Plasma Cleaning at FNAL: LCLS-II HE vCM Results and Ongoing Studies on Spoke Resonators

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SRF 2023 Grand Rapids

Outline

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

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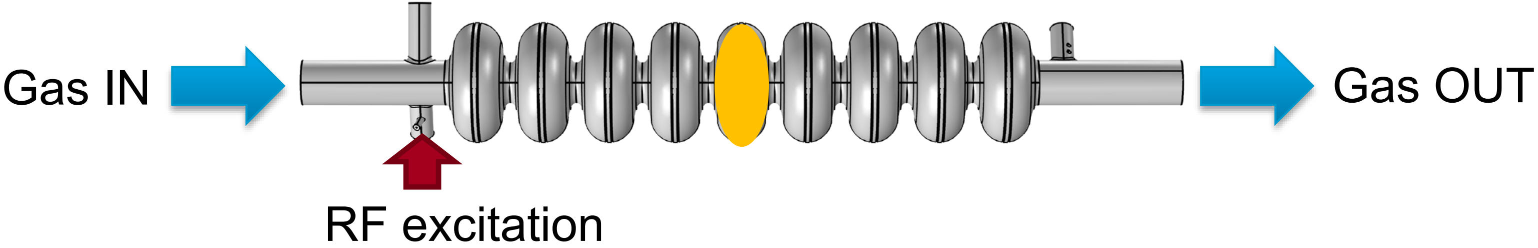
Plasma processing for SRF cavities



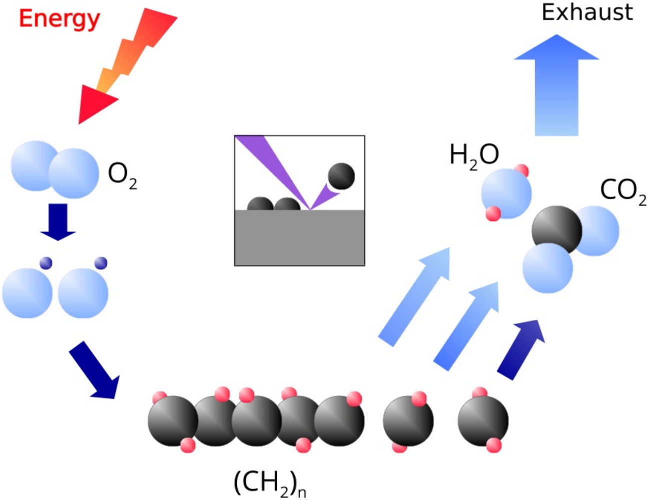
- Gas flow of Ne-O mixture (few % of O_2, mostly Ne) at p ~ 75-150mTorr
- Once plasma is ignited, oxygen reacts with hydrocarbons;
- Reaction products (mostly CO, CO_2, H_2O) are pumped out;
- Work function increases, reducing FE and enabling operation at higher E_{acc}.

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

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

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

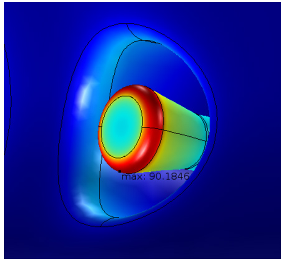
Increasing Φ by 10 % means increasing E_{acc} of about 15 %



M. Doleans et al, NIMA 812 (2016)

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

- **HOMs Plasma ignition** with the first and second dipole pass-band allowed overcoming limitations imposed by fundamental modes
- **Plasma can be ignited, transferred and tuned in each cell reliably**: the technique has been used for cleaning the vCM of LCLS-II HE
- **The Neon-Oxygen mix from SNS remained unchanged**, total pressure was reduced to 75 mTorr



LCLS-II plasma ignition	
Total P_f [W]	350
$E_{coupler}$ [kV/m]	90
E_{cavity} [kV/m]	12

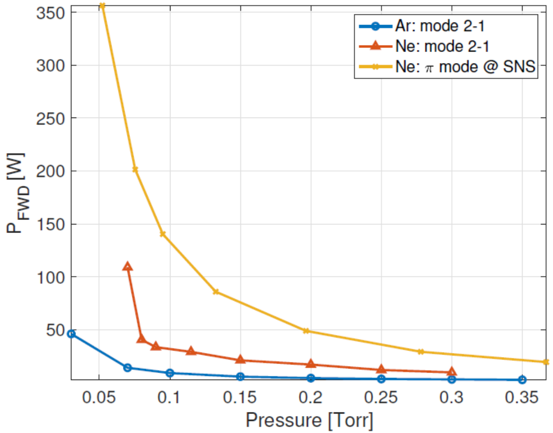
Field at the FPC for pi-mode ~ 7.5 (for SNS ~ 3)

