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The Application of Viscoelastic Damping Materials to Control the Vibration of Magnets in a Synchrotron Radiation Facility

by

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ABSTRACT

The Advanced Photon Source at Argonne National Laboratory is a facility designed to produce extremely brilliant X-rays for materials, chemistry, and medical research. In this facility, positrons are first produced and accelerated to energy levels of 7-GeV. The positrons are then injected into a 1104-meter circumference storage ring where they circulate, for periods up to 18 hours, and emit high-intensity X-rays as the circulating beam is oscillated by insertion devices. The beam is positioned and its size controlled by large electromagnets.

The magnets are mounted on 200 individual girder assemblies, with each assembly having several magnets mounted on it. Of prime concern are the girder assemblies supporting the quadrupoles, or focusing, magnets. These magnets must satisfy very stringent vibration criteria, with motion restricted to less than a micron over a broad frequency range. Therefore, amplification at resonant frequencies of the girder assemblies must be minimized. To accomplish this, various viscoelastic damping materials and their placement in the system were evaluated.

As a result of the study, dynamic magnification factors were reduced to a value of five with no detectable increase in static deflection. The damping materials and methods used to accomplish this in massive systems of 7,500 kg or greater, where the displacements are on the order of 0.1 micron or less, will be useful for many less demanding situations.

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INTRODUCTION

The Advanced Photon Source (APS), a synchrotron radiation facility under construction at Argonne National Laboratory, will be the source of the world's most brilliant X-ray beams which will be used for research by other national laboratories, academic institutions, governmental bodies, and industrial firms in a wide range of technical fields. Synchrotron radiation, which are X-rays, are produced by undulating, or "wiggling" positron beams, and are used as a source of X-rays for probing the structure of matter and studying various chemical and physical processes.

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 synchtrotron to accelerate 450-MeV positrons to an energy of 7 GeV, a positron storage ring that is 1104 meters in circumference (separated into 40 sectors, each consisting of 5 girder assemblies), and approximately 70 experimental photon beam lines utilizing the synchrotron radiation for experimental studies.

Each of the 40 sectors of the storage ring has five individual magnet support sections (girder assemblies, numbered 1 to 5) for a total of 200 sections. Girder assemblies 1 and 5 are basically identical, girder assemblies 2 and 4, with large massive bending magnets, are identical, while girder assembly 3 is unique. Fig. 2 illustrates girder assembly 1 with its arrangement of magnets. The quadrupole magnets are the most sensitive from a vibration standpoint.

Each girder assembly weighs 7,500 kg. or more. A cross section of a girder assembly is shown in Fig. 3. The measurement directions on the girder assemblies include the X (horizontal, transverse to beam), Y (vertical), and Z (horizontal in the beam direction). For this study, girder assembly 1 was the primary focus.

Vibration criteria were developed on the basis of the requirement that emittance growth of the positron beam be limited to 10%. An extremely stable positron (the positively charged "anti-particles" of electrons) closed orbit is necessary for the successful operation of the APS in regards to acceptable beam emittance growth. The positrons circulate in the storage ring with a current of 0.1 A and a mean positron-beam lifetime of 10 hours. Of the various magnets in the storage ring, the quadrupole magnets have the most significant effect on beam stability and emittance growth (which is related to the divergence of the beam). These magnets serve as a focusing lens for the positron beam.

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.[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 306 m/s which was measured as a part of the geotechnical investigation at the APS site.

Table 1. Vibration criteria: maximum allowable vibration amplitudes

	Displacement (μm)	
Vibration Type	**Horizontal**	**Vertical**
Single Quadrupole	2.2	1.29
Random (all quadrupoles)	0.34	0.12
Plane Wave (v=306 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
$f > 13.5$	0.9	0.28

The most stringent criteria are those associated with random vibration of the storage ring quadrupole. As such, these criteria will be taken as the vibration criteria to be met for vibration amplitudes. Relative to frequencies, low-frequency vibrations (<10 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 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 X- and Y-direction 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.

Vibration of the storage ring quadrupole magnets, even in the sub-micron range, would result in reduced positron-beam lifetime. This emittance growth and the fact that similar operating synchrotron radiation sources have experienced vibration-induced problems[2] provides the basis for this study. While the dynamics of the quadrupole magnets is of prime importance, the vibration of the other magnets is also an important consideration because of the coupled responses to the system/girder assembly/floor.

