DEVELOPMENT OF A SUPERCONDUCTING HALF-WAVE RESONATOR FOR PXIE *

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Abstract

An ambitious upgrade to the FNAL accelerator complex is progressing in the Project-X Injector Experiment (PXIE). The PXIE accelerator requires 8 superconducting half-wave resonators optimized for the acceleration of 1 mA β = 0.11 H^- ion beams. Here we present the status of the half-wave resonator development, focusing particularly on cavity design, with a brief update on prototype fabrication.

INTRODUCTION

Project-X is based upon a 1-5 mA H^- linear accelerator to be constructed at FNAL to support advanced intensity frontier physics over the next several decades in the US [1]. The Project-X Injector Experiment (PXIE), is being designed, built and commissioned as a demonstration of the most critical R&D issues related to the front-end of the driver linac [2].

The PXIE project will include the beam source, LEBT, RFQ, MEBT, and two superconducting cavity cryomodules. The first superconducting cavity cryomodule will house 8 half-wave resonators, 8 magnets which integrate the focusing solenoids with x-y steering coils [3], and all of the necessary peripherals for operation, e.g., power couplers, slow tuners, etc. This half-wave cryomodule is being designed and built at Argonne National Laboratory.

The initial half-wave resonator design was presented in [4, 5], which contains the main cavity RF performance parameters. In this paper we update the status of the half-wave resonator design. We address methods of minimizing cavity frequency dependence on changes in external pressure (df/dP), simulations of the slow-tuner performance and the pressure safety analysis of the cavity.

MINIMIZING df/dP

The half-wave resonators in PXIE will be operated at 2 K. While this greatly reduces the external fluctuations in helium pressure relative to a 4 K cryogenic system, variations of 1-2 mbar are expected. To accommodate this, the cavities were designed to have a df/dP = 6 Hz/mbar. This enables operation with RF amplifiers of ~4 kW, requiring no mechanical fast tuner, at the desired accelerating gradient of 8.2 MV/m for a 1 mA beam current.

df/dP ~ 6 Hz/mbar is a good compromise minimizing the fabrication cost and complexity simultaneously with the df/dP, which results in a more stable and reliable accelerator system and smaller RF amplifiers. A 0.125 inch helium jacket with a df/dP = 6 Hz/mbar satisfies our design requirements, but we spent a little additional time to determine how we may zero df/dP if it proves necessary after prototyping or in future projects.

The cavity Nb design is the results of detailed electromagnetic studies and was taken as the starting point for our design [4, 5]. The cavity is formed from 0.125 inch thick Nb sheet. We have recent experience with using 0.125” and 0.187” thick stainless steel helium jackets on superconducting cavities. We prefer to use 0.125 inch thick stainless steel but were unsure of its effect on df/dP. The cavity is shown in figure 1. Table 1 gives the results of varying the stainless steel material thickness of this model.

A novel technique to reduce df/dP is to add a flat or a dish to the side of the cavity in the high-electric field region. This increases the negative frequency shift due to deformations resulting from increases in the external pressure. Figure 2 shows a dish geometry in a half-symmetry cavity model and its displacement, please note that the helium jacket is not shown in this picture. Table 2 gives the results of varying the dish depth, where the depth is measured inward from the cavity surface. The peak surface electric field was not increased by more than 2% in these simulations.

Notice that df/dP may be controlled in finished cavities by choosing a dish which yields df/dP < 0. The dish may then be stiffened with a small gusset which may be subsequently weakened via machining to tune df/dP to zero. A similar gusset weakening procedure was employed in [6].

SLOW-TUNER PERFORMANCE

Our half-wave resonator design is highly re-entrant at the beam ports. This breaks the cylindrical symmetry in the high-electric field region which, in the past, has limited the slow-tuning range of half-wave cavities squeezed at the beam ports. We will employ the pneumatic ANL slow-tuner design discussed in [4]. Our simulations found that the tuning sensitivity for an applied force will be 84 kHz/kN for the 0.187 inch thick and 93 kHz/kN for the 0.125 inch thick helium jackets. The later sensitivity will be verified with the prototype cavity which is under construction.

