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An Investigation of Low Beta Triplet Vibrational Issues At Fermilab's Collider Detector*

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Abstract

The vibrational aspects of recent disturbances at the low beta focusing quadrupoles, which caused proton beam loss at the Collider Detector at Fermilab (CDF), are discussed. Two low beta focusing quadrupoles are supported by a girder, which is extended over the CDF collision hall pit on each side. The low beta girder has a ledge mount support at an alcove's face and two Invar rods near the opposite end. Forced response measurements were taken on the low beta girder, where the power spectral density (PSD) function was used to obtain RMS displacement. The effects of local excitation due to operating equipment and near-field excitation due to ambient ground motion caused by local traffic are examined. The discussion explores dynamic response characteristics of the low beta quadrupoles and supporting girder using beam loss as the vibrational stability criteria. This paper also presents practical problem-solving approaches for similar accelerator components.

1. Introduction

Vibrational issues affect beam stability of the circular accelerator called the Tevatron a 900 GeV proton-antiproton collider at Fermi National Accelerator Laboratory through beam jitter and emittance dilution. The Tevatron is a super-conducting accelerator, which is 6.4 km in circumference. Fermilab's primary Run IIa goal is to increase luminosity to the Collider experiments and proton losses (emittance growth) directly impede that goal. Understanding these vibrational issues requires access time and extensive data taking which is quite limited due to constant Tevatron operation. Access may be as infrequent as once every one to three months. The purpose of these measurements was to assess the effect of ambient vibration and other excitation forces which were caused by local traffic on the proton beam. Once gaining an understanding, a plan of action was formulated to correct or minimize this effect, if possible.

1.1. Proton/Antiproton Losses

The effect of the vibration was first experienced as proton/antiproton losses within the Tevatron. Evidence of the vibrational source was recorded and shown in Figure 1. These losses were measured using the beam shower counters (BSC) located closest to the B0 interaction point at CDF. A BSC station consists of 4 scintillator panel counters, which are arranged in quadrants around the beam pipe at a longitudinal distance of +/- 5 m from the interaction point. Each counter has an active area range in terms of radius from the beam pipe axis between 4.4 cm and 7.0 cm. The BSC measures losses by tracking counts (in terms of frequency), which are coincident between the individual devices and the proton/anti-proton bunch while crossing the counter's plane [1].

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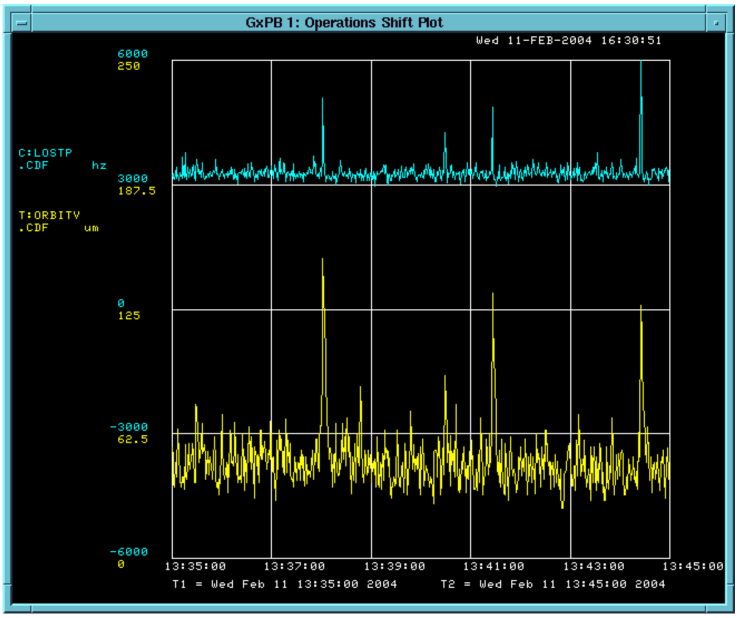


Figure 1 Plot of LOSTP and ORBITV was taken from the Fermilab Tevatron electronic log (e-log) posted on 11 Feb 04.

