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SURFACE TREATMENT EXPERIENCE OF THE ALL SUPERCONDUCTING GUN CAVITIES*

E. Vogel†, S. Arnold, D. Bazyl, T. Buettner, B. van der Horst, D. Klinke, D. Reschke, M. Schmoekel, J. Sekutowicz, S. Sievers, N. Steinhau-Kuehl, J.-H. Thie, J. Ziegler
DESY, Hamburg, Germany
T. Konomi‡, FRIB, East Lansing, MI 48824, USA
E. Kako, M. Omet, K. Umemori, KEK, Tsukuba, Japan

Abstract

The performance of superconducting cavities depends extremely on the material and surface properties. In the last decades processes have been developed for the successful serial production of accelerating cavities for large scale facilities like the European XFEL. A main feature of these cavities are relatively large diameter beam ports on both sides which can be used for the surface treatment processes. In contrast, superconducting gun cavities have only one beam port and a half-cell with a back-wall acting as mirror plate with some small hole for the cathode in the center. Being apparently only a small feature, it turned out to require special attention for the surface treatment. This is in particular the case, when the target gradients are as high as gradients for the accelerating cavities. In our contribution we present the experience made within the last years and how we finally achieved high gradients.

INTRODUCTION

A future upgrade of the European XFEL [1, 2] foresees High-Duty-Cycle (HDC) operation ranging from continuous wave (CW) and 100% duty-cycle giving maximum flexibility for the laser pulse timing to about 8% duty-cycle for high energy electrons send to the undulator sections. This requires a photoinjector operating continuous wave (CW).

High gradient gun cavities enable "pancake" emission of beams and direct matching into the subsequent linac [3]. An additional buncher section as required in other setups [4] can be omitted. The pulsed normal conducting (NC) L-band RF guns developed by DESY and operated at DESY's FLASH facility and the European XFEL follow this scheme [5]. L-band superconducting RF (SRF) gun technology has the potential of similar high gradients like the pulsed L-band NC RF guns operating CW [6]. It is the first choice for the planned HDC operation of the European XFEL.

L-band SRF gun technology with load-lock system for in-situ cathode exchange is operated at HZDR [7–9] and under development at HZB [10–12] and KEK [13] with different requirements (e.g. larger emittance). The peak electric field on axis gradients of the SRF guns at HZDR and at HZB are (still) significantly lower than those needed for the European XFEL. However, the SRF gun developed at KEK demonstrated sufficiently high peak field on axis gradients in vertical tests [13].

Load-lock systems at SRF gun cavities differ from those at NC gun cavities. The cathode stalk is located in an evacuated channel at the cavity backside avoiding any mechanical contact to the SRF cavity. A choke filter cell prevents RF leakage towards the load-lock system [9]. This constitutes challenges for cleaning the cathode channel, for contact less cathode transfer and also for cathode cooling during operation.

The concept of an all superconducting gun cavity foresees a closed cavity back-wall to avoid these challenges [7, 14]. The quantum efficiency (QE) of bulk niobium is too low to use it as the emitter [15, 16]. Initial attempts depositing lead as cathode material [17–19] to the center of a closed cavity back-wall turned out very demanding [20–22]. Separating the cavity preparation from the cathode preparation was the natural next step. The resulting cavity design foresees a cathode plug screwed to the cavity back-wall [23, 24]. Indium is used for sealing and for good thermal contact. The first prototype cavity 16G2 of this kind achieved in vertical tests in 2012, 2014 [25, 26] and 2016 already peak field on axis gradients[1] of 54 MV/m and beyond. Buffered chemical polishing (BCP) [27] with subsequent vertical fine electro polishing (EP) [26, 28] before the later tests has been applied.

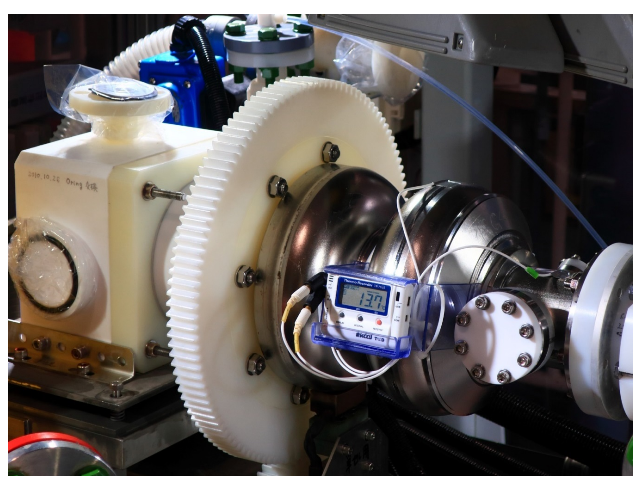

Figure 1: Horizontal EP of SRF gun cavity 16G4 at KEK.

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† elmar.vogel@desy.de

‡ The work at KEK presented here was carried out when T. Konomi was still employed as a scientist at KEK, Tsukuba, Japan.

