Fermilab

Feb 05, 2026

In-situ processing of SRF cavities in cryomodules: Potential and further R&D directions

Bianca Giaccone

GARD RF Roadmap

Many thanks to the colleagues from Argonne, Fermilab, FRIB, IJCLab, JLab, LASA, ORNL, and beyond, who contributed input to this talk, and apologies to anyone I may have missed in reaching out to.

U.S. DEPARTMENT of ENERGY

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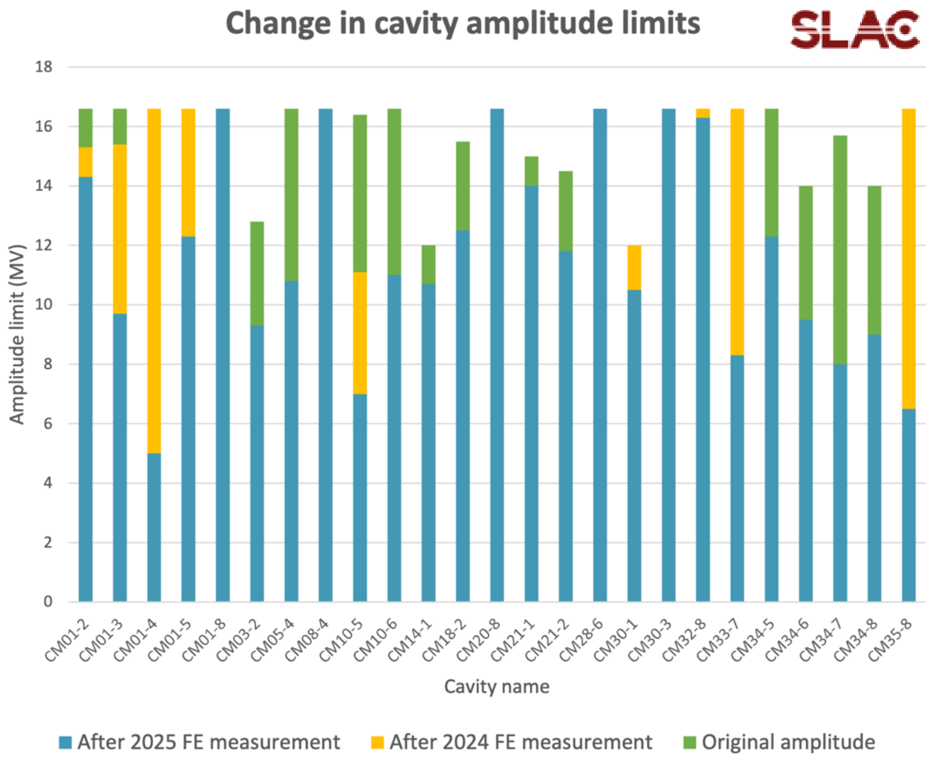
FERMILAB-SLIDES-26-0005-SQMS

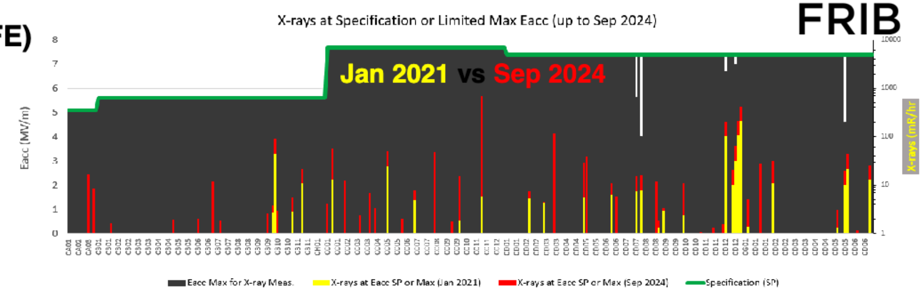
The importance of *in-situ* techniques

- Field emission has been observed to degrade over time in SRF machines (see for example SNS, CEBAF, FRIB, LCLS-SC)
- *In-situ* techniques can allow to mitigate FE and MP without requiring CM disassembly → can be applied directly in the tunnel or offline on individual cryomodules
- Huge potential gain: from LCLS-II-HE estimates rebuilding 1 CM requires 4 months of work and approximately $1.5M
- Drawbacks: *in-situ* techniques are not (yet?) effective on all types of contamination

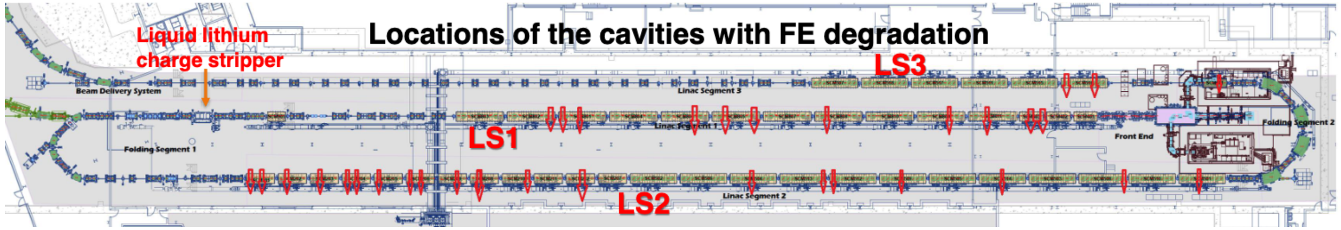


L. Alsberg, LCLS-SC Operations Status and LCLS-II-HE Upgrade. SRF25

Cavity field emission (FE) changes since end-of-commissioning

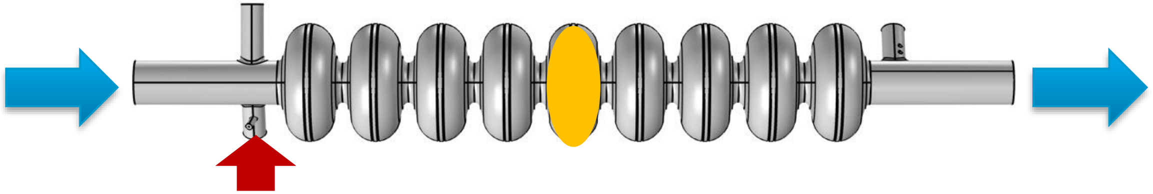


FRIB

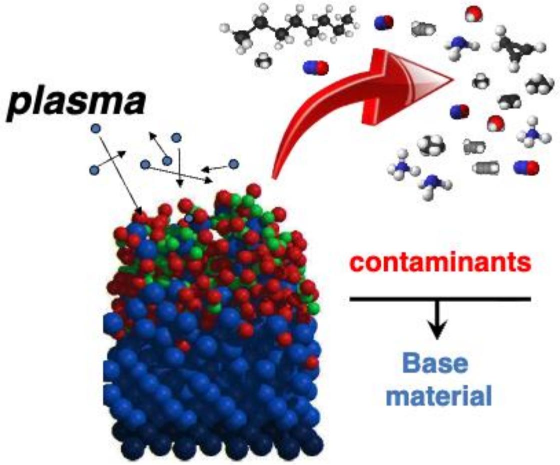


Chang, Field Emission Performance of FRIB Linac SRF Cavities. TTC2024

Intro to Plasma Processing



- Carried out at room temperature
- Flow of inert gas mixed with few % of O_2 at p ~ O(20-200) mTorr;
- Use resonant modes of the cavity to ignite a glow discharge in the RF volume O(10-100)W. Once plasma is ignited, reactive oxygen reacts with hydrocarbons;
- Volatile byproducts (mostly CO, CO_2, H_2O) are pumped out;
- Work function increases, reducing FE.