Although the damping materials used are very thin, typically 0.004"-0.016", the effect of viscoelastic material flow over long time periods (creep) were also investigated with respect to the static displacement of the girder assembly and the change of dynamic characteristics, primarily the magnification factor and resonant frequency. Additionally, the viscoelastic material must operate in a radiation environment and therefore the effects of radiation were also studied.

MEASUREMENT TECHNIQUES

The instrumentation used to measure the motion were seismometers with a sensitivity of 500 volts per G with a frequency response of 1-100 Hz. A Zonic Fast Fourier Transform (FFT) analyzer performed signal processing, such as integrating the seismometer acceleration signal, and processes the data "on line." Two methods, forced excitation and ambient ground excitation, are used to measure the dynamic characteristics of the storage ring assemblies. A block diagram of the instrumentation and data analysis equipment is shown in Fig. 4.

The first type of vibration measurement, forced excitation, is where the magnet/girder assembly was excited by a electrodynamic shaker, capable of producing an RMS output force of ≈0.5 lb., fastened to the girder. Typically, mainly X-direction measurements were made. Forced excitation is used to measure the modal damping factor (using the half power bandwidth method)[3] and the system response frequencies. The frequency was controlled by a Zonic FFT, which provided a constant-amplitude voltage to the power amplifier and varied the frequency usually from 7-13 Hz, in increments of 0.1-0.2 Hz to generate a "pseudo swept sine" response. The quadrupole magnet's dynamic response was measured and normalized to a displacement input to the girder assembly; damping factor and magnification factor were calculated from the normalized response. The damping factor of a system is defined in terms of the ratio of the energy dissipated to the energy stored. The magnification factor (Q) is equal to 1/2 times the reciprocal of the damping factor.[3] For small quadrupole magnet motion (<20 microns), the damping was determined to be essentially independent of force level, and therefore judged to behave linearly (i.e., amplitude independent). The exciter was oriented in either of three orthogonal directions: X-horizontal, transverse to the beam, Y-vertical, or Z-horizontal, in line with the beam. The X-direction response is the main focus of this study due to the large magnification factor.

The second type of vibration test (ambient floor excitation) is the measurement of the system response to ambient floor vibration which is used to measure response frequencies, response amplitude, and the transfer function as a function of clock time. Typically, the root-mean square (RMS) data is ensemble averaged for approximately three minutes and usually ten ensembles are used for a total observation time of 30 minutes. Power spectra density data are also recorded for each ensemble to observe spectral content and compare with the previously measured data. The value of the ambient floor excitation transfer function is higher than that of the forced excitation transfer function (magnification factor) due to measurement locations and mode shape considerations.

Typical outputs from the Zonic FFT (Fig. 4) analyzer would be RMS amplitude as a function of clock time, power spectral density plots at selected times, and pseudo swept sine plots. Measurement locations were on the pedestal in the X - and Y-directions, on the quadrupole magnet in the X and Y directions, and on the girder surface.

RESPONSE OF UNMODIFIED GIRDER ASSEMBLY

For an unmodified girder assembly, girder assembly 1, the ambient excitation response (RMS) is shown in Fig. 5 and the PSD is shown in Fig. 6 for the girder assembly without plates for the three orthogonal directions. There is a large response at 11 Hz in the X-direction. The predominant response direction is the X-direction and this is due to construction of the girder assembly. Mode shape analysis has shown the motion to be basically a rigid body motion with rotation about the jack/pedestal area.

While the Y direction response is approximately the same as the pedestal response, there are some minor responses observed in the Z-direction. Fig. 7 shows a typical measured forced excitation response with the calculated value of 61 for magnification factor in the X-direction. The discrete frequency steps, which are used to generate the pseudo swept sine excitation can be seen. Although the resolution of the measurement is somewhat limited, the measured magnification factor is considered too high for the required system requirements.

DISCUSSION OF DAMPING PLATES

In order to reduce the magnification factor of the storage ring girder assemblies, many different techniques to reduce them were evaluated. Most had considerable implementation problems when one would consider the operating environment. The most workable solution, from both an implementation and operations standpoint, was to use damping plates, which consisted of steel plates with viscous damping materials between them, placed in the subplate region, the area between the top of the pedestals and the bottom of the alignment jacks (see Figs. 2 and 3).

