NATURE OF QUALITY FACTOR DEGRADATION IN SRF CAVITIES DUE TO QUENCH*

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Abstract

Superconductive quench is a well-known phenomenon that causes magnetic flux trapping in superconducting accelerating cavities increasing the radio-frequency surface resistance. This paper is addressed to the understanding of the quench-induced losses nature. We present the proof that the real origin of quench-related quality factor degradation is consequence only of ambient magnetic field trapped at the quench spot. Also, we show how the quality factor can be fully recovered after it was highly deteriorated quenching several times in presence of external magnetic field. Such phenomenon was found to be completely reliable up to certain values of applied magnetic field, above that the cavity quality factor cannot be fully recovered anymore.

INTRODUCTION

Superconducting radio frequency (SRF) accelerating cavities are resonating structures that allow to accelerate charged particles up to energies of TeV. The limiting factors of such accelerating structures are represented by the finite value of intrinsic quality factor (Q_0), related to the cryogenic cost needed to their operation, and by the radio frequency (RF) field breakdown due to quench, that limits the maximum accelerating gradient (E_{acc}) achievable.

During the quench event a large area of the cavity becomes normal-conducting. This leads to a sudden increase of the surface resistance, that causes the suppression of the RF field in the cavity. Many well-known mechanisms [1–5] may lead to such phenomenon, and it was hypothesized that when the normal conducting region is created some magnetic flux can be trapped causing extra dissipation [7].

The origin of such trapped magnetic flux was ascribed to different mechanisms, such as: thermocurrents driven by the local thermal gradient in the quench zone [7], RF field trapped within the penetration depth region, or ambient magnetic field [8]. Anyhow, the real origin of Q_0 degradation after a quench is still not well understood and source of discussion in the SRF community.

Some studies [8] were performed at Fermi National Accelerator Laboratory (FNAL) on the degradation of the quality factor of superconducting resonators (high and medium β), with the purpose of finding a criterion to define the amount of ambient magnetic field trapped during the quench. In such work was also discussed the possibility of the complete recovery of the quality factor quenching in absence of external magnetic field.

In the present study we report the experimental prove that the Q_0 degradation due to quench is direct consequence of trapped ambient magnetic field, ruling out any other possible mechanism. We also demonstrate that fully recovery of the Q_0 after a quench can be achieved when the cavity is quenched in absence of external magnetic field, without warming the cavity above the critical temperature.

We discuss the configuration of the magnetic field trapped at the quench spot, and how this is the key to understand the recovery phenomenon.

It was also observed that not always the recovery of the quality factor is possible. If the trapped field is large enough, it migrates far from the quench spot, and the quality factor cannot be completely recovered anymore.

EXPERIMENTAL SET-UP

Some quench experiments were performed using several niobium nitrogen doped [6] 1.3 GHz TESLA-type cavities (TABLE 1), which were tested at the FNAL vertical test facility (VT). A scheme of the single cell cavities instrumentation is sketched in Fig. 1.

Single cell cavities were equipped with a T-map system [9] in order to map the temperature variation of the cavity

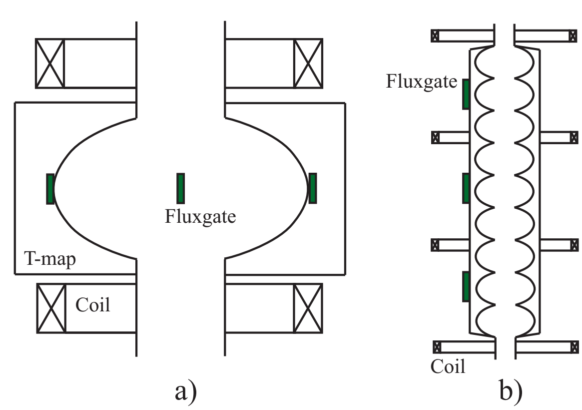

Figure 1: Experimental set-up for: a) single cell cavities, b) 9-cells fully dressed LCLS-II cavity.

