STATUS OF 3.9 GHZ SUPERCONDUCTING RF CAVITY TECHNOLOGY AT FERMILAB*

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Abstract

Fermilab is involved in an effort to assemble 3.9 GHz superconducting RF cavities into a four cavity cryomodule for use at the DESY TTF/FLASH facility as a third harmonic structure. The design gradient of the cavities is 14 MV/m. This effort involves design, fabrication, intermediate testing, assembly, and eventual delivery of the cryomodule. We report on all facets of this enterprise from design through future plans. Included will be test results of single 9-cell cavities, lessons learned, and current status.

INTRODUCTION

Fermilab has entered into an agreement with DESY to provide a cryomodule containing 4-3.9 GHz superconducting RF cavities to be placed in TTF/FLASH. These cavities are TM010 structures designed to linearize the accelerating gradient of the 1.3 GHz accelerating cavities in this accelerator, thus providing improved longitudinal time structure. The required operating gradient is 14 MV/m. Table 1 contains a list of parameters.

Table 1: Parameter List

Number of Cavities	4
Active Length	0.346 meter
Gradient	14 MV/m
Phase	-179°
R/Q	750 Ω
E_{peak}/E_{acc}	2.26
B_{peak} (E_{acc} = 14 MV/m)	68 mT
Q_{ext}	9.5 X 10^5
Geometry Factor (G1)	275 Ω
BBU Limit for HOM, Q	<1 X 10^5
Total Energy	20 MeV
Beam Current	9 mA
Forward Power/Cavity	11.5 kW
Peak Coupler Power	45 kW

As a byproduct, another goal of this project is to develop SCRF infrastructure at Fermilab by designing and assembling the necessary components including:

- Cryomodule for 4 cavities
- 4 (+2 spare) dressed cavities with couplers
- Tuners, magnetic shielding, assembly tooling
- Surface processing infrastructure (BCP, HT, HPWR)
- Apparatus and infrastructure for vertically testing single undressed cavities
- Horizontal test cryostat and testing infrastructure for individual dressed cavities including main input coupler
- Cavity string and cryostat assembly infrastructure
- Shipping equipment for cryomodule transport to DESY.

With the design effort virtually complete, effort has turned towards fabrication and testing. It is intended that this work will be completed during late 2007 and the cryomodule delivered to DESY early in 2008.

CAVITIES

Eight 3.9 GHz cavities have now been fabricated. Blank material for two more is available as needed. A summary of fabrication and testing can be found in Table 2. The first two are prototypes and not envisioned to be made operational. However, Cavity #1 is fitted into a prototype helium vessel and was recently 'dressed' with input coupler, blade tuner, Higher Order Mode antennae and magnetic shielding for test fitting into the Horizontal Test Stand.

Cavity #2 underwent vertical testing, but was limited by heating in the Higher Order Mode (HOM) coupler areas. Post-test visual inspection revealed fractures at the weld joints of the Formteils within the HOM's. Analysis concluded that the failures were due to high stresses induced by overheating of the Formteil when power was applied, with multipacting being a probable cause. Finite element analysis (FEA) of the Formteil indicates maximum thermal stresses at the exact same location where the fracture occurred. More details on analysis and remediation is reported elsewhere [1].

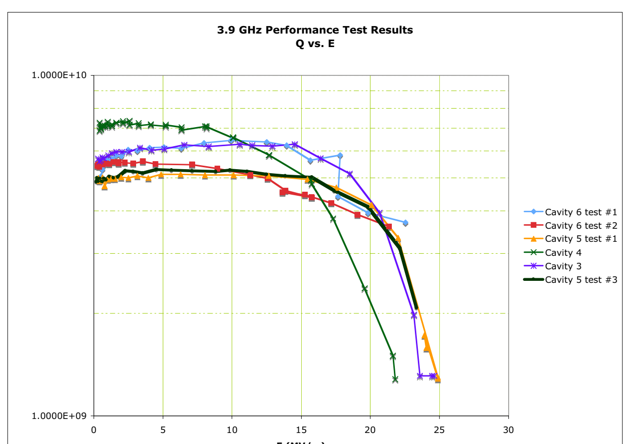

Figure 1: Cavity Q vs. E performance to date

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Cavities #3, #4, #5 and #6 have undergone extensive vertical testing and are awaiting welding into helium vessels. All four cavities have successfully achieved gradients of 21 MV/m or better and meet specifications as Figures 1 and 2 indicate.