For the first monopole pass-band:

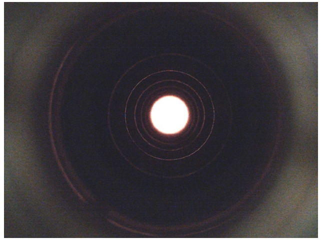
$$\beta = \frac{Q_0}{Q_{ext}} \approx 0.003 \rightarrow |\Gamma|^2 \approx 0.99$$

For the first two HOM pass-bands:

$$0.01 < \beta < 1.17 \rightarrow 0.006 < |\Gamma|^2 < 0.94$$



		CELL #	1	2	3	4	5	6	7	8	9
HOMs plasma ignition	MODE1	MODE#	2-4	2-6	2-2	2-5	2-1	2-5	2-2	2-6	2-4
		AMP	0.51	0.89	0.94	0.4	1	0.9	0.84	0.76	0.5
	MODE2	MODE#	1-6	1-4	1-3	1-4	-	1-3	1-4	1-9	1-4
		AMP	0.49	0.11	0.06	0.6	-	0.1	0.16	0.24	0.5
	Pf TOT W		4.71	8.97	6.35	5.89	2.97	7.78	6.02	7.23	7.28



P. Berrutti, et al., J. Appl. Phys. 126, 023302 (2019)

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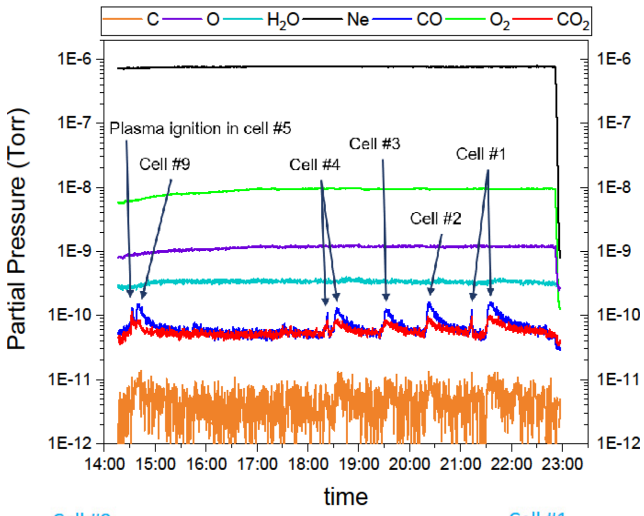
Plasma Processing Plan for vCM

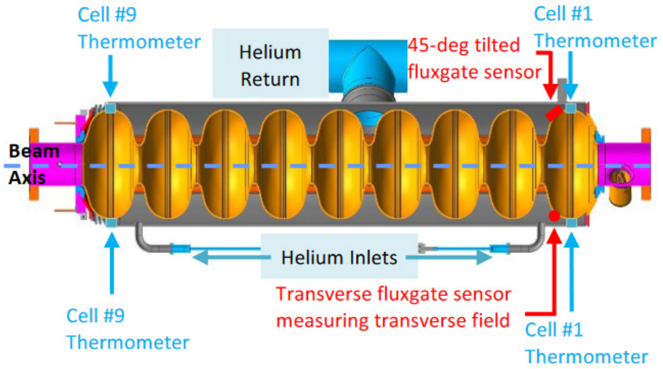
Only 4 cavities plasma cleaned:

- cavities #1 and #8 at the CM ends
- Cavities #4, #5 in the middle

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 (instrumentation installed before jacketing)





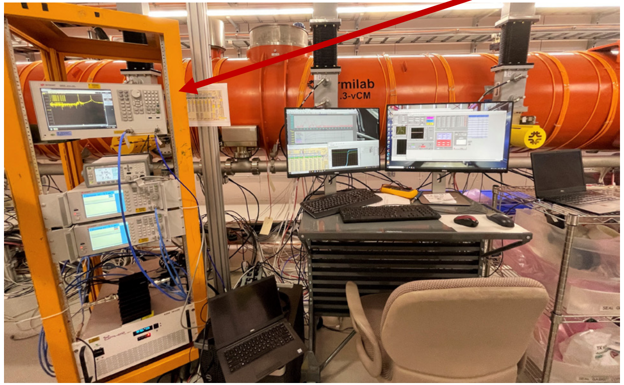
Connections between gas/vacuum systems and CM

