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PLASMA PROCESSING TO REDUCE FIELD EMISSION IN LCLS-II 1.3 GHz SRF CAVITIES*

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Abstract

In-situ plasma cleaning for LCLS-II (Linac Coherent Light Source-II) 9-cell 1.3 GHz cavities is under study at Fermi National Accelerator Laboratory (FNAL). Plasma processing can help mitigate hydrocarbon related field emission (FE) in SRF cavities using a $Ne-O_2$ mixture. Starting from Oak Ridge National Laboratory (ORNL) method, a new technique for plasma ignition has been developed at FNAL using higher order modes (HOMs). The new procedure has been applied to a 9-cell cavity assembled with view-ports and contaminated with carbon-based ink in order to study the removal of artificial contamination. Plasma processing has been applied to a Nitrogen doped (N-doped) cavity to study the possible effect of the glow discharge on the surface treatment. Cavities contaminated with various sources have been treated with plasma cleaning in order to study its effectiveness. The results of 2 K RF tests measured before and plasma after treatment are discussed here in terms of Q_0 and radiation vs E_{acc}. An example of Residual Gas Analyzer spectrum, acquired during plasma processing of a 9-cell cavity, is also presented.

INTRODUCTION

An in-situ plasma processing technique is being developed at FNAL to mitigate hydrocarbon related field emission [1] in 1.3 GHz cavities. This project is a collaboration between FNAL, SLAC National Accelerator Laboratory and ORNL to adapt plasma processing to LCLS-II 9-cell N-doped [2] cavities.

The newly developed method for plasma ignition uses HOMs (Higher Order Modes) to ignite the glow discharge with only few watts [3,4]. The plasma is ignited in one cell per time and can be transferred through the cavity using a superposition of HOMs.

Starting from SNS experience [5,6] and using the new ignition method, plasma processing has been applied to multiple 1.3 GHz cavities. The first study focused on the removal of artificial contamination from the iris of a 9-cell cavity assembled with view ports. This allowed to identify a first recipe in terms of pressure, duration, plasma density and O_2 percentage. Using these parameters it was verified that plasma processing does not affect N-doping and preserves the high quality factor (Q_0) and quench field. Subsequent studies applied the same recipe to 1.3 GHz cavities with various type of contamination. Cryogenic RF tests of the cavities before and after plasma processing show an increase in performance in all cases; the results are shown here in terms of Q_0 and radiation vs E_{acc}.

PLASMA METHODOLOGY TO REDUCE FIELD EMISSION

Field emission has multiple causes, as metal particles, surface defects, hydrocarbon contaminations and adsorbates. Hydrocarbons (C_xH_y) lower the work function (Φ) of the cavity surface, increasing field emission. Plasma processing focuses on the removal of C_xH_y in order to restore Φ and increase the threshold for field emission, enabling the cavity to operate at higher accelerating field [5].

Plasma processing uses an inert gas (as Neon or Argon) to ignite and sustain the glow discharge in the cavity. A low percentage of Oxygen is added to react with the hydrocarbons adsorbed on the cavity surface. The volatile byproducts are pumped out of the cavity and monitored with a Residual Gas Analyzer (RGA). The procedure is performed at room temperature; the cavity is assembled with two valves, one on each end, to allow the flow of gas. Neon and Oxygen are mixed before reaching the cavity and their ratio is controlled with the RGA. The cavity pressure is set between 70-200 mTorr. Figure 1 shows the vacuum and gas system, the RF instrumentation needed for plasma ignition is also included.

PLASMA IGNITION

Plasma processing for SRF cavities has been first developed at ORNL for the Spallation Neutron Source (SNS) high beta cavities. Starting from ORNL expertise, a new method has been developed at FNAL for LCLS-II cavities. At room temperature the coupling between the cavity ($Q_0 \approx 10^4$) and the fundamental power coupler (FPC, $Q_{ext} \approx 7 \cdot 10^5$, [7]) is extremely low, meaning that more forward power would be necessary to ignite the glow discharge in the cavity. Due to the peak field enhancement at the coupler, the increase in forward power would also intensify the risk of plasma ignition at the antenna.

