Plasma Cleaning R&D at FNAL

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Plasma Processing activities at FNAL

Plasma cleaning R&D is ongoing at FNAL for 1.3 GHz 9-cell, LCLS-II, cavities:

- Ne-Oxygen plasma SNS recipe will be used on LCLS-II cavities.
- Plasma ignition and plasma detection RF techniques need to be adapted/modified for 1.3 GHz cavities.
- 1-cell, 9-cell offline cavities processing and finally in-situ cryomodule cleaning.

1.3 GHz 1-cell

1.3 GHz 9-cell in HTS

LCLS-II cryomodule

Collaboration for LCLS-II Plasma Processing

Oak Ridge National Laboratory

- Successful experience with plasma processing
- Guidance for design and sample studies for LCLS-II plasma cleaning

SLAC National Accelerator Laboratory

- Simulation for applicability of ORNL plasma processing to LCLS-II cavities
- Use the system to perform cleaning in the accelerator tunnel

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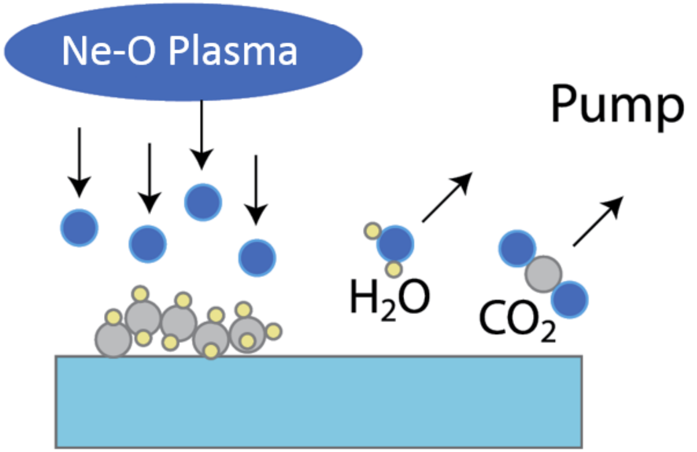
- Adapt the ORNL plasma cleaning technique to LCLS-II cavities and cryomodules
- Provide a system capable of efficiently process LCLS-II cavities/cryomodules

Project supported by DOE - Basic Energy Sciences (BES)

Plasma Processing at ORNL/SNS

- **Reducing FE by increasing work function** of cavity RF surface
  - Hydrocarbon contaminants observed on all Nb cavities
  - Hydrocarbons and adsorbates lower work function of Nb
- Enabling operation at higher accelerating gradients

$$O_2 + C_xH_y \rightarrow CO + CO_2 + H_2O$$



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

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

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

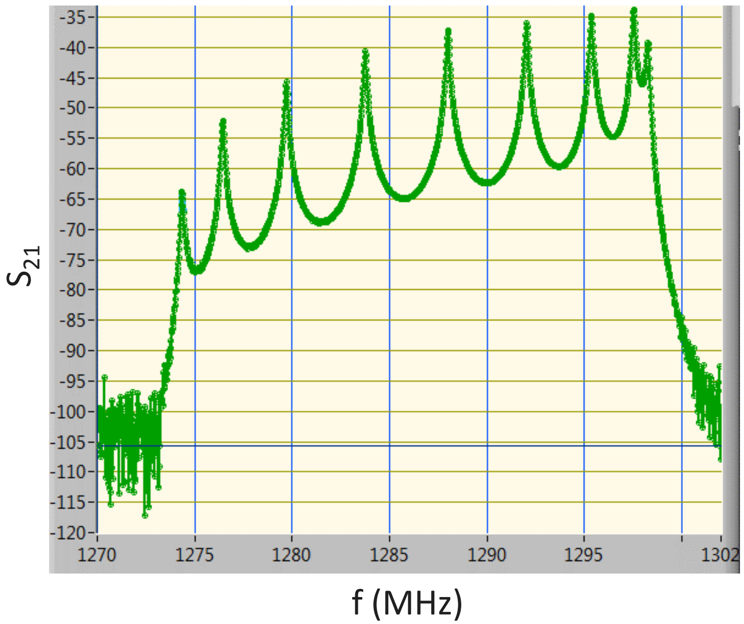
Increasing Φ by 10 % means increasing E_{acc} of about 15 %

