SUPERCONDUCTING RF DEVELOPMENT FOR FRIB AT MSU*

K. Saito#, N. Bultman, E. Burkhardt, F. Casagrande, S. Chandrasekaran, S. Chouhan, C. Compton, J. Crisp, K. Elliott, A. Facco, A. Fox, P. Gibson, M. Johnson, G. Kiupel, B. Laxdal, M. Leitner, S. Lidia, D. Morris, I. Malloch, D. Miller, S. Miller, D. Norton, R. Oweiss, J. Ozelis, J. Popielarski, L. Popielarski, A. Rauch, R. Rose, T. Russo, S. Shanab, M. Shuptar, S. Stark, N. Usher, G. Velianoff, D. Victory, J. Wei, G. Wu, X. Wu, T. Xu, Y. Xu, Y. Yamazaki, Q. Zhao, W. Zheng,
FRIB, Michigan State University, 640 South Shaw Lane East Lansing, MI 48824, USA
K. Hosoyama, KEK, 1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305-0801, Japan

Abstract

The Facility for Rare Isotope Beams (FRIB) is a high intensity, heavy ion SRF CW linac for nuclear science. FRIB SRF cryomodule design addressed four critical issues: high performance, stable operation, easy maintainability, and low cost construction, each presenting a unique challenge. FRIB SRF system design and R&D are almost complete. This paper presents unique R&D done in past 2-3 years for FRIB.

FRIB PROJECT

FRIB is a Department of Energy (DOE) joint project operated at MSU and obtained CD3-B approval in August 2014. Conventional facilities construction began in March 2014. The accelerator system construction will begin in October 2014, and will be completed in 2022 (CD4). A new SRF highbay has been constructed for SRF mass-production, and technical equipment is being installed [1].

Fig. 1 shows FRIB machine configuration in the tunnel, which consists of three folded linac segments with a total length about 500 m. It accelerates from proton to uranium up to 200 MeV/u, with beam power of 400 kW on the target. FRIB is the intensity frontier machine for heavy ions - for example it accelerates ^{238}U to $5\cdot10^{13}$ /s, 250 times greater than ATLAS. FRIB applies SRF technology from low β(v/c) =0.041 to medium β=0.53 acceleration sections. FRIB cryomodules include two cryogenic circuits, 2K for cavities and 4.5K for solenoid operation [2].

FRIB SRF SCOPE

FRIB uses two types of SRF cavities: Quarter Wave Resonators (QWR) for β=0.041 and 0.085, both operated at 80.5 MHz, and Half Wave Resonators (HWR) for β=0.285 and 0.53, both operated at 322 MHz. Fig. 2 illustrates these four cavities. RF parameters are summarized in Table 1. The operating gradients are ~5.5 MV/m @ $Q_O = 2x10^9$ for the QWRs and ~7.5 MV/m @ $Q_O = 9x10^9$ for the HWRs. These performance levels are a challenge compared to existing heavy ion linacs. However, advanced cavity design with a lower B_p/E_{acc} and operation at 2K can achieve these goals. The required number of cavities are 12 for β=0.041, 88 for β=0.085, 72 for β=0.285, and 144 for β=0.53. In total, 333 cavities are required. All four cavity families have been prototyped and their

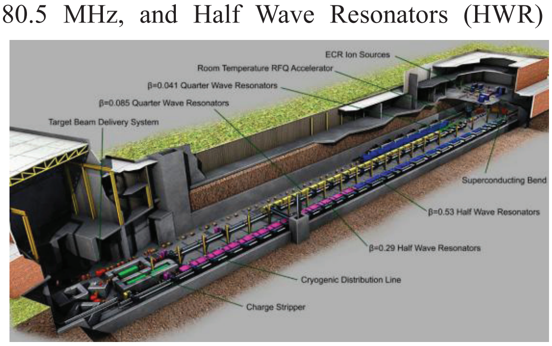

Figure 1: Linac configuration in FRIB tunnel.