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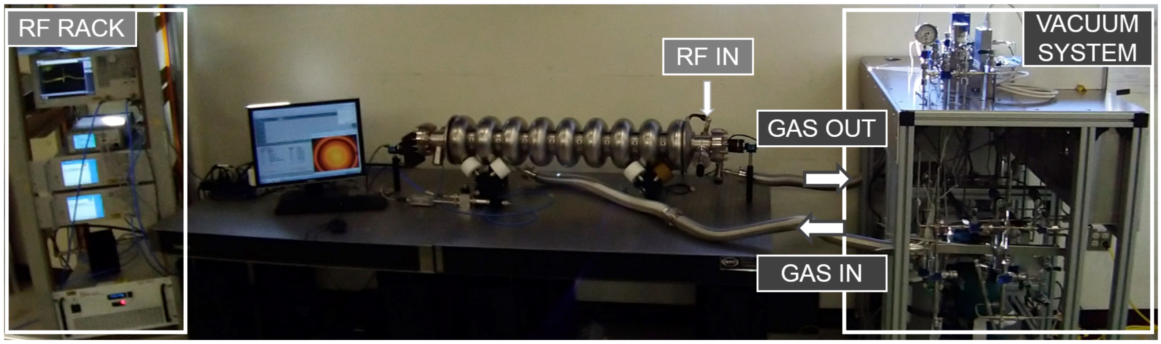
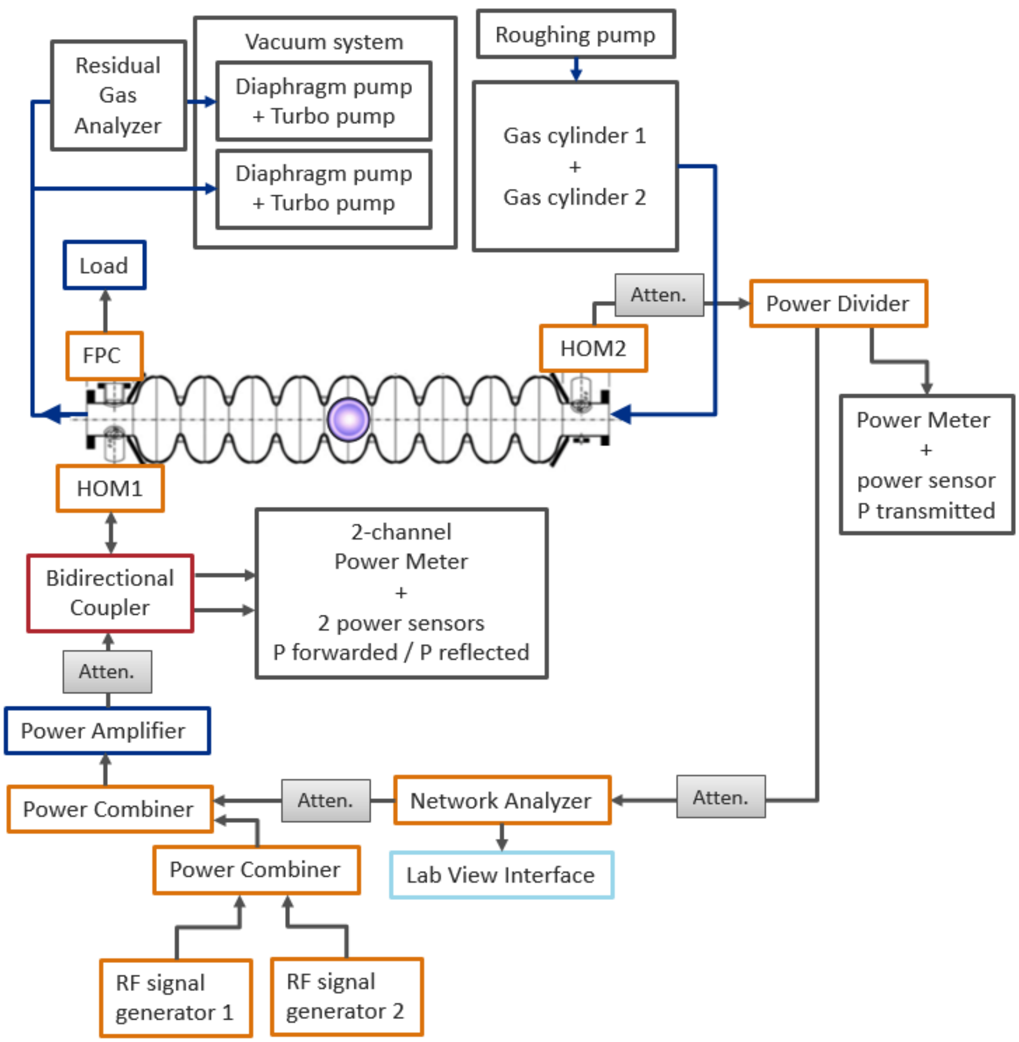


