DESIGN OF SINGLE SPOKE RESONATORS FOR PROJECT X*

L. Ristori†, S. Barbanotti, M. Champion, M. Foley, I. Gonin, C. Grimm, T. Khabiboulline, N. Solyak, V. Yakovlev, Fermilab, Batavia, IL 60510, USA.

Abstract

Project X is based on a 3 GeV CW superconducting linac and is currently in the R&D phase awaiting CD-0 approval. The low-energy section of the Project X H^- linac includes three types of super-conducting single spoke cavities operating at 325 MHz. SSR0 (18 cavities), SSR1 (20 cavities) and SSR2 (44 cavities) have a geometrical beta of β = 0.11, 0.21 and 0.4 respectively. Single spoke cavities were selected for the linac in virtue of their higher r/Q values compared to standard Half Wave Resonator. Quarter Wave Resonators were not considered for such a high frequency.

In this paper we present the decisions and analyses that lead to the final design of SSR0. Electro-magnetic and mechanical finite element analyses were performed with the purpose of optimizing the electro-magnetic design, minimizing frequency shifts due to helium bath pressure fluctuations and providing a pressure rating for the resonators that allow their use in the cryomodules.

INTRODUCTION

The Project-X, a multi-MW proton source, is under development at Fermilab [1]. It enables a world-leading program in neutrino physics, and a broad suite of rare decay experiments. The facility is based on a 3 GeV, 1 mA, CW superconducting linac (see Figure 1). After the linac, about 5-9% of the H^- beam is accelerated in an SRF pulsed linac to the Recycler/Main Injector. The main portion of the H^- beam from the 3 GeV linac is directed to three different experiments.

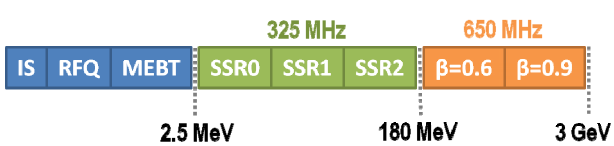


Figure 1: The Project X CW linac.

The beam originates from a DC H^- source. The beam is then bunched and accelerated by a CW normal-conducting RFQ to 2.5 MeV and the bunches are formatted by a chopper following a pre-programmed timeline. From 2.5 MeV to 3 GeV the H^- bunches are accelerated by a CW super-conductive linac. The CW linac consists of a low-energy 325 MHz SCRF section (2.5 - 180 MeV) containing three different types of single-spoke resonators (SSR0, SSR1, SSR2) having β = 0.11, 0.21 and 0.4, and two types of 650 MHz elliptical cavities having β = 0.6 and 0.9 (180 MeV - 3 GeV). The feature of the linac is small beam loading, and thus narrow cavity bandwidth. In Table 1 it is shown for each section the number of cavities, the maximal H^- energy gain for zero synchronous phase, and the bandwidth of the matched cavity. Since the bandwidth of the matched SSR cavities is only 20-40 Hz, microphonics are an issue. In order to mitigate microphonics, several means are typically used. First of all one can over-couple the cavity in order to increase the bandwidth. This leads to input power overhead. Another approach is to utilize active microphonics compensation (e.g., a fast tuning system). In any case it is beneficial to increase the mechanical stability of the cavity against helium pressure fluctuations, in other words decreasing the value of *df/dP* as much as possible (*f* is the cavity resonance frequency, *P* is helium pressure).

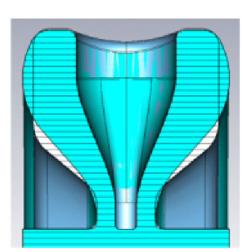
Table 1: Cavities for the Project X linac [2].

