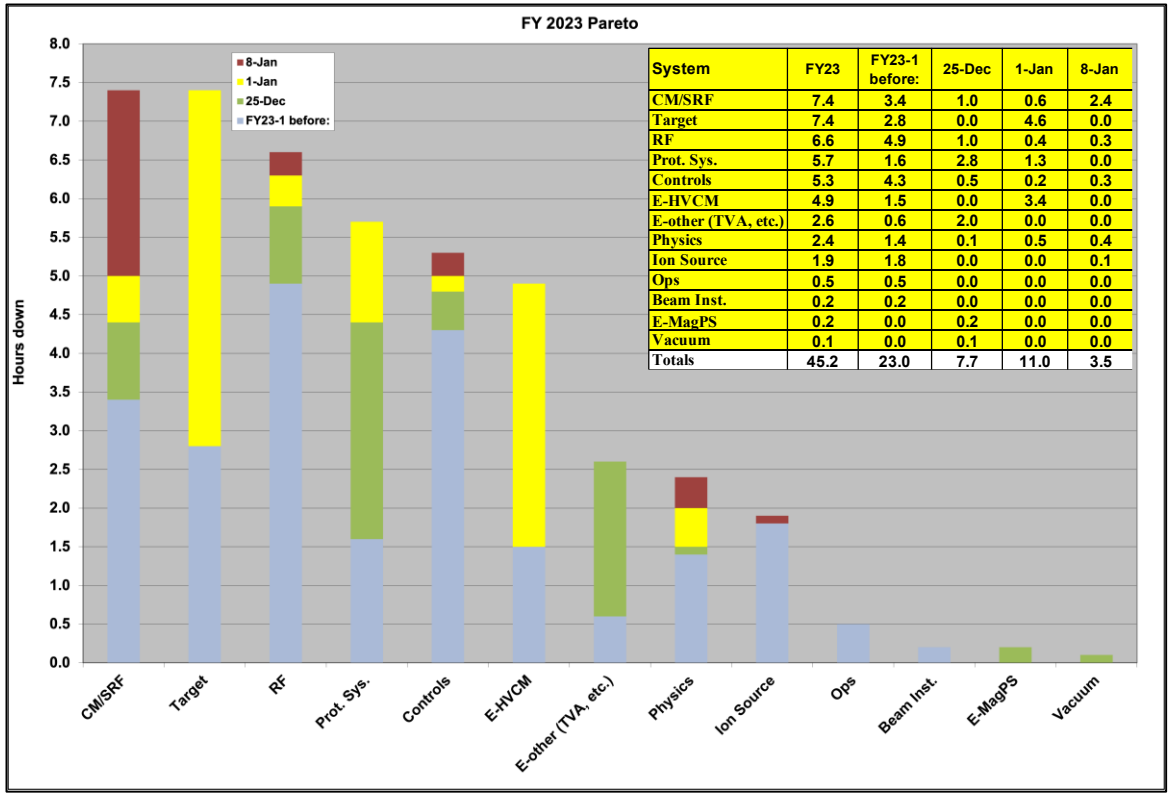


Downtime metrics provide areas of focus for resources

- Continuously automating/simplifying data recording and providing analyses
  - Metrics utilizing operator recorded downtime
    - System downtime trends for the week, run, year