(a)



(b)

Figure 1: Figure 1a shows the experimental set up used for plasma processing; Figure 1b contains a more detailed schematic of the RF, vacuum and gas systems. HOM1 and HOM2 are the higher order modes couplers on the cavity, FPC is the fundamental power coupler.

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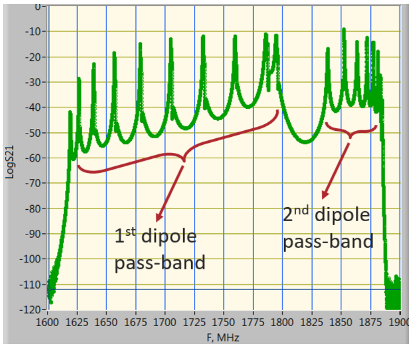

Figure 2: Spectrum of the first and second dipole pass-bands. These modes present good coupling at room temperature and are used for plasma ignition and plasma transferring.

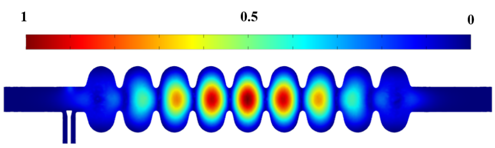

Figure 3: Normalized electric field of the first mode of the second dipole pass-band. This mode is used for plasma ignition in the central cell of the cavity.

The use of HOMs to ignite the glow discharge allows to overcome these issues. Using modes that belong to the first and second dipole pass-bands (shown in Fig. 2) it is possible to ignite the glow discharge in the central cell and to transfer it to the rest of the cavity through adjacent cells. A superposition of higher order modes is used to transfer the plasma. Figure 3 shows the normalized electric field of the first mode of the second dipole pass-band, used for plasma ignition in the central cell. A detailed discussion about plasma ignition studies in 1.3 GHz LCLS-II cavities is presented in [8].

Method to Locate Plasma Position Inside 9-cell Cavity

Of critical importance is also the capability of identifying the location of the plasma inside the cavity volume. Using Slater's theorem [9] and SNS experience [10], it is possible to relate the frequency shift of the resonance peaks to the presence of the plasma. The location of the plasma determines the perturbation on the resonance frequencies: the frequency shift (Δf) of each mode is proportional to the intensity of its electric field in the cell of plasma ignition. Using finite element simulations [11] the Δf caused by the plasma have been calculated for each mode in each cell. This has allowed to identify a pattern of Δf for the first dipole pass-band corresponding to the plasma being ignited in each cell of the cavity. A LabVIEW® [12] program, that measures the frequency shifts and compares them to the simulations data, has been developed to automatically identify the location of the plasma inside a 9-cell cavity.

REMOVAL STUDY ON CONTAMINATED CAVITY

The first application of plasma processing on a 9-cell 1.3 GHz cavity has been done at FNAL with the purpose of studying the removal of artificial carbon-based contamination. The cavity has been assembled with view ports and cameras on both ends and has been artificially contaminated with permanent marker ink on the inner iris of the first cell. Permanent marker ink is made of C-compound, for this reason it has been used to contaminate the cavity. Its composition has been analyzed using Energy Dispersive X-ray Spectroscopy (EDS) and is shown in Fig. 4.

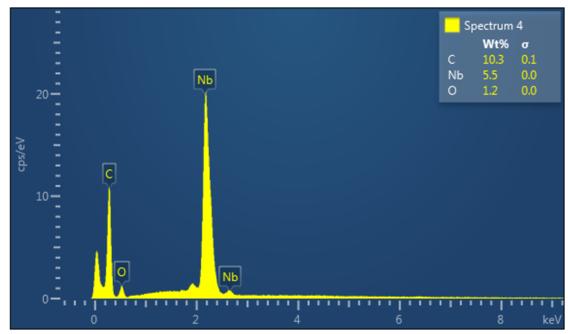

Figure 4: Spectrum of permanent marker ink acquired with Energy Dispersive X-ray Spectroscopy; it indicates that the ink is made of Carbon compounds.

