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FRIB

Performance Evolution of FRIB SRF Cavities During Linac Operation for High-Power Heavy-Ion Beams

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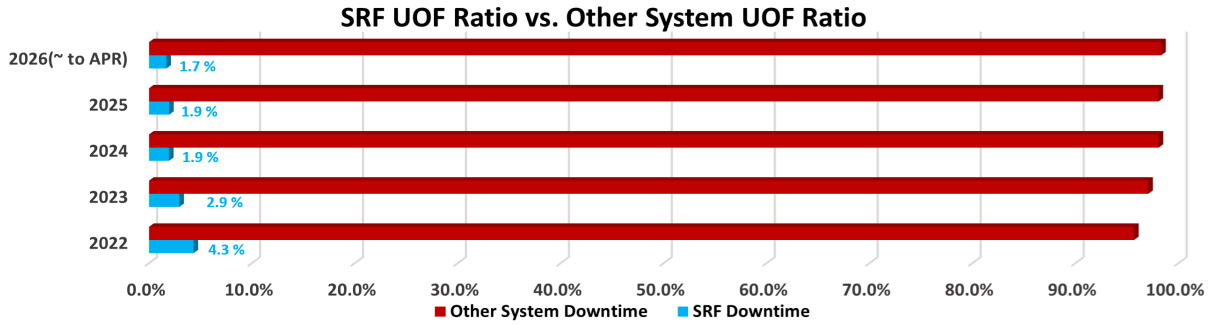
SRF Cavity Overall Performance

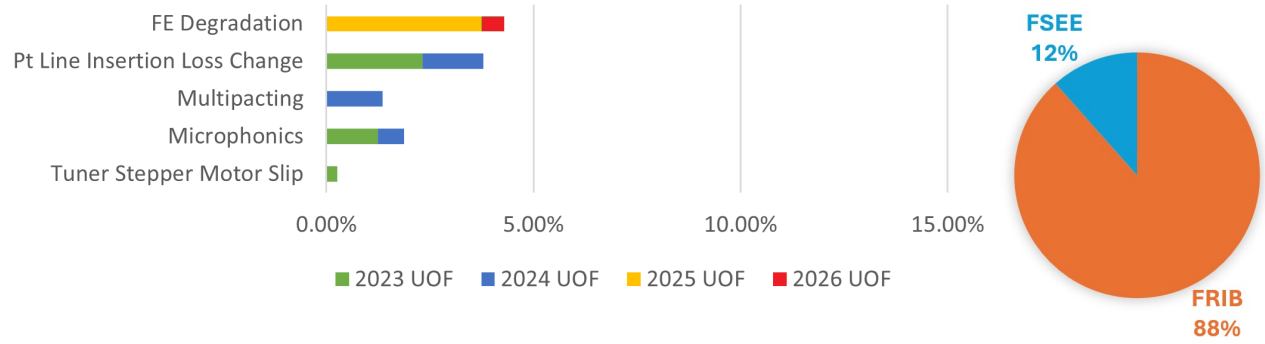
- SRF systems are performing with high availability
  - SRF down time: largest share is due to field emission for recent years
  - Three unused cavities were restored in Summer 2023; one cavity is kept off due to frequency issue

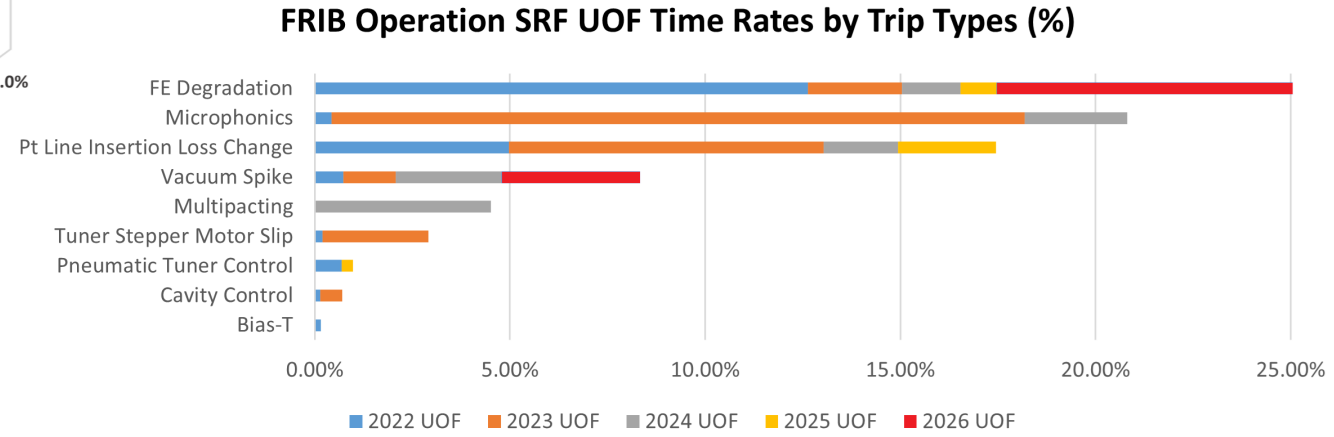
UOF = unscheduled down time



Unused cavities (out of 324 total)

