

First experience with He conditioning of a superconducting rf photoinjector

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The recent achievements in the performance of superconducting rf (SRF) photoinjectors have opened a new era in the development of reliable high-brightness cw electron sources. While the SRF guns become one of the most promising technologies, the compatibility of the SRF environment with the complex photocathodes remains at the forefront of the modern accelerator science. The SRF cavities operate at cryogenic temperatures providing the ultrahigh vacuum environment highly beneficial for the photocathode performance. However, the necessity to keep the photocathodes at room temperature while being surrounded by the cavity walls that are kept at cryogenic temperatures creates an additional complexity for the SRF gun design and operation. The complex and volatile chemical compounds used for photocathodes have a high chance of contaminating the surfaces of the SRF cavity. When deposited, such compounds could create centers for cold electron emission which degrade the performance of the SRF guns. Such a circumstance would require the development of the *in-situ* processing techniques for restoring the SRF cavity performance. This paper presents the results of the successful implementation and application of the He conditioning method for cavity restoration using the existing SRF photoinjector at Brookhaven National Laboratory (BNL). The method has proven to be extremely effective and resulted in a dramatic improvement in the BNL gun performance.

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I. INTRODUCTION

The future development of modern x-ray free electron lasers (XFELs), γ -ray sources, fixed target, and collider experiments for Nuclear and High Energy Physics (NP&HEP) and a variety of other scientific, industrial, and medical applications rely heavily on the ability to produce low emittance and high current continuous wave (cw) electron beams [1]. The development of reliable electron sources has been a major enabling technology for achieving such beams. The recent progress in the field of SRF photoinjectors has demonstrated a successful performance confirming that, indeed, the SRF environment and high quantum efficiency (high-QE) photocathodes are compatible and can produce high-brightness beams with low transverse emittances [2]. Nevertheless, the nature of the photoinjector operation requires systematic cathode exchange, which puts the cleanliness of the photoinjector

cavity at risk. A reliable *in-situ* cavity restoration procedure can be of great importance when it comes to cavity performance and maintenance.

Successful performance of an SRF photoinjector is a delicate balance of maintaining the good quality of operation for both the photocathodes and the cavity itself. The introduction of a photocathode into an SRF environment comes with a great risk of cavity contamination by the particulates produced during the process of the cathode insertion/removal and deposition of volatile or highly emissive compounds from the cathode (Cs, Na, K, etc.) onto the walls of the cavity during operation. Such contaminants create emission centers on the cavity surface and result in a significant cavity performance degradation caused by excessive production of *dark current* and enhanced strength of *multipacting* barriers—the phenomena common to the SRF cavities that we will detail below.

Dark current is an undesirable emission of electrons from the regions of high electric fields on the cavity surface caused by particulate contamination. An excessive dark current results in an increased generation of x rays, higher consumption of liquid He, and, possibly, quenching of the cavity. The presence of a photocathode within the cavity body increases the risk of the reduced operational accelerating voltage of the photoinjector and subsequent degradation of the beam quality.

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The resonant buildup of the secondary electrons within the cavity body—*multipacting* (MP)—strongly depends on the secondary emission yield (SEY) of the cavity wall material and is directly impacted by the presence of external contaminants. MP prevents the cavity from reaching operational voltage, causes local overheating of the cavity surface, and may result in cavity quenching.

Both phenomena described above demonstrate an example of the damage to the cavity coming from the introduction of the photocathode into an SRF environment. If the cavity has strong MP barriers, the electron bombardment which occurs as one attempts to push through them can significantly damage the cathode surface and dramatically decrease the cathode lifetime. To address the issue of the inevitable contamination of the cavity walls, reliable *in-situ* cavity restoration techniques must be developed. A variety of surface treatment techniques applicable for SRF cavities have been developed throughout the years, but their applications to the restoration of the SRF photoinjectors are still under investigation.

