

Numerical modeling and experimental investigation of rf heating for midtemperature baking of a TESLA 9-cell srf cavity

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Medium-temperature baking, denoting an in-vacuum heat treatment of superconducting rf cavities in the 220–350 °C range, has recently revealed significant beneficial effects on cavity performance by increasing its intrinsic quality factor. The baking process reduces the thickness of the niobium oxide surface layer and diffuses oxygen into the bulk material. Generally, heat treatment is performed in a vacuum furnace, which, however, has some disadvantages, including risk of contamination in the furnace and subsequent handling or later regrowth of the oxide layer. To eliminate these issues, ideally the heat treatment should be carried out within the module (“*in situ*”) with the cavity assembled in the cold string and thereby avoiding the need for an external vacuum furnace treatment. First, proof-of-principle experiments have demonstrated the feasibility of *in situ* treatment but required the installation of heat tape and temperature controllers. In this paper, we explore an alternative approach by heating the cavity with rf power in a cavity mode, thereby predominantly using the existing rf infrastructure and no need for extra ancillaries. Nevertheless, several challenges need to be addressed, including the need for sufficient rf coupling, providing homogeneous power deposition (especially in multicell cavities), and the drift of both the resonance frequency and the mode’s field pattern with temperature. The results from the rf heating experiments on a TESLA 9-cell cavity at HZB’s HoBiCaT facility are presented in this paper, including simultaneous bead-pull measurements to monitor the field profile of the different modes. In addition, a numerical model was developed to calculate the heat deposition profile. Benchmarking the model with the experimental results allowed for the successful determination of its free parameters. This model can help to predict the rf heating effects under various conditions to guide the implementation of an effective rf heating “recipe.” The model was used to demonstrate the feasibility of a heating scheme alternating between two modes to reach a sufficiently high and homogeneous temperature profile as required for mid-T baking.

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I. INTRODUCTION

Many modern particle accelerator projects, where long-pulse or continuous-wave (cw) operation is required, rely on superconducting radio-frequency (srf) cavities made of niobium as state-of-the-art technology to achieve the required large accelerating field gradients. In order to ensure the best possible performance, srf cavities undergo a series of surface treatments that can be considered a standardized recipe: electropolishing or buffered chemical polishing, followed by hydrogen degassing at 600–800 °C, high-pressure rinsing, and low-temperature baking (120 °C). These treatments result in state-of-the-art cavities

exhibiting high quality factors ($Q_0 > 10^{10}$). Consequently, these recipes can be reliably applied in large-scale projects, such as the more than 800 TESLA cavities produced for the European XFEL [1] and more than 250 for the LCLS-II [2].

A complementary heat treatment method, known as medium-temperature (mid-T) baking, in which cavities are heated to 200–400 °C for several hours under ultrahigh vacuum conditions, has been shown to be capable of further enhancing the quality factors of cavities [3–5]. It has been experimentally demonstrated that in-vacuum mid-T baking reduces the Nb₂O₅ surface layer via diffusion [6], possibly by inducing a permanent doping effect or by other still unclear mechanisms [7] that improve cavity performance and increase the intrinsic quality factor Q_0 potentially up to a factor of 2 [4].

Presently, mid-T baking is performed as a final treatment step within the fabrication process, making use of a vacuum furnace prior to the cavity installation into an accelerator module.

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Even though this nowadays is a routine operation, cavity installation under nonvacuum conditions results in partial reoxidation of the niobium surface [8]. Controlled protective atmospheres, such as inert gas environments designed to minimize oxygen and moisture exposure, can be used but require cumbersome handling procedures and are demanding with respect to avoid particulate contamination. Thus, having the ability to perform an “*in situ*” baking treatment would enable the removal of oxidized layers without a previous oven treatment (and its associated particulate contamination and handling risks) directly after module mounting and without the risk of intermediate reoxidation, thus resulting in a performance increase.

Here, the term *in situ* shall be understood as a cavity prepared for cold operations and fully installed in a module, which has experienced only minor modifications in order to be compatible with the heating process.

Recent experiments using heat tape have demonstrated the potential benefits [4] of local resistive heaters at the cavity’s outside surface when compared with conventional oven heating.

Additionally, operation at cryogenic temperatures turns srf cavities into effective cryopumps [9], enabling the adsorption of residual gas species on the inner surface, particularly after vacuum disturbances [10,11]. Adsorbed gas species can modify the surface properties and have been associated with increased residual resistance and reduced Q_0 [12]. Some, though not all, of these degradations can be eliminated by thermal cycling or rf processing [13]. Therefore, mid-T baking under ultrahigh vacuum conditions may enable partial recovery of the cavity performance and could be a second use case of the approach. Similarly, in warm and vented conditions, residual water films can form on the inner cavity surface, which can effectively be desorbed by a bakeout at temperatures around 120 °C [14,15], a process that would be inherently included in the method reported here.

This raises the question of whether existing infrastructure could be repurposed for an *in situ* (within the srf cryomodule), simpler in-vacuum radio-frequency (rf) heating procedure for srf cavities [16]. In this context, “rf heating” is considered as a localized way of supplying heating power, using rf fields in the cavity and the associated power dissipation. Naturally, one would aim to utilize existing coupler and cable/waveguide infrastructure, ideally including the installed power amplifiers; however, dedicated, temporarily connected rf power sources are also conceivable.

This work represents not a full proof-of-principle, but a first step toward investigating the feasibility and limitations of using rf power in order to deposit sufficient energy with an appropriate distribution on the inner cavity surface. Both a thorough empirical understanding of the dynamics and limitations of rf-based heating and an accurate modeling seem prerequisite for a successful cavity treatment.

It is not expected that the use of rf fields will initiate nonthermal surface material modifications, which makes the spatial and temporal temperature distribution the relevant figure of merit to determine the baking effect. In this study, we restrict ourselves to monitoring a single temperature per cell, acknowledging that there will be a certain but limited temperature gradient along the cavity surface. It will be left to further experiments with more sensors and also an extended model to study such. Also, we are not yet able to present a full sequence of initial cold testing, rf-heated baking, and cold test repetition, demonstrating a Q improvement, which we leave to the future.

With the final goal to enable *in situ* processing, several module components also need to prove compatibility with the cavity temperatures elevated to 220–350 °C for several hours. Likely among other possible points of concern, the thermal stability of the innermost (i.e., hottest) multilayer insulation may be limiting; thermal expansion of the cavity during the heating process may become mechanically critical; unwanted outgassing into the insulation vacuum may require precautions; and temperatures or gradients in dielectrics and soldered joints in the fundamental power coupler (FPC), HOM antennas, or HOM absorbers may reach undesirable levels. With the exception of FPC heating, we leave these considerations to future studies.

In the paper, an experimental campaign on rf-driven heating of a niobium TESLA-9-cell cavity is described. The data obtained there were used to train a numerical model capable of predicting the cell temperatures as a function of heating power, field pattern, and time.

The experimental setup and measurement results are presented in the first section. The second section describes the numerical model and its parametrization. Experimental results of several measurement runs are shown, and the predictive performance of the model is benchmarked. The model is further used to estimate the absolute temperatures and temperature variations along the cavity for certain heating strategies.

For this study, a TESLA 9-cell cavity without a helium tank (“undressed”) has been used, utilizing the modes of the fundamental TM_{010} passband for rf heating. The experimental setup for this study was implemented in the Horizontal Bi-Cavity Test Stand (HoBiCaT) [17] at Helmholtz-Zentrum Berlin (HZB).

The numerical model developed to predict the cavity’s thermal behavior was implemented in Python and benchmarked against the experimental data collected in this study. As also shown, the model is capable of predicting power requirements for temperatures higher than those experimentally reached so far due to the administrative limit implemented to avoid damage to key components.

II. EXPERIMENTAL SETUP

The experimental setup consists of the following main parts: A TESLA 9-cell cavity serves as a representative

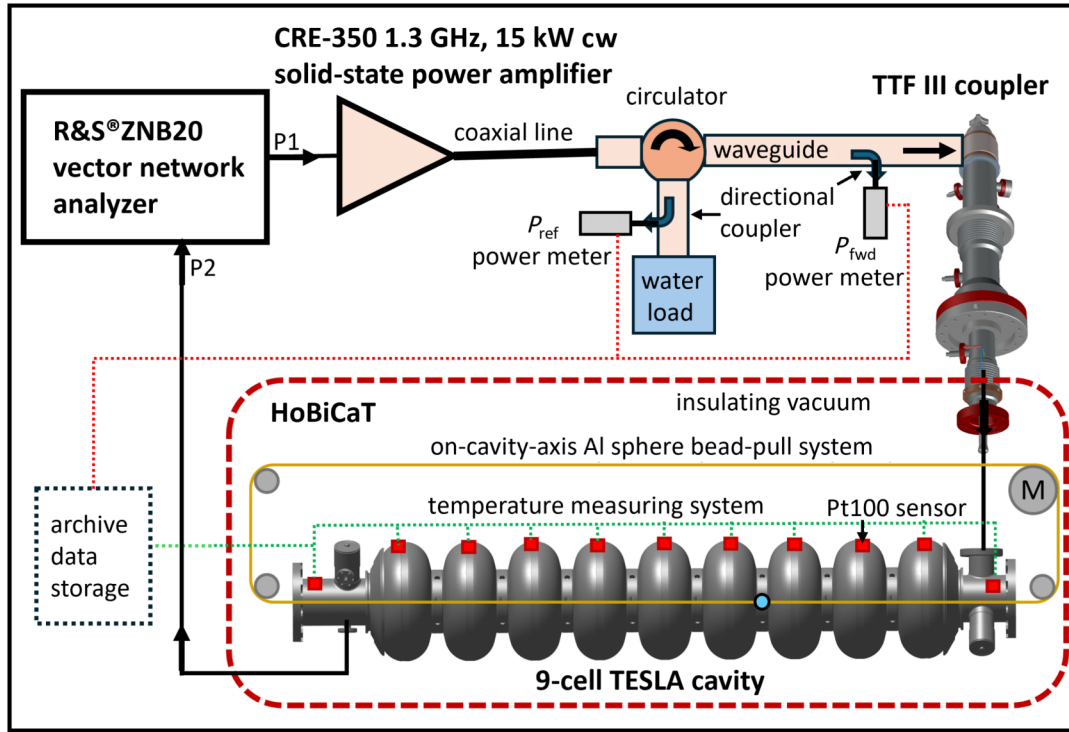


FIG. 1. Schematic overview of the experimental setup. It includes a phase-sensitive rf transmission measurement and an rf heating system, both driven by a vector network analyzer and a power amplifier, a motorized in-vacuum bead-pull setup pulling a small aluminum sphere along the cavity's axis, and a temperature readout system with sensors mounted on each cell of the TESLA 9-cell cavity and both beam pipes. The TTF-III coupler connects the external power waveguide to the cavity.

example of a multicell srf cavity. A TTF-III fundamental coupler is used to input rf power into the cavity. The rf power supply and measurement system aim to deliver the rf signal to the coupler and to monitor the system parameters. A bead-pull system is integrated in order to measure the field profiles inside the cavity. Finally, temperature sensors are used to monitor the surface temperature along the cavity body. Figure 1 shows a general schematic overview of the experimental setup, details of which are given in the following subsections.