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

Experimental systems: gas injection, vacuum & RF

Vacuum cart – connected to Endcap side

RF system, computers



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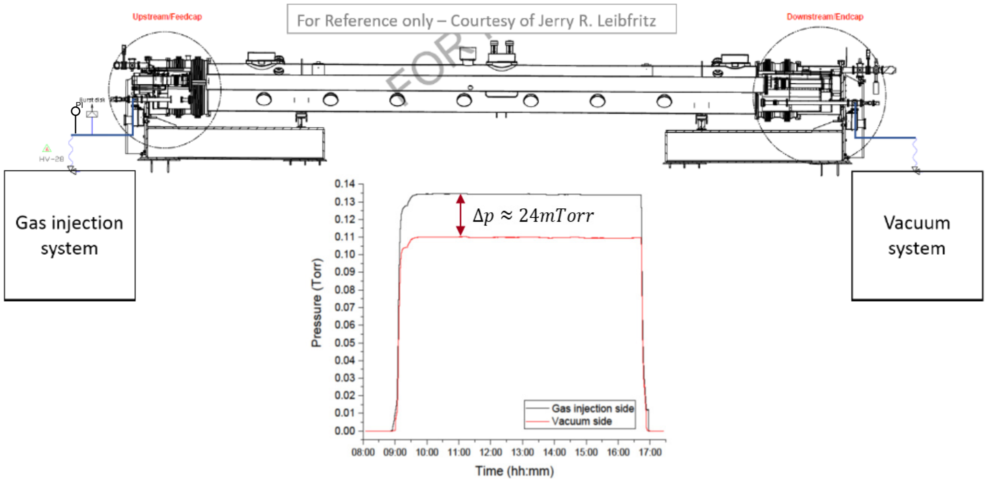
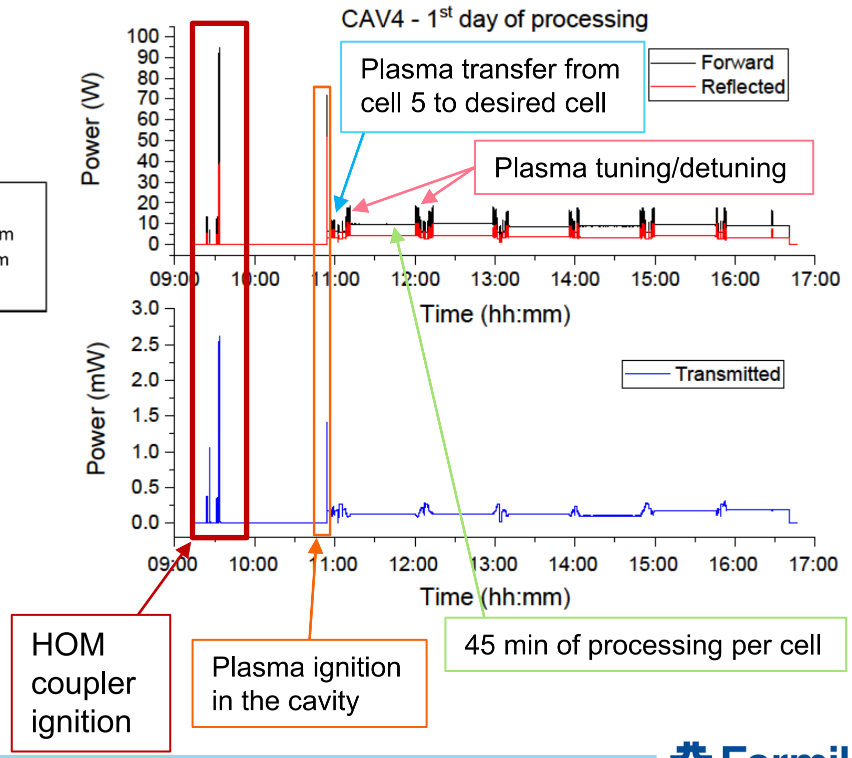
Plasma processing applied to vCM

Plasma cleaning a CM for the first time was not trivial: pressure drop along the CM and a case of plasma ignition in the HOM coupler.





Each morning the gas flow was established through the vCM

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Questions to address after plasma processing

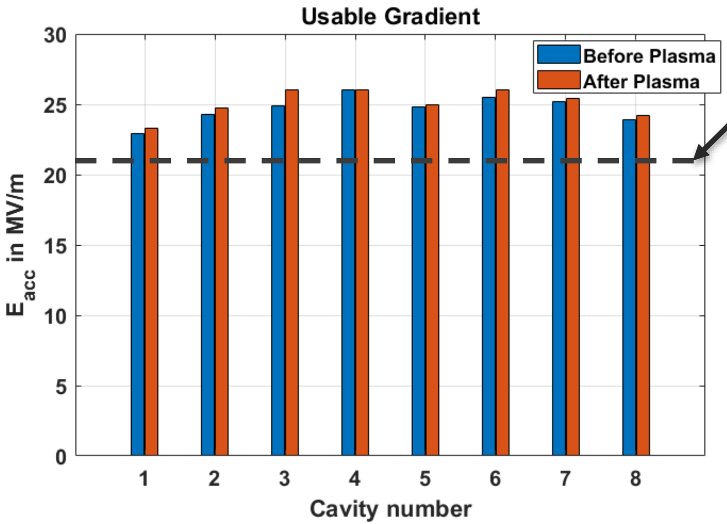
LCLS-II HE vCM before plasma: No FE and world record cryomodule!