In this paper, we present our experience with handling the 113-MHz SRF photoinjector with a warm CsK₂Sb cathode throughout several years of operation. We report the complications encountered throughout these years and the solutions that were found to overcome these challenges. First, we will provide a brief overview of a few major SRF cavity restoration techniques available to date in the application to the SRF accelerating structures. We will then proceed by providing a description of the 113-MHz SRF gun cavity at Brookhaven National Laboratory (BNL) and its performance in Sec. III. Section IV describes our experience in the application of the He conditioning technique for restoration of the BNL SRF gun performance and reports on the progress achieved using this treatment.

II. CAVITY RESTORATION TECHNIQUES

With the variety of restoration techniques applicable for the SRF cavities, there are a few that currently stand out when it comes to the prevention of the field emission: high power processing (HPP), He processing, and plasma treatment [3,4]. These methods are generally implemented as *in-situ* restoration techniques and have demonstrated significant improvement in the cavity performance. The general principles of these and several other restoration techniques available to date are outlined below.

cw rf processing or cold conditioning (CC) technique is fairly straightforward and involves the operation of the cavity in a cw mode for an extended period of time while monitoring the rf losses and x-ray radiation levels from the cavity. An rf conditioning in a sense is quite similar to a dc breakdown when an applied surface electric field causes an explosive event resulting in the vaporization of a surface emitter. The event of an emitter explosion is accompanied by a rapid drop in the field emission current, rf losses, radiation activity, and results in an immediate improvement

of the cavity performance that reaches higher operational voltage levels [3].

High power processing (HPP) is a natural second step in the cavity conditioning after the CC method has reached its limits. HPP involves the pulsed operation of the cavity which is beneficial for the emitter vaporization due to the ability to achieve higher surface electric fields at a reduced power dissipation and liquid helium consumption compared to the CC. This is possible only when high power pulsed sources are available at the cavity frequency.

Helium conditioning (HeC) is usually performed at the operational cryogenic temperatures of the cavity by filling the cavity volume with pure He gas at pressures ranging from 10⁻⁶ to 10⁻⁵ Torr. Subsequent application of short high voltage rf pulses creates an electric field at the surface of the dark current emitters above the critical level. When such high electric fields are applied to the impurity, the emitted burst of electrons ionizes the surrounding He gas, and He ions bombard the source and efficiently destroy such emitters.

In the past decades, HeC has been well established as a valuable method for reducing field emission in the SRF cavities. There are numerous examples of successful applications of this technique that demonstrated improvement in the cavities' accelerating gradient, quality factor, and radiation levels. The technique has been implemented and utilized for the treatment of CEBAF SRF cavities at JLAB [5], with the recent progress in the performance of the C100 cryomodule, part of which was limited by field emission, but was successfully recovered from 9.3 MV/m to 13.1 MV/m on average [6]. The efficiency of the HeC in combination with other treatment methods, such as rf conditioning or subsequent high-pressure rinsing, was evaluated in application to high- and low-beta cavities at KEK [7] and CiADS [8].

Thermal cycling is typically used to eliminate the cryogenic adsorption on the cavity surface. Since an SRF cavity functions as a cryopump at the operational temperatures, the residual gases and contaminants tend to adsorb on the cavity walls. In order to desorb the named contaminants, one must perform thermal cycling by warming up the cavity to a higher (usually room) temperature and pumping the residual gas out. While the method has shown to be efficient in the removal of the emitting sites responsible for the field emission, in some cases, it can cause the opposite and lead to the appearance of the new emitters on the cavity surface [9–11].

Plasma treatment (PT) of the SRF cavities is a relatively new method. PT is performed at room temperature and involves filling the cavity with a mixture of noble gases (such as Ne or Ar) and oxygen at pressures of 70–200 mTorr followed up with ignition and sustenance of an rf discharge. 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). Ne and O₂ are mixed before reaching the cavity and their ratio is controlled using an RGA. The *in-situ* PT technique was developed mostly to mitigate hydrocarbon related field emissions. Starting from the spallation neutron source (SNS) experience [12,13] and using the new ignition method, PT has been adapted and applied to multiple 1.3-GHz LCLS-II cavities and to the LCLS-II-HE verification cryomodule [14] at Fermi National Accelerator Laboratory (FNAL) and extended to using higher order modes (HOM) couplers to ignite the glow discharge with only a few watts of required rf power [4,15,16]. In multicell cavities, the plasma can be ignited one cell at a time using a superposition of HOMs.

