Plasma Processing R&D for LCLS-II

Martina Martinello
On behalf of the FNAL, SLAC, ORNL plasma processing collaboration
(supported by DOE BES)

IPAC 2017, Copenhagen

Outline

- Motivation
- SNS experience with plasma processing
- Joint collaboration: plasma processing for LCLS-II
- SRF technology for LCLS-II
- First investigation results
  - Simulations of plasma ignition in LCLS-II cavities
  - Possibility of plasma ignition at the FPC
- Design of the plasma processing system
- Conclusions

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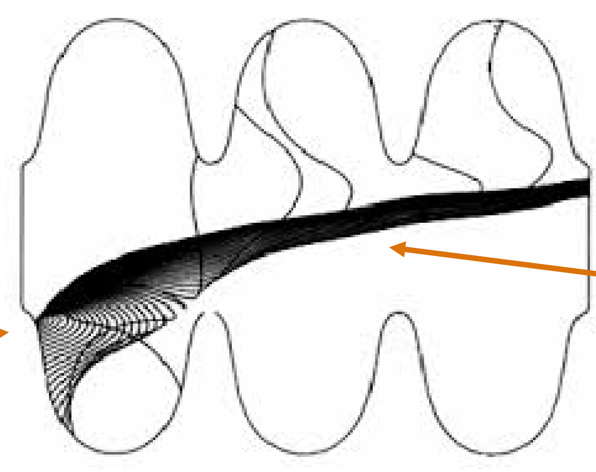
Field Emission in SRF Cavities

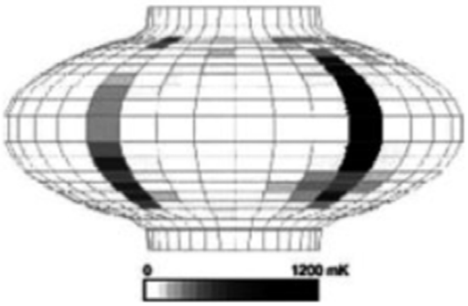
Emission of electrons from **high electric field** region on the cavity surface

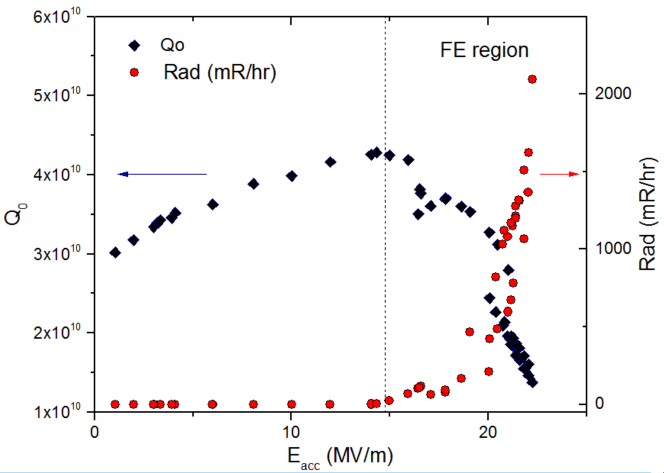
emitter



e- trajectories: same meridian of starting point

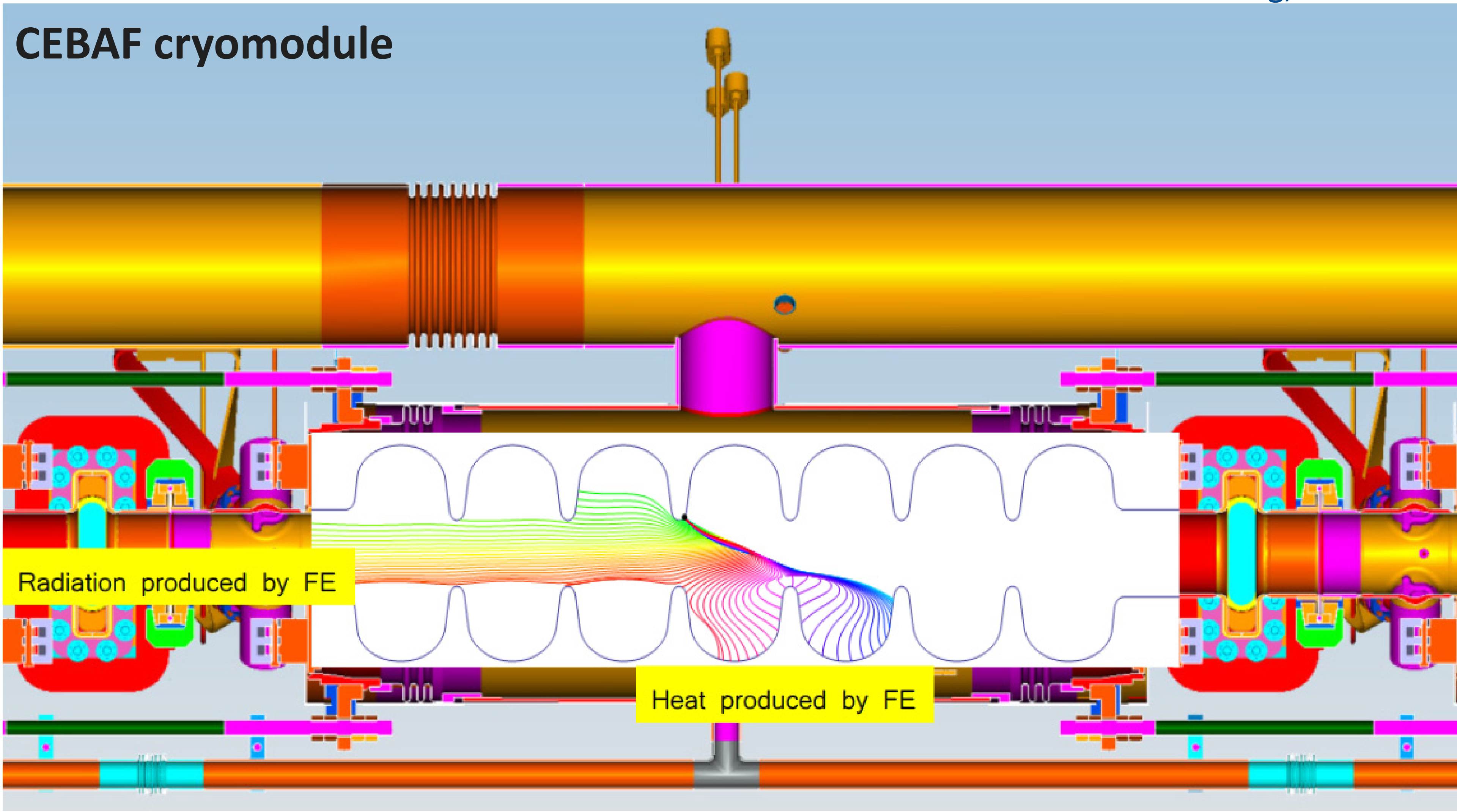
e^- strike the wall of the cell producing **heat** and **x-rays**





Degradation in CM due to Field Emission

R.L. Geng, IPAC 2016



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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

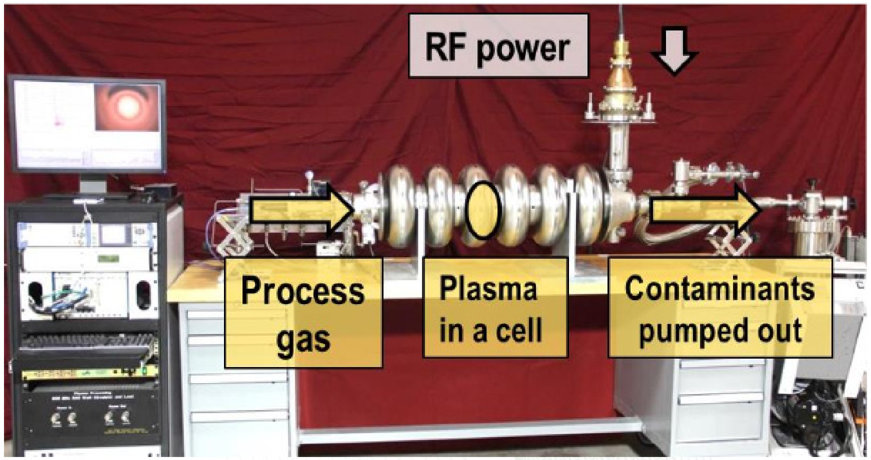
Increasing Φ by 10 % means increasing E_{acc} of about 15 %

