MODELING AND SIMULATION OF RFQS FOR ANALYSIS OF FIELDS AND FREQUENCY DEVIATIONS WITH RESPECT TO INTERNAL DIMENSIONAL ERRORS *

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Abstract

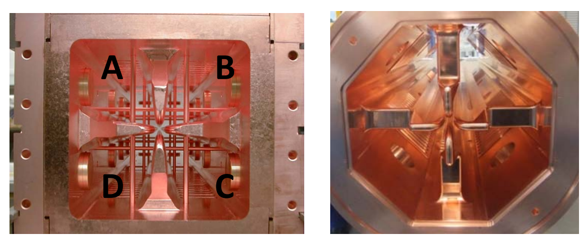
Performance of radio frequency quadrupole (RFQ) is sensitive to the errors in internal dimensions which shift resonance frequency and distort field distribution on the beam axis along the structure. The SNS RFQ has been retuned three times to compensate the deviations in frequency and field flatness with suspected dimensional changes since the start of the project for continuous operation with H^- ion beams. SNS now has a new RFQ as a spare that is installed in beam test facility (BTF), a low energy test accelerator. In order to understand and predict the performance deviation, full 3D modeling and simulation were performed for the SNS RFQs. Field and frequency errors from hypothetical transverse vane perturbations, and vane erosion (and metal deposition such as Cesium introduced by the ion source operation) at the low energy ends are discussed.

INTRODUCTION

SNS project now has two RFQ structures: the first one being used in the SNS linac that was built and delivered at the beginning of the project in 2002 and the second one built as a spare and delivered in 2014. The new RFQ is now installed in BTF that is a separate low energy test accelerator for full tests of the new RFQ with beam and future science [1]. Both RFQs have the vanes designed for the same particle beam dynamics. Figures 1(a) and 1(b) show the cross sections of the two RFQs. The first SNS RFQ has a square wall cross section in two layers, outer layer in GlidCop for strength and the inner layer in OFHC copper. The second RFQ has an octagonal wall cross section in a single layer copper structure. The first RFQ was built with PISLs while the second one employed end-wall rods for dipole mode stabilization.

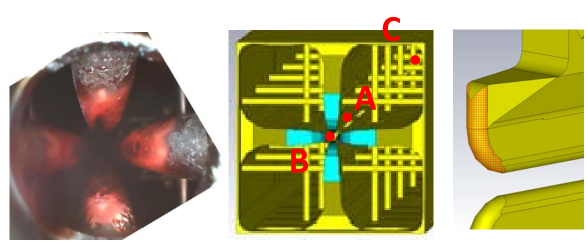
An RFQ is tuned for the design field distribution and the resonance frequency of the quadrupole mode after manufacturing. In this tuning process, bead-pull measurements [2] are usually performed in the four RFQ quadrants near vane gaps (point A) or near the wall (close to point C) as indicated in Figure 2(b) since the narrow gap length on the beam axis between the vanes (point B) makes it hard to pull a bead. Slug tuners shown in Figures 1(a) and 1(b) are used to tune the measured fields to the design fields. Magnetic pickup probes measure the fields with magnetic fields near the cavity wall at point C in each quadrant as shown in Figure 2(b).

In 2003 and 2009, the RFQ was found detuned with the distorted fields and the shifted resonance. The incidents caused investigation of the problems using computer simulations of the structure [3]. Then, distorted fields were found in 2013 with unknown reason. Slight degradation of performance of the RFQ led to the findings. The RFQ structure was retuned successfully and reused for operation every time. In the third incident, the field error resembled the fields expected with reduced capacitance at the low energy end of the vanes. Thus, for suspected erosion of the vane ends at the low energy end, 3D RF simulation was performed. Borescope image of the vanes at the low energy entrance of the RFQ is shown in Figure 2. The image is not clearly showing if vane erosion occurred in the RFQ. Figures 2(b) and 2(c) show the vane erosions modeled for the 3D RF simulation.



