FINAL CLEANING AND ASSEMBLY

Detlef Reschke*, DESY, Hamburg, Germany

Abstract

For high gradients at high Q-values in superconducting (s.c.) cavities the final cleaning and assembly procedures are of well-known importance. Starting from the experiences with the standard processes used for 1.3 GHz nine-cell cavities of the TESLA Test Facility at DESY, various methods of cleaning, assembly, drying and pumping are presented. Improvements of the established procedures as well as some alternative approaches are discussed.

1 INTRODUCTION

At present field emission (FE) imposes the major limitation of s.c. cavities for high gradient accelerator applications like TESLA [1, 2]. Particles, surface irregularities and hydrocarbons have been identified as major sources of field emission by several investigations on niobium samples and cavities [2, 3]. This stresses the importance of the final cleaning and assembly procedures applied to the cavity and its auxiliaries. Moreover particular care has to be taken avoiding any re-contamination during the subsequent cavity handling and the operation of the accelerator modules.

Applying standard preparation procedures, e.g. for the nine-cell TTF cavities at 1.3 GHz shown in Fig.1, typically field emission loading in well-prepared multi-cell cavities starts at gradients E_{acc} of (20 - 25) MV/m. In contrast to older results [4] no systematic degradation between vertical and horizontal tests is found [1]. In the TTF linac modules field emission is observed at gradients of about 20 MV/m. Causing additional cryogenic losses and high dark currents, it finally limits the operational gradient. Single-cell cavities with their relaxed complexity of necessary components and assembly often achieve gradients far beyond 30 MV/m without field emission [5, 8].

Starting with the final chemical or electrochemical treatment, this paper describes the present status of final cleaning, dustfree assembly and vacuum pumping of the cavity and its auxiliaries. The important topic of cavity independant quality control of the preparation process will not be discussed in this paper due to two reasons. Obviously, the level of necessary quality control differs widely between prototype single-cell preparation and the proposed mass production of TESLA cavities. Second, for several preparation steps the exact procedures of quality control are not laid down or still under development.

An extensive overview of niobium production, cavity fabrication and basics of cavity handling, treatment and testing is given in [2].

2 CONTAMINATION AND CLEANING

In a simplified view a relevant 'contamination' for a high gradient, high Q-value cavity either causes field emission, strong additional losses or results in a local thermal breakdown. The latter two will not be discussed here. Well-known sources of FE are metallic particles, hydrocarbons and surface irregularities like scratches. Mechanical irregularities can be effectively suppressed by careful fabrication and handling of the resonators. The use of oil-free pump stations (see below) and thorough cleaning of the vacuum system eliminate the risk of hydrocarbon contamination. Thus, avoiding particles, of which only a fraction of about 5 % act as emitters [35], plays the major role for the suppression of field emission. Particle contamination of a cavity either can be transported into the cleanroom, i.e. due to insufficient cleaning of the cavity and its components, or it is created inside the cleanroom, i.e. during assembly and disassembly of flanges [6].

The complex shape of the cavities prevents the application of most of the surface analysis techniques to the inner surface. For qualitative and quantitative FE investigations samples or - as a destructive method - cut cavities have to be used [7]. Samples of a few cm^2-size can be prepared and handled easily. Thus they are well suited for detailed qualitative analysis as well as for experiments with intentional contamination. Dis-advantageous is their small surface compared to a cavity resulting in a poor statistics for 'natural' emitters. The analysis of a rf tested and subsequently cut cavity gives highest correlation between the preparation procedure and the rf field emission characteristic. Though these experiments are very costly and work intensive, the continuation would be useful to deepen the understanding.

A particulate contamination can be chemically dissolved, thermally evaporated or physically removed. The latter is based on overcoming the sticking force of the particle at the surface and the subsequent transport out of the cavity. The basics of cleaning technology are described in many publications, e.g. [26, 27]. Many cavity relevant aspects are discussed in [25].

