ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THOBB01

PURSUING THE ORIGIN AND REMEDIATION OF LOW Q_0 OBSERVED IN THE ORIGINAL CEBAF CRYOMODULES*

R.L. Geng#, J. Fischer, F.S. He##, Y.M. Li###, C.E. Reece, T. Reilly
JLAB, Newport News, VA 23606, U.S.A.

Abstract

We report on results of a new investigation into the Q_0 degradation phenomenon observed in original CEBAF cavities when assembled into cryomodules. As a result, the RF dissipation losses increased by roughly a factor of two. The origin of the degradation, first observed in 1993, has remained unresolved up to current period, despite much effort. Recently, a new investigation has been launched, in parallel with cryomodule refurbishment. Systematic measurements are conducted with respect to the magnetic shielding effects of the double-layer shields and the magnetic properties of various components within the inner shield. This resulted in the new discovery of strongly magnetized strut springs as a major source of remanent magnetic flux near a cavity inside of all magnetic shielding. New springs with superior magnetic properties have been found, evaluated and implemented. Preservation of Q_0 from vertical testing to cryomodule testing in tunnel at 5 MV/m gradient in the range of 79-88% has been measured. Studies for complete Q_0 preservation and possible Q_0 remediation for those 330 cavities already installed in CEBAF are carried out and preliminary results are also presented.

INTRODUCTION

The superconducting RF (SRF) accelerator at Jefferson Lab, CEBAF, was originally completed in 1994[1]. It is 1.4 km in circumference and has a race-track shape, of the recirculated linear accelerator type. A beam current of up to 200 μA at 4 GeV in CW mode is provided. Two linacs on opposite sides of the racetrack each provide a designed energy of ≥400 MeV per pass [2]. Each linac consists of 20 cryomodules (each 8.25 meter long). Additionally 2.25 cryomodules are installed in the injector section. In total, 338 cavities were installed in 42.25 cryomoudles.

Each cryomodule consists of 4 cryo units (see Fig. 4 in Ref. [2]). A pair of 1.5 GHz 5-cell Cornell-type SRF niobium cavities is the heart of the cryo unit. Around the cavity, HOM dampers, tuners and fundamental power couplers are integrated into the helium (He) vessel, which defines the envelope of the cryo unit. When in operation, the He vessel is filled with 2 K liquid He. A layer of mu-metal is wrapped over the outer surface of the He vessel, forming the inner cold magnetic shield. Another layer of mu-metal is mounted near the inner surface of the vacuum vessel, forming the outer warm magnetic shield.

The original CEBAF cavity performance specification for the initial construction was 5 MV/m gradient with 2.4×10^9 unloaded quality factor (Q_0) at 2 K. The cryo plant was sized to provide 5 kW cooling power at 2 K (corresponding to a liquefier operating power of 5 MW). Over time, the accelerating gradient of CEBAF cavities has been improved by in-situ He processing [3] and cryomodule refurbishment [4], ultimately leading to an average gradient of 7.5 MV/m, raising the CEBAF energy reach to 6 GeV [5]. Running at higher gradient necessitates a higher Q_0 because of fixed cooling capability. Currently, CEBAF is being upgraded to an energy reach of 12 GeV [6]. 10 new cryomodules have been added (5 each for each linac). This, together with the existing cryomoudles, provides 1.1 GeV acceleration per linac. The performance specification for new cavities is 19.2 MV/m acceleration gradient with at 7.2×10^9 Q_0 at 2 K [7]. A second cryo plant is added, doubling the 2 K cooling power to ~ 10 kW (corresponding to a liquefier operating power of ~ 10 MW).

ISSUE OF LOW Q_0 AND PRIOR EFFORT

The low Q_0 issue was first observed in 1993. On average, the Q_0 of cavities during vertical qualification testing was 1×10^{10} at 5 MV/m at 2K [8]. It degraded on average to 6×10^9 when measured in cryomodules installed in CEBAF tunnel [9][10]. It should be noted that Q_0 specification (2.4×10^9 at 5 MV/m) was still exceeded in most cases despite this degradation. Some effort was devoted later on, including investigation of ambient magnetic field, cavity cool down rate etc, but no major culprit was found [11].

