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MAGNETIC FLUX GENERATED BY THERMAL CURRENT IN CEBAF 5-CELL CAVITY SYSTEM*

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Abstract

The unloaded quality factor Q_0 of many 5-cell CEBAF cavities was lowered by a factor of ~2 from their vertical qualification testing to their beam operation in CEBAF tunnels. Causes of this Q_0 degradation were studied previously, including a more recent one addressing static flux arising from magnetic components near these cavities. This paper reports on a preliminary study of the dynamic flux generated by a thermal current, arising from the Seebeck effect and flowing in closed-loops formed by a niobium cavity and its surrounding tuner rods and liquid helium vessel made of stainless-steel. Flux generation in response to various thermal profiles in a 5-cell CEBAF cavity with integrated tuner rods were studied through varied cool-down cycles in a vertical dewar at JLAB. One outcome of this study is a proposed cool-down procedure for eliminating the thermal current generated magnetic flux around 5-cell cavities placed in CEBAF tunnels. This procedure may be useful for improving cavity Q_0 in a cost-effective manner, which in turn saves cryogenic expenditures for more efficient CEBAF operation.

INTRODUCTION

The unloaded quality factor of an RF cavity Q_0 can be described by $Q_0 = {}^{G}/_{R_s}$, where G is the geometry factor determined solely by the cavity geometry and resonating mode, R_s is the RF surface resistance which consists of the BCS term R_{BCS} and residual term R_{res}. The Q_0 values of many original 5-cell cavities placed in the CEBAF tunnels were degraded by a factor of ~2 as compared to that measured during their vertical qualification testing. The origin of this Q_0 degradation is attributed to an increase of R_{res}. Magnetic flux trapped in the RF penetration layer of an SRF cavity during its cool-down crossing Tc contribute to R_{res}, as it has been well established. Sources of magnetic flux include *static* ones, such as the remaining earth magnetic field inside the magnetic shielding, magnetized components enclosed in the inner magnetic shield, and *dynamic* ones such as thermal current generated magnetic flux. A recent prior work revealed large remnant magnetic fields in various magnetic components being near a cavity yet enclosed inside the inner magnetic shield [1]. That work led to a change in CEBAF cryomodule refurbishing practice. Non-magnetic strut springs made of 316L stainless-steel (SS) replaced their magnetic counterparts starting at the 11th rework module C50-11, eliminating one source of static magnetic flux that was enclosed in the inner magnetic shield. In the best case for C50-11, the cavity Q_0 at 5 MV/m measured in cryomodule was preserved at 88% of the value measured during its vertical qualification. However in the worst case, the preservation was still poor, at 40% level, begging additional effort.

More recently, systematic measurements of an original CEBAF cavity in a vertical cryostat with progressively added cryomodule components were carried out with an effort of degaussing the remaining magnetic components enclosed in the inner magnetic shield [2]. That work led to a new change in refurbishment practice starting at C50-12. The tuner components and helium vessel were all degaussed with a surface demagnetizer. In the best case for C50-12, the cavity Q_0 at 5 MV/m measured in cryomodule was preserved at 100% of the value measured during its vertical qualification. However in the worst case, the preservation was still ~ 60%, despite the static magnetic flux having fallen into the specification of ±10 mG for that cavity when measured in the tunnel.

Aiming for CEBAF operation with improved energy efficiency, the effort is continuing at JLAB, in pursuit of origin and remediation of the low Q_0 observed in original and refurbished 5-cell cavity cryomodules placed in linac tunnels. In this contribution, we report on preliminary studies of a *dynamic* source for magnetic flux, arising from the thermal-electric effect. Similar effects were observed in 9-cell cavities jacketed with titanium helium vessels [3]. Through these elementary studies, we seek ways for thermal-current elimination and raising Q_0 [4].

5-CELL CAVITY SYSTEM

As completed in 1994, the original CEBAF accelerator was consisted of 338 L-band (1497 MHz) 5-cell SRF niobium cavities hosted in 42 8-cavity cryomodules plus an additional 2-cavity cryomodule. The basic building block is a cryo-unit as shown in Fig. 1. Two 5-cell cavities are connected back-to-back, which in turn are enclosed in a 610 mm diameter liquid helium vessel made of SS. Each end of the unit is isolated by a gate valve (not shown in Fig. 1). The overall length of this unit is about 1778 mm.

