FRIB TECHNOLOGY DEMONSTRATION CRYOMODULE TEST*

J. T. Popielarski*, E. C. Bernard, S. Bricker, C. Compton, S. Chouhan, A. Facco#, A. Fila, L. Harle, M. Hodek, L. Hodges, S. Jones, M. Klaus†, M. Leitner, D. Miller, S. Miller, D. Morris, J. P. Ozelis, R. Oweiss, L. Popielarski, K. Saito, N. Usher, J. Weisend, Yan Zhang, Z. Zheng, S. Zhao
FRIB, East Lansing, Michigan, USA
#INFN/LNL, Legnaro (PD), Italy, † Technische Universität Dresden, Dresden, Germany

Abstract

A Technology Demonstration Cryomodule (TDCM) has been developed for a systems test of technology being developed for FRIB. The TDCM consists of two half wave resonators (HWRs) which have been designed for an optimum velocity of beta=v/c=0.53 and a resonant frequency of 322 MHz. The resonators operate at 2 K. A superconducting 9T solenoid is placed in close proximity to one of the installed HWRs. The 9T solenoid operates at 4 K. A complete systems test of the cavities, magnets, and all ancillary components is presented in this paper.

INTRODUCTION

The SRF Department at Michigan State University had developed and tested four cryomodules prior to the first demonstration cryomodule for FRIB. Two of the cryomodules are working reliably in the ReA3 linac at MSU [1]. The TDCM, shown in figure 1, is the first cryomodule that demonstrates FRIB specific technology and encourages a transition to large scale engineering and quality assurance methods [2].

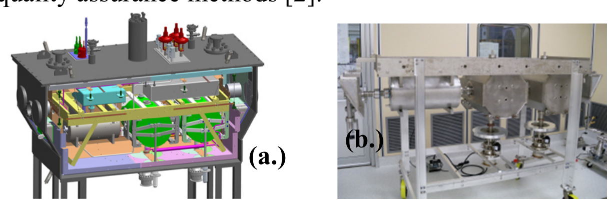

Figure 1: (a.) Rendering of TDCM in cryostat (b.) Cold mass assembly in cleanroom.

In developing the FRIB TDCM, a baseline cryomodule production method evolved for FRIB. The technical and schedule related setbacks encountered during the TDCM campaign eventually yielded reliable fabrication, processing, and certification techniques. SRF-related infrastructure and utility usage required for the TDCM assisted in finalizing planning for a new SRF high bay which will support FRIB cavity processing, vertical testing, cold mass assembly, and cryomodule bunker tests.

TDCM RELEVANCE TO FRIB

The TDCM is a developmental snapshot, and much of the technology improved as more detailed engineering analysis and sub component testing programs provided opportunities for design optimization [3- 5]. Some of the key differences are: a "bottom-up" style from the "top-down" TDCM style [4]; the rail system, support system, heat and magnetic shields assemblies were simplified; Improvements to alignment methods; an internal heat exchanger replaces the external heat exchanger; the 4K thermal intercepts will be parallel circuits as opposed the series connection in the TDCM.

With much of the cryogenic circuitry and alignment systems optimized in the baseline design before TDCM testing took place, alignment and continuous 2K operation aspects were not tested. The plumbing of the RF coupler 4K intercepts [6] required steady flow in the static state required continuous overfilling of the 4K header to ensure the couplers stayed cooled during RF conditioning.

TDCM DEVELOPMENT

Individual tests or more detailed engineering analyses conducted on the cavities, couplers, tuners, and cryogenic circuits used in the TDCM led to design optimizations and improved processing [7- 9].

Initial dunk tests showed low field emission onset values and thermal breakdown below the operating gradient; FRIB processing optimization for the HWR began during the TDCM campaign. The TDCM cavities were field emission-free [10] prior to the installation of the helium vessels.

Initial tests still showed signs of multipacting in the cavity. Repeated measurements on several cavities show a recurring barrier at 2 MV/m E_{acc}. This barrier self-conditioned as the RF power was raised, and in most tests only observed during initial 4K measurements.

During the initial dunk tests, it was discovered Q_0 was lower after a thermal cycle with no change otherwise. A closer investigation for *Q*-disease showed a strong reduction in the Q_0 after a 15 hour soak at 100K. The cavities were sent to JLAB for a furnace treatment to remove hydrogen from the bulk. Subsequent '*Q*-soaks' and thermal cycles showed no signs of degradation. A 600°C furnace treatment was added to the baseline processing plan and a furnace has been installed at MSU [9].

After being jacketed with a helium vessel, the 1st cavity was certified using the vertical cryostat configuration [5], and no field emission was observed. This helium vessel design utilized a titanium bellows at the beamport to reduce the tuning force required for the scissor-jack tuner.