A. TESLA srf cavity

The test cavity is an undressed 1.3 GHz 9-cell cavity made of RRR300 fine-grain niobium. Its field profile is not flat, as it was verified by bead-pull measurements (see below). This complicated the study since the poor field flatness found for some (not all) modes of the fundamental passband also was reflected in the corresponding heating profiles. An initial tuning of the cavity for achieving a reasonable flatness specification of $> 90\%$ (π -mode) was discarded, not only due to the extra efforts required, but also to investigate the process in a nonideal scenario.

The whole experiment was conducted with open beam pipes and therefore both the cavity volume and the test vessel (HoBiCaT) shared the same isolation vacuum; this did not exceed 10^{-4} mbar during the measurements.

In a most realistic scenario, the cavity would be enclosed within a helium vessel, which would act as a reflective intermediate layer reducing radiative heat losses. In the present setup, however, the cavity is instead fully wrapped in some layers of aluminum foil in order to mimic such a shielding. Generally, the presence of a helium vessel is considered as beneficial for the applicability of the method since it reduces radiation losses and could also help in temperature homogenization when filled with a thermally conductive medium, such as gaseous helium, even more if the gas is under convective or driven movement. In this study, a helium vessel would hinder the mounting of temperature sensors on the cavity's outer side, which here caused the choice of an undressed cavity.

Figure 2 depicts the cavity equipped with the bead-pull setup mounted onto the support structure before being inserted into HoBiCaT.

B. TTF-III fundamental power coupler

The FPC is the original version of the TTF-III power coupler without an active inner-conductor cooling, as described in [18]. Operating the niobium cavity above room temperature inevitably reduces (compared to superconducting conditions) its unloaded Q value by about 6 orders of magnitude, making the coupler significantly undercoupled, so most of the rf power gets reflected. This

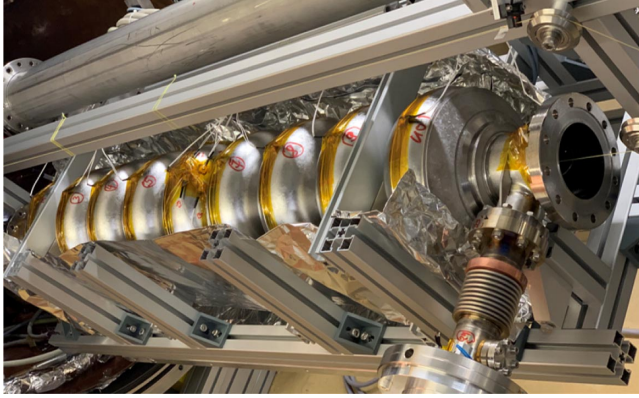


FIG. 2. TESLA 9-cell cavity test setup under preparation outside HoBiCat. PT100 temperature sensors are mounted with thermal paste and fixed under Kapton® tape. The “cold part” of the TTF-III coupler is installed. Aramid cord with guiding pulleys needed for the bead-pull measurements is visible. The top cover of the aluminum foil wrapping is taken off.

severe undercoupling is a drawback of the rf heating approach, making a variable coupler with a wide coupling range strongly desirable. In the described setup, this was achieved by compressing the cold-part bellows to its mechanical limit, as shown in Fig. 2, thereby shifting the FPC tip by an additional 5.9 mm into the beam pipe for an external coupling of $Q_{\text{ext}} = 1 \times 10^6$ [19].

An almost full reflection further increases the field strength at the maxima of the standing wave pattern by a factor of 2 compared to a purely propagating wave. If such a maximum is found in the dielectric FPC windows, the local power dissipation may be increased by a factor of 4. In order to minimize the risk of damaging the coupler during these experiments and in accordance with previous studies [18,20], for the forward power (P_{fwd}) of the amplifier, an administrative limit of 2 kW was set.

Nevertheless, higher power levels may be considered, since modified TTF-type fundamental power coupler designs rated for cw operation at power levels exceeding 4 kW are available. Examples of those are the modifications studied at HZB [18], the modified TTF-III coupler developed for the LCLS-II project [21,22], and the successful testing of more than 20 couplers with 7 kW in cw standing wave operation, as reported in [23,24]. Common to those designs is an active cooling of the inner conductor, which was not available in the present study.

C. rf measurement and power supply setup

In the rf system, a Rohde & Schwarz ZNB20 vector network analyzer (VNA) forms the core of the driving rf source and the S_{21} scattering-parameter measurement loop. The VNA port 1 drives a Cryoelectra CRE-350F 1.3 GHz, 15 kW cw solid-state power amplifier. The signal from the cavity’s pickup antenna is fed back to the VNA port 2 to complete the S_{21} measurement loop.

The S_{21} measurement is needed both for frequency tuning and bead-pull field profile measurements. The amplifier’s output is connected to the cavity’s FPC via an air-cooled semirigid coaxial cable (RFS Heliflex® HCA295-50) followed by a waveguide and a circulator terminated with a water-cooled load.

The forward power to the cavity, P_{fwd} , is measured using a calibrated directional coupler and a power meter located between the circulator and the FPC. This ensures that the incoming rf power to the FPC is controlled throughout the heating process and that the administrative limit is respected to protect the FPC. The reflected power P_{ref} is measured by using a second directional coupler between the circulator and the load (cf. Fig. 1). Since a measurement may span a frequency band of up to 2 MHz, the P_{ref} -data are less suitable for the power balance analysis, because they are determined by several dispersive quantities, such as the phase advance in the cabling and the FPC, and the cavity coupling crossing the resonance.

The setup is highly versatile. First, it allows driving the power amplifier directly from the VNA output power for direct monitoring of the passband mode frequencies and coupling strengths. Accordingly, it enables manual tracking of the resonance frequency during the thermal expansion of the cavity, which implies a frequency shift. Furthermore, it provides a recording of the phase shift during the bead-pull measurements.

D. Bead-pull system

To implement the bead-pull field measuring technique, an aluminum sphere is threaded and fixed onto a 0.4 mm-diameter braided aramid cord (“Arabraid,” Kanirope® GmbH, Dortmund, Germany), which is specified to be heat-resistant up to 500 °C. The cord is guided over several metallic pulleys (cf. Fig. 2), one of which is spring-loaded to apply a constant tension and compensate for the negative thermal expansion of the aramid cord, while another is driven by a stepper motor. The thread is aligned with the geometric cavity axis. Deviations due to weight forces are estimated to be less than 2 mm.

The on-axis bead-pull measurement system allows for direct measurements of the field distribution for the fundamental TM_{010} passband modes. As it is well known for small perturbations of volume δv , the classical formulation by Maier and Slater [25] leads to the form of the phase/frequency perturbation Eq. (1) [26].

$$\frac{1}{2Q} \tan[\Delta\phi(S_{21})] = \frac{\Delta f}{f_0} = -\frac{\delta v}{4U} \left(\epsilon_0 E^2 - \frac{1}{2} \mu_0 H^2 \right). \quad (1)$$

In this expression, U denotes the stored field energy, Q denotes the mode’s quality factor, ϵ_0 denotes the vacuum permittivity, μ_0 denotes the vacuum permeability, and E and H denote the average electric and magnetic field in the bead volume δv . The relative shift of the resonance

frequency $\Delta f/f_0$ can also be expressed in terms of the phase shift [26].

Using the small-angle approximation $\tan(\phi) = \phi$, which applies for small perturbations, the following holds for modes of TM_{0np} -type (monopole TM-modes), such as those of the fundamental passband:

$$\Delta\phi(S_{21}) \propto E^2. \quad (2)$$

Therefore, the measurement of the phase shift in this configuration provides the distribution of the electric field on the axis of the TESLA cavity, which, in some approximation, also allows one to infer the distribution of wall losses along the cavity. A VNA is ideally suited for time-based phase measurements during the bead's movement. We demonstrated this here with high power levels, including the power amplifier in the measurement loop. The amplifier's own phase noise is considered negligible, while care was needed (fast measurements, temporarily reduced power) to ensure thermal stability of the cavity during the bead-pull measurements to avoid a significant thermally induced transmission phase drift.

E. Temperature diagnostic

For precise measurement of the cavity temperature, PT100 temperature sensors are mounted on the outer surface radius of each cell using thermal paste and Kapton[®] tape (cf. Fig. 2). Additional sensors are installed on the beam pipes, on the FPC, and at several positions on the cavity support frame for temperature monitoring.

As discussed, the resonance frequency also shifts significantly due to the thermal expansion of the niobium with increased temperatures, which, under the assumption of an isotropic heating, follows:

$$\Delta f_{\text{thermal}} = f - f_0 \approx -f_0 \alpha \Delta T, \quad (3)$$

with a thermal expansion coefficient of $\alpha = 7.4 \times 10^{-6}/\text{K}$ for niobium at 400 K [27] (p. 236). This highlights the need to track the resonance frequency (in this case, manually) during the heating process. The frequency shift can be estimated by $\Delta f_{\text{thermal}}/\Delta T \approx 9.6 \text{ kHz/K}$ at 1.3 GHz. A similar value can be inferred from Fig. 3.

III. EXPERIMENTAL RESULTS

As a preliminary measurement, the gain curve of the amplifier was measured under fully reflective conditions, using a waveguide terminated with a metal plate instead of the FPC, with the reflected power directed through the circulator into the water load. In addition, frequency spectra of the fundamental passband were investigated at different cavity temperatures.

Figure 3 shows the measured S_{21} for the fundamental TM_{010} passband at two different temperatures as an illustration of the expected heat-induced frequency deviation.