*detlef.reschke@desy.de

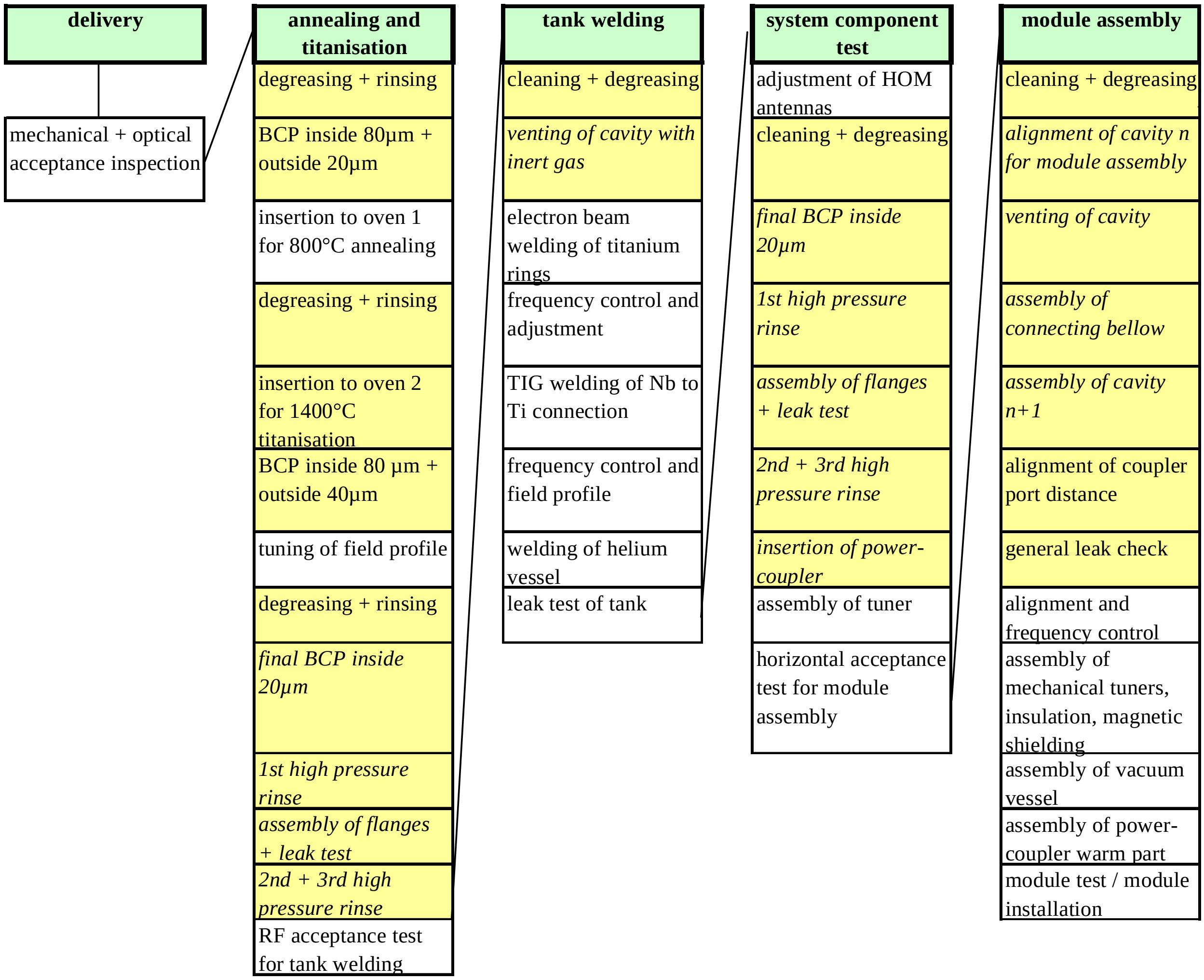

Figure 1: Overview of the preparation procedure of the TTF nine-cell cavities. The actions listed in yellow cells take place inside the cleanroom. The preparation steps of the final cleaning and assembly procedures are highlighted in italic.

3 STANDARD PROCEDURES

The standard preparation procedure of the nine-cell TTF cavities starting from delivery by industry until the final module installation is shown in figure 1. The preparation steps of the final cleaning and assembly procedures are highlighted in italic. The actions listed in yellow cells take place inside the cleanroom.

The TTF procedures, which are based on contributions by many laboratories of the SRF community, are taken as a typical example of the state-of-the-art. Of course it is tried to discuss relevant differences in procedures at other laboratories to the author's best knowledge. Starting with the final chemical treatment this chapter describes the high pressure rinsing, the drying, the assembly and the vacuum pumping of cavities. Finally, the risk of contamination during these preparation steps is discussed.

3.1 Final chemical treatment

Beginning with a number of excellent results on electropolished L-band single-cell cavities at KEK [8, 9], the discussion of the superior surface treatment [10, 34] - buffered chemical polishing (BCP) vs. electropolishing (EP) - came up again during the last years. At present the results of numerous single-cell cavities support a higher reproducibility of gradients above 35 MV/m using electropolishing [5]. The application to multi-cell cavities is in progress with promising first results [5]. Possible 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 [11].

