DEVELOPMENT OF COMPACT CRYOMODULES HOUSING HWRS FOR HIGH-INTENSITY SC CW LINACS*

P.N. Ostroumov#, Z.A. Conway, S. Gerbick, M. Kedzie, M.P. Kelly, S. Kim, S.V. Kutsaev, R. Murphy, B. Mustapha, T. Reid, ANL, Argonne, IL 60439, U.S.A.
S. Nagaitsev, Fermilab, Batavia, IL 60510, USA
D. Berkovits, Soreq NRC, Yavne 81800, Israel

Abstract

Acceleration of high-intensity, above ~10 mA, light-ion beams immediately after an RFQ requires a compact accelerating and focusing lattice with a high packing factor. We have developed a 6-meter long cryomodule for Project X at FNAL which satisfies this requirement. The cryomodule has eight accelerating-focusing periods, in each period one 162.5-MHz SC HWR and one SC solenoid. The solenoid has integral x-y steering coils, and a beam position monitor. The highly optimized EM parameters of the cavity were achieved with hourglass shaped inner and outer conductors. All sub-systems inside the cryomodule are in advanced stages of prototyping and testing. A similar concept has been developed for the design of several cryomodules for a 40 MeV proton/deuteron 200 kW linac at SNRC (Soreq, Israel). These cryomodules house two types of 176 MHz half-wave resonators and require only modest modifications of the Project X design. This paper will discuss the status of the FNAL cryomodule design and sub-systems fabrication and its implications for future HWR cryomodules such as those for the SNRC project.

INTRODUCTION

Technologies for SC RF successfully developed for the ATLAS efficiency and intensity upgrade [1-3] are being applied in future high-power CW accelerators. Particularly, we are developing and building the first cryomodule with β_{OPT}=0.11 HWRs for the Project X Injector Experiment (PXIE) at FNAL [4] and developing two cryomodules with different β_{OPT} for the SARAF accelerator facility at SNRC [5]. In this paper we discuss the status of the SARAF and PXIE cryomodule development.

In high-intensity light-ion accelerators, to reduce space charge effects, the fundamental frequency should be high as compared to heavy-ion linacs. SC HWRs are superior to QWRs at operational frequencies above ~150 MHz and optimal beta $\beta_{OPT} \geq 0.1$. The fundamental frequency of Project-X is 162.5 MHz which is defined by the RFQ. Therefore we are developing a cryomodule with 8 HWRs for the acceleration of H-minus ions from 2.1 MeV to 11 MeV [6]. Similar HWRs operating at 176 MHz are designed for the SARAF Phase II 5-mA proton and deuteron linac [7]. To increase the available accelerating voltage, the HWR shape is highly optimized reducing both B_{PEAK}/E_{ACC} and E_{PEAK}/E_{ACC} [8]. Optimization of the cavity shape was performed taking into account die-forming fabrication technology available from industry [9]. The final cavity shape has tapered central and outer conductors as was discussed in an earlier publication [8]. The confidence in the proposed HWR design and predicted performance is based on the very successful design, construction and testing of conical QWRs for the ATLAS upgrade. The results of the EM optimization are summarized in Table 1.

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#ostroumov@anl.gov

Table 1: HWR Performance Parameters

Parameter	PXIE	SARAF	
Frequency, MHz	162.5	176	
Operating temperature, K	2	4	
Optimal beta, β_{OPT}	0.11	0.089	0.16
$L_{EEF}= \beta_{OPT}\lambda$, cm	20.7	15.2	27.3
Aperture, mm	33	33	36
Accelerating voltage, MV	1.7	1.0	2.1
E_{PEAK}/E_{ACC}	4.7	5.3	4.7
B_{PEAK}/E_{ACC}, mT/(MV/m)	5.0	5.6	5.6
$G = Q_0R_S$, Ω	48	40	60
R/Q_0, Ω	272	231	296

DESIGN AND FABRICATION OF HWR

Below we discuss the mechanical design, fabrication status and plans for the RF surface processing for the PXIE HWRs. A similar approach is being applied to the SARAF HWRs. The primary scope of the mechanical design of the cavity and its helium jacket is identical to that reported in our previous publications [10]. Using HWRs in the PXIE requires two major sub-systems: a 15-kW RF coupler and a slow tuner. A capacitive RF coupler [11] was built and is being tested with 10 kW RF drive power. The RF power is provided through a port perpendicular to the cavity beam axis (Fig. 1).