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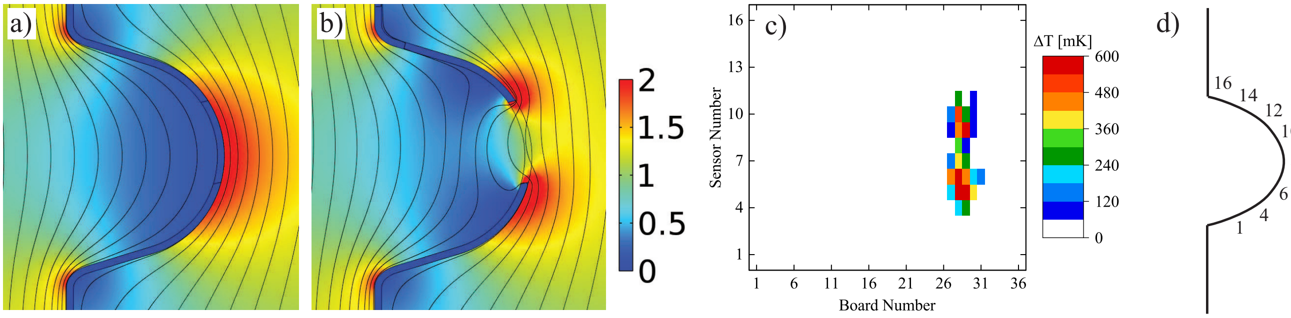

Figure 2: Symulations of magnetic flux penetration at the quench spot: a) before quench, b) during quench. The color scale represent the ratio between the local magnetic field and the magnetic field applied. In c) a T-map of AES019 after multiple quenches in 500 mOe is reported. A schematics of the thermometers position is sketched in d).

due to quench and localize the quench spot site. The thermal sensors are placed on a total of 36 boards - 16 per board - positioned every 10°. The external magnetic field was sustained by axial Helmholtz coils and measured with four single-axis Bartington Mag01H cryogenic fluxgates magnetometers positioned at the equator, axially to the cavity, every 90° (Fig. 1a).

One fully dressed LCLS-II 9-cells cavity was equipped with two couples of Helmholtz coils as shown in Fig. 1b, and with three single-axis Bartington Mag01H cryogenic fluxgates magnetometers outside the helium vessel in order to measure the external magnetic field applied.

Except for the 9-cell cavity (measured at 2 K), all the measurements were done at the lowest temperature achievable by the cryo-plant, around 1.5 K, in order to neglect the temperature dependent part of the surface resistance.

MAGNETIC FIELD TRAPPING DYNAMICS

The first important step is to understand the dynamics of the magnetic flux trapping during the quench event.

In order to visualize this, some time-dependent COMSOL® simulations were performed. The normal conducting region that opens up during a quench was represented by a not-perfect-dielectric hole in the superconducting wall of the cavity. The simulations are shown in Fig. 2.

The position of the normal conductive hole in the simulation was chosen wisely considering that the quench does not likely happen right at the equator, but in the equatorial zone, just above or below it.

The magnetic force per unit of volume, is described by the following formulation of the Lorentz force:

$$\begin{aligned} \mathbf{f_m} &= \mathbf{j} \times \mathbf{B} \\ &= -\nabla\left(\frac{B^2}{2\mu_0}\right) + \frac{(\nabla \cdot \mathbf{B})\,\mathbf{B}}{\mu_0} \end{aligned} \qquad (1)$$

Where the first term correspond to the magnetic pressure, while the second one to the magnetic tension. The magnetic pressure is directed perpendicular to the magnetic field lines, with aim opposite to their gradient.

The magnetic tension is instead only present when the magnetic field is bent. It has radial direction with aim directed toward the center of curvature. It introduces the same restoring action that the elastic force has when a stiff slab is bent. The magnetic tension then exerts a force to straighten the magnetic field.