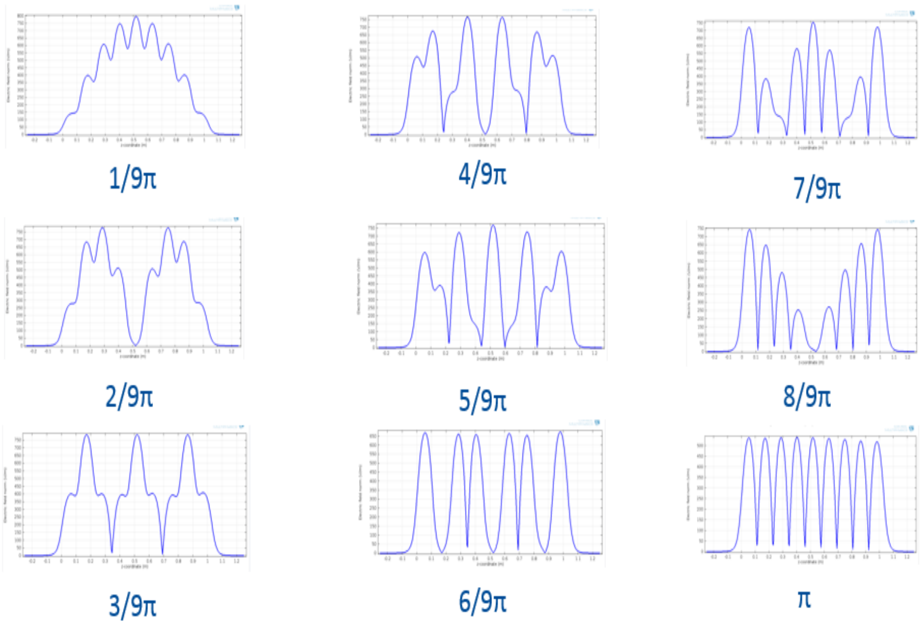
M. Doleans et al. NIMA 812 (2016) 50-59

Plasma Ignition in LCLS-II Cavities with TM_{010} modes

- Plasma ignited sequentially cell-by-cell
- **Dual tone excitation** to ignite plasma in the desired cell (M. Doleans, J. Appl. Phys. 120, 243301 (2016))
  - 2 fundamental modes mixed to increase field amplitude in one cell (and its mirror images)
  - Off-resonance excitation introduce asymmetry in the cell amplitude

LCLS-II 9-cells - 1st pass-band modes





Plasma Ignition in LCLS-II Cavities with TM_{010} modes

To obtain 10 kV/m, **more power is needed** comparing with SNS cavities:

- 9-cells instead of 6
- Larger mismatch at room T:
  - $Q_0 = 1 \cdot 10^4$ for Nb
  - SNS FPC: $Q_{ext} = 7 \cdot 10^5$
  - LCLS-II FPC: $Q_{ext} = 3 \cdot 10^7$
  - For LCLS-II only 1% of the power is transmitted to the cavity

Cell #	Mode 1	Amp	dF (HBW)	Mode 2	Amp	dF (HBW)	Pf FPC (W)
1	8/9 pi	0.67	0	pi	0.33	1.5	**160**
2	8/9 pi	0.75	-1.5	3/9 pi	0.25	0	**200**
3	5/9 pi	0.75	0	8/9 pi	0.25	-1.5	**130**
4	7/9 pi	0.58	1.5	4/9 pi	0.42	1.5	**280**
5	7/9 pi	0.75	0	5/9 pi	0.25	0	**80**
6	7/9 pi	0.5	-1.5	4/9 pi	0.5	-1.5	**310**
7	5/9 pi	0.75	0	8/9 pi	0.25	1.5	**130**
8	8/9 pi	0.71	1.5	3/9 pi	0.29	0	**200**
9	8/9 pi	0.67	-1.5	pi	0.33	-1.5	**160**

- Plasma ignition using fundamental modes/pass-band is highly dependent on coupling coefficient at RT!
- Two possible scenarios when mismatch between cavity and coupler is high:
  - NO PLASMA IGNITION
  - **PLASMA IGNITION IN THE COUPLER!!!**

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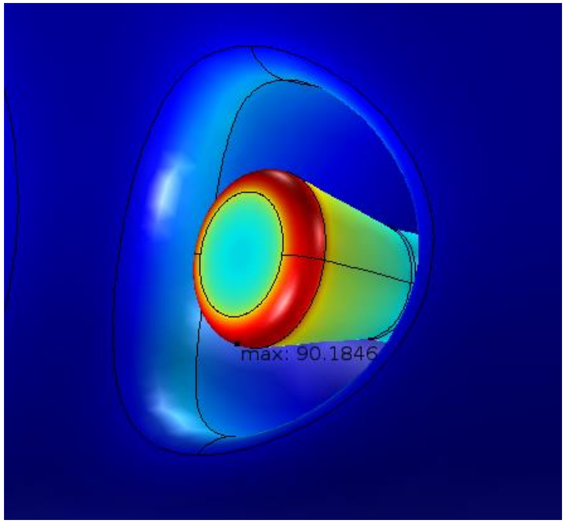
Field Enhancement at the LCLS-II FPC

- **Field enhancement** at the coupler due to **larger mismatch at room T and different FPC geometry**