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. 1 and 2. Simulations of the slow tuner were performed by applying a force to the SS

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flanges of the helium jacket. For example, a 10 kN force results in a frequency shift of -120 kHz.

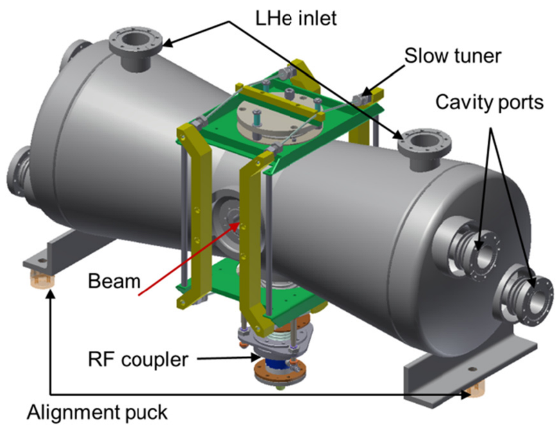

Figure 1: A cavity 3D model in INVENTOR.

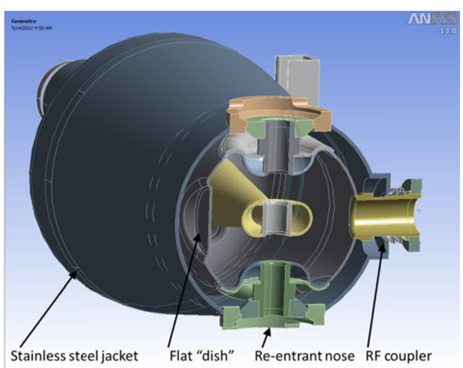

Figure 2: A half cavity model in ANSYS.

Minimization of the cavity frequency sensitivity to fluctuations in the helium bath pressure was achieved by optimizing a flat dish penetration as shown in Fig. 2. A fast tuner is not required for the PXIE and SARAF applications once 4-kW RF power supplies are available. This power is sufficient to support the 1 mA beam loading with an 80 Hz loaded RF bandwidth in PXIE HWRs. SARAF HWRs are designed to accelerate up to 10 mA CW beams therefore much higher loaded bandwidths will be available.

The engineering analysis was performed using the ANSYS multiphysics Finite Element 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. 1. 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 final design meets and exceeds all evaluation criteria for the niobium and the stainless steel (SS) parts respectively [12].

Currently, we are completing the fabrication of two HWR prototypes for PXIE. Fig. 3 shows the modelled and the actual cavity niobium parts. The fabrication process involves die forming of niobium parts, machining, wire EDM and electron beam welding (EBW). The helium jacket will be manufactured from 0.125"-thick stainless steel. Niobium-stainless steel braze transitions will be used to accommodate TIG welding of the helium jacket.

Four cavity ports shown in Fig. 1 will be used to accommodate electropolishing cathodes. Fig. 4 shows an engineering model of the HWR installed into an existing EP apparatus. The cavity 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 3: Modelled (left) and actual (right) niobium parts of the cavity.

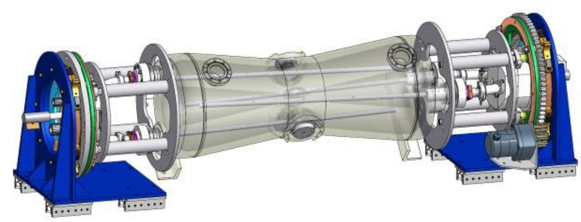

Figure 4: 3D model of the cavity with electropolishing cathodes inserted through two ports at each end.

