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Modeling of Thermal Quench in Superconducting RF Cavities

Mohamed H. Awida, Ivan Gonin, Timergali Khabiboulline, and Vyacheslav P. Yakovlev

***Abstract*—Superconducting radio frequency (SRF) cavities are often limited by thermal quench, which is an excessive electromagnetic heating that occurs in the high magnetic field area and expands thereafter forcing the cavity to lose its superconducting state. In this paper, we demonstrate how the quench phenomena can be modeled using a coupled electromagnetic thermal analysis. The proposed model takes into account the nonlinearity of the material properties at cryogenic temperature and the effect of Kapitza resistance. The proposed approach is used to compute the thermal quench field of a 3.9 GHz 9-cell accelerating cavity, a 2.815 GHz deflecting cavity, and a 1.3 GHz 9-cell accelerating cavity. The computed values of quench field are in good agreement with the measured ones observed during vertical testing at 2 K. Without loss of generality, the proposed methodology can be applied to other cavity geometries.**

I. Introduction

SUPER conducting radio frequency (SRF) cavities are essential components in modern particle accelerator machines. SRF cavities offer the advantages of being extremely low loss with superior quality factors, which makes them favorable for modern particle accelerators [1-2].

Quench phenomena occurs in SRF cavities when the cavity material loses its superconductivity either due to localized heating above the critical temperature (what we will refer to thereafter as thermal quench) or because of exceeding the superconducting critical magnetic field. In either case, the localized quench emerges and then propagates along the surface of the cavity due to electromagnetic heating causing the cavity to give up its superconducting state and return to the normal conducting state. Quench location is tightly connected to where the peak magnetic field exists as the surface electromagnetic heating is caused by the magnetic field [2-3]. Defects also can cause significant field enhancement causing an early quench. In this paper we assume that cavities are free from defects.

SRF cavities are typically optimized to reduce the ratio of the peak surface magnetic field to the accelerating gradient (B_p/E_{acc}) in the cavity, which extends the range of operating gradients of the cavity before quench. On the other hand, the value of thermal quench field is also strongly dependent on how efficient the cooling of the cavity structure is. The better the cooling, the higher the field the cavity can sustain before reaching the thermal quench limit.

SRF cavities having relatively high frequency (>2 GHz) are used in accelerators for different applications – harmonic cavities for better bunching as in XFEL [4], and LCLS-II [5], or for bunch lengthening [6], or deflecting cavities [7]. At these relatively high frequencies, thermal quench (breakdown) is one of the most important factors that limit the cavity performance, because the Ohmic losses in this case are determined by BCS resistance, which increases as frequency squared [2]. To design an SRF cavity at such frequencies, it is essential to analyze thermal quench and optimize the cavity to operate at high acceleration field.

Computing the value of the thermal quench field during the course of cavity design is imperative in order to make sure that the cavity would reach the targeted values of operating gradient and is not limited by thermal quench, especially for new cavity geometries. However, modeling such a phenomenon is quite complicated as it requires coupling the electromagnetic and thermal physics of the cavity. Moreover, the material properties of the cavity assembly at cryogenic temperatures, which are highly non-linear, need to be defined as inputs to the multiphysics problem. Several attempts have been exercised to define the thermal conductivity of various material at cryogenic temperatures [8-10].

Meanwhile, Kapitza resistance [11-12], which is a measure of interfacial resistance to a thermal flow, is critically required in the thermal quench analysis to accurately compute the quench field taking into account the interface resistance of the cavity walls to the thermal flow of superfluid helium. Several models have been developed to account for Kapitza resistance [8, 13-15].

In this paper, we tackle the challenge of modeling the thermal quench phenomena in superconducting cavities using multiphysics analysis presenting a methodology to compute the thermal quench field limit. The proposed methodology serves as an essential tool for better engineering of SRF cavities and it complements the ultimate magnetic quench studies which is highly dependent on the surface treatment performed on the cavities [16-19]. In section II, we summarize the material properties at cryogenic temperatures of essential materials that are typically used in SRF cavities assemblies, then we briefly go over the different Kapitza models in Section III. The proposed multiphysics analysis is discussed in Section IV, followed by demonstrations in Section V using realistic examples of computing thermal quench limit in three different SRF cavities. We finally conclude our paper in Section VI.

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II. Material Properties at Cryogenic Temperatures

To accurately compute the thermal quench using multiphysics analysis, it is imperative to include the material properties namely surface resistance, and thermal conductivity as functions of temperature.

SRF cavities are conventionally made from pure niobium, which is a type II superconducting material with a critical temperature of 9.2 K. Niobium cavities have been deployed in particle accelerators since 1970 and underwent a long way of developments to overcome performance barriers like multipacting, field emission, and early quenches [2].

Despite that all of the cavity walls are made of niobium, the assembly of an SRF cavity would consist of various other metals and ceramics that are typically used in the feed-through of the main coupler, pick up, and higher order mode (HOM) couplers. Fig. 1 shows the thermal conductivities of various metals classified in two categories; relatively high thermal conductivity metals, which include copper OFHC, niobium (RRR=300), and molybdenum in Fig. 1(a), and relatively low thermal conductivity metals, which include titanium grade II, and stainless steel 316, as shown in Fig. 1(b), following [10]. It is worth noting that all of them exhibit strongly nonlinear behavior with temperature peaking at a certain temperature except in case of stainless steel 316.

