Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Recent Progress in Plasma Cleaning 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

Motivations for in-situ plasma cleaning

Cavity	Cryomodule Max Gradient* [MV/m]	VTS Max Gradient [MV/m]	Usable Gradient** [MV/m]	FE onset [MV/m]	Cryomodule Q_0 @16MV/m*** Fast Cool Down	Q_0 @16MV/m at VTS
TB9AES021	21.2	23.0	18.2	14.6	2.6e10	3.1e10
TB9AES019	19.0	19.5	18.8	15.6	3.1e10	2.8e10
TB9AES026	19.8	21.5	19.8	19.8	3.6e10	2.6e10
TB9AES024	21.0	22.4	20.5	21.0	3.1e10	3.0e10
TB9AES028	14.9	28.4	14.2	13.9	2.6e10	2.6e10
TB9AES016	17.1	18.0	16.9	14.5	3.3e10	2.8e10
TB9AES022	20.0	21.2	19.4	12.7	3.3e10	2.8e10
TB9AES027	20.0	22.5	17.5	20.0	2.3e10	2.8e10
Average	**19.1**		**18.2**	**16.5**	**3.0e10**	**2.8e10**
Total Voltage	**154.6 MV**		**148.1 MV**			

Acceptance = 128 MV

* Administrative limit 20 MV/m
** Radiation <50 mR/h
*** TB9AES028 Q_0 was at 14 MV/m

Courtesy of G. Wu

In-situ plasma processing of cryomodules will allow:

- Increasing maximum gradient
- Reducing radiation level
- Preserving high-Q

In-Situ:
NO NEED OF DISASSEMBLY!!

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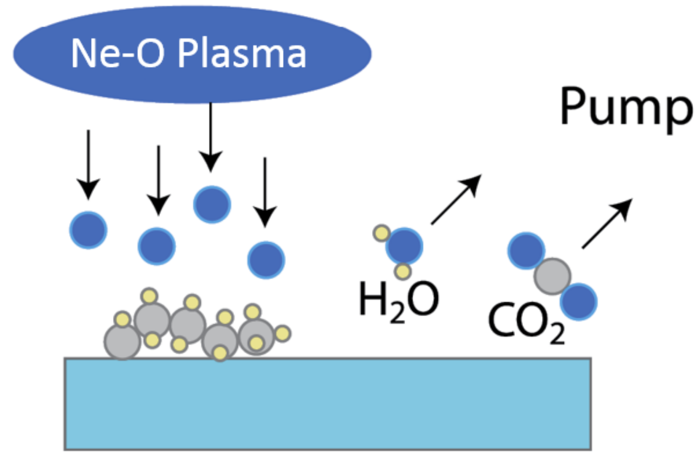
- Adapt the ORNL plasma cleaning technique to LCLS-II cavities and cryomodules
- Provide a system capable of efficiently process LCLS-II cavities/cryomodules

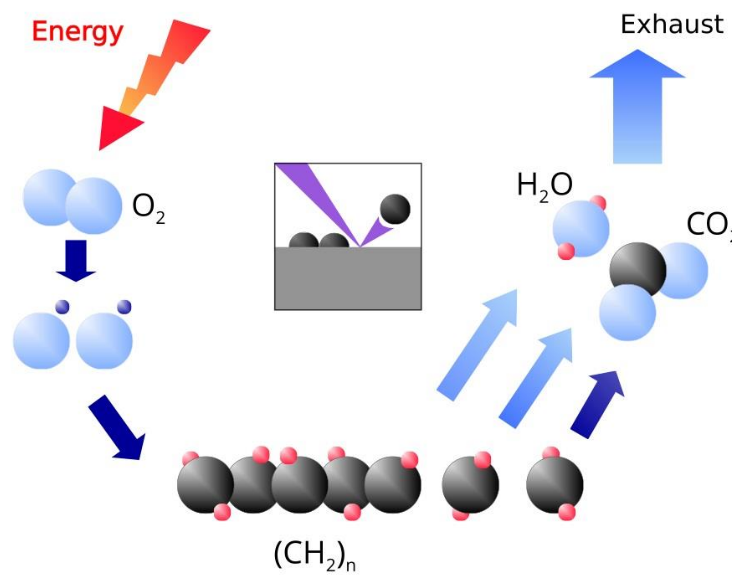
Project supported by DOE - Basic Energy Sciences (BES)

Plasma Cleaning for SRF Cavities at ORNL/SNS

- **Oxygen plasma at room temperature** (reactive environment with ions, e-, neutrals, radicals, etc.)
- **Volatile by-products** are formed through oxidation of hydrocarbons and **pumped out** and monitored (RGA)
- **Mixture of Neon-Oxygen:**
  p~100 – 200 mTorr, 2 % O_2
  - $\boldsymbol{Ne}$ → <u>support gas</u> to create a stable glow discharge
  - $\boldsymbol{O_2}$ → <u>cleaning agent</u>, react with carbon forming volatile species

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





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

Plasma Processing at ORNL/SNS

Plasma process at ORNL/SNS focused on:

