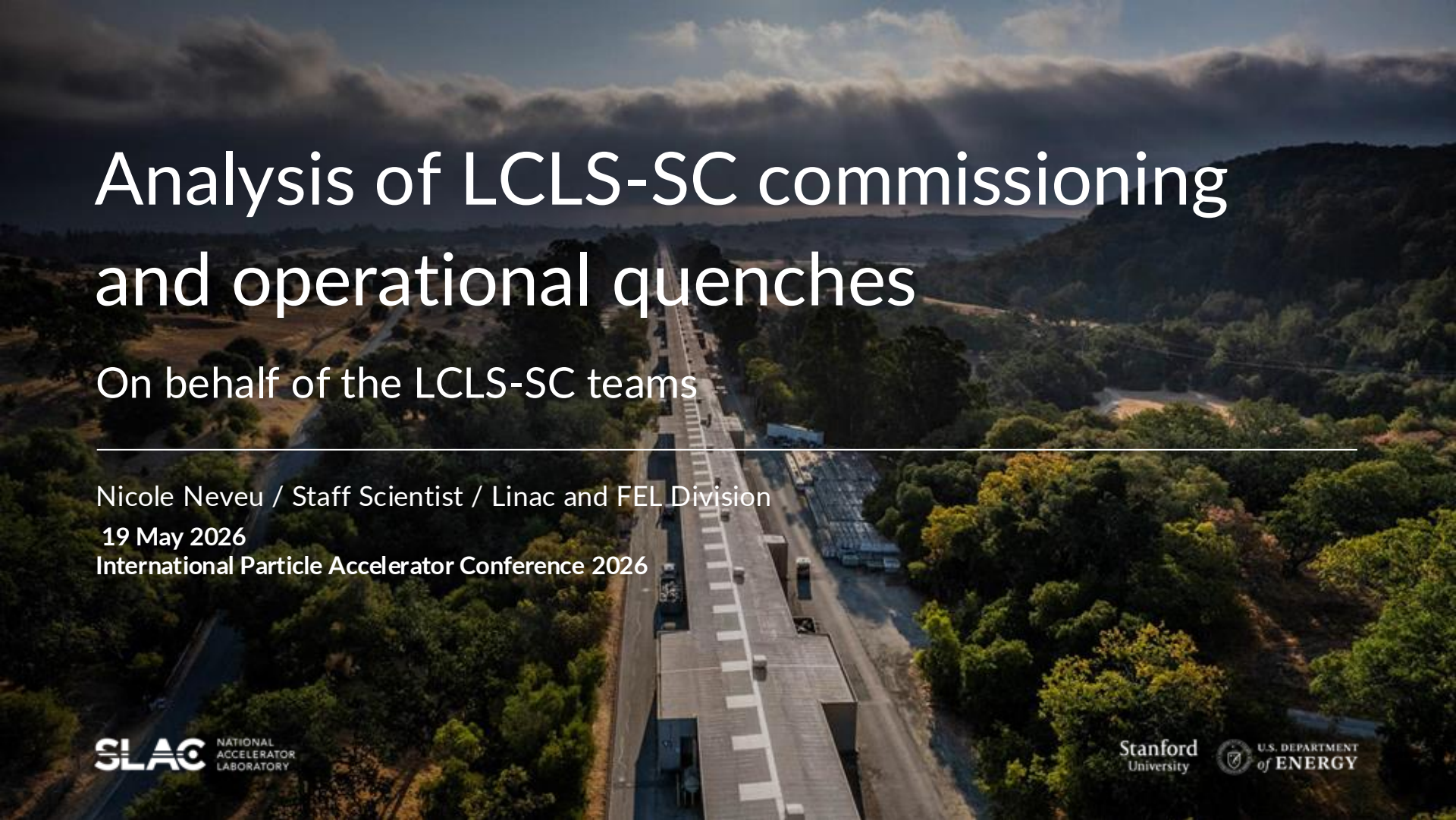


Analysis of LCLS-SC commissioning and operational quenches

On behalf of the LCLS-SC teams

Nicole Neveu / Staff Scientist / Linac and FEL Division

19 May 2026
International Particle Accelerator Conference 2026

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University

U.S. DEPARTMENT of ENERGY

Overview

Introduction: LCLS-SC

Facility introduction

Commissioning and operation timeline

Quench classification

Current analysis framework

LCLS-SC Quench data

2022 - 2025

1 - Introduction

LCLS-SC Facility (Linac Coherent Light Source - Superconducting linac)

Commissioning and operations timeline

Linac Coherent Light Source (LCLS)

LCLS-NC (normal conducting)

- ~15 years of FEL operations.
- Last 1 km of original tunnel.
- Continues to operate and deliver to users on 24/7 schedule.
  - Planned planned tunnel access periods for maintenance and installation 2x/month.

LCLS-SC (superconducting)

- Spans full 3 km tunnel.
  - Cryomodules ~⅓
  - Transport line ~⅔
- Dedicated cryoplant.
- Cryomodules built and shipped by:
  - Fermilab + JLab

A community effort:

Fermilab
Argonne NATIONAL LABORATORY
BERKELEY LAB
Jefferson Lab
SLAC NATIONAL ACCELERATOR LABORATORY

