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SUPERCONDUCTING RF CAVITY MATERIALS RESEARCH AT THE S-DALINAC*

R. Grewe[†], L. Alff, M. Arnold, J. Conrad, S. Flege, M. Major, N. Pietralla
 Technische Universität Darmstadt, Darmstadt, Germany
 F. Hug, Johannes Gutenberg-Universität Mainz, Mainz, Germany

Abstract

Current state-of-the-art superconducting rf (srf) accelerators are mostly using cavities made of high RRR bulk niobium. The maximum field gradients and quality factors (Q_0) of these cavities are basically reached now. To further increase the srf cavity properties for future accelerator facilities, research of new materials for srf cavity applications is necessary. The current research at the S-DALINAC [1] is focused on the development of bake-out procedures of Nb samples and cavities in nitrogen atmosphere of 100 mbar and up to 1750°C to nucleate the δ -phase of the Nb-N binary system. The δ -phase has superconducting properties which exceed the properties of bulk Nb. This makes the δ -phase attractive for srf applications. The vertical test cryostat (VT) at the S-DALINAC has been upgraded and recommissioned to allow investigations of the quality factor and accelerating field gradients of cavities before and after bake-out. The VT upgrade includes a newly developed variable input coupling to allow matching of the external q-factor (Q_{ex}) to Q_0 . The results of the ongoing research of the nitrogen atmosphere bake-out procedures and the upgrade of the VT will be presented.

INCREASING SRF CAVITY PERFORMANCE

Today's superconducting accelerators are relying on radio-frequency (rf) cavities made of bulk niobium. The performance of these cavities, defined by the quality factor Q_0 and maximum accelerating field gradient E_{acc} is used to full capacity at modern accelerators like the European XFEL [2]. The wish to further increase the performance has lead to research of alternative, niobium based materials like Nb_3Sn and NbN. The solid solution of nitrogen in niobium (Nb-N, α -phase) is already used for the srf cavities of the LCLS-II project [3]. The current research at the S-DALINAC is focused on the δ -NbN, which has a higher critical temperature $T_c = 16.5$ K and higher critical field $H_{c2} = 15$ T than bulk niobium. In Table 1 the figures of merit of niobium compared to NbN and Nb_3Sn are given. The formation of the δ -phase NbN begins at temperatures higher than 1300°C as shown by the phase diagram in Fig. 1. The "Wuppertal" UHV furnace [5] at the Institute for Nuclear Physics at Technische Universität Darmstadt achieves temperatures of up to 1750°C. During a recommissioning of the furnace, it was upgraded to allow controlled nitrogen injection [6]. The UHV

Table 1: Comparison of Bulk Niobium to Niobium-tin Compound and δ -phase Niobium Nitride [4]. Even though the expected performance of cavities made of Nb_3Sn , the much easier process with nitrogen atmosphere made NbN the chosen research topic.

Element	T_c in K	$\mu_0 H_{c1}$ in T	$\mu_0 H_{c2}$ in T
Nb	9.25	0.18	0.28
Nb_3Sn	18	0.05	30
NbN (δ)	16.2	0.02	15

furnace has since then been used to to bake out niobium samples of 5×5 mm² and 10×10 mm² at temperatures of up to 1550°C in nitrogen atmospheres of up to 100 mbar for 10 minutes (Fig. 2). The materials science analysis results are shown in the contribution MOP028 [7].

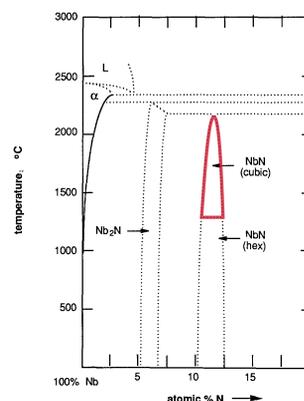


Figure 1: Nb-N binary phase diagram. The cubic δ -NbN, on which the research at the S-DALINAC is concentrated is highlighted. It forms at temperatures above 1300°C [8].