	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}

- Did plasma processing deteriorate cavity performance in any way?
- What about performance of cavities that were not plasma cleaned?
- Did plasma processing have an impact on multipacting at all?

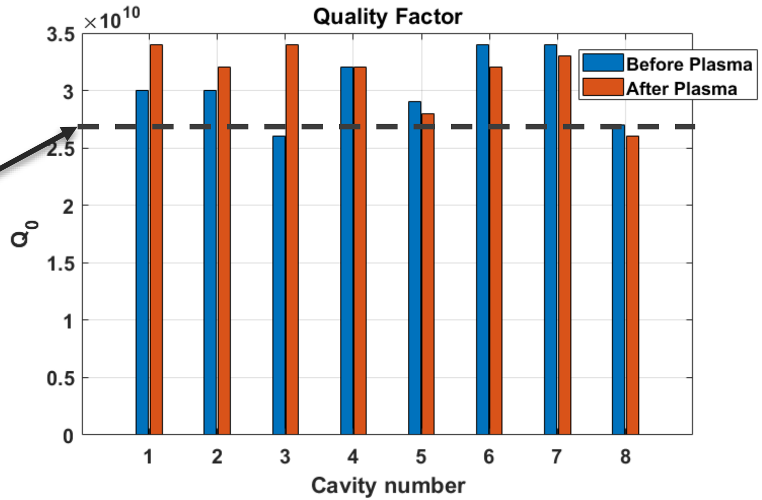
A cold RF test after plasma processing helped finding the answers and quantifying changes in performance post cleaning procedure…

vCM performance before and after plasma processing



E_{acc}= 21 MV/m

Q_0=2.7E10 @ 21 MV/m



RF test after plasma processing demonstrated that:

- **vCM performance** are **preserved**
- Plasma processing did not introduce any contamination: **vCM still FE-free**
- **the 4 plasma processed cavities do no exhibit any MP quench→ MP intensity greatly reduced!**

Cavity	Multipacting Quenches		
	Before plasma Processing		After Plasma Processing
	1^{st} cooldown	2^{nd} 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, P. Berrutti, et al. Phys. Rev. Accel. Beams 25, 102001

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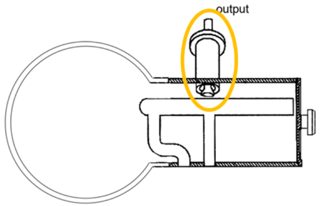
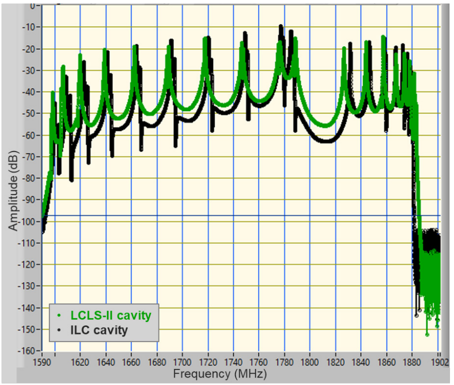
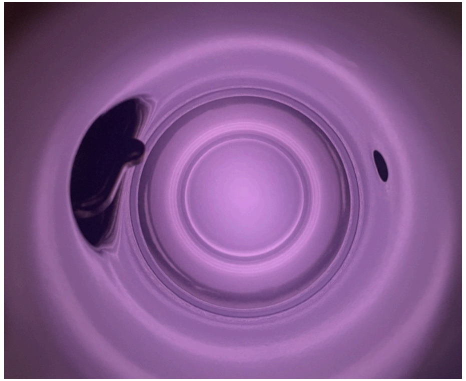
Plasma processing for ILC 1.3GHz cavities



