Detection and location of SRF bulk niobium cavities quench using second sound sensitive sensors in superfluid helium

M. Fouaidy, D. Longuevergne, F. Dubois, O. Pochon, J-F. Yaniche

IPN Orsay, 16 rue Georges Clemenceau 91406 Orsay, France

fouaidy@ipno.in2p3.fr

Abstract. We developed sensors and instrumentation dedicated to detection and location of thermal quenches in SRF cavities via 2nd sound events in HeII. We studied 2 types of Quench Detectors (QD): 1) Oscillating Super leak Transducer (OST), 2) LOw REsponse Time resistive Thermometers (LORETIT). The QD were characterized in He II bath (Temperature $T_0 = 1.6\text{ K}$ - $T_x$). The SRF cavity quench is experimentally simulated using resistors of different sizes and geometries. High pulsed heat flux $q_\phi$ ($q_\phi < 2\text{MW/m2}$) were applied to these heaters and the dynamic response of QD were investigated as function of several parameters ($T_0$, $q_\phi$, distance to heater). The OST were used for locating quench on different SRF cavities resonating at 2 frequencies $f_0$ ($f_0 = 88\text{ MHz}$ or $f_0 = 352\text{ MHz}$). The quench dynamics and critical size of normal resistive area leading to quench were investigated. Furthermore, a Second Sound Resonator (SSR) equipped with a pair of OST at each extremity (2nd sound generator (G) and detector (D)), a low thermal capacity heater (G) and a LORETIT (D), was successfully operated in the resonating and in the pulsed mode. The measured 1st sound and 2nd sound spectra were compared theoretical results and a good agreement is obtained.

1. Introduction

Thanks to the tremendous R&D effort made by different laboratories and to the use of high purity niobium (e.g. Nb of Residual Resistance Ratio RRR>300), well assessed fabrication techniques and preparation procedures, high accelerating gradient $E_{acc}$ are achieved with SRF bulk Nb cavities. In the framework of the ILC R&D program at KEK (test facility STF-1 [1]), using 9 cells (Fig.1) SRF bulk Nb, $\beta=v/c=1$ cavities (v: particle velocity, c: speed of the light), operated at a frequency $f=1.3\text{ GHz}$, the achieved $E_{acc}$ was in the range 33.8 MV/m – 40.9 MV/m for 13 resonators tested [2]. However, the maximum achieved accelerating gradient in SRF Nb cavities, is often limited the quench. More precisely [2], 51 quench events were observed for 28 9-cells cavities tested at KEK: the observed quench fields are in the range 10 -35 MV/m. The quench is generally due to anomalous RF losses (i.e. Joule heating) of normal-resistive defects or inclusions embedded onto the RF surface [2]. The typical effective radius $r_D$ and normal surface resistance $R_{ND}$ of these defects are respectively in the range 1-100 $\mu$m and 1-10 m$\Omega$. Considering an ILC cavity (Fig.1), operated at $E_{acc}=33\text{ MV/m}$ corresponding to a maximum surface magnetic field $H_{Smax}=1.110^3\text{ A/m}^2$ in the equator region, the local RF losses in defect area are $Q_{Defect}=0.5 R_{ND} H_{Smax}^2=31\text{MW/m}^2$. Furthermore, unloaded quality factor $Q_0 = 2.110^6$ was achieved at $E_{acc}=20\text{MV/m}$ with a low loss ILC cavities [3]: this value of $Q_0$ corresponds to a surface resistance $R_S=14\text{ n}$ is at $T_0=2\text{K}$ in the accelerating mode (frequency $f=1.3\text{ GHz}$). At $E_{acc}=33\text{ MV/m}$, the resulting Joule RF losses in the superconducting surface region are $Q_{SRF}=0.5 R_S H_{Smax}^2=82\text{ W/m}^2$. 

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The cavity could be modeled (Fig. 1b) as a circular Nb plate (radius R >> r_D, thickness e = 3-4 mm) with the following boundary conditions: 1) RF surface subjected to a non-uniform prescribed heat flux, 2) Heat transfer at the cavity wall cooled by superfluid helium (He II), controlled by the Kapitza conductance at Nb-He II interface, 3) Adiabatic side wall. Using this thermal model, we have solved the steady-state heat equation. The analytical solution obtained were used to compute the variations of the temperature T_{RF} at the center of the defect (radius: R_{D} = 10 µm), located on the RF surface of the cavity, as function of E_{acc}. The results (Fig. 2) show a strong increase of T_{RF} with E_{acc}, which is naturally due to the quadratic dependence of RF losses with E_{acc} (e.g. qα R_s H_s^2 α R_s E_{acc}^2).