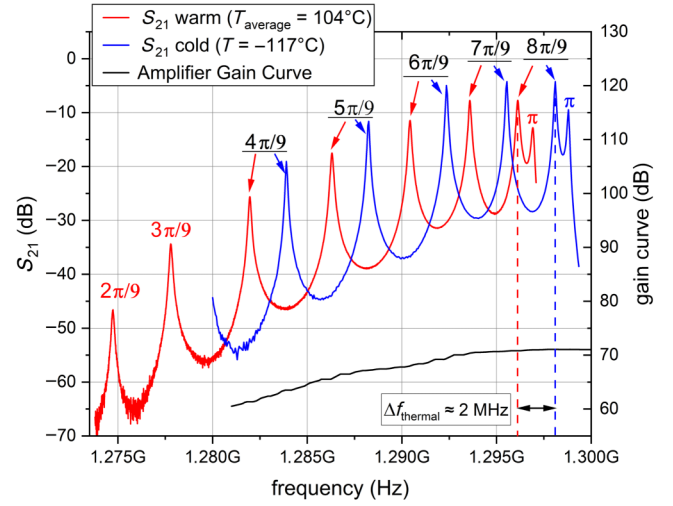


FIG. 3. Cavity passband measured at $T = -117^\circ\text{C}$ (blue) and at $T_{\text{avg}} = 104^\circ\text{C}$ (red). Note that the frequency dependent amplifier gain (black, here depicted for the maximum power of 9.5 kW at the load) will skew the measured spectra.

The red graph is recorded for the warm TESLA cavity with an average cell temperature of $T_{\text{avg}} = 104^\circ\text{C}$ (mean cell temperature after a heating experiment; nonuniform distribution, not shown), while the blue graph shows the measured spectrum of the cold cavity, with all cells held at a uniform temperature of $T = -117^\circ\text{C}$. The resonant modes are labeled with their common designations.

Since the scattering-parameters measurement is influenced by the coupling through the FPC, the field distribution inside the cavity, the coupling of the pickup antenna and in this particular setup also the amplifier gain curve (shown in black), the true power coupling can only be inferred to a limited extent. However, it can be clearly seen that the $8\pi/9$ -, the $7\pi/9$ -, and the $6\pi/9$ -modes exhibit the strongest transmission patterns. As a second step, and to ensure the validity of subsequent conclusions, the baseline model (cf. Fig. 4) was benchmarked by comparing the field profiles obtained from simulations with those measured experimentally using the bead-pull technique. In Fig. 5, a comparison is shown between the measured bead-pull field profile at room temperature (295 K) normalized to unity and a likewise normalized squared electric-field profile from cst studio suite[®] 2024 [29] simulation along the cavity axis for the π -, $8\pi/9$ -, and $7\pi/9$ -modes. The baseline geometry (cf. Fig. 4) of the TESLA 9-cell cavity, used for the eigenmode simulation, was extracted from [28], including asymmetric end cells. Therefore, the field distribution of the π -mode is not expected to be perfectly flat (cf. Fig. 5, red curve). However, the measurement reveals that the field flatness of the tested cavity exhibits an even stronger asymmetry, most prominently visible in the π -mode, but also clearly apparent in the $8\pi/9$ -mode. The measurement of the $7\pi/9$ -mode shows a more even field distribution with only small deviations from symmetry. Thus, only a relative

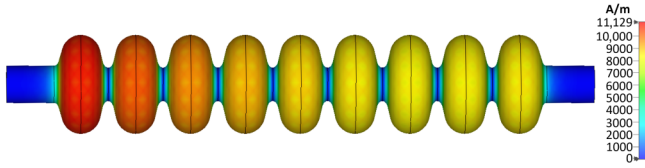


FIG. 4. cst model used for field profile simulations, here with the simulated wall current distribution of the π -mode and normalized to 1 J of stored energy. The model geometry includes two slightly asymmetric end cells and identical inner dumbbells as parameterized in [28]. The beam pipes are shortened, no ports were included. The simulated pattern is remarkably not flat, which resembles the measured properties to a certain extent (cf. Fig. 5).

difference of 15% is observed between cells 4 and 6, whereas the field distribution in the edge cells (C1 and C9) exhibits symmetric field strengths consistent with the simulation. Similarly, the remaining lower passband modes ($6\pi/9, \dots, 1\pi/9$) are close to symmetry (field distributions not shown).

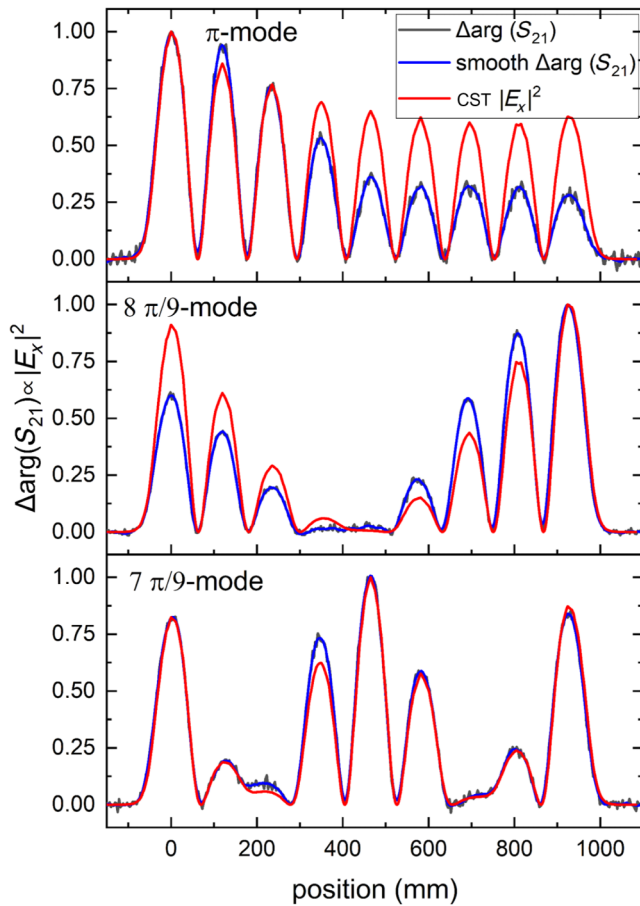


FIG. 5. Comparison between normalized phase shift of the bead-pull measurement (raw black, smooth blue) and the on axis $|E_x|^2$ -field from cst studio suite®-simulation (red) for the π -, the $8\pi/9$ -, and the $7\pi/9$ -mode.

One can conclude that rf heating of multicell cavities almost inevitably has to rely on uneven power deposition profiles. That is a natural property of all but the 0- and π -modes even in an ideally tuned cavity and often is enhanced by tuning imperfections. So it is key to understand and quantify the effect of uneven field distributions on the inhomogeneity of temperature profiles generated by rf heating and to develop strategies to reduce it as far as possible.

To this end, a test campaign was started in order to correlate the field profiles with cell surface temperatures. These results will not only be used to understand the dynamics of the rf heating but also to serve in parts both as training and test data to parameterize and to validate the numerical model presented in the following section. A total of 14 measurement runs were carried out using the described setup. Each run consisted of a heating phase, lasting between 2 and 6 h, and a cooling phase of at least 20 h to ensure sufficient cooldown of the cavity and thus identical initial conditions before the next cycle. For comparability, the amplifier output was kept in a range of 1.8–2.0 kW throughout the entire course of experiments with a few exceptions of reduced power needed to assess and handle unexpected events. The actual P_{fwd} power level was recorded and is shown in several plots. Twelve of the measurement runs were started at room temperature of about 300 K (27 °C)¹ (referring to the initial temperature of both the cavity and the HoBiCaT environment), while two additional measurements were started at lower cavity temperatures of 150 K (−123 °C) and 170 K (−103 °C); this was due to simultaneous (cryogenic) measurements for other experiments in HoBiCaT.

In order to gain some phenomenological understanding of the heating characteristics of different modes, it is valuable to compare their measured field profiles with the highest cell temperatures taken close to saturation, as shown in Figs. 6–8. It should be noted that in the fundamental TM_{010} passband the electric field peaks on the cavity axis, accompanied by a magnetic field and a wall current distribution both of azimuthal symmetry, the latter with highest current densities, and consequently highest power deposition, near the cell equators. Therefore, the cell-to-cell profile of the power deposition mainly resembles that of the electric field measured by the bead-pull procedure (cf. also Figs. 14 and 17). This does not necessarily hold for the temperature distribution as well, which also reflects all thermal power propagation through radiation and heat conduction in the cavity wall (cf. Figs. 7 and 8).

Figure 6 shows the results obtained for the π -mode after an rf heating run of 3 h. Since the coupling of the π -mode is

¹For improved readability, measured and simulated values in Kelvin are additionally provided in Celsius (in parentheses), rounded.

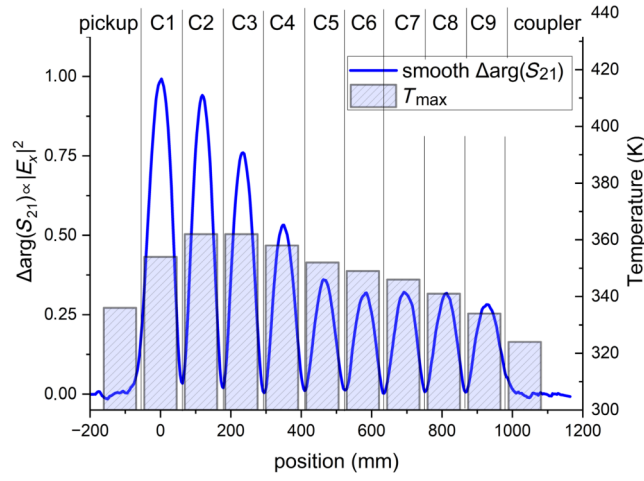


FIG. 6. Comparison of the π -mode initial field distribution along the cavity axis (bead-pull measurement at room temperature, line) and the distribution of the maximum cell temperatures (measured at the cavity equator surface after a heating period of 3 h at a P_{fwd} of approximately 1.8 kW, bars).

reduced by more than 5 dB compared to the $8\pi/9$ -mode and the $7\pi/9$ -mode, the maximum temperature of 362 K (89°C) for cells C2 and C3 is lower than when those modes are used. As expected, the nonuniform field distribution led to nonuniform maximum temperatures in the cells [C9 reached 334 K (61°C)].

This corresponds to a temperature difference of $\Delta T = 28$ K between the maximum in cells C2, C3 and the minimum in cell C9. It should be noted that the beam pipes also heat up, even though no field was measured there. Furthermore, and opposite to intuition, cell C1 does not reach the highest temperature despite having the highest field energy according to the bead-pull measurement. The reason can be attributed to heat transferred into the beam pipe area by thermal conduction.

The $8\pi/9$ -mode was used in the experiment shown in Fig. 7, which compares the maximum cell surface temperature after 2 h of rf heating and the mode's field distribution. Unlike the π -mode, the $8\pi/9$ -mode exhibits relatively strong coupling, resulting in higher rf power levels in the cavity and consequently higher heating rates. The maximum cell surface temperature reached is 429 K (156°C) at cell C8, while the lowest cell temperature was measured at only 340 K (67°C) at cell C1, corresponding to a temperature spread of $\Delta T = 89$ K between them. As with the π -mode, the initially asymmetric field distribution leads to asymmetric heating behavior of the TESLA cavity.