When the appropriate restoration methods are applied, the performance of an SRF cavity can be significantly improved resulting in higher achieved electric fields, lower consumption of liquid He, and lower radiation levels. The investigation of the application of such methods to SRF photoinjectors is crucial for the advancement in the development of novel SRF electron sources.

III. 113-MHZ SRF GUN

The 113-MHz SRF gun was built for the Coherent electron Cooling Proof of Principle (CeC PoP) [17] experiment at BNL and is a VHF-type quarter-wave resonator (QWR) made of bulk niobium. The gun operates at a very low frequency which provides the beneficial condition for photoelectrons to be generated at the peak of the accelerating field (10–20 MV/m at the photocathode surface). While the detailed design of the cavity body and its auxiliaries can be found in [18–21], here we will limit the description only to a general system overview with the focus on the specifics of the cathode delivery system as it's critical for the purpose of this paper. The full assembly of the QWR cavity in the cryostat with its surroundings is shown in Fig. 1. The cavity is maintained at 4 K and uses

the liquid He (LHe) from the refrigeration systems of the Relativistic Heavy Ion Collider (RHIC). The green 532-nm laser light is transported to the cathode surface through the laser cross and the hollow fundamental power coupler (FPC) that serves two purposes—delivers power from the 4 kW solid-state amplifier to the cavity and acts as a frequency tuner. The room temperature hollow Cu-coated stainless steel stalk resides inside the 4 K SRF gun. The stalk has an impedance transformer and functions as a half-wave choke that is shorted outside the cryostat. The cathode is delivered inside the cavity through the stalk with the use of the magnetic cathode manipulator system. The cathode delivery system has three UHV arms used to transport the cathode pucks from a storage unit called “garage” into the cavity. The long manipulator arm delivers the cathode to the end of the stalk, where it is grounded to the stalk by the rf spring fingers (the details of the cathode and cathode manipulator end effector are illustrated in Fig. 2). Controlling the depth of the stalk insertion with respect to the cavity nose allows for the control of the primary beam focusing near the cathode surface, which significantly improves the beam quality at the exit of the gun.

The CsK₂Sb photocathode material is deposited onto the polished surface of Mo puck using a dedicated cathode deposition system. The garage, equipped with mobile UHV ion and sublimation pumps, can be attached to the system via a load-lock and can hold up to three photocathodes at a time. When it is detached, the garage is transported to the RHIC tunnel, where it is connected to the gun's load-lock. After a brief bakeout, the cathodes can be transferred into the gun. Overall, the cathode exchange between the gun and the garage takes about 30 min.

The cavity was manufactured by Niowave but has never achieved its design voltage of 2 MV due to the limitations during the production process. The routine CeC PoP operation requires the gun to deliver 1.25-MeV electron beams with a headroom of 200 kV, which was easily achievable. Overall, the cavity has shown an impeccable

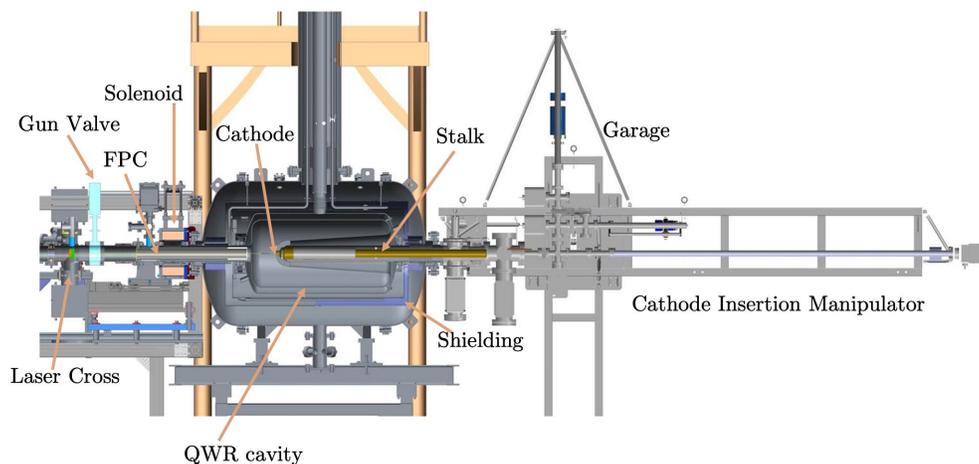


FIG. 1. Schematic of the CeC SRF gun assembly indicating the major system components.

