DEVELOPMENT OF HIGH STABILITY SUPPORTS FOR NSLS-II RF BPMS*

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Abstract

The NSLS-II Light Source being built at Brookhaven National Laboratory is expected to provide submicron stability of the electron orbit in the storage ring in order to fully utilize the very small emittances of the electron beam. This requires high stability supports for BPM pick-up electrodes located near insertion device sources. Here we provide details for the design and development of these supports as well as measurement of thermal and vibrational stability of a prototype support.

INTRODUCTION

The National Synchrotron Light Source II (NSLS-II) is a 3GeV, medium-energy storage ring capable of producing world-leading levels of brightness, flux, and small beams over a very broad energy range [1]. One pre-requisite for this level of performance is to provide a high degree of electron beam orbit stability, on the order of 10% or better of the beam's size and divergence. The most stringent case of this occurs in the short straight sections of the NSLS-II lattice, where the vertical beam size and divergence (σ_y and $\sigma_{y'}$) are 3.1μm and 2.6μrad, respectively. The horizontal σ_x and $\sigma_{x'}$ are 29.6μm and 16.9μrad, respectively. If we attribute 100nm of noise due to BPM electronics, this puts an exceptionally high tolerance on the mechanical stability of the BPM at this location. As such, the requirements for NSLS-II as defined in the preliminary design call for high-stability stands secured to the storage ring floor to support the BPMs upstream and downstream of the short straight sections. The BPM chambers at these locations will be mechanically isolated from girder sections and insertion devices via welded stainless steel vacuum bellows. The stability requirements for these stands are shown in Table 1 below [2].

Table 1: Mechanical Stability Requirements

	Bandwidth	Vertical	Horizontal
Vibration	50–2000 Hz	10 nm rms	25 nm rms
	4–50 Hz	25 nm rms	60 nm rms
	0.5–4 Hz	100 nm rms	100 nm rms
Thermal	1 min to 8 hr	100 nm rms	250 nm rms

AMBIENT CONDITIONS

The ambient conditions of NSLS-II that influence the design of a high-stability BPM support can be categorized as both vibrational and thermal. Ground motion at the NSLS-II site is expected to be on the order of 15 nm rms from 4–50 Hz. One of our design goals for a stable structure is to have its lowest natural frequency of vibration above 30 Hz where ambient ground motion is very small (~1nm), thereby minimizing any amplified motion.

By far the most challenging requirement for this design is the thermal stability of 100nm rms in the vertical direction. There are two modes of heat transfer that contribute to thermal deformation: convection due to changes in ambient air temperature, and conduction at the base of the structure due to temperature changes of the storage ring floor.

Tunnel temperatures in the storage ring of NSLS-II will be controlled to ±0.1°C with a 1-hour cycle. On the surface, this implies an inherent coefficient of thermal expansion (CTE) of 0.83ppm/°C, which is well beyond the performance of most conventional materials. However, if one considers that the structure will only see a fraction of the ambient temperature change due to the thermal cycling, then this value can be somewhat relaxed. A low CTE material is, of course, still desirable.

DESIGN CONSIDERATIONS

The initial design concept for a high-stability BPM support called for the use of a low-CTE carbon fiber/epoxy tube as the primary structural element. CTE values as low as 0.1ppm/°C have been advertised for this material, but in order to meet the vibrational requirements, a 250mm diameter tube with a Young's modulus of 10 GPa in the transverse direction was specified. The consensus from multiple manufacturers was that an expensive, high modulus fiber would be required to meet this performance requirement. In addition, it was difficult to find a manufacturer able to certify the thermal and mechanical performance of the tubes in question. The performance values that were supplied were essentially computer generated. We did select a manufacturer to provide several first article tubes for our review. Measurements performed at BNL revealed a CTE of 3ppm/°C and $E_{Transverse}$ of 4 GPa, well outside the advertised performance.

The final design concept utilizes Invar alloy for the primary structural element and consists of an array of four 50mm diameter rods bolted to a base plate. A set of steel rod spacers with split collar joints are arrayed along the height of the structure to dampen vibration and raise the natural frequency. Figure 1 shows a rendering of this design.

Invar is well known for its thermal stability, with an average CTE of 1.3 ppm/°C up to 93°C, but it also has a

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comparatively low thermal diffusivity (2.5e-06 m^2/s), roughly five times lower than steel and 28 times lower than aluminum, which makes it very slow to respond to changes in temperature.