It should be noted that cells C4 and C5 also heat up, even though their on-axis field is close to zero. In this case, heat transfer occurs through thermal conduction and radiation from the neighboring cells. Additionally, a strong temperature rise of the beam pipe on the coupler side can be observed. Reaching 380 K (107°C), it is heated more strongly than cells C1 to C5, even though a significant

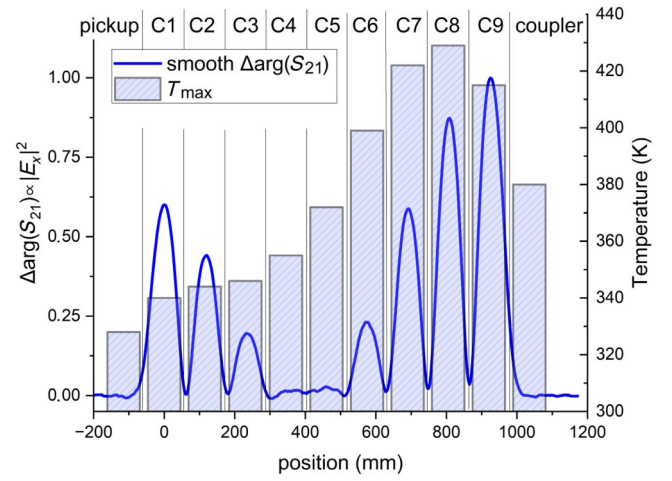


FIG. 7. Comparison of the $8\pi/9$ -mode initial field distribution along the cavity axis (bead-pull measurement at room temperature, line) and the distribution of the maximum cell temperatures (measured at the cavity equator surface after a heating period of 2 h at a P_{fwd} of approximately 1.8 kW, bars).

initial field distribution was measured in cells C1 to C3. This illustrates the impact of both heat conduction from the neighboring cells and power deposited in the coupler, also driving the coupler-side beam pipe. Figure 17 shows the power deposition as computed by the parameter optimization and how it shifted during the course of the heating process.

In a similar style, Fig. 8 shows the initial field distribution of the $7\pi/9$ -mode in comparison to the temperatures reached after two hours of rf-heating. Here, the more symmetric field distribution leads to a more uniform heating profile. Accordingly, end cells C1 and C9 differ by

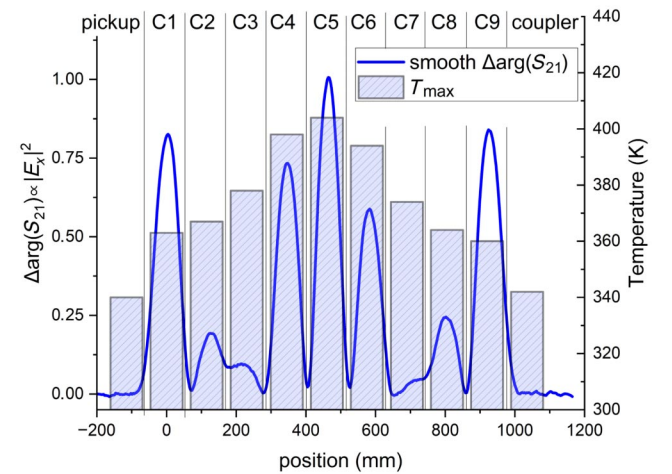


FIG. 8. Comparison of the $7\pi/9$ -mode initial field distribution along the cavity axis (bead-pull measurement at room temperature, line) and the distribution of the maximum cell temperatures (measured at the cavity equator surface after a 2 h heating period at a P_{fwd} of approximately 1.8 kW, bars).

only $\Delta T = 3$ K, reaching 363 K (90 °C) and 360 K (87 °C), respectively. The highest cell temperature is observed in the middle cell C5, reaching 404 K (131 °C). The resulting temperature spread amounts to $\Delta T = 44$ K between the hottest and the coldest cell surface, which is far from uniform.

Additionally, to provide insight into the heating dynamics and the temporal temperature evolution of the individual cavity cells during the rf heating process, the temperature versus time traces for the π -, $8\pi/9$ -, and $7\pi/9$ -modes are depicted in Figs. 9(a)–9(c). The cell equator surface temperatures are shown in color, while the beam pipes are represented in gray. To visually identify potential symmetric or asymmetric heating behavior, identical colors with different line styles are mirrored with respect to cell C5. In addition, P_{fwd} is plotted (solid black). It can be inferred that P_{fwd} increases abruptly with an initial overshoot followed by a slight decay. This behavior is found routinely and can be attributed to internal thermal drift of amplifier components. Furthermore, short drops in P_{fwd} can be observed. Those occurred whenever the power meter acquired a reading at the same time the VNA frequency setting was manually retuned. This action induced a very brief interruption of the rf power, which reduced the delivered average power by less than 0.1%.

In Fig. 9(a), the results obtained for the π -mode are depicted. As can be observed, once a significant amount of P_{fwd} is provided by the amplifier, the cell surface temperatures, represented by the colored curves, begin to rise. With a temporal delay, the temperatures of the beam pipes, shown in gray and dashed gray, also increase. This indicates that the heating power reaches the beam pipe temperature sensor positions only after some delay, presumably due to heat conduction in the end-group region.

As the cell temperatures rise during the 3-h heating period, the asymmetric heating behavior quickly becomes evident in the diagram through the increasing divergence of curves with identical colors but different line styles. It can also be observed that once the rf power is switched off, the cavity cells quickly initiate the cooldown process while the beam pipe continues to increase in temperature for a short period. This provides additional evidence for thermal coupling to the cavity via heat conduction and/or thermal radiation.

Figure 9(b) shows the temperature evolution of the $8\pi/9$ -mode. During the heating process, a vacuum event was detected in the TTF coupler. As this was the first measurement campaign after assembly, it is likely that this event was caused by conditioning-related outgassing. In the black P_{fwd} trace, a precautionary shutdown of the rf power can be observed. This happened after approximately one hour in order to prevent potential arcing in the coupler. After the vacuum level stabilized again, the power was raised in two steps back to approximately 1.8 kW. Prior to switching off the rf power, P_{fwd} was reduced in two steps

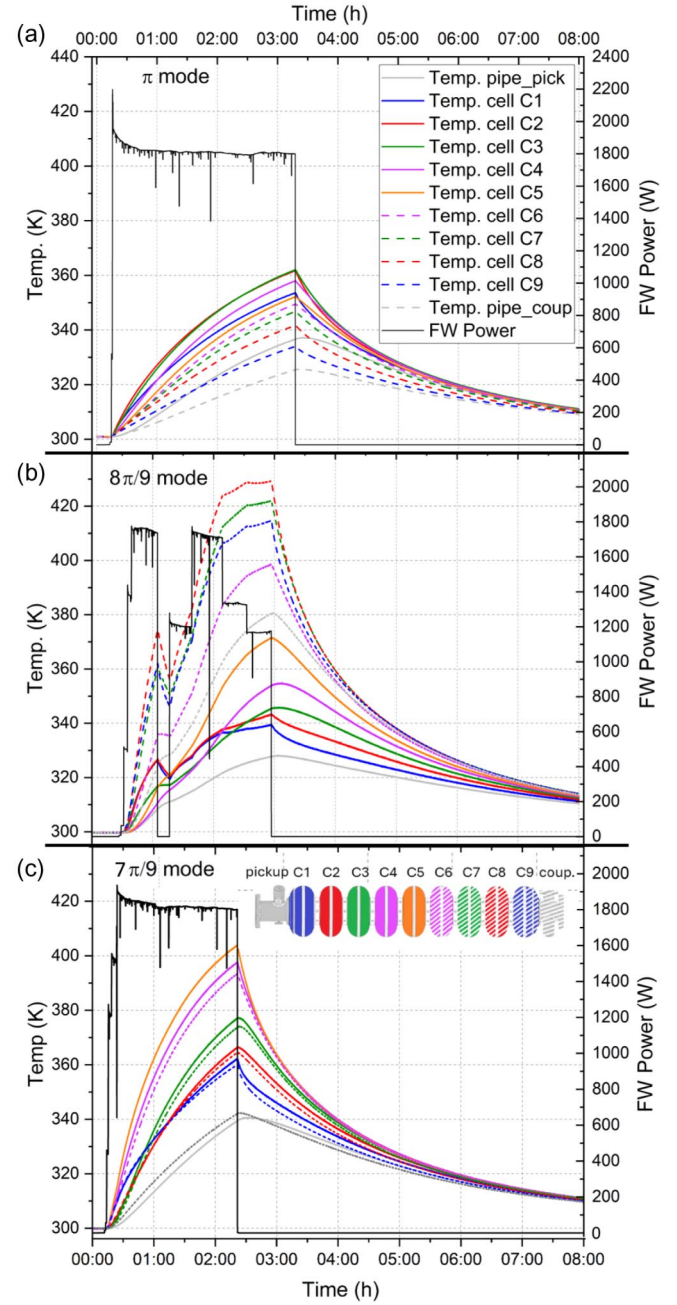


FIG. 9. Time-dependent temperature measurements at a single equator location of each of the cavity cells (colored) and at the beam pipes (gray) during rf heating experiments in the TM_{010} π -mode (a), $8\pi/9$ -mode (b), and $7\pi/9$ -mode (c). The forward rf power measured by the power meter is shown in black.

in an attempt to reach a thermally stable cavity condition with a minimal frequency drift. As already shown in Fig. 7, it can again be observed that the cavity heats up very asymmetrically in this mode. It is clearly visible that cells with identical color markings exhibit a large temperature difference. For example, cells C2 and C8 differ by $\Delta T = 85$ K.

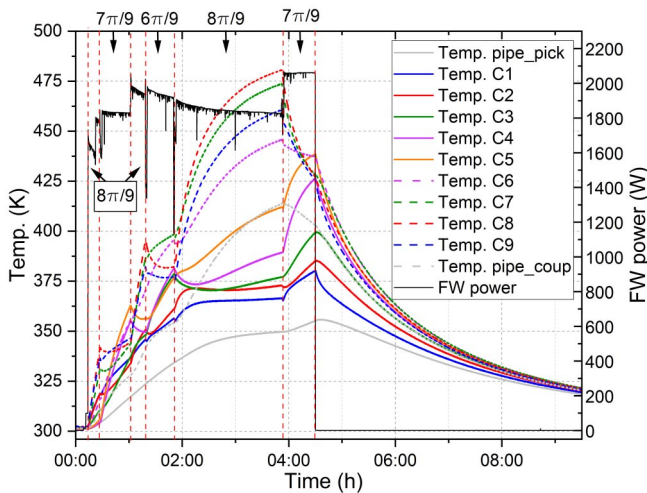


FIG. 10. Multimode operation time-dependent temperature measurements for each cavity cell (colored) and the beam pipes (gray). The smoothed P_{fwd} measured by the power meter is shown in black. The different heating phases corresponding to the various modes are separated by red dashed lines.