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

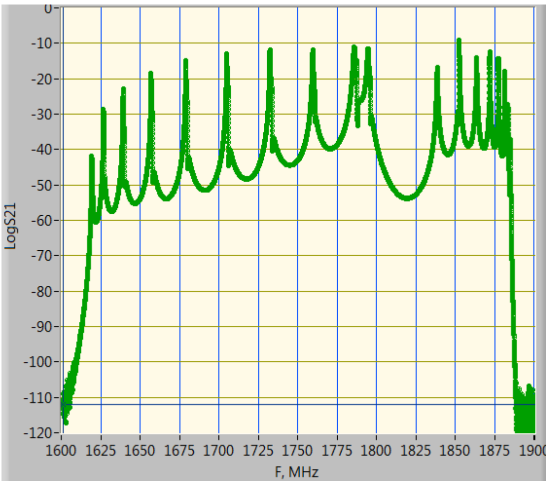
Field enhancement at the coupler ~ 7.5 (for SNS ~ 1.5)

- Suggest larger probability to ignite the plasma at the coupler

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

New Idea: Plasma Ignition Using HOMs

HOM couplers are designed to extract power at HOMs frequencies: Good coupling also at room temperature!



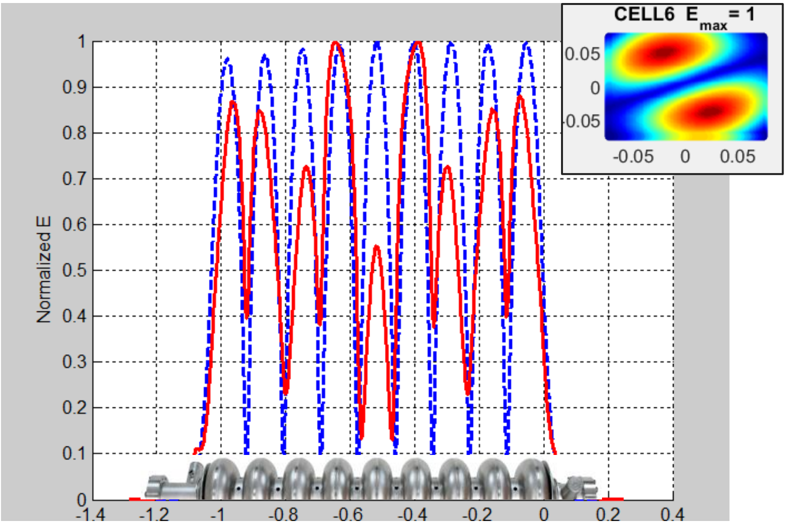
For the first two HOM pass-bands:

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

First plasma ignition test on 1.3 GHz 9-cell cavity, 200 mTorr of Ar: results show only few Watts are needed to ignite a glow discharge.

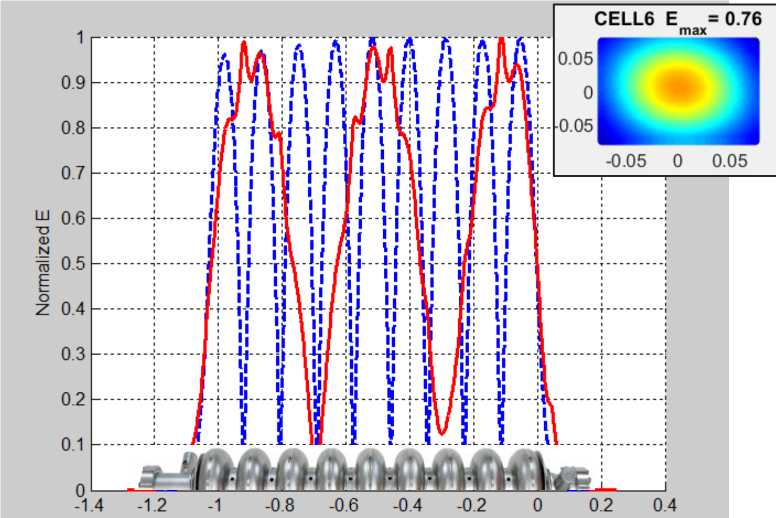
	CELL #		1	2	3	4	5	6	7	8	9
HOMs plasma ignition	MODE1	MODE#	2-4	2-6	2-2	2-5	2-1	2-5	2-2	2-6	2-4
		AMP	0.51	0.89	0.94	0.4	1	0.9	0.84	0.76	0.5
	MODE2	MODE#	1-6	1-4	1-3	1-4	-	1-3	1-4	1-9	1-4
		AMP	0.49	0.11	0.06	0.6	-	0.1	0.16	0.24	0.5
	Pf TOT W		**4.71**	**8.97**	**6.35**	**5.89**	**2.97**	**7.78**	**6.02**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