The viscoelastic materials used in this study are primarily a family of solvent-free permanent adhesives designed to bond many materials, particularly in the automotive industry. Typically, the materials are used in constrained layer damping schemes, in systems with much higher resonant frequencies (>100 Hz). Shear modulus and loss factor of the materials are a function of operating temperature and frequency and must be taken into account when damping systems which use this type of material are designed. A typical plot of damping properties of one of the materials used in this study, ISD 112, is shown in Fig. 8. The temperature and frequency effect on the shear modulus and loss factor can be observed. An excellent discussion of viscoelastic damping materials and their uses can be found in Ref. 4.

Various plate arrangements were evaluated including bi-plates, consisting of two plates with a single layer of damping material between them; tri-plates, consisting of three plates with a single layer of damping material between each plate; and finally five-plates, consisting of five plates with a single layer of damping material between each plate (see Fig. 9). The thickness of the damping material varied from 0.004"-0.016" while the plates were usually 1/8" thick. The plates dimensions were 12" x 8.5". Various damping materials were tested including: ISD 112, ISD 3126, ISD 3127, ISD 3128, C-1002, Norwood 220, and Durotak 2235.

RESPONSE OF GIRDER ASSEMBLY WITH DAMPING PLATES

Bi-plates

Table 2 summarizes a series of tests using the bi-plate configuration. The horizontal alignment mechanisms of the girder assemblies were loose for the majority of these tests. Magnification factor varied from a high of 23.7 for Durotak 2235 with a 0.003" thickness to a low of 5.61 for ISD 3127 with a 0.004" thickness.

Table 2. Measured Girder Assembly Dynamics with Various Materials

Material	Thickness (inches)	Frequency (Hz)	Magnification Factor
Bi-plates			
ISD 112	0.01	9.376	12.8
ISD 465	0.004	8.903	12.4
ISD 468	0.004	9.63	9.54
ISD 3127	0.002	9.01	16.3
ISD 3127	0.004	8.672	5.61
ISD 3127	0.004	9.143	10.7
ISD 3127	0.008	8.922	6.87
ISD 3128	0.004	8.757	7.81
ISD 3128	0.008	8.835	7.99
C-1002	0.015	9.79	14.8
Durotak 2235	0.003	9.302	23.7
Tri-plates			
ISD 112	0.01	8.942	6.19
ISD 113	0.01	8.132	7.22
ISD 468	0.012	9.506	10.2
ISD 3127	0.008	8.864	6.35
ISD 3127	0.008		

ISD 3128	0.008	8.748	6.18
ISD 3128	0.008	9.521	33.5
Norwood 220	0.036	9.734	28.2
Five-plates			
ISD 3128	0.008	9.048	6.3
ISD 3128	0.016	8.916	5.1
ISD 3128	0.016	8.492	4.85
ISD 3128	0.016	8.196	4.16
Durotak 2235	0.006	9.557	16.2

Response frequency usually follows the magnification factor, that is, the lower magnification factor values have lower response frequencies, the higher magnification factors values have higher frequencies. The frequencies range from a high of 11 Hz to a low of 8.67 Hz.

Various thickness layers of the damping materials were used; however, no direct relationship between magnification factor and thickness was observed in Table 2. The "resolution" of the measurements may have been less than that required to observe a magnification factor-thickness relationship as various girder assemblies were used and the disassembly/reassembly required for each test. This may be observed in the ISD 3127 material data where for one test using a 0.004" layer of material the measured Q was 5.61 and a retest with identical conditions yielded a magnification factor of 10.7.

Tri-plates

Table 2 also summarizes the measurements for the tri-plates. For these measurements, the alignment bolts and rods were loose. Magnification factor values varied from a high of 33.5 for ISD 3128 with a 0.008" thickness of viscoelastic material to a low of 6.18 for ISD 3128 with a 0.008" thickness of viscoelastic material. No relationship was noted for the thickness of the damping material with the value of magnification factor. Fig. 10 is a plot of a forced excitation response (or magnification factor) of a typical girder assembly using ISD 3128 tri-plates in the jack/pedestal interface.

The large variation between the two tests of ISD 3128 may be the uncertainty of the test setup, such as, an irregular surface of either the jack or pedestal which resulted in localized contacting between plates, rather than an indication of a gross change in material properties.

Five-plates

A list of the measured dynamic characteristics of the storage ring girder assembly using various damping materials in a five-plate configuration is shown in Table 2. All of the measured values of magnification factor were equal to or less than 6.3 with the exception of Durotak 2235, which had a value of 16.2. The characteristics of this test series were basically the same as those of the bi-plate and tri-plate tests.

