UPDATE ON SSR2 CAVITY EM DESIGN FOR PIP-II*

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Abstract

Proton Improvement Plan II (PIP-II) is the future plan for upgrading the Fermilab proton accelerator complex to a beam power capability of at least 1 MW delivered to the neutrino production target. A room temperature section accelerates H- ions to 2.1 MeV and creates the desired bunch structure for injection into the superconducting (SC) linac. SC linac using five cavity types. One 162.5 MHz half wave resonator, two 325 MHz spoke resonators and two 650 MHz elliptical 5-cell cavities, provide acceleration to 800 MeV. The EM design of the second family of spoke resonator is presented in this paper. The work reported is a thorough electromagnetic study including: the RF parameters, multipacting mitigation and transverse field asymmetry. The cavity is now ready for structural design analysis.

INTRODUCTION

PIP-II stands for Proton Improvement Plan-II [1]: it is Fermilab plan for future improvements to the accelerator complex, aimed at providing LBNE (Long Base Neutrino Experiment) operations with a beam power of at least 1 MW on target. The central element of the PIP-II is a new superconducting linac, injecting into the existing Booster. The PIP-II 800 MeV linac derives from Project X Stage 1 design. The room temperature (RT) section includes a Low Energy Beam Transport (LEBT), RFQ and Medium Energy Beam Transport (MEBT), accelerating H- ions to 2.1 MeV and it creates the desired bunch structure for injection into the superconducting (SC) linac. PIP-II will use five SC cavity types: one 162.5 MHz half wave resonator (HWR), two single spoke resonator sections at 325 MHz (SSR1 and SSR2), lastly two families of 650 MHz elliptical cavities low beta (LB) and high beta (HB). The technology map of the PIP-II linac, Fig. 1, shows the transition energies between accelerating structures, and the transition in frequency. This article will discuss the electromagnetic (EM) design of the second type of spoke resonators (SSR2): the design has been updated mainly to mitigate multipacting, trying to preserve the cavity performance. The phenomenon of multipacting (MP) consists in electron multiplication at surfaces exposed to an oscillating electromagnetic field, which can represent a serious obstacle for operation of particle accelerator and their RF components. Multipacting, in the previous design of SSR2, has been studied in [2]: the results showed higher intensity and wider power range than for SSR1 cavities, already built and tested at FNAL [3] [4]. The new design lowers the MP intensity and reduces the gradient range in which MP occurs, without compromising the EM cavity parameters. This article summarizes all the studies on SSR2 design for PIP-II: EM parameters, quadrupole field asymmetry and multipacting simulations are presented.

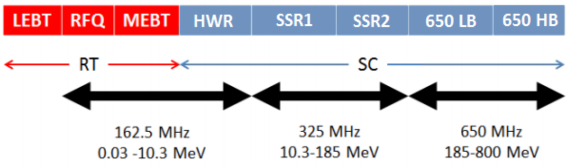

Figure 1: PIP-II linac technology map.

GEOMETRY AND RF PARAMETERS

SSR2 is a single spoke resonator operating at 325 MHz, it will be used in PIP-II linac, for particle acceleration from 35 MeV to 185 MeV. Figure 2 shows the new SSR2 RF design (version 2.6) Y-Z cross-section where Z represents the beam axis, all the main geometry parameters are shown in the picture, their values are reported in Table 1. Electric and magnetic 3D fields have been simulated with COMSOL multiphysics and are plotted in Fig. 3.

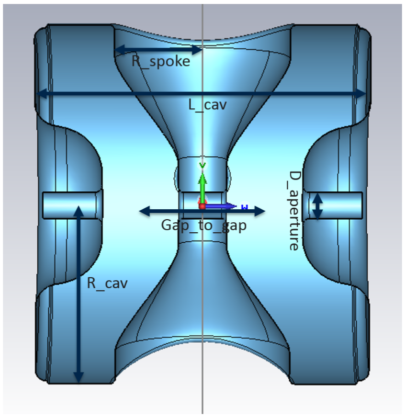

Figure 2: SSR2 v. 2.6 cavity Y-Z cross-section.

