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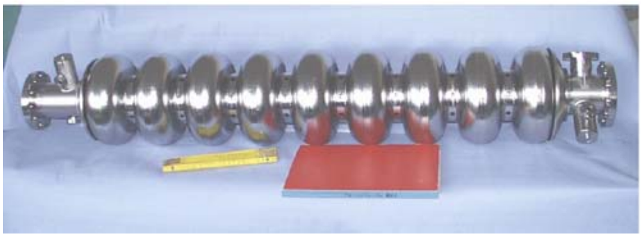

CARE/JRA1 Deliverable for WP 5.4

Deliverable 5.4.4.2: Vertical Test CO_2 cleaning of 9-cell cavities: evaluation of experimental results
Deliverable 5.4.6.2: Dry-ice cleaning of horizontal 9-cell cavities: evaluation of experimental results

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Abstract

High gradients in superconducting (s.c.) cavities require surfaces free of enhanced field emission. To the present knowledge, field emission is dominantly caused by metallic particles, but also by other surface contaminations. The dry-ice cleaning (DIC) technique using the sublimation-impulse technique removes particulate and film contaminations without any residues. The gases involved in this process, i.e. CO_2 and N_2 are chemically inert. Thus no negative impact on materials like niobium, copper, aluminum etc. used in superconducting accelerators is expected. The liquid carbon dioxide flows through a ring-type nozzle and forms a jet of a dry-ice and gaseous CO_2 by expansion. The surrounding nitrogen shapes and accelerates the jet. A set-up for horizontal and vertical cleaning of 1-3-cell niobium cavities as well as samples has been successfully commissioned. A preliminary parameter set for effective final cleaning is established. Several cavities have been cleaned and tested without any detectable field emission up to 36 MV/m. A layout for the horizontal cleaning of nine-cell has been developed.

Vertical as well as horizontal dry ice cleaning has been investigated. The critical parameters as mass flow of dry ice, profile of the dry ice jet or heating of the object to be cleaned do not differ for both arrangements. For large objects like 9-cell cavities a horizontal set up is easier to install and to handle.

Acknowledgements

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Introduction

In order to achieve high gradients for future accelerators like European XFEL, ILC, etc. without field emission loading advanced cleaning and handling procedures must be applied. Surface contaminations like particles, hydrocarbons, etc. and mechanical damages like scratches have been shown to cause enhanced field emission limiting the usable gradient of accelerating structures. The presently used technique of high pressure water rinsing (HPR) as a final cleaning step is proven to be effective, but requires a vertical position of the cavity and is incompatible with the humidity sensitive high power coupler. Dry–ice cleaning (DIC) might have additional cleaning potential exceeding HPR. DIC is a dry cleaning technique, which allows a horizontal cleaning of fully assembled nine-cell accelerator structures, and avoids a wet cavity surface with its enhanced sensitivity against recontamination. It needs to be emphasized, that DIC is an additional cleaning method and not a replacement of the well-proven HPR. Furthermore, high power normal conducting RF gun cavities applied in linear accelerators like FLASH and European XFEL require an effective and dry cleaning procedure in order to avoid dark current generation and an oxidation of the sensitive copper surfaces.

When applying state-of-the-art preparation procedures to Nb accelerator structures, typical field emission loading in well-prepared 1.3 GHz nine-cell cavities starts at gradients E_{acc} of (20–25) MV/m. Best nine-cells cavities achieve gradients up to 40 MV/m without detectable x-rays. No systematic degradation between vertical tests and horizontal results is found in contrast to older results. Single-cell cavities with their relaxed complexity of necessary components and assembly often achieve gradients far beyond 30 MV/m without field emission.

Final Chemical/Electrochemical Treatment

Beginning with a number of excellent results on electropolished L-band single-cell cavities at KEK, the discussion of the superior surface treatment - buffered chemical polishing (BCP) vs. electropolishing (EP) - came up again during the last years. At present the results of numerous single-cell cavities and nine-cell cavities show a higher reproducibility of gradients above 35 MV/m using electropolishing. Explanations discussed for the superiority of EP are the differences in surface roughness, formation of oxide layers, etching at grain boundaries and residues of the used acids.

The commonly used EP mixture consists of HF and H_2SO_4 in a volume ratio of 1:9. For best removal of hydrogen, produced during the chemical reaction, a horizontal set-up is preferred. If a copper electrode is used, an additional oxipolishing with HNO_3 and HF is necessary to remove copper traces from the niobium surface. The standard BCP mixture contains $HF:HNO_3:H_3PO_4$ in a volume ratio of 1:1:2. Typical for both final treatments is a removal of (10 - 40) µm of the niobium surface. After draining the acid, the cavity is rinsed immediately with water of at least DI-quality. For best removal of acid residues, typically the rinsing is performed in several steps ending with an ultra-pure water rinse ($\rho \geq 18$ MΩcm; particle filtered $\leq 0{,}2$ µm). Both for BCP and EP, closed PLC controlled systems with integrated rinsing capability for DI or pure water are state-of-the-art (Figure 1). The applied acid quality varies, but is often “pro analysi” or better. Additional particle filtration is often integrated in the chemical system.

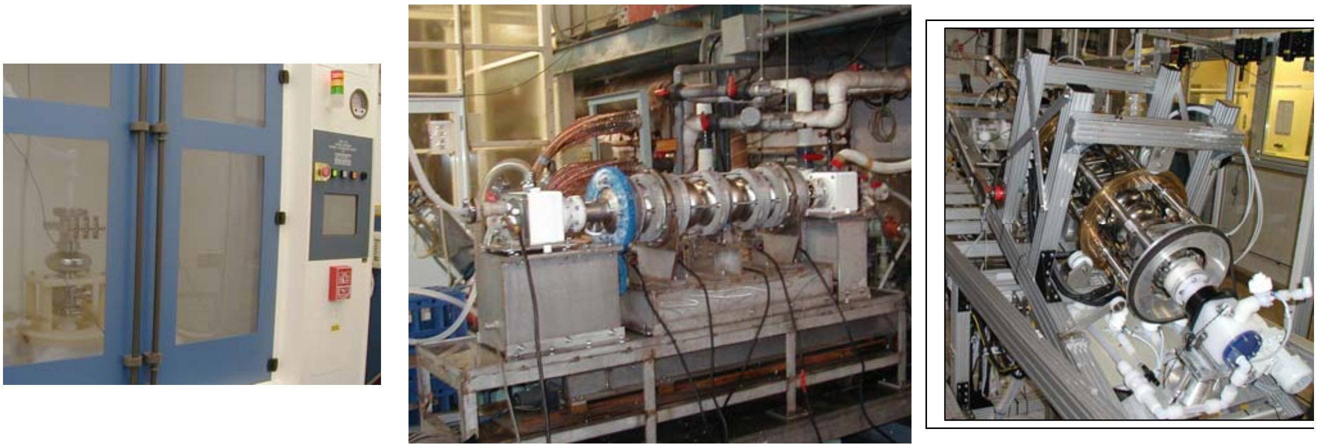


Figure 1: Closed circuit BCP facility at JLab (courtesy of Jefferson Lab), EP facility at Nomura Plating (courtesy of Nomura Plating, Japan), EP facility at DESY

High Pressure Rinsing

At present, repeated rinsing with high-pressure ultra-pure water (HPR) is the most effective available tool to avoid field emission loading. Typically, HPR systems work with a water flow between 7 l/min and 20 l/min and a pressure between (80 - 150 bar), which allows removal of particles larger than a few micrometer. In order to avoid any recontamination, the cavity is rinsed in a cleanroom environment, in a glove box or is closed with protection flanges. Depending on the complexity of the assembly procedures, the number of rinses varies up to seven times, e.g. the TTF nine-cell cavities are rinsed once after the BCP or EP treatment and additionally up to six times after the assembly of the flanges. The repeated rinses are advantageous in order to rinse out particles, which have been loosened off the cavity surface, but depending on the water flow conditions have been transported and re-deposited inside the cavity. Experience at DESY showed that it is important to avoid drying before starting the first rinse. A possible explanation is that after drying particles stick stronger to the surface and removal becomes more difficult.