Transfer functions were also measured using the ambient ground excitation response. However, the average value of transfer function measured using the ambient ground excitation response was on the average 1.6 times greater than that of the forced excitation response. This difference is due to the mode shapes of the girder assembly. The forced excitation method assumes a center of mass of the system, while the ambient ground measurement method is sensitive to transducer location.

CONCERNS ABOUT USING DAMPING MATERIALS FOR THIS APPLICATION

There are two primary concerns pertaining to the use of the viscoelastic material for this application. One is the long-term flow of the material from between the plates, the other is the effect of radiation on the viscoelastic properties.

Although the layers of damping materials used between the damping plates are small, between 0.004"-0.016", they have very high viscous properties and long-term flow may occur. If the material does flow, the static and dynamic properties of the system would change. The static displacement would be limited to the thickness of the damping material, which would be in the range of or less than the anticipated displacement resulting from ground settlement. However, the dynamic characteristics would be highly effected.

A series of tests were conducted on two girder assemblies using two damping materials (ISD 3127 and ISD 3128) in the bi- and tri-plate configurations in order to evaluate the effect of long-term creep on the girder assembly system. The measured magnification factors, as a function of time, are shown in Fig. 11.

Although there is some variation of magnification factor with time for Fig .11, the measurement, the range of variation and trends are valid for this type of measurement. The slight increase of magnification factor with time for the ISD 3128 material may be an indication of creep. As the viscoelastic material layer becomes thinner, more energy is dissipated for unit volume of the material, thus slightly increasing the magnification factor.

The location of the damping plates, which are located between the jacks and pedestals, in the subplate region, offers a great amount of shielding from radiation. Additional shielding is offered by the stainless steel plates. It is expected that in the vicinity of the beamline the radiation will reach 10^5 rad and immediately above and below the beamline the radiation will reach 10^9 rad. A series of radiation tests was conducted, and the magnification factor, as a function of the average amount of radiation received by the various viscoelastic materials is illustrated in Fig. 12. Gamma radiation from cobalt sources was used to irradiate the plates. Three sets of measurements were made: (1) no radiation, (2) approximately 10^5 rad, (3) and approximately 10^6 rad.

The viscoelastic damping material, amount of radiation received, and results of the tests is shown in Fig. 12. All of the materials exhibited an increase in measured magnification factor with an increase in the amount of radiation. However, this effect may be partially due to the increase in temperature within the irradiated materials during irradiation, and not exclusively by irradiation. Also, some variation of the data is caused by the actual testing procedure in which the girder is jacked up in order to change the plates. Overall, ISD 3128 consistently had the lowest magnification factor for the test series.

DISCUSSION

A summary of the various tests using the viscoelastic material, ISD 3128, in various plate configurations and thicknesses is shown in Table 3 along with several measured responses of the unmodified girder assembly. This material has the desired dynamic characteristics for applications relating to the storage ring girder assemblies, therefore, a more detailed investigation was conducted. Several individual measurements (bi-plate and five-plate configurations) were recorded in Table 3 to observe the repeatability of the material with respect to its dynamic characteristics. The repeatability was acceptable, considering that the girder assembly had to be jacked up and possibly shifted between measurements.

Table 3. Measured Girder Assembly Dynamics with ISD 3128

Material	Thickness (inches)	Frequency (Hz)	Q
No Plates			
None		12.21	61.1
None		10.8	58
Bi-plates			
ISD 3128	0.004	8.757	7.81
ISD 3128	0.008	8.835	7.99
Tri-plates			
ISD 3128	0.008	8.748	6.18
Five-plates			
ISD 3128	0.008	9.048	6.3
ISD 3128	0.016	8.916	5.1
ISD 3128	0.016	8.492	4.85
ISD 3128	0.016	8.196	4.16

The effect of viscoelastic material thickness did not have any significant effect on the dynamic characteristics of the girder assemblies.

Due to time limitations, a detailed study of the mechanics of the system could not be undertaken and no effort was made to choose an optimum viscoelastic material.

CONCLUSION

- Dynamic magnification factors were reduced to a value of approximately 5 from approximately 60 for an unmodified girder assembly.

- Although the tests to measure the creep (long-term viscoelastic material flow) were somewhat inclusive, it appears that creep will be sufficiently low and acceptable in this application.

- The resolution of the test setups were not sufficient to determine the specific effects of radiation on the plates other than that there were not any large effects which could cause a gross change in the dynamic characteristics under the test conditions. Of the materials tested, radiation resistance should be considered a secondary factor.

- These damping materials, used to reduce the magnification factor in massive systems, where the displacements are small, on the order of 0.1 micron or less, will be useful in many less demanding situations.