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Figure 1: The half-wave cavity. (Top) the helium jacket. (Bottom) the niobium parts of the cavity.

Table 1: df/dP Dependence on Helium Jacket Thickness

Wall Thickness (inches)	0.125	0.187	0.250	0.312”
df/dP (Hz/mbar)	6.0	6.8	7.1	7.2

PRESSURE SAFETY

A critical design constraint is proving that the cavity design satisfies the FNAL pressure safety guidelines. The pressure safety analysis follows the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) [7]. To satisfy these requirements we successfully demonstrated:

- That the cavity assembly is structurally stable under loading
- That the cavity structure will not buckle.
- That the cavity will not fail due to localized stresses.
- That the cavity will not fail due to thermal or pressure cycling and the fatigue associated with it.

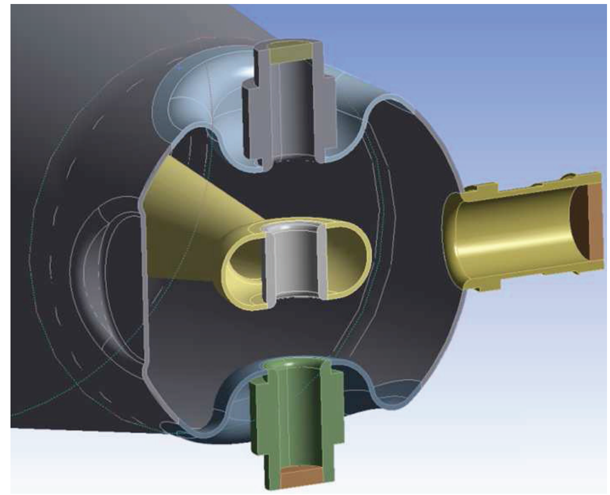

Figure 2: Dish in half-symmetry model of cavity.

Table 2: df/dP Dependence on Dish Depth

Depth (cm)	None	0.5	1	3
df/dP (Hz/mbar)	6.0	5.9	5	2.5

The room temperature and 2 K material properties we used for the simulations are given in [8]. For the design, the maximum allowable working pressures are given, by FNAL for this project, to be 2 bar at 293 K and 4 bar at 2 K.

The limit-load method specified in the BPVC, which uses an elastic-perfectly plastic material model (Figure 3), was used to check for plastic collapse. Plastic collapse is indicated if the ANSYS program fails to converge on a stable solution. The assumption of perfectly plastic response and the use of load factors to account for modelling uncertainty produce a fairly conservative result. Under all loading conditions, the analysis converged on a structurally stable solution, demonstrating protection against plastic collapse. This is largely due to the fact that high stresses were localized, and loads were easily transferred to the rest of the structure after plastic action at these locations.

Figure 4 shows the niobium stress when applying the maximum allowable working pressure at room temperature with a few almost negligible loads (e.g., the weight of the slow tuner and helium gas). Notice that the regions of maximum stress occur around the doughnut shaped center conductor. This is due to the inner conductor pushing in on the doughnut. The toroids on either end of the cavity roll inward upon pressurizing the helium space, a mode which may result in the buckling of the center conductor. The results at 2 K and for the helium jacket are not shown since they resulted in much higher levels of safety.

A linear-elastic pre-stressed eigenvalue buckling analysis was used to check for buckling. The BPVC specifies a baseline minimum buckling load factor, with additional capacity reduction factors applied to account for manufacturing uncertainty in cylindrical and spherical

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sections. The load factor calculated by ANSYS for the first mode was 4.57, with buckling occurring in a cylindrical shell. After applying the appropriate capacity reduction factor, the required load factor was 2.5, for a safety factor with respect to buckling of 1.83. In the torispherical heads, a load factor less than this value (0ver 60) were extracted and none were found to show buckling in this area. Figure 5 shows two of the buckling modes found. These figures show normalized mode shapes, so they are snap-shots of the cavity during buckling and are not equilibrium solutions.