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

Fermilab

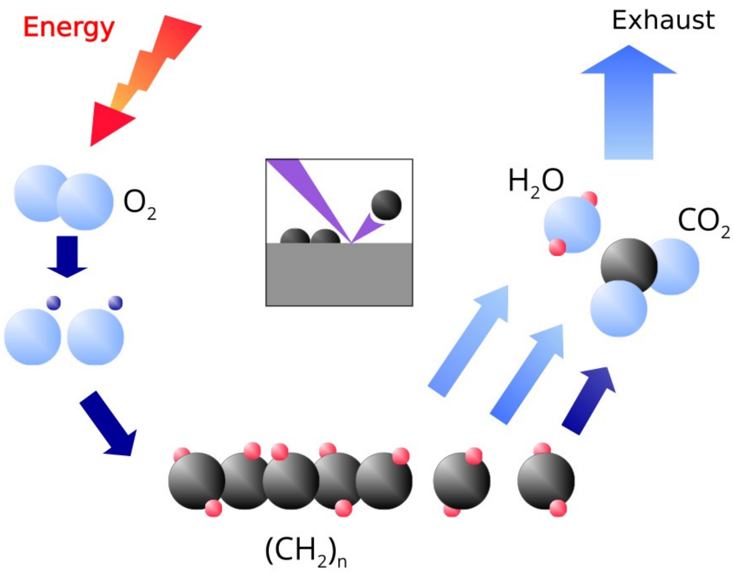
Reactive Oxygen Plasma to Remove Hydrocarbons

- **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:**
  $p \sim 100 - 200$ mTorr, 2 % O_2
  - $\boldsymbol{Ne}$ → <u>support gas</u> to create very stable discharge
  - $\boldsymbol{O_2}$ → <u>cleaning agent</u>, react with carbon forming volatile species

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

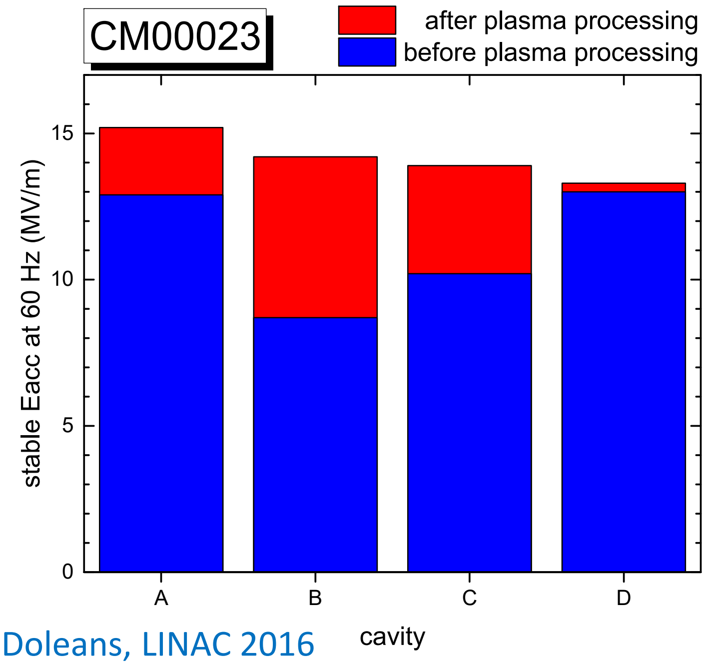


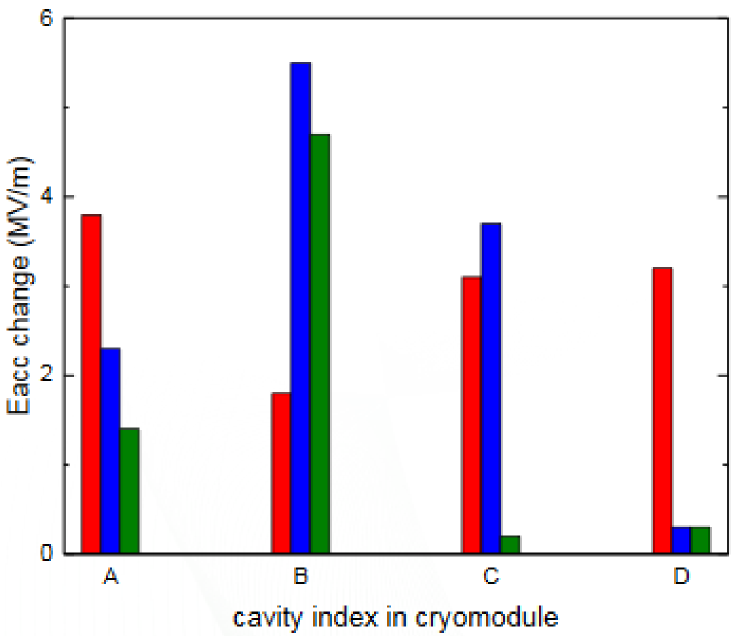
M. Doleans et al. NIMA 812 (2016) 50-59

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 so far





M. Doleans, LINAC 2016

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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

Fermilab

- 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 for LCLS-II Timeline

2017

Present

- Applicability of SNS plasma processing to LCLS-II cavities
- Design of RF and vacuum system

Goals

- Plasma processing of 1.3 GHz single-cell cavity
- RF test in VTS

2018

Goals

- Plasma ignition in 9-cells cavity
- Plasma processing and RF test of 9-cell cavities in VTS
- Improve maximum E_{acc} of field emitting cavities

2019

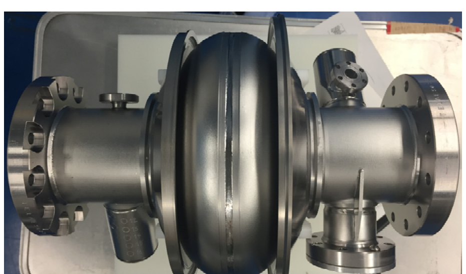
Goals

- Plasma processing in-situ in a cryomodule-like environment (HTS)
- Monitor of plasma ignition based on resonance shift

2020

Goals

- Plasma processing in-situ in LCLS-II cryomodules
- Improve maximum E_{acc} of ~ 15-20 %



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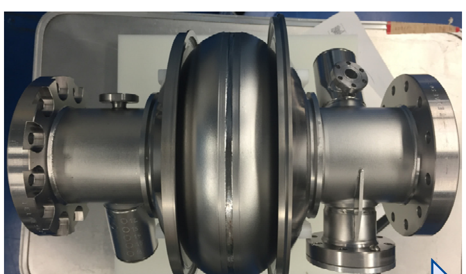

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Plasma ignition in 9-cells cavity

Plasma processing and RF test of 9-cell cavities in VTS

Improve maximum E_{acc} of field emitting cavities

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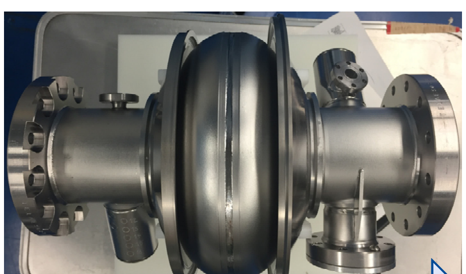

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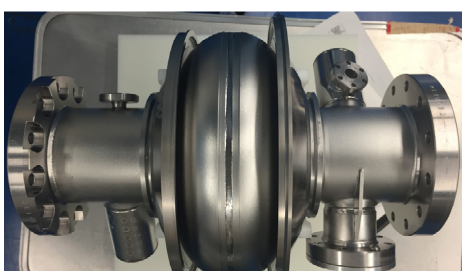

