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STC QUALIFICATION TESTS OF PIP-II HB650 CAVITIES

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Abstract

Design of the high beta 650 MHz prototype cryomodule for PIP-II is currently undergoing at Fermilab. The cryomodule includes six 5-cell elliptical SRF cavities with accelerating voltage up to 20 MV and low heat dissipation ($Q_0 > 3.3 \cdot 10^{10}$). Characterization of performance of fully integrated jacketed cavities with high power coupler and tuner is crucial for the project. Such a characterization of jacketed cavity requires a horizontal test cryostat. The Fermilab Spoke Test Cryostat (STC) has been upgraded to accommodate testing of 650 MHz cavities. Commissioning of upgraded STC has been reported at SRF'19 conference. In this paper we present results of testing of the prototype HB650 cavity in upgraded STC facility. We characterize cavity performance and qualify it for the prototype HB650 cryomodule assembly.

INTRODUCTION

Ongoing upgrade of the Fermilab proton source, Proton Improvement Plan II (PIP-II), aimed to deliver intense neutrino beam to LBNF/DUNE and support frontier particle physics experiments [1, 2]. Major part of PIP-II accelerator is a Superconducting RF (SRF) linac, accelerating 2 mA beam of H^- ions up to 800 MeV. To optimize performance, the SRF linac employs five different types of cryomodules. The last section of linac has four cryomodules, containing six 5-cell elliptical high-beta ($\beta = 0.92$) 650 MHz (HB650) cavities providing accelerating voltage up to 20 MV with low heat dissipation, $Q_0 > 3.3 \cdot 10^{10}$. Design of the prototype HB650 cryomodule is completed and cryomodule assembly will start soon. Successful cryomodule construction requires characterization of performance of fully dressed HB650 cavities assembled with high power coupler and tuner in a horizontal test facility. Earlier we described the upgrade of the Fermilab Spoke Test Cryostat (STC) which included installation of the STC vacuum vessel extension with magnetic and thermal shields, modifications of cryogenic connections and RF infrastructure to accomodate testing of 650 MHz cavities, while also retaining capability of testing SSR1 and SSR2 cavities [3]. First cold test of HB650 cavity in STC was performed in 2020. The goals of the test were threefold: 1) Commissioning of STC for 650 MHz testing, including facilities (mechanical, instrumentation, vacuum, cryogenic, RF systems, safety/interlocks), procedures, documentation; 2) Validation of 650 MHz high power coupler and tuner design; 3) Qualification of the prototype HB650 cavity (s/n `B9A-AES-010`, $\beta = 0.9$). Here we report results of this test.

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CAVITY PREPARATION AND INSTALLATION TO STC

Standard procedure for HB650 cavities processing before testing at STC and/or assembly in cryomodule includes bulk material removal with electropolishing (EP), high temperature bake with N-doping option, tuning cavity frequency and field flatness, light EP, HPR, and assembly for vertical testing in cleanroom [4]. After jacketing of cavity `B9A-AES-010` its field flatness degraded, which required additional re-tuning. This jacketed cavity hasn been tested at the Fermilab Vertical Test Stand (VTS) and achieved $Q_0 \approx 2 \cdot 10^{10}$ at 20 MV/m.

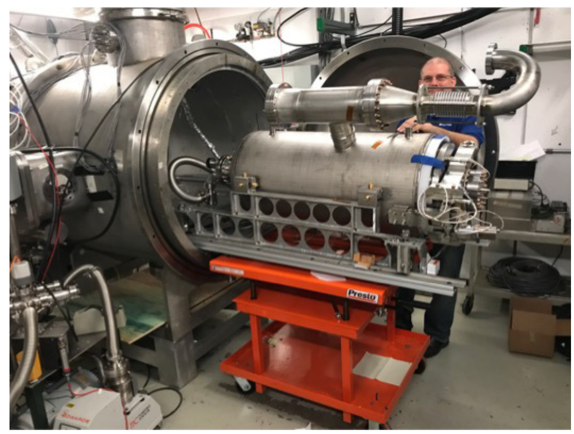

Figure 1: HB650 $\beta = 0.9$ cavity assembled with the cold part of the high power coupler, tuner, LHe fill line and the interface elbow.