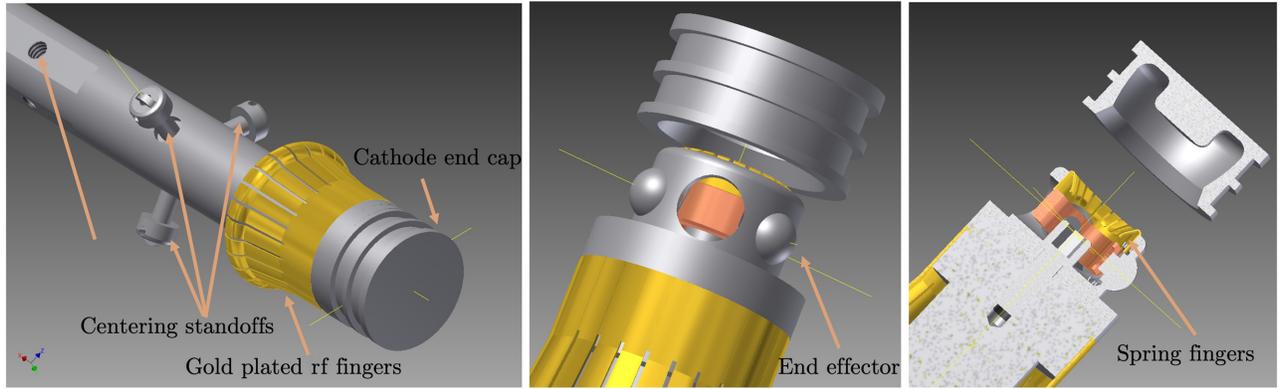


FIG. 2. Detailed schematic of the cathode puck and cathode manipulator end effector assembly.

performance by sustaining cw operation during the CeC experimental runs (continuous use of the gun for 5–6 months each year). The early stages of operation were challenged by the presence of persistent low-level MP barriers, but the issue was methodically evaluated and successfully resolved resulting in the complete elimination of MP as an obstacle for the cavity operation. The detailed description of our MP studies and the dedicated start-up procedure developed to avoid the MP issue can be found in [22].

The cavity performance as a photoinjector has been rather impressive: the gun demonstrated the ability to deliver high-brightness electron bunches with low transverse emittances (e.g., 0.15 mm mrad slice emittance for 100 pC, 400 ps bunches) and has also generated record high charges per bunch (up to 20 nC) [2]. The cavity employs high quantum efficiency (QE) room temperature CsK₂Sb photocathodes and has demonstrated the ability to maintain the cathode's QE of 3–4% for several months of continuous operation [23].

IV. HE CONDITIONING IN APPLICATION TO THE BNL SRF GUN

During the multiple years of the gun operation, we have learned that the development of *in-situ* methods of cavity performance restoration is crucial for routine photoinjector maintenance. There are always multiple sources of possible SRF gun cavity contamination, including particulates generated by inserting and removing cathodes or those migrating from other parts of the vacuum system, which can result either in reduced performance of the SRF gun or even in the loss of a valuable piece of equipment. One of the successful methods that we have implemented for improving the performance of our SRF gun is He conditioning (HeC). Although widely applicable to the SRF cavities, HeC has not been thoroughly studied in the application to the SRF guns. The treatment has been previously applied to the HZB 1.4-cell elliptical gun cavity [24,25]; however, a detailed description of the procedure or a comprehensive evaluation of the HeC effectiveness has

not been reported. The HeC system for the BNL SRF gun was implemented at the early stages of the gun commissioning and demonstrated to be successful [19]. However, at the time, the methodical evaluation of the treatment procedure and the treatment efficiency was not properly evaluated. The system for HeC of the CeC SRF accelerator, designed and built by the BNL vacuum group, is shown in Figs. 3 and 4. In this paper, we present two examples where HeC was crucial for the performance of the BNL SRF gun, and the method has shown to be extremely effective. We outline the specifics of the method that has been developed and discuss the cavity performance before and after the HeC was used.