The common 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 [11]. The standard BCP mixture contains HF : HNO_3 : H_3PO_4 in a volume ratio of 1:1:2. Typical for the final treatment is a removal of (10 - 20) 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 (ρ ≥ 18 MΩcm; particle filtered ≤ 0,2 µm). First installed at CEA Saclay closed circuit systems with stabilised acid temperature, controlled by PLC and without open acid container, are state-of-the-art (figure 2).

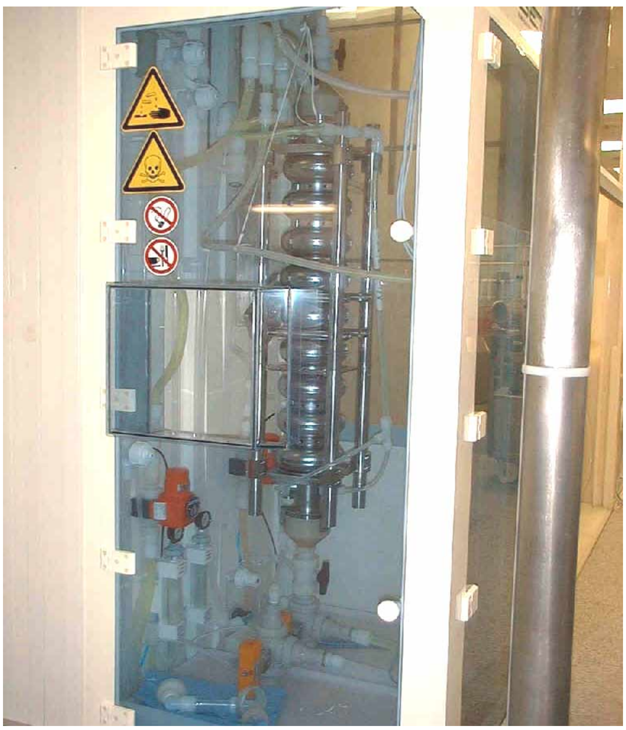

Figure 2: Electropolishing of a single-cell cavity at CERN (upper, by courtesy of CERN) and BCP of a TTF nine-cell cavity at DESY (lower)

Though the described EP and BCP recipes are well-proven for cavity preparation since years, the fundamental question of the chemical or electrochemical process for the ultimate cavity performance is still open. Only few investigations using alternative mixtures [12, 13] are published. Further open questions of practical and cost relevance, especially for large-scale production, concern the required purity of the acid mixture as well as the cleanliness of the environment, where the surface treatment takes place.

3.2 High Pressure Rinsing

At present repeated rinsing with high-pressure ultra-pure water (HPR) is the most effective tool to avoid field emission loading [14, 15]. Typically, HPR systems (figure 3) work with a water flow between 7 l/min and 20 l/min. The water pressure is around 100 bar (80 - 150 bar), which allows the removal of particles larger than a few micrometer [25]. To avoid any re-contamination, the cavity is rinsed in a cleanroom environment, a glove box or is closed with protection flanges. Depending on the complexity of the assembly procedures, the number of rinses varies between one and three, e.g. the TTF nine cell cavities are rinsed once after the chemical treatment and additionally two times after the assembly of the flanges. The repeated rinses are advantageous in order to rinse out particles, which have been taken off during the first rinse, but by chance have been transported and deposited inside the cavity, yet.

The technical installations like pump, piping, turntable and nozzle system differ widely and so are not described. It only should be stressed, that the final particle filter (pore size ≤ 0,2 µm) has to be placed as close to the nozzle as possible with no moving parts (i.e. valves) between filter and nozzle.

Figure 3: Saclay-type high pressure rinsing system for single-cell cavities. The turn-table (with red ring) is moving up and down on a fixed thread with the nozzle on its top. The cavity is fixed by the grey plastic clamps.

3.3 Drying

Due to the enhanced sensitivity of a wet surface to particle trapping [16], the drying procedure requires highest cleanliness. Depending on the laboratory, the type of cavity and the preparation status (cavity with open or closed flanges), the drying differs:

- Drying of an open cavity in a cleanroom environment better than class 100 or a comparable glove box requires minimum handling of the cavity and is used widely.
- Drying by vacuum pumping is best suited for a rinsed cavity with its flanges assembled and requires a water-resistant pumping station. An additional gas by-pass can improve the pumping conditions.
- Drying using a particle-filtered flow of pure gas needs additional handling and assembly, if a closed connection between cavity and supply line is required. The danger of recontamination has to be carefully considered to the gain in drying time compared to an open drying.

