High Field $Q$ Slope and the Effect of Low-Temperature Baking at 3 GHz

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A strong degradation of the unloaded quality factor with field, called high field $Q$ slope, is commonly observed above $B_p \approx 100$ mT in elliptical superconducting niobium cavities at 1.3 and 1.5 GHz. In the present experiments several 3 GHz niobium cavities were measured up to and above $B_p \approx 100$ mT. The measurements show that a high field $Q$ slope phenomenon limits the field reach at this frequency, that the high field $Q$ slope onset field depends weakly on the frequency, and that the high field $Q$ slope can be removed by the typical empirical solution of electropolishing followed by heating to 120°C for 48 hrs. In addition, one of the cavities reached a quench field of 174 mT and its field dependence of the quality factor was compared against global heating predicted by a thermal feedback model.

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I. INTRODUCTION

Radio-frequency surface resistance of superconducting niobium exhibits field dependence, which changes drastically with surface treatment and preparation. One of the common field dependencies, typically observed after chemical treatment in 1.3 and 1.5 GHz elliptical cavities, is the so-called high field $Q$ slope (HFQS). The high field $Q$ slope was identified in the 1990s [1], when advances with high pressure rinsing allowed for field emission free cavities reaching peak magnetic fields ($B_p$) above 100 mT. Since the typical ratio of peak magnetic field to accelerating gradient in elliptical cavities is about 4–5 mT/(MV/m), cavities were reaching accelerating gradients ($E_{acc}$) in excess of 20 MV/m. At this field a strong degradation in the quality factor was consistently observed in 1.3 and 1.5 GHz cavities without any x-ray production. Further experiments with temperature mapping indicated broad heating in the high magnetic field regions [2–4]. In the late 1990s–early 2000s an empirical solution was found to remove the degradation: 120°C baking for 48 hours [5,6]. The solution resulted in high gradient niobium cavities and is used today as a standard treatment for many projects.

As part of a new material development program, 3 GHz cavities were built out of niobium to serve as a substrate for future new material coatings. The cavities received the standard cavity processing and were measured at the helium bath temperature ($T_b$) of 2.0 K to confirm their suitability as a substrate. Several cavities reached high fields and were limited by a $Q$ slope reminiscent of the high field $Q$ slope.

There are ample data on this degradation in elliptical cavities at 1.5 and 1.3 GHz, but fewer rf measurements have been done at other frequencies [7–10]. Hence, one of the questions regarding HFQS is its frequency dependence. Since most of the data related to the degradation were collected at 1.3 or 1.5 GHz, models are required to predict the frequency of the onset of the HFQS. This question was addressed in the past using the data sets available at the time [11,12]. Results at 3 GHz reported here suggest that 3 GHz cavities are limited by the same phenomenon that can limit the field reach at lower frequencies. The results also show that accelerating gradients above 30 MV/m, and in one case up to ~41 MV/m, can be reached even at these frequencies with the correct treatment.

The importance of this finding is illustrated, for example, by the fact that the choice of frequency for TESLA cavities was in part driven by what was considered to limit high frequency cavities [13].

II. CAVITY PROCESSING AND TEST RESULTS

Five cavities, designated FH3A, FH3C, FH3D, FH3E, and FH3F were used in these experiments. The cell shape is that of the TESLA long end half cell [13] scaled to 3 GHz, Fig. 1. The main electromagnetic parameters are
$B_p/E_{\text{acc}} = 4.23 \text{ mT}/(\text{MV/m})$, $G = 277.9 \Omega$, which is the geometry factor, and $R/Q = 105 \Omega$, which is the shunt impedance divided by the quality factor. The half cells were stamped from 3 mm high purity (RRR $\sim 300$) niobium disks, mechanically polished, and electron beam welded together along with cutoff tubes and flanges to form 3 GHz single-cell cavities. FH3A, FH3C, FH3D, and FH3E were made out high purity fine grain material, and FH3F was made out of high purity large grain material. FH3A, FH3C and FH3D received $80 \mu m$ of buffered chemical polishing, BCP (1:1:1). The chemical etching was split into four steps to improve the removal uniformity with cavity being flipped between each treatment. After BCP the cavities were annealed in a vacuum furnace at 600 °C for 10 hours followed by an additional etching with BCP (1:1:1) solution to remove 10 $\mu m$. Additional treatments consisting of centrifugal barrel polishing, vacuum annealing at 600 °C for 10 hours and electropolishing (EP) were applied to FH3A to improve its performance. FH3E received 110 $\mu m$ BCP (1:1:1), was annealed at 800 °C for 2 hours, and etched for an additional 60 $\mu m$ with BCP (1:1:1). FH3F received 90 $\mu m$ BCP (1:1:1), was annealed at 800 °C for 3 hours, and etched for an additional 25 $\mu m$ with BCP (1:1:1). Prior to the cryogenic rf power test, each cavity was high-pressure rinsed with ultrapure water, assembled with rf antennas and vacuum flanges and evacuated to $< 10^{-7}$ mbar.

