MECHANICAL ANALYSIS OF THE PROTOTYPE UNDULATOR FOR THE LINAC COHERENT LIGHT SOURCE

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Abstract

The Linac Coherent Light Source (LCLS) will require undulators with unprecedented mechanical precision in order to achieve the magnetic field requirements. Distortion of the undulator strongback due to the thermal effects and magnetic and gravitational forces could seriously degrade the performance. To minimize the distortion, a C-type, fixed-gap undulator with titanium strongback will be used. An analysis of the design of the structure and a comparison of the predicted results with the mechanical requirements and with magnetic measurements is presented.

INTRODUCTION

The LCLS undulator will consists of 33 individual undulator segments. Each segment will be a permanent–magnet device, 3.42 m long, with 226 poles per jaw. Undulator segments will have a fixed gap of 6.3 mm. The electron beam trajectory has to be straight to within a few microns over a distance of ~10 m, thus limiting trajectory walk-off from a straight line to ≤ 2 μm per segment [1].

Challenges in the mechanical design of the undulator segments are threefold. The material selected for the strongback has to be nonmagnetic but provide minimal deformation, the shape has to be optimized to provide maximum freedom of access for magnetic tuning, and the design should allow accurate assembly to provide the required geometry. This paper discusses the selection of the material and the effect of the selected shape on the strongback's deformation. The issues related to the assembly and alignment are discussed elsewhere [1, 2].

ANALYSIS OF THE UNDULATOR SEGMENT DEFORMATION

The mechanical structure of LCLS undulator segments is shown in Figure 1. It consists of a strongback (1), magnetic structure (2), and upstream and downstream supports (3). The structure deforms due to attractive (magnetic) forces between the halves of magnetic structure, the weight of the halves and the strongback itself, and the changes in ambient temperature. Residual stresses introduced during the machining can also contribute to the deformation.

The attractive force and the weight of the magnetic structure are given in Table 1. Temperature changes influence deformation in two ways: ambient temperature can be uniform but different than the reference (zero strain) temperature, and a temperature gradient can develop within the strongback due to the spatial gradient of ambient temperature. The residual stresses due to the machining cannot be properly quantified, and their effect on the deformation is discussed only qualitatively.

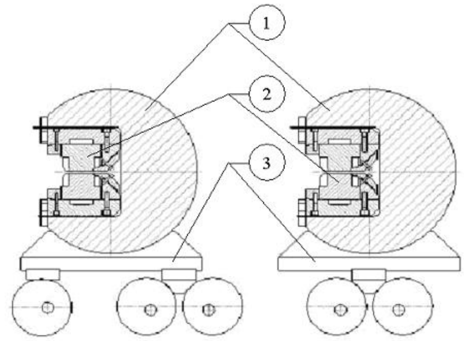

Figure 1: Undulator segment – schematic view

In the initial stages of the design, two possible cross-sectional shapes, "C" and "O", were considered. A C shape introduces asymmetry and is disadvantageous when deformation is considered, but the advantages of having open access to the magnetic structure and the vacuum chamber decided in favor of a C-shaped strongback.

Table 1: Undulator Segment Parameters

Parameter	Value
Attractive force (per jaw)	58.3 kN
Magnetic structure weight (per jaw)	123.4 kg
Vertical sag due to the weight	0.002 mm
Pole gap tolerance	±0.006 mm
Pole transverse displacement	± 0.2 mm
Pole displacement in Z-direction	±0.10 mm
Zero-strain ambient temperature	293.15 K

The Selection of Strongback Material

The choice for the strongback material is limited since it has to be nonmagnetic. Brass, bronze, aluminum and titanium-based alloys and austenitic stainless steels are nonmagnetic and were considered. Brass and bronze were eliminated due to their poor strength-to-weight ratio. Material properties [3] of the remaining three classes of material were compared using the following criteria:

- Young's Modulus, E
- Coefficient of thermal expansion, α
- Specific stiffness, $M_1 = E/\rho$
- Thermal performance index, $M_2 = \lambda/\alpha$

Young's modulus was used to evaluate the material performance under the magnetomechanical loads other than the weight of the strongback. The coefficient of thermal expansion was used to compare the effect of temperature changes on geometry. Specific stiffness and thermal performance index [4] were used to compare the influence of the weight and temperature gradients within the material, respectively. Normalized criteria for different materials are shown in Figure 2. Aluminum 6061-T6 properties were used for normalization. Austenitic stainless steels have the best overall mechanical and the