Selective cell ignition: HOMs superposition example



MODE 2-5: symmetric field CELL#4&6

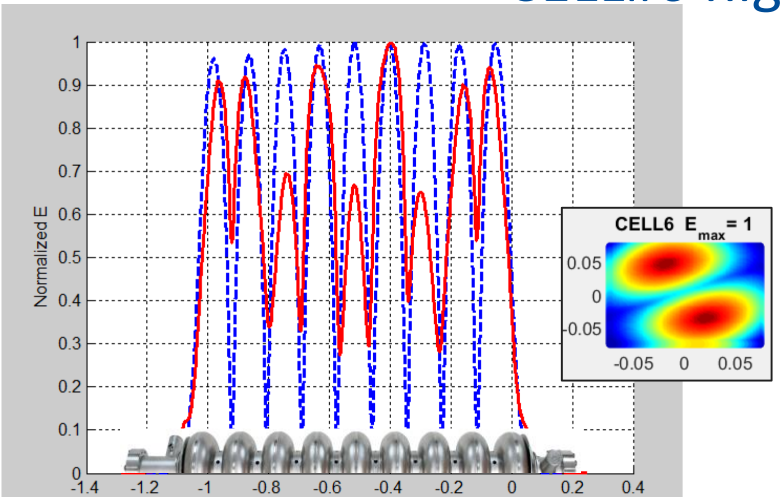
+



MODE 1-3: asymmetric field, CELL#6 higher

=

Field amplitude maximized in cell #6



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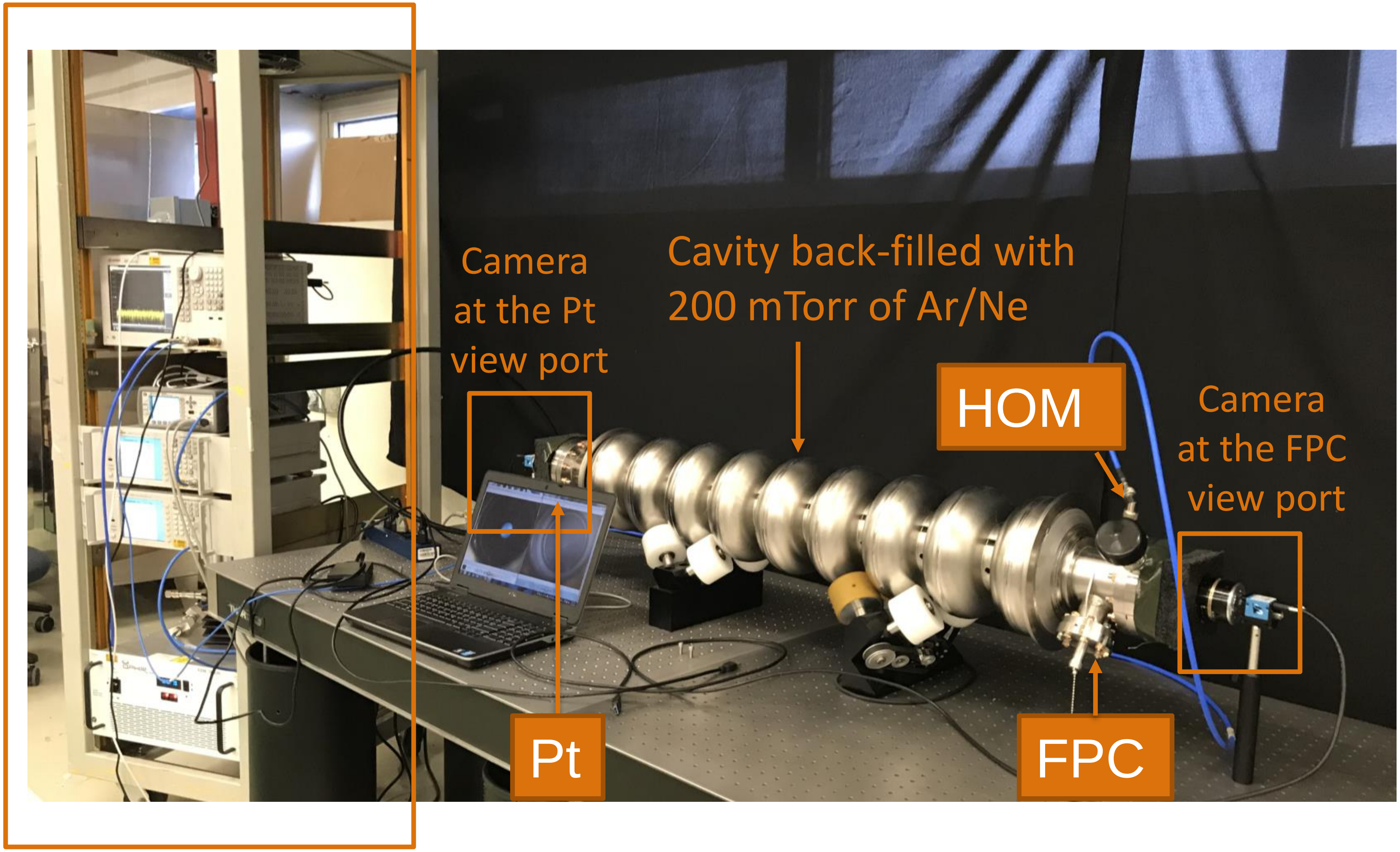
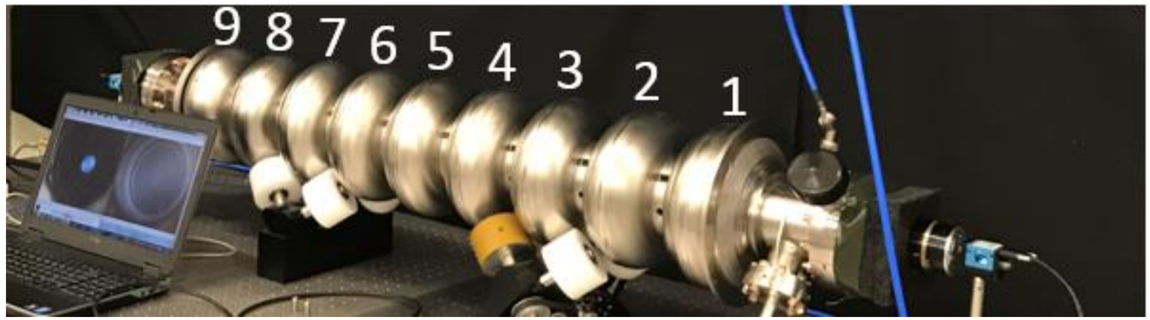
Set-up Plasma Ignition Studies