1.2. Vibrational Effect on Proton/Antiproton Losses

A 12-Hz excitation was first noticed in the proton beam and after further investigation it was then found that proton losses seen by the device, LOSTP, were correlated to random traffic patterns [2]. Spikes were seen in both devices, LOSTP (moving from 3,000 to 6,000 Hz) and ORBITV (moving from 60 to 150 microns). ORBITV monitors the vertical position of the proton beam orbit and is located one km downstream of CDF. Subsequently, an experiment involving an 18,000-kg truck confirmed that proton losses occurred were due to excitation near the B0 service building within the Tevatron ring (shown in Figure 2). The excitation force was developed when the truck passes over a depression found on the Main Ring road coincident to the B0 service building.

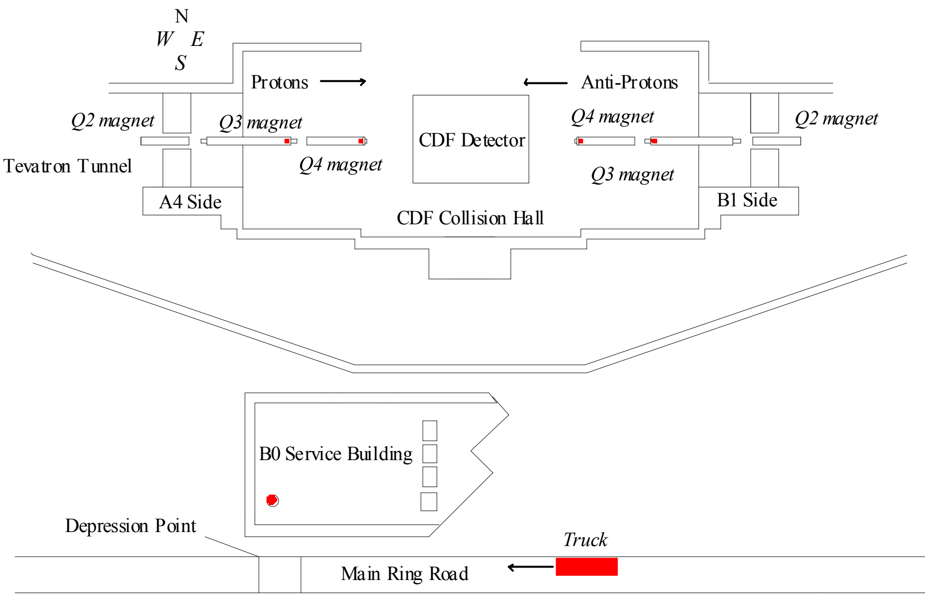


Figure 2 Plan view of B0 service building and CDF's Collision Hall.

1.3. Low Beta System

The low beta triplet which is comprised of magnets: Q2, Q3 and Q4 is found on both sides of the CDF Collision Hall as shown in Figure 2. Low beta is defined as emittance or cross-section of the beam. The Q3 and Q4 magnets are suspended 4.5 m above the floor and 5.4 m from the ceiling within a girder. The other ledge mount-type support location exists within an alcove upstream (Figure 3). Steel shielding which is 40 cm thick in each direction encloses the girder and protects CDF from radiation longitudinally stemming from the Tevatron. The girder is physically isolated from the shielding in order to avoid physical disturbances to the low beta system. The low beta quadrupoles focus the proton/anti-proton beams in the x- and y- plane, prior to the collider experiment. The Q2 magnet is supported on the floor of the Tevatron and spans the concrete interface between the Tevatron and the CDF Collision Hall. The low beta system is critical to Collider operations as proton and anti-protons are delivered via this magnetic conduit.

Figure 3 Low beta magnets and girder suspended at A4 within the Collision Hall.

2. Problem-Solving Approach

Our approach to this vibrational issue began with evaluating the proton beam stability by monitoring the beam losses at B0 and other points around the Tevatron ring. Next, we assembled the vibrational equipment that had the proper range and sensitivity with the ability to be isolated from AC voltage sources. Then, we consulted vibration experts from others Laboratories that had surmounted similar issues. Finally, several measurements were made after waiting for sufficient access time, with the results guiding our trouble-shooting flow chart.

