

HIGHEST PERFORMANCE OF TESLA 9-CELL SUPERCONDUCTING RF CAVITIES BY OVERCOMING QUENCHES IN SUPERFLUID LHe*

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Abstract

Accelerating gradients $E_{acc} = 26$ MV/m with a world record Q of 3×10^{10} in 9-cell TESLA superconducting RF (SRF) cavities have been reached in CW and pulsed RF modes. On the way to reaching the excellent performance, we experimentally characterized quench natures (most serious obstacle to higher gradients), investigated the Kapitza conduction and boiling heat transfer between cavities and LHe II, and studied the quench behaviors both in He II and normal LHe. Finally, we discuss the possibilities of further greatly raising the accelerating gradients to 50- 100 MV/m by use of Nb₃Sn and some HTc superconducting materials.

I. INTRODUCTION

Accelerating gradients in SRF cavities have been a determinative factor in a cost-affordable design, particularly for TESLA with a 20-Km-long active SRF accelerator. The international TESLA (TeV Energy Superconducting Linear Accelerator) collaboration has a two-step goal: 15 MV/m for its test facility (TTF), and 25 MV/m for TESLA[1].

Most of the TESLA 9-cell cavities tested are limited by quenches[2]. There are three factors that influence quench fields: heat production by thermal breakdown (TB) or field emission (FE), heat transported to surrounding areas, and power dissipated in the neighboring Nb. We have experimentally and theoretically investigated various phenomena relevant to TESLA cavity quenches. We also look for the future possibilities of using superconducting materials other than Nb for much higher gradients.

The TESLA collaboration has utilized almost all of the advanced SRF technologies developed in many labs around the world and developed a first-class infrastructure for SRF cavity processing. All of the cavities tested were treated at high temperature with Ti-purification (RRR values are about 500). In 9 tested 9-cell prototype cavities, average gradients of 18 MV/m in CW and 25 MV/m in pulsed RF mode of 800 μ s have been achieved.

II. REPRESENTATIVE PERFORMANCE

Fig 1. shows representative performance of a 9-cell TESLA SRF cavity with E_{acc} of 26 MV/m at Q of 3×10^{10} in a CW mode. This cavity was Ti-purified^[3, 4] at 1400 °C (HT) for 4 hours raising the cavity RRR to 500 from 250 to increase thermoconductivity of the cavity wall. The HT was then followed by a chemistry processing (BCP) taking 80 μ m materials from inside RF surface and 30 μ m from outside surface to remove all Ti contamination. The cavity was rinsed with high pressure (200 bar), pure water (15 M Ω -m) (HPR). The cavity has reached 12 MV/m and is limited by strong FE (point A). In order to remove the possible surface defects and field emission (FE) particles, the cavity was subjected to a second BCP to remove an additional 100 μ m material from the inner surface and then HPR again. During the cavity processing, the high peak RF power processing (HPP) was intentionally by-passed. A record high performance in TESLA cavities (both accelerating field of 26 MV/m and Q of 3×10^{10}) was achieved at point B.

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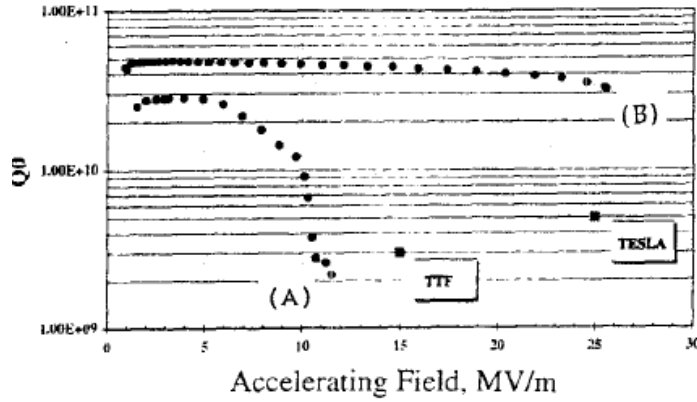


Fig. 1. An overall RF performance of a TESLA 9-cell cavity.