Table 1: Main Geometric Parameters

Parameter	Length [mm]
L_cav	500
R_cav	271.6
R_spoke	130.7
D_aperture	40
Gap_to_gap	185.9

The value of $\beta_{opt} = 0.47$ has been chosen after optimization of the SSR2 section of PIP-II in [5]. SSR2 design v1.0 and v2.6 EM parameters are reported in Table 2. One can see how the two designs are capable of delivering the same

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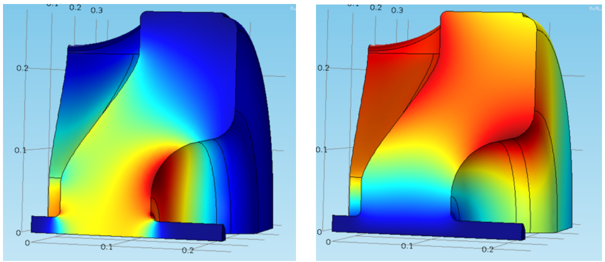


(a) (b)

Figure 3: Electric field (a) and magnetic field (b) in SSR2 cavity.

level of performance, in terms of acceleration and peak surface fields. The gradient E_{acc} is defined over the effective length $L_{eff} = \beta_{opt}\lambda$, where λ is the electromagnetic field wavelength at 325 MHz.

Table 2: SSR2 EM Parameters Design Comparison

Parameter	SSR2 v1.0	SSR2 v2.6
Frequency [MHz]	325	325
Optimal beta β_{opt}	0.471	0.475
Effective length $L_{eff}[m]$	0.435	0.438
E_{peak}/E_{acc}	3.45	3.38
B_{peak}/E_{acc} mT/(MV/m)	6.11	5.93
G [Ohm]	113	115
R/Q [Ohm]	290	297
Max en. gain[1] [MeV]	4.98	5.17

TRANSVERSE FIELD ASYMMETRY

Spoke resonators have a central electrode that lies on one of the axes perpendicular to the particles motion, breaking the axial symmetry of the cavity. The lack of azimuthal symmetry affects transverse electric and magnetic fields, introducing a perturbation to beam dynamic: a particle will be subject to non-uniform radial kick. This might result in an issue since the focusing in SSR2 cryomodules relies upon solenoids, which provide uniform radial correction. Transverse field asymmetry has been studied for all PIP-II superconducting cavities [6], since the design of SSR2 has been updated it was necessary to study its transverse field perturbation. The transverse momentum gain can be calculated using the formulae 1, 2, where $\beta = v/c$ is considered constant through the cavity, Z_0 is the impedance of free space and α is the angle on the x-y plane with respect to the x axis.

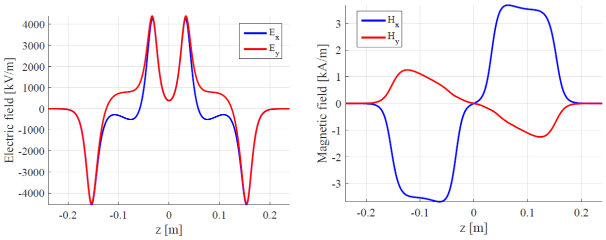
$$\Delta p_x(r,\alpha)c = \int_{z_i}^{z_f}\left(\frac{E_x(r,\alpha)}{\beta} - Z_0 i H_y(r,\alpha)\right)e^{i\frac{kz}{\beta}}\,dz \quad (1)$$

$$\Delta p_y(r,\alpha)c = \int_{z_i}^{z_f}\left(\frac{E_y(r,\alpha)}{\beta} + Z_0 i H_x(r,\alpha)\right)e^{i\frac{kz}{\beta}}\,dz \quad (2)$$

Since the transverse field asymmetry will induce a quadrupole kick, one can define the parameter Q, defined in Eq. (3), which is directly proportional to the quadrupole strength.

$$Q = \frac{\Delta p_x(r,0)c - \Delta p_y(r,\pi/2)c}{\left(\Delta p_x(r,0)c + \Delta p_y(r,\pi/2)c\right)/2}, \quad (3)$$

Figure 4 shows the difference between the transverse components of electric and magnetic fields for SSR2 cavity v2.6. Integrating the transverse fields for all the particle β between 35 and 185 MeV one can calculate the asymmetry parameter Q. Figure 5 compares the quadrupole parameter for SSR2 v1.0 and v2.6, both curves show a significant x-y asymmetry for the momentum gain. SSR2 v2.6 shows the same quadrupolar strength as SSR2 v1.0. Since the quadrupole of SSR2 v1.0 could be managed by the existing corrector design the same applies to SSR2 v2.6 field asymmetry.



(a) (b)

Figure 4: Transverse electric (a) and magnetic (b) fields in SSR2 v2.6.

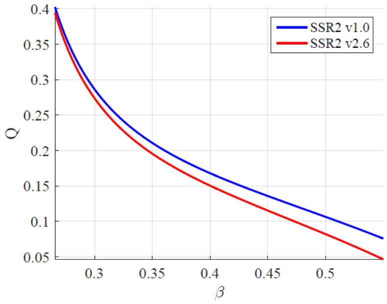


Figure 5: Q parameter vs β from 35 to 185 MeV.