Picture source: SLAC flickr

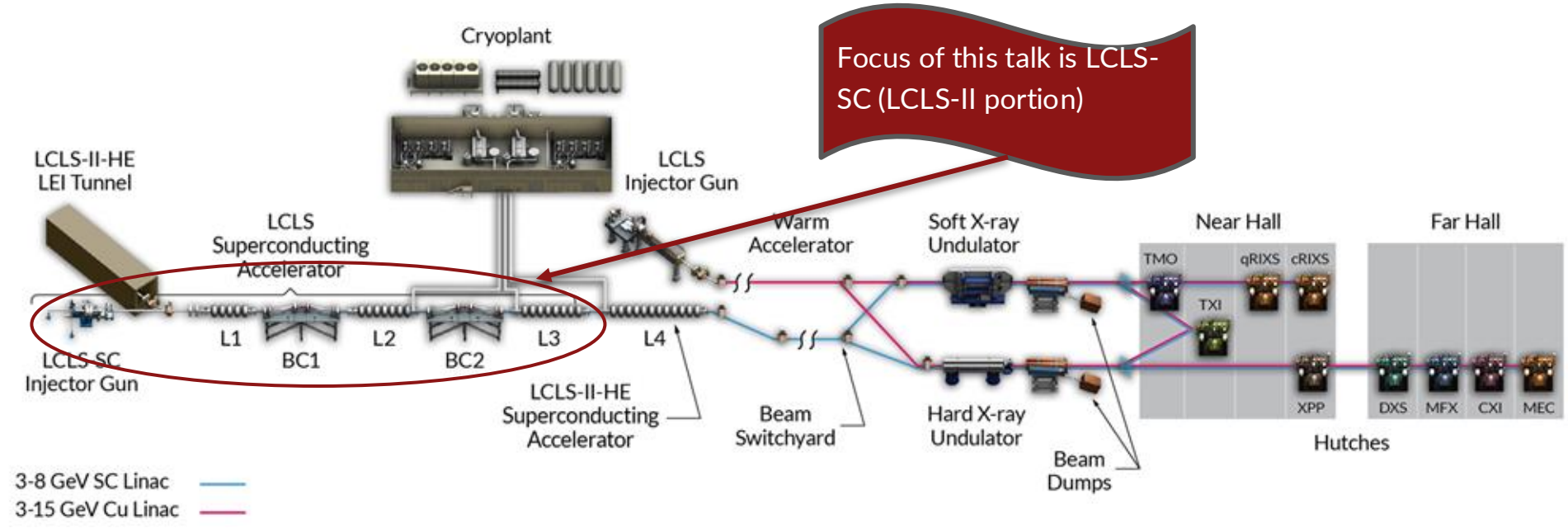
LCLS facility: LCLS-SC + LCLS-NC

LCLS-SC: LCLS-II + LCLS-II-HE

- Three accelerators operate simultaneously in the 3km tunnel: LCLS-SC, LCLS-NC and FACET-II.
- LCLS-SC and LCLS-NC are shown here.
- LCLS-II construction started in 2016.

LCLS-II-HE construction started Jan. 2026.

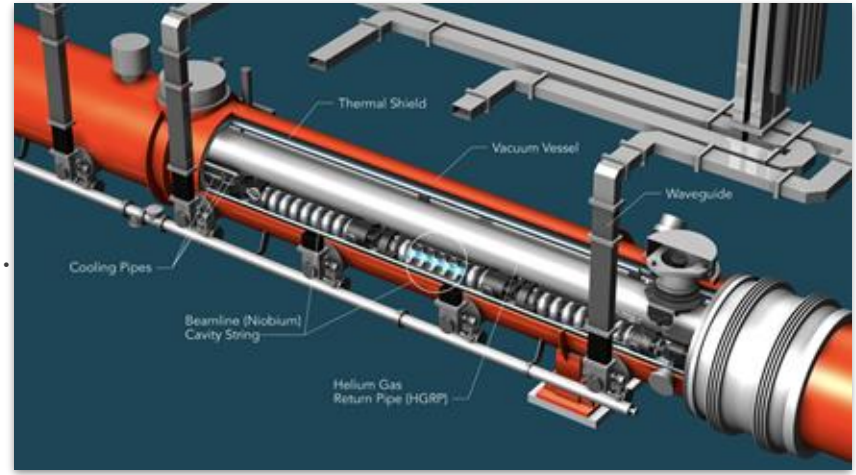
- 23 Cryomodules are being added to LCLS-SC linac.
- New tunnel is being dug for low emittance injector.
- Doubling energy from 4 GeV to 8 GeV.
- Undulator upgrades ongoing.



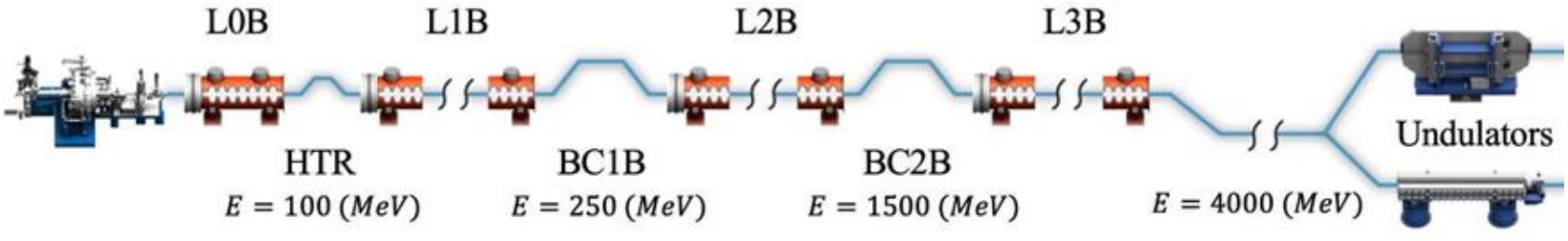
LCLS-SC (LCLS-II) layout

LCLS-SC layout currently includes:

- 35 Cryomodules at 1.3 GHz .
- 2 Cryomodules at 3.9 GHz.
  - 8 cavities each - total of 296 SRF cavities.
  - TESLA style cavity design (9 cell).
- Typical operation energy 3.8 GeV.
  - Energy can reach 4.0 GeV.
- Operational repetition rate: 1 Hz - 93 kHz.
  - Ramping up to 1 MHz.



Picture source: SLAC flickr



LCLS-SC (LCLS-II) commissioning & operations timeline

May - July 2022: SRF Linac commissioning.

2022

2023

August 2023: First lasing.

Machine development and early user delivery.

2024

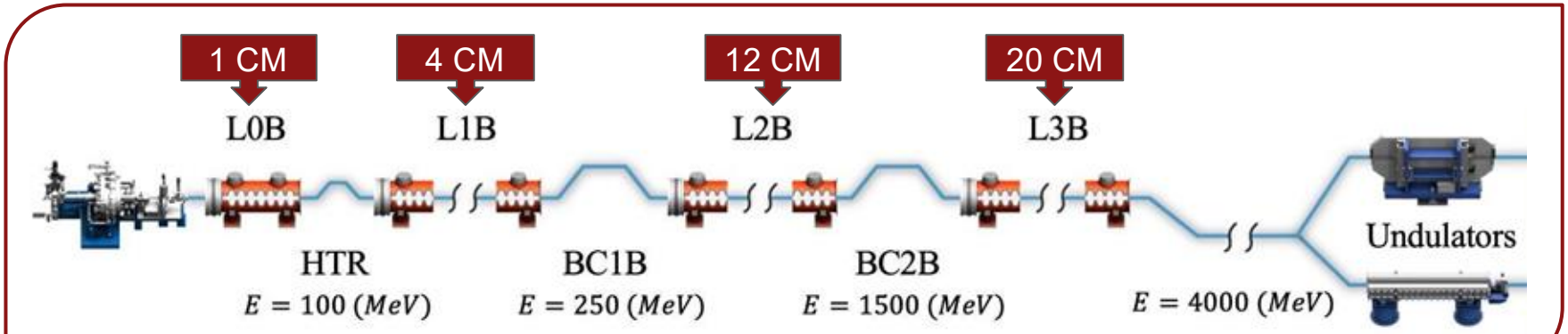
Continuous operations up to 3.8 GeV and 93 kHz.

2025

March 2025: First hard/soft x-ray simultaneous delivery.

Operations stopped for LCLS-II-HE installation.

2026



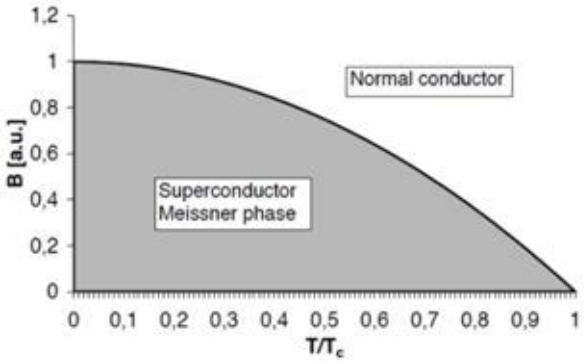
2 - Quench classifications

LCLS-SC current validation method

Quenches…

What is an SRF cavity quench?