FH3C was first tested at 2.0 K. The cavity had a low-field quality factor of about $8 \times 10^9$ at $T_b = 2.0$ K. Above $E_{\text{acc}} = 20 \text{ MV/m}$ a rapid degradation of the quality factor set in. The cavity was limited to $E_{\text{acc}}$ of about 30 MV/m, where the quality factor degraded to about $1 \times 10^9$, Fig. 2. At this point the test was limited by the 60 Watt available rf input power due to the coupling mismatch of the fixed coupler. With the cavity still in the Dewar, the Dewar was topped off with liquid helium the next day and the cavity was tested at $T_b = 1.8$ K and $T_b = 1.6$ K. The low-field quality factor has improved reaching $1.5 \times 10^{10}$ at $T_b = 1.8$ K and $5.3 \times 10^{10}$ at $T_b = 1.6$ K. However, the $Q$ drop was still present and limited the cavity to $E_{\text{acc}} \approx 30 \text{ MV/m}$.

FIG. 1. The photo of FH3A assembled for testing is shown in the top. The sketch of the cavity shape, which is the TESLA long end half cell [13] scaled to 3 GHz, is shown in the bottom. Dimensions are in mm [inches].

FIG. 2. FH3C test results after BCP treatment for three different helium bath temperatures, 2.0, 1.8, 1.6 K and after EP treatment and mild baking at $T_b = 2.0$ K. Note the increase in the low-field quality factor as expected for lower helium bath temperatures, but similar $Q$ drops. Also, note the absence of the high-field degradation in the test after the EP and mild baking.

FIG. 3. FH3D test results at $T_b = 2.0$ K before and after baking at 120 °C for 48 hours. No radiation was observed during the measurements.
No x-ray radiation was observed during the measurements. After the test FH3C was removed from the Dewar and disassembled. FH3C was then chemically treated again. This time the JLab horizontal electropolishing machine was used. The cavity was electropolished similar to the 12 GeV CEBAF upgrade cavity (C100) electropolishing procedure [14], except a special aluminum cathode was built to accommodate smaller beam tubes. The cavity was electropolished in two steps for a total of 40 μm. After electropolishing FH3C was HPRed, assembled in a cleanroom, evacuated, and tested again at 2 K. $Q_0$ dropped to about $2 \times 10^9$ at $E_{acc} = 30.5$ MV/m, limited by available rf power. No x rays were observed in the test. After the second test, FH3C was removed from the Dewar, baked in situ at 120°C for 48 hours, and tested again at 2 K. After baking, the low-field quality factor improved to about $6 \times 10^9$ at 2 K. The cavity was still limited to a similar gradient of $E_{acc} = 30$ MV/m by a strong $Q$ drop. However, during this test x rays up to 0.2 mSv/hour at the highest gradient were observed. Finally, the cavity was removed from the Dewar, disassembled, HPRed, assembled in the...
cleanroom, and tested again at 2.0 K. In the rf test at 2 K, the low-field quality factor was again at about $6 \times 10^9$. This time, no x rays were observed, and the cavity reached $E_{\text{acc}} = 36.1$ MV/m without strong quality factor degradation. The cavity was limited by the repeated quench at the highest field, Fig. 2.