ACKNOWLEDGMENTS

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REFERENCES

1. J. A. Jendrzejczyk and M. W. Wambsganss, "Vibration Considerations in the Design of the Advanced Photon Source at Argonne National Laboratory," *Vibration Control in Microelectronics, Optics, and Metrology*, SPIE Vol. 1619, p. 115, Nov. 1991.

2. K. Huke, "Correlation between the Movement of the Light Source Building and the Vibration of the Synchrotron Radiation Axis," *Japanese J. Appl. Physics*, vol. 26, no. 2. pp. 285-288, 1987.

3. R. Plunkett, "Measurement of Damping," *Structural Damping*, J. E. Ruzicka, ed., pp. 117-131, ASME Publication, 1959.

4. A. Nashif, D. Jones, and J. Henderson, *Vibration Damping*, John Wiley & Sons, Inc., New York, 1985.

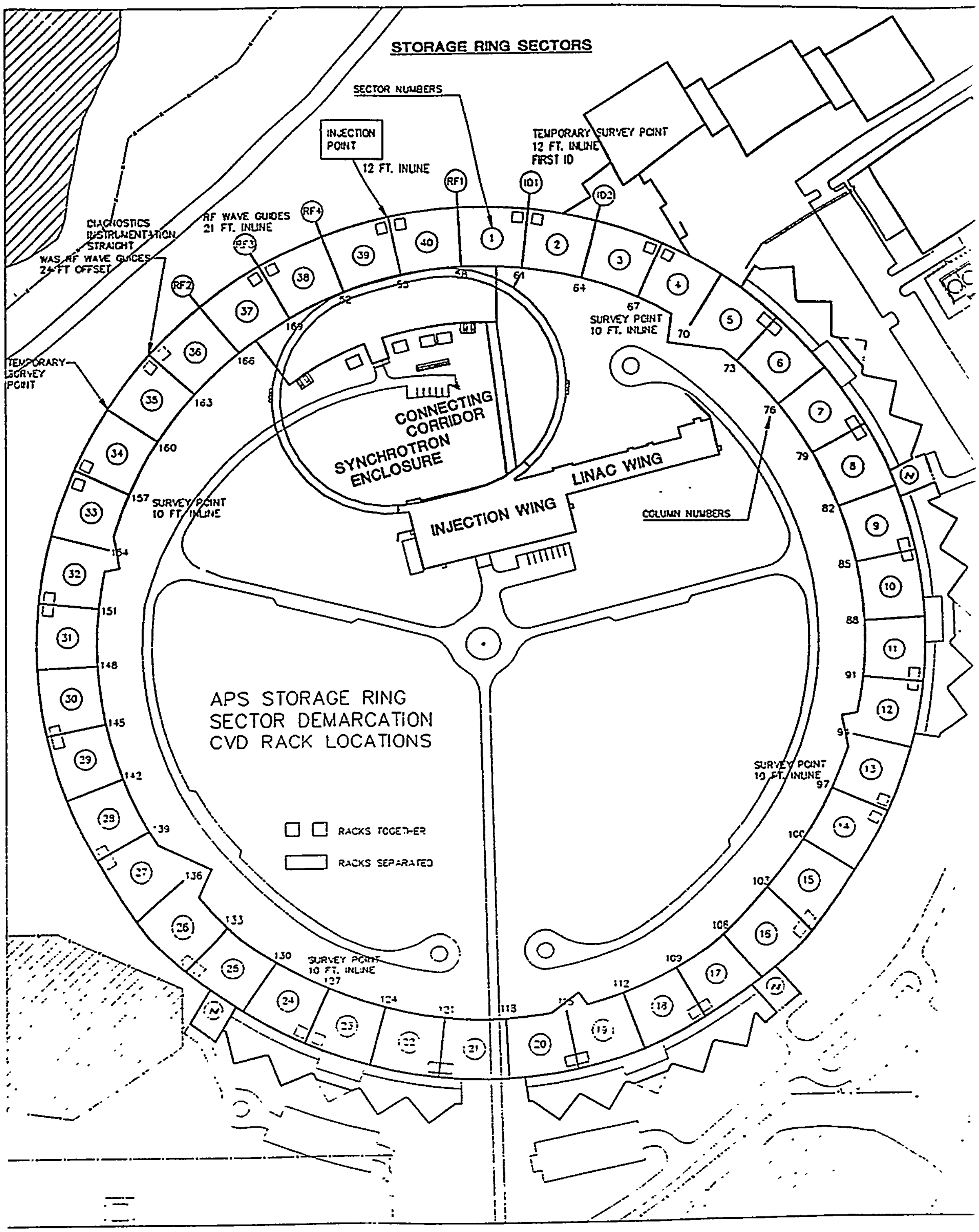

Fig. 1, General layout of APS facility.