The technical installations like pump, piping, turntable and nozzle system differ widely. It only should be stressed, that the final particle filter (pore size ≤ 0.2 μm) has to be placed as closely to the nozzle as possible with no moving parts (i.e. valves) between filter and nozzle.

Figure 2: HPR for single-cells (top); DESY HPR stand for nine-cells (bottom)

Dry-ice cleaning set-up

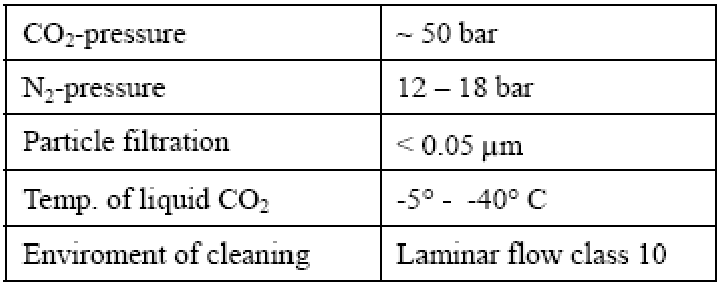
Principle of Operation

A jet of pure carbon dioxide snow loosens and removes different types of surface contaminations by its unique combination of mechanical, thermal and chemical effects. The cleaning process acts local, mild and dry, without residues and requires no additional cleaning agent. The spontaneous relaxation of liquid carbon dioxide (temperature of app. - 15 °C) leaving the nozzle results in a snow/gas mixture with 45 % snow and a temperature of 194.3 K (- 78.9 °C). This jet is surrounded by supersonic nitrogen, which firstly gives acceleration and focusing of the jet and secondly partially prevents the condensation of humidity at the cleaned object. The cleaning effect is based on thermomechanical and chemomechanical forces. The former is created by three effects: i) The contamination becomes brittle as a result of rapid cooling (shock-freezing); ii) the high pressure and shearing forces due to the high momentum of the snow crystals hitting the surface and iii) the powerful rinsing due to the 500 times increased volume after sublimation. Particles down to 100 nm can be removed. Chemomechanical forces occur when high momentum snow particles hitting the surface partially melt at the point of impact. In its liquid phase carbon dioxide is a good solvent for non-polar chemicals, especially for hydrocarbons and silicones. The thermal effect of shock-freezing is thereby directly correlated with the snow intensity, while the mechanical effect however depends on the velocity and angle of the jet. The chemical effect depends on the momentum of the crystals. An optimal cleaning impact is achieved, if the thermal gradient between contamination and substrate is high. To avoid recontamination an effective and well-defined exhaust system is necessary. In summary the advantages of the carbon dioxide dry ice cleaning are:

- dry cleaning process,
- no cleaning agents,
- removal of particulate and film contaminations,
- no polluting residues.

The basic cleaning parameters are shown in Table 1:

Table 1: Dry ice cleaning parameters



CO_2-pressure	~ 50 bar
N_2-pressure	12 – 18 bar
Particle filtration	< 0.05 µm
Temp. of liquid CO_2	-5° - -40° C
Enviroment of cleaning	Laminar flow class 10

The purpose of DIC is a final effective cleaning in addition to HPR or other established methods. In order to utilize the cleaning potential of DIC in the best possible way, a proper pre-cleaning of the component is mandatory. Nb cavities and samples require state-of-the-art degreasing, etching or electropolishing including ultra pure water rinse and first HPR treatments. HPR is necessary in order to dissolve and remove chemical residues of the acids as well as the strong surface contamination with large particles (up to several hundred micrometers) after the flanging and handling during the chemical treatment. Copper RF gun cavities are soldered at about 800 °C as final manufacturing step, which effectively removes most hydrocarbons. In either case any recontamination should be avoided – as usual for sensitive clean components.

Pre-Tests

Pre-tests on Nb samples and single-cell cavities started in 2001 at the Fraunhofer Institute for Manufacturing Engineering and Automation (Fraunhofer IPA, Stuttgart, Germany) and at DESY.

First sample cleanings were done after an intentional contamination with dust, metal or Latex particles in close collaboration with Fraunhofer IPA and Wuppertal University. The samples are made of Niobium sheets (RRR = 300) typically used in cavity production with a diameter of 28 mm. Before the DIC the field emission properties were checked using the field emission scanning microscope at Wuppertal (WP 6.3). In addition particle counting and a surface check with an optical microscope were done at Fraunhofer IPA. The cleaning was done with a perpendicular orientation of the nozzle to the surface (Figure 3), a distance of 20 mm and with linear scanning. The width of the dry-ice jet was app. 3 mm. The sample was dried using the nitrogen jet only adjusting the nozzle over the center of the sample. After the cleaning the optical microscope inspection and field emission scanning were re-done in order to evaluate the cleaning effect.