During the period of 2007-2009, the 10 weakest CEBAF cryomodules were refurbished [12]. This effort resulted in successful improvement in acceleration gradient and elimination of field emission of 80 cavities because of modern-day processing, such as high pressure water rising and clean room assembly (not available during the original CEBAF construction). Unfortunately, Q_0 degradation at the same scale was still observed from vertical testing to commissioning in CEBAF tunnel. The RF dissipation losses of re-processed cavities essentially remain the same as compared to their previous operational values. As all re-processed cavities are vacuum furnace heat treated, hydrogen Q-disease is undoubtedly ruled out. Some effort was then devoted in the middle of refurbishment effort, with a focus on possible magnetic components near the cavities. One magnetized component (ball screw) in the tuner assembly was found. Wrapping a magnetic shielding around the ball screw resulted in some

---

* Work supported by DOE. Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

geng@jlab.org
Graduate student from Peking University. Now with IHEP, CAS.
Graduate student from Peking University, Now with IMP, CAS.

improvement [13]. Some simulation studies on magnetic shielding were carried out at the time [14], leading to some exploration of inner cold magnetic shielding, such as closing the ends of cryo unit and replacing material with cryoperm. Despite these efforts, no cavity in cryomodule met the set Q_0 goal of 6.8×10^9 at 12.5 MV/m gradient at the end of the refurbish effort [4].

NEW EFFORT

Taking advantage of the most recent refurbishment effort, a new effort was launched in January 2013. The cryomodule was pulled out from the 9th cryomodule slot in the south linac (SL10).

Magnetic Properties of Components

First of all, we conducted a magnetic survey in the as-found condition of the cryomodule. A single-axis sensor was inserted into the inner cavity space. This measurement was repeated after the components inside the He vessel were all remove. A comparison of the two measurements is given in Fig. 1. It shows clearly the presence of magnetized components inside the He vessel, and they are responsible for 70% of the measured flux. Additional probing in the space between cavity outer surface and the He vessel inner surface revealed sharply varying magnetic flux with peak amplitude in the range of 200-250 mG. This is to be compared to a slowly varying flux in the range of 40-80 mG measured between the inner and outer magnetic shield. This level of flux is compatible with the observed Q_0 degradation, due to the “frozen flux effect”. Therefore, the remanent magnetic field due to components inside the He vessel is clearly established as the main source of the low Q_0 issue.

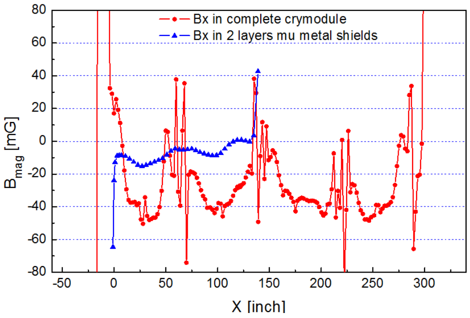

Figure 1: Comparison of near axis axial magnetic field. Under as-found condition (red circle) over entire module length; After components inside liquid He vessel were removed (blue triangle) over half module length.

Ultimately, we inspected the magnetic properties, including the remanent field by using a pocket magnetometer and the magnetic permeability by using a permeability indicator, of all components contained inside the He vessel, piece by piece. A major new discovery is that many strut springs (see Fig. 2) near the cavities have a shockingly large remanent magnetic field (worst case 6 G at contact). To further confirm the finding, a 1-cell 1.3 GHz niobium cavity test was carried out at 2 K with three strut springs mounted near the cavity equator. The Q_0 dropped from 2×10^{10} to 1×10^9 up to 8.5 MV/m gradient! The second offending component is the threaded rod (see Fig. 2) in the driver shaft of the tuner assembly, measuring a remanent field with a peak value at contact in the range of 0.5-1.7 G. The 3rd offending component is the ball bearings in various places of the tuner assembly (typical peak remanent field at contact < 0.5 G).

