ORIGIN OF TRAPPED FLUX CAUSED BY QUENCH IN SUPERCONDUCTING NIOBIUM CAVITIES*

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Abstract

In this study we prove that the mechanism at the basis of quality factor degradation due to quench involves the entrapment of ambient magnetic field. The cavity quench in the absence of magnetic field does not introduce any extra losses, and a clear trend between the external field and the extra losses introduced by the quench was observed.

It is demonstrated that the quality factor can be totally recovered by quenching in zero applied magnetic field. A dependence of the amount of quality factor degradation on the orientation of the magnetic field with respect to the cavity was also found.

INTRODUCTION

Superconducting accelerator cavities are devices used in accelerator physics to accelerate charged particles [1, 2]. Such accelerating structures are limited in field (E_{acc}) by the quench of the superconductive state, which leads to the break-down of the resonating electromagnetic field. During such phenomenon a normal conducting region is created on the cavity wall, whose dimension is related to the stored energy of the cavity at the moment of quench. When this normal conductive hole opens, some magnetic flux may be trapped [3], adding extra losses to the resonator and lowering its quality factor (Q_0).

Several different hypotheses where formulated in the past regarding the origin of trapped magnetic field during the quench, such as: thermocurrents driven by the local thermogradient in the quench zone [3], RF field trapped in the penetration depth, or ambient magnetic field. In this study the results obtained at Fermilab, indicate that trapping of ambient magnetic field is the principal cause of the quench-related Q_0 degradation, ruling out the other two proposed mechanisms.

EXPERIMENTAL SET-UP

In this study we used a bulk niobium 1.3 GHz TESLA type cavity nitrogen-doped with the recipe adopted for LCLS-II: 2 min at 800°C in 20 mTorr of N_2 plus a diffusion step of 6 min at 800°C followed by 5 μm EP removal. All the vertical tests were performed at the Fermilab vertical test facility.

The schematic of the setup is shown in Fig. 1. In order to resemble as much as possible the cryomodule situation, the cavity was hanged in the cryostat horizontally, so the cooling started at the very bottom equator point to the very top - also equator - point of the cavity. The cavity was equipped with two Helmholtz coils, capable of creating the magnetic field parallel and orthogonal with respect to the cavity axis, and the magnetic field was measured by means of four single-axis Bartington Mag-01H cryogenic flux-gates magnetometers. Two flux-gates were aligned axially to the cavity, one on top and the other at the middle position, while the other two were set vertically, one on top and one at the bottom.

The helium bath temperature was always maintained around 1.5 K, so the temperature dependent part of the surface resistance can be neglected. The quench study was performed by recording the degradation of Q_0 at the fixed accelerating field after RF quenching the cavity ($E_{quench} \simeq 29MV/m$) in the presence of external magnetic field. After every quench we also tried to recover the Q_0 by quenching in zero magnetic field.

RESULTS AND DISCUSSION

We performed two series of quenching with either non-zero axial or non-zero orthogonal components of the ambient field H only. The change in the residual resistance

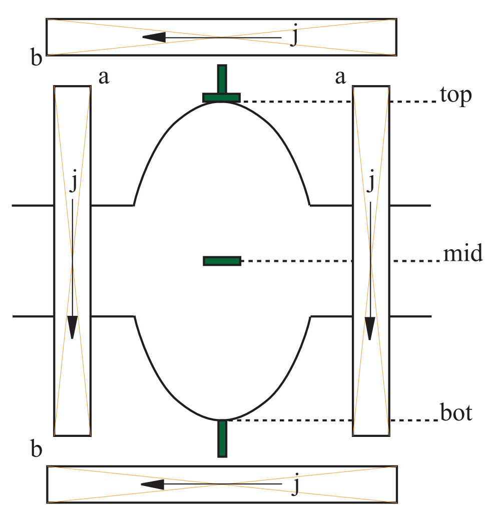

Figure 1: Experimental set-up. The flux-gates are represented by green rectangles, while the letters *a* and *b* indicate the two Helmholtz coils: axial and orthogonal respectively.