- Sudden transition of SRF cavity back to normal conducting.
  - Small spot on surface becomes NC and dissipates heat
- Not as violent as magnet quenches.
- Once cavity cools, it can operate again.



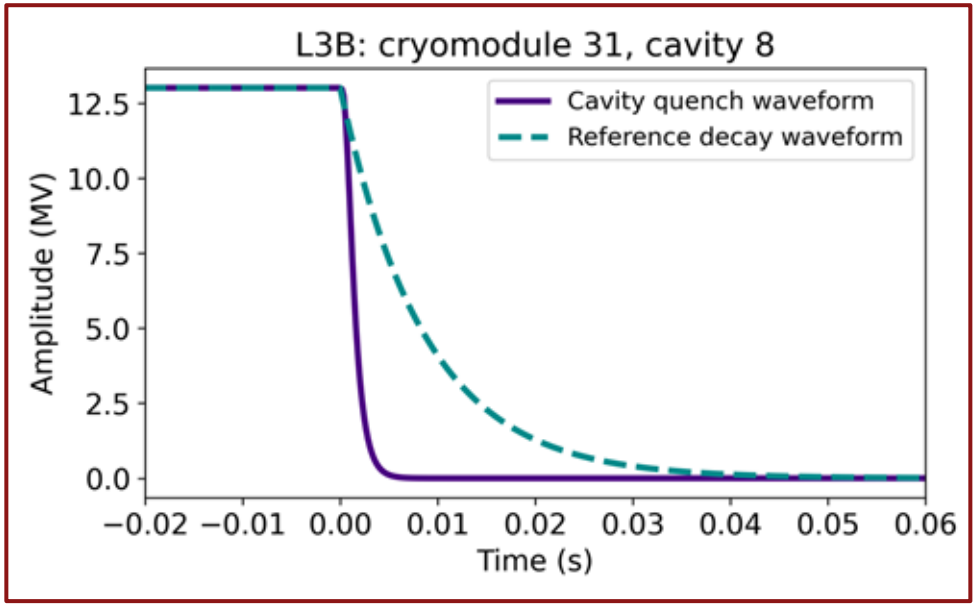
L. Lilje. PhD thesis. Unviersität Hamburg. 2001.

Why do we care?

- Operational disturbance, can create down time, order of minutes.
- During quench: We need an interlock to prevent disturbances in helium bath/high heat loads. Could cause order hour of downtime w/o interlock.
- After quench: Potential to trap magnetic flux which lowers quality factor (Q) of the cavity, which increases the heat load on the cryoplant. No permanent damage, but persistent until next fast cooldown.

$$Q_0 = \frac{G}{R_s} = \frac{\omega U}{P_d}$$

Quench waveforms



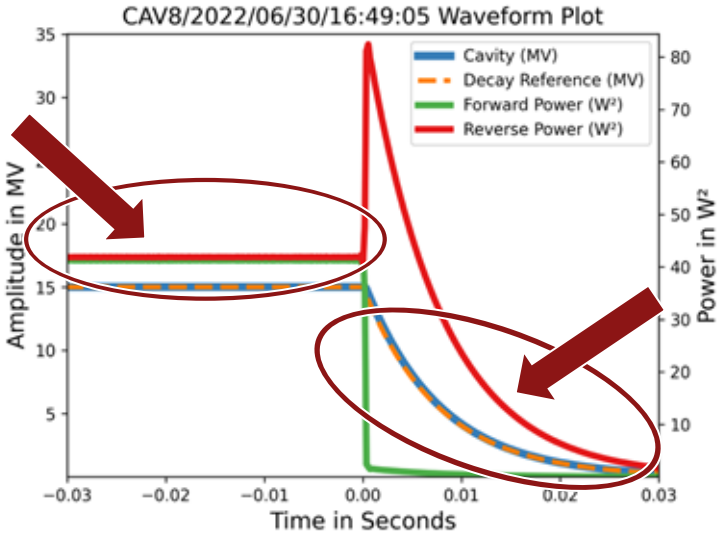
Real vs. 'False' quenches:

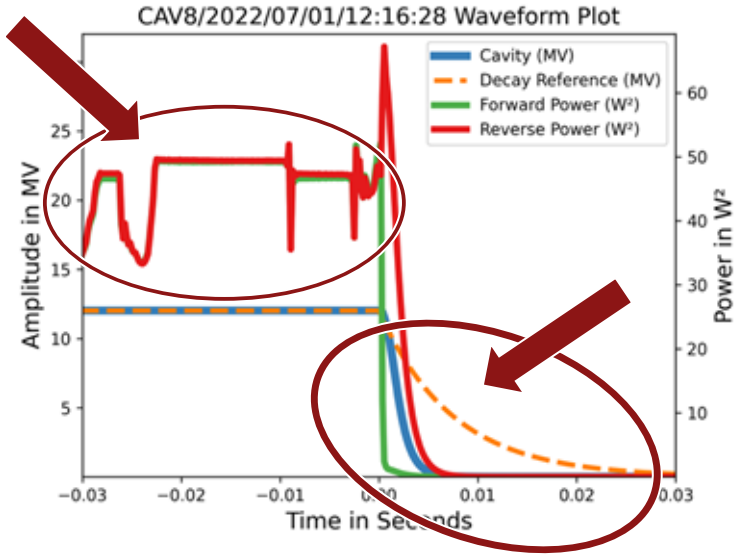
A cavity can turn off for a variety of operational reasons:

- Tunnel access, equipment health, beam program, etc.
- Decay pattern for a standard cavity turn off is shown with the dotted line.
- Quench decay is a steep drop off in power, reflected power jumps because the cavity is no longer superconducting and matched.

Curve fitting is used to determine automatically if a decay pattern is typical or a quench.

Quench classification example





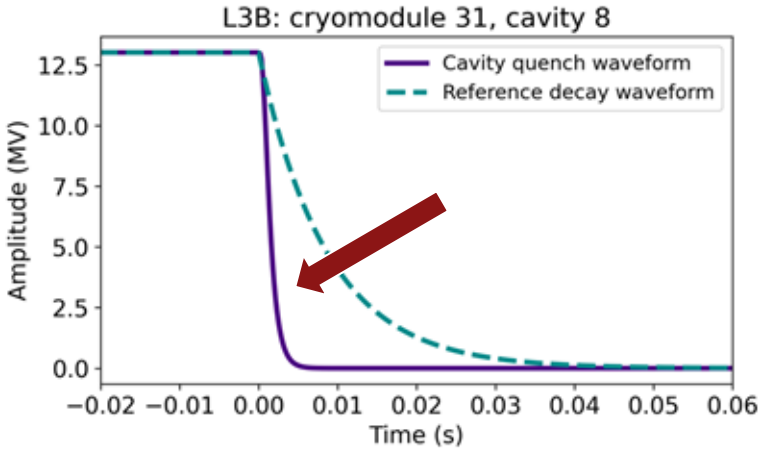
Classification: False Quench

1. Stable flow of forward and reverse power.
2. Cavity amplitude matches the decay reference.

Classification: Real Quench

1. Unstable flow of forward and reverse power.
2. Cavity amplitude falls more quickly than decay reference.

Current classification method



$$A(t) = A_0 \cdot e^{-\frac{\pi f t}{Q_L}}$$

$$ln\left(\frac{A_0}{A(t)}\right) = \frac{\pi f t}{Q_L}$$

Step 2: Exponential fit

The standard decay equation (P. Hassan) is assumed. Polyfit in Python is used to linearize the decay waveform and solve for the slope.