On the other hand, Fig. 2 shows the thermal conductivities of three ceramics, namely; sapphire, alumina, and Teflon that are typically used in the feed throughs of antennas on SRF cavities [9]. Sapphire is the best ceramic that can be used from the thermal conductivity point of view, as shown in Fig. 2(a), but is significantly higher in cost when compared to alumina. Teflon on the other hand has a very poor thermal conductivity as shown in Fig. 2(b).

Alongside, we have represented the surface resistance as

$$R_s = R_{S0} + R_{Sf} \tag{1}$$

where R_{S0} is the residual resistance with an assumed value of 10 nΩ and R_{Sf} is the temperature and frequency dependent surface resistance defined as

$$R_{Sf} = \frac{2e^{-4}}{T}\left(\frac{f}{1.5}\right)^2 exp\left(-\frac{17.67}{T}\right) \tag{2}$$

where T is the temperature in K and f is the frequency in GHz [2]. Fig. 3 demonstrates the surface resistance of niobium at three frequencies of interest, namely; 1.3 GHz, 2.8 GHz, and 3.9 GHz. It is worth noting how the surface resistance exponentially increases with temperature. Moreover, this exponential increase in surface resistance becomes sharper when increasing the frequency, as shown in Fig. 3. The increase of the surface resistance has a dramatic effect on increasing the electromagnetic heating, thus causing the thermal quench. That is also why higher frequency cavities are more susceptible to thermal quench.

In fact, the heat flux (Pl) is directly proportional to the surface resistance such that

$$Pl = \frac{1}{2} R_s |H|^2 \tag{3}$$

Where H is the surface magnetic field.

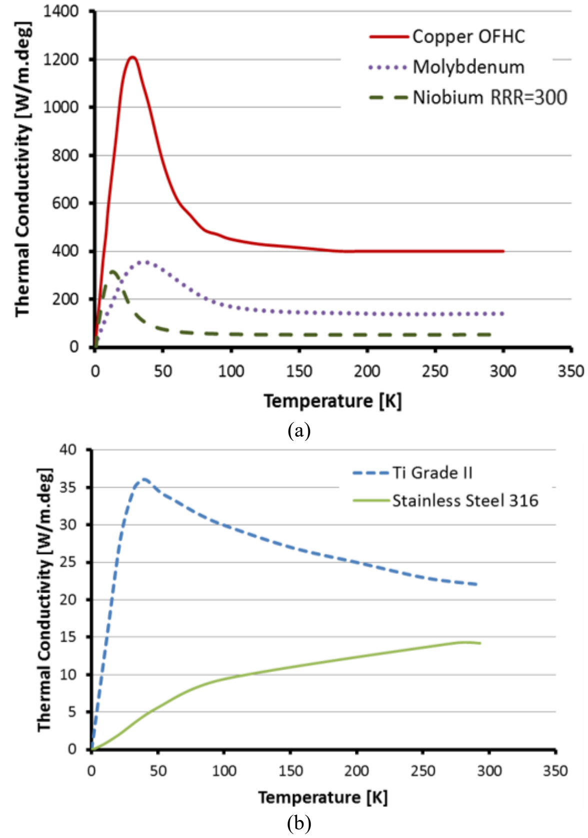


Fig. 1. Thermal conductivities of various metals typically used in the assemblies of superconducting cavities [10]. (a) Copper OFHC, molybdenum, and niobium (RRR=300). (b) Titanium grade II and stainless steel 316.

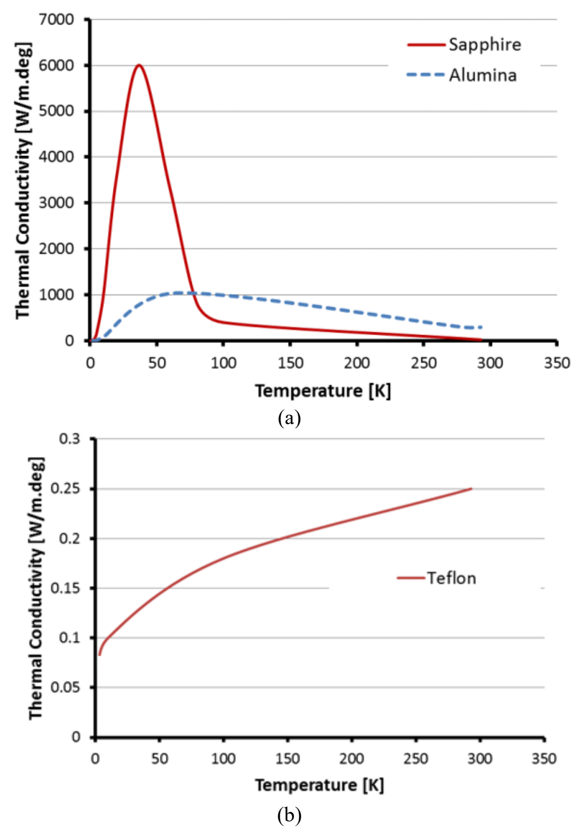


Fig. 2. Thermal conductivities of various ceramics typically used in the assemblies of superconducting cavities [9]. (a) Sapphire and alumina. (b) Teflon.