M. Doleans et al, NIMA 812 (2016)

Increasing Φ by 10% means increasing E_{acc} of about 15%

$$j = \beta \frac{AE^2}{\Phi} e^{-B\frac{\Phi^{3/2}}{\beta E}}$$

$$dj = 0 \qquad \frac{dE_{acc}}{E_{acc}} \approx \frac{3}{2}\frac{d\Phi}{\Phi}$$

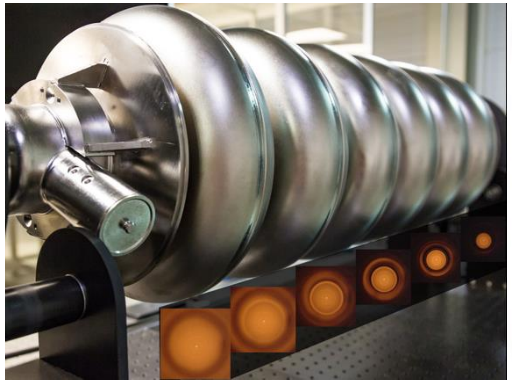
J: current density
E: surface electric field
Φ: work function
β: enhancement factor (≈10 to 100)
A, B: constants

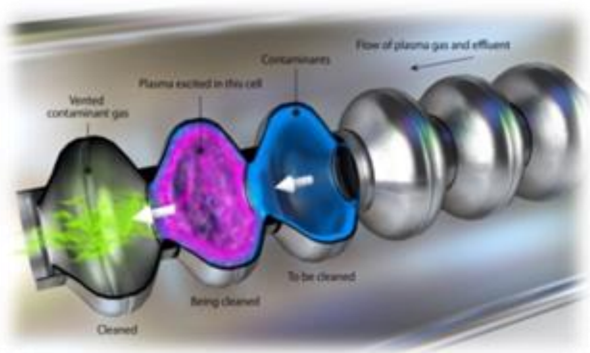
- Plasma ignition causes change in dielectric constant → the whole process can be followed via RF diagnostics (VNA, power sensors)

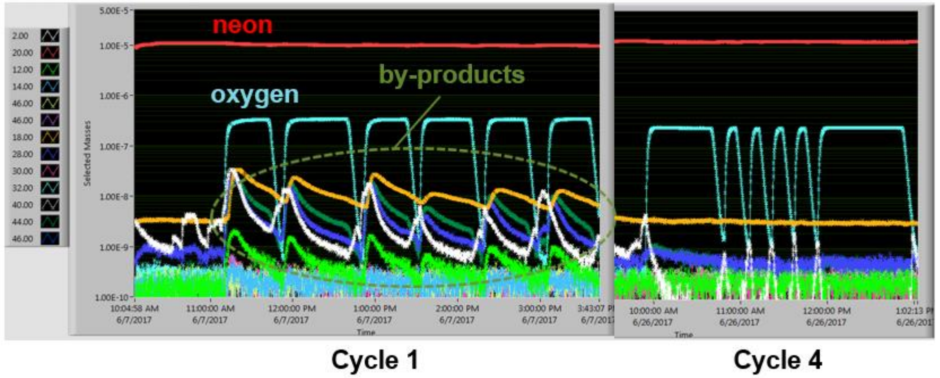
ORNL

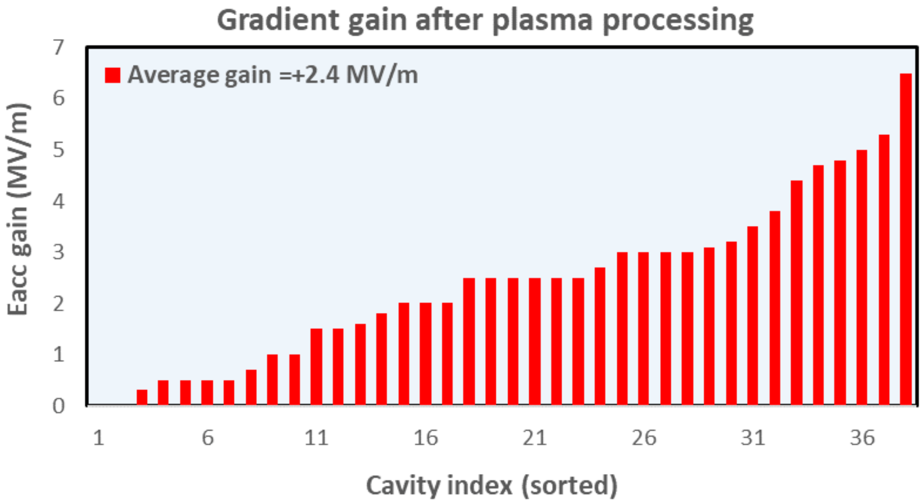
Oak Ridge National Laboratory

- TM_{010} dual tone ignition (on resonance + off resonance), Ne+O_2
- 10 cryomodules plasma processed at SNS either in offline facilities or directly in the linac tunnel
  - 8 High-beta CMs
  - 2 Medium-beta CMs
- Cleaning of the cavity surfaces revealed by the significant reduction of by-products' partial pressures over time
- **38 cavities plasma processed at SNS with an average E_{acc} increase of 2.4 MV/m**





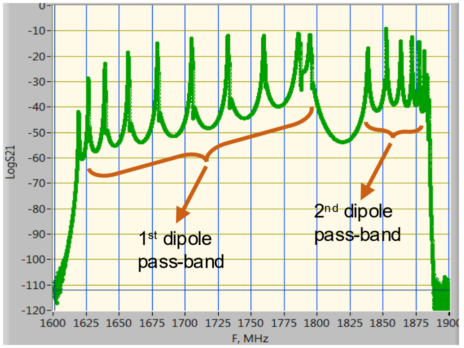


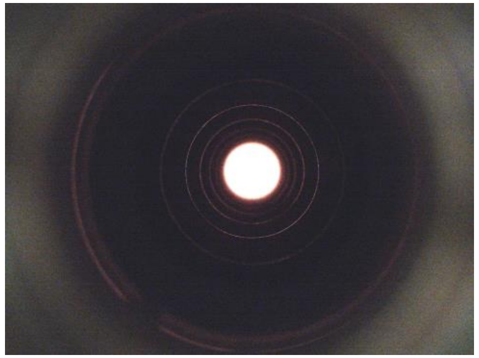


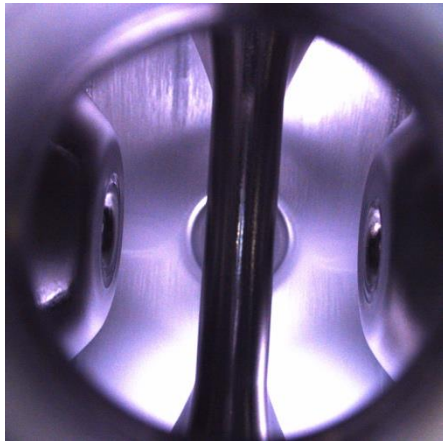
M. Doleans *et al.*, NIMA 812 (2016);
M. Doleans *et al.*, J. Appl. Phys., 120, 243301 (2016)