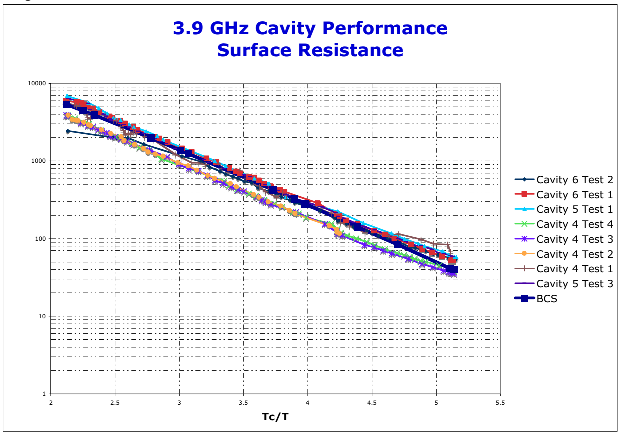

Figure 2: Surface resistance of vertically tested cavities

Fabrication

All component parts and end tube subassemblies were fabricated under the direction of Fermilab personnel. Cavities #3 through #6 were assembled and welded at Jefferson Lab using welded end subassemblies provided by Fermilab.

Table 2: Cavity Fabrication & Testing Status

Cavity	Assembled by	Completion Date	Vertical Test Results
#1: 2-leg HOM	Fermilab	January 2006	Never tested – HOM membrane break during cleaning
#2: 2-leg HOM	Fermilab	February 2006	12 MV/m limited by HOM heating - fractured Formteils
#3: 2-leg HOM, trimmed after initial tests	Fermilab JLab	August 2006	24 MV/m, achieved after HOM trimming
#4: 2-leg trimmed HOM	Fermilab JLab	March 2007	23 MV/m
#5: 2-leg trimmed HOM	Fermilab JLab	May 2007	25 MV/m
#6: 2-leg trimmed HOM	Fermilab JLab	May 2007	22 MV/m
#7 – single-post HOM	Fermilab JLab DESY	October 2007	n/a first test expected November 2007
#8 – single post HOM	Fermilab DESY	October 2007	n/a processing in progress, first test expected late October 2007

The first six cavities contain a 2-leg Formteil design. Modification involving removal of 3mm of the Formteil tip was done following the discovery made on Cavity #2. Cavities #3 and #4 contain such trimmed pieces.

Cavity #3's was done is situ following initial vertical testing. Cavities #7 and #8 were assembled at Jefferson Lab and Fermilab respectively using a revised single post Formteil design [1]. The single post Formteils were welded into the HOM housing at DESY.

Details as to processing and vertical testing procedures have been reported elsewhere [2], [3].

OTHER COMPONENTS

HOM Coupler Feedthroughs

Two designs for HOM coupler feedthroughs based on DESY and JLAB experience were investigated.

The first, based on a high alumina ceramic insulator, was abandoned due to low yield and long delays from the vendor. Achieving acceptable hermetic joints between the insulator and center conductor proved difficult. Nine such pieces were received and are used for parasitic tests. Four prototypes with a sapphire insulator were obtained in a timely fashion and achieved good results both in yield and performance during cold tests. Heating seen during cold testing underscores the need to provide for adequate thermal contact in regular operation when the feedthough will not be in a complete superfluid helium bath as is the case during vertical tests.

The remaining required pieces are now in hand and many have been subjected to vacuum leak testing both before and after being cooled to 1.8K in the A0 vertical test stand. Results continue to be encouraging. As testing permits, these are fitted on to cavities for electrical and thermal evaluation during RF testing.

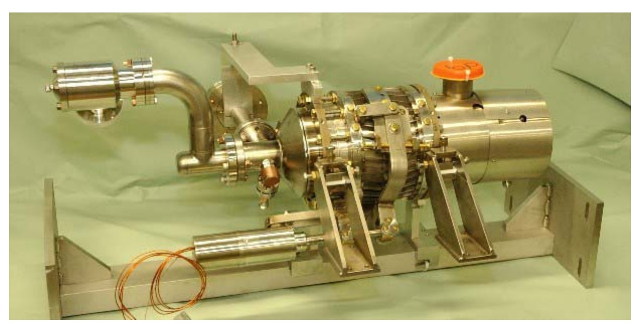

Figure 3: Prototype Cavity #1 welded into a Helium vessel and dressed with input coupler, 'blade' tuner, and magnetic shielding.