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#popielar@frib.msu.edu

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After this cavity had been installed on the TDCM cold mass, the next jacketed cavity developed a large leak from the helium to insulating space found at the titanium bellows. The bellows were removed from the already certified cavity, requiring additional machining and welding.

TDCM TESTING

RF Amplitude and Phase Control

The resonators in the FRIB linac will operate with a very narrow BW for amplitude and phase control. For the HWR, the 30 Hz RF bandwidth available for control presents a technical challenge and increasing the RF BW has a very large impact on cost. The low level RF controller was developed at MSU and employs an ADRC algorithm [11] which is required to ensure a dynamic stability within 2% (peak-to-peak) amplitude and 2 degrees (peak-to-peak) phase. The resonators do not have fast tuning implemented to cancel microphonics. Measurements were done using a fast (1.6 kHz) data acquisition of the RF signals. The results are shown in figure 2, where the measured cavity and amplitude stability is within the limits of the measurement uncertainty. During the measurements, the cavity field was kept just below a multipacting barrier in the cavity and with the slow tuning feedback to the scissor-jack mechanical tuner turned off.

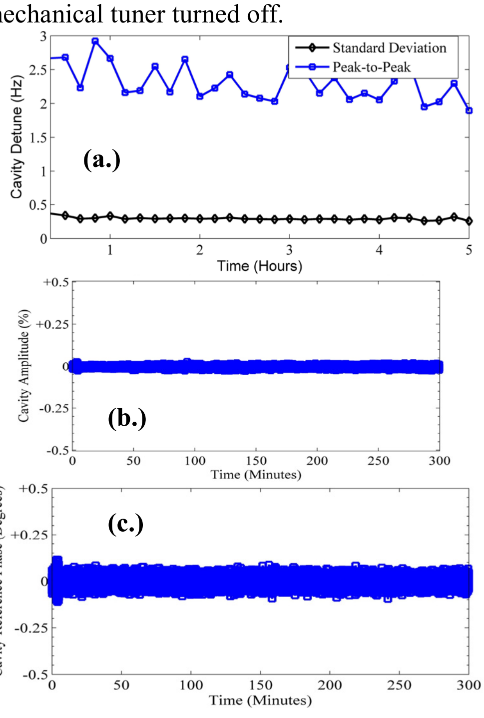

Figure 2: (a) Closed loop detuning, calculated from the forward phase changes while regulating with the cavity amplitude and phase (b, c) well within the design specification.

The 'cavity detune' (Δf) in Figure 2a is inferred from the changes in the forward phase ($\Delta\varphi_f$) and is calculated from $\Delta f = BW \times \Delta\varphi_f$. The closed loop detune inferred from the measurement agreed well with some shorter duration open loop measurements done a 2K. A slow drift of 8 Hz over five hours was measured, justifying the necessity of a slow tuner. During this measurement, the bath pressure was well regulated (less than 0.7 Torr peak-to-peak).

The next round of measurements was performed using the feedback to the slow tuner. The measured amplitude and phase stability was higher (1.4%, 0.6°, peak-to-peak), but still within the FRIB specification. It was noticed that the tuner drive was constantly moving, which created a mechanical oscillation at 110 Hz, causing a closed loop detune of 24 Hz peak-to-peak.

RF Couplers

The RF couplers had been conditioned for multipacting barriers prior to the installation into the cold mass [6]. The multipacting that was conditioned had returned after installation to and cooling of the TDCM, with similar onset levels. Coupler conditioning did not completely remove the multipacting from the coupler above 2 kW after 10 hours of RF pulses. The multipacting was suppressed by applying an external magnetic field through a coil winding around the coupler. Figure 3 shows a plot the current on the probe near the ceramic disk; 6.8 kW peak power was achieved with 4.5 kW average forward power while driving 1 MHz off-resonance. A detailed multipacting analysis [12] shows that the location of the two-point multipacting in the coaxial line depends strongly on the boundary condition at the cavity port. With the rf system 'detuned' from the cavity, the boundary condition at the coupler port is that of a short circuit, and a single two-point multipacting node exists at the voltage peak, which is approximately half way between the coupler port and the ceramic disk. However, when driving the cavity on resonance, two voltage peaks exist on the transmission line. The magnetic field suppression did not suppress the multipacting when locked to the cavity resonance.