Fermilab

- Started from BES grant: from SNS experience, collaboration of Fermilab, SLAC and ORNL to develop plasma processing for **LCLS-II**
- Fermilab developed method that uses HOM modes and couplers to ignite plasma in central cell and transfer it via mode superposition. Gas mixture: 50-150 mTorr, O_2 partial pressure ~ 1-2.5% of Ne
- Successfully applied method to several individual cavities and the LCLS-II-HE vCM demonstrating effectiveness on hydrocarbon-induced FE and MP!
- Extended method to ILC cavities (≠ HOM couplers)
- Now focusing on **PIP-II cavities**: **SSR1** (with IJCLab), **SSR2**, and **650LB** (with INFN LASA and CEA Saclay)





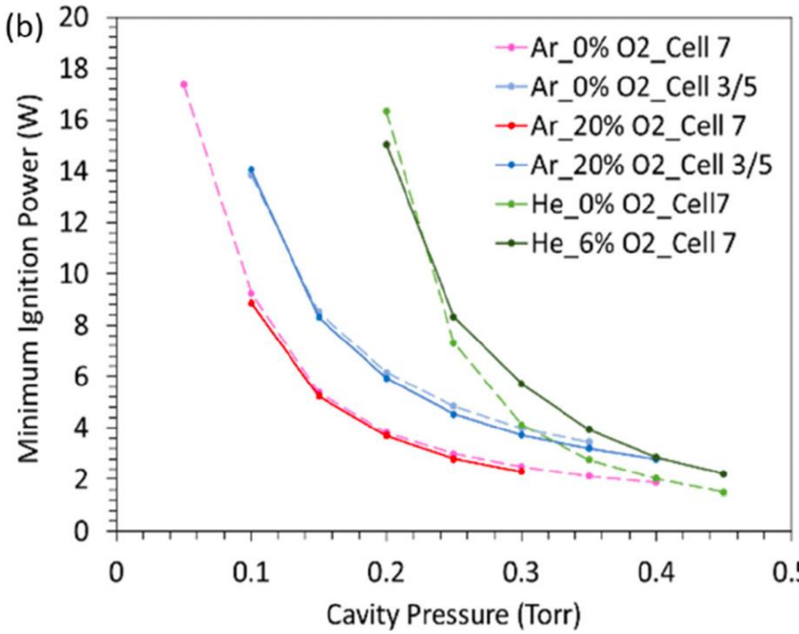


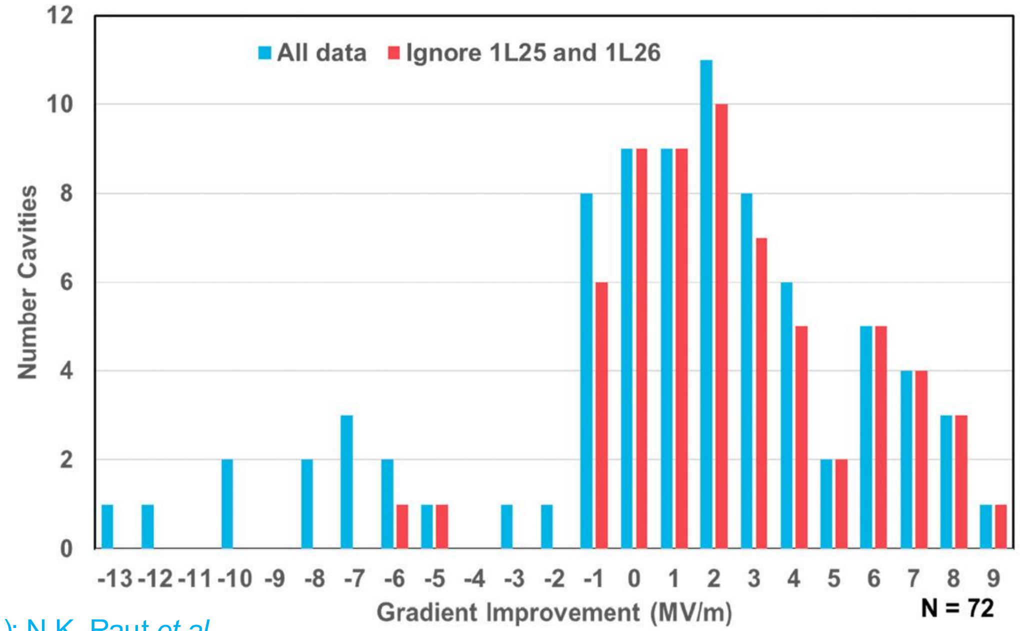
- LCLS-II(-HE): P. Berrutti *et al.*, J. Appl. Phys. 126, 023302 (2019); B. Giaccone *et al.*, Phys. Rev. Accel. Beams 24, 022002 (2021); B. Giaccone *et al.*, Phys. Rev. Accel. Beams 25, 102001 (2022)
- PIP-II: D. Longuevergne *et al.*, doi:10.18429/JACoW-SRF2025-MOP43 (2025); E. Del Core *et al.*, doi:10.18429/JACoW-SRF2025-TUP41 (2025); B. Giaccone *et al.*, MOP42 at SRF25 (2025)

JLab Jefferson Lab

- Developed method for C100 and C75 cavities using Argon/Oxygen or Helium/Oxygen mixture and HOM and HOM couplers
- Processed 15 CMs (both C100 and C75) in CEBAF tunnel (10) and in offline facility (5)
  - Average improvement on all cavities: 1.82MV/m; excluding 2 problematic CMs: 2.3MV/m
- Built 6 RF test stands, 3 clean pumping systems, 2 gas supply systems
- Simulation studies to understand gas dynamics in CEBAF cavities

C100 Off-Line Bench Setup





T. Powers *et al.*, arXiv:2204.02903 (2022); T. Powers *et al.*, doi:10.18429/JACoW-SRF2023-WEPWB054 (2023); N.K. Raut *et al.*, doi:10.18429/JACoW-SRF2023-WEPWB053 (2023); T. Powers *et al.*, THXA005 LINAC24 (2024); T. Powers, TTC24 Lund (2024); T. Powers, 2025 NP Accelerator R&D PI Exchange Meeting

