PRESERVATION OF VERY HIGH QUALITY FACTORS OF 1.3 GHZ NINE CELL CAVITIES FROM BARE VERTICAL TEST TO DRESSED HORIZONTAL TEST

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Abstract

At FNAL, a series of 1.3 GHz nine cell cavities have been treated with nitrogen doping, and vertically tested first as bare cavities, then dressed in different styles of Helium vessels (ILC and LCLS-2), tested vertically again post dressing and then horizontally tested in a one cavity cryomodule configuration, with magnetic shielding, RF ancillaries etc. In this contribution we summarize the quality factor evolution from vertical bare test to final cryomodule configuration horizontal test and highlight the important parameters we found for Q preservation.

INTRODUCTION

Record high operational quality factors have been routinely and systematically demonstrated in nitrogen doped niobium cavities in more than hundred vertical tests at different laboratories [1, 2, 3]. In the past years lots of attention has been dedicated to the potential effect of Q changes because of change in trapped flux induced residual resistance, depending on the details of cooling in dressed cavities. This is now understood to be potentially coming from different sources: a) the strong effect of cooldown through critical temperature on the efficiency of magnetic flux expulsion [4, 5, 6]; b) the change in magnetic fields surrounding the cavity surface during cooldown [7] that may arise depending on temperature differences between cavity, vessel, and other potential circuit loops of dissimilar metals. In this work, we study for the first time the full step-to-step evolution of the quality factor of very high Q N doped nine cell cavities from bare vertical test, to vertical test post dressing, to horizontal test with unity coupling and finally in full cryomodule environment with high power coupler all RF ancillaries. This way we can track if changes in Q occur at any of these steps and trace clearly to their origin. We find that even in very low magnetic fields < 4 mGauss - achieved via double cryoperm shields plus active compensation [8]- slow and homogeneous cooling through transition in horizontal tests always leads to worse quality factors then for fast cooling in agreement with the findings from vertical tests of single and nine cells [4]. A procedure yielding repeatedly optimal Q in horizontal dressed cavity configuration is described, together with the key parameters/knobs that may lead to better or worse final Q results. Non-trapped flux related conditions encountered that can deteriorate Q will also be described.

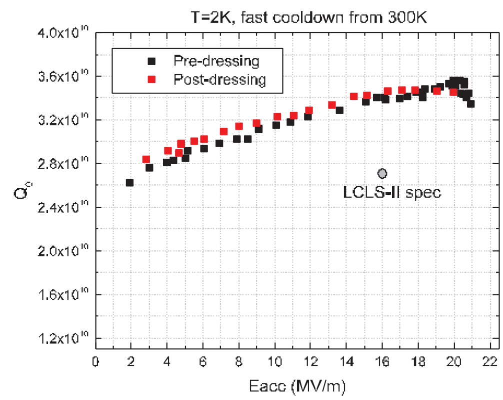

Figure 1: High N doped nine cell pre and post dressing performance comparison in vertical test. No degradation is encountered with He vessel welding.

VERTICAL TEST RESULTS FOR DOPED NINE CELL BARE VERSUS DRESSED CAVITIES

More than 10 nine cell 1.3 GHz cavities have been doped at FNAL as part of this study, mostly treated with the LCLS-2 baseline doping recipe known as “2/6” + 5 microns EP, meaning that nitrogen gas is injected at 800°C for 2 minutes at partial pressure of ~25 mTorr, then cavity is annealed at 800°C in HV for 6 minutes, then 5 microns EP. This is one of the optimal doping recipes found so far, leading to optimal R_{BCS} (16MV/m, 2K, 1.3GHz) = 4.5 nΩ, optimal non flux related residual < 2nΩ, and to a sensitivity to trapped magnetic flux of ~1.2 nΩ/mGauss [9]. One of the nine cell studied TB9AES011 was doped with a different recipe yielding to a much larger sensitivity to trapped flux of ~2 nΩ/mGauss. The plots below (Fig. 1) show this particular cavity before and after helium vessel welding in vertical test, both curves for fast cooldowns from 300K in 5 mGauss dewar ambient field. The results show that no degradation occurs during the dressing process, even for these very

ISBN 978-3-95450-178-6

high Q. Moreover, the cavity was tested in the VT dewar with temperature sensors attached on the cavity cell 1 and 9 monitoring the total thermogradient across the nine cell during cooldown, with fluxgates in longitudinal direction on cell 1, 5 and 9, and transverse direction on cell 1. In Fig. 2 the magnetic fields as a function of cooldown are recorded, showing a large peak of thermally induced magnetic field in the expected transverse direction, and interestingly some larger magnetic fields are also observed in the longitudinal direction mimicking the transverse thermoelectric induced component, indicating that thermocurrents may be flowing with a certain angle. As it can be seen in Fig. 2, because of the favorable symmetry in VT [10], and/or because of the large thermogradients yielding to full flux expulsion [5], there is no effect on Q even with 150 mGauss thermoelectrically induced field at transition.