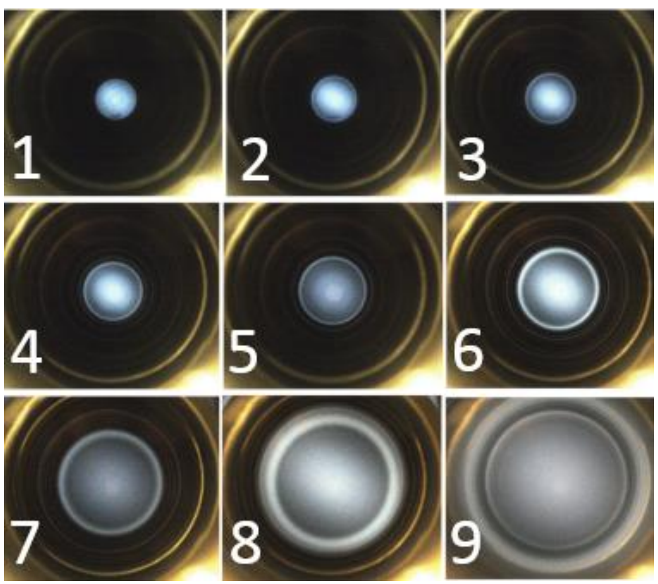
RF rack

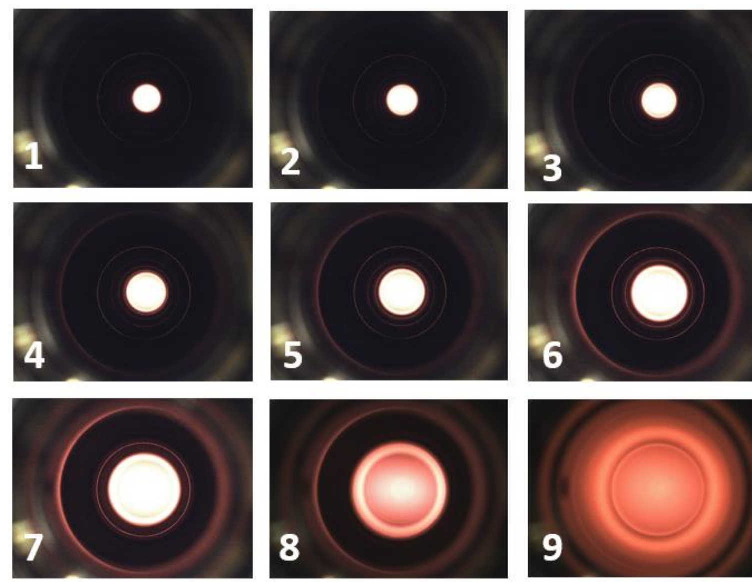


Selective Plasma ignition in 9-cell cavities

- Plasma has been ignited in each cell of a 1.3 GHz cavity using HOMs
- **The technique has been proven to work on two cavities: TB9NR011 and TB9NR014 both in 200 mTorr of Ar (left) and also with Neon (right) at different pressures**







