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Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Plasma processing for *in situ* performance improvement

Bianca Giaccone

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Outline

- Introduction on plasma processing
- Plasma processing applied to LCLS-II-HE vCM
- Plasma processing experience at other laboratories
- Proposal to apply plasma processing to CM2

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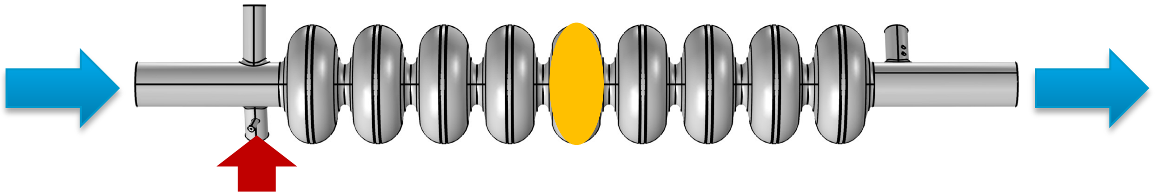
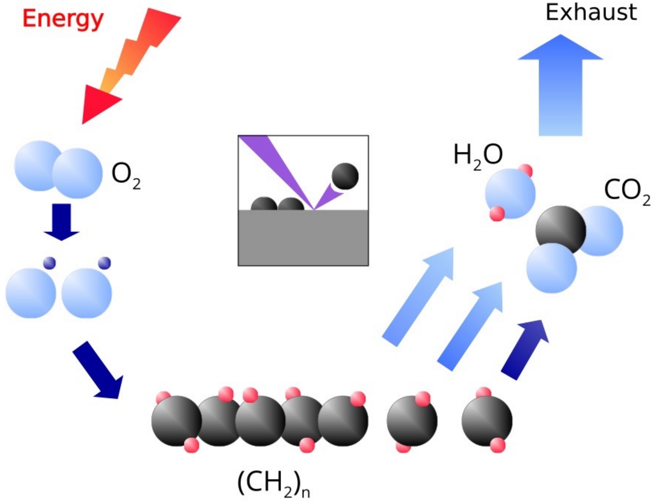
Plasma processing (PP) for field emission mitigation



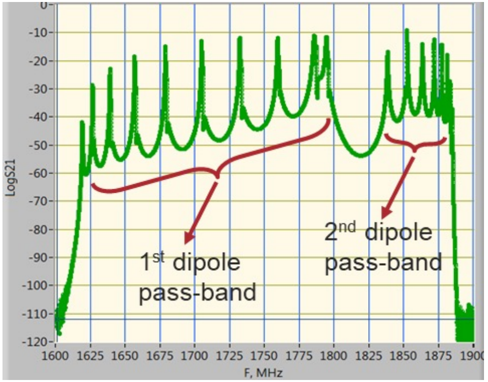
- Gas flow of Ne-O_2 mixture (few % of O_2, mostly Ne) at p ~ 75-150mTorr;
- Once plasma is ignited, oxygen reacts with hydrocarbons;
- Reaction products (mostly CO, CO_2, H_2O) are pumped out;
- Work function increases, reducing FE.

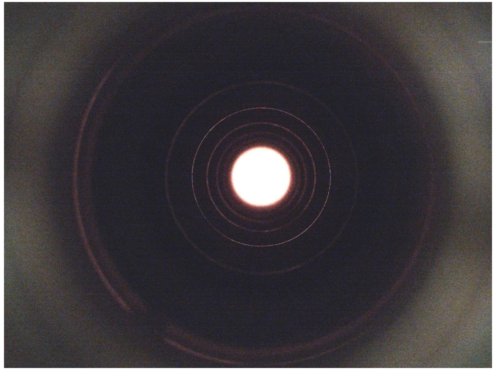


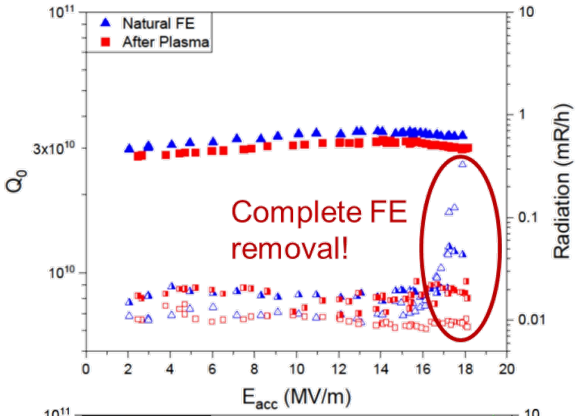
M. Doleans et al, NIMA 812 (2016)

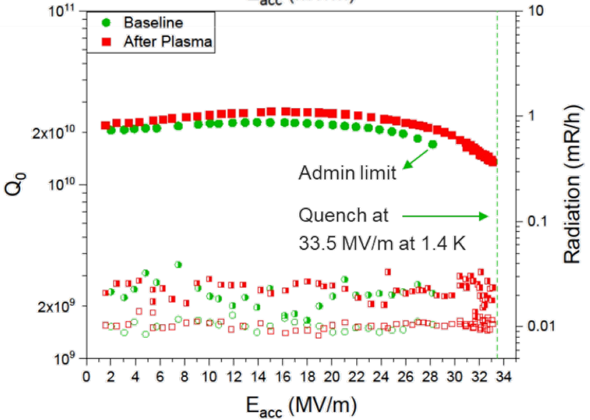
PP for LCLS-II(-HE): individual cavities

- Plasma ignition sequentially cell-by-cell using HOM modes and antennas
- Plasma is ignited in the central cell and moved to adjacent cells using a superposition of HOMs
- We demonstrated removal of hydrocarbon induced FE
- And no negative effect of plasma processing on N-doping: high Q_0 and quench field are preserved









P. Berrutti, et al., J. Appl. Phys. 126, 023302 (2019)
B. Giaccone et al., Phys. Rev. Accel. Beams 24, 022002

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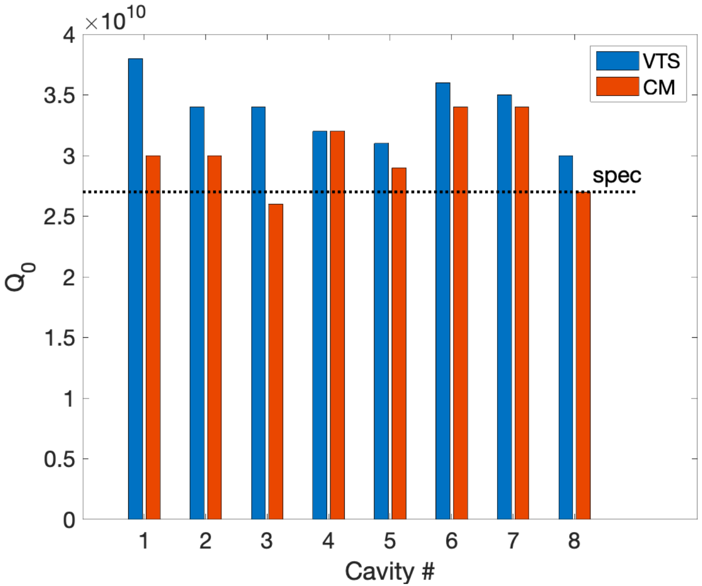
The LCLS-II-HE verification cryomodule (vCM)

- Verification cryomodule → opportunity to: verify assembly and testing procedure at Fermilab and evaluate operations of 1.3GHz CMs at higher gradient

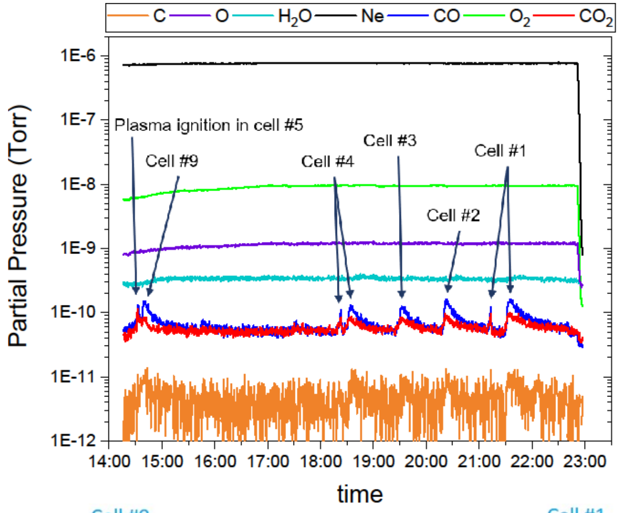
World record breaking performance, considerably above the ambitious specification!