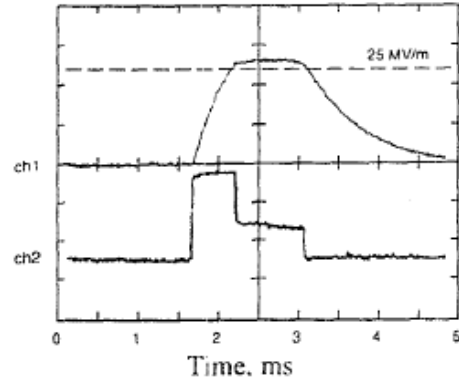


Fig. 2. The performance of a TESLA 9-cell cavity in a pulsed RF power test.

4 TESLA cavities reached accelerating gradients in excess of 25 MV/m when operated with the TESLA time structure. Fig. 2 shows the field amplitude and the RF forward power in a pulsed RF power test. The upper trace gives the gradient as a function of time while the lower one is the measured forward power. The total RF pulse length is 1.3 ms, the first 500 μ s are the filling time (exponential growth of the field gradient). At a reduced forward power the gradient was kept above 25 MV/m until 800 μ s, the exponential decaying gradient relates to a switch off forward power. The decay time corresponds to the loaded quality factor (the unloaded quality factor has been above 10^{10}).

III. EXPERIMENTALLY CHARACTERIZE QUENCH NATURES

Elimination of quenches in SRF cavities obviously becomes a top priority in the efforts for reaching highest possible accelerating gradients. To eliminate quenches, one must understand what causes quenches.

A. Quenches by Thermal Breakdown

A TESLA 9-cell cavity (D-4) has been Ti-purified at 1400°C for 4 hrs. It reached $E_{acc} = 12.5$ MV/m with a $Q = 7 \times 10^9$ at 1.8 K and was limited only by a quench.

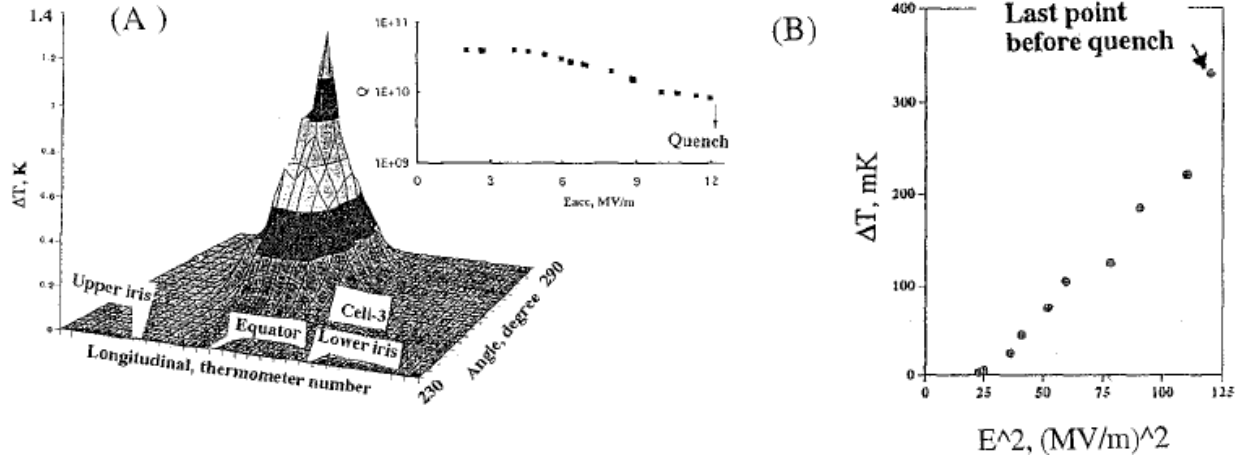


Fig. 3. (A) The strong heated area during a TB-caused quench at 12 MV/m in He II; (B) ΔT at the quench origin as a function of $(E_{acc})^2$ before quench.