Eight dots have been drawn on the cavity iris.. Using the method discussed in the previous section and in [8], the glow discharge has been ignited in the central cell and transferred to the contaminated cell. The location of the plasma in the cavity has been confirmed both visually and using the detection program developed in LabVIEW®. Figure 5 shows the initial and final state of the cavity, while Fig. 6 offers a close up of the initial, intermediate and final state. After 19 h the contamination has been removed.

This first test confirmed that plasma processing is able to remove carbon contaminations from LCLS-II cavities and allowed also to develop a first recipe in terms of duration of the process, O_2 percentage, pressure and plasma density. The following tests on 1.3 GHz cavities have been performed using this recipe. A study to optimize each parameter is now ongoing.

The Residual Gas Analyzer has been used during the entire processing to monitor the concentration of Oxygen in the mixture and the byproducts of the reaction between O_2 and the hydrocarbons on the cavity surface. An example of RGA spectrum is shown later in the text.

EFFECT OF PLASMA PROCESSING ON N-DOPED CAVITY

A single cell cavity equipped with HOM couplers (shown in Fig. 7) has been used to study the effect of plasma processing on N-Doping. The quality factor versus accelerating field of the cavity has been measured at 2 K in vertical test.

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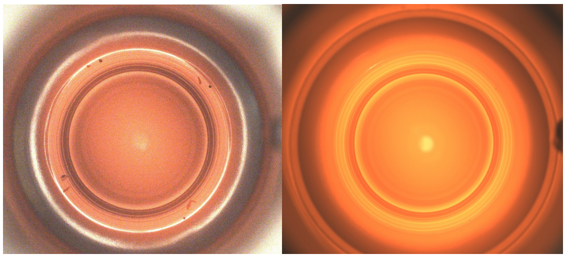
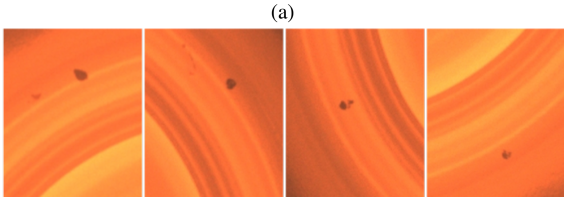


(a) (b)

Figure 5: Glow discharge ignited in the end cell contaminated with permanent marker dots. Figure 5a shows the initial state of the contamination, while 5b shows the state of the contamination after 19 hours of plasma processing.

(a)



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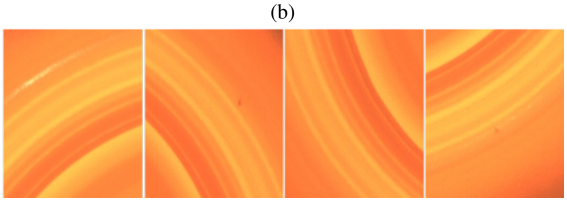

(c)

Figure 6: Close up of the contamination showed in Fig. 5. Initial state of the contamination is shown in 6a, final state in 6c. Figure 6b shows the progress after 5 hours of plasma processing.

Following the baseline test, the cavity has been connected to the experimental setup shown in Fig. 1 and processed for 16 h with Ne – O_2 plasma. At the end of the procedure the cavity has been vertically tested again to measure Q_0 versus E_{acc}. The results of the RF tests of the cavity before and after plasma processing are shown in Fig. 8. The baseline test at 2 K was intentionally stopped before quench to measure the cavity Q_0 at 1.4 K, where the cavity reached 33 MV/m. The comparison between the RF tests before and after plasma processing confirms that the procedure preserves the high quality factor and quench field of N-doped cavities.

STUDIES ON CONTAMINATED CAVITIES

To study the effectiveness of plasma cleaning under different conditions, plasma processing has been applied to

Figure 7: Single cell cavity equipped with higher order modes couplers.