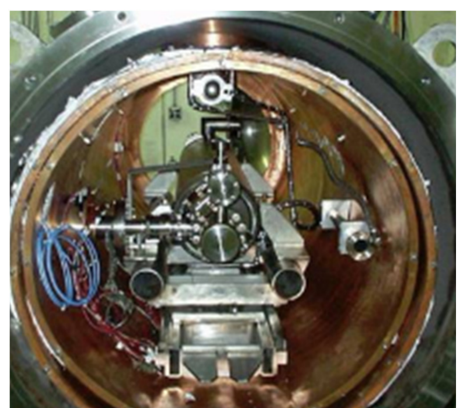

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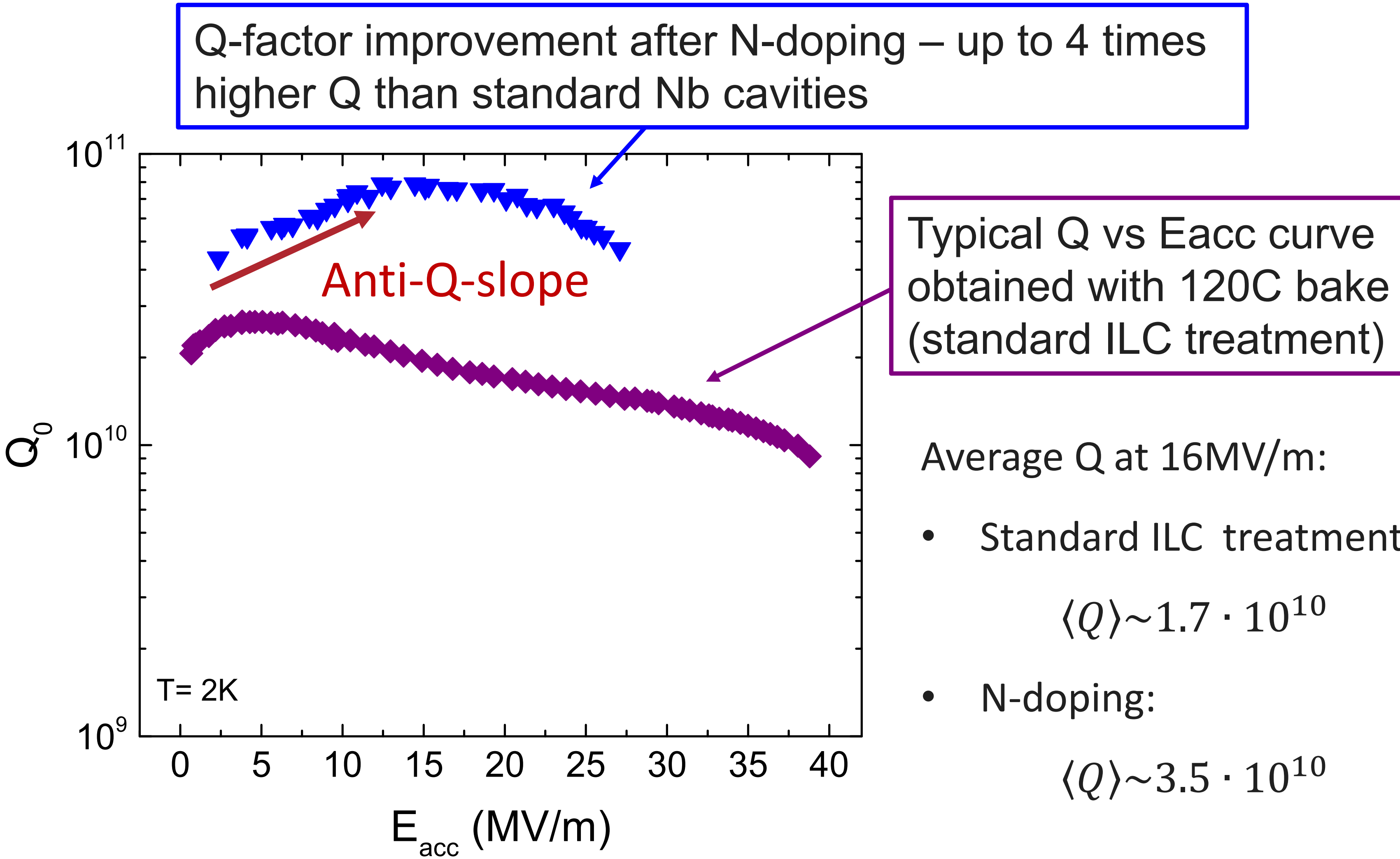
N-doping technology for LCLS-II



Average Q at 16MV/m:

- Standard ILC treatment:

$$\langle Q \rangle \sim 1.7 \cdot 10^{10}$$

- N-doping:

$$\langle Q \rangle \sim 3.5 \cdot 10^{10}$$

A. Grassellino et al., Supercond. Sci. Technol. **26**, 102001 (2013) – Rapid Communications

LCLS-II Prototype Cryomodule Result (FNAL)

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

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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
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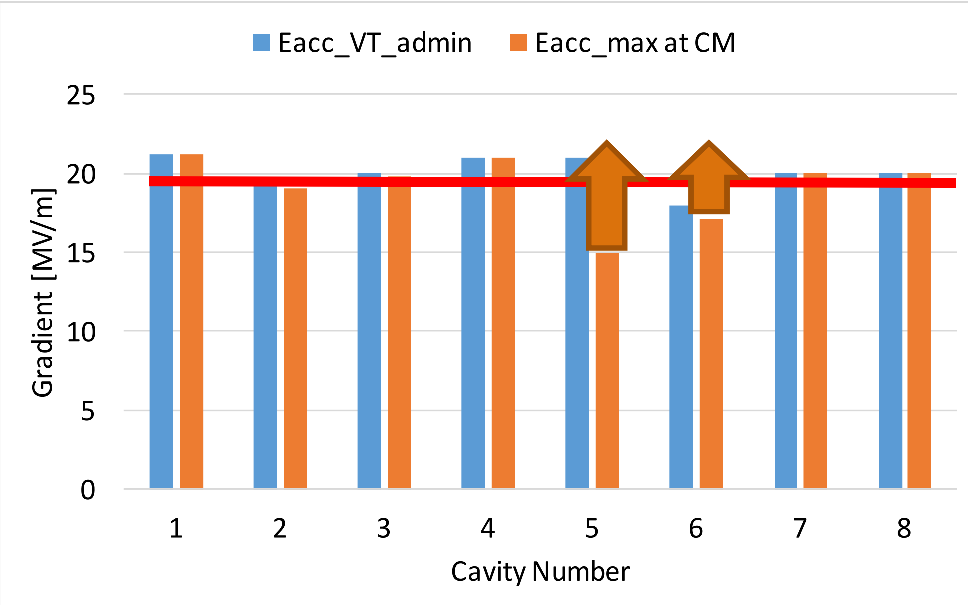
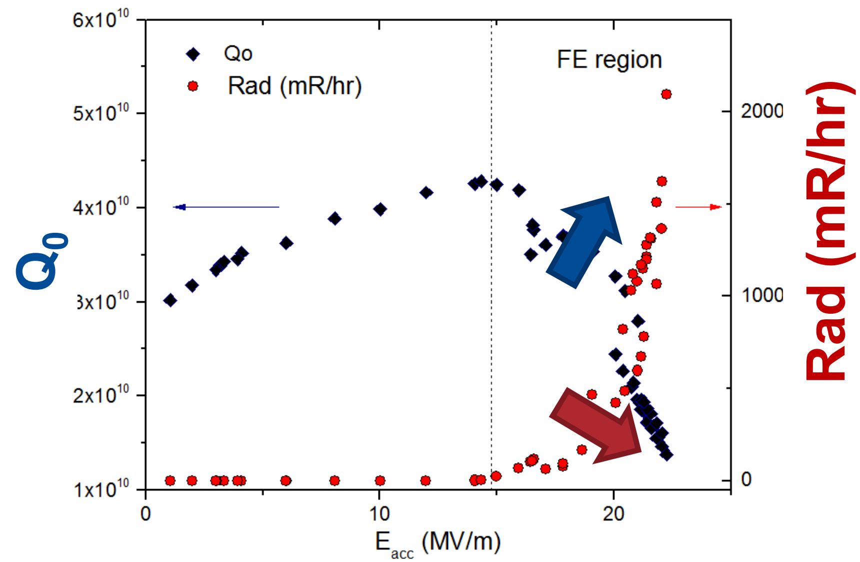
Courtesy of G. Wu

All cavities were FE free during vertical test, therefore some cavities slightly degraded after cryomodule assembly

Plasma Processing for LCLS-II Project Goals





Process cavities in-situ in cryomodules to:

- Increase maximum gradient
- Reduce radiation level
- Preserve high-Q

Reduce FE in cryomodule without needed to disassembly it

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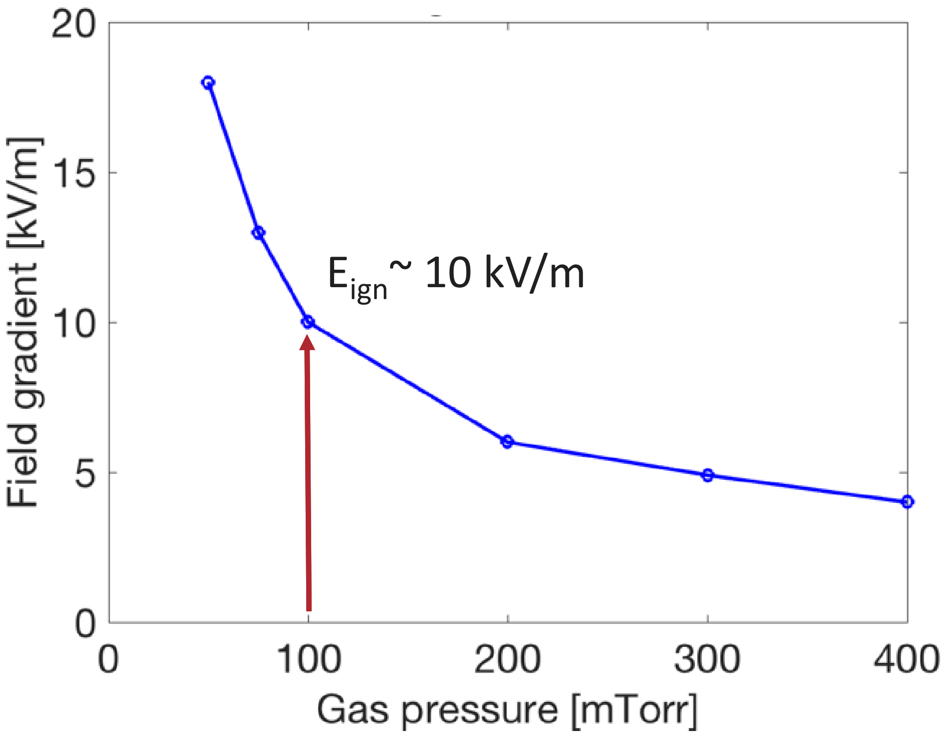
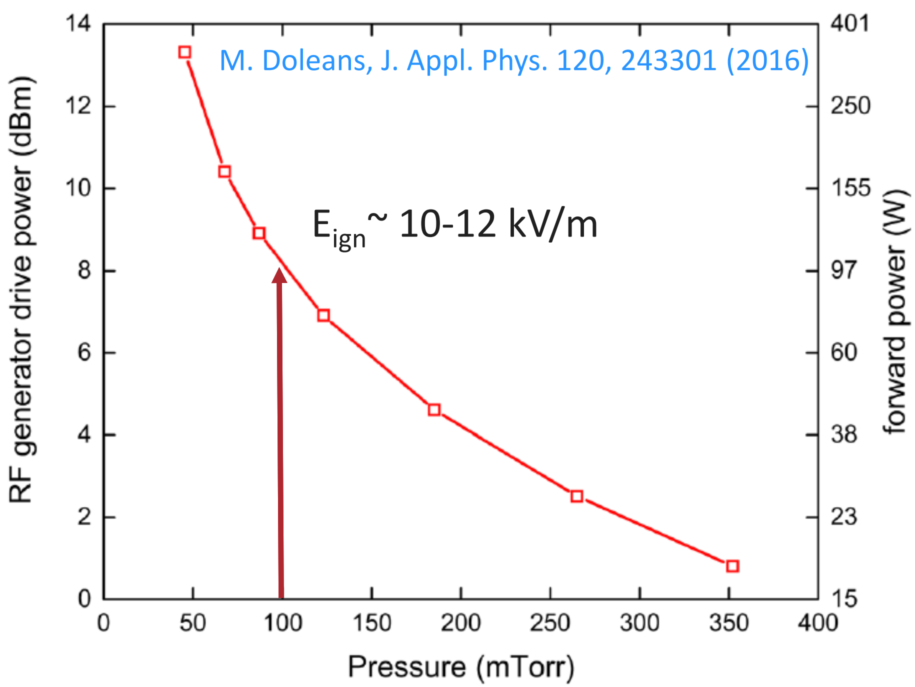
Plasma Ignition Simulation at 1.3 GHz

- **WARP simulation** of plasma ignition on a cubical box with dimensions 1/2 wavelength of 1.3 GHz oscillation
- Results suggest ignition field at 1.3 GHz is around 10 kV/m

Ne gas ionization 1.3 GHz pill-box



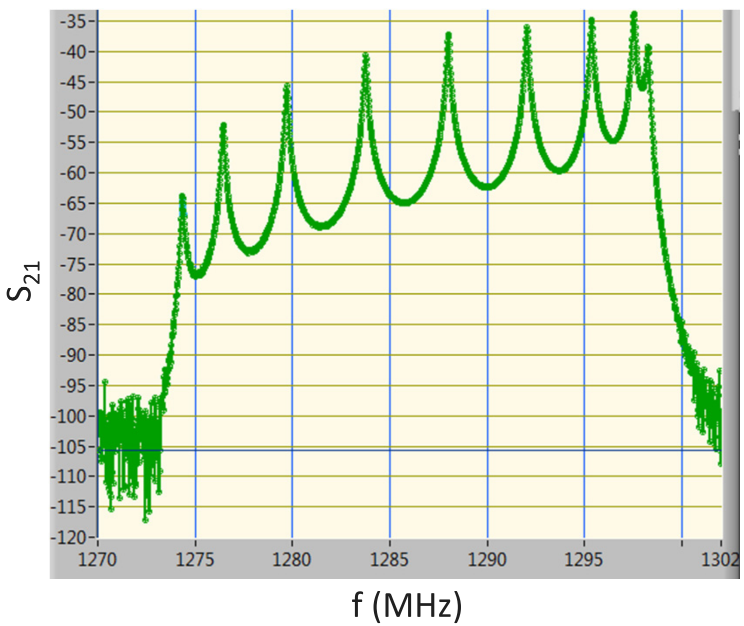
Plasma ignition 6-cells HB 805 MHz

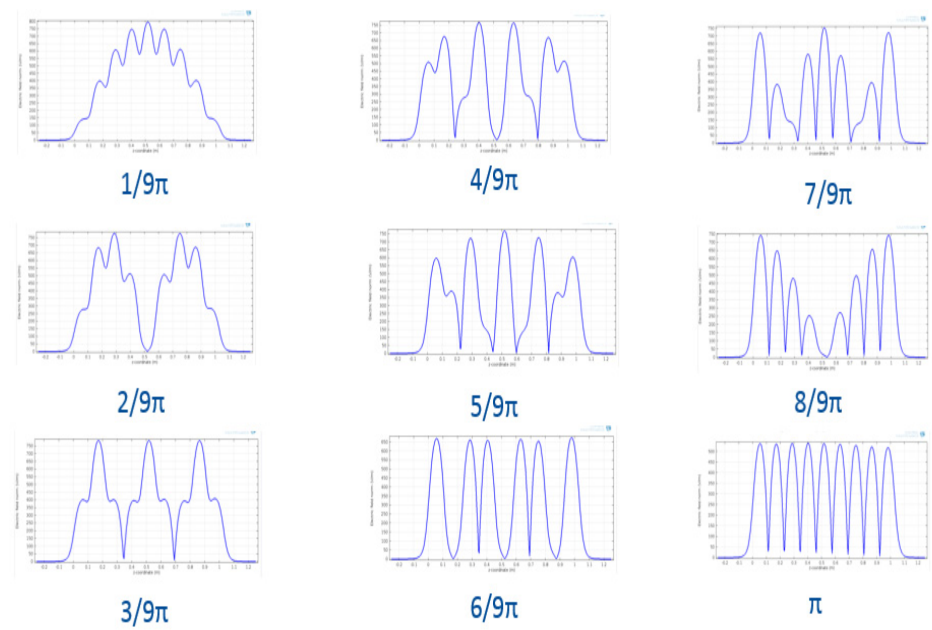


Plasma Ignition in LCLS-II Cavities

- 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





Mode	1/9 π	2/9 π	3/9 π	4/9 π	5/9 π	6/9 π	7/9 π	8/9 π	π
f (MHz)	1274.479	1276.640	1279.862	1283.821	1288.107	1292.125	1295.429	1297.615	1298.331

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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: $Q_{ext} = 4 \cdot 10^6$
  - For LCLS-II only 1% of the power is transmitted to the cavity

Cell #	Mode 1	Amp	dF (MHz)	Mode 2	Amp	dF (MHz)	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**

New Idea: Plasma Ignition Using HOMs

Solution proposed to minimize power at the FPC:

→ **Multi-tone excitation:** mixing **2 modes from 1st pass-band + one HOM** well coupled at room temperature

- For the **first pass-band** only 1% of the power transmitted to the cavity
- For some **high order modes (HOMs)** almost all power gets to the cavity (Power reflection is very low)

	CELL #		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
First pass-band	**MODE1**	MODE#	8/9pi	8/9pi	5/9pi	8/9pi	7/9pi	8/9pi	5/9pi	8/9pi	8/9pi
		AMP	0.47	0.53	0.6	0.27	0.5	0.27	0.6	0.53	0.47
	MODE2	MODE#	pi	3/9pi	8/9pi	4/9pi		4/9pi	8/9pi	3/9pi	pi
		AMP	0.23	0.17	0.2	0.1		0.1	0.2	0.17	0.23
HOM (2nd dipole band)	**MODE3**	MODE#	5th	2nd	2nd	1st	1st	1st	2nd	2nd	5th
		AMP	0.3	0.3	0.2	0.63	0.5	0.63	0.2	0.3	0.3
	Pf coupler		**80 W**	**100 W**	**85 W**	**50 W**	**30 W**	**50 W**	**85 W**	**100 W**	**80 W**
	Pf HOM						**<5 W**				