When the cavity is in the Meissner state, the magnetic field is deflected around it as shown in Fig. 2a (for axial field). This implies that where the magnetic field lines are denser and more bend, both the magnetic pressure and the magnetic tension are directed towards the cavity wall. This effect is enhanced on the equatorial zone of the cavity, where the magnetic field has an higher distortion grade, and where the quench most likely happens.

During the cavity quench, a normal conducting hole opens on the cavity wall and the magnetic field that was excluded from the cavity internal volume is now allowed to penetrate driven by the sum of the magnetic pressure and magnetic tension contributions, as shown in the simulation Fig. 2b.

Table 1: Cavities studied with respective thermal treatments and quench field

Cavity	Thermal treatment	Cell number
AES011	800 °C, 2 min w 25 mTorr N_2 + 6 min w/o N_2 and 5 μm EP	Single
AES019	800 °C, 10 min w 25 mTorr N_2 and 5 μm EP	Single
ACC002	800 °C, 20 min w 25 mTorr N_2 and 5 μm EP	Single
AES014	120 °C bake	Single
AES024	800 °C, LCLS-II N-doping treatment	Dressed 9-cells

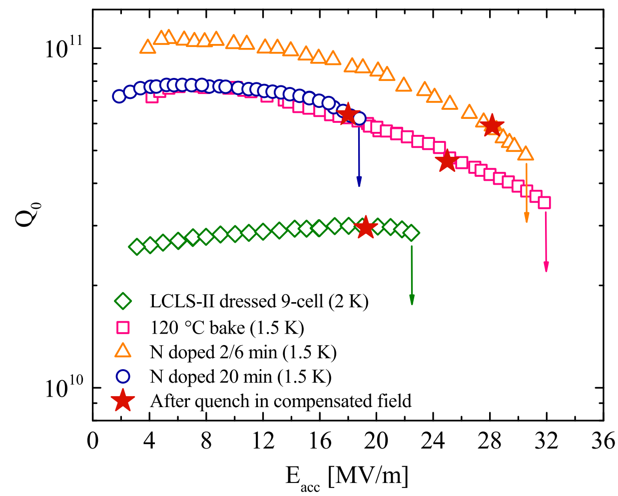

Figure 3: Q_0 versus accelerating field curves acquired before any quench. The red stars correspond the the Q_0 point acquired just after the quench in compensated external magnetic field.

In such situation when the flux is trapped both fluxoids and anti-fluxuoids are formed. The magnetic field can therefore enter from a fluxoid and exit from an anti-fluxoid - or vice versa - creating a loop in the cavity volume. Such magnetic field configuration is confirmed by the experimental data.

In Fig. 2c a T-map image of cavity AES019 just after a series of quenches in 500 mOe is reported (Fig. 2d can be used as reference to understand the T-map image orientation). It can be clearly seen that the shape of the dissipative region presents two lobes of higher temperature due to a higher concentration of trapped magnetic flux. Such magnetic field configuration is in agreement with the simulations for which the magnetic field lines are bent inside the cavity volume, and cross two times the cavity wall.

DATA ANALYSIS AND DISCUSSION

All the quench studies were performed by quenching the cavity in presence of external magnetic field (H) or in compensated magnetic field, and by recording the degradation of Q_0 at fixed accelerating field just after the quench. The condition of compensated magnetic field was achieved by acting on the Helmholtz coils current in order to compensate the magnetic field naturally present in the VT cryostat, till the magnetic field value recorded was lower than 1 mOe.

The first series of quench studies were done on cavities processed with different thermal treatments. All the cavities were quenched in compensated external magnetic field by means of the RF field. As Fig. 3 clearly shows, no appreciable extra dissipation was introduced by quenching in compensated external magnetic field for the all the cavities studied.

Such phenomenon is important as it rules out other possible mechanisms of magnetic flux generation and trapping during quench, as those would necessarily lead to a decrease of Q_0 even in zero ambient field - magnetic flux trapped at the quench spot is not intrinsic but extrinsic to the cavity.