- **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

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

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

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

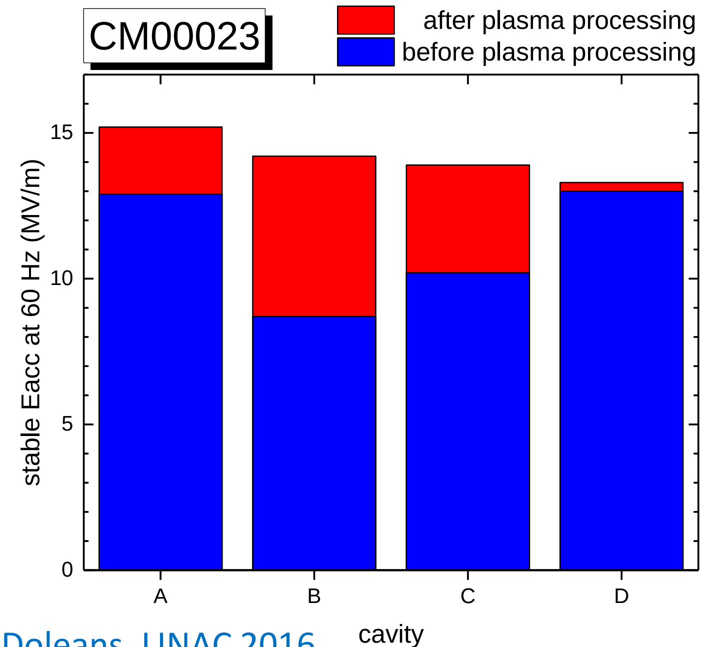
Increasing Φ by 10 % means increasing E_{acc} of about 15 %

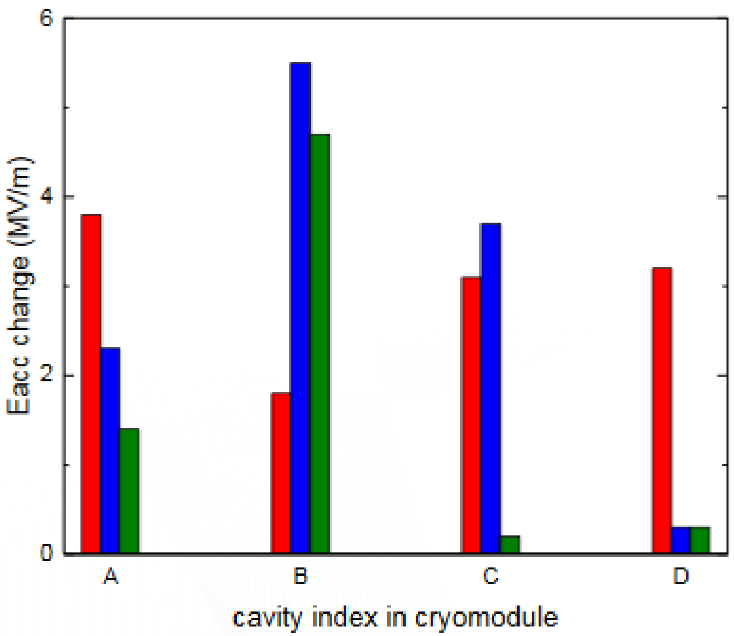
M. Doleans et al. NIMA 812 (2016) 50-59

Eacc Increasing in SNS Cryomodule After Plasma Processing

SNS linac output beam energy is being increased

- One cryomodule has been processed offline
- Two cryomodules have been plasma processed directly in the SNS linac tunnel
- 20% Improvement of accelerating gradients on average!

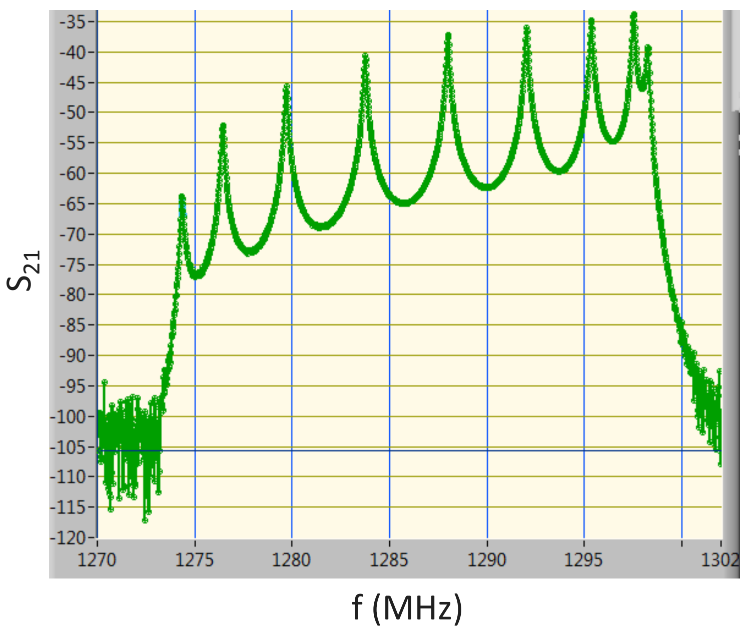




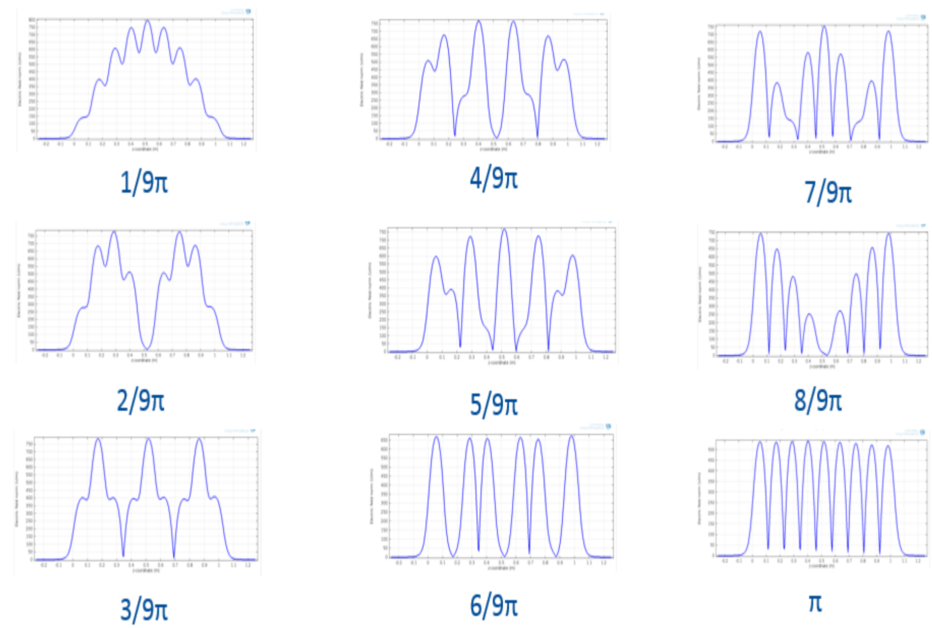
M. Doleans, LINAC 2016

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))
  - <u>2 fundamental modes mixed</u> to increase field amplitude in one cell (and its mirror images)
  - <u>Off-resonance excitation</u> introduce asymmetry in the cell amplitude