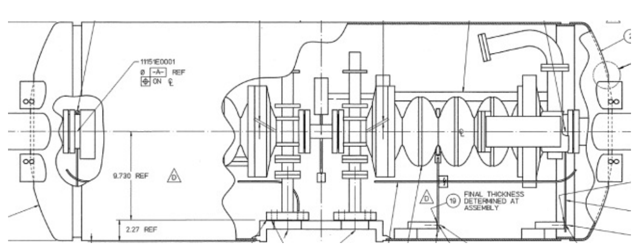

Figure 1: CEBAF Cryo-unit. Each cryomodule consists of four of such cryo-units.

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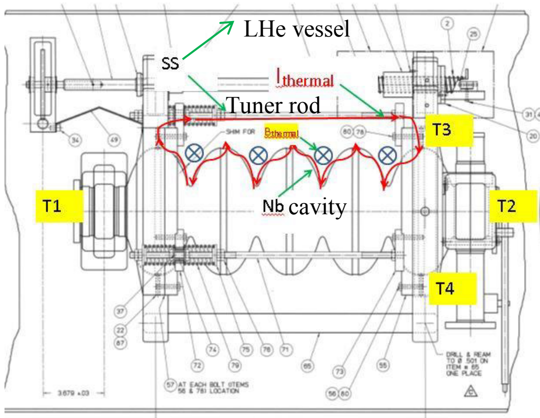

Figure 2: CEBAF 5-cell niobium cavity system with mounted SS tuner components.

Figure 2 illustrates the CEBAF 5-cell cavity system consisting of a 5-cell niobium cavity and its tuner components, including three SS supporting rods. A closed-loop is formed by the niobium cavity and SS tuner rods. During cryomodule cooldown process, the initial temperature equilibrium over the cavity length is broken until equilibrium is restored when the cavity is fully immersed in liquid helium bath. During this cool-down period, two cavity ends are at different temperatures, T_1 and T_2. A thermal current, $I_{thermal}$, is resulted due to Seebeck effect and it flows in the closed-loop mentioned above, as depicted in Fig. 2. Dynamic magnetic flux generated by this transient thermal current, $B_{thermal}$, may be trapped in the RF penetration layer of the cavity when it is cooled across the transition temperature of niobium. Like trapped *static* flux, the trapped *dynamic* flux will contribute to surface resistance as well, lowering the cavity Q_0.

EXPERIMENTAL APPARATUS

We carried out measurements of magnetic flux of a simplified 5-cell cavity model system subjected to various thermal profiles by cool-down and warm up the measurement apparatus. The 5-cell cavity was vertically oriented with one SS tuner rod mounted, forming a close loop including aluminium blocks between cavity end cells and the rod. A sketch and a photo are shown in Fig. 3.

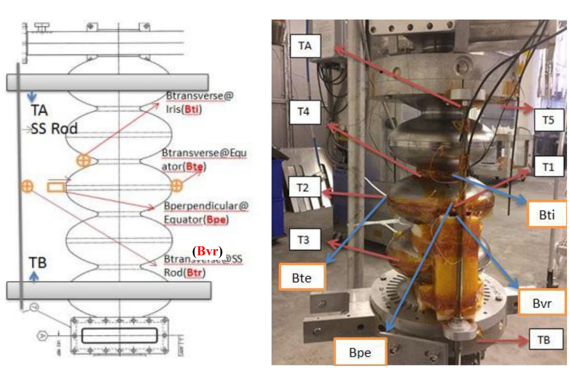

Figure 3: Instrumented experimental apparatus modelling one closed loop in the 5-cell cavity system.

Four Bartington single-axis fluxgate magnetometers were mounted at locations indicated in Fig. 3. Three of them were oriented for the maximum sensitivity to azimuthal flux (Bte at middle-cell equator, Bti at iris above middle-cell, Bvr at center of rod). One was oriented for the maximum sensitivity to the flux normal to the outer surface of the middle-cell equator (Bpe). Each magnetometer was accompanied by a temperature sensor. Additional temperature sensors were placed at the aluminium blocks holding the end cells. A key control parameter was the temperature difference DeltaT between the upper block (TA) and lower block (TB).

