A new 2 Kelvin Superconducting Half-Wave Cavity Cryomodule for PIP-II

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Abstract. Argonne National Laboratory has developed and is implementing a novel 2 K superconducting cavity cryomodule operating at 162.5 MHz. This cryomodule is designed for the acceleration of 2 mA H⁻/proton beams from 2.1 to 10 MeV as part of the Fermilab Proton Improvement Project-II (PIP-II). This work is an evolution of techniques recently implemented in two previous heavy-ion accelerator cryomodules now operating at Argonne National Laboratory. The 2 K cryomodule is comprised of 8 half-wave cavities operated in the continuous wave mode with 8 superconducting magnets, one in front of each cavity. All of the solenoids and cavities operate off of a single gravity fed 2 K helium cryogenic system expected to provide up to 50 W of 2 K cooling. Here we review the mechanical design of the cavities and cryomodule which were developed using methods similar to those required in the ASME Boiler and Pressure Vessel Code. This will include an overview of the cryomodule layout, the alignment of the accelerator components via modifications of the cryomodule vacuum vessel and provide a status report on the cryomodule assembly.

1. Introduction

Fermi National Accelerator Laboratory’s (FNAL’s) PIP-II is a multi-faceted project dedicated to increasing the available proton beam intensity for high energy physics experiments [1]. One portion of PIP-II is the fabrication of a high-intensity, 1 mA, H⁻ linear accelerator which will phase-out the now 40 year old 116 MeV 200 MHz drift tube accelerator supplying all of the protons used by the US High Energy Physics experimental program. This upgrade is motivated by experimental need for higher-intensity high-availability proton beams for the investigation of fundamental physical phenomena at the intensity, energy and cosmic frontiers of high energy physics research.

A key phase of the PIP-II plan is the demonstration of the new accelerator front end. This involves the implementation of a negative hydrogen ion source, a room temperature RFQ, a superconducting Half-Wave Resonator (HWR) cryomodule and a superconducting single-spoke cavity cryomodule [2]. The focus of this paper is on the design and fabrication status of the HWR cryomodule. The HWR cryomodule is comprised of 8 162.5 MHz half-wave resonators optimized for ion velocities of 11.2% the speed of light and 8 superconducting 6 T solenoids with integrated x-y steering and bucking coils all operating at 2 K to accelerate H⁻ ions from 2.1 to 10 MeV [3]. The 3D model of the HWR cryomodule is shown in Figure 1 with the major sub-components labeled.
The half-wave resonator cryomodule is a modified version of our previous 4 K box-type cryomodules which have been in operation since 2009 [4] and 2014 [5]. Argonne box cryomodules rely upon the implementation of several techniques to achieve their high-performance levels, such as: electropolishing in the ANL low-beta EP tool [6], high-pressure high-purity water rinsing with clean-room handling [7] and separate cavity/insulating vacuum systems enabling a cryomodule design which enables the clean assembly to be hermetically sealed prior to installing the “dirty” subsystems of the cryomodule [8]. Here the technology has been extended to 2 K operation with the addition of a 2/5 K heat exchanger and a J-T expansion valve. The total 2 K thermal load is expected to be 50 W, of which 25 W are from the 48 90 A conduction-cooled magnet leads.

The remainder of this paper will highlight select 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 [9], FNAL Safety [10] and the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) Section VIII [11] and (2) a brief update of the future fabrication plans leading to the operation of this cryomodule at 2 K.

2. Design Overview of the Cryomodule and Cavities

The first step in developing a new accelerator cryomodule is the accelerator design. During the accelerator design the accelerator component electromagnetic structures, locations and tolerances are defined. The design process for the half-wave cavities and cryomodule follow practices established within the Physics Division Linac Development Group at Argonne. Cavity geometries are optimized using CST Microwave Studio [12] and the cryomodule’s accelerator lattice is developed using TRACK [13]. With a finished accelerator design the mechanical optimization of the accelerator components begins with detailed structural analyses of the their geometries and balance the operational requirements with safety guidelines defined by Fermi National Accelerator Laboratory’s Environment, Safety and Health Manual (FESHM). In the remainder of this section we will review this work for the cavities and the cryomodule.

2.1 Cavities

The cavity mechanical design is performed using Autodesk Inventor and ANSYS. The complete niobium cavity with integral stainless steel helium vessel geometry is modelled to analyse the system response to fluctuations in helium system pressure, appurtenance loading of the slow-tuner and the
safety of the design. Figure 2 shows a cut-away view of the cavity together with an image of the finished hardware.