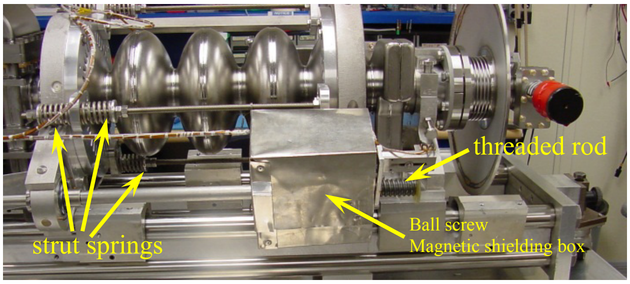

Figure 2: Picture of near-cavity components enclosed inside He vessel. Indicated by arrow are strut springs & threaded rod. A shielding box wrapped around ball screw (an outcome of prior mitigation effort) is also indicated. Photo credit: M. Mccrea, JLab.

Magnetic Shielding of Cold & Warm Shields

The effectiveness of the two magnetic shielding layers was evaluated at room temperature by carrying out 3-axis magnetic field measurements inside the He vessel space of two cryo units with all components inside the He vessels removed. With an ambient magnetic flux of ~ 500 mG, our measurements established, within the space occupied by the cavities, a shielding factor of > 10 and ~ 2 for the outer and inner shielding, respectively. The external magnetic field is reduced to a typical value of 12-20 mG. Some local high field regions are observed. These are correlated with the inevitable shielding penetrations for waveguide and He supply and return pipes etc. The peak value though is < 25 mG in the worst case.

Ambient Magnetic Field in CEBAF Tunnel

The ambient magnetic field in CEBAF tunnel has been previously surveyed systematically by a contractor [15]. The peak field was found to be on the level of a few Gauss at 1 meter above ground level. Our new survey focused on the space occupied by cavities along the beam line. Over the module length in the SL10 slot, the magnetic field amplitude varies in the range of 0-1 G.

NEW MITIGATION

Based on the above finding, we developed a logical mitigation procedure (in order of precedence):

1. Replace magnetized components inside He vessel
2. Improve magnetic shielding
3. Mitigate ambient field in CEBAF tunnel

After some discussion with the vendor of the original strut spring, new springs were produced and received. The new springs were inspected for its magnetic & mechanical properties. In addition, the 1-cell cavity testing previously mentioned was repeated by replacing the three original springs with three new springs. The cavity Q_0 remained at 2×10^{10} up to a 15 MV/m gradient. 48 new springs (6 for each cavity) were ultimately installed in the cryomodule at location SL10 (a.k.a C50-11). We also have in hand 5 new threaded rods made of 316L stainless-steel. But they were not installed due to schedule constraint. Table 1 gives a summary and comparison of magnetic properties of the springs and threaded rods. All ball bearings were degaussed to a peak flux at contact of < 0.04 G. All ball-screws were wrapped with shielding boxes, a mitigation developed previously.

Table 1: Comparison of Spring and Threaded Rods

	Unit	Original spring	New spring	Original rod	New rod
Material	-	302 SS	316 SS	unknown	316L SS
Bpk	G	6	< 0.1	1.7	0.03
μ_r	-	> 6	< 1.08	> 6	< 1.6

B_{pk}: Peak magnetic flux at contact; μ_r: Relative magnetic permeability; SS: stainless-steel.

Color code: Original (Red); New implemented (Green); New to be implemented (Yellow).

In addition, we developed a procedure for avoidance of re-magnetization of degaussed components. We surveyed all hardware components attached to cavities (fasteners, feedthrough etc). We inspected all assembly toolings. We investigated magnetic field generated by the current flowing through the current leads of the TIG welding machine. A suite of recommendations was delivered.

RESULTS

Preservation of Q_0 at 5 MV/m gradient in the range of 79-88% is measured in three cavities (Fig. 3). Four cavities showed ~ 50% preservation. One cavity (C50-11-3) was not measured in module due to tuner issue. It is noted that the ball-screw shielding box for the first 4 cavities are different from that for last 4 cavities, possible reason for different responses. No correlation with the ambient magnetic field at SL10 seems to be obvious despite large field amplitude variation from 0-1 G.