P. Berrutti, TTC Meeting 2017

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		AMP	0.47	0.53	0.6	0.27	0.5	0.27	0.6	0.53	0.47
	MODE2	MODE#	pi	3/9pi	8/9pi	4/9pi		4/9pi	8/9pi	3/9pi	pi
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HOM (2nd dipole band)	MODE3	MODE#	5th	2nd	2nd	1st	1st	1st	2nd	2nd	5th
		AMP	0.3	0.3	0.2	0.63	0.5	0.63	0.2	0.3	0.3
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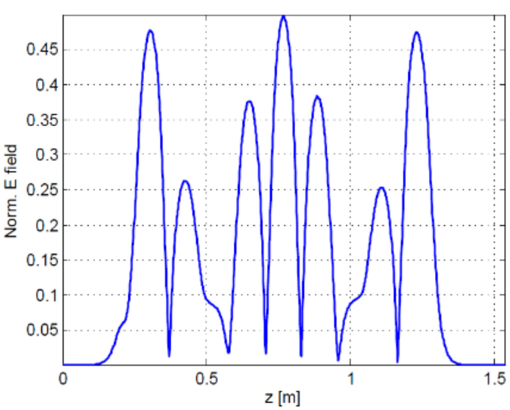
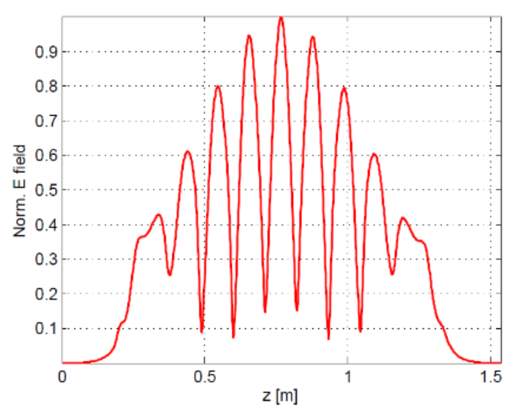


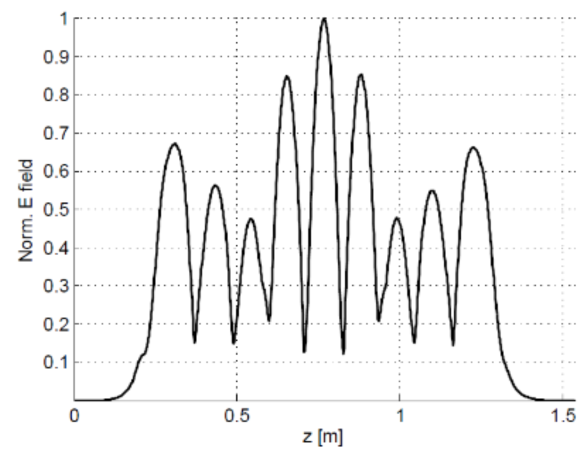
1st pass-band: 7/9pi mode

$\beta = 0.0046$



2nd dipole band: 1st mode

$\beta = 0.97$



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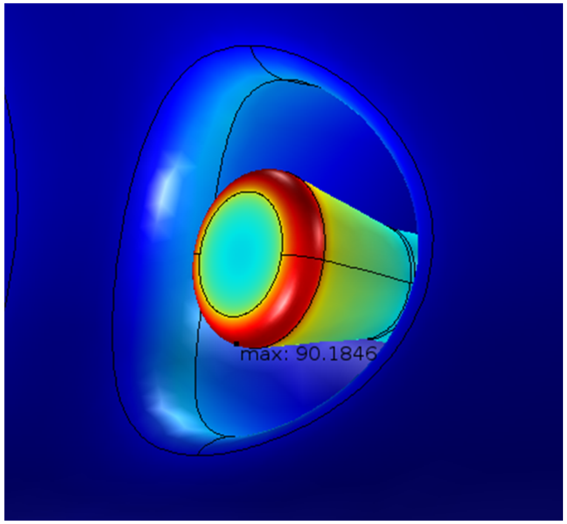
Field Enhancement at the LCLS-II FPC

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



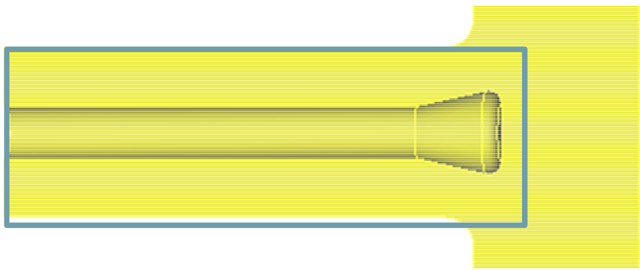
9-cell plasma ignition	
Total P_f [W]	350
$E_{coupler}$ [kV/m]	90
E_{cavity} [kV/m]	12

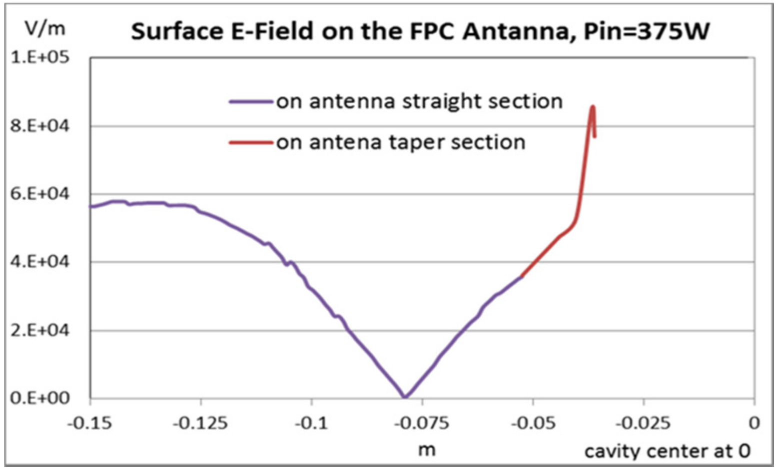
Field enhancement at the coupler ~ 7.5 (for SNS ~ 3)

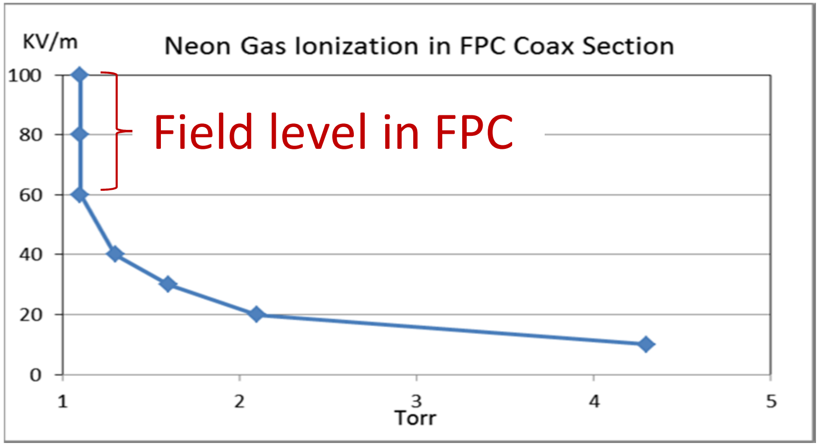
- Suggest larger probability to ignite the plasma at the coupler
- To be verified experimentally first in single-cell than in 9-cell cavity
  - The geometry of the antenna plays an important role in determining the plasma ignition level: the distance between the antenna tip and the outer conductor << cavity gap → **different field level needed to ignite plasma**

Neon Gas Ignition Simulation in FPC Coax WG

- Integrate ACE3P RF fields in FPC into **WARP**
- Determine minimum gas pressure for gas ionized for a specified field level







- The energy gained in the FPC narrow gap is small compared with that in the cavity
- **The gas pressure to ignite plasma in FPC coax WG is 10 times larger than that in the cavity**

Dual vs Multi-tone Excitation

- **Dual-tone**

CELL #		1	2	3	4	5	6	7	8	9
MODE1	MODE#	8/9pi	8/9pi	5/9pi	7/9pi	7/9pi	7/9pi	5/9pi	8/9pi	8/9pi
	AMP	0.67	0.75	0.75	0.58	0.75	0.5	0.75	0.71	0.67
MODE2	MODE#	pi	3/9pi	8/9pi	4/9pi	5/9pi	4/9pi	8/9pi	3/9pi	pi
	AMP	0.33	0.25	0.25	0.42	0.25	0.5	0.25	0.29	0.33
Total Pf at FPC		**160 W**	**200 W**	**130 W**	**280 W**	**80 W**	**310 W**	**130 W**	**200 W**	**160 W**

- **Multi-tone**

CELL #		1	2	3	4	5	6	7	8	9
MODE1	MODE#	8/9pi	8/9pi	5/9pi	8/9pi	7/9pi	8/9pi	5/9pi	8/9pi	8/9pi
	AMP	0.47	0.53	0.6	0.27	0.5	0.27	0.6	0.53	0.47
MODE2	MODE#	pi	3/9pi	8/9pi	4/9pi		4/9pi	8/9pi	3/9pi	pi
	AMP	0.23	0.17	0.2	0.1		0.1	0.2	0.17	0.23
MODE3	MODE#	5^{th}	2^{nd}	2^{nd}	1^{st}	1^{st}	1^{st}	2^{nd}	2^{nd}	5^{th}
	AMP	0.3	0.3	0.2	0.63	0.5	0.63	0.2	0.3	0.3
Pf coupler		**80 W**	**100 W**	**85 W**	**50 W**	**30 W**	**50 W**	**85 W**	**100 W**	**80 W**
Pf HOM						**<5 W**				

Dual vs Multi-tone Excitation

- **Dual-tone**

CELL #		1	2	3	4	5	6	7	8	9
MODE1	MODE#	8/9pi	8/9pi	5/9pi	7/9pi	7/9pi	7/9pi	5/9pi	8/9pi	8/9pi
	AMP								0.71	0.67
MODE2	MODE#								3/9pi	pi
	AMP								0.29	0.33
Total Pf at FPC									**200 W**	**160 W**

The power needed at FPC is reduced by 50%

Risk of FPC ignition mitigated!