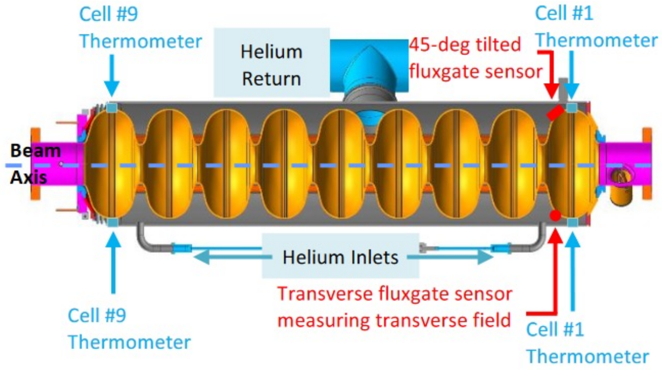


S. Posen et al., Phys. Rev. Accel. Beams 25, 042001

Preparation for PP on the vCM

- Conducted risk & mitigation analysis for vCM
- Parameters monitored during PP:
  - Partial pressure of Ne, O_2, C, CO, CO_2, H_2O
  - Pressure at the two ends of the cryomodule
  - RF signals (forward & reflected power from HOM1, transmitted power from HOM2)
  - Temperature of HOM1 cable connector, can and clamp
  - Cavity temperature
- We decided to process 4 cavities





Experimental systems: gas injection, vacuum & RF

Gas cart – connected to Feedcap side

Vacuum cart – connected to Endcap side

RF system, computers

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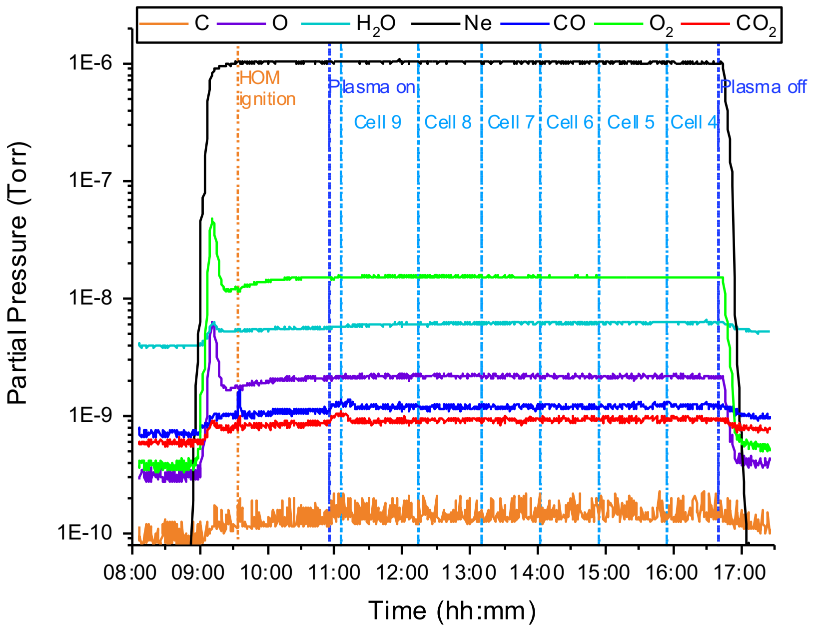
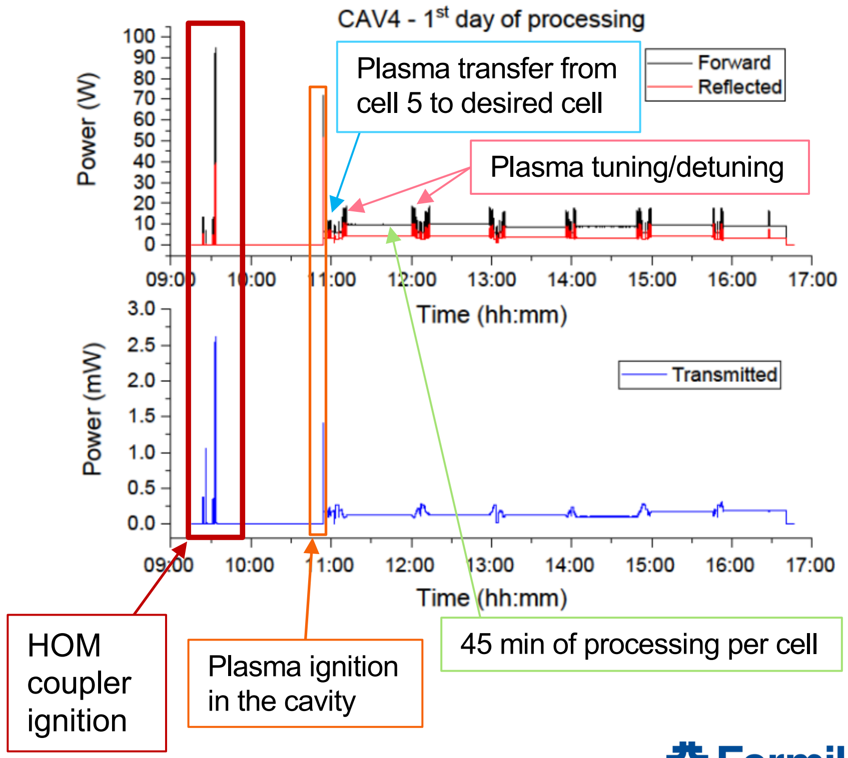
Connections between gas/vacuum systems and CM

Connections between vacuum/gas systems and vCM: conducted in cleanroom to minimize risk of particle contamination

PP applied to vCM (1)

Example of experimental data collected during plasma processing of CAV4. This includes a rare case of plasma ignition at the HOM coupler





