Plasma processing at FNAL

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TTC2022 Aomori

*The slides are prepared by B. Giaccone and P. Berrutti

Outline

- Plasma processing applied to LCLS-II-HE vCM
- Plasma processing studies for ILC cavities
- Plasma processing for SRF gun

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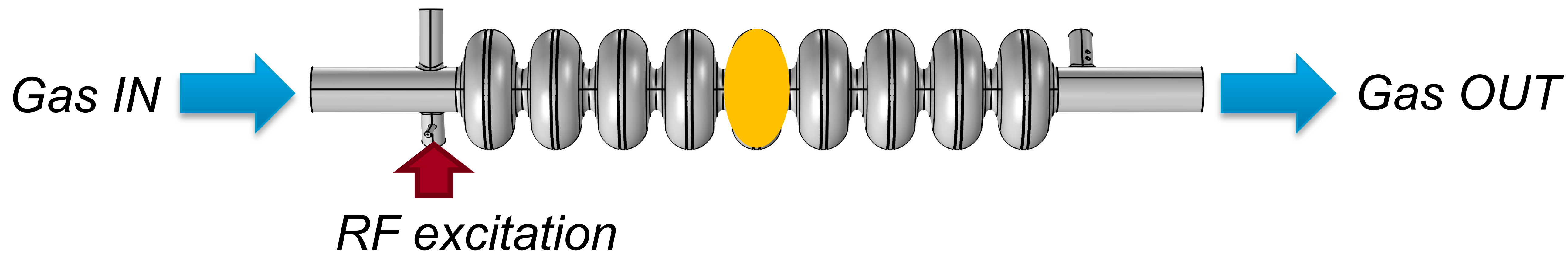
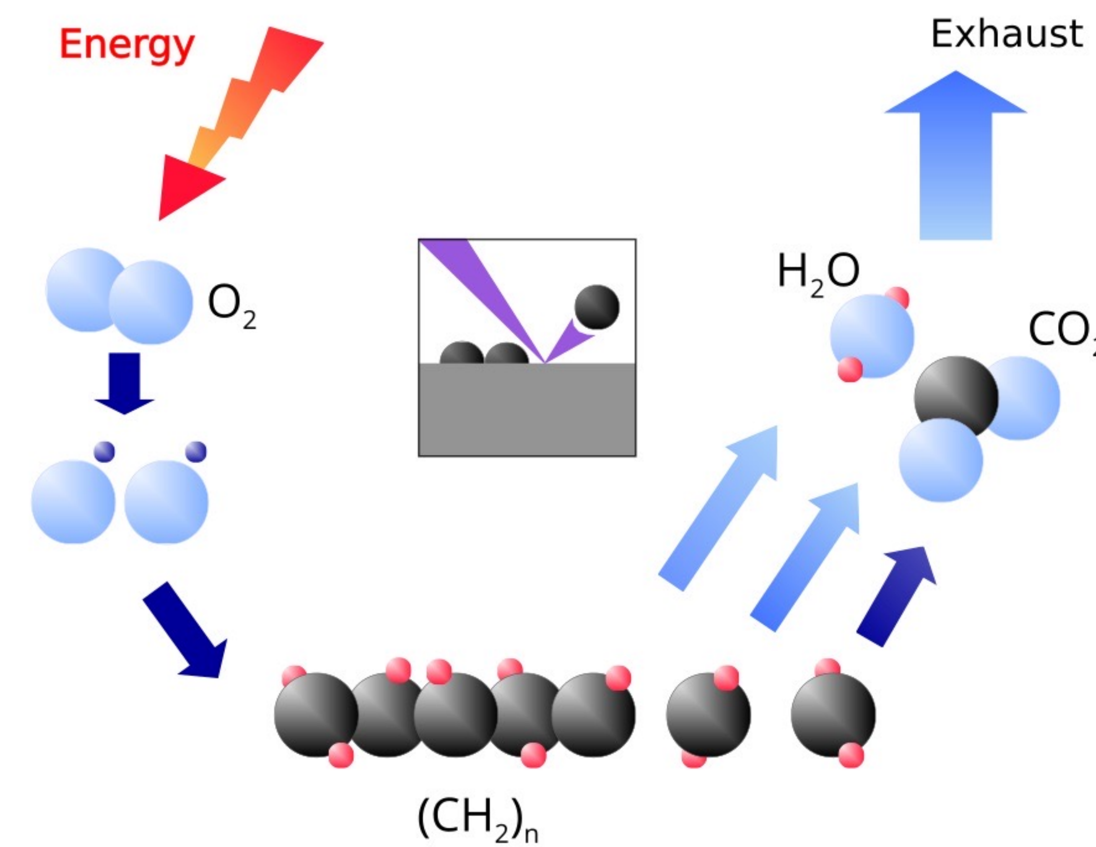
Plasma processing for field emission mitigation



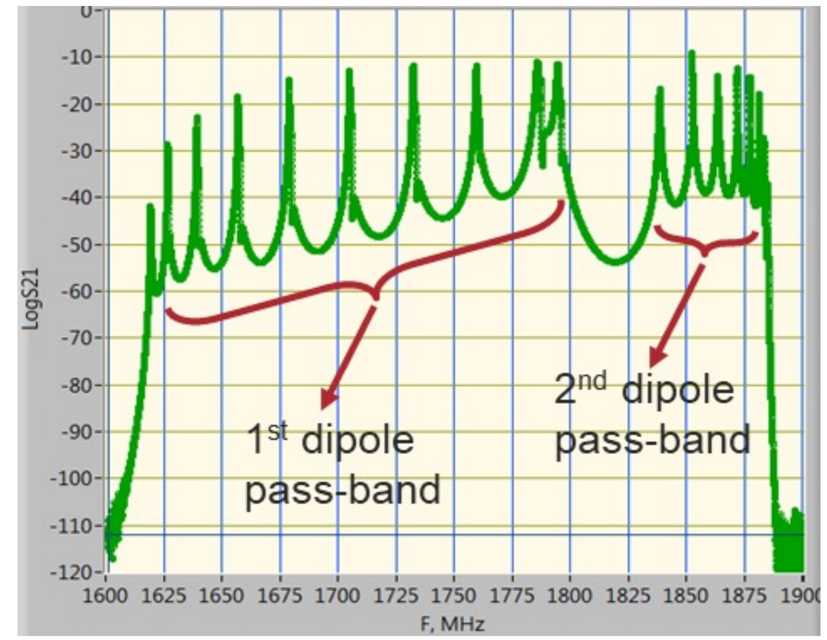
- Gas flow of Ne-O mixture (mostly Ne with a few % of O_2) at $p \sim$ 75-150 mTorr
- Once plasma is ignited, oxygen reacts with hydrocarbons
- Reaction products (mostly CO, CO_2, H_2O) are pumped out
- Work function increases, reducing FE

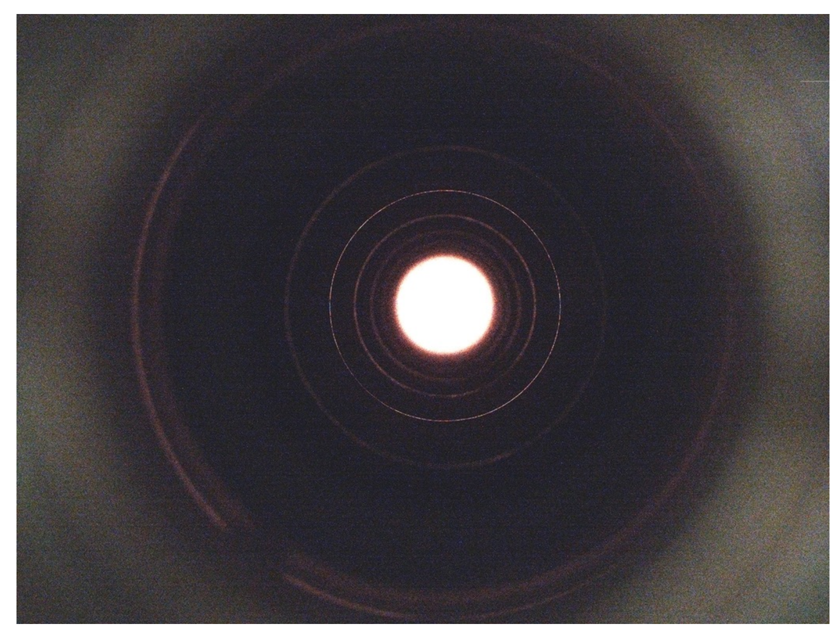


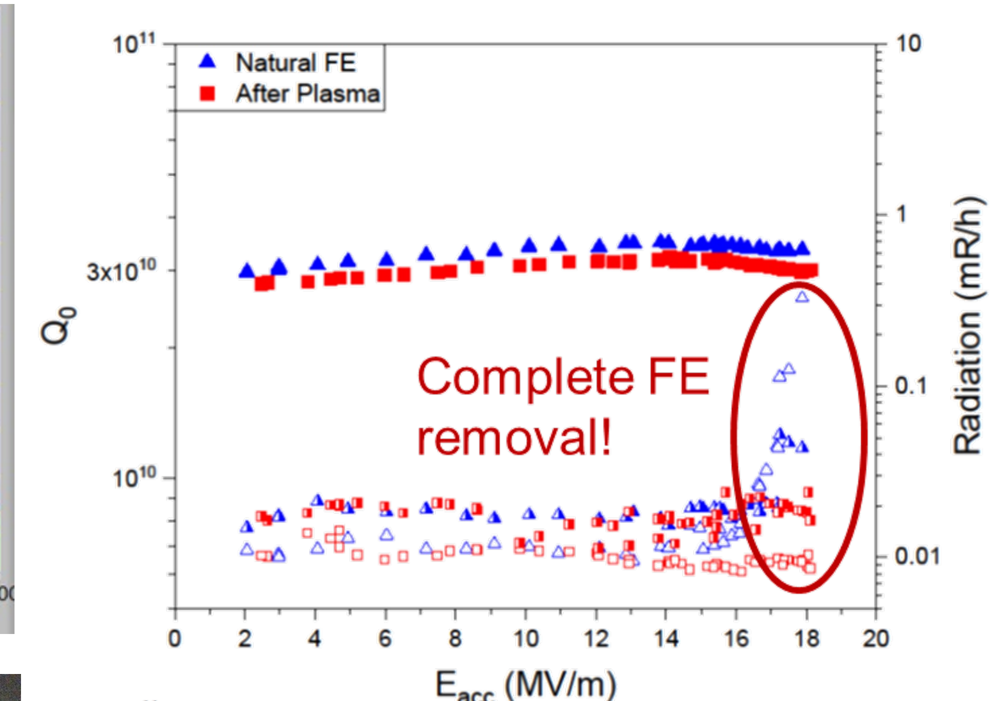
M. Doleans, et al., *Nucl. Instrum. Methods Phys. Res. A* **812**, 50-59 (2016)