Following VTS testing, cold part of the power coupler was installed on the cavity. After installation of safety brackets, which prevent cavity without tuner from movement and deformation, cavity was evacuated and moved for the installation to the STC facility building. In order to move cavity into the STC enclosure, two concrete blocks were removed from the enclosure roof, the cavity was lifted from its transportation crate and lowered to the insertion cart at the assembly table inside enclosure using building crane. Since this was the first HB650 cavity in STC, after alignment of the cavity inside cryostat with respect to the coupler port, the elbow interfacing the cavity 2-phase pipe and the cryostat 2 K helium header was field fitted. For tuner installation cavity beam line vacuum space had to be backfilled to 1 atm. We modified STC vacuum system to accomodate slow backfill with dry nitrogen and slow evacuation. Figure 1 shows cavity ready for insertion to STC cryostat.

STC cryostat, cavity and coupler are instrumented with temperature and magnetic field sensors. `B9A-AES-010` has additional sensors installed inside helium vessel, as shown in Fig. 2.

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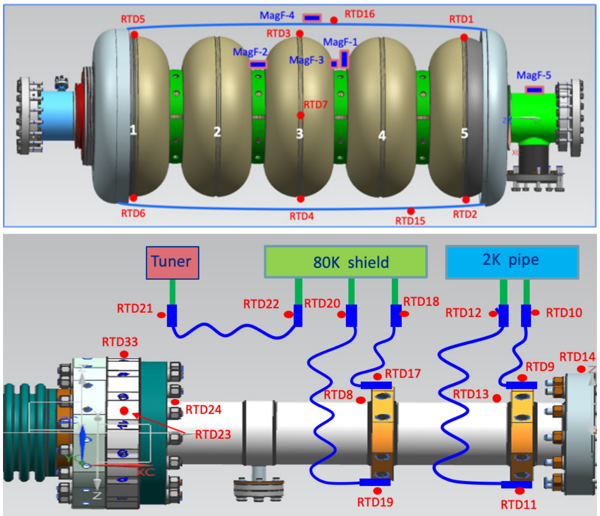

Figure 2: Cavity (top) and coupler (bottom) instrumentation.Temperature sensors are marked as RTD*xx*, and magnetic field sensors designated with MagF-*y*.

COOLDOWN

Initial cool down of cavity proceeded well down to temperature 30–40 K, at which point a problem with cool down line valve developed, limiting valve opening and preventing enough supply flow of the cold helium gas into cavity helium vessel.[1] Attempt of further cool down using only Joule-Thompson (JT) line did not work. Finally we were able to cool down and get liquid helium at 4 K in STC using a non-standard procedure, with gas supplied via connection at exhaust line to the STC 2K header. With cavity full with 4 K liquid helium we switched back to standard procedure regulating liquid level by JT valve opening and helium pressure/temperature by evacuating gas phase in 2K header.

After quick tuner checkout at 4 K, cavity was successfully pumped down to 2 K, with cryogenic parameters reaching stable operation within couple hours.

STC cryostat insulating vacuum was 7-8 mTorr[2] before cool down, and went down below 2.5 mTorr (lower limit of the insulating vacuum system gauge) after cool down. Cavity beam line vacuum was better than 10^{-8} Torr during entire test sequence.

RF TESTING AND QUALIFICATION

Typical horizontal test of cavity at STC includes the following steps: calibration of LLRF system (attenuation in LLRF cables and circuits and adjustment of software coefficients in LLRF program); measurement of cavity spectrum and loaded quality factor, Q_L; conditioning of high power coupler off-resonance; qualification of tuner and measurements of tuner range and sensitivity; tuning cavity to resonance at 650 MHz; conditioning of multipactor (MP) in cavity; measurement of the cavity maximum field and determination of the factors limiting maximum field, field emission radiation (if present) onset field and the radiation at the maximum cavity field; measurement of the cavity Q_0 as a function of cavity accelerating gradient, E_{acc}; determination of cavity detuning sensitivity due to liquid helium bath pressure variations, df/fp, and Lorentz force detuning (LFD).

Results of the 650 MHz cavity tuner validation and qualification are presented in a separate contribution at this conference [5].