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



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  - 2 fundamental modes mixed to increase field amplitude in one cell (and its mirror images)
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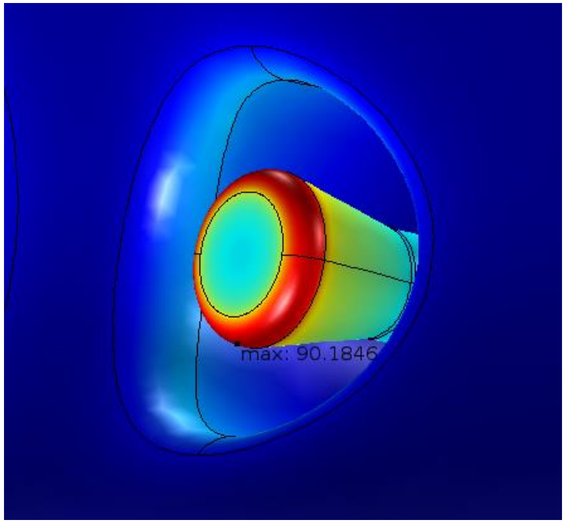
To obtain 10 kV/m, **more power is needed** comparing with SNS cavities:

- 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**

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 ~ 3)

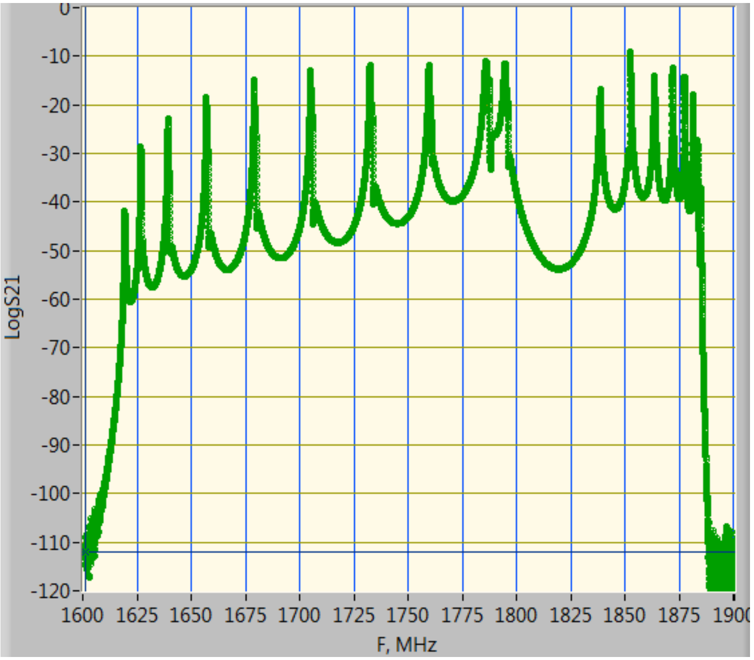
- Suggest larger probability to ignite the plasma at the coupler

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

New Idea: Plasma Ignition Using HOMs I

- 1st pass-band modes capable of building electric field in each cell.
- Poor coupling at room temperature represents a limitation.
- Is there an efficient way of coupling power to the cavity at room temperature?

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



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:

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

New Idea: Plasma Ignition Using HOMs II

Solution to avoid ignition of the FPC:

→ **Use mixture of HOMs instead of the FPB modes to ignite plasma**

- For the **first pass-band** only 1% of the power transmitted to the cavity
- Most dipoles of 1st and 2nd passband almost all power gets to the cavity (very good coupling at room T)
- **Plasma will be still ignited sequentially cell-by-cell using HOMS**

	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

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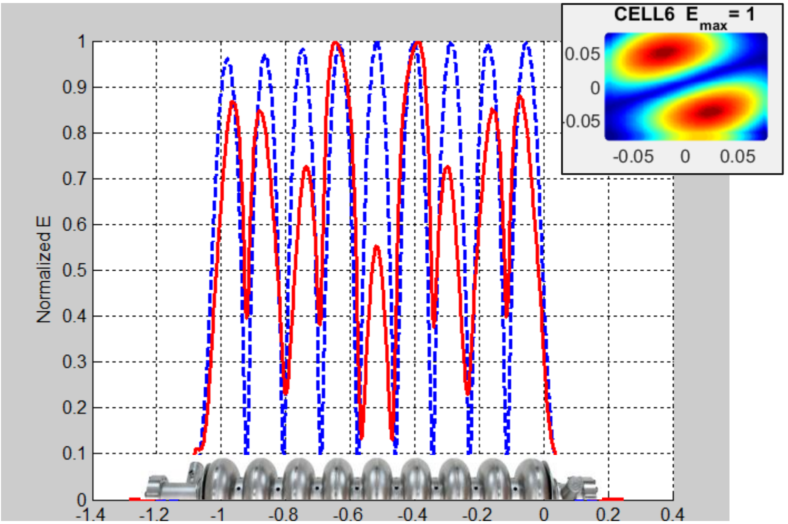
New Idea: Plasma Ignition Using HOMs (example)