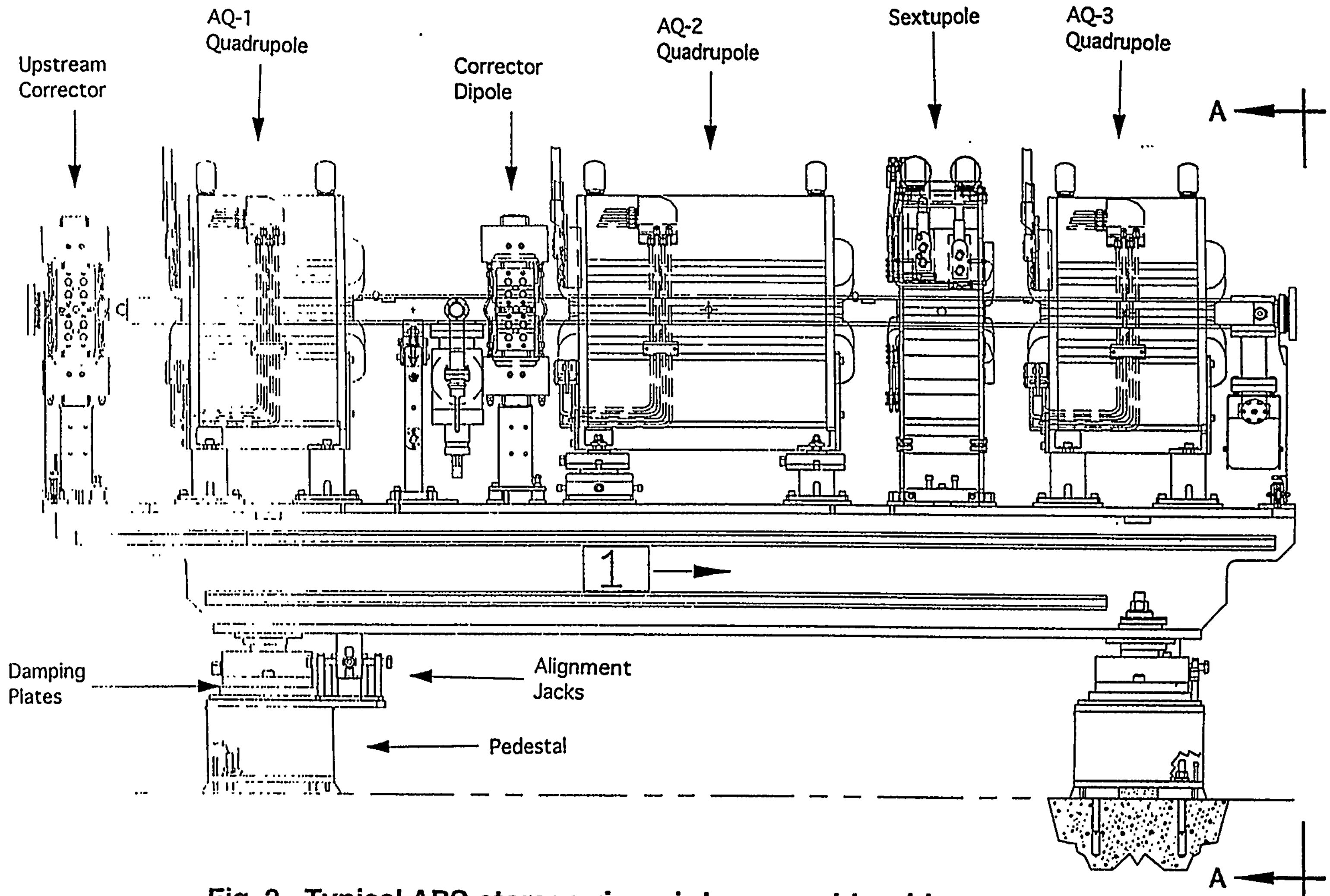

Fig. 2, Typical APS storage ring girder assembly, side view.