FH3D was first tested at 2.0 K. FH3D had a low-field quality factor of about $6 \times 10^9$, which stayed constant with field up to $E_{\text{acc}} = 20$ MV/m. Above $Q$ slope onset of $E_{\text{acc}} = 20$ MV/m, a strong $Q_0$ degradation was observed, and the cavity was limited by the available power at $E_{\text{acc}} \approx 30$ MV/m, Fig. 3. FH3D was then removed from the vertical testing Dewar, baked in situ at 120°C for 48 hours. The cavity was then put back in the Dewar, tested at 2.0 K, and then tested again at 2.0 K two days later. The low-field quality factor improved to about $1 \times 10^{10}$, but degraded with field to about $7 \times 10^9$ at $E_{\text{acc}} = 20$ MV/m. The cavity was limited by a high field $Q$ slope to about $E_{\text{acc}} = 37$ MV/m, Fig. 3. No radiation was observed during the measurements.

FH3E was tested at 2.0 K. The cavity had a low-field quality factor of about $5 \times 10^9$ at $T_e = 2.0$ K. Above $E_{\text{acc}} = 27$ MV/m a rapid degradation of the quality factor set in. The cavity was limited to $E_{\text{acc}}$ of about 30 MV/m, where the quality factor degraded to about $2 \times 10^9$, Fig. 4. The test was limited by the available rf power. No x rays were observed in the test.

FH3A was tested at 2.0 K. The quality factor at low field was $\sim 6 \times 10^9$ which stayed nearly constant up to $E_{\text{acc}} \sim 27$ MV/m above which $Q$ slope set in and $Q_0$ degraded nearly a factor of 3 at 32.5 MV/m. No x rays were observed in the test. The cavity was baked at 120°C for 48 hours and retested at 2.0 and 1.8 K. The quality factor at low field at 2 K was $\sim 7 \times 10^9$ and the cavity quenched at 41 MV/m. No x rays were observed in the test. After quenching at 2 K, the surface resistance increased by about 5 nΩ due to trapped magnetic flux. The cavity was warmed up to room temperature to release the trapped flux and cooled back down to 1.6 K. The quality factor at $\sim 4.2$ MV/m was measured as a function of the helium bath temperature between 3.7 and 1.6 K, which was then used to calculate the average surface resistance using $\langle R_s \rangle = G/Q_0$, where $G$ is the geometry factor of the cavity, Fig. 5. The $R_s(T)$ data were used to calculate $Q_0(T, B_p)$ using the thermal feedback model as discussed in Sec. III. At 1.6 K, $Q_0(E_{\text{acc}})$ was measured,