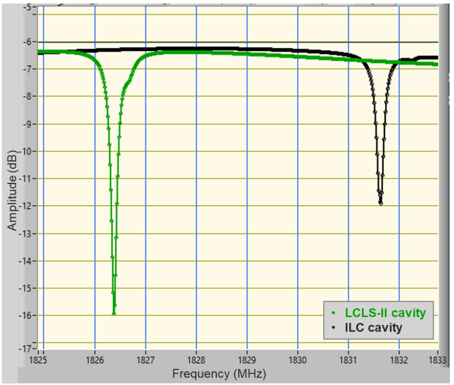
- **HOMs Plasma ignition** method developed for LCLS-II **can be used for ILC**: same cavity design different HOMs feedthroughs and cables, coupling at RT not significantly different from LCLS-II case.
- Achieving ILC gradient requirement can be challenging, plasma processing could help.
- HOMs cables: LCLS-II rated 10W, **ILC rated 1W→ Necessary to limit ignition power!!!**
- **Argon**: lower 1st ionization energy → lower ignition power. At 50 mTorr only 45-55 W are needed for ignition, safe for cables used in ILC CMs.



S21 dipole passbands



Ar glow discharge in ILC cavity



S11 2D1 used for ignition

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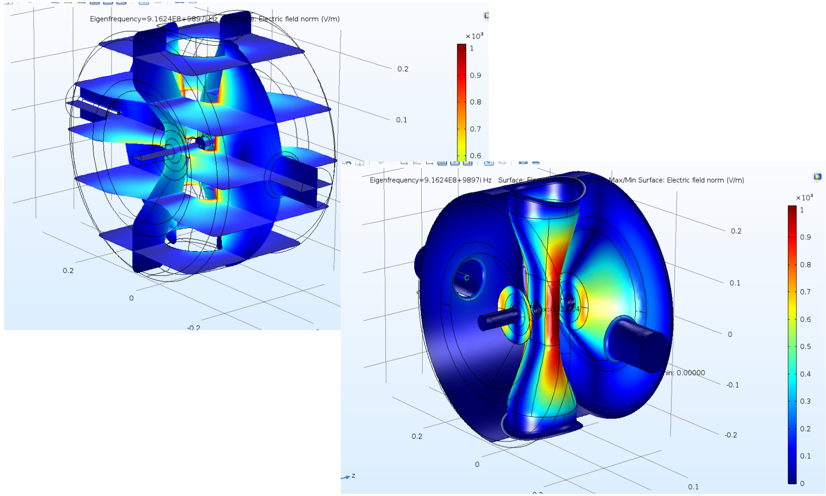
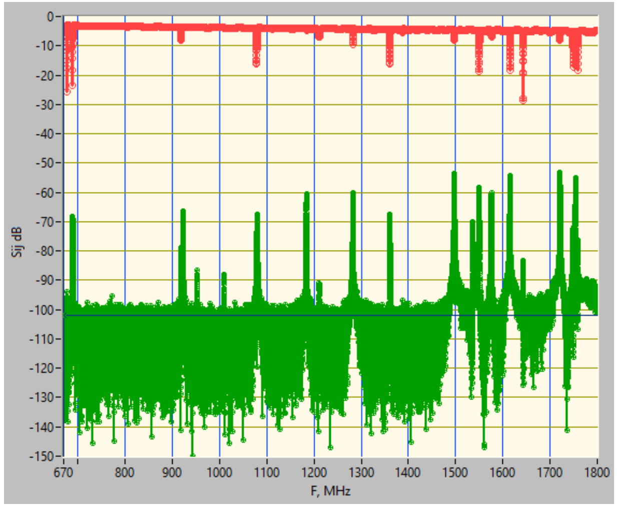
HOMs plasma ignition for coaxial resonators SSR

- Coaxial resonators may benefit from plasma cleaning (MP processing, FE), usually Q_0 at RT is ≈5E3: lower than multi-cell structure → coupler-cavity mismatch very high at RT.
- **HOMs can couple to FPC very effectively at RT→ $\beta = \frac{Q_0}{Q_{ext}} \approx$ 1** for several modes!
- Drawback: HOMs in spoke cavities may have complicated field distribution…



Example of Volume and Surface field distribution of a dipole-like HOM in SSR1



S11 (red) and S21 (green) SSR1 HOMs measurements

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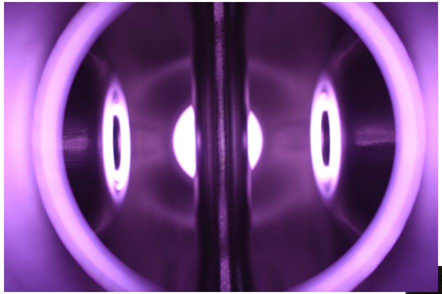
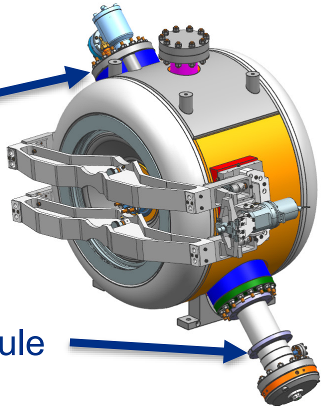
Plasma ignition SSR1 spoke cavity at FNAL I

