PROGRESS TOWARDS A 2.0 K HALF-WAVE RESONATOR CRYOMODULE FOR FERMILAB'S PIP-II PROJECT*

Z.A. Conway†, A. Barcikowski, G.L. Cherry, R.L. Fischer, B.M. Guilfoyle, C.S. Hopper, M.J. Kedzie, M.P. Kelly, S-h. Kim, S.W.T. MacDonald, P.N. Ostroumov and T.C. Reid, Argonne National Laboratory, Argonne, IL 60439, U.S.A.
V.A. Lebedev, A. Lunin, Fermi National Accelerator Laboratory, Batavia, IL 60510, U.S.A.

Abstract

In support of Fermilab's Proton Improvement Plan-II project Argonne National Laboratory is constructing a superconducting half-wave resonator cryomodule. This cryomodule is designed to operate at 2.0 K, a first for low-velocity ion accelerators, and will accelerate ≥1 mA proton/H$^-$ beams from 2.1 to 10.3 MeV. Since 2014 the construction of 9 162.5 MHz $\beta = 0.112$ superconducting half-wave resonators, the vacuum vessel and the majority of the cryomodule subsystems have been finished. Here we will update on the status of this work and report on preliminary cavity test results. This will include cavity performance measurements where we found residual resistances of < 3 nΩ at low fields and peak voltage gains of 5.9 MV, which corresponds to peak surface fields of 134 MV/m and 144 mT electric and magnetic respectively.

INTRODUCTION

Fermi National Accelerator Laboratory (FNAL) is upgrading its existing accelerator complex to achieve beam power on the Long-Baseline Neutrino Facility (LBNF) target of > 1 MW [1, 2]. FNAL's current injector consisting of the Linac and the Booster accelerators is limited to ~4.4×10^{12} protons per Booster pulse by beam loss. It is the major bottleneck in the string of accelerators limiting the LBNF power. To address this increase of the 300 MeV Booster injection energy is required [2].

The next-generation facility chosen by FNAL to supply the LBFN target calls for an increase in the Booster injection energy with the replacement of the existing 400 MeV Linac by a new 800 MeV superconducting (SC) linac [3, 4]. The first SC cryomodule in the new 800 MeV linac contains 8 half-wave resonators (HWRs) and 8 SC solenoids for the acceleration of an H$^-$ beam from 2.1 to 10.3 MeV. This cryomodule, supplied by Argonne National Laboratory (ANL), will be commissioned as part of the injector accelerator demonstration experiment referred to as the Proton Improvement Plan-II Injector Test (PIP2IT) [5]. The aim of the work presented here is to document the progress toward operating the HWRs in PIP2IT by presenting the cryomodule assembly progress and results for the HWR 2.0 K testing.

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and High-Energy Physics, under Contract No. DE-AC02-76-CH03000 and DE-AC02-06CH11357. This research used resources of ANL's ATLAS facility which is a DOE Office of Science User Facility.
† zconway@anl.gov

CRYOMODULE

The HWR cryomodule design is an evolution of the top-loaded box cryomodule design used successfully at ANL for two separate successful upgrades of the Argonne Tandem Linear Accelerator System [6, 7, 8]. Argonne box cryomodules rely upon the implementation of several techniques to achieve their high-performance levels, such as: electro-polishing in the ANL low-beta EP tool [9], high-pressure high-purity water rinsing with clean-room handling [10] and separate cavity/insulating vacuum systems enabling a cryomodule design which allows the clean assembly to be hermetically sealed prior to installing the "dirty" subsystems of the cryomodule [11]. Compared to other ANL cryomodules the technology has been extended to 2.0 K operation with the addition of a 2/5 K heat exchanger and a J-T expansion valve. The total 2.0 K thermal load is expected to be 50 W, of which 25 W are from the 48 conduction-cooled magnet leads feeding the 8 SC solenoids and the x-y steering coils integrated into each solenoid.

The remainder of this section highlights selected aspects of the design and fabrication status for the HWR cryomodule: (1) the mechanical design of the cavities and cryomodule developed to comply with the DOE Vacuum Vessel Consensus guidelines [12], FNAL Safety [13] and the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) Section VIII [14] and (2) a brief update of the future fabrication plans leading to the operation of this cryomodule at 2.0 K.

Cryomodule Design

The half-wave cavity cryomodule vacuum vessel design balances the need to house a 6 meter long accelerator string with all of its support systems inside the limited space available for assembly while maintaining compliance with FNAL's safety standards. Figure 1 shows a cross section view of the assembly. Figure 2 shows a picture of the cryomodule vacuum vessel prior to a test of the 70 K coolant systems.