Step 1: Trim the data

We trim the data and only analyze the decay waveform.
Stable/unstable amplitude data prior to quench not currently used.

$$slope = \frac{\pi f}{Q_L}$$

$$Q_L = \frac{\pi f}{slope}$$

$$\text{is\_real} = Q_L < \text{threshold}$$

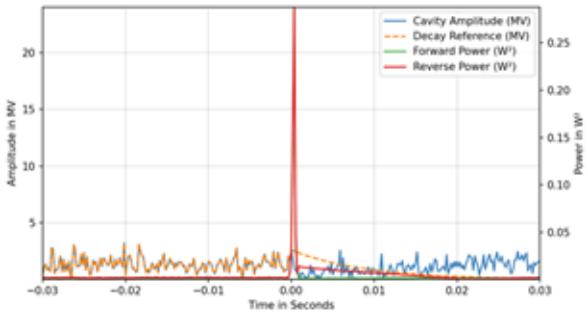
Step 3: Classification

Compare the loaded $\boldsymbol{Q}_\mathrm{L}$ value (measured) to the saved value, $\boldsymbol{Q}_\mathrm{S}$. We use a threshold to determine real/fake classification.

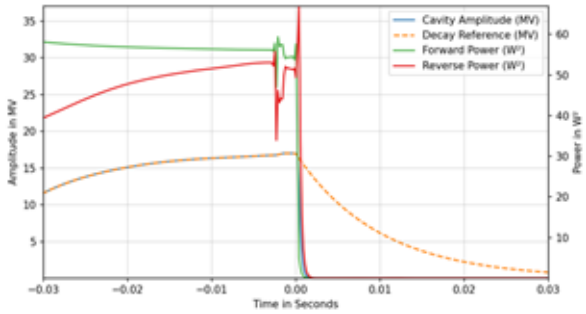
Note on misclassifications

Currently not handled in our classification method.

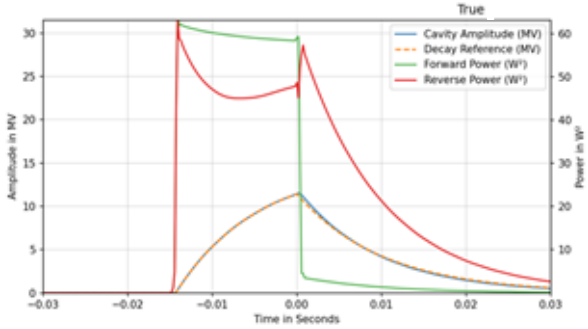
- Waveforms can be neither a quench or false quench.
  - Future work planned to account for these cases.
  - Initial estimates on other classifications < 5%



Misclassified as Real



Misclassified as False



Misclassified as Real

3 - Quench data

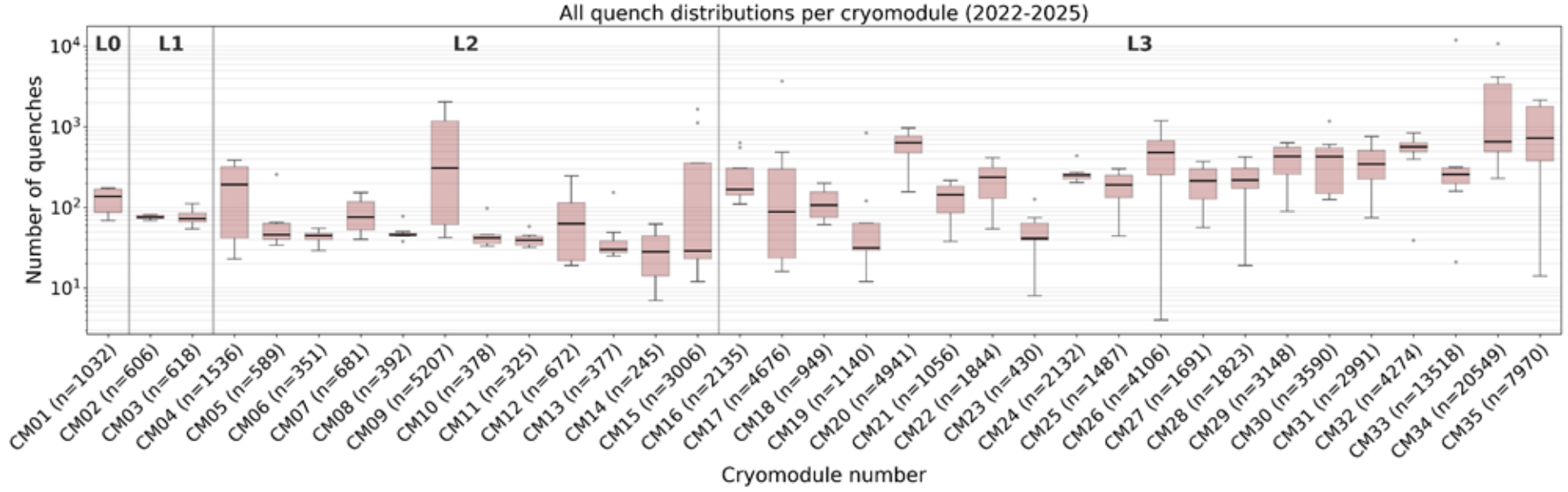
LCLS-SC 2022 - 2025

Bird’s eye view: all ‘quench’ events in LCLS-SC to date

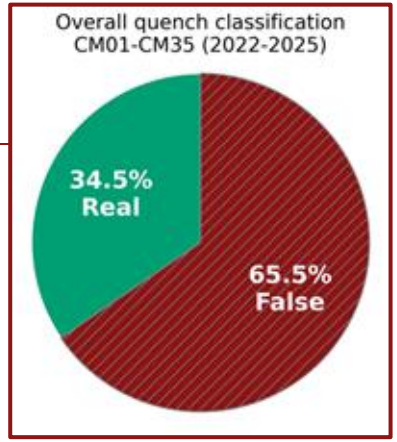
Questions we can begin asking:

- How many are real vs. false?
- How does this look if you remove MP processing?
- Do quench events increase or decrease by year?
- Which CM quenched the most and can we say why?
- Which cavity quenched the most and can we say why?

- This data includes false, real, and misclassified quenches.
- Total 105,481 interlock events.
- Anything that was recorded by the interlock is shown here.