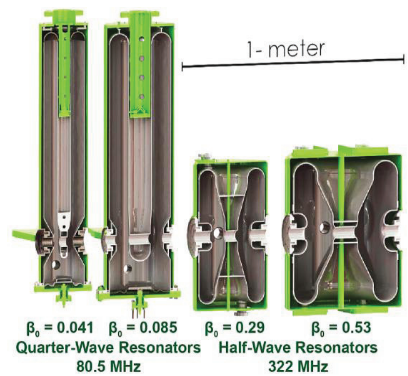

Figure 2: FRIB SRF cavity families

Table 1: RF Parameters for FRIB Cavities

Cavity Type	QWR	QWR	HWR	HWR
β_0	0.041	0.085	0.285	0.53
f [MHz]	80.5	80.5	322	322
V_a [MV]	0.810	1.80	2.09	3.70
E_{acc} [MV/m]	5.29	5.68	7.89	7.51
E_p/E_{acc}	5.82	5.89	4.22	3.53
B_p/E_{acc} [mT/(MV/m)]	10.3	12.1	7.55	8.41
R/Q [Ω]	402	455	224	230
G [Ω]	15.3	22.3	77.9	107
Aperture [m]	0.036	0.036	0.040	0.040
$L_{eff} \equiv \beta\lambda$ [m]	0.153	0.317	0.265	0.493
Lorenz detuning $[Hz/(MV/m)^2]$	< 4	< 4	< 4	< 4
Specific Q_O @VT	$1.4x10^9$	$2.0x10^9$	$5.5x10^9$	$9.2x10^9$

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

Copyright © 2014 CC-BY-3.0 and by the respective authors

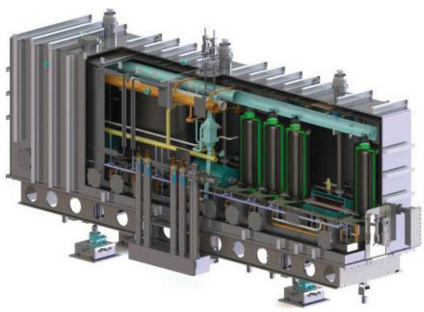

Figure 3: FRIB 0.085QWR cryomodule.

performance validated with helium vessels. All FRIB production cavity orders have been placed.

Fig. 3 shows a β=0.085 QWR FRIB cryomodule. Notable FRIB cryomodule features are: 1) local magnetic shielding for cost-effective and reliable magnetic shielding, 2) bottom-up assembly for easy module assembly and better alignment, 3) 2K operation which yields higher cavity performance and more stable helium pressure control for reduced microphonics. The required number of cryomodule are 3 for β=0.041, 11 for β=0.085, 12 for β=0.285, 18 for β=0.53, and 5 additional beam matching cryomodules in the folding segments. Totally 49 cryomodules are required. The first cryomodule (0.041) will be delivered early 2016, with the β=0.085 CMs, β=0.285 CMs, and β=0.53 CMs delivered successively through 2018. Cryomodule production yield will be 1.5 CM/month.

FRIB CRYOMODULE PROTOTYPING

ReA Project at NSCL in MSU

MSU is constructing the Re-Accelerator (ReA) facility, which will be part of FRIB. ReA includes re-acceleration system of rare isotopes, and nuclear physics experimental systems. Fig. 4 shows the Re-accelerator located at NSCL. It consists of an ion source, a normal conducting RFQ, a SRF buncher cryomodule (CM#1, consisting of one 0.041QWR and one 20cm solenoid) and a SRF accelerator module (CM#2, consisting of six 0.041QWRs and three 20 cm solenoids). These modules were assembled utilizing the top-down design approach. This system (box area in Fig. 4) has been operational with beam at 4.5K since 2012 [3]. FRIB chose 2K operation and the bottom-up assembly strategy, however this system provides an excellent FRIB benchmark.

FRIB's SRF department is constructing an additional ReA cryomodule (0.085QWR, CM#3) in parallel with FRIB development and so accumulating module construction and operation experience. The CM#3 was installed in June 2014 (Fig. 4 middle) [3]. It is currently being commissioned. During this construction, much valuable experience was gained. A FRIB 0.085QWR module (bottom-up) is now being constructed and it is to be tested in early December 2014 (Fig. 4 right).