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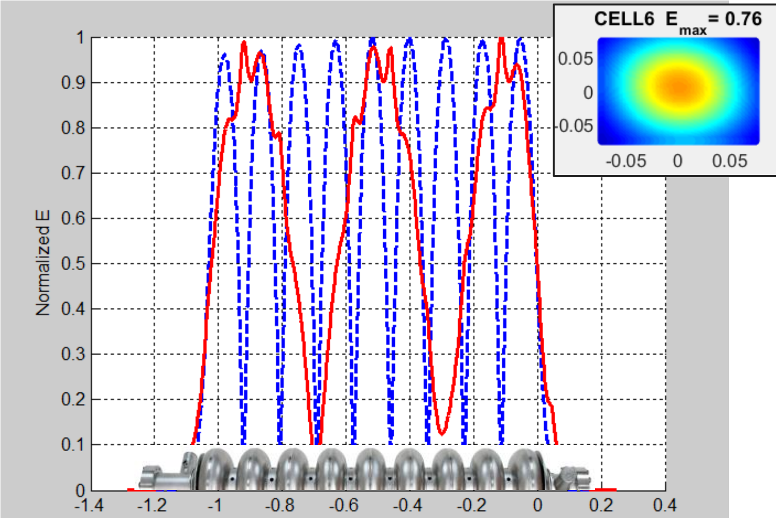
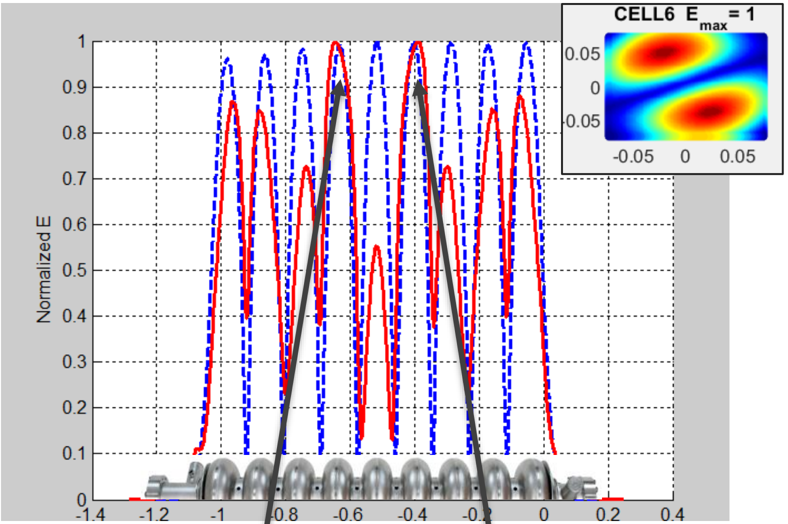


5th of 2nd dipole pass band (2-5)

3th of 1st dipole pass band (1-3)

New Idea: Plasma Ignition Using HOMs (example)



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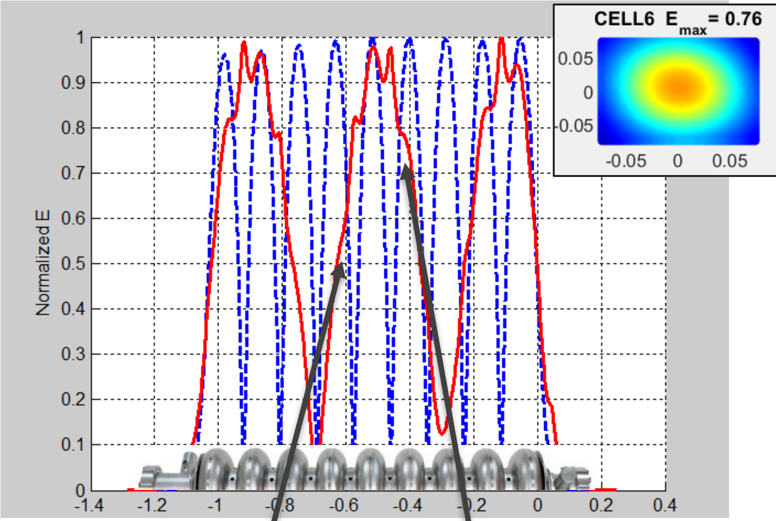


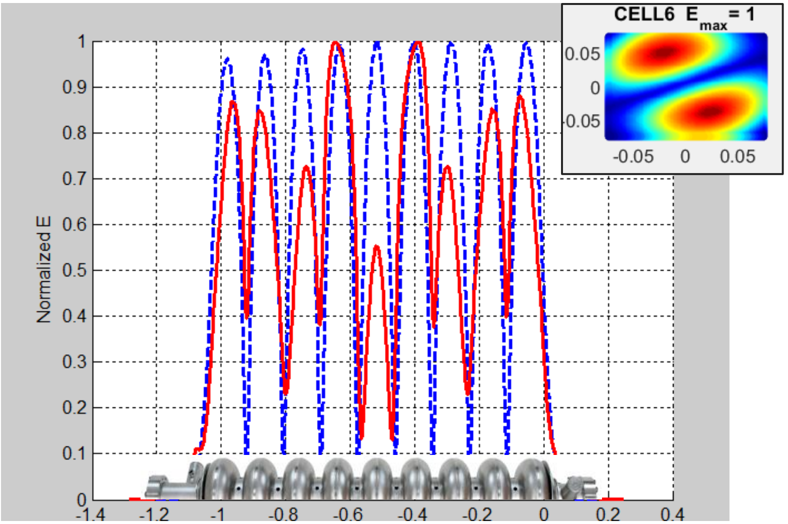
5th of 2nd dipole pass band (2-5)

3th of 1st dipole pass band (1-3)

Maximize field in cells #4 and #6

Creates the asymmetry needed to maximize the field only in one of the cell (in this case cell #6)

New Idea: Plasma Ignition Using HOMs (example)



