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# OPTIMIZATION OF CLEAN ROOM INFRASTRUCTURE AND PROCEDURE DURING LCLS-II CRYOMODULE PRODUCTION AT FERMILAB*

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*Abstract*

Optimization of Fermilab string assembly procedure and infrastructure has yielded a significant improvement of cryomodule particulate counts. Late production of LCLS-II cryomodules were tested at CMTF at Fermilab and showed little to no x-ray up to administrative limit. The paper describes the field emission measurement instrumentation, field emission results of Fermilab's LCLS-II cryomodules, clean room infrastructure upgrade and procedure optimization.

## INTRODUCTION

LCLS-II cryomodule production is shared between Fermilab and Jefferson Lab. Fermilab's string assembly procedure closely follows the XFEL cryomodule assembly. All cavities are vertically tested with a low power unity coupler. Once accepted, cavities are transported to a cryomodule assembly facility. Cavities are kept under vacuum and undergo careful cleaning of external surface in three stages from a clean room preparation area, ISO-4 clean room and ISO-5 clean room.

Once in a clean room coupler assembly area named as workstation 0 (WS0), a cavity is connected to a vacuum system through the cavities pumping manifold that was previously attached to the cavity's beam pipe at the power coupler side. The cavity is then vented to allow the removal of the unity power coupler and the assembly of a high power coupler.

Cavities then are connected one by one with inter cavity bellows, the gate valve sub-assembly and magnet spool lines. This is named workstation 1 (WS1).

The entire string assembly is evacuated, and leak checked. It is then back filled with filtered boil off nitrogen to proceed to next workstation 2 (WS2).

At the end of the cryomodule assembly at workstation 5 (WS5), beam line is once again evacuated to conduct another leak check. At this time, cryomodule beamline space is kept under vacuum and transported to a test facility until accepted and then transported to a partner lab for installation.

At the beginning of the cryomodule production, each of the first six cryomodules had several cavities that experienced field emission onset field degradation.

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Two clean room audits were conducted. One internal audit was during F7 assembly and one external audit was during F9 assembly.

After several infrastructure and procedural improvements, the Fermilab built cryomodules have seen field emission dramatically improved with many cryomodules showing no detectable x-rays.

## FIELD EMISSION INSTRUMENTATION

The Cryomodule Test Facility at Fermilab has unique instrumentation of radiation detectors [1]. There are eight wall mounted detectors closely matching the locations of eight cavities in cryomodules. Each is approximately two meters from cavity location in a cryomodule. On each of cryomodule ends, there is one detector. Three additional detectors are located further away from cryomodule and are used for safety purposes and not for cryomodule x-ray measurement. There are two more x-ray detectors that are not permanently attached, and they are usually placed near the cavity locations where x-ray is detected highest from permanently attached detectors.

The eight wall mounted detectors allow the x-ray measurement for field emission that tends to create radiation sideways compared to those mounted on the ends of the cryomodule that measure the x-ray generated by axially accelerated field emission electrons. The measurement details and results were reported earlier [2].

## STRING ASSEMBLY IMPROVEMENT

Two audits were conducted at Fermilab that carefully investigated both infrastructure and procedures for potential improvement. The audit covered cavity related infrastructure and procedures exhaustively that included cavity preparation after acceptance tests to beam line connection at the cryomodule test facility.

Following six steps are important to maintain a high quality and to minimize the particulate contamination to the cavities.

1. Preparation and cleaning of cavity after vertical tests.
2. Inspection and cleaning of beam line components.
3. Power coupler assembly at WS0
4. String assembly at WS1
5. Beam line evacuation and leak checking at WS5
6. Cryomodule installation at test cave

In addition to the audits, purging and evacuation parameters were re-evaluated to ensure the particulates movement in the cavity string was minimized.

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### *Infrastructure*

The Fermilab string assembly procedure or coupler assembly required the cavity to be purged at a mass flow rate of 1 liter per minute. In a previous configuration, Nitrogen purging, and cavity evacuation was merged at the one end of a long-corrugated vacuum hose. The other end of the vacuum hose joins the cavity end. This was adopted to simplify the connection of the cavity side as shown in Figure 1.

Figure 1: Nitrogen purging and evacuation merges at the beginning of the corrugated vacuum hose.