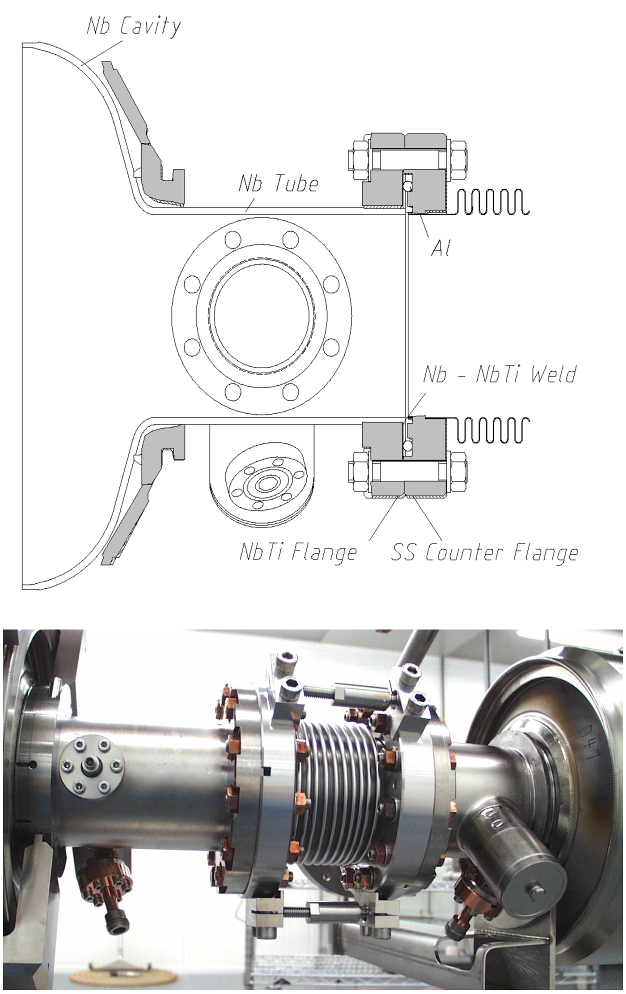

Figure 4: Flange design (upper) and bellow connection (lower) of the TTF cavities using niobium-titanium flanges and massive aluminium gaskets.

To accelerate the drying procedure, the cavity can be rinsed with alcohol, methanol, etc. or the temperature can be increased. Methanol rinsing was widely used with good results in the past, but at present it is to a great extent avoided due to handling and safety reasons. Moreover, the improved quality of the final water rinses made the additional cleaning effect of the alcohol dispensable. The realisation of an increased temperature ($T > 50$-$60°C$) in a high quality laminar flow gives substantial technical difficulties and is not applied up to now. In contrast, warming up a cavity during vacuum pumping under relaxed cleanroom requirements (> class 1000) is used in several laboratories with good success and lead to the discovery of the “baking effect” [17].

After washing and rinsing, the components attached to the cavity are dried similarly to the above described procedures. A final comparative assessment of the different drying procedures with respect to the cavity results cannot be given, because no systematic investigations with otherwise unchanged preparation parameters are published.

3.4 Assembly

The importance of a contamination free assembly for a good cavity performance is beyond any doubt. Nevertheless it is often overlooked, that essential conditions for a contamination-free assembly are given by the design of all involved components long before the cleanroom actions start. An unsuited design results in difficult and inadequate cleaning as well as improper assembly conditions. Especially the flange connections and the gaskets attached to the cavity, which necessitate an easy handling as well as a reliable leak tightness, are of outstanding importance [18] (figure 4).

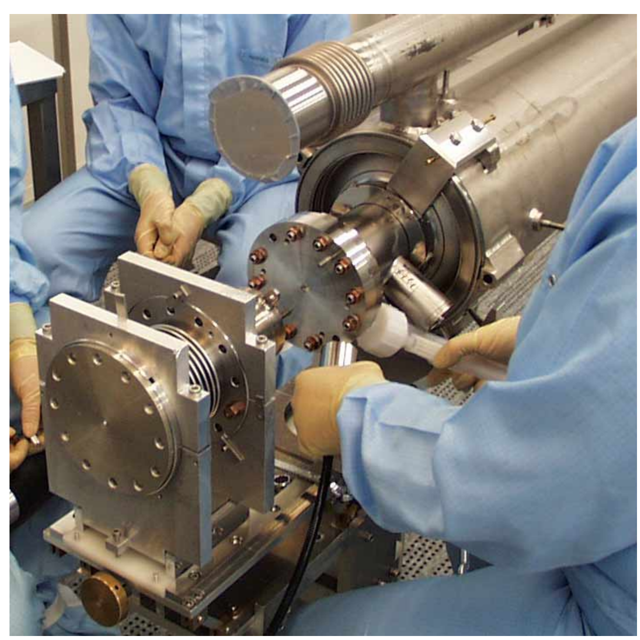

Figure 5: Preparation of cavity connection. The flange bore holes are cleaned using ionized pure nitrogen gas under control of a particle counter.