MULTIPACTING MITIGATION

SSR2 design has been modified since studying multipacting for the previous cavity design predicted strong and wide MP barriers [2]. Almost all electrons trajectories seemed to be located at the blend between cavity wall and cylindrical shell. The implemented geometrical modification consists in adding a small step in this area, as shown in Fig. 6. Multipacting simulations have been done using CST microwave and particle studio. This software offers two solvers for MP simulations, TRACK and PIC solvers, they have been used both and their results seem to agree. In this paper TRACK

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[1] Calculated at peak field limitations of 40 MV/m and 70 mT.

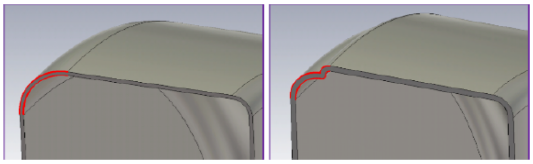


Figure 6: Difference between SSR2 v1.0 (left) and SSR2 v2.6 (right).

solver simulation results will be discussed, but the comparison between the two can be found in [7]. The simulations carried out were based on a eighth of cavity volume, to increase the mesh cell density per unit of volume. The mesh available when using TRACK solver is hexahedral; it is very important to have a fine representation of the cavity surface since the MP develops, mostly, in a layer around the cavity surface. Both field levels, electric and magnetic, and particle tracking are affected by the mesh quality, these are the reasons why one eighth of model has been chosen. CST offers various choices for Niobium secondary emission yield, in this paper only the lowest yield is considered corresponding to discharge cleaned niobium. Choosing higher emession properties for the surface generate usually more secondaries, speeding up the MP process in time which reduces the simulation time steps needed. Having more particles to track increases the computational complexity of the simulations and increases the MP barriers strength and width in gradient. When comparing experimental results and simulations the lowest secondary emission yield seems the best choice [2], since the MP barrier can be identified more clearly.

MP Figures of Merit

Once the cavity fields have been simulated and the electrons have been tracked for several RF periods, if MP is present, particle multiplication over time can be noticed from the plot of total number of particle vs time. A typical resonant multipacting scenario is presented in Fig. 7, where the number of particles is exponentially increasing with time: once the MP process is started the number of particles $N(t)$ can be written as $N(t) = N_0 e^{\alpha t}$. Given the exponential dependence of the particle number vs time one can define two figures of merit, the growth rate α which is the exponential coefficient of the particle number fit, and the secondary electron multiplication $\delta = N(t+T)/N(t) = e^{\alpha T}$, where T corresponds to 1 RF period.

MP Results

The new SSR2 v2.6 shows improved multipacting characteristics compared to the v1.0, the MP is not suppressed but its intensity and gradient range are reduced for the new cavity design. The Fig. 8 shows growth rate and δ for both SSR2 v1.0 and v2.6; also SSR1 results are plotted to give a comparison with a cavity that has been built and tested. SSR2 v2.6 has the lowest growth rate and δ among the three cavities, this implies that most likely the multipacting barriers of SSR2 v2.6 are going to be easier to overcome during cold tests.

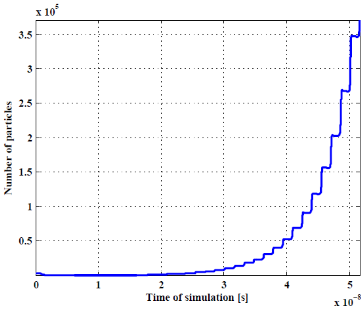
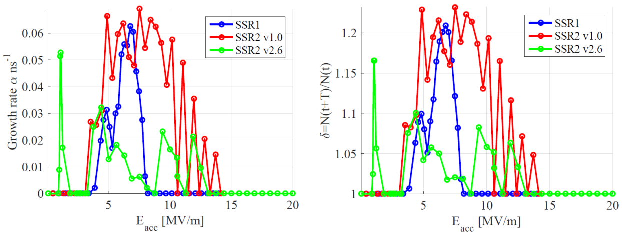


Figure 7: Particle number exponential growth due to multipacting.



(a) (b)

Figure 8: Growth rate (a) and secondary electron multiplication (b) comparison between spoke resonator designs.

CONCLUSION

SSR2 cavity for PIP-II EM design is completed, cavity performance are adequate for machine operation providing enough acceleration for the given limitations on peak fields. Quadrupole field asymmetry has been studied and does not represent an issue since the solenoids within cryomodules are going to have vertical and horizontal correctors. Multipacting barriers have been mitigated modifying the cavity corner: the new SSR2 v2.6 shows lower MP intesity than SSR1 cavity already built and tested. The cavity design is now ready for mechanical study and optimization.

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