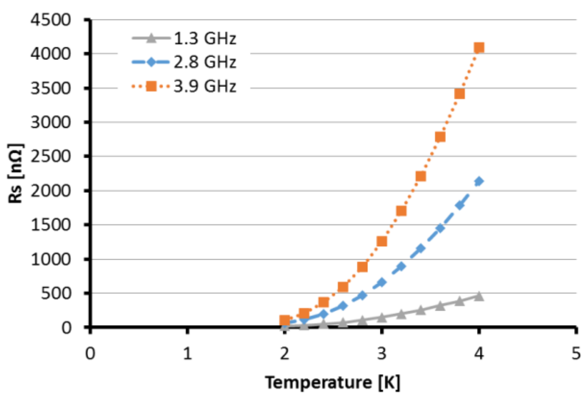


Fig. 3. Surface resistance of niobium at several frequencies assuming 10 nΩ residual resistance.

III. Kapitza Resistance

The effect of Kapitza resistance is critical in computing the thermal quench field as the walls of the cavity would have significant thermal resistance to the superfluid helium at the interface.

The thermal conductivity of the interface layer; K_{Kap} can be represented as

$$K_{Kap} = \sigma_{Kap} \cdot \delta_{Kap} \quad (4)$$

Where σ_{Kap}, and δ_{Kap} are the thermal conductivity and the thickness of the Kapitza layer, respectively. Several models have been proposed for the thermal conductivity of the Kapitza layer based on measurements performed on different samples of niobium with different chemistry treatments [8, 13-15].

In general, all models take the form of

$$\sigma_{Kap} = A \cdot T^B \cdot F \quad (5)$$

Where T is the temperature, A and B are model parameters, while F is a correction factor that has been used in some models. The correction factor introduced by Mittag in [8] takes the form

$$F = 1 + \frac{3}{2}\left(\frac{\Delta T}{T}\right) + \left(\frac{\Delta T}{T}\right)^2 + \frac{1}{4}\left(\frac{\Delta T}{T}\right)^3 \quad (6)$$

Where ΔT is the temperature difference between the cavity outer surface and the bath temperature. Table I reviews the model parameters for three Kapitza models as was summarized in [20].

Table I: Parameters of various Kapitza models.

Model Name	Sample	Surface Treatment	A	B	F
Simple	N/A	N/A	0.0500	3	1
Mittag1	Reactor grade Ni containing 500 ppm Ta	E-Beam melted	0.0170	3.62	Eq.6
Mittag2	Reactor grade Ni containing 100 ppm Ta	E-Beam melted	0.0200	4.65	Eq.6
Amrit1	RRR=178	CE(~30µm)	0.0935	3.55	1
Amrit2	RRR=178	EP	0.0469	4.11	1
Amrit3	RRR=647	A+CE(~30µm)	0.0621	3.93	1
Amrit4	RRR=647	A+CE+EP	0.0523	3.61	1

Figure 4 illustrates the thermal conductance in $W/(cm^2 \cdot K)$ for the various Kapitza models plotted in the range from 1.6 to 2.5 K. The lowest thermal conductivity is exhibited by Mittag1 model, while the highest thermal conductivity is exhibited by Amrit1 model. It is worth noting here, that we expect lower quench fields with lower thermal conductivity for the Kapitza interface.

IV. Multiphysics Analysis

The thermal quench field can be computed by simulating the electromagnetic heating effect in the cavity under various peak surface magnetic field scenarios. Figure 5 explains the process of modeling thermal quench using multiphysics analysis.

The multiphysics model shall contain an artificial thin Kapitza interface layer of relatively small thickness δ_{Kap} created on the outside cavity surface, where it is exposed to superfluid helium. All material properties of the different parts of the cavity assembly should be defined with non-linear representation along the temperature range from 2-10 K, as we indicated earlier in Section II. The multiphysics simulation starts by computing the cavity's resonance frequency of interest and the associated electromagnetic field of that mode.

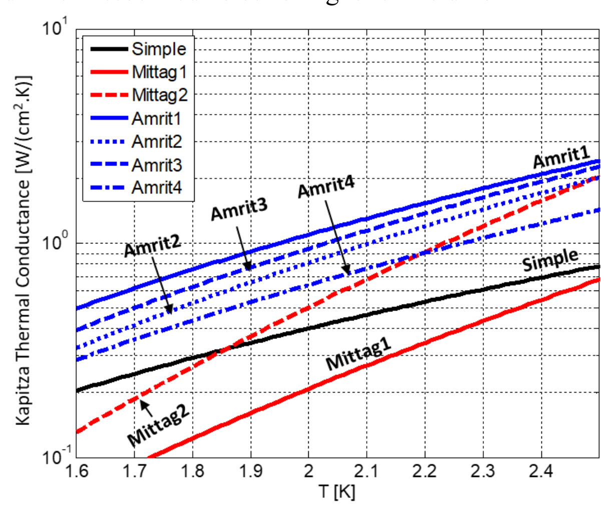


Fig. 4. Thermal conductance of the Kapitza interface between superfluid helium and niobium in [W/(cm².K)] based on the various models listed in Table I.

