FIRST EXPERIENCE WITH LIQUID NITROGEN CLEANING

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Abstract

Field emission caused by microscopic particulate contamination is a limiting factor for the performance of superconducting RF (SRF) cavities. In an SRF based accelerator, particulates may be transported over the surface of an operational SRF cavity, becoming field emitters and consequentially degrading the performance of the SRF cavity. The most commonly used method for removing particulates from cavity surfaces is high-pressure ultra-pure water rinsing. We are developing a novel high-pressure liquid nitrogen cleaning technique that may possibly enable superior cleaning power and particulate removal from cavities in a cryomodule without taking apart the cryomodule components. This technique provides cleaning mechanisms beyond what are accessible by its high-pressure water rinsing counterpart and leaves no residues on the cleaned surface.

INTRODUCTION

Performance degradation of SRF cavities due to field emission has become one of the major limiting factors in SRF accelerator technology. Field emission is observed to increase after assembling SRF cavities with auxiliary equipment and subsequent assembly in multiple cavity strings that are inserted in cryomodules and installed in accelerators. Additional performance degradation has also been observed during long-term operation in the CEBAF accelerator which has warm-to-cold transitions between each and every 8-cavity cryomodule. Observed performance degradation by increased field emission has been linked to surface pollution by particulates and hydrocarbons. Sources of surface pollution have been identified as both material defects and contaminants introduced during processing and assembly. These observations and associated studies have been richly published in conference proceedings and scientific journals.

While some surface pollution is assumed to be introduced during initial fabrication, others are introduced during assembly, operation or maintenance. Combinations of cleaning processes are used to mitigate field emission. These are however not always successful and the established procedures are often impossible to apply after a cavity has been assembled into a cryomodule. No well defined final cleaning method does yet exist. Several specific cleaning processes have been developed or proposed over the years to help in this effort such as high-pressure ultra-pure water rinsing, helium processing, plasma processing, and dry-ice cleaning. We started a new effort based on the idea of liquid nitrogen jet cleaning.

LIQUID NITROGEN CLEANING

The liquid nitrogen jet was developed as a technique for cutting materials [1] and industrial cleaning services [2]. The technique presented here was proposed for cleaning CEBAF cryomodules by removal of microscopic particulates [3]. In this process, filtered liquid nitrogen flows through a booster pump to increase the pressure and is then supplied to a lance inside the cavity. The liquid nitrogen exits through a small nozzle at the end of the lance, producing a high pressure liquid nitrogen jet as shown in Fig. 1.

The liquid nitrogen cleaning technique shares ideas and essence with both high pressure rinsing with ultra-pure water [4, 5] and dry-ice cleaning [6–9]. Both methods have shown to eliminate field emission or at least to increase the electric gradient at field emission onset. Liquid nitrogen cleaning combines the high velocity jet from high pressure water rinsing with the thermal impact of dry-ice cleaning. The liquid nitrogen jet is supposed to remove particulates from the cavity surface by multiple actions such as aerodynamic drag, impact, and thermal shock. As with dry-ice cleaning, the liquid nitrogen jet should not leave a residue when drying. An important aspect for future in-situ cleaning of cryomodules.

A moving fluid creates an aerodynamic drag on a particulate of which the force is proportional to the cross sectional area of the particulate. However, the fluid velocity becomes zero at the cavity surface area, resulting in a decreased aerodynamic force for tiny particulates stuck to the surface. Therefore the drag force on small micron-sized particulate can be less than the surface adhesion force. The typical cross-over point is suggested to be for particulates between 0.5 and 1.0 µm in diameter [7]. The evaporation of the liquid nitrogen fluid when touching the warm cavity

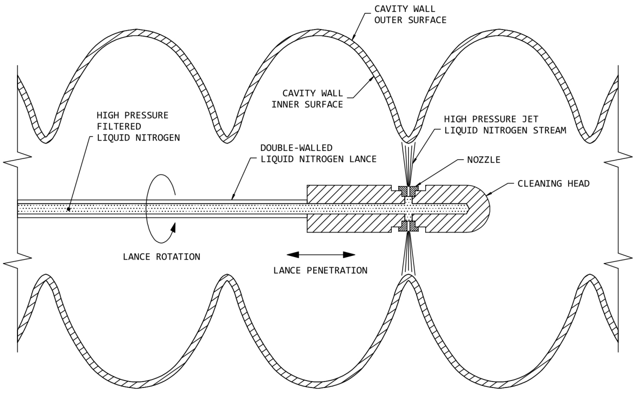

Figure 1: Concept of a high pressure liquid nitrogen jet stream cleaning a cavity surface [3].

