4 K ALIGNMENT OF SUPERCONDUCTING QUARTER-WAVE CAVITIES AND 9 T SOLENOIDS IN THE ATLAS INTENSITY UPGRADE CRYOMODULE*

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Abstract

The superconducting cavities and, especially, the magnets in high intensity ion linacs need to be aligned to the beam with typical transverse tolerances of ±0.25 mm and ±0.1 degrees at temperatures of 1.8 – 4.5 K. This is necessary to limit the emittance growth and minimize the beam losses. A new cryomodule with 7 superconducting quarter-wave resonators and 4 superconducting solenoids has been installed and is now operated at the Argonne Tandem Linear Accelerator System (ATLAS). We developed the techniques necessary to assemble the superconducting components in this cryomodule at room temperature so that they are aligned to the beam axis at 4.5 K. We achieved transverse alignment tolerances of <0.2 mm RMS. In this paper, we will present the details of the alignment hardware, procedures and results.

INTRODUCTION

Several new high-intensity hadron linear accelerators which require low-beta ($\beta = v/c < 0.5$) superconducting cavity resonators and superconducting magnets are being built and proposed, e.g., the Proton Improvement Project (PIP-II) at Fermi National Accelerator Laboratory, Argonne Tandem Linear Accelerator System (ATLAS) Intensity Upgrade at Argonne National Laboratory, and the International Fusion Materials Irradiation Facility Project. These and other high-intensity accelerators aim at achieving beam currents of several to hundreds of milliamps. Emittance growth and beam losses <1 W/m, to limit activation of the accelerator components [1], require alignment errors of the superconducting magnets to be less than 250 µm RMS and 0.1° with relaxed tolerances for the superconducting cavities [2,3]. Achieving this high alignment accuracy is non-trivial for components which should be assembled at room temperature but operated at 2-4.5 K in cryomodules. The alignment procedure must take into account the mechanical displacement of components due to thermal contraction and vacuum/pressure loading to obtain the desired accuracy at the operating temperature and pressure. One example of alignment techniques in such cryomodules is the low-CTE invar rod and the sliding cavity support to decouple longitudinal thermal motion of the cavity jacket from the fixture attached to the helium gas return pipe used in the TESLA Test Facility (TTF) cryomodule [4].

At Argonne we have recently commissioned a superconducting cavity cryomodule with 7 β=0.077 superconducting quarter-wave cavities and 4 superconducting 9 T solenoids contained in a single 5.2 meter long cryomodule [5,6]. In this cryomodule, the solenoids are required to be aligned to the beam at 4.5 K with transverse tolerances of 0.25 mm RMS as shown in Table 1 and the tolerances of the cavities are 4 times looser than the solenoids. In this paper, we present the alignment hardware used for satisfying these alignment tolerances, procedures of alignment and measurement, and alignment results measured at 4.5 K.

Table 1: Alignment tolerances of the solenoids in the ATLAS Intensity Upgrade Cryomodule

Coordinate	Alignment Tolerance
X/Y	0.25 mm RMS
Z	1 mm RMS
Pitch/Yaw/Roll	0.1° RMS

ALIGNMENT HARDWARE

The cavities and solenoids are loaded and aligned on the spanning titanium rail system, called strongback as shown in Fig. 1, which is suspended from the cryomodule lid [6]. Each cavity and solenoid mounts on top of the strongback with its own kinematic-alignment hardware. Details of this hardware are as shown in Fig. 2. The brackets are firmly attached to the solenoids and cavities and 3 balls, which are a part of the Kelvin type kinematic coupling [7], are attached to the brackets. The counter parts of the kinematic coupling are “ring”, “vee”, and “flat” [7]. The first two are attached on the runner which sits on the rail and vertically and horizontally movable by the adjustable screws during room temperature fine alignment. On the other side of the runner where the “flat” coupling sits on the rail the vertical position is adjusted by the screws and stainless steel shims.

ALIGNMENT PROCEDURES

The cavities and solenoids are aligned warm to an axis, which is translated from the cold beam axis by 3.0 mm vertical and 0.4 mm horizontal, to compensate for the expected thermal contraction of the cold mass and deflection of the titanium strongback due to the deflection of the hangers attachment points on the cryomodule lid

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with the application of vacuum. During room temperature alignment, the position of the cavities and solenoids are identified by fiducials placed on their helium jacket which are measured by using the optical level and transit.