Lessons Learned in ReA3 CM #3 Construction

Eleven ReA3 0.085QWRs with titanium helium jacket were fabricated and cold tested for CM#3 in 2011-2012. The typical cavity performance is presented in Fig. 5. Many of them were performance limited below FRIB specifications. These QWRs have a demountable structure as part of the bottom flange. The lower performance is attributed to the poor conduction cooling of the tuning plate, which is sandwiched by two bottom flanges using double indium seals. The cavity bottom flange is made of NbTi

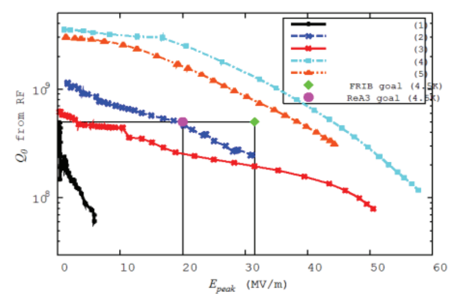

Figure 5: ReA3 QWR cavity performance in the early test. Q_O goes down at very low field, steep Q-slope is also seen.

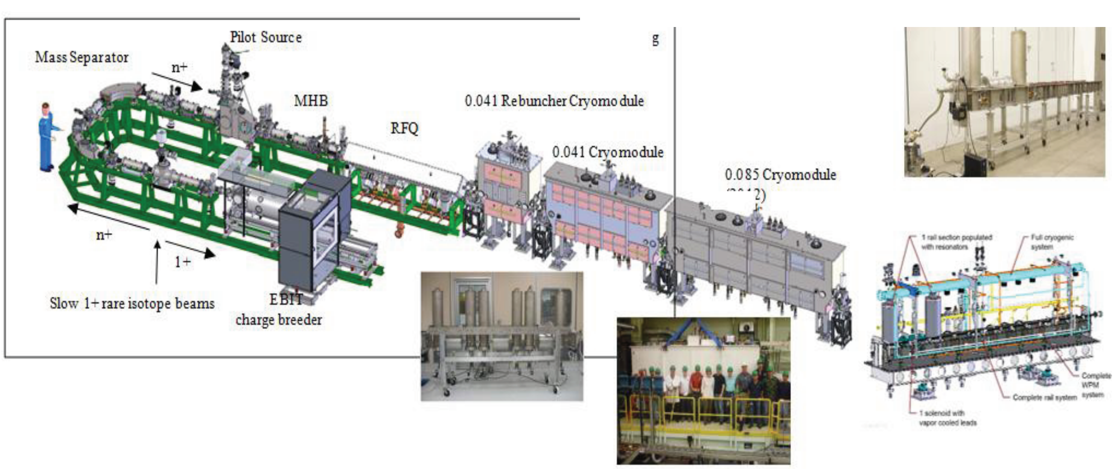

Figure 4: ReAproject in MSU. The box designates the existing system, CM#3 (pictured) is under comissioning and one more 0.085QWR cCM (right) which is exactly the same specification as the FRIB 0.085QWR CM, but including only two cavities and one solenoid.The coldmass assembly was completed in June 2014 and is now undergoing cryomodule assembly.

ISBN 978-3-95450-142-7

Copyright © 2014 CC-BY-3.0 and by the respective authors

and has poor thermal conductivity (1/10 of Nb at 2K). The cavity bottom flange was redesigned (Fig. 6 left). Niobium sheet was electron beam welded on the NbTi flange. Cooling channels were machined to have direct liquid helium contact on the niobium sheet. This significantly improved the performance as seen in Fig. 11 left top [4].

As a backup plan, a bottom flange using a metal gasket is under development (Fig. 6 right), which uses hard copper (NC50) for the cavity bottom flange. NC50 is non-magnetic, with hardness comparable to stainless steel, and has good thermal conductivity. Niobium tube is HIP (Hot Isostatic Pressing) bonded inside the hard copper tube. Leak tightness and good RF contact have been confirmed, which will be fully tested on a QWR later this year.

