RF TESTS OF DRESSED 325 MHz SINGLE-SPOKE RESONATORS AT 2 K

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Abstract

Fermilab has recently completed an upgrade to its spoke resonator test cryostat to enable testing of cavities in superfluid helium. Two single-spoke resonators with differing helium vessel designs have been tested in this new configuration. Gradient and Q_0 performance was studied along with microphonics control and sensitivity of the resonant frequency to pressure variations. A description of the testing and the results obtained are presented.

INTRODUCTION

Fermilab's Proton Improvement Plan (PIP)-II project (essentially equivalent to Stage 1 of Project X) includes an 800 MeV superconducting continuous-wave (CW) H^- linac that makes use of five different types of radiofrequency (RF) cavities [1]. One of these is a superconducting single-spoke resonator (SSR1) operating at a frequency of 325 MHz [2]. These cavities are first tested "bare" at Fermilab's Vertical Test Stand (VTS) before being welded inside a helium jacket. The "dressed" cavity can then be tested in a cryomodule-like environment at the Spoke Test Cryostat (STC) facility located in Fermilab's Meson Detector Building (MDB). Cavity performance at STC is evaluated in terms of maximum accelerating gradient, Q_0, and field emission in order to qualify cavities for assembly into an accelerator cryomodule.

THE STC FACILITY

Over the past year the STC was upgraded to allow operation at superfluid helium temperatures. The central component of this upgrade was a new feed can housing a Joule-Thomson heat exchanger for cooling helium to 2 K and supplying it to the cavity. This new feed can is shown in Fig. 1 and described in detail in [3].

RF power is provided by a 200 W solid state amplifier driven by a digital low-level RF (LLRF) system [4] that processes the I and Q of the cavity forward, reflected, and transmitted power signals. This system employs a phase-locked loop to keep the RF power matched to the cavity resonance when the cavity bandwidth is narrow (< 1 Hz). A Labview application serves as an interface to the LLRF system and also provides online calculations of cavity Q's and gradients.

X-rays from field emission are measured with two detectors, one on each end of the test cryostat. All cavity, RF, and cryo data are continuously archived through the dataloggers available from Fermilab's ACNET controls system.

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Figure 1: The Spoke Test Cryostat with upgraded feed can.

COMMISSIONING RESULTS

The SSR1 cavity S1B-ZN-101 was used to re-establish operations at STC. This cavity was previously tested at 4.5 K at STC prior to the upgrade, and thus serves as a good benchmark for assessing 2 K operations. It was assembled in a configuration identical to its previous CW test [5], with a prototype slow tuner, fast piezo tuners, and a high-Q_{ext} input coupler.

The cavity was installed in STC and actively pumped throughout its test with a 20 L/s ion pump. It was cooled to 2 K without incident, and after tuning up the helium pressure and liquid level regulation loops RF operations began.

Measurements of the forward, reflected, and transmitted powers, along with the time constant of the decay of the cavity field after turn-off of the RF at low power, enable the determination of the cavity Q_0 and voltage at any power level. To define the accelerating gradient for the spoke cavity the convention $L = \beta\lambda = 0.203$ m was adopted, where L is the effective RF length (the geometrical β for the SSR1 cavity is 0.22). After calibrating the LLRF system in this way, the forward power was slowly increased.

Multipacting in the cavity was observed in the approximately 3-8 MV/m region. It could be processed away by holding the forward power constant at a level several watts higher than where the multipacting began, increasing the power as needed. This process took on the order of 10 hours.

After multipactor processing the 2 K Q_0 vs. E_{acc} curve shown in Fig. 2 was mapped out. The cavity was limited by quenching at around 22 MV/m. The Q_0 at low field was considerably lower than that measured in VTS at 2 K; see the discussion in [6]. Also shown in Fig. 2 is a Q_0 vs. E_{acc} curve taken at 4.5 K to compare with the cavity's previous STC test prior to the upgrade. The agreement is excellent.

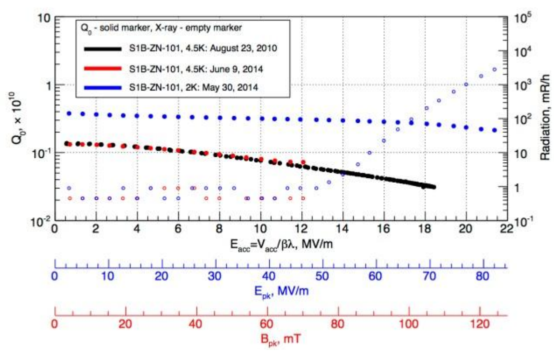

Figure 2: Q_0 vs E_{acc} curves taken at 2 K (blue) and 4.5 K (red) for cavity S1Z-NR-101 at the upgraded STC. The black points are the 4.5 K data for the cavity's STC test prior to the upgrade. X-ray flux is also shown (open circles).

In addition to these measurements, an effort to understand the effect of circulator reflections on the Q measurements was undertaken. A phase shifter was inserted between the circulator and the cavity and swept through a full 2π rotation. As shown in Fig. 3, this resulted in a variation in the Q_L measurement of ±8%. An additional two phase shifters were then inserted between the original phase shifter and the circulator in order to create a matching network to minimize reflections (Fig. 4). By adjusting the phases of the matching network the Q_L variation was reduced to ±3%, with the possibility of further reduction with additional fine-tuning.