Operation Period	Number of Unused cavities	Reason
ARR07 commissioning	0 (0%)	-
May 2022 – Jul 2023	4 (1.2%)	HWR tuner blockage (2x), FPC CCG failure (1x), tuning range (1x)
Sep 2023 – Apr 2026	1 (0.3%)	Tuning range





FRIB Ops: both QWRs and HWRs
FSEE Ops: QWRs only

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Cavity Field Emission Degradation Tracking

- LS cavity FE degradation: locations and periods
  - "New degradation" = FE X-ray increase by one order of magnitude and exceed 1 mR/hr
  - The distribution shows no signs of contamination from warm sections upstream or downstream of SRF linac segments
  - We reduce the operating gradient limit (max E_a) if FE degradation observed (keep X-rays < 30 mR/hr)
  - Some cavities' performance was improved via pulse conditioning
  - Some HWRs running 5% above field spec during FY2026 operation

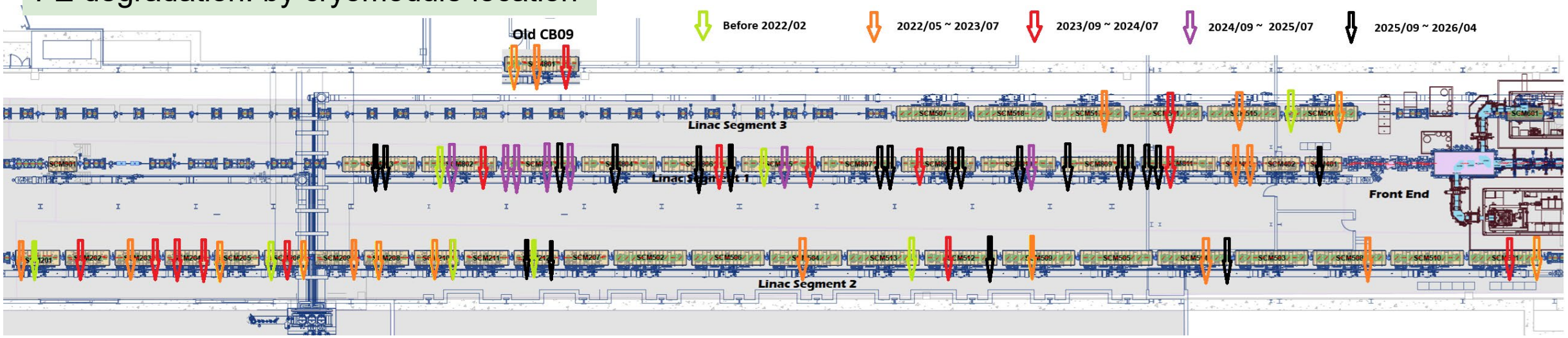
E_a administrative limit

	CA	CB	CC	CD
2022 Oct	95.4%	99.3%	99.7%	98.4%
	-1.4 %		-0.9 %	
2024 Jul	94.0%	99.3%	98.8%	98.4%
	+1.8 %(1)	-0.6 %		+0.2 %(1)
2025 Apr	95.8%	98.7%	98.8%	98.6%
	-1.7 %	-0.8 %	+1.7 %(2)	+2.6 %(2)
2026 Apr	94.1%	97.9%	100.5%	101.2%

