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Advanced Photon Source at Argonne National Laboratory**

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Vibration considerations in the design of the Advanced Photon Source at Argonne National Laboratory

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ABSTRACT

The Advanced Photon Source (APS), a new synchrotron radiation facility being built at Argonne National Laboratory, will provide the world's most brilliant X-ray beams for research in a wide range of technical fields. Successful operation of the APS requires an extremely stable positron closed orbit. Vibration of the storage ring quadrupole magnets, even in the submicron range, can lead to distortion of the positron closed orbit and to potentially unacceptable beam emittance growth, which results in degraded performance. This paper presents an overview of the technical approach used to minimize vibration response, beginning at the conceptual stage, through design and construction, and on to successful operation. Acceptance criteria relating to maximum allowable quadrupole magnet vibration are discussed. Soil properties are used to determine resonant frequencies of foundations and to predict attenuation characteristics. Two sources are considered to have the potential to excite the foundation: far-field sources, which are produced external to the facility, and near-field sources, which are produced within the facility. Measurements of ambient ground motion, monitored to determine far-field excitation, are presented. Ambient vibration was measured at several operating facilities within Argonne to gain insight on typical near-field excitation sources. Discussion covers the dynamic response characteristics of a prototypic magnet support structure to various excitations, including ambient floor motion, coolant flow, and magnet power.

1. INTRODUCTION

The Advanced Photon Source (APS) is a synchrotron radiation facility under construction at Argonne National Laboratory. Upon completion in 1996, it will be the source of the world's most brilliant X-rays. The APS will be a user facility for research on the structure of materials, X-ray imaging, coronary angiography, and many other fields.

An overall view of the facility is shown in Fig. 1. The facility consists of a 200-MeV electron linear accelerator (linac), a tungsten converter target to produce positrons, a positron linac, a positron accumulator ring (PAR), a booster synchrotron to accelerate 450-MeV positrons to an energy of 7 GeV, a positron storage ring that is 1104 m in circumference, and many experimental photon beam lines utilizing the synchrotron radiation for experimental studies. The positrons circulate in the storage ring with a current of 0.1 A and a mean positron-beam lifetime of 10 h. A cross section of the experimental hall is shown in Fig. 2. The basement supporting the storage ring beam line is approximately twice as thick as the remainder of the experimental hall floor; the two are separated by an expansion joint. Figure 3 illustrates one of 40 identical sectors in the storage ring lattice, an arrangement of bending magnets and quadrupole magnets that focuses the particle beam.

Unprecedented precision and stability in aligning the storage ring magnets is a requirement for successful operation of the APS. One source of instability is vibration of the storage ring quadrupole magnets. This can lead to distortion of the positron closed orbit and to potentially unacceptable beam emittance (which is related to the size of the beam) growth. This, and the fact that vibration-induced problems have been experienced in other similar operating synchrotron radiation sources,^{1,2} provides the motivation for the subject studies.

2. VIBRATION CRITERIA

Vibration criteria were developed on the basis of the requirement that emittance growth be limited to 10%. Of the various magnets in the storage ring magnet lattice, the quadrupole magnets have the most significant effect on beam stability and emittance growth. Three different vibration scenarios were considered with respect to the quadrupole magnets: (1) vibration of a single quadrupole within the storage ring, (2) random vibration of all quadrupoles in the ring, and (3) the hypothetical

case of a plane wave sweeping across the site and the quadrupoles following the motion of the plane wave. The maximum allowable peak vibration amplitudes corresponding to these three vibration scenarios are given in Table 1. The criteria associated with the passage of a plane wave is dependent on wavelength, or alternatively on frequency, given the wave speed. The wave speed used in Table 1 is that measured as a part of the geotechnical investigation at the APS site.

From Table 1, it can be seen that the most stringent criteria are those associated with random vibration of the storage ring quadrupoles. As such, these criteria will be taken as the vibration criteria to be met for vibration amplitudes. Relative to frequencies, low-frequency vibrations (<10-20 Hz) can be controlled with steering magnets using feedback systems, provided the vibration amplitudes are within the dynamic range of the controllers. High-frequency (>10-20 Hz) vibration amplitudes, on the other hand, are out of the range of the controller, and therefore must be limited to ensure that beam emittance growth will not exceed the prescribed value.

The horizontal and vertical displacements of Table 1 are peak values; allowable root-mean-square (RMS) levels will be lower, depending on the characteristics of the signal, e.g., sinusoidal or random.