Once the cavity string is assembled into the cryomodule box, the cross-hair targets attached on the cavities and solenoids were measured through the view ports on the cryomodule box before and after evacuation of the cryomodule and the subsequent cooldown. Shift of the centrelines of individual cavities and solenoids are derived from these measurements. The open wire targets are employed to minimize distortion of the image observed through the targets. The open wire target positions are surveyed with an optical transit and changes in position are monitored throughout the cryomodule assembly.

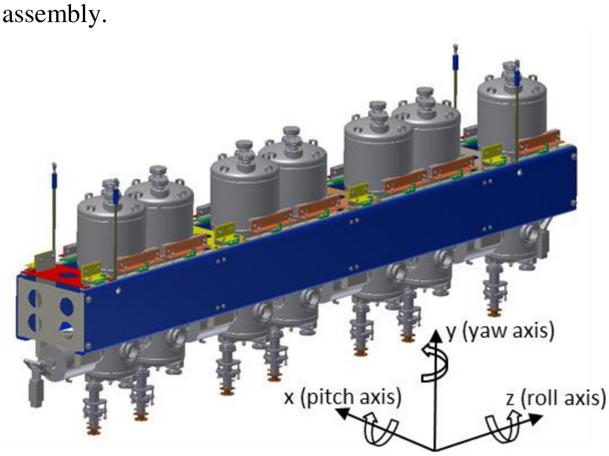

Figure 1: 7 cavities and 4 solenoids mount on the strongback (blue) with their own kinematic-alignment hardware (orange for cavity and yellow for solenoid). 4 supporting hangers are hung on the cryomodule lid which is transparent in this model view.

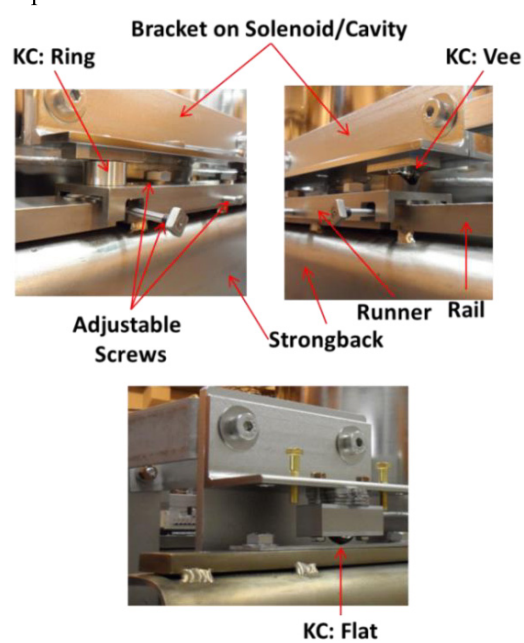

Figure 2: Pictures of the kinematic-alignment hardware: the top two ones show one side of the strongback and the bottom one shows the other side.

RESULTS AND DISCUSSION

At room temperature, we aligned the solenoids to the warm axis with a horizontal variation of 0.08 mm RMS and a vertical variation of 0.17 mm RMS. The pitch and yaw of the solenoids are measured to be 0.03 degrees RMS and 0.08 degrees RMS, respectively. The room temperature alignment results of the cavities, for which 4 times looser tolerances than the solenoids are allowed, are horizontal 0.36 mm RMS, vertical 0.21 mm RMS, yaw of 0.07 degrees RMS, and pitch of 0.15 degrees RMS. During alignment we learned that the evacuation of the cavity string gives extra force to the cavities and solenoids in addition to gravity which leads to increase the time consumed for alignment.

Measurements of the open wire targets for vertical shift on evacuation of the cryomodule and the subsequent cooldown are as shown in Fig. 3. The lines in Figure 3 show the expected target behavior. The average shift of the solenoid targets is 3.57 mm and it is in good agreement with the calculated shift of 3.60 mm, which is derived by thermal contraction of the cold mass and vertical shift of the lid due to vacuum pressure. The deviation of the target position from the calculated axis is a measure of alignment error; here the deviation is 0.08 mm RMS for the solenoids and 0.17 mm RMS for the cavities. Notice that some cavities have two target but the others have only one whereas all solenoids have two targets which is as many targets as practical. For the devices which have two targets, we used the average measured displacement.