The vacuum vessel has two cryogenic input streams: (1) 5 K 3 bar and (2) 70 K 20 bar gaseous helium. The 70 K helium stream cools the radiation shielding and is used for thermally intercepting penetrations running from room temperature. The 5 K helium coolant stream is split for two separate purposes. One 5 K branch is used for thermal intercepting while the second branch is used for the production of 2.0 K helium. Cooling to 2.0 K is achieved by heat exchanging the input 5 K helium

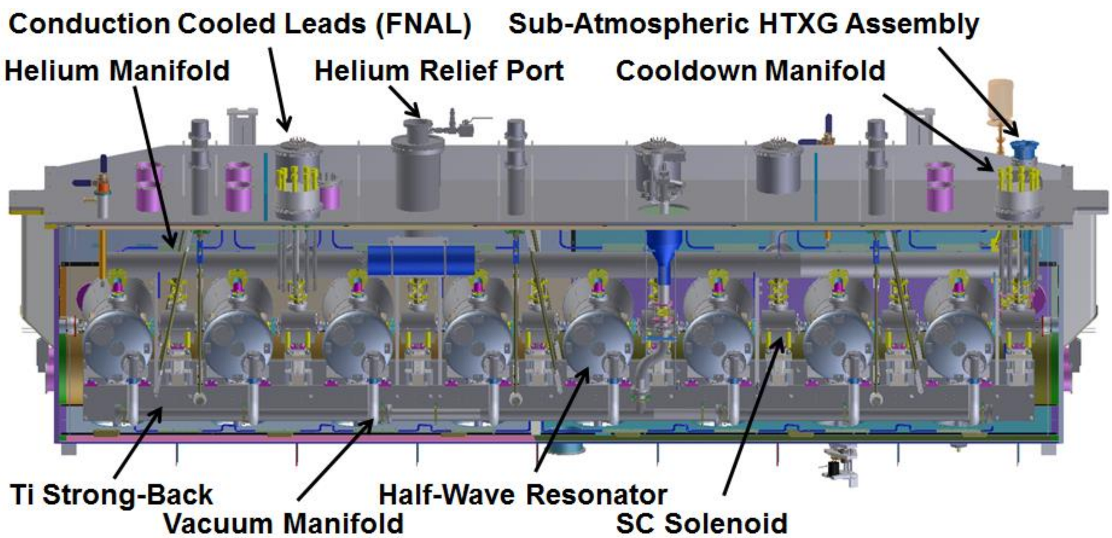

Figure 1: (Top) Cross section view of the PIP2IT HWR cryomodule.


Figure 2: Picture of the cryomodule assembly prior to operating the 70 K coolant systems.

gas with the 2.1 K exhaust gas and then J-T expanding the pre-cooled input to drop the 3 bar supply pressure to 32 mbar for 2 K liquefaction [15]. The manifolds, heat exchanger and reservoirs these coolant streams occupy are all designed to comply with ASME B31.3, the process piping standard [16], and the ASME BPVC. All systems have their own independent relieving system sized for the Maximum Allowable Working Pressure (MAWP). The safety reliefs are all located outside of the cryomodule and vent to atmosphere. In this manner the pressure systems of the cryomodule are separated from the insulating vacuum vessel. This allows us to define the cryomodule box as a vacuum vessel since it is not part of any pressure system boundary, saving considerable design and fabrication costs.

The FNAL safety requirements do not make the ASME BPVC mandatory for vacuum vessels but recommend applying the rules anyway. Because of this the design was developed using the requirements of the ASME BPVC even though the code explicitly excludes devices with static pressure gradients less than 15 psi. This analysis method allowed for relatively rapid evaluation of the complex vacuum vessel design which resulted in significant time-savings relative to traditional hand-based calculations. The ASME BPVC Section VIII Division 2 gives the required procedures for analyzing the 304 SST vessel material properties (yield and ultimate strengths), strain limits, buckling load factors, cyclic loading and collapse criteria. These analysis procedures, when combined with the ASME fabrication and inspection requirements, protect against failure modes of the device: plastic collapse, local failure, buckling and cyclic loading. We performed our analysis following these requirements and the results are reviewed below.

The vacuum vessel is evacuated to <1e-6 Torr and a static pressure gradient of ~14.7 psi will exist in operation rounding up gives a 15 psi MAWP which is used for all analyses. All simulations presented here were done with ANSYS [17]. The assembly was restrained by placing constraints equivalent to the kinematic mounting system designed for the vessel. The model analyzed was loaded with the weight of all elements and appurtenance loads.