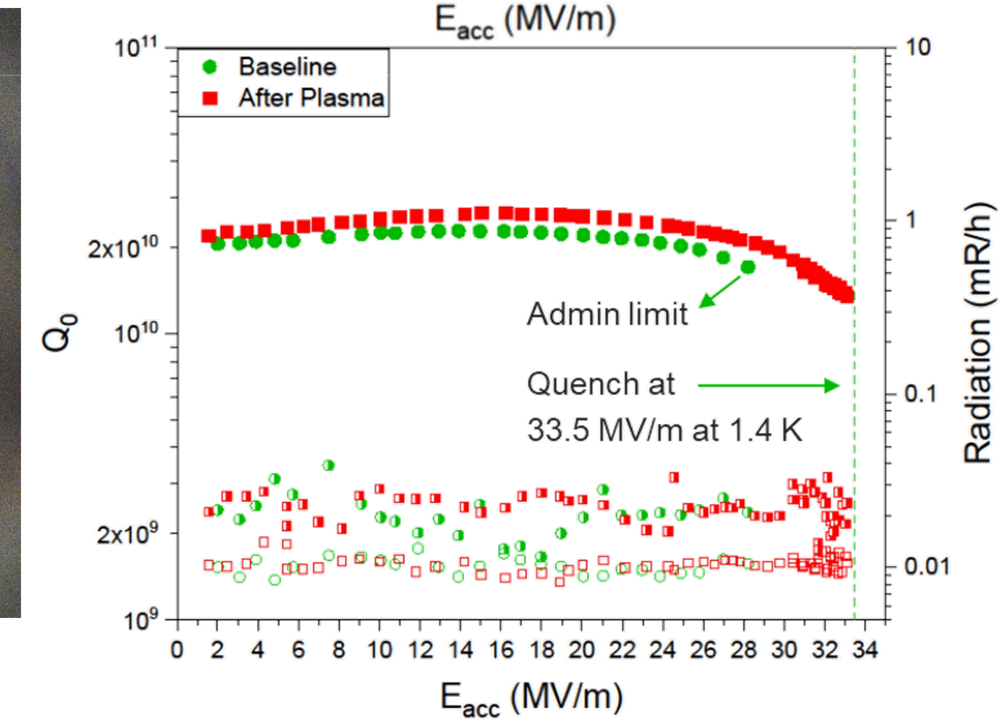
Plasma processing for LCLS-II and LCLS-II-HE

- 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 (2021)

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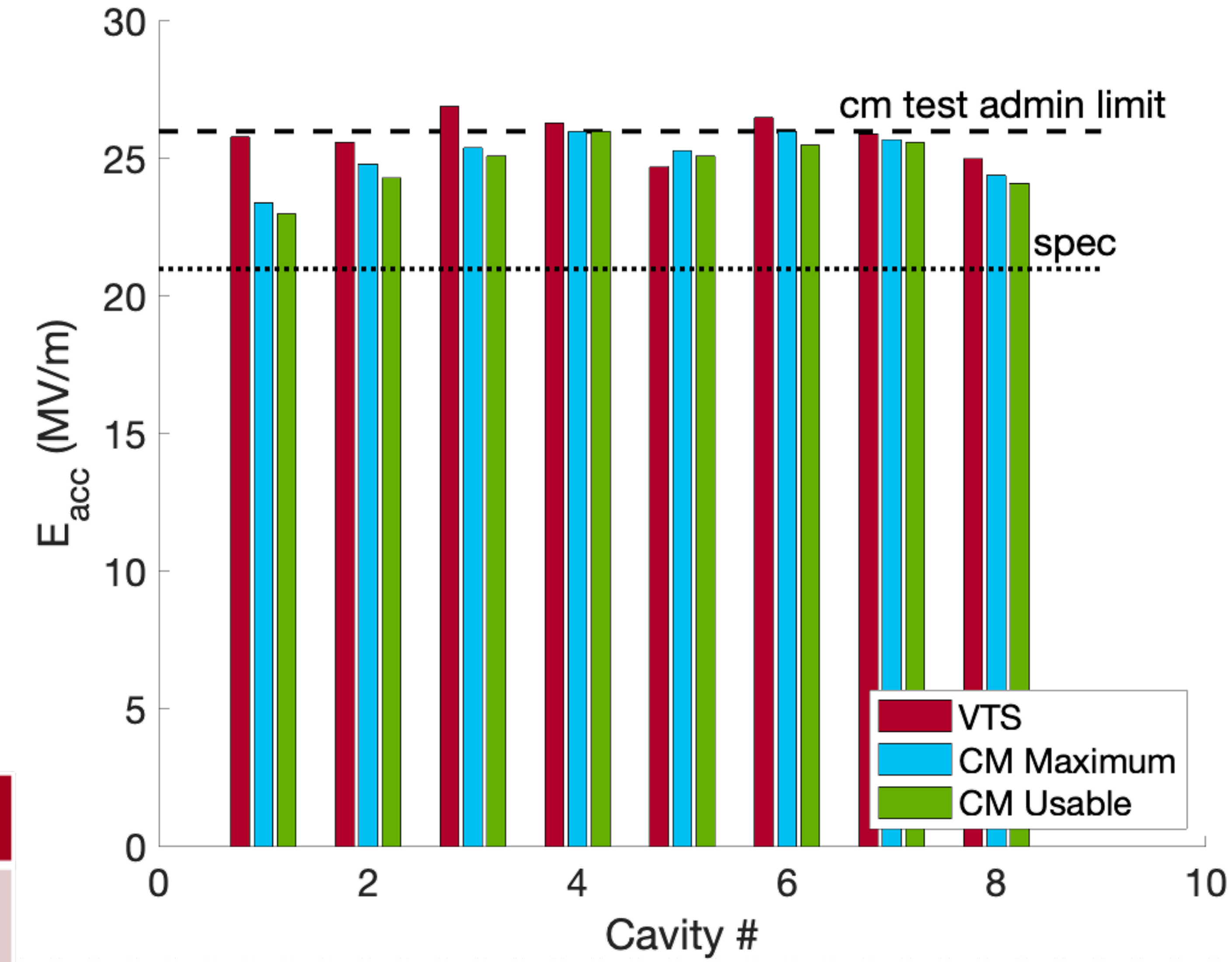
LCLS-II-HE verification Cryomodule

- Verification CM for LCLS-II-HE: assembled and tested at Fermilab
- **Gradient and Q_0 in all 8 cavities exceeds the ambitious LCLS-II-HE specification**
- No field emission observed at any gradient in any cavities after processing

World record cryomodule!

	E_{acc} Spec	E_{acc} avg	Q_0 Spec	Q_0 avg
HE vCM (8 cavities)	**21 MV/m**	**25 MV/m**	**2.7×10^{10}**	**3.0×10^{10}**
LCLS-II prod'n (280 cavities)	16 MV/m	19 MV/m	2.7×10^{10}	2.9×10^{10}

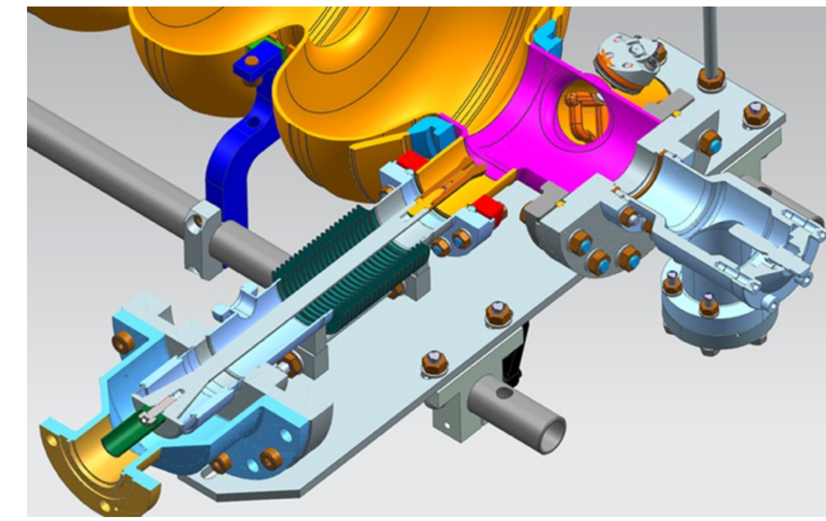


S. Posen et al., *Phys. Rev. Accel. Beams* **25**, 042001 (2022)

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 ($\Delta T < 3$ K). Previously verified that applying 100 W for 30 min does not degrade cables/connectors and do not cause excessive heating.
- **Heating of cavities**: the vCM insulating vacuum was spoiled.