Interesting to notice how also for a fully dress 9-cell cavity treated with the LCLS-II recipe it was possible to avoid extra dissipation by quenching in compensated field. The average magnetic field value recorded just before its quench was lower than 2 mOe, but still no appreciable extra dissipation was introduced.

A second series of experiments were done. In such quench studies some magnetic field was applied outside the cavity before quenching. The degradation of the Q-factor was recorded after every quench.

After that, the cavity was quenched again several times in compensated field. Surprisingly, Q_0 could be totally recovered to its value just before any quench without needing of warming up the cavity above the critical temperature (T_c).

As shown in Fig. 4a, the variation of residual resistance $\Delta R_0(H)$ changes with the value of applied magnetic field outside the cavity ($\Delta R_0(H)$ correspond to the difference be-

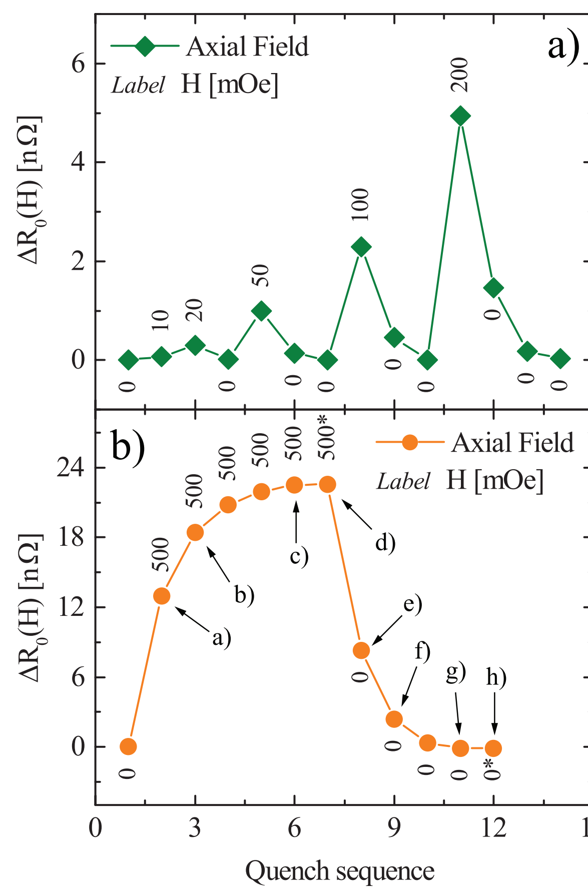

Figure 4: Quench study per formed on cavity ACC002: a) variation of the residual resistance due to quenches in presence of external magnetic field. b) saturation of the residual resistance due to multiple quenches in the same external field. The labels "0" indicates the condition of compensated field, while the symbol "*" refers to multiple quenches. With arrows and letters are indicated the $\Delta R_0(H)$ points that correspond to the T-maps of Fig. 5.

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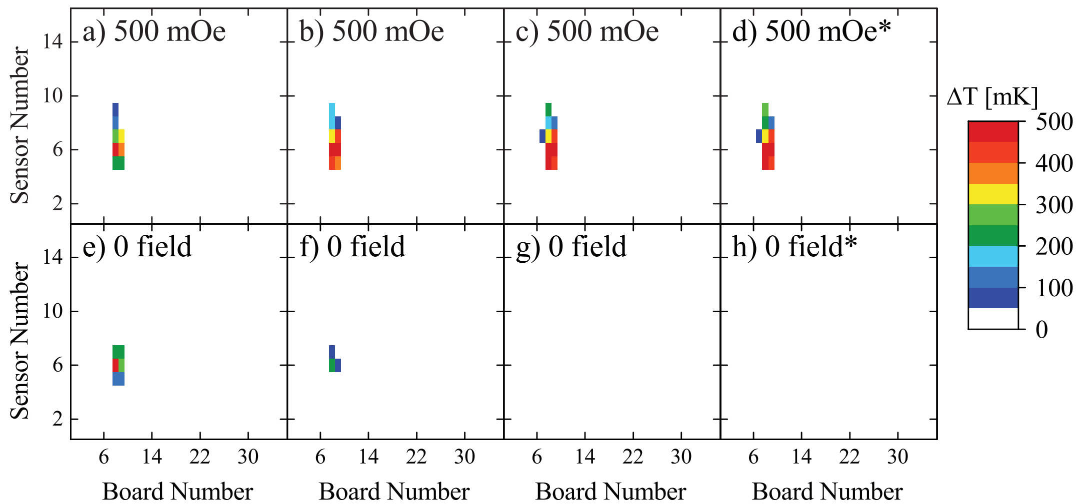