(a) (b)

Figure 1: Internal views of the two SNS RFQs at the low energy end: (a) first RFQ being used for neutron production and (b) new RFQ installed in BTF.



(a) (b) (c)

Figure 2: (a) Borescope image of the vane ends at the low energy entrance (2015) of the first RFQ. (b), (c) The models setup for the 3D RF simulations of the RFQs.

Figure 3(a) shows the initial fields and the fields after the two incidents of detuned RFQ that distorted the field flatness up to ± 15% and shifted the resonance by - 420 kHz and - 230 kHz, respectively. The averages of the fields in four quadrants are shown. The four quadrants are numbered following the definition in Figure 1. Figures 3(b) – 3(e) show the third finding of the field error in 2013 and subsequent retuning for the field flatness in the RFQ structure. Figure 3(b) shows the retuned fields in 2009 and Figure 3(c) shows the tilted field found in 2013. The field error was tuned again for a better field flatness (Fig 3(d)). This time the tuning was performed by using

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the slug tuners mainly positioned near the low energy input side of the RFQ. The latest measurement showed a slight tilt in the flatness again at the low energy end in Figure 3(e).

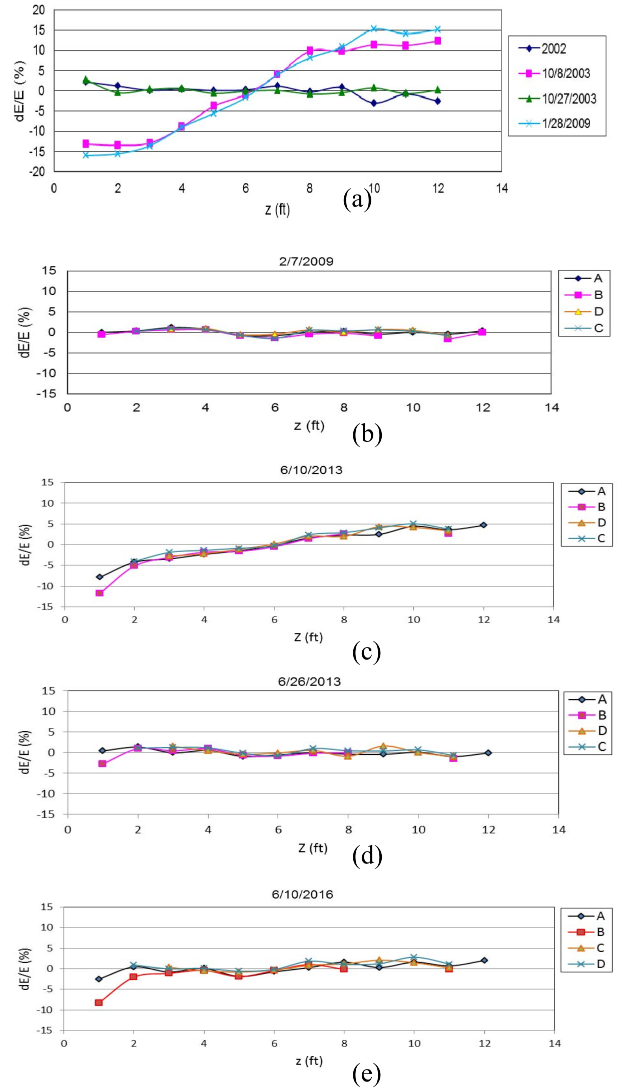

Figure 3: Measured RFQ field flatness errors in four quadrants over years of operation. (a) detuning events until 2009 shown with average of the fields in four quadrants, (b) retuned fields in 2009, (c) tilted field found in 2013 with unknown reason, (d) field error retuned for the field flatness, (e) latest measurement with a slight tilt.

SIMULATION

The two types of RFQs have been modeled to simulate (1) potential erosion problem of vane ends in low energy side and (2) effect of the vane distortions in the RFQ built with end-wall rods for dipole mode stabilization. The effects of the vane distortions in the RFQ built with PISLs were previously reported [3]. With the results shown in this report, the sensitivity with the vane distortions can be compared between the two RFQs.