B. Giaccone, et al., Phys. Rev. Accel. Beams 25, 102001 (2022)

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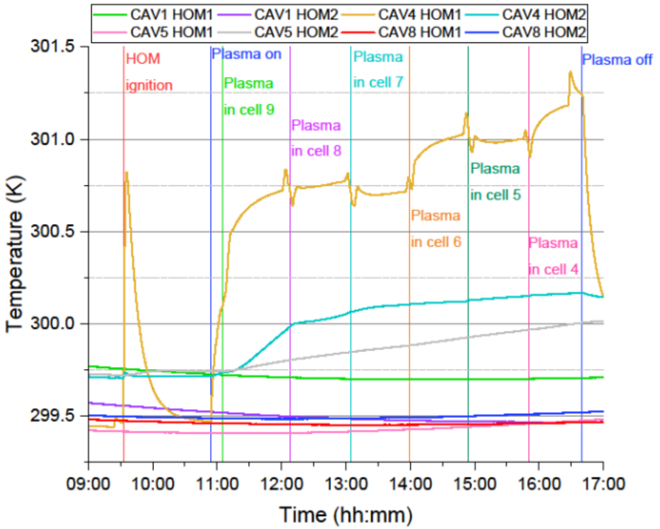
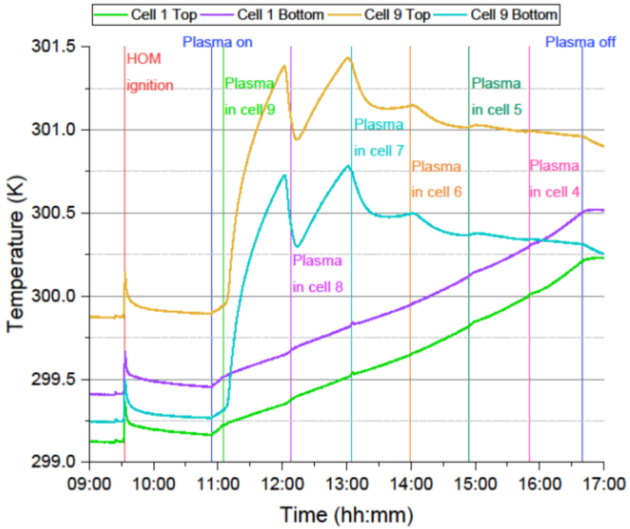
PP applied to vCM (2)

Example of experimental data collected during plasma processing of CAV4. This includes a rare case of plasma ignition at the HOM coupler





Temperature increase on:

- HOM1 cable < 2K
- HOM2 cable < 0.5K

During coupler ignition: 1.4K increase on HOM1 cable

Temperature increase on:

- Cell # 1 < 1.2K
- Cell # 9 < 1.6K
- During coupler ignition: 0.3K

B. Giaccone, et al., Phys. Rev. Accel. Beams 25, 102001 (2022)

Questions to address after PP

RF test after processing to monitor changes in performance:

- Maximum gradient and usable gradient
- X-ray & Dark current
- Q-factor at 20.8 MV/m
- Check that cavities can sustain stable operation at 20.8 MV/m
- Time necessary to process multipacting

- Did plasma processing deteriorate cavity performance in any way?
- Did plasma processing have an impact on multipacting?

B. Giaccone, et al., Phys. Rev. Accel. Beams 25, 102001 (2022)

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vCM performance before and after plasma processing

Cavity	Before Plasma Processing Max E_{acc} (MV/m)	Usable E_{acc} (MV/m)	Q_0 at 21 MV/m $\times 10^{10}$	MP quenches	After Plasma Processing Max E_{acc} (MV/m)	Usable E_{acc} (MV/m)	Q_0 at 21 MV/m $\times 10^{10}$	MP quenches
1	**23.4**	**22.9**	**3.0**	**Yes**	**23.8**	**23.3**	**3.4**	**No**
2	24.8	24.3	3.0	Yes	25.2	24.7	3.2	Yes
3	25.4	24.9	2.6	Yes	26.0	26.0	3.4	Yes
4	**26.0**	**26.0**	**3.2**	**Yes**	**26.0**	**26.0**	**3.2**	**No**
5	**25.3**	**24.8**	**2.9**	**Yes**	**25.5**	**25.0**	**2.8**	**No**
6	26.0	25.5	3.4	Yes	26.0	26.0	3.2	Yes
7	25.7	25.2	3.4	Yes	25.9	25.4	3.3	Yes
8	**24.4**	**23.9**	**2.7**	**Yes**	**24.7**	**24.2**	**2.6**	**No**
Average	25.1	24.7	3.0		25.3	25.1	3.1	
Total	209	205			210	208		

RF test after plasma processing demonstrated that:

- **vCM performance** are **preserved**
- Plasma processing did not introduce any contamination: **vCM still FE-free**

B. Giaccone, et al., Phys. Rev. Accel. Beams 25, 102001 (2022)

vCM performance before and after plasma processing

Cavity	Before Plasma Processing: Max E_{acc} (MV/m)	Before Plasma Processing: Usable E_{acc} (MV/m)	Before Plasma Processing: Q_0 at 21 MV/m $\times 10^{10}$	Before Plasma Processing: MP quenches	After Plasma Processing: Max E_{acc} (MV/m)	After Plasma Processing: Usable E_{acc} (MV/m)	After Plasma Processing: Q_0 at 21 MV/m $\times 10^{10}$	After Plasma Processing: MP quenches
1	**23.4**	**22.9**	[illegible]	[illegible]	[illegible]	[illegible]	**3.4**	**No**
2	24.8	24.3	[illegible]	[illegible]	[illegible]	[illegible]	3.2	Yes
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Average	25.1	24.7	[illegible]		[illegible]	[illegible]	3.1	
Total	209	205			[illegible]	208		

Plasma processing procedure is fully validated!

RF test after plasma processing demonstrated that:

- **vCM performance** are **preserved**
- Plasma processing did not introduce any contamination: **vCM still FE-free**

B. Giaccone, et al., Phys. Rev. Accel. Beams 25, 102001 (2022)

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vCM performance before and after PP

B. Giaccone, et al., Phys. Rev. Accel. Beams 25, 102001 (2022)

	Before Plasma Processing				After Plasma Processing			
Cavity	Max E_{acc} (MV/m)	Usable E_{acc} (MV/m)	Q_0 at 21 MV/m $\times 10^{10}$	MP quenches	Max E_{acc} (MV/m)	Usable E_{acc} (MV/m)	Q_0 at 21 MV/m $\times 10^{10}$	MP quenches
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Total	209	205			210	208		

Plasma processing **can eliminate multipacting:**

- **the 4 plasma processed cavities do no exhibit any MP quench**, contrary to the other 4 cavities

We could **address both FE and MP in situ at the same time!**

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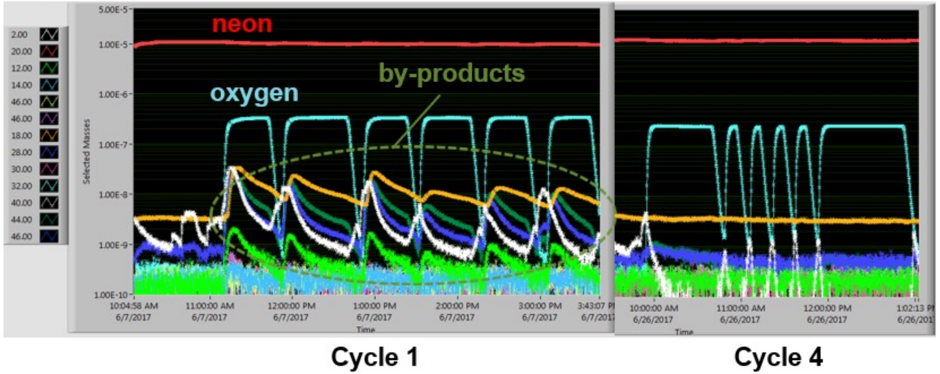
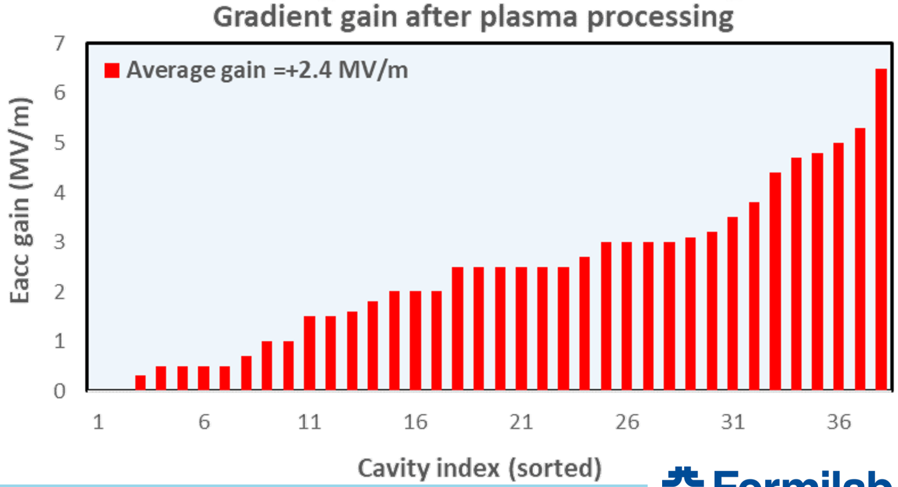
PP at ORNL-SNS

