

IN-SITU PROTON IRRADIATION AND MEASUREMENT OF SUPERCONDUCTING RF CAVITIES UNDER CRYOGENIC CONDITIONS

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Abstract

The Accelerator Production of Tritium (APT) Project is investigating using a superconducting linac for the high-energy portion of the accelerator. As this accelerator would be used to accelerate a high-current (100-mA) CW proton beam up to 1700 MeV, it is important to determine the effects of stray-beam impingement on the superconducting properties of 700-MHz niobium cavities. To accomplish this, two 3000-MHz elliptical niobium cavities were placed in a cryostat, cooled to nominally 2 K in sub-atmospheric liquid helium, and irradiated with 798-MeV protons at up to 490-nA average current. The elliptically shaped beam passed through the equatorial regions of both cavities in order to maximize sensitivity to any changes in the superconducting surface resistance. Over the course of the experiment, 6×10^{16} protons were passed through the cavities. After irradiation, the cavities were warmed to 250 K, then re-cooled to investigate the effects of a room-temperature annealing cycle on the superconducting properties of the irradiated cavities. A detailed description of the experiment and the results shall be presented. These results are important to employing superconducting RF technology to future high-intensity proton accelerators for use in research and transmutation technologies.

1 INTRODUCTION

A significant driver for the APT conceptual design is the minimization of beam loss through the accelerator, which would allow hands-on maintenance. Extensive steering error and beam halo studies have been used to keep stray beam to a maximum of 0.2 nA/m in the overall design. However, even at this low level, the question remained as what effect this amount of lost beam might have on the superconducting properties of a niobium accelerator cavity.

In a previously published paper [1], an experiment was done where a superconducting cavity was irradiated and measured under cryogenic conditions. The results of the experiment indicated a deleterious effect on the cavity Q_0 at a proton fluence comparable to the 0.2 nA/m figure calculated for APT. While the experiment was done over 25 years ago and many things in superconducting cavity technology have changed since these early days, the reported change in the Q_0 was enough to motivate further investigation.

Work supported by the US Department of Energy

2 EXPERIMENTAL APPROACH

The intent of the experiment was to evaluate, in a timely manner, if there was an observable effect on the superconducting properties of a niobium cavity that was exposed to a relatively large fluence of high energy protons. Given the constraints on beam availability, cost, and schedule, the experiment was designed to look for an overall effect, instead of trying to closely emulate the actual "spilled beam" configuration a real accelerating cavity may see. This was seen as a way of bounding the problem.

The approach was to measure the cavity Q_0 as a function of fluence. Changes in the Q_0 would indicate a change in the surface resistance (R_s). To see subtle changes in the Q_0 , the cavities were operated between 1.8 and 2.2 K.

To increase sensitivity further, the cavities were irradiated on their equators with an elliptical beam profile of 1x3 cm to achieve the largest practical radiation-affected zone relative to the active cavity area. Irradiating the cavities while immersed in liquid helium was done to mimic the actual environment of the cavities in a working accelerator. This also allowed us to evaluate what effect room-temperature annealing had on the superconducting electrical properties due to healing radiation damage, in the event changes were observed.

To do this, the assembly was warmed to 250 K, then re-cooled to 2 K and measured before the cavities were physically moved, in order to minimize possible contamination. A schematic layout of the configuration is shown in Figure 1.

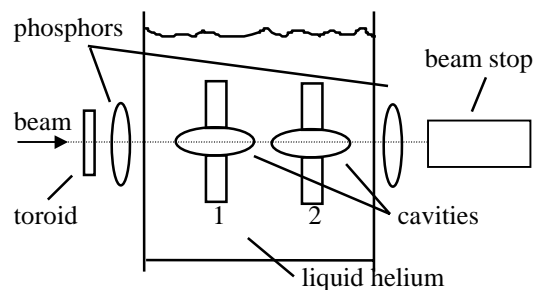


Figure 1. Schematic of the experimental set up, showing the beam going through a current toroid, the phosphors, the cryostat, the two 3 GHz cavities, and stopping in the beam stop.

3 BEAM DELIVERY

The cavity and cryostat assembly was irradiated using the LANSCE accelerator in an area called the Blue Room. The Blue Room is a shielded area that can be configured for direct access to 798-MeV protons with average currents up to 500 nA.

Since a major goal of the experiment was to measure the cavity properties as a function of proton fluence, accurate beam measurements were important. Beam current was directly measured using a beamline toroid upstream of the Blue Room. The measurement was corroborated using an additional toroid before the cryostat.

Phosphors were used primarily for profiling the beam going into and coming out of the cryostat. They also served to give another corroboration of the overall beam current profile by looking at the digitized light intensity from the phosphors.

Finally, induced-activity dosimetry was done on the cavities and confirmed the cavities did indeed have the beam delivered on the equator.

During the actual measurement, the beam was run for prescribed amounts of time at increasing average current levels. RF measurements of the cavities were done both while the beam was on and when it was off between irradiations. There was no observed difference in the measured values between beam on and beam off, indicating beam-induced secondaries were not a problem. The cumulative profile of the fluence achieved is shown in Figure 2.

Achieving a fluence of 5×10^{15} p/cm², which corresponds to a beam loss of 0.2 nA/m, was the minimum goal. In the actual experiment, we achieved fluences in excess of 1.5×10^{16} p/cm², which was a factor of 3 greater than the expected worst-case lifetime beam-loss fluence for APT.