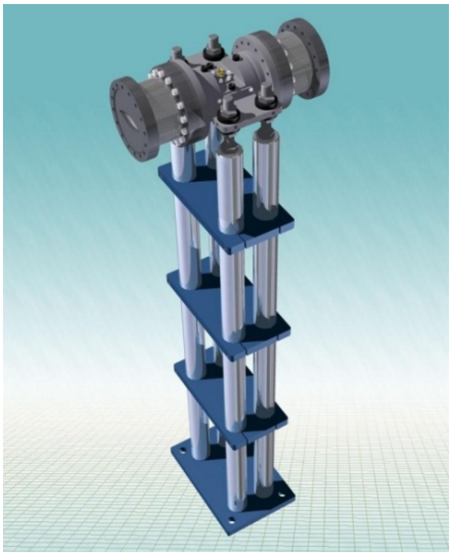


Figure 1: Rendering of high-stability Invar support.

With the ambient temperature of the NSLS-II storage ring cycling at ±0.1°C per hour, it was anticipated that the Invar components would see a small fraction of this change. This, combined with a low expansion coefficient, would yield a thermally stable structure. The Young's modulus for Invar is also fairly stiff, at 148 Gpa, making it attractive from a vibrational standpoint.

THERMAL ANALYSIS

A transient thermal finite element analysis was performed on this design using a free convection heat transfer coefficient of 8 W/m^2-°C applied to all exposed surfaces with a temperature of 25.0±0.1°C per hour. The floor temperature boundary condition was set to 25.0±0.1°C per 24-hr period. The resulting distribution reveals the maximum temperature rise occurring at t=6.5 hr, shown in Figure 2. The base of the structure is thermally anchored to the floor and is coupled to the floor temperature. However, the upper 90% of the structure is dominated by the convective condition and is regulated to ±0.01°C. The net effect of this is roughly ±30nm of thermal deformation in the vertical direction over a 1-hr interval.

MEASURING THERMAL STABILITY

Measurements were made in a temperature-controlled room where it was possible to simulate the NLSL-II tunnel temperature conditions. The experiment involved bolting the prototype structure to the concrete floor. An insulated Invar post was bolted to the floor adjacent to the prototype and served as a stable reference to which a differential variable reluctance transformer (DVRT) was mounted. This sensor is capable of resolving displacement

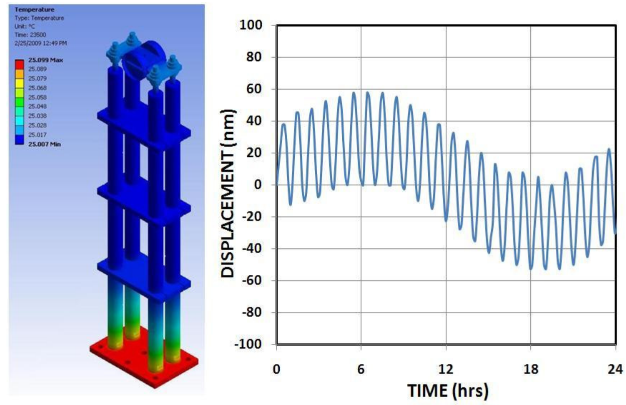


Figure 2: Temperature distribution (left) and plot of vertical deformation.

to a resolution 10nm and, because of its unique design, is immune to changes in temperature. An array of variable resistance temperature sensors were installed in both the prototype and reference stands, as well as sensors to monitor floor and air temperature. Over short periods of several hours, vertical motion of ±30nm to ±40nm was consistently observed. However, it became clear after several days of data that the insulated reference stand was thermally unstable over long periods of time, with temperature changes of more than 1°C being observed. The average temperature of the prototype was ±0.015°C and was synchronized with the cycling ambient temperature cycle. Using a value of 1.6 ppm/°C for Invar (calculated from data collected) applied to the 1.2m length of the prototype stand yields a vertical stability of ±30nm. Figure 3 shows a plot of calculated vertical displacement, average stand temperature, and air temperature vs. time for 56 hours.

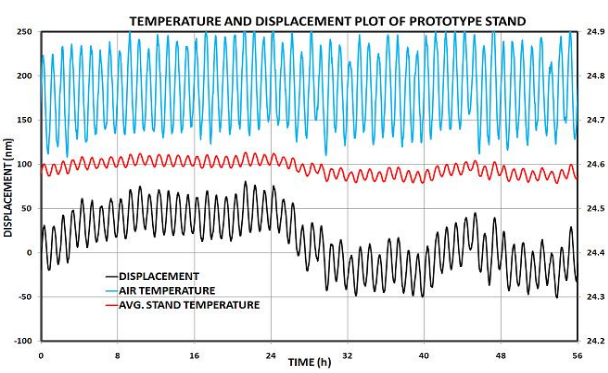


Figure 3: Temperature and displacement plot.

Due to the erratic behavior of the reference stand over the long durations, an alternative approach for measuring the vertical stability of the prototype was implemented. Using a laser interferometer mounted directly to the stand at 1.2m, it was possible to measure the vertical displacement of the stand with respect to the ground to a precision of 20nm. For long-term measurement, it was necessary to compensate for the ambient conditions (i.e., temperature, pressure and humidity) that alter the refractive index of air. The results of this are shown in

Figure 4. For comparison, a calculated position is also shown based on average stand temperature and CTE.