Section	Number of cavities/ c.modules	Max gain per cavity (MeV)	Minimum bandwidth (Hz)	Maximum loaded Q	Power per cavity (kW)
SSR0	18/1	1.0	35	9.2e6	1.0
SSR1	20/2	2.2	36	9.1e6	2.2
SSR2	44/4	3.9	24	1.3e7	3.9
LE650	42/7	11.6	21	3.1e7	11.6
HE650	152/19	17.4	24	2.7e7	17.4

SSR0

SSR0 is the smallest of the three single spoke resonators. With a geometrical beta of β = 0.11, two gaps measuring only 17.7 mm and a sensitivity of 1.8 MHz/mm to elastic end-wall deformations, it is also the most sensitive to helium bath pressure variations.

An initial optimization of the electro-magnetic design with a fixed cavity length of 175.5 mm, produced excellent field enhancement factors.



	Flat	Convex
β optimal	0.114	0.115
Diameter (mm)	416.5	406.8
R/Q (Ω)	108	109.2
G (Ω)	50	51
E_{max}/E_{acc}	5.63	5.66
H_{max}/E_{acc} (mT/MV/m)	6.92	6.83
$D_{eff}(2*\beta_{opt}\lambda/2)$ (mm)	105	106

Figure 2: Comparison between the original and convex RF design of SSR0. The final design is highlighted in blue. The table to the right shows that the main RF parameters were virtually unaffected.

---
* Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy.
† email: leoristo@fnal.gov

The resulting volume presented end-walls with flat areas that showed structural issues during the first analyses. In order to assure the integrity of the cavity, traditionally a 20 mm high donut rib is utilized on each end-wall. Given the tight longitudinal space constraints, it was decided to study an alternative RF design with a convex shape for this region to avoid the donut rib and reduce the overall cavity length. The space that we were able to save was about 10 mm per side. The comparison between the original design and the convex design is shown in Figure 2.

Features

The shape of the spoke evolves from a race-track section at the beam axis to an elliptical section at the intersection with the cylindrical body. The end-walls are axially symmetric with a profile composed of tangent curves. Other than a small area in the center of the spoke, the RF surface of this resonator is entirely curved. An exploded view of SSR0 is shown in Figure 3.

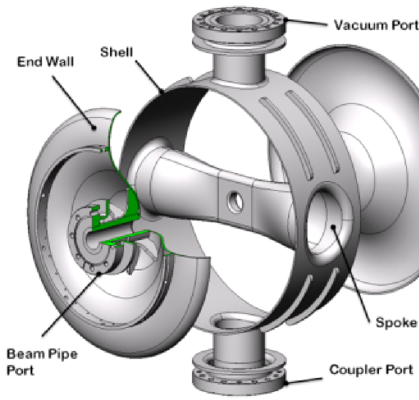


Figure 3: Exploded view of SSR0.

Sensitivity to Helium Pressure (df/dP)

In order to meet the requirements of a low sensitivity to helium pressure variations (< 25 Hz/torr), an extensive series of studies were performed to optimize the design of the system comprised of the cavity, the stiffeners and the helium vessel. The conclusion was that the end-walls of the cavity needed to be structurally coupled with the helium vessel walls similarly to what was done in [3]. An excerpt of those simulations is shown in Figure 4 where one can see the deformations due to a helium pressure of 1 atm. The beam pipe on the right is welded to the helium vessel, the one on the left is connected with a bellows. The main features that were studied and optimized to reduce df/dP were the diameter of the bellows and the diameter of the circular rib that connects the end-wall to the helium vessel.

The possibility is under investigation to adjust the df/dP of the cavity after the helium vessel is assembled and df/dP is measured. This could be achieved by adding or removing stiffening ribs on the helium vessel affecting the rigidity of the cavity-vessel system. Another option currently under study is to utilize a thicker wall for the helium vessel and later machine circular grooves to reduce its stiffness if necessary.