The experimental apparatus was suspended in a vertical testing dewar in JLAB VTA area. Cold helium gas was injected from the bottom of the dewar. The dewar space was shielded from earth magnetic fields as usual. Residual background magnetic flux were recorded initially and subtracted later on in data analysis for obtaining the flux entirely originated from the thermal-electric currents. Warming up was realized by turning on a resistive heater placed at the bottom of the dewar.

A natural consequence of our experimental arrangement is that a superconducting phase front appears first at the lower cavity flange. That front then moves upward as the cooling continues, ultimately sweeps through the entire cavity length. This arrangement leads also to a temperature profile in which TA > TB, thus a positive DeltaT at any instant during cool-down. Such a profile is desirable for creating needed control in DeltaT.

EXPERIMENTAL RESULTS

A series of measurements were carried out in the spring of 2015. Of interest to us are data taken after the appearance of a superconducting phase front, hence only data for TB < 10 K will be presented. A typical result is shown in Fig. 4, illustrating the dependence of Bte, Bvr and Bti with DeltaT for two sequential cooldown cycles. Thermal current generated magnetic flux is evident from Bte, Bvr, and Bti during the 1st cool-down cycle, which started at room temperature, resulted in a DeltaT of 30 - 90 K for TB < 10 K. In contrast, negligibly small flux is detected during 2nd cool-down cycle where DeltaT < 10 K.

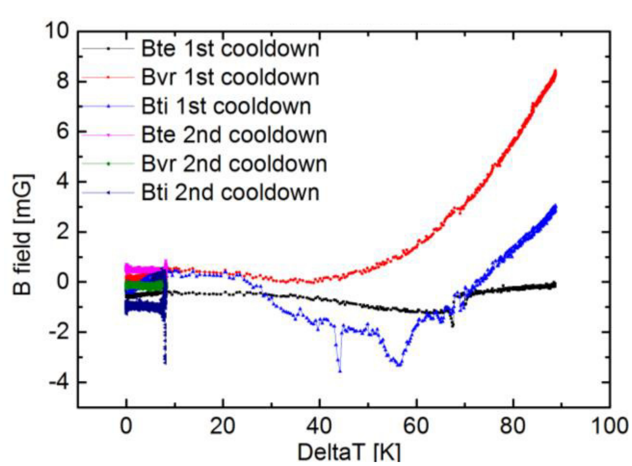

Figure 4: Test results for two sequential cooldown cycles.

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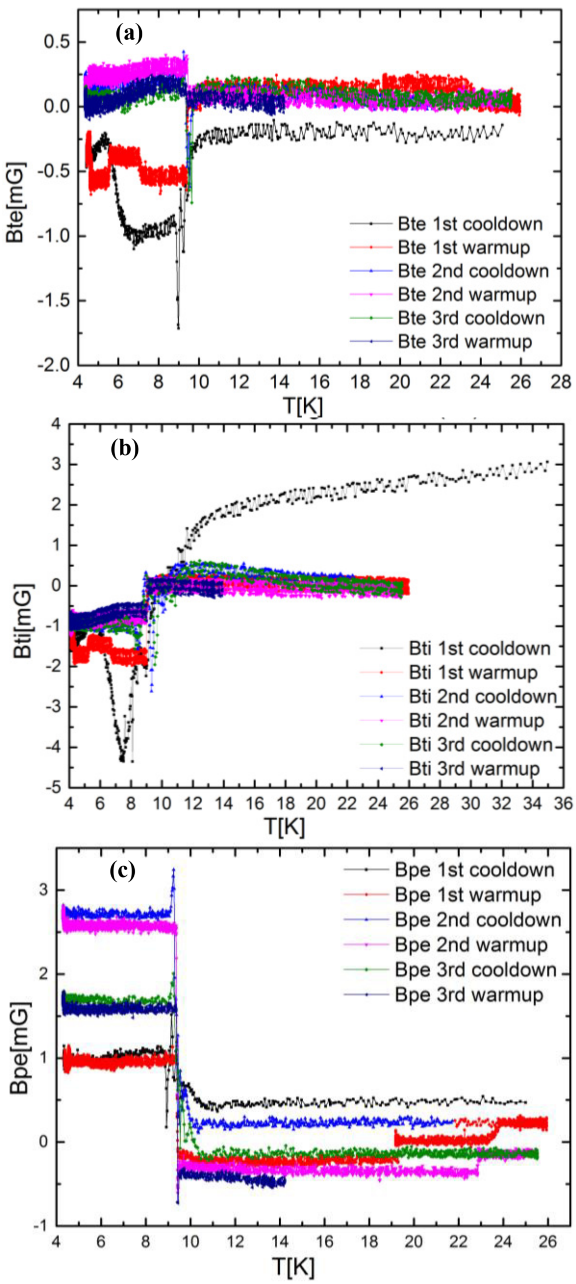

Figure 5: Dependence of flux densities on local temperatures for three sequential cooldown cycles. (a)Bte, (b)Bti, and (c)Bpe.

