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# Mock-ups and a Model Used to Predict BCAM Targets and Beam Axis Displacements of Cavities and Solenoids in PIP-II SSR2 Cryomodule

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**Abstract.** The string components of the SSR2 cryomodule of PIP-II need to stay in alignment, which is studied as acceptable beam deflection, offset, and defocusing, which may otherwise cause beam loss. To study the alignment of SSR2 cavities and solenoids to in the cryomodule, mock-ups were designed based on the models. The models of the cavity and solenoid mock-ups were studied to find the maximum rotations and translations possible. A mathematical model was created to predict the movement of the beam axis when the adjustment kit parameters are adjusted, which can be calculated using trigonometric relations and vectors. Once the parts have been procured, the maximums and the mathematical model can be validated using the assembled physical mock-ups.

## 1 Introduction

### *1.1 PIP-II and Cryomodules*

PIP-II, (Proton Improvement Plan 2) is a high-intensity proton beam facility that is being developed to provide proton beams that can be used to produce other types of particles for multiple Fermilab experiments. The heart of the project will be the linear accelerator, which uses superconducting radio frequency cavities to accelerate a beam of ions from 2.1 MeV up to 800 MeV. The beam is then directed to the Fermilab accelerator complex, where the ions are turned into protons, and accelerated further before being directed to experiments. There are 5 different types of SRF cavities that will be used in the linear accelerator, and these cavities are assembled into units called cryomodules, which are vessels that house a string of the cavities at very low temperatures and vacuum.

SSR2 (Single-Spoke Resonator Type-2) cavities are housed in the third type of cryomodule in the accelerator, along with focusing lens solenoids. These string components need to stay in alignment, which is studied as acceptable beam deflection, offset, and defocusing, which may otherwise cause beam loss.

### *1.2 Motivation*

The cavities and solenoids in SSR2 are mounted on adjustment kits, which are used to move cavities and solenoids into alignment during the string assembly process. Adjusting a system of set screws and rod ends allows for movement of the components in 3 axes, with 5 degrees of freedom. However, the movement had not previously been analyzed. The displacements caused by adjusting each kit parameter and the movements limits allowed by the kits needed to be studied or calculated. A way to study the alignment of each string component was needed to be able to make the adjustments during the assembly process.

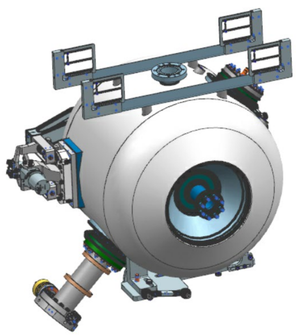

Figure 1. SSR2 Cavity

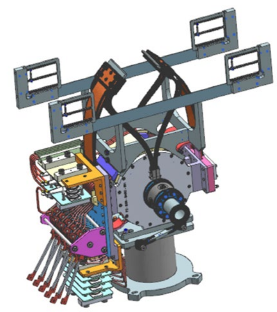

Figure 1. SSR2 Solenoid

**2 Methodology**

To study the alignment of SSR2 cavities and solenoids to in the cryomodule, mock-ups were designed based on the models. Identical cavity and solenoid alignment adjustment kits would be used in each mock-up, as well as the same BCAM targets. Aluminum extrusions hold the BCAM targets at the same relative position for each component based on measurements taken from the models. An aluminum target bar was used to represent the beam axis, held by aluminum extrusions such that its axis was at the same position as the beam axis would be.

Figure 1. SSR2 Cavity Mock-up

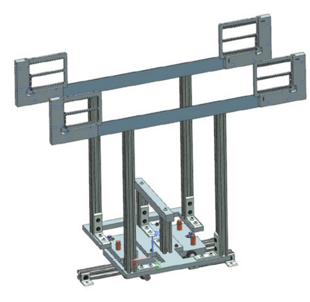

Figure 2. SSR2 Solenoid Mock-up

The models of the mock-ups could be used to analyze the degrees of freedom for each string component and find their maximum rotations and displacements. To calculate the approximate adjustments of each alignment adjustment kit parameter

A frame was designed to hold the BCAMs during the mock-up testing using the actual cryomodule BCAM mountings. The BCAM mountings are also attached to aluminum extrusions, and the heights of the BCAMs can be adjusted to match up to the heights of the mock-ups, using the extrusions and the set screws in the mountings. A mask is also attached to the frames to simulate the cryomodule viewport that the BCAMs look through. The BCAM mountings and viewport can be validated during testing with the mock-ups.