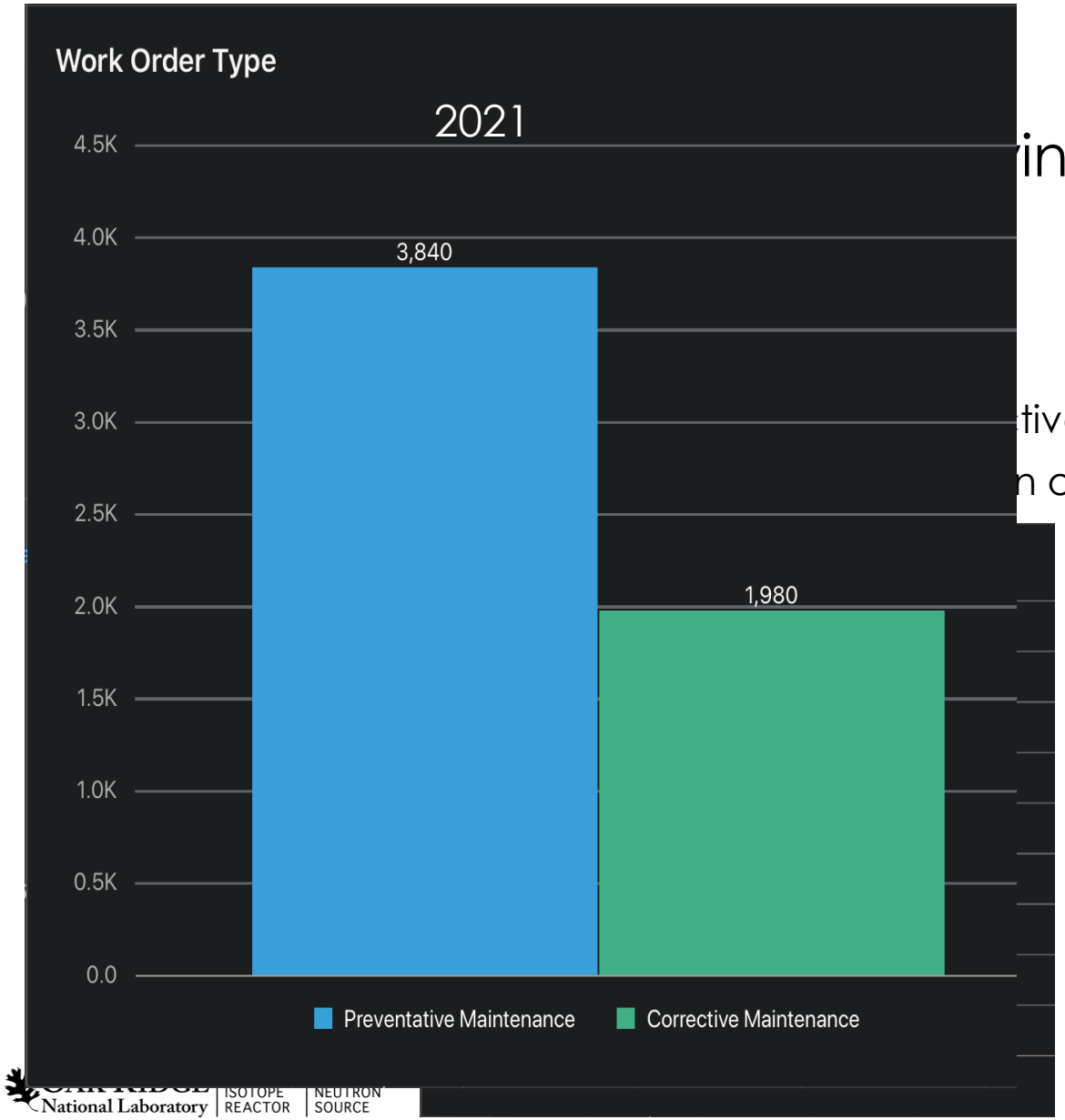


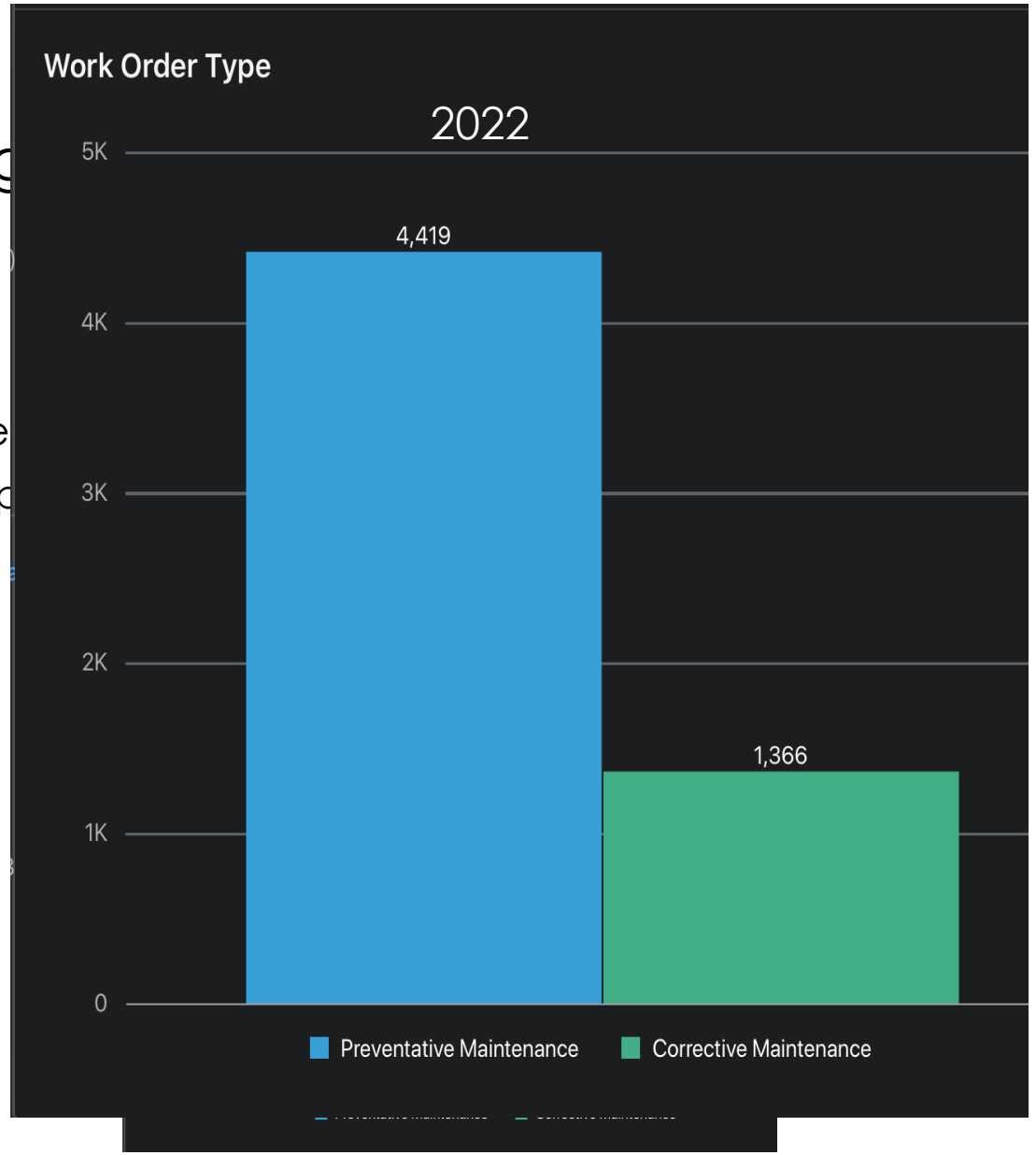
Group	Hours	% of breakdown total
CM/SRF	2.4	68.6
AP	0.4	11.4
RF	0.3	8.6
Controls	0.3	8.6
Ion Source	0.1	2.9
Total	3.5	100.0



System	FY23	FY23-1 before:	25-Dec	1-Jan	8-Jan
CM/SRF	7.4	3.4	1.0	0.6	2.4
Target	7.4	2.8	0.0	4.6	0.0
RF	6.6	4.9	1.0	0.4	0.3
Prot. Sys.	5.7	1.6	2.8	1.3	0.0
Controls	5.3	4.3	0.5	0.2	0.3
E-HVCM	4.9	1.5	0.0	3.4	0.0
E-other (TVA, etc.)	2.6	0.6	2.0	0.0	0.0
Physics	2.4	1.4	0.1	0.5	0.4
Ion Source	1.9	1.8	0.0	0.0	0.1
Ops	0.5	0.5	0.0	0.0	0.0
Beam Inst.	0.2	0.2	0.0	0.0	0.0
E-MagPS	0.2	0.0	0.2	0.0	0.0
Vacuum	0.1	0.0	0.1	0.0	0.0
Totals	45.2	23.0	7.7	11.0	3.5

Asset Management Data Usefulness Improving





Summary

- Continually improving and maintaining high availability is a high priority at all accelerators
- Control systems and specialized detection systems provide data to guide maintenance
- CMMS software can be used to track maintenance trends for budgeting purposes
- Utilizing machine learning for fault prediction may be a key to reaching ADS goals

Thank you for your attention
QUESTIONS?