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UPDATE ON PLASMA PROCESSING R&D FOR LCLS-II*

P. Berrutti†, A. Grassellino, T. Khabiboulline, M. Martinello, Fermilab, Batavia, IL, USA
M. Doleans, S. Kim, K. Tippey, ORNL, Oakridge, TN, USA
D. Gonnella, G. Lanza, M. Ross, SLAC, Menlo Park, CA, USA

Abstract

SRF cavities performance preservation is crucial, from vertical test to accelerator operation. Field emission is still one of the main problems to overcome and plasma cleaning has been proven successful by SNS, in cleaning field emitters and increasing the work function of Nb. A collaboration has been established between FNAL, SLAC and ORNL with the purpose of applying plasma processing to LCLS-II cavities, in order to minimize and overcome field emission without affecting the high Q of N-doped cavities. The recipe will follow the neon-oxygen active plasma adopted at SNS, allowing in-situ processing of cavities and cryomodules from hydrocarbon contaminants. A novel method for plasma ignition has been developed at FNAL: a plasma glow discharge is ignited using high order modes to overcome limitations imposed by the fundamental power coupler. The results of experiments on 9-cell LCLS-II cavity are presented, along with plasma ignition studies. In addition the RF system is shown and N-doped Nb samples studies are discussed.

INTRODUCTION

Plasma processing allows in-situ cleaning of SRF cavities for field emission mitigation purposes. The technique has been proven to be effective on SNS HB cryomodules [1]. A collaboration between ORNL, SLAC and FNAL is working on adapting the plasma cleaning to LCLS-II cavities. The main objective is SRF cavities performance recovery via reduction of field emission (FE) without affecting the high Q_0 of the N-doped cavities. The Neon-Oxygen recipe developed at ORNL is effective in reducing FE by increasing the work function of the Nb. A plasma glow discharge is ignited within the cavity RF volume, filled with about 200 mTorr of Neon, subsequently a small percentage of Oxygen is introduced in the cavity while the plasma is ignited. The plasma is kept glowing until the exhaust gas shows negligible traces of hydrocarbons byproducts, this process is applied at all of the cavity cells. In order to successfully clean a SRF cavity it is necessary to ignite the plasma, control its intensity and locate which cell is hosting the glow discharge. ORNL has developed the dual tone excitation for plasma ignition in SNS HB cavities [2] and the same could be applied to LCLS-II cavities. Simulations have shown the ignition of the power coupler is very likely in LCLS-II cavities, since at room temperature the mismatch between $Q_0 \approx 1E4$ and $Q_{ext} \approx 4E7$ is larger than for SNS HB cavities. Since Plasma ignition in the coupler is dangerous for the antenna itself, an alternative technique for plasma ignition has been developed at FNAL: using HOMs it is possible to overcome the limitations imposed by the low coupling of the fundamental pass-band. Experimental setup and results of Plasma ignition in 9-cell 1.3 GHz cavities are presented, along with visual plasma detection using cameras, see Fig. 1. Selective plasma ignition for each cell has been achieved at very low power $P_{Fwd} \approx 3$ W. At ORNL studies of Nb N-doped samples show an increase in the work function after plasma treatment [3]. The increase of work function observed in N-doped samples is comparable with the one observed for regular Nb, which suggests that also N-doped SRF cavities will benefit from plasma cleaning.

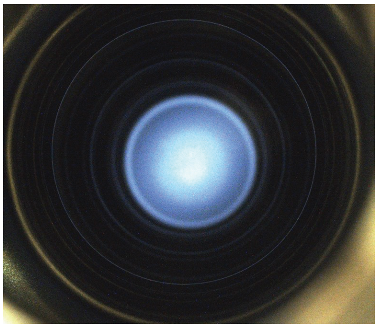

Figure 1: Ar plasma glowing in cell 5 of a LCLS-II cavity, $P = 200$ mTorr, $P_{FWD} = 3$ W.