The first steps of procurement for the components of each mock-up were completed for the project. The amount of custom parts in the designs of each mock-up were minimized to decrease cost and procurement time. A sheet was created with all the details for each mock-up component sourced from vendors, as well as stock material for the custom components. To ensure that the aluminum extrusions were within a tolerance acceptable for the physical mock-up testing, the vendors were contacted to confirm their capacities.

## 3 Analysis

### *3.1 Maximums*

Since the effects of turning the set screws or rod ends of the alignment adjustment kits on the positions of the string components hadn't been studied yet, the maximum rotations and translations at their limits wasn't known. These movements of the mock-ups are limited by the threaded lengths of the rod ends and set screws, the lengths and positions of the constraint bolt slots, and the upper plate or feet coming into contact with the lower plate. The required maximum rotations needed to be at least 2+- degrees from nominal, and the translations needed to be at least 5mm from nominal. These goals were calculated based on the predicted alignment needs for each string components.

| | DOF | Max | Set Screws A/B/C (Turns) | | | Rod Ends ED/GF (Turns) | |
|---|---|---|---|---|---|---|---|
| Rotations (Degrees) | x+ | 3.3 | -4.1 | 10.6 | 10.6 | 0.0 | 0.0 |
| | x- | 3.2 | 8.7 | -6.1 | -6.1 | 0.0 | 0.0 |
| | y+ | 4.2 | 3.3 | -3.9 | 10.6 | 0.0 | -3.4 |
| | y- | 4.2 | 3.3 | 10.6 | -3.9 | -3.4 | 0.0 |
| | z+ | 2.8 | 0.0 | 0.0 | 0.0 | -1.2 | 8.0 |
| | z- | 2.8 | 0.0 | 0.0 | 0.0 | 8.0 | -1.2 |
| Translations (mm) | x+ | | | | | | |
| | x- | | | | | | |
| | y+ | 18.3 | 0.0 | 0.0 | 0.0 | -7.2 | -7.2 |
| | y- | 20.7 | 0.0 | 0.0 | 0.0 | 8.8 | 8.8 |
| | z+ | 13.2 | 8.6 | 9.0 | 9.0 | -1.6 | -1.6 |
| | z- | 7.1 | -4.7 | -4.7 | -4.7 | 0.6 | 0.6 |

**Figure 5. SSR2 Cavity Maximum Rotations and Displacements with Required Set Screw and Rod End Adjustments**

| | DOF | Max | Set Screws A/B/C (Turns) | | | Rod Ends ED/GF (Turns) | |
|---|---|---|---|---|---|---|---|
| Rotations (Degrees) | x+ | 5.6 | 9.3 | -3.4 | -3.4 | 0.0 | 0.0 |
| | x- | 6.2 | -5.3 | 11.3 | 11.3 | 0.0 | 0.0 |
| | y+ | 12.4 | 4.0 | 11.3 | -3.4 | -3.2 | 0.8 |
| | y- | 12.4 | 4.0 | -3.4 | 11.3 | 0.8 | -3.2 |
| | z+ | 7.8 | 0.0 | 0.0 | 0.0 | -10.4 | 0.0 |
| | z- | 7.8 | 0.0 | 0.0 | 0.0 | 0.0 | -10.4 |
| Translations (mm) | x+ | | | | | | |
| | x- | | | | | | |
| | y+ | 22.4 | 0.0 | 0.0 | 0.0 | -8.8 | -8.8 |
| | y- | 12.4 | 0.0 | 0.0 | 0.0 | 4.8 | 4.8 |
| | z+ | 14.0 | 9.3 | 9.3 | 9.3 | -1.4 | -1.4 |
| | z- | 5.1 | -8.4 | -8.4 | -8.4 | 0.8 | 0.8 |

**Figure 6. SSR2 Solenoid Maximum Rotations and Displacements with Required Set Screw and Rod End Adjustments**

The models of the cavity and solenoid mock-ups were studied to find the maximum rotations and translations possible. The assembly constraints in the models on NX could be adjusted to change the positions of the mock-up. The models were adjusted until they reached the limits of the alignment adjustment kits, and the distance constraints were recorded for each parameter. Using the pitch of each set screw and rod end, these distances could be converted to turns from nominal component positions. The maximum rotations and displacement were all within the adjustment goals.