Furthermore, the cavity is thermally stable (i.e. in superconducting state) if T_{RF} < T_C(E_{acc}), where is T_C(E_{acc}) is the Nb critical temperature. At the quench field E_{acc}^0, the cavity transits to the normal resistive state: Q_0 decreases exponentially dropping by ~3-4 decades, with a time constant \tau_{cav}=100 \mu s [5]. This decrease of Q_0 is due to the large difference between the surface resistances of normal Nb (R_s^N ~10mΩ) and superconducting Nb (R_s^S ~20nΩ). Considering a SRF cavity with a total RF surface area A_C, at the quench field, the area of the normal zone A_N [5], which is inversely proportional to R_s^N, is A_N \approx 0.1 A_C.

By introducing the above values of R_s^N, R_s^S, and A_N/A_C in the relationship (2), one finds Q_0^S/Q_0^N = 5.10^3, which is close to the observed experimental data (Fig. 4). Further, when Q_0 decreases, the coupling factor \beta = Q_0/P_F, initially close to 1 decreases: the forward RF power P_F is then completely reflected from the cavity, leading to the observed decrease of the RF fields (e.g. E_{acc} \propto (P_F/Q_0^S)^{1/2}). Then the cavity cools down, resulting in a decrease of the hot spot temperature T_{RF} below T_C: the cavity is now superconducting and Q_0 increases by factor \approx 10^5.
As the cavity is again matched (e.g. \( \beta \sim 1 \)), the RF field could be raised again and a self-sustained cycle is repeated. Obviously, the thermal quench of SRF cavity is easily detectable with RF probes (i.e. transmitted power \( P_t \) versus time \( t \)). But, as \( P_t \) vs. \( t \) curve is an overall measurement, it is insufficient neither to characterize completely the quench, nor to locate the quench source. Local diagnostic tools are then needed for locating and characterizing quench source.

2. Brief history of thermal diagnostic tools of anomalous rf losses in srf cavities

The first generation of sensors used for quench detection was developed in \( \sim 1980 \). These sensors are surface thermometers sensing the outer surface temperature \( [5-9] \) of the cavity cooled by Liquid Helium (LHe). These thermometers operate in sub-cooled, boiling normal LHe or He I and in superfluid helium (HeII, bath temperature \( T_0 < T_J \)). Two types of thermometers were used: a) Scanning Surface Thermometers (SST), b) Fixed Surface Thermometers (FST). Due to the cooling medium and the measurement configuration, SST are intrinsically limited \([5-8]\) when operated in He II: 1) low measurement efficiency (~1-2%), 2) lack of reliability and repeatability. FST are also practically limited because a large number (i.e. >>100) of such sensors is needed \([5-8]\), in order to ensure a good spatial resolution. Second generation of quench detectors in He II, namely OST (Oscillating Superleak Transducer), were initially developed in 1970 for studies on He II hydrodynamics \([10]\). The OST are capacitive Quench Detectors (QD), sensing second sound (e.g. temperature wave) events in (He II): they were applied to SRF cavity thermal breakdown studies 7 years ago \([11]\). Note that LOw REsponse Time (\( \ll 1 \text{ms} \)) resistive Thermometers (LORETIT) could also be used as quench detectors.

3. Experimental set-up

3.1 Description of OST developed at IPN Orsay

We developed \([12]\) a first generation of OST with 31.5 mm O.D. The OST is a capacitive sensor consisting in 4 parts: 1) the rigid brass electrode (O.D: 16 mm, Thickness: 4.1 mm) equipped with a SMA base connector, 2) the sensor body made of Al alloy, 3) the dielectric and bonding agent (epoxy resin), 4) the deformable active electrode made of a thin (thickness: 6-11 \( \mu \text{m} \)) porous (Pores diameter: 0.2 \( \mu \text{m} \)) polycarbonate membrane, coated with 50 nm thick Al or Au onto its upper surface for electrical contact.

![Fig. 5: Photographs of first (1), second (2) generation of OST and SEM image (3) of the membrane.](image)

Compared to the 1\( \text{st} \) generation of OST, the 2\( \text{nd} \) generation have the following main features: 1) smaller footprint (O.D:13 mm) and better mechanical precision, leading to a higher spatial resolution, 2) nearly unchanged sensitivity, 3) a better reliability and reproducibility of OST mechanical and electrical capacitance.