The measurements in the horizontal direction are as shown in Fig. 4. A yaw of 0.01 degrees over the entire strongback is observed and it is supposed due to imperfect dimensions of the formed titanium sheets used in the strongback. Nevertheless, this yaw could be compensated by adjusting the cryomodule box then the average horizontal shift of the solenoid centers is 0.38 mm which is in good agreement with the calculation of 0.40 mm. The deviation is 0.09 mm RMS for the solenoids and 0.26 mm RMS for the cavities.

These alignment errors induced on cooldown are combined with the room temperature alignment error then final alignment errors are summarized in Table 2.

Table 2: Final alignment error

Direction	Solenoid	Cavity
Horizontal	0.12 mm RMS	0.50 mm RMS
Vertical	0.18 mm RMS	0.28 mm RMS

In the calculation of the target shifts presented above the thermal contraction and insulation vacuum force acting on the cryomodule lid are taken into account. The other effect such as changes of the strongback bending with temperature and deformation of the helium jacket due to cavity vacuum and liquid helium pressure could affect the position of both the component center and the targets. However, finite element analysis showed that these effects result in <30 μm shifts [8] and are ignored during the alignment of this cryomodule.

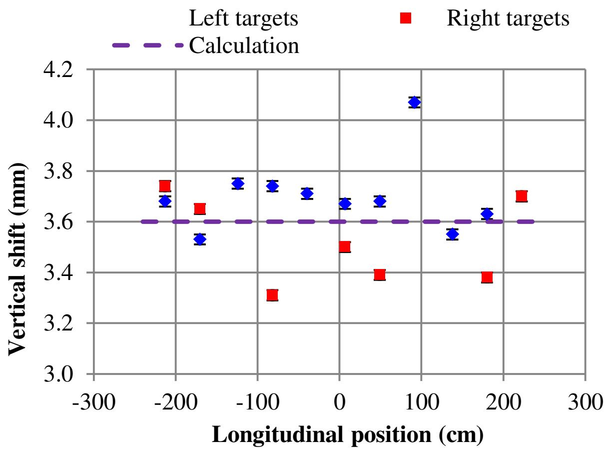

Figure 3: Vertical shifts of crosshair targets on evacuation of the cryomodule and the subsequent cooldown. The cavity string configuration is S-C-C-S-C-C-S-C-C-S-C from the left end, where S denotes solenoid and C denotes cavity.

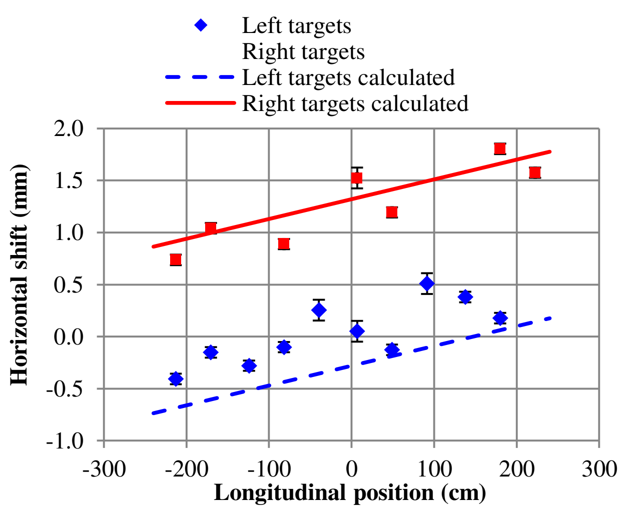

Figure 4: Horizontal shifts of crosshair targets on evacuation of the cryomodule and the subsequent cooldown.

SUMMARY

We used the Kelvin type kinematic coupling mount for the positioning of 7 superconducting quarter-wave cavities and 4 superconducting solenoids and achieved <0.2 mm RMS alignment errors at 4.5 K in the ATLAS Intensity Upgrade Cryomodule. This alignment technique can be utilized in future high intensity hadron linacs, e.g. PIP-II and SARAF HWR Cryomodules whose alignment tolerances are similar to the ATLAS Intensity Upgrade Cryomodule.

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