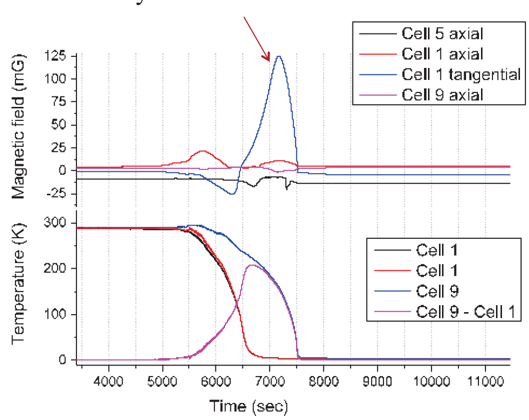

Figure 2: Magnetic field at the cavity surface (longitudinal and transverse) recorded during cooldown in the vertical test dewar from 300K.

The same cavity was then studied for fast cooldowns from 300K and 15K, and a slow cooldown through T_c. As for bare cavities, Fig. 3 shows that even in ~ 5 mGauss background field the degrading effect of slow cooling on Q is quite dramatic. Figure 4 shows that the origin of the degradation is in the residual resistance, as expected for trapped flux induced resistance. This again points to the need of paying particular attention to the cooling regime and to achieve high thermogradients in cryomodule to efficiently sweep flux out. Table 1 summarizes the results for N doped nine cells dressed vs bare in vertical tests, for the LCLS-2 baseline 2/6 doping recipe. A total average degradation of 10% is encountered from bare to dressed cavity test. It is important to remark that this is not a systematic effect occurring with the process of dressing, as it can be noticed from the individual tests, but simply environmental/sporadic tied to different conditions of the test (FE, larger magnetic fields). Another suspected cause of degradation for some of these cavities has been traced to strong oxidation of the surface likely traceable to a) excessive cumulative HPR time; b) sporadic HPR tool failures consistent with localized oxidized spots and in one instance a surface scratch observed on one of the f-hooks potentially due to cavity/wand misalignment. The optical inspection pictures shown in Fig. 5 show some of the features described above. It was then decided to perform a light EP of one of the dressed cavities (~3 microns EP) to clean the surface from heavy oxidation, and the cavity performed with a better Q post EP (improvement ~ 1.5 nΩ).

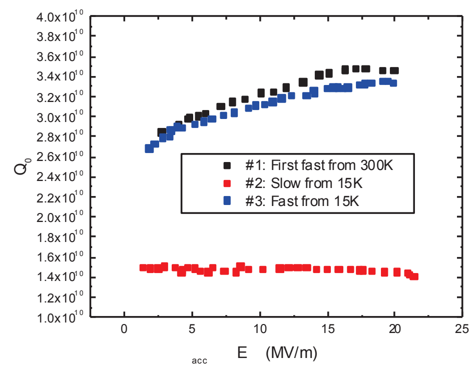

Figure 3: Slow vs fast cooling vertical test results for the dressed N doped nine cell TB9AES011.

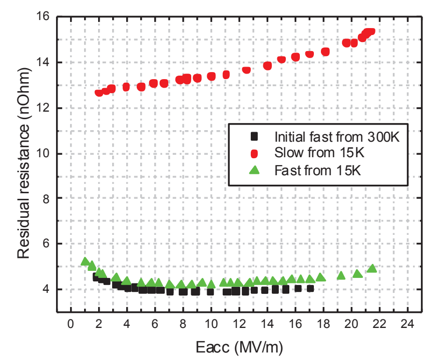

Figure 4: Residual resistance obtained from the deconvolution of surface resistance for the three different cooldowns, revealing the trapped flux induced residual resistance changes.