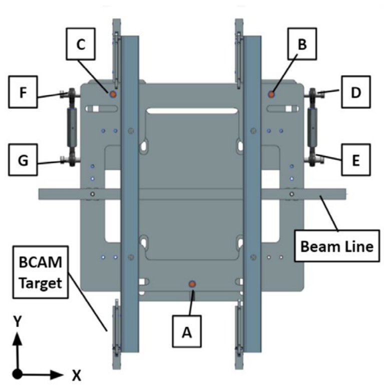


**Figure 7. SSR2 Cavity Mock-up Diagram**

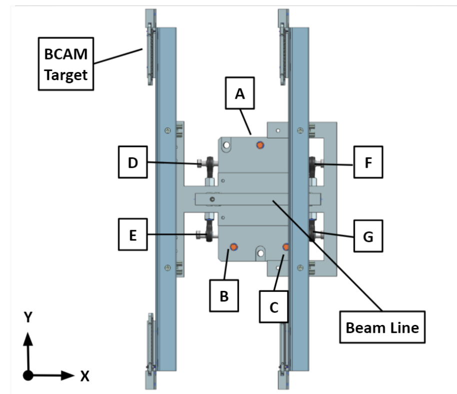


**Figure 8. SSR2 Solenoid Mock-up Diagram**

*3.2 Mathematical Model*

The movement of the beam axis when the adjustment kit parameters are adjusted can be calculated using trigonometric relations and vectors. A mathematical model was created with MATLAB using measurements taken from the component models in NX. The script takes the nominal positions of each set screw and vector are calculated between them. By inputting the desired positions of the set screws, the vectors change, and the new positions of the set screws are found, from which the position of two points on the beam axis, at points representing the end flange of the cavity, can be found.  During the writing of the codes, the movement predictions were validated against the models, and eventually they will be checked against the physical mock-ups when they are made. So far, the model can track two points on the beam axis to within 1mm for each xyz coordinate in the worst case.

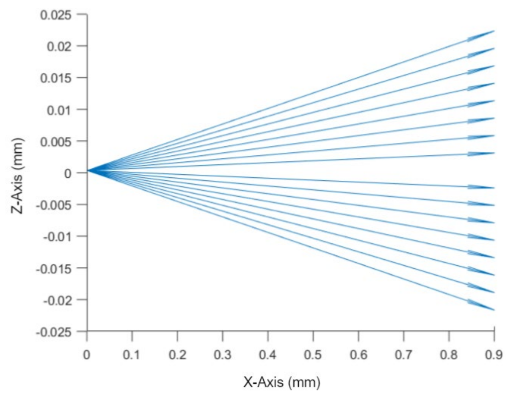


*Figure 9. SSR2 Cavity Beam Axis Vectors, Each Vector Representing the Position Of The Beam Axis After Set Screw B or C Have Been Given One Full Turn*

### *3.3 Physical Mock-up Testing*

Once all the mock-up components have been procured, the mock-ups will be assembled and tested. Each mock-up will be secured to a metrology table, along with a BCAM frame that will hold BCAMs in the same relative heights to the mock-up as in the cryomodule. The BCAMs will survey the BCAM targets on the mock-ups, and will be used to calculate the target displacements, and a dial gauge indicator will measure the position of the target bar representing the beam axis. A weight will be placed on the upper plate of each mock-up to simulate the effect of the weight of each string component.

The effects of changing the adjustment kit parameters can then be physically measured with the mock-ups. The mock-ups can be set up in the nominal position, and the set screws can be turned one at a time, while the displacements of the mock-up are measured by the BCAMs and dial gauge indicators. The mathematical model can be validated using the data collected from this process.

## 4 Conclusions and Future work

This project presents the use of mock-ups to study the alignment of SSR2 cavities and solenoids. Their analysis could greatly increase the efficiency and understanding of the alignment process. Once the mathematical model has been shown to be accurate, it can be used to automate the assembly alignment process of the cryomodules. During the process the BCAMs can measure the displacements of the targets and calculate the displacement of the beam axis for each component. The data can be plugged into the mathematical model, which would output the required alignment adjustment kit parameter changes to bring each string component into alignment. Actuators can then be installed on each set screw and rod end nut to make precise turns for each component. Using the new parameters, the actuators would bring each cavity and solenoid into alignment automatically.

**5 Acknowledgements**

I wish to recognize my supervisors Silvia Zorzetti and Jacopo Bernardini for their oversight and guidance throughout the summer. I'd also like to thank Fermilab and the SIST Internship for this valuable opportunity to achieve experience working at a national laboratory.

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