DEVELOPMENT OF A HALF-WAVE RESONATOR FOR PROJECT X*

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Abstract

We have developed an optimized electromagnetic and mechanical design of a 162.5 MHz half-wave resonator (HWR) suitable for acceleration of high-intensity proton or H-minus beams in the energy range from 2 MeV to 10 MeV. The cavity design is based on recent advances in SRF technology for TEM-class structures being developed at ANL. Highly optimized EM parameters were achieved by adjusting the shapes of both inner and outer conductors. This new design will be processed with a new HWR horizontal electropolishing system after all mechanical work on the cavity including the welding of the helium jacket is complete. The prototype HWR is being fabricated by domestic vendors under ANL's supervision.

INTRODUCTION

Fermilab is developing a high-intensity CW H^- ion linac for fundamental research, this project is commonly known as Project X. The main design parameters of the linac as reported at PAC'11 [1] are listed in Table 1. The ion source and RFQ will be capable of producing and accelerating beam currents of up to 5 mA. A fast beam chopping system integral to the MEBT creates an arbitrary pattern of bunches defined by the beam time structure required for simultaneous operation of several experiments. The beam chopping reduces the average beam current to 1 mA. The RFQ frequency was selected to be lower than the linac frequency to reduce the RF power losses in a normal conducting CW structure to manageable levels. The Project X Injection Experiment (PXIE) is being pursued by Fermilab to demonstrate the most critical R&D issues related to the front-end of a CW high-power H^- and proton linac [2].

Table 1: Project X linac parameters

Parameter	RFQ	MEBT	Low energy	High energy
Frequency, MHz	162.5	325	325	650
Output energy, MeV	2.1	2.1	160	3000

162.5 MHz SC SECTION OF THE PXIE

The original design of PXIE included 325 MHz Single Spoke Cavities of type 0 (SSR0), to accelerate the H^- beam from 2.1 to 10 MeV. To maintain a high beam quality, adiabatically ramping the real-estate accelerating gradient is necessary. To satisfy adiabaticity, 3 cryomodules comprising 24 SSR0 cavities were required. We have developed an alternative design for the 10 MeV SC section of the linac based on 162.5 MHz HWRs. This design has several substantial advantages as compared to the 325 MHz SSR0 option:

- Only 8 HWRs are required to accelerate the beam to 10 MeV and maintain a high beam quality.
- Reduced rf defocusing due to both the lower frequency and the lower phase angle results in a much faster energy gain without emittance growth.
- Opens the possibility to use 162.5 MHz re-bunchers in the MEBT to allow for longer drift spaces for the fast beam choppers.
- Significant cost reduction due to the reduced component count.

ELECTROMAGNETIC DESIGN

The beam dynamics optimization has resulted in an optimal cavity beta of β_{OPT}=0.112. The cavity design is based on recent advances in SRF technology for TEM-class structures being developed at ANL. Highly optimized EM parameters were achieved using a conical shape for both the inner and outer conductors.

The highest performing HWR geometries use a center conductor with a race-track shaped cross section in the high-electric field region [3]. Detailed studies of the electric field distribution in the accelerating gaps revealed an appreciable defocusing quadrupole component of the electric field in the HWR with a race-track shape central conductor. The latter is not acceptable in high-intensity ion linacs with a solenoid-based symmetric focusing and leads to emittance growth. Therefore, we developed a "donut" shaped drift tube in the center conductor as is shown in Fig. 1. Table 2 summarizes the relevant cavity parameters for both center conductor geometries. An elliptical beam aperture in the central conductor could also significantly reduce the quadrupole

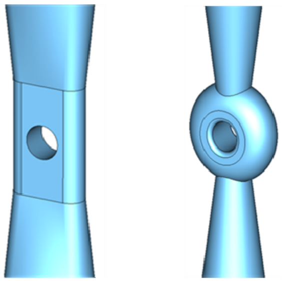

Figure 1: Two shapes of the central conductor have been studied: race-track (left) and donut (right).

