CM01 Field Emission Workshop Report

Introduction

The injector cryomodule CM01 in the superconducting linac of the LCLS facility has suffered from a sudden onset of field emission in multiple cavities end of September 2023. The accelerating gradient of several cavities had to be reduced from their previous nominal setpoints to stay within the administrative radiation limits. After some initial changes the level of radiation now remains constant. As of today, no clear root cause could be identified.

The purpose of this workshop, held on January 28 & 29 2025, was to gather experts from various related fields and laboratories that design, build and operate SRF based accelerators for discussion of potential reasons, diagnostics and ways to improve the situation.

The total attendance was 32 participants, distributed between 15 from SLAC and 17 from other institutions, including Arizona State University, CEA Saclay, DESY, Fermilab, Helmholtz-Zentrum Dresden-Rossendorf, INFN LASA, Jefferson Lab, Los Alamos National Laboratory and TRIUMF. Participation was both in person as well as remote via Zoom and a focus was put on open discussion over frontal presentations. The next section lists the set of questions serving as workshop scope and basis for the presentations and discussion.

The full agenda and presented material can be found on the workshop indico page under https://indico.slac.stanford.edu/event/9439/

Workshop scope questions

- SQ1: Are there similarities to field emission problems at other accelerator facilities?
- SQ2: Can we determine the root-cause for the field emission onset in CM01? Several theories have been discussed but none has been fully ruled out or confirmed yet (Latent particle contamination from assembly, new contamination with external particulates, hydro-carbons, cesium migration from the gun cathode, adsorbed gases from cooldown) (SQ2)
- SQ3: Which diagnostic methods would be suitable to be applied on the cryomodule while installed in the tunnel (invasive or non-invasive)?
- SQ4: What kind of simulations can be run to better understand the situation?

- SQ5: Is there an optimal way to operate to cryomodule post field-emission onset? Should the amplitudes be lower or could they be higher than the current values?
- SQ6: We are considering full replacement or plasma processing. What other potential avenues have been applied to recover cryomodule performance from field emission? What are the associated risks of each method?
- SQ7: Even if a root-cause can not be found, are there ways to prevent something similar from happening again? What are potential mitigations for risks of a repeat if CM01 is replaced with a new cryomodule?
- SQ8: Are there spatial patterns for field emission over the full machine and within cryomodules in the LCLS SC linac?

Timeline of field emission onset in CM01

- 09/23/2023
    - Higher than expected beam losses were observed during commissioning of the beam loss monitor system near the injector and were found to be dependent on cavity CM01-4 amplitude
- 09/27/2023
    - During the next access for planned maintenance, the Decarad radiation monitoring system was moved next to CM01.
    - In the evening, re-characterization of CM01 found radiation in cavities 2 through 5
        - CM01-2: Had previously been offline since initial commissioning for beam optics reasons. Brought back online and observed radiation during the first power rise. Radiation onset at 13MV, 50mR/hr limit at 15.6MV
        - CM01-3: Radiation onset at 9.5MV, 50mR/hr limit at 10.9MV
        - CM01-4: Radiation onset at 9MV, 50mR/hr limit at 10MV
        - CM01-5: Radiation onset at 10MV, 50mR/hr limit at 12.3MV
    - No radiation was measured in cavities CM01-1, CM01-6, CM01-7 and CM01-8
    - The beam program was resumed with lowered amplitudes in affected cavities until a buncher trip during the night
- 09/28/23

    - Another measurement in the morning showed radiation in CM01-4 had increased by orders of magnitude compared to the measurement the day before, all other cavities remained unchanged. Lowered amplitude in CM01-4 to 5MV to prevent further degradation.
- Re-measurements of CM01 field emission were performed roughly every two weeks (before and after planned maintenance periods)
- 10/25/23
    - Observed radiation in CM01-8 for the first time. Radiation onset around 15.5MV with levels just above background. No impact on operational amplitude limit.
- Re-measured CM01 in regular intervals since, no significant further changes observed