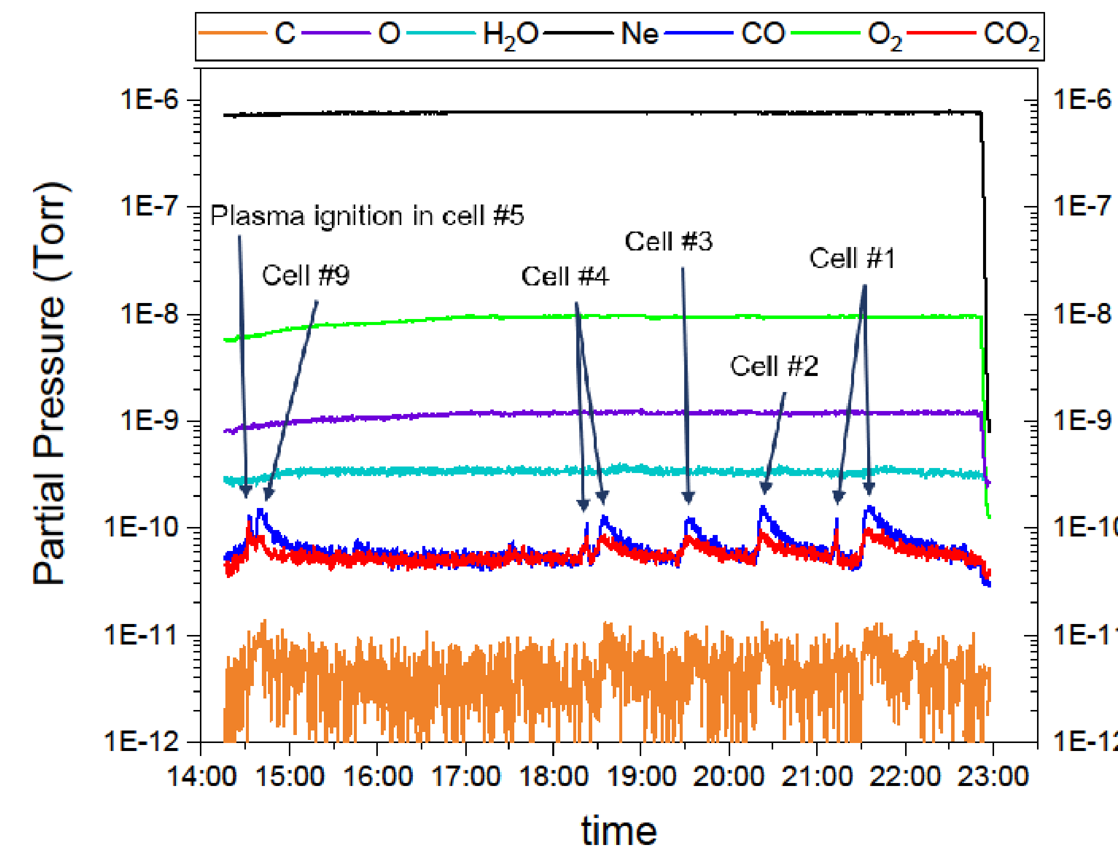


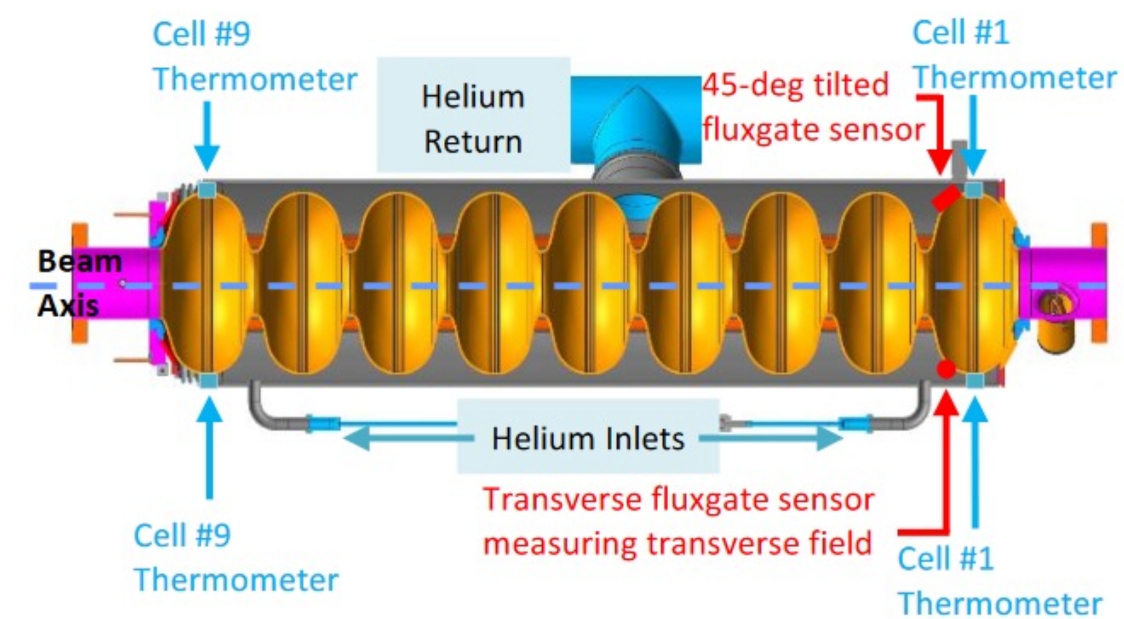
B. Giaccone et al., *Phys. Rev. Accel. Beams* **25**, 102001 (2022)

Plasma Processing Plan for vCM

Parameters monitored during plasma processing

- 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





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Experimental systems: gas injection, vacuum & RF

Gas cart connected to the Feedcap side

Vacuum cart connected to the Endcap side

RF system, computers

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Connections between gas/vacuum systems and CM

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



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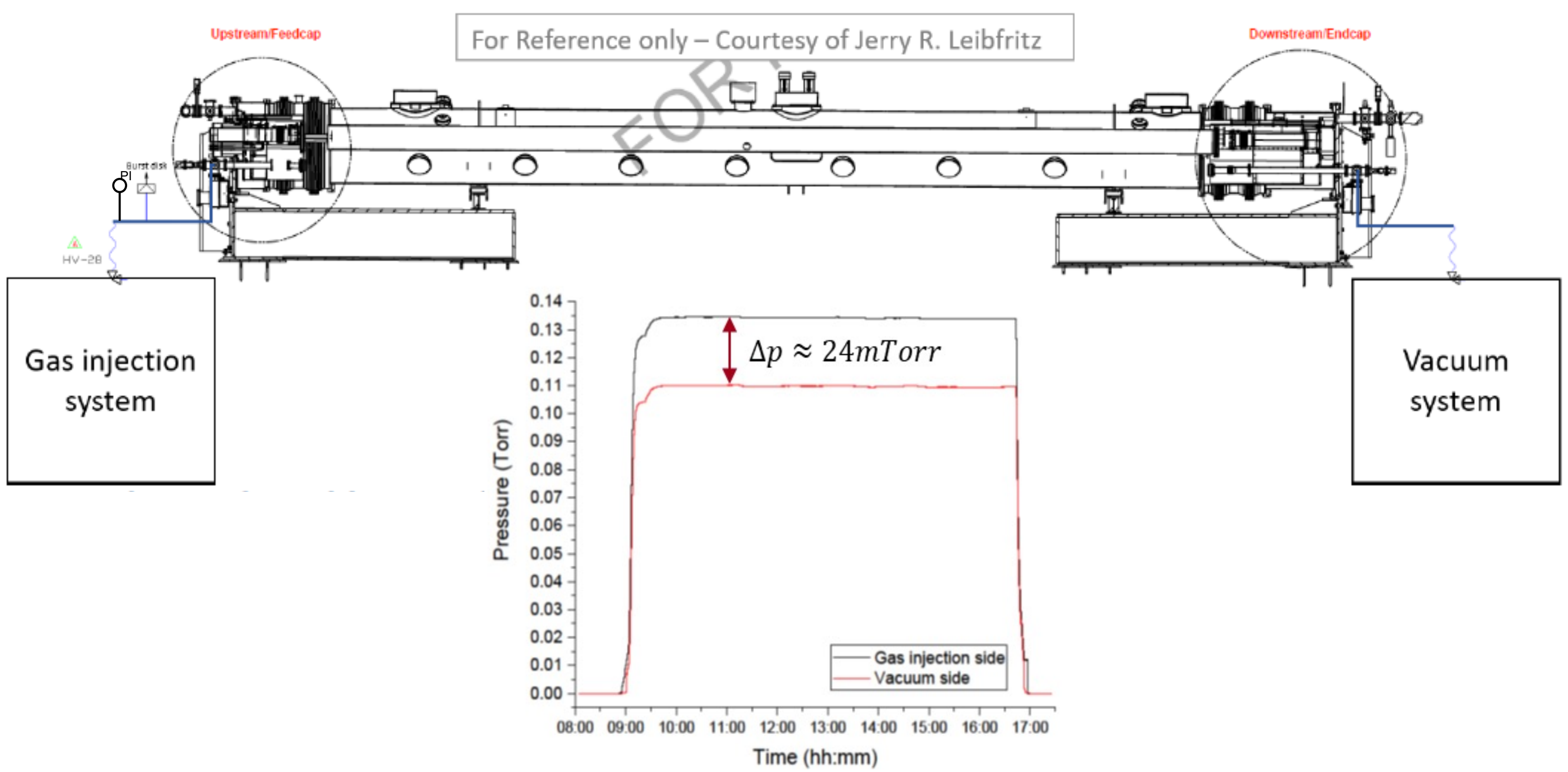
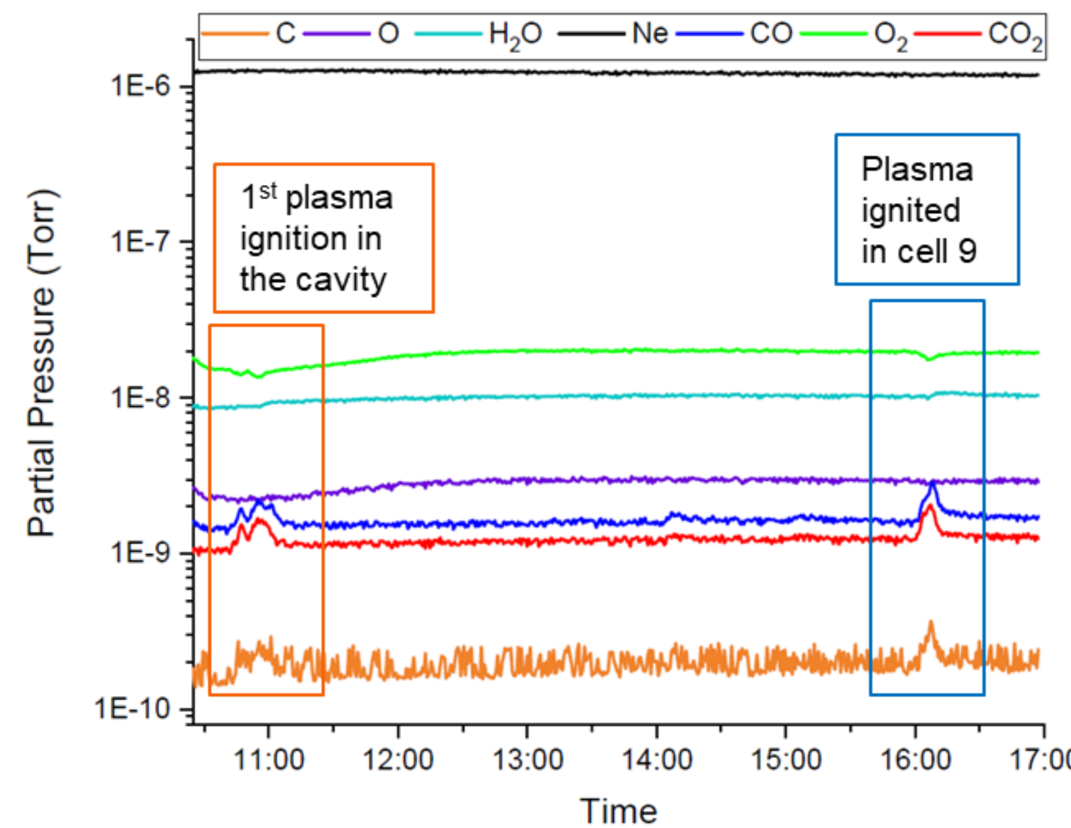
Plasma processing applied to vCM (1)