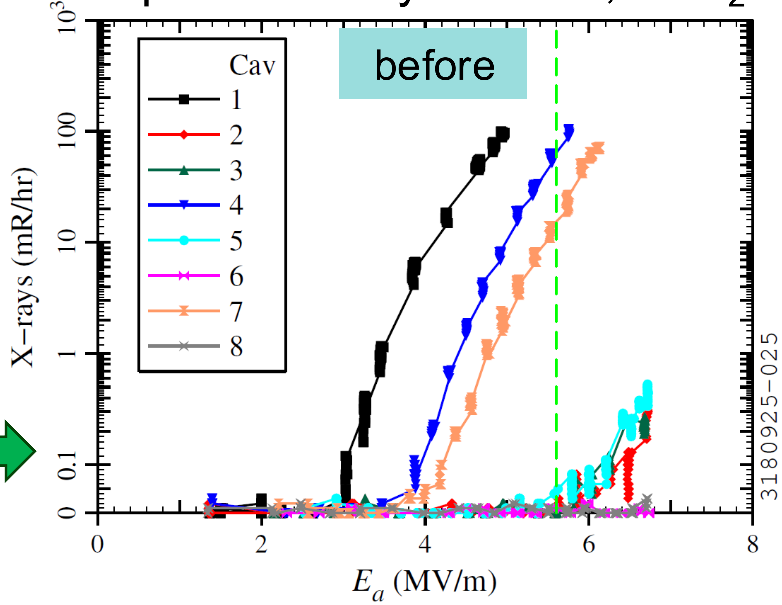
FRIB-MSU

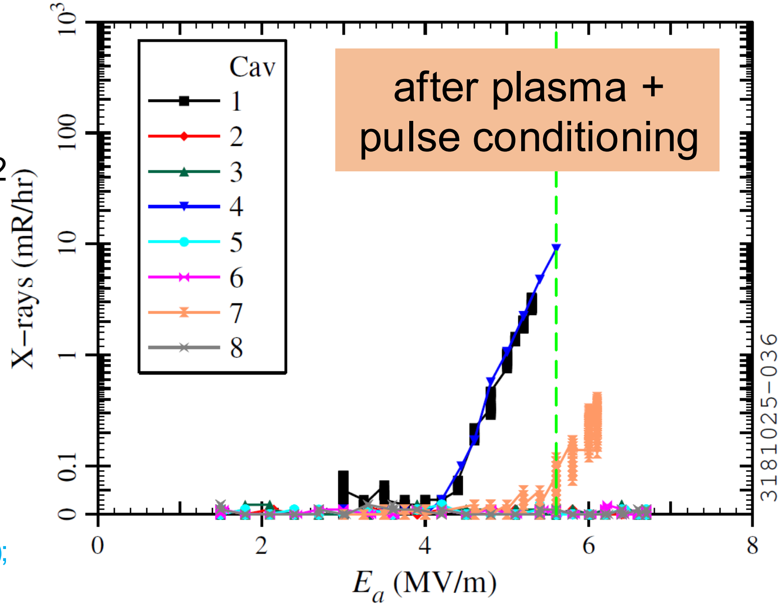
FRIB

Challenges
- Little prior experience with QWRs & HWRs
- FRIB FPCs are poorly matched at room temperature; no HOM couplers
- Limited plasma visibility from access ports

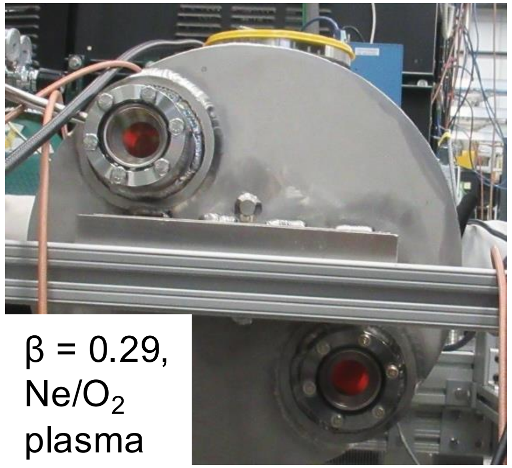
Early implementation phase: β = 0.085 QWRs
- TEM 5λ/4 mode (404 MHz)
- In-bunker plasma processing: Jan 2024
- First in-tunnel plasma processing: Summer 2025
- In progress: optimization

β = 0.085 cryomodule, Ar/O_2

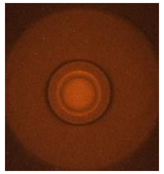




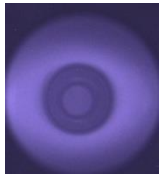
Development phase: HWRs
- Fundamental mode (322 MHz)
- β = 0.53: cold-test results are promising
- β = 0.29: early stages
- DC bias on FPC (per IJCLab): helpful to raise coupler ignition threshold



β = 0.29, Ne/O_2 plasma



Ne/O_2, TEM λ/2



Ar, dual-drive

β = 0.53

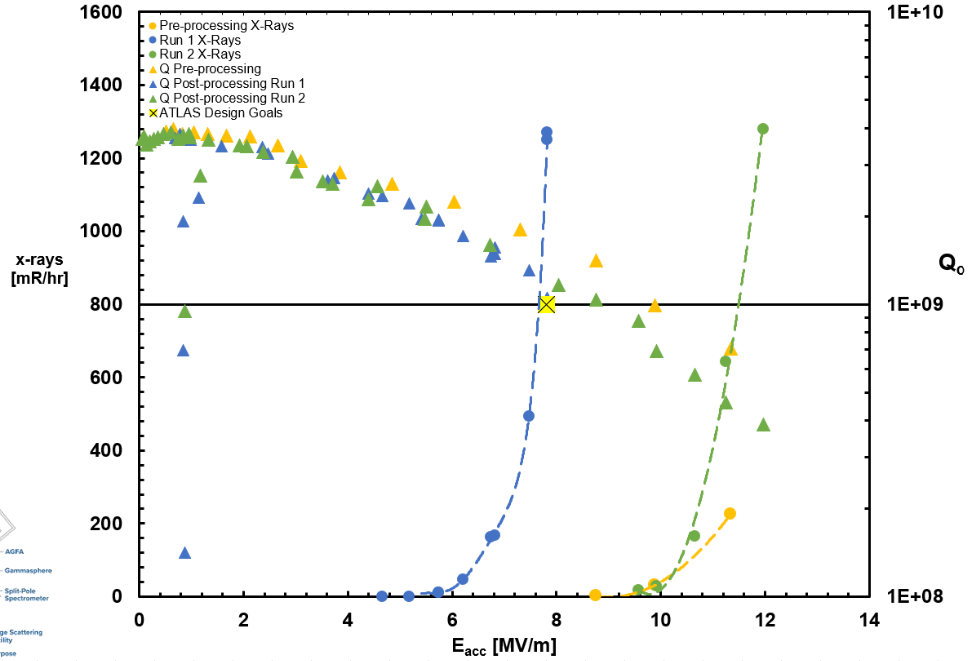
Benefiting from informal collaboration with other β < 1 plasma processing teams

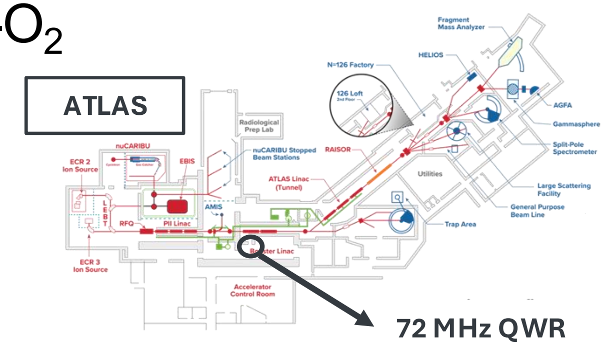
W. Hartung *et al.*, doi:10.18429/JACoW-SRF2023-THIXA01(2023); P. Tutt *et al.* doi:10.18429/JACoW-SRF2023-WEPWB127 (2023); W. Hartung et al., doi:10.18429/JACoW-HIAT2025-TUC03 (2025), Z. Hosek et al., doi:10.18429/JACoW-HIAT2025-TUP08 (2025); P. Tutt *et al.* TUB05 at SRF25 (2025), W. Hartung et al., PRAB 29, 102003, doi:10.1103/psx7-jp78 (2026).