<table>
<thead>
<tr>
<th>ID</th>
<th>Helium bath temperature [K]</th>
<th>$Q_0$ at $E_{\text{acc}} \geq 5$ MV/m</th>
<th>$Q_0$ at $E_{\text{max}}$</th>
<th>$Q$ slope onset $E_{\text{acc}}$ [MV/m]</th>
<th>FE onset $E_{\text{acc}}$ [MV/m]</th>
<th>Maximum $E_{\text{acc}}$ [MV/m]</th>
<th>Limitation</th>
<th>Latest treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>FH3C</td>
<td>2.0</td>
<td>$(8.2 \pm 1.3) \times 10^9$</td>
<td>$(2.0 \pm 0.2) \times 10^9$</td>
<td>$\approx 20$</td>
<td>$28.2 \pm 1.3$</td>
<td>$Q$ slope</td>
<td>Same</td>
<td>$80 \mu$m BCP (1:1:1) +</td>
</tr>
<tr>
<td>FH3C</td>
<td>1.8</td>
<td>$(1.3 \pm 0.3) \times 10^{10}$</td>
<td>$(2.7 \pm 0.3) \times 10^9$</td>
<td>$\approx 20$</td>
<td>$30.0 \pm 1.4$</td>
<td>$Q$ slope</td>
<td>Same</td>
<td>$600^\circ C \times 10$ hrs +</td>
</tr>
<tr>
<td>FH3C</td>
<td>1.6</td>
<td>$(4.2 \pm 2.7) \times 10^{10}$</td>
<td>$(1.4 \pm 0.1) \times 10^9$</td>
<td>$\approx 25$</td>
<td>$20$</td>
<td>$30.6 \pm 1.4$</td>
<td>$Q$ slope +40 $\mu$m EP</td>
<td>$10 \mu$m BCP (1:1:1) +</td>
</tr>
<tr>
<td>FH3C</td>
<td>2.0</td>
<td>$(5.6 \pm 0.6) \times 10^9$</td>
<td>$(2.0 \pm 0.2) \times 10^9$</td>
<td>$\approx 20$</td>
<td>$21$</td>
<td>$31.3 \pm 1.5$</td>
<td>$Q$ slope +120°C × 48 hrs</td>
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</tr>
<tr>
<td>FH3C</td>
<td>2.0</td>
<td>$(6.0 \pm 0.8) \times 10^9$</td>
<td>$(1.0 \pm 0.1) \times 10^9$</td>
<td>$\approx 20$</td>
<td>$36.1 \pm 2.8$</td>
<td>Quench + another HPR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FH3D</td>
<td>2.0</td>
<td>$(6.4 \pm 1.6) \times 10^9$</td>
<td>$(5.7 \pm 1.4) \times 10^9$</td>
<td>$\approx 20$</td>
<td>$29.8 \pm 1.3$</td>
<td>$Q$ slope</td>
<td>Same</td>
<td>$80 \mu$m BCP (1:1:1) +</td>
</tr>
<tr>
<td>FH3D</td>
<td>2.0</td>
<td>$(6.0 \pm 0.9) \times 10^9$</td>
<td>$(1.2 \pm 0.1) \times 10^9$</td>
<td>$\approx 20$</td>
<td>$37.1 \pm 1.7$</td>
<td>$Q$ slope</td>
<td>+120°C × 48 hrs</td>
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<tr>
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<td>2.0</td>
<td>$(1.1 \pm 0.2) \times 10^{10}$</td>
<td>$(2.2 \pm 0.2) \times 10^9$</td>
<td>$\approx 25$</td>
<td>$30.4 \pm 1.6$</td>
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<td>$(2.5 \pm 0.4) \times 10^{10}$</td>
<td>$(5.5 \pm 0.7) \times 10^9$</td>
<td>$\approx 27$</td>
<td>$32.4 \pm 2.2$</td>
<td>$Q$ slope</td>
<td>$80 \mu$m BCP (1:1:1) +</td>
<td></td>
</tr>
<tr>
<td>FH3A</td>
<td>1.8</td>
<td>$(5.9 \pm 1.0) \times 10^9$</td>
<td>$(2.4 \pm 0.3) \times 10^9$</td>
<td>$\approx 27$</td>
<td>$27$</td>
<td>$35.9 \pm 2.7$</td>
<td>$Q$ slope +120°C × 48 hrs</td>
<td></td>
</tr>
<tr>
<td>FH3A</td>
<td>1.6</td>
<td>$(7.2 \pm 0.9) \times 10^9$</td>
<td>$(3.1 \pm 0.4) \times 10^9$</td>
<td>$\approx 28$</td>
<td>$41.2 \pm 2.1$</td>
<td>Quench + another HPR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FH3F</td>
<td>2.0</td>
<td>$(7.6 \pm 3.2) \times 10^{10}$</td>
<td>$(1.4 \pm 0.2) \times 10^9$</td>
<td>$\approx 28$</td>
<td>$41.4 \pm 8.0$</td>
<td>Quench + another HPR</td>
<td></td>
<td></td>
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Fig. 6. A few quenches occurred from $E_{\text{acc}} \sim 41 \text{ MV/m}$, causing an increase in the surface resistance by about $10^6 \Omega$, probably due to the trapped magnetic flux and $Q_0$ drop to $3.6 \times 10^9$ at 41.9 MV/m where repetitive quenches were observed. No x rays were detected in this test. The curves $Q_0(E_{\text{acc}})$ before and after baking are shown in Fig. 6.

FH3F was tested at 2.0 K. The quality factor at low field was $\sim 7 \times 10^9$ which stayed nearly constant up to $E_{\text{acc}} \sim 28 \text{ MV/m}$ above which $Q_0$ degraded more than a factor of 3 at 33.9 MV/m, as shown in Fig. 7. X rays corresponding to a dose rate up to $\sim 0.001 \text{ mSv/hour}$ were observed in the test above $E_{\text{acc}} \sim 27 \text{ MV/m}$. The test results from all tests are summarized in Table I.