Each morning the gas flow was established through the vCM

CAV1: 1st day of plasma processing



- 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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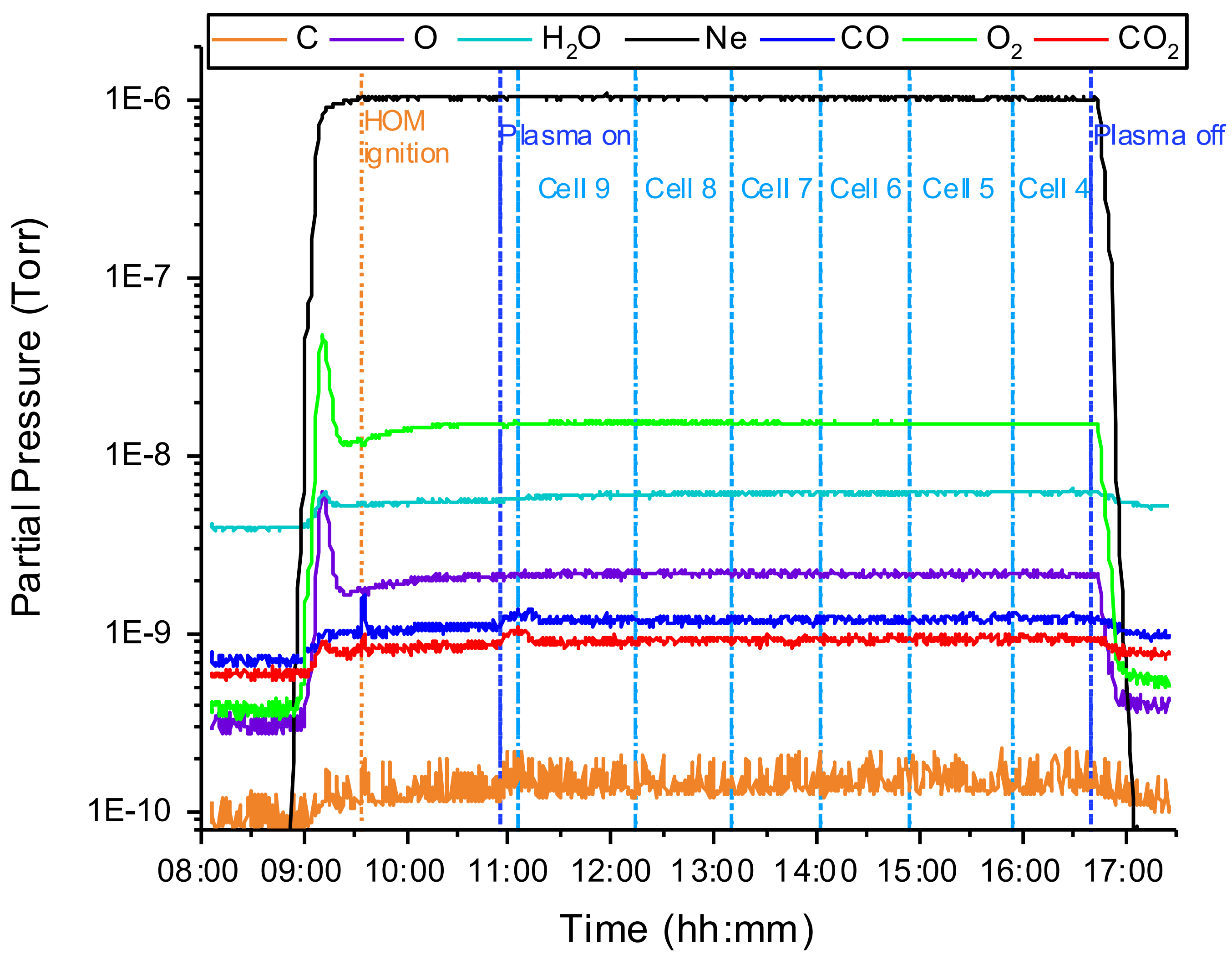
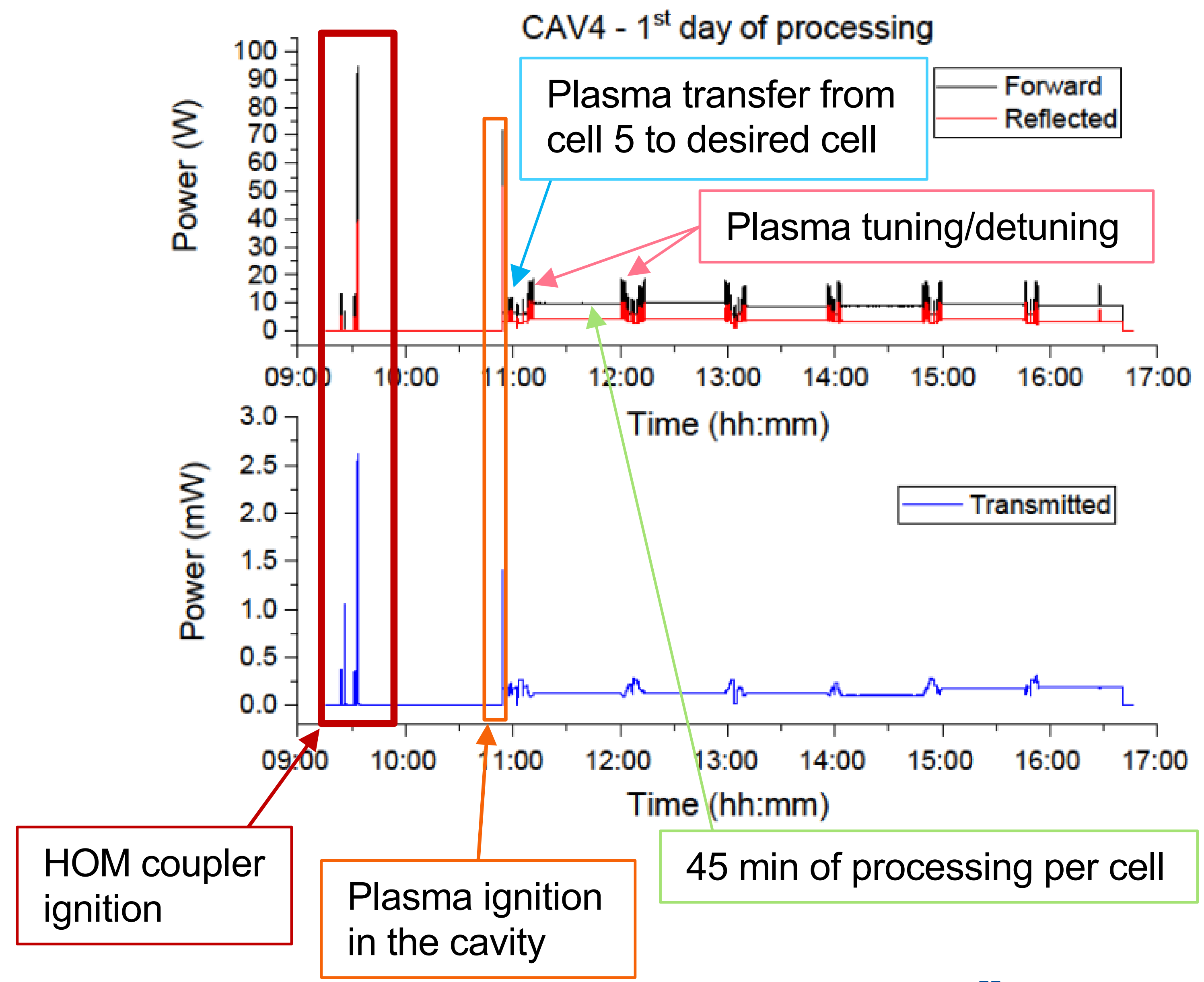
Plasma processing applied to vCM (2)

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





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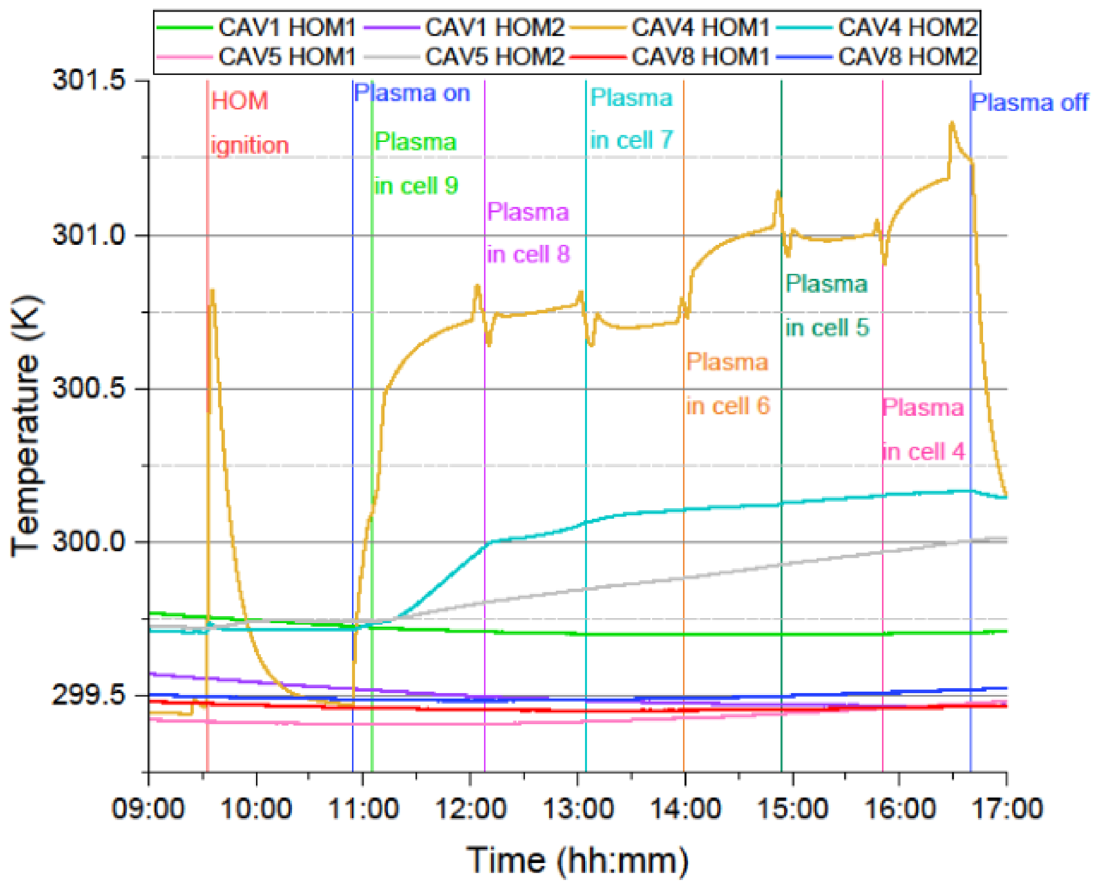
Plasma processing applied to vCM (3)