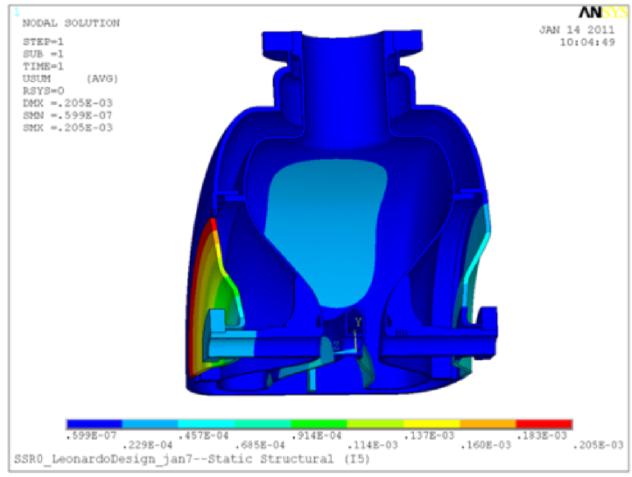


Figure 4: Optimization of the position of the circular rib to minimize df/dP. The left beam pipe is connected with bellows to the helium vessel, the right one is welded. This analysis produced a result of 5 Hz/torr.

Between the various options available for connecting the Niobium cavity to the Stainless Steel helium vessel, a bolted joint was selected. A groove in the niobium rib engages with a tooth on the steel rib providing the necessary precision and avoiding any slippage during operation. A cross section of this joint is shown in Figure 5. Prototypes of this connection will be subjected to thermal cycles and tensile tests to optimize the design and select the most appropriate hardware.

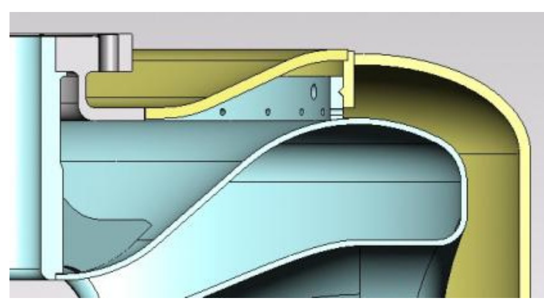


Figure 5: Details of the bolted connection between the end-wall and the helium vessel of SSR0.

The expected spring constant of the end-wall is 100 kN/mm. This high value is mostly due to the presence of this connection. With a requirement for the tuning range of 200 kHz and a sensitivity of 1800 kHz/mm, the maximum force that the tuner will need to produce is estimated to be 11 kN.

Pressure Rating

The necessary pressure rating (or MAWP, maximum allowable working pressure) for this cavity is set to 2 bar with material properties at room temperature and 4 bar with properties at 2 K.

To verify compliance with this requirement, several analyses were performed including elastic, elasto-plastic, buckling and convergence simulations.

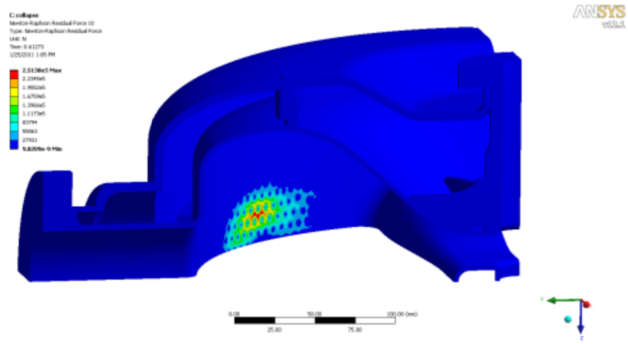


Figure 6: Analysis showing the location of collapse due to external pressure.

The pressure-limiting factor for this cavity appeared to be the collapse due to external pressure in the region of the shell as can be seen in Figure 6. A total of 8 reinforcing elements were added on the shell to obtain the necessary pressure rating, these can be seen in Figure 3. The layout chosen for these ribs leaves room for a piezo-electric fast tuner in the region of the spoke collar where magnetic fields are high.

An elasto-plastic simulation performed cycling between the relaxed position and a pressure load of 2.5 bar showed residual plastic deformations in the cavity under 100 µm with the maximum in the spoke center region shown by the red area in Figure 7.