The entire surface of the 9-cell cavity was scanned by the rotating T-R mapping system[5]. The quench was identified in cell-3. The quench origin was located in a strongest heating area centered at the equator (thermometer-7). The entire heated area crosses over 70 degrees in azimuth and 12 thermometers in longitudinal, as shown in Fig. 3 (A). The quench did not propagate to the adjacent cells.

The ΔT at the quench origin is approximately, linearly proportional to $(E_{acc})^2$ before quench as in Fig. 3

(B). This heating profile indicates that the quench is a thermal breakdown with a nature of normal conductor since a magnetic breakdown would not show a strong pre-heating and a FE heat would show a exponential heating profile with T rising.

B. Quenches by Field Emission

The TESLA prototype cavity (T-1) previously was limited by a thermal breakdown at about $E_{acc} = 10$ MV/m. Afterwards, the cavity T-1 was Ti-purified at 1400°C for one hour and followed by a standard processing. The cavity has then reached 21 MV/m and is limited by strong FE. We successfully locate the heated areas and their intensities associated with processing of cavity RF test. The heating shows a clear exponential ΔT profile with rising T.

Fig. 4(A) indicates an important heated region delimited by 3.3K. The integration of the product of Kapitza conductance and ΔT over the heated region leads to a total heat power going to He bath: Q-100 W. This value is consistent with the RF measurements of the experiment. However, the measured hot spots by FE only indicate the landing of impacting FE electrons, but not the emitter. The simulation of FE electron trajectories indicated that a emitter at location S=8 cm of cell-5 with emitter area $S_e = 1 \times 10^{-13} \text{ m}^2$ and $\beta = 400$ at the same E_{acc} will generate a similar heating profile to the measured heating areas, as shown in Fig. 4(B).

A detailed analyses can be found in ref. [5].

12 thermometers (#53 to #64) are centered close to the equator of the 5th cell, across 40 degrees (angles). Outside of this region the heating is very low. The ΔT value in this region is 100mK - 3.3K.

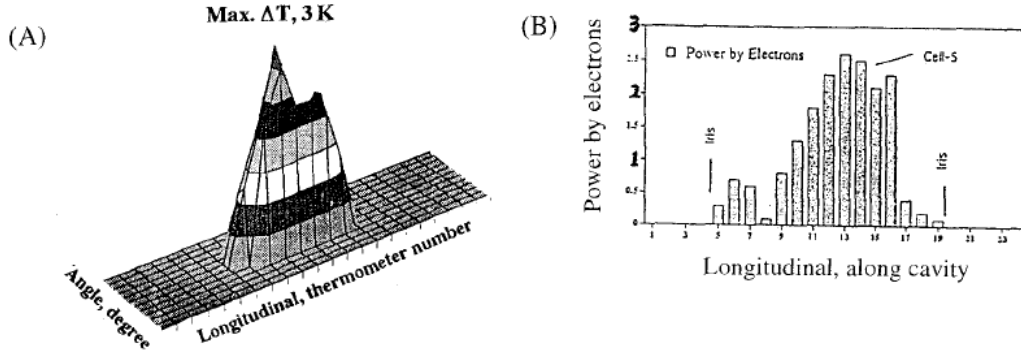


Fig. 4. (A) The measured heating profile of a cavity caused by a strong FE emission. (B) The simulated electron-deposit heating profile by a emitter located at s=8 cm of cell-5.

IV. KAPITZA CONDUCTION & BOILING HEAT TRANSFER BETWEEN CAVITY & He II

Understanding the heat transfer between a SRF cavity and He II is important in reaching the highest gradients. The experiments in simulation of the heat transfer between cavities and He II before and during quench were conducted [6]. The thermometers are mounted in the real operating conditions of the cavity test scanning device. The heat flux through the surface varied from tens mW/cm^2 to $2.8 \text{ W}/\text{cm}^2$. The temperature was measured by the surface scanning thermometer as functions of the heat flux. It is observed in Fig. 5. that the Kapitza heat transfer regime is effective until $2.2 \text{ W}/\text{cm}^2$, a critical point. Heat transfer is then governed by film boiling as heat flux $Q > 2.2 \text{ W}/\text{cm}^2$.