Figure 3:
Niob-Probe in the CO2-installation

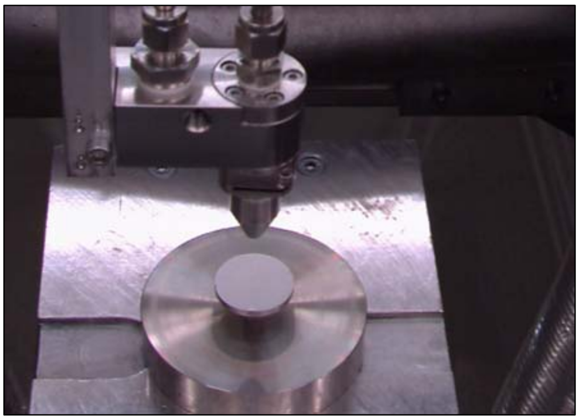


Figure 4: upper part
Sample **before DIC**

Magnification: 200x

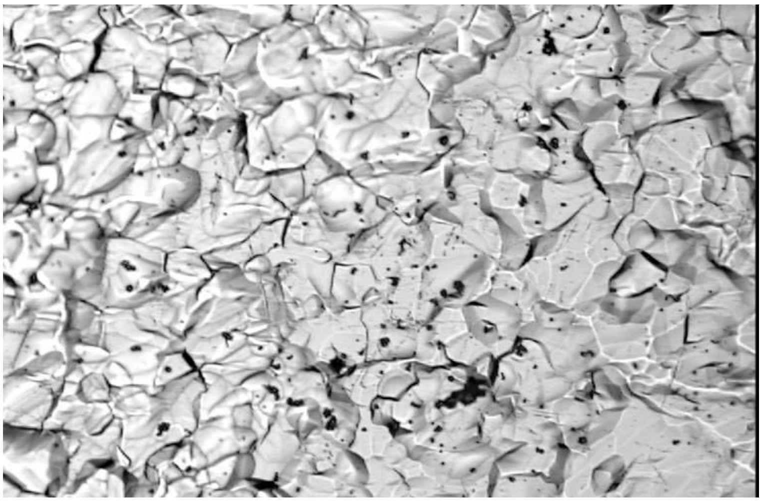


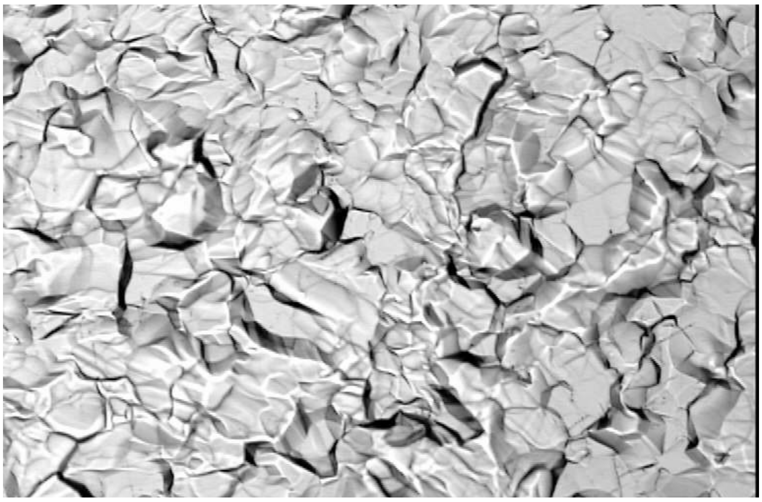
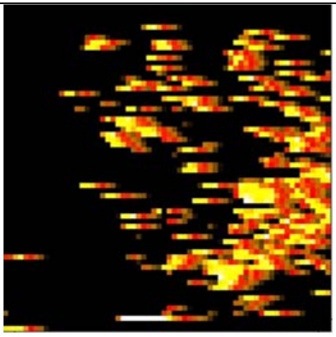
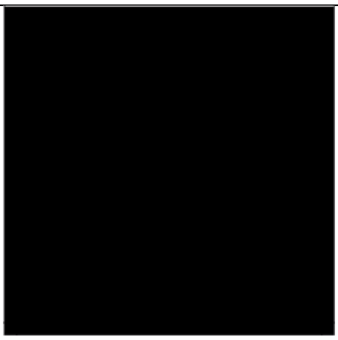
Figure 4: lower part Sample **after DIC** Magnification: 200x	

Figure 4 gives an example of the nearly complete removal of Fe and Cu particulate contamination without any visible damage of the Nb surface. In Figure 5 the number of field emitters is compared before and after DIC. No field emission is visible until a surface field of 110 MV/m on a surface area of 5 mm x 5 mm. This would correspond to a gradient of about 55 MV/m in a TESLA shape 1.3 GHz cavity.

	
Scan at U = 4 kV / d = 50 – 75 µm / 1x1 cm^2 / 0,5 nA => 101 Emitter at 55 – 80 MV/m	Scan at U = 7 kV, 5 x 5 mm2, d ~ 65µm, I~ 3nA => no Emitter at 110 MV/m
Figure 5: Number of field emitters before (left) and after (right) DIC Yellow and red spots show a field emission activity	

First cleaning of single-cell cavities was performed using temporary set-ups at Fraunhofer IPA (Figure 6, left) and DESY (Figure 6; middle + right.). The two-nozzle spraying head is described below. Both, the electric hot air-blowers and the preliminary IR heaters visible were identified to be insufficient resulting in freezing of the cavity. Other weak points of the temporary set-ups were the missing gas exhaust resulting in personal safety problems due to harmful CO_2 concentration and difficulties in a “clean” diss-assembly from the cleaning set-up free of re-contamination. Typically, the RF measurements showed the expected high Q-values clearly indicating, that the DIC process neither damaged nor systematically contaminated the cavity surface. On the other hand the first RF tests showed strong field emission caused by a particulate contamination, which was either not removed sufficiently or re-contaminated.

Figure 6: Vertical set-up for pre-tests on single-cell cavities at Fraunhofer IPA (left) and DESY (middle + right)

Installation

A dedicated two-nozzle spraying head for 1.3 GHz s.c. TESLA shape accelerating cavities was developed at Fraunhofer IPA (Figure 7). The angle of the opposite directed nozzles is 30 °degree up and down to the horizontal plane in order to realize an as much as possible perpendicular impact at the iris areas as well as cleaning of the equator area of the resonator cell. In order to reduce the cooling of the cavity and the consumption of CO_2, nozzle capillaries of 12 % lower diameter have been tested successfully and are in use since 2007. Both, the optical impression of the jet as well as the RF cavity results kept unchanged. For a dedicated cleaning study see below in section “Future developments”. A reduction of the cavity cooling is important to keep a high temperature gradient on the inner surface for an optimum cleaning efficiency (see Introduction).

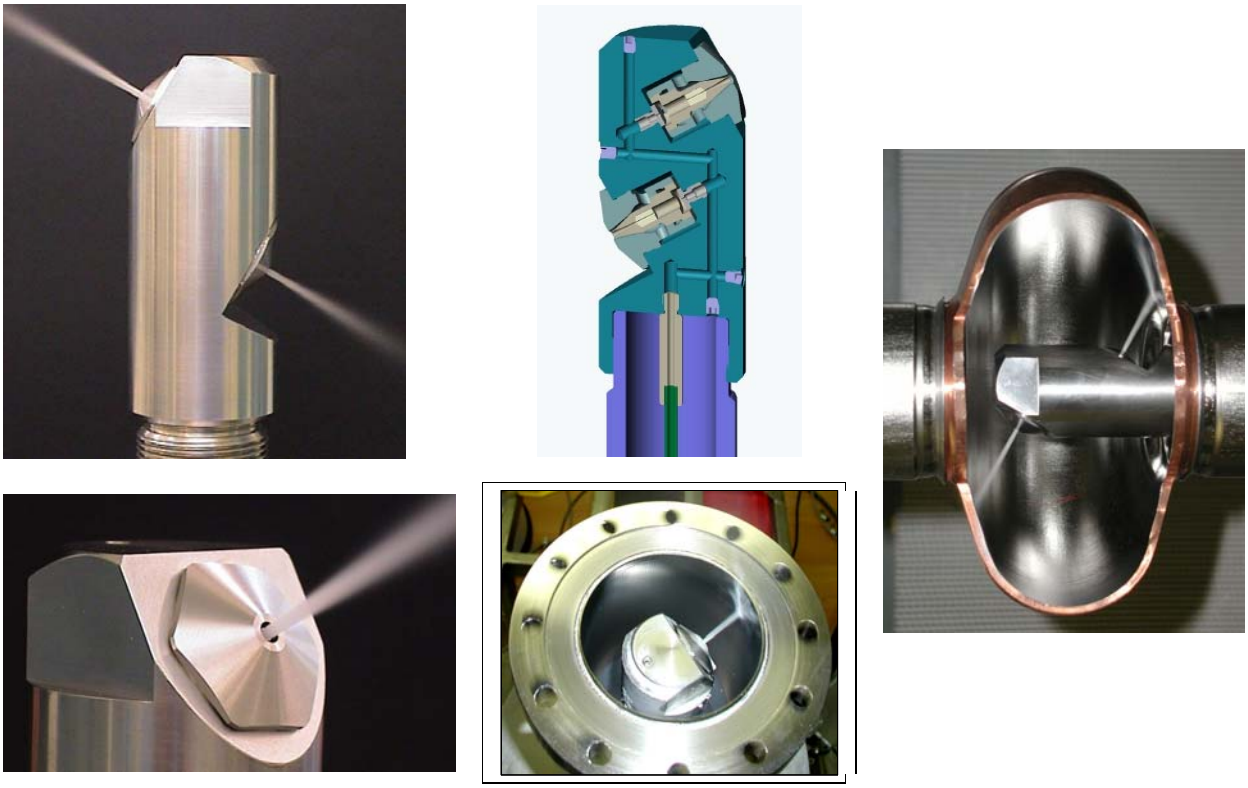


Figure 7: Two-nozzle spraying head (upper row left, middle) and test in a cut 1.3 GHz resonator (upper row right) during commissioning of the system. Optical checks of the jet under different conditions (lower row).