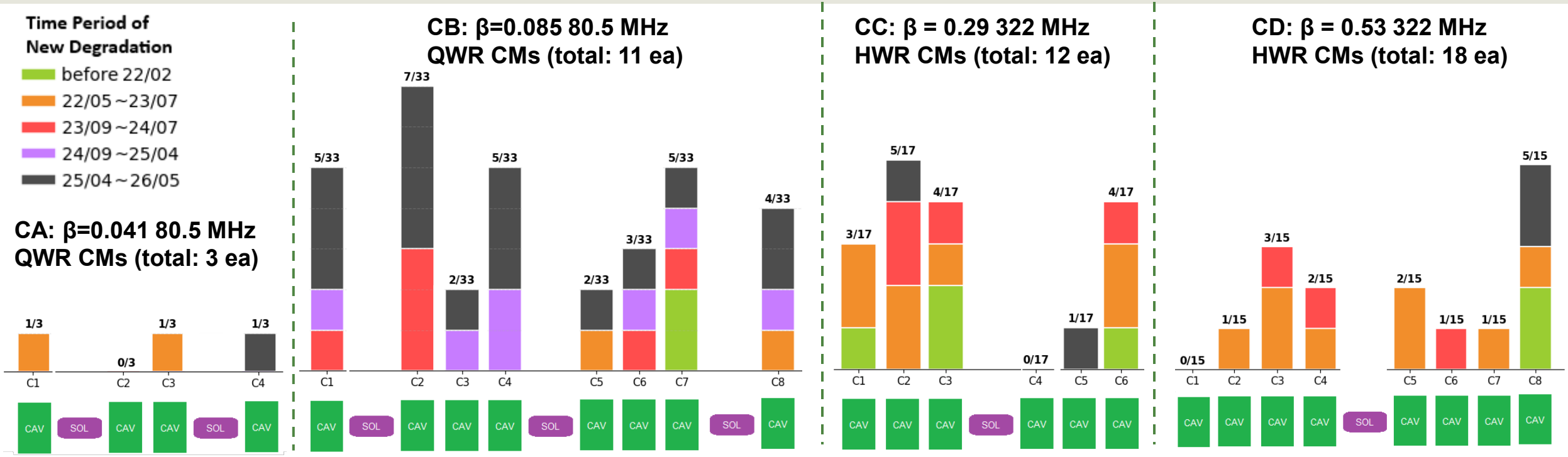
(1) Improved by pulse conditioning

(2) Some CC and CD cavities running 5% above field spec during FY2026 operation

FE degradation: by cryomodule location



Field Emission Degradation: by cavity location in cryomodule

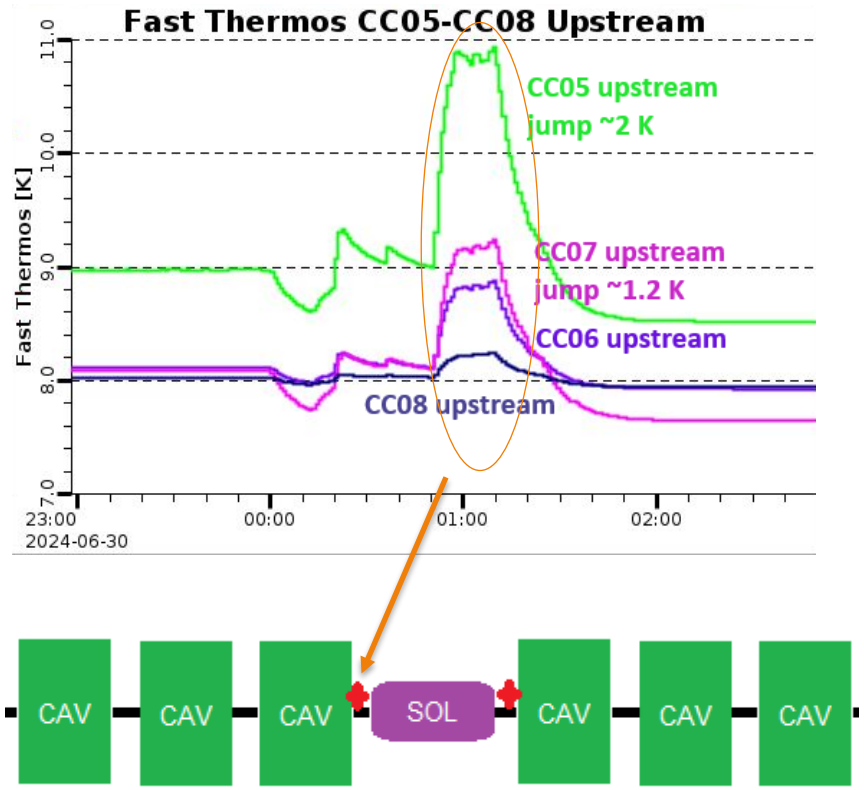


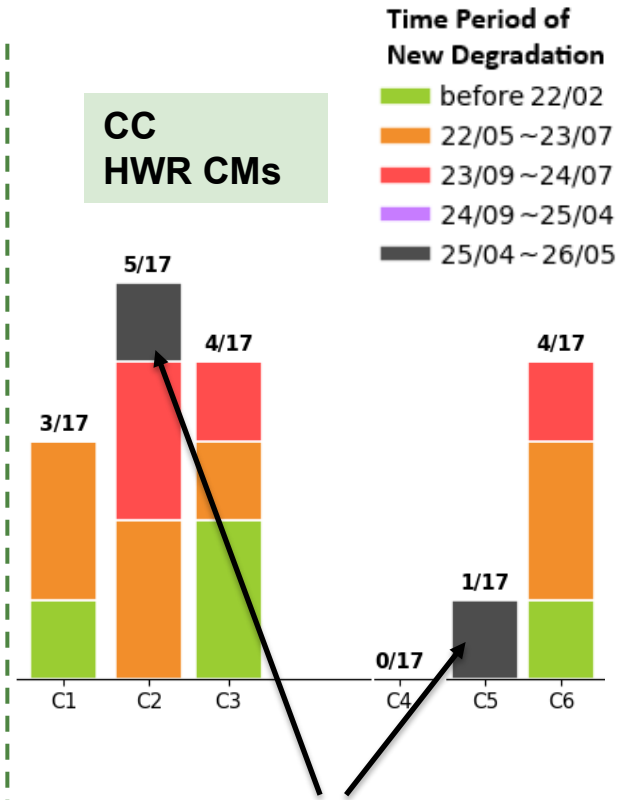
- No obvious signs of higher degradation in the “end” cavities, adjacent to cryomodule beam line gate valves and warm diagnostics boxes.
- LS2-CC degradation: beam losses due to unstable thickness of the liquid lithium charge stripper—improvements made.
- LS1-CB degradation: more observed in the last year. No clear evidence to show that it is due to beam loss—under investigation.