[1] The peak field on axis gradient is relevant for photoemitted electrons starting with zero velocity at the cathode. It is about 1.9 times the accelerating gradient seen by electrons traveling with the speed of light.

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SRF GUN CAVITY DESIGN

The mechanical and RF design of the SRF gun cavity with the cathode plug screwed to the back-wall underwent several iterations. A basic feature are rips outside the mill-cut cavity back-wall. The mechanical weakness of the 16G2 cathode plug design has been avoided for the cavities 16G3 and 16G4 [29]. We fabricated the cavities 16G5 until 16G8 with closed metal sheet back-walls to study surface treatment procedures [30] without the complication of a cathode hole and to tailor the RF geometry. Combining the tailored RF geometry from 16G7/8 with the mechanical back-wall of 16G3/4 resulted in the design of the cavities 16G09 and 16G10. Close production supervision and additional effort for the RF frequency tuning was provided to meet the cathode laser frequency acceptance. For the cavities 16G11 and 16G12 the cavity end group design has been optimized to minimize negative effects on the beam quality keeping mechanical changes as small as possible [31]. First vertical tests of 16G09/10 are expected at the time of this publication. The process to start the 16G11/12 fabrication is under way.

SURFACE TREATMENT RECIPE

Well established surface treatment recipes are available for TESLA type accelerating cavities [32–34]. As previously mentioned, these cavities have large beam tubes at both sides used for the surface treatment processes. The special design feature of the SRF gun cavity half-cell with back-wall requires adaptation of the established techniques [26, 35]. The main surface treatment and preparation steps for our SRF gun cavities are:

- main (BCP) treatment, 110 µm in one or more steps
- several cleaning steps applying high pressure water rinsing (HPR) and ethanol rinsing
- 800°C annealing
- cavity tuning
- fine treatment by BCP of about 20 µm or horizontal EP for improved smoothness and performance [27]
- several cleaning steps applying HPR and partially ultrasonic cleaning (US)
- cathode plug assembly
- HPR
- 90°C baking

In the last years, we tested many variations of these steps before achieving systematically high peak field on axis gradients at the subsequent vertical tests.

ELECTRO POLISHING

Motivated by the success of performing vertical electro polishing (EP) to the cavity 16G2 [26], we applied in 2017 a vertical main EP at DESY to the newly fabricated cavities 16G3 and 16G4. Dents in the 16G3 back-wall lead to the modification of the nozzle inclination before applying the same process to 16G4 [29]. Unfortunately, all subsequent vertical tests where very disappointing [30]. BCP applied to these cavities in 2018 in industry didn't improve the performance [30].

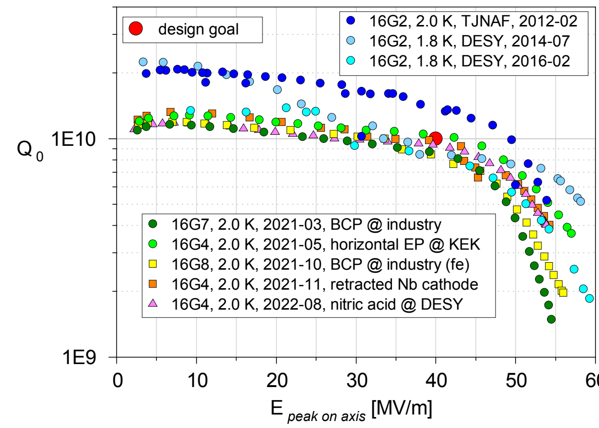

Figure 2: Examples of successful vertical test results of SRF gun cavities with metal sheet back-walls (16G7, 16G8) and cathode plugs screwed to the back-wall (16G2, 16G4).

In summer 2019 we decided to apply horizontal EP at KEK [36–38] in the STF-EP facility [39, 40] to the cavity 16G4, Fig. 1. Beginning 2020 all required preparations and equipment adaptations where finished and the cavity was transferred to KEK. From Mid-February until Mid-March 2020, we performed a full surface treatment campaign, applying the subsequent main steps: horizontal main EP, 800°C annealing, cavity tuning [35], horizontal fine EP, cathode plug assembly, 90°C baking and vertical testing (required steps in between not listed). Unfortunately, the test result was again disappointing. Optical inspection revealed indium used for the cathode plug sealing has been squeezed into the cavity volume and most likely distributed in the cavity by an HPR water jet directly pointing to the cathode area. The cathode area also showed blue coloration (oxidation).

Meanwhile we suspected the cavity back-wall surface structure created by the very first vertical main EP in 2017 being also one major reason for the repeatedly bad performance. As a consequence, we applied drastic measures to restart with a fresh surface by removing the collection of bad residues created by all the different treatments. In early summer 2020 the cavity back-wall of 16G4 was mechanically grinded at the KEK workshop before starting another full horizontal EP treatment campaign at KEK.