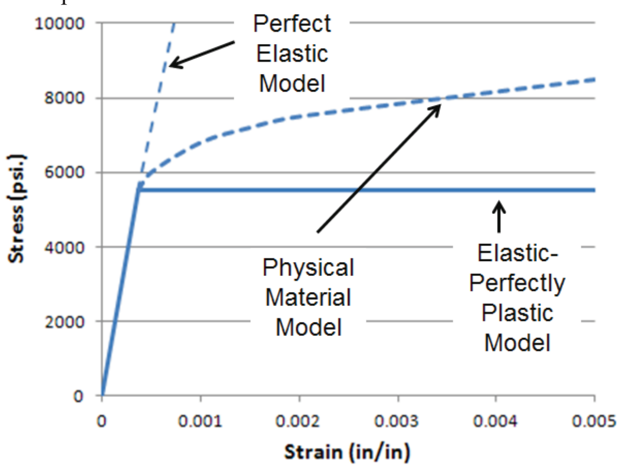

Figure 3: Material stress strain curves for Nb. For our plastic collapse simulations we used the elastic perfectly plastic material model.

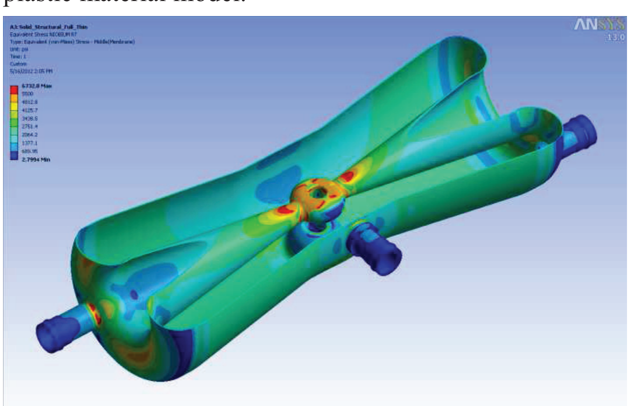

Figure 4: Niobium stresses at room temperature due to a static pressure gradient of 1.5 times the maximum allowable working pressure. The maximum stress (red) is 6700 psi, the minimum (dark blue) is 3 psi.

FUTURE WORK

The cavity structural design is well understood in simulations. We are currently building two prototype cavities to develop our fabrication procedures and to benchmark our simulation results against experimental measurements. We expect to finish the first prototype late summer 2013. Experimental results will be presented as they are collected.

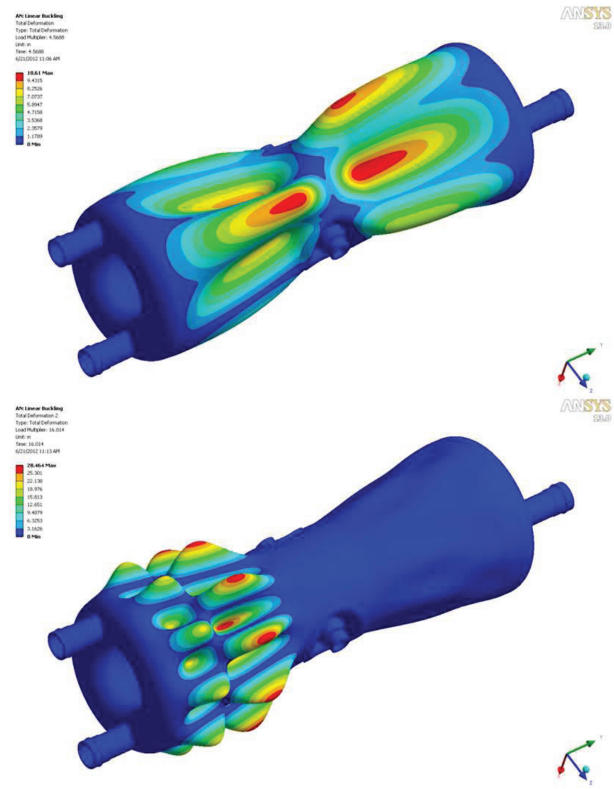

Figure 5: Two examples of buckling modes of the cavity. (Top) The mode with the lowest factor of safety; 1.8. (Bottom) factor of safety of 6.4 times the code requirement.

ACKNOWLEDGMENTS

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