2.1. Vibrational Equipment

The ground, magnet and Invar rod measurement set-up involved the following equipment:

- Sony Laptop

- National Instruments DAQ card AI 16 XE-50, 16 bit, 16 single analog inputs
- Charge Amplifiers, SC-2040 (6 channels) with DC power supply
- Velocity Sensor, HS1 Geophone, (4) vertical and (4) horizontal (4.5 Hz to 1 KHz range)
- Velocity Sensor, Sercel Mark L4 Geophone, (2) vertical (0.1 Hz to 750 Hz range)

2.2. Vibrational Measurements

On March 15, 2004, the initial vertical response measurements were taken of the four low beta magnets (these positions are shown in red in Figure 1). These measurements involved the ambient response at the B0 service building and the excitation force of the truck, which initially revealed the problem in the proton beam. Six velocity sensors were fed into an amplifier and through a laptop via an I/O card and each signal was imported into Labview and recorded digitally. The velocity sensor data was converted into displacement within the time domain and spectra power within the frequency domain using Matlab software.

It was important to implement practical measures such as protecting the device connections from AC sources in order to prevent a shorting case of connectors to ground. Also, mounting each velocity sensor properly to a flat surface with adhesive was critical. A special aluminum (low mass) clamshell clamp was designed for the Invar rod mounting with a threaded hole for each sensor. The more sensitive Sercel Mark L4 Geophones were used to measure vibration at different ground levels and also to confirm the vertical measurement on the Q3 magnet at A4. The measurements were taken in a 25-second "snap-shot" and a longer 25-minute integrated measurement was taken to study the ambient vibration.

2.3. Ambient Sources

Independent measurements in the area local to the CDF enclosure were completed and several potential driving sources were found [2]. There are many types of reciprocating pumps associated with the support of utilities in the area which are not transmitted perfectly with frequencies of 26 Hz (1,725 rpm) and a fan motor at 38 Hz (2,400 rpm). Pressure surges from compressors found in the helium suction return lines provide a 10-Hz resonance source. Low-Conductivity Water (LCW) lines transmit 17 Hz (1080 rpm) from rotating pumps. Fundamental frequencies of 4.6 Hz (300 rpm) and 8.5 Hz (600 rpm) propagate from two types of compressors located near CDF at the Central Helium Liquefier (CHL) Plant [3].

AC electrical noise is undesirable and this source can be eliminated from the measurement by using DC supply sources only. Often, it is possible for external AC harmonics to be electro-magnetically coupled into the measurement via the cable. The 60-Hz measured spikes and higher multiples were experienced from sources internal to the service building such as large transformers and magnet power supplies, however these false measurements did not affect the data. It was important to understand the source of these peaks and whether they were external "hum" or actual resonance [4].

2.4. Spectra Power Analysis

Spectra power plots were extracted from the initial measurement data and developed using Matlab software. These plots provide the vertical response (relative motion) of both the magnets and points on the ground at different frequencies. Also, horizontal and longitudinal motion of the Invar rods was considered. These plots account for all of the displacements found at or below that frequency until the next peak is approached. The contribution from one frequency was judged by taking the difference in displacement between that peak and the proceeding peak in frequency.

2.5. Enclosure Motion and Supporting Structure

The enclosure measurements were divided into three areas: the B0 service building, the CDF Collision Hall proper and the Alcove. The appreciable spectra ambient response at the B0 service building, shown in Figure 4(a), began at 60 Hz climbing from 38 nanometers to 200 nanometers due to strong AC coupling, growing more at 4.6 Hz (moving from 200 to 220 nanometers). In each case, the forced response involved an 18,000-kg truck moving at 40.2 kph. This response, which is shown in Figure 4(b), became noticeable also at 60 Hz climbing from 8 to 80 nanometers, growing again at 17 Hz (increasing from 80 to 230 nanometers) with only a small influence from CHL at 4.6 Hz (moving from 230 to 300 nanometers). AC noise was noticed at 120 Hz (well below 30 nanometers in both cases).

