# EM DESIGN OF THE LOW-BETA SC CAVITIES FOR THE PROJECT X FRONT END*

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*Abstract*

The low-energy part of the Project X H-linac includes three types of superconducting single spoke cavities (SSR) with β = 0.11, 0.21 and 0.4 operating at the fundamental TEM-mode at 325MHz. In this paper we present the detailed EM optimization of cavity shapes having the goal to minimize the peak electric and magnetic fields. We also discuss the importance of the integration of EM and mechanical design.

## 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. The CW linac consists of a low-energy 325 MHz SCRF section (2.5 - 160 MeV) containing three different families of single-spoke resonators (SSR0, SSR1, SSR2) having β = 0.11, 0.21 and 0.4, and two families of 650 MHz elliptical cavities having β = 0.61, 0.9 (180MeV - 3 GeV). The feature of the linac is small beam loading, and thus narrow cavity bandwidth, 20-40 Hz [2], which creates problems with microphonics. In order to fight microphonics, one should increase cavity mechanical stability versus the He pressure fluctuations, i.e., decrease the value of $df/dP$ as much as possible ($f$ is the cavity resonance frequency, $P$ is He pressure). In addition, a cavity should sustain a pressure of 2 bar (warm) and 4 bar (cold). The cavity and the He vessel constitute a common mechanical system. Thus, a self-consistent electromagnetic and mechanical design is necessary to achieve the demanded mechanical stability. The SSR1 cavity has been successfully designed, developed and tested at Fermilab [3]. This paper presents the EM design of modified SSR0 and SSR2 cavities.

## SSR0

CW SSR0 cavities will be used for acceleration of the beam energy from 2.5 MeV to 11.4 MeV. The RF parameters of the SSR0 have initially been optimized for a scaled version of SSR1 β = 0.21. The scaled SSR0 cavity has "flat" end-walls as shown at Figure 1a. Due to longitudinal restrictions, the EM design of the SSR0 cavity doesn't take advantage of a re-entrant shape similar to SSR1. For better mechanical stability of the SSR0 cavity the "flat" end-walls shape has been changed to a convex profile as shown in Fig. 1b. The detailed advantages of the modified SSR0 cavity mechanical design are presented in [4]. In previous presentations [5,6] the EM design of SSR0 with "flat" end-walls has been described. Because of basic changes occurring at the outer shell and spoke base area, the magnetic field enhancement factor has been re-optimized.

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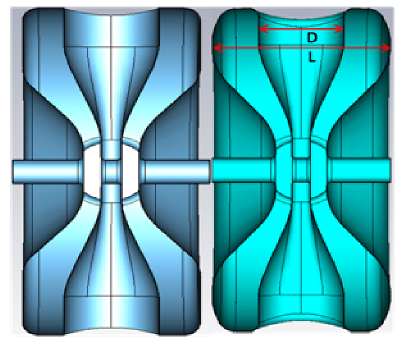



Figure 1: a) Left: SSR0 original geometry scaled from SSR1 with "flat" end-walls, b) Right: SSR0 with modified convex end-walls.

Fig. 2 shows the dependence of magnetic field enhancement factor vs. the ratio D/L where D is the spoke base diameter and L is the total length of the cavity, see Fig. 1b. There is an optimal D/L ratio where the $B_{peak}/E_{acc}$ reaches a minimum. For all peak ratio values in this paper we use the effective length definition $L_{eff} = \beta_{optimal} \cdot \lambda$.

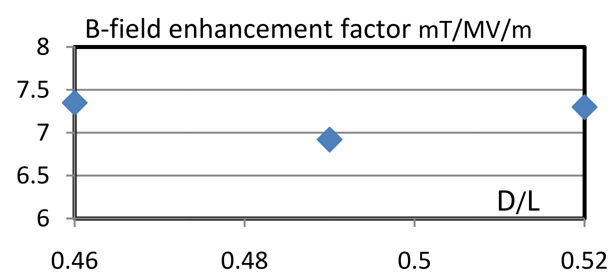



Figure 2: B-field enhancement factor vs. D/L ratio.

Table 1 summarizes the main RF parameters of both "flat" and convex end-wall versions of the SSR0 design.