In Fig. 5, Bte, Bti, and Bpe are plotted against their local temperatures for three consecutive cool-down cycles on March 9, 2015. A step transition in the flux density near the cavity wall (Bte, Bti, and Bpe) at Tc crossing is consistent with the well-established picture of flux expulsion from that wall upon its phase transition from normal state into Meissner state. In contrast, no such step transition is apparent in Bvr (not shown), despite a large value being detected during the 1st cool-down cycle. Absence of step transition in Bvr seems to be reasonable as a result of its sensor being remote to cavity surface.

Once again, the generated magnetic flux during the 1st cycle (large DeltaT) is highly distinguishable as compared to subsequent 2nd and 3rd cycles (small DeltaT by warming up to 40 K followed by re-cooldown).

DISCUSSIONS

It is worth noting that Bpe (Fig. 5(c)) exhibits well-defined step transitions as well. This is a surprise as the sensor is oriented normal to the local cavity surface, hence insensitive to generated flux. Presently, this observed behaviour is not understood, but we speculate that it is connected with the dynamical process of fluxoid formation and movement. A possible explanation is flux tube re-orientation preferentially in the normal direction.

Additional tests were carried out with three SS rods attached to the same 5-cell cavity, resulted in similar observations. An apparent deviation lies in a much larger Bte and Bti as compared to 1-rod. This can be understood as a result of additive effect of currents as the number of rod increases. The SS helium vessel hosting the cavity pair in cryomodules can be regarded as a limiting case with many rods (see Fig. 1). Its presence may give rise to a significant magnetic flux generation. It should be mentioned that testing of a 5-cell cavity with tuner components was done in [2] and no significant change in Q_0 was observed between fast and slow cool down. This suggests that the thermal current from tuner rods alone maybe not significant. Further tests are required for assessment the effect of the SS helium vessel, including the effect of its deviation from the axisymmetric configuration [5]. Studies may be extended to new 7-cell cavities for their helium vessels, albeit compact, are made of SS as well.

We should point out that this study is not intended to be systematic. Rather it addressed two limiting cases, practically large and small DeltaT. These controls resulted in two outcomes: (1) Direct observation of magnetic flux generated by thermal currents in CEBAF cavity systems; (2) A proposed cool-down procedure for eliminating the thermal current generated magnetic flux:

- Standard initial cool-down to 4 K.
- Warm up to 40 K.
- Re-cool-down to 4 K, keep DeltaT < 10 K.
- Pump to 2K.

CONCLUSION

We carried out a series of experimental measurements with a 5-cell CEBAF niobium cavity system with integrated SS tuner rod, instrumented with thermometers and magnetometers, with which the *dynamic magnetic flux* generated by a thermal current was established. A surprising result is the observation of a large transient step in the flux density detected at the outer surface, in normal direction, of the cavity equator region. This puzzling phenomenon deserves further studies. This work resulted in a proposed cool-down procedure for eliminating the thermal-electric current generated magnetic flux around 5-cell cavities placed in CEBAF tunnels. This procedure may be useful for improving cavity Q_0 in a cost-effective manner, which in turn saves cryogenic expenditures for more efficient CEBAF operation.

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REFERENCES

[1] R. L. Geng et al., in *Proc.* IPAC2014, Dresden, Germany, 2014, pp. 2828-2830.

[2] G. Ciovati et al., *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, p. 3500106, 2017.

[3] J. -M. Vogt, O. Kugeler, and J. Knobloch, Phys. Rev. Spec. Topics – Accel. and Beams, 18, 042001, 2015.

[4] S. C. Huang, R. L. Geng, JLAB Internal Tech Note, JLAB-TN-18-003, 2018.

[5] Anthony C. Crawford, arXiv: 1403.7996, 2014.