- 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

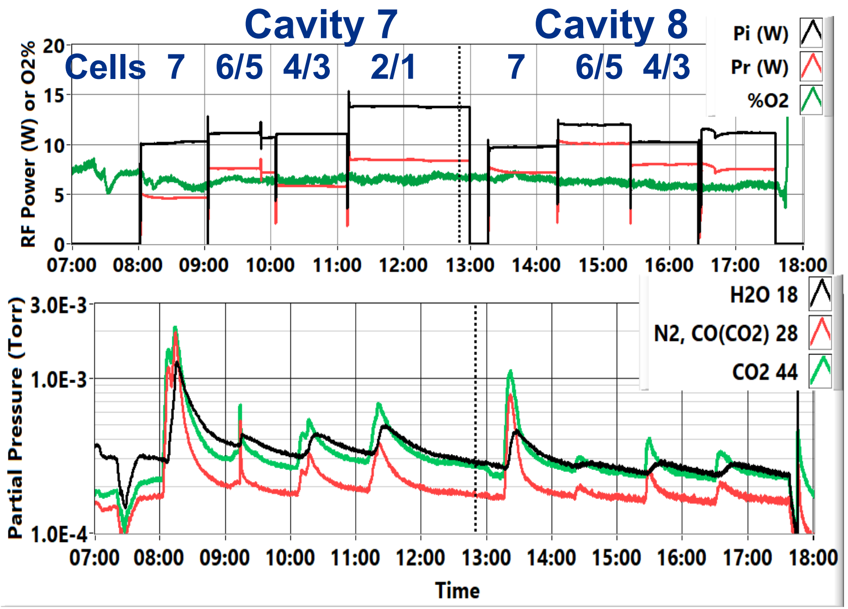




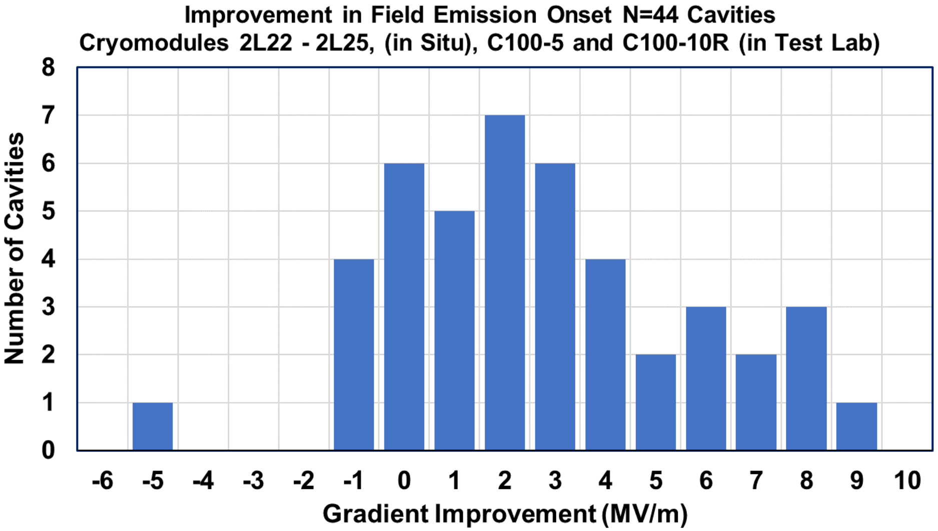
M. Doleans et al., NIMA **812** (2016)
M. Doleans J. Appl. Phys., **120**, 243301 (2016)
P.V. Tyagi et al., Applied Surface Science **369** (2016)

PP at JLab on C100 cavities and CMs

- JLab uses Argon/Oxygen or Helium/Oxygen mixture for PP on C100 cavities using HOM and HOM couplers (Fermilab ignition method)
- Processed several CMs in offline facility



- Average improvement in field emission onset: 2.7 MV/m
- The 4 cryomodules processed *in-situ* had a 59 MeV improvement in FE onset.
- 6 of the 44 cavities went from FE to FE-free after processing

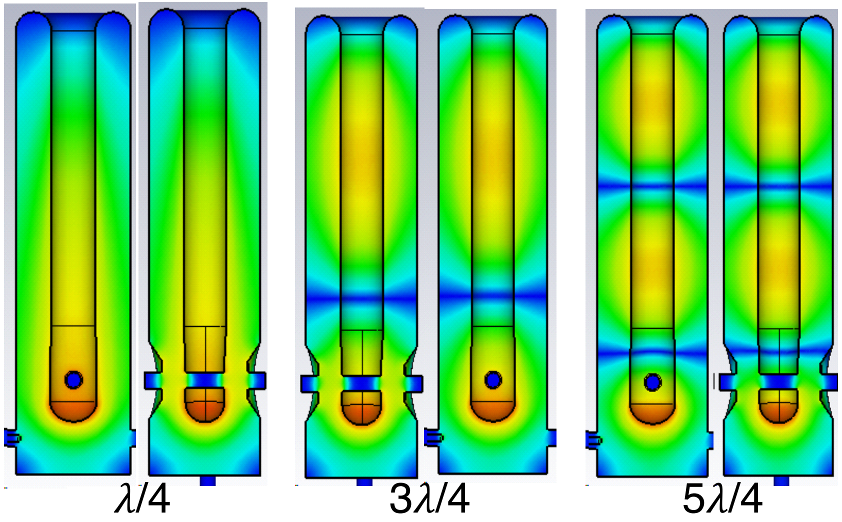


Adapted from T. Powers, SRF 2023 (WEPWB054) and TTC 2023

PP experience at other US and international laboratories

FRIB

Studying PP for HWR and QWR: several promising tests on the two geometries. Recently processed spare QWR CM → waiting for results

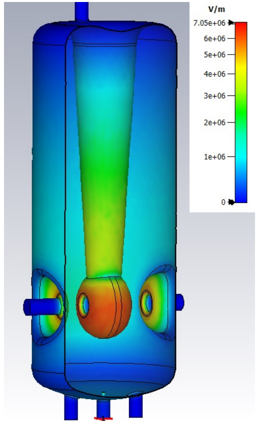


W. Hartung, SRF 2023 (THIXA01) and P. Tutt, TTC 2023

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

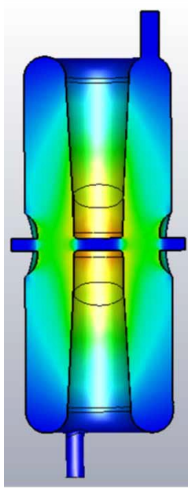
C. Cheney, TTC 2023

Studying PP for SPIRAL2 QWR: Ar/O_2 mixture, investigating fundamental mode vs HOM for PP, deep study of coupler breakdown



Argonne NATIONAL LABORATORY

Interested in PP for ATLAS HWR ad QWR: Ar/O_2 mixture, investigating fundamental mode vs HOM for PP on 172MHz HWR



M. McIntyre, SRF 2023 (MOPMB049)

Conclusions so far:

