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

R. L. Geng†, S. C. Huang†, Jefferson Lab, Newport News, VA 23693, USA

Abstract

The unloaded quality factor $Q_0$ of many 5-cell CEBAF cavities was lowered by a factor of $\sim 2$ 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 $\sim 2$ 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 $T_c$ 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 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 $\sim 60\%$, despite the static magnetic flux having fallen into the specification of $\pm 10$ 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.

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†geng@jlab.org.
††former graduate student, presently at IMP, CAS.

Figure 1: CEBAF Cryo-unit. Each cryomodule consists of four of such cryo-units.
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.
to subsequent 2\textsuperscript{nd} and 3\textsuperscript{rd} 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 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.
REFERENCES