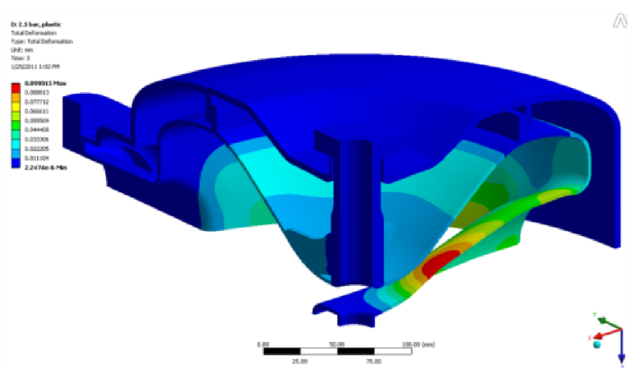


Figure 7: Residual plastic deformation (under 100 µm) after the application of 2.5 bar of pressure and relaxation.

Helium Vessel

The design of the helium vessel is still in progress. Nevertheless, the main characteristics have already been defined during the df/dP study.

It will be constructed of stainless steel and designed according to the ASME pressure vessel code Section VIII Division 2 (Design by analysis). This will allow utilizing more complex shapes in the intent of meeting the requirements of the design. Another benefit will be the reduced weight of the vessel designed according to this division.

The niobium to stainless steel transition joints will be manufactured with the established copper-brazing technique described in [4] and successfully implemented in the fabrication of SSR1 cavities [5].

Although at this point a design for the tuner is not complete, this cavity will be tuned only from one side at the beam pipe. The helium vessel will be connected to the cavity with a bellows on the tuner side. The other beam pipe will be welded to the vessel as shown in Figure 8.

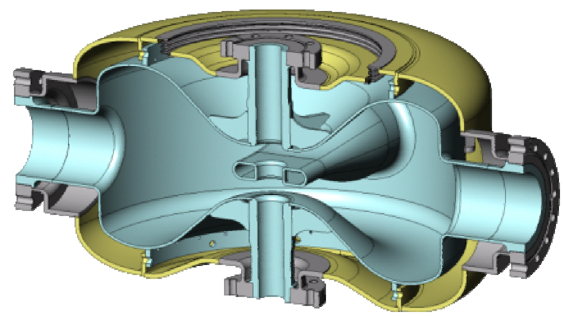


Figure 8: Design of the jacketed SSR0.

OTHER SSR RESONATORS

The same design principles are being applied to the larger resonators SSR1 and SSR2. With larger shells and thus larger areas of high magnetic fields, these resonators present naturally smaller values of df/dP compared to SSR0. The smaller sensitivity to end-wall deformations also contributes to a smaller sensitivity to helium pressure variations.

As a product of the HINS R&D program (a high intensity pulsed proton linac), we have already developed SSR1 in the past years [5] [6] and we have several SSR1 cavities available at Fermilab. We are currently studying how to adapt the available design for this cavity to CW operation. This may involve the redesign of the helium vessel and stiffening system.

REFERENCES

[1] S. Nagaitsev, "Project X, new multi megawatt proton source at Fermilab", Invited talk, PAC 2011, New York.

[2] W. Schappert et al., "Microphonics control for Project X", PAC 2011, New York.

[3] A. Facco et al., "A Superconductive low beta single gap cavity for a high intensity proton linac", Proc. of the XX Int. Linear Accel. Conference, LINAC 2000, Monterey, Canada.

[4] J. D. Fuerst et al., "Niobium to stainless steel braze transition development", Proc. of the 11th workshop on RF-superconductivity, SRF 2003, DESY, September 2003.

[5] L. Ristori et al., "Design, Fabrication and Testing of single spoke resonators at Fermilab", SRF 2009, Berlin, Germany.

[6] L. Ristori et al., "Development of 325 MHz Single Spoke Resonators at Fermilab", Applied Super Conductivity 2008, Chicago, US.