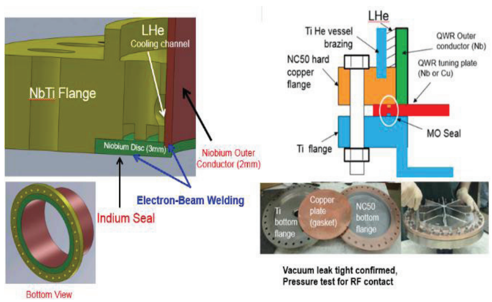

Figure 6: Redesigned bottom flange (left) with indium seal, and metal gasket bottom flange utilizing NC50 under development (right).

Cryomodule Prototyping for FRIB

FRIB changed the following cryomodule specifications in the period 2011-2013, 4K to 2K operation, global magnetic shield to local shield, top-down assembly to bottom-up. The FRIB approach to validation of these modifications is depicted in Fig. 7.

TDCM (Technology Demonstration Cryomodule)

TDCM is the first test cryomodule to demonstrate 2K operation without beam and to confirm the module assembly sequence, which was tested in 2012-2013 [5]. TDCM utilized global magnetic shielding because it was the current FRIB approach at that design stage. TDCM contained two 0.53HWRs and one commercial 9 T solenoid adjacent to a cavity. The cryomodule was successfully confirmed leak tight under 2K operation. Cavity performance was measured at the cavity furthest from the solenoid (Fig. 8). The cavity field was limited by field emission (FE), however unloaded Q (Q_O) was the same as that measured in the VTA test, up to E_p ~10MV/m. The Fundamental Power Coupler (FPC) could withstand power up to 8 kW CW and was operated stably at 6-7 kW CW, even while multipacting (MP) was rather strong above 2kW. This FPC operation met the FRIB specification. Pressure of the 2 K helium bath was very stable, showing $\Delta p < \pm 0.1$ mbar. The tuner system (JLab-type scissor tuner) in the TDCM had two issues: magnetization of ferromagnetic tuner components and noisy operation. This experience with the tuner operation in TDCM led to adoption of the ANL-type pneumatic tuner for FRIB HWRs.

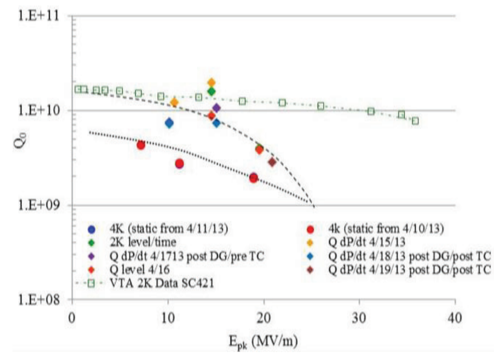

Figure 8: Cavity performance in the TDCM. Squares are baseline performance in the VTA test.

ETCM (Engineering Test Cryomodule)

ETCM was developed as an engineering prototype for technical demonstration of the bottom-up assembly concept, especially the self-aligning cavity support system utilizing four G10 posts mounted on linear bearings. ETCM used simulated cold mass components (two cavities and one solenoid between them) mounted on the support rail in a vacuum vessel, comprising a 1/3 FRIB CM model. This system was cooled down to liquid nitrogen temperatures. Cavity alignment could be maintained within 0.1 mm as expected, exhibiting a linear response as seen in Fig. 9 [2, 5]. The FRIB CM design will divide the cavity support rails into three sections to minimize total integrated contraction. Results from the ETCM studies led to adoption of more support posts in the rails sections to further reduce the amplitude of low frequency mechanical modes.