An ultra-pure gas supply system for both carbon dioxide and nitrogen was integrated and successfully tested in the existing clean room. A schematic scheme of the cleaning system is shown in Fig.8. The used nitrogen is of quality 5.0 (purity > 99,999 %); the CO_2 is of quality 3.0 (purity > 99,9 %; minor components: $O_2 + N_2 \leq 500$ Vol-ppm; $H_2O \leq 250$ Vol-ppm; $C_nH_m \leq 50$ Vol-ppm). Beginning of 2005, the CO_2 cooler/purifier unit, delivered by ACP GmbH, Germany (Fig.10,left) was commissioned as an important component in order to filter, purify and liquefy the CO_2. The gaseous CO_2 first is cleaned by a hydro carbon absorber and a 0,01 µm particle filter. Then it is liquefied and cooled to a temperature of typically (-10 - -20)°C with a capacity of > 1 l/min. The liquid CO_2 is filtered again down to 0,01 µm and transferred with a short (app. 2 m) ultra pure gas connection to the spraying cane.

For the first tests four 50 l CO_2 pressure bottles in parallel have been used. A general drawback was the cooling of the bottles during withdrawal of gas, which resulted in a significant, undesirable pressure reduction. Therefore, a CO_2-tank (Fig. 9 left) was installed outside of the hall and ensures a constant pressure gas flow of app. 55 bar.

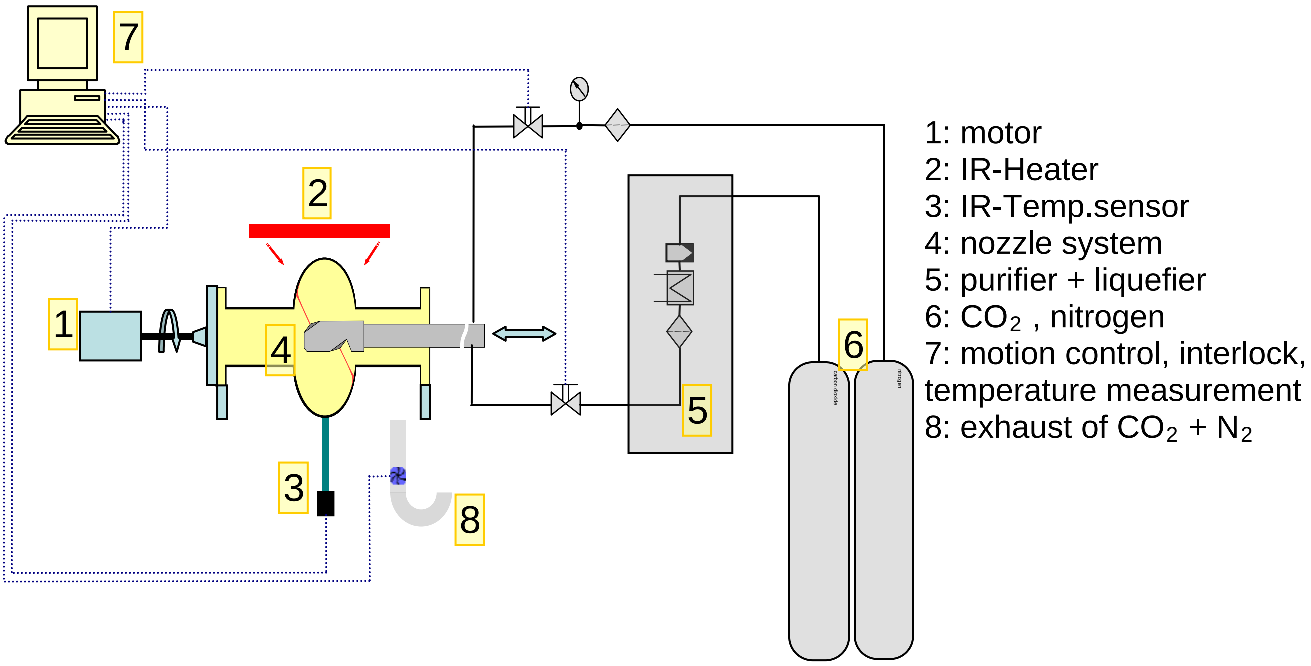


Figure 8: Schematic and flow scheme of the dry-ice cleaning set-up

Cavity rotation and linear drive are actuated by step motors (Stoegra Antriebstechnik GmbH, Germany), except the vertical lifting columns for the Gun cleaning unit (RK Rose + Krieger GmbH, Germany). The step motor control unit (Stoegra Antriebstechnik GmbH, Germany) is programmed in a PLC-like description via software on a laptop computer. The lifting columns are controlled with a hand-held unit manually, but will be integrated in a programmable logic controller in future.

In order to fulfill the requirements of personal safety for routine operation an interlock system allows the operation under defined conditions, only (Fig.9, right). A minimum cleanroom airflow must be present in order to avoid a dangerous increase of CO_2 and N_2 content in the ambient air. This is ensured by speed monitoring one fan motor belonging to the airflow-system of the cleanroom. In addition, the function of the exhaust is controlled via a swing type check valve. Moreover, the oxygen and CO_2 content of the air is monitored by gas monitors (Draeger Savety, Germany) installed close to the cleaning set-up and just in front of the cleanroom. If limit values are exceeded, the cleanroom is evacuated and the DESY safety group is alarmed immediately.

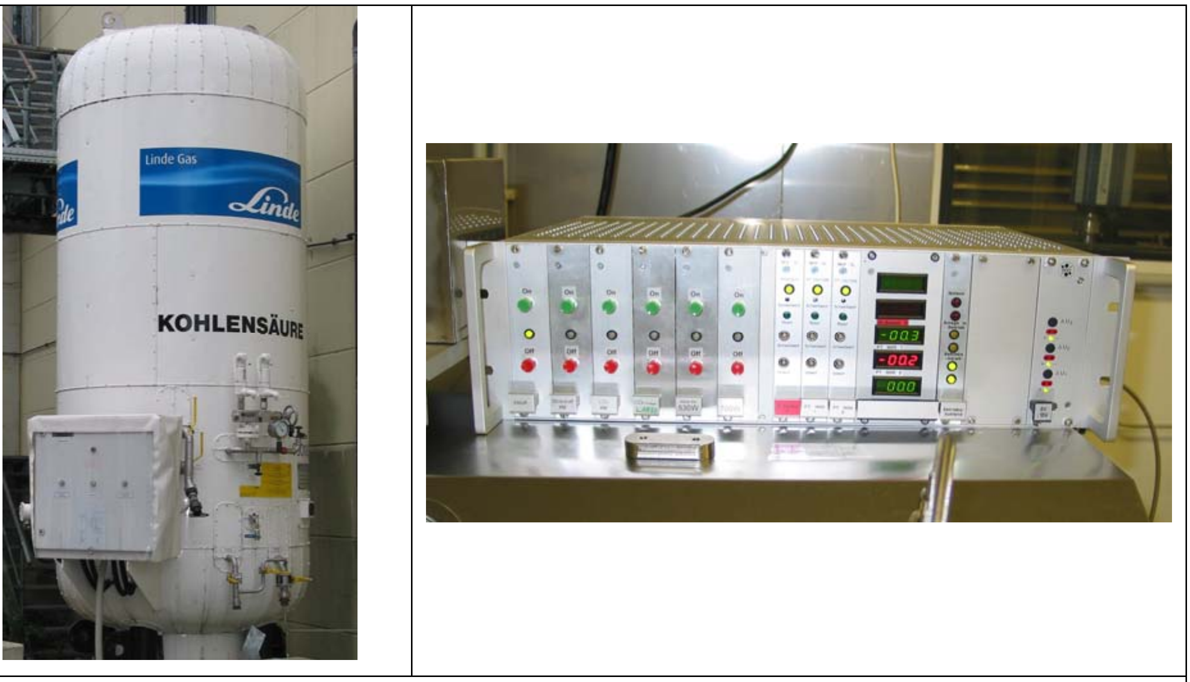


Figure 9: CO_2-storage tank (left) and DIC control + interlock unit (right)

Set-up for horizontal cleaning of 1-3 cells Nb cavities

As described above, dry-ice cleaning allows horizontal cleaning of s.c. cavities. Though no detailed calculations have been made, some simple estimates and literature research indicate that the transport of particles of about < (10 – 20) µm is dominated by the airflow. The gravitational force acting on a metal particle of 10 µm is a factor of 100 less than the force of an air flow of 2 m/sec. Strongly simplified a 10 µm particle nearly instantaneously follows velocity changes of the air flow.