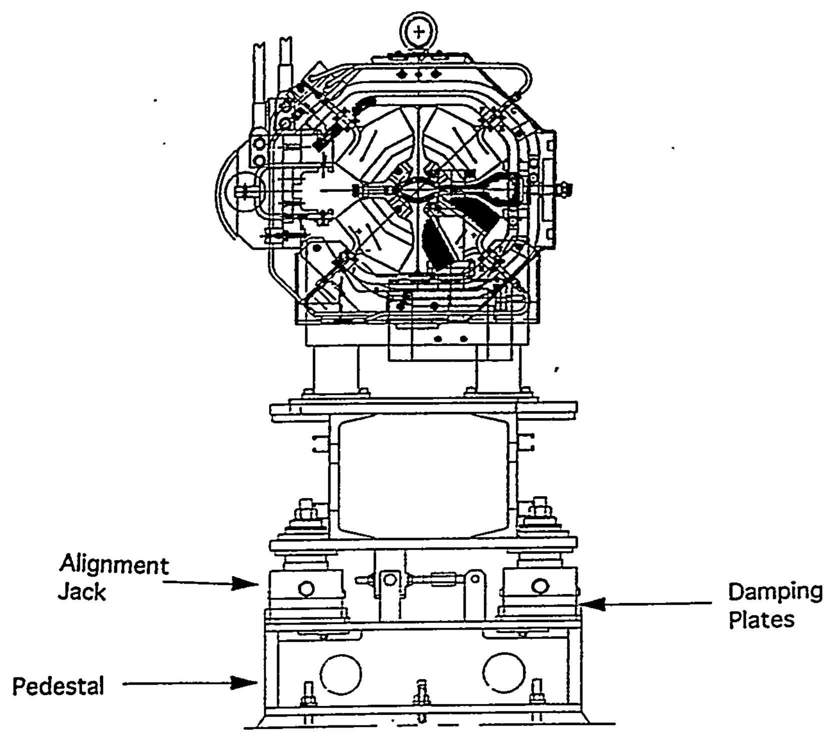

Fig. 3, Typical APS storage ring girder assembly, cross-sectional view.