Table 1: Main RF Parameters of Two Versions of SSR0.

| | "flat" | convex |
|---|---|---|
| β, optimal | 0.114 | 0.115 |
| Diameter, mm | 416.54 | 406.84 |
| Length, mm | 175.5 | 190 |
| R/Q, Ω | 108 | 109.2 |
| G, Ω | 50 | 51 |
| $E_{peak}/E_{acc}$ | 5.63 | 5.66 |
| $B_{peak}/E_{acc}$, mT/(MV/m) | 6.92 | 6.83 |

## SSR2

The third family of spoke resonators will be used for acceleration of the beam energy from 43 MeV to 179 MeV. The optimization of RF parameters of the SSR2 cavity with "flat" end-walls for β =0.4 has been presented in [5,6] for 2 different beam pipe diameters, 30 and 40 mm. As for SSR0, for better mechanical stability of the SSR2 cavity the "flat" end-wall shape has been changed to a convex profile. The basic version of the SSR2 is β =0.4. However, further optimization of the cavity geometrical betas of the cavities and transition energies gave the evidence that utilization of a cavity with higher geometrical beta, β =0.47, may help to improve the acceleration efficiency and, thus, reduce the fields in the SSR2 cavities at fixed section length. Thus, EM design of SSR2 has been done for both β = 0.4 and 0.47. The cavity aperture radius is 20 mm. Fig. 3 shows the cross-section of the SSR2 cavity and the main dimensions used in the process of EM optimization. The EM optimization has been done for L=406 and 500mm for β=0.4 and for L=406, 500 and 550 mm for β=0.47. All calculations have been done using Microwave Studio (MWS) and COMSOL software.

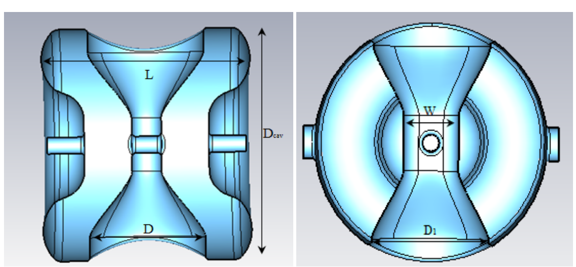



Figure 3: Cross section of the SSR2, L – cavity length, D – spoke diameter, W – spoke width, $D_{cav}$ – cavity diameter.

The goal of the EM design is the minimization of peak surface fields. Fig. 4 shows the electric and magnetic fields distribution in 1/8 of the SSR2 cavity.

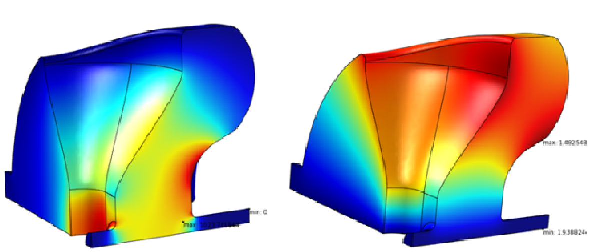


Figure 4: Electric (left) and magnetic (right) fields in SSR2. The field strength increases as the color changes from blue to yellow to red.

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 is equal to βλ/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 $D_{cav}$ Fig. 5 shows the dependence of the field enhancement factors vs. spoke width W, shown in Fig. 3. This plot shows that the physically minimal W value is optimal.

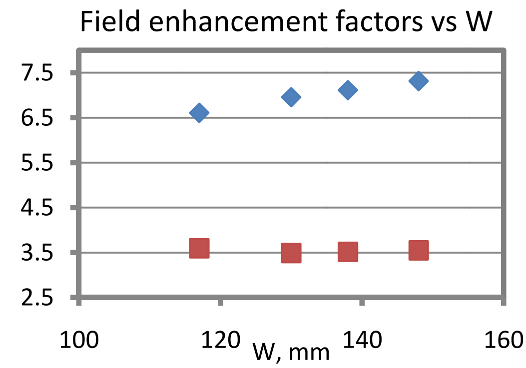
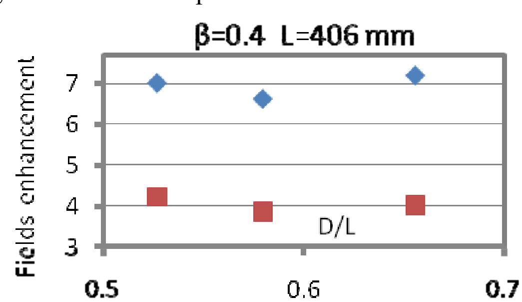



Figure 5: Field enhancement factors vs. W, red - $E_{peak}/E_{acc}$, blue - $B_{peak}/E_{acc}$ (mT/MV/m).

The optimization of magnetic field has more options. $B_{peak}/E_{acc}$ depends on:

- D/L ratio (Fig. 3 left)
- Cavity length
- Ellipticity of spoke base

For fixed longitudinal cavity length L, both the electric and magnetic fields enhancement factors have a minimum value for some D/L ratio in both β=0.4 and β=0.47 cases. Fig. 6 shows these dependences.