Figure 9(c) shows the temperature evolution during two hours of resonant rf heating in the $7\pi/9$ -mode. In general, the temperatures of the cells with identical colors lie close together, indicating a more symmetric field distribution and thus more homogeneous heating behavior. In addition to the beam pipes, cells C2 and C3 as well as cells C7 and C8 exhibit a delayed temperature response and a positive curvature shortly after switching on the rf power. Referring back to Fig. 8, it can be observed that although these particular cells show a relatively low initial field amplitude compared to the others, they can still be heated, similar to the beam pipes, via thermal conduction and radiation from the neighboring cells.

The experience with heating using single modes confirmed the conclusion that their individual use is not suitable to achieve sufficient temperature homogeneity. This is in agreement with the field profiles both seen in the field simulation and the bead-pull measurements. It is observed that the $7\pi/9$ -mode predominantly heats the inner cells C4, C5, and C6, while the $8\pi/9$ -mode leads to enhanced heating of the cells C7, C8, and C9 (cf. Fig. 9). This raises the question of whether switching between the modes of the fundamental passband is beneficial for achieving higher and/or more homogeneous cell temperatures. Here we will denote such an approach as mode alternation. In order to test this experimentally, a heating run using three modes was performed (cf. Fig. 10). In this run, switching of the modes was not optimized but was based solely on observation of the temperature evolution of the individual cells. Temperatures higher than 473 K (200 °C) were reached in cells C7 and C8 after some initial mode switches, followed by a period of about 1 h using the $8\pi/9$ -mode. Whilst this marked the highest

temperatures observed in the study, homogeneity was poor with temperatures measured in cells C1 to C5 about 100 K lower. This span was reduced to 60 K by finally switching to the $7\pi/9$ -mode for about 20 min, both raising the temperatures of the cells previously colder and lowering that of the hottest ones. While the temperature evolution delivered by this actual heating sequence was not homogeneous enough for a baking process, it illustrated the additional degree of freedom of the mode alternation approach compared with single mode heating.

With the help of an accurate modeling of the heating process and properly chosen switching criteria, which typically may be temperature thresholds in individual cells, a much better homogeneity may be achieved. This will be illustrated once the modeling is described.

The experimental results demonstrate that the TESLA cavity can be rf heated within certain limits under the power restriction imposed by the TTF-III coupler. The lack of field flatness in the π -mode, as well as in the $8\pi/9$ -mode, which is actually best suited for rf heating due to the higher coupling strength, indicates that the cavity should first undergo mechanical tuning to achieve a proper field flatness level. Furthermore, the question arises of whether merely removing the power limitation of the coupler and tuning the cavity would be sufficient to reach evenly distributed cavity temperatures above 200 °C. These points are addressed in the following chapter.

IV. MODELING

The experimental results demonstrate that the temperature distribution and dynamics in multicell cavities are highly complex. Since precise temperature control is required to benefit from mid-T baking [4], a model capable of predicting the temperature distribution in multicell cavities is required. In this section, a numerical method is developed to predict the thermal behavior of the TESLA cavity during a baking run. This numerical method is based on a thermal model and trained with the data experimentally obtained from the measurement campaigns in order to make predictions. In this way, we are then capable of estimating factors such as the minimum power required, the thermal drift of the different cells, and the final temperatures attainable in the steady state. The code is developed in PYTHON and the debugging was supported by OpenAI's ChatGPT (GPT-5.1), which was used as an interactive programming assistant [30].

Figure 11 provides a schematic overview of the assumptions made for the model development. The model structure essentially is a linear chain of 11 nodes, each of them featuring a temperature, a heat capacity, radiative and conductive power exchange with next neighbors, radiative power exchange with the environment and a deposited thermal power. The nodes are indexed from node 0, which represents the pickup beam pipe, nodes 1–9, which

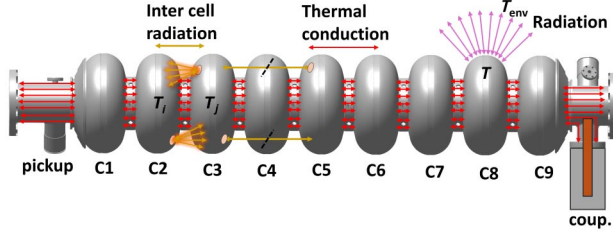


FIG. 11. Illustration of the different channels of conductive (red) and radiative power exchange (purple: to the environment, yellow: in between neighboring cells) and the allocation of the 11 temperature quantities simulated in the model.

correspond to cells C1–C9, to node 10 representing the coupler-side beam pipe.

For simplicity, radiative exchange between next-nearest neighboring cells and beyond is neglected. However, due to the hollow geometry of the TESLA cavity, small radiative view factors A_{ij} between nonadjacent cells do exist. Nevertheless, those are neglected since, for general geometric reasons, they are much smaller than next-neighbor contributions and would significantly raise the number of unknown parameters. The model as used is able to predict the measured temperature time dependencies with an error smaller than 2 K (cf. Fig. 12), which is understood as sufficiently accurate. This leads to a system of 11 ordinary differential equations of the form:

$$C_i \frac{dT_i}{dt} = \sum_j K_{ij} T_j \underset{\text{heat conduction}}{\quad} - \epsilon \sigma A_i (T_i^4 - T_{\text{env}}^4) \underset{\text{rad. to the environment}}{\quad} - \sum_{j \neq i} \epsilon \sigma A_{ij} (T_i^4 - T_j^4) \underset{\text{rad. between cells}}{\quad} + Q_i \underset{\text{heating term}}{\quad}. \quad (4)$$

Herein denotes $C_i = m_i \cdot c_{\text{Nb}}$ the heat capacity of the i th node with m_i the mass of the node and c_{Nb} the specific heat capacity of niobium. In matrix form, the heat capacity matrix is given by

$$\mathbf{C} = c_{\text{Nb}} \begin{pmatrix} \text{mass_end1} & 0 & 0 & \dots & 0 \\ 0 & \text{mass_endcell} & 0 & \dots & 0 \\ 0 & 0 & \text{mass_cells} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & \text{mass_end2} \end{pmatrix}.$$

Furthermore, Eq. (4) includes the emissivity ϵ , the Stefan-Boltzmann constant σ , the surface area of the i th node A_i , the ambient temperature T_{env} , and the effective radiative exchange area between nodes i and j A_{ij} . Radiative coupling is restricted to nearest neighbors only ($A_{ij} = 0$ for all nonadjacent node pairs. As a test, the next-nearest neighbor was included in the model in a single

optimization run. However, this did not reduce the overall approximation error, and the corresponding view factor was found to be only about 5% of that of the nearest neighbors. It was therefore omitted.) The corresponding matrix representation is given by

$$\mathbf{A} = \begin{pmatrix} 0 & A_{01} & 0 & \dots & 0 \\ A_{01} & 0 & A_{12} & \ddots & \vdots \\ 0 & A_{12} & 0 & \ddots & 0 \\ \vdots & \ddots & \ddots & 0 & A_{9,10} \\ 0 & \dots & 0 & A_{9,10} & 0 \end{pmatrix},$$

where each nonzero entry is defined as $A_{ij} = (A_i f_i, A_j f_j)$ with:

$$f_i = \begin{cases} A_{\text{fac_end1}}, & i = 0, \\ A_{\text{fac_cells}}, & 1 \leq i \leq 9, \\ A_{\text{fac_end2}}, & i = 10. \end{cases}$$

The effective radiative exchange area A_{ij} is represented by a symmetric band matrix.

It should be noted that the ambient temperature did not change significantly during the measurement periods, which is due to the large thermal capacity of the HoBiCaT vessel. For example, at a temperature measurement point on the base plate beneath the cavity mounting frame, a temperature increase of 2 K/h was measured at a P_{fwd} of 1.8 kW. Therefore, it is a reasonable approximation to keep T_{env} as a constant parameter in the simulations. To ensure energy conservation, the matrix coefficients K_{ij} are defined in terms of the pairwise thermal conductances k_{ij} as follows:

$$K_{ij} = \begin{cases} k_{ij}, & i \neq j, \\ -\sum_{k \neq i} k_{ik}, & i = j. \end{cases}$$

Here, k_{ij} denotes the thermal conductance between nodes i and j . This construction results in a tridiagonal matrix with zero row sum, as shown below:

$$\mathbf{K} = \begin{pmatrix} -k_{\text{end1}} & k_{\text{end1}} & 0 & \dots & 0 \\ k_{\text{end1}} & -(k_{\text{end1}} + k_{\text{mid}}) & k_{\text{mid}} & \ddots & \vdots \\ 0 & k_{\text{mid}} & -2k_{\text{mid}} & \ddots & 0 \\ \vdots & \ddots & \ddots & \ddots & k_{\text{end2}} \\ 0 & \dots & 0 & k_{\text{end2}} & -k_{\text{end2}} \end{pmatrix}.$$

In this representation, adjacent inner cells are coupled by a thermal conductance k_{mid} , whereas distinct conductances k_{end1} and k_{end2} are assigned at the two cavity boundaries. Q_i denotes the heat input power in cell i .

In the first step, the differential evolution parameter optimization algorithm from the SCIPY package (available

for PYTHON 3.13 [31]) was applied to derive the free model parameters, as they are listed in Table I from the measured temperature cooldown curves ($Q_i = 0$). To ensure convergence within reasonable computation times and to exclude fixed points outside the range of physical plausibility, the parameter boundaries were restricted in advance. The parameter boundaries and the optimized values are shown in Table I. It should also be noted that the thermal conductances k_{end_1} and k_{end_2} are deliberately treated separately, since the pipe lengths and the positions of the PT100 sensors are at different distances from the nearest cell, and therefore different thermal conductances are to be expected. Since the coupler is

directly flanged to the cavity, thereby influencing the modeled mass and surface area on that side, the parameter limits were chosen more generously here.

The parameter optimization is carried out in a single run using the cooling curve sets of the five different modes as a single common dataset. Thus, data with different starting temperatures were combined in a common dataset in order to gain the system-specific parameters. It should be noted that three approximately symmetric initial conditions, derived from the cooling curves of the heating campaigns at $5\pi/9$ -, $6\pi/9$ -, and $7\pi/9$ -, as well as the asymmetric initial conditions of the $8\pi/9$ - and π -modes, were used. The emissivity value of $\varepsilon = 0.13$ obtained from the optimization algorithm is in good agreement with values expected for a shiny metallic surface with an oxide layer, as assumed for the niobium cavity studied here. The optimized $\text{mass}_{\text{cells}}$ of 6.69 kg (see Table I) is in good agreement with the CAD value of 6.66 kg, and the optimized $\text{mass}_{\text{endcell}}$ of 4.19 kg coincides with the CAD value within the given accuracy. The quoted uncertainties are derived from a limited statistical sample of five simulations and should therefore be considered indicative rather than exact error bounds.