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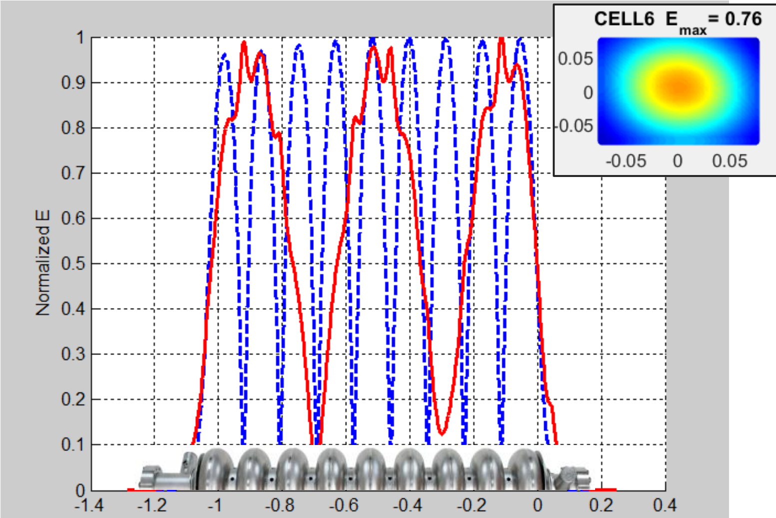
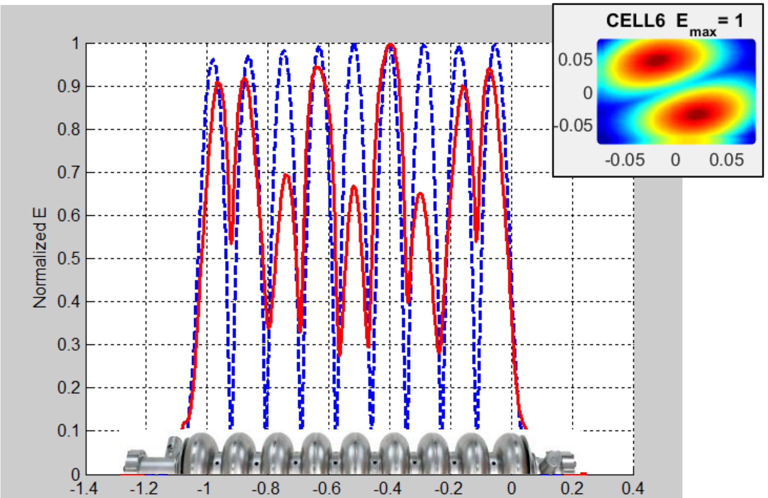


5th of 2nd dipole pass band (2-5) = 3th of 1st dipole pass band (1-3)

Field amplitude maximized in cell #6



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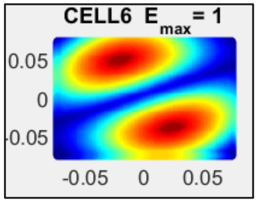
Plasma tuning after ignition to increase homogeneity

Ignition in cell # 6

5^{th} of 2^{nd} DPB



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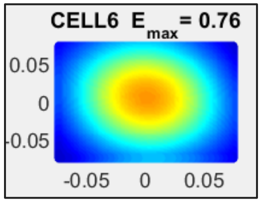
3^{rd} of 1^{st} DPB



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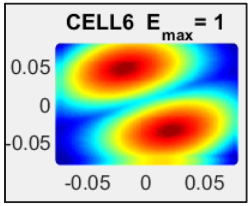
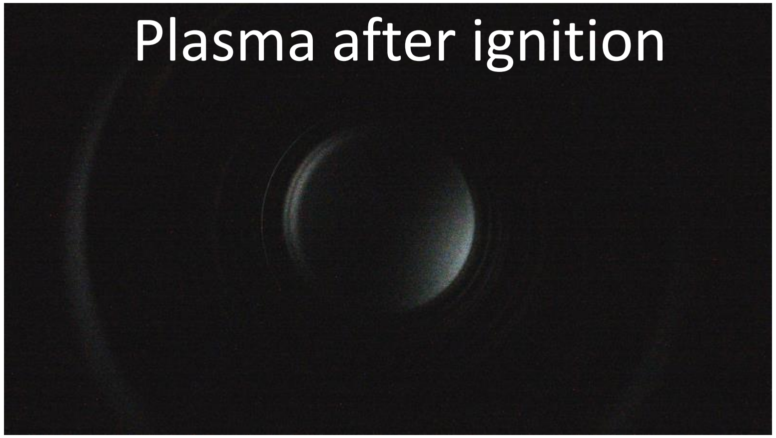
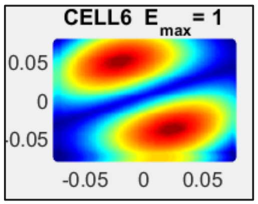




Plasma tuning after ignition to increase homogeneity

Ignition in cell # 6

5th of 2nd DPB



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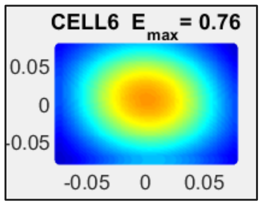
3rd of 1st DPB



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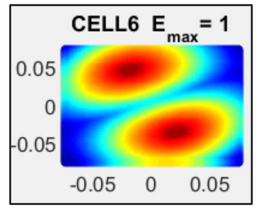
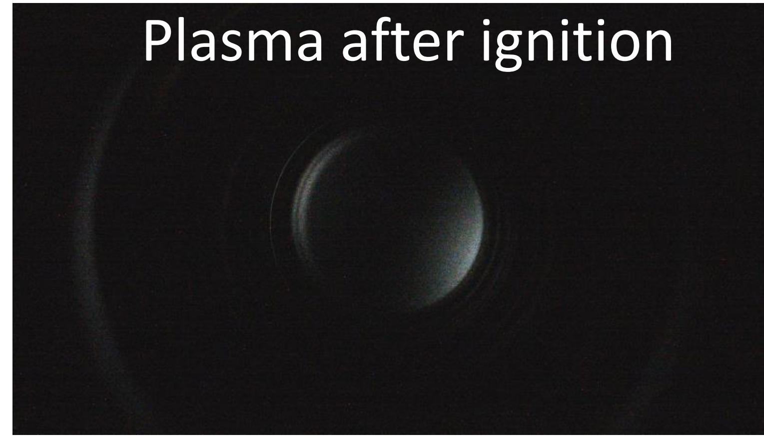
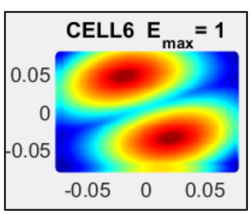