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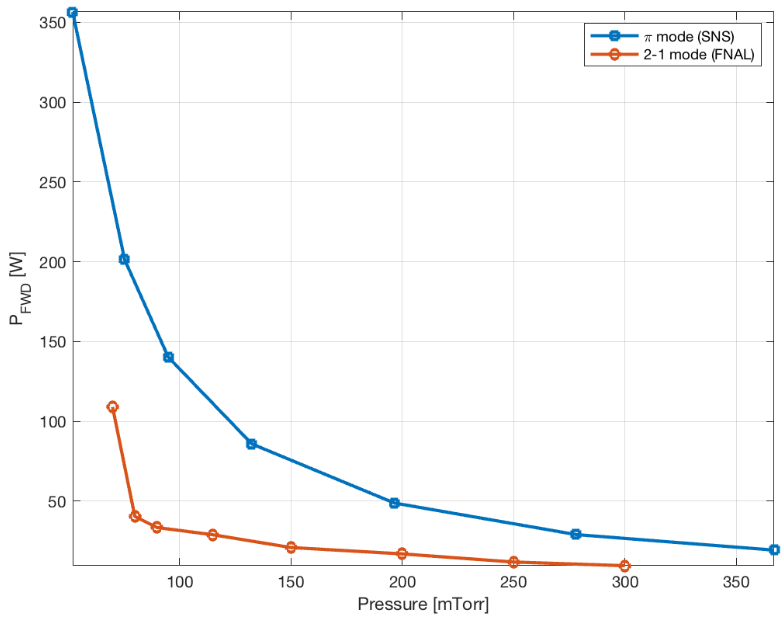
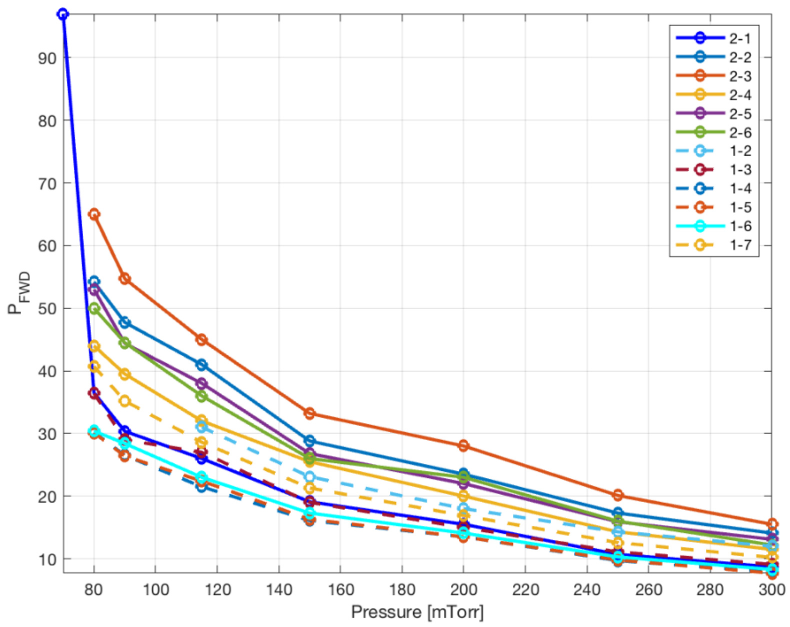
Paschen Curve for 1.3 GHz 9-cell

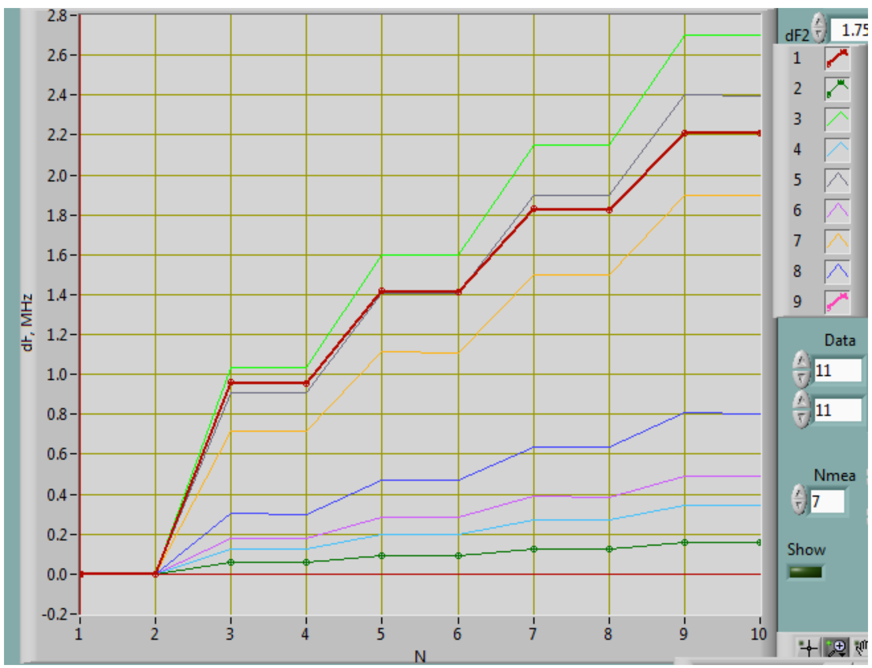
- Plasma ignition power has been measured for 1.3 GHz 9-cell cavities using HOMs, different HOMs have been used to ignite plasma.
- Plasma ignition experimentally observed in a quite large pressure range from 70 to 300 mTorr, Paschen curve for Ne shown below.
- The power needed to ignite plasma has been compared to SNS HB data: required power is lower **200 mTorr ignition of Ne at ≈17W, Ar at ≈5W!**

