1. Introduction
Plasma processing for LCLS-II 1.3GHz SRF cavities was developed at FNAL to address in situ field emission mitigation, and it was extensively tested on individual cavities on a benchmark setup. Here plasma processing is applied for the first time to a full scale 1.3GHz cryomodule, the LCLS-II HE verification cryomodule (vCM). We compare the results of RF cold tests conducted on the vCM before and after plasma processing. We show that the vCM integrity and record-breaking performance was preserved, no field emitters were introduced maintaining the vCM field emission-free. In addition, plasma cleaning completely removed multipacting (MP) in the processed cavities. This important test enabled us to fully validate the plasma processing procedure for LCLS-II and HE CMs, showing that plasma cleaning has the capability to reduce both FE and MP in situ in CMs.

M. Dolanias, et al., NIMA 812 (2016) 50-59

2. Plasma processing for SRF cavities
Hydrocarbon ($C_nH_y$) contaminations and adsorbates → lower the cavity surface work function ($\Phi$) → increase Field Emission (FE)
Plasma processing → removes $C_nH_y$ → cavity can operate at higher $E_{acc}$

\[
\text{Gas IN} \xrightarrow{\text{RF excitation}} \text{Gas OUT} \rightarrow C_nH_y + O_2 \rightarrow CO + CO_2 + H_2O
\]

Plasma cleaning: glow discharge ignited at room temperature using inert gas (often Ne or Ar).
A low % of $O_2$ is added to react with hydrocarbons.

Plasma cleaning for LCLS-II and HE 1.3GHz cavities
Ignition accomplished using Higher order modes and HOM antennas. R&D carried out on individual 1.3GHz cavities.
Demonstrated:
- removal of hydrocarbon induced FE
- no negative effect of plasma processing on N-doping: high $Q_0$ and quench field preserved


3. Risk & mitigation analysis for vCM
Major risks for applying plasma processing to vCM:
- Unstable pressure in CM: new vacuum circuit
- FPC ignition: ‘dummy’ variable CM-style FPC installed on 9-cell cavity, tested during plasma processing on benchmark setup
- Heating of HOM cables: cables temperature monitored during plasma processing ($\Delta T < 3K$)
  Intensively tested HOM cables up to 100W for 30min: no RF degradation of cables or connectors
- Heating of cavities: decided to release the vCM insulating vacuum


4. Plasma processing plan for vCM
vCM: World record high $Q_0$ and accelerating voltage, FE-free, affected by MP-induced quenches during power rise to max gradient. All 8 cavities required MP processing.

Plasma processing for vCM:
No cavity with FE → process 4 instrumented cavities (CAV1, CAV4, CAV5, CAV8).
Parameters to monitor during plasma cleaning on vCM:
- Partial pressures of $Ne$, $O_2$, C, CO, CO$_2$, H$_2$O with RGA
- Total pressure at two ends of CM
- Temperature of HOM1 and HOM2 cables
- RF signals from/to HOMs


5. Experimental data from vCM plasma cleaning
- Observed $\Delta p = 24$mTorr between CM ends: no issue for plasma ignition or processing
- Example of experimental data collected on CAV4 including rare occurrence of plasma ignition at the HOM
  - Temperature increase on:
    - HOM1 cable < 2K
    - Cell 1 < 1.2K
    - HOM2 cable < 0.5K
    - Cell 9 < 1.6K


6. vCM performance before & after plasma processing

<table>
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<th>Cavity</th>
<th>Max $E_{acc}$ (MV/m)</th>
<th>Before Plasma Processing</th>
<th>$(Q_0 + 2M)^{1/2}$ in MV</th>
<th>MP quenches</th>
<th>After Plasma Processing</th>
<th>$(Q_0 + 2M)^{1/2}$ in MV</th>
<th>MP quenches</th>
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</tr>
</tbody>
</table>

Average: 25.1 24.7 3.0 25.1 25.1 3.1

After plasma processing:
- vCM performance are preserved
- We did not introduce any harmful contamination: vCM still FE-free

Plasma processing procedure on 1.3GHz CMs is fully validated!
Plasma cleaning can also eliminate MP:
- the 4 plasma processed cavities do not exhibit any MP quench, contrary to the other 4 cavities.

300 295

6.5 min of processing per cell

7. Conclusions
- Application of plasma processing to vCM enabled to fully validate plasma cleaning procedure for 1.3GHz CMs
- Test showed preservation of vCM performance, no introduction of FE
- Plasma processing can eliminate MP-induced quenches from CMs!
- We could address both FE and MP at the same time in situ in CMs, reducing CMs testing time, accelerator commissioning time and cost.