- Starting from SNS successful experience, plasma processing has been developed for multiple types of SRF cavities
- **Fermilab** developed a **new ignition technique for 1.3GHz** LCLS-II cavities and fully validated it on individual cavities and on the LCLS-II-HE vCM **demonstrating that PP can reduce hydrocarbon-induced FE and MP *in situ***
- Many laboratories are now developing PP for different geometries of SRF cavities
  - **ORNL-SNS** and **JLab-CEBAF** both processed several cryomodules, showing positive results in FE mitigation and performance recovery

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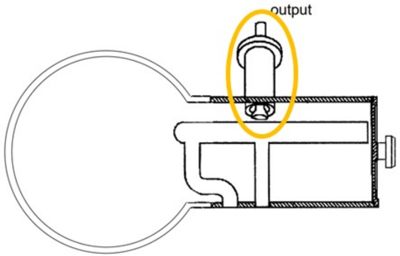
Proposal of PP for CM2: motivation

- Demonstrated efficacy of *in situ* plasma processing for hydrocarbon-induced FE and MP mitigation
- Additionally PP can achieve 5-10% increase of E_{acc}
- For ILC style CMs: gradient requirement is extremely ambitious. *In situ* method for gradient recovery: crucial for high gradient operation projects
- ILC cavity design is extremely similar to LCLS-II cavities: little effort, high reward



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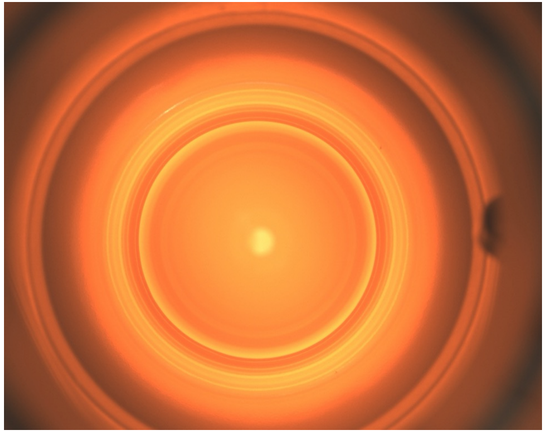
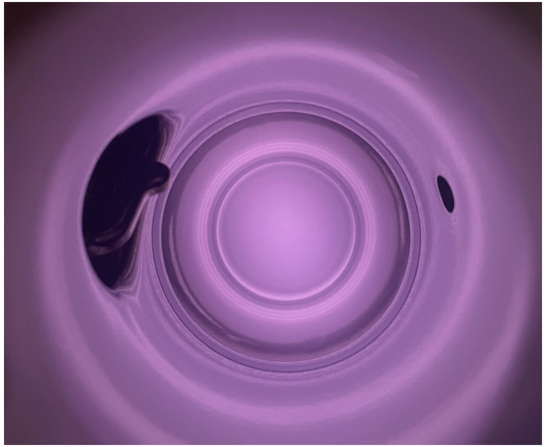
Plasma processing for ILC 1.3GHz cavities

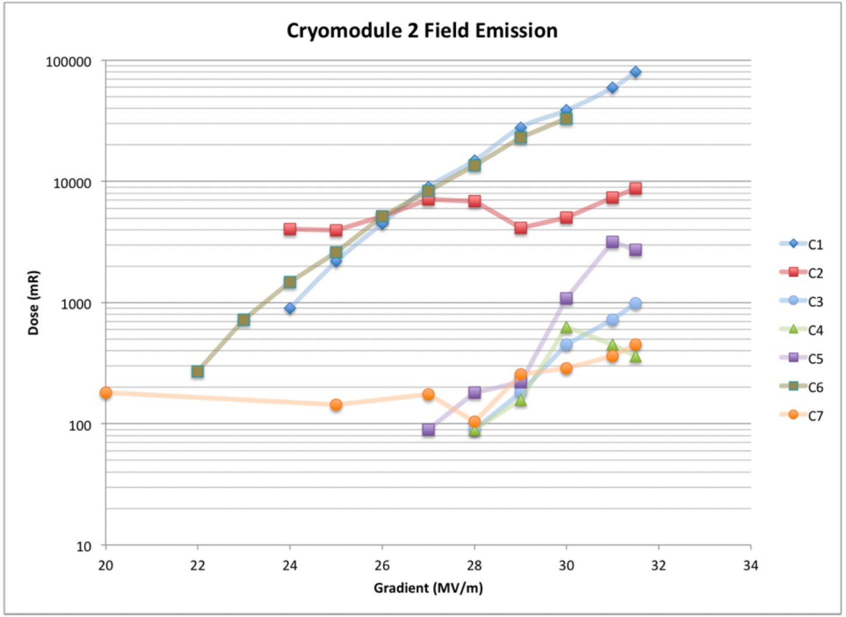
- Recipe optimization:
  - ✓ Power decrease to respect HOM cables power specs (Neon → Argon, lower 1st ionization energy)
  - ❑ Plasma parameter optimization with Argon to maximize PP efficacy **(in progress)** → on 1.3GHz single cell with RGA, once optimized it will be demonstrated on 9-cell through consecutive cold RF tests





Proposal for PP on CM2

- Motivation:
  - CM2 cavities achieve high fields (> 30MV/m) but are affected by FE > 20MV/m
    - Data as of 2014. More recent data, if available, would be useful for PP planning and comparison
  - PP is a **safe technique** that can address **FE, MP and gradient recovery *in situ***
    - Only requires: flow of gas through beamline and RF hardware present in CM. If possible, releasing the insulating vacuum should be considered.



E. Harms, AWLC14 – Americas Workshop on Linear Colliders 2014

Proposal for PP on CM2: Resources needed

- RF and vacuum/gas hardware:
  - RF cart: 1 is available at Fermilab, a 2nd system may be available as well and would allow to process 2 cavities at the same time.
  - Vacuum and gas system: Gas injection system is available, vacuum system available as well. No modifications needed. Would need to order pure Argon and Oxygen/Argon gas cylinders for CM2 PP.
- Manpower:
  - 1 Associate Scientist working (almost) full time on PP for the duration of CM2 processing
  - 1 RF engineer working (almost) full time on PP for the duration of CM2 processing
  - 1 technician for vacuum connections and vacuum operations of CM2 + transport, setup and disassembly of the hardware needed
- RF cold tests:
  - To determine PP efficacy: compare CM2 performance at operational temperature before and after PP. Measure Q vs E, FE onset (and MP-induced quenches).

Proposal for PP on CM2: Timeline

- 1 week to transport, connect and disconnect vacuum and gas systems
- At the same time: connect RF system(s) and measure S21, S11 on all cavities
- PP duration for 8 cavities:
  - ➢ With 1 RF system:
    - 22-25 work days
  - ➢ With 2 RF systems:
    - 11-15 work days
  - Use of 1 vs 2 RF systems will determine gas consumption
- Procedure could be applied as early as summer 2024 shutdown if compatible with your activities

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Proposal for PP on CM2: Timeline

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What questions and requirements would you have for us to consider applying plasma processing on CM2?

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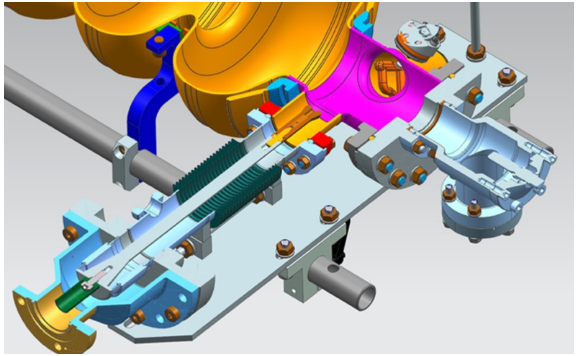
In summary: **plasma processing is a safe *in situ* technique with demonstrated efficacy on both hydrocarbon-induced FE and MP mitigation** and it can be adapted to multiple purposes (different cavity geometries, SRF guns, …). Lots of potential!

