SRF DEVELOPMENTS AT MSU FOR FRIB*

K. Saito#, N. Bultman, F. Casagrande, S. Chandrasekaran, S. Chouhan, C. Compton, K. Elliot, A. Facco, M. Johnson, S. Jones, M. Leitner, S. Miller, R. Oweiss, J. Ozelis, J. Popielarski, L. Popielarski, S. Shanab, J. Wei, T. Xu, Y. Yamazaki, Y. Zhang, Z. Zheng,
FRIB, MSU, MI 48824, USA
K. Hosoyama, KEK, Accelerator Lab, KEK, 305-0081, Japan

Abstract

FRIB status is now in the CD-3a stage, and civil construction is ready to begin. CD-3b, which is FRIB accelerator system ready for construction, will be in mid-2014. MSU has made or is making many developments before CD-3b. This paper will report summaries about these developments: Technology Demonstration Cryomodule (TDCM), fundamental power coupler (FPC) development, tuner development for HWR, magnetic shielding and superconducting solenoids, and Engineer Test Cryomodule (ETCM).

TDCM

The cryomodule (CM) is a key component for FRIB. FRIB CMs contain SRF QWRs (β= 0.041, 0.085)/ HWRs (β= 0.29, 0.53) and 8T superconducting solenoid coils for beam focusing [1]. They constitute both the bulk of the cryogenic load and a significant fraction of the accelerator cost. The proper design, production, test and validation of these CMs are critical to the success of FRIB. Therefore, a decision was made to build a Technology Demonstration Cryomodule (TDCM), to operate at 2K, which is a 1/3 scale model of FRIB 0.53 CM as illustrated in Figure 1.

The TDCM includes two 0.53 half wave resonators (HWRs) and 8kW fundamental power coupler (PFC), mechanical tuner on each cavity, and one 9T solenoid package. The intent is to demonstrate: production, processing and testing of all the individual components, their assembly into a cold mass, the cold mass assembly into a cryomodule, the design and installation of supporting cryogenics, vacuum, controls, RF and safety systems, and finally a full RF test of the cryomodule under vacuum at 2K.

The first TDCM test was done in spring 2012 but the remnant magnetic field from the tuner components limited the cavity Q_O to lower value ~ 5E+9 at 2K. The second test was done in November 2012 after removing the most of the magnetic components in the tuner. However, a leaking LN_2 line in the thermal shield limited the experiment. The third test took place after installing a supplementary LN_2 cooling loop and produced successful results. High Q performance was demonstrated in the third TDCM experiment, as shown in Figure 2. Below are main achievements of these experiments.

1) Demonstrated successful 2K operation.
2) Demonstrated FPC performance up to 8kW in the third test after $140^{O}C$ baking
3) Confirmed long term stable cavity operation even without tuners in the TDCM first test.
4) High Q performance (1E+10 at Ep=15MV/m) at 2k after the removal of magnetized components from tuner.
5) Successful 9T solenoid operation but in short term.
6) Confirmed degaussing effect in the third test.

The detailed reports of the TDCM tests are in [2] and [3].

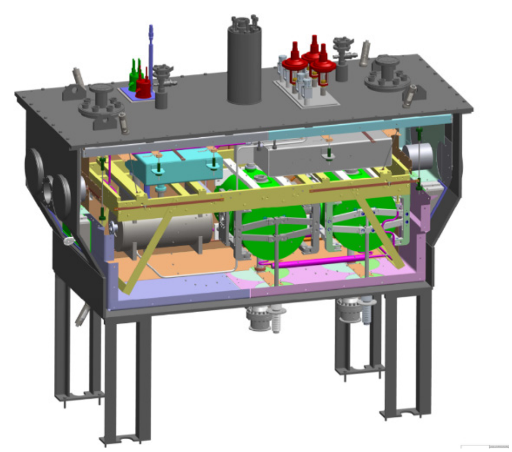

Figure 1: TDCM cut-away graphic showing two HWRs, scissors-jack tuners straddling each HWR and a solenoid to the left.