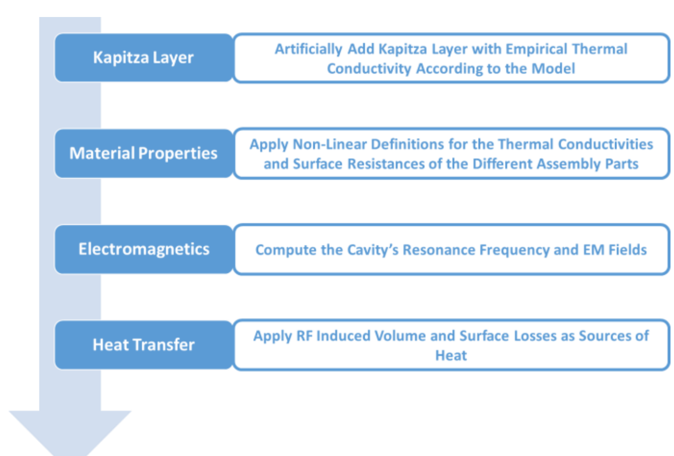


Fig. 5. Flow chart explaining the multiphysics simulation process for the thermal quench analysis.

The computed magnetic field is then used to impose heat flux on the cavity's inside wall surface according to Eq. (3). In that perspective, the analysis is repeated under various energy normalization to scale up the magnetic field. A curve for the maximum temperature inside the cavity versus the peak surface magnetic field can then be produced. Upon observing the maximum surface temperature, we straightforwardly oversee when the temperature sharply increases. Beyond a certain limit the solution won't converge and that is actually when the thermal quench would happen.

V. Examples of Thermal Quench Analysis

In this section, we demonstrate the proposed thermal quench modeling approach in determining the quench field with good accuracy for three cases. The first case is for an accelerating 9-cell elliptical cavity operating at 3.9 GHz, second one is for a 3-cell deflecting cavity operating at 2.815 GHz, and the third case is for a 1.3 GHz 9-cell elliptical cavity with higher order mode (HOM) feedthroughs.

A. 3.9 GHz 9-cell Elliptical Cavity

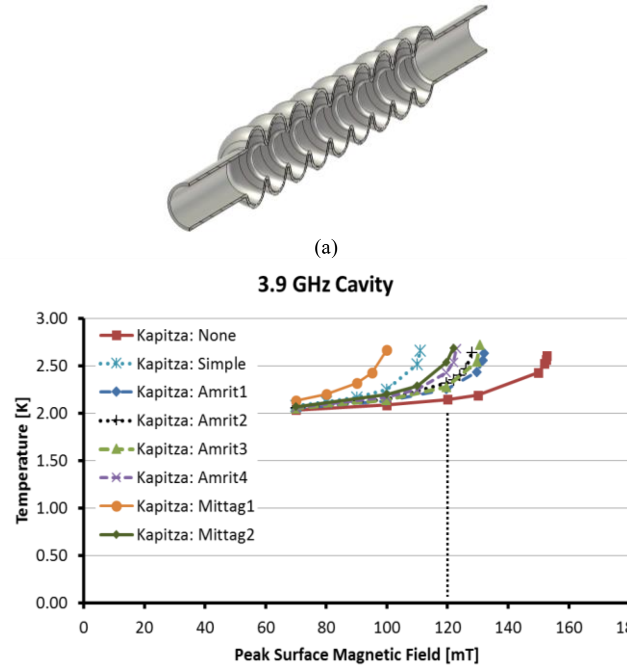
The 3.9 GHz cavities are designed to operate at the 3rd harmonic frequency of the popular 1.3 GHz. The third harmonic cavities are conventionally used in particle accelerators for bunch linearization to improve beam stability and compensate for the distortion that could happen between the sinusoidal accelerating field and the relatively long beam bunches [21].

Third harmonic cavities are currently in production for several projects. For instance, SLAC's LCLS-II [5].

Using Comsol multiphysics [22], we have run the quench analysis for the 3.9 GHz cavity assuming various models for the Kapitza resistance. Figure 6 illustrates the temperature versus peak surface magnetic field for the various cases depicting the thermal quench in each case, as summarized in Table II. Clearly, it is imperative to include the effect of Kapitza resistance to realistically compute the thermal quench limit. In the event of ignoring the effect of Kapitza resistance, the cavity would show a relatively higher thermal quench field in simulation (153 mT), which won't reflect a realistic expectation for the performance of the cavity. On the other hand, using Mittag1 or the simple models would give a pessimistic expectation for the thermal quench, since the Kapitza resistance is overestimated in these cases. Other models, namely; Mittag2 and Amrit models give fairly close thermal quench fields to the actual measured value (120 mT as indicated in [23]), with Mittag2 being the closest model to measurements. Therefore, Mittag2 model is adopted in the forthcoming quench analysis for the other two cavities.

A. 2.815 GHz Deflecting Cavity

A compact efficient deflecting cavity was under development in a collaboration effort between Fermi and Argonne national laboratories. Cavity was designed to be used in the Short Pulse X-rays (SPX) at the Advanced Proton Source (APS) of Argonne national laboratory [7, 24]. Using a deflecting cavity for SPX was initially suggested by Zholents, et al. in [25].



