MEASUREMENT OF RF SURFACE EFFICIENCY AT CRYOGENIC TEMPERATURES USING A COAXIAL RESONANT CAVITY

G. O. Bolme, G. P. Boicourt, L. Booth, N. K. Bultman, E. Foley, D. J. Liska, R. A. Lohsen, J. B. Niesen, J. Rose,† B. Rusnak, G. Spalek, and N. G. Wilson
Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract

Exploiting the potential efficiency gain of a normal conducting rf accelerator operated at cryogenic temperatures requires careful preparation of the rf conducting surface. Experimental apparatus has been assembled to study the surface conductivity to rf currents at 425 MHz and 850 MHz through a temperature range from room temperature to 14 K. The apparatus is built around an open-ended coaxial cavity with the cavity tubular ends below the cutoff frequency at resonance. The center conductor in the coaxial cavity is the test sample, and the use of a dielectric stand-off for the center conductor precludes the need for an rf contact joint and facilitates sample changes. The rf testing is conducted under vacuum with low-power rf. A CTI-Cryogenics cryopump coldhead is used for cryogenic temperature cycling of the test cavity. A detailed description of the apparatus and measurement procedures are presented.

Introduction

The H$^-$ accelerator for the Ground Test Accelerator (GTA) has the purpose of verifying much of the space-traceable technology for the Neutral Particle Beam (NPB) program. Included in the space-traceability is the demonstration of increased efficiency and stability of operating normal-conducting, rf accelerating structures at cryogenic temperatures. The many different rf components in the GTA accelerator require varied fabrication processes, and the understanding of the fabrication processes and their effect on efficiency were not well known. The Cryogenic Test Fixture (CTF) was designed and assembled to provide a dedicated experimental facility for testing the rf structure efficiency of test surfaces and other cryogenic components. The CTF combines an rf coaxial cavity, a vacuum system, a cryogenic cooling system, temperature monitors, and the support diagnostics for measurements directed at this very specific technology issue.

Design Objectives of the CTF

A limitation of many of the surface efficiency experiments is associated with the expediency of testing and the capacity to limit the test to a specific uniform surface finish. The expediency of testing requires that the surface sample preparation be simple and uncomplicated, and that installation into the apparatus and subsequent testing be easy and rapid. Obtaining and testing a representative, uniform surface finish precludes the use of rf seals and the testing of an interior surface where machining, abrasive polishing, plating, and electropolishing give inconsistent results. These design requirements generated our decision to use an open-ended coaxial cavity for our testing program. Using the open-ended cavity and dielectric standoffs for supporting the center conductor results in a test cavity with no rf seals and in which the center conductor is easily replaced. By using only the center conductor as the sample, the test surface is mechanically simple and all processes are applied to an outside surface where uniformity is easier to achieve. Furthermore, the current densities are highest across the central region of the center conductor where the surface uniformity is best, and the current diminishes rapidly near the ends where the fabrication processes may change. A drawback to using a common outer conductor for all testing is that this conductor, necessarily, has a different conductivity, and only relative results for comparison of processes can be directly measured.

CTF Apparatus

The coaxial resonant cavity outer conductor is a 24-in. long cylinder fabricated from a 4-in. o.d. by 0.5-in. wall OFE-HIT copper tube. The tube length was selected from calculations and measurements, which guarantee that power leakage out of the cavity ends is far below 1%. The inside of the tube was turned down to an inside diameter of 3.530 in. as a compromise between reducing mass, removal of the sacrificial metal, maintaining cavity strength, and leaving sufficient material for mounting the diagnostic hardware. The inside machining was done with conventional techniques to rough dimensions, and the final three finishing cuts of less than 0.003 in. were made with a diamond tool at slow speed and feed. Two outer conductors have been prepared. Each outer conductor has been machined in a similar fashion, but one includes a final 500 C anneal and chemical polish for additional conductivity enhancement.

