THIRD HARMONIC SYSTEM AT FERMILAB*/FLASH

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Abstract

A 4-cavity 3.9 GHz cryomodule has been constructed at Fermilab and delivered to DESY. Its intended use is to linearize the non-linear beam energy-time profile produced by the 1.3 GHz accelerating gradient and thus improve the operating characteristics of FLASH for its users. First cold testing of the module is expected in the near future prior to its installation. We will report on the performance of the cavities, assembly and transport of the module as well as anticipated testing, installation, and commissioning plans.

INTRODUCTION

Fermilab has constructed a cryomodule containing four superconducting radio frequency (SRF) cavities operating at 3.9 GHz for the Free electron LASer in Hamburg (FLASH) facility at the Deutsches Elektronen-SYnchrotron (DESY) laboratory. This cryomodule, known as ACC39, was proposed to linearize the energy distribution along a bunch upstream of the bunch compressor. The four 9-cell cavities were designed to operate at 2 K in the TM_{010} π-mode at an accelerating gradient E_{acc} = 14 MV/m. Table 1 contains a list of parameters.

Table 1: Cryomodule Parameters

Number of Cavities	4
Active Length	0.346 meter
Gradient	14 MV/m
Phase	-179°
R/Q [$=U^2/(\omega W)$]	750 Ω
E_{peak}/E_{acc}	2.26
B_{peak} (E_{acc} = 14 MV/m)	68 mT
Q_{ext}	1.3×10^6
BBU Limit for HOM, Q	$<1 \times 10^5$
Total Energy	20 MeV
Beam Current	9 mA
Forward Power, per cavity	9 kW
Coupler Power, per coupler	45 kW

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MOTIVATION

In response to a TESLA study in 2001 [1] and the ensuing Phase 2 Report in 2002 [2] regarding the addition of a 3.9 GHz module to correct the distortion in the longitudinal phase space, it was proposed that Fermilab construct and deliver a cryomodule containing four superconducting radio frequency (SRF) cavities operating at 3.9 GHz for what has come to be known as the Free electron LASer in Hamburg (FLASH) facility at the Deutsches Elektronen-SYnchrotron (DESY) laboratory. ACC39 will be installed in the DESY FLASH injector just after the 1.3GHz ACC1 (first) cryo module as depicted in figure 1.

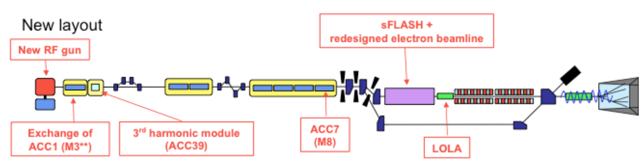

Figure 1: FLASH layout with 3rd Harmonic module.

The 3rd harmonic module will be used in conjunction with ACC1 in order linearize the bunch energy vs. time over the bunch length. This in turn should make “bunch compression” to very short bunches with high peak currents more efficient, or a more controlled longer bunch charge distribution. The SASE FEL operation should become more efficient and stable seeded operation (sFlash) possible. This is an important proof of principle not only for FLASH and XFEL but also for accelerator-photon physics.

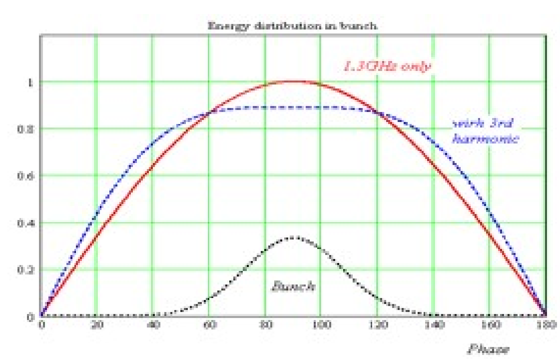

Figure 2: Effect of Third Harmonic waveform on RF and bunch structure.

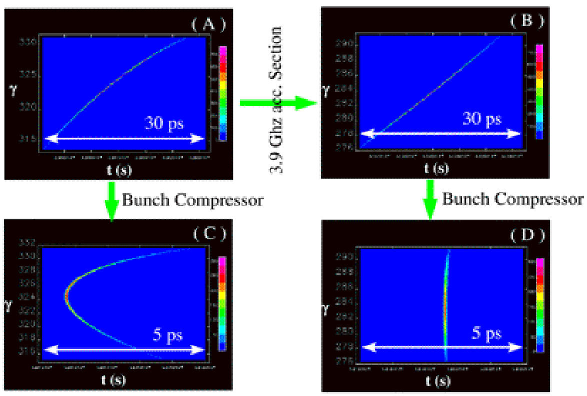

Figure 3: FLASH Longitudinal Bunch distribution without (left column) and with (right column) ACC39.