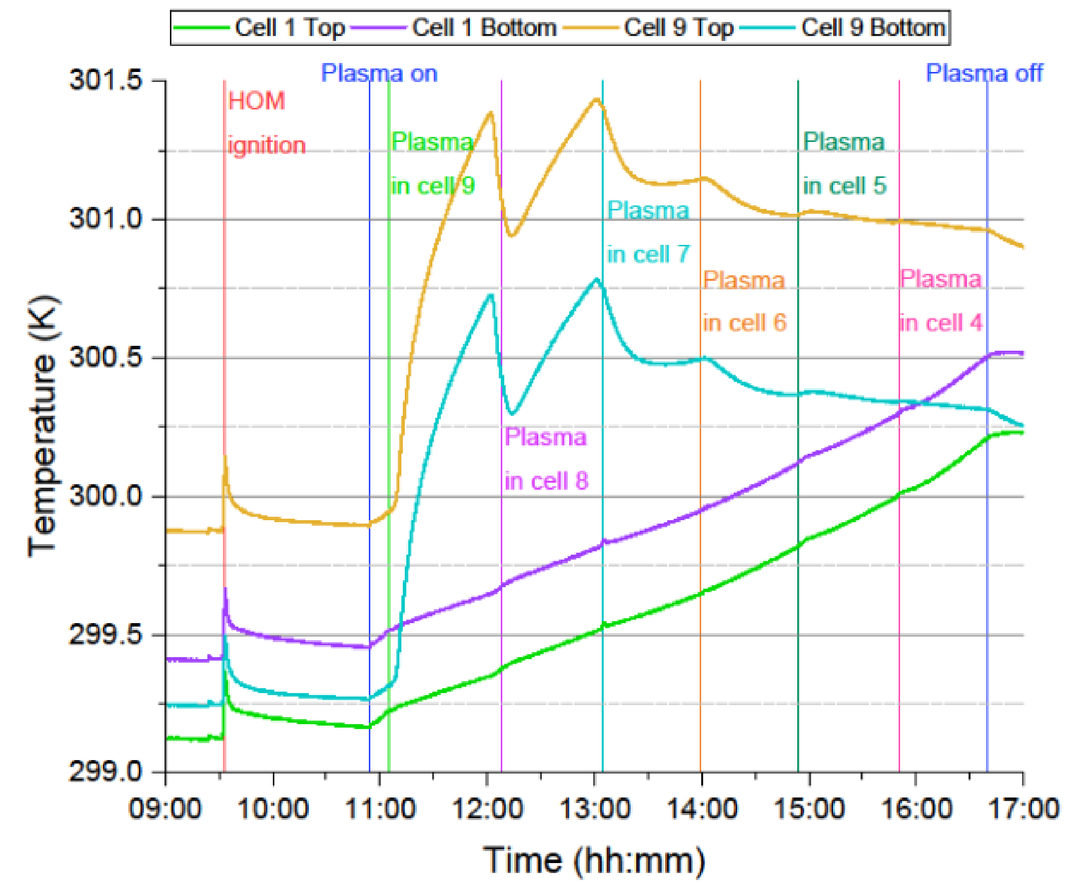
Example of experimental data collected during plasma processing of CAV4. This includes a rare case of plasma ignition at the HOM coupler



Temperature increase on:

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

During coupler ignition: 1.4 K increase on HOM1 cable



Temperature increase on:

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

Questions to address after plasma processing

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?

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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**	[illegible]	[illegible]	[illegible]	[illegible]	**3.4**	**No**
2	24.8	24.3	[illegible]	[illegible]	[illegible]	[illegible]	3.2	Yes
3	25.4	24.9	[illegible]	[illegible]	[illegible]	[illegible]	3.4	Yes
4	**26.0**	**26.0**	[illegible]	[illegible]	[illegible]	[illegible]	**3.2**	**No**
5	**25.3**	**24.8**	[illegible]	[illegible]	[illegible]	[illegible]	**2.8**	**No**
6	26.0	25.5	[illegible]	[illegible]	[illegible]	[illegible]	3.2	Yes
7	25.7	25.2	[illegible]	[illegible]	[illegible]	[illegible]	3.3	Yes
8	**24.4**	**23.9**	[illegible]	[illegible]	[illegible]	[illegible]	**2.6**	**No**
Average	25.1	24.7	[illegible]		[illegible]	[illegible]	3.1	
Total	209	205			[illegible]	[illegible]		

Plasma processing procedure is fully validated!

RF test after plasma processing demonstrated that:

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

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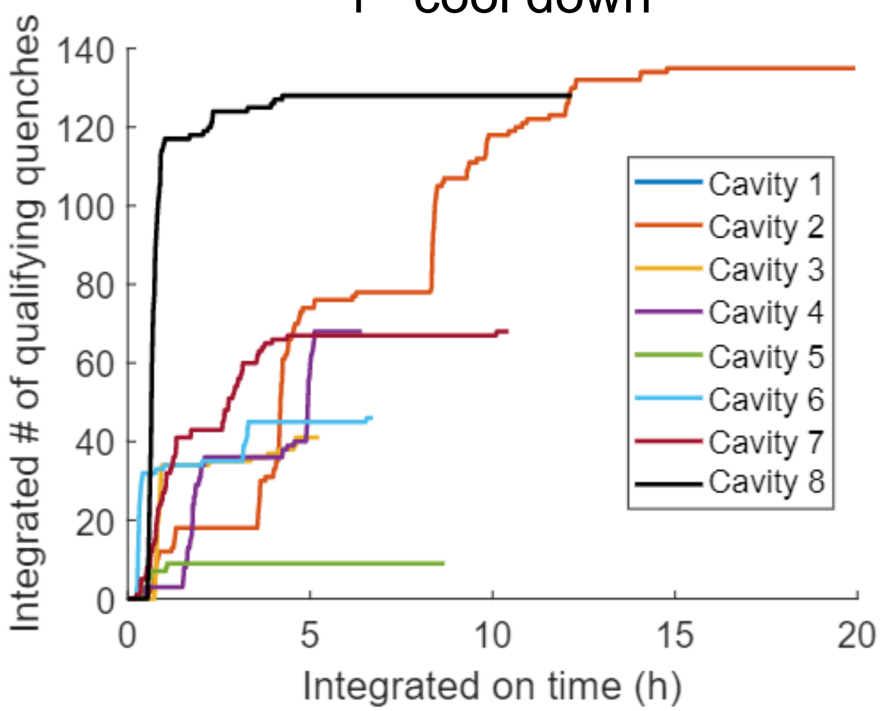
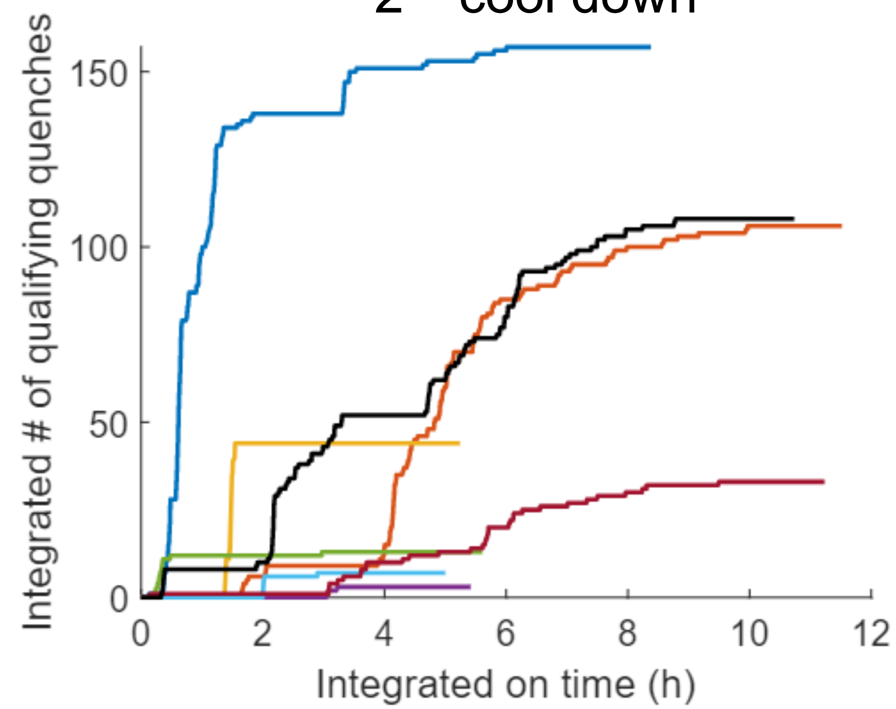
vCM performance before and after plasma processing

