TRANSVERSE KICK ANALYSIS OF SSR1 DUE TO POSSIBLE GEOMETRICAL VARIATIONS IN FABRICATION*

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Abstract

Due to fabrication tolerance, it is expected that some geometrical variations could happen to the SSR1 cavities of Project X, like small shifts in the transverse direction of the beam pipe or the spoke. It is necessary to evaluate the resultant transverse kick due to these geometrical variations, in order to make sure that they are within the limits of the correctors in the solenoids. In this paper, we report the transverse kick values for various fabrications errors and the sensitivity of the beam to these errors.

INTRODUCTION

Spoke cavities as a low β accelerating cavities plays a major role in the continuous wave linac of Project X. Project X is conceived as the next generation superconducting linac to be built in Fermilab targeting the intensity frontier with focus on the study of rare subatomic processes and supporting neutrino experiments [1-2]. Two kinds of spoke cavities namely SSR1 and SSR2 will be used to accelerate the proton beam at relative velocity of β=0.22 and β=0.47, respectively. SSR1 cavities are currently under production for the Project X injection experiment (PXIE) which is planned to test the integrated systems of Project X front end [3-4].

PXIE consists of an ion source capable of delivering 5 mA (nominal) at 30 keV followed by a LEBT section, a 5 mA RFQ, a MEBT section with integrated wideband chopper, as shown in Fig. 1. Two superconducting crymodules are then used to accelerate the beam from 2.1 MeV at the end of the MEBT section to 40 MeV. The two crymodules are one of seven half wave resonators (β=0.11) and the other is of eight spoke cavities (SSR1, β=0.22) [5].

Due to the sensitive nature of CW linacs to losses and activation, stringent requirements are imposed on the cavities design, specially the losses of higher order modes and the beam kicks. In case of the spoke cavities, transverse beam kicks could happen due to possible geometrical variations that might happen due to fabrication tolerances, which include:-

- Beam pipe shift in transverse direction.
- Spoke shift in transverse direction.
- Spoke shift in longitudinal direction.

It is imperative to study the effect of these geometrical variations on the performance of the cavity especially from transverse kick point of view. In this paper, we report the transverse kick values for SSR1 due to various

Figure 1: PXIE Layout.

fabrications' geometrical variations and the sensitivity of the beam to these errors.

SSR1

Figure 2 shows a quarter of SSR1's RF domain. The cavity gap distance was designed to accelerate particle at relative velocity β=0.22. Cavity operates at 325 MHz (sub-harmonic of 1.3 GHz) with bandwidth of 90 Hz. The nominal gain per cavity is 2 MeV with projected maximum magnetic field of 60 mT and max surface electric field of 39 MV/m.

Figure 2 depicts the possible geometrical variations that could induce transverse beam kicks. PXIE lattice includes correctors on the focusing solenoid in between cavities (c-s-c-c-s-c-c-s-c-c-s-c) to correct for such beam kicks. Each solenoid has two correctors; one for each transverse direction that can correct for up to 10 mrad angular beam deviation [6]. Therefore, it is imperative to investigate the possible beam transverse kicks and make sure that they are well below this limit.

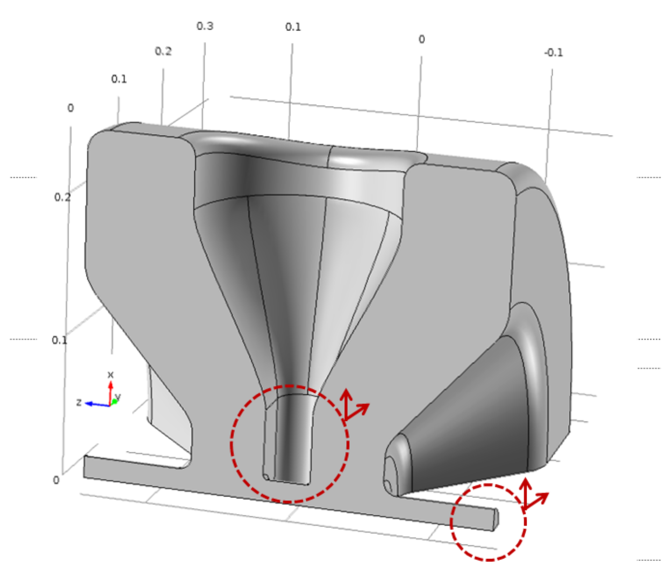

Figure 2: SSR1 geometry and the possible geometrical variations.

