DESIGN OF SINGLE SPOKE RESONATORS FOR PROJECT X*

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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 current proposal for the low-energy section of the Project X H^- linac includes three types of superconducting single spoke resonators (SSR0, SSR1 and SSR2) operating at 325 MHz and accelerating the beam from 2.5 MeV to 180 MeV. Single spoke cavities are being favored for the linac in virtue of their higher r/Q values compared to standard Half Wave Resonators (HWR). At the moment, the use of HWR is still considered an option for the SSR0 section. Quarter Wave Resonators were not considered for such a high frequency. The β values for SSR0 and SSR1 are 0.115 and 0.215 respectively. For the SSR2 section an iterative RF optimization has been performed recently to take into consideration several changes in the lattice and characteristics of the linac such as the introduction of a low-β (0.6-0.9) section operating at 650 MHz replacing the Triple Spoke Resonator section. The study shows that the geometrical β of SSR2 should be changed from 0.414 to 0.480. Among other benefits, this new beta value allows to use a smaller number of cavities.

In this paper we present the decisions and analyses that lead to the final RF/Mechanical design of SSR0 which is currently finalized and awaiting approval for fabrication. 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.

SSR1 prototypes were originally developed for the HINS R&D linac [1] and were successfully tested as bare resonators in the FNAL Vertical Test Stand and in the test cryostat at the FNAL Superconducting Cavity Test Facility [2, 3] after the installation of the helium vessel and two tuners. With Project X being a CW machine, (HINS was a pulsed machine) a redesign of the helium vessel of SSR1 resonators was necessary to address frequency stability issues due to helium pressure fluctuations.

INTRODUCTION

The Project-X, a multi-MW proton source, is under development at Fermilab [4]. 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.

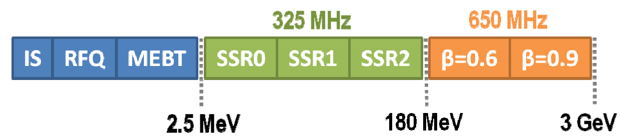

Figure 1: The Project X CW linac.

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) and two types of 650 MHz elliptical cavities (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.

Table 1: Cavities for the Project X linac. Two options are shown for the SSR2 section, the decision between the two designs has not been made yet.

	SSR0	SSR1	SSR2 A	SSR2 B
β optimal	0.115	0.215	0.414	0.480
CMs x Cavities	2 x 9	2 x 10	4 x 10	4 x 8
Design Eacc [MV/m]	9	11	10	10
Max surf Field [mT]	61	64	56	59
Q_0	> 6.5E6	> 6.5E6	> 6.5E6	> 6.5E6
Bpeak/Eacc [mT/$^{MV}/_{m}$]	6.83	5.81	5.64	5.9
Epeak/Eacc	5.66	3.84	3.78	3.5
Leff (2*βλ/2) [mm]	106	198	382	443
G [Ω]	51	84	109	119
R/Q_0 [Ω]	109.2	242	247	304
TOT FE length [m]	59/54.3	59/54.3	59	54.3

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

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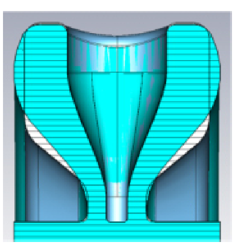
increase the bandwidth. This leads to input power overhead. Another approach is to utilize active microphonics compensation (e.g., a fast tuning system). In any case it is beneficial to increase the mechanical stability of the cavity against helium pressure fluctuations, in other words decreasing the value of *df/dP* as much as possible (*f* is the cavity resonance frequency, *P* is helium pressure).

SSR0

SSR0 is the smallest of the three single spoke resonators. With a geometrical beta of β = 0.115, 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.

The main parameters of the latest (convex) SSR0 are summarized in Figure 2.



	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.

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.

Figure 3 shows the dependence of magnetic field enhancement factor vs. the ration D/L where D is the spoke base diameter and L is the total length of the cavity. There is an optimal D/L ratio where B_{peak}/E_{acc} reaches a minimum. For all peak ratio values in this paper we use the effective length definition $L_{eff}=\beta_{optimal}\cdot\lambda$

The space that we were able to save was about 10 mm per side.