A. He Conditioning: Case 1

At the beginning of the CeC experimental run 2021, the gun showed signs of significant performance degradation: rapid decay of the cathode quantum efficiency, appearance of new low-level multipacting barriers, and increased radiation and LHe consumption compared to the routine operation levels. These observations were then followed by



FIG. 3. Detailed view of the SRF gun cryostat with the critical vacuum components. The cathode insertion is on the right side of the schematic and the FPC is on the left side. Here ip = ion pump; tc = thermal conductivity gauge, reads pressure from atmosphere to 1×10^{-3} Torr; cc = cold cathode gauge, reads 1×10^{-3} to 1×10^{-11} Torr; sv = vacuum valve.

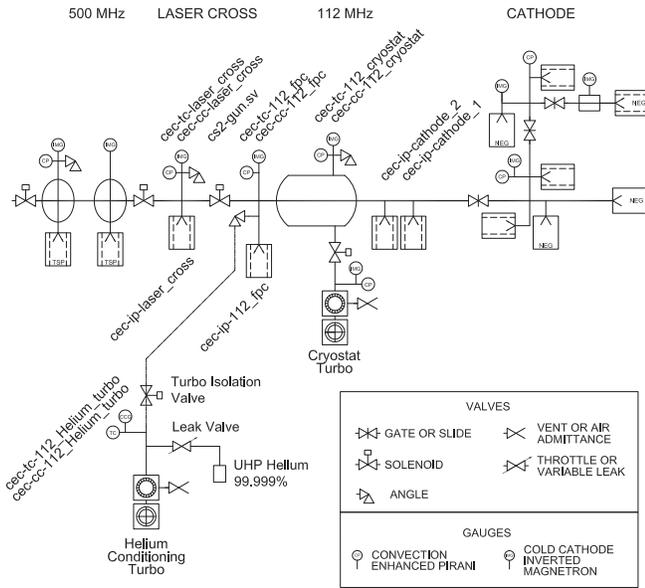


FIG. 4. Schematic of the clean He gas delivery system for the conditioning of the CeC SRF cavities. Here ip = ion pump; tc = thermal conductivity gauge; cc = cold cathode gauge; sv = vacuum valve; NEG = nonevaporable getter pump; UHP = ultrahigh purity grade.

a series of dramatic changes in the beam dynamics within the cavity. The measured axis of the beam propagation has shown a significant deviation from the straight path: the beam axis was tilted by 22 mrad horizontally indicating the corresponding tilt of the cathode surface (see [26] for the detailed description of the gun axis measurement procedure). This fact was then confirmed by the direct observation of the asymmetry in the cathode placement within the cavity nose (see Fig. 5). The reported behavior indicated potential damage to the cathode delivery system and the inevitable presence of the cavity surface contamination. Upon a detailed inspection, the damage to the cathode end effector was found to be the issue. When the puck was removed, a close-up inspection found evidence that the manipulator had been damaged due to either poor or inattentive handling of the end effector or horizontal manipulator. As can be seen from Fig. 6, at least one of the rf spring fingers clearly showed a burn mark, which is the evidence that particulates were generated that may have escaped through the gap between the puck and the end effector registration surface.