Helium Vessels

Following acceptable vertical performance testing, each cavity is fitted into a titanium helium vessel. A prototype vessel, fabricated by Fermilab, was successfully welded to Cavity #1. Cavities #3 - #6 are now ready to be outfitted. Unfortunately, the bellows to titanium welds in the vessels fabricated by an outside vendor were flawed. Improper welding techniques appear to be the root cause.

Design modification and careful documentation of welding guidelines has now been done and an alternate vendor has provided satisfactory pieces. One new vessel is being constructed in-house to have it available in as quickly as possible. An acceptable vendor has been contracted for the remaining ones and confidence is high that they will be available in a timely and satisfactory manner.

THERMAL ANALYSIS

The cavity performance data as shown in Figures 1 and 2 is quite reproducible and though they are not great in number, statistics indicate a limit of about 24-25 MV/m for these cavities. It becomes interesting to try to perform a simple thermal analysis to compare with the measurements. Such an analysis might give an indication as to how close the global thermal breakdown limitation is being approached. Because the BCS surface resistance scales with f^2, one would expect this to be a much more significant issue than in 1.3 GHz cavities.

The thermal model used in this case includes the measured R_S vs. T_c/T of the cavity, a Kapitza conductance, and a thermal conductivity model. The latter are adjusted to give an approximate fit to the data.

The Kapitza conductance has been measured recently by Aizaz et al [4]. He quotes Bousson et al [5]. The conductivity h_k scales approximately as T^3 in the region of interest. Other older data vary by about an order of magnitude. The value chosen is critical to the fit. A value of $h_K = 0.3$ W/cm^{2}K at 1.8K was chosen, somewhat above the upper range of that measured by Aizaz [4]. Their highest value resulting after titanification was about 0.25 W/cm^{2}K at 1.8K, but the value used here is still lower than some in the literature.

The thermal conductivity model is illustrated in Fig 4. It includes three models for the phonon peak contribution at low temperature, below 3K, and is scaled to give a conductivity at 4.2K of k(W/mK) = RRR/4 and a temperature dependence at temperatures above 3K typical of that found in the literature [4], [6], [7].

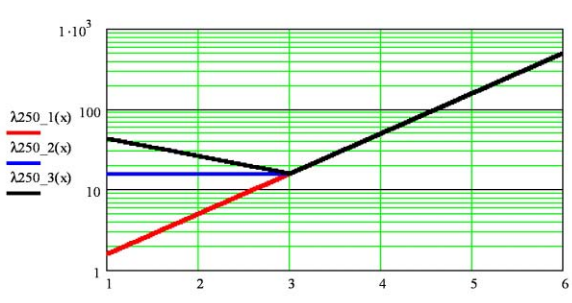

Figure 4. Thermal conductivity model, T(K) vs. k(W/m-K) for RRR 250. Case 1 - red; Case 2 – blue; Case 3 - black

In case 1 the conductivity continues to fall exponentially at low temperature. In case 2 it remains flat. This is most typical of the data of Reschke [7]. In case 3 it rises similarly to the observed by Reference [4] under some circumstances. Other data [6] indicate that the phonon peak can be about two times greater than used here.

Two different models for consideration of surface magnetic field have been applied. In the first case uniform distribution of field was assumed and in the second the real magnetic field along the 9-cell cavity surface calculated by HFSS™ [8] was taken into account. In the second model Q was calculated by (1), where V is the effective voltage, R/Q – shunt impedance and P are the power losses taking into account nonlinear behavior of the surface resistance R_s.

$$Q = \frac{V^2}{(R/Q)*P}, \text{ where } \quad P = 1/2 * \int R_s H_s^2 ds \qquad (1)$$

The results of the fits are shown in Figure 5 for a wall thickness of 2.6 mm and a RRR of 250. The cavity material thickness is 2.6 mm but it has been machined to 1.5 mm at the equator weld area. The high magnetic field region extends beyond the machined extent so a thickness of 2.6 mm is more appropriate than 1.5 mm. For case 2 the 1.5 mm thickness would increase the thermal limit by about 10%.