Note that, for continuous beam operation with the RFQ, the suspected mechanical problems could not be precisely examined for the incidents of the detuned RFQ. Therefore, the work with modeling and analysis has been limited for selected cases with simple geometrical changes like partial vane movement or erosion of vane ends. However, the simulation results can still be useful for understanding certain problems with RFQ structures.

Erosion of Vane Ends

Figures 4 and 5 show the results of RF simulations for the potential erosion at the vane ends in two types of RFQ structures. It can be seen that, if the vane erosion problem exists, the RFQ with end-wall rods is more stable than the RFQ with PISLs in both the field tilt and the shift of the resonance frequency.

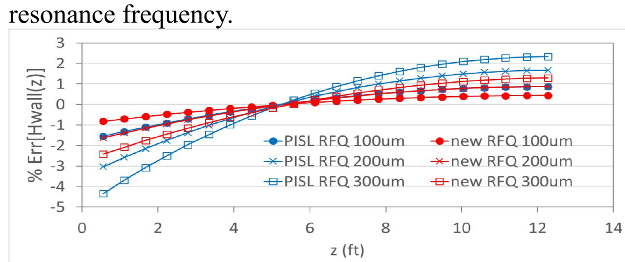

Figure 4: Fields with simulated erosion (100um - 300um) at the vane ends in low energy entrance of the RFQ stabilized with PISL and the RFQ stabilized with end-wall rods.

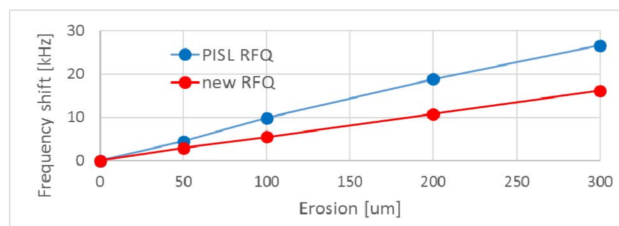

Figure 5: Frequency shifted with simulated erosion at the vane ends in low energy entrance of the RFQ stabilized with PISL and the new RFQ stabilized with end-wall rods.

Vane Perturbation

The RFQ inter-vane gap is designed to be small to increase focusing field strength that makes the structure very sensitive to deformations of the vanes. The perturbation analysis presented in [3] can be done similarly for the new SNS RFQ using the four section model for comparison.

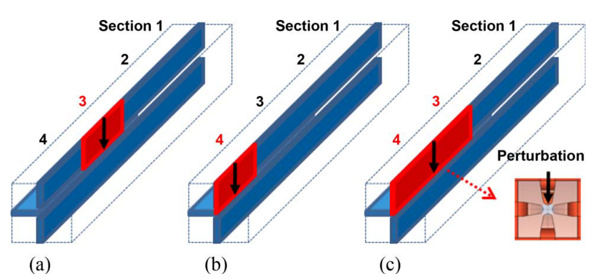

Figure 6: Three types of single vane perturbation (a) Case 1 with vane 3 movement only, (b) Case 2 with vane 4 only, and (c) Case 3 with vanes 3 and 4.

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Figures 6(a)-6(c) show three example cases for the RFQ modeled with the vane perturbations. The field errors due to the vane distortions in the RFQ with end-wall rods are compared to flat fields and shown in Figures 7, 8, and 9.

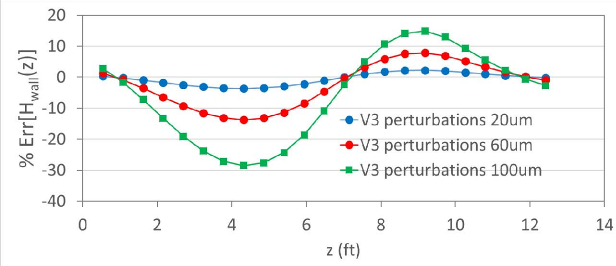

Figure 7: Field errors along the structure on the wall only with vane 3 movement in the RFQ with end-wall rods.