3. TECHNICAL APPROACH

The technical approach is illustrated in flow-diagram format in Fig. 4. The major thrust of the studies is to estimate magnet vibration from both near-field (internal) excitation sources and floor motion, to assess the estimated response relative to the vibration criteria, and—based on that assessment—to make a decision as to how to proceed with design and construction or with redesign.

As illustrated in Fig. 4, vibration of the quadrupole magnets will be determined by the dynamic characteristics (natural frequencies, modes, and damping) of the magnet/girder/support assemblies and the excitation sources. Internal excitation sources include the coolant flow in the magnet, header, and return piping. The magnet support system will also respond to motion of the experimental hall floor slab, in particular the storage ring basemat.

Vibration of the basemat, in turn, will be determined by the design of the experimental hall and foundation, soil properties at the site, far-field excitation in the form of ground motion due to natural and cultural sources, and internal (to the experimental hall) excitation associated with pumps, compressors, HVAC equipment, and the like. Program elements defined in Fig. 4 and relating to the motion of the experimental hall floor slab and storage ring basemat, design to minimize floor motion, and vibration studies of the storage ring magnet/support assemblies have been addressed and reported.³⁻¹⁸ The results of these investigations are summarized in the following sections.

Table 1. Vibration criteria: maximum allowable vibration amplitudes

Vibration Type	Displacement (μm)	
	Horizontal	Vertical
Single Quadrupole	2.2	1.29
Random (all quadrupoles)	0.34	0.12
Plane Wave ($v = 306 \text{ m/s}$; f in Hz)		
$f < 2.2$	16.1	4.4
$2.2 < f < 4.6$	16.1	4.4-0.28
$4.6 < f < 7.7$	16.1	0.28
$7.7 < f < 13.5$	16.1-0.90	0.28
$f > 13.5$	0.90	0.28

4. GEOTECHNICAL INVESTIGATION

A geotechnical investigation that used more than 28 boreholes was completed.³⁻⁵ Field testing, crosshole seismic testing, and laboratory testing were part of this investigation. A soils consultant performed the soil borings, field tests (including crosshole seismic), and laboratory tests. The Illinois State Geological Survey was responsible for collecting regional geological and geotechnical data such as ground-water levels, and for measuring the continuity of subsurface bedrock.

The site soil profile, from surface to bedrock, is as follows:

Fill materials consisting of silty clay were encountered at various locations.

Weathered till was encountered in all of the boring extending to depths of 10 to 24 ft it consists of hard to very stiff brown silty clay.

Unweathered till was encountered underlying the weathered till and consists of grey silty clay containing traces of sand, gravel, and shale. It has a low plasticity and generally a hard to very stiff consistency.

Outwash deposits consisting of sand, silt, and occasionally gravel were encountered sporadically across the site. These deposits were relatively thin and discontinuous.

Lemont drift was encountered underlying the unweathered till and extending to the bedrock surface; it consists of a dense to extremely dense formation of sand, silt, and gravel.

Bedrock, consisting of dolomitic limestone, was encountered underlying the Lemont drift. Bedrock surface elevation varied from 613 to 643 ft.

Among other things, the results provided information on foundation bearing capacities and settlement. It was concluded that bearing soils found at design subgrade level are generally suitable (competent and stable) for support of the storage ring basemat and experimental hall basemat on grade. Results from the crosshole seismic testing gave information on shear and compressional wave speeds that, in turn, allowed computation of soil moduli values; such information is needed for analyzing soil/foundation interaction.

5. SOIL/FOUNDATION INTERACTION

Soil/foundation interaction was analyzed to develop an understanding of the dynamic characteristics (in particular, resonant frequencies and damping) to be expected with the slab on grade construction.¹¹ Equivalent-lumped-parameter modeling based on elastic-half-space theory was used with the soil shear modulus and density obtained from the geotechnical investigation. The modeling was evaluated with available test data on large foundations and was shown to be generally applicable. The significant conclusion from the analysis is that the large plan dimensions of the APS storage ring basemat and experimental hall floor slabs result in very large damping values; this, in turn, implies that dynamic magnification factors will be negligible. As a consequence, amplification of ground motion as a result of soil/foundation interaction dynamics is not a concern. Conservatively, the floor can be assumed to follow the motion of the ground. However, experience suggests that with large slabs, floor motion will actually be smaller than ground motion due to, among other things, "waveform averaging."¹⁹