Figure 5: Evolution of the dissipation due to trapped field at the quench spot for ACC002 after quenching: a) a single, b) two, c) five, d) multiple times in 500 mOe, and after quenching e) a single f) two, g) four, h) multiple times in compensated field. The symbol * identifies multiple quenches.

tween R_0 after a quench and R_0 before any quench). After the quality factor was degraded by quenching in presence of external field, the magnetic field was compensated, the cavity quenched again several times, and the quality factor could be totally recovered.

It was observed that quenching multiple times in the same field the residual resistance reached a saturation value, as reported in Fig. 4b. Such saturation suggests that the maximum value of of magnetic flux trapped at the quench spot for a specific external magnetic field level was reached. Anyhow Q_0 could be totally recovered quenching several times in zero field.

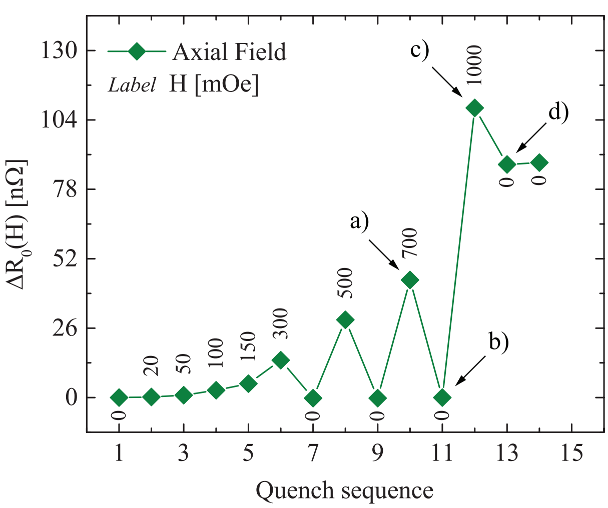

Figure 6: Residual resistance evolution of AES019 after quenching in different field values. Every point in the graph correspond to multiple quenches in the same applied field. The arrows indicates the data points that correspond to the T-maps of Fig. 7. The labels "0" indicates the condition of compensated field.

By means of T-map images it is possible to have more feeling on what happens during the saturation and recovery of Q_0. In Fig. 5 a sequence of temperature maps of the evolution of the magnetic flux trapped at the quench spot are reported. The respective variation of residual resistance are highlighted with arrows in Fig. 4b.

Initially the cavity was quenched a single time in compensated field (Fig. 4b), and no extra dissipation due to trapped flux was recorded. A field of magnitude 500 mOe was then applied axially to the cavity which was quenched a single time. Extra heating at the quench area was recorded (Fig. 5a), meaning that some magnetic flux was trapped.

The cavity was then quenched multiple times in the same field till it reached the residual resistance saturation (Fig. 5d). The extra heating introduced by the trapped field increased substantially, and the maximum amount of flux was trapped at the quench spot - during every quench only part of the local magnetic field at the quench spot is trapped, the saturation occurs when all the available local magnetic field is trapped.

The external field was then compensated again, and the cavity quenched multiple times. All the extra heating at the quench spot vanished, meaning that the trapped flux was annihilated (Fig. 5h).