3.2 Test Cells and configuration of Sensors

We have developed a test facility allowing the calibration and full characterization of various quench detectors in LHe bath: the temperature \( T_0 \) range is 1.55 K– 4.25K. The quench of SRF cavities is experimentally simulated by means of Joule heated resistors. In order to investigate the effect of the heater geometry, and the distance of the sensors to the quench-like source, we performed experimental runs with 6 different configurations (6 test cells) using either cylindrical or flat SMD resistors of different sizes. However, due to space limitation only data obtained with the test-cells #1 and #2 will be reported here. The description of these 2 test-cells is summarized in Table 1 and a photograph of all the 6 test cells used is shown in Fig. 6. Moreover, we used as LOw REsponse Time resistive Thermometers (LORETIT), two industrial bare ship resistors (Cernox 1050 BC) named CX here after.
Fig. 6: Photographs of the six test-cell used with OST and low response time thermometers

4. Experimental results and discussion
Several experimental runs were performed at different $T_0$. The CX resistors were in-situ calibrated (e.g. Resistance vs. Temperature) prior to the measurements of their response to a pulsed heat flux in He II. For the calibration, we used the saturated LHe bath as thermostat: the temperature is regulated to better than $0.2 \, \text{mK}$ for $T_0 < T_\lambda = 2.1768 \, \text{K}$, via precise control of vapour pressure (butterfly valve).

4.1 Improvement of the signal conditioner for OST sensors
For OST readout electronics, during the first tests [11] we used, as signal conditioner (SC#1), a basic current amplifier (Fig. 7) similar to that used by other groups. But, the output signal of SC#1 we obtained in characterization experiments or quench detection on cavities were too noisy, which is a limitation for the measurements. In order to increase both the gain of the SC and the output signal to noise ratio (SNR), we developed a new high performance SC (SC#2) for the OST. The two signals recorded by the same OST with the SC#1 and SC#2 are compared in Fig. 7: 1) the signal level is improved by a factor $V_{SC#1}/V_{SC#2}$~555, 2) The SNR was also improved. Note that in the case of SC#1, due to the low SNR, we have to perform the integration of 200 samples in order to obtain a useful signal.

Fig. 7 a) Comparison of the performances of the 2 signal conditioner SC#1 and SC#2, b) diagram of SC#1

4.2 Response of cernox thermometers at $T_0=1.9 \, \text{K}$
Using the cell #2 (SMD heater #1, heater area: $2.5 \, \text{mm}^2$), we succeeded to measure at $T_0=1.9 \, \text{K}$, the response of CX#1 and CX#2 to a pulsed heat flux applied to the heater (Peak value: $q_0$ 15.2 MW/m$^2$, pulse duration: $\tau_P=100 \, \mu\text{s}$). The corresponding results are shown in Fig. 7.
Fig. 7: Response of CX#1 and CX#2 - 1) Measured signals, 2) Thermometric signals using sensor sensitivity (Pulsed heat flux: $q_p=15.2$ MW/m$^2$, pulse duration: $\tau_p=100$ µs)

It should be stressed that it was really challenging to perform such measurement of fast and weak transient thermometric signals in He II with a small heater (e.g. area=2.5 mm$^2$) in a large bath (I.D: 350 mm, Height: 100 mm-750 mm). Note that, for the above data, we achieved a resolution better than 2µV at a sampling rate of 100 kHz with a baseline signals ~100 mV. Moreover, for a sensing current of 20 µA, the measured peak values are ~100 µV-300 µV leading to a peak transient heating~100 µK: our results are in good agreement with the few data, in our knowledge, previously reported [13]. Furthermore, the observed time lag between the first observed signal peaks of the sensors CX#1 and CX#2 is $\Delta t=770$ µs, resulting in a second sound velocity $u_2=20$ m/s, measured by a pulse method at $T=1.9$ K: this value is close (e.g. 6.1%) to the data (e.g. $u_2=18.77$ m/s) reported previously by Donnelly team [14] using a 2$^{nd}$ sound resonator.

4.3 Response of OST sensors to pulsed heat flux

Using the heater #1 (heater area: 2.5 mm$^2$) of cell#1, we thoroughly investigated at 1.9K, the response of OST#8 and OST #7 to various pulsed heat flux: we varied the peak value $q_p$, while the pulse duration was kept constant $\tau_p=100$ µs. The results are illustrated in Fig. 8. These data clearly show a linear behavior with respect to $q_p$: the peak amplitude of OST signal $V_{OST}$ is proportional to $q_p$ (Fig.8-Fig. 9). These behavior were observed for both OST sensors, located respectively at $r=35.7$ mm and $r=60.8$ mm as illustrated in Fig. 9. For the SMD resistors (e.g. heaters configuration corresponding to a spherical symmetry), one expects a quadratic decrease of the heat flux with the distance $r$ to the heater (e.g. q $\propto r^{-2}$) as it is clearly observed in Fig. 9.