After the unsuccessful attempts to bring the cavity to the regular operational state by using CC and HPP, it was decided to proceed with He conditioning. The He conditioning of the CeC gun cavity typically adheres to the following procedure. First, before the He is introduced into the cavity, with the He leak valve and all the surrounding valves of the CeC system closed and the cathode puck retracted, the gun voltage must be brought up well above the MP levels, usually at a baseline of 700–750 kV. The

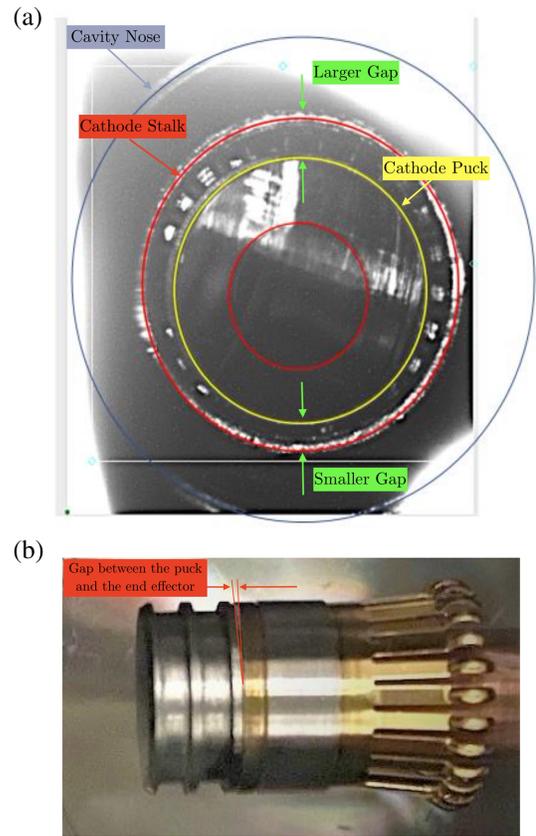


FIG. 5. (a) Cathode installed at the end of the cathode stalk. An asymmetric circular pattern can be seen here. (b) After the cathode was extracted from the gun, this image shows a gap that had opened up between the puck and the end effector.

protection mechanism for monitoring the cavity voltage is then enabled to prevent the cavity from falling into multipacting for a prolonged period of time. The implemented protocol is registering the cavity voltage, and once the level is detected to be below the multipacting threshold (usually below 400 kV), the cavity is immediately turned off. The pulsing with 10-Hz repetition and pulse width of 1–2 ms is then introduced on top of the baseline similar to one shown in Fig. 7(b). Once the pulsing event is set, the He leak valve is opened to introduce He into the cavity at the desired pressure level, typically in the range of $2\text{--}5 \times 10^{-6}$ Torr with the He pressure measured with gauges at

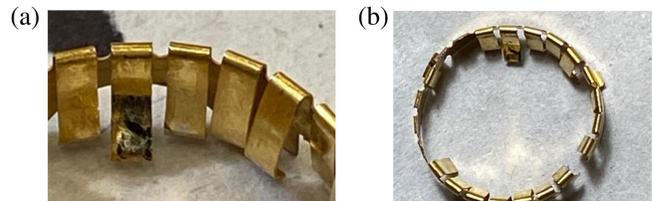


FIG. 6. (a) Spring finger element. One of the fingers clearly shows a burn mark. (b) Shows the plastic deformation of the spring finger being “pulled forward”.

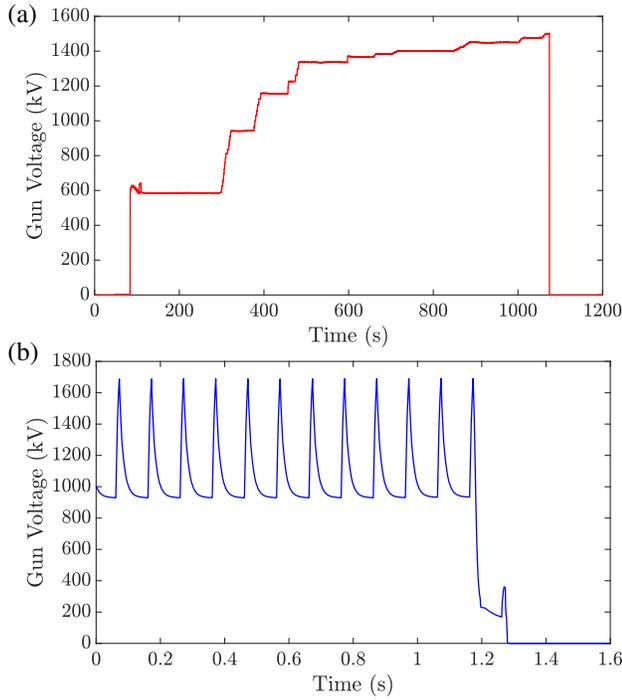


FIG. 7. The highest achieved cw (a) and pulsed (b) cavity voltage after the first case of He conditioning.