Till now we have demonstrated that the cavity quality factor can be totally recovered by quenching in compensated external magnetic field, but this is not always possible. Once the cavity is quenched multiple times - the residual resistance is saturated - in higher values of magnetic field, the cavity quality factor cannot be recovered to its original value before any quench. It can be only partially recovered.

As showed in Fig. 6 for AES019, the residual resistance could be recovered to its original value till the quench was performed in magnetic field values higher or equal to 700 mOe.

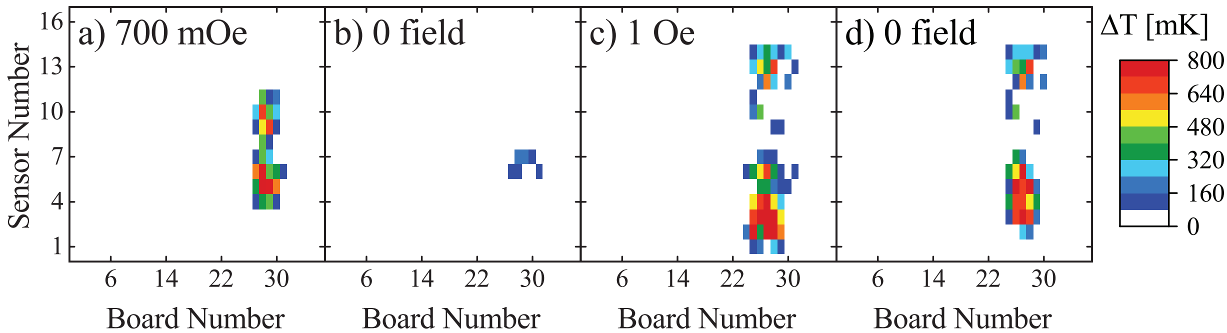

Figure 7: T-map images acquired after the cavity AES019 was quenched in presence of external magnetic field with the following sequence of magnitudes: a) 700 mOe, b) zero field, c) 1 Oe and d) zero field. Such sequence shows the impossibility of Q_0 recovery after the cavity was quenched in 1 Oe. The most part of the trapped flux could not be annihilated quenching again in zero field.

After the cavity was quenched several times in 1 Oe its quality factor could not be completely recovered anymore, even by quenching several times in compensated field.

The same behavior was observed also for cavity ACC002 and AES011. In these cases though the magnetic field threshold above that the quality factor could not be completely recovered was 700 mOe and 300 mOe respectively.

It worthies to mention that the first quench done in compensated field did increase the surface resistance. Since it was the only quench in compensated field recorded that introduced extra dissipation, its causes has then to be extrinsic to the cavity as well. The most probable explanation to such event is the presence of non axial components of the magnetic field inside the VT cryostat during the test. $\Delta R_0(H)$ of Fig. 6 is then calculated as the difference between R_0after a quench and R_0 after the first quench.

In Fig. 7 the evolution of the trapped field at the quench spot is reported. The respective residual resistance variation is reported in Fig. 6.

Figure 7a refers to the trapped magnetic flux dissipation after cavity AES019 was quenched several times in 700 mOe. The field was then compensated outside the cavity in order to minimize it as much as possible, and the cavity was quenched again several times.

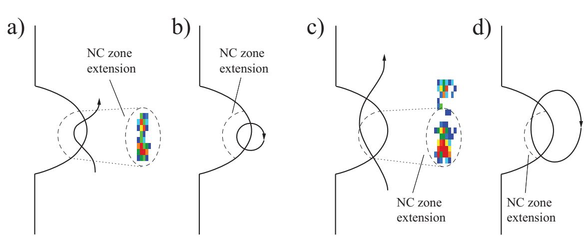

Figure 8: Sketch of the magnetic field trapped at the quench region: a) cavity quenched in presence of external magnetic field. The T-map shows a two-lobed-shaped dissipation. b) after the external field compensation. c) trapped magnetic flux after the flux migration. The T-map shows two hot spots. d) field compensated after the magnetic flux migration.