- **Multi-tone**

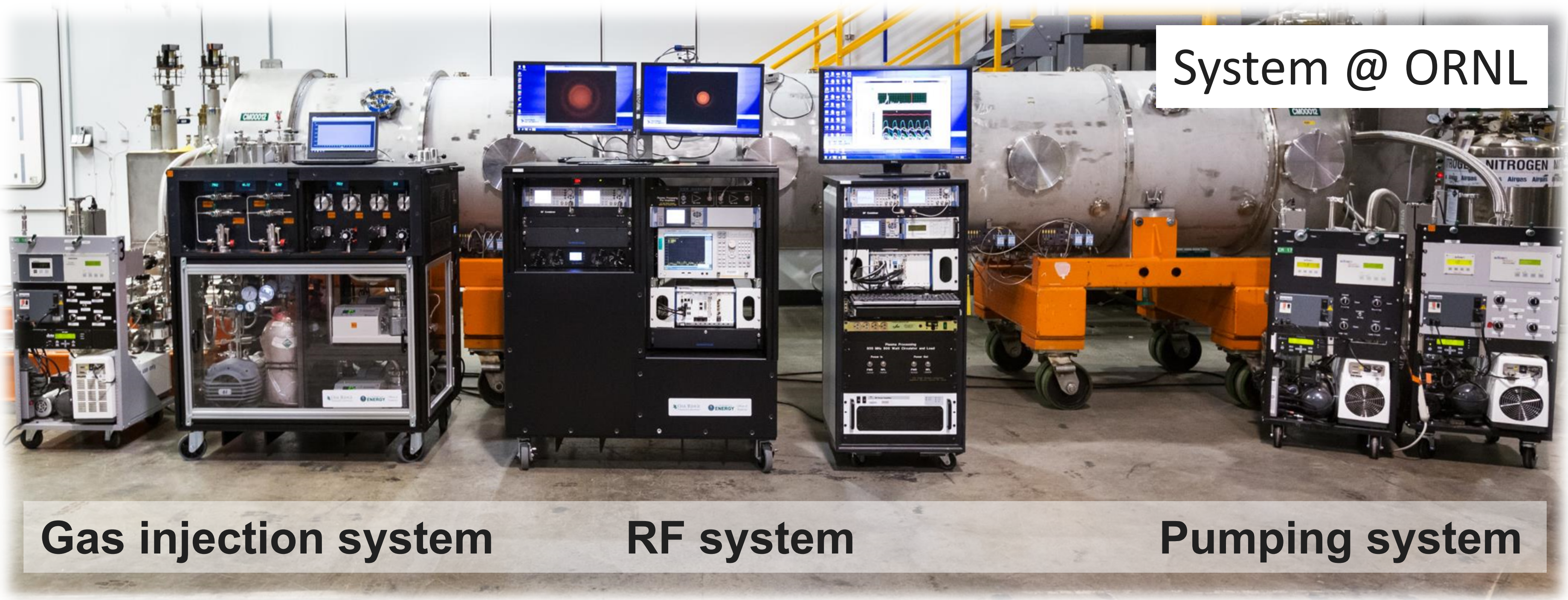
CELL #		1	2	3	4	5	6	7	8	9
MODE1	MC								8/9pi	8/9pi
	A								0.53	0.47
MODE2	MC								3/9pi	pi
	A								0.17	0.23
MODE3	MC…								2nd	5th
	AMP	0.3	0.3	0.2	0.63	0.5	0.63	0.2	0.3	0.3
Pf coupler		**80 W**	**100 W**	**85 W**	**50 W**	**30 W**	**50 W**	**85 W**	**100 W**	**80 W**
Pf HOM						**<5 W**				

Outline

- Motivation
- SNS experience with plasma processing
- SRF technology for LCLS-II
- Joint collaboration: plasma processing for LCLS-II
- First investigation results
  - Simulations of plasma ignition in LCLS-II cavities
  - Possibility of plasma ignition at the FPC
- **Design of the plasma processing system**
- Conclusions

Set-up Plasma Processing for LCLS-II

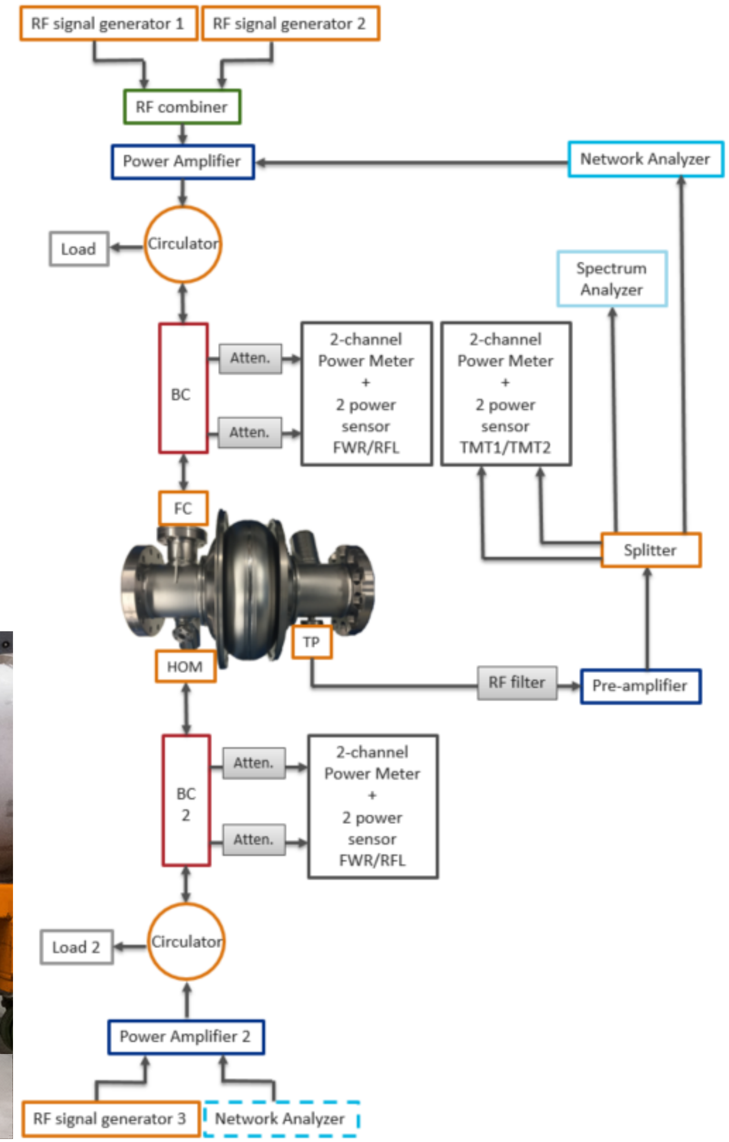
- Hardware set-up for LCLS-II cryomodules will be similar to ORNL
  - Gas injection system (compliant with LCLS-II standards)
  - RF system (fundamental and higher-order-modes passbands)
  - Pumping system (compliant with LCLS-II standards)



RF System

- 3 signal generators, 1 RF combiner
- 2 Power Amplifier
  - High power for 1st pass-band modes (1.5 kW)
  - Broad-band for HOMs (0.8-2.5 GHz)
- 2 circulators, 2 loads
- 3 power meters, 6 power sensors
- Spectrum and Network analyzers