(b)

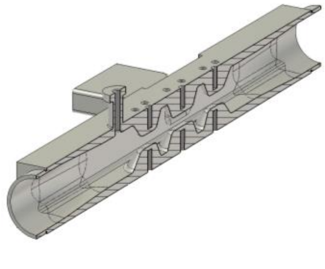
Fig. 6. Thermal quench analysis of the 3rd harmonic 3.9 GHz cavity using various Kapitza resistance models (a) Half section of the cavity. (b) Temperature versus peak surface magnetic field.

Table II: Thermal quench fields for the 3.9 GHz cavity computed from the thermal analysis based on various Kapitza resistance models.

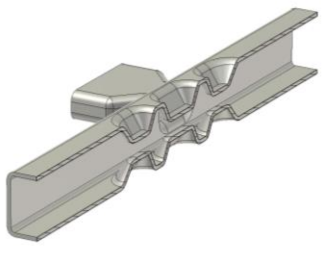
Kapitza Resistance Model	B_{peak} [mT]
None	153
Mittag1	100
Mittag2	122
Simple	111
Amrit1	132
Amrit2	128
Amrit3	131
Amrit4	123

The cavity was designed to meet stringent requirements on both electromagnetic and mechanical performances. Cavity operates at 2.815 GHz with an optimal group velocity of 1. The cavity should produce a nominal kick voltage of 2 MV, while keeping the peak surface electric field below 55 MV/m to avoid surface emission and the peak surface magnetic field below 80 mT to avoid thermal quench.

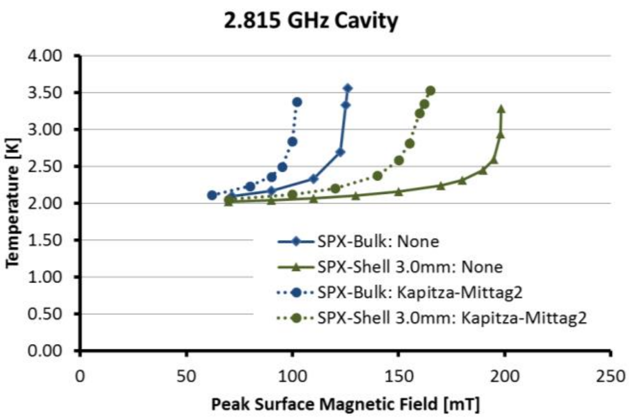
One of the design goals of the deflecting cavity was to avoid thermal quench. Cavity is required to sustain at least 100 mT peak surface magnetic field (25% safety margin). In that perspective, the geometry of the cavity has been optimized to reduce the peak surface magnetic field to 75 mT at nominal gradient. On the other hand, two fabrication scenarios have been proposed to the deflecting cavity; one starting from a bulk niobium piece and the other using sheets of niobium. The two fabrication scenarios would end up obviously with cavity



(a)

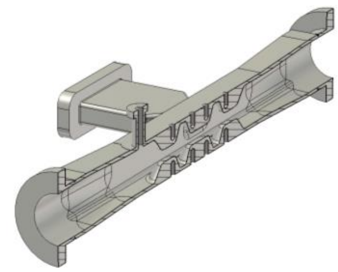


(b)

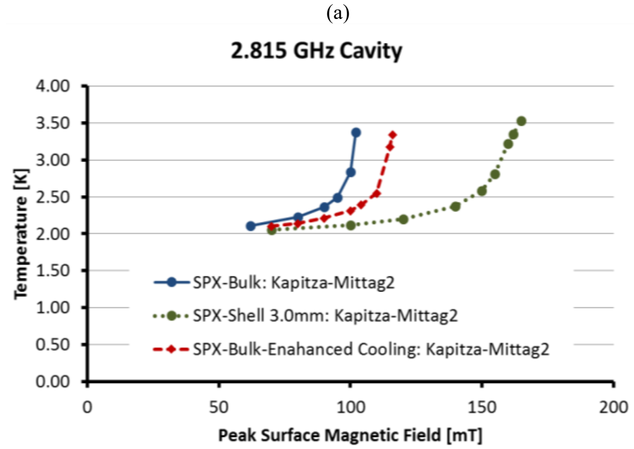


(c)

Fig. 7. Thermal quench analysis of the 2.815 GHz deflecting cavity using Kapitza Mittag2 model. (a) Cavity made from bulk niobium. (b) Cavity made from niobium sheets. (c) Temperature versus peak surface magnetic field.



(a)



(b)

Fig. 8. Thermal quench analysis of the final design for the 2.815 GHz deflecting cavity using Kapitza Mittag2 model. (a) Final cavity design made from bulk niobium with enhanced cooling. (b) Temperature versus peak surface magnetic field.

structures of different cooling schemes, as shown in Fig. 7(a) and (b). In fact, there was a concern that the bulk niobium structure might be susceptible to thermal quench at early gradient because of the relatively thick walls. Therefore, we investigated the thermal quench field of each structure. Fig. 7(c) illustrates the maximum temperature on the cavity structure versus the peak surface magnetic field for both the bulk and shell structures with and without taking into account the effect of Kapitza resistance (assuming Mittag2 model). Clearly, the shell cavity structure has a higher quench field rather than the bulk cavity one. Moreover, the effect of Kapitza resistance is crucial to realistically predict the quench field in each case. Without taking the effect of Kapitza resistance into account, the cavity would quench at 195 mT, 125 mT for the shell and bulk structures, respectively. Thermal quench field would lower to 155 mT, 100 mT after accounting for Kapitza resistance for the shell and bulk structures, respectively.