PP on CM2 could increase FE onset and increase operational gradient.


Thank you!

Risk & mitigation analysis for vCM

Major risks for applying the plasma processing in the vCM:



- **Unstable pressure in the cryomodule**: new vacuum cart was assembled and tested on single cavity.
- **FPC ignition**: ‘dummy’ variable FPC was installed on 9-cell cavity and subjected to plasma processing. It was verified that there was no ignition in the FPC during processing. Optical inspection of cavity and FPC after plasma processing showed no discoloration.

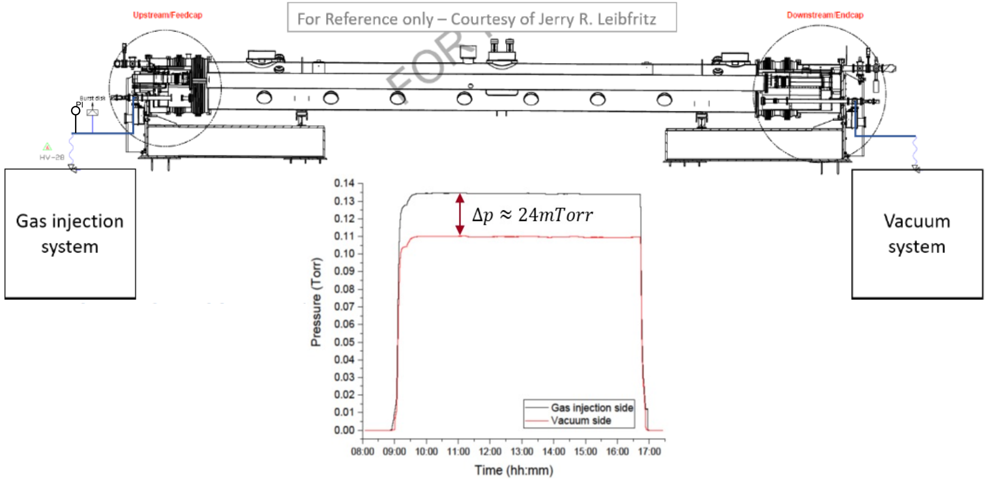
- **Heating of HOM cables**: cables and cavity temperature were monitored during plasma processing on vCM (ΔT<3K). Previously verified that 100W for 30min do not degrade cables/connectors and do not cause excessive heating.
- **Heating of cavities**: the vCM insulating vacuum was released.

B. Giaccone, et al. arXiv:2201.09776 (2022)

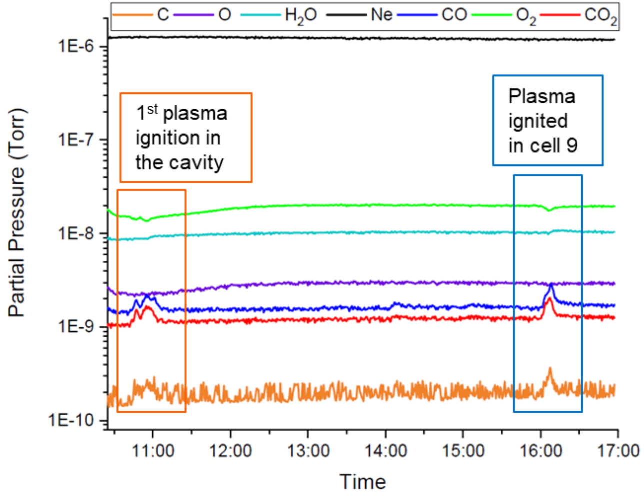
Timeline & Procedure

- No cavity with FE in vCM → processed 4 instrumented cavities (CAV1, CAV4, CAV5, CAV8)
- Processing order: started from CAV1 (closest to vCM end, gas injection side) and proceeded to CAV4, CAV5, CAV8 following the direction of gas flow.
- Processing time: 1.5-2 hours/cell -> 13.5-18 hours/cavity
- Plasma ignition procedure:
  - Plasma is ignited in cell # 5 (requires ≈60-70W)
  - Plasma is transferred to cell # 9 (going through cell # 6, 7, 8)
  - Plasma density is maximized in cell # 9 and cell processed for 45 min
  - Plasma density is detuned and plasma is transferred to cell #8
  - Procedure is repeated for each cell

Plasma processing applied to vCM (1)



CAV1: 1st day of plasma processing



Each morning the gas flow was established through the vCM

- Increase in CO,CO_2, C signals is observed along with decrease in O_2 signal
- Almost no by-products measured by RGA during 2nd day of plasma processing.

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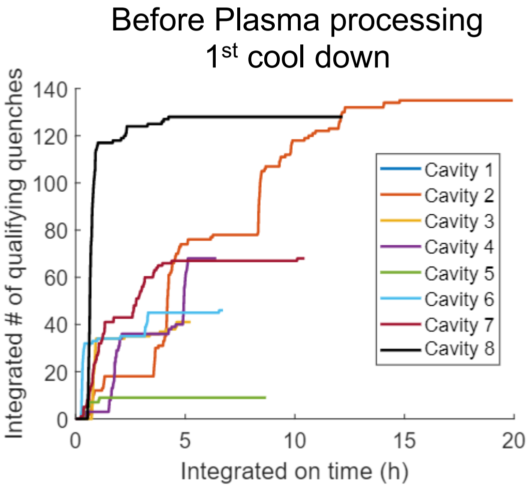
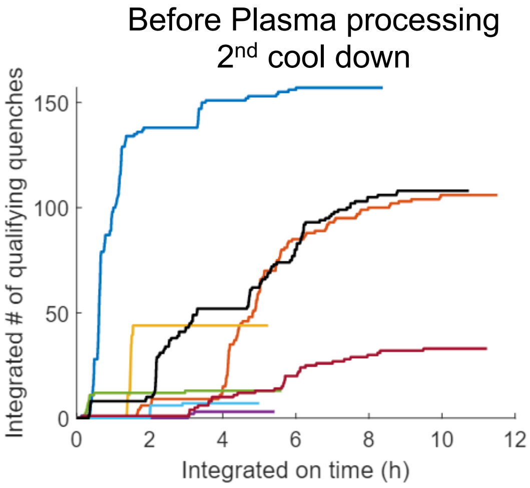
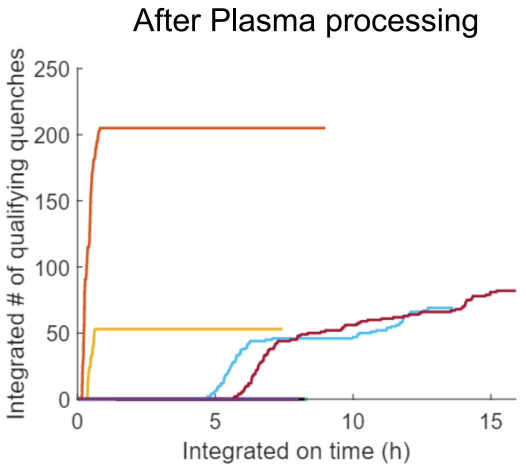
vCM performance before and after plasma processing







Plasma processing **can eliminate multipacting:**

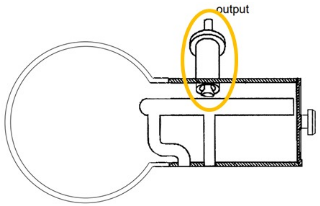
- **the 4 plasma processed cavities do no exhibit any MP quench**, contrary to the other 4 cavities