As shown in Fig. 7b the most part of the dissipation introduced by the quench vanished. Still, some flux remained trapped at the quench spot, probably because introduced by the presence of non axial field components of the field in the VT cryostat that could not be compensated.

The external magnetic field was then set to 1 Oe and the cavity quenched several times. The respective T-map is reported in Fig. 7c. The fluxoid dissipation configuration is now spreader than before. The two lobes became two individual hot spots separated by a non-dissipative region in the middle.

At this point the field was again compensated and the cavity quenched, several times. Figure 7d shows the T-map acquired just after several quenches. It appears clear that no complete field annihilation occurred now, and some redistribution of the magnetic flux was recorded.

The last two points on Fig. 6 correspond to such T-map, the quality factor could not be completely recovered this time, lot of magnetic flux remained trapped at the quench region even by quenching in very low values of external magnetic field.

The suspected mechanism at the basis of such phenomenon is the annihilation of the magnetic field trapped at the quench spot when the cavity is let quenching again in zero field [10].

With a finite magnitude of applied magnetic field, the magnetic field lines incoming in a fluxoid and outgoing from an anti-fluxoid, will create a close loop passing through the two Helmholtz coils (Fig. 8a). But, when the external field is compensated the trapped magnetic field lines must create a closed loop by themselves, being sustained only by the screening currents in the superconductor, respecting the Ampere's law (Fig. 8b).

When the quench occurs, a normal conducting region is created at the quench spot, and the superconducting screening currents that sustain the trapped field annulled with the vanishing of the superconductive phase. In such scenario the Ampere's law is not respected anymore, and the trapped field is annihilated.

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Therefore the trapped magnetic flux can be annihilated only if: i) it is trapped in the loop configuration, and ii) if fluxoids and respective anti-fluxoids lobes are both inside the maximum extension of the normal conductive area during the quench.

When the condition ii) is not respected (Fig. 8c), and one of the two lobes falls outside the maximum extension of the normal conducting zone during the quench, even if the external field is compensated and the cavity quenched, superconducting currents that sustain the field will always exist. One of the two lobes will be surrounded by superconducting phase, preventing the annihilation of the trapped magnetic flux during the quench.

Summarizing then, the trapped flux at the quench spot redistributed away from its original position when the cavity was quenched in 1 Oe. The new magnetic flux configuration do not guarantee that both lobes fall inside the maximum extension of the normal conductive region during the quench, and the flux cannot be completely annihilated quenching in compensated external magnetic field.

The quality factor recovery highlights even more the extrinsic nature of the flux trapping during a quench. If the magnetic flux generation during the quench were intrinsic to the cavity, then the recovery of Q_0 could be achieved only by warming the cavity above T_c. Quenching in zero applied magnetic field would only been source of extra dissipation as any other quench.

MAGNETIC FLUX MIGRATION

The motion equation of a fluxoid not subjected to a drifting current is [11, 12]:

$$-S \cdot \nabla T - \eta \mathbf{v} - f n_s e \left(\mathbf{v} \times \phi_0 \hat{\mathbf{u}}_\mathbf{n} \right) - \mathbf{f_p} = 0 \qquad (2)$$

The first term corresponds to the thermal force, whose direction depends only on the thermal gradient ∇T. Fluxoids are subjected to a thermal force that moves them from hot regions to cold regions [11–14]. Here S is the transport entropy per unit of length, equal to [11, 12]:

$$S = -\phi_0 \frac{\partial H_{c1}}{\partial T}$$

where H_{c1} is the lower critical field and ϕ_0 the flux quantum.