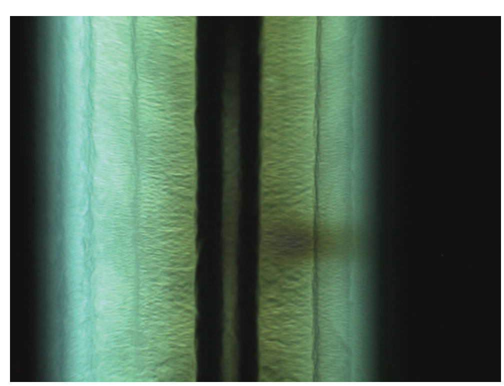

Figure 5: Heavy oxidation encountered at irises of some of the dressed cavities. Darker localized spots are noticed.

HORIZONTAL TEST RESULTS

After proving that the process of dressing does not impact Q in vertical test, we proceed to study N doped cavities dressed in different kind of vessels in horizontal tests. The two vessels used for these studies are substantially different: one is the ILC style vessel, the other is the LCLS-2 style where the chimney has been widened for CW applications and moved to the center, with symmetric inlet ports one left and one right to eliminate left-right cooling asymmetry and attempt to reduce thermocurrents. The differences between the two vessels can be noted from Fig. 6. The ILC vessel has one inlet port on bottom of cell 1 and a smaller chimney on top of cell 3. Interestingly, thermoelectrically induced fields are not reduced by the symmetric configuration of the LCLS-2 vessel but actually increased compared to the ILC vessel for cooldowns from same starting temperature.

Table 1: Q values at 16 MV/m, 2K, for 1.3GHz nine cell cavities pre and post dressing.

Cavity ID #	Qo@16MV/m, 2K - VT bare	Qo@16MV/m, 2K - VT dressed
AES	E10	E10
16	3.0	-
19	3.2	3.1
21	3.4	2.8
22	3.1	-
24	3.2	3.2
26	2.8	2.8
27	3.6	2.7
28	3.5	3.0
AVERAGE	**3.2**	**2.9**

The Table 2 contains the results of the comparative studies and highlights the Q changes from undressed to dressed in VT and from dressed VT to HT. Almost no degradation is encountered for ILC vessel dressing. In the case of LCLS-2 vessel the difference post dressing is attributable to the higher remnant fields in the dewar where LCLS-2 cavities are tested and the previously shown HPR oxidation issue. Because of the double cryoperm shielding configuration for LCLS-2 [8], fields are lower in horizontal test, which can explain why Q in HT can exceed VT for LCLS-2 dressed cavities. On the contrary, magnetic fields are higher in horizontal test than in vertical test for the ILC dressed cavity, again explaining the slight degradation in performance from VT to HT.

Table 2: Q values and Rs changes at 16 MV/m, 2K, for 1.3GHz nine cell cavities pre and post dressing in VT and HT.

Cavity ID #	Qo@16MV/m, 2K - VT bare	Qo@16MV/m, 2K - VT dressed	Qo@16MV/m, 2K - HTS	ΔRs bare → dressed [nΩ]	ΔRs VT → HT [nΩ]
ACC002/ILC	3.5E10	3.2E10	2.8E10	+0.7	+1.2
AES011/ILC	3.4E10	3.4E10	2.7E10	0	+1.9
AES021/LCLS2	3.35E10	2.75E10	3.1E10	+1.8	-1.3
AES027/LCLS2	3.5E10	2.7E10	2.75E10	+2.3	-0.2
AVG	3.44E10	3.01E10	2.84E10	+1.2	+0.4

It is important to remark that a record Q ~ 3.1e10 at 16 MV/m, 2K of a N doped LCLS-2 dressed cavity is achieved in the first fully integrated horizontal test of a LCLS-2 cavity with high power coupler, HOMs magnetic shielding, tuner etc [11] for a fast cooldown from 45 K starting T, as shown in Fig. 7. This test represents an important milestone proving that little to no degradation occurs between vertical bare test all the way down to cryomodule environment, with the right magnetic field management and cooldown protocols.