ReA6-Phase1

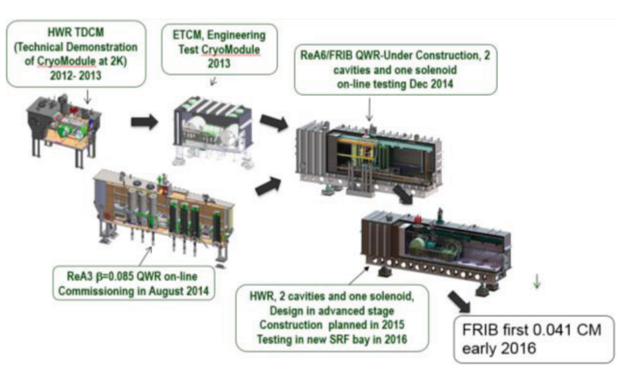

Figure 7: FRIB cryomodule prototyping approach.

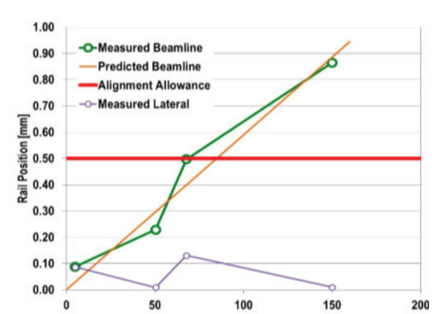

Figure 9: Alignment validation of bottom-up assembly in ETCM. Alignment error within 0.1mm is confirmed.

Copyright © 2014 CC-BY-3.0 and by the respective authors

The ReA6 CM (Phase1) is the first demonstration of the FRIB bottom-up cryomodule design with actual coldmass components. It includes two 0.085QWRs and one solenoid which will provide for an early test of the design, rather than waiting to build a fully populated version (Fig. 4, right). Cold testing is scheduled for December 2014. In 2015, the first 0.53HWR CM will be assembled and tested, similar to the ReA6 CM program.

FRIB CAVITY AND COMPONENTS

Niobium Material for FRIB Cavities

FRIB project uses vendor-etched niobium materials with RRR > 250 for cavities and NbTi materials for flanges. All the materials were ordered and 60% of them have been delivered. The final delivery is scheduled for the end of 2014. FRIB has developed its own acceptance tests: two samples per production lot are used for dimensional and surface finish inspections, mechanical tests (ultimate yield, elongation, and hardness), metallurgical properties measurement (grain size, crystal orientation, and recrystallization), RRR and thermal conductivity measurements. A rigorous material quality control program has been established at FRIB [6].

FRIB Processing Control

In order to minimize costs, FRIB has chosen buffered chemical polishing (BCP, 1:1:2) for cavity etching, with acid temperature control. This is used to achieve 150 µm of cavity inner surface removal (bulk etching). Final (light) etching is done post hydrogen degassing (600 ^{O}C x 10 hr). Subsequently, the cavity is rinsed with ultrapure water and successively high pressure water rinsed (HPR) at 1000 psi. A unique QA process adopted at FRIB is the particle count contamination control during HPR and cavity assembly [7]. Fig. 10 shows the correlation between the particle counts and FE onset field with 0.085QWRs. Except in the case of known exceptions, a good correlation is observed. Low temperature baking at 120 ^{O}C is also applied in the FRIB processing recipe. Cleaning of the fundamental input coupler closely adheres to the same cavity processing standards and QC procedures.

FIRB Final Cavity Design and Validation

FRIB has modified the cavity design to increase the usable gradient. The outer diameter of the cavity was

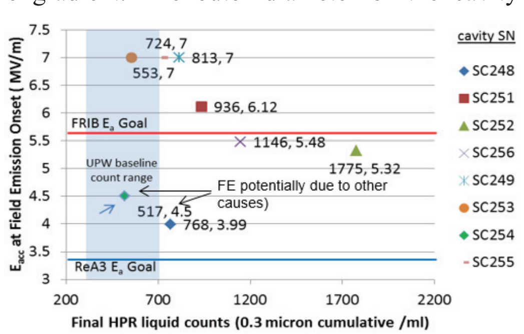

Figure 10: Good correlation between particle count and FE onset at FRIB QWR preparation.