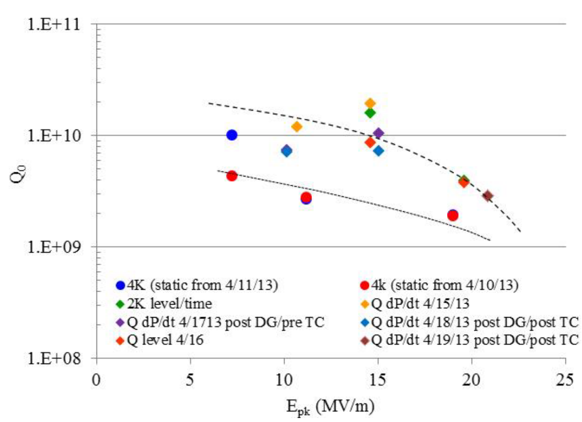

Figure 2: Summary of 4K and 2K Q_0 measurements in the third TDCM test.

*Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661.
#Saito@frib.msu.edu

FPC DEVELOPMENT FOR FRIB HWR

TDCM experiment was successful and many lessons were learnt at MSU. R&D of multipacting (MP) free FPC is one of them. In the third TDCM experiment, the FPC finally achieved 8kW FRIB specification after 140^{O}C baking, but persistent multipacting conditioning with all phases of the standing wave was needed. The RF conditioning effort needed more than 16hrs, which is a time consuming process. In the FRIB operation this might be an issue.

Multipacting in the FPC was analysed in detail. MP free FPC design was developed for FRIB HWRs [4]. Figure 3 shows the comparison of the designs between TDCM FPC and new MP free FPC. Figure 4 shows the MP performance. The new design has no MP on cavity resonance and 1/10 of the TDCM FPC on cavity detuned. The key point of this design is increased impedance in the coaxial wave guide from 50Ω to 75Ω to push MP away. The fabrication of new FPC is under way.

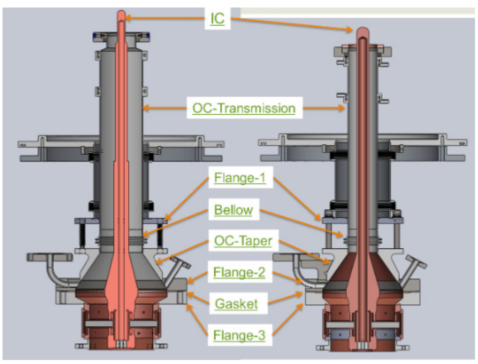

Figure 3: Comparison of design between TDCM FPC (left) and new MP free FPC (right).

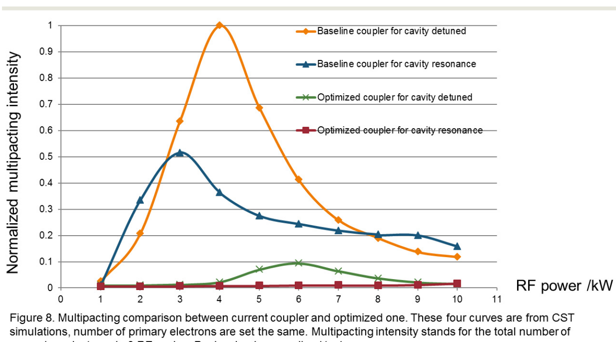

Figure 4: Comparison of MP between the TDCM FPC and new MP free coupler.