Key topics covered

- Experience with field emission at other facilities

  (Presenters were provided with a set of slide prompts to facilitate comparability, see Appendix A)

    a. DESY
        i. Radiation sensors are a mix of stationary continuous sensors (RadFET, RadCon) and mobile robot MARWIN (gamma & neutron sensor)
        ii. Out of the 103 CMs built for EU-XFEL only 3 were completely field emission free during acceptance testing and thus during commissioning
        iii. In total 8 cavities are currently not in use (detuned) because of field emission exceeding the operational limits. Mostly known cases from acceptance testing, one newly degraded during operations.
        iv. Observed degradation in two cavities when RF power in one linac section was ramped up too fast after shutdown period while quadrupole magnets where off, likely resulting in high dark current.
        v. Using pulsed processing to recover degraded cavities (e.g. the two mentioned above). Performance was fully restored.
    b. HZDR

   i. Had history of hydro-carbons on EPDM gate valves. Possible source of contamination, but no longer see traces of hydro-carbons in the machine.
   ii. Another suspected degradation mechanism are movable beamline elements close to the cryomodules.
   iii. Applying high power pulsed processing for the cavities in the ELBE cryomodule ~annually to recover lost performance.
   iv. Had incident of cesium evaporating off Cs2Te cathode in SRF gun due to overheating in 2015, resulting in 20% performance loss. Room temperature cycle recovered most, but not all of it.
   v. Have tried helium processing but not seen improvements.
c. TRIUMF
   i. Suffered severe cavity degradation from a vacuum incident venting the beamline of ISAC-II linac
   ii. Routinely do pulsed RF processing after thermal cycles of the ISAC0II linac (e.g. after shutdown period) to recover cavity performance.
   iii. See linear dependency (with factor ~0.7) between peak accelerating electric field Eacc during pulsed processing and achievable operating Eacc afterwards.
   iv. In ARIEL e-linac have done pulsed RF processing as well as helium processing. Both have helped to mitigate but not fully remove field emission. Helium processing has not improved the radiation onset field, but slowed the increase in radiation with increasing field.
d. JLAB
   i. Have seen increases in field emission over the (long) lifetime of CEBAF.
   ii. Often have to run cavities very close to or at their limit in order to be able to achieve required total beam energy.
   iii. Multiple degradation mechanisms identified over time
      1. Gas load from warm beamline sections in-between cryomodules
      2. Particulate contamination from:
         a. Initial assembly (clean room practices for initial cryomodules were not as developed as nowadays)
         b. Excessive opening and closing of vacuum valves due to vacuum interlock trip thresholds set too low
         c. Degraded Viton gaskets from radiation damage
         d. Titanium from ion pumps
   iv. Remediations used:

        1. Helium processing
        2. High power pulsed processing
        3. Plasma processing (seeing evidence for plasma processed modules degrading less afterwards, compared to non-processed modules)
        4. Replacement of individual cryomodules (~2-3 per year)
- Simulations on ion migration from the injector towards CM01 and cesium migration on and off the cathode by Dave Dowell
    - The LCLS-SC gun emits a dark current, mostly originating from near the nose cone, on the order of uA.
    - Simulations show that within CM01 the highest amount of dark current is lost in the entrances of cavities 1 through 3.
    - LCLS-SC cathodes develop an area of lower Q(E) in the center after operating for a while
        - Potential mechanisms to explain this are cesium mobility due to heating as well as preferential sputtering from back-bombardment via ions that are created by the dark current originating at the gun
        - There is currently no full understanding if cesium could be leaving the cathode and if there is a mechanism for it to travel all the way to CM01. This would need more simulations and ideally a way to detect cesium along the injector beamline.
    - Performed simulations of charged particles (hydrogen ions) along the electric fields into CM01. Have not done other ion species yet
- Radiation measurements and sensor development at CEA for ESS
    - Working on time-resolved gamma spectrum detection adequate for pulsed RF operation of ESS cryomodules.
    - Several generations: Plastic scintillator with photo-multiplier, additional fast amplifier, multi-pixel photon-counter with dedicated ASIC readout.
    - Benchmarking with NaI(Tl) detectors
    - Using particle tracking code for detector optimization and prediction of energy spectrum
    - Ability to distinguish between radiation from field emission and multipacting in the fundamental power coupler