After cleaning and drying, the cavity and its components are assembled in a cleanroom environment better than class 100 or a comparable glove box. Blowing off both, the components and tools, with pure ionized gas immediately before the assembly in front of a particle counter can be used as a good check for the particle contamination as well as a final removal of remaining particles (figure 5). This is of particular importance during the final assembly of a cavity or the connection of cavities before beam operation, where no cleaning can be applied afterwards. It is evident, that the handling and assembly time at an open cavity should be as short as possible. Finally, best design and cleaning will not help, if the cleanroom staff is not well trained and highly motivated.

3.5 Pumping and venting

To avoid any risk of a harmful hydrocarbon contamination [19], oil-free pump stations (figure 6) equipped with helium leak detector and residual gas analyser became standard technique for the evacuation of s.c. cavities and accelerator modules [20]. Usually, after the installation of the modules to the accelerator, the beam vacuum is pumped by additional ion getter pumps.

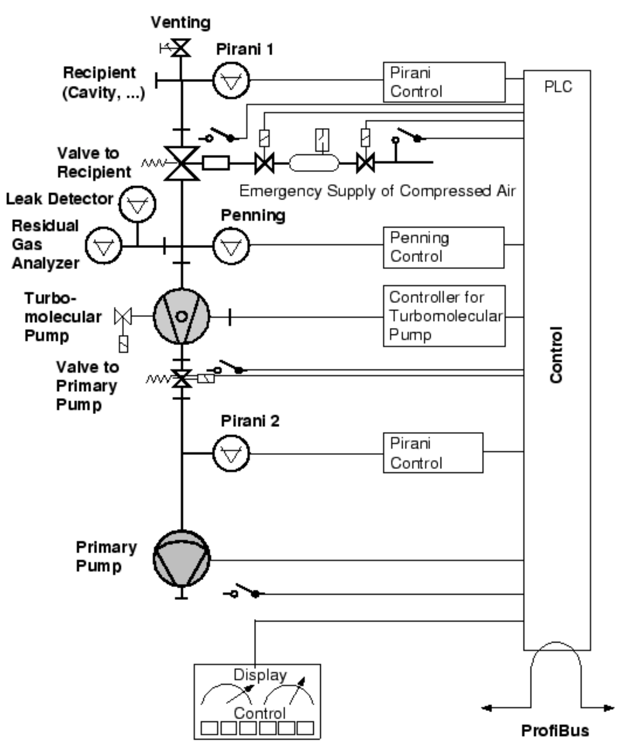

Figure 6: Schematic layout of the oil-free pump station at TTF.

The cleaning and assembly of vacuum connections inside the cleanroom are described above. Outside the situation becomes more difficult, but careful double-layer wrapping with anti-static foil, thorough manual cleaning (e.g. wiping with alcohol, blowing with pure gas) and the use of mobile local cleanrooms allow clean vacuum connections. Though it is still common practice during the vertical cavity tests to connect the pump line partially without local cleanrooms, this needs to be improved. In any case back streaming towards the cavity has to be prevented.

Venting is done using pure, dry and particle filtered nitrogen or argon gas to avoid contamination with particles and humidity [20]. Laminar venting prevents particle transport due to turbulences in the pump line and cavity (figure 7).

Closely related is the influence of various gases on the cavity performance. Unfortunately different investigations came to contradicting results [21]. Without doubt is the harmful impact of hydrocarbons, i.e. caused by a defect of a conventional pump stand using an oil-sealed rotary pump. No negative effect was reported yet for the relevant vent gases nitrogen, argon and air, but due to a recent publication, argon maybe favourable compared to nitrogen [22].