TUNER DEVELOPMENT FOR FRIB HWRS

Baseline Change with HWR Tuner

The second lesson learnt from TDCM is about tuners. Scissors-jack tuner (Figure 5 left) was the original baseline for FRIB HWR's mechanical tuner. However, this tuner uses magnetized materials (420SS) at the flex pivots and results in high remnant field ~ 1G in the cryomodule [2]. The replacement to nonmagnetic components is not cheap. High Q was limited in the first TDCM experiment. In the second TDCM experiment, the magnetic components were mostly taken off. However, Q measurement was impossible in the second test due to a leaking LN_2 thermal shield line. The third test after installing a supplementary LN_2 cooling loop was successful. High Q performance of the cavity was demonstrated as already shown in Figure 2.

This tuner operation was very noisy in the first TDCM experiment. In addition, this tuner system has a weakness. There is no way to perform offline tests in the current vertical test system used for cavity certification. MSU has now decided to apply the ANL type pneumatic tuner showed in Figure 5 right, which is very well established at ANL. This tuner utilizes Helium pressure to actuate for cavity tuning mechanism. This pressure causes the bellows to expand and push down on the frame and pulls on the cable attached to the tuning arms.

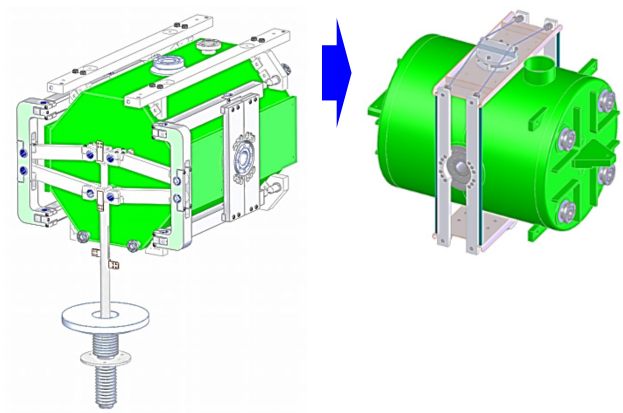

Figure 5: The baseline change from the scissors-jacket tuner to ANL type pneumatic tuner for FRIB HWRs.

Prototyping of ANL Type Pneumatic Tuner

This pneumatic tuner was prototyped as shown in Figure 6 and bench tested at room temperature and in a Dewar at cryogenic temperatures [5]. Figure 7 shows one example result, with a tuning range up to 70psi of Helium gas pressure. Tuner speed was also measured at cold temperature and found to be 0.5 kHz/s. The performance is summarized in Table 1.

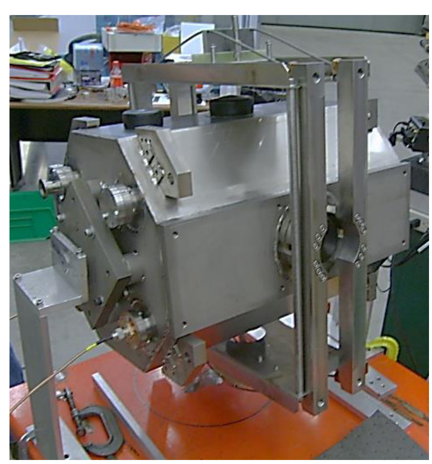

Figure 6: Prototyped pneumatic tuner on a β=0.53 HWR.

ISBN 978-3-95450-143-4

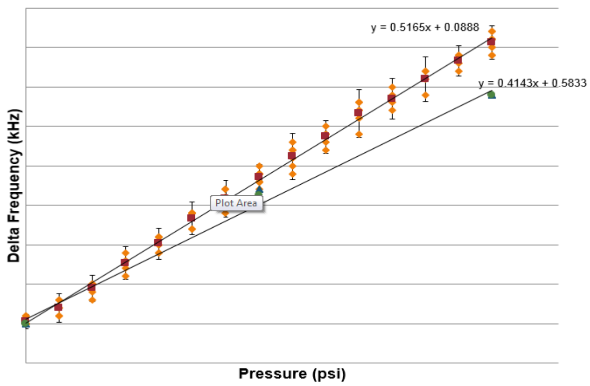

Figure 7: Tuning range experiment result, Helium pressure up to 70 psi. vs. cavity frequency shift at warm and cold temperature.