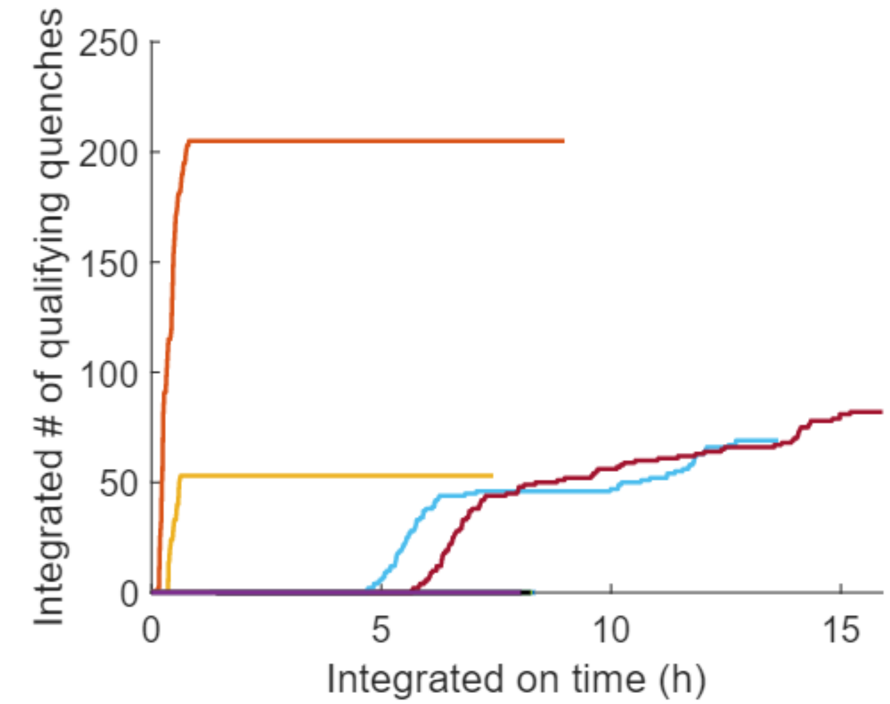
Before Plasma processing
1st cool down



Before Plasma processing
2nd cool down



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, 1st cooldown	Multipacting Quenches: Before plasma Processing, 2nd cooldown	Multipacting Quenches: After Plasma Processing
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., *Phys. Rev. Accel. Beams* **25**, 102001 (2022)

Conclusions for Plasma processing applied to LCLS-II-HE vCM

- Plasma processing was already validated in test bench setup on N-doped LCLS-II 9-cell cavities, no *Q*-factor degradation observed
- Through this test the **procedure was fully validated on a CM**: plasma processing has the potential of not only reducing field emission but also fully eliminating multipacting in cryomodules.
- **Multipacting mitigation through plasma processing** could:
  - significantly reduce cryomodule testing time
  - decrease the accelerator commissioning time and cost (for example: cavities can require up to 1 day of processing in case of severe multipacting, with an average of 2 hours per cavity)
  - increase reliability during operations

Outline

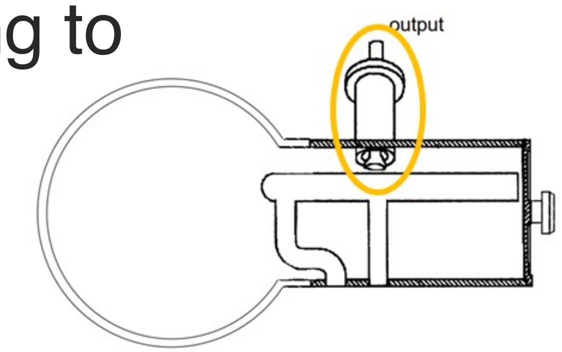
- Plasma processing applied to LCLS-II-HE vCM
- Plasma processing studies for ILC cavities
- Plasma processing for SRF gun

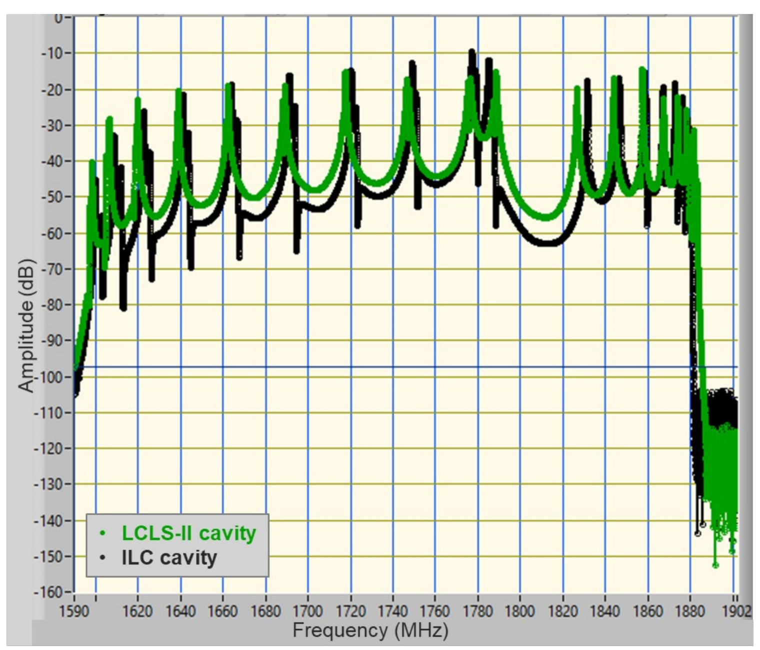
Motivation for applying plasma processing to ILC cavities

- Demonstrated efficacy of *in situ* plasma processing for FE and MP mitigation and gradient recovery
- For ILC style machine: gradient requirement is ambitious. Plasma processing can ensure 5-10% increase of $E_{acc} \rightarrow$ crucial for high gradient operation projects
- ILC cavity design is similar, so the technique should require little effort to be adapted to ILC HOM couplers but could bring high reward

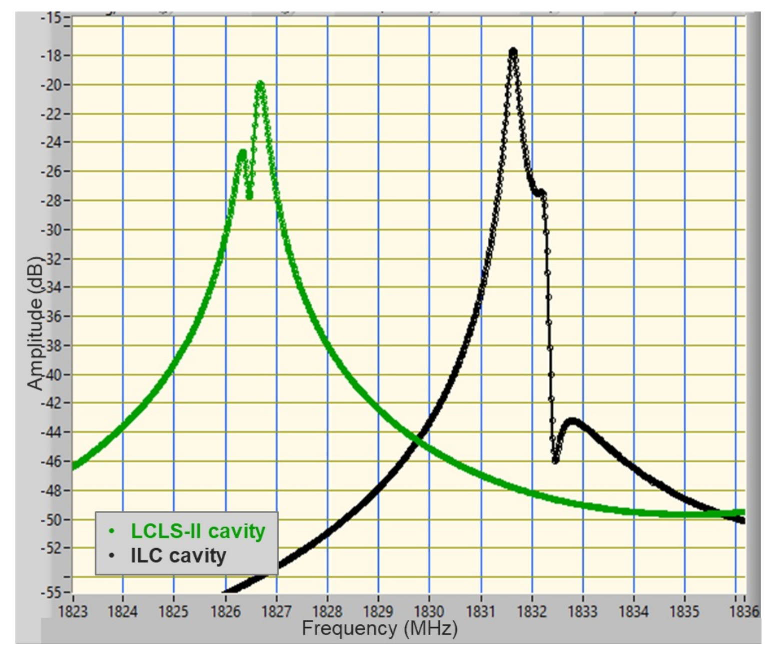
Plasma processing for ILC 1.3 GHz cavities

- Plasma ignition method developed at FNAL for LCLS-II(-HE): uses **HOM1 and HOM2 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 10 W, for ILC rated for 1 W!