6. AMBIENT GROUND MOTION

There are two sources of ambient ground motion: near-field sources, which are generated within the site, and far-field sources, which are generated external to the site. Ground motion may occur in response to natural sources such as microtremors or to cultural sources such as road and/or rail traffic, reciprocating machinery, unbalanced rotating machinery, mining, and the like. The near-field sources can be considered to be within the control of the APS facility and can be minimized or eliminated by proper design. Because far-field sources may or may not be controllable (depending on source, location, and transmission path), a detailed investigation of ambient ground motion was required to ensure site acceptance. Surveys of ground motion were made in the vicinity of various Argonne buildings external to the APS site,^{6,7} as well as at the APS site.⁸⁻¹⁰

At the APS site, six simultaneous measurements were made on what would correspond to the circumference of the storage ring.⁸ Accelerometers were oriented vertically and mounted on 24-in. long steel rods driven into the ground at the locations shown in Fig. 5. The accelerometers were connected to double integrator circuits and an FM tape recorder via 750-ft lengths of coaxial cable. Continuous recordings of displacement-time data were made over a 24-h period. The data were then analyzed with spectrum analysis techniques, integrated over 8-min intervals to obtain RMS values, and then plotted as a function of time; typical results are shown in Figs. 6 and 7.

In Fig. 6, several interesting observations can be made from the RMS displacement: (1) Ground motion is considerably higher at location 2, which is approximately 400 ft closer to a building than is location 1; this is a good example of how distance can provide attenuation. (2) An increase in ground motion, as a function of time, at location 2 can be related to the work day (an inherently active period) at Argonne. (3) Several large "spikes" are the result of transients. (4) Overall amplitude at either location is well below the established criteria. The frequency content of the ground motion displacement-time signals includes several distinct frequencies: low-frequency integration noise (<4 Hz), 7.81 Hz, and 10.5 Hz. The 7.81- and 10.5-Hz components are thought to be associated with the vibration of large civil structures, such as buildings.

Total displacement at locations 3 and 4 for the corresponding time period is shown in Fig. 7. One can readily observe that at approximately 19:00 on Wednesday, a large increase in ground motion occurs at both locations. The amplitude correlation between each location is clearly seen. A subsequent frequency response analysis showed that the large amplitude is associated with 18.4- and 60-Hz displacement components. Because it is present only at locations 3 and 4, it is assumed to be a near-field source; as a result of soil attenuation characteristics, a far-field source would result in detectable ground motion at the other locations as well. Because these components of ground motion exceeded the allowable vibration amplitude criteria, with frequencies above the upper limit for correction with the feedback system and steering magnets, the displacement amplitude at location 3 was monitored for a 1.5-year period.⁹ However, during that period, only one positive occurrence was detected and that was within one month of the initial measurement. Frequency analysis showed that the 7.81- and 10.5-Hz displacements are present at a higher level at locations 3 and 4 than at location 2.

Several transients were observed during the 24-h monitoring period. The transients can be categorized into three types: (1) Near-field, low-energy, observed only on a specific transducer, locally generated close to a transducer, such as would result from human activity. (2) Near-field, medium-energy, observed at all transducer locations, with a wave velocity of 1,100 ft/s, which could result from a vehicle driving over a discontinuous pavement. (3) Far-field, high-energy, observed at all locations, with a wave velocity of $>18,000$ ft/s. The amplitudes of the various transients were relatively high, up to $1.2\text{ }\mu\text{m}$ peak-to-peak; however, with a characteristically short time duration and a large frequency content, they will contribute very little to the response of a large massive mechanical structure.

7. VIBRATION AT AN OPERATING FACILITY

To gain insight into the vibration levels that might be expected at an accelerator facility located at Argonne, a vibration survey was performed at the Laboratory's Intense Pulsed Neutron Source (IPNS).¹² This facility has many components that are similar to those in the APS storage ring lattice, such as bending magnets, quadrupole magnets, magnet support assemblies, cooling water headers, and cooling water flow through the magnet coils. The survey included measurements of experimental hall floor vibration at several locations, floor vibration at the base of the magnets, and magnet vibration. To determine the effect of various types of equipment on vibration levels, vibration measurements were made with selected IPNS equipment operating and not operating.

Among other things, the survey led to the conclusions that (1) the magnet/support assemblies can provide dynamic amplification of floor motion, and (2) energizing the quadrupole magnets results in increased vibration levels by a factor greater than 2. Nevertheless, in the frequency range of 10 to 250 Hz, measured RMS vibration levels were in the range of 0.02 to $0.08\text{ }\mu\text{m}$, well within the allowable limits established for the APS quadrupoles. Further, energization of the APS quadrupole magnets will probably not contribute as much to the vibration level because their input power is controlled differently than in the IPNS.