Mitigation for LS2-CC Cryomodule FE Degradation

- Fluctuations in the liquid lithium film thickness → beam losses in LS2
  - Saw correlation between temperature sensor signals (due to beam loss) and FE degradation in CC cavities
- Mitigations developed by accelerator team
  - Compensate for downstream energy fluctuations due to Li film thickness fluctuations via upstream RF voltage adjustment
  - "Stop-start" feedback: stop the beam quickly (chopper) after observing beam losses due to Li film thickness change
- These mitigations have significantly reduced beam losses and FE degradation in downstream cryomodules

CC temperature sensor response to beam losses due to liquid Li film thickness change

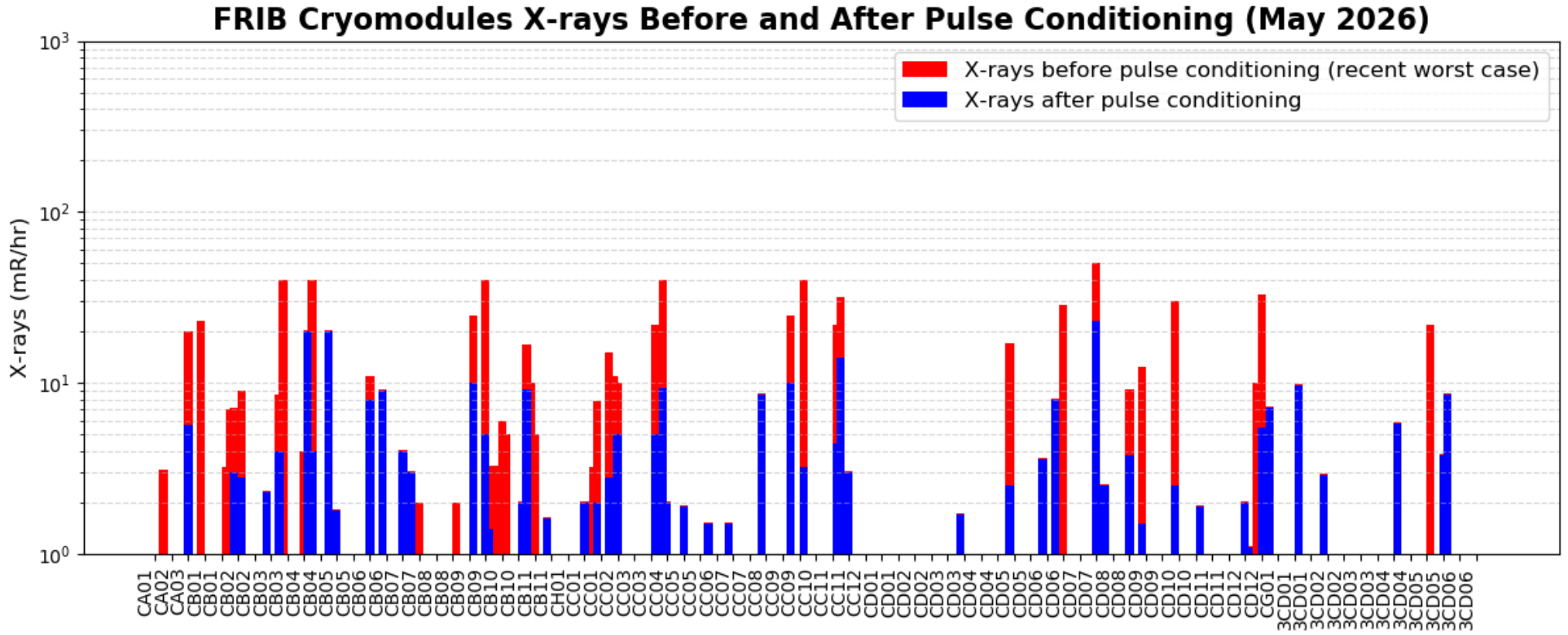




Degradation rate reduced:
2 HWRs degraded in last 2 years

Performance Recovery: RF Pulse Conditioning

- RF pulse conditioning has been a useful technique to reduce FE X-rays and maintain accelerating gradient in FRIB cryomodules
  - However, we observed several cases in which performance improvements were limited; this supports plasma processing as a long-term solution