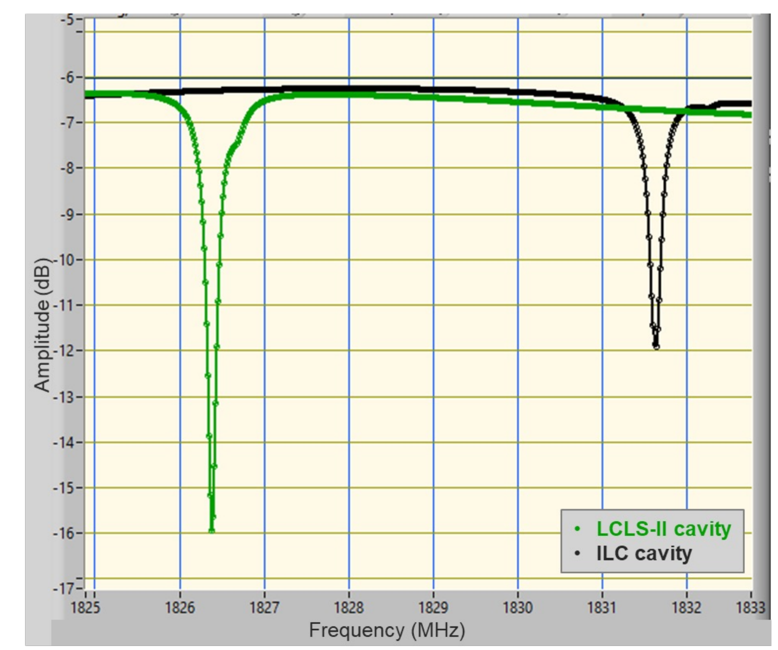




S21 – 1D and 2D passbands



S21 – zoom on 2D-1



S11 – zoom on 2D-1

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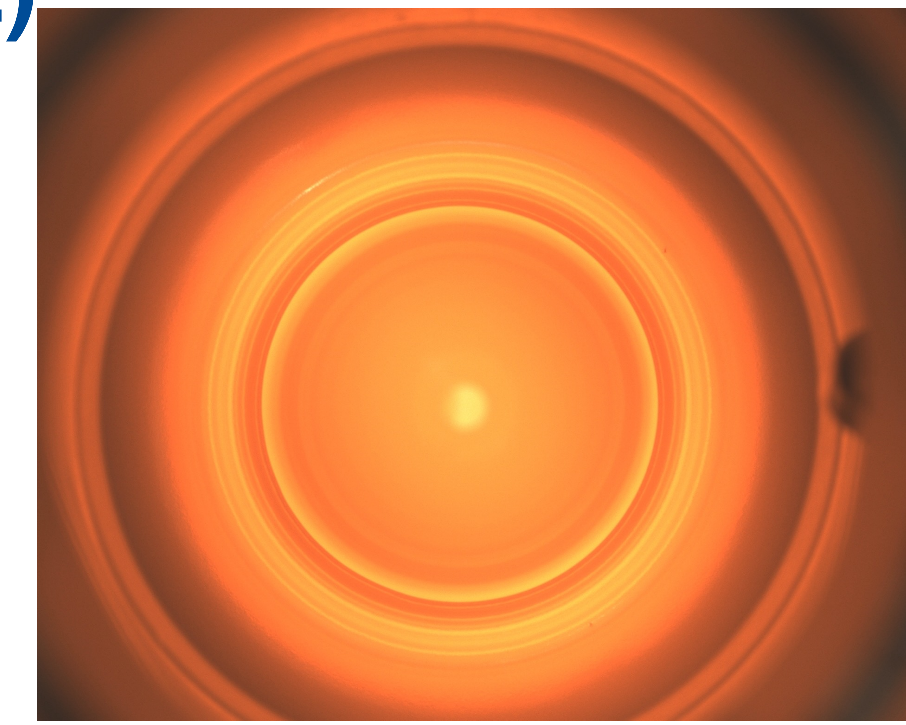
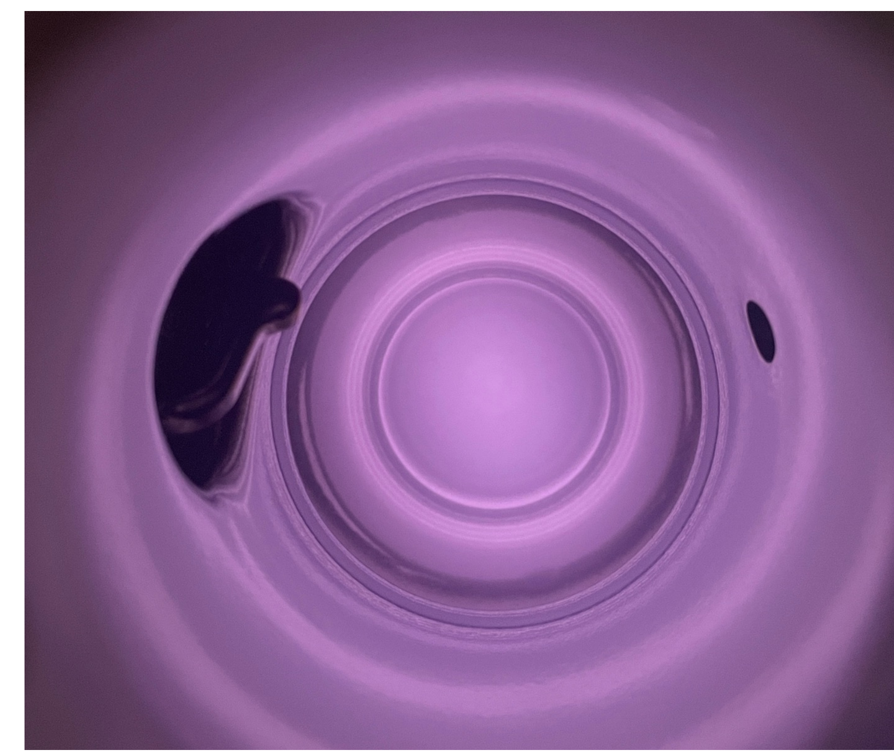
Plasma processing for ILC 1.3 GHz cavities (2)

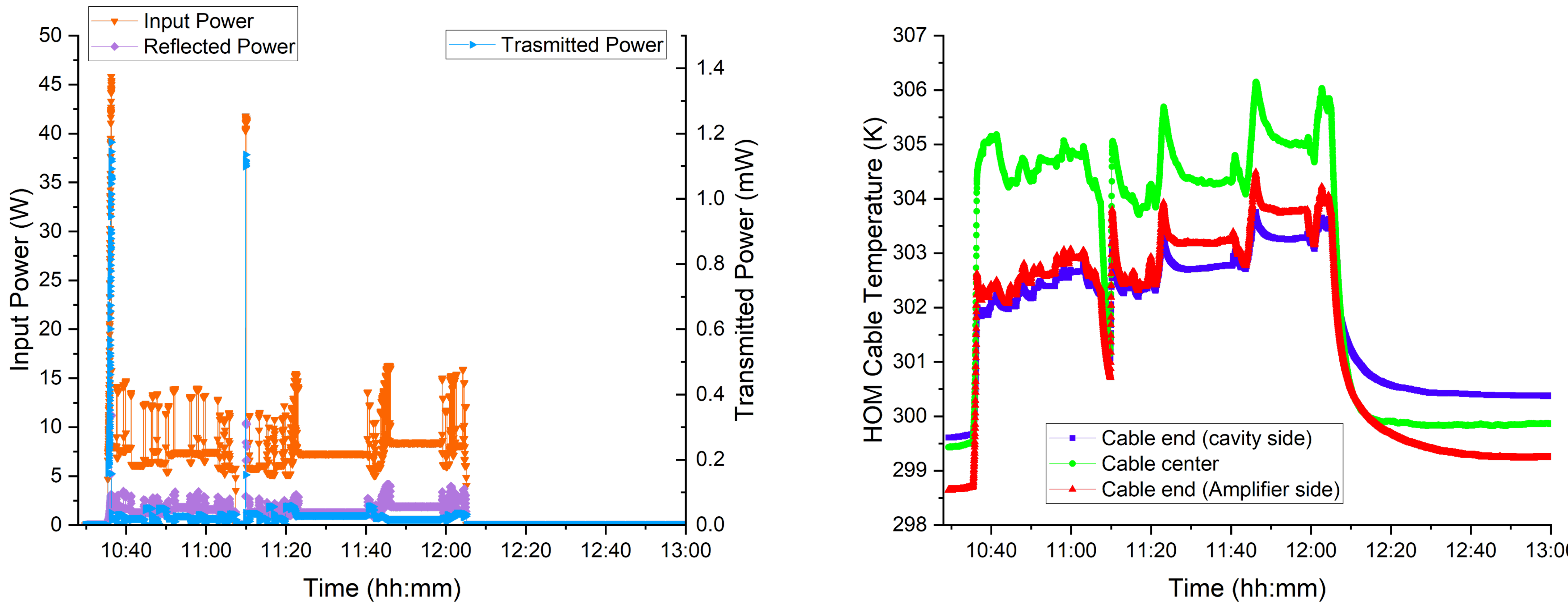
- Starting point: **LCLS-II recipe → ignition method works**, BUT excessive power required at ignition for ILC HOM cables (1W rated)
- Conducted ignition and transfer tests with **Neon** and **Argon** at various pressures
- **Argon**: lower 1st ionization energy → lower ignition power. Tested multiple pressure levels, monitoring **ignition power, cable temperature, plasma transfer and tunability**





Potential recipe for ILC cavities

Argon at $p \approx 50\ \mathrm{mTorr}$, $P_{IN}^{ignition} = 45 - 55\ W$, **max observed** $\Delta T = 7\ \mathrm{K}$
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

Outline

- Plasma processing applied to LCLS-II-HE vCM
- Plasma processing studies for ILC cavities
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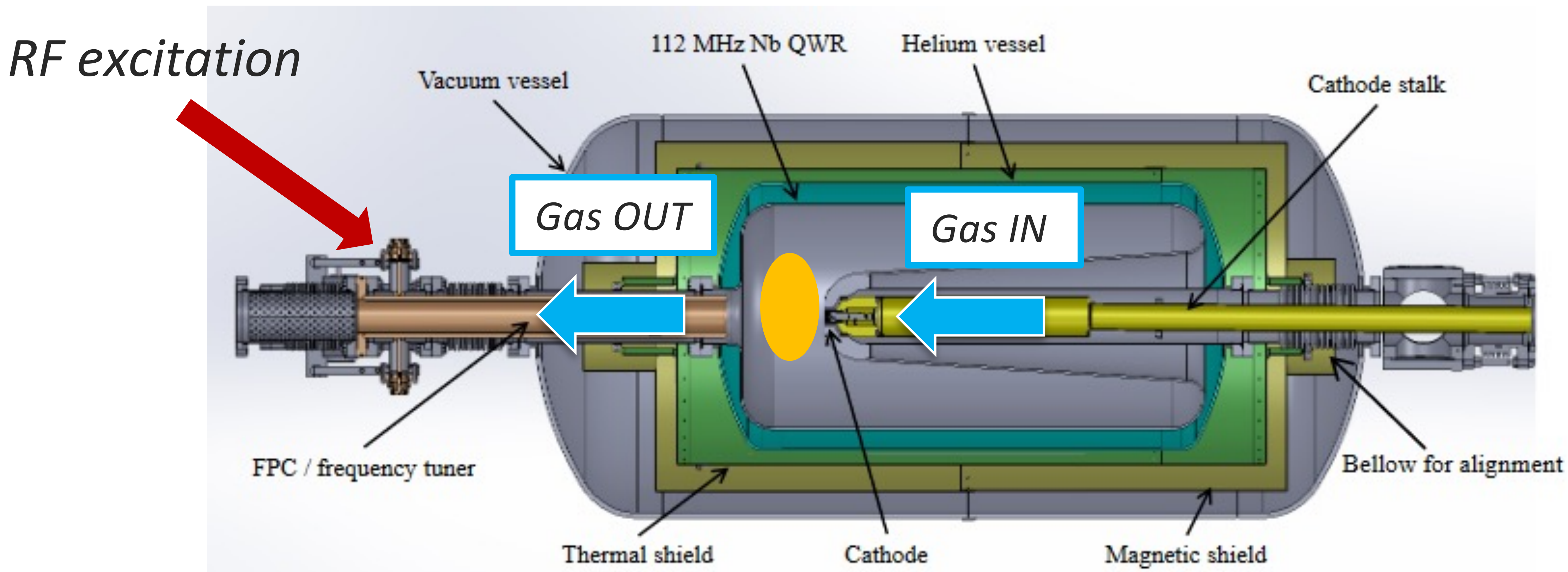
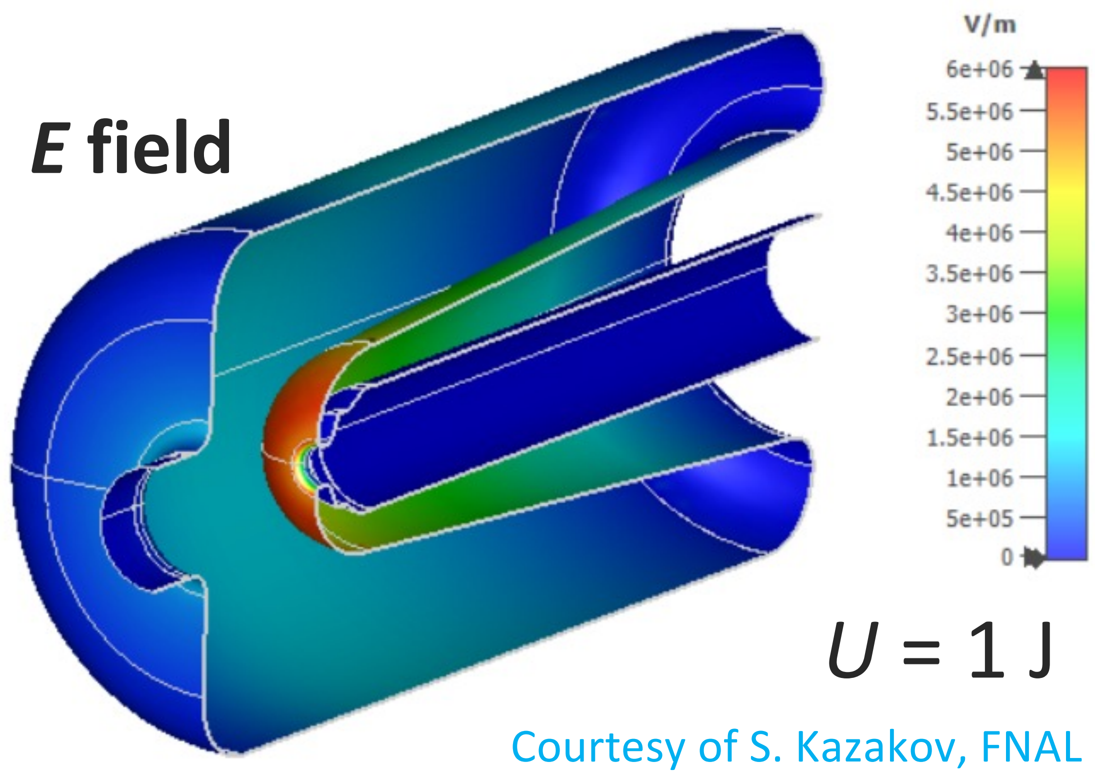
Plasma processing on 112 MHz SRF gun: Gas injection and vacuum design