The center conductor samples are 0.971-in. diameter cylinders which result in a 77 ohm (maximum Q) configuration for the cavity. A smaller diameter would have resulted in greater domination of the measured data by the test sample; however, the selected diameter has greater rigidity for consistent machining. Each end of the cylinder has a 0.25-in. radius to diminish sharp edge effects during plating or electropolishing. Each end also has a 1/4–20 tapped hole as point of attachment for plating, electropolishing, and other processing as necessary. The sample lengths are 32.852 cm, 32.159 cm, and 15.160 cm resulting in resonance frequencies of 425 MHz, 433 MHz, and 850 MHz, respectively.

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The center conductor is supported at its center by a 0.5-in. thick, wedge-shaped beryllium oxide (BeO) dielectric standoff. BeO was selected for this application over boron nitride, alumina, polyethylene, and teflon because it retains both high electrical resistivity and high thermal conductivity across the entire temperature span of testing. The center conductor is held in place on the standoff by a spring-loaded BeO post. The spring loading is maintained by five Belleville washers mounted in series to accommodate the expansions and contractions of thermal cycling.

RF diagnostics connection to the resonant cavity is provided by two magnetic coupling probes located opposite each other around the circumference at the cavity longitudinal center.

A stainless steel, cylindrical vacuum vessel provides a clean vacuum environment for rf testing and cryogenic operation. Inside dimensions of 17-in. diameter by 44-in. length provide ample room for the cavity and other equipment. Access to the interior at each end of the vessel is provided by hinged, o-ring sealed flanges which are held closed under high vacuum by atmospheric pressure. These doors give access to the entire inside diameter when opened. The vacuum vessel is mounted on a moveable stand along with the following support equipment:

1. A Leybold-Heraeus Turbomolecular vacuum pumping system.
2. A CTI-CRYOGENICS gaseous helium refrigerator.
3. A Lake Shore Cryotronics diode thermometer system.
4. An AC heater system for cavity temperature control.

RF Cavity Modeling

For an rf resonant structure, the cavity Q is a scaled factor of the stored field energy divided by the required power, thus Q is directly related to efficiency.

$$Q_U = \omega \frac{E_{stored}}{P_{total}} \qquad (1)$$

The computed Q from an rf cavity modeling code provides the theoretical value for data comparison

An analytic solution of the coaxial cavity can be done if the boundary conditions for the cavity ends are clipped at the end of the center conductor. The analytic solution is informative; however, the end effects are extensive and require more detailed modeling. The SUPERFISH family of codes provides theoretical predictions for the resonant frequency, the cavity Q, and the power distribution between the center and outer conductors. The resonant frequency and field distributions are first-order calculations in SUPERFISH and have estimated accuracies of better than 1%. Cavity Q and power distributions are second-order calculations and, as such, have been assigned estimated accuracies of 2%, accordingly. Laboratory measurements of the cavity frequency for all three center conductors agree to well within 1% of the SUPERFISH prediction based on careful measurements of the component dimensions. Although end effects for the 433-MHz cavity result in an 8% difference in frequency between the SUPERFISH prediction and the analytic solution, the Qs for the two calculations agree to within 1%.[1]

Because most rf structures are built to specifications based on SUPERFISH modeling, power estimates for operation are scaled by the measured Q versus the SUPERFISH Q. For this reason any CTF Q measurements, which are scaled against the SUPERFISH Q, have value in predicting the performance of accelerator rf structures.

Testing Procedure

The unloaded Q is the quality factor of the rf structure alone with no external perturbations; however, the measurement of Q requires coupling the cavity to an external system. Our laboratory measurements, therefore, measure the cavity loaded Q, Q_L, and the unloaded Q must be extracted by also measuring the coupling of the field-sampling loops, β_1 and β_2. Q_U can then be calculated from Q_L using equation 2.[2]

$$Q_U = (1 + \beta_1 + \beta_2) Q_L \qquad (2)$$

For our test program, Q_L is measured by the bandwidth method, and β_1 and β_2 are calculated from a reflected power measurement of each port.

All measurements are made using a Hewlett Packard 8753B Network Analyzer. Because lengthy cables are used inside the vacuum to reduce thermal losses, it is impossible to calibrate the Network Analyzer to accommodate the cable losses at the field-sampling loops. As a result, it is necessary to determine the field-sampling loop coupling by measuring the ratio of resonance reflected power to the nominal, off-resonance reflected power for that port.