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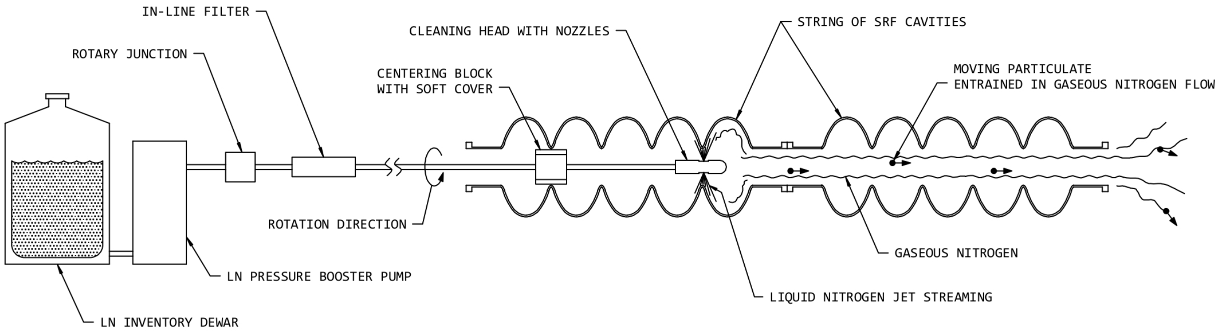

Figure 2: Conceptual idea for liquid nitrogen jet cleaning of a cryomodule.

surface increases the fluid flow along the particulates. This creates a local enhancement of the aerodynamic drag force.

The sound shock wave is a combination of the aerodynamic drag force and momentum transfer on impact of an incident particle on the particulate. The high-momentum impact of the liquid jet on the surface particulate can help to overcome the surface adhesion force for smaller particulates. When the impact force exceeds the adhesion force, the particulate can be removed from the surface and carried away by the aerodynamic drag.

The thermal shock effect is a cold shrinkage differential that works by freezing-out surface particulates. Exposure of a microscopic particulate to the liquid nitrogen creates a thermal gradient and a thermal contraction of the particulate. The local cooling combined with different thermal shrinkage between particulate and surface creates a shear stress. The effective contact area between particulate and cavity surface decreases, reducing the adhesion force between particulate and surface. Hence, less force is needed to overcome the surface adhesion force and remove the particulate.

The strength of materials decreases at lower temperatures causing embrittlement in a variety of organic and metallic materials. The material's elasticity and adhesiveness reduces. Hence, less force is required to overcome the adhesive force and remove particulate. For larger surface contaminations, the material can form cracks which leads to breaking and easier removal [10].

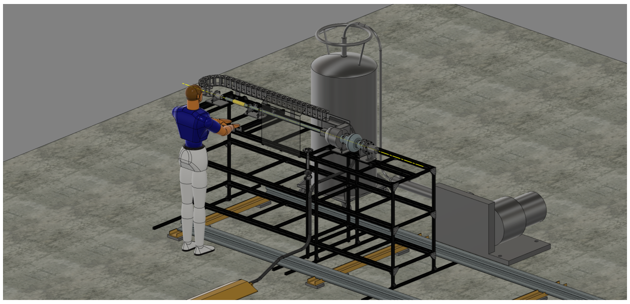

Figure 3: Layout of the liquid nitrogen cleaning set-up presently under development.