Table 1: Cavity Spectrum at 2 K

Mode	Frequency, MHz
π	650.000
$4\pi/5$	649.506
$3\pi/5$	648.058
$2\pi/5$	646.296
$\pi/5$	644.876

Cavity tuner is preloaded during assembly that cavity is tuned at approximately 60 kHz above 650 MHz (so called *2 K landing frequency*), when cooled down to 2 K. Table 1 shows frequency of cavity modes at 2 K, after cavity fundamental mode is tuned to exactly 650.000 MHz. Using network analyzer, we measured cavity loaded Q-factor to be $8.5 \cdot 10^6$, which is within coupler specifications: 10^7 with 20% margin.

During RF operations HV bias of 4 kV was applied to coupler to suppress multipactor. RF system was interlocked on coupler bias, requiring $V_{\mathrm{bias}} > 3.5$ kV and $I_{\mathrm{bias}} < 2$ mA. Off-resonance coupler conditioning was done in pulsed mode, with pulse frequency 20 Hz and pulse width changed in steps 1, 2, 4, 8 ms (duty cycle from 2 to 16 %). In each step forward power to the coupler was gradually increased up to maximum operating level of 30 kW, with dwell time of 15–20 minites at highest power. Conditioning was completed in CW mode, with up to 2 hours of dwell time at maximum power. Coupler inner conductor was cooled by dry air supplied at the rate 7 SCFM, while ceramic window was cooled by conduction. During coupler operation at maximum power window temperature raised by 15 K from room temperature; 5 K[3] and 80 K flanges temperature increased by 10 K and 5 K, respectively, corresponding to the heat load of 2.8 W and 2.7 W at 5 K and 80 K circuits.

After tuning cavity on resonance cavity multipactor was conditioned by gradually increasing cavity field. This cavity had strong MP in extended range 7.5–22 MV/m, accompa-

[1] Later, after STC warm up and cavity removal, we found a mechanical problem with the cool down line valve. It has been replaced with a new valve with larger aperture, which will help us in future STC tests of 650 cavities to perform and optimize fast cool down procedures, required to preserve quality factor of high-Q_0 cavities.

[2] Note, that cool down procedure requires insulating vacuum to be better than 100 mTorr.

[3] STC does not have a dedicated 5 K circuit inside the cryostat. We attached thermal straps from coupler 5 K flange to the STC 2 K header.

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nied by strong radiation. Some MP was cleaned after more than 20 hours of processing, with persistent MP remained in 12–16 MV/m range, and intermittent MP in 7.5–12 MV/m and 16-17.5 MV/m ranges. Cavity reached 22 MV/m maximum gradient in pulsed mode (18 MV/m in CW mode) limited by the available power from RF amplifier, which kept tripping on internal interlock of the maximum reflected power at forward power levels above 22 kW, when cavity was tuned on resonance. No radiation associated with field emission was observed off MP bands.

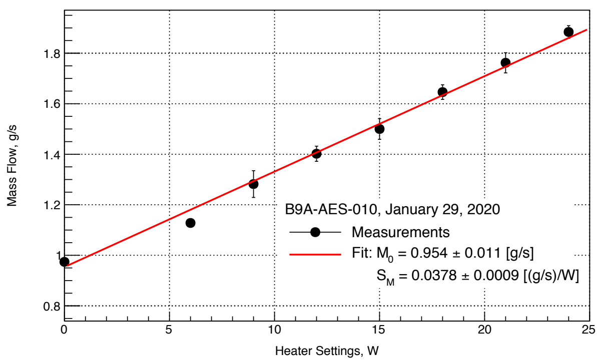

Figure 3: Heater calibration for dynamic heat load measurements.

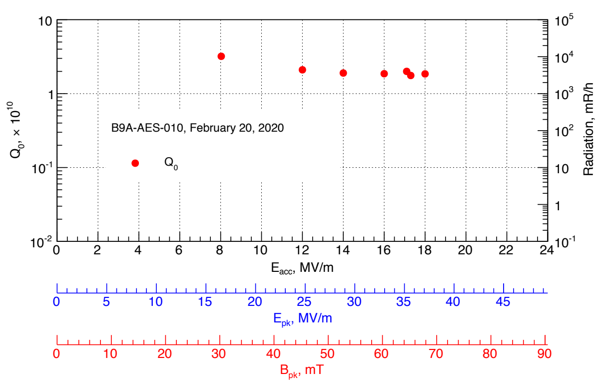

Figure 4: Cavity Q_0 measurements.