Regardless the better performance of the shell structure, it was decided to fabricate the cavity from bulk niobium to reduce the fabrication cost. However, the cooling of the structure was improved by enlarging the cooling holes, as shown in Fig. 8(a). The thermal quench performance of the final design with enhanced cooling is shown in Fig 8(b), compared to the structures in Fig. 7(a) and (b). The thermal quench field of the final design with enhanced cooling is calculated to be 110 mT. Cavity was fabricated and tested meeting the design goals [26].

B. 1.3 GHz 9-Cell Accelerating Cavity with HOMs

The 1.3 GHz 9-cell elliptical cavities are very popular in superconducting particle accelerator machines. The TESLA cavity style was proposed in the early 1990s [27] as a prominent candidate for high gradient superconducting accelerating cavities that fit the needs for electron positron collider, which was named later as International Linear Collider (ILC).

Fig. 9 illustrates the geometry of the 1.3 GHz cavity, depicting the higher order mode coupler assembly in (b) including the antenna and the f-part, as shown enlarged in (c). In fact, the f-part acts as a notch filter to reject the propagation of the operating mode (pi-mode) at 1.3 GHz.

In order to maintain a safe operation for the cavity up to relatively high gradients (40 MV/m), it is necessary to make sure that the HOM coupler assembly won't thermally quench before these high gradients. In that perspective, the thermal quench analysis is required during the cavity design.

In fact, the quench of the HOM coupler assembly is largely dependent on the material used in the constituting parts and the amount of coupling between the HOM antenna and the cavity. Figure 10 depicts the different constituting parts of the ILC HOM coupler, which basically are the antenna tip, the feed through ceramic, the socket, the pin, the connectors and the flange. Different options exist for the material to be used in each part of the assembly. Antenna tip is typically made of niobium to minimize the surface resistance. The feed-through assembly proposed for ILC, which is conceived as a good option for a pulsed machine, consists of a stainless-steel socket, a stainless-steel pin, an alumina ceramic, and an antenna tip of 24 mm in diameter with a 0.5 mm gap to the f-part.

Figure 11 demonstrates the maximum temperature along the cavity versus the peak surface magnetic field assuming continuous wave (CW) operation. The maximum temperature is actually located on the HOM coupler antenna for the ILC design. In this case, the cavity is limited to only 60 mT peak surface magnetic field of continuous wave operation.

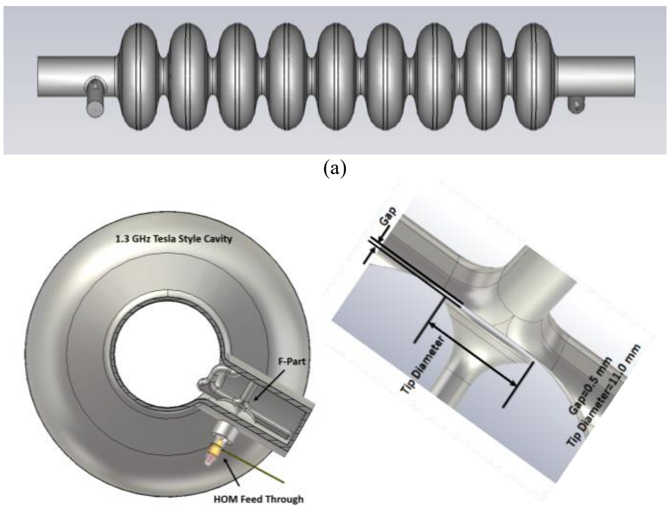


Fig. 9. Geometry of the ILC 1.3 GHz elliptical cavity. (a) Top view. (b) Side view with a cut to show the higher order mode feed through, antenna, and f-part. (c) Geometry of the antenna and f-part.

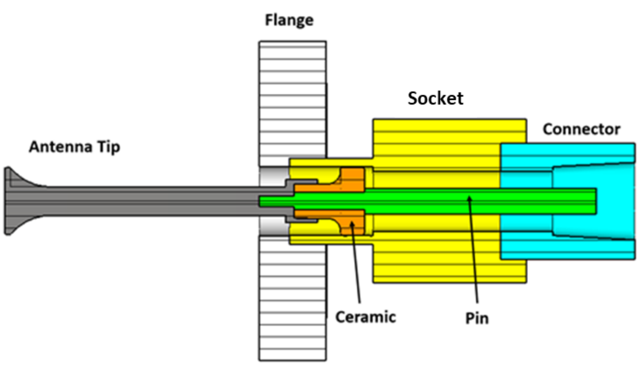


Fig. 10. Higher order mode feed through depicting the various constituent parts.

Modifying the antenna tip to become 1.5 mm in diameter can reduce the coupling and significantly boosts the cavity performance to 170 mT, as shown in Figure 11. However, modifying the antenna would also affect the external quality factor of the higher order modes, limiting the capability of the HOM coupler in getting rid of some of the dangerous higher order modes.