The regions of the cavity with appreciable surface electromagnetic fields are formed from high-purity (Residual Resistance Ratio, RRR > 250) 0.125"±0.010" thick niobium sheet and are the cavity outer conductor, inner conductor, toroid ends, re-entrant noses, re-entrant nose doubler plates and coupling port extension tubes. Please note that the re-entrant nose doubler plates are made from the same size sheet as the re-entrant noses and both parts are made from RRR > 250 niobium to avoid mixing low-/high-purity sheets in fabrication even though the doubler plates are completely shielded from the cavity electromagnetic fields. The toroid gussets were machined from ½” thick RRR ~ 25 niobium plate while the beam ports (RRR > 250), coupling ports (RRR ~ 25) and inner conductor drift tube (RRR > 250) were machined from bar stock. The sheet niobium forming and subsequent machining was done by Advanced Energy Systems in Medford, New York, and Adron EDM in Menomonee Falls, Wisconsin. The machining of the bar stock was done by Numerical Precision in Wheeling, Illinois, while the toroid gussets were wire-electrostatic discharge machined (EDM) at Adron EDM.

The integral helium vessels surrounding the niobium cavity are fabricated using 304L stainless steel (SST). Niobium-to-stainless steel braze transitions [14] are utilized for joining the SST helium jacket with the niobium cavity at seven locations: 2 for the beam ports, 1 for the power coupler port and 4 for the toroid coupling ports. The cavity mechanical structure is designed to satisfy FNAL’s safety requirements. These requirements include the niobium within the pressure boundary, prohibiting the application of any class of ASME U-stamp. To provide an equivalent level of safety in the design the analysis performed uses the techniques and rules set forth by the ASME boiler and
pressure vessel code Section VIII, Division 2, Part 5, Design by Analysis with niobium material properties given in [15]. Using this the ASME BPVC was applied to the complete niobium/SST structure to demonstrate protection against failure for a 2 bar Maximum Allowable Working Pressure (MAWP) at 293 K and a 4 bar MAWP at 2 K; we found that any analysis which passed with the 293 K material properties and 2 bar MAWP would pass at 2 K, even with the greater MAWP. This is due to the increased low temperature strength of the niobium material. The cavity region with the smallest factor of safety, but still an acceptable one, is the area around the inner conductor drift tube. This region was reinforced by increasing the wall thickness of the solid rod used to fabricate the inner conductor drift tube. The thicker wall reinforced the area ensuring safe operation above the safety analysis requirements. Figure 3 shows the cavity niobium strain from a limit-load analysis. The central portion of the inner conductor is the most susceptible to plastic collapse but still exceeds the FNAL safety requirements.

2.2 Cryomodule

The overall design of the half-wave cavity cryomodule is an evolution of the top-loaded box cryomodules used successfully for an energy upgrade of ATLAS in 2009 [4] and for an intensity upgrade of ATLAS in 2014 [5]. The half-wave cavity cryomodule is assembled in stages. First, the low-particulate clean assembly of the cavities, RF power couplers, RF pick-up probes, solenoids, beam-line gate valves, vacuum manifold and titanium strong-back support structure is carried out in a Class 100 clean room. This assembly is hermetically sealed and removed from the clean room. This separates the “clean” low-particulate beam-line vacuum system assembly from the “dirty” portions of the cryomodule assembly work, preserving, to the best of our ability, the cavity performance. Once out of the clean room the helium distribution system will be installed and the assembly is then hung from the lid of the cryomodule. Once hung, the remainder of the cryomodule subsystems are installed such as the slow tuners, instrumentation, alignment targets, solenoid conduction cooled leads, thermal intercepts and RF transmission lines. The complete lid assembly is then lowered into the lower vacuum vessel completing the cryomodule.

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. The vacuum vessel has two cryogenic input coolant streams: (1) 5 K 3 bar gaseous helium 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

![Figure 3](imageURL). Niobium material strain from a limit-load analysis of the half-wave cavity. Areas of high strain are around the ports and in the center of the inner conductor where the beam passes. No strain values are given due to the unrealistic material properties used in a limit-load analysis.
room temperature. The 5 K helium coolant stream is split for two separate purposes in the cryomodule. One 5 K branch is used for thermal intercepting while the second branch is used for the production of 2 K helium. 2 K is achieved by heat exchanging the input 5 K helium 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. 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 following 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 2010 release of the ASME BPVC Section VIII Division 2, Part 5, 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 here.

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 and used a model with no symmetry planes. The assembly was restrained by placing constraints equivalent to the kinematic mounting system designed for the vessel. The model analyzed was also loaded with the weight of all elements and appurtenance loads.