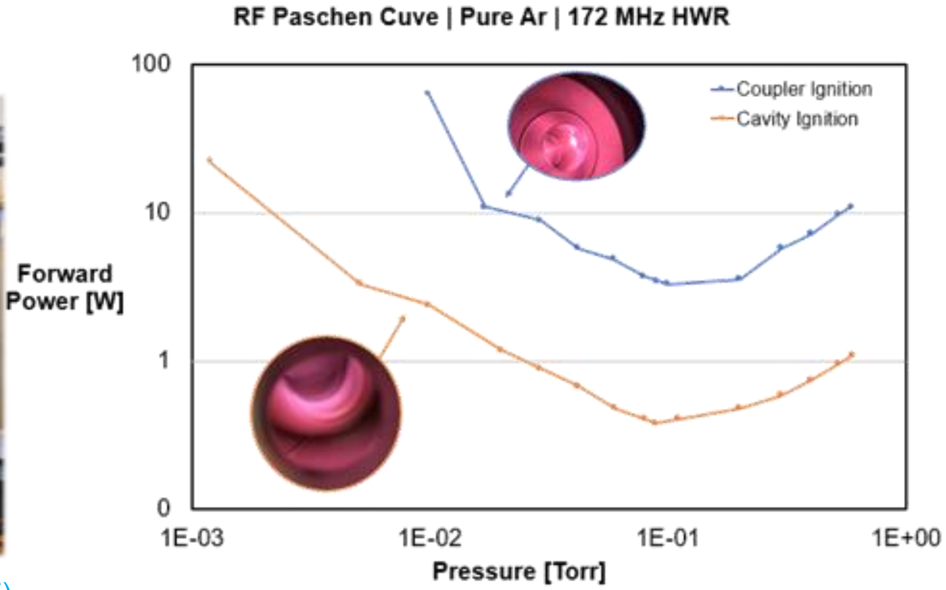
Argonne

Argonne NATIONAL LABORATORY | Argonne Tandem Linac Accelerator System

- Develop plasma cleaning for the ATLAS superconducting linac
- Developed method for 72MHz QWR using fundamental mode and HOMs and for 172HWR, working at 50-90mTorr with $Ar\text{-}O_2$
- Demonstrated offline that method can mitigate FE after accidental valve incident
- The first online processing of ATLAS is currently underway!
- **1st direct comparison of PP and He pulse processing on same ATLAS cavity coming in March 2026**

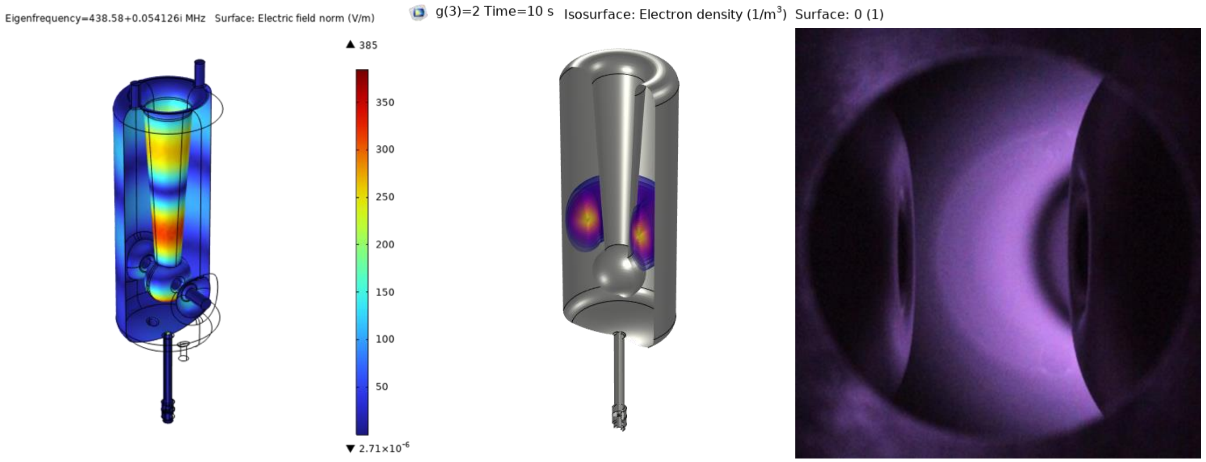


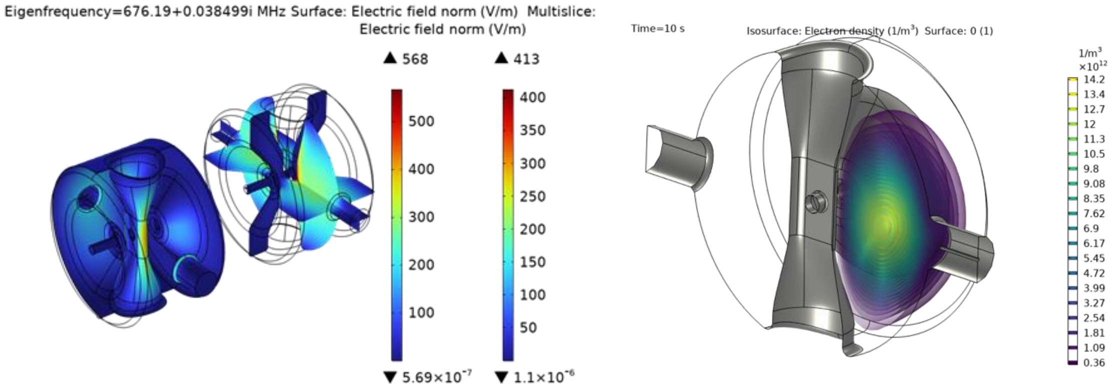


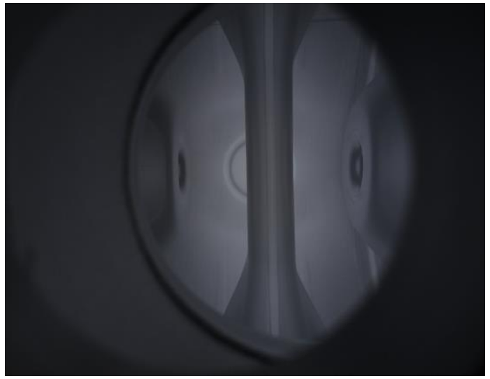


M.E. McIntyre *et al*., doi:10.18429/JACoW-SRF2023-MOPMB049 (2023); M.E. McIntyre *et al*., TUP44 SRF25 (2025)

- **Past and Ongoing Activities**
  - **Development of plasma processing procedures for SPIRAL2 QWR (β=0.12)**
    - Use of HOMs to drive the plasma
    - Optimization of processing parameters through plasma diagnostics:
      - Langmuir probe (measures plasma parameters: n_e, T_e, V_p, EEDF…)
      - Optical Emission Spectroscopy (OES)
      - Quartz crystal microbalance (measure decontamination rate)
  - **Plasma simulations with COMSOL Multiphysics**
    - Help to understand plasma parameters and dynamics
  - **Collaboration with Fermilab: plasma processing of PIP-II/SSR1 spoke cavities**