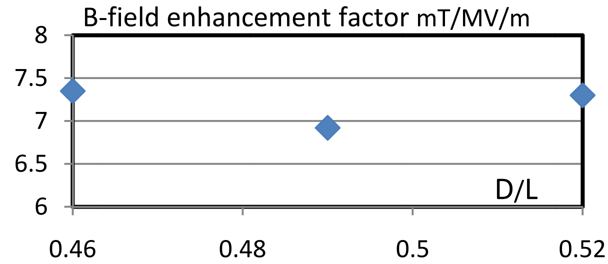


Figure 3: Magnetic field enhancement factor vs. D/L ratio for SSR0 with convex end-walls.

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 4.

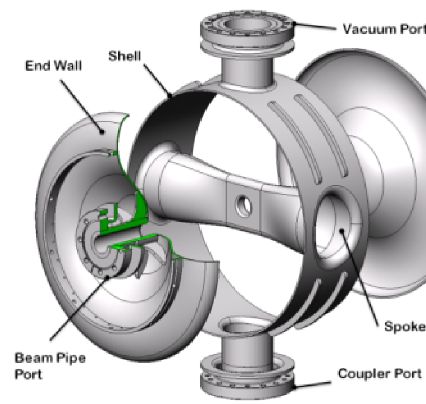


Figure 4: Exploded view of SSR0.

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 [5]. An excerpt of those simulations is shown in Figure 5 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.

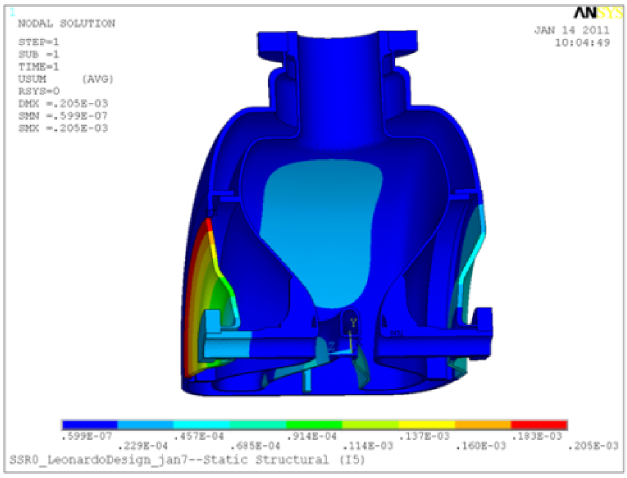


Figure 5: Optimization of the position of the circular rib to minimize df/dP. The left beam pipe is connected with bellows to the helium vessel, the right one is welded. This analysis produced a result of 5 Hz/torr.

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.

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 6. Prototypes of this connection will be subjected to thermal cycles and tensile tests to optimize the design and select the most appropriate hardware.

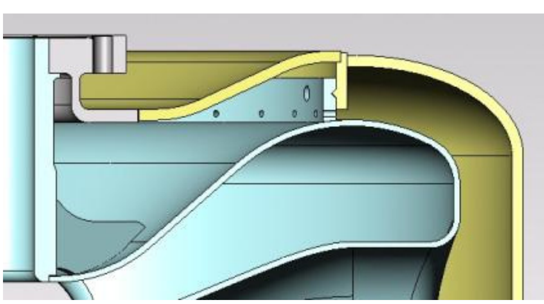


Figure 6: Details of the bolted connection between the end-wall and the helium vessel of SSR0. The end-wall shown is the one without a bellows.

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 7).

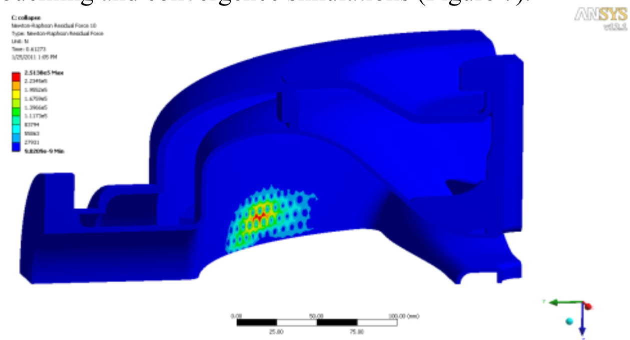


Figure 7: Analysis showing the location of collapse due to external pressure.