Unfortunately, this configuration under estimated the particulates that could potentially be generated in the corrugated hose. In the event of purging mass flow, higher mass flow would increase the particulates movement.

In a simple measurement, it was found there are non-negligible particle counts that come from the corrugated vacuum hose as the nitrogen purge was at nominal 1 liter per minute. When the corrugated hose was disturbed, the particle count flared up. This was not a surprise since a corrugated vacuum hose is notoriously hard to be cleaned and remove the particulates.

It was concluded it would benefit to relocate the nitrogen purging to the cavity side of the corrugated vacuum hose as shown in Figure 2.

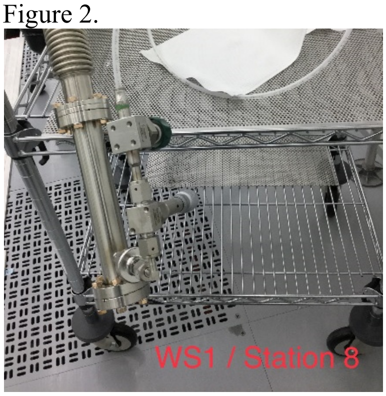


Figure 2: Nitrogen purging is relocated at the cavity side of corrugated vacuum hose.

In this configuration, nitrogen purging does not go through long corrugated vacuum hose. The section after the nitrogen filter is considered much easier to clean. The downside is the parts that are connected to cavity were more complex. The particulates in this configuration was tested and no particulates were recorded even at higher mass flow of nitrogen purging.

### *Procedural Improvement*

Most of the audit recommendation focused on procedures.

In parts preparation, particulates blowing time was increased to ensure the particle counters have at least three averaging cycles after the particle counts reach zero. The nitrogen ionization tool was reduced to 90 psi which provided the best ionization according to manufacturing specification.

The string assembly back fill rate was reduced to below 0.25 liter per minute at WS1. This was much reduced from earlier one (1) liter per minutes. This is much different from the purging rate. Calculation showed previous rate of back fill was 10 times that typically experienced in vertical test preparation where abundant data was available to indicate a high risk of particulates contamination when the mass flow exceeded 0.25 liter per minutes. For the same reason, the WS5 evacuation mass flow was also reduced to 0.25 liter per minute.

The coupler installation at WS0 required an evacuation and leak checking after coupler was installed. This step was skipped to reduce the evacuation and back fill cycle. The risk was estimated to be low for a coupler vacuum joint to leak after a string assembly is completed. One cryomodule after the audit did experience a coupler sealing problem which ended up with a cavity in a completed string assembly being replaced with a fresh cavity. That cryomodule unfortunately did experience the elevated field emission.

The cavity string pressure data is now recorded in traveler at the WS1 and WS5. Nominal back-fill pressure was set at 796 torr. The vacuum hose at WS5 was reduced to 780 torr before vacuum cart vacuum space was connected to string vacuum space. This is a midpoint between 796 torr and 760 torr. A few cryomodules have experienced string pressure variation between 758 torr and 822 torr due to temperature and other factors. 780 torr was considered low risk based on the string pressure uncertainty.

Helium injection into vacuum vessel was then increased during leak checking in WS5 to ensure a minimum 5 torr of helium partial pressure. This was to ensure that sufficient helium had a chance to go through the vacuum vessel and cover any vacuum joint.

There were many small details to be improved throughout the string beam line activities. They were not considered high risks and were not discussed here.

## CRYOMODULE TEST RESULTS

Fermilab has completed the testing of 18 cryomodules. Field emission for all these cavities were plotted in Figure 3. All cavities were tested and field emission free unless indicated otherwise.