Therefore, after the vertical pre-tests (see Figure 6) it was decided to design the set-up for cleaning of 1-3-cell cavities in order to establish horizontal cleaning in an early stage of the development differing from the original proposal of WP 5.4.

The horizontal motion unit using the existing spraying cane and a new commercial linear drive (RK Rose + Krieger GmbH, Germany) unit is shown in Fig. 10, right.

The heat removal from the cavity during operation of the dry-ice jet makes it necessary to apply a heater system. For the 1-3-cell cleaning installation, after pre-tests with an integrated heating and exhaust box an easy accessible and open heater design was preferred to a closed heating jacket (see below in “Future Developments”), because of simplicity and cleanroom requirement compatibility. A first semi-industrial prototype infrared heater (IR) system showed to be insufficient due to improper IR wave length. A dedicated short wavelength (peak power wave length 1,0 – 1,4 µm) IR heater with a total power of 5,6 kW was designed and supplied by Heraeus Noblelight GmbH, Germany (Fig 11, 12). This heater system fully meets its requirements and allows continuous dry-ice cleaning nearly without freezing of the cavity. It is attached to a vertical linear drive unit, which allows adjusting the heater between the upper position for cavity assembly (Fig. 11) and the lower operation position (Fig.12).

In order to allow a clean and easy assembly of the auxiliary parts like pumping / antenna unit and the transportation frame a simple fixture tool was realized inside the cleanroom close to the cleaning system.

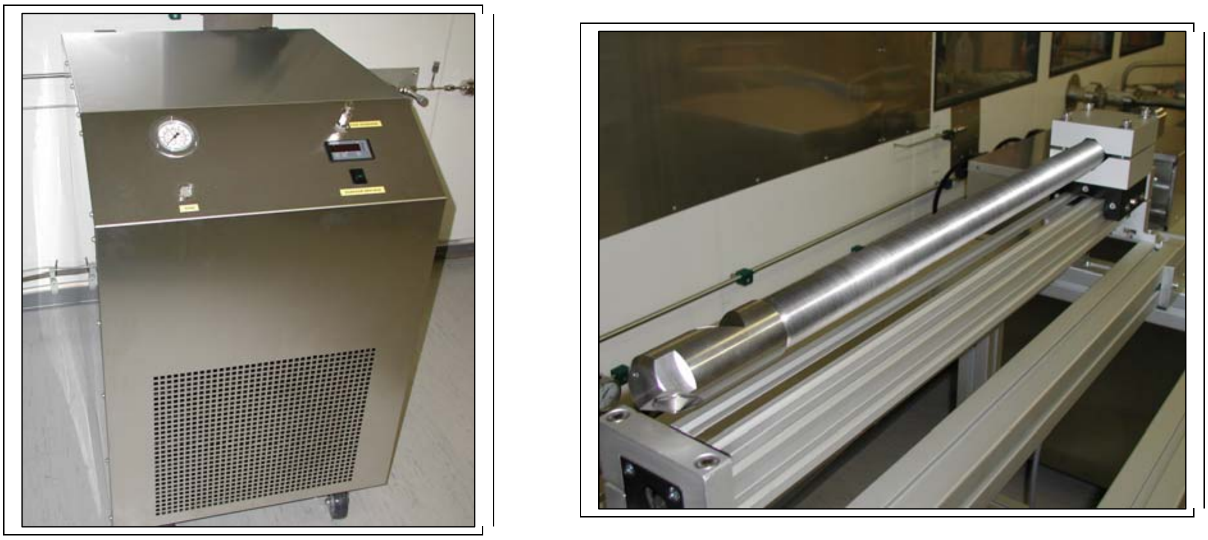


Figure 10: CO_2- cooler/purifier unit (left) and horizontal motion unit with the spraying cane assembled on the linear drive (right)

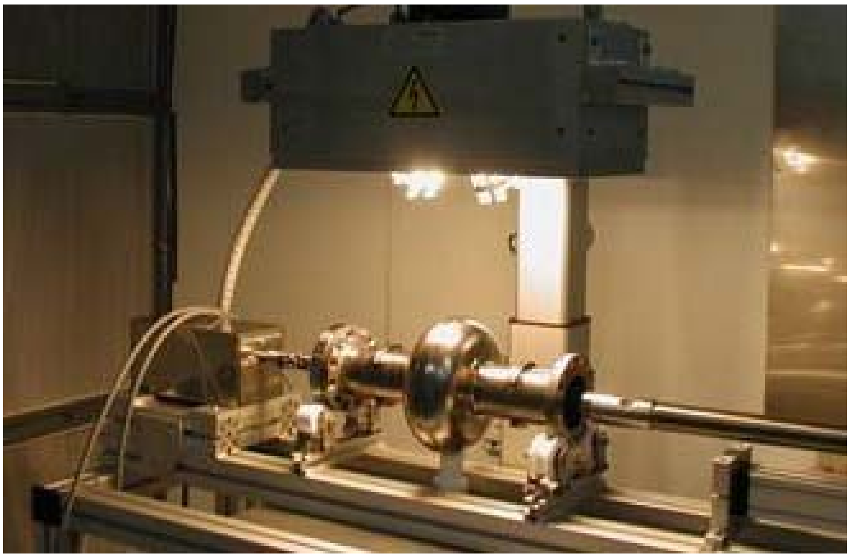


Figure 11: Dry-ice cleaning system with IR heater in upper rest position and horizontal nozzle system. The exhaust system (not visible) acts from the bottom close to the open cavity flange.

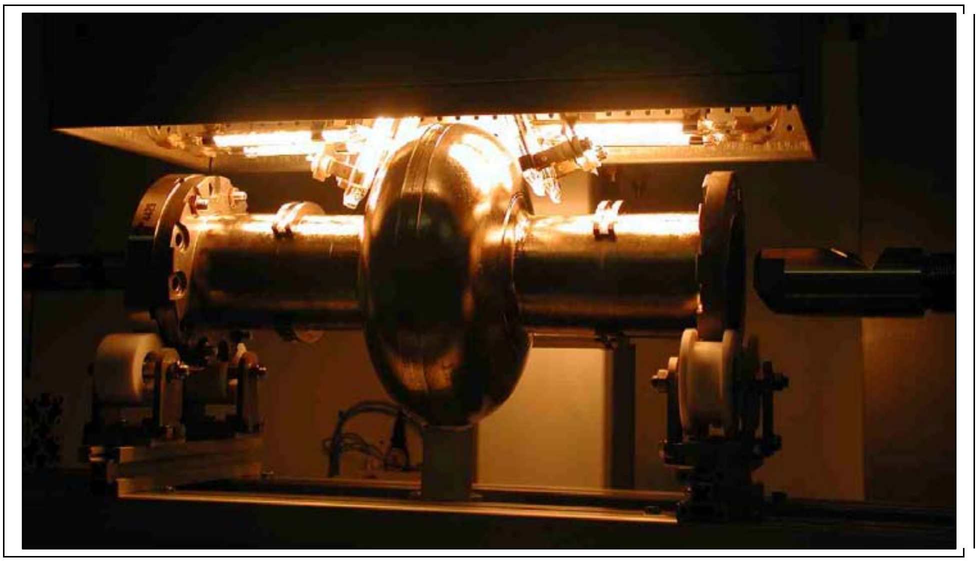


Figure 12: The new IR heater system in operation

The operational and cleaning parameters have been improved successively. In order to monitor the particle removal depending on the cleaning position, a commercial air particle counter is used systematically. The Nb cavity is cleaned with assembled top flange. Typically, three runs with a duration of app. 30 min. (single-cell cavity) each are applied, followed by a final double-speed run with nitrogen only. Though previously thoroughly cleaned and not directly hit by the snow jet, the pick-up feed through could be identified as a significant source of particles, even after several DIC runs (Fig. 13). Therefore, during the last DIC run the motion range of the snow jet is reduced now. Finally, the cavity is mounted vertically to its support frame, the pumping port with RF antenna is assembled, and the cavity with its flanges is evacuated and leak checked.