The thermal force will act against the Magnus force $f n_s e \left(\mathbf{v} \times \phi_0 \hat{\mathbf{u}}_\mathbf{n} \right)$, the viscous damping drag force $\eta \mathbf{v}$ and the pinning force $\mathbf{f_p}$. Where n_s is the electron density, f the fraction of the Magnus force that is active, and η the fluxoid's motion viscosity per unit of length [15]:

$$\eta = \frac{3}{2} \frac{\sigma_n \phi_0^2}{\pi^2 \xi_0 l}$$

with σ_n the electrons' conductivity, ξ_0 the coherence length and l the electrons' mean free path.

Usually the faction of Magnus force active is much smaller than one, and it can be neglected. Only for extremely pure superconductors this plays an important role [11, 12].

The condition to move fluxoids is match when the thermal force is bigger than the pinning force [12, 13]. The critical temperature gradient $S \cdot \nabla T_k$ for which a fluxoid can move is then defined as:

$$-S \cdot \nabla T_k = \mathbf{f_p} \qquad (3)$$

The time constant of the quench phenomenon must be smaller than the one corresponding to such flux diffusion mechanism. During the quench the temperature increases drastically and at a certain instant - when still below T_c - it is certainly big enough to move the flux trapped satisfying Eq. 3. Evidently, the time for which such temperature lasts is not enough to let the flux move. The flux migration should otherwise been observed after every quench, regardless of the amount of magnetic flux trapped.

Such description would work good for fluxoids and anti-fluxoids that do not share the same magnetic field lines because no magnetic tension (second term in Eq. 1) would be present in their interaction. In the configuration we are considering fluxoids and anti-fluxoids are mutually connected and the shared magnetic field lines that pass through them are bent inside the cavity volume. It means that the magnetic tension will always play the role of straightening the magnetic field lines, pulling apart fluxoids and anti-fluxoids.

Introducing such extra force in Eq. 2 we are able to explain why the lobes mean motion happens in a straight line. If we take into account the thermal force as driving force only, then the net motion would be isotropic, i.e. we would see the lobes becoming spreader and blurrier. We see instead that the lobes are moving in a straight line one in the opposite direction with respect to the other as expected if the magnetic tension was active.

It follows that the trapped flux migration should be driven by the combination of magnetic tension and thermal force acting together in moving apart the two lobes. Both contributions are dependent on the amount of magnetic field trapped during the quench. The higher the magnetic field the larger the thermal gradient generated by the trapped flux when the RF field is reestablished inside the resonator, and the larger would be the thermal force. At the same time the magnetic tension is proportional to B^2, with B being the trapped magnetic field, so the higher the field the more important is the magnetic tension effect. That can explain why we observed such migration mechanism only after the cavity was quenched in presence of 1 Oe and not after quenches performed in lower values of magnetic field.

The magnetic flux migration should take place when the sum of magnetic tension and thermal force is larger than the pinning force. The condition described in Eq. 3 should then considered also the magnetic tension.

CONCLUSIONS

In this paper we have demonstrated that the origin of the magnetic flux trapped at the quench spot is environmental only, and therefore extrinsic to the cavity. Quenching in zero field no extra dissipation is introduced and Q_0 not affected. This is the prove of the extrinsic nature of trapped magnetic field. Every kind of intrinsic mechanism of flux trapping as generation of thermal currents or trapping of RF field can be ruled out, the only source of trapped magnetic field during the quench is environmental.

Such thesis is corroborated by the fact that the quality factor could be totally recovered after the cavity was quenched in presence of magnetic field by simply compensating the external field and quenching few times, without warming the cavity above T_c. Such behavior is found to be reproducible for low magnetic field values, while for larger values the Q-factor recovery may not be complete.

With some simulations and experimental proves we where able to visualize the configuration of the trapped magnetic flux. This results in a two-lobes-shaped dissipation which is clearly showed by the T-maps.

For high values of trapped magnetic flux a migration mechanism of fluxoids and anti-fluxoids was observed. Such migration process attributed to the synergistic action of thermal force and magnetic tension acting on the trapped flux lobes is the cause of the not complete recovery of the quality factor by quenching in compensated external magnetic field.

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