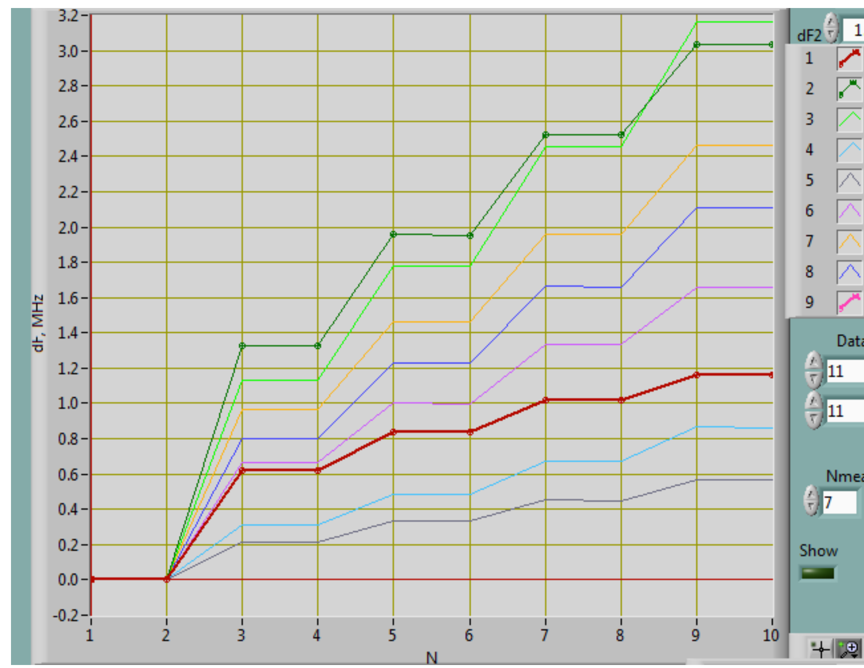




Plasma Tuning and Detection for 1.3 GHz 9-cell

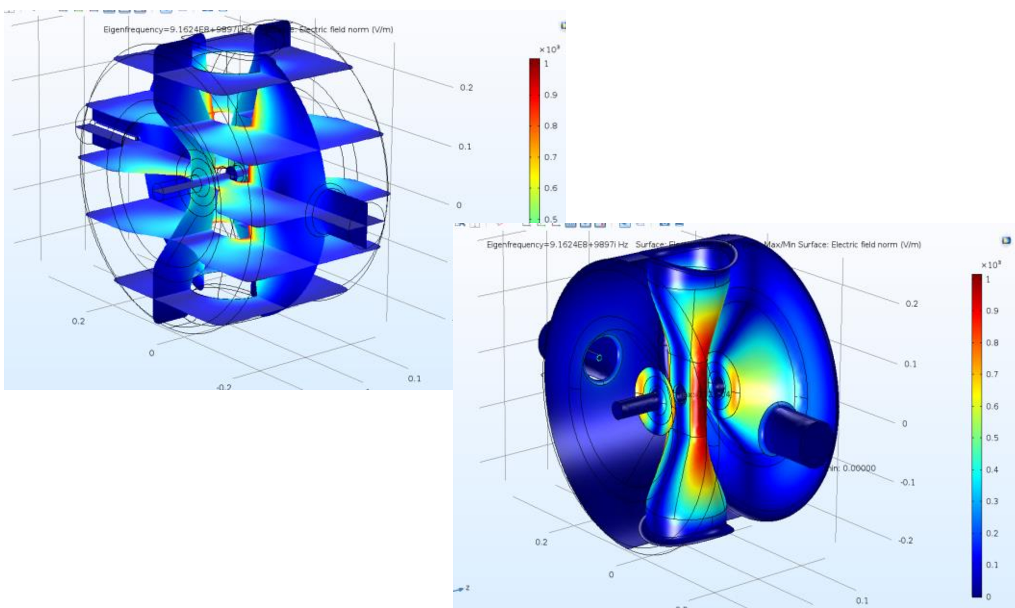
- Plasma density is related to dielectric constant: plasma density can be calculated from measurement of RF frequency.
- Position of plasma in cavity can be detected by measuring a set of mode frequencies.
- Two examples of RF measurements are shown below, cell#5 (left) cell#8 (right): reference frequency values without plasma.
- RF power used for plasma tuning ≈2-3W.