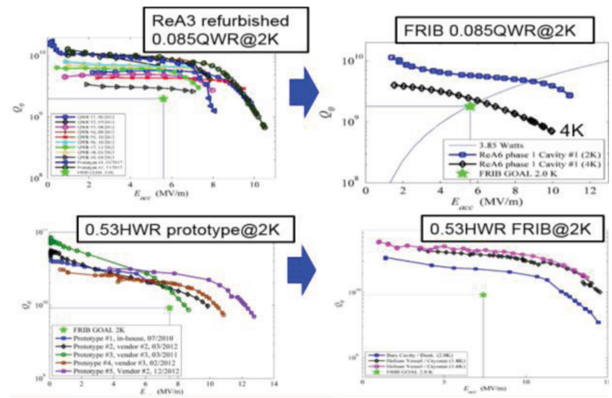

Figure 11: Improved cavity performance in the final cavity design. Left is the original and right final design.

enlarged to reduce E_p and B_p. Fig. 11 compares the cavity performance between original and final design for the 0.085QWR and the 0.53HWR. The effect on performance of the high Q-slope was mitigated in the final cavity by adopting a design with smaller B_p/E_{acc}, which allows sufficient operating margin for gradient and Q. FRIB has validated all 4 cavity families with helium jacket in vertical testing at 2K. FRIB production cavity orders have already been placed with vendors.

Fundamental Power Coupler (FPC) and Tuner

FRIB uses two FPCs: a coaxial coupler for 0.041/0.085 QWRs based on an ANL design, and a KEK/SNS type coupler for 0.0285/0.53 HWRs. Both FPCs have been successfully high power tested on the cavity and met FRIB requirements [2]. As a backup plan, a multipacting-free coupler for HWRs is being developed and under preparation for prototyping.

Two tuner families are used in FRIB: an adjustable tuning plate operated by a stepping motor for QWRs and the ANL-type pneumatic tuner for HWRs. The QWR tuner has bene successfully demonstrated in ReA operation. The HWR pneumatic tuner has been successfully tested in a partial integrated test with a cavity in the vertical Dewar at 2K [5]. A full integration (cavity, tuner, and FPC) test in vertical Dewar is under preparation and scheduled for later in 2014.

CAVITY/FRINGE FIELD INTERACTION

Solenoid

FRIB CM consists of solenoids and cavities in the common vacuum vessel. In the event of quench, the ion beam would hit SRF cavity surfaces, result in serious damage and failure. For the reliable solenoid operation of the accelerator, sufficient current and temperature margins are required. Commercially available 9 T solenoids made of NbTi wire have a limited temperature margin and also 9 T operation is critical due to higher field in the coil. FRIB has decreased the solenoid field requirement from 9 T to 8 T by adopting constant beam size optics. In the present linac design, total 74 solenoids are required and eight of them have an effective length of 25 cm and the remaining

Copyright © 2014 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-142-7

Figure 12: Dry winding (no epoxy used) at KEK

sixty-six have an effective length of 50 cm. An existing MSU/KEK collaboration has successfully designed 8 T 25/50 cm solenoid packages included steering coils with 0.5 K operation temperature margin, and prototyped a 25cm solenoid package by dry winding (Fig. 12). The peak field of the solenoid reached 8.9 T without any training. Thermal cycling from room temperature to liquid nitrogen temperature (12 times) did not degrade the performance. The steering dipoles were also fabricated by dry winding, and tested. These coils could be energized independently up to 100 A without any training. In the full excitation test (solenoid + steering coils), one steering coil quenched at 87.3 A, which is significantly above the design goal (50A). The dry winding simplifies solenoid/steering coil fabrication and has potential cost savings. This fabrication technique has been demonstrated through this prototyping.

Cavity/Fringe Field Interaction

Cavity/fringe field interaction is of concern in the FRIB CM. It was investigated using a 0.53HWR at 2K (Fig. 13), and confirmed that cavity performance was unchanged up to 2500 G applied field if the cavity did not quench. At cavity quench, a Q-drop occured (Q dropped below FRIB spec. at 4 G). The Q-drop could be partially recovered by the "quench annealing" process [8].