The effect of coolant flow on magnet and floor motion was also measured. Displacement response of the bending magnet to coolant flow was negligible, while a measurable, but small, increase was detected in the response of the quadrupole magnet; no increase was detected in floor response.

8. DYNAMIC RESPONSE OF STORAGE RING GIRDER ASSEMBLY

The APS storage ring is divided into 40 sectors, each consisting of 5 individual magnet support sections for a total of 200 sections. Typically, there will be two groups of 80 and one group of 40 similar sections. A cross section of a quadrupole magnet support assembly is shown conceptually in Fig. 8, while a side view of a typical section is shown in Fig. 9. The storage ring magnets are mounted on girders that, in turn, are supported on jackscrew/pedestal support assemblies. It should be noted that the various sections also include beam-position monitors, vacuum-chamber support structures, and vacuum pumps; these are not shown in Figs. 8 and 9.

The vibrational characteristics (natural frequencies, modes, and damping) of the magnet/girder support system will determine the response of the magnets to floor motion and coolant flow. Dynamically, the storage ring magnet/support systems are very complicated, with many degrees of freedom, large mass (typically >6,800 kg), and a high center of gravity. The height of each section can be varied 0.038 m from the mean height of 1.4 m with the leveling jacks. Also, the height of the individual magnets can be varied with small jackscrews. The girder and magnet jacks represent the most significant unknown in predicting the frequency characteristics of the overall system.

From the standpoint of positron beam stability and control, two elements are very critical: (1) the position of the beam-position monitors, which are mounted on the vacuum chamber, relative to the positron beam; and (2) the position of the quadrupole magnets with respect to the positron beam. If the beam-position monitors move because of vacuum-chamber movement, the feedback control system would sense that motion as a change in beam position and initiate an unwanted correction. Any extraneous motion of the quadrupole magnets will result in unwanted motion of the beam. If the dynamic range and frequency response of the feedback control system is not exceeded, the effect of quadrupole magnet motion can be compensated for.

Perturbation of the storage ring quadrupole magnets, and hence the positron beam, can be caused by three different excitation sources. Motion of the storage ring basemat, in response to ambient ground motion and/or equipment operating within the experimental hall, may couple through the girder/support assemblies to the quadrupole magnets or vacuum chamber. The second potential source of motion is equipment directly mounted to the girder section, because such equipment can give rise to eddy-current response between the vacuum chamber and magnets. The third source is coolant flow through the manifolds and magnet windings.

At present, the magnets and many of the other components to be mounted on the girder are in the design stage. As a consequence, a complete system was not available to test. To circumvent this problem and to obtain design information at an early date, concrete shielding blocks were used to simulate the magnet masses. As prototype components become available, they are evaluated relative to the overall vibration response and the established vibration criteria, thereby providing the option to redesign if unacceptable response is observed. In the following, vibration studies of the storage ring magnet/support assemblies and vacuum chamber are summarized.

8.1. Magnet/support assembly

A vibration study, which consisted of an integrated analytical/experimental investigation of the APS storage ring magnet/support assembly, was performed.¹⁵ Two girder support configurations were analyzed and tested. Theoretical vibration frequencies were calculated from a finite-element code, based on a jack stiffness that was back-calculated from experimental measurements. Natural frequencies and mode shapes were determined from measurements made with a structural dynamics measurement analysis program. Table 2 shows a comparison between theoretical and experimentally measured natural frequencies for one support configuration. The experimental out-of-plane (horizontal) low-frequency modes (5.0 and 8.3 Hz) compare well with the theoretical. Measured damping factors associated with these modes are 33% and 17%, respectively. The 53.6-Hz mode is a bending mode with a damping factor of 2.75%. Measured in-plane (vertical) modes of 36.8 and 87.6 Hz are girder bending modes, having damping factors of 5.8% and 1.75%, respectively.

While several response frequencies were observed, the associated damping factors were reasonably high, resulting in small magnification factors. Assuming that the dynamic range of the feedback control system is sufficiently large, the 5.0- and 8.3-Hz responses can be controlled. Because the girder is a relatively "stiff" member, there is a question as to whether sufficient energy can be coupled to it to excite the bending modes.