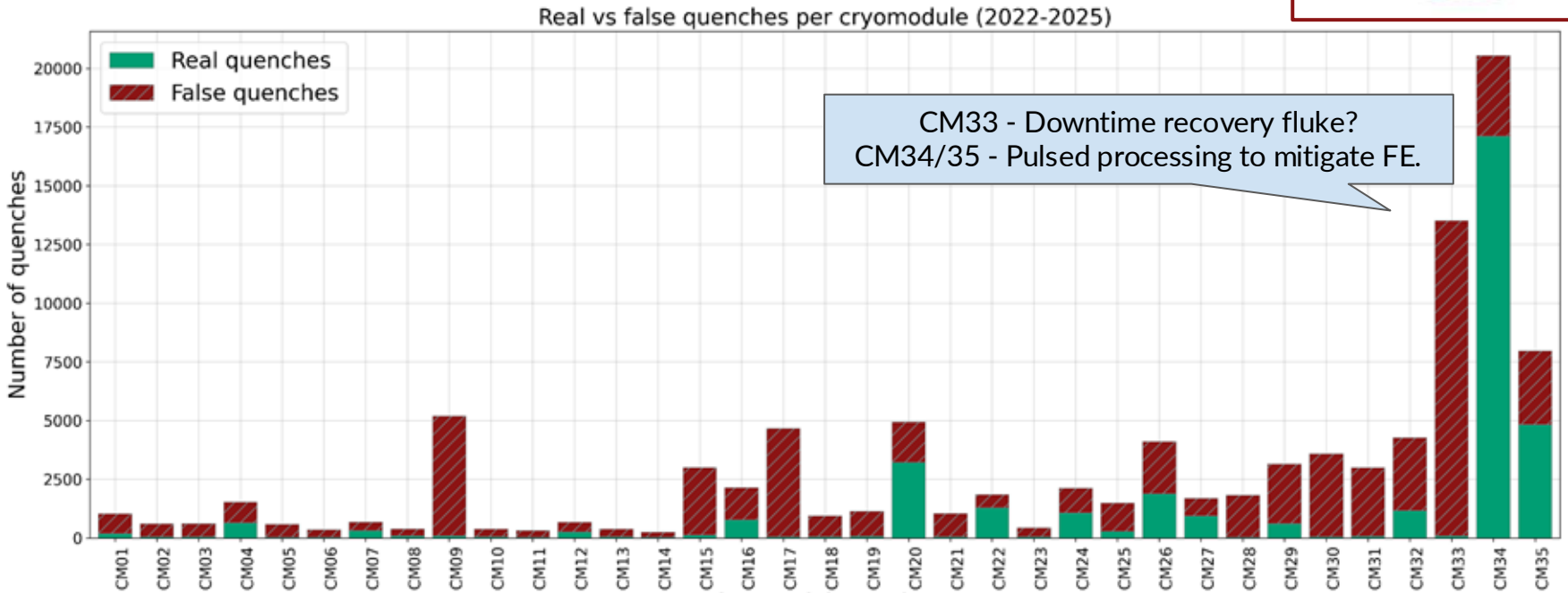
Removing false quenches



Using current classification method.

- Method is overly conservative, which was desired during commissioning and early operations.
- Next slides will consider real quenches.

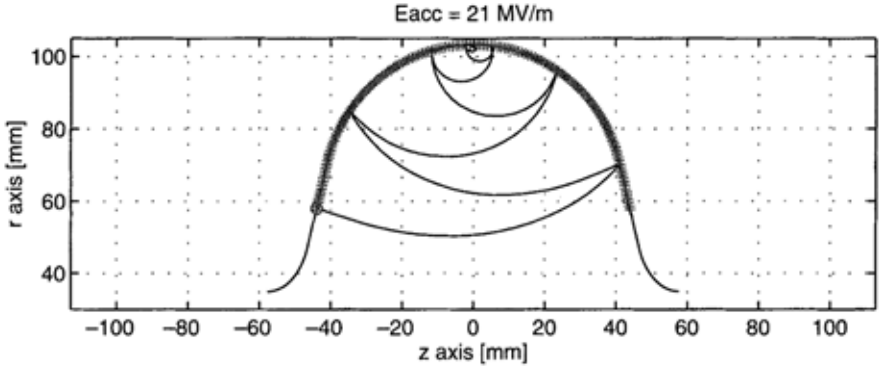
- Total: 105,481
  - False - 69,054
  - Real - 36,427



Considering multipacting (MP) processing

What is multipacting?

- Similar to NC concept.
- Electrons are emitted from the cavity surface
- Electrons can hit the surface again, releasing more electrons (secondary emission)
- **Operationally this means:**
  - Raising input power does not increase gradient.
  - Typically accompanied by a burst of radiation and/or a quench.
- Processing is necessary to reach gradient goals for some but not all cavities.



P. Yla-Oijala, Particle Accelerators, Vol. 63, pp 105-137.

When did MP processing occur?

- MP processing is not a done during normal operations (i.e. machine development or user delivery).
- A limited amount of MP occurred during initial commissioning (2022). Cavities were not pushed beyond operational needs.
- A second round of MP was performed on select cavities in 2024 to gain energy/overhead in the linac.

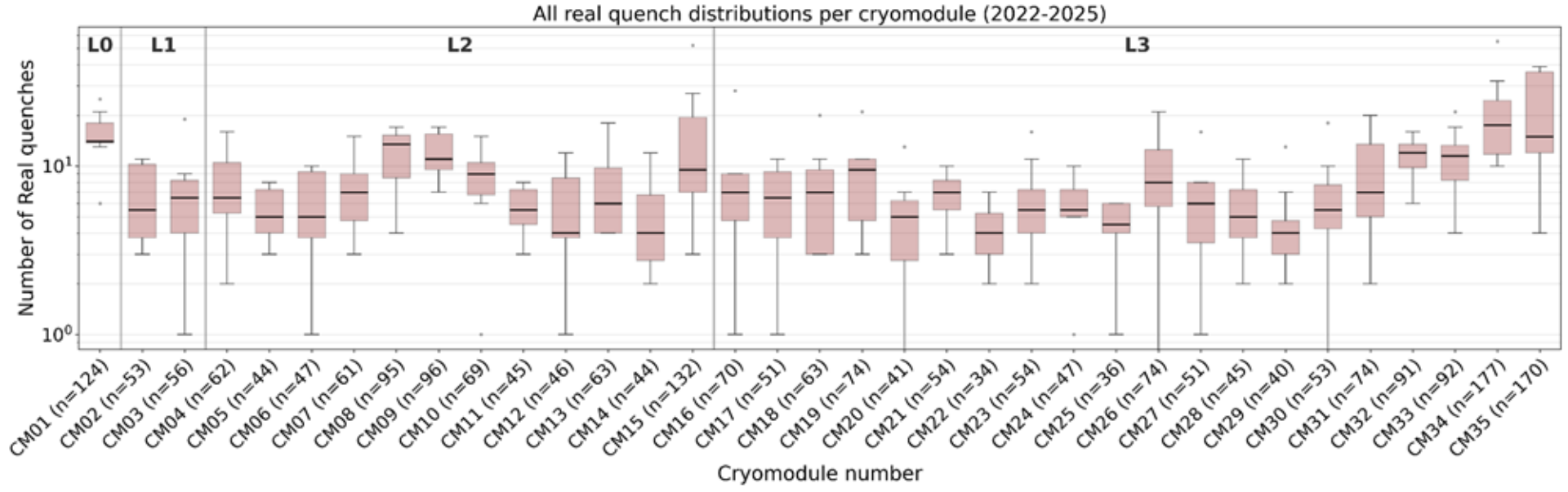
Revisiting the box plot…

What is excluded now:

- Commissioning MP.
- Second round of MP in 2024.
- False quenches.