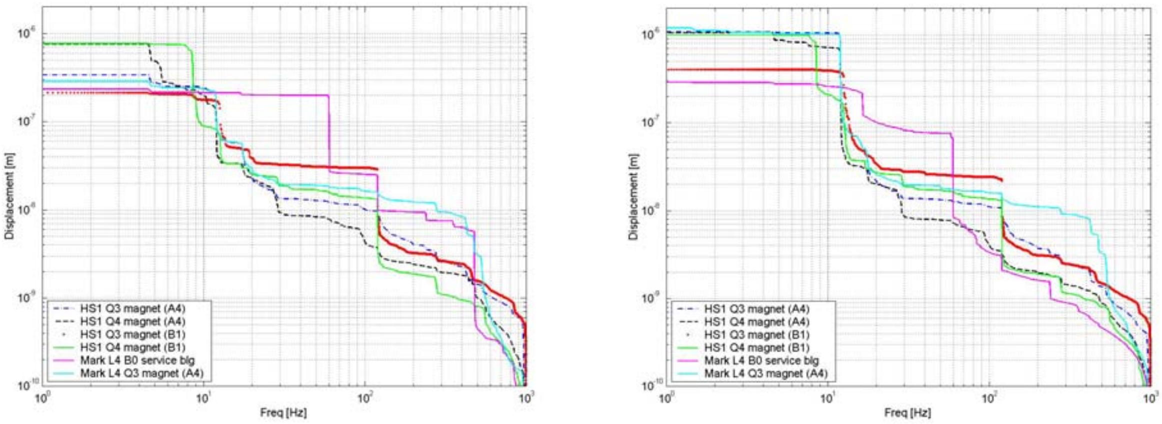
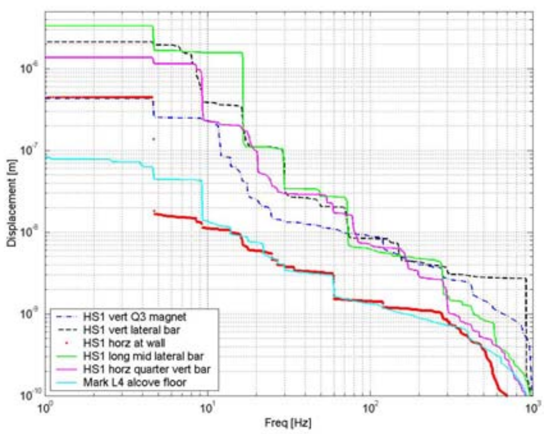


Figure 4(a) Low Beta spectra power plot with a forced excitation. **Figure 4(b)** Corresponding spectra of ambient response.

Vertical and horizontal measurements were taken where the lateral Invar is attached to the wall. The ambient response to horizontal motion in Figure 5(a) became noticeable at 4.6 Hz, growing from 9 to 450 nanometers. The vertical alcove movement, also found in Figure 5(a) was appreciable at 9.2 Hz, moving from 10 to 50 nanometers and at 4.6 Hz, extending up to 80 nanometers. CHL was seen as the primary source of 4.6 Hz and 9.2 Hz.

Three points of interest were considered during another access opportunity on May 17, 2004: the mid-span of the ceiling concrete block near the Invar connection, the top of the “S” beam flange near the concrete ceiling and on the Collision hall floor. The ambient vertical response on top of the “S” beam near the vertical Invar connection was most noticeable at 4.6 Hz (moving from 85 to 110 nanometers) and at 9.2 Hz (moving from 50 to 85 nanometers). The ceiling motion also had a frequency of 4.6 Hz (with slightly lower movement from 80 to 95 nanometers) and 9.2 Hz (moving from 50 to 80 nanometers). An important distinction in terms of vertical motion was seen between the “S” beam resonance at 12 Hz and concrete ceiling resonance at 14 Hz. Clearly, the supporting structure, girder and Q3 magnet at A4 is resonant at 12 Hz. However this response has not surfaced in the enclosure.



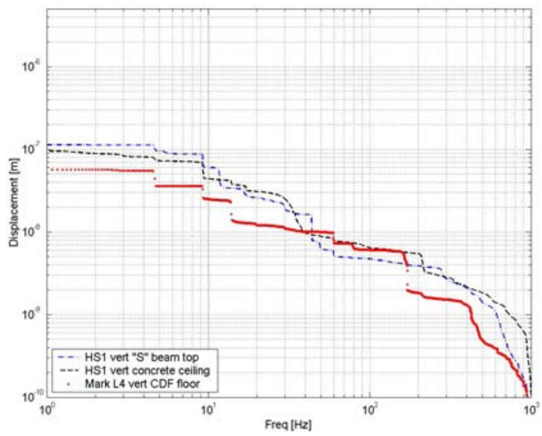


Figure 5(a) Spectra plot for the Invar system at A4. **Figure 5(b)** Spectra plot of enclosure and supporting structure.