Table 1: Test Result of the Pneumatic Tuner

	Warm Test	Cold Test
Frequency Shift (kHz)	35.6	23.8
df/dx (kHz/mm)	57.8	-
df/dF (Hz/N) [Calculated]	3.3	2.22
dF/dx (kN/mm) [Calculated]	17.2	-
df/dP (kHz/psi) (Piston)	0.52	0.34

Tuner Operation Demonstration with Cavity at 2K

This tuner has been operation tested with a HWR at 2K and demonstrated the cavity stable operation under the tuner operation. Figure 8 shows the cavity phase locking and the amplitude stability by the tuner operating. When cavity RF frequency was actively modulated around at 0.7Hz/s within a bandwidth, both phase and field amplitude of the cavity nicely locked.

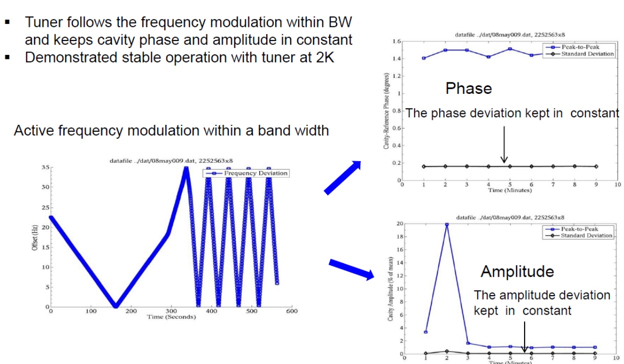

Figure 8: Demonstration of the tuner operation with a HWR at 2K.

CM LOCAL MAGNETIC SHIELD

Local Magnetic Shielding for FRIB CMs

FRIB CM is long and needs thicker µ-metals (3.2mm) in global shielding scheme to attenuate the earth's magnetic field to less than the FRIB specification of 15mG [6]. The local shield scheme, shown in Figure 9, allows for such shielding with 1.0mm thick cryomagnetic materials like Cryoperm or A4K [6]. Another benefit of this scheme is more reliable shielding performance against fringe fields from the SC solenoid coil located in the vicinity of the cavities. From the shielding performance and cost optimization point of view, FRIB finally chose local magnetic shield scheme with a contingency option for global shield.

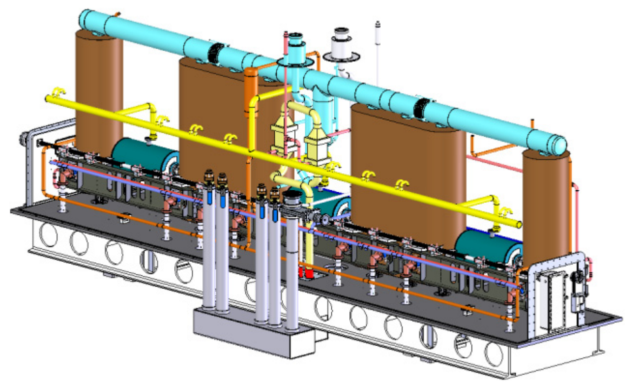

Figure 9: Local shielding scheme to be applied for FRIB cryomodules. 8T SC solenoid coils are located between cavities (green components).

Magnetic Shield Material Study

A cryogenic magnetic shielding material (Cryoperm or A4K) has to be used in this scheme, however these materials have very low magnetic saturation behaviour at below 10 G [7]. The shield will be exposed to a fringe field of about 130G under 8T solenoid operation. The magnetic shield performance is worrisome for such high magnetic field exposure. Magnetic material characterization is important for the local magnetic shield to be a success. MSU has started a magnetic shielding material characterization program [8]. Here, the AC magnetic permeability is measured and its frequency dependence investigated. The estimated DC magnetic permeability from these measurements are shown in Figure 10.