After ignition, it is possible to pick a mode with uniform field distribution in the ignited cell and use it for plasma tuning. For example in cell #6: shut off 1-3, add 1-6 and shut off 2-5.



2-5 and 1-3

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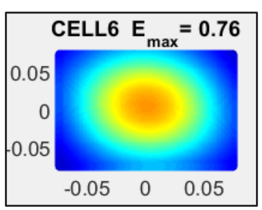

3rd of 1st DPB

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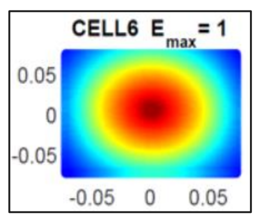

6th of 1st DPB

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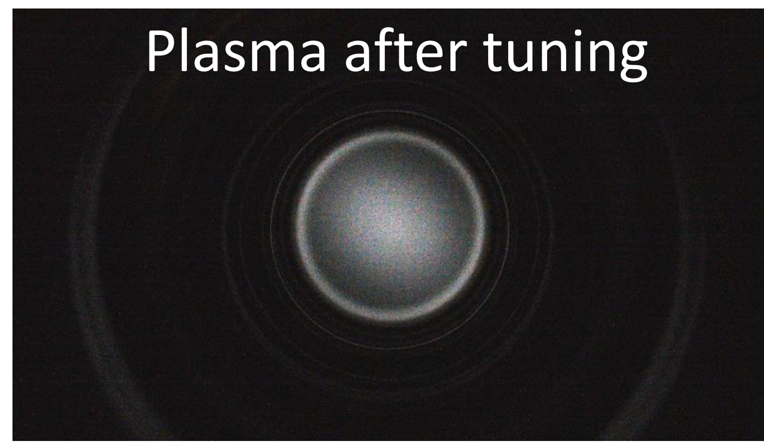
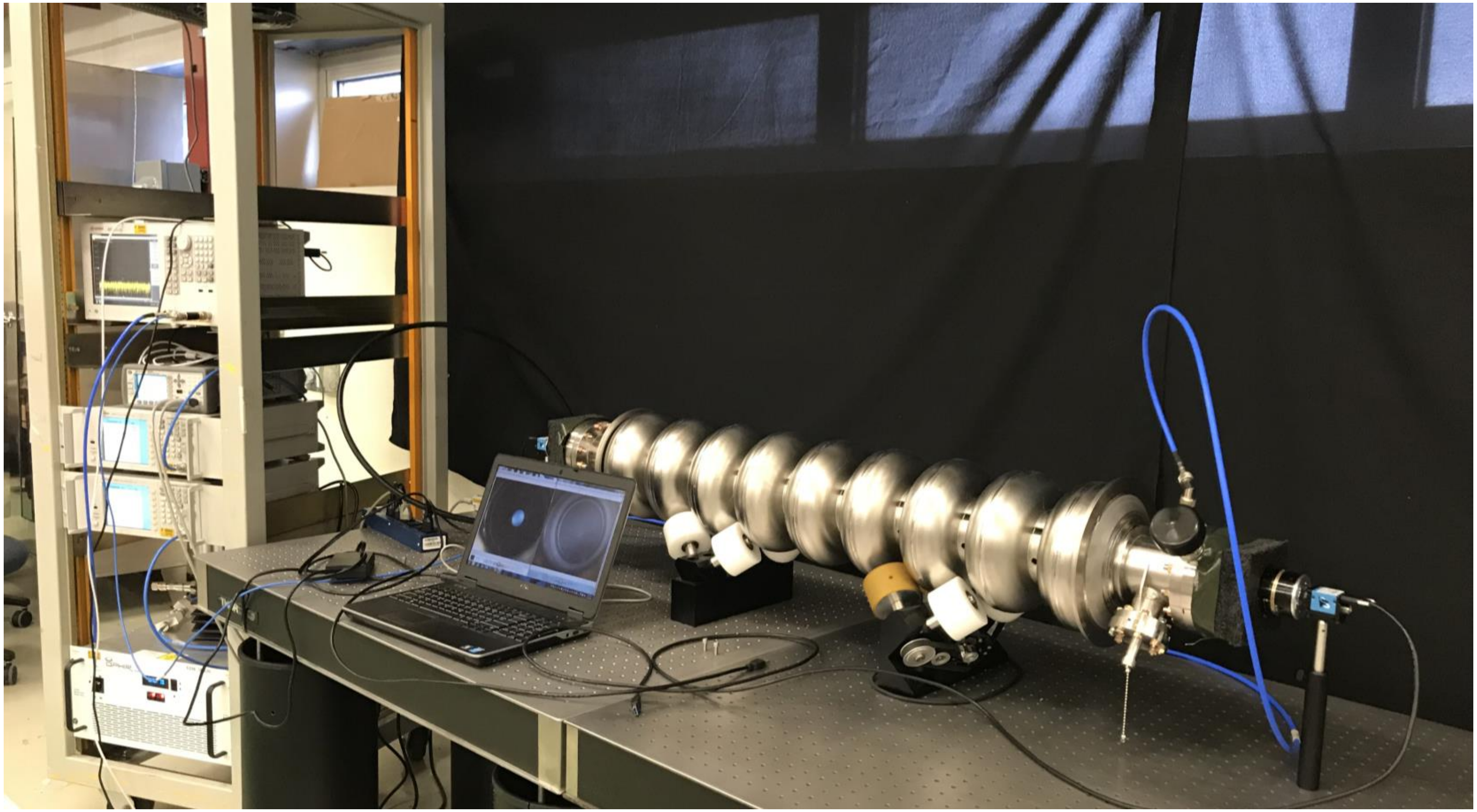
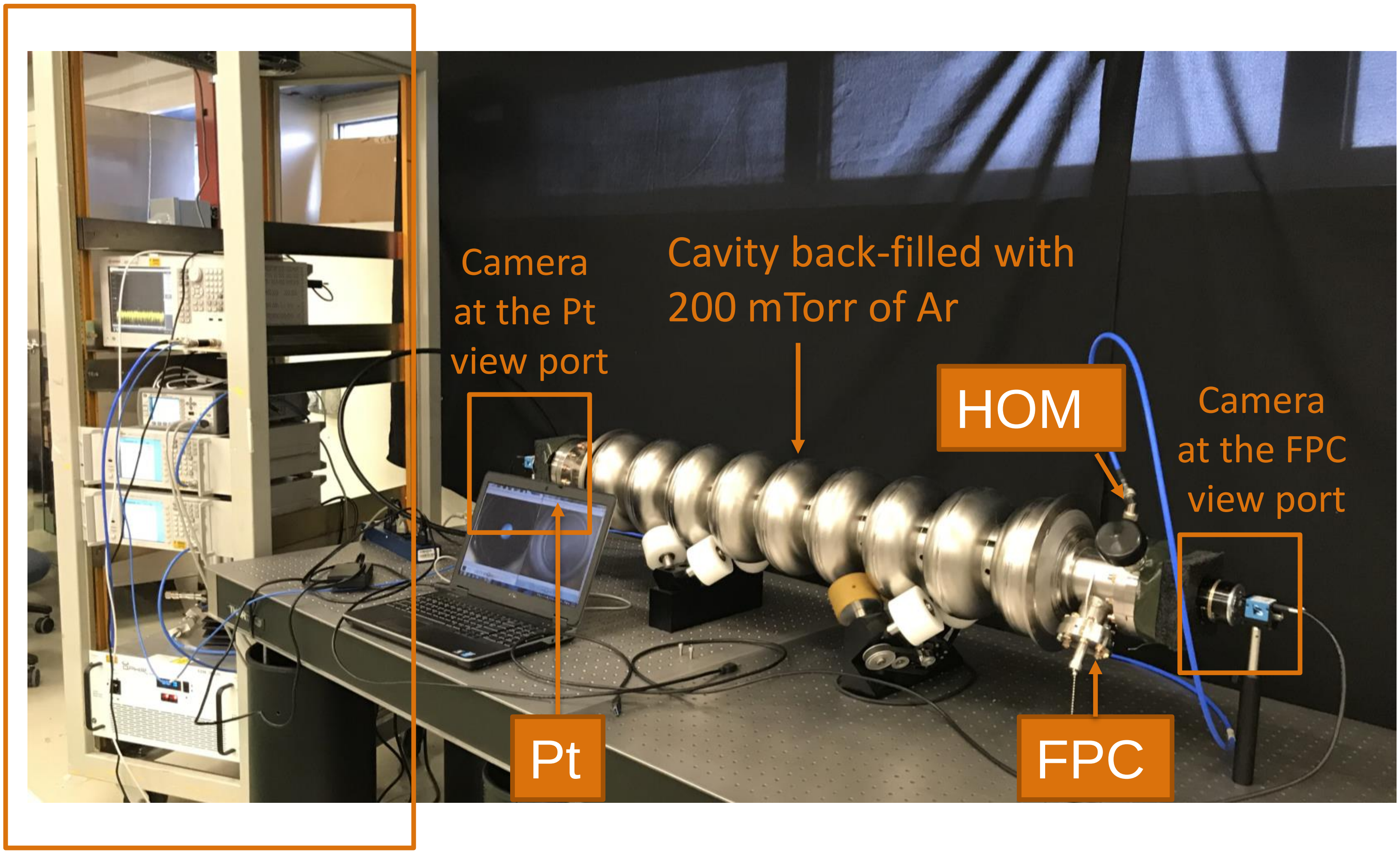