Another way of improving the HOM coupler for CW operation is to pick better materials for the assembly in terms of thermal conductivity. Both DESY [28], and JLAB [29] suggested the use of sapphire instead of alumina for the feed-through ceramic, molybdenum for the pin instead of stainless steel and copper for the socket instead of stainless steel, as well. Figure 12 demonstrates the effect of each of these changes in terms of improving the thermal quench field of the cavity by plotting again the maximum temperature versus the peak surface magnetic field. Clearly, each of this modification significantly boosts the thermal performance of the HOM assembly. Once, the quench field passes 200 mT, the cavity is not anymore limited by thermal quench on the HOM coupler, but it will actually be limited by the ultimate magnetic quench in niobium cavities at 200 mT.

The three examples we have presented in this section

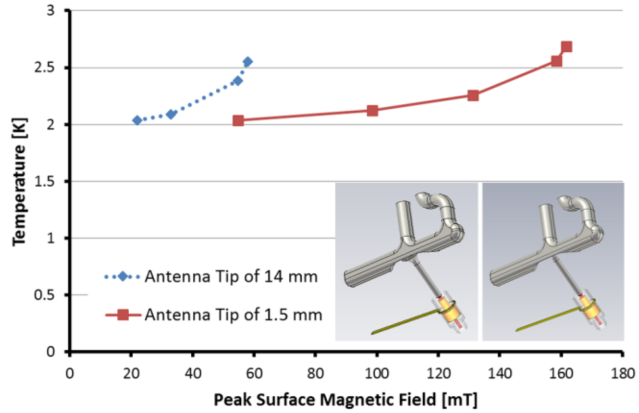


Fig. 11. Thermal quench analysis of the 1.3 GHz cavity with various sizes of the antenna tip.

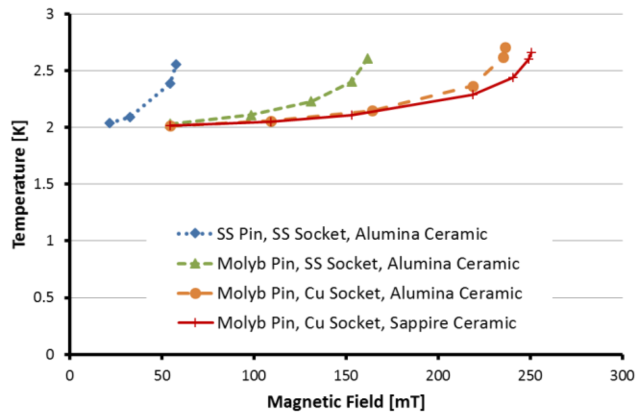


Fig. 12. Thermal quench analysis of the 1.3 GHz cavity with various combinations of materials in the feed through assembly.

demonstrate how the thermal quench phenomena can be modeled in SRF cavities to compute the quench limit and proactively modify the geometry of the cavity during the course of design to avoid any limitation on the performance due to a relatively low thermal quench field.

VI. Conclusion

We presented a methodology to model the thermal quench in SRF cavities using multiphysics analysis. The proposed methodology complements the ultimate magnetic quench studies that carefully consider the surface treatments of cavities and is essential for relatively high frequency (>2GHz) cavities where the cavity performance is mostly limited by heating due Ohmic losses. Thermal quench analysis helps in the course of cavity design to make sure that localized heating above critical temperature in cavity walls will not limit the cavity performance. Modeling thermal quench is done based on coupled electromagnetic thermal simulation and by taking into account the nonlinearities in the thermal conductivity of the cavity's materials and Kapitza resistance of the helium niobium interface. The method assumes that the cavity is defect free and is not prone to early quench. Different models of the Kapitza resistance have been studied. It has been shown that ignoring Kapitza resistance will lead to overestimated thermal quench limit, while using simple model can also lead to underestimated one. The proposed method has been applied successfully on three different examples of different cavities at 3.9 GHz, 2.815 GHz, and 1.3 GHz and led to good estimates of the thermal quench limits that are in good agreement with experimental results.

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Mohamed H. Awida (S'04–M'12) received the B.Sc. and M.Sc. degrees in electrical engineering from Ain Shams University, Cairo, Egypt, in 2002 and 2006, respectively, and the Ph.D. degree in electrical engineering from the University of Tennessee at Knoxville, Knoxville, TN, USA, in 2011.

From 2002 to 2005, he was a research and teaching assistant at Ain Shams, where he was engaged in the research and development of miniaturizing techniques for passive microwave circuits. From 2006 to 2010, he was a research and teaching assistant at the University of Tennessee at Knoxville, where he was engaged in the research and development of low-profile high-performance antenna arrays for mobile platforms. From Oct. 2008 to May 2009, he was a research assistant in the Spallation Neutron Source, Oak Ridge National Lab., where was involved in the design of twisted waveguide accelerating structures. In 2010, he joined Fermilab where he is currently a senior RF engineer at the superconducting RF department of the applied physics and superconducting technology division. He is currently engaged in the design, fabrication, and testing of superconducting RF cavities for particle accelerators and quantum systems. He has authored and coauthored more than 80 technical papers and reports. He holds a U.S. patent for the invention of a novel RF tuning technique using pressurized balloons. His research interests include superconducting RF cavities for particle accelerators, superconducting quantum systems based on Josephson junctions, antenna arrays for mobile platforms, and compact microwave structures.