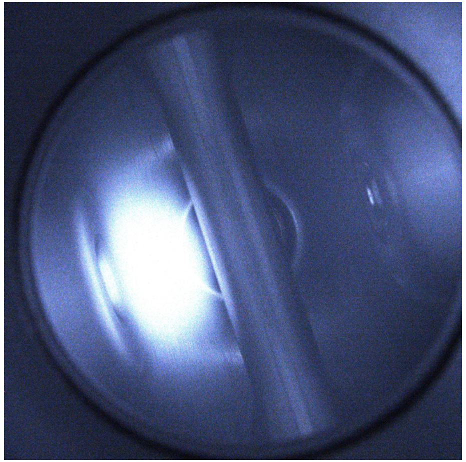
- SSR1 backfilled with **Ar at 200-10 mTorr** requires **RF power ranging from ≈0.3W to ≈80W to ignite glow discharge** depending on pressure and frequency selected.
- Correct mix of modes to ignite areas of interest has been studied:
  - accelerating gaps
  - spoke base
  - spoke side
  - cylindrical shell

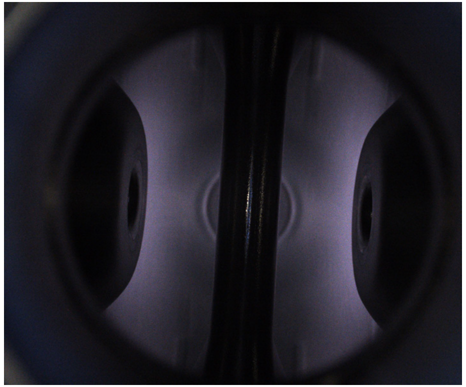


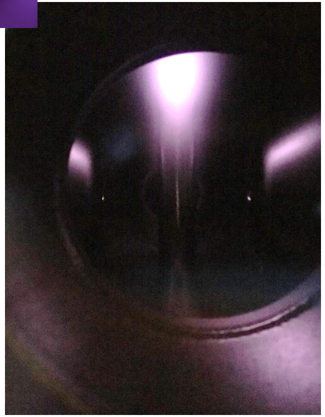
PU flange needs to be replaced with view-port for initial studies