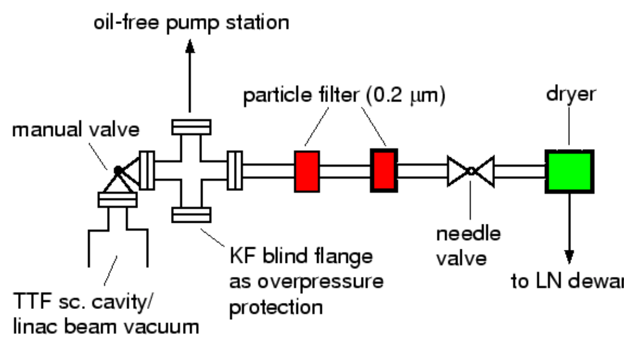

Figure 7: Schematic lay-out of the set-up used for venting of cleaned vacuum systems at TTF

3.6 Risks of Contamination

The described cleaning steps and handling procedures have proven their suitability for good and reliable cavity performance during the last years. Nevertheless in some cases field emission at low gradients or a degradation of the cavity performance, e.g. between horizontal test and beam operation, occurs. Often the source of the contamination is hardly to determine after the event, but careful analysis of test results showed a significant reduced onset of field emission gradient, if irregularities during preparation could be identified [23, 24]. Typical irregularities are vacuum leaks, faulty assemblies and problems during chemical treatment or HPR. Furthermore the complexity of the preparation process hinders or prevents to test the influence of one individual step alone. A typical example is the high pressure rinsing, which is followed by at least drying and pumping.

Besides irregularities even the regular preparation process contains procedures, which hold a high risk of contamination.

- During the TTF preparation the final HPR cleans a single cavity without its power coupler (HPR would destroy the gain of a former rf conditioning of the power coupler). So until beam operation it is necessary to disassemble and assemble three flange connections at each cavity without further possible cleaning.

- After the final horizontal system test of a TTF cavity, the accelerator module has to be completed, equipped, transported and assembled to the accelerator. Depending on the exact procedures, up to five times evacuating and venting is necessary. Though extensive precautions are taken (see above), the risk of particle contamination is present.
- There is a general risk of insufficient cleaning of the partially complex components, i.e. power coupler, gate valve, beam position monitors, etc., attached to cavity and accelerator module. Often the design makes an effective cleaning difficult.

Some improvements, which partially require substantial new developments, are described in the next chapters.

4 IMPROVEMENTS OF STANDARD PROCEDURES

The first topics to be mentioned result from general rules of cleanroom work, practical experiences of cavity preparation and common sense. In fact, they are less technical improvements than good laboratory practice, but nevertheless often ignored. As mentioned above, the design of all used components must be adapted to cleanroom requirements, i.e. well selected materials, good cleaning possibility, suited for easy handling and assembly. A good organisation of the work flow as well as a suited design of the infrastructure simplify the preparation and avoid unnecessary actions. The treatments of each cavity inside and outside the cleanroom as well as the condition of infrastructure have to be documented. A complete documentation is essential for cavity data analysis and failure search. The cavity preparation has to be stopped in case of any irregularity, which made a successful rf test doubtful, and to be started again with an adequate cleaning.

The important question of the best choice of acid mixture for the EP or BCP surface treatment is discussed in chap. 3.1. Rinsing of the cavity with hot pure water ($T \geq 80°C$) after etching or polishing can improve the removal of acid residues due to the high solubility. Experiences in high purity stainless steel tube production show a faster drying after hot instead of cold water rinse. Thus, the risk of recontaminating the sensitive wet surface of a cavity or component after the final (high pressure) rinse is reduced.

The operation experience of various HPR systems during the last years shows some ways for technical improvements of this proven concept.

- The spray cane of the present HPR systems is in contact with one or more bearings. Due to their signs of wear, this gives a high risk of contamination transport into the cavity. An improved design with fixed cane, enclosed bearings and all moving parts as far as possible away from the cavity is in preparation at TTF.
- Though the outside of the cavity is cleaned while entering the cleanroom, an additional outside HPR maybe helpful to avoid contamination transport from the typically cl.10000 chemistry area to the cl.100 assembly area. This holds especially for multi-cell cavities with their complex shape.
- Obviously, a higher pressure than 100 - 150 bar, which is widely used at present, results in a reduced size of removable particles. Calculating the forces [25], the particle size decreases inversely to the square root of the pressure. Within the limits given by damaging the niobium surface [28] only limited gain of 30 - 40 % reduction in particle size can be achieved.
- Though quality control during cavity preparation is not the subject of this paper, operational experiences at DESY strongly support the need of a high pressure supply line for analysis purposes close to the nozzle for future HPR systems [23, 24].

5 ALTERNATIVE APPROACHES

Following the requirements of semi-conductor industry a number of advanced cleaning techniques have been developed for smooth wafers [25, 26, 27]. Due to the complex shape of the inner surface most of them are not applicable to cavities. After first considerations and pilot tests only megasonic and dry-ice cleaning seem to have potential for cavity cleaning.