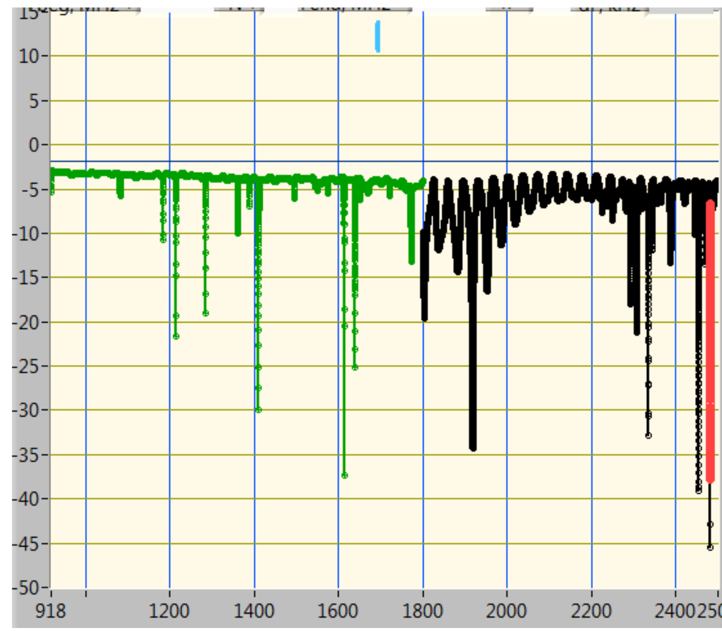


HOMs plasma ignition in SSR1 spoke cavities

- Spoke 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 better than fundamental mode at RT!
- Drawback: HOMs in spoke cavities have complicated field distribution…see example below.



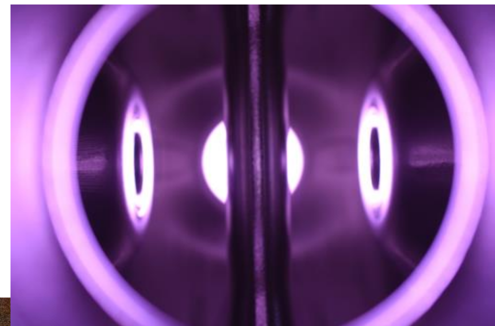
Example of Volume and Surface field distribution of HOM in SSR1 (FNAL)



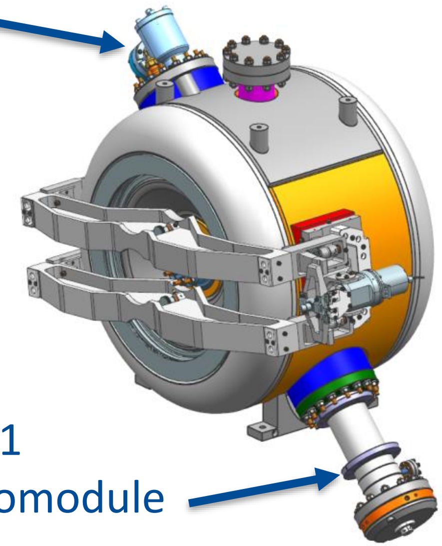
S11 measurements of SSR1 FPC

Plasma ignition SSR1 spoke cavity

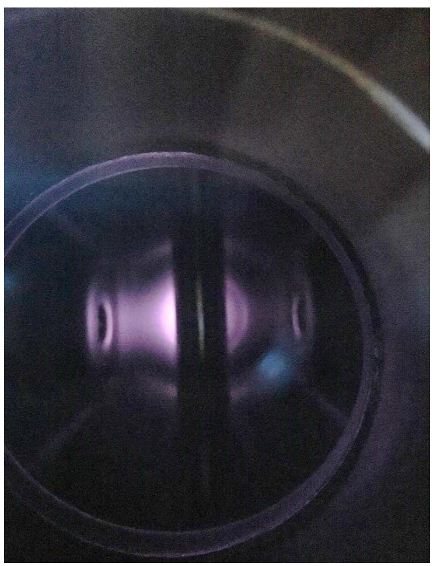
- Ar at 250 mTorr requires RF power ranging from ≈2W to ≈30W (depending on the mode) to ignite glow discharge.
- Plasma distribution follows electric field distribution.
- Correct mix of modes to ignite areas of interest:
  - accelerating gaps
  - spoke base
  - spoke side
  - cylindrical shell

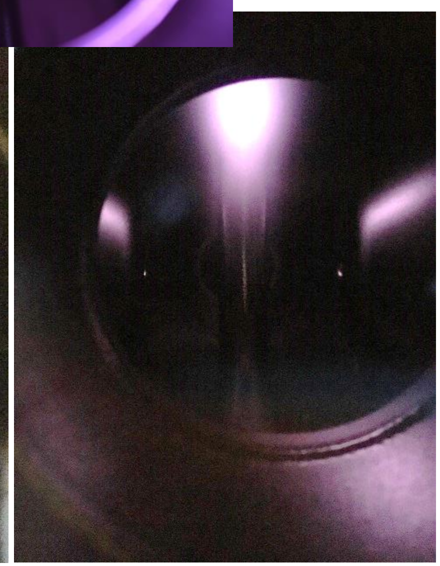


PU flange needs to be replaced with view-port



SSR1 Cryomodule FPC





Conclusions

- Plasma Cleaning R&D at FNAL is showing applicability to 1.3 GHz 9-cell cavities:
  - Low power plasma ignition with HOMs
  - Plasma tuning and detection study show promising results for in-situ applicability on cryomodules
- HOMs plasma ignition allows overcoming limitations imposed by RT mismatch between cavity and couplers:
  - Possibility of plasma cleaning for cavities in cryomodule configuration without using variable couplers
  - Applicability to Spoke Resonators is being studied at FNAL, initial results are promising

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Thank you for your attention!

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