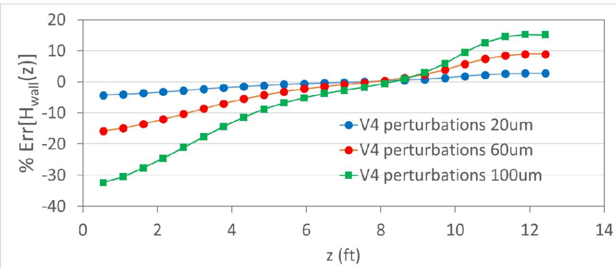

Figure 8: Field errors on the wall only with vane 4 movement in the RFQ with end-wall rods.

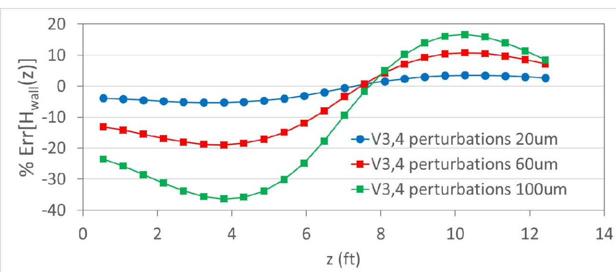

Figure 9: Field errors on the wall with movements of vanes 3 and 4 in the RFQ with end-wall rods.

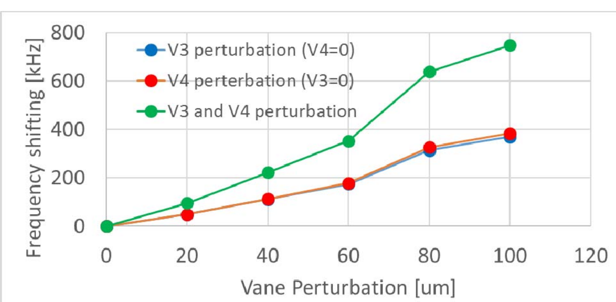

Figure 10: Frequency shift with vane distortions in RF simulation for new RFQ.

Figure10 shows the frequency shifts of the RFQ structure with end-wall rods perturbed with the vane movements of the three cases shown in Figure 6. When the above results are compared to the result obtained in the previous distortion analysis [3] for the RFQ with PISLs, it can be seen that the RFQ with end-wall rods has greater field error if the vane distortions occur.

DISCUSSION AND CONCLUSION

In some RFQ structures, slight vane perturbations may appear for various mechanical reasons. A complete 4 section 3D model of the SNS RFQ structure with end-wall rods for dipole mode stabilization has been used to investigate perturbation effects on the frequency and field distributions. The simulations provided the information on the frequency and the fields that can be compared with the analysis done for the RFQ with PISL stabilization for the cases with vane distortions [3]. In summary, the RFQ with PISLs has more stability compared to the RFQ with end-wall rods for the distortions with vane movements. The new RFQ structure was built to have enhanced strength for minimized accidental deformations combined together with robust support structure for the RFQ.

The result of simulation for the erosion of the vane ends may not show the actual problem even if the vane surface erosion existed. The pattern of surface erosion may be different from what we can do with simple modeling and simulation. If the vane erosion exists, the RFQ with end-wall rods is more stable than the RFQ with PISLs partly for both the fields and the resonance frequency. The better stability in the RFQ with end-wall rods may be explained with the significant capacitive coupling between the rods and the vane ends away from the beam center where the erosion may not take place.

Deposition of metal on the low energy vane ends was another hypothetical case like Cs deposition that could be of interest for H^- ion accelerators. The case was modeled for simulation to see the effect. The result showed that the field tilt and the frequency shift both reversed compared to the case with vane erosion. That was with higher field at the low energy end but with reduced resonance frequency. Using Cs material deposition did not make any difference compared to the deposition of other good conductors like copper.

The erosion case has the frequency shift much less than the case of vane movement. The sources of the events of the field and frequency errors have not been clearly identified and will have to be investigated if the structure is available for careful inspection.

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