Fig.8 Effect of peak heat flux on OST response at $T_0=1.9$K

4.4 Quench detection on SRF cavities

In this paper, we will present on test performed on Quarter-Wave Resonator (QWR, frequency:
88MHz) prototype (Fig. 10) developed at IPNO for SPIRAL2 (SP2) project. The RF parameters of the SP2 cavity are: a) particle velocity \( \beta = v/c = 0.12 \), b) \( E_{\text{acc}} = 6.5 \) MV/m, c) peak surface magnetic field \( B_{pk} = 65 \) mT, d) quality factor \( Q_0 = 1.5 \times 10^9 \) at 2 K, corresponding to a heat load of 10W. The cavity is equipped with its LHe tank. Four OST fabricated at IPNO were used for quench location (Fig. 10).

Fig. 10 a) Photograph of the SP2 prototype named Tokyo, b) magnetic field map, c) sketch of 2nd sound event trajectories during when the cavity quenches.

At \( T_0 = 1.8 \) K, the cavity Tokyo quenched at \( E_{\text{acc}}Q = 8.8 \) MV/m: \( Q_0 = 1.3 \times 10^9 \) at the quench field. Second sound signals induced by the quench were recorded by the OST assembly (Fig. 11).

Fig. 11 Measured 2nd sound events during the quench of the SP2 prototype cavity Tokyo. The x-axis, which is usually time, was converted in distance using 2nd velocity \( U_2 = 19.87 \) m/s at 1.8 K.

The analysis of OST signals lead to the following conclusion: 1) as expected, the quench source is located on the critical welding [2] between the cavity dome and the tube, where the surface magnetic field is high, 2) as expected the adiabatic walls reflect the 2nd sound wave, 3) as 2nd sound wave is attenuated, no sizable signal is recorded by the OST#3 located at 70 cm from the quench source.
5. SECOND SOUND RESONATOR

5.1 Description of the second sound resonator

In order to perform precise measurements of the 2nd sound velocity \( u_2 \) in He II, we developed a Second Sound Resonator (SSR). This SSR (Fig. 12) is equipped with a pair of OST at its 2 extremities as thermal source (OST#1) and sensor (OST#2), and a low thermal capacity heater with 2 thermometers CX#1 and CX#2. This SSR could be operated in the standard standing wave mode or in pulsed mode (i.e. thermal shock waves). Further 2nd sound could either thermally generated (e.g. Joule heating) or via the normal fluid flow induced by the motion the OST#1 membrane (e.g. mechanic-heat effect). Conversely, 2nd sound could be detected either with the thermometer or with OST#2.

![Fig. 12](image)

Fig. 12 a) Details of its instrumentation of SSR, b) Photograph of SSR, c) Block diagram of SSR test

5.2 Theory

The second-sound velocity \( u_2 \) will be determined experimentally as a function of temperature by measuring the frequency of one of resonant modes of the SSR. The resonance frequencies \( f_{mn} \) of the different modes of the cylindrical SSR are given by:

\[
f_{pmn} = \frac{1}{2} u \left[ \left( \frac{p}{L} \right)^2 + \left( \frac{a_{mn}}{R} \right)^2 \right]^{1/2}
\]

Where \( u \) is the sound velocity, the integer \( p \) is the mode number (pth harmonic) and \( R \) the radius of the resonator. The parameter \( a_{mn} \) is the n
th root the equation:

\[
\frac{d[J_m(\pi a)]}{da} = 0
\]

Where \( J_m \) is the Bessel function of the first kind and of order \( m \).

5.2 Results and discussion

The SSR was first tested as first sound resonator in gaseous helium (pressure: 1013 mbar, T~300 K) then in LHe at 4.2 K. The measured and computed spectra using equation 1 are in very good agreement: more than 11 resonating mode were compared and the relative difference between measured and calculation results was less than 4.5 % (Fig. 13).

![Fig. 13](image)

Fig. 13 Measured and computed first sound spectrum in LHe at T=4.2K
The measured 2\textsuperscript{nd} sound spectra at T=1.7 K, 1.9 K and 2.1 K are presented in Fig. 14. The data clearly show an increase of resonant frequencies f for all the modes when T is decreased. This is simply due to the temperature dependence [12, 14] of the 2\textsuperscript{nd} sound velocity $u_2$: as f is proportional to $u_2$, f increases when T is lowered because $u_2$ increases when T decreases.

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