- To create a gas flow in the SRF gun system: gas can be injected from cathode side and pumped out from the FPC side
- Can use same design of the gas injection and vacuum system cart currently employed at FNAL for LCLS-II and HE cavities

Analysis of plasma ignition in the SRF gun

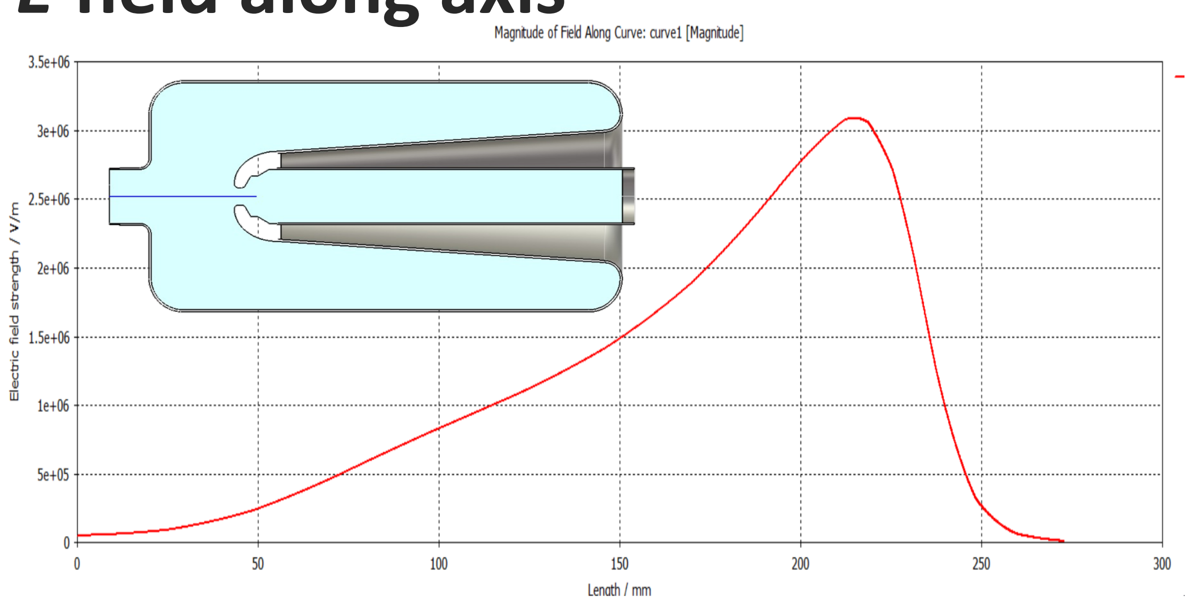
E field



$U = 1$ J

Courtesy of S. Kazakov, FNAL

E field along axis



- E_{max} is close to cavity inner conductor → plasma ignition area
- At room temperature plasma can be ignited by exciting the cavity fundamental mode with just a few watts

Q_{ext}	9.3e4
Q_0	4.8e3
β	0.051
$\|\Gamma\|^2$	0.81
E_{pk} [kV/m]	10*
U [J]	2.78e-6
P_c [W]	0.41
P_f [W]	2.2 W

* For elliptical cavities $E_{pk} \sim 10$ kV/m is needed to ignite plasma. It is necessary to verify experimentally that the same applies to this geometry.

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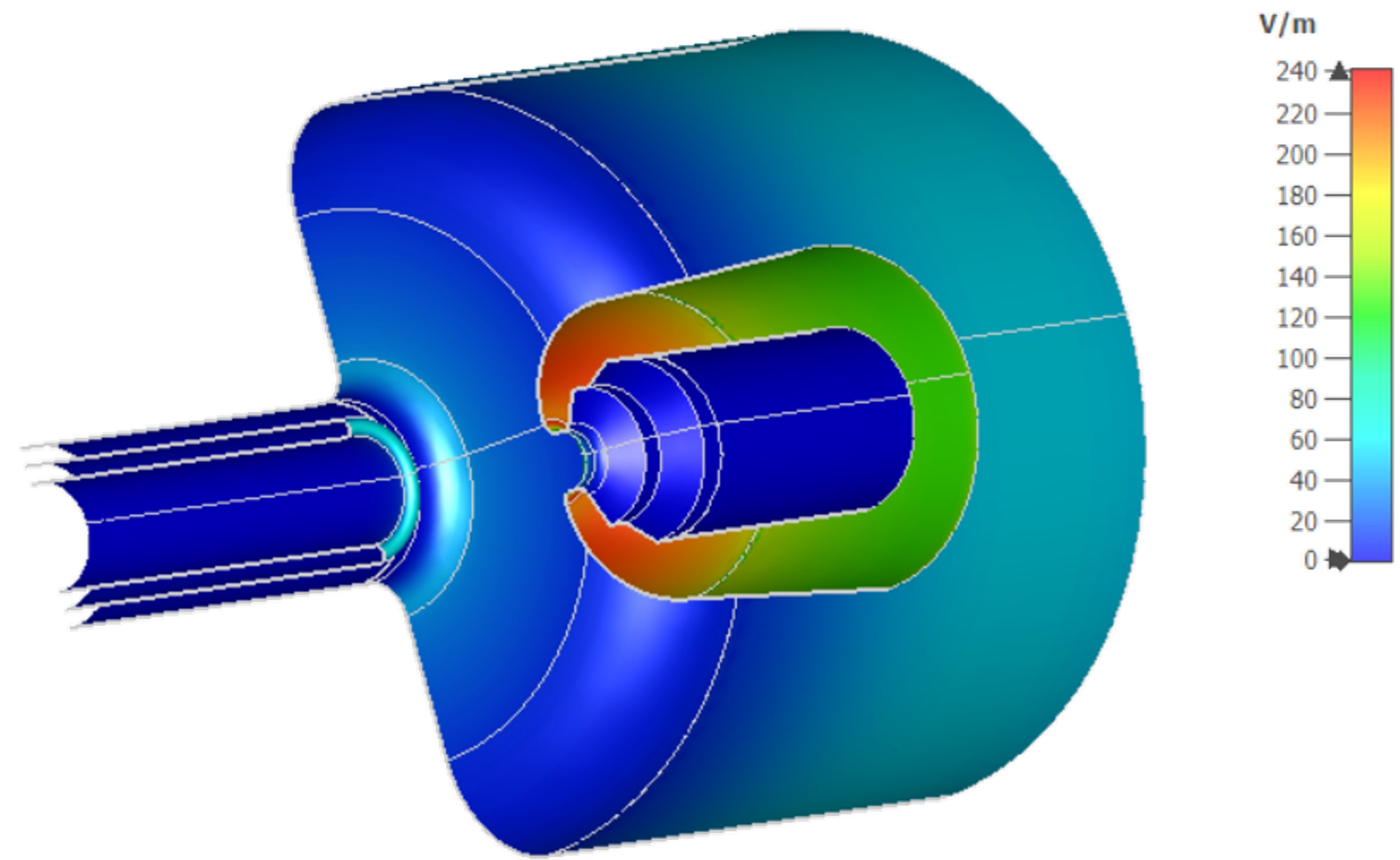
Analysis of plasma ignition in the SRF gun

E field is maximized on the cavity surface (inner conductor), not at the FPC antenna tip:

$$\frac{E_{pk,cavity\,surface}}{E_{pk,antenna\,tip}} = 3.7$$

No risk of plasma ignition at the FPC!



Courtesy of S. Kazakov, FNAL

Conclusions for plasma processing feasibility for the SRF gun

- **Preliminary analysis** suggests that **plasma processing** looks **easily applicable to the 112 MHz SRF gun**
- From simulations: plasma ignition can be achieved using fundamental mode at a few watts → needs to be experimentally verified, E_{pk} needed for ignition may be higher than in case of elliptical cavities
- No risk of igniting plasma at the antenna tip since field is maximized at the cavity surface
- FNAL gas injection and vacuum cart design can be applied to the SRF gun system, only minor modifications are expected

Summary

- **Plasma processing is an *in situ* technique with demonstrated efficacy to mitigate FE and MP in elliptical cavities**
- It can be adapted to other cavity geometries (e.g., SRF gun). There is a lot of potential!

Thank you for your attention!