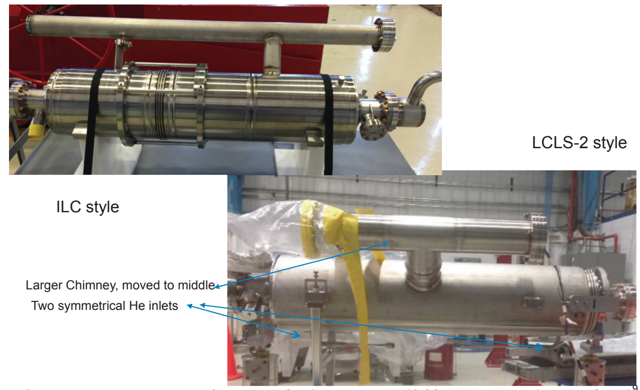

Figure 6: Comparison of the two different styles of Ti vessels used – ILC and LCLS-2.

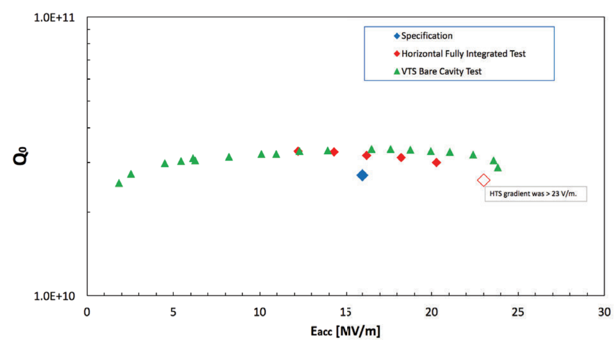

Figure 7: Record Q >3e10 at 16MV/m, 2K for a LCLS-2 dressed cavity in fully integrated horizontal test (with high power coupler, HOMs, tuner etc).

OPTIMAL COOLDOWN PROCEDURE AND OTHER CONSIDERATIONS TO OBTAIN HIGH Q IN CRYOMODULE

In this paragraph we will describe the results obtained horizontally for different cooling conditions. Several fast cooldowns from a starting T ~ 45K have been performed yielding repeatedly the same very high quality factors for cavities TB9AES027 and TB9AES021 in LCLS-2 vessel >2.7e10 at 16MV/m, 2K. Slow cooling through Tc was also explored, and found to always produce lower performance than fast cooling, even in the very low remnant fields <4 mGauss achieved via double cryoperm shielding plus active coil compensation, as it can be seen in Fig. 8. Fast cooldowns from T <35K are found to also produce lower Qs because of insufficient temperature gradient for maximum flux expulsion. The cavities under study were instrumented with T sensors placed inside the Helium vessel at the bottom and top of cell 1, 5 and 9, and with magnetic fluxgates at the bottom and top of cell 1 in longitudinal/45 degress (top) and transverse (bottom)

ISBN 978-3-95450-178-6

direction. This diagnostics is crucial to understand the details of the cooldown and gain insights on the details of Q improvement as a function of cooling. Pressure at the ¼ inch Helium inlet and flow rates are also monitored during cooldown and provide valuable insight on how to practically achieve best cooling conditions for efficient flux expulsion. Beampipes are also instrumented with T sensors and longitudinal fluxgates.

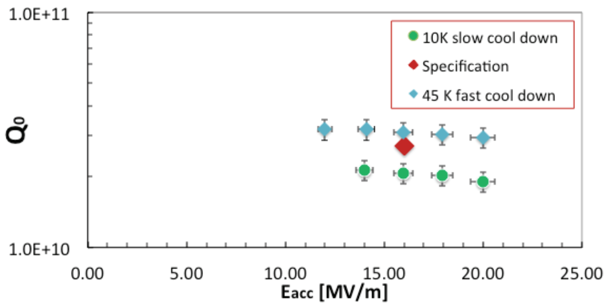

Figure 8: Fast versus slow cooldown results of record LCLS-2 N doped dressed nine cell TB9AES021 in dressed horizontal test with < 4 mGauss field.

Figure 9 shows the temperature and magnetic fields evolution recorded by the instrumentation on the cavity cells for a typical cooldown from 45K. The transverse magnetic field recorded by the fluxgate on the bottom of cell 1 shows the thermoelectrically induced component quickly dropping below 10 mGauss (at the outer cavity surface) when cavity goes through transition temperature. The fluxgate returns to near zero field after cavity has transitioned indicating that in that point close to no magnetic field was trapped and all the field present during the transient was efficiently expelled. Similarly to that, the fluxgate on top of cell 1 which captures longitudinal and vertical components of the magnetic field, shows very low field levels maintained throughout the cooldown and post cooldown, indicating again close to no magnetic field trapped at that cavity point.