room temperature outside the cavity (see Fig. 4). The conditioning procedure consists of a gradual increase of the peak cavity voltage that can be achieved through either increase in the pulse length of the pulsing event or an increase in the baseline level. Since the increase in the baseline level requires higher LHe consumption, the conditioning is usually performed by the adjustment of the pulse length of the pulsing event. One needs to gradually increase the pulse width in the steps of ~ 0.5 ms, stay at each level for an extended period of time (10–15 min), and simultaneously monitor the gun voltage behavior, radiation levels, mass flow of liquid He, pressure in the gun cavity, and gauges of the ion pumps providing the pressure levels of the He used for conditioning. During the HeC, He and the loose debris are constantly pumped out of the cavity by a turbo pump. The overall process of HeC is rather delicate and sudden increases in the applied power could result in interruption by the cavity machine protection system (MPS). If the gun trips, the protection mechanism turns the cavity off, one must close the He leak valve and wait for the vacuum to recover to $\sim 1 \times 10^{-7}$ Torr before turning the system back on.

After a couple of days of He conditioning, the cavity showed significant performance improvement: the gun reached the all-time highest voltage demonstrating 1.5 MV cw and 1.7 MV pulsed. The radiation level at the CeC operational level of 1.25 MV cw has also improved dramatically and reduced to ~ 380 mR/h with ~ 2 g/s LHe consumption (corresponding to the heat load of 44 W). Figure 7 shows the final test of the cavity operation in cw

and pulsed modes after the completion of the He conditioning. The cw voltage limit is defined by the maximum available LHe consumption of 8 g/s (heat load of 174 W). A quench-like limit occurs at 1.7 MV in pulsed mode as indicated by the steep drop of the cavity voltage in Fig. 7(b). The mechanism of capturing the cavity voltage when it falls below the MP level during the HeC pulsing procedure was implemented after this event, hence the appearance of the small spike in Fig. 7(b) is an indication that the cavity was not turned off soon enough after the cavity tripped.

B. He Conditioning: Case 2

In February 2022, during a mundane cathode exchange, it was found that the cathode puck was not fully engaged with the end effector of the cathode manipulator once the old cathode was extracted. While attempting to insert a replacement cathode, an obstacle was encountered inside the cathode stalk that prevented the team from inserting the cathode, unless a significant adjustment of the horizontal angle of the insertion arm was applied. The cathode was installed, but the cavity demonstrated an immediate performance degradation: although the MP barriers were surpassed without an issue, the cavity would not be able to exceed 600 kV, showing a significant amount of dark current in the cathode area and several spots of visibly glowing emitters. An attempt to clean the cavity by using traditional cw or high-power processing (HPP) was successful at first but eventually resulted in a cavity trip followed by significantly aggravated MP levels that were impossible to overcome. The cathode was extracted, and after several attempts of HPP, it was decided to switch to HeC. Within the course of a few days, we performed HeC and studied in detail how the amount of the delivered He affects the cleaning process. The evolution of the cavity voltage and respective cavity pressure and radiation levels are shown in Fig. 8. The same procedure as in the previous case was applied, but the He pressure levels were adjusted in the range between 2×10^{-6} and 6×10^{-6} Torr based on the cavity behavior. Overall, HeC procedure was highly successful and resulted not only in the complete cavity recovery but also in an all-time low x-ray radiation from the cavity (~ 250 mR/h, compared to ~ 380 mR/h before the incident and ~ 750 mR/h right after the incident) at the operational voltage of 1.25 MV.