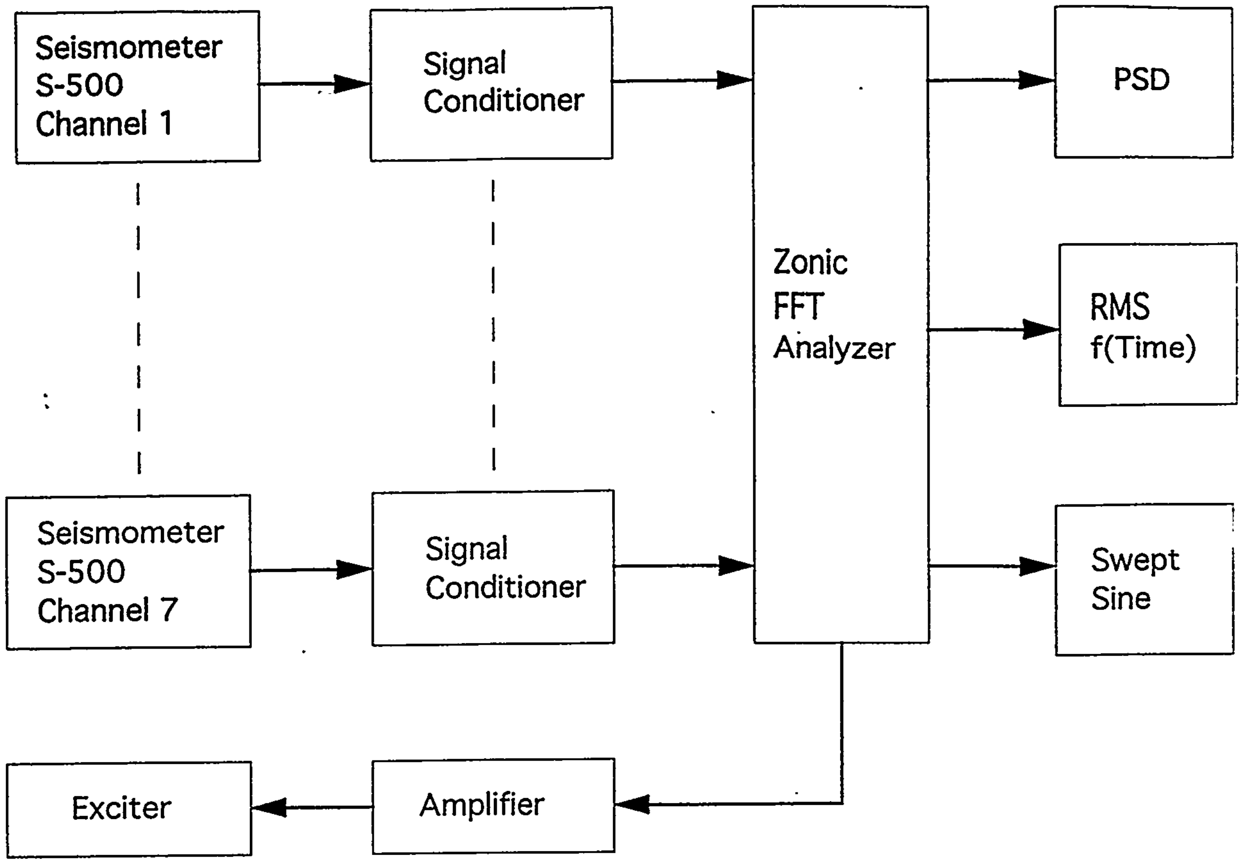

Fig. 4, Block diagram of instrumentation and analysis equipment.

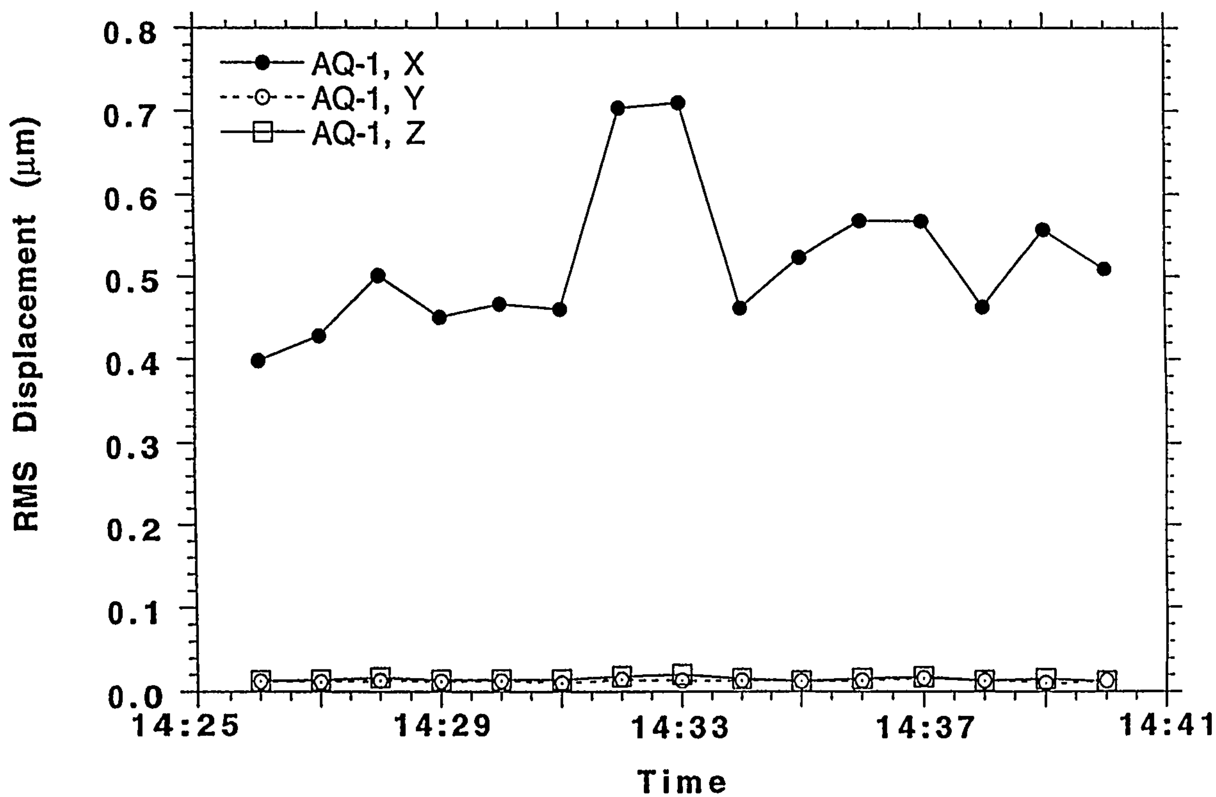

Fig. 5, Measured RMS quadrupole magnet displacements in three orthogonal directions of a typical girder, ambient ground motion excitation, as built configuration.