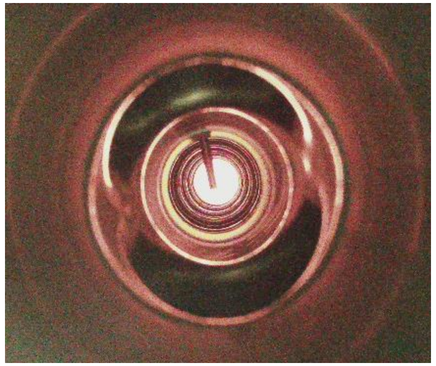


C. Cheney, TTC2023; D. Longuevergne *et al.*, doi:10.18429/JACoW-SRF2025-MOP43 (2025);
C. Cheney et al., TUB06C SRF25 (2025)

INFN LASA

Present Activities:

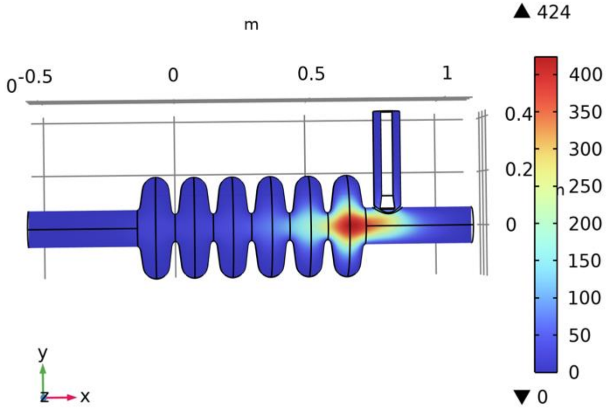
E. Del Core *et al.*, doi:10.18429/JACoW-SRF2025-TUP41 (2025)



- 704.4 MHz MB ESS:
  - Bare cavity. Ignition of an N_2 plasma and bridging across all six cells using a custom and well-coupled antenna.
- 704.4 MHz HB ESS:
  - RF Measurements through FPC and PU on cavities in string in Cryomodule and corresponding simulations to identify suitable modes for plasma processing.

Future Activities:

- Dedicated gas injection and vacuum chart under development, compatible with the ESS and PIP-II cryomodule setup.
- MB ESS:
  - Plasma processing via FPC on bare cavity— suitable modes identified. Waiting for coupler and adapter from CEA/ESS
  - Move from N_2 to Ar/O_2 mixture and implement residual gas monitoring system
- PIPII LB650:
  - PP on a prototype cavity 001 using the FNAL FPC. Components assembly on-going. Simulations studies completed.

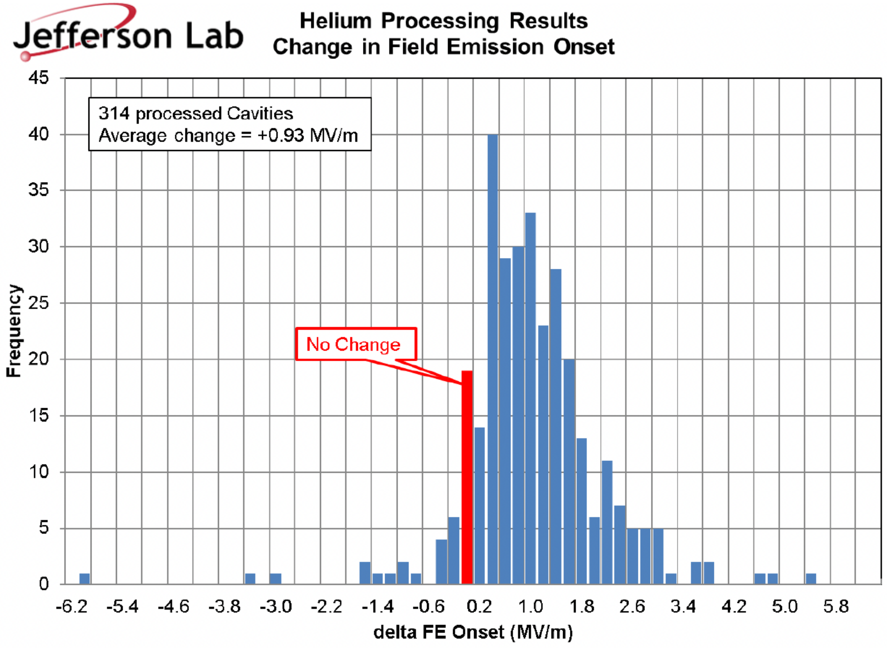


These activities are part of a collaboration between INFN-LASA, ESS, CEA and FNAL

Helium RF Processing

- Carried out at cryo-temperature
- Hundreds to kW power to drive the cavity at gradients above FE onset
- FE e⁻ ionize He gas near the FE site, He ions strike the surface
- After He processing, the CM is actively pumped and cycled to 40K to remove the gas
- He processing at CEBAF (2K, 0.4 mTorr): T. Powers, TTC24 Lund (2024)
  - 1997 and 2015 campaigns. In 2015: 314 cavities in 45 CMs with 201MeV net gain corresponding to average increase in FE onset =0.93MV/m. In 1997 it was 1.4MV/m. In 2015: He processing did not work well in C100 CMs
- He pulse conditioning at ATLAS (4K, 0.05 mTorr): M. Kelly, M. McIntyre, private communications
  - Has been used for decades
  - Latest campaign on 72MHz QWR: 7 cavities in Nov 2025, consistent 15% improvement
  - 1st direct comparison of PP and He pulse processing on same ATLAS cavity coming in March 2026

Jefferson Lab



[2] Drury, et. al., Results of the 2015 helium processing of CEBAF cryomodules, NAPAC 2016

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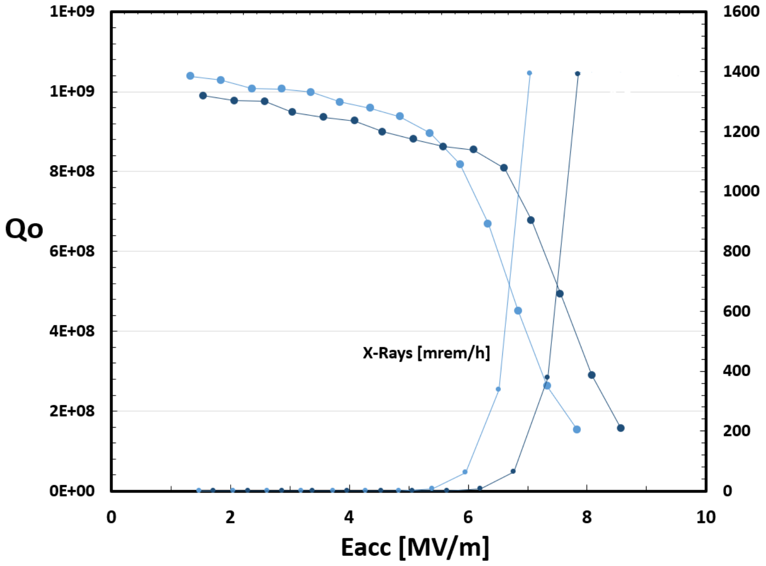
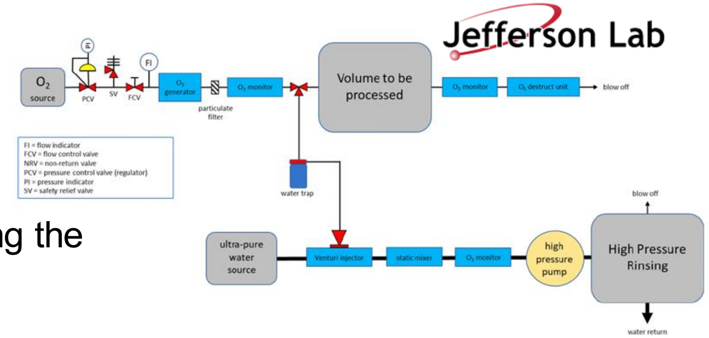