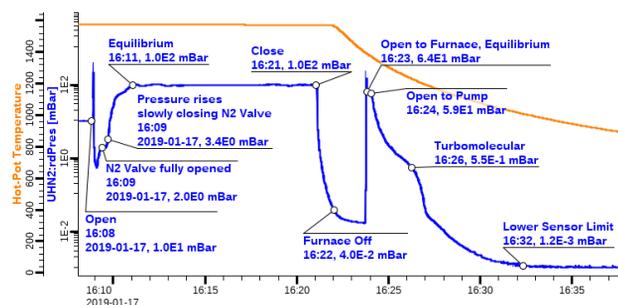


Figure 2: Temperature of the furnace and vacuum pressure of the hot-pot during bake-out of samples in a 100 mbar nitrogen atmosphere.

* Supported by BMBF through 0518RDRB2
[†] rgrewe@ikp.tu-darmstadt.de

UPGRADE OF THE VERTICAL TEST CRYOSTAT

The optimized parameters for δ -phase NbN growth found with Nb samples will be applied to single cell cavities. To allow sophisticated measurements of the performance of 3 GHz cavities in terms of Q_0 and E_{acc} , the VT insert has undergone a complete redesign. The new insert allows the measurement of the relevant parameters for the 20-cell cavities of the S-DALINAC, the new 6-cell injector trapping cavity currently in production (MOP065[9]) and for the single cell cavities used for the research on NbN. The new input coupler, shown in Fig. 3, allows variation of the external quality factor Q_{ex} , matching it to the intrinsic quality factor Q_0 of the cavity. With $Q_0 \approx Q_{ex}$ the measurement uncertainties are minimized. The variation of Q_{ex} is controlled externally by means of the manually operated custom nut shown in Fig. 4.

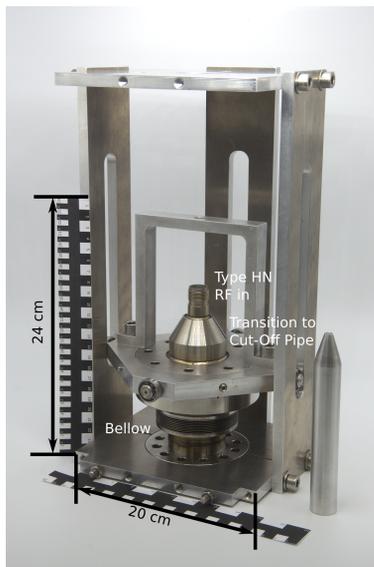


Figure 3: Newly designed variable input coupler for VTC Q_0 and E measurements with minimal uncertainties. The coupler is mounted on top of the cavity, allowing variation of Q_{ex} during measurement. The input antenna is shown right of the coupler. The coupler is build from steel 1.4429 and aluminium.

Electromagnetic field simulations with CST Microwave Studio [10] have been carried to optimize the transition from the HN-Type vacuum feedthrough to the cavity cut-off pipe. The simulation is evaluated by means of the S -parameters of the coupler. A field map of the cross section of the coupler is shown in Fig. 5, indicating simulation ports. Between the HN-Type vacuum feedthrough at *Port 1* and *Port 2* a geometric size matching between the vacuum feedthrough and the cut-off pipe of the cavity was optimized by maximizing the transmission coefficient to $S_{21} = -0.038$ dB (99.1%). This leads to an overall transmission coefficient of $S_{31} = -0.242$ dB (94.6%).