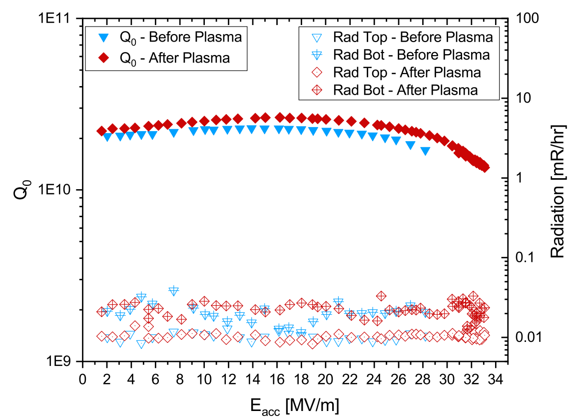

Figure 8: Effect of plasma processing on N-doping: RF tests measured at 2 K before (light blue) and after (dark red) plasma processing. The solid triangles and diamonds show the Q_0 vs E_{acc} curve, while empty triangles and diamonds are used to plot the radiation levels vs E_{acc}. The curve measured before plasma has been intentionally limited at 28 MV/m at 2 K, the cavity reached E_{acc} = 33 MV/m at 1.4 K. The after plasma curve confirms that plasma processing preserves the high quality factor of the cavity and its original quench field.

cavities with various sources of carbon-related contamination:

- simulated vacuum failure;
- iris contaminated with carbon-based paint;
- natural field emission, two cavities as received from vendor.

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Simulated Vacuum Failure

A 9-cell 1.3 GHz cavity has been used to test the effectiveness of plasma processing in case of vacuum failure. For this scope the cavity has been prepared with high pressure rinsing (HPR), top flange and antennas assembly, second HPR, final assembly and slow pumping. To simulate a vacuum failure the evacuated cavity has been exposed to clean room air by opening one the valves. After sitting at atmosphere pressure for a few minutes, the cavity has been slowly evacuated again.

As for the previous test, the contaminated cavity has been RF measured at 2 K to acquire the quality factor and radiation versus accelerating field curves. The curves are shown in blue in Fig. 9. The solid squares are used for the Q_0 vs E_{acc} curve, while empty squares indicate the radiation levels. Top and Bottom indicate the radiation measured from the detector located respectively on top and on the bottom of the cryogenic dewar. The RF test on the contaminated cavity shows that the cavity quenched at 22.5 MV/m showing intense radiation due to field emission. The X-ray onset has been registered at 18.5 MV/m. The final Q_0 versus E_{acc} curve has been measured at 1.4 K and Fig. 9 shows the X-rays registered during the last power rise, which was stopped before the cavity quench. The comparison between the X-rays measured during the first and final power rise shows that some processing occurred during the RF test, however the cavity continued showing significant field emission.

The cavity has been treated with plasma processing, each cell has been processed for almost 2 h. The entire process has been monitored with the Residual Gas Analyzer to study the byproducts generated in the cavity by the reaction of O_2 with C_xH_y.

Figure 9 shows also the results of the 2 K RF test measured after plasma cleaning. The quality factor of the cavity is preserved and the radiation is completely removed after plasma processing.

Artificial Carbon-based Contamination

The single cell cavity equipped with HOM couplers has been used also to test the effectiveness of plasma processing on an artificial carbon-based contamination. Aquadag® [13] is a conductive paint composed by graphite and ultra pure water. A small drop of highly diluted Aquadag® has been deposited on the iris of the single cell. Figure 10 shows images of pure and diluted Aquadag® acquired with the Scanning Electron Microscope (SEM). The dilution chosen to contaminate the cavity is shown in Fig. 10c: only few particles of graphite are deposited on the Nb surface.

The result of the 2 K RF test is shown in blue in Fig. 11, labelled as Contaminated. Compared to the previous test (red curve in Fig. 8, Q_0 = 2.6E10 at E_{acc} = 16 MV/m) the cavity exhibits a degradation in the quality factor and quench field: Q_0 = 1.7E10 at E_{acc} = 16 MV/m, quench field is registered at 18.5 MV/m.

Plasma processing was applied to the contaminated single cell cavity for a total of 17 h, the results are shown in Fig. 11.