Performance Recovery: First In-Tunnel Plasma Processing

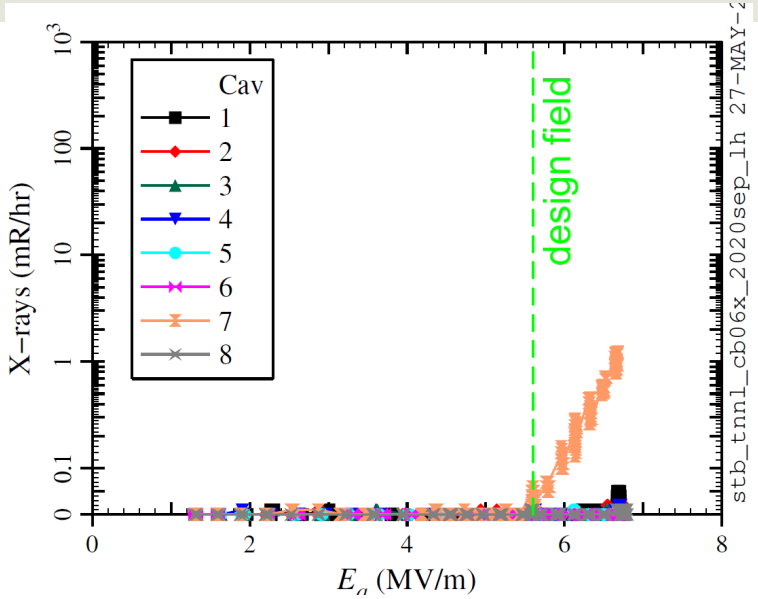
Next step: plasma processing of 2 QWR cryomodules, planned Summer 2026

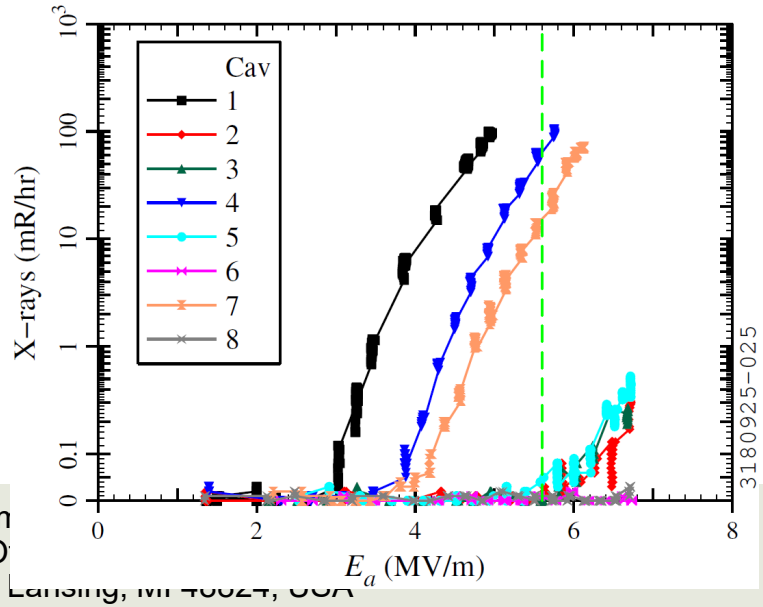
FRIB QWR cryomodule (CB06 / SCM805)

Linac commissioning (Sep 2020)

After Linac Ops, before plasma (Jul 2025)