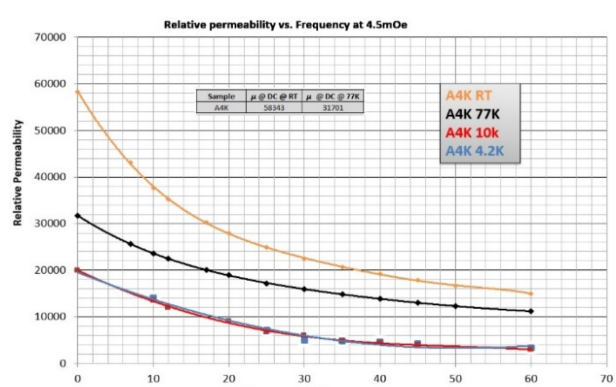

Figure 10: Frequency dependence of magnetic permeability at room temperature and cryogenic temperatures.

Magnetic Shielding Attenuation Study

The direct magnetic attenuation measurement for several 100G is very important at cold temperatures. FRIB is preparing for this kind of test. This test will start mid-October 2013 at both room and cold temperatures. At room temperature, demagnetization of the magnetic shield material will also be investigated.

PROTOTYPING OF 8T SC SOLENOID PACKAGE PROTOTYPING

FRIB original linac optics design applied 9T SC solenoids made of NbTi wire, but was very critical for NbTi wire, especially due to very small margin (0.1K) in operation temperature at 4.5K [9]. The design has been changed to 8T applying constant beam size optics [10]. FRIB cryomodules need 6 pieces of 8T SC 25cm solenoid packages for low β=0.041 section, and 63 pieces of 8T SC 50cm solenoid packages for high β=0.085-0.053 sections. These solenoid packages consist of an 8T main solenoid, two corrector diploe coils for X-Y directions, and iron yoke on the outside of the helium vessel. MSU has started 8T SC solenoid package prototyping program, in order to estimate the cost with high accuracy, under the MSU/KEK collaboration [8].

8T Solenoid Design

8T 25cm solenoid cold mass has been completed, which includes a 8T SC 25cm solenoid with bobbin and two SC 25cm dipole coils shown in Figure 11. The solenoid design is summarized in Table 2.

Status of Prototyping

8T 25cm solenoid prototyping is starting at KEK. Solenoid bobbin parts were already fabricated and fitting check was completed on the winding machine. Solenoid winding work and cold test of the main solenoid itself is planned in October 2013.

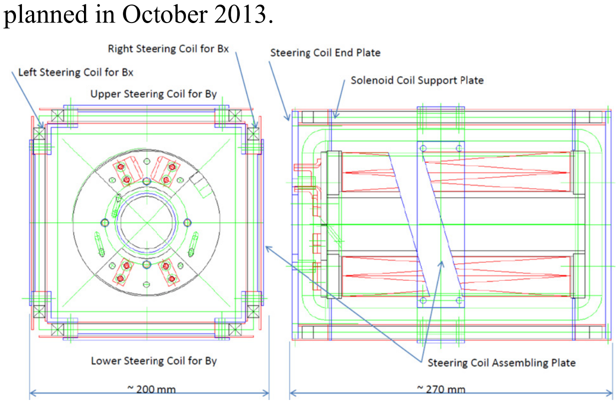

Figure 11: SC 8T 25cm cold mass design.

ETCM

FRIB changed the cryomodule assembly strategy from Top-down to Bottom-up. In this new procedure, cold mass is mounted on a cold rail supported by G-10 posts on the bottom plate of vacuum vessel, and then vacuum vessel top is covered as shown Figure 12.