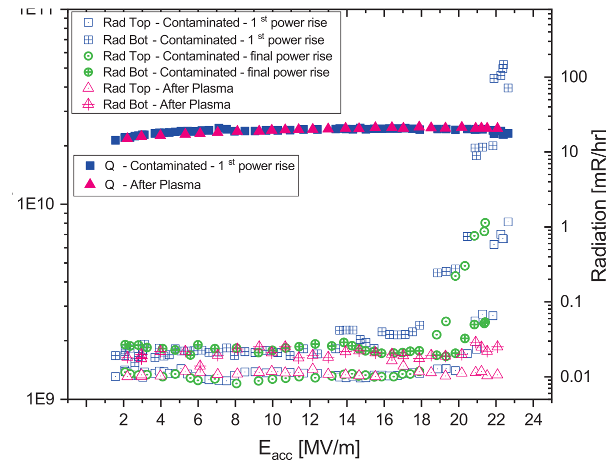
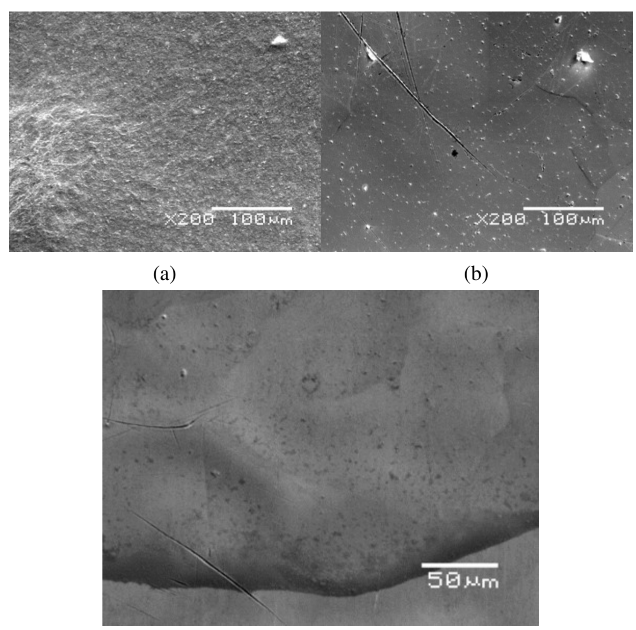


Figure 9: Simulated vacuum failure: RF tests measured at 2 K before and after plasma processing. The blue curves show quality factor and X-rays of the contaminated cavity measured during the first power rise, before plasma processing. The green curves show the X-rays measured during the last power rise registered before plasma processing; the X-ray onset is 18.3 MV/m for the top detector, 20.5 MV/m for the bottom. The pink curves show the RF results after plasma: the radiation has been completely removed and the quality factor is preserved.



(a) (b)

(c)

Figure 10: Scanning Electron Microscope images of pure (10a) and diluted Aquadag® on Nb substrate. Figure 10b shows Aquadag® diluted of a factor 100 with ultra pure water, while 10c shows Aquadag® diluted of a factor 2E4. The dilution factor is measured as the ratio between H_2O mass and Aquadag® mass.

The quality factor of the cavity increased from Q_0 = 1.7E10 to Q_0 = 2E10 at E_{acc} = 16 MV/m; the difference between this test and Fig. 8 could be due to difference in trapped

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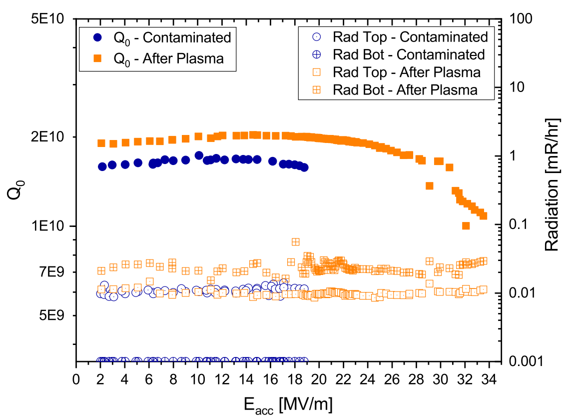

Figure 11: Cavity contaminated with diluted carbon paint: RF tests measured at 2 K before and after plasma processing. The contaminated cavity shows a degradation in quench field and quality factor (blue curve). Once processed with $Ne-O_2$ plasma, the cavity exhibits a complete recovery in E_{acc} (quench field is 33.5 MV/m) and an increase in quality factor (Q_0 = 2E10 at 16 MV/m).