Cannot further improve with pulse conditioning



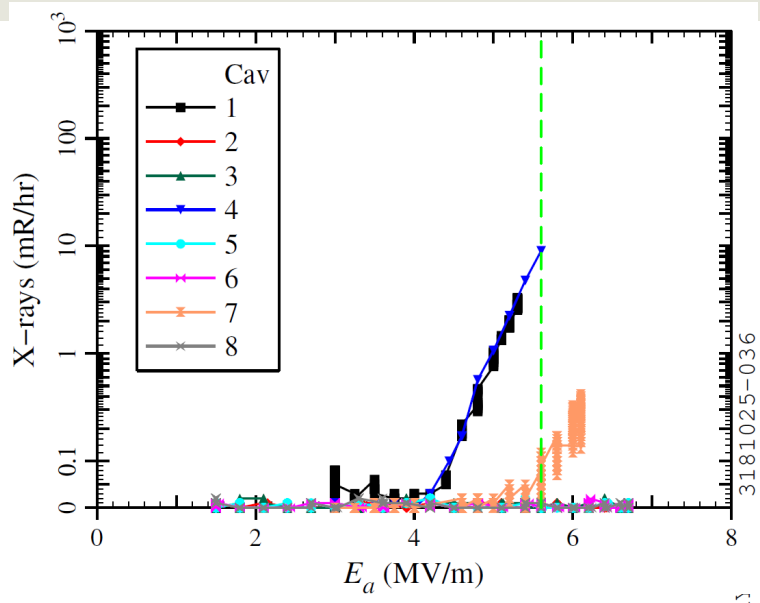


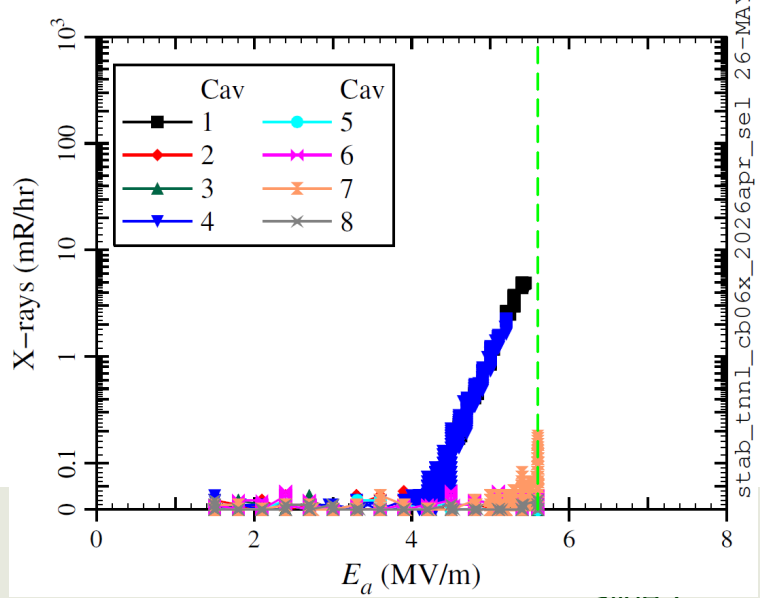
After plasma + conditioning (Oct 2025)

Improved beyond the limits of pulse conditioning

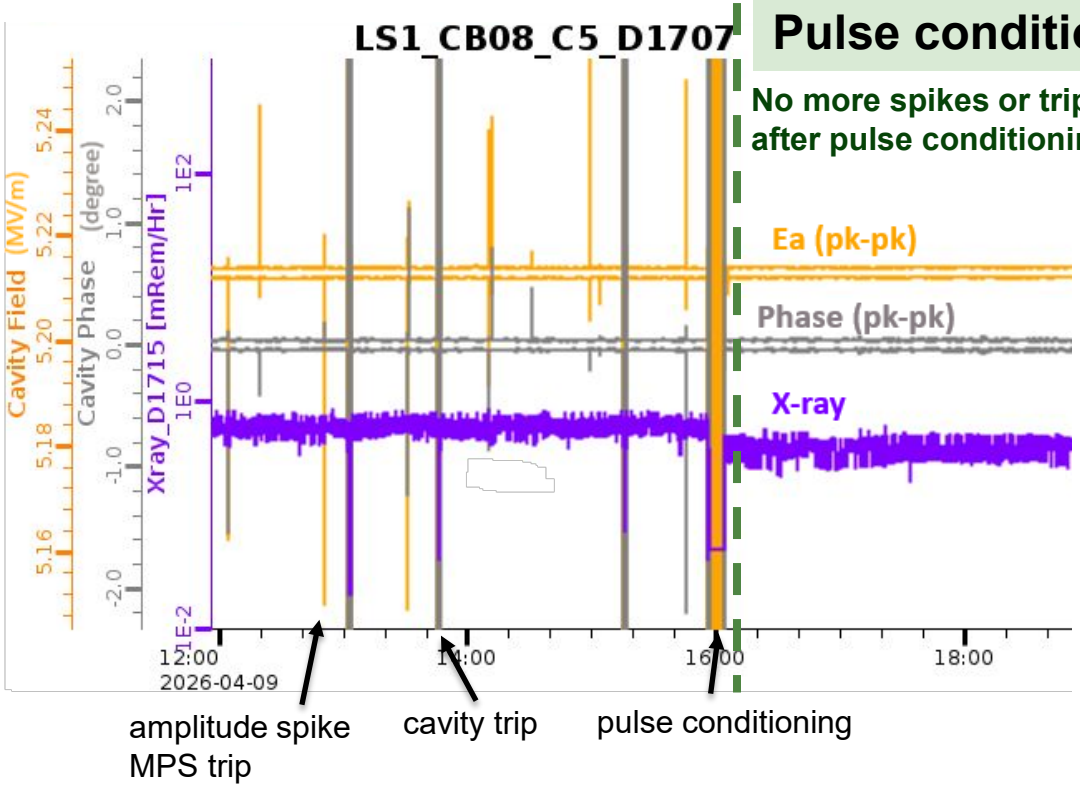
After Linac Ops + conditioning (Apr 2026)