As a result of this agreement with DESY Fermilab has been able to make much progress in developing its SRF infrastructure from cavity fabrication and processing through all phases of testing, string and cryomodule assembly. Valuable experience in transport has also been gleaned by this effort.

CAVITY FABRICATION, PROCESSING, AND TESTING

Eight cavities have been fabricated and undergone various levels of testing. A summary of test results and status of each is found in Table 2.

Fabrication

Material to construct a total of ten 3.9 GHz cavities was procured. All component parts and end tube subassemblies were fabricated under the direction of Fermilab personnel. Cavities #3 through #6 were assembled and welded at Jefferson Lab using welded end subassemblies provided by Fermilab.

The first six cavities contain a 2-leg Formteil design. Discovery of fractured F-piece legs during initial vertical testing of Cavity #2 prompted a redesign of the piece. An interim solution was to remove approximately 3mm of the Formteil tip. Cavities #3 and #4 contain such trimmed pieces. Cavity #3's was done is situ following initial vertical testing.

Cavities #7 and #8 were assembled at Fermilab using a revised single post Formteil design. The single post Formteils were welded into the HOM housing at DESY. A full account of this issue and redesign has been reported previously [3].

Processing

All cavities underwent a standard protocol of surface processing including Buffered Chemical Processing (BCP), high temperature hydrogen degasification bake, and High Pressure Rinse (HPR) prior to initial tests. This sequence was modeled after the DESY BCP processing cycle.

Table 2: Cavity Fabrication and Testing Status

Cavity	Assembled by	Completion date	Test results and status
#1: 2-leg HOM	Fermilab	January 2006	- Never tested: HOM membrane break during cleaning - Used as horizontal test prototype
#2: 2-leg HOM	Fermilab	February 2006	- Best vertical test: 12 MV/m limited by HOM heating - Fractured Formteils - Repair attempted
#3: 2-leg trimmed HOM	Fermilab JLab	August 2006	- Best Vertical test: 24.5 MV/m, achieved after HOM trimming - Horizontal testing: 22.5 MV/m, limited by quench ***- Part of final string assembly***
#4: 2-leg trimmed HOM	Fermilab JLab	March 2007	- Best Vertical test: 23 MV/m - Horizontal testing: 18 MV/m, limited by quench
#5: 2-leg trimmed HOM	Fermilab JLab	May 2007	- Best Vertical test: 24 MV/m - Welded into Helium vessel - Horizontal testing complete: 22.5 MV/m, limited by quench ***- Part of final string assembly***
#6: 2-leg trimmed HOM	Fermilab JLab	May 2007	- Best Vertical test: 22 MV/m - Faulty welds repaired - Awaiting final vertical test with HOM feedthroughs
#7 single-post HOM	Fermilab JLab DESY	November 2007	- Best Vertical test: 24.5 MV/m - Horizontal testing: 26.3 MV/m, limited by quench ***- Part of final string assembly***
#8 single-post HOM	Fermilab DESY	October 2007	- Vertical test: 24 MV/m - Horizontal testing: 24 MV/m, limited by quench ***- Part of final string assembly***

Depending on the results of vertical tests some cavities received additional inside etches and high pressure rinses. Of the cavities comprising the final string only one required re-processing. Total elapsed time for cavity processing (from completion of fabrication until ready to test) was of order 25 working days.

Vertical Testing

All fabricated cavities underwent a series of tests at the A0 vertical test stand as 'bare' cavities. To date there have been a total of 67 tests performed. The cavities selected for inclusion in the string were tested an average of seven times each – two undergoing only four tests and Cavity #3 subjected to ten. Those welded into helium vessels were given an additional test prior to dressing to ensure that the welding process did not significantly degrade each cavity's performance. Results of these tests have been described previously [4]. Q vs E curves for the four cavities of the module is shown in figure 4. As conditions allowed, tests were conducted at both 1.8K, the default A0 vertical test stand operating temperature, and 2K, the FLASH operating temperature.