To evaluate the accuracy of the parameter optimization and to rule out any inconsistencies, temperature simulation runs of the model were plotted together with the corresponding measurement data for comparison. Figure 12 shows two comparisons of measured cooling curves (colored and gray curves), with the corresponding simulations (black dashed) for the $8\pi/9$ -mode (top) and the $7\pi/9$ -mode (bottom). The simulation curves accurately follow their corresponding measurement values. Below each plot, the temperature difference between measurement and simulation is shown. The deviation between simulation and measurement never exceeds 2.0 K; the

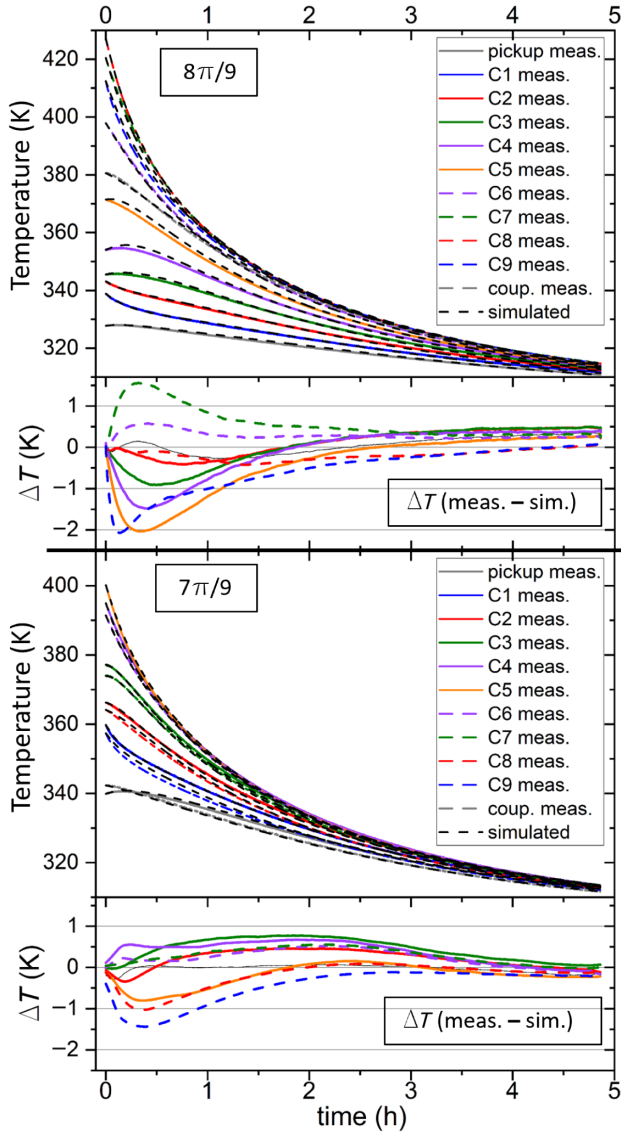


FIG. 12. Measured cooling curves, displayed in color (cells) and gray (beam pipes), of the $8\pi/9$ -mode (top) and the $7\pi/9$ -mode (bottom). Corresponding simulations black dashed. The cell-temperature difference ΔT between measurement and simulation is shown below each plot.

TABLE I. Imposed algorithm parameter limits (“range”) and optimized values (“value”).

Parameter name	Range	Value	Unit
$A_{\text{fac_end}_1}$	(0.05, 0.5)	0.07 (+0.1)	%
$A_{\text{fac_end}_2}$	(0.05, 0.5)	0.22 (± 0.1)	%
$A_{\text{fac_cells}}$	(0.1, 0.5)	0.47 (± 0.1)	%
k_{mid}	(0.1, 1.0)	0.76 (± 0.03)	W/K
k_{end_1}	(0.1, 0.5)	0.30 (± 0.05)	W/K
k_{end_2}	(0.1, 0.5)	0.43 (± 0.09)	W/K
emissivity	(0.05, 0.5)	0.13 (± 0.02)	%
$\text{mass}_{\text{end}_1}$	(2.75, 3.5)	2.93 (± 0.2)	kg
$\text{mass}_{\text{end}_2}$	(2.75, 10.0)	9.49 (± 0.5)	kg
$\text{mass}_{\text{cells}}$	(2.60, 2.8)	2.69 (± 0.02)	kg
$\text{mass}_{\text{endcell}}$	(4.0, 4.3)	4.19 (± 0.04)	kg
$A_{\text{surface_endcell}}$	(0.05, 0.12)	0.11 (± 0.01)	m^2
$A_{\text{surface_end}_1}$	(0.02, 0.2)	0.10 (± 0.04)	m^2
$A_{\text{surface_end}_2}$	(0.02, 0.5)	0.30 (± 0.1)	m^2
$A_{\text{surface_midcell}}$	(0.05, 0.1)	0.07 (± 0.01)	m^2

maximum deviation can be observed at cells C5 and C9 in the upper plot. With very few exceptions, the deviations remain within a range of ± 1.5 K for both the $8\pi/9$ -mode and the $7\pi/9$ -mode.

These deviations are attributed to the intrinsic simplifications made in the model, i.e. the reduction of the surface temperature distribution to a set of 11 discrete values, the assumed absence of interactions beyond the nearest neighbors, the neglect of temperature variations of HoBiCaT's outer wall and similar effects. Nevertheless, the model provides sufficient accuracy to address the initial research questions. In a second step, the model is used to determine a spatial heating pattern, i.e., a distribution of heating power levels Q_i in the individual cavity cells using the system parameters listed in Table I. This constitutes a second instance of the optimization procedure. The time dependence of the incident rf power, individually measured for each heating experiment (cf. the black dotted lines in Figs. 13 and 15), was used as a common multiplicative factor for all Q_i within a single simulation run.

An example that compares measured and model-generated temperature curves is shown in Fig. 13. Here the heating was done using the $7\pi/9$ -mode [cf. also Fig. 9(c)]. The simulated values (black dashed lines) are consistently close to the respective experimental data. The average heating power determined by the model is 145 W, a quantity which can be easily derived from the optimized Q_i values. In comparison with the 1.8 kW average forward power measured in this experiment this illustrates the poor rf coupling, causing strong reflection.

To evaluate whether a constant heating-power distribution is sufficient for the model or whether a field shift between cells or a significant field reduction occurs during heating caused by changes in the niobium surface resistance, simulated heating-power distributions are compared with bead-pull measurements at different temperatures. In Fig. 14, the field distributions at room temperature [$T = 300$ K (27°C), red] and at an average cell temperature of $T_{\text{avg}} = 382$ K (109°C) (black) are compared. It can be seen that the field in the cells weakens slightly, but the reduction is distributed uniformly across all cells. A similar plot is shown for the $8\pi/9$ -mode in Fig. 17. Furthermore, both plots show the heating-power distribution obtained from the simulation, displayed as bar charts. At first glance, both simulated heating patterns correlate very well with the measured field distributions. The most significant deviation is found at the beam pipe of the coupler side: whilst there is only a vanishing on-axis field strength measured by the bead-pull, a significant power deposition is computed by the optimization. This discrepancy is not found at the pick-up-side beam pipe, which leads to the conclusion of coupler-specific power dissipation there adding to the thermal balance. It is noteworthy that the simulations assign a non-negligible fraction of the total heating power to the coupler beam pipe. Simulations

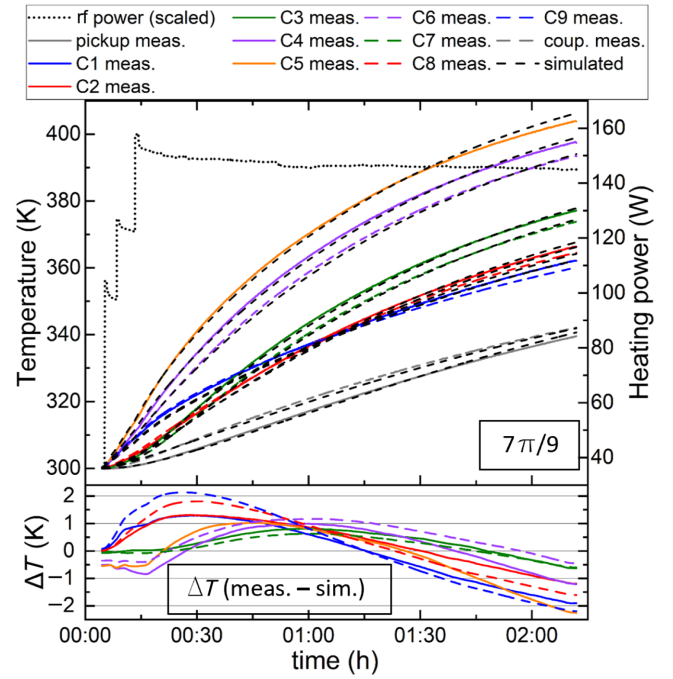


FIG. 13. Measured rf heating curves of the $7\pi/9$ -mode are shown in color and gray. The black dashed lines represent the corresponding simulations, while the black dotted line shows the effective total heating power obtained from the simulation, scaled from the P_{fwd} power meter readout. The temperature difference ΔT between measured and simulated cell temperature is shown below.

in which the energy deposition in this region was artificially suppressed led to substantial deviations in the simulated temperature evolution. Rather, these results indicate that the coupler itself heats up during the rf heating process, as also observed experimentally, and contributes to the energy deposition into the cavity by thermal conduction or radiation. With an initially symmetric field distribution, the heating behavior is likewise symmetric, and as shown in Fig. 8, this results in a correspondingly symmetric detuning of the field profile due to the thermal expansion of the cavity resonator (cf. Fig. 14).