Did not see more degradation after 8 months





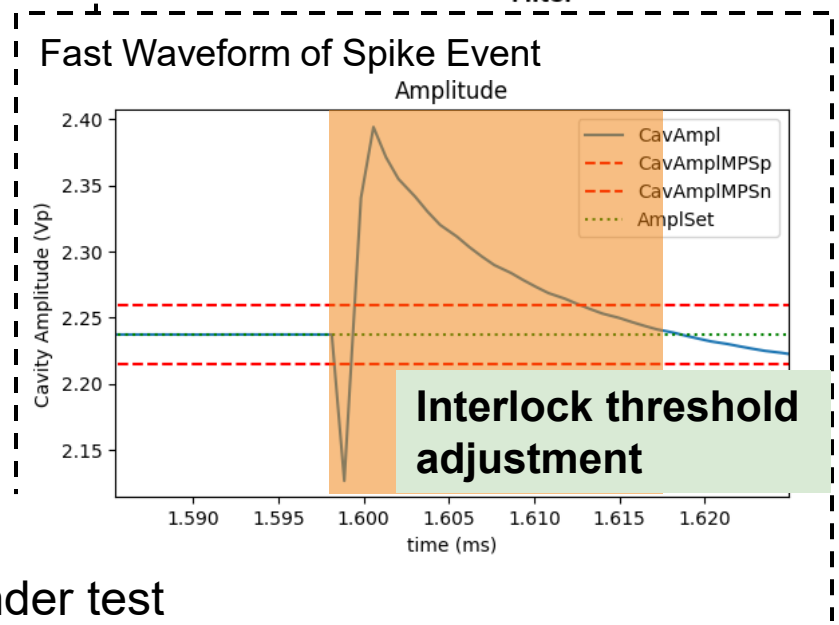
Mitigation of Trips due to FE-Induced Amplitude and Phase Spikes in QWRs

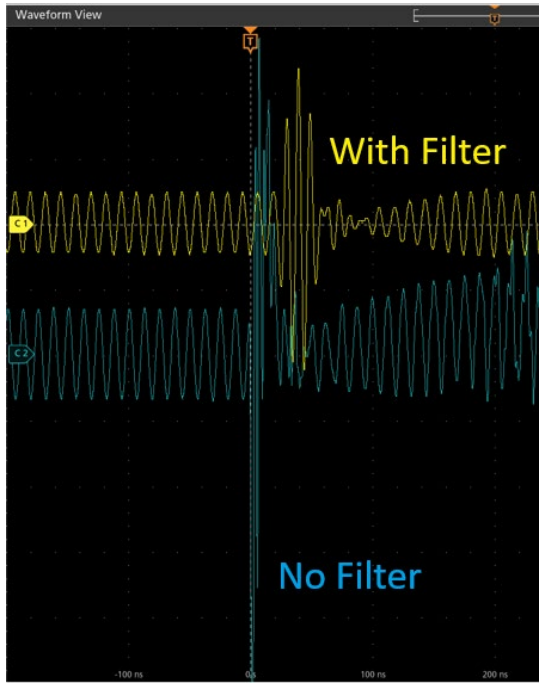


Pulse conditioning

No more spikes or trips after pulse conditioning

Filter pick-up signal





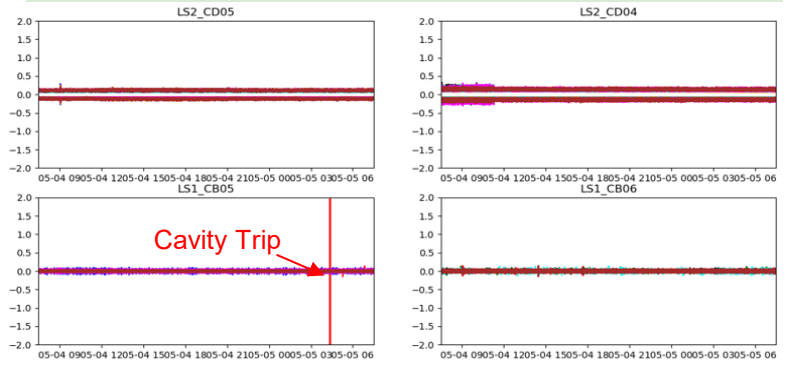
- Mitigation methods:
  - Pulse conditioning: improves performance
  - Filter on pick-up line to reduce peak voltage: under test
  - Set Machine Protection System (MPS) interlock threshold = 20 μs to filter out the spike: under test