PLASMA IGNITION STUDIES

The studies of plasma ignition started from ORNL expertise on high beta (HB) SNS cavities, the adaptation of the dual tone excitation to LCLS-II was a natural consequence of ORNL successful prior experience. The dual tone excitation [2] consists in superimposing two modes from the fundamental pass-band in order to generate asymmetry in the field distribution between cavity cells. The plasma will then glow in the cell where the ignition level has been reached $E \approx 10$kV/m. This technique works extremely well for SNS cavities, it has been proven reliable and several cryomodules have been processed at ORNL. At room temperature SNS high beta cavities have a $Q_0 \approx 1E4$ while the power coupler has $Q_{ext} \approx 7E5$ for the operating mode. LCLS-II cavities have approximately the same Q_0, at room temperature, while the Q_{ext} of the power coupler is set to roughly 60 times the SNS value. Lower coupling implies more forward power needed to ignite the plasma discharge and higher peak field on the coupler tip, hence higher risk of plasma ignition in the antenna. The ratio between peak field in LCLS-II coupler and in the cavity, suggested that the risk of antenna ignition is very high. For a peak field of 10 kV/m in cavity, the peak value at the coupler is 90 kV/m, see Fig. 2. Since plasma

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† berrutti@fnal.gov

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ignition in the coupler has several negative effects, from arcing to deposition of metal particles on the ceramic window, an alternative and more secure method has been developed at FNAL.

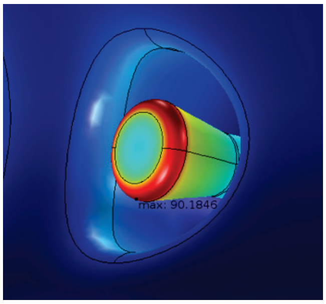


Figure 2: LCLS-II coupler E_{peak} in kV/m for cavity surface field of 10 kV/m.

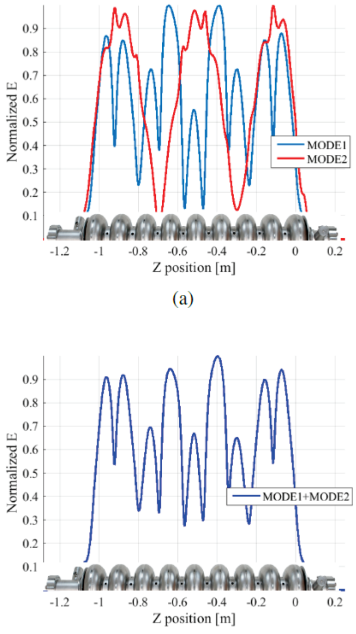
HOMs Plasma Ignition

The alternative studies for plasma ignition involve HOMs of 1.3 GHz cavities [4], several modes and pass-bands have been analyzed and dipole modes have been identified as good candidates for plasma ignition. The HOMs plasma ignition technique is very efficient and requires only few Watts of RF power, overcoming limitations imposed by the poor coupling of the fundamental pass-band. First and second dipole pass-bands are strongly coupled through both HOM couplers at room temperature: reflection coefficient $|\Gamma|^2 \approx 0.01 - 0.3$ while for the fundamental pass band $|\Gamma|^2 \approx 0.99$. The first approach was to use the HOMs to increase the electric field in the cavity using the fundamental pass-band to generate the asymmetry between one cell and the others. After further studies selective ignition of each cavity cell has been theorized and achieved, using HOMs only, experimental results are presented in the next section. An example of selective cell ignition is reported in Fig. 3: the field distribution of MODE1 in Fig. 3(a) would ignite either cell 4 or 6, one can generate asymmetry by superposing MODE2 in the same figure which creates asymmetry between cell 4 and 6.

As a result of mode superposition the highest electric field is located in cell 6, shown in Fig. 3(b), and therefore a plasma discharge is going to ignite preferably at this location. Using the field distribution from RF simulations it is possible to find which combination of HOMs ignites each cell in LCLS-II cavities. For all cells, exception made for cell 5, two HOMs are needed for plasma ignition and the proper amplitudes can be calculated using field distribution from RF simulations. This HOMs plasma ignition technique has been proven effective and results are presented in the next section.

EXPERIMENTAL SETUP AND RESULTS

The plasma cleaning RF setup consists in: VNA, two signal generators, RF power amplifier, bidirectonal coupler and paower meters. The VNA is used to measure and track cavity frequency prior and during plasma ignition via S21 meaurements through HOM couplers. The signal generators are needed for mode superposition and they generate the input of the RF power amplifier, which goes to one of the cavity HOM couplers after passing into the bi-directional coupler. The setup is then completed with cameras on each side of the cavity. A vacuum system is also going to be used for supplying gases and evacuating the cavity from by-products of the processing. The vacuum setup is going to be very similar to what is currently being used at ORNL for SNS HB plasma cleaning.