Table 2: 8T SC Solenoid Design Parameter

Operation Temperature (K)	4.5
SC Wire	NbTi
Number of different wire for grading	2
Solenoid coil length(cm)	25/50
Core Diameter (mm)	46
B_{max} (T)	8.13
B_O (T)*	8.10
Integrated B2 (T^2m)	
Solenoid operation current (A)	100
Operation temperature margin (K)	0.3
Correction dipole field (T)	0.6
Correction dipole current (A)	40

* Defined as maximum field on beam axis

This scheme should allow better alignment tolerance compared to Top-down assembly. As shown in Figure 12, both ends of the coldmass have vacuum hoods to make easy installation of vacuum components. However, this assembly needs three way O-ring seals, which has been specially developed with industry. This bottom-up assembly is the first of its kind, while existing low beta linacs are using Top-down assembly. Vibration of the cryomodule also has to be investigated. Before going into FRIB production, these potential issues have to be verified: FRIB alignment strategy, FRIB T-type non-commercial O-ring sealing concept, rail support system with mechanical vibration, and so on.

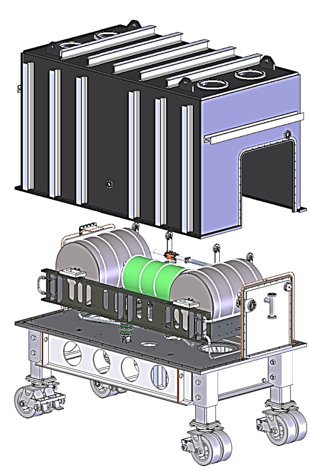

Figure 12: ETCM

ETCM Program

MSU has decided on an Engineering Test Cryomodule (ETCM) program to demonstrate these issues at liquid nitrogen temperature. ETCM is a 1/3 module assembly of a β=0.53 cryomodule, which includes one solenoid dummy between two β=0.53 HWR dummies as seen in

ISBN 978-3-95450-143-4

Figure 12. In addition, optical targets and one wire position monitor (WPM) are mounted on the rail dummy cavities and dummy solenoid for tracking during thermal transitions [1].

Tolerance Tacking

The ETCM was completed in January 2013 and the test was continued intermittently for about 8 months. The O-ring sealing concept has been successfully demonstrated to be leak tight up to 6×10^{-7} torr at least.

ETCM was cooled several times to 80K. Optical measurement and WPM measurement were repeated during the cooling cycles. The movement of rail position was tracked during these thermal cycles as shown in Figure 13. Dummy cavities and solenoid also were measured. The dummy cavities stayed within ±80μm horizontally, within ± 50μm vertically. The WPM displayed within ±80μm horizontally, and within ± 30μm vertically. Both results are consistent within measurement error. On the other hand, the optical result on the dummy solenoid was within ±150μm horizontally, and within ±30μm vertically. The WPM result on the dummy solenoid was within ±180μm horizontally, and within ±30μm vertically. Both results were consistent. For better alignment in a FRIB Linac, the solenoids are the beam aliment reference, so solenoids must be more stable than cavities. ETCM has a plan to analyse the solenoid constrain further to optimize the design.

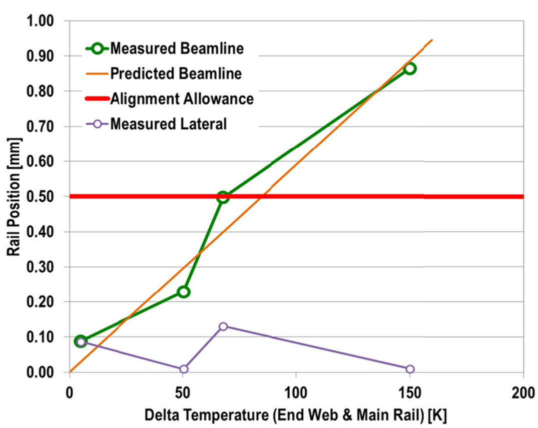

Figure 13: The tracking of the rail motion during cooling down from room temperature to 80K.