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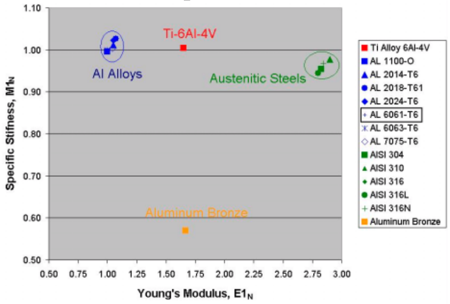
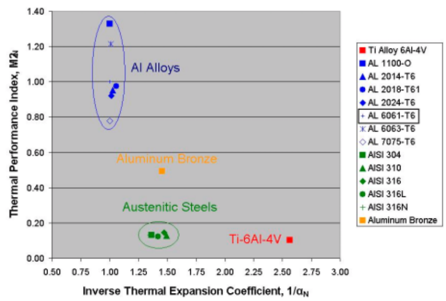
worst thermal properties. Titanium alloy Ti-6Al-4V has good strength-to-weight ratio, good torsion strength and moderate Young's modulus. It expands the least but has the lowest M_2 values. Aluminum alloys have the best strength-to-weight ratio but lowest torsion strength and Young modulus. They have excellent thermal performance index but expand the most.



a) Mechanical properties



b) Thermal properties

Figure 2: Normalized material properties.

The Finite Element Method Analysis

Comparison of material properties was inconclusive, and FEM analysis was performed. Deformation due to the gravity and attractive forces was computed for different materials. Also, the effect of temperature changes was computed for uniform changes in ambient temperature of ±2K and for a 2K ambient temperature gradient along the strongback. Model loads and restraints are shown in Figure 3. The magnetic structure was not included in the model due to the minor influence on the stiffness of the structure. However, its weight was taken into account as two uniformly distributed loads of 1.2 kN each, acting in the same direction. Attractive forces were represented as uniformly distributed forces of 58.3 kN acting in opposite directions. One support had no translational degrees of freedom, while the other could translate in the Z direction only. The zero strain temperature was 293.15K.

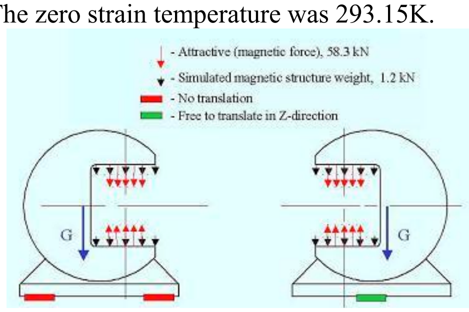


Figure 3: FEM loads and restraints

FEM Analysis Results

The weight-caused displacements computed for different materials are shown in Figures 4 - 6.

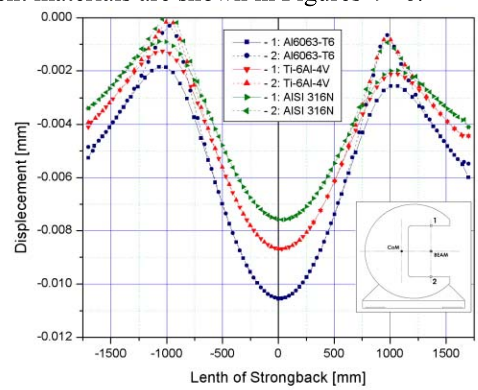


Figure 4: Gravitational Y-displacement in the beam plane.

The aluminum strongback deforms the most. Maximum Y displacement (12.5 μm) appears in the center of the strongback at the outer end of the upper jaw. The Y displacement decreases towards the center of the profile, and, in the plane of the beam, the maximum is 10.6 μm (Figure 5). Similar behavior is observed for titanium alloy and AISI 316N steel, but the computed values are lower, 8.8 μm for titanium alloy and 7.5 μm for stainless steel.

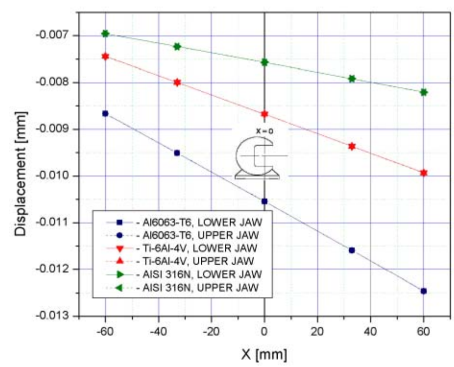


Figure 5: Gravitational Y displacement in the central cross section.

Calculated X displacements indicate that jaws displace in opposite directions (so-called rolling of the profile, Figure 6). The upper jaw displaces outwards and lower one inwards. Rolling is the most obvious for the aluminum strongback and the least visible for the stainless-steel one.

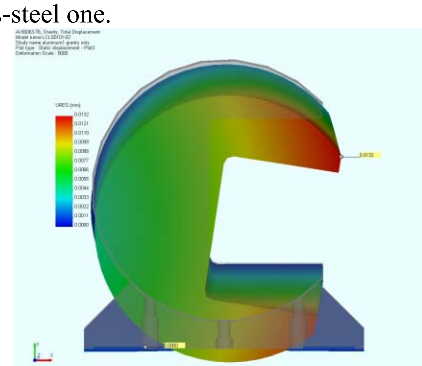


Figure 6: Rolling of the profile.