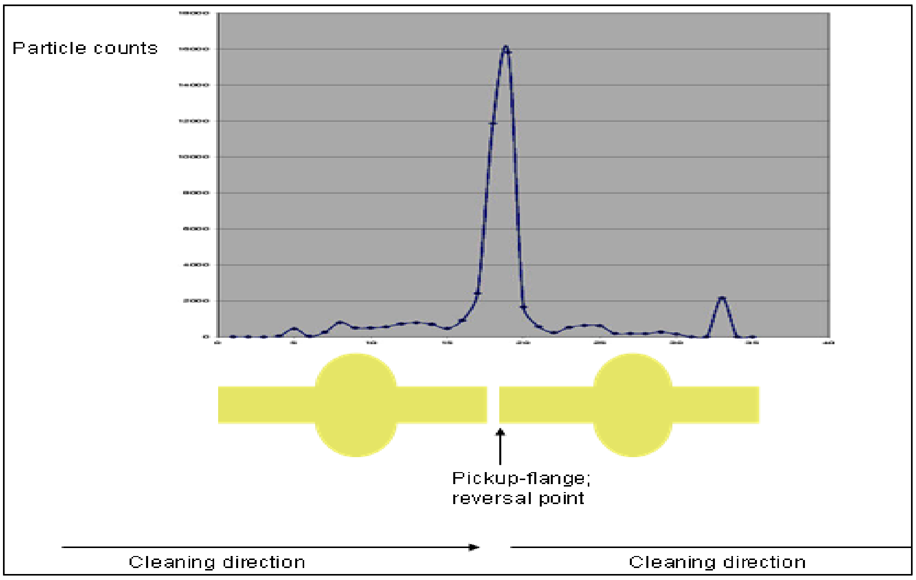


Figure 13: Particle counts corresponding to position of nozzle during DIC of a 1-cell cavity applying the primarily “old” motion parameters with a movement of the spraying cane close to the cavity flange

In addition to the cleaning of cavities for system tests and for RF measurements, several Nb and copper samples have been cleaned within the framework of WP 6.3 (Fig.14).

Figure 14: Cleaning of a Nb sample for the investigation of field emission properties within the frame work of WP 6.3

Set-up for cleaning of copper RF gun cavities

In order to provide low dark currents in the gun cavity of the photo injector of FLASH and for the upcoming European XFEL, a dedicated vertical cleaning set-up (Figure 15) was constructed, commissioned and started up. Compared to the previously applied cleaning using high pressure ultra-pure water rinsing, the risk of an objectionable oxidation of the sensitive RF surface is minimized.

For cleaning the cavity is rotating while the vertical position is adjusted using two industrial lifting columns. Remarkable is the new nozzle system with a 110° degree rotateble nozzle (Figure 16) developed at the Fraunhofer Institute for Manufacturing Engineering and Automation (Fraunhofer IPA, Stuttgart, Germany). This design is necessary in order to assure a complete and effective cleaning of the RF gun geometry, i.e. the surface close to the cathode and the first cell of reduced length. In order to avoid any particulate recontamination created by the motion of the nozzle, the nozzle system is exhausted.

In principle the cooling pipe system of the gun cavity can be used for heating. Due to the complex mechanics and additional piping system containing the danger of contamination, this was not applied yet.

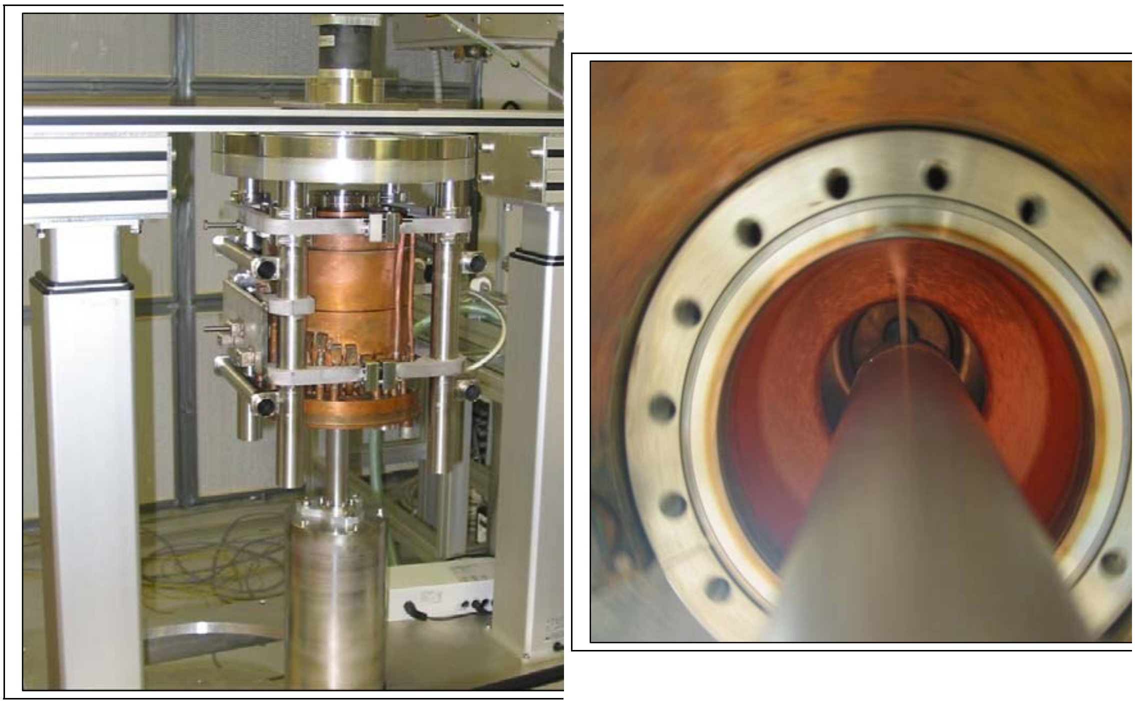


Figure 15: Vertical cleaning set-up for copper RF gun cavities (left) and bottom-up view during cleaning (right)

Figure 16: 3D-model of gun cavity with rotateble nozzle (left); rotatable nozzle (middle); cross-sectional view of the nozzle

RF Results on Nb Cavities

On Nb samples reproducibly excellent cleaning results with respect to the field emission properties have been achieved and are reported in WP6.3. An example is given in Table 2.

Tab. 2: Improvements on electropolished Nb samples after HPR and DIC from WP 6.3 (N is the number of emitting sites per cm^2; β is the local field enhancement factor)

Treatments on Nb	EP	EP + HPR	EP + HPR + Dry-ice
Eonset (1 nA)	40 MV/m	60 MV/m	90 MV/m
N @120 MV/m	30 / cm^2	14 / cm^2	< 2 / cm^2
β values	(31-231)	(17-167)	(17- 80)

On single- and two-cell Nb cavities no or low field emission has been found in 5 of the latest 7 tests up to E_{acc} = 36 MV/m (Figure 17) applying the improved cleaning parameters. The tested three single-cell cavities are limited by quench at 33 – 36 MV/m; the two cell cavity at 22 MV/m, respectively. In a test series on one cavity (1DE11), between the tests the cavity outside is pre-cleaned before entering the cleanroom, the cavity vented with pure nitrogen under defined conditions, disassembled, dry-ice cleaned, assembled and evacuated for the next RF test. DIC and assembly are performed as described above.