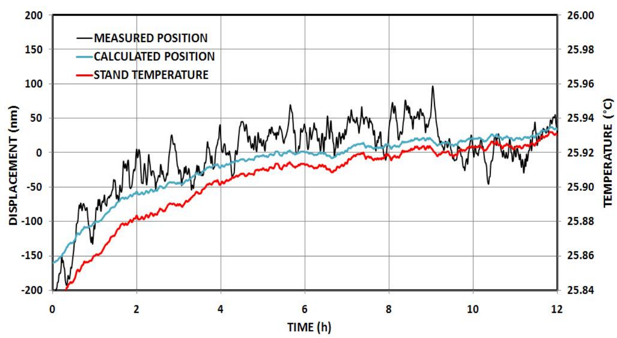
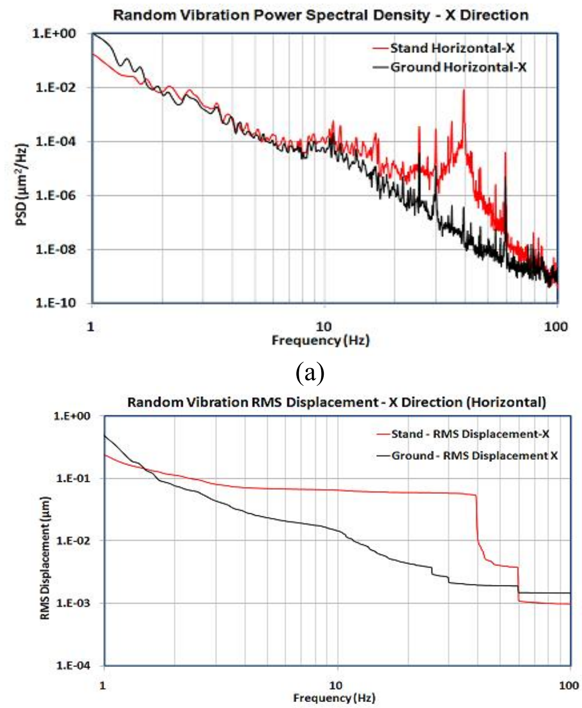


Figure 4: Plot of positional data from laser interferometer.

VIBRATION ANALYSIS

In order to achieve the required vibrational performance of the structure, a modal analysis was performed using ANSYS Workbench with a fixed support condition at the base. The simulation revealed f_{1X} = 47 Hz and f_{1Z} = 37 Hz where X and Z are the transverse and longitudinal directions respectively. This was followed by dynamic measurement of the first eigen-frequencies of the prototype structure in the X and Z directions. In addition, RMS motion was measured in the 4-100Hz band in the three principal directions in order to estimate amplification of ground vibration. Figure 5(a) and (b) show the result of vibration measurements in the horizontal or X direction. The PSD plot in Figure 5(a) shows the first eigenfrequency occurring at 39.3 Hz, which agrees with the predicted FEA value to within 20%. The difference is likely due to the fact that a "fixed" boundary condition does not accurately simulate the bolted connection at the base/floor interface. The displacement plot in Figure 5(b) shows the RMS ground motion from 4-100 Hz of 29nm. The horizontal motion of the prototype stand at 1.2m in this regime was measured at 71 nm resulting in an amplification factor of 2.45. With the ground motion of NSLS-II estimated at 15nm, we can expect the horizontal motion of the stand during operation to be on the order of 40nm or better which satisfies the horizontal vibration requirement.

As expected, there was no significant amplification in the vertical direction. Given that the ground motion at the NSLS-II site is on the order of 15nm, this design should satisfy the vertical vibrational requirement.



(a) (b)

Figure 5: (a) Power spectral density and (b) RMS displacement plots for horizontal vibration.

CONCLUSIONS

The initial design of a high stability BPM support utilizing Invar component satisfies both the thermal and vibrational stability requirements for NSLS-II. Finite element analysis and discrete measurement of thermal deformation show that given an ambient temperature condition of ±0.1°C per hour, the specification of ±100nm vertical stability is easily met.

The relatively high Young's modulus of Invar, combined with an array of steel rod spacers, raise the natural frequency of the prototype structure above 30 Hz so as to effectively minimize the amplification of ground vibration.

Work done on similar support structures at the SSRF have shown significant improvement in vibrational performance by changing the connection between the support and ground from a bolted joint to a full grout [3]. Future studies of this design will involve testing the effects of a grouted joint on modal vibration and long-term thermal stability.

REFERENCES

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[2] I. Pinayev and B. Kosciuk, "Performance Requirements and Engineering Specifications - High Stability BPM Support," unpublished paper.

[3] X. Wang, Y. Cao & L. Yin, "Dynamic Performance of the Beam Position Monitor Support at the SSRF", Journal of Synchrotron Radiation (2009).