Dr. Awida is listed in Who's Who in the World 2006 and is a member of Phi Kappa Phi honor society. He is an active Member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S), and the IEEE Antenna and Propagation Society (IEEE AP-S). He is the recipient of Fermilab's John Bardeen fellowship of in 2010, exceptional performance recognition award in 2018, and inventor recognition award in 2019 and 2020.

Ivan V. Gonin received the MS degree in Computational Mathematics and Cybernetics from Moscow State University, Moscow, Russia in 1982.

From September 1982 to May 1995 and from May 2000 to March 2001 he was an engineer then a research scientist with the Institute for Nuclear Research of Russian Academy of Science, Moscow, Russia. In 2001, he joined Fermi National Accelerator Lab. where he is currently a senior RF engineer at the superconducting RF department of the applied physics and superconducting technology division. He has expertise in complex investigation and design of components of normal and superconducting particle accelerators. He also possesses an advanced knowledge of modern software for comprehensive analysis of multi physical processes in accelerator components: MWS Studio, COMSOL, HFSS, ANALYST, ANSYS, MICHELLE and is experienced in the development of large, industrial quality software for finite element method; 2D/3D mesh generation, visualization, pre- and post-processing, animation to the solution of challenging engineering and scientific problems. He is highly skilled in analysis and solution of problems in a variety of application areas: optimization in RF structures, coupled RF-mechanical R&D of accelerating cavities, design of power and HOM couplers and other components of particle accelerators. He has successfully completed researches in projects: Moscow Meson Factory, S-band and TESLA Linear Collider, NLC, RUN II, XFEL, Proton Driver, ILC, LCLS-II, PIP-II and others.

Mr. Gonin holds two patents and is the author/co-author of over 60 publications including Phys. Rev. and IEEE Transactions on Nuclear Science Journal.

Timergali Khabiboulline received the Master of Science degree in Radio-electronic devices from Moscow Institute of Physics and Technology, General and Applied Physics Department in 1985.

From 1985 to 2001, he was a Research Scientist in the Institute for Nuclear Research in Moscow where he worked on the RF investigation of different physical processes in standing wave accelerating structures (RFQ, DAW, and DTL), and RF tuning of the standing wave DAW sections for linear accelerator of Moscow Meson Factory. He improved the techniques of RF measurements and developed a new procedure for RF tuning of the 4-section accelerating structure of the linear accelerator of Moscow Meson Factory. From 1993 to 2001, he was a guest scientist at DESY, Hamburg, Germany, within the frame of DESY/INR collaboration. Over there he developed a new procedure/software for RF tuning of traveling wave accelerating structure of SBLC project, worked on RF tuning of DESY Linac-II traveling wave accelerating structures by using this procedure, automation of the SBLC tuning machine, and software development for Tuning Machine for RF tuning of TESLA project accelerating cavities. He developed cavity straightness measurement system and alignment technique for 9-cell cavity, as well. He joined Fermilab in 2001, where he is currently a Principal Engineer and an RF group leader within the SRF Department at the Applied Physics and Superconducting Technology Division. In Fermilab, he worked on the RF optimization of the accelerating structures and couplers for LCLS-II, PIP-II, ILC, HINS, SMTF, Project X and PXIE. He also developed a new RF tuning procedure for CKM 9-cell and 13-cell superconducting deflecting mode cavities. He worked also on the 3rd harmonic cavity optimization, development and implementation of the vertical RF tuning stand for 3rd Harmonic and ILC/TESLA cavities, development and implementation of HOM coupler notch frequency tuning of elliptical cavities, and development and implementation of new alignment measurements technique based on bead-pull measurements for RF cavities.

Mr. Khabiboulline is the author/co-author of more than 90 publications and technical reports.

Vyacheslav P. Yakovlev received his MS degree in physics from Novosibirsk State University (NSU), Russia, in 1977, and PhD in accelerator physics from Budker Institute for Nuclear Physics (Budker INP), Novosibirsk, Russia, in 1988. From 1977 to 1988 he was a Research Scientist, then from 1988 to 1996 a Senior Scientist at Budker INP. From 1994 to 1996 he was an Associate Professor at Novosibirsk State Technical University. Since 1996 he works at Yale Beam Lab, Physics Department, Yale University, and Omega-P Inc as a Senior Research Scientist. Since 2007 he works at Fermilab as a Senior Scientist, and from 2011 to present he is the head of the SRF Department at the Applied Physics and Superconducting Technology Division of Fermilab. From 2017 to present he is an Adjunct Professor of Accelerator Science, FRIB, Michigan State University.

The scope of his professional interest includes physics and techniques of particle accelerators, namely: theory and simulations of the fields and beam dynamics in linear and circular accelerators; physics and technique of RF accelerator structures, superconducting cavities, ferrite-tuned cavities, high power RF systems for accelerators, tuning systems and cryo-modules design.

Dr. Yakovlev has over 300 publications. He is a member of American Physical Society.