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Table 2: Cavity main parameters

Parameter	Race-track	Donut
Frequency, MHz	162.5	
Optimal beta, β_{OPT}	0.112	
L_{EEF}= $\beta_{OPT}\lambda$, cm	20.7	
Aperture, mm	33×36	33
G = Q_0R_S, Ω	48	48
R/Q_0, Ω	199	272
E_{PEAK}/E_{ACC}	4.57	4.67
B_{PEAK}/E_{ACC}, mT/(MV/m)	5.7	5.0

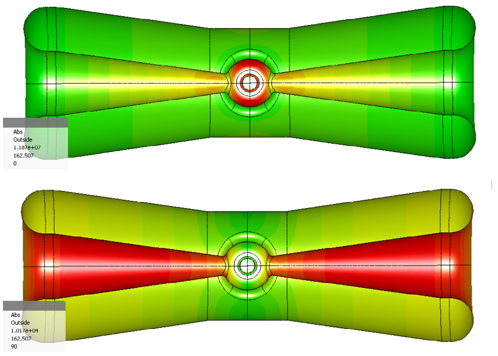

Figure 2: A half-wave resonator model in MWS. The electric (top) and magnetic field (bottom) distributions on the surface were obtained with tetrahedral mesh. Red is high intensity and green is zero.

component of the electric field in the race-track geometry while the aperture may remain circular in the "donut" geometry. A comparison of the quadrupole component in the relevant velocity range shows better performance with the donut geometry. In addition, the donut geometry has a higher shunt impedance as discussed in [4]. Figure 3 shows MWS results of the electric and magnetic surface field distributions in the "donut" HWR.

MECHANICAL DESIGN AND ENGINEERING ANALYSIS

The primary scope of the mechanical design of the cavity and its helium jacket is identical to that reported in our previous publication [3]. The engineering analysis was performed using the ANSYS multiphysics Finite Elemental Analysis (FEA) software. The cavity mechanical model including stainless steel helium vessel, RF coupler and slow tuner used for the FEA analysis is shown in Fig. 3.

Using the HWR in the PXIE, two major sub-systems are required: a 10-kW RF coupler and a slow tuner. A capacitive RF coupler has been designed and is being constructed [5,6] and will provide RF power through the port which is perpendicular to the beam axis (Fig. 3).

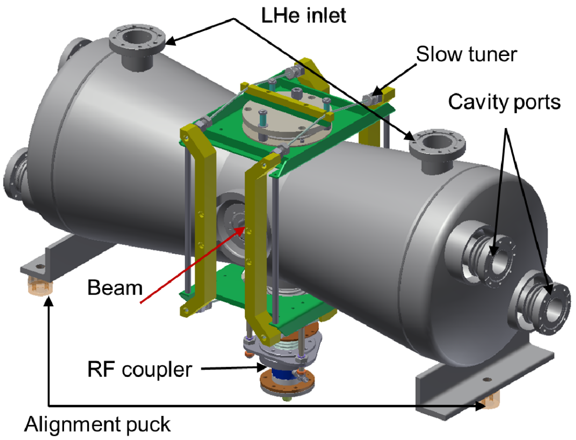

Figure 3: A cavity 3D model in INVENTOR.

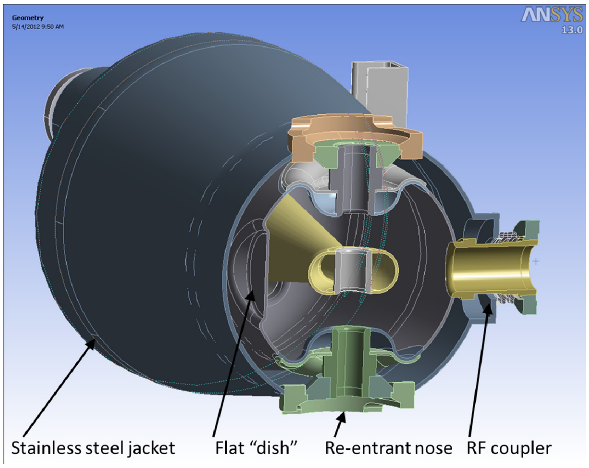

Figure 4: A half cavity model in ANSYS.