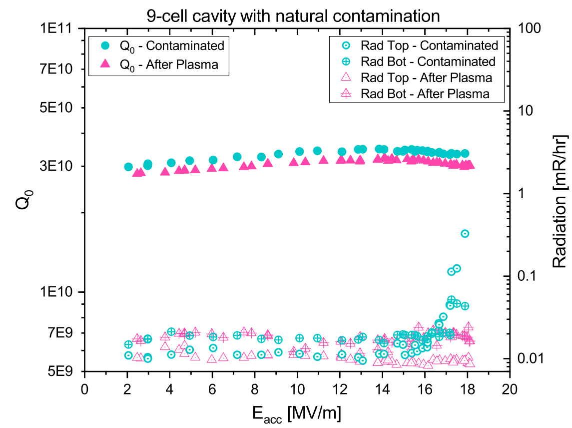

Figure 12: First natural field emitting cavity: RF tests measured at 2 K before and after plasma processing. The X-ray onset has been registered at 16 MV/m before plasma processing. Plasma cleaning completely removed field emission: the RF test measured after the treatment shows no X-rays.

flux during cooldown. Plasma cleaning allowed to completely restore the initial accelerating field, reaching quench at E_{acc} = 33.5 MV/m and resulting in a 15 MV/m increase due to plasma processing.

Natural Contamination

In order to study the effectiveness of plasma cleaning on natural contamination, the processing has been applied on two 1.3 GHz cavities that presented field emission as received from the vendor. The 9-cell cavities showed X-rays during the first RF test at FNAL. The cavities have been assembled with a second valve to connect them to the vacuum-gas system showed in Fig. 1. Both cavities have been tested again after valve assembly.

The results of the first cavity are shown in light blue in Fig. 12. This 9-cell cavity reached E_{acc} = 18.5MV/m with X-rays starting from 16 MV/m and 17 MV/m for top and bottom radiation detectors respectively.

Plasma processing has been applied to the 9-cell cavities, treating each cell for almost 2 h.

The RF test measured after plasma processing on the first cavity is shown in pink in Fig. 12. The cavity reached E_{acc} = 18 MV/m showing no X-rays: plasma processing completely removed field emission. The spectrum measured with the Residual Gas Analyzer during the first day of plasma treatment is discussed in the following section and shown in the last figure on the next page.

Figure 13 shows the results of the second naturally field emitting cavity. In blue is shown the performance of the cavity before plasma processing: the X-ray onset has been registered at 8.5 MV/m and 9.5 MV/m for top and bottom radiation detectors respectively. The RF test was stopped before reaching the cavity quench field due to intense radiation

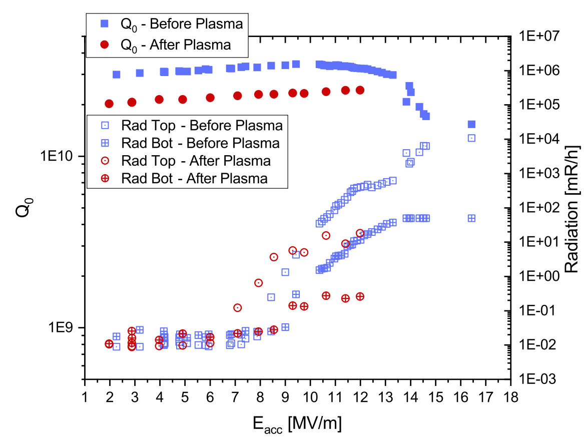

Figure 13: Second natural field emitting cavity: RF tests measured at 2 K before and after plasma processing. The blue curves show quality factor and radiation levels vs accelerating field measured before plasma processing. Cavity started field emitting at 8.5 MV/m, the test was stopped before reaching quench field due to intense radiation levels. The RF test measured after plasma processing is shown in red. This cavity showed no increase in performance due to plasma processing.

levels (1E4 mR/hr at 16.5 MV/m). The RF test measured after plasma processing is shown in Fig. 13 as well. The degradation in quality factor can be attributed to higher ambient magnetic field during cooldown, which results in increased trapped magnetic flux in the cavity. The X-ray onset is 7 MV/m for the top detector, 9.5 MV/m for the bottom radiation detector. As for the first test, the RF test was stopped before quench field due to radiation levels. In this case plasma processing was not effective in decreasing field emission. A possible explanation is that FE may be caused

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by surface defects or metal particles and not by hydrocarbons contaminations on the cavity surface.