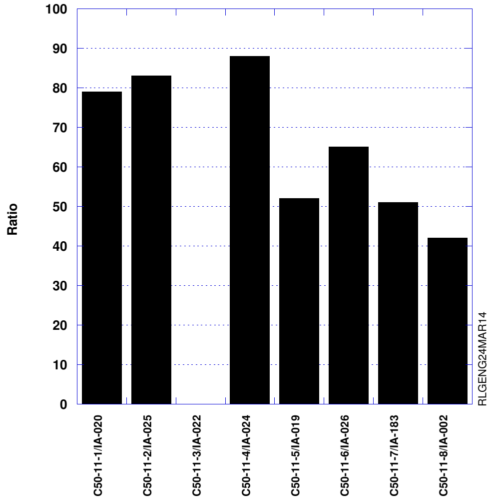

Figure 3: Ratio of cavity Q_0 at 5 MV/m measured in cryomoudle in CEBAF tunnel to that in vertical testing.

CONCLUSION AND OUTLOOK

The origin of the low Q_0 problem in original CEBAF cryomoduels is further understood. Magnetized strut springs with large remanent flux are found to be the leading culprit. New mitigation procedure has been identified and partially implemented in the latest refurbished cryomodule (C50-11). The best preservation of Q_0 at 5 MV/m is measured to be 88%. For future refurbishment, new threaded rods should replace the old rods. Elimination of internal magnetized components now allows us to further assess the magnetic shielding effect, which will be a future effort. We have also experimented techniques of manipulating trapped fluxes by thermal cycling [16]. We proposed a partial warm up to 20 K followed by rapid cooling with a “mobile shield” as a practical remedy to improve the Q_0 of cavities in-situ in CEBAF tunnel [17]. This remedy could provide a cost-effective interim solution before an expensive cryomodule refurbishment opportunity arrives. Any saving in cooling power can be used to enhance the acceleration voltage and improve the robustness of the energy reach of CEBAF.

REFERENCES

[1] H. Grunder, “CEBAF Commissioning and Future Plans”, PAC 95 Proc., pp1–3 (1995).

[2] B. Almeida et al., “RF superconductivity at CEBAF”, SRF 89 Proc., pp1-18 (1989).

[3] C. Reece et al., “Improvement of the operational performance of SRF cavities via in situ He processing and waveguide vacuum processing”, PAC 97 Proc., pp3105-3107(1997).

[4] M. Drury et al., “Summary report for the C50 cryomodule project”, PAC 11 Proc., pp.1044-46 (2011).

[5] C.W. Leemann, D.R. Douglas, G.A. Krafft, Annu. Rev. Nucl. Sci., 51(2001)pp413-50.

[6] L. Harwood, “Upgrading CEBAF to 12 GeV”, PAC 03 Proc., pp586-588 (2003).

[7] J. Hogan et al., “Overview and lessons learned of the Jefferson Lab cryomodule production for the CEBAF 12 GeV upgrade”, PAC 13 Proc., pp749-53(2013).

[8] C. Reece et al., “Production vertical cavity pair testing at CEBAF”, SRF 93 Proc., pp650-58(1993).

[9] J. Mammosser, “Status report: SRF activities at CEBAF”, SRF 93 Proc., pp33-48(1993).

[10] M. Drury et al., “CEBAF cryomodule commissioning in the south linac”, SRF 93 Proc., pp.610-16(1993).

[11] W.J. Schneider et al., “Anomalous Q_0 results in the CEBAF south linac”, SRF 93 Proc., pp659-69(1993).

[12] Y. C. Chao et al., “CEBAF accelerator achievement”, Journal of Physics: Conf. Series 299 (2011)012015.

[13] M. Drury et al., “Overview of the first five refurbished CEBAF cryomodules”, LINAC 08 Proc., pp1084-86(2008).

[14] G. Cheng, Private communication (2013).

[15] VitaTech Engineering, LLC Report, Feb. 22, 2006.

[16] R.L. Geng et al., to be published at LINAC14.

[17] R.L. Geng, “C50-11 Q_0 analysis”, CEBAF SRF/RF/cryo Workshop, JLab, April 3, 2014 (2014), https://www.jlab.org/indico/conferenceDisplay.py?confId=69