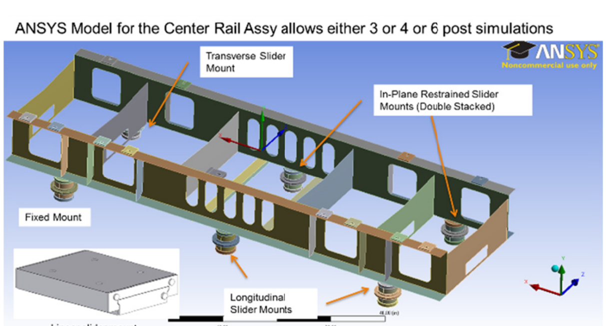

Figure 14: Support system of the cold rail, example of 6 posts support.

Investigation of Vibration

The vibration modes will depend on the supporting system. Three, four, and six supports by G-10 posts are being investigated (Figure 14 and Figure 15) [11]. ETCM experimental results will be compared with the simulation. The analysis is under way.

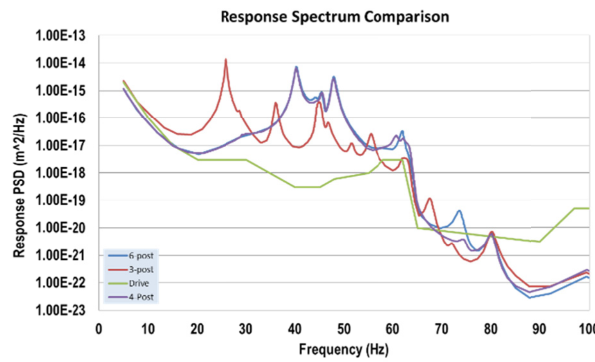

Figure 15: Simulation of vibration of the cold rail in ETCM.

ACKNOWLEDGEMENTS

The authors thank the NSCL & FRIB staff whose effort has made a contribution. We thank Mike Kelly, at ANL, for his help on pneumatic tuner. We recognize the impact of our SRF teleconference, with special thanks A. Facco, Bob Laxdal and Peter Kneisel for their contributions.

REFERENCES

[1] S. Miller et al., "LOW-BETA CRYOMODULE DESIGN OPTIMIZED FOR LAREGE-SCALE LINAC INSTALLATIONS", in this workshop, THIOA04.
[2] Edited by L. Harle, "TDCM Final Report", FRIB-Internal Note, FRIB-T30603-TD-000392-R001, October 2012.
[3] K. Saito, "Cavity, Tuner, Magnetic Shielding, Solenoid and TDCM", Presentation in FRIB ASAC Review, June 2013, to be published the TDCM 2nd report in the FRIB Internal report.
[4] Z. Zheng, "Multipacting suppression modelling for Half Wave Resonator and RF coupler", proceeding of Linac2012, Tel-Aviv, Israel.
[5] S. Miller, "ETCM, Tuner Tests, Cryomodule Diagnostics", Presentation in FRIB ASAC Review, December 2012.
[6] X. Xu, "FRIB ReA6 Cryomodule Magnetic Shield Analysis," Magnetic Shielding Workshop in MSU, March 6-7, 2013.
[7] M. Adolf, Amuneal Manufacturing Corp.,"Magnetic Shield Properties and Handling of Amumetal 4K/A4K", Magnetic Shielding Workshop in MSU, March 6-7, 2013.
[8] K. Saito et al., Magnetic Material Characterization & SC Solenoid Package Design for FRIB, In this workshop, THP046.

[9] K. Hosoyama,"9T SC Solenoid Design, Fabrication and Issues", Magnetic Shielding Workshop in MSU, March 6-7, 2013.
[10] Q. Zhao, et al.,"Lower Setting of the Superconducting Solenoids in the FRIB Driver Linac", FRIB-Internal-Note, May 2013.
[11] N. Bultman, "Bottom-up Cryomodule Alignment and Vibration Quantification", Presentation in FRIB ASAC Review, December 2012.

ISBN 978-3-95450-143-4