Fundamental R&D - Nb processing (doping, heat treatment)

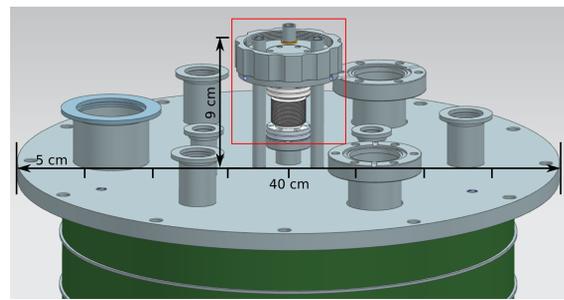


Figure 4: Highlighted is the nut assembly in the center of the VT closure which allows changing of Q_{ex} during measurement runs.

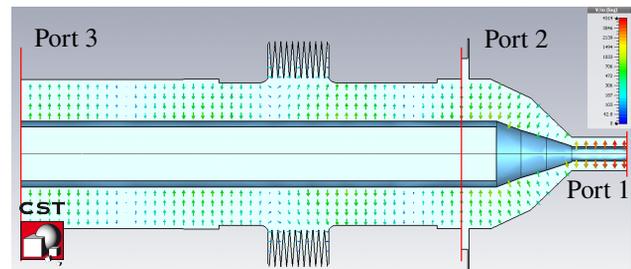


Figure 5: Cross section view of the CST MWS simulation of the variable input coupler for the vertical bath cryostat. The scattering matrix components have been calculated for different port combinations. The port locations are indicated by the red lines.

FIRST TEST OF THE NEW VT INSERT

For the initial tests of the new insert a single cell cavity was mounted in the clean room, as shown in Fig. 6. The insert assembly was put into the VT, and the VT was cooled down with liquid helium. During cooldown, the bandwidth of the resonance of the cavity has been tracked with a computer controlled vector network analyzer (VNA). The graph of bandwidth vs. temperature in Fig. 7 has a large change of the slope as soon as T_c of Nb is undercut. This can be useful to indicate a successful δ -phase NbN ($T_c = 16.2$ K) growth at the cavity surface.



Figure 6: Photograph showing a 3 GHz single cell cavity in the VT assembly. The input coupler is mounted on the left side (top in VT) of the cavity. The as well new designed output coupler is mounted on the right side (bottom in VT) of the cavity.

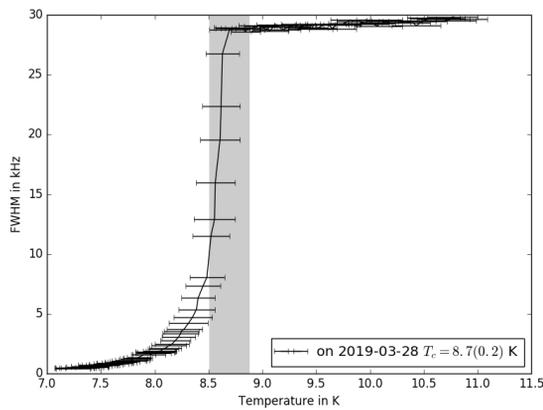


Figure 7: Tracking of the cavity resonance with a vector network analyzer during cooldown gives a hint of the value of the critical temperature T_c of the cavity.

The VT was successfully pumped from 1 bar to 35 mbar to lower the temperature from 4 K to 2 K. At this temperature the Q_0 vs. E_{acc} graph has been measured using a decay time method [11]. The result of the measurement is shown in Fig. 8. The performance in terms of Q_0 and E_{acc} of the measured single cell cavity is as high as expected with values of $Q_0 = 1.5(0.4) \cdot 10^9$ and $E_{max} = 5(1)$ MV/m, where the breakdown occurred. With an optimized rf measurement layout, the measurement uncertainties are going to be further reduced.