Two production cavities, #'s 4 and 6 have yet to be fully qualified as spares. Although initial vertical tests of both as bare cavities resulted in good Q and gradients of 22 MV/m or better both have suffered reduced output. #6 has not returned to its initial performance since a cracked weld was discovered and repaired. Cavity #4's performance degraded following a failure of the High Pressure Rinse system despite additional BCP and HPR with a known good system. Work continues to restore these cavities.

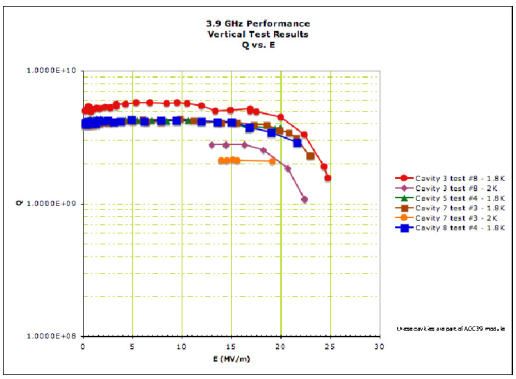

Figure 4: Q vs E from Vertical tests of the four cavities comprising ACC39.

Horizontal Testing

Five cavities are now welded into helium vessels and have undergone Horizontal tests at the Fermilab Horizontal Test Stand (HTS) located in the former Meson Detector Building (MDB) as complete 'dressed' cavities outfitted with magnetic shielding and blade tuners.

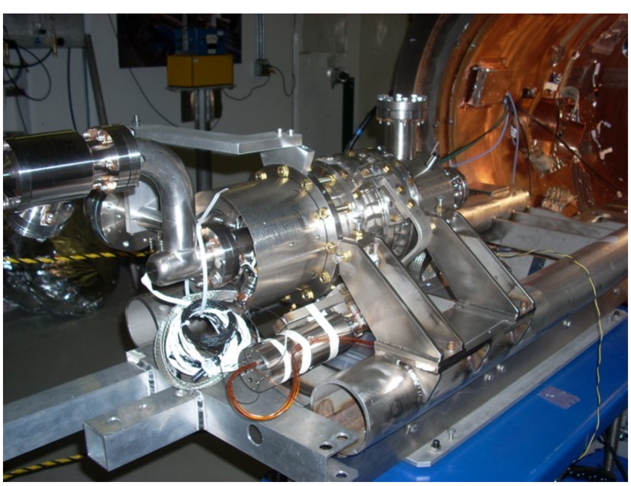

Figure 5: Dressed cavity being installed into the Horizontal Test stand.

All cavities tested to date have reached gradients of at least 18 MV/m, with most achieving a gradient in excess of 22 MV/m. Of the four selected for ACC39 string assembly, all reached at least 22 MV/m. HTS is described elsewhere [5]. Figure 6 shows Q_0 vs E results for the four cavities of the string assembly. Onset of field emission and magnitude of x-rays produced is shown in Figure 7 and in Figure 8 the dark current as measured by Faraday cups at each end of the cavity under test is plotted.

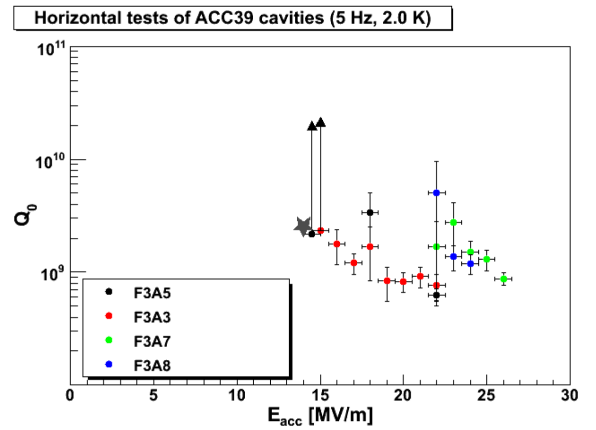

Figure 6: Q_0 vs E for the 4 cavities in the String assembly. The star indicates the design goal.