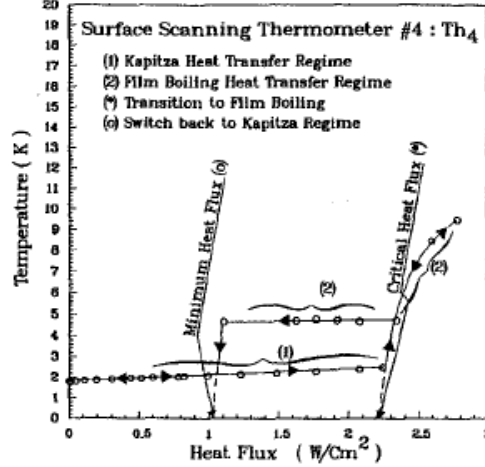


Fig. 5. Heat transfer between a heated surface and He II with large heat fluxes. The transition between the Kapitza regime and film boil is identified.

In this regime, temperatures increased sharply. When heat flux was reduced from film boil regime, a transition regime was observed before the heat transfer switched back to Kapitza behavior. The minimum heat flux for returning to Kapitza regime is about 1 W/cm².

From the temperature map measured in Fig 3. (b), the second point before the quench shows a ΔT of about 220 mK which represents a heat flux of 0.75 W/cm² that is, in the Kapitza regime. The last point before quench shows ΔT of about 320 mK which indicates a heat flux of 1.2 - 1.3 W/cm² that is in the transition loop. The temperature map measured during the quench, Fig 3. proves that a strong film boil takes place between the cavity surface and He II with $\Delta T > 700$ mK and an average heat flux much larger than 2.5 W/cm².

V. QUENCHES IN SUPERFLUID LHe AND SUBCOOLED LHe

For a long time we have been interested in experimentally investigating the differences of cavity quenches in He II and normal LHe in light of the cavity operations, such a study was carried out with cavity D-6 both in superfluid He and in subcooled LHe. Fig. 6 (A,) shows the overall RF performance respectively at 1.8K with quench Eacc: 12.6 MV/m, $Q = 1 \times 10^{10}$ and at 2.3K with quench Eacc: 11.5 MV/m, $Q = 3 \times 10^9$.

The quench was found in cell-5 and centered longitudinally around thermometer 4 and 110° in azimuth. The thermometer system was turned and fixed directly against the quench origin with 14 thermometers covering longitudinally over each cavity cell. Then the RF power was turned on in CW ($P_f = 90$ W) mode and the self-pulse quench & quench recovery of the cavity were observed. RF measurement shows the quench decay time (dissipation of 1/2 stored energy) is 1.4 ms at 12 MV/m in He II (1.8K, saturated).

Fig. 6 (B) & (C) shows the longitudinal temperature distribution as a function of time in the quench origin during self pulse quenches under CW RF power respectively at 1.8 K and 2.3K (subcooled, $P = 0.3$ atm.). In both cases, normal zones are limited within one cell. The heated area covered 1/2 of the cell-5 in longitudinal at 1.8K, while most of entire longitudinal was covered by heated area at 2.3K. In terms of self-recovery time (heated areas disappeared) it takes 140 ms in He II and 340 ms in subcooled LHe. With self-recovery, the cavity can remain in a superconducting state before the next quench, 240 ms in He II and 140 ms in subcooled LHe ($P_f = 120$ W).