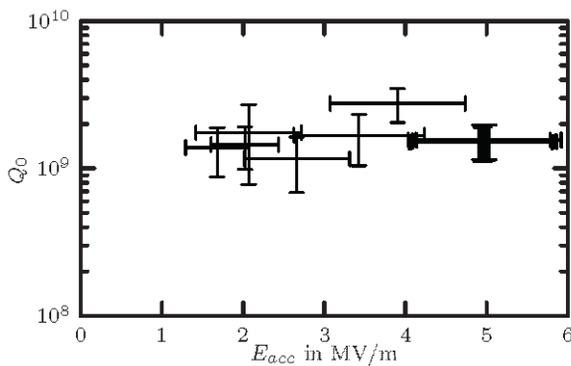


Figure 8: Measured Q vs. E values of a single cell cavity. By reasons of erroneous rf equipment the uncertainties are large and the results will be corrected in a repeated measurement.

SUMMARY AND OUTLOOK

The sample bake-out under nitrogen atmosphere at the UHV furnace of the S-DALINAC is ongoing, showing promising results. Bake-out of samples will continue with increase of time (> 10 min) at the same pressure

(100 mbar) for a thicker growth of the NbN layer. For measurement of the cavity performance parameters Q_0 and E_{acc} before and after a bake-out in nitrogen atmosphere in the furnace, the VT at the S-DALINAC has undergone an ambitious redesign, including a new, variable input coupling. The first test of the new VT insert was successful, including first Q_0 vs. E_{acc} measurement of a untreated cavity. The final commissioning of the new VT insert is still ongoing, including an improved rf layout and measurement of Q_{ex} range of the variable input coupling to further minimize measurement uncertainties.

REFERENCES

- [1] N. Pietralla, "The institute of nuclear physics at the tu darmstadt," *Nuclear Physics News*, vol. 28, no. 2, pp. 4–11, 2018. doi:10.1080/10619127.2018.1463013
- [2] M. Altarelli *et al.*, Eds., *XFEL: The European X-Ray Free-Electron Laser*. Technical design report. 2006, ISBN: 9783935702171. doi:10.3204/DESY_06-097
- [3] J. N. Galayda, "The LCLS-II: A High Power Upgrade to the LCLS," in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, paper MOYGB2, Vancouver, Canada, Apr. 2018, p. 18. doi:10.18429/JACoW-IPAC2018-MOYGB2
- [4] W. Martienssen and H. Warlimont, Eds., *Springer Handbook of Condensed Matter and Materials Data*. Springer, 2005, ISBN: 3-540-44376-2.
- [5] R. Grewe *et al.*, "Nitrogen Bake-Out Procedures at the Vertical High-Temperature UHV-Furnace of the S-DALINAC," in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, paper THPAL126, Vancouver, Canada, Apr. 2018, p. 3937. doi:10.18429/JACoW-IPAC2018-THPAL126
- [6] J. Conrad *et al.*, "Upgrade of a UHV Furnace for 1700 C Heat Treatment and Processing of Niobium Samples," in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, paper THPMY024, Busan, Korea, May 2016, p. 3709. doi:10.18429/JACoW-IPAC2016-THPMY024
- [7] M. Major *et al.*, "Materials science investigations of nitrogen-doped niobium for srf cavities," in *Proc. 19th Int. Conf. on RF Superconductivity (SRF'19)*, paper MOP028, Dresden, Germany, Jun. 2019, this conference.
- [8] T. P. Hennessey and J. E. Morral, "Oxidation and nitridation of niobium in air above 1150°C," *Oxidation of Metals*, vol. 38, no. 1, p. 163, 1992.
- [9] S. Weih, "Upgrade of the S-DALINAC Injector Capture Section," in *Proc. 19th Int. Conf. on RF Superconductivity (SRF'19)*, paper MOP065, Dresden, Germany, Jun. 2019.
- [10] Computer Simulation Technology, *CST Studio Suite 2016*, Computer Software, CST AG, Darmstadt, Germany. <https://www.cst.com/Products/CSTMWS>
- [11] R. Grewe, "In-Situ Quality Factor Measurement of the Superconducting S-DALINAC Cavities," Master-thesis, Technische Universität Darmstadt, Darmstadt, Germany, 2014.

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