III. DISCUSSION

The quality factor field dependencies observed in all five cavities after EP or BCP have many characteristics of the high field $Q$ slope commonly observed in 1.3 and 1.5 GHz SRF cavities. The high field $Q$ slope is commonly referred to as the degradation of the quality factor at accelerating gradients above 20 MV/m without x rays. While no x rays were observed in the first experiments with the cavities (Figs. 2–4), it may be argued that it was the case due to the smaller accelerating gap of these cavities, of just 5 cm, hence, the same field emission sites may not induce enough radiation to be detected with the standard instrumentation. One possible check in this case would be to test the cavity with a thermometry setup, but such capability was not available at the time. However, the consistency of the observed $Q$ degradations at high field in all four cavities would be surprising to be caused by such a random effect as field emission. Additional indirect evidence, which excludes x rays as the cause for the observed degradation, is the test of FH3C after EP and bake, Fig. 2. After some processing, the cavity was limited by a similar $Q$ slope, but in this test x-ray radiation was observed and was correlated to the quality factor degradation. This supports the viewpoint that x rays will be detected if the heating from field emitted electrons is contributing to the quality factor degradation at the gradients of interest, even in these smaller cavities. Furthermore, in Fig. 8 earlier data on a 3 GHz cavity reproduced from [15] is shown along with our results. The $Q$ slope in the older data has been reported to be common and the thermometry results on those cavities showed broad areas of heating, which indicates that a field emitter was not the limiting cause in those test. The field emission also does not improve after the mild baking [16], which was the case with FH3D, Fig. 3, or FH3A, Fig. 6. Hence, we conclude that the slope in our cavities was not caused by field emission.

In Fig. 9, the rf results after mild baking applied to the BCPed and to the EPed cavity are compared at this frequency. Similar to what has been observed at lower frequencies, mild baking completely eliminates the high field $Q$ slope in the EPed cavity, but does not completely remove it in the fine-grain BCPed cavity. There is a significant improvement in the BCPed cavity after mild baking, but some $Q$ drop persists at high fields. The cavity FH3A quenched at a remarkably peak surface magnetic field of $\sim 180 \text{ mT}$ after baking and the $Q$ vs field curves show a mild $Q$ degradation above $\sim 35 \text{ MV/m}$ (148 mT).

Thermal feedback can be suggested as the cause of degradation. In the older measurements, reproduced in Fig. 8, the helium bath temperature was not constant during

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FIG. 7. FH3F was tested at 2.0 K. The quality factor at low field was $\sim 7 \times 10^9$ which stayed nearly constant up to $E_{\text{acc}} \sim 28 \text{ MV/m}$ above which $Q_0$ degraded more than a factor of 3 at 33.9 MV/m, as shown in Fig. 7. X rays corresponding to a dose rate up to $\sim 0.001 \text{ mSv/hour}$ were observed in the test above $E_{\text{acc}} \sim 27 \text{ MV/m}$. The test results from all tests are summarized in Table I.

FIG. 8. FH3C, FH3D, and FH3E at $T_b = 2.0 \text{ K}$ are plotted here along with the earlier data reproduced from [15]. $E_{\text{peak}}/E_{\text{acc}} = 1.83$ was used for the 3 GHz cavities. Note that the temperature of the helium bath increased from about 1.4 K to about 1.8 K with rf dissipated power during the earlier measurements in 1991.

FIG. 9. FH3A, FH3C, and FH3D results before and after mild baking are plotted here. All data is measured at $T_b = 2.0 \text{ K}$. No field emission was observed in any test.
the rf test, so the $Q$ degradation at high field could be due to increasing He bath temperature [15]. During rf measurements of the cavities reported in this paper, the He bath temperature was kept constant, within $\approx 10$ mK. The rf test of FH3C at three different bath temperatures shows that the slope is not sensitive to such bath temperature variation.

