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SUPERCONDUCTING ACCELERATING CAVITY PRESSURE SENSITIVITY ANALYSIS AND STIFFENING

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Abstract

The Soreq Applied Research Accelerator Facility (SARAF) design is based on a 40 MeV 5 mA light ions superconducting RF linac. Phase-I of SARAF delivers up to 2 mA CW proton beams in an energy range of 1.5 - 4.0 MeV. The maximum beam power that we have reached is 5.7 kW. Today, the main limiting factor to reach higher ion energy and beam power is related to the HWR sensitivity to the liquid helium coolant pressure fluctuations. The HWR sensitivity to helium pressure is about 60 Hz/mbar. The cavities had been designed, a decade ago, to be soft in order to enable tuning of their novel shape. However, the cavities turned out to be too soft. In this work we found that increasing the rigidity of the cavities in the vicinity of the external drift tubes may reduce the cavity sensitivity by a factor of three. A preliminary design to increase the cavity rigidity is presented.

INTRODUCTION

Phase-I of the Soreq Applied Research Accelerator Facility (SARAF) proton/deuteron linac is currently operational at Soreq Nuclear Research Center [1]. Phase-I of the linac has been built in order to study and prove novel acceleration technologies for intense CW beams. The SARAF Prototype Superconducting Module (PSM) houses six 176 MHz Half Wave Resonators (HWR) and three Super Conducting (SC) 6T solenoids. The PSM was designed and built by Accel/RI [2] (Fig. 1). The PSM accelerates protons and deuterons from 1.5 MeV/u to 4 and 5 MeV [1], respectively. The HWR nominal design goal was 850 kV for a 4 mA ion beam at β_{opt}=0.09. The HWRs were found to be highly sensitive to the coolant liquid helium pressure fluctuations. The measured HWRs sensitivity to helium pressure, 60 Hz/mbar, is an order of magnitude larger than currently designed similar shape cavities. Reducing the cavity sensitivity to the helium liquid coolant pressure fluctuations may enable SARAF Phase-I to reach a CW proton beam current and energy of 4 mA and 4 MeV, respectively.

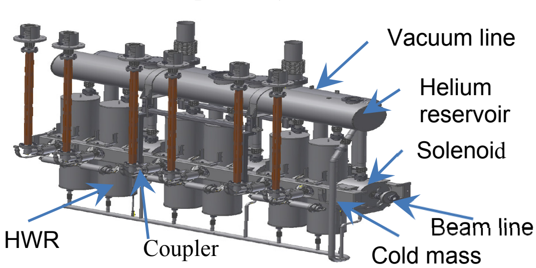

Figure 1: The inner parts of the 2.5 m long PSM.

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The 3 mm thick, single wall, bulk Nb superconducting cavity is assembled in a SS liquid helium (LHe) vessel (Fig. 2,3,4). The Nb cavity and the SS vessel are connected by bellows in the beam, vacuum and coupler ports.

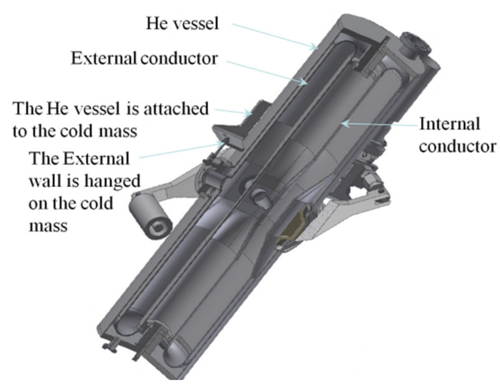

Figure 2: The HWR liquid helium vessel with the superconducting HWR assembly.

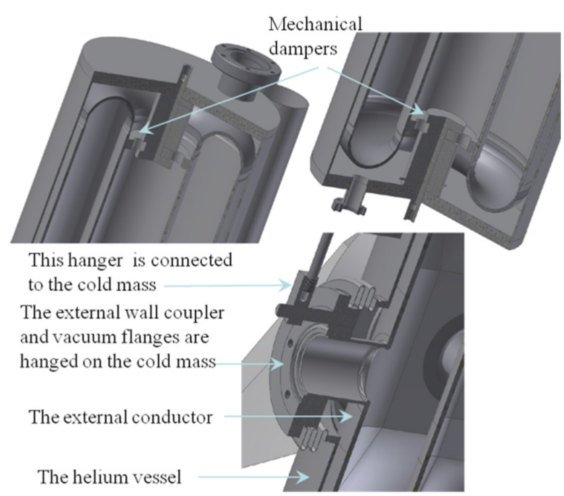

Figure 3: The top and bottom mechanical dampers fix the horizontal position of the HWR internal wall. The mechanical hanger fixes the position of the external wall, coupler and vacuum SS flanges.