2.6. Low Beta Quadrupole Motion

The largest baseline response to ambient environmental and equipment noise was noticed at each Q4 magnet (on both the A4 and B1 side in Figure 4(b)) with roughly 800 nanometer of vertical motion. The frequencies were different between these two devices, 4.6 Hz (at A4) and 8.5 Hz (at B1). Physically, the quadrupoles and supporting system is symmetric about the interaction point of CDF, however there are slight differences in frequency response due to proximity of the driver (CHL).

Each Q4 magnet is cantilevered past the Invar rod support where the weight of the entire magnet is forward of this support point. Clearly, the end of the Q4 magnet is most susceptible to vertical motion and if ground vibration was affecting these magnets then it would be seen here. The vertical displacement response to forced excitation for each Q4 magnet was nearly identical, reaching one micron as shown in Figure 4(a). Both responded at 12 Hz (rising from 35 nanometers): however the Q4 magnet on the A4 side climbed to 600 nanometers, and then on to one micron at 4.5 Hz.

The next largest displacement was seen at the forward edge of the A4 Q3 magnet, moving 650 nanometers at 12 Hz. This is thought to have the largest affect on the proton beam. The Q3 magnet on the B1 side was moving much less at about 100 nanometers, but also at 12 Hz. In this case, very little anti-proton losses are seen, which is consistent with beam study measurements.

2.7. Invar Motion

The Invar rod is steel (consisting of 36% Nickel) with a very low thermal expansion coefficient (1.18 x 10^{-6} cm/cm degrees C, from 30 to 100 degrees C) that protects against temperature gradients, which affect both lateral and vertical motion. The collision hall temperature varies between 3 to 4 degrees Celsius. The estimated natural frequency of the lateral Invar rod, based on measured deflection (sag) was roughly 4.5 Hz. Mounting positions at quarter and midpoints of the vertical Invar rod is shown in Figure 6(a) and lateral Invar rod in Figure 6(b).

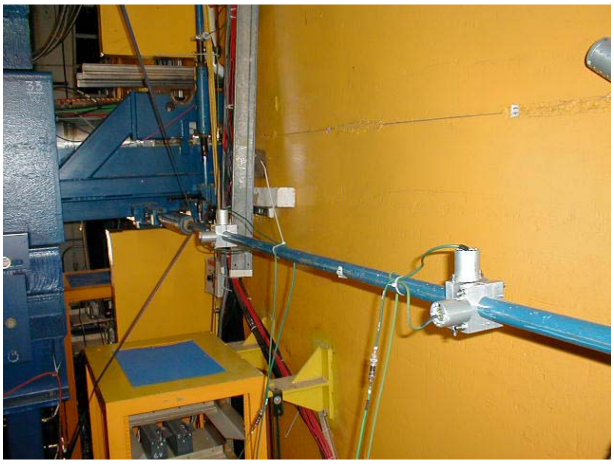
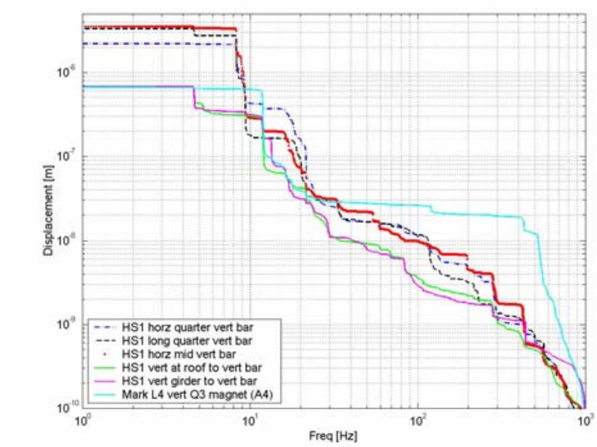


Figure 6(a) Velocity sensor installation along vertical Invar rod. **6(b)** Velocity sensor positioning on lateral Invar rod.