Many RF tests of dry-ice cleaned cavity show a processable multipacting barrier in the typical gradient range between 15 – 21 MV/m. If this is significantly enhanced compared to HPR cleaned resonators needs to be clarified with more tests.

A direct comparison of HPR and DIC as final cleaning step is available for single-cell 1DE11.As shown in Figure 18, the first RF test after HPR showed moderate field emission. A first attempt applying DIC with the previously used (“old”) operation parameters in order to improve the cavity performance failed. The cavity was limited by strong field emission. After an additional DIC sequence using improved operation parameters, the cavity was free of field emission and limited by quench at E_{acc} = 36 MV/m.

Within the limited statistics on Nb cavities no final judgment about the superiority of DIC or HPR can be given. Though more data on the efficiency of both cleaning techniques are necessary and helpful, it needs to be emphasized strongly, that DIC gives additional cleaning options instead of replacing HPR.

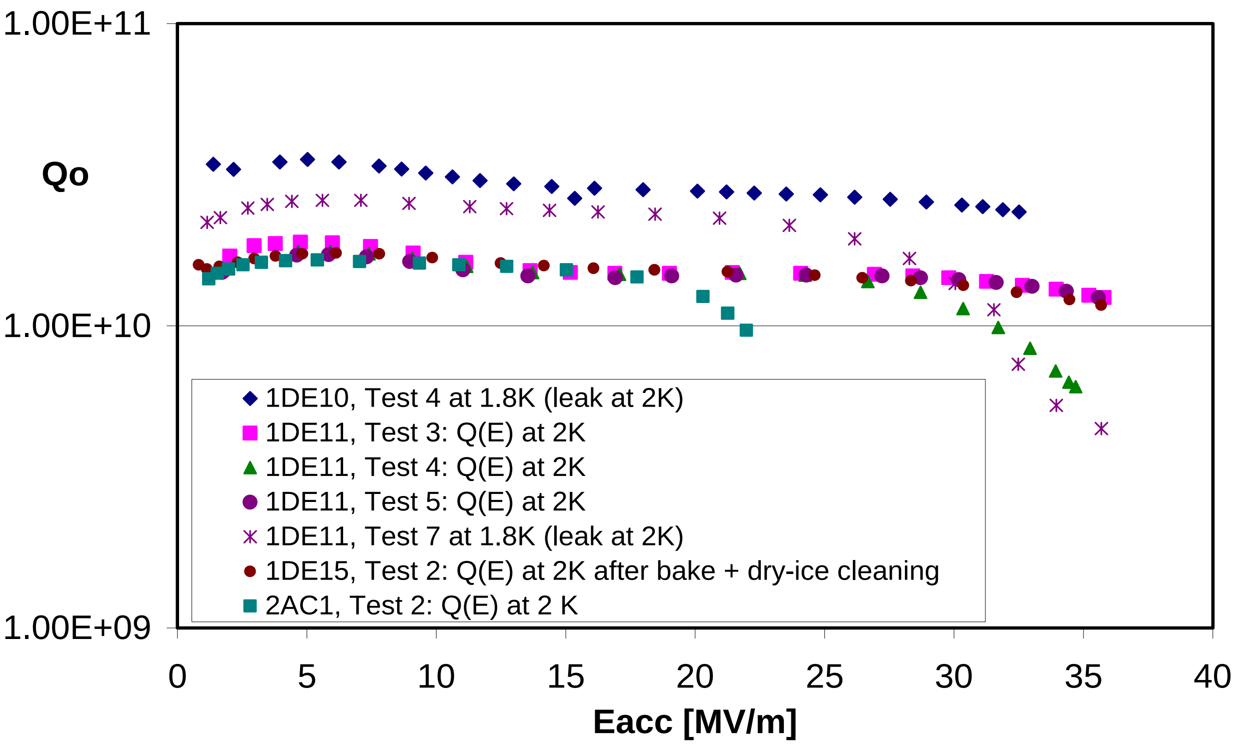


Figure 17: $Q_0(E_{acc})$ – performance of the latest 7 DIC cleaned cavities at 2 K

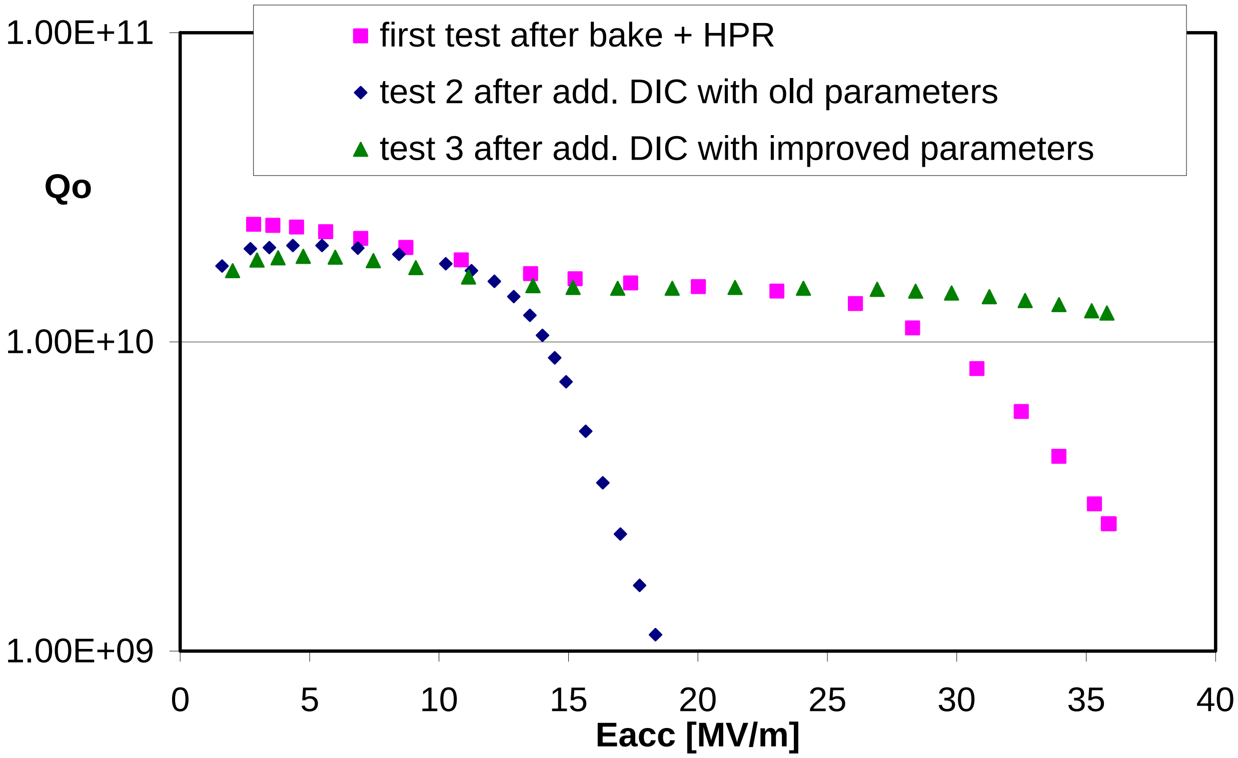


Figure 18: $Q_0(E_{acc})$ – performance of single-cell 1DE11 after HPR (pink), DIC with old parameters (blue) and DIC with improved parameters

Results on Cu RF gun cavities and auxiliary components

Up to now two gun cavities have been cleaned. While the second cavity is not measured yet, the first one (Gun 4.2) showed excellent results. On the processing stand it showed a factor of 10 less dark-current compared to former gun cavities cleaned with previous HPR cleaning procedures (Figure 19).