Table 2. Theoretical and experimental frequency response of the magnet support assembly (Hz)

Horizontal Out-of-Plane Mode (Y)		Vertical In-Plane Mode (Z)		Axial Mode (X)	
Theory	Experiment	Theory	Experiment	Theory	Experiment
5.7	5.0	21.2	—	6.1	—
7.8	8.3	29.6	36.8	284.8	—
62.4	53.6	67	87.6	—	—
103.2	—	165.5	—	—	—
241.5	361	396.2	—	—	—
419.5	—	485.8	—	—	—
539.6	—	—	—	—	—

8.2. Storage ring vacuum chamber/girder.

Vacuum chamber vibration is a concern because the beam-position monitors mount to it. Therefore, a vibration study of the APS storage ring vacuum chamber/girder was carried out with the objective of obtaining insights into the dynamic coupling between vacuum chamber and girder.¹⁶ The vacuum chamber is supported from the girder by one stiff and two flexible (in the axial direction) supports. In the study, a prototypic vacuum chamber, including ion pump, was mounted on a girder. Due to the configuration of the vacuum chamber, it was not possible to simulate the magnet weight; thus, emphasis was placed only on vacuum-chamber dynamics. Two excitation methods were employed: (1) force excitation with an electromagnetic shaker and (2) ambient floor motion. Vacuum-chamber motion was measured at the beam-position monitors, because this is the most critical location. A summation of the measured frequencies and transfer functions is given in Table 3. The largest transfer function of 8.33 is associated with the lowest vertical bending mode of the vacuum chamber. The next largest transfer function (7.14) is associated with a coupled vacuum-chamber/girder out-of-phase response.

8.3. 0.8-meter quadrupole magnet/girder

The availability of a prototypic 0.8-m quadrupole magnet allowed a vibration study of the coupled response of the magnet mounted to the girder assembly.¹⁷ The weights of the other magnets on the girder were simulated by concrete shielding

Table 3. Transfer functions (TF) between vacuum chamber and girder

f_n (Hz)	TF (X) Axial	TF (Y) Horizontal (Out-of-Plane)	TF (Z) Vertical (In-Plane)
8.80	1.33	1.39	1.92
9.50	1.05	1.27	1.10
12.90	1.67	0.45	1.23
15.60	2.38	1.22	1.47
23.70	7.14	3.45	5.56
30.00	0.90	1.67	2.56
45.90	1.33	2.56	8.33
86.70	4.17	4.35	6.25
108.10	0.51	2.63	3.13
116.90	0.31	2.33	2.27
126.00	0.81	3.33	3.23

blocks. The leveling jack pedestals were bolted securely to the concrete floor. A schematic diagram of the test article, including exciter and accelerometer locations, is shown in Fig. 10. Three excitation force methods were employed: (1) an electrodynamic shaker, used to produce random or sinusoidal forcing, (2) an impulse hammer, and (3) ambient floor motion. A large response at 7.62 Hz was observed; magnification factors were 56 and 70 in the X and Y directions (see Fig. 10), respectively. Table 4 shows the displacement response to ambient floor excitation at 7.62 Hz. It appeared that the response was the result of a coupled resonance involving the magnet and girder. A similar response was observed at 10.9 Hz, but the magnification factor was approximately one-half that of the 7.62-Hz response; this also appeared to be a coupled response.

A series of tests was conducted to determine the cause of the large 7.62-Hz response. It was concluded that the response was primarily due to the position of the jackscrew within the leveling jack. This was caused by the lateral load applied to the jackscrew by the adjustment base (see Fig. 9). When the 7.62-Hz response was large, the jackscrews were centered within the leveling jack housing; in the magnet/support assembly study,¹⁵ the jackscrews were laterally loaded and contacting the leveling jack housing, thus exhibiting increased stiffness. Because variable response of the girder assembly, such as described above, cannot be tolerated in the APS storage ring components, a redesign of the leveling jacks has been initiated.*

8.4. 0.8-meter quadrupole magnet

The 0.8-m quadrupole magnet tested previously was mounted to the girder with three small jackscrews (see Fig 8). Because variable response was observed in the leveling jacks and the three jackscrews are of a similar design, a study of the 0.8-m quadrupole magnet/support assembly was conducted.¹⁸ Tests were made to (1) determine the effects of the jackscrews and mounting base on the vibrational characteristics of the magnet and support assembly, (2) determine if the construction of the magnet proper is sufficiently rigid to eliminate unwanted responses, and (3) measure the effect of cooling-water flow through the magnet coils. For various tests, the magnet was supported either on a large 3,628-kg concrete block with prototypic mounts, or on a concrete floor with and without the prototypic jackscrew mounts. A summation of the measured response frequencies is given in Table 5.