RESIDUAL GAS ANALYZER SPECTRA

The RGA has been used to monitor the composition of the gas flowing out of the cavity during all the tests described in the previous sections. Plasma processing is applied twice to the cavity. During the first treatment the cavity often shows peaks in C, CO, CO_2 in correspondence with the glow discharge being transferred to a new, non-processed cell. The increase in the C-related signals shows that the Oxygen contained in the plasma is reacting with the hydrocarbons on the cavity surface. These peaks decrease in time, reaching the background level in approximately 30 min. During the second run of plasma processing, the cavity usually does not show any increase in C, CO, CO_2.

Figure 14 shows a typical example of RGA spectrum registered during the plasma processing of a 9-cell cavity. The RGA records from 1 to 50 amu, in this plot are shown only the elements of interest. The peaks visible in the signals of CO and CO_2 correspond to the ignition of the plasma in a non-processed cell. The carbon signal shows peaks in correspondence with the CO, CO_2 peaks, however the partial pressure of C is lower and more affected by noise.

The first peak, before 14:30, corresponds to the ignition of the plasma in the central cell, while the peak registered a few minutes later (just after 14:30) corresponds to the plasma in cell #9. The CO and CO_2 peaks around 18:30 coincide to the plasma being transferred to cell #4. The 19:30 peaks corresponds to cell #3, the 20:30 to cell #2, the 21:30-22:00 to cell #1. Cell #4 and cell #1 exhibit a double peak due to the plasma being accidentally turned off while reaching the desired plasma density.

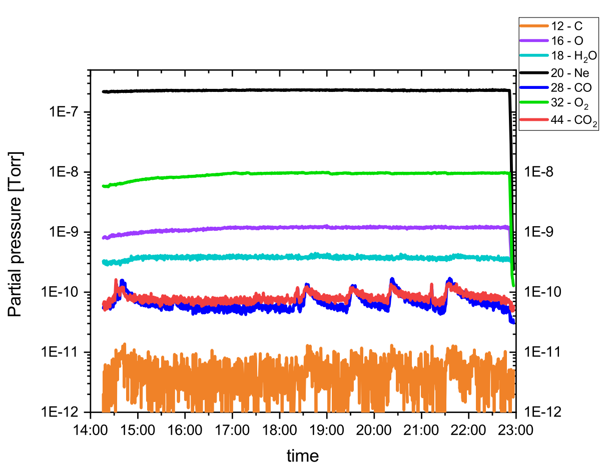

Figure 14: Example of Residual Gas Analyzer spectrum acquired while processing a 9-cell cavity. This spectrum has been measured during the first day of processing of the 9-cell cavity affected by natural field emission. The peaks visible in the C, CO, CO_2 signals highlight the time when the glow discharge is transferred from a processed cell to the adjacent, non-plasma processed, cell.

CONCLUSION

The newly developed method for plasma ignition in LCLS-II cavities uses higher order modes, requiring only few watts. Once ignited the plasma is transferred to the other cells using a superposition of higher order modes. A method to locate the position of the plasma in the cavity has been developed and implemented with a LabVIEW® program. Plasma processing has been first applied to a 9-cell cavity artificially contaminated with permanent marker ink and assembled with view-ports. The test has allowed to study the removal of the artificial contamination and to develop a first recipe in terms of duration of the process, O_2 percentage, pressure and plasma density. The recipe has been applied to a N-doped cavity and it has been verified that plasma processing preserves the high quality factor and accelerating field. Cavities contaminated with various sources (vacuum failure, carbon-based paint and natural FE) have been cleaned with plasma processing and RF tested before and after the treatment. Three out of four tests were successful, the processed cavities showed an increase in performance due to plasma processing; the fourth cavity showed no reduction in field emission as the FE may be not caused by particles or surface defects and not be Carbon-related.

The treatment will be applied to more LCLS-II cavities in order to acquire statistics. Further studies to optimize the plasma parameters are now ongoing to maximize its effectiveness in terms of pressure, plasma density, duration and O_2 percentage.

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