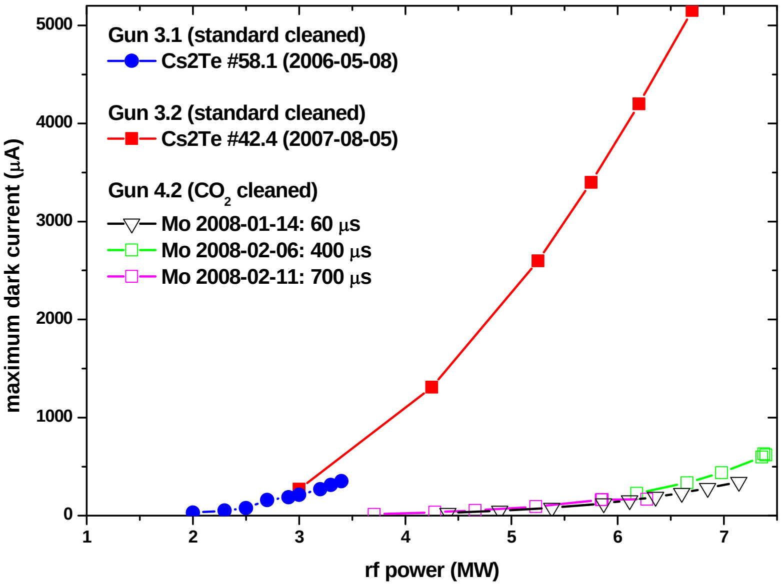


Figure 19: Dark current vs. RF power during processing of different gun cavities.CO$_2$ cleaning of gun 4.2 results in a significantly reduced dark current compared to previously applied HPR

In addition to the gun cavities auxiliary components like waveguide input coupler and waveguide connector have been cleaned. In order to ensure a clean surface of the cathode plug (Figure 20) before coating with the sensitive Cs$_2$Te also the plug has been cleaned.

Figure 20: Cathode plug (in the center) in transport frame

Dry-ice cleaning of horizontal 9-cell cavities

Goal of WP5.4 was the horizontal cleaning of TESLA shape nine-cell cavities. This could not be achieved with the limited availability of man power and due to technical problems and delays reported in the WP5.4 progress reports. As a major system component, the gas supply system for CO_2 and N_2 including the cooler / purifier unit is fully compatible for the cleaning of nine-cell cavities.

The existing cleaning set-up can be used up to three-cell cavities (Figure 21). An extension for nine-cell resonators **without** their Helium tank is designed and can be realized based on the existing installation. This is still under preparation at DESY, but delayed due to the limited budget caused by the preparation of the European XFEL. From the technical point-of-view a new linear drive and spraying cane compatible with the length of a nine-cell cavity is necessary. Both types of existing spraying heads can be used. The support unit also needs extension. Major necessary component is an IR heater with an active length of app. 1000 mm.

DIC of a nine-cell cavity **with** Helium tank attached requires a new mechanical cavity support and a fundamental change of the heating concept. IR heating is no longer applicable. Most promising seems the combination of a housing in order to avoid any humidity in the cavity with a warm inert gas flow through the He-tank.

Figure 21: Three-cell Nb cavity ready for horizontal DIC

Future development of Nb cavity cleaning

Further-investigations of the dry-ice cleaning process have been discussed with experts of the Fraunhofer IPA. A list of open topics with respect to cavity cleaning is given below:

- <u>What is the preferable design of the nozzle head</u>?
  With the movable nozzle the jet can be always adjusted perpendicular to the surface ensuring the best possible cleaning effect. Two or more fixed nozzles may allow a faster cleaning, but increase the problem of humidity condensation (see below) and of a reduced temperature gradient between surface and jet temperature.

- The combination of cleaning parameters needs further investigation, in order to exploit the full potential of DIC. The most prominent parameters are
  i) angle dependence of cleaning efficiency,
  ii) cleaning efficiency depending on cleaning speed,
  iii) cleaning efficiency depending on distance between nozzle and cavity surface,
  iv) influence of nitrogen pressure on jet properties and cleaning.
  A study of these parameters on intentionally and defined contaminated samples is prepared, but no funding is available in the moment.
- In order to reduce consumption of CO_2 and moisture condensation, smaller CO_2 capillary size in the nozzle combined with a high cleaning speed requires evaluation.
- The drive system of Nb cavity rotation has to be modified and improved in order to reduce the danger of particle contamination and allow cleaning of nine-cell cavities without and with Helium tank.
- Depending on the cavity type and the necessity of heating the cavity, the possible application of warm inert gas needs to be evaluated, especially for Nb nine-cell cavities with their He-tank.
- Based on the commissioning and first operational experiences, the mechanics and control of the gun cleaning installation are under improvement. The goal is an easy and reliable routine cleaning procedure of the gun cavities for FLASH and the European XFEL.

Conclusions and Future

The dry-ice cleaning has shown its capability for successful cleaning of Nb samples, Nb single + two-cell cavities as well as copper RF gun cavities and auxiliary components. A set-up for the horizontal and vertical cleaning of single- to three- cell cavities is in successful operation. The present parameter set of DIC gives reproducible gradients of 35 MV/m in single-cell cavities with no or low field emission loading. The next intermediate step is the extension of the existing set-up to nine-cell cavities without He-tank as soon as funding is available. The goal is a cleaning facility for fully equipped nine-cell accelerator cavities with He-tank.

An additional cleaning set-up for copper RF gun cavities has been commissioned successfully. A second nozzle system with 110 ° degree rotatable nozzle has been developed for effective surface cleaning of the complex surface geometry. The first DIC processed gun cavity showed a drastically reduced dark current during RF conditioning compared to standard HPR cleaning.

Further optimization and better knowledge of the process are necessary as well as more cleaning and RF test cycles. Several relevant topics for optimization and improvement are identified, e.g. nozzle design, cleaning speed and angle, heating options.

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References

These publications address several aspects of dry-ice cleaning:

1) “Dry-ice cleaning for SRF Applications”, D. Proch et al., Proc. of the 10th Workshop on RF superconductivity, KEK Proc. 2003-2, Tsukuba-shi, Japan (2003)

2) “First experience with dry-ice cleaning on SRF cavities”, D. Reschke et al., Proc. Lin. Acc. Conf. LINAC 2004, THP71, Lübeck, Germany (2004)

3) Presentation at the ELAN Meeting, May 4th – 6th 2004, Frascati, Italy

4) “Further improvements with dry-ice cleaning on SRF cavities”, A. Brinkmann et al., Proc of the 11th Workshop on Rf superconductivity, Cornell, USA (2005)

5) “Dry-ice cleaning on SRF cavities”, A. Brinkmann et al., Proc. of the EPAC 2006, Edinburgh, Great Britain (2006)

6) Reports of CARE SRF WP6.3, G.Müller, University of Wuppertal

7) “Dry-ice cleaning: The most effective cleaning process for SRF cavities?” D. Reschke et al., Proc of the 12th Workshop on Rf superconductivity, Beijing, China (2007)

8) “Various Applications of Dry Ice Cleaning in the field of Accelerator Components at DESY”, A.Brinkmann et al. Proc. Of the LINAC08, Victoria, B.C., Canada (2008)

9) CONDITIONING OF A NEW GUN CAVITY TOWARDS 60 MV/m AT PITZ, S. Lederer et al., Proceedings of EPAC08, Paper MOPC078

10) A. Dangwal et al., “Effective removal of field emitting sites from metallic surfaces by dry-ice cleaning”; J. Appl. Phs. 102, (2007)

11) A. Dangwal et al., “Field emission from single-crystal and large grain Nb cathodes”, WEP24, Proc of the 12th Workshop on Rf superconductivity, Beijing, China (2007)