Key takeaways / Summary

- SQ1:

  - Similarities in field emission problems are seen at other facilities, but no identical cases with an onset so sudden and dramatic as CM01 (without known cause such as vacuum venting event).
- SQ2:
  - No clear root cause for the sudden onset of field emission in CM01 can be determined at this time. There is not enough data to distinguish between potential mechanisms.
- SQ3:
  - More detailed radiation measurements, for example resolving the energy spectrum of the gamma radiation (instead of just radiation dose rates) as well as the spatial distribution around CM01 in conjunction with simulations (see SQ4) would help narrowing down the exact location of the field emitters within CM01 cavities.
- SQ4:
  - Additional simulations on particulate and ion movement would help to better understand and/or rule out the potential various contamination mechanisms.
  - Simulations of radiation propagation inside and outside CM01 (benchmarked by the measurements mentioned in SQ3) would help narrowing down the exact location of the field emitters within CM01 cavities.
- SQ5:
  - JLab operates with much higher field emission and radiation limits but also notes that operating close to absolute maximum likely contributes to further degradation over time. Current LCLS-SC limits are based mainly on long-term radiation damage to components, could consider raising amplitudes short term if necessary.
- SQ6:
  - Pulsed RF processing
    - High power pulsed RF processing has been used with good success to recover field emission induced performance degradation at multiple other facilities. This can be performed while the cryomodule is at 2K.
  - Helium processing
    - Has been used with some success at other facilities. Further degradation of cavities has been observed in some cases [2]. Benefit would be that it can be used without having to warm up CM01 all the way to room temperature (temperature range of 2K to 40K)

- SQ7:

    - Without knowing what happened it is hard to prevent. However, it would be beneficial to eliminate (or minimize) as many potential causes as possible (e.g. more pumping between CM01 and the gun, minimize gun dark current)
    - For the case that a re-occurrence cannot be prevented, any modifications that make diagnostics and remediation easier would be beneficial, e.g. additional diagnostic ports and modifications to the cryogenic system that would allow a room-temperature warmup of CM01 alone.
- SQ8:
    - There is no consistent pattern along the machine. Within CM01, the fact that cavity 4 in the middle of the cryomodule is affected most is unusual when thinking about contaminants that would be entering the cryomodule from the ends.

Additional references

[1] G. Hallilingaiah: 'Two decades of CW SRF experience at ELBE', TTC2024 Meeting, Lund, Sweden

[2] M. Drury et.al., "Results of the 2025 helium processing of CEBAF cryomodules", NAPAC16, Chicago, USA

Appendix

A) Slide prompts for "Experience at other facilities" presentations
    a. General facts about the accelerator
        i. Year built/commissioned
        ii. Cryomodule string layout (continuously cold, warm sections,...)
        iii. Particle free installation practices/protocols applied
        iv. Nominal operating gradient
        v. Administrative/operational radiation limits
        vi. Accelerated particle species and beam parameters
    b. Instrumentation to measure/monitor radiation

   i. Type of sensors
   ii. Locations and coverage of the machine
   iii. Continuous monitoring or interval of measurements?
   iv. Alternative ways to detect field emission?

c. Field emission situation during commissioning
   i. Comparison to cavity performance before installation / during acceptance testing
   ii. Field emission situation as measured during commissioning
   iii. Any known causes for the field emission (e.g. vacuum/gas sources, particulate sources,…)?

d. Evolution of field emission
   i. How has field emission in the machine changed over time (location and magnitude)?
   ii. Are there any spatial patterns observed?
   iii. Are there known reasons or events this can be correlated with?
   iv. How much performance has been lost due to the increase in field emission?

e. Field emission remediation
   i. Have there been attempts to decrease field emission in situ?
   ii. If yes, what and to what level of success?
   iii. If cryomodules have been removed due to field emission, has the issue resurfaced in the replacement?