Several analyses were performed to protect against cryomodule failure. The first one is a static structural analysis of an elastic-perfectly-plastic vessel model which demonstrated the design was protected against plastic collapse and predicted the deflections due to evacuating the vessel, which the vessel passes. Figure 3 shows the cryomodule vessel deflections from the elastic analysis. Some local high membrane stresses are predicted but do not fail under cyclic loading or the limit load analysis. These stress concentrations are located on the reinforcing gussets where the largest bending occurs, the weld joint between the cryomodule end-walls and side-walls and on the 4 mounts on the base of the cryomodule.

Cryomodule Assembly Update

Most of the parts required to finish the HWR cryomodule assembly are in hand at ANL. A practice assembly is conducted immediately before the final cleaning of the cryomodule components, such as the cavities, started in September 2016. At the writing of this paper 5 of the 8 cavities and all of the solenoids have been installed and aligned on the titanium strong-back rail system which supports them in the box assembly. Figure 4 shows the cavities and solenoids on the titanium strong-back.

ISBN 978-3-95450-169-4

Over the next 3 months the remained of the cryomodule

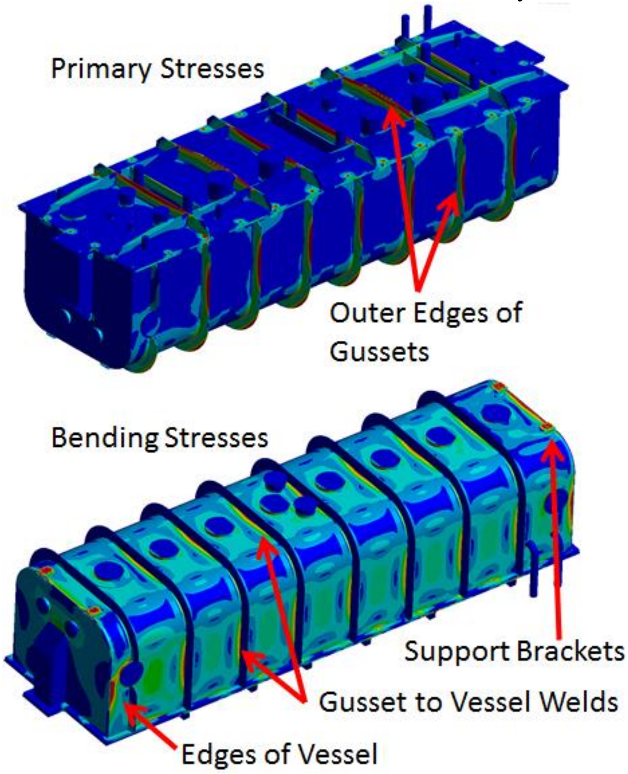

Figure 3: Vacuum vessel membrane stresses using an elastic material model for the 304 SST. (Top) Primary stresses. (Bottom) Bending stresses. Areas of high stress, 20 ksi for primary and 30 ksi for secondary stresses as set forth in the ASME BPVC, are specified with arrows and labels.

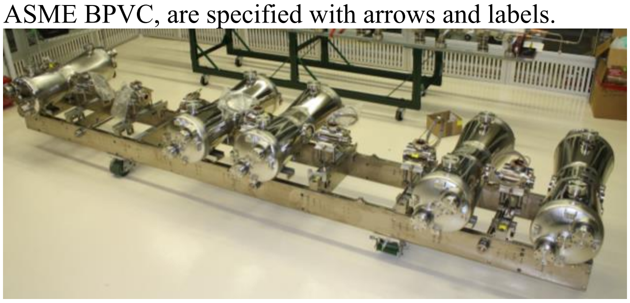

Figure 4: The cavities and solenoids on the Ti strong-back.

assembly will be finished and then disassembled. The disassembled components will then be cleaned for the final low-particulate assembly.

CAVITY PERFORMANCE

Upon cooling to liquid helium temperatures and a few minutes of conditioning low-level multipacting, the performance shown in Fig. 5 was measured for the 6 HWRs tested to date. The cavities were operated continuous wave, and unity coupling, at all accelerating gradients shown. There was no observable field emission, next to the test cryostat on the inside of the test cave, up to peak surface electric field of 70 MV/m for all tests. Three of the six cavities had no measureable field emission up to 90 MV/m. At the nominal design gradient of 9.7 MV/m (2 MV/cavity) at 2.0 K [3] the measured RF losses are ≤ 1 W for all cavities.