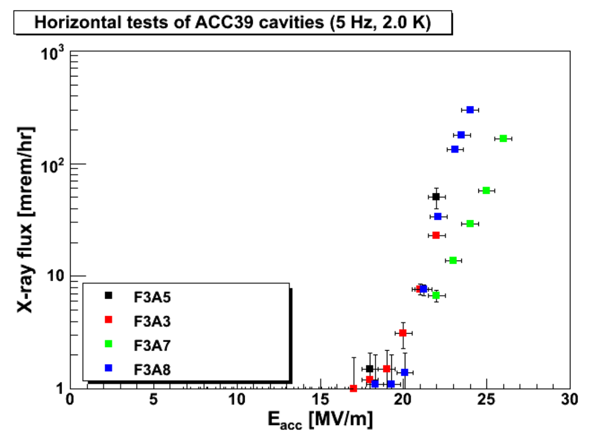

Figure 7: Onset and magnitude of x-ray production as a function of gradient.

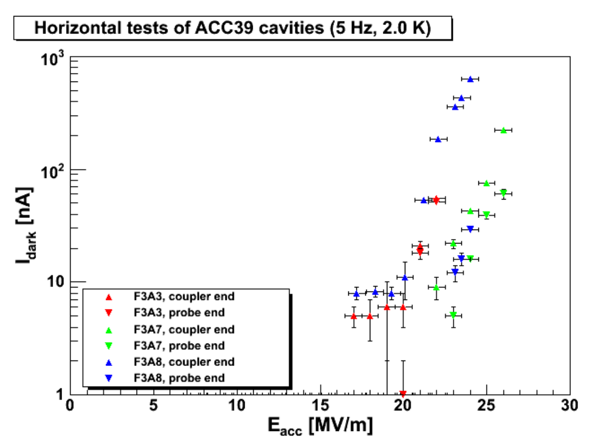

Figure 8: Dark Current for the 4 cavities in the String assembly.

With the experience gained in testing several cavities in short order, testing turnaround time was reduced from 4 months to two weeks including time to remove one cavity and install and leak check the next one.

STRING ASSEMBLY

The first four cavities to be tested at the Horizontal Test Stand exceeded design specification and were assigned to be part of the 4-cavity string assembly. Two of the cavities contain the original 2-post Formteil Higher Order Mode (HOM) couplers while the remaining two were fabricated with the re-designed single-post Formteil. Assembly was such that the cavities alternate with styles of Formteil. This was motivated by a desire to equally distribute HOM frequencies along the beam pipe [6].

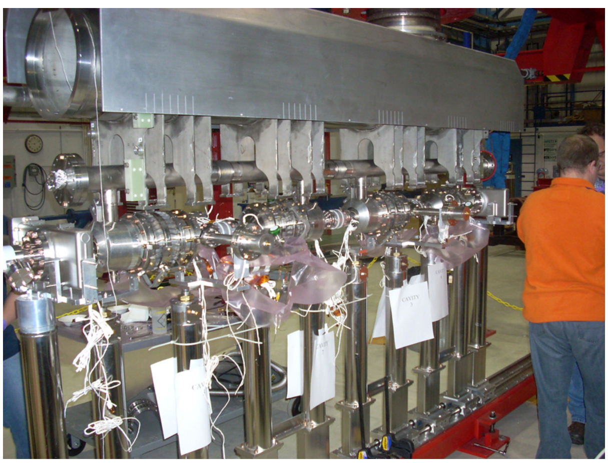

Figure 9: Completed String Assembly.

The entire string consisting of the four cavities and a gate valve at each end was assembled and leak checked beginning in late 2008. String assembly commenced on 11 December 2008 when three cavities were first available. They and a gate valve were joined in Fermilab's MP-9 clean room in a little over three days. When the fourth cavity was available in early January 2009, it as well as the other vacuum gate valve and a manifold to allow remote monitoring of the vacuum in the string were attached. Once a successful leak check of the string was completed, the string was rolled out of the clean room for mating to the 300 mm gas return pipe, which acts as the cold mass spine, and return pipe welding. Welding these titanium return pipes proved to be challenging and it was necessary to cut out and re-weld two sections due to a momentary loss of Argon purge gas.

The completed string assembly was transported by truck on 6 February 2009 to the Fermilab Industrial Center Building for cold mass assembly. This move afforded an opportunity to prepare for actual transport of the completed module. The assembly was loaded onto the shipping fixture designed for the complete module and outfitted with vibration and g-force sensors to measure the response during truck transport. The adequacy of the transport design was confirmed with this exercise.