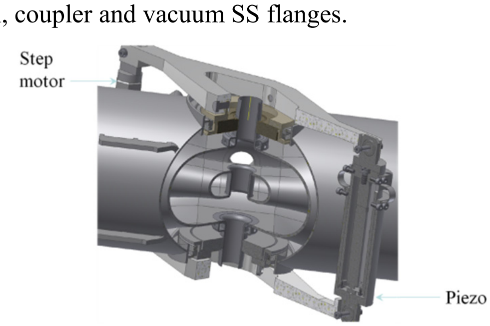

Figure 4: The piezo and step motor mechanical tuning system that controls the HWR resonance frequency [3].

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ANALYSIS

To analyse the effect of the HWR Eigen-mode frequency sensitivity to helium pressure, the following formula is used [4]: $P_g=\frac{V_c^2}{R_{sh}}\frac{(1+\beta)^2}{4\beta}\frac{1}{cos^2\varphi}\left\{\left[cos\theta+\frac{I_b R_{sh}}{V_c(1+\beta)}cos^2\varphi\right]^2+\left[sin\theta+\frac{I_b R_{sh}}{V_c(1+\beta)}cos\varphi sin\varphi\right]^2\right\}$ where P_g is the power required to excite the cavity, V_c is the cavity voltage, R_{sh} is the cavity shunt impedance, β is the cavity coupling constant, I_b is the beam current, θ is the relative phase angle between the point of maximum acceleration of the cavity RF and the center of the beam bunch being accelerated, and φ is the cavity detuning angle (microphonics).

The effect of cavity detuning, $\Delta f_{pk\text{-}pk}$, on its required RF forward power is given in Fig. 5. The detuning angle φ is evaluated by: $\varphi=\tan^{-1}(\Delta f_{pk\text{-}pk}/(f_0/Q_{load}))$. The cavity parameters in Fig. 5 are: $Q_0 = 5\times10^8$, $V_c = 850$ kV, $I_b = 4$ mA, $R_{sh}/Q_0 = 163$, $\beta = Q_0/Q_{ext}$ and a synchronous phase $\theta=-20^o$. Q_0 was measured at SARAF and R_{sh}/Q_0 was evaluated in the CST MWS [5] simulations.

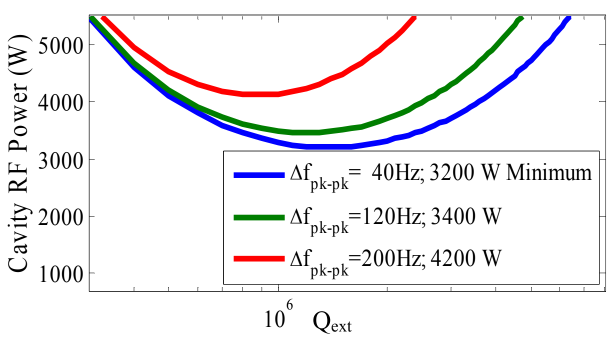

Figure 5: The required cavity RF power for 40, 120 and 200 Hz peak-to-peak microphonics detuning amplitudes, including helium pressure fluctuations.

As mentioned above, the measured sensitivity to helium pressure is 60 Hz/mBar as shown in Fig. 6. The cavity FWHM is: $2\Delta\omega=\omega_0/Q_{load}=130Hz$. The detuning signal is dominated by the helium pressure drift. Detuning sometimes exceeds +/-200 Hz (~ +/-2 BW).

The evaluation of the cavity Eigen mode frequency sensitivity to helium pressure fluctuation is based on the following:

The radiation pressure on the cavity surface due to EM fields is evaluated by [6]: $P=-(\varepsilon_0 E^2-\mu_0 H^2)/4$

The Eigen mode frequency deviation due to helium hydrostatic pressure induced HWR cavity surface deformation, is evaluated by [6]:

$$\frac{\Delta\omega}{\omega}=\frac{\Delta U}{U}=\frac{1}{4U}\int_{\Delta V}\left(\varepsilon_0 E^2-\mu_0 H^2\right)dV=\frac{1}{4U}\int_S\left(\varepsilon_0 E^2-\mu_0 H^2\right)\delta_{norm}ds$$