Results from this series of tests leads to several conclusions: (1) the jackscrew/mounting base assembly exhibited no large response, (2) the magnet was sufficiently rigid to eliminate unwanted response, and (3) coolant water flowing through the magnet coils at up to the maximum flow rate of 4.44 gal/min produced no noticeable increase in magnet displacement. Due to the high weight of the magnet (1,723 kg) and its high stiffness, system dynamics were controlled principally by the interface between the magnet and/or magnet base and its supporting surface. For example, a small 0.318-cm thick sheet of neoprene placed between the magnet and its supporting surface approximately tripled the measured system damping, indicating the importance of the interface in system response. The neoprene was used only to establish the importance of the interface conditions; no recommendation is made for its use in the actual system.

Table 4. Dynamic response at 7.62 Hz

Measurement Position	Displacement (μm , RMS)
X, Magnet	0.0368
Y, Magnet	0.5
Z, Magnet	0.0282
X, Floor	0.0428
Y, Floor	0.0392
Z, Floor	0.000428

* Currently, a "sliding-wedge" jack is being considered as an alternative to jackscrews to increase the overall stiffness of the jack/pedestal assembly.

Table 5. System response frequencies for the 0.8-m quadrupole magnet

Frequency, Hz	System Frequency Response
8.01	Building response
11.52	Shielding block
13.87	Magnet, Y-direction, rigid body mode
16.21	Ambient response on magnet
18.55	Magnet, X-direction, rigid body mode
29.69	Magnet, Z-direction
31.25	Magnet, Z-direction

9. CONCLUSIONS

The ambient ground motion study indicates that with the exception of the 18- and 60-Hz components, the site is quiet and is suited to the construction of a vibration-sensitive facility such as the APS. Because the 18- and 60-Hz displacements were detected only on one occasion (summer of 1988) and not later, they are assumed to be of a temporary nature and not a long-term concern. Very large damping values will be associated with the APS storage ring basemat and experiment hall floor slab, ensuring that dynamic magnification of ground motion will be negligible. Further confidence in the ability to construct a facility at the Argonne site that meets the stringent vibration criteria set forth was provided by the results of the vibration study of an operating accelerator, which demonstrated that measured response was generally within the allowable range established for the APS. Dynamic response measurements on prototypic APS storage ring components identified a large resonant response due to excessive clearances in the leveling jacks. This potential problem will be circumvented by redesign of the jacks. Finally, because accurate analytical modeling of system dynamics is not possible, further vibration testing of completed assemblies will be necessary and is being planned.

Based on the information developed to date, we can conclude that a continuing program of cautious design, testing, and monitoring will result in successful operation of the APS facility from a vibration standpoint. Here, cautious design includes ensuring that any equipment, within or near the experimental hall, is properly balanced and provided with vibration isolation.

10. ACKNOWLEDGMENTS

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Fig. 2. Cross section of experimental hall.

Fig. 3. Typical sector in storage beam line.

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graph TD
    A[Design of Experimental Hail and Foundation] --> D[Foundation Vibration  
(Floor Response to External/Internal Excitation Sources)]
    B[Geotechnical Investigation  
(Soil Properties)] --> D
    C[External Excitation  
(Ambient Ground Motion)] --> D
    E[Attenuation Characteristics of Soil  
(Geometric and Soil Damping)] --> D
    D --> F[Magnet Vibration  
(Response to External/Internal Excitation Sources)]
    G[Internal Excitation  
(Pumps, Compressors, Coolant Flow, Etc.)] --> F
    H[Design of Magnet Support Structures  
(Dynamic Characteristics)] --> F
    I[Internal Excitation  
(Coolant Flow,)] --> F
    F --> J{Acceptance Criteria*}
    J -- No --> A
    J -- Yes --> K[Construct Experimental Hail and Storage Ring]
    K --> L[Monitor Vibration Response  
(Floor and Magnets)]
    L --> M{Acceptance Criteria*}
    M -- No --> N[Provide Additional Isolation for Internal Sources and/or Magnets]
    N --> H
    M -- Yes --> O[Yes - Facility will Operate Free of Vibration Problems]
  
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Fig. 4. Technical approach.

Fig. 6. Total displacement for locations 1 and 2.

Fig. 7. Total displacement for locations 3 and 4.

Fig. 8. APS storage ring magnet support assembly, cross-sectional view.

Fig. 9. APS storage ring magnet support assembly, side view.

Fig. 10. Schematic diagram of magnet/girder test article.

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