CRYOMODULE

Both the PXIE and the SARAF HWR cryomodule designs are an evolution of the top-loaded box cryomodule used successfully in two ATLAS upgrades. The accelerator lattice of the PXIE and the first SARAF cryomodules was determined with careful beam-dynamics simulations and estimates of recently demonstrated cavity performance. As a result of these studies, each focusing period contains a solenoid-BPM-HWR sequence. Each solenoid is equipped with dipole coils for beam steering in both planes and integral return coils to damp external fields. The cryomodule design is developed around these requirements. The side cross-section view of the PXIE cryomodule is shown in Fig. 5. The compact design of the cryomodule provides 68.6 cm long focusing period.

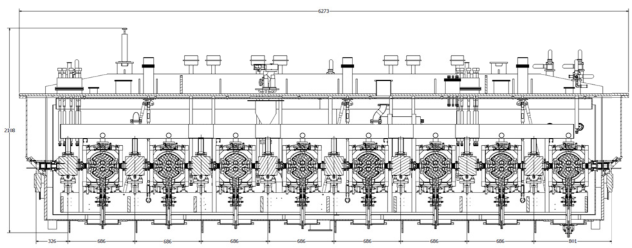

Figure 5: The side cross-section of HWR cryomodule for PXIE.

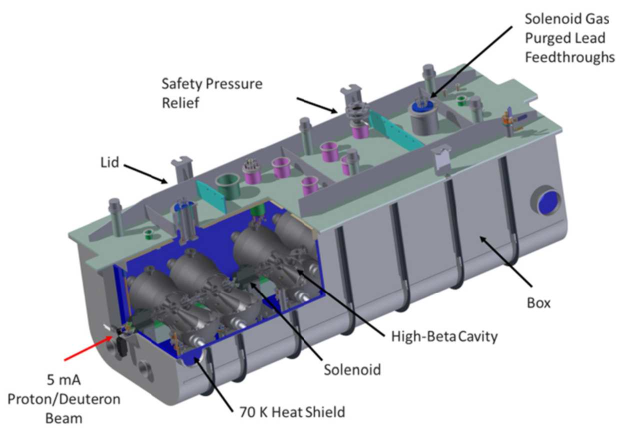

Figure 6: Assembly of the high-β cryomodule for SARAF.

The first cryomodule of the SARAF linac is similar to the PXIE cryomodule except it contains 7 focusing periods instead of 8, and it is designed to operate at 4K.

The remaining 3 SARAF cryomodules consists of 7 high-β cavities and 4 SC solenoids as shown in Fig. 6. The layout of the 40- MeV 5-mA proton & deuteron linac for SARAF is shown in Fig. 7.

PRODUCTION CAVITIES FOR PXIE

Niobium parts for all seven production cavities have been fabricated as is shown in Fig. 8. The major niobium sub-assemblies (toroids with extension tubes/gussets and port flanges, center conductors, and outer conductors/re-entrant noses) will be electron beam welded and ready for the welding of cavity assemblies by the time of testing of the prototype cavities in early 2014.

Figure 8: Nb parts for PXIE production cavities.

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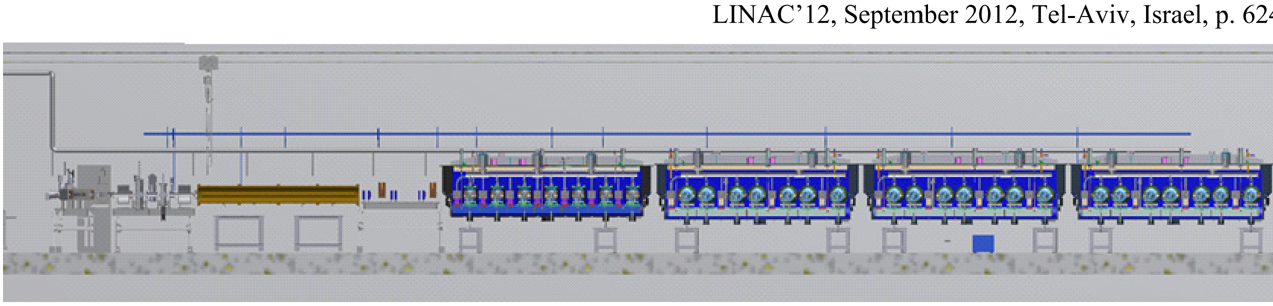

Figure 7: The side cross-section of SARAF 200 kW proton & deuteron linac.