The horizontal main EP performed then produced a shiny back-wall surface except from a circular region around the cathode hole where it looked orange-peel skin like. This region stays permanently below the acid surface level. The size of this area cannot be reduced further. Hydrogen gas bubbles caused by the electrochemical EP process bust when reaching the acid surface level. Bubbles not reaching the surface stick permanently at fixed locations. This is the case near the cathode hole and the main reason for the orange-peel skin surface. The area around the cathode hole was again mechanically grinded after the 800°C annealing and before the fine EP treatment. No orange-peel skin surface appeared and the cavity reached a maximum peak field on

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axis gradient of about 54 MV/m in the subsequent vertical test in October 2020.

Another vertical test at KEK with similar result followed in February 2021 after the installation of a fixed antenna used for the shipment of the cavity under vacuum back to DESY for a comparative vertical test at DESY with no manipulation of the cavity in between. The test performed at DESY in May 2021 showed the same result (Fig. 2) as the test performed at KEK.

BUFFERED CHEMICAL POLISHING

BCP is less sensitive to the cavity geometry than EP as there is neither an EP cathode nor an electric field involved in the surface treatment process. However, the acid flow plays a role and is quite different to standard accelerating cavities with big beam ports at both ends. A special connection to run in and out the acid via the single beam port and covering the cathode hole preventing acid flowing through it are required [30]. The setup went through several iterations and led to a "chemistry flange" with a filling tube feeding a watering can shaped nozzle head located close to the back-wall and an outlet for the acid and rinsing water. The nozzle head was optimized studying the back-wall removal homogeneity for the cavities 16G5 until 16G8 (closed metal sheet back-walls) via ultrasonic wall thickness measurements [35]. This activity took place in close collaboration with industry. Nowadays, our BCP surface treatment setup and procedures provides SRF gun cavities showing typical maximum peak field on axis gradients around 55 MV/m in vertical tests.

HPR AND DRY-ICE CLEANING

The cathode plugs with special prepared surfaces for high QE are screwed in the clean room to the cavity back-wall. To achieve high gradients repetitively, some cleaning should be applied afterwards. The HPR spray heads developed for the accelerating cavities [41] are not optimal for cleaning SRF gun cavity back-walls. A new spray head is under development to clean the cavity back-walls but avoiding a high impact in the center to avoid damaging the cathode surface [35].

Dry-ice (CO_2) cleaning is a standard method at DESY for cleaning normal conducting copper gun cavities [42, 43]. Hence, it was a natural consideration [44] to test likewise dry-ice cleaning at our SRF gun cavities. An open question was, if the pick-up (PU) and antenna feed through dielectrics will withstand potential thermal shocks due to this cleaning process. First tests revealed that both work normally after dry-ice cleaning. The tests are still in an initial stage and it is to early to draw conclusions on the effect of dry-ice cleaning on our SRF gun cavities.

CATHODE PLUGS

The magnetic field is low in the cathode area and the electric field perpendicular to the surface. Calculations predict, our SRF gun cavities should likewise work with cathode plugs made of copper instead of niobium. The much higher thermal conductivity of copper provides better transfer of the heat introduced by the cathode laser to the helium bath. Plain copper cathodes will be robust against SRF cavity cleaning and potentially already provide the QE needed. A better adhesion of lead on copper than on niobium is expected, too. End 2021 we screwed a lead coated copper cathode plug to the cavity 16G4, applied the usual HPR and performed a vertical test. The maximum field reduced by one half. We suspected lead has been spread around in the cavity causing the bad performance. Applying HPR in combination with cleaning with 20% to 30% nitric acid and re-attaching a niobium plug recovered the performance of the cavity measured in Summer 2022, Fig. 2. Due to the many treatments including two times mechanical grinding of the back-wall, the area around the 16G4 cathode hole is mechanically unstable and requires meanwhile mechanical back deformation from the cavity inside before each new cathode plug assembly. Further testing of cathode plugs and materials is planned with the cavities 16G09/10.

SUMMARY AND OUTLOOK

In recent years we developed surface treatment procedures for the SRF gun cavities with a cathode plug screwed to the back-wall providing typical maximum peak field on axis gradients around 55 MV/m in vertical tests providing sufficient margin to the design goal of 40 MV/m. This is the case for BCP treatments. Applying EP in addition increases high gradient Q-values, Fig. 2. We identified quite some potential for further optimizing our surface treatment processes and are working on them.

Nevertheless, we have the first main prerequisite for a CW photoinjector for "pancake" beam emission and direct matching into the subsequent linac in hand by achieving the required high gradients on a regular basis.

The other main prerequisite are photocathodes which are robust against the exposure to air and the usual SRF cavity cleaning procedures. In contrast to the commonly used photocathode materials, our cathodes have to be out of metals. In the case of coatings, we need to improve significantly the adhesion. Other options are nanostructured metal surfaces [45, 46]. Plain copper cathodes may already provide the QE needed after applying RF conditioning in combination with laser cleaning [47, 48].

The study of this cathodes will be one major focus for us in the next years in addition to the setup of a SRF photoinjector test stand for the study of beam properties provided by a L-band SRF photoinjector.

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