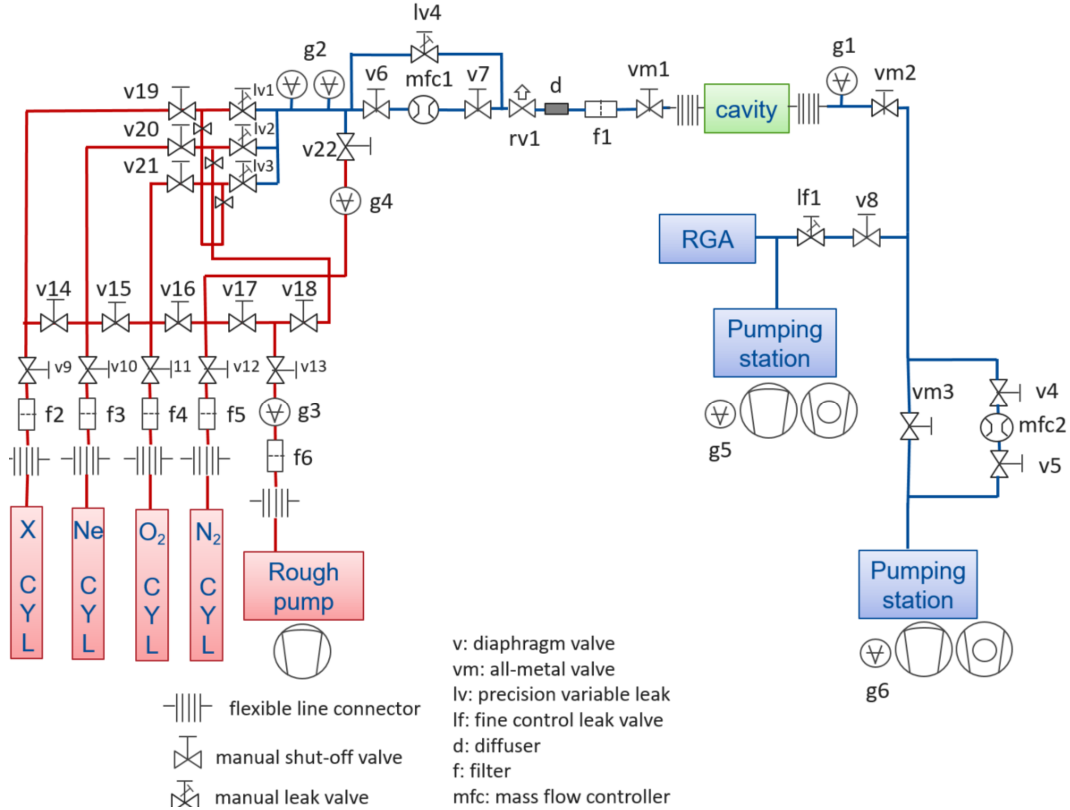
RF system



Gas Injection System

- Possibility of mixing up to 3 gases
- Mass Flow Controller (MFC) to set the desired flow and avoid turbulences
- Analysis of gas species throughout Residual Gas Analyzer (RGA)
- Possibility of pumping the cavity through the system itself

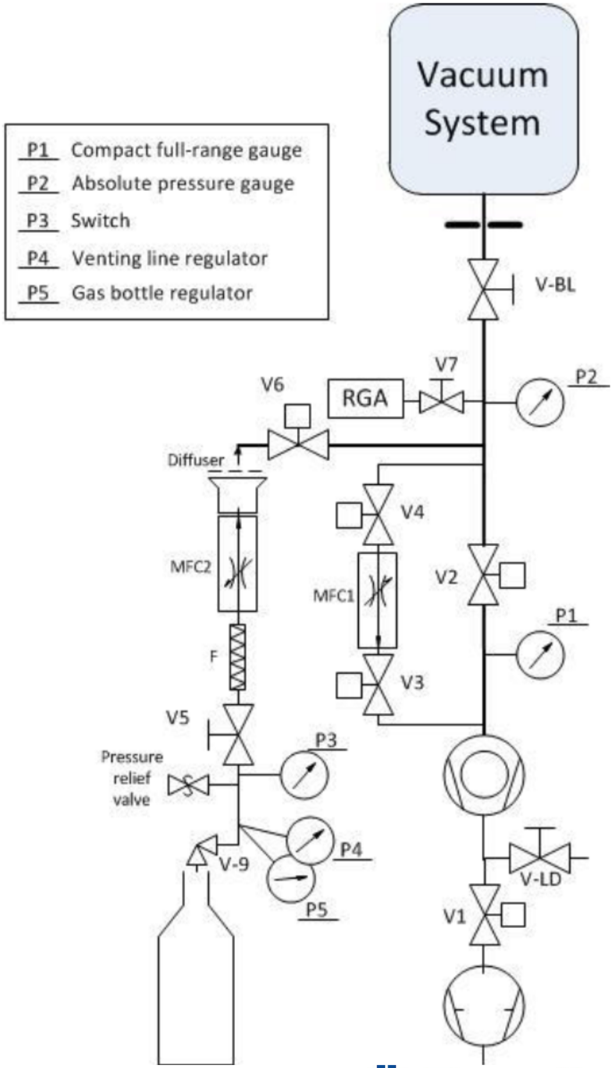
Gas Injection Cart



Pumping System

- "Particle Free Cart" in agreement with LCLS-II beamline pumping protocol
- Pumping down through a MFC to avoid turbulences and particle movement
- RGA to analyze the pumped out species
- Fully compatible with LCLS-II cryomodule

Particle Free Cart



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Conclusions

- ORNL demonstrated that plasma processing is a successful technique to reduce FE in-situ in cryomodules
- Possibility to increase maximum field also in LCLS-II cryomodules via plasma processing
- Simulations have demonstrated that dual tone excitation can work for LCLS-II cavities but more power is needed at the FPC
- Plasma ignition can be facilitated using HOM couplers → reduced risk of FPC ignition
- RF and vacuum system designs complete
- First experiments of plasma processing on a single-cell cavity will be carried out in fall 2017

Thank you for your attention

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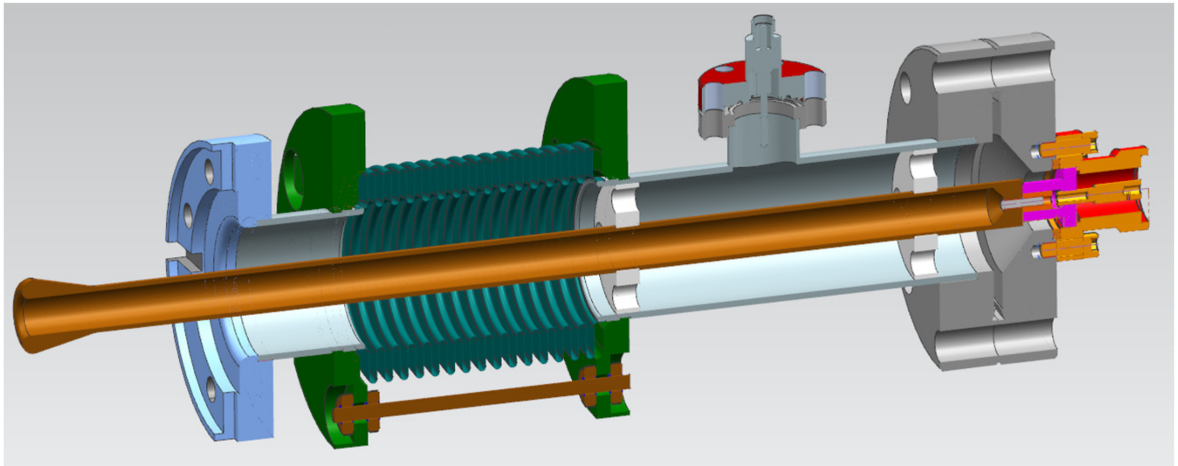
- Kristin Tippey
- John Mammosser

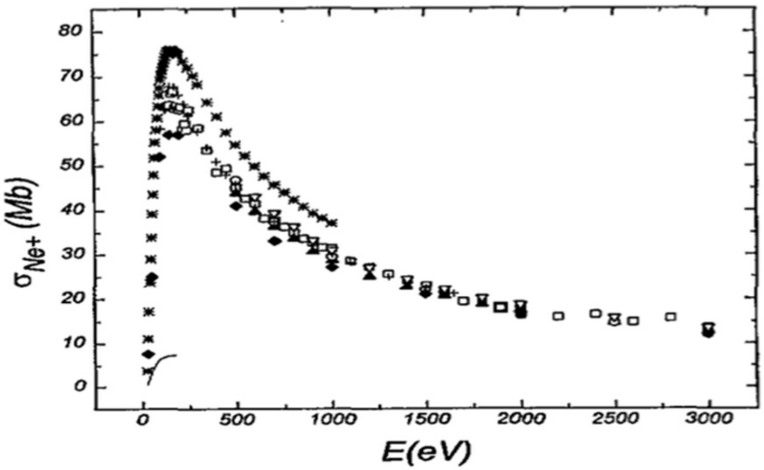
Movable Coupler for VTS Test after Plasma Processing

- **VTS test will be performed before and after plasma processing** the cavity
- **No exposure of the inner cavity surface to external environment** between the processing and the test
- **Movable power coupler**:
  - Emulate LCLS-II FPC during plasma processing
  - Close to critical coupling during VTS



Gas Ignition by Accelerated Electrons in Warp

- Define neon gas by its density and subsequent ionization states
- Define background electrons with a specified density, accelerated by an external RF field impacting on gas
- Ionization governed by electron-neon impact cross section
- Not simulate reactive species of the plasma interacting with surface hydrocarbons and generate volatile by-products



Electron-neon impact ionization cross section (Almeida et al.)