For the originally asymmetric field distribution present in the $8\pi/9$ -mode, the situation is different. In Fig. 15, selected measured temperatures are again shown in color and gray for ease of comparison, while the corresponding simulations are plotted as black dashed lines. The effective total heating power, scaled from the measured forward power, is indicated by a black dotted line. Due to the model assumption of a constant heating-power distribution, discrepancies arise between simulations and measurements. For example, in cells C6, C7, and C8, the model clearly overestimates the cell temperature at the beginning of the heating phase and significantly underestimates it at the end. The opposite behavior is observed on the other side of the cavity in cells C1, C2, and C3. The deviation reaches values

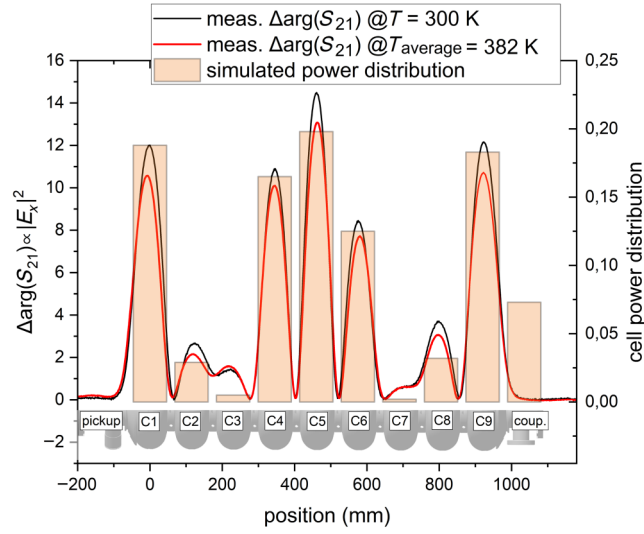


FIG. 14. Field distribution from the bead-pull measurement of the $7\pi/9$ -mode, shown in black at $T = 300$ K (27°C) and in red at an average cell temperature of $T_{\text{avg}} = 382$ K (109°C). The beige bars indicate the simulated constant heating-power distribution.

of up to 8 K, much higher than deviations seen otherwise. To investigate this issue, separate heating-power distributions Q_i were simulated for (a) the early phase of the heating process and (b) the late heating phase (both marked by yellow boxes in Fig. 15). Figure 16 shows the results for both regions (a) and (b) plotted separately. It can be seen that the temperature deviations ΔT between simulations and measurements correlate well (i.e., deviations less than 1 K) when the heating power pattern is independently optimized for these short time intervals. Now, these results are compared with the field distributions obtained from the cold and warm bead-pull measurements. In Fig. 17, bead-pull measurements are shown for two conditions: the black curve represents the field distribution at $T = 300$ K (27°C), while the red curve was recorded at a significantly elevated and nonuniform cell temperature, with the maximum temperature in cell C9 reaching $T_{\text{max}} = 457$ K (184°C) and the minimum temperature in cell C1 being only $T = 343$ K (70°C). A clear shift of the field toward the coupler side can be observed, and the asymmetric field distribution inherent to the detuned cavity is further amplified by the heating process. The beige bars (black frame) represents the heating-power distribution from the model corresponding to Fig. 16 (a, early heating). The distribution closely resembles the structure of the measured field profile at room temperature. The dashed bars (red frame), obtained from the model simulation at a later time in Fig. 16 (b, late heating), exhibits the same structural shift as the red curve from the warm bead-pull measurement. However, there are discrepancies between the measurement and the simulation. For example, in cell C5, a finite field is

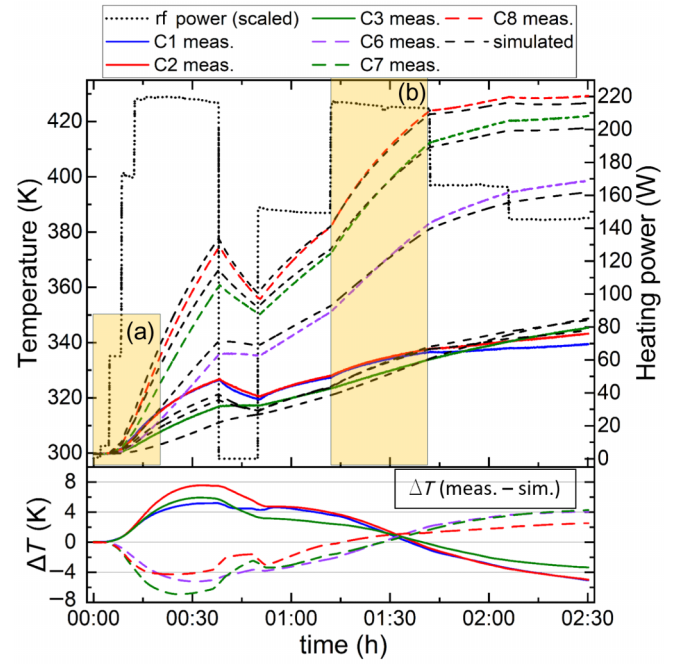


FIG. 15. Selected measured rf heating curves of the $8\pi/9$ -mode are shown in color and gray. The black dashed lines are the corresponding simulations. The black dotted line is the simulated, effective total heating power, scaled from the P_{fwd} readout. Early and late time intervals are highlighted by yellow boxes and labeled (a) and (b). The temperature difference ΔT between measured and simulated cell temperatures is shown below.

observed in the measurement, whereas the simulation does not deposit any power at this location. It should be noted, however, that the bead-pull measurement was performed at a significantly higher overall temperature and thus with a much larger spread in individual cell temperatures, resulting in a stronger field shift than in the time interval used for the simulation. Furthermore, the energy contribution from the coupler is again visible, with the contribution being smaller in the early-heating simulation than in the late-heating simulation. The coupler is a relatively massive component that heats up only with a temporal delay.

The model development is completed with the determination of the heating-power distribution for the fundamental modes and can now be used for predictive simulations.

A. Model predictions

First, simulations were used to determine which cell temperatures can be reached over an extended heating period with the coupler's 2 kW power limitation. In Fig. 18, a simulated 12 h-heating period with constant heating power is shown for the $8\pi/9$ -mode with $P_{\text{heat}} = 237$ W (above) and the $7\pi/9$ -mode with $P_{\text{heat}} = 161$ W (below). In the $8\pi/9$ -mode, with the given power, the three cells C9, C8, and C7 can reach temperatures above 473 K

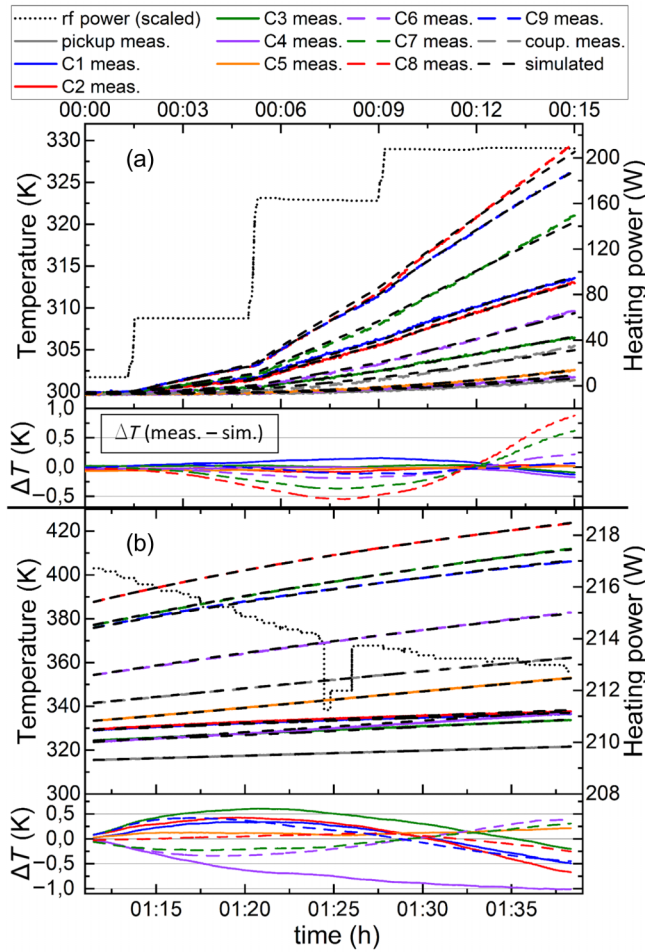


FIG. 16. Measured rf heating curves using the $8\pi/9$ -mode together with the corresponding simulations (black dashed lines); effective total heating power obtained from the simulation, scaled from the measured P_{fwd} (black dotted line). ΔT between measured and simulated cell temperatures shown below each plot.

(200°C) and would therefore be within the range of the intended mid-T baking temperature regime (this simulation was performed using the “late-heating” power distribution seen in Fig. 17). In the simulation with the $7\pi/9$ -mode, under the given conditions, only a maximum temperature of 444 K (171°C) could be reached in cell C5, and therefore the possibility for the desired surface processing is not provided in this case.

For reasons of symmetry, in a flat-tuned cavity the fundamental $8\pi/9$ -mode is likewise symmetric with respect to the fifth cell [32]. In Fig. 19, a simulation of the $8\pi/9$ -mode is shown in which the heating-power distribution (small figure) has been symmetrically normalized. The heating contribution resulting from the coupling to the warm coupler has been retained. It can be seen that curves of the same color lie close to each other in the simulation, which corresponds to a symmetric heating behavior. With the 237 W heating power, only a maximum

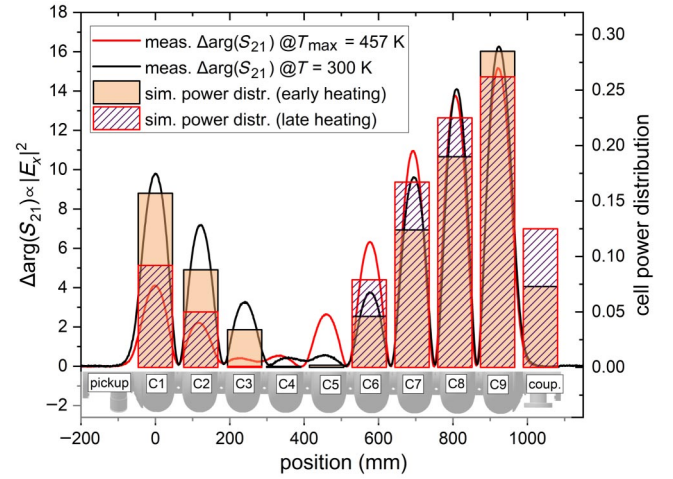


FIG. 17. Bead-pull measured field distribution of the $8\pi/9$ -mode at $T = 300$ K (27°C) (black curve) and at a maximum cell temperature of $T_{\text{max}} = 457$ K (184°C) (red curve) (different measurement). The bars indicate the simulated constant heating-power distribution, shown with beige fill for the early heating phase [box (a) in Fig. 16] and with dashed fill for the late heating phase [box (b) in Fig. 16].

temperature of 454 K (181°C) in cell C8 and of 452 K (179°C) in C2 can be reached, in contrast to the detuned cavity simulation. Therefore, these temperatures are insufficient for the intended mid-T processing. To clarify whether a homogeneous temperature distribution in all nine cells is achievable, the model was used to simulate an

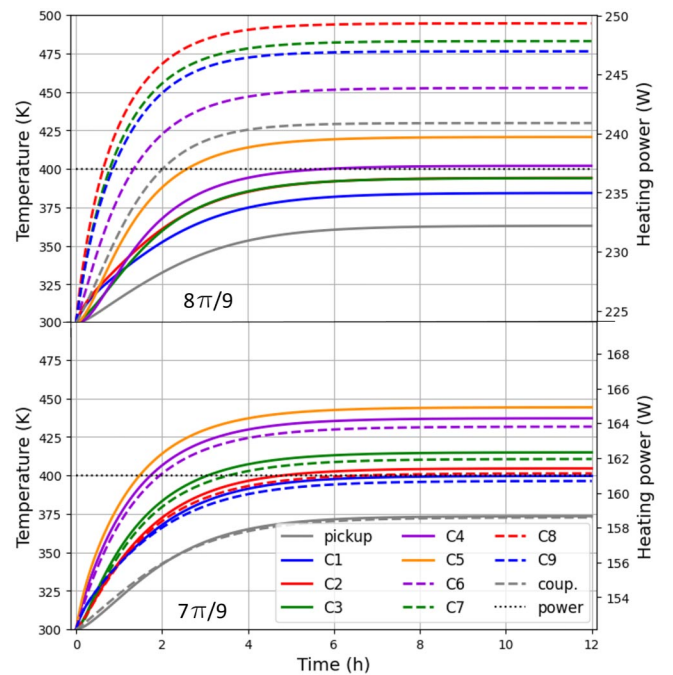


FIG. 18. Simulations of 12 h of rf heating driven with 2 kW of forward power using (above) the $8\pi/9$ -mode ($P_{\text{heat}} = 237$ W), and similarly (below) using the $7\pi/9$ -mode ($P_{\text{heat}} = 161$ W).