The $Q$ vs field curves measured for cavity FH3A after baking have been analyzed with a thermal feedback model as described in what follows. The surface resistance as a function of the temperature of the inner surface, $R_s(T_s)$, consists of the sum of an analytic expression derived from the Bardeen-Cooper-Schrieffer theory valid in the dirty limit and $T < T_c$ [17] and the so-called residual resistance, $R_i$:

$$R_s(T_s) = \frac{A}{T_s} \ln \left( \frac{2.246k_B T_s}{h f} \right) e^{-\frac{\Delta}{k_B T_s}} + R_i,$$

where $k_B$ is the Boltzmann’s constant, $h$ is Planck’s constant, $f$ is the resonant frequency and $\Delta$ is the energy gap. $A$ is a factor that depends on material parameters and it is proportional to $f^2$. The parameters $A$, $\Delta$ and $R_i$ were obtained by fitting Eq. (1) to the $R_s(T_b)$ data, Fig. 5, using the self-consistent method described in [18] to determine the temperature of the inner surface. The values of the fit parameters are $A = 4.5 \times 10^{-5} \Omega K$, $\Delta = 1.36$ meV and $R_i = 7.1$ n$\Omega$. The temperature of the inner surface is calculated as a function of the peak surface magnetic field by solving the one-dimensional heat balance equation [19],

$$\frac{1}{2} R_s(T_b) H_p^2 = \frac{T_s - T_b}{R_B(T_b)},$$

where $R_B(T_b)$ is the thermal boundary resistance and $H_p = B_p/H_0$. $Q_0(B_p)$ can then be estimated as

$$Q_0(B_p) = \frac{G}{R_s[T_s(B_p)]}.$$ 

Equation (2) has a real-valued solution only up to a maximum $H_p$ value, $H_b$, which corresponds to the condition of thermal instability or quench. The values of $R_B$ were chosen such that $H_b$ is equal to the measured quench field for each bath temperature and they were 11, 6 and $4.1$ cm$^2$ K/W at 1.6, 1.8 and 2.0 K, respectively. Such values of $R_B$ are consistent with those recently measured in 1.3 GHz cavities [20]. The $Q_0(B_p)$ curves calculated with the thermal feedback model are shown in Fig. 10 along with the experimental data. The results from the calculation agree qualitatively with the data at 2.0 and 1.8 K and suggest that the $Q$ reduction at high field could be related to a global thermal instability. The model does not reproduce the $Q$ slope measured at 1.6 K and the reason for this is unclear and might be related to an intrinsic nonlinearity of

![Image](https://via.placeholder.com/150)

FIG. 10. FH3A test results for three different helium bath temperatures, 2.0, 1.8, 1.6 K (symbols) along with results from a thermal feedback model calculation for each temperature with values of the thermal boundary resistance matching the experimental quench fields (solid lines).

the surface resistance becoming more pronounced at lower temperatures.

In Fig. 11, we plot our results along with two results for 1.3 and 1.5 GHz single-cell cavities for comparison. In this plot we show a 1.5 GHz one-cell cavity C3C4, which received 20 $\mu$m BCP (1:1:2) as the final treatment and a 1.3 GHz one-cell cavity TE1G001, which received 25 $\mu$m EP as the final treatment. No x rays were detected in any of the tests. The low-field quality factor of the lower
frequency cavities is higher, as expected from the frequency dependence of the BCS part of the surface resistance. At high fields all cavities are limited to about $B_p = 120-130$ mT, and the onset of the high field $Q$ slope is qualitatively quite similar. Onset values for the high field $Q$ slope ranging between 80–125 mT in 1.3–1.5 GHz cavities have been reported in the literature [21,22].

IV. CONCLUSION

The unloaded quality factors of five 3 GHz niobium cavities after various treatments were measured at cryogenic temperatures. A characteristic degradation, the high field $Q$ slope, was observed in all cavities at high fields. The onset of the high field $Q$ slope in the tested 3 GHz cavities was close to 100 mT. The standard solution of electropolishing followed by heating to 120 °C for 48 hours eliminated the high field $Q$ slope in two of the cavities, with one of them reaching 174 mT at 2.0 K. Such a quench field is consistent with the possibility of reaching a global thermal instability as predicted by the standard thermal feedback model.

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