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 7. A total of 8 reinforcing elements were added on the shell to obtain the necessary pressure rating, these can be seen in Figure 4. 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 8.

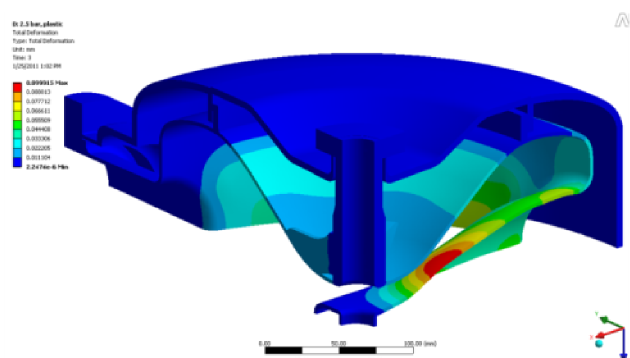


Figure 8: Residual plastic deformation (under 100 µm) after the application of 2.5 bar of pressure and relaxation.

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.

With reference to Figure 9, 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.

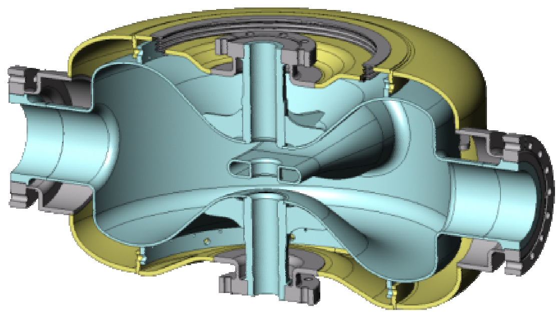


Figure 9: Design of the jacketed SSR0. The Niobium components are shown in light blue color, The stainless steel parts are instead shown in yellow and gray colors.

The niobium to stainless steel transition joints will be manufactured with the established copper-brazing technique described in [6] and successfully implemented in the fabrication of SSR1 cavities [2].

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.

SSR1

SSR1 was the first superconducting spoke resonator developed at FNAL. It was the first superconducting resonator in the HINS lattice. The RF and mechanical design of this resonator has been discussed in [2] and the results of the tests at low and high power have already been reported in [2, 3]. The helium vessel for the first prototype was designed with the main goal of meeting the pressure requirements for safe operation in the cryomodule. The sensitivity of the cavity-vessel system to helium pressure fluctuations was not minimized at that time: HINS was a pulsed machine where the behavior of the resonators is dominated by Lorentz force detuning. The sensitivity of the first prototype was measured at ~|140| Hz/torr. With Project X being a CW machine, it was necessary to revisit the design of this resonator to reduce considerably df/dP. This consisted in adopting a design similar to SSR0 by coupling the helium vessel with the end-wall of the resonator. The proposed new helium vessel design shown in Figure 10 is expected to have a df/dP < |5| Hz/torr.

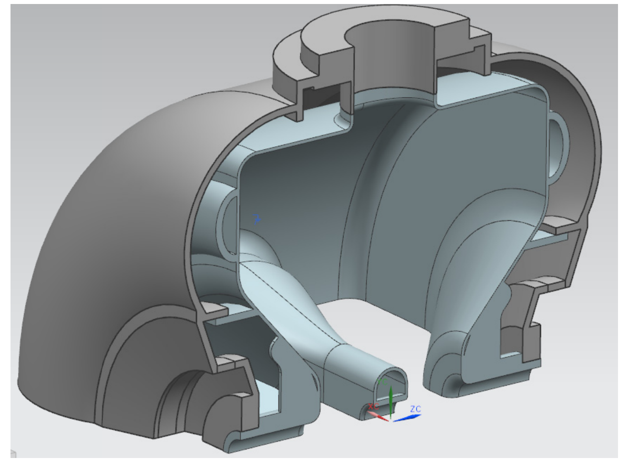


Figure 10: SSR1 with the new helium vessel design for project X. Both walls of the helium vessel (in gray color) are coupled to the end walls of the cavity (in light blue) by means of a bolted connection.