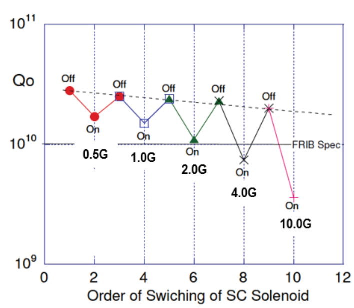

Figure 13: Q-drop depending on fringe field strength and Q-recovery by "quench annealing" process.

Magnetic Shield

FRIB CM design uses local magnetic shielding for cavities. In this configuration, the shield is exposed to a strong fringe field (~550 G) from the solenoid. Cryogenic magnetic shield material like A4K or Cryoperm will be used for the local shielding but the performance is unknown with high field exposures. Saturation fields of shielding was measured (Fig. 14). The performance is degraded to 60% at 10 K, for example 365 G at 300 K and 260 G at 10 K. Nevertheless, the fringe field (600 G) does not penetrate to the high RF magnetic field area of QWR was confirmed in a cold shielding test [9]. A field enhancement of a factor 2 was observed on the shield surface, which makes shielding difficult.

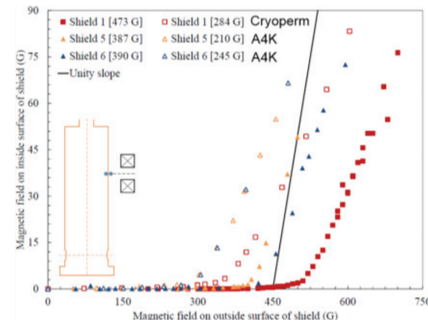

Figure 14: Saturation field of the cryogenic shield at 300 K and 10 K.

3D Full Simulation

Full solenoid simulation: solenoid package, shield, and cavity was done by 3D modelling. A fringe field of ~100G exposes the cavity outer surface through the shield on both QWR and HWR, when the 8 T solenoid package is in operation. If the cavity does not quench, it is not problematic. However, potential mitigations for post-quench Q degradation are being developed. The addition of Meissner shielding achieved by tightly wrapping niobium foil only on the helium vessel facing the solenoid might be a cost-effective solution. A fully integrated test (cavity, shield, and solenoid) in the vertical Dewar is being prepared.

CONCLUSION

FRIB SRF components have been designed and validated. As the final stage, the full integration testing of these components and sub-systems in a vertical Dewar is being pursued. Additionally, validation of full-scale cryomodule is also underway and progressing steadily.

REFERENCES

[1] L. Popielarski, et al., "SRF Highbay Technical Infrastructure for FRIB Production at Michigan State University", THPP046, in this conference.

[2] M. Leitner, et al., "The FRIB Project at MSU", proceedings, SRF2013, MOIOA01, Paris, France.

[3] T. Xu, et al., "MSU Re-Accelerator ReA3 0.085 QWR Cryomodule Status", MOPP044, in this conference.

[4] A. Facco, et al., "Faced Issues in ReA3 Quarter-Wave Resonators and Their Successful Resolution", SRF2013, THIOD02, Paris, France.

[5] K. Saito et al., "SRF Developments at MSU for FRIB", SRF2013, MOP013, Paris, France.

[6] C. Compton, et al.," Quality Assurance and Acceptance Testing of Niobium Material for Use in the Construction of the Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU)", SRF2013, MOP033, Paris, France.

[7] L. Popielarski, "Process Development for Superconducting RF Low Beta Resonators for the ReA3 Linac and Facility for Rare Isotope Beams", LINAC2012, Tel-Aviv, Israel.

[8] T. Khabiboulline, et al., "SSR1 Cavity Quenching in the Presence of Magnetic Field, FNAL Note TD-12-007.

[9] S.Chandrasekaran, et al., "Magnetic Shield Material Characterization for the Facility for Rare Isotope Beams Cryomodules", IEEE Trans. Appl. Supercond., under review.

Copyright © 2014 CC-BY-3.0 and by the respective authors