S1H-NR-107 RESULTS

The next cavity tested was S1H-NR-107, which features a redesigned helium vessel optimized for minimal sensitivity of the resonant frequency to pressure (*df/dP*) [7]. After cooling down to 2 K, an initial look at *df/dP* was done by varying the helium bath pressure from 18 to 43 Torr and measuring the location of the peak of the cavity resonance with a network analyser. As seen in Fig. 5, a sensitivity of 4-5 Hz/Torr was observed, in good agreement with expectations.

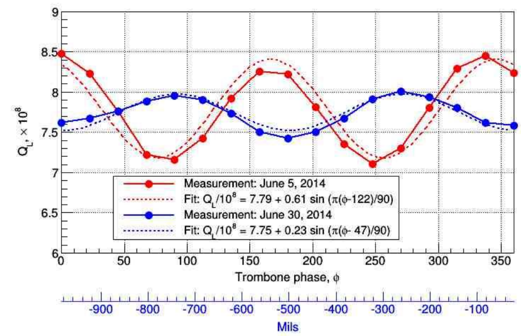

Figure 3: Variation in Q_L with phase delay. The data shown in blue and red correspond to with and without the matching network of Fig. 4, respectively.

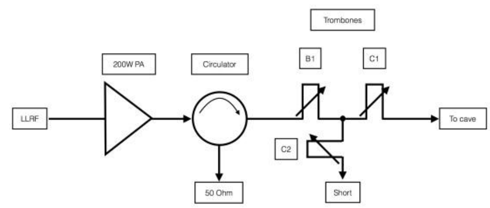

Figure 4: Phase shifter matching network implemented to minimize and measure circulator reflection effects. "C1" is the phase shifter varied to produce Fig. 3.

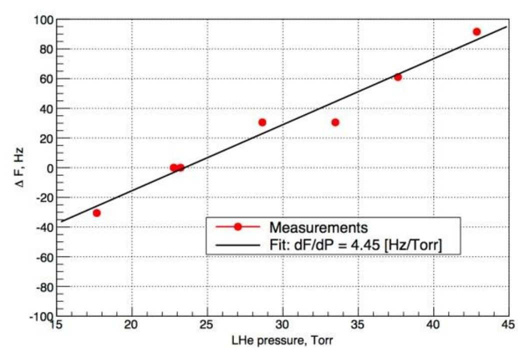

Figure 5: *df/dP* for cavity S1H-NR-107.

RF testing proceeded in a similar manner as for S1B-ZN-101. Multipacting was again observed at similar gradients and processed in a similar amount of time. A quench limit of 19 MV/m was observed, along with a significantly higher Q_0; see Fig. 6.

An additional study carried out with this cavity was a measurement of Lorentz force detuning. The LLRF system continuously records the frequency offset of its phase-locked loop, which is a measure of the detuning of the cavity with respect to the frequency of the master RF generator. As shown in Fig. 7, this detuning increases as the square of the gradient [-4 Hz/(MV/m)^2].

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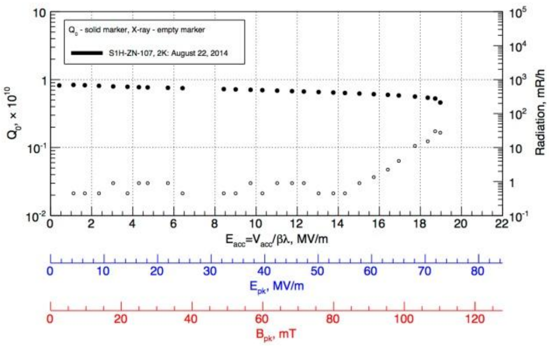

Figure 6: Q_0 vs. E_{acc} curve and X-rays for S1H-NR-107.

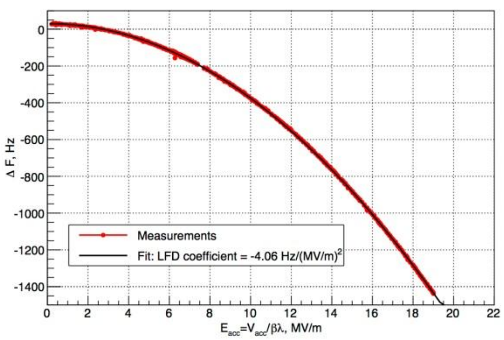

Figure 7: Detuning of S1H-NR-107 from Lorentz forces at various gradients. The black curve is a second-degree polynomial fit to the data (red points).

FUTURE PLANS

Tuners for cavity S1H-NR-107's new helium vessel design were not available at testing time. However, a set of piezo tuners were installed on the cavity along with a dummy tuner manually adjusted to give the correct preload on the piezos. Therefore this cavity will be used for detailed studies of microphonics compensation and resonance control.

In addition, measurements of Q_0 from the dynamic heat loads to the 2 K cryo system will be performed in order to cross-check/calibrate against the measurement based on the RF system. This is in anticipation of testing in a strongly overcoupled regime with a high-power input coupler, where measurement of Q_0 from the RF is difficult if not impossible. Prototypes of such a high power coupler have recently been successfully tested at Fermilab.

CONCLUSION

The STC facility at Fermilab was successfully upgraded and commissioned for CW operations at 2 K. Cavity S1H-NR-107 performed well from both an RF and a mechanical perspective, qualifying it as the first of eight SSR1 cavities to be assembled into a cryomodule and also validating the new helium vessel design and fabrication process. Critical tests of microphonics and resonance control for SSR1 cavities will be performed in the coming months in parallel with qualifying additional cavities.

ACKNOWLEDGMENTS

We heartily congratulate the engineering and technical staffs of Fermilab's Accelerator and Technical Divisions for the successful upgrade of the STC to 2 K, and are grateful to them the opportunity to test spoke resonators in this new regime.

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