The principle of megasonic cleaning is similar to ultrasonic, but with frequencies around 1 MHz. The cleaning effect is based on high power pressure waves inside the cleaning solution less than on cavitation. Particles down to 0,1 µm can be removed from wafer surfaces. First cavity results showed promising results [29], but also the need to develop an oscillator applicable inside the cavity to realise a high transmission of megasonic power. The transportation of particles out of the cavity requires a high flowrate, which is no problem for an open cavity, but might need some technical effort for cavities with assembled flanges.

Dry-ice cleaning with CO_2-snow allows effective cleaning of sub-micron particles and film contamination by a combination of mechanical, thermal and chemical effects (figure 8). The cleaning process acts local, mild, dry, without residues and requires no additional cleaning agent. Cleaning of niobium samples shows promising results [30]. The application to cavities is in preparation [30, 31], which requires the development of a nozzle system adapted to cavities and gas suction for particle transport out of the cavity. A possible mechanical design for vertical cleaning is similar to existing HPR systems. As the particle transport is based on a gas flow out of the cavity, horizontal cleaning of cavities seems to be possible in contrast to HPR. Furthermore, the dry cleaning would preserve the effect of preconditioning of a rf power coupler attached to a cavity (see chapter 3.6).

The welding of the beam tubes seems to be a clean alternative to connect two cavities avoiding a bolted flange connection with its high risk of particle contamination. Both, electron beam welding or laser welding seem to be applicable due to pilot tests [32]. First tests with two 1.3 GHz seven-cell cavities connected by electron beam welding will be carried out soon within the framework of the superstructure concept for TESLA [1, 33].

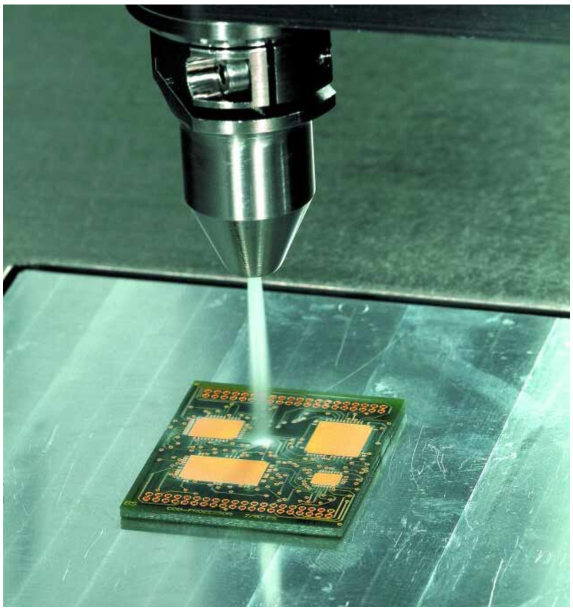

Figure 8: Dry ice cleaning of an electronic circuit

6 CONCLUSION

Standard cleaning and assembly procedures allow high quality cavity performance in vertical tests as well as during beam operation. Nevertheless for multi-cell accelerator cavities field emission induced dark currents and enhanced cryogenic losses keep a severe problem for operating gradients above 20 MV/m at 1,3 GHz. Using the optimisation and improvement potential of the standard techniques, in all probability higher gradients, i.e. for the TESLA 500 design with E_{acc} = 23 MV/m, will be at hand reliable and with negligible field emission in the next future. Gradients of 35 MV/m (design of TESLA 800) have been surpassed in several single-cell cavities using EP. Few multi-cell cavities came close to this value in pulsed operation. Though the improved standard techniques and new alternative approaches look promising for a further increase of gradients, still major efforts are necessary to meet this ambitious goal.

7 ACKNOWLEDGEMENT

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8 REFERENCES

[1] Editors: R. Brinkmann, K. Flöttmann, J. Rossbach, P. Schmüser, N. Walker, H. Weise; TESLA Technical Design Report, DESY 2001 - 011, ECFA 2001 - 209, TESLA Report 2001 - 23, TESLA - FEL 2001 - 05 (2001)

[2] H. Padamsee et al.; "RF Superconductivity for Accelerators"; John Wiley & Sons Inc., ISBN 0-471-15432-6, 1998

[3] Several contributions to the Proc. Workshops on RF Superconductivity, especially by Cornell University, CEA Saclay and BUGH Wuppertal

[4] T. Furuya, "Preparation and Handling of Superconducting RF Cavities", Proc. 4th Workshop on RF Superconductivity, Tsukuba, Japan, p. 305, 1989

[5] L. Lilje," High accelerating gradients in 1.3 GHz Cavities", invited talk, this workshop

[6] A. Matheisen, D. Reschke, "Control of Particle Contamination with Liquid and Air Particle Counters during Preparation of TTF 1.3GHz Resonators", Proc. 8th Workshop on RF Superconductivity, Abano Terme, Italy, p.640, 1997