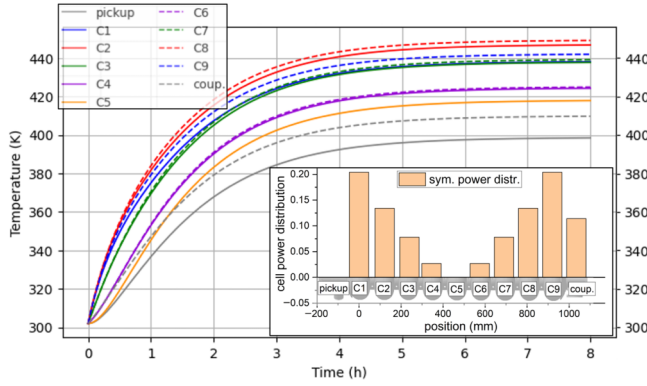


FIG. 19. Simulation of 8 h rf heating using the $8\pi/9$ -mode of an TESLA 9-cell cavity with flat tuning at $P_{\text{heat}} = 237$ W, equivalent to $P_{\text{fwd}} = 2$ kW. The inset shows the used symmetrized heating-power distribution.

alternating mode heating of the $7\pi/9$ - and $8\pi/9$ -modes. In Fig. 20 the mixed-mode heating is shown. The simulations were carried out under the assumption of a flat-tuned cavity, meaning with a symmetric normalized heating-power distribution for both modes. The mode switch occurs when any cell temperature exceeds the selected trigger temperature. Through many iterations, and for the given power settings, the objective was to achieve the smallest possible temperature spread. In Fig. 20 (bottom), the simulation assuming 2 kW forward power, which in our case corresponds to a total heating power of $P_{\text{heat}} = 161$ W in the $7\pi/9$ -mode and $P_{\text{heat}} = 237$ W in the $8\pi/9$ -mode, is shown. The switch trigger temperature, and thus the maximum cell temperature, was set to 433 K (160°C), which results in a minimum cell temperature of 423 K (150°C) in the outer cells C1 and C9. The temperature spread is therefore 10 K. To determine whether exceeding the P_{fwd} coupler limitation would be beneficial for reaching the target process temperature of above 200°C, simulations with higher power levels were carried out. In Fig. 20 (middle), a simulation with an equivalent of 3 kW is shown, which corresponds to a heating power of $P_{\text{heat}} = 241.5$ W for the $7\pi/9$ -mode and $P_{\text{heat}} = 355.5$ W for the $8\pi/9$ -mode. For this assumption, a linear relationship between the increase in P_{fwd} and the heating power actually delivered in the cavity was used as an approximation. For the narrowest possible cell temperature distribution, the trigger temperature was set to 472 K (199°C). The minimum cell temperature in the outer cells is 460 K (187°C), resulting in a cell-temperature spread of 12 K. With this switching-mode-method to achieve a minimal temperature spread, the additional 1 kW of P_{fwd} , corresponding to an estimated one-half higher heating power, results in an increase of only about 40 K. In Fig. 20 (top), the simulation performed with an assumed 4 kW of P_{fwd} is shown. The heating powers used are $P_{\text{heat}} = 474$ W for the

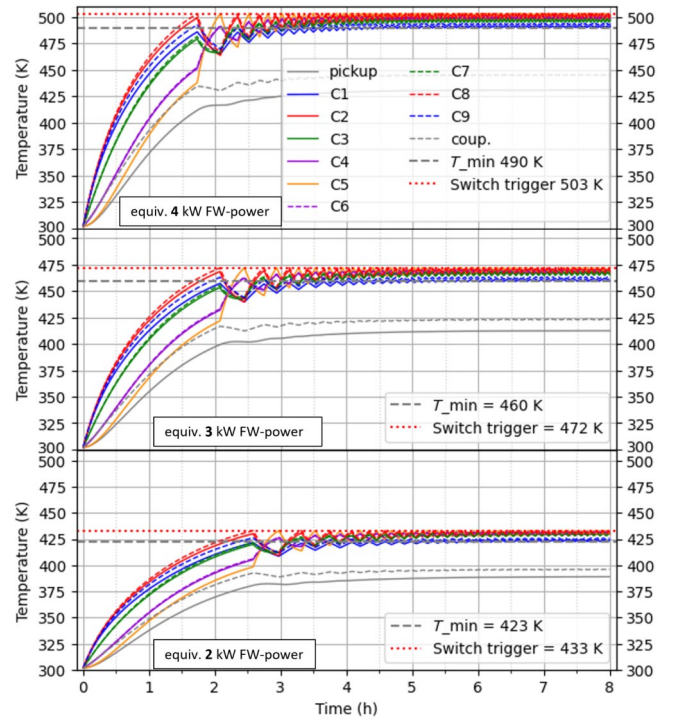


FIG. 20. Alternating-mode-switching simulations of an assumed flat-tuned cavity are shown for three P_{fwd} -power levels: (bottom) 2 kW with related heating powers of $P_{\text{heat}} = 237$ W ($8\pi/9$) and $P_{\text{heat}} = 161$ W ($7\pi/9$), (middle) 3 kW with $P_{\text{heat}} = 355.5$ W and $P_{\text{heat}} = 241.5$ W, and (top) 4 kW with $P_{\text{heat}} = 474$ W and $P_{\text{heat}} = 322$ W, respectively.

$8\pi/9$ -mode and $P_{\text{heat}} = 322$ W for the $7\pi/9$ -mode. The mode-switching trigger temperature was set to 503 K (230°C), which again results in a minimum cell temperature of 490 K (217°C) in the outer cells C1 and C9. The resulting temperature spread is therefore 13 K. Under these conditions, namely a flat-tuned cavity and 4 kW of P_{fwd} with the given coupling, the simulations indicate that a relatively uniform process temperature for mid-T baking is achievable.

V. SUMMARY AND CONCLUSION

This work has demonstrated that rf heating of a TESLA 9-cell cavity, which serves here as a prominent example of a multicell srf cavity, via the TTF-III FPC is feasible with different modes of the fundamental TM_{010} passband. For this purpose, a dedicated experimental setup was employed in which a VNA drives the power amplifier and, alternatively, allows for bead-pull measurements to obtain information about the field distribution under different heating conditions. For the TTF-III coupler in use without active cooling of its warm section's inner conductor, a conservative administrative power limit of 2 kW was implemented. This led with the strongest coupling, which was reached with the maximum beam

pipe penetration depth of the inner conductor limited by the coupler's bellows and at the edge of its mechanical specifications, to temperatures of two cells above 200 °C when driven with mode alternation.

With the $7\pi/9$ - and $6\pi/9$ -modes, cell temperatures above 130 °C were obtained, even though a full steady state had not yet been reached. The other modes were less suitable for the heating process due to insufficient coupling, reducing the heating power. The field profiles of the cavity used in the experiment turned out to be strongly nonflat, as confirmed by bead-pull measurements, and this behavior is also reflected in the heating characteristics of the individual cells.

Using a physics-based 11-node model implemented in Python, the best parameter choice was determined with a multidimensional optimization of the model prediction in comparison with the experimentally obtained cooldown curves. In a second step, using the measurement data obtained during the heating of the cavity, the heating-power distribution among the individual cells was optimized, now adjusting a set of unknown heating power values, one per cell. From the resulting heating-power distributions, conclusions about the field geometry can be drawn. For example, the shifts of field profile and power deposition of the $8\pi/9$ -mode observed in the bead-pull measurements, which were taken during the heating process, are well reproduced by separating the optimization into an early and a late stage.

With the optimized parameters describing the power deposition, the model was then used to simulate the steady-state temperature for long heating campaigns in the different modes. Furthermore, assuming a flat-tuned cavity, a symmetric heating-power distribution was applied in simulations including the alternation of the mode in use. This achieved the most homogeneous cell temperatures seen over all nine cells. The alternating mode heating was simulated with up to 4 kW of input power, exceeding the administrative power limit used in the experiments. In practice, this is an achievable value if a TTF-coupler equipped with an additional cooling of the inner conductor is used. Cell temperatures in the range of 217 to 230 °C were obtained, enabling a mid-T baking process within reasonable processing times.

That said, this study revealed the feasibility of mid-T baking of a multicell cavity driven by rf heating using a predictive model, which was robustly validated against a large set of experimental data. This key result holds under certain restrictions: The FPC coupling strength has a paramount impact on the available heating power, making the π -mode less attractive. This holds even in the case of good field flatness due to its systematically weaker coupling compared to the $7\pi/9$ - and $8\pi/9$ -modes. Hence, rf heating by alternating between the modes of this pair is favored. Such a mode alternating scheme also allows for

the compensation of the peripheral power loss through the beam pipes whilst preserving sufficiently homogeneous cell temperatures.

Studies currently under preparation foresee an experimental qualification of the existing TTF-III coupler with powers above the 2 kW administrative limit. Furthermore, an automated transmitter frequency tracking option including the option of mode alternation is in preparation in order to extend the study.

The use of a dressed cavity is also planned for future work. Both the presence of the helium tank and its gas filling are expected to be beneficial for reduced temperature variations, since they will strengthen radiative and convective heat exchange. The numerical model then will need moderate adaptations in order to account for the increased number of thermal couplings. An assessment of cold cavity performance before and after rf heating will be the subject of future studies.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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