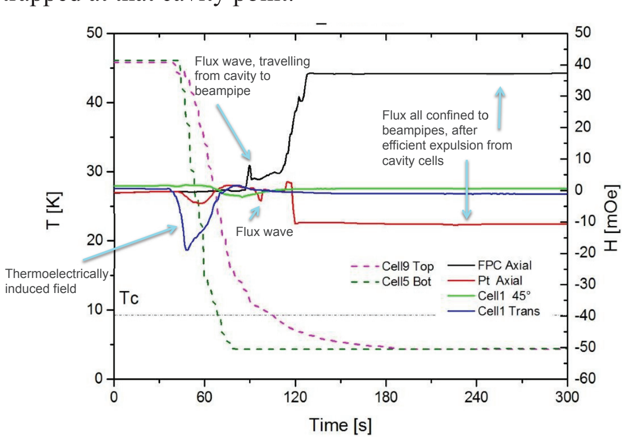

Figure 9: Temperature and magnetic field recordings during a cavity cooldown from 45K.

It is also interesting to observe the evolution of magnetic fields recorded by the longitudinally positioned beampipes fluxgates. About half minute after last cavity points pass transition temperature, the two probes record a travelling wave of magnetic flux. About half a minute later, the probes record a large amount of magnetic flux growing in coincidence with the beampipes temperature dropping, perhaps gradually growing more as parts of the beampipes become superconducting. The beampipes fluxgates which pre-cooldown were seeing < 1 mGauss, read now a magnetic field ~ 40 mGauss. A correlation is found between Q performance, bottom to top thermogradients, and level of magnetic field in the beampipes. Our interpretation of these observations is that fast cooldowns with larger thermogradients help expel magnetic field from the cavity more efficiently; flux then gets pushed and confined in the beampipes. When slow cooldowns are performed, the field at the beampipes does not change (remains same as pre-cooldown) indicating no flux has been efficiently extracted from the cavity and Q values are indeed the lowest.

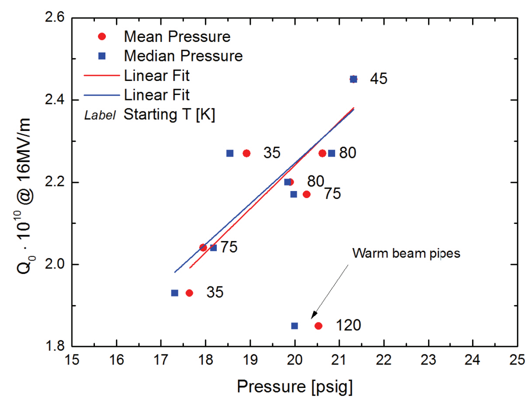

Figure 10: Temperature and magnetic field recordings during a cavity cooldown from 45K.

A large number of fast cooldowns were performed from different starting temperatures. One clear thing emerging from the study is that the starting T is not the only important parameter for Q maximization. Pressure at the He inlet, flow rates and starting T all determine how the interface SC-NC moves along the cell profile [], and it was noted that for several cooldowns with too small inlet pressure < 20 psig the temperature gradient at the SC-NC boundary would slow down significantly towards the top, causing more trapping at the cavity top. Interestingly, too high pressures > 30 psig also caused lower performance, in particular we observed that cooling became more turbulent and the T sensor at the top of cell 1 first transitioned below 9.2K, then above and then again below, which would lead to full flux trapping. The correlation between Q and pressure can be observed in Fig. 10. A solenoidal study was also performed for two different cooldowns from 45K, setup and results are shown at the top and bottom of Fig. 11. We find that flux expulsion efficiency is high in horizontal dressed tests: with 20 mGauss field applied longitudinally, and for a cooldown with bottom to top thermogradients of ~ 7K, we find an increase in residual resistance (compared to a cooldown with bottom to top gradients ~ 10K but no field applied) of 5 nΩ, which corresponds to a sensitivity of 0.25 nΩ/mGauss. For the second cooldown in 20 mGauss, which achieved more modest bottom to top thermogradients (~ 5K), the sensitivity extracted was 0.5 nΩ/mGauss. This data confirms that overall flux expulsion efficiency is higher for fast cooldowns with larger bottom to top thermogradients, in agreement with [5, 6], and that for reasonably achievable bottom-top thermogradients > 5K the sensitivity to be expected is <0.5 nΩ/mGauss.