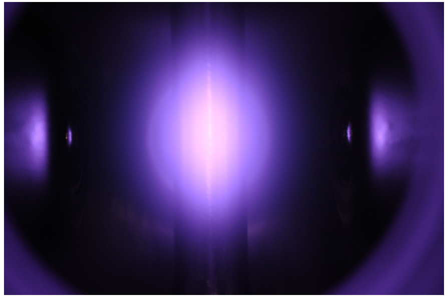


SSR1 Cryomodule FPC



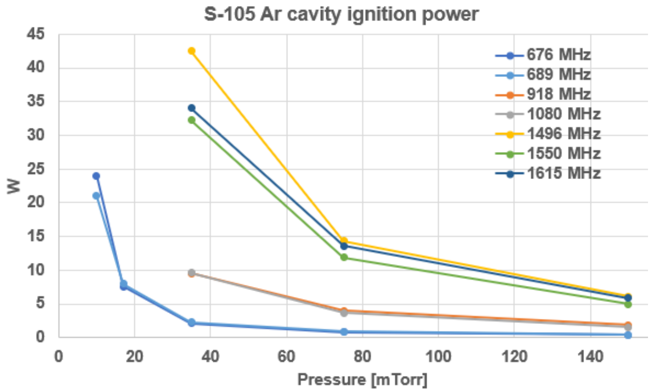


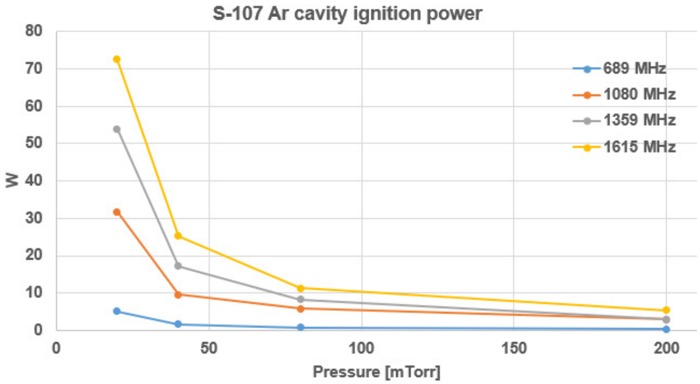


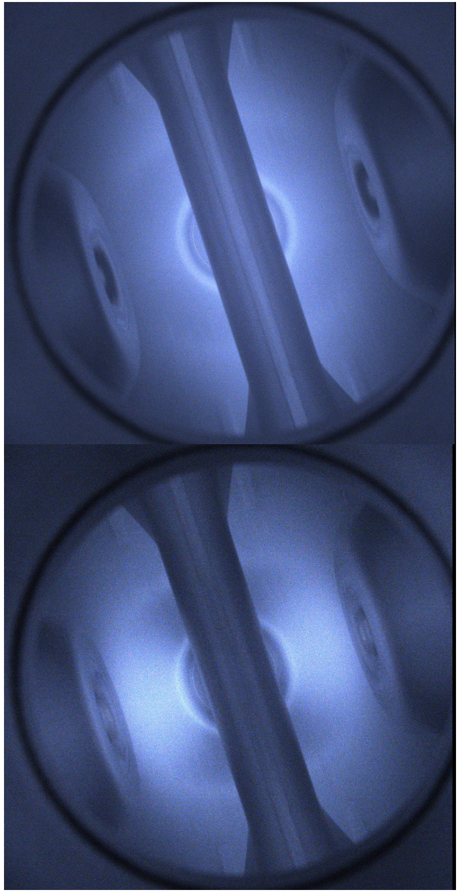


Plasma ignition SSR1 spoke cavity at FNAL II

- **Dependable plasma ignition**: it has been tested on 3 different SSR1 cavities
- Ignition power levels are consistent for a given mode and pressure (200-10 mTorr)
- Ar pressure can be lowered as much as 10 mTorr without affecting easiness of plasma ignition.
- **Less than 6W** of forward RF power are enough **to ignite the whole SSR1 cavity at 40 mTorr** (lower frequencies only)
- Higher frequency is usually related with higher plasma ignition power.







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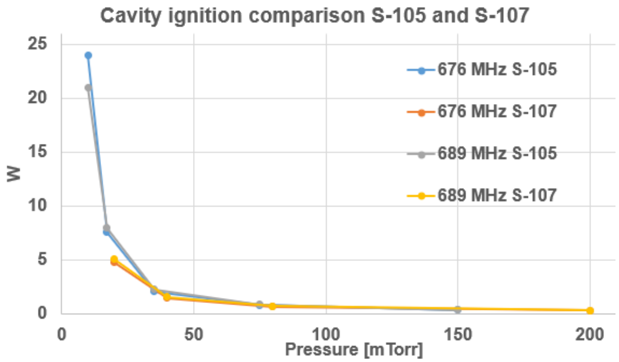
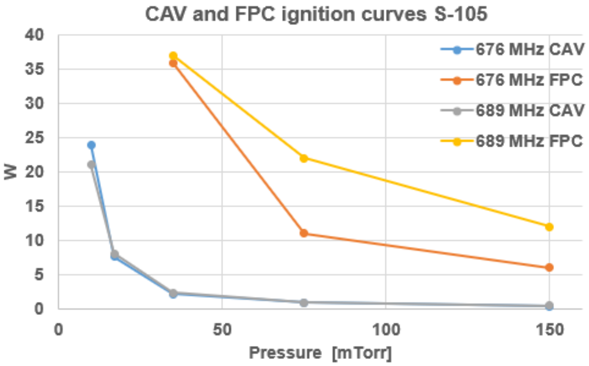
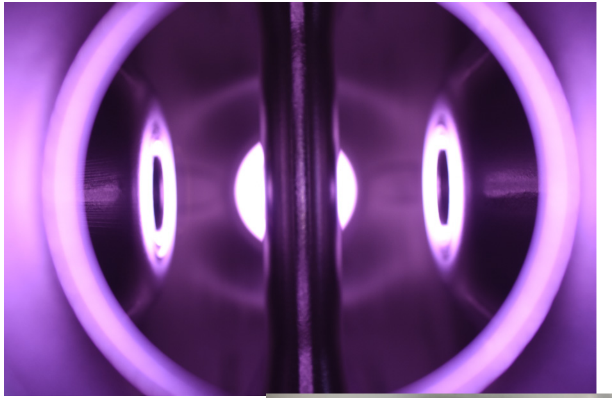
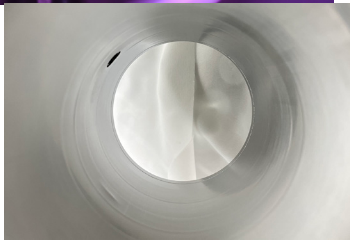
Plasma ignition in the SSR: cavity and coupler ignition