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ISBN 978-3-95450-168-7

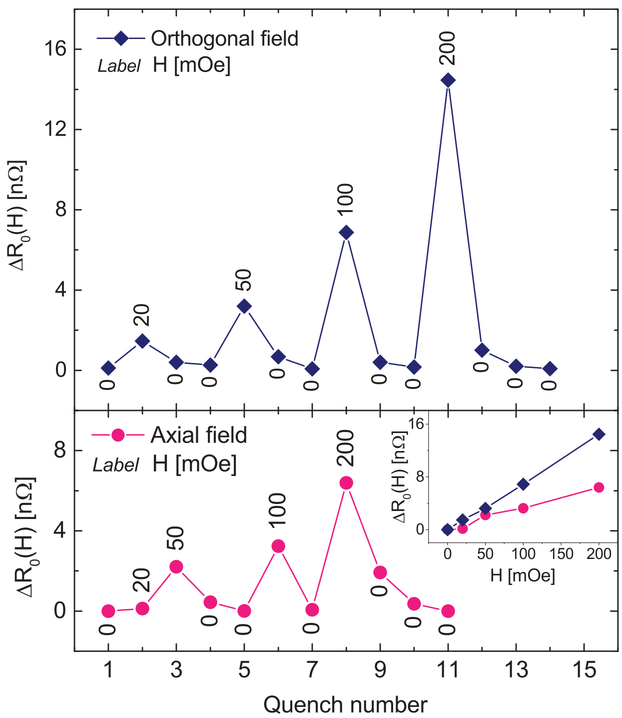

Figure 2: Variation of the magnetic field dependent residual resistance as a function of the numbers of subsequent quenches, both for orthogonal and axial magnetic field.

($\Delta R_0(H)$) was calculated as the difference between the residual resistances (R_0) after the quench and before any quenches, where R_0 =270 Ω/Q_0.

In Fig. 2, $\Delta R_0(H)$ versus the number of subsequent quenches is plotted. The first quench for both series was done in 0 mOe and no increase in R_0 was found, meaning that no magnetic flux was trapped. 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 the increase in R_0 even in zero ambient field.

Quenching in higher ambient fields is directly related to the higher increase in the residual resistance, as shown in the inset of Fig. 2.

Finally, after each degradation we were able to fully recover the Q_0 to its value before the quenches by just zeroing again the ambient field and re-quenching the cavity several times.

A possible mechanism to explain such recovery of the quality factor is the following: when the Helmholtz coils are on, the external field is sustained by the currents in the coils **j** (Fig. 3a). Indeed, because of the Ampere's law, the line integral of the magnetic field along the closed circuit γ, is equal to the flux of the current density **j** across the surface Σ with boundaries γ:

$$\oint_\gamma \mathbf{H} \cdot d\mathbf{r} = \mu_0 \int_\Sigma \mathbf{j} \cdot \hat{n} d\Sigma$$

where $\hat{n}$ is the normal at the surface.

During the quench the magnetic field lines can penetrate into the normal conducting region, but they cannot be broken. Therefore, to satisfy the condition $\nabla \cdot \mathbf{H} = 0$, they have to enter and exit from the same normal conductive region, and once this region becomes again superconductive the field will remain trapped there.

Zeroing the field outside the cavity simply means that ideally there will be no more external magnetic field sustained by the current in the coils, so the external field trapped at the quench spot will be totally sustained by the screening currents in the superconductor (Fig. 3b). The line integral of the field along the close circuit γ' is then equal to the flux of the superconductive current density ($\mathbf{j_s}$) across the surface Σ' with boundaries γ'.

The quench event will destroy the superconductive state around the trapped field, meaning that no more superconducting screening currents will be available to sustain it. Thus, because of the Ampere's law this field will vanish and Q_0 will be recovered.

Ideally, when the field is zeroed outside the cavity all the flux lines trapped at the quench spot will not be sustained by the coils currents anymore, then all the trapped field should be annihilated by a single quench only. In reality, when $H_{ext} = 0$ at the flux gate, it may not be zero at the quench spot, but more likely drastically lowered. In such a situation the external field trapped will be partially sustained by the coils and partially by the screening currents in the superconductor (Fig. 3c), so only the latter will be annihilated during the quench.

After the first quench the magnetic flux which is not annihilated is redistributed, and part of it now occupies positions where the external field is actually zero. Such flux is again completely sustained by the superconductive screening currents only, meaning that it can be annihilated by quenching. After every subsequent quench this redistribution mechanism can happen again, till all the trapped flux is annihilated. This may explain our experimental observation that after quenching in higher ambient fields more than one subsequent quenches in zero field are needed to completely recover Q_0.

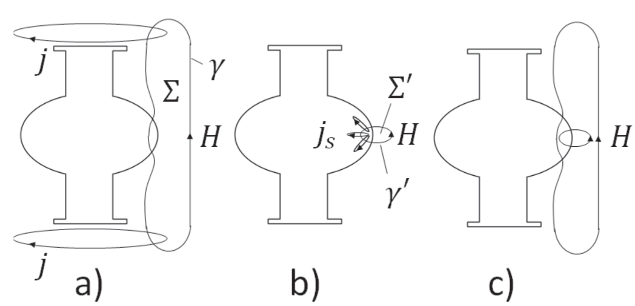

Figure 3: Schematics of the external magnetic field trapped at the quench spot when: a) sustained by the Helmholtz coils current **j** if $H_{ext} \neq 0$, b) ideal case when $H_{ext} = 0$ and c) real case when $H_{ext} = 0$.