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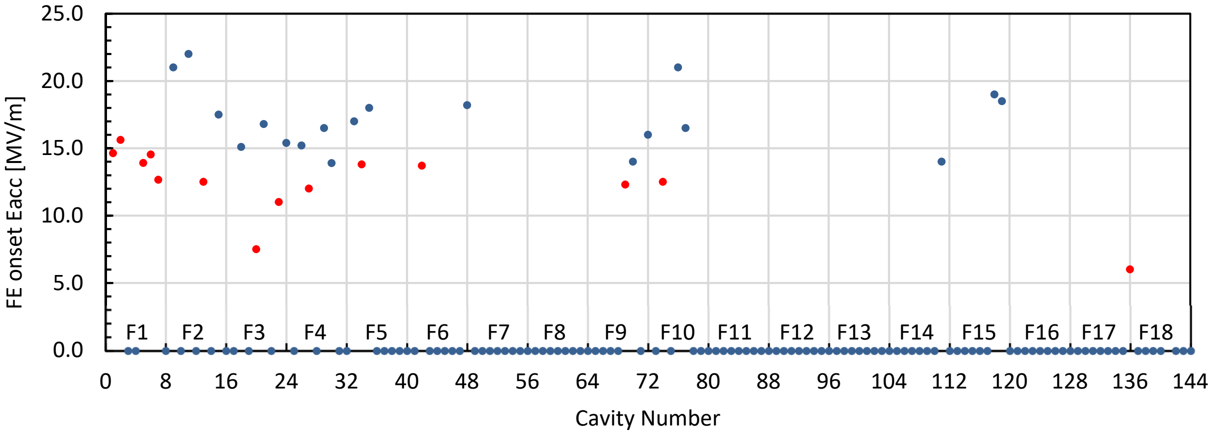


Figure 3: Field emission onset gradients for all 18 Fermilab built cryomodules. The blue dots on the axis indicated no x-ray was detected for that cavity. Red dots indicated the field emission for that cavity reduced the cavity performance.

For LCLS-II cryomodules, 50 mR/h x-ray from any detectors is considered the safe operation specification. Any cavities that generated 50 mR/h would be considered performance limited at its measured gradient up to the administrative limit of 21 MV/m. To simplify the discussion, all Fermilab cryomodules were simplified by F and followed by cryomodule numbers such as F1 represents F1.3-01.

The first internal audit was conducted during F7 assembly. Procedural improvement was implemented in F7 assembly and the benefit was immediate. F7 was the first cryomodule that there was no x-ray detected throughout up to administrative limit. The second audit was conducted during F9 assembly. Most of the audit recommendation was implemented starting at F11 assembly.

These are recorded events for all the cryomodules. F2 experienced uncontrolled beam line pressure change due to unfamiliarity with the gate valves that resulted gate valves not being fully closed. F5 had a cavity high order mode feedthrough replaced at cavity location one at work station 3 with non-ideal clean room setup. F9 experienced a minor leak that resulted two extra cycles of evacuation and back-fill. F10 coupler #6 cannot achieve leak tightness and the cavity had to be extracted from the completed string assembly and replaced with a new cavity.

## DISCUSSION

The nitrogen purging rate was once proposed to be increased to 3 liters per minute. This was not adopted due to the complexity to adjust the flow control at Fermilab facility. The back fill after leak checking requires the back-fill mass flow to be 0.25 liter per minute. Future upgrade may need to rebuild the nitrogen distribution system to allow easy adjustment.

One may argue that the backfill rate is contradicted to the purging rate. In our experience, the backfill takes longer hours compared to short period of purging when cavities are joined. The particulates movement is assumed to be proportional to the duration of turbulent nitrogen flow.

The evacuation rate at WS1 is still to be improved. The current configuration limited the evacuation mass flow at 4 liters per minutes. This was identified to be a future upgrade.

Since the WS0 evacuation and back-fill were dramatically improved, the risk of particulates contamination is much reduced. We recommend bringing back the cavity/coupler leak check as we have seen the risk is too high in cryomodule F10.

Another important recommendation was to conduct WS0 work at WS1 location that could potentially reduce a few cycles of right-angle valve operations and connections during previous WS0/WS1. This will be implemented in future after the evacuation configuration is improved.

## CONCLUSION

The audits were extremely useful and the improvement of Fermilab infrastructure and assembly procedures indicated a field emission free cryomodule can be reliably achieved up to 21 MV/m in a CW measurement mode.

With additional improvement implementations planned in future, we are confident the field emission in LCLS-II type cryomodule can be eliminated that will be beyond the state of art of cryomodule assembly.

## ACKNOWLEDGEMENT

We were grateful the partner lab managements in LCLS-II project that gave us the opportunity to conduct a careful audit and implement the improvement in the middle of important cryomodule production. The result did not disappoint.

We also thank many LCLS-II team members for their hard work and support.

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