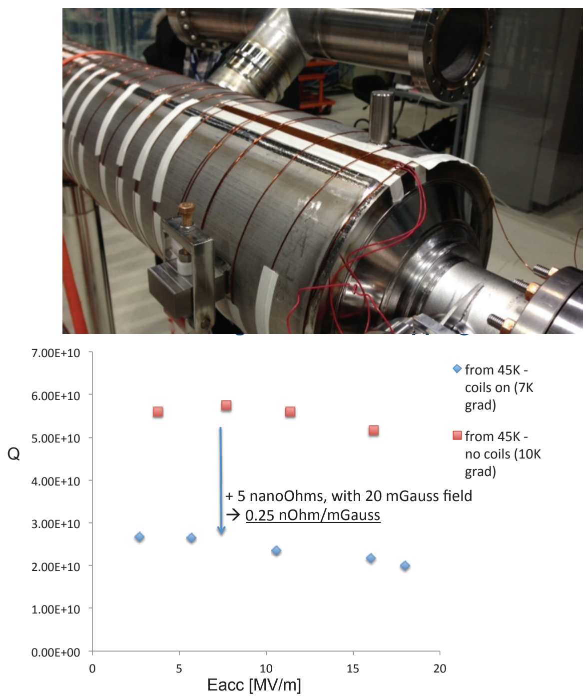

Figure 11: Top: solenoid wrapped around the helium vessel for flux expulsion efficiency studies. Bottom: Q vs E results for fast cooldown in applied zero vs 20 mGauss.

It is interesting to notice that the transient magnetic fields behave differently compared to the solenoidally imposed (and therefore remnant) ones in terms of flux expulsion efficiency: as it can be noted from Fig. 9 and for the extreme case in Fig. 12, thermoelectrically induced fields reach up to 150 mGauss during cavity critical temperature transition, but below 9.2K the probe indicates < 1 mGauss, meaning that all the transient flux was expelled, indicating a sensitivity of < 0.01 nΩ/mGauss, even for the case of Fig. 9 which has bottom to top thermogradients comparable to the ones achieved in the solenoidal study. The root of this different sensitivity to “permanent” remnant fields and “transient” ones may lay in the fact that larger transient fields are accompanied by large thermogradients, and therefore -fortunately- the source of these large fields may also simultaneously be the cure. Large transient fields always come with large expelling force. When the thermogradients and expelling force go down, the fields are low. However, in light of recent findings [12] where certain bulk material properties may require larger thermogradients for full flux expulsion, it may be prudent to avoid too high starting temperatures before fast cooldown. Therefore, our recommended procedure for the LCLS-2 vessel/cryomodules which has lead systematically to Q >2.7e10 at 2K, 16MV/m in horizontal tests of N doped cavities is to cool from the optimal found starting T ~ 45K which has thermoelectrically generated fields quickly falling below 5 mGauss throughout the cavity transition but leaves enough ‘room’ for obtaining good bottom to top expelling thermogradients; pressure at the helium inlet ~ 22psig, flow rates ~ 4 g/sec. One more important parameter found to play a role in the overall Q value is the temperature of the beampipes during cavity operation; it was found that several days and proper thermal strapping is needed for beampipes T to cool down everywhere < 8K, and that it is important to maintain all beampipes points below this 8K threshold to avoid Q degradation that can be > 20%.

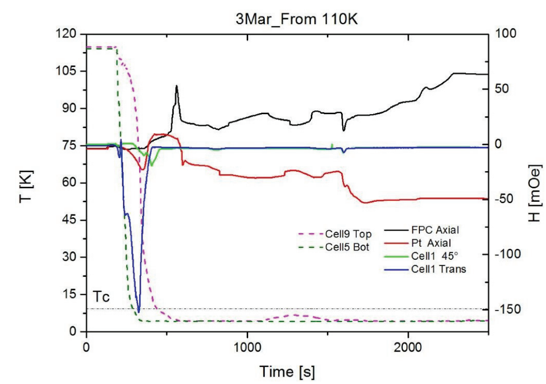

Figure 12: Large thermoelectrically induced field ~ 150 mGauss returning to ~zero after cavity transition, indicating that close to none of the transient field was trapped at the cavity surface.

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ISBN 978-3-95450-178-6