We could **address both FE and MP in situ at the same time**

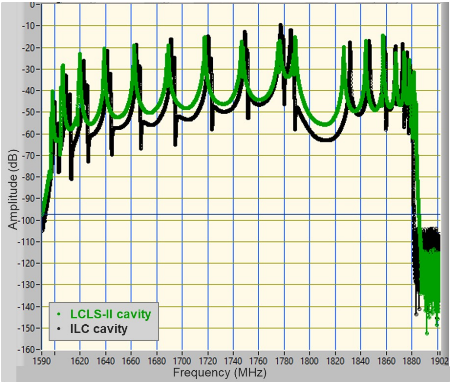
Cavity	Multipacting Quenches		
	Before plasma Processing		After Plasma Processing
	1st cooldown	2nd cooldown	
1	/	**157**	**0**
2	135	106	205
3	41	44	53
4	**68**	**3**	**0**
5	**10**	**16**	**0**
6	46	7	69
7	68	33	82
8	**128**	**108**	**0**

B. Giaccone, et al. arXiv:2201.09776 (2022)

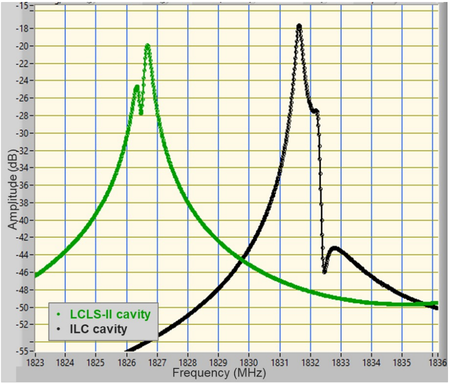
Plasma processing for ILC 1.3GHz cavities



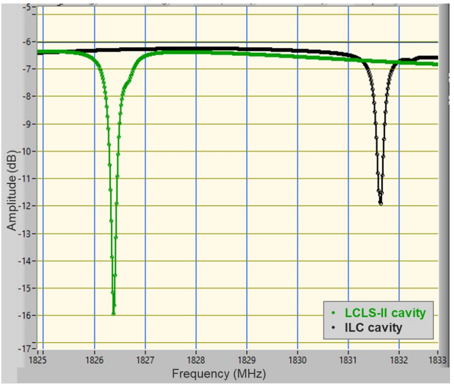
- Plasma ignition method developed at FNAL for LCLS-II(-HE): uses **HOM and HOM couplers** to ensure good coupling at RT
- Antenna tip for LCLS-II and ILC HOM couplers is different → different coupling to 1D and 2D modes → can we still use same ignition method?
- Comparison of RT S21, S11, S22 measurements on ILC style and LCLS-II cavities: no dramatic difference in coupling to dipole modes
- Possible issue: CM HOM cables: for LCLS-II rated for 10W, for ILC rated for 1W!



S21 – 1D and 2D passbands



S21 – zoom on 2D-1

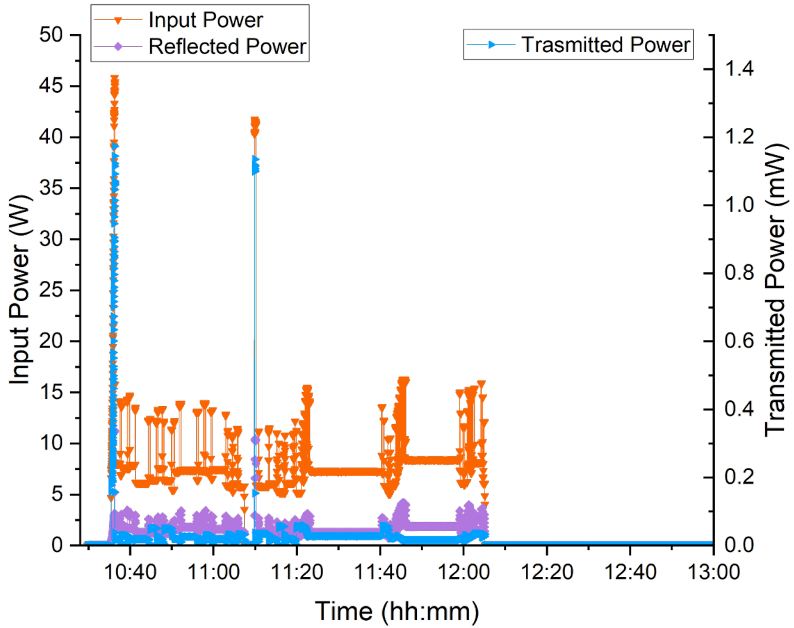


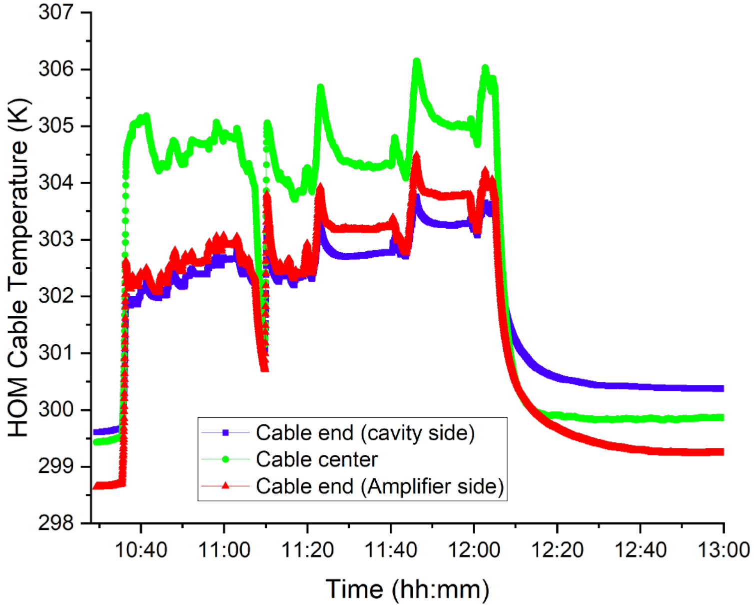
S11 – zoom on 2D-1

Fermilab

Potential recipe for ILC cavities

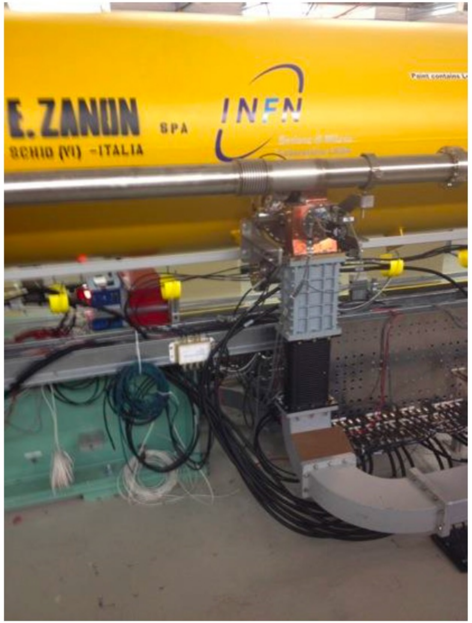
Argon at $p \approx 50mTorr, P_{IN}^{Ignition} = 45 - 55W$, **max observed** $\Delta T = 7K$ on ILC HOM CM-style input cable