SSR2

SSR2 resonators occupy the last portion of the 325 MHz section accelerating the beam up to 180 MeV for the transition to 650 MHz. The optimization of RF parameters of the SSR2 cavity was performed similarly to SSR0. The convex end-wall design was adopted for the same reasons as for SSR0. SSR2 was initially designed to be utilized in the HINS linac with β= 0.414.

A second RF optimization has been performed recently to take into consideration several changes in the lattice of the linac such as the introduction of the low-β (0.6-0.9) section operating at 650 MHz which replaced the Triple Spoke Resonator section. The study shows that the geometrical β of this cavity should be changed from 0.414 to 0.480. Among other benefits, this new beta value allows to use a smaller number of cavities (see Table 1).

The aperture of the cavity is 40 mm. Figure 11 shows the cross-section of SSR2 and the main dimensions used in the optimization. All calculations have been done using Microwave Studio (MWS) and COMSOL software.

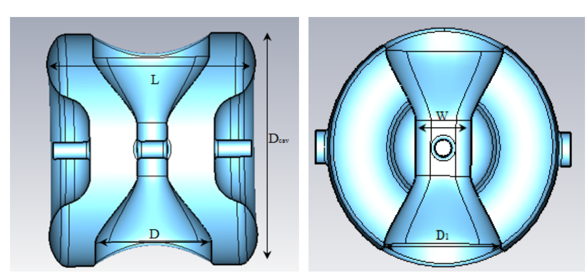


Figure 11: Cross-section of SSR2. L – cavity length, D – spoke diameter, W – spoke width, D_{cav} – cavity diameter.

The goal of the EM design is the minimization of peak surface fields. Figure 12 shows the electric and magnetic fields distribution in 1/8 of the SSR2 cavity.

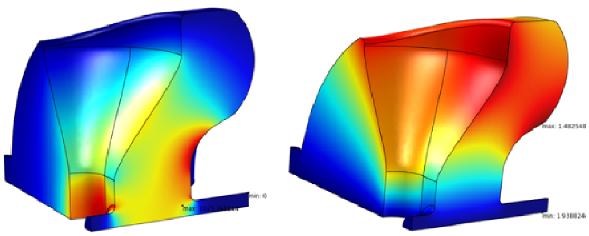


Figure 12: Electric (left) and magnetic (right) fields in SSR2. The field strength increases as the color changes from blue to yellow to red.

The electric field is concentrated near the beam axis, and the magnetic field near the outer shell and spoke base area. The distance from gap-center to gap-center is predefined by the choice of β and equal to β·λ/2. The end-wall profile near the axis, spoke thickness and spoke rounding radius have been optimized to minimize the peak electric field. Changes in the cavity frequency due to geometry changes are compensated by adjusting the cavity diameter D. Figure 13 shows the dependence of both field enhancement factors vs. spoke width (W). It appears that one should use the smallest value of W possible.

The main parameters for the two options are summarized in Table 1.

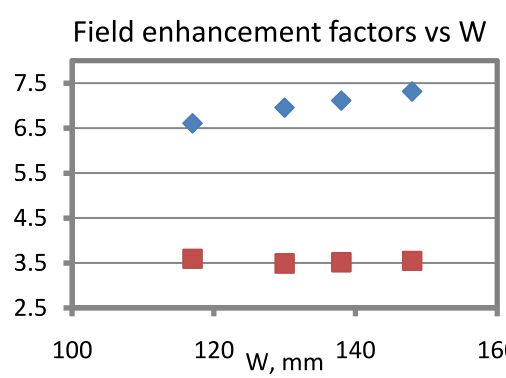


Figure 13: Field enhancement factors vs. W. Red E_{peak}/E_{acc}, blue B_{peak}/E_{acc} (mT/$^{MV}/_{m}$).

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