An assembled coaxial cavity with a test sample is installed in the CTF and is under high vacuum for all rf testing. Q measurements are made of the first- and third-cavity resonance modes for the 425-MHz and 433-MHz cavities; however, only the first mode of the 850-MHz cavity is measured because of power leakage out of the cavity ends for the third mode. Q measurements are taken at room temperature prior to turning on the refrigeration system. The cavity is then cooled to cryogenic temperatures using the CTI gaseous helium refrigerator. Q measurements are then taken at three cryogenic temperatures (the coldest operating temperature, ~20 K, and ~35 K) by using the heaters for selecting the given temperatures. For each of the above four temperatures, the network analyzer system is calibrated at the connection port to the vacuum feedthrough connector, thus assuring some degree of measurement consistency. After completing these four calibrated measurements, the coaxial cavity is again cooled to its lowest temperature. A sequence of Q measurements is then started for the duration of the warm-up cycle with the network analyzer now under the control of a Hewlett Packard Computer. Because the region between 15 K and 40 K is especially interesting, approximately ten temperature points are set and stabilized using the heaters up to 40 K, and Q data collection is initiated by the computer. Without temperature control below 40 K, the temperature rises too rapidly for meaningful measurements. Above this temperature region, both the heaters and the refrigeration are turned off, and data is collected on a timed cycle for the remainder (approximately 2 days) of the warmup to room temperature. The network analyzer system is uncalibrated for the measurements made during the automated warm-up cycle.

Copper Surface Preparation Studies

The CTF has been most effective in accomplishing a surface efficiency study for identifying the best cavity fabrication processes for the GTA 850 MHz DTLs. This study used 17 different samples to compare various surface preparation techniques and the sequence of the preparation steps. Figure 1 displays the Q enhancement values relative to the SUPERFISH room-temperature, predicted Q for these samples. Each row is a different sample for a fabrication technique. Across each row is a check mark if a process was done on the sample or a numerical value for the Q enhancement if the sample was measured at that particular step. This study assisted the design engineers in selecting optimal sequences for the DTL fabrication and verified the safe application of some processes for the cryogenic structures.

	Samples \ Processes	Machined Finish	e Beam Weld	Anneal @ 1010C for 1 hour	Anneal @ 500C for 1 hour		Chemical Polish for 1 hour	Chemical Polish for 2 hours	SHIPLEY CHEM-POLISH 14	Diamond Grit Polish	Electropolish		Final rf Test
Heavy Machined Samples	1H *	2.84											2.84
	2H	X					4.04						4.04
	3H *	X			X			5.75					5.75
	4H *	X		4.76				X					4.76
	5H	X			X					X	6.27		6.27
	6H *	3.00			4.28								4.28
	7H *	X						3.42	X				3.42
Light Machined Samples	1L *	2.91			4.45								4.45
	2L	X					3.52						3.52
	3L *	2.87			X			5.80	6.12	X	X		6.12
	4L	X	X				5.15						5.15
	5L *	X	X		5.78			5.80	X				5.80
	6L	X			X					X	5.94		5.94
	7L	3.04			4.69								4.69
	8L *	2.86		4.47	4.55								4.55
	9L *	X						3.33	5.27				5.27
	10L *	X	X					2.24	X				2.24

* Priority Sample ** Annealed by D. Precechtal

Fig. 1. Q enhancement of the GTA 850 MHz DTL Copper Surface fabrication processes.

Conclusions

The understanding of the affect of the near-surface conductive region on surface conductivity and rf structure efficiency has been used to design the features of the CTF. As a result, the CTF generates data directed specifically at technology issues for the NPB program.

The CTF has been a useful facility for the rf surface testing already completed for the GTA program. It has been used to verify the suitability of the rf surface for the GTA RFQ, to accomplish an extensive program of evaluating copper surface preparations for the GTA 850-MHz DTLs, and to evaluate the effect of single rf contacts at cryogenic temperatures. In the future, data from the CTF should be applied directly during the rf structure design phase to more accurately predict power and cooling requirements.

References

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