The HWR EM fields were simulated with CST MWS. The fields, shown in Fig. 7, demonstrate high electric fields in the vicinity of the flat shape of the external conductor around the beam line. In this region, the external conductor deformation, due to helium hydrostatic pressure, reaches the maximal value as shown in Fig. 8. The cavity evaluated sensitivity due to the asymmetrical radial structure in this zone is consistent with the HWR measured values (60 Hz/mbar). The simulated cavity sensitivity values are:

$$\frac{\partial f}{\partial P}=-60.6\,\frac{Hz}{mBar}$$

$$P=10\,mBar\ \Rightarrow\ \delta_{norm\ \ beam\ \ line}=-0.7\,\mu$$

$$\delta_{norm\ \ max}=-0.98\,\mu\qquad\sigma_{max}=0.56\,MPa$$

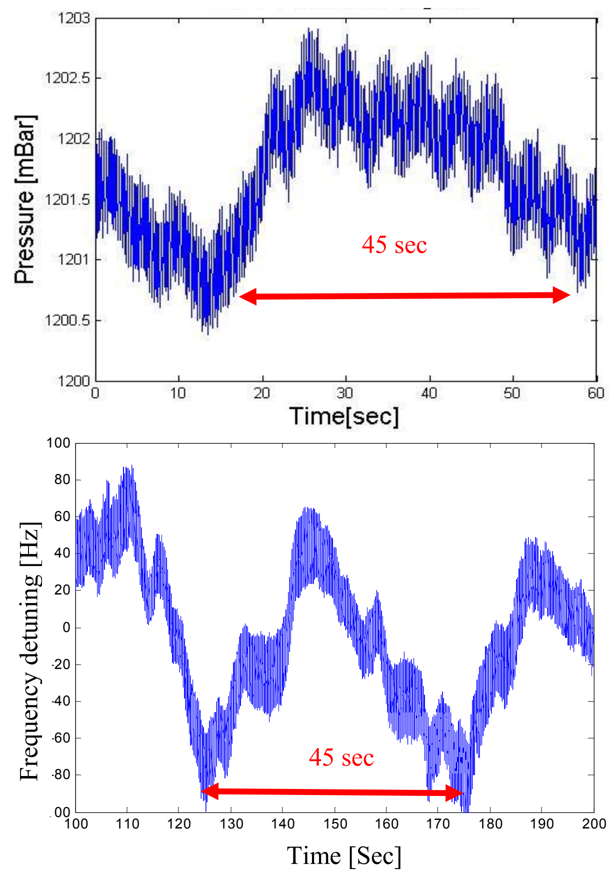

Figure 6: HWR Microphonics measurements.

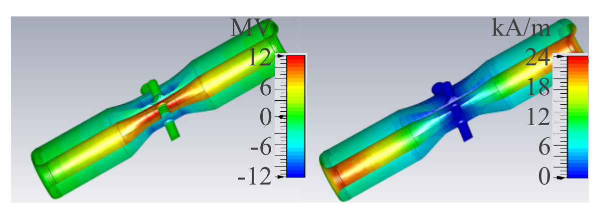

Figure 7: HWR E (left) and H (right) fields.

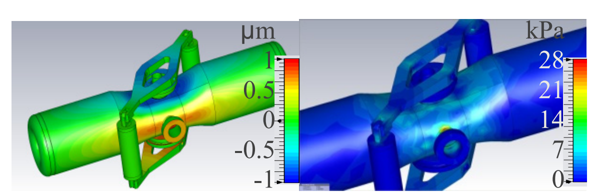

Figure 8: The normal deformation (left) and the stress (right) due to hydrostatic helium pressure.

Increasing the rigidity of the tuning fork and adding ribs at the vicinity of the beam line (Fig. 9) are the two measures to reduce the sensitivity of the HWR to helium pressure. The modified evaluated values are:

$$\frac{\partial f}{\partial P} = -21\frac{Hz}{mBar}$$
$$P = 10mBar \Rightarrow \delta_{norm\ beam\ line} = -0.15\mu$$
$$\delta_{norm\ max} = -0.38\mu \quad \sigma_{max} = 0.34Mpa$$

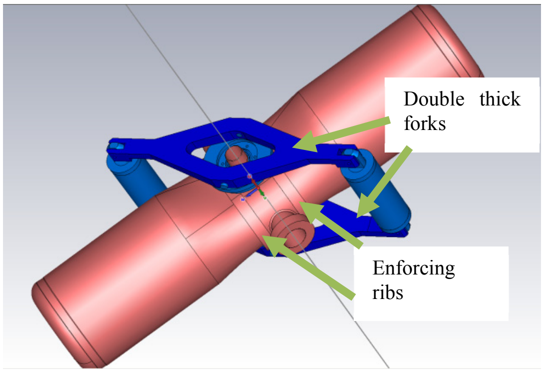

Figure 9: A double thick fork with enforced ribs at the cavity neck.