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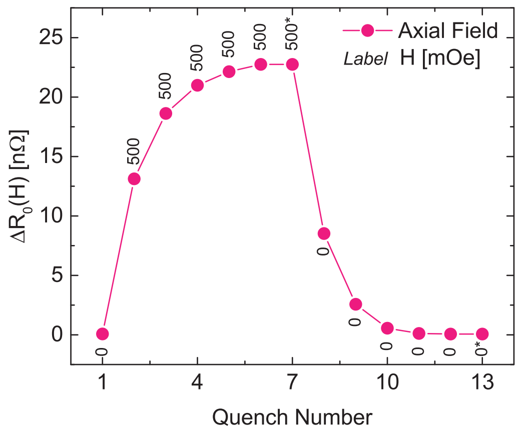

Figure 4: Saturation of the additional residual resistance as a function of subsequent quenches in the axial external magnetic field. The sign * indicates multiple quenches.

Figure 2 also highlights the fact that trapped flux losses are larger for quench in the orthogonal field as compared to axial. This effect can be explained by geometric considerations. In the Meissner state the external field will be bent, so its value may be enhanced in some zones than others. Because of the cylindrical symmetry of the system, the actual value of the axial field at the quench spot will depend only on the radial coordinate. Instead, there is only a two fold symmetry when the field is applied in the orthogonal direction, and therefore the real field value at the quench spot will depend on polar and azimuth angles and radial coordinate of the quench spot.

This difference in the symmetry of the system for the two external field components implies that their values may differ at the same quench position. Therefore, we should expect different Q_0 degradation applying different magnetic field components - the actual local field will be different.

In Fig. 4 the saturation phenomenon of the quench-induced residual resistance is showed. Quenching five times in 500 mOe and letting the cavity quenching in the same field, the saturation value of $\Delta R_0(H)$ was reached, meaning that the maximum amount of magnetic flux was trapped. Even if the saturation of $\Delta R_0(H)$ was reached, it was possible to complete recovery the cavity quality factor (Fig. 4). Q_0 was totally recovered by quenching five times in zero field, then the cavity was the let quenching several times in 0 mOe without affecting Q_0.

As highlighted, Q_0 decreases with the number of subsequent quenches till saturation. Such a situation may be explained by means of Fig. 5, where the correspondent temperature map [4] of the trapped magnetic flux at the quench spot is shown. Figure 5a shows how the flux is trapped when quenching a single time in 500 mOe axial field. Figures 5b, c, d, e and f correspond to subsequent quenches, and show how the saturation of magnetic flux at the quench spot takes place. The larger the number of quenches, the higher the amount of flux trapped, the higher $\Delta R_0(H)$ up to saturation.

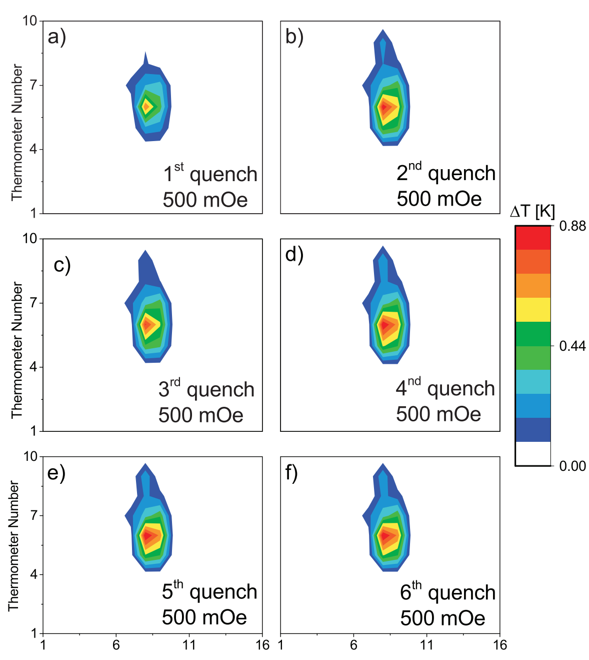

Figure 5: Temperature map of the quench spot after quenching in 500 mOe axial magnetic field: a), b), c), d) and e) after single quench and f) alter multiple quenches.

CONCLUSIONS

In this study we have shown that the only mechanism at the basis of Q_0 degradation after quench is related to the trapping of external magnetic field, as it is the only possible mechanism that does not add any extra losses when the quench happens in zero ambient field. Also, the dependence of $\Delta R_0(H)$ on the mutual orientation of the magnetic field with respect to the cavity corroborates even more the fact that the origin of Q_0 degradation is external to the cavity.

We also showed that the complete recovery of Q_0 is possible when quenching in zero magnetic field, even if the saturation limit of trapped flux is reached.

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ISBN 978-3-95450-168-7