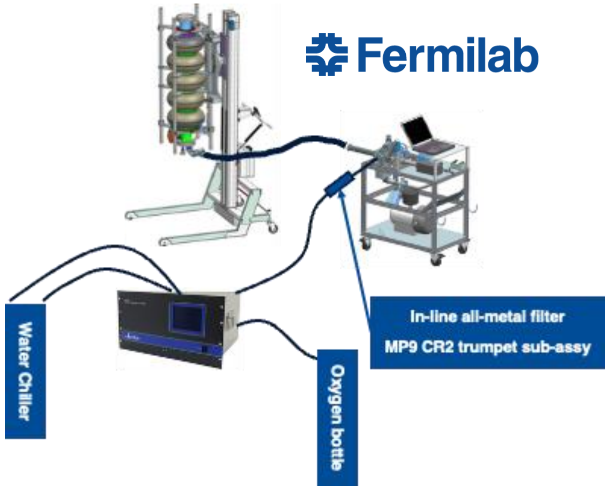
Ozone Processing

Ozone (O_3): formed from O_2 by UV light or electric discharge, half life depends on environmental conditions, O(few hours). Poses a potent respiratory hazard (~50ppm over 30min). Widely used for a variety of applications (water and food treatment, semiconductor industry).

- JLab: in situ O_3 processing at ~83-84℃ for O(5-10 h) with 6-8 wt% and 0.7 l/min applied to 2(+) cavities → treatment decreased FE and did not affect the cavity performance negatively! R. Ruber, Phys. Rev. Accel. Beams 27, 122001 (2024) & JLab Seminar 03/06/2025
  - Similarly to plasma processing, O_3 treatment increases the Nb work function, decreasing FE
  - Subsequent Methane processing (used by T. Powers as controlled contamination in plasma experiments) was not effective after O_3 processing
  - Ozone is an effective cleaning agent, hypothesized to improve the Nb_2O_5 surface layer reducing the adsorption of hydrocarbons
  - Similar effectiveness to plasma processing, but simple and promising method for all cavity shapes
  - Further studies are needed/underway to test effect of O_3 on other CM components/materials such as ion pumps and ferrite of HOM loads

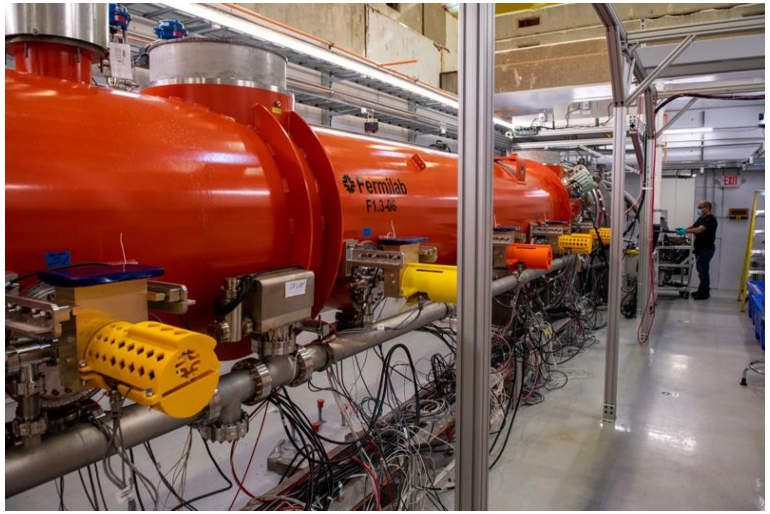


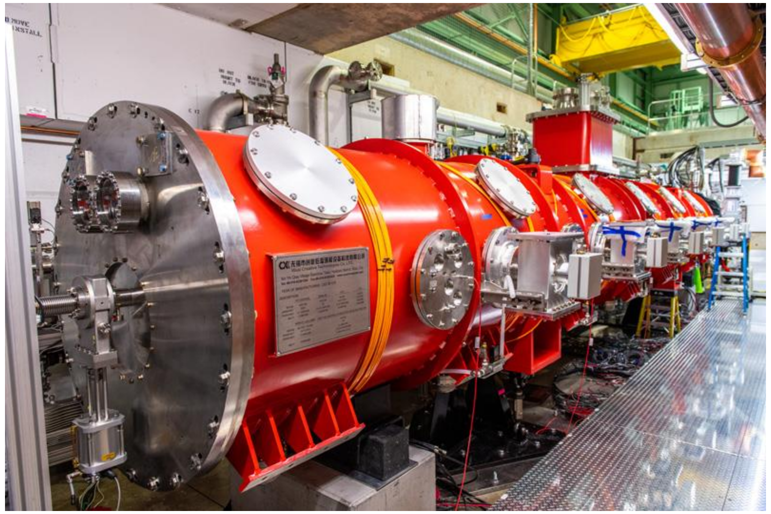
- Fermilab: In early stages of system design and procurement, focused on O_3 in situ processing only (no ozonized HPR) G. Wu, V. Chou, private communications
  - Immediate goal: validate no harm to cavity processing (EP/120℃, N-doping, Mid-bake, …), no harm to coupler ceramic and copper plating; test and treat cavity with FE and optimize the recipe
  - Longer term goal: demonstrate routine effectiveness of the treatment and being able to apply it to string assembly, cryomodule, reducing both MP and FE



Potential and Further R&D Directions

- Need to develop clear understanding of complementarity and applicability of the three *in-situ* techniques
- Some R&D aspects are common to the three techniques (at different levels):
  - Need for improved understanding of the phenomena (empirical vs fundamental understanding)
  - Studies on safety or effects of the techniques on other CM components
  - Recipe optimization
  - Mitigation of risks for applying the techniques in CMs