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KICK ANALYSIS

In order to analyse the transverse kick that could happen to the beam due to certain geometrical variations, we have built a simulation model for SSR1 in Comsol Multiphysics [7]. The three kinds of geometrical variations have been considered namely; displacements in the spoke location with respect to the symmetry plane of the cavity both in the transverse and longitudinal directions of up to 1 mm and displacement in the beam pipe location in the transverse direction of up to 1 mm. Four cases of these geometrical variations, as listed in Table 1, have been simulated to get the electric and magnetic fields both on axis and 5 mm off axis. Using the transverse electric and magnetic fields, the transverse kick could be calculated according to [8] as

$$\Delta Px.c = \int_{-L}^{L}\left(\frac{Ex}{\beta} - jZ_0 Hy\right) e^{j\frac{k}{\beta}z}\, dz \qquad (1a)$$

$$\Delta Py.c = \int_{-L}^{L}\left(\frac{Ey}{\beta} + jZ_0 Hx\right) e^{j\frac{k}{\beta}z}\, dz \qquad (1b)$$

Meanwhile, using the longitudinal electric field off axis, the transverse field could be also calculated using Panofsky's theorem [6] as

$$\Delta Px.c = \frac{j}{k}\int_{-L}^{L}\frac{\left(Ez^{+\Delta x} - Ez^{-\Delta x}\right)}{2\Delta x} e^{j\frac{k}{\beta}z}\, dz \qquad (2a)$$

$$\Delta Py.c = \frac{j}{k}\int_{-L}^{L}\frac{\left(Ez^{+\Delta y} - Ez^{-\Delta y}\right)}{2\Delta y} e^{j\frac{k}{\beta}z}\, dz \qquad (2b)$$

Both methods have been used to cross-check the calculated transverse kick values. On the other hand, the model was meshed with various mesh sizes to check the dependence of the calculated kick values on the mesh size. Complex kick values corresponding to the converged fine mesh, we have used, are reported in Table 1.

Displacing the beam pipe by 1 mm in y direction, would induce a kick of 35-j45 keV in the same direction, while displacing the spoke in y direction seems to have more pronounced effect as the kick value would be 83-j2 keV. On the other hand, displacing the spoke in x direction has a little bit different kick effect, rather than in y direction, of about 102-j1 keV, which is expected because of the asymmetry of the cavity geometry. Finally, displacing the spoke in longitudinal direction has very negligible kick effect.

Table 1: Transverse Kick Due to Various Geometrical Variations (in keV for 2 MeV energy gain per cavity).

Margin	Using Transverse Fields	Using Panofsky Theorem
Beam Pipe 1mm Shift in y	ΔPy.c=35.16-j45.17	ΔPy.c=35.26-j45.29
Spoke 1 mm Shift in x	ΔPx.c=83.33-j1.8	ΔPx.c=83.96-j1.86
Spoke 1 mm Shift in y	ΔPy.c=101.67-j1.26	ΔPy.c=101.8-j1.36
Spoke 1 mm Shift in z	~0	~0

In fact, the actual value of kick depends on the particle phase relative to the RF. As, a worst case scenario the largest transverse kick that could happen is about 102 keV in y direction with a particle of zero phase, in case of a spoke shift of 1 mm in the same direction.

Assuming a particle with energy of 10 MeV and β=0.146 (thus with momentum $P_{\parallel}c$= 137 MeV), the calculated maximum kick value would induce a beam deviation:

$$\Delta\alpha = \frac{\Delta P_{\perp}.c}{P_{\parallel}.c} \qquad (3)$$

of 0.74 mrad, which could be easily corrected with the Project X specified correctors.

MEASUREMENTS ON THE FABRICATED CAVITIES

Six cavities have been already fabricated and were tested (SSR1-105 to SSR1-110).

CMM Measurements

Upon passing the visual inspection of the cavities, they were subject to physical dimension measurement using coordinate measuring machines (CMM). Figure 3 shows the measuring setup of the CMM. Various dimensions are checked with special consideration given to the entities nearby the beam axis, where dimensions M5 and M6 shown in Fig. 3 were measured at various locations along the beam axis; specifically at the beam pipe flange "out", half way of the beam pipe "mid" and at the start point of the cavity gap "in". Also these measurements were done at both ends of the spoke; "spk1", "spk2".

Table 2 summarizes the various CMM measurements that were done to check the alignment of the beam pipe and the spoke with respect to the beam axis in the two transverse directions; parallel (x) and perpendicular (y) to the spoke. From these measurements, it seems that the largest y-misalignment happens in SSR1-109 (0.78 mm, 0.75 mm on the spoke), while the largest x-misalignment happens in SSR1-108 (0.43 mm, 0.40 mm on the spoke).

Bead Pull Measurements

Off axis bead pull measurements were done on the six cavities measuring the longitudinal electric field on a 5 mm off axis distance in directions parallel and perpendicular to the spoke, as shown in Fig. 4.