Consideration of increased RRR to 750 results in only about a 10% increase for Case 2 but a more dramatic effect for case 1 of about 25%.

One can see that the cases where the thermal conductivity stays flat or rises as the temperature is lowered below 3K lead to a reasonable agreement with the measured end point.

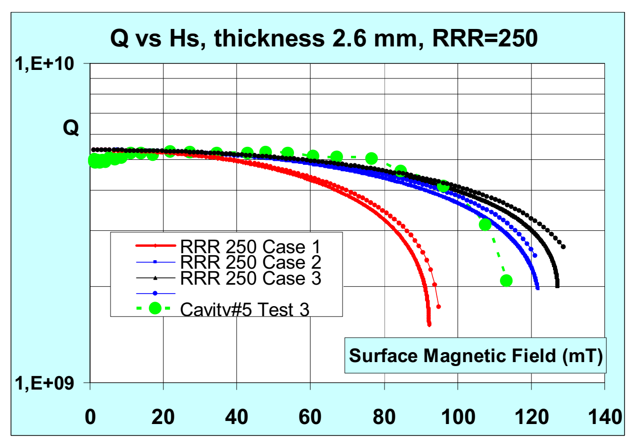

Fig 5. Q vs. H. Comparison of measured data for Cavity #5 (green dashed) with models for the three thermal cases of thermal conductivity with RRR250 and a material thickness of 2.6mm. h_k=0.3 W/cm^{2}K at 1.8K. Case 1 - red, Case 2 - blue, Case 3 – black. Solid lines are for the constant surface magnetic field model, dotted for real fields calculated by HFSS™.

The simple models used here show more of a slope at medium field than the data. Such flat behavior of measured curves is typical for all cavities tested to date. However the comparison does indicate the possibility that these cavities are performing close to their global thermal limit.

Better thermal and Kapitza conductivity data is necessary to further carry out the comparison of models with data. It would be interesting to see results of titanification of these cavities as well as low temperature bake and EP.

Paper TUP27 of this conference reports a similar analysis.

SUMMARY

Fermilab has embarked on its first significant foray into SCRF technology with the fabrication of a 3.9 GHz cavity string for use in DESY's TTF/FLASH facility. Seven cavities have been fabricated and five have gone through vertical testing, four of them extensively. These four have achieved the necessary design parameters and have operated at gradients of at least 21 MV/m with acceptable Q_{ext}. Two more cavities will shortly undergo the first phase of testing once their processing is completed.

Most major components are now in hand or are due in the near future. Critical steps remain: receipt of and welding into helium vessels, horizontal testing, assembly into a 4-cavity string, final assembly, and shipping to DESY. The expectation is to test the module in the DESY Module Test Facility in spring of 2008.

A preliminary study of thermal analysis indicates that these cavities may be operating at close to their global thermal limit.

ACKNOWLEDGEMENTS

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REFERENCES

[1] T. Khabiboulline et al, "New HOM Coupler Design for 3.9 GHz Superconducting Cavities at FNAL," PAC '07, Albuquerque, June 2007, p. 2259.

[2] E. Harms et al, "Status of 3.9 GHz Superconducting RF Cavity Technology at Fermilab," PAC '07, Albuquerque, June 2007, p. 2254.

[3] N. Solyak et al, "3.9 GHz Superconducting Accelerating 9-cell Cavity Vertical Test Results," PAC '07, Albuquerque, June 2007, p. 2295.

[4] A. Aziz et al, "Performance of Superconducting Radio Frequency Cavities for Accelerators: A Novel Approach to Overcome Thermal Limitations," ASC '06, Seattle, August 2006, to be published in IEEE Transactions.

[5] S. Bousson et al, "Kapitza Conductance and thermal conductivity of materials used for SRF cavities fabrication," *Proceedings of 9th Workshop on RF Superconductivity* (1999).

[6] H. Padamsee et al, R F Superconductivity for Accelerators, J. Wiley & Company, 1998.

[7] D. Reschke, private communication. Collection of data for RRR 40 to 760.