COLD MASS ASSEMBLY

The final major assembly work at Fermilab was the Cold Mass assembly. This consisted of encasing the cavity string in first a 4K, then 80K thermal shields interspersed with multiple layers of MLI. All additional piping was installed as well. The entire assembly was then inserted into its vacuum vessel and final alignments performed. In addition, instrumentation cabling needed to be routed, terminated, and checked for functionality. Final quality assurance checks including vacuum leak checking and a test fit of warm part input couplers was carried out. All external joints were verified leak tight and finally the vacuum vessel was slightly pressurized to 50 mbar with dry nitrogen just prior to shipment. A review of the Operation Readiness of ACC39 was performed prior to shipment.

TRANSPORT TO DESY

With Cold Mass assembly complete, the module departed Fermilab on 24 April 2009 and was delivered to DESY four days later. Transport was accomplished:

- Via truck from Fermilab to Chicago O'Hare airport
- Air cargo transport to Paris, Charles de Gaulle airport
- Overland transport via truck from Paris to Hamburg.

All critical transfer points were witnessed by Fermilab as well as DESY personnel once the module arrived in Europe.

Great care went into the design and construction of the carrier fixture and techniques to minimize shock and vibration to components within the vacuum vessel – input couplers and cavities most notably. The completed module mounted on the transport frame is shown in Fig.10.

Figure 10: ACC39 on its shipping mount prior to shipment. The base frame is black and the isolation frame upon which the module is directly placed is blue.

The choice and placement of diagnostics to monitor shock and vibration during transport was also done with deliberation. A full description of the transport system and complete results from the transatlantic shipment are reported previously [5]. Figure 11 and 12 show the amplitude of acceleration in all planes during transport as a function of time on the isolation and base frames respectively. Acceleration of the cryomodule during all phases of transport was maintained at or below 1.2 g in all planes – well within the specified criteria.

The cavity string was shipped under vacuum and instrumentation was installed during cold mass assembly to allow one to monitor the vacuum pressure prior to, during, and after shipment. A pressure of 4.8 X 10^{-4} Torr was measured prior to departure from Fermilab on 23 April, some two weeks after active pumping was ceased on the string. Upon arrival in Paris late on 27 April it was found to be 7.7 X 10^{-4} Torr and remained at this level when checked during overland transport and upon arrival at DESY.

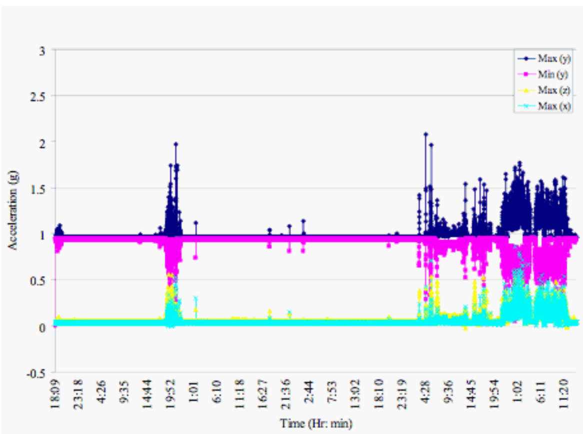

Figure 11: Vertical, horizontal and longitudinal variation of Isolation frame acceleration during transport from Fermilab to DESY.

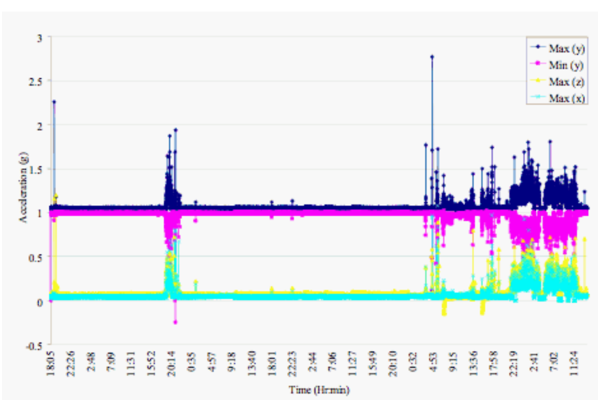

Figure 12: Vertical, horizontal and longitudinal variation of Base frame acceleration during transport from Fermilab to DESY.