Displacements due to the gravity and attractive forces are shown in Figures 7 and 8. The tendencies remain the same, but the influence of the attractive forces is visible in the increase in displacement of the upper jaw and decrease in displacement of the lower. Again, the aluminum strongback deforms the most and the Y displacement of the upper jaw in the beam plane is 22.5 μm (112% increase). For the titanium strongback, the computed increase is 88% (16 μm), and for steel 71% (12 μm). The rolling of the profile is also more pronounced.

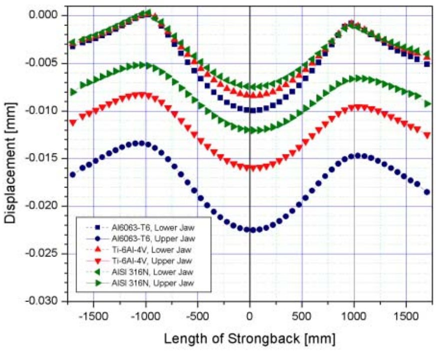


Figure 7: Y displacement in the beam plane due to gravity and attractive forces.

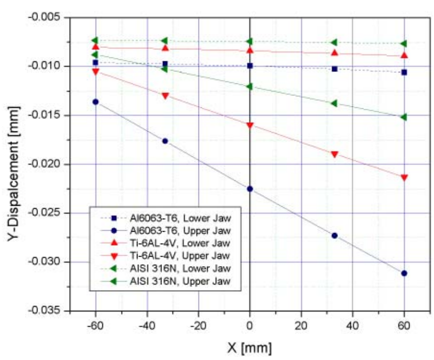


Figure 8: Y displacement in the central cross section due to gravity and attractive forces.

Differences in deformation of the lower and upper jaw affect the gap width along the entire section. The gap reduction is shown in Figure 9.

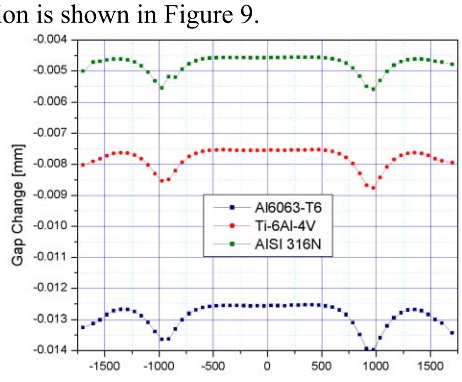


Figure 9: Gap change due to gravity and attractive forces.

Analysis of the influence of temperature gradients shows that ambient heating or cooling affects deformation more than temperature gradients within the material. The largest displacement in this case is in the Z direction. Again, aluminum displaces the most, the overall Z displacement is 0.16 mm (Figure 10), stainless steel displaces 0.11 mm and titanium displaces 0.06 mm. It is interesting to note that heating-related expansion reduces the displacement in the Y direction and the gap change.

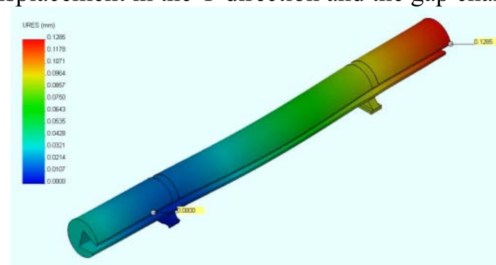


Figure 10: Z Displacement in the aluminum strongback due to the 2K increase in ambient temperature.

CONCLUSIONS

Results of FEM analysis show that both titanium alloy Ti-6Al-4V and AISI 316N stainless steel strongbacks surpass aluminum one in both mechanically and thermally related deformation. Easier machining [5], lower magnetic permeability, and absence of need for stress relieving provide titanium alloy with the advantage over austenitic stainless steels despite larger deformation and somewhat higher price of the entire device.

Computed deformation levels were somewhat higher than specified except for thermal expansion. Regardless of that, the results of magnetic measurements [6] performed on the prototype made of titanium alloy were satisfactory, which confirms the initial design assumption that the success of the device depends more on the ability to adjust and magnetically fine tune than on manufacturing precision.

REFERENCES

[1] J. Arthur et al, Linac Coherent Light Source Conceptual Design Report, SLAC-R-593, April 2002, p. 8.1-8.99.

[2] E. Trakhtenberg, V. Tcheskidov, M. Erdmann, I. Vasserman, N. Vinokurov, O. Makarov, P. Den Hartog, "First Prototype Undulator for the LCLS Project – Mechanical Design and Prototype Lessons," MEDSI 2002, Argonne, September 2002, p. 339.

[3] http://www.matweb.com/

[4] D. Cebon and M.F. Ashby, "Materials Selection for Precision Instruments," Meas. Sci. Technol. 5 (2002) 297.

[5] "Guide to Machining Carpenter Stainless Steels and Specialty Metals," Carpenter Technology Corporation, 1993, USA.

[6] I.B. Vasserman, S. Sasaki, R.J. Dejus, O.A. Makarov, E.R. Moog, E.M. Trakhtenberg, N.A. Vinokurov, "Magnetic Measurements and Tuning of the LCLS Prototype Undulator," FEL 2002, Argonne, September 2002, to be published.