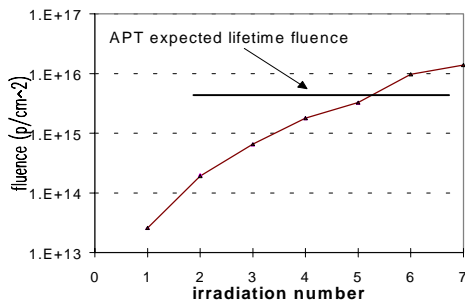


Figure 2. Plot showing proton fluence as a function of time in arbitrary units. The horizontal line shows the expected 40 year lifetime fluence for APT.

4 LOW-POWER MEASUREMENTS

Irradiating two cavities was done primarily for redundancy, in the event one leaked. However, since neither cavity leaked, having two cavities allowed running one at low power until the end of the experiment. This was desirable as it was a way to eliminate the changes in the Q_0 that could occur due to RF conditioning at higher fields.

The first cavity in the beam was run only at low power levels, less than 50 mW, throughout the run. With E_0T field levels in the cavity held consistently around 4-5 MV/m, conditioning-related changes in Q_0 were kept to a minimum. Only after the low power data was obtained was the power level in this cavity increased to determine its field performance at full fluence. Low power points from the second cavity were also examined for corroborative purposes. The low power data for both cavities is shown in Figure 3. Within experimental accuracy, there was no observable change in the Q_0 with increased fluence.

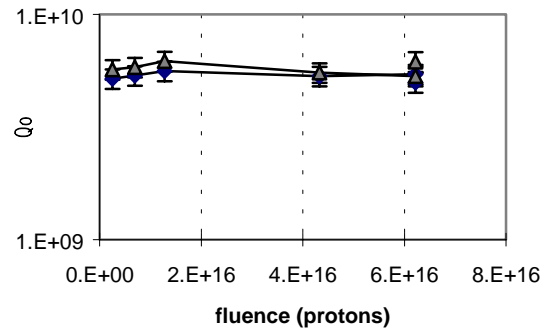


Figure 3. Plot showing the low-power unloaded Q_0 of both cavities as a function of proton fluence. Data normalized to 2.0 K.

5 HIGH-POWER MEASUREMENTS

The second cavity in the beam path was swept in power after each incremental increase in the fluence. The intent was to look for degradation in performance as a function of increased radiation damage. As shown in Figure 4, a variation in the Q_0 as a function of power was observed for increasing fluence that is attributed primarily to uncertainties in the temperature normalization and errors in the measurement of the Q_0 .

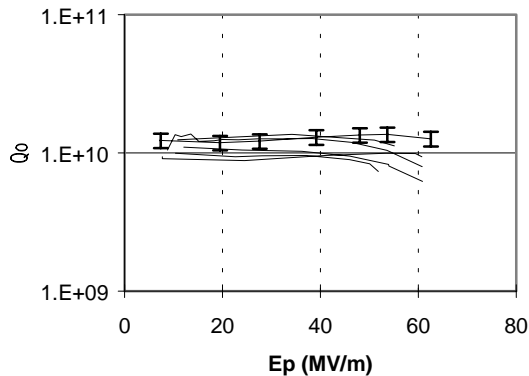


Figure 4. Variation of the Q_0 related to the peak surface electric field. The different curves represent different fluence levels. The downward trend did not consistently correlate with increased fluence. Data normalized to 1.8 K.

For the quench field level, a mild downward trend of approximately 15 % was observed in the second cavity up to a fluence of 4.3×10^{16} protons, as shown in Figure 5. Above this level, mechanical problems necessitated running the cavity at a higher temperature (2.0-2.2 K), and the resultant larger temperature normalization as well as changes in the niobium thermal conductivity are seen as contributing to the observed recovery in the quench field level to pre-irradiation levels.

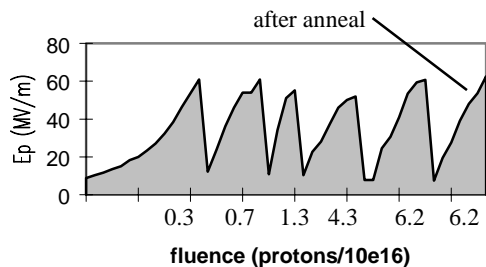


Figure 5. Peak electric fields obtained in multiple power sweeps as a function of fluence.

In general, no significant degradation in Q_0 was observed with increased radiation damage, and a mild downward trend in the quench field was observed. As the field levels for the APT cavities are conservative, i.e., not near the quench limit, this magnitude of change in quench field is not a concern.

6 CONCLUSION

The objective of this experiment was to evaluate the effect proton irradiation had on the superconducting properties of cryogenic niobium cavities. To a fluence level of 6.2×10^{16} protons (1.6×10^{16} p/cm²) at 798 MeV, there was no significant degradation observed in the Q_0 . After the 250 K anneal, changes of less than 13% in the low-power cavity Q_0 were observed.

A downward trend of approximately 15% in the cavity quench field was also observed, but for the modest gradients needed for APT, this is not a concern.

7 ACKNOWLEDGMENTS

The authors would like to express their gratitude to Frank Krawczyk, George Morgan, Brock Roberts, Bob Hammock, Ernie Newman, and Marv Barney for their help with the experiment fabrication, set up, and operation.

REFERENCES

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