Results:

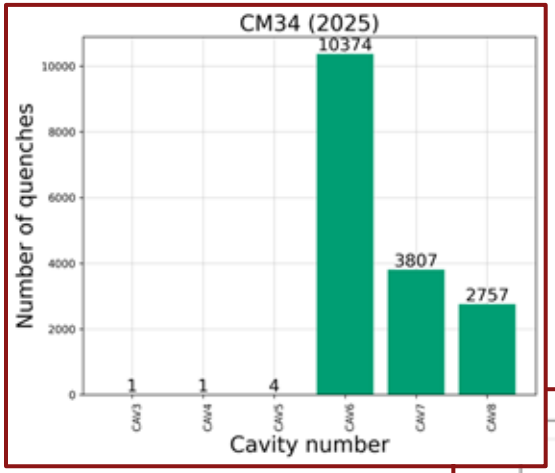
- Max quenches per CM now 177 events.
  - Previous max was in the 1000's.
- **Linac operation stable with less than 1 quench per day on average, per CM.**

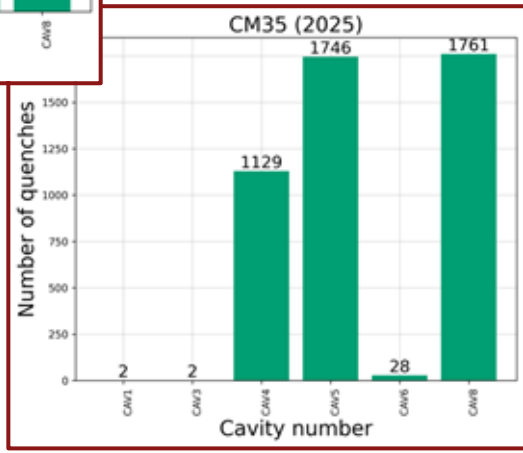


What is going on with the outliers 34/35?

Pulsed processing:

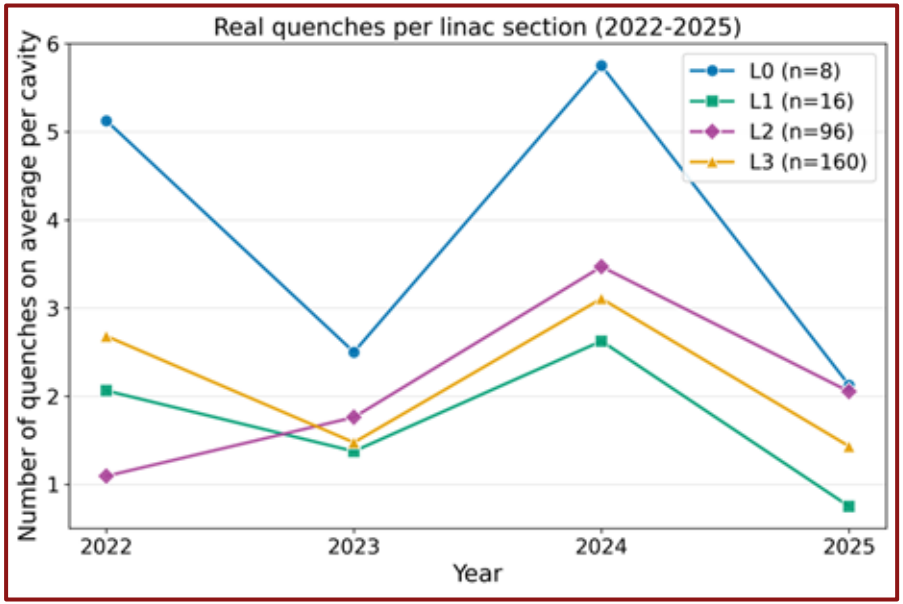
- Field emission is when an emitter (contamination on the cavity surface) produces radiation during operation.
- Unexpected FE was observed on CM01.
- Pulsed processing has worked in the community to improve stable gradients in cavities with FE.
  - This method pushes past stable CW RF field and disrupts geometry at FE site.
  - Demonstrate to reduced sustained radiation in CW mode at ELBE, TRIUMF and RIKEN.
- CM34/35 served as tests before trying pulsed processing FE mitigation on CM01.
- FE was already present in CM34/35.
- We knew we were replacing CM34.





Operational quench trends 2022-2025

- Only showing real, non MP quench events.
- Normalized to number of cavities per section.
- Drop in 2023 probably due to end of commissioning, things dialing in.
- Small bump in 2024 is transition to longer operation hours / more user delivery.
  - L0 bumps will be investigated further.
- 2025, linac operation stable and has low quench rates during normal operations.
  - Less than 5 quenches per year per cavity, on average.



Summary

- LCLS-SC has operated successfully from 2022-2025.
- Initial quench classification method was conservative, as designed.
  - ~65% of quench interlocks were false, and ~35% were real events.
- Vast majority of real recorded events are intentional, MP processing or pulsed processing.
- Real quench rates during nominal operations are low, indicating health of the SRF linac has been maintained.
  - Less than 5 quenches per year on average, per cavity.
- Future work:
  - Improve quench classification.
  - Evaluate relaxing interlock based on data analysis.

Thank you! Questions?