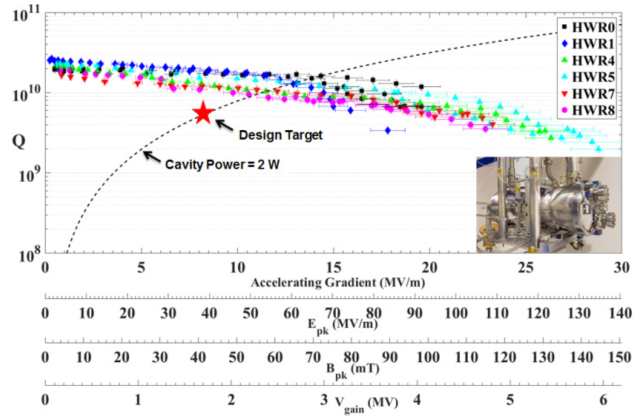

Figure 5: Measured 2.0 K HWR performance.

ACKNOWLEDGMENT

We would like to thank G. Wu, A. Rowe and M. Merio of FNAL for providing much needed help with the hydrogen degassing of all 6 HWRs prior to 2.0 K cold testing.

REFERENCES

[1] "Proton Improvement Plan-II," projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1232, Dec. 2013.

[2] P. Derwent, S. Holmes, and V. Lebedev, "An 800 MeV superconducting linac to support megawatt proton operations at FNAL," in *Proc. 27th International Linear Accelerator Conf. (LINAC'14)*, Geneva, Switzerland, Aug. 2014, paper THIOA05, pp. 807.

[3] "The PIP-II Reference Design Report," http://pip2-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=1&filename=PIP-II_RDR_v0.0.pdf&version=1, June 2015.

[4] E.J. Prebys et al., "Long term plans to increase FNAL's proton intensity to meet the needs of the long baseline neutrino program," in *Proc. 7th Int. Particle Accelerator Conf.* (IPAC'16), Busan, Korea, May 2016, paper TUOAA03, pp. 1010.

[5]S. Nagaitsev et al., "PXIE Design Handbook," http://projectx-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=1148&filename=Design%20Handbook_v1_01.pdf&version=5, Jan. 2013.

[6] J.D. Fuerst, "The ATLAS energy upgrade cryomodule," in *Proc. 14th Int. Conf. on RF Superconductivity* (SRF'09), Berlin, Germany, Sept. 2009, paper MOOCAU04, pp. 52.

[7] M.P. Kelly et al., "Commissioning of the 72 MHz quarter-wave cavity cryomodule at ATLAS," in *Proc. 27th Linear Accelerator Conf.* (LINAC'14), Geneva, Switzerland, Aug. 2014, paper TUPP002, pp. 440.

[8] Z.A. Conway et al., "A new 2 Kelvin superconducting half-wave cavity cryomodule for PIP-II," *IOP Conf. Series: Mat. Sci. and Eng.* Vol. 102, pp. 012019, 2015.

[9] S.M. Gerbick et al., "A new electropolishing system for low-beta SC cavities," in *Proc. 15th Int. Conf. on RF Superconductivity* (SRF'11), Chicago, IL, U.S.A., July 2011, paper WEIOA03, pp. 576.

[10] R.C. Murphy et al., "A flexible system for the high pressure rinsing of SRF cavities," in *Proc. 15th Int. Conf. on RF Superconductivity* (SRF'11), Chicago, IL, U.S.A., July 2011, paper TUPO034, pp. 456.

[11] P. Kneisel, B. Lewis, and L. Turlington, in *Proc. 6th Workshop of RF Superconductivity* (SRF'93), Newport News, VA, U.S.A., October 1993, pp. 628.

[12] R. Casey et al., "Vacuum Vessel Consensus Guidelines for Department of Energy Accelerator Laboratories," *BNL Report*, BNL-81715-2008-IR, 2008.

[13] Fermi National Accelerator Laboratory Environment, Safety and Health Manual (Batavia, IL: Fermilab) `esh.fnal.gov/xms/ESHQ-Manuals/FESHM`

[14] American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section VII, 2010.

[15] V. Ganni and P. Knudsen, "Optimal design and operation of helium refrigeration systems using the Ganni cycle," *AIP. Conf. Proc.* vol. 1218, pp. 1057, 2010.

[16] American Society of Mechanical Engineers Process Piping Standard B31.3, 2010.

[17] ANSYS® Mechanical, Version 13, Build date 11/2/2009, Ansys, Inc., Pittsburg, PA.

ISBN 978-3-95450-169-4