INITIAL CLEANING SETUP

The conceptual design idea for the high pressure liquid nitrogen jet cleaning of a cryomodule is shown in Fig. 2. The lance with cleaning head enters the cryomodule on one end and the nitrogen gas stream removing the particulates leaves at the other end. The present objectives are reduced to develop an elementary setup for a series of proof-of-principle experimentations. Figure 3 shows the layout of the constructed test setup. A pressurized dewar provides a liquid nitrogen stream to a lance inserted into the cavity to be cleaned. The lance is equipped with a 6 nozzle spray-head similar as used in the JLab high pressure water rinsing station. The lance can be moved forwards and backwards manually and can be rotated too. The lance is also equipped with an in-line particulate filter. The cavity is mounted between a safety cap and end-cap. The safety cap prevents complete retraction of the lance ensuring that the nozzle head stays inside the enclosure of caps and cavity. This avoids that the liquid nitrogen jet can hit external equipment or operators. The end-cap allows for a back-stream of filtered nitrogen gas. This is used to pre-fill the cavity with nitrogen gas, preventing humidity that would freeze on the cavity surface when starting the liquid nitrogen jet. A low temperature liquid pressure booster pump can be installed between the dewar and lance to increase the liquid nitrogen pressure up to 100 bar.

To verify overall safety, a first run was performed in March 2023 outdoors on a JLab parking lot as shown in Fig. 4.

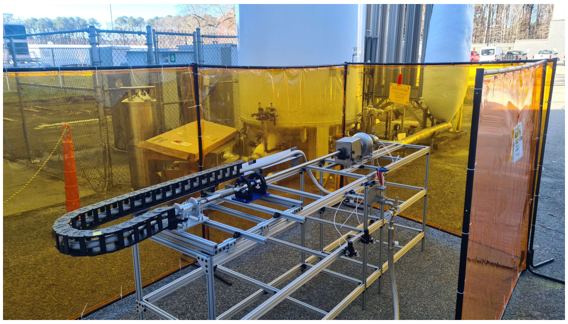

Figure 4: First setup for a safety test run.

Except the pressure booster pump, all elements of the setup were in place and the system was operated successfully. The safety cap and end-cap enclosing the cavity performed as intended and prevented spillover of liquid nitrogen.

The setup was equipped with an exhaust duct below the outlet of the safety cap. Using a strong fan, it evacuates all of the nitrogen fluid away from the setup and its operators. A nitrogen gas bearing was installed in front of the safety cap to guide and support the lance.

FIRST CLEANING EXPERIENCE

A 1.3 GHz single-cell cavity made of ingot niobium was designated for the first cleaning test. This cavity, with identification TC1N1, reached up to 11.5 MV/m field emission free in 2015 [11]. The cavity has been open to air in storage for several years since then. Cavity, safety cap and end-cap were degreased with water and detergent in an ultra-sonic tank, air dried and bagged. The liquid nitrogen cleaning setup was installed inside a cleanhood. Then cavity and caps were installed on the setup as shown in Fig. 5. The lance was cooled down with the nozzle spray-head inside the safety cap. After liquid nitrogen started to flow, the lance was moved slowly through the cavity and pulled back. At that moment unfortunately the nitrogen gas bearing failed and the rotational joint froze. It was not possible to perform a second run through the cavity nor was it possible to rotate the spray-head. The cavity was removed from the setup, bagged, and mounted on a vertical dewar test stand in the cleanroom. The vertical test exposed power limitation at 4.5 MV/m with field emission onset at 4 MV/m.

CONCLUSIONS AND OUTLOOK

We build a proof-of-principle test setup for liquid nitrogen jet cleaning, performed safety checks, and a first cavity cleaning test. The experimental liquid nitrogen jet cleaning setup is being modified to simplify installation of cavities. The failed nitrogen gas bearing has been removed. A nitrogen gas manifold and fan will be installed to prevent the rotational joint from freezing. The pressure booster pump will be introduced into the setup to increase the nitrogen jet pressure. We will start a cycle of tests using the same single-cell cavity to study the effect of liquid nitrogen jet cleaning under different parameters. The setup will be continuously improved to adapt to the best conditions possible.

Figure 5: First single-cell cavity prepared for a test run.

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