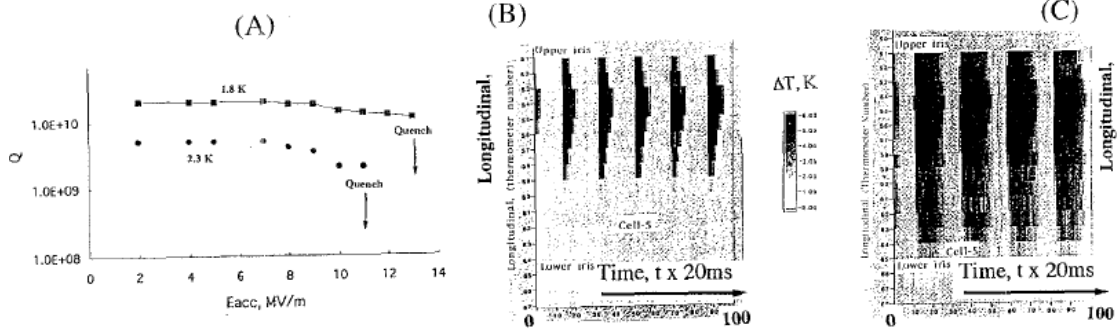


Fig. 6. (A) Overall RF performance of cavity D-6 both in He II and normal LHe; (B) ΔT as a function of time in He II longitudinally fixed over quench origin during self pulse quench and-recovery; (C) ΔT as a function of time in subcooled LHe longitudinally fixed over quench origin during self pulse quench and-recovery.

VI. EXISTING APPROACHES AND FUTURE TECHNOLOGIES

A. Existing Approaches

Many of the existing advanced approaches have been adopted and further developed by the TESLA collaboration at DESY to reach the highest gradients[7,8].

Cleaning techniques similar to those utilized in the semiconductor industry are used to remove most of the FE particles and some TB defects from the cavity's RF surfaces. We built a clean room or 300 m² with class 10 and 100 areas in 1993 for chemical etching, High pressure water rinsing, and cavity assembling (also we can load cavities into the UHV oven in a clean room area).

High pressure water rinsing (HPR) is very helpful in removing foreign particles which are difficult to remove by regular water rinsing. Significant successes have been obtained in CEBAF and KEK. With HPR, a CEBAF singlecell cavity has reached E_{acc} of about 40 MV/m without Ti-purification & without high RF power processing (HPP) [9].

Industrial sheet Nb for cavities has been improved to RRR=250-300 by better removing most of the dissolved impurities of O, N, H, C, etc. A higher RRR (500) is desired for reaching a $E_{acc} > 25$ MV/m. To increase the RRR in labs it is necessary to employ solid state gettering [3,4], where cavity surfaces are exposed to Ti vapors at 1400°C for 2-4 hrs. The oxygen which diffuses to the cavity surface is getterred by the evaporated layer. After improvement of RRR, both surfaces are etched to remove the foreign metal layer.

Despite the quality of the job performed to eliminate FE, there is always a possibility that particles escape removal and stay on the cavities surfaces. A technique, called HPP - high power processing, developed at Cornell University, applies a high power RF pulse to the cavity in situ and eliminates the FE through an explosive process [10].

B. Future Technologies

Using a rule of thumb that 40-45 Gauss is equivalent to 1-MV/m accelerating gradient in cavities with a TESLA shape, the theoretical limit for Nb (by Bsh) is then about 45 MV/m. and for Nb₃Sn is about 100 MV/m. Therefore, one has to reach out for new cavity materials & new technologies other than Nb for raising the E_{acc} over 50-100 MV/m.

One effort along this line has successfully been carried out by Wuppertal University & Jefferson Lab (CEBAF)[11]. They optimize the vapor diffusion technique to coat high purity Nb cavities up to RRR= 1000 with a micron-thick Nb₃Sn layer without loss of the thermal stabilization of defects. The 1.5 GHz single cell cavities fabricated by this method provided Q_0 up to 10^{11} at 2K and above 10^{10} at 4.2K until 5 MV/m of E_{acc} (up to 10 MV/m of E_{acc} , the Q is still above 10^9). The maximum E_{acc} obtained is 15 MV/m.

LANL and other labs have developed a HTc material of Ba-K-Bi-O which is a BCS type of bulk superconductor with T_c about 30K [12]. Its B_c is about 8000 Gauss which implies a 150 MV/m of E_{acc} theoretically. This material can be deposited on a metallic surface by the ion beam assisted deposition. One has a long way to go in reaching an application with this kind of materials. However, we also know the more difficult the challenges are, the brighter the futures are.

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