Based on the lessons learned from the two unfortunate cases of the BNL SRF cavity contamination, one can conclude that the cathode exchange assembly appears to be the Achilles' heel of the system and requires careful handling during the cathode replacement. After the incidents, the system was equipped with a shaft collar dedicated to prevent an accidental injection of the manipulator. The cathode exchange procedures are now accompanied by simultaneous videos showing how the cathode registers on the end effector and how it resides inside the

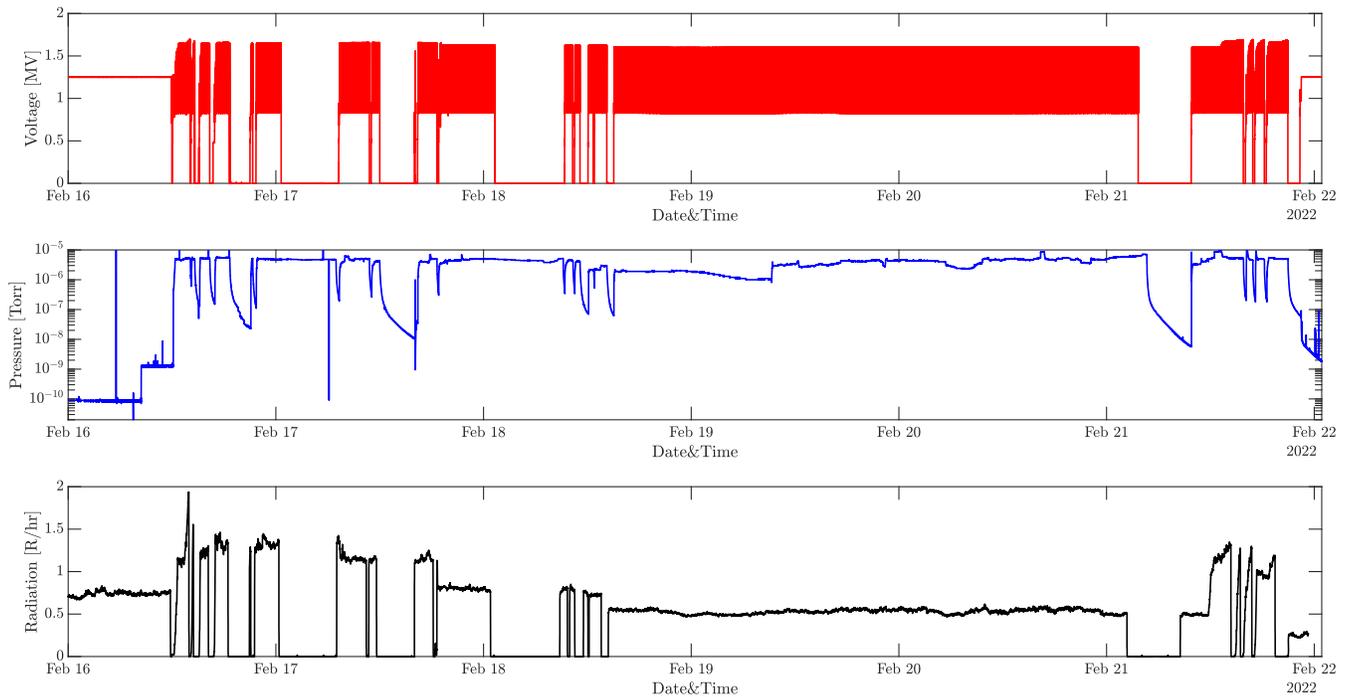


FIG. 8. Gun voltage, pressure in the cavity, and radiation levels during HeC.

stalk. During the cathode replacement, the pressure gauges located along the assembly are monitored to ensure the proper insertion of the cathode manipulator. This allows us to take immediate measures if some misalignment is detected which is indicated by the spikes in the system vacuum.

V. CONCLUSIONS

The development of cavity restoration techniques in application to the SRF photoinjectors is highly valuable for the future development and maintenance of the SRF electron sources. In the example of the BNL SRF photogun, we have proven that the He conditioning technique is highly successful in restoration of the cavity performance and allows to effectively remove contamination, reduce LHe consumption and radiation levels, resulting in the improved performance of the gun cavity.

ACKNOWLEDGMENTS

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Correction: The omission of the names of the fifth, sixth, and seventh authors has been fixed.