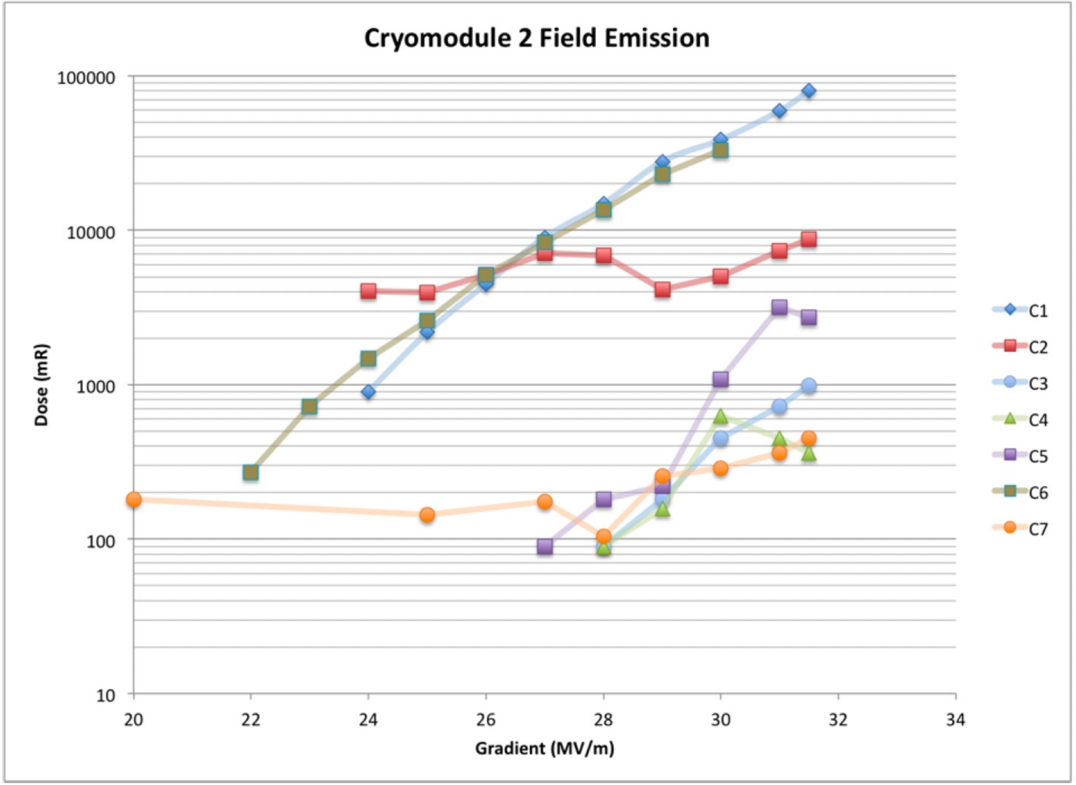




Power levels and corresponding cable heating recorded during plasma ignition, transfer to each cell and tuning tests for modes 1D-5, 1D-6, 1D-7

Dark Current/X-rays





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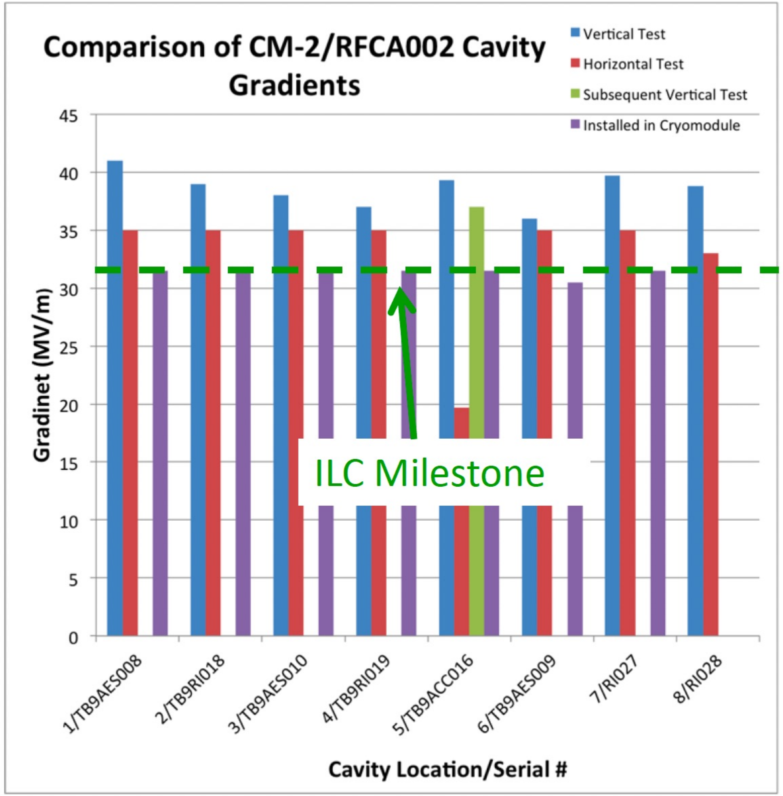
Performance to Date - Gradient



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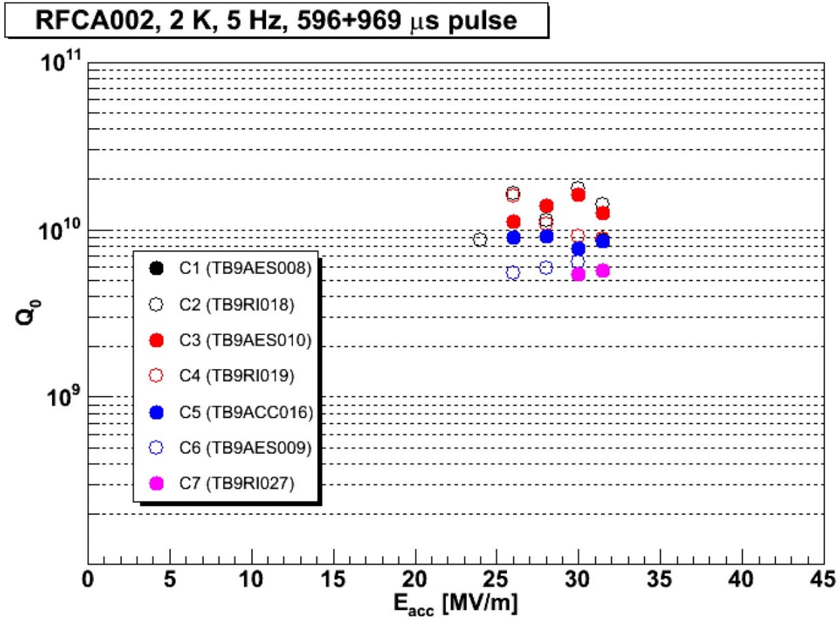
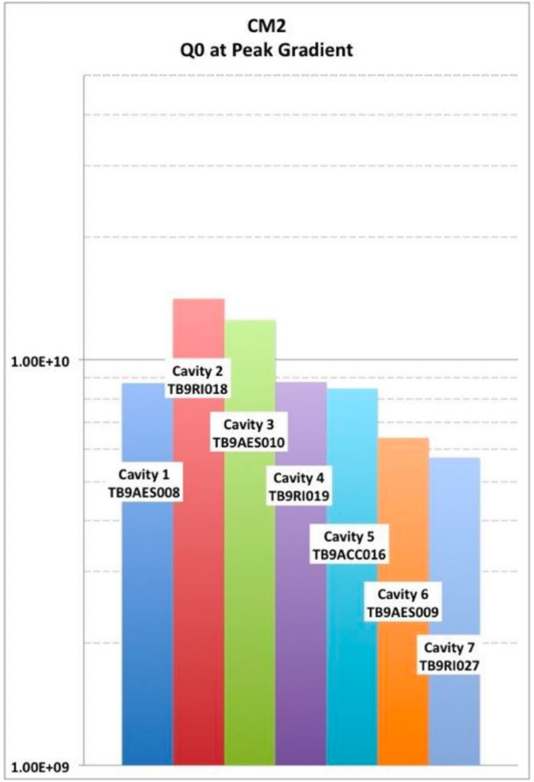
Performance to Date – Q_0





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