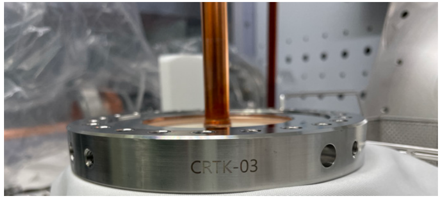
- **Cavity plasma ignition power levels are consistent for different cavities**
- **Coupler purposely ignited several times** to understand implications of its ignition
- After US cleaning no residual signs of oxidation or damage on the FPC Cu, SS or Ceramic parts→ **HOMs plasma ignition seems to be safe for SSR1**
- Cavity vs Coupler ignition curves have been measured → lower Ar pressure may mean extra power margin to avoid FPC ignition
- **No FPC ignition when pressure lower than 35 mTorr**





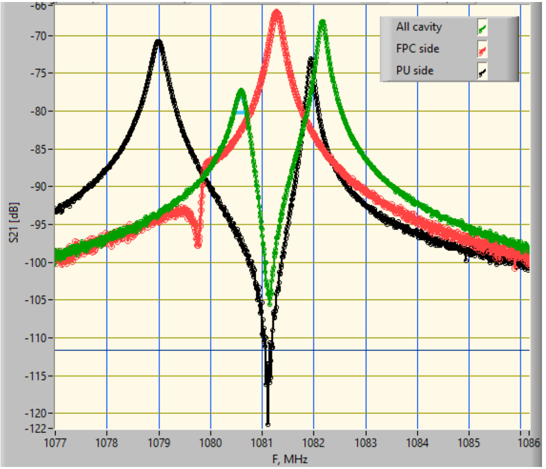


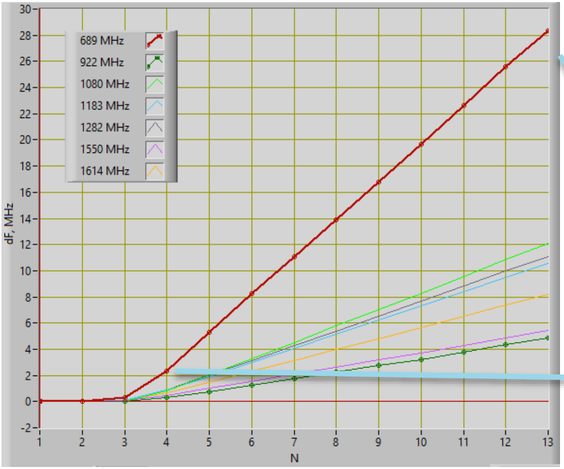


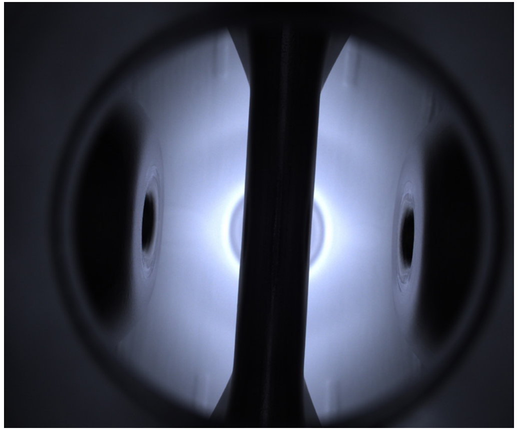


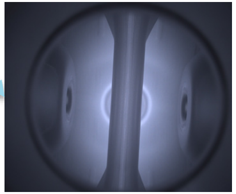
Plasma tuning and detection SSR1 spoke cavity at FNAL

- Plasma ignition with dipoles in SSR1 can be achieved in half or whole cavity: **no view ports during in situ processing → detect plasma conditions with RF measurements**
- **Plasma tuning and detection on SSR1 are working well** and in agreement with simulations → **blind test (full CM configuration) coming next.**
- **After testing plasma without visual reference, cleaning of SSR1 cavities in a cryostat can be attempted…**

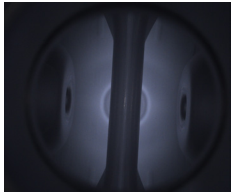








At 10 mTorr
$\Delta f_{max} > 30\text{MHz}$
$\varepsilon_{real} \approx 0.94$



At ignition (whole cavity)
$\Delta f_{min} \approx 2\text{MHz}$

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The effectiveness of plasma processing is proven for in situ FE and MP mitigation.

HOMs plasma ignition allows application of plasma cleaning to virtually any cavity geometry (coaxial resonators, e.g. SSR1).

What would you "plasma" next? Crab Cavities?

Thank you for your attention

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