(a)

(b)

Figure 3: Electric field ditribution of HOMs used to ignite cell 6 (a) and final field distribution after superposition (b).

Plasma Ignition Experiments

The first successful plasma ignition experiments on 1.3 GHz 9-cell cavities have been carried out at FNAL earlier this year. Thanks to the extremely favorable coupling of the HOM couplers for LCLS-II project only few watts are needed to ignited a glow discharge in the cavity. Argon has been used, in place of Neon, at a pressure of 200 mTorr, which matches the working pressure for SNS cavities plasma cleaning. A neon experiment is scheduled soon along with a study of the ignition power in function of the gas pressure, similarly to what has been done at ORNL [2]. Fig. 4 shows Ar plasma in LCLS-II cavity from cell 1 (top left) to 9 (bottom right).

Only modes from the first and second dipole pass-bands have been used, and for all the modes used from the second pass-band it was possible to identify exactly the ignition power. Using the field distribution from simulation it is possible to calculate amplitude, coefficients for all modes needed. Combining these two one can calculate exactly how much power is needed from the second pass-band. Table 1 presents ignition power values for all cells, using

Table 1: HOMs Plasma Ignition for 9-cell LCLS-II Cavity at 200 mTorr Ar: Modes and Power in Watts Needed to Ignite Each Cell

CELL	MODE1	MODE2	P_{Fwd1} Calc	P_{Fwd1} Meas	P_{Tot}
1	2-4	1-6	1.50	1.49	4.71
2	2-6	1-4	5.46	5.45	8.97
3	2-2	1-3	4.85	4.90	6.35
4	2-5	1-4	1.13	1.13	5.89
5	2-1		2.97	2.97	2.97
6	2-5	1-3	3.90	3.91	7.78
7	2-2	1-4	3.87	3.85	6.02
8	2-6	1-9	3.98	4.00	7.23
9	2-4	1-4	1.48	3.86	7.28

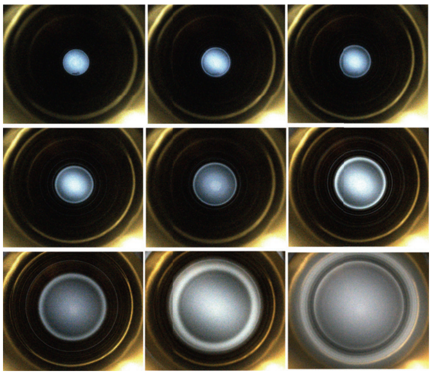


Figure 4: Ar plasma in each cells (1 to 9) of a LCLS-II cavity, field probe side view.

a mode from the second pass-band (2-X) and one from the first dipole band (1-Y). Measured power values for the second band modes are in exceptional agreement with the one calculated, except for cell 9. A further study will follow shortly but the proof of principle experiment has given very good results and the HOMs plasma ignition appears to be a promising method for plasma cleaning of SRF cavities.

NB SAMPLES RESULTS

The effect of plasma cleaning has been studied on different Nb samples at ORNL [3]: both regular Nb and N-doped Nb samples have been plasma cleaned. Different samples had different treatment done prior to plasma cleaning, and samples from different manufacturers have been analyzed. The work function has been measured after several processing steps, Fig. 5: SiC polishing (SiC), electropolishing (EP), nitrogen doping (N2) and plasma cleaning. Since the N-doped Nb processed with plasma shows a much higher work function it should be able to withstand higher RF surface fields than the same Nb prior to cleaning.

CONCLUSIONS

Plasma glow discharge has been ignited in 9-cell LCLS-II cavities thanks to the new HOMs plasma ignition method, developed at FNAL, which allows igniting the plasma with usage of very low RF power (≈3 W). The study of samples at ORNL has shown N-doped Nb should benefit from plasma cleaning as regular EP Nb does. The first plasma cleaning tests will follow shortly this year.

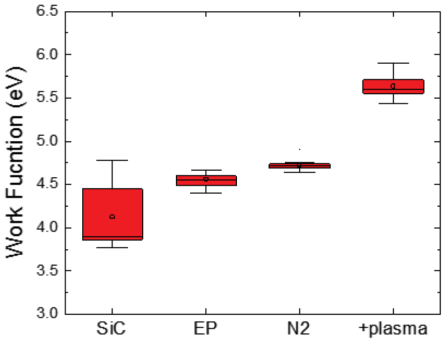


Figure 5: Work function plotted vs final processing step and plasma processing.

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