Several analyses are presented here. The first 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. Figure 4 shows the cryomodule vessel deflections from the limit load analysis, which the vessel passes. Most areas display stresses well below the allowable for both membrane and bending analyses. Some local high membrane stresses are predicted, and Figure 5 shows the primary membrane stress results from a linear elastic analysis of the cryomodule. Contour levels in Figure 5 have been adjusted such that all stresses over 20 ksi are red and are indicated with labels. 20 ksi represents the allowable limit for 304 SST in the ASME BPVC at room temperature. The 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.

Beyond demonstrating that the design protects against plastic collapse the ASME BPVC requires several other analyses to demonstrate that a design protects against local failure, buckling and cyclic loading. The local failure analysis requires that at each point in the component the sum of the primary membrane and the principle bending stresses shall not exceed 4 times the allowable stress or 80 ksi for 304 SST. This was trivially satisfied with an elastic-material analysis at all locations. Protection against collapse from buckling must also be demonstrated for a vessel with a compressive stress field under the design loads. A bifurcation buckling analysis was performed using an elastic 304 SST material model free of geometric nonlinearities in the solution to determine the pre-stress in the vessel. The acceptance criterion is that the buckling load factor be greater than 2/β_cr where β_cr is the capacity reduction factor given in the ASME BPVC. Since the vessel contains ring stiffened cylinders under external pressure, β_cr = 0.80 and the minimum required buckling load factor is 2.5. The lowest buckling mode load factor was found to be 3.17 exceeding the minimum requirement of 2.5 predicting that the device will not buckle under the applied loads. Finally, the ASME BPVC requires that the
Figure 4. Limit-load analysis deflection. The labelled area on the side of the cryomodule corresponds to a simulated deflection of 0.269". The measured deflection during the first pump-down found it to be 0.240" giving good confidence that the vessel exceeds our design expectations.

Figure 5. 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.
vessel will not fail under cyclic loading. The cyclic loading analysis requires two evaluations: one to protect against high cycle fatigue and another to protect against ratcheting. The evaluation for high cycle fatigue is not required if the total number of cycles is low as defined in the code. We expect to have only 80-100 full and partial loading cycles over the lifetime of the vacuum vessel, which does not come close to the cycle requirement of >1,000, the level where a more detailed analysis is required. Because of this we determined that we satisfied the high-cycle fatigue loading requirements. A ratcheting analysis evaluates the performance of the device if the material stresses exceed yield. This analysis was done and demonstrated Protection Against Ratcheting.

The half-wave cryomodule was fabricated by Meyer Tool and Manufacturing in Oak Lawn, Illinois. Meyer Tool assembled the magnetic shielding and the 70 K radiation shielding with 32 layers of MLI on the exterior and 16 layers on the interior sides as part of the fabrication contract. Figure 6 shows the complete vacuum vessel at Argonne.

3. Cryomodule Design and Alignment
The above analyses give confidence that the half-wave cryomodule vacuum vessel is safe. Another constraint in this design which falls outside the scope of the safety analysis requires that the internal components aligned to ±0.250 mm are not perturbed in an unpredictable or large manner during the evacuation and cryogenic cooling of the vessel. Failing in either of these requirements will complicate the accelerator component alignment adding schedule time and hardware cost. The accelerator component motion due to the static differential vacuum pressure gradient across the vessel walls and the thermal contraction of cryomodule components was optimized by varying the design of the lid gussets and hanger locations.

The aligned components sit on a titanium strong-back which is hung from the lid via 6 hangers. Deflections of the hanger ports during evacuation will perturb the alignment. It is not feasible to make the ports to which the hangers attached infinitely rigid. Instead an additional gusset was added next to each pair of hangers. The distance of this gusset from the center of the hangers and the hanger locations were varied to minimize the differential hanger deflection. Initial differential deflections of the hanger ports exceeded 0.125° and 1°. After optimizing the lid gusseting the deflections were made as uniform as possible between each of the hanger attachment points. Figure 6 shows the deflections of the lid hanger ports where all of which move down by 0.080”±0.020” and the differential angular deflection has been reduced to 0.2 degrees. Overall this design is expected to perturb our overall alignment by ~0.030”. This offset will be measured during a test cooldown and compensated for by offsetting the accelerator components during assembly and, for monolithic deflections, by offsetting the entire box in the beamline.

4. Conclusion and Future Plans
Work to complete the assembly of the entire half-wave resonator cryomodule is underway. The design is an evolution of the successful 4K cryomodules built at Argonne over the past several years. We have kept the design features which aided previous work while modifying designs to accommodate the end-user, FNAL. Hardware fabrication is proceeding as allowed by funding. The half-wave cavity cryomodule is expected to be finished and delivered to FNAL in 2018.

Figure 6. Left, the finished cryomodule vessel at Argonne. Right, lid hanger port deflections
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