Impact ionization in Warp

$$N = n_g \sigma v \Delta t$$

where N = Number of events

n_g = Gas density

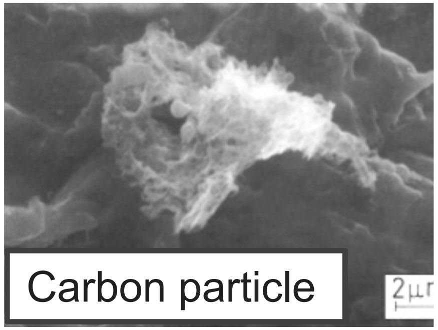
σ = Cross section

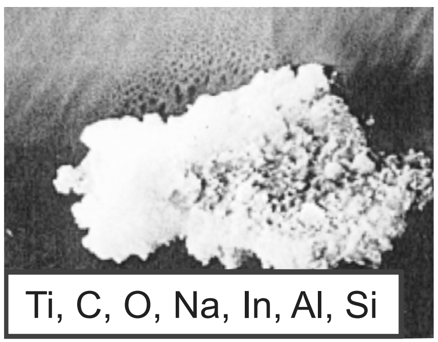
v = Relative velocity

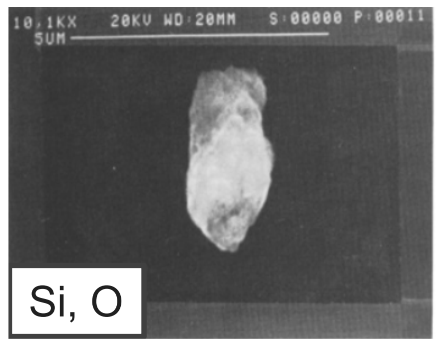
Δt = Time step

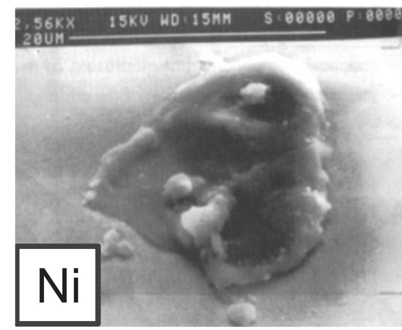
For simulation, choose constant σ = 25 Mb

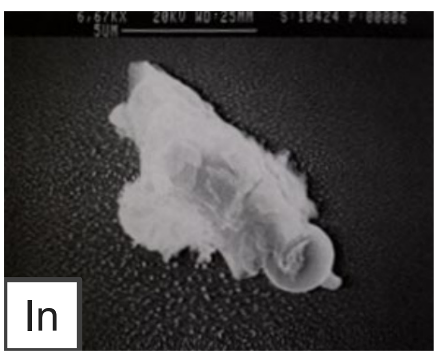
Common Field Emitters

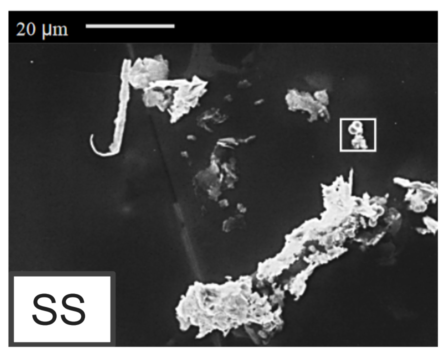


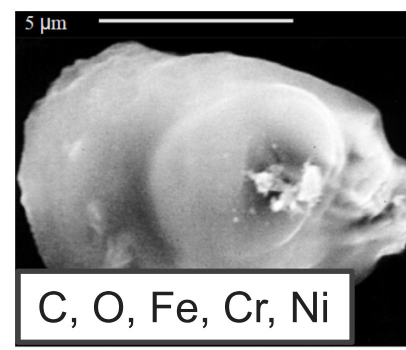




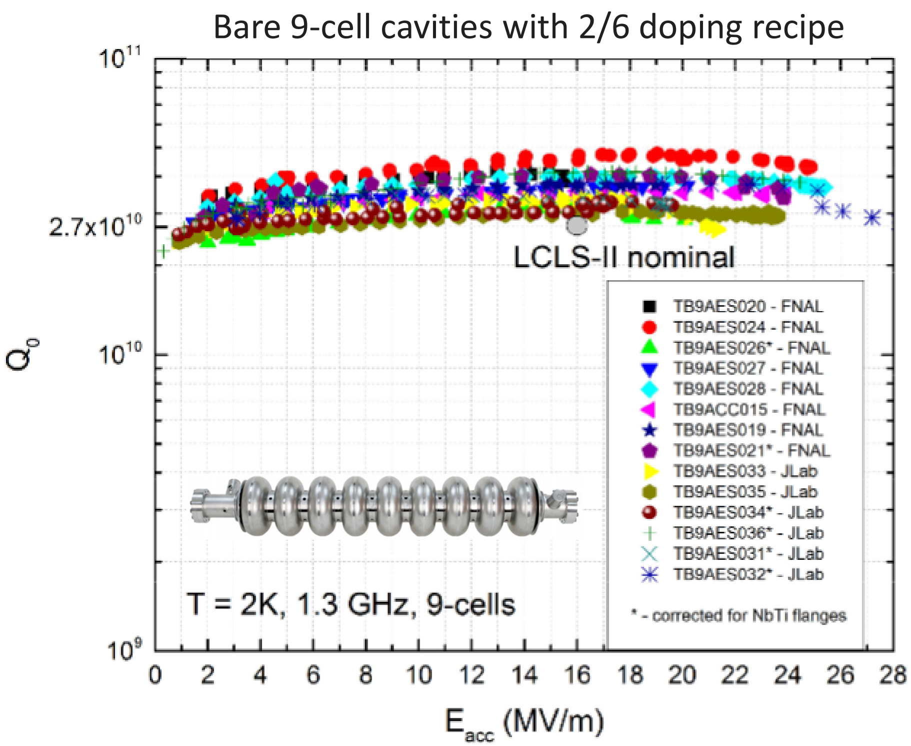


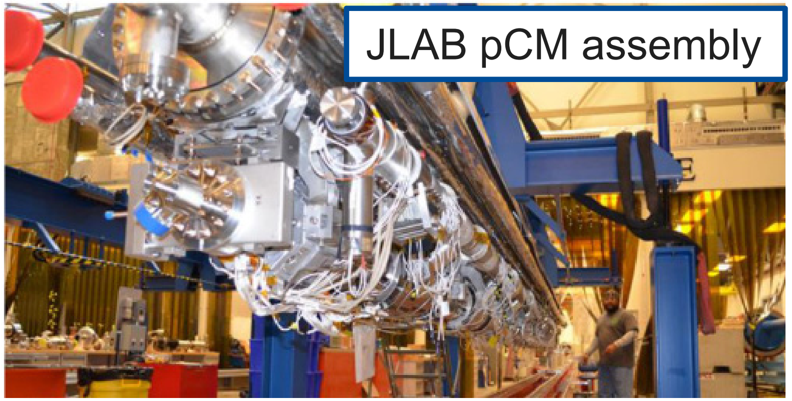


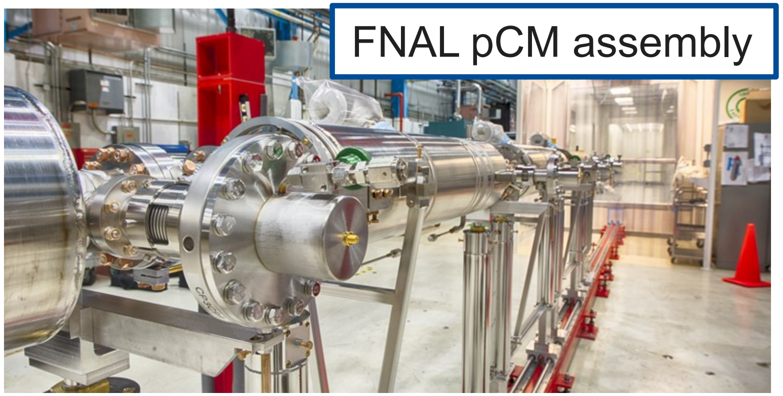




N-doping from R&D to production







- Many recipes were studied on single-cell cavities: **light doping seemed the best in terms of both Q-factor and quench field**
- Best recipe transferred to 9-cell cavities that were then assembled in the two prototype cryomodule (FNAL and JLAB)