SRF Operation: Performance Tracking with Automation

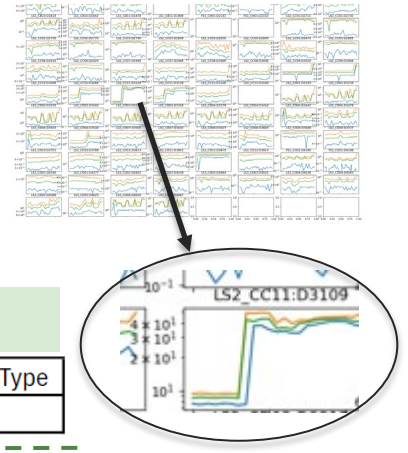
- Cavity performance tracking automation tools: generate daily reports
  - Cavity amplitude and phase errors
  - X-rays and fast thermometer signals (beam loss)
  - Trip reports: RF and MPS
  - Check for cavity operating parameter changes (presently run manually, automation planned)

- Tools for performance tracking
  - X-rays vs E_a scans: comparison plots (end-to-end: raw data processing and visualization)
  - Cryomodule vibrations: joint time-frequency analysis

Cavity phase error reports

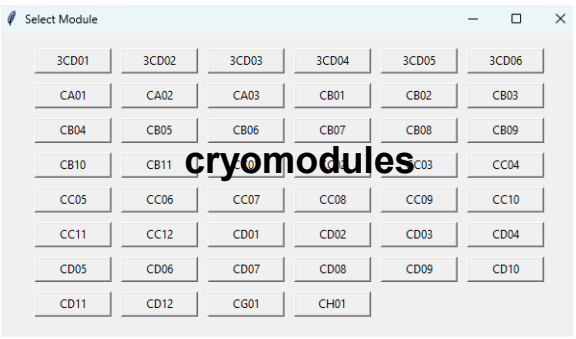


Fast thermometers and X-rays report

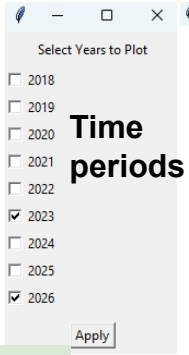


Trips report

Date	Time	DeviceName	CavityNumber	InterlockType
5/7/2026	6:46:24	LS1_CB05:RFC_D1484	1	RFL

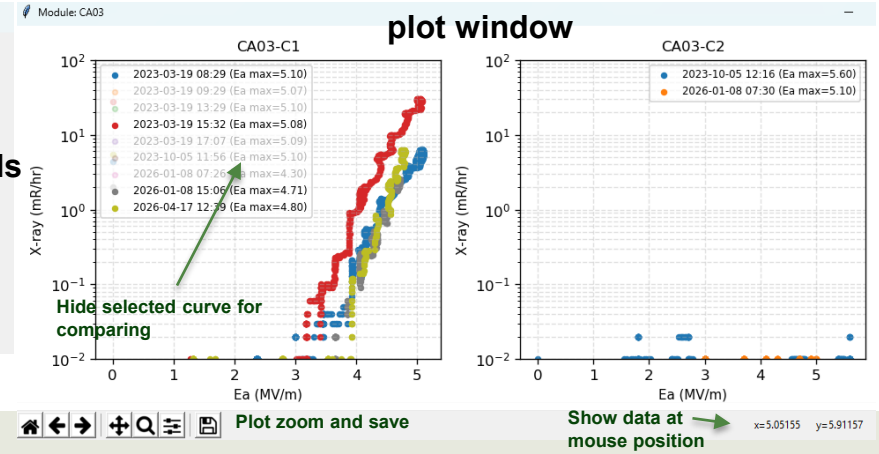


cryomodules



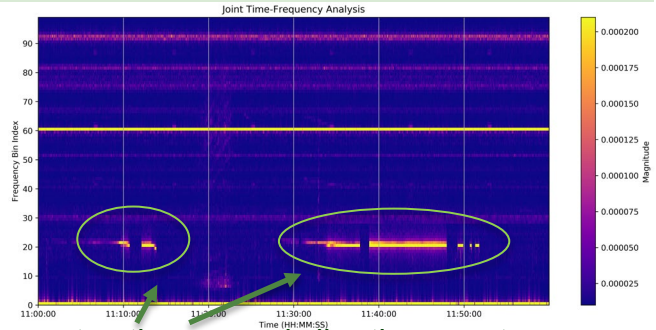
Time periods

plot window



X-rays vs E_a comparison program

Time-frequency plot for cryomodule vibration tracking



construction caused vibration events

Summary

- Field emission (FE) degradation performance mitigation is the primary challenge at present
  - RF pulse conditioning helps restore performance in the short term
    - » Presently: implemented during short term maintenance time by experts. Future: automation tools are under development for use by operators.
  - Plasma Processing: in early stages
    - » First in-tunnel plasma processing on a QWR cryomodule (Summer 2025): performance improved by plasma processing + pulse conditioning; better performance than pulse conditioning alone.
    - » Planned: plasma processing of 2 QWR cryomodules in Summer 2026.
  - FE-induced amplitude and phase spikes: trip rate has been mitigated with pulse conditioning
- Performance tracking, improvement and automation/AI-assisted development tools will continue to be improved.