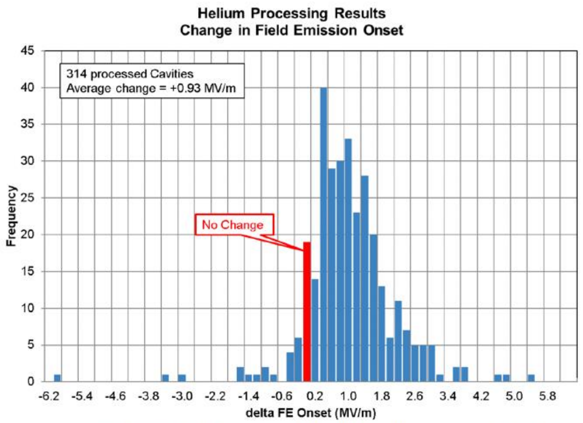
Potential and Further R&D Directions

- Plasma processing:
  - General aspects:
    - Material sciences studies (if/how does plasma alter Nb surface and its oxides, SEY impact) without breaking the vacuum and plasma diagnostics to drive recipe optimization;
    - Further develop finite element simulations of Plasma and RF drive (JLab, IJCLab, MSU);
    - Alternative approaches (different gases achieving different results, different modes);
    - Can we address other FE sources beyond hydrocarbons? → extend plasma capabilities
  - Cavity/Coupler specific: Develop/safely apply method to other cavity geometries in CMs (ad hoc)
- Helium processing:
  - More well-established technique, but improved understanding could be beneficial to improve efficiency of processing, reproducibility of results and reducing risk of damaging couplers or windows
- Ozone processing:
  - Newer/recently rediscovered technique, more R&D still needed to solidify its initial promising results
  - Test effect on cavity surface treatments and on other materials and components used in CM
  - Recipe optimization
  - Demonstrate deployment on full CM

Improving Project Performance with *In-Situ* Techniques

Jefferson Lab — CEBAF

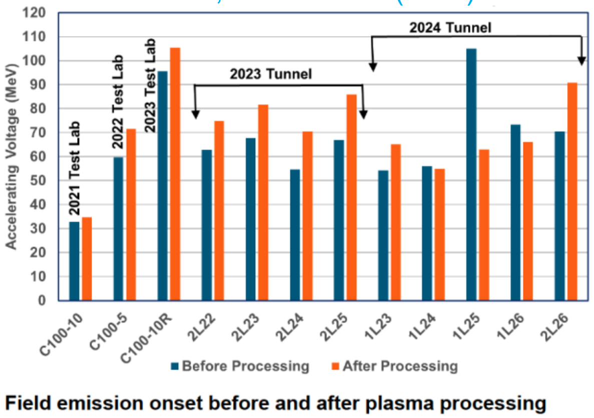
He Processing: avg improvement 1.4MV/m (1997) and 0.93MV/m (2015) giving net gain 63 MeV (90 cavities) + 201 MeV (314 cavities)



[2] Drury, et. al., Results of the 2015 helium processing of CEBAF cryomodules, NAPAC 2016

T. Powers, TTC24 Lund (2024)

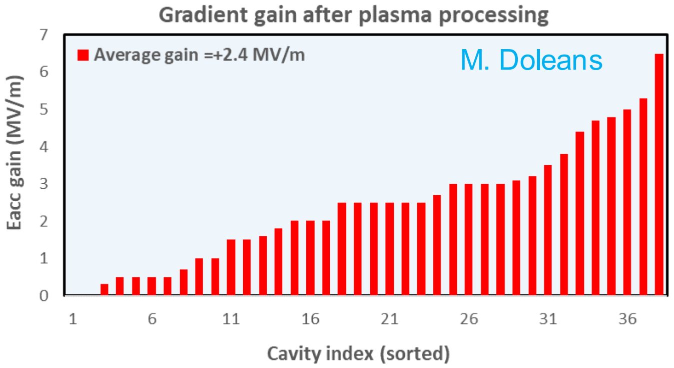
Plasma Processing: applied to 15 CMs, avg improvement 2.3MV/m



T. Powers, 2025 NP Accelerator R&D PI Exchange Meeting

Oak Ridge National Laboratory — SNS

Plasma Processing: 10 CMs (high and medium beta), 38 cavities avg increase of 2.4 MV/m



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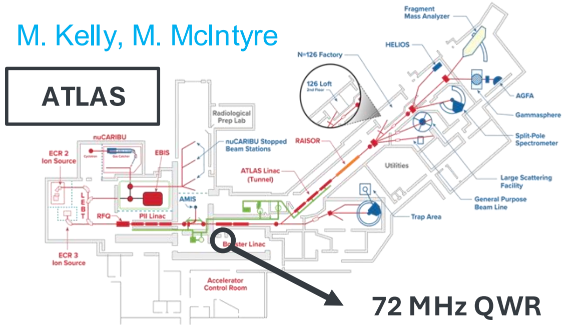
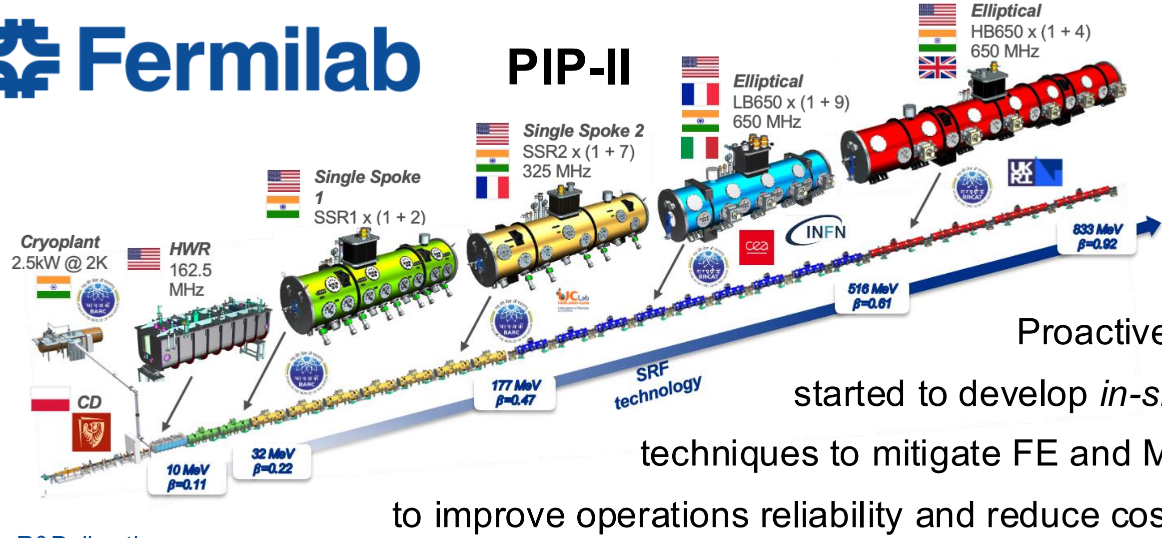
M. Kelly, M. McIntyre



He Processing: latest campaign demonstrated 15% improvement

Fermilab — PIP-II



Proactively started to develop *in-situ* techniques to mitigate FE and MP to improve operations reliability and reduce costs

Summary of Future Directions

- Short Term R&D:
  - Optimize recipes and demonstrate, when needed, applicability to full sized CMs (ozone processing, plasma processing for new geometries)
- Mid/Long Term R&D:
  - Gain better fundamental understanding of the physical phenomena and diagnostic techniques
  - Deploy ozone treatment as a safe and simple technique to address hydrocarbon-induced FE and MP in CMs
  - Extend plasma processing applicability beyond hydrocarbon contamination
- Long Term Goal:
  - Having a set of techniques that can be deployed on CMs *in-situ* as needed, safely and readily to recover performance affected by FE and/or MP for current and future projects


Thank you!

Fermilab

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