The tuning system cavity pretension effect to keep the piezo under pressure is demonstrated in Fig. 10. The demonstration is done for 200 µm tension displacement of both sides of the step motor and piezo (equivalent to a total 800 µm step motor expanding displacement) and 1.2 bar He pressure. This simulation may be used to explore the stresses on the cavity during the cool down and warm up procedures that are used in SARAF. The calculated sensitivity values for the original cavity and tuning system are:

$$P = 1.2Bar \quad \delta_{norm\ beam\ line} = 39\mu$$
$$\delta_{piezo\ step\ motor\ both\ sides} = 200\mu \Rightarrow \quad \delta_{norm\ max} = 39\mu$$
$$\sigma_{max} = 62.4MPa$$
$$\Delta f = -5.302kHz$$

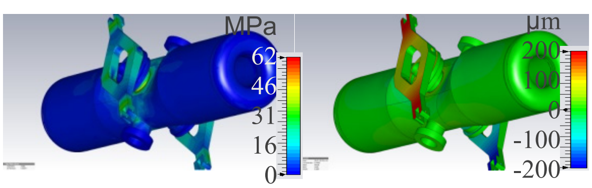

Figure 10: The HWR stress (left) and normal displacement (right) due to 200 µm pretension displacement of both sides of the step motor and piezo and 1.2 bar He pressure.

Table 1 summarizes the three simulations scaled to 1.2 Bar. It is shown that by increasing the rigidity of the cavity in the vicinity of the beam line, which is dominated by high electric fields, the displacement is reduced. The Eigen-mode frequency sensitivity to helium pressure is reduced as well. The third simulation demonstrates that cavity pretension enhances the cavity support by the tuning system and as a result the stresses in the cavity due to the helium pressure are reduced. Applying measures to reduce the sensitivity of the HWR to helium pressure is quite complicated. Adding ribs to the HWR enforces major disassembly of the PSM cold mass and disconnecting the HWR niobium cavities from the SS LHe vessel in a clean room. Replacing the fork with a stiffened one requires the opening the high vacuum beam line in the PSM. As an easier applicable alternative we explored stiffening the existing fork with minor disassembling of the PSM, as discussed below.

Table 1: The three simulated cases scaled to 1.2 Bar

Simulated Case	Δf (kHz)	σ_{max} (MPa)	δ_{beam} (µ)	δ_{max} (µ)
Original cavity	-73	67	84	120
Rigid cavity and fork	-25	41	18	46
Original cavity + 200µ tuning tension excitation	-5.3	62	39	39

A DESIGN OF A STIFFENED FORK

The mechanical tuning system has a very compact and tight design. In order to stiffen the HWR tuning fork we need to consider the limited space around the fork (Fig. 11). We designed a stiffened fork not malfunctioning the mechanical tuning system, and simulated both forks for bending [7]. We found that the new designed fork is 4 times stiffer (Fig. 12), while in the preliminary study (Fig. 9) we simulated an 8 times stiffer fork. The expected interpolated sensitivity for the stiffened fork is:

$$\frac{\partial f}{\partial P} =\sim -40\frac{Hz}{mBar}$$

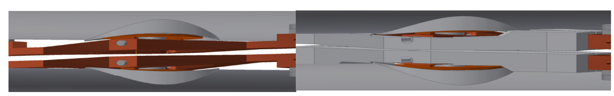

Figure 11: left – The original forks tight space, right – with the stiffened forks.

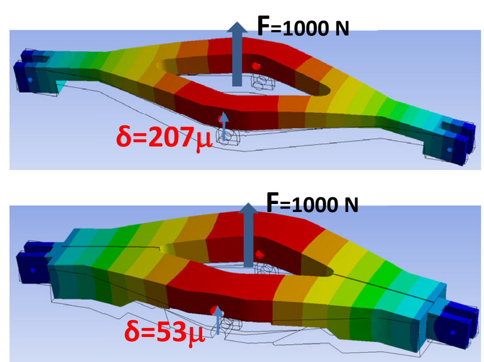

Figure 12: The original and the stiffened forks deflection due to bending.

SUMMARY

The measured sensitivity of the cavity was evaluated and it is fully consistent with the measured values. It was found that the tuning system (the fork structure) has a significant contribution to the cavity sensitivity. By using ribs or by modifying the rigidity of the fork the HWR sensitivity can be reduced. Cavity pretension, in order to keep the piezo under pressure, may relieve the stresses in the cavity due to the helium pressure. Further cool down and warming up stress analysis of the HWR cavity can be done using the tools and knowledge acquired in this work.

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