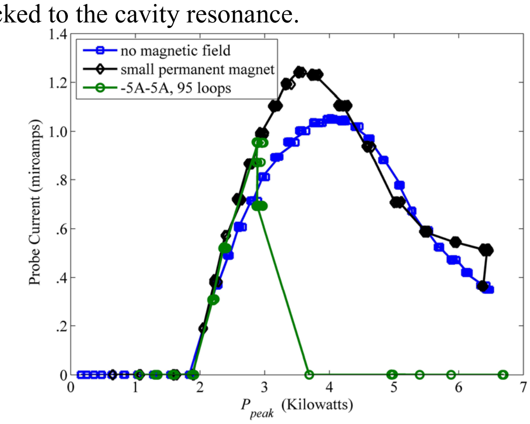

Figure 3: Multipacting suppression in the FPC while driving from the cavity off-resonance.

Tuners

The bellows used to reduce the force required to tune the cavity was replaced with a rigid connection to the helium vessel. A measurement of the tuning ratio of

360:1 greatly exceeds the expected 8:1 ratio showing that the scissor-jack mechanism was not performing as expected. This resulted in a reduced tuning sensitivity of the actuator controller (from 1.8 Hz/step to 0.03 Hz/step), which may explain the mechanical effects on the performance of the LLRF with the tuner engaged. Additional testing will be performed on an alternate tuning concept which utilizes a pneumatic drive.

Cryostat

Static load measurements on the TDCM cryostat were performed by recording liquid level as a function of time using the level sensor to infer the evaporation rate. This rate was calibrated by using a gas meter to measure the mass flow of the helium gas at room temperature. The mass flow measurement and nominal liquid volume boil-off from the header dimensions had roughly good agreement. Neither the level vs time nor the gas meter methods were calibrated with a known heat source. An evaporation rate of 2.85 W to the 2K header and 4.0 Watts to the 4K header was measured and repeated four times, with a spread of 0.22 W peak to peak.

Cavity Dynamic Load

The cavity dynamic loads, measured the same as the static load measurements described above, could not be accurately measured below the multipacting barriers (1.67 MV/m E_{acc}), since the resolution of this type of measurement is ~0.5 W. This resolution exceeds the heat load measured in the last Dewar test (0.10 Watts at 1.67 MV/m). With helium processing, a reasonable field level (4 MV/m) was reached. The dynamic load of 1.5W @ 4 MV/m yields a Q_0 of 1.2E10. This measurement was done in the last hours of the TDCM test. The load from the RF coupler at this field (850W forward power) was negligible considering a load measurement done with 4.5 kW forward power off resonance was less than the measurement resolution.

Magnets & Magnetic Field Interactions

The Earth's magnetic field is shielded from the cavities with a global mu-metal shield. Measurements on the shield showed an attenuation factor of at least 25 was achieved; however accurate measurements of the residual magnetic fields with the cold mass installed were not performed. Prior to energizing the magnets, the low field Q_0 (@1.67 MV/m) showed the possibility of high residual magnetic fields trapping fluxes up to 200 mG, but the Q drop at this field could also be explained as either measurement error or multipacting.

The 9T solenoid has a fringe field such that the flux at the nearest cavity surface is 250 Gauss. The revised FRIB specification for this fringe-field is 650 Gauss. The magnet was powered to full field; the cavities were warmed up to 30 K, and then re-cooled. The dynamic loads were measured again at 2K. The difference in the dynamic loads was less than the 0.5 W measurement resolution. A magnetic field cancellation procedure was performed by varying the power supply current, *I*, in a decreasing and alternating manner, e.g. a series, $\{(-0.9)^n I\}_{n=0}^{40}$ which took 5 hours to complete. The dynamic load measurement performed after this degaussing and further RF conditioning yielded a quality factor close to that measured in the vertical test.

TDCM Outlook and Future Tests

The TDCM test ended abruptly after taking only limited dynamic load data due to an unexpected cryoplant failure. A suspected helium leak in the transfer line that supplied the TDCM required mass flow rates of 3-5 g/s to maintain level in the liquid helium levels, though static load measurements indicate only 0.5 g/s is required. Therefore, running the TDCM test in parallel to NSCL experimental programs in impossible due to the unavailability of this LHe supply rate.

Though the TDCM completed a successful first round of testing in mid-2012, additional testing will be done by end of 2012. The next round of testing will focus primarily on the high power RF conditioning that commenced in the later stages of the TDCM measurements.

A new transfer line is being procured and installed to supply the TDCM from a refrigerator that is separate from the NSCL experimental program. While the transfer line is being built, the cryostat is being opened up to make some adjustments. Magnetic material found on the internal scissor jack tuning mechanisms is being removed. The RF couplers are undergoing an in-situ bake (~100-120C, 72 hours) in an effort to reduce the multipacting intensity. Additional measurement equipment will be installed to determine the dynamic load of the couplers to the intercepts and the remnant fields from the 9T solenoid before and after degaussing steps.

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