[7] J. Knobloch, H. Padamsee, 7th Workshop on RF Superconductivity, Gif sur Yvette, France, p. 95, 1995

[8] M. Ono et al., "Achievement of 40 MV/m Accelerating Field in L-Band SCC at KEK" and K.Saito et al., "Superiority of Electropolishing over Chemical Polishing on High Gradients", 8th Workshop on RF Superconductivity, Abano Terme, Italy, p.472, 1997

[9] K. Saito, "Recent Developments in SRF Cavity Cleaning Techniques at KEK", 9th Workshop on RF Superconductivity, Santa Fe, USA, p.118, 1999

[10] P. Kneisel, "Surface Preparation of Niobium", Proc. 1st Workshop on RF Superconductivity, Karlsruhe, Germany, p. 27, 1980 and references therein

[11] L. Lilje, "Experimental Investigations on Superconducting Niobium Cavities at Highest Radiofrequency Fields", Thesis, Hamburg University and DESY, 2001

[12] C.Z. Antoine et al., "Alternative Approaches for Surface Treatment of Nb Superconducting Cavities", Proc. 9th Workshop on RF Superconductivity, Santa Fe, USA, p.109, 1999 and references therein

[13] L. Ponto, M. Hein, "Verfahren zur Elektrochemischen Politur von Niob", external report, WUB 86-17, BUGH Wuppertal, Germany, 1986 and references therein

[14] Ph. Bernard et al., Proc. 3rd Europ. Part. Acc. Conv., Berlin, Germany, p.1283, 1992

[15] P. Kneisel et. al., Proc. 6th Workshop on RF Superconductivity, Newport News, USA, p. 628, 1993

[16] K. Saito et al., "Study of Ultra-Clean Surface for Niobium SC Cavities", Proc. 6th Workshop on RF Superconductivity, Newport News, USA, p. 1151, 1993

[17] B. Visentin et al., Proc. 6th Europ. Part. Acc. Conv., Stockholm, Sweden, Vol.3, p. 1885, 1998

[18] K. Zapfe-Düren et al., "A New Flange Design for the Superconducting Cavities for TESLA", 8th Workshop on RF Superconductivity, Abano Terme, Italy, p.457, 1997

[19] D. Reschke et al., Proc. 6th Workshop on RF Superconductivity, Newport News, USA, 1993, p. 1095

[20] M. Böhnert et al., "Oil-free Pump Stations for Pumping of the Superconducting Cavities of the TESLA Test Facility", this workshop

[21] D. Reschke, "Feldbegrenzungen und Verlustmechanismen in supraleitenden 3 GHz-Beschleunigungsresonatoren aus Niob", external report, WUB-DIS 95-5, BUGH Wuppertal, Germany 1995 and references therein

[22] K. Saito, "Basic Study for Degradation Free Final Horizontal Cavity Assembly with High Gradient Niobium SC Cavities, this workshop

[23] C. Antoine, "A Statistical Analysis of the Risk of Dust Contamination during Assembly of RF Superconducting Cavities", Proc. 6th Workshop on RF Superconductivity, Newport News, USA, p. 1047, 1993

[24] D. Reschke, "New Aspects of Quality Control during Preparation of TTF 1.3GHz Cavities", Proc. 9th Workshop on RF Superconductivity, Santa Fe, USA, p.159, 1999

[25] P. Kneisel, B. Lewis, Proc. 7th Workshop on RF Superconductivity, Gif sur Yvette, France, 1995, p. 311

[26] D. L. Tolliver ed., "Handbook of Contamination Control in Microelectronics", Noyes Publications, ISBN 0-8155-1151-5, 1988

[27] W. Kern ed., "Handbook of Semiconductor Cleaning Technology," Noyes Publications, ISBN 0-8155-1331-3, 1993

[28] D. Bloess, private communication

[29] K. Saito et al., Proc. 7th Workshop on RF Superconductivity, Gif sur Yvette, France, 1995, p. 379

[30] D. Reschke et al., "Dry Ice Cleaning for SRF Applications", Poster, this workshop

[31] L. Philips, JLab, private communication

[32] J. Dicke, DESY, private communication

[33] J. Sekutowicz, "Status of the Superstructure", invited talk, this workshop

[34] D. Bloess, "Chemistry and Surface Treatment", Proc. 2nd Workshop on RF Superconductivity, Geneva, Switzerland, p. 409, 1984

[35] B. Bonin,"Field Emission Studies at Saclay", Proc. 6th Workshop on RF Superconductivity, Newport News, USA, p. 1033, 1993