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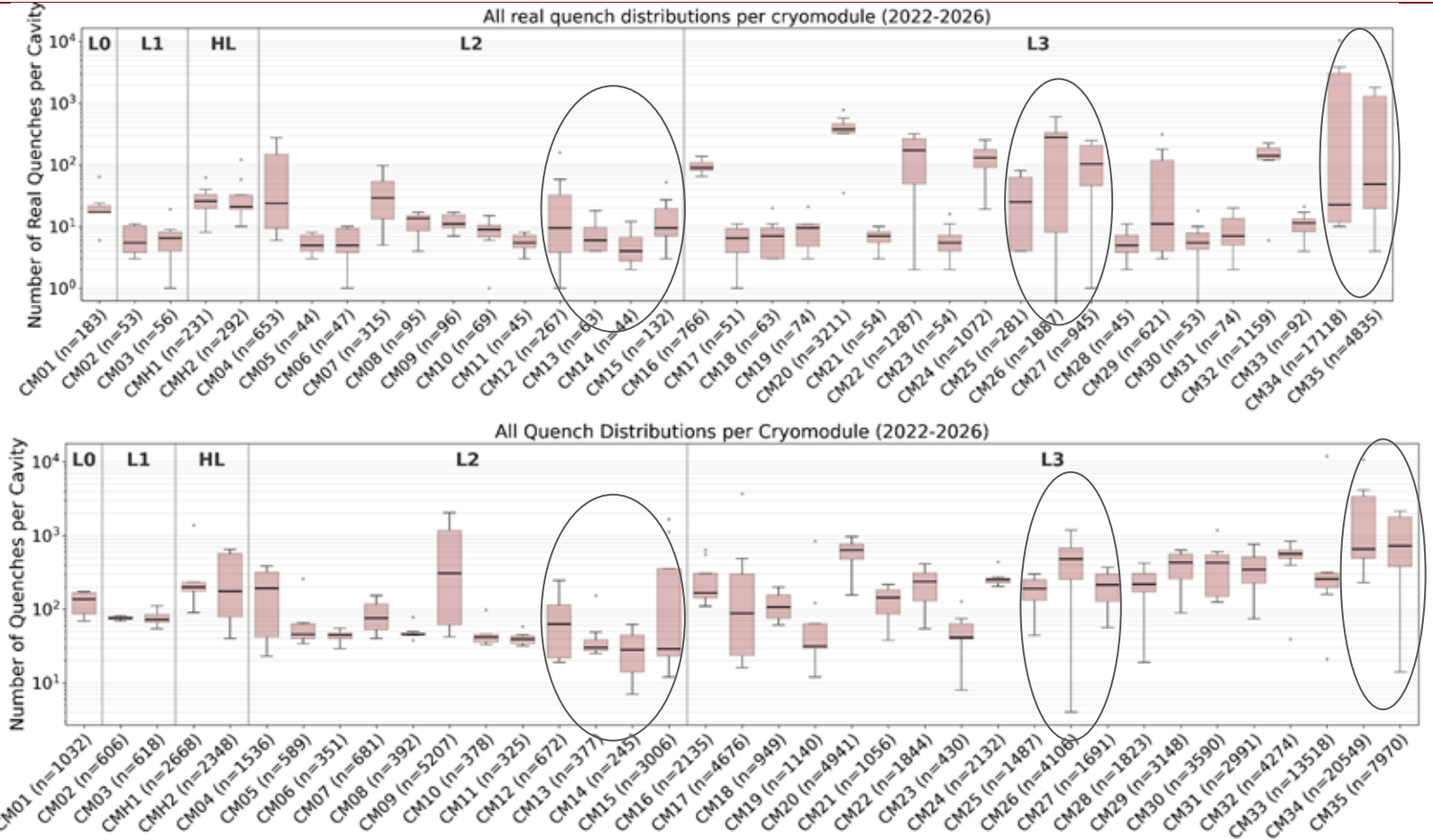
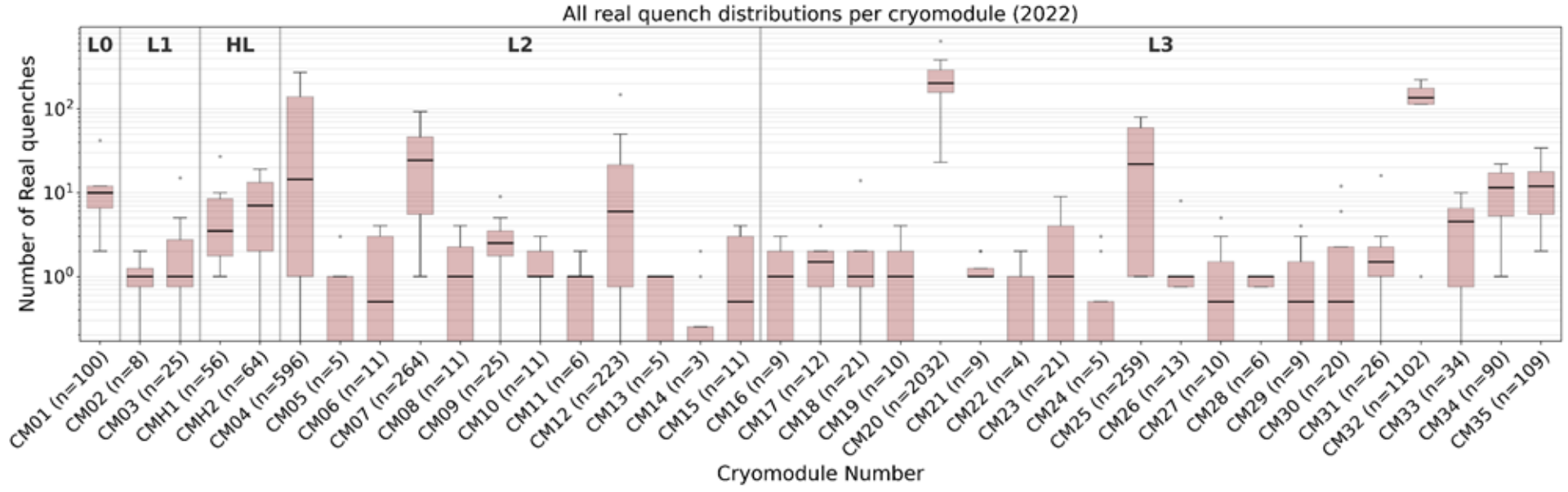
Backup slides