A comparison of ambient relative motion of the vertical and lateral Invar rods is shown in Figure 5(a). The midpoint horizontal motion response of the vertical Invar rod at 4.6 Hz climbed from 1 to 4 microns and at 9.2 Hz changed from 210 nanometers to 1 micron. A large mid-point horizontal response was seen on the lateral Invar at 4.6 Hz climbing from 8 to 34 microns and at 17 Hz moving from 100 nanometers up to 8 microns. The corresponding vertical motion of the Q4 magnet at 4.6 Hz changed from 9 nanometers to 41 nanometers. Figure 7(b) summaries the modal shapes of vertical and lateral Invar rod. Each vertical Invar rod had horizontal and longitudinal orbital motion and each lateral Invar rod had an orbital path that moved in the vertical and longitudinal plane.



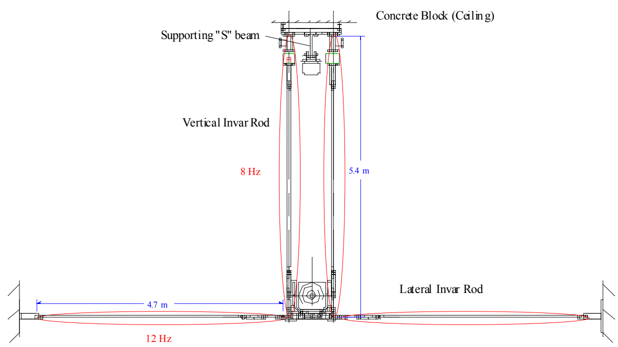


Figure 7(a) Spectra plot for the Invar system at A4. **Figure 7(b)** Cross-sectional view of magnet, girder and Invar at A4.

2.8. Tensioning of Invar Rod

The only short-term solution involved the adjustment of the lateral Invar rods. Normally, these rods are pre-loaded between 890 to 2,200 Newtons axially in order to maintain lateral alignment stability. The decision was made to tension the lateral Invar up to 13,300 Newtons, since unloading could potentially affect alignment stability. We found a decoupling after applying more tension to lateral Invar rod beam stability as our vibrational criteria. After start-up of the Accelerator, the vertical motion of the beam was relatively the same, however a slight horizontal movement has surfaced. It was difficult to pinpoint the source of this problem, since other work within the Tevatron had been completed during the shutdown which may also have affected the beam.

3. Qualitative Studies

Modeling this structure revealed that the estimated natural frequencies did not follow the measured resonant peaks. The model using Multiframe software involved the two S18 x 70 structural beams and a transversely attached W18 x 97 structural beam as shown in Figure 8. It was difficult to properly define the constraints and accurately represent the real structure in terms of a computer-generated model. This model still provided a qualitative measure or indication in terms of minimal motion response or minimization of energy within each structural beam. Therefore, from the Multiframe modal analysis, points of possible constraint were defined to minimize the supporting structure's response to ambient vibration and also forced excitation.