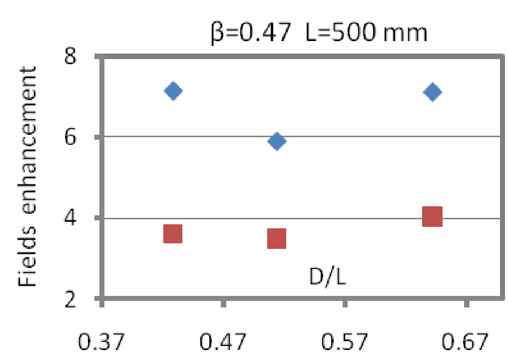




Figure 6: Field enhancement factors vs. D/L with fixed cavity length L: upper for β=0.4 L=406 mm and lower for β=0.47 L=500mm. Red - $E_{peak}/E_{acc}$, blue - $B_{peak}/E_{acc}$ (mT/(MV/m)).

The longitudinal cavity length L has the most influence on the $B_{peak}/E_{acc}$ factor. Fig. 7 shows an almost linear drop of $B_{peak}/E_{acc}$ vs. L for β=0.47. One can conclude that a minimum magnetic field enhancement factor is obtained for a longer longitudinal cavity length L.
Another option to minimize the magnetic peak field is to give the spoke base an elliptical cross section. Fig. 8 shows the distribution of the magnetic field at the outer shell of SSR2 for β=0.47 and L=406 mm. The geometry with an ellipse axis ratio $D_1/D$=1.15 has a more uniform magnetic field distribution and provides about a 5% decrease of the peak magnetic field.

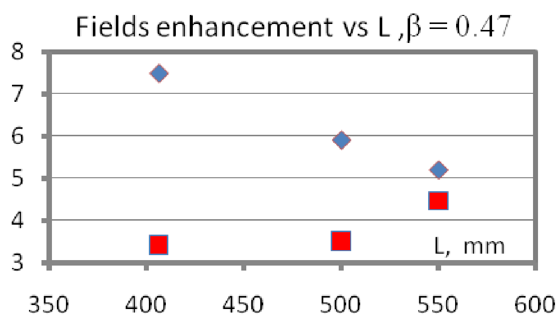



Figure 7: Field enhancement factors vs. L for β=0.47. Red - $E_{peak}/E_{acc}$, blue - $B_{peak}/E_{acc}$ (mT/MV/m).

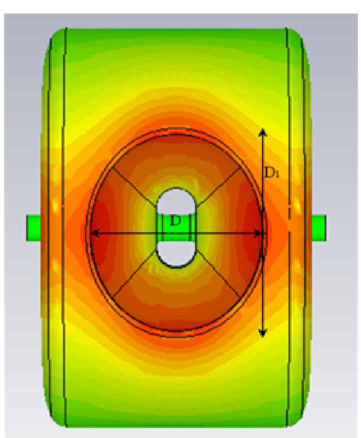



Figure 8: Magnetic field distribution for SSR2, with β=0.47 and L=406 mm. The $D_1/D$ ellipticity ratio is 1.15.

Tables 2 and 3 summarize the main RF parameters of the SSR2 cavities for β = 0.4 and 0.47 and different cavity lengths L.

Table 2: Main RF Parameters of SSR2 β=0.4 for Cavity Length L=406 and 500mm.

| Cavity Length, mm | 406 | 500 |
|---|---|---|
| $\beta_{optimal}$ | 0.405 | 0.41 |
| $E_{peak}/E_{acc}$ | 3.86 | 3.78 |
| $B_{peak}/E_{acc}$ mT/(MV/m) | 6.62 | 5.64 |
| G, Ω | 103.1 | 108.9 |
| R/Q, Ω | 242 | 247 |
| D/L | 0. 58 | 0.53 |
| Elliptical $D_1/D$ ratio | 1.1 | 1.1 |

Table 3: Main RF Parameters of SSR2 β=0.47 for Cavity Length L=406, 500 and 550mm.

| Cavity Length, mm | 406 | 500 | 550 |
|---|---|---|---|
| $\beta_{optimal}$ | 0.464 | 0.48 | 0.488 |
| $E_{peak}/E_{acc}$ | 3.41 | 3.5 | 4.46 |
| $B_{peak}/E_{acc}$ mT/(MV/m) | 7.49 | 5.9 | 5.18 |
| G, Ω | 101.9 | 119.1 | 126.3 |
| R/Q, Ω | 224.5 | 304.3 | 306.8 |
| D/L | 0.63 | 0.51 | 0.50 |
| Elliptical $D_1/D$ ratio | 1.15 | 0.9 | 1.04 |

## CONCLUSIONS

The EM design of two families of single spoke resonators was presented: SSR0 having β=0.11 and SSR2 having β=0.4. An alternative version of SSR2 with β=0.47 was considered also. Both cavity geometries have been modified to improve the mechanical properties. Another option to minimize the magnetic peak field is utilization of a spoke base with elliptical cross section.

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