Quenches (real and false) per cryomodule

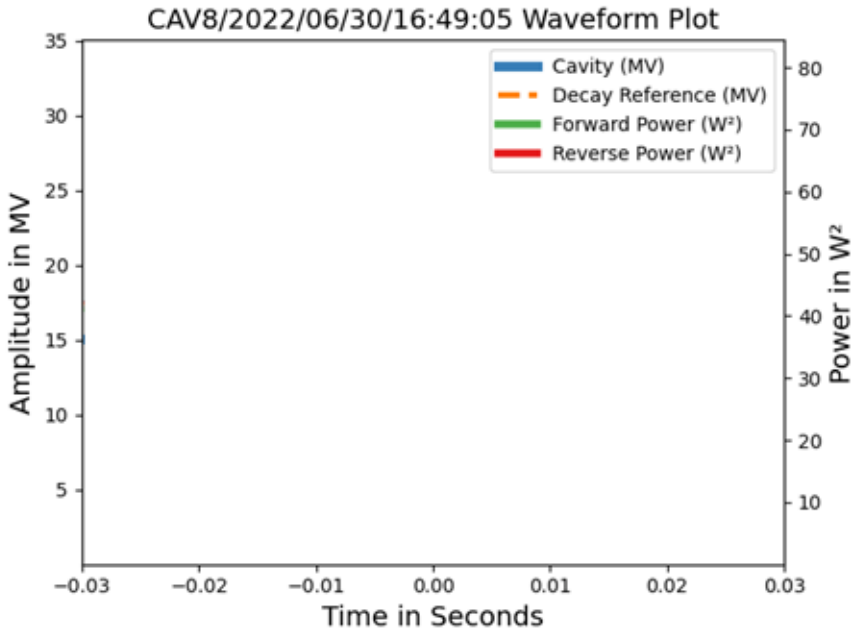


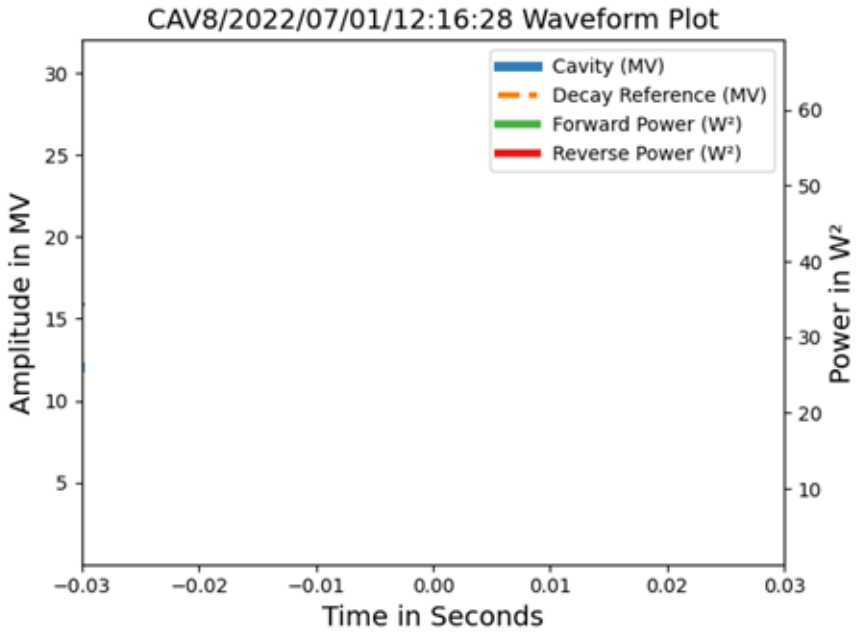
Real quench distribution during commissioning

Only 2022 data shown here.



Operational examples: real and false quenches





Parsing through quench files

```
ACCL:L3B:3180:RFSTATE 2022-06-30_15:46:04.719878 1
ACCL:L3B:3180:BCOEFM 2022-06-30_15:37:57.252968 221.07435463709857
ACCL:L3B:3180:BCOEFP 2022-06-30_15:37:57.279315 5.664899244579876
ACCL:L3B:3180:PROBECALTS 2022-06-30_15:37:42.360745 2022-06-30-15:37:42
ACCL:L3B:3180:PROBECALSTS 2022-06-30_15:38:32.791301 1
ACCL:L3B:3180:CAV:CALSUM 2022-06-30_15:37:57.605129 0
ACCL:L3B:3180:CAV:CALSTAT 2022-06-30_15:37:57.605109 63
ACCL:L3B:3180:SSA:DRV_MAX 2022-06-30_14:47:25.174895 0.74
ACCL:L3B:3180:SSA:REACTIVE 2022-06-29_19:08:26.798939 0.2
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ACCL:L3B:3180:SSA:CALSTAT 2022-06-30_14:46:31.548094 0
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ACCL:L3B:3180:CTRL:FLTLIMS_QL 2022-06-30_15:46:04.412635 0.0
ACCL:L3B:3180:CTRL:FLTLIMS_QH 2022-06-30_15:46:04.412635 0.0
ACCL:L3B:3180:CAV:FLTAWF 2022-06-30_15:46:04.712966 10.51457 10.51449 10.51474 10.51466 10.51462 10.51462 10.51458 10.51482
10.51441 10.51467 10.51468 10.51448 10.51486 10.51463 10.51446 10.51471 10.51473 10.51455 10.51476 10.51445 10.51465 10.51469
10.51446 10.51482 10.51451 10.51461 10.5148 10.51451 10.51458 10.51472 10.51456 10.51464 10.51489 10.51464 10.51413 10.51483
10.51495 10.51407 10.51455 10.51488 10.51484 10.51443 10.51462 10.51447 10.5148 10.51453 10.51457 10.51473 10.51457 10.51456
10.51462 10.51469 10.51472 10.51427 10.51496 10.51466 10.51439 10.51481 10.51448 10.51474 10.51474 10.51441 10.51446 10.51495
10.51441 10.51448 10.51479 10.51459 10.51465 10.51448 10.51466 10.5147 10.51446 10.51464 10.5147 10.51468 10.51463 10.51458
10.51434 10.51477 10.51472 10.51457 10.51436 10.51517 10.51439 10.51441 10.51474 10.51474 10.51425 10.51446 10.5155 10.51431
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10.51455 10.51462 10.51466 10.51438 10.51484 10.5146 10.51454 10.51476 10.51449 10.51468 10.51471 10.51476 10.51431 10.51449
```

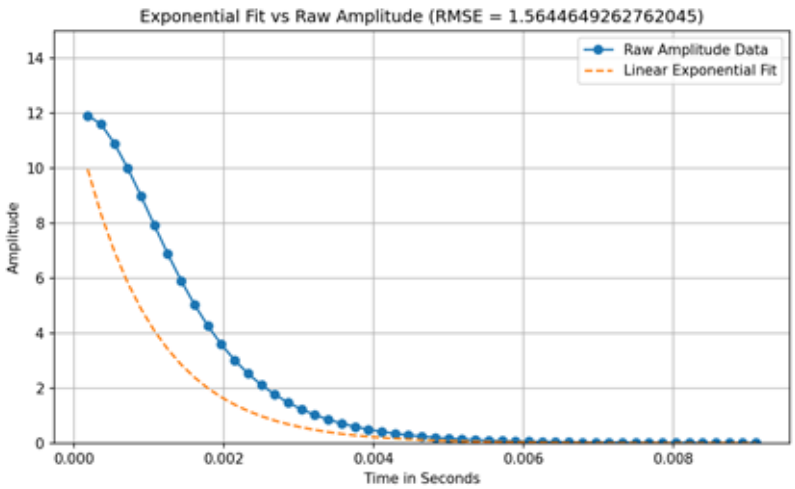
Task One:

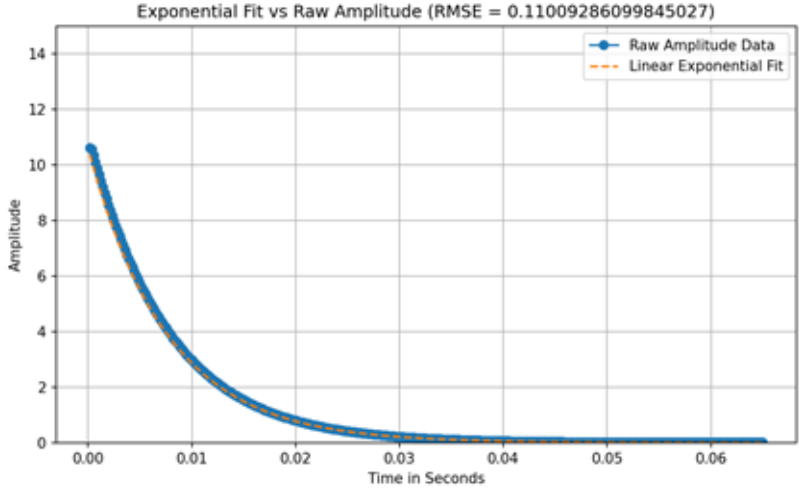
(a) Extract waveform data from the archived text files

(b) Plot the waveforms

(c) Determine whether they are real or fake quenches upon observation.

Visualizing the Fitting Curves





Real vs Fake Quench Exponential Decay Fitting Curves

Fitting Curve Equation: $A_f(t) = A_0 \cdot e^{-slope \cdot t}$