CHECKOUT AND PREPARATION FOR TESTING AT DESY

DESY staff in cooperation with their Fermilab counterparts performed a post-transport checkout to verify vacuum leak tightness and that no significant misalignment of the cavity string occurred during transport. While successful transport was verified in these regards, misalignment of some of the needle bearings which are critical to maintain the cavities' positions during thermal cycling was discovered. This necessitated the partial disassembly of the module and a longitudinal realignment of the cavity string ~4mm upstream of its initial location with respect to the fixed support post. Some faulty thermometry splices were similarly discovered and corrected.

The module was shipped with the warm ends of the input couplers not installed. Fermilab staff were responsible for installing these components and verifying leak tightness once the re-alignment was completed. External electrical connections to internal instrumentation and tuner motors has been operated and verified as well.

Two checks of the string alignment and the cavities relative to each other have been undertaken since the module's arrival at DESY – an initial entry check and following the longitudinal move. These results were checked against those of the final alignment check at Fermilab prior to shipping. Deviation has been found to be less than 0.1mm, within specification.

A cold power test of the completed module was initially not contemplated and thus was not part of the technology agreement between Fermilab and DESY. Nevertheless, this has been determined to be a responsible step to take and the Cryomodule Test Bed (CMTB) was modified to support such a test. As of September 2009 the necessary changes to the test stand were completed and the module installed. Vacuum and cryogenic connections have been made and verified; the module is considered ready for cool down. Prior to that, however, the input couplers will be re-conditioned warm. Preparations are in progress and is expected to commence in late September 2009.

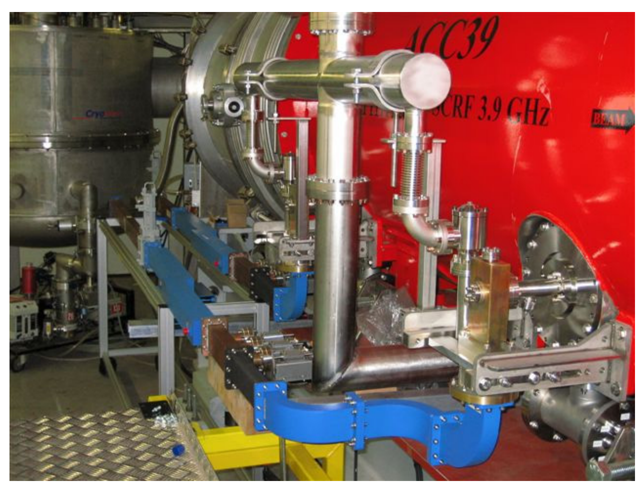

Figure 13: ACC39 installed and being readied for cold testing at DESY's Cryomodule Test Bed.

NEXT STEPS & SCHEDULE

After input coupler conditioning is completed ACC39 will be cooled down for powered testing at CMTB. This is expected to continue through October. Installation in the FLASH enclosure will coincide with the scheduled maintenance period – now planned for December 2009.

Technical commissioning is scheduled for March 2010 with beam commissioning to follow thereafter.

SUMMARY

Fermilab has now successfully completed construction of a Superconducting RF module containing four 3.9 GHz cavities each of which have achieved a gradient in excess of 22 MV/m and met all other design criteria. The module was transported to DESY and is now installed on DESY's Cryomodule Test Bed in preparation for warm coupler conditioning and cold powered testing. Installation and beam commissioning in DESY's FLASH free electron laser is expected to follow beginning in late 2009.

This effort has proven to be far more than merely a scaled version of a 1.3 GHz TESLA module. With this work largely complete, Fermilab has gained valuable experience in designing, fabricating, and assembling SRF devices as well as building up the necessary expertise and infrastructure.

ACKNOWLEDGEMENTS

The success of this venture would not have been possible without the dedication and efforts of many people in the Accelerator and Technical Divisions at Fermilab who are part of the expanding SRF effort. Of particular note are the AD/A0 SRF and TD/MP-9 mechanical technicians without whom ACC39 and its contents would exist. Significant advice and technical support from colleagues at DESY, Jefferson lab, and Argonne National Laboratory was invaluable in this achievement. Colleagues from INFN, Milano have provided technical advice as well. Upon its arrival at DESY the module has received much attention from members of many DESY groups including MKS 1, MEA 2, MIN, and MHF-sl. The support and patience of colleagues at DESY cannot be underscored enough.

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