To calculate cavity Q_0, cavity dynamic heat load was estimated using the calorimetric method, by measuring the mass flow rate of the helium gas at 2 K vacuum pump. We calibrated mass flow as function of dissipated power by applying power to the heater installed inside the STC 2 K header liquid level instrumentation canister. Figure 3 shows results of heater calibration, with calibration constant 0.0378 ± 0.0009 (g/s)/W obtained by linear fit. Using this calibration cavity Q_0 was calculated. Results are shown in Fig. 4. Q_0 for this cavity is $\approx 2 \cdot 10^{10}$ at E_{acc} = 12–18 MV/m, which is in agreement with VTS measurements. Note, that due to schedule limitations and issues with cool down line valve, we did not perform fast cool down with this cavity. Also, at the time of cavity installation to STC, the cavity individual magnetic shield was not available. Both of these factors might lower Q_0 perfromance of cavity `B9A-AES-010` during this STC test. We should expect to demonstrate higher Q_0 in the future tests.

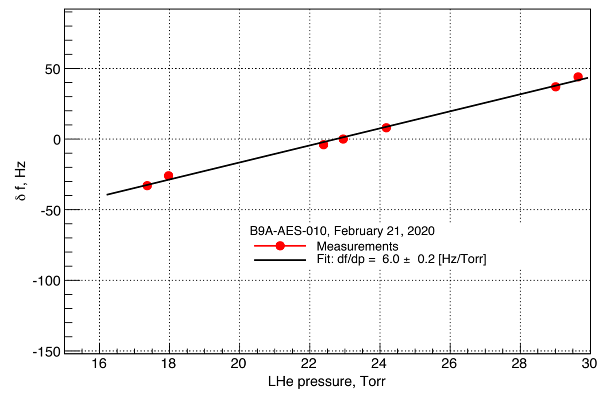

Figure 5: df/dp measurements.

We measured sensitivity of cavity detuning to variation of liquid helium bath pressure. We set cavity field at ≈ 1 MV/m and varied liquid helium bath pressure in the range 15–30 Torr, observing detuning parameter within LLRF software, which drove cavity in self-excited loop (SEL) mode tracking cavity frequency w.r.t. local oscillator. Figure 5 shows results, with df/dp = 6 Hz/Torr.

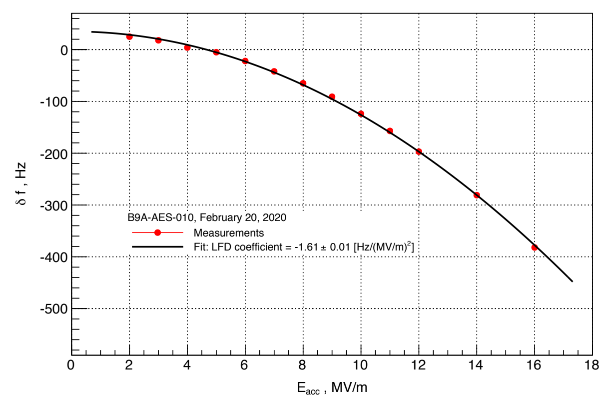

Figure 6: Lorentz force detuning measurements.

Measurements of cavity detuning due to Lorentz force are shown in Fig. 6. LFD coefficient is -1.6 Hz/(MV/m)^2

We estimated cavity microphonics, detuning due to acoustical and mechanical noise, to be better than 10 Hz, peak to peak, by observing detuning waveforms in LLRF program.

CONCLUSION

We successfully commissioned Fermilab Spoke Test Cryostat for horizontal testing of fully dressed 650 MHz cavities of PIP-II project. Design of 650 MHz coupler and tuner has been validated, with performance reaching project specifications. HB650 (β = 0.9) cavity `B9A-AES-010` has been characterized, with $Q_0 \approx 2 \cdot 10^{10}$ at 18 MV/m, df/dp = 6 Hz/Torr, LFD coefficient -1.6 Hz/(MV/m)^2, and microphonics better than 10 Hz peak to peak. In the future STC tests we will develop and optimize fast cooldown procedure and

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install cavities with individual magnetic shield. These will allow us to validate high Q_0 values ($> 3.3 \cdot 10^{10}$) required by PIP-II project.

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