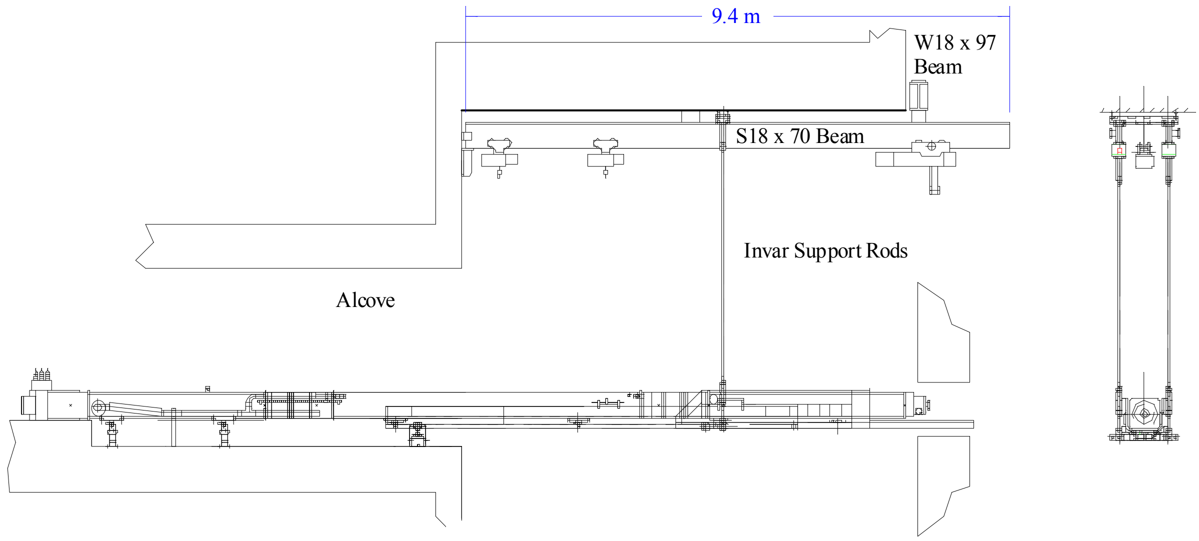
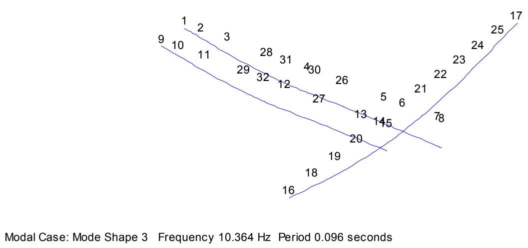


Figure 8 Elevation view of low beta system with overhead supporting structure at A4.

3.1. Multiframe Analysis

The weight and stiffness of each beam was considered in the Multiframe analysis with the load of 60,495 Newtons applied by the low beta girder. An estimated vertical displacement of 1.69 cm at the Invar connection (node 30 in Figure 9(a)) and 1.35 cm at the "S" and "W" beam connection (node 6) was found by considering the maximum static deflection results, which are not shown. A modal analysis of the structure is outlined in Table 1 and the third modal shape given in Figure 9(a). Figure 9(b) represents the third modal shape case, where wooden wedges were added to specific locations to minimize the vertical displacement response to a broad-band frequency excitation.



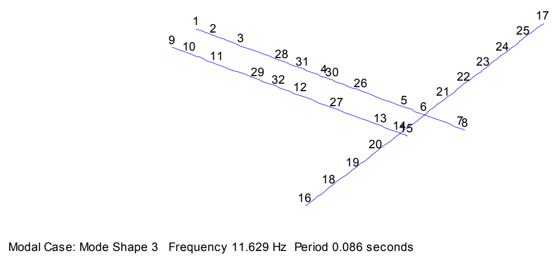


Figure 9(a) Modal shape of structure prior to addition of constraints. **Figure 9(b)** Modal shape of constrained structure.

After adding stiffeners consisting of 4 wooden wedges to the model, the first few modes of natural frequency were shifted only slightly, however the vertical displacement response approached zero. It was difficult to properly define the boundary conditions for the model, however it will be possible to shift the natural frequency higher than estimated. Our plan involves positioning the wedges which can be mechanically expanded at nodal points: 26, 27, 28 and 29 in Figure 9(b).

Table 1 Modal analysis result for supporting structure.

	Mode 1		Mode 2		Mode 3		Mode 4		Mode 5	
	f (Hz)	δy(mm)	f (Hz)	δy(mm)	f (Hz)	δy(mm)	f (Hz)	δz(mm)	f (Hz)	δz(mm)
Original	7.26	0.127	9.16	-0.127	10.3	25.4	11.6	-22.4	13.6	22.8
Wedges	7.45	0.0	9.54	0.0	11.6	0.0	13.8	0.051	15.2	0.051

4. Conclusion

We have identified a continuous ambient vibration problem that has caused proton beam loss. This problem also is sensitive to local traffic under certain conditions. Through a systematic process of elimination, the source of the excitation has been uncovered. Yet, the permanent solution remains unclear, since lack of enclosure access has hampered progress. Wooden wedges will be installed against the concrete ceiling and "S" beams in specific locations in order to minimize the energy (displacement) and shift the resonant frequency of the supporting structure and low beta system into a higher range. Nevertheless, the complexity and actual response of the girder, Invar supports, magnets and supporting structure still may limit the effectiveness of the proposed solution.

4.1 Acknowledgements

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