Set-up Plasma Ignition Studies for LCLS-II

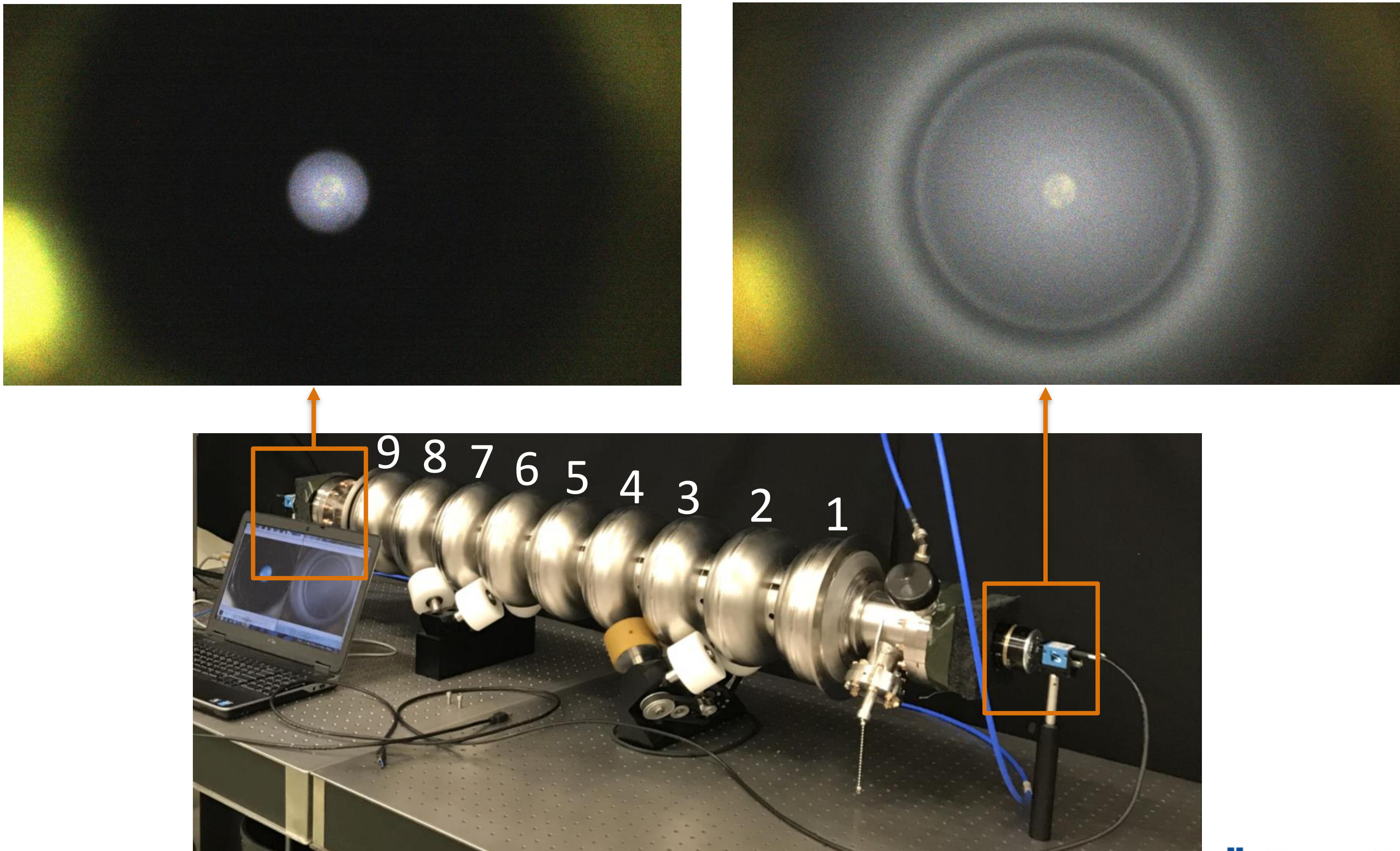


Set-up Plasma Ignition Studies for LCLS-II

RF rack

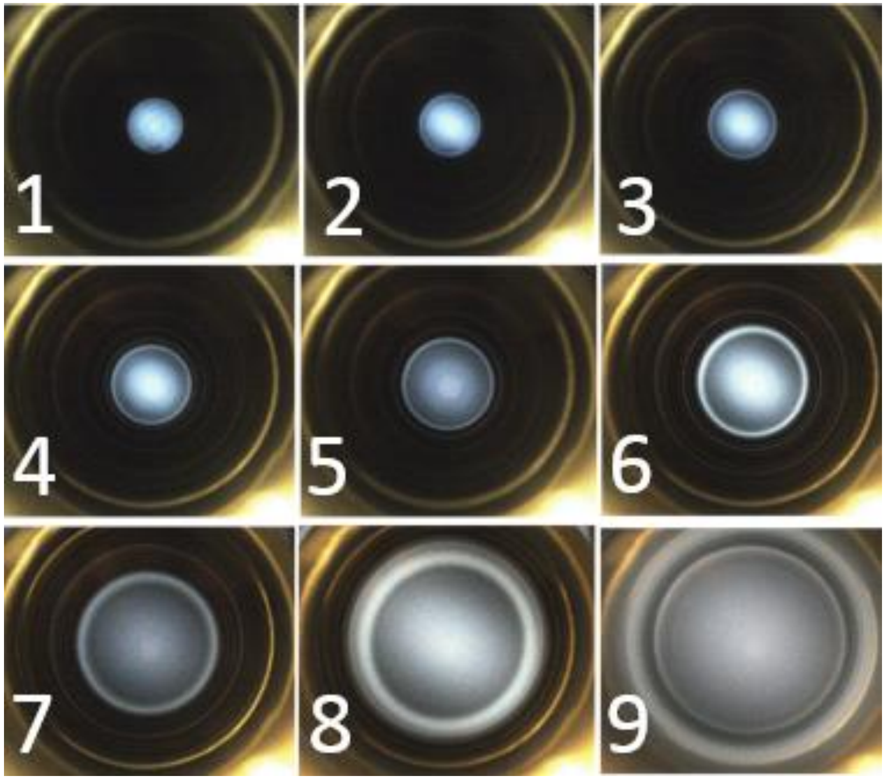


Selective Plasma ignition in 9-cell cavities



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.**
- Neon experiment to come soon along with first cleaning of a 1-cell



Conclusions

- Simulations have demonstrated that:
  - Plasma can be ignited in LCLS-II cavities using the fundamental pass band but lot of power is needed
  - Plasma ignition can be facilitated using HOM, reducing the risk of plasma ignition at the FPC
- Plasma successfully ignited in both 1-cell and 9-cell LCLS-II cavities back-filled with 200 mTorr of Ar, using HOMs
- Plasma after the ignition may be tuned to improve homogeneity
- HOMs ignition seems reliable and gave consistent results on 2 cavities.
- First experiment of plasma cleaning will follow soon!!

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- Simulations have demonstrated that:
  - Plasma can be ignited in LCLS-II cavities using the fundamental pass band but lot of power is needed
  - Plasma ignition can be facilitated using HOM, reducing the

Thank you for your attention!

- Plasma after the ignition may be tuned to improve homogeneity
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- First experiment of plasma cleaning will follow soon!!