A pneumatically actuated mechanical slow tuner which compresses the cavity along the beam axis is located outside of the helium vessel and will be attached to the SS flanges shown in Fig. 3. The design of the slow tuner is based upon the slow tuner design used since 2009 in the Argonne ATLAS energy upgrade cryomodule [7]. A fast tuner is not required for the PXIE application once a 4 kW RF power source is available. This power is sufficient to support the 1 mA beam loading with an 80 Hz loaded bandwidth.

The engineering analysis of the cavity included simulations to evaluate the integrity of the cavity and protect against plastic collapse, buckling, and fatigue failure to ensure that the operating loads are below the maximum allowable limits. The maximum load is determined by the design pressure set by the operation of the cryogenic system and the pressure relief valve. The evaluation was performed for 30 psig at room temperature and 60 psig at 2 Kelvin in the helium space of the cavity. In general, the over pressure condition could occur during the initial cryogenic cooling with the cavity structure at or near room temperature; since the room temperature strength limits (i.e., yield and ultimate) are lower than for

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cryogenic temperatures and the operating margin is smaller here, the room temperature limits were studied in more detail. The stress analysis was performed in the presence of the slow tuner and other appurtenance loads. The final design exceeds all evaluation criteria for the niobium and the stainless steel (SS) parts respectively.

Two methods have been studied for minimization of the cavity frequency sensitivity to fluctuations of the helium pressure, $\partial f / \partial P$: (1) adding gusseting to reduce the cavity deflections in the high magnetic and electric field regions and (2) varying the depth of the flat dish located in the opposite side to the RF coupler port (Fig. 4). The results of these studies showed that no gusseting is required; a minimal value of $\partial f / \partial P$ =+1.4 kHz/atm was achieved by optimal choice of the flat dish penetration.

Simulations of the slow tuner were performed by applying a force to the SS flanges of the helium jacket. For example, a 10 kN force results in a frequency shift of -120 kHz.

The details of HWRs integration into the cryomodule are given elsewhere [8].

ELECTROPOLISHING

Recently, we have successfully applied electropolishing to a complete cavity with the integral helium jacket installed [9]. Excellent performance of the QWR [10] constitutes and advance in the state-of-the-art of this design approach, fabrication and RF-surface processing technique. The mechanics of electropolishing low-beta resonators, where the center conductor and outer conductor are coaxial, is somewhat similar to the highly optimized procedure for polishing elliptical cell cavities for the ILC. This is true, in particular, for HWRs. Fig. 5 shows an engineering model of the HWR installed into an existing EP apparatus. This new design will be processed with a new HWR horizontal electropolishing system after all mechanical work on the cavity, including the welding of the helium jacket, is complete.

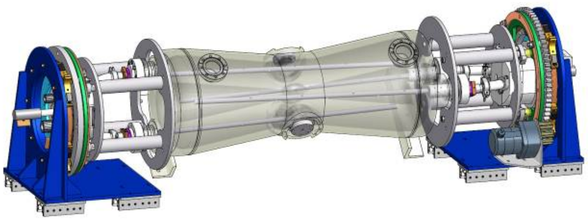

Figure 5: 3D model of the cavity with electropolishing cathodes inserted through two ports at each end.

HWR OPERATIONAL PARAMETERS

The proposed operational parameters for the new HWR are listed in Table 3 and based on our recent experience with the ATLAS energy upgrade cryomodule [7] and its long term operation. Recent tests of new 72 MHz cavities show significantly higher performance. Therefore, we expect that these HWRs can be reliably operated to provide accelerating voltages up to ~2.7 MV with a residual resistance below 10 nΩ, at the operating field level, and without large field emission. The expected performance parameters are shown in the 3rd column of Table 3. The peak fields shown in Table 3 were taken directly from the CST MWS screen in simulations with ~200K tetrahedral mesh cells.

Table 3: HWR operational parameters

Parameter	Design	Expected
Operating temperature, K	2	2
Accelerating voltage, MV	1.7	2.7
Peak electric field, MV/m	38	60
Peak magnetic field, mT	41	65
Residual resistance, nΩ	<5	<10
Stored energy, J	10.4	26

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