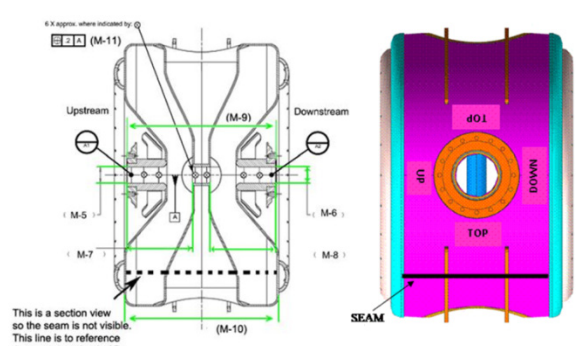

Figure 3: CMM Measurements of SSR1 Cavities.

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Table 2: Summary of the CMM Measurements of the SSR1 Cavities

		M5 out	M5 mid	M5 in	Spk1	Spk2	M6 in	M6 mid	M6 out
106	y	0	0.13	0.25	0.35	0.23	-0.14	-0.07	0
	x	0	0.06	0.12	-0.11	-0.07	0.28	0.02	0
107	y	0	0.01	0.02	-0.22	-0.04	-0.09	-0.05	0
	x	0	-0.06	-0.12	-0.09	-0.07	0.056	0.027	0
108	y	0	0.09	0.18	-0.13	-0.26	-0.08	-0.04	0
	x	0	0.02	0.38	0.43	0.40	0.3	0.15	0
109	y	0	-0.14	-0.27	-0.78	-0.75	-0.18	-0.09	0
	x	0.01	0.15	0.28	-0.41	-0.43	0.01	0	0
110	y	0	-0.10	-0.20	-0.49	-0.31	-0.22	-0.11	0
	x	0	0	0	-0.29	-0.24	0.16	0.08	0

Again using Panofsky's theorem we can calculate the transverse kick from the measured longitudinal fields. Alignment of the bead was kept within ± 0.5 mm using a cross-holed flange, as shown in Fig. 4.

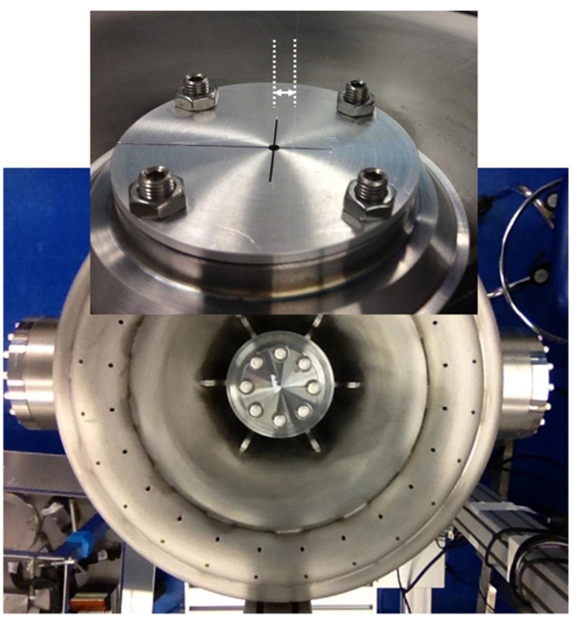

Figure 4: Bead-pull measurements of SSR1 cavities.

Table 3: Summary of the Measured Kick of the Different SSR1 Cavities in keV for 2 MeV energy gain per cavity.

	$\Delta P_{x.c}$	$\Delta P_{y.c}$
105	-36.6	-15.2
106	3.5	24
107	-25.6	-1.3
108	105.7	3.2
109	-40.1	-154.3
110	-0.63	-72.6

Each measurement was repeated five times and average real values of these measurements are reported in Table 3 (only the real values are reported, as the imaginary part is more susceptible to noise).

The largest transverse kick in y direction is of 154 keV and it occurs in SSR1-109, while the largest one in x direction is of 106 keV and it occurs in SSR1-108. This is consistent with the CMM measurements shown previously in Table 2. A 154 keV kick would induce 1.12 mrad beam deviation, which is still manageable to correct using the 10 mrad specified correctors of Project X.

CONCLUSION

Transverse kick that could happen in SSR1 cavities due to geometrical variations of the fabricated cavities from the designed geometry has been analysed and evaluated. From fabrication experience, three kinds of variations were under investigation concerning the alignment of both the beam pipe and spoke with respect to the beam axis. Simulation study has been carried out implementing these variations in the simulation model. CMM measurements of five fabricated SSR1 cavities were carried out to investigate the amount of physical misalignments of the beam pipe and spoke. Bead-pull measurements were also conducted to evaluate the transverse kick values in the fabricated cavities. Simulation and measurements are relatively in good agreement. Maximum kick in the fabricated cavities is within 154 keV that would induce about 1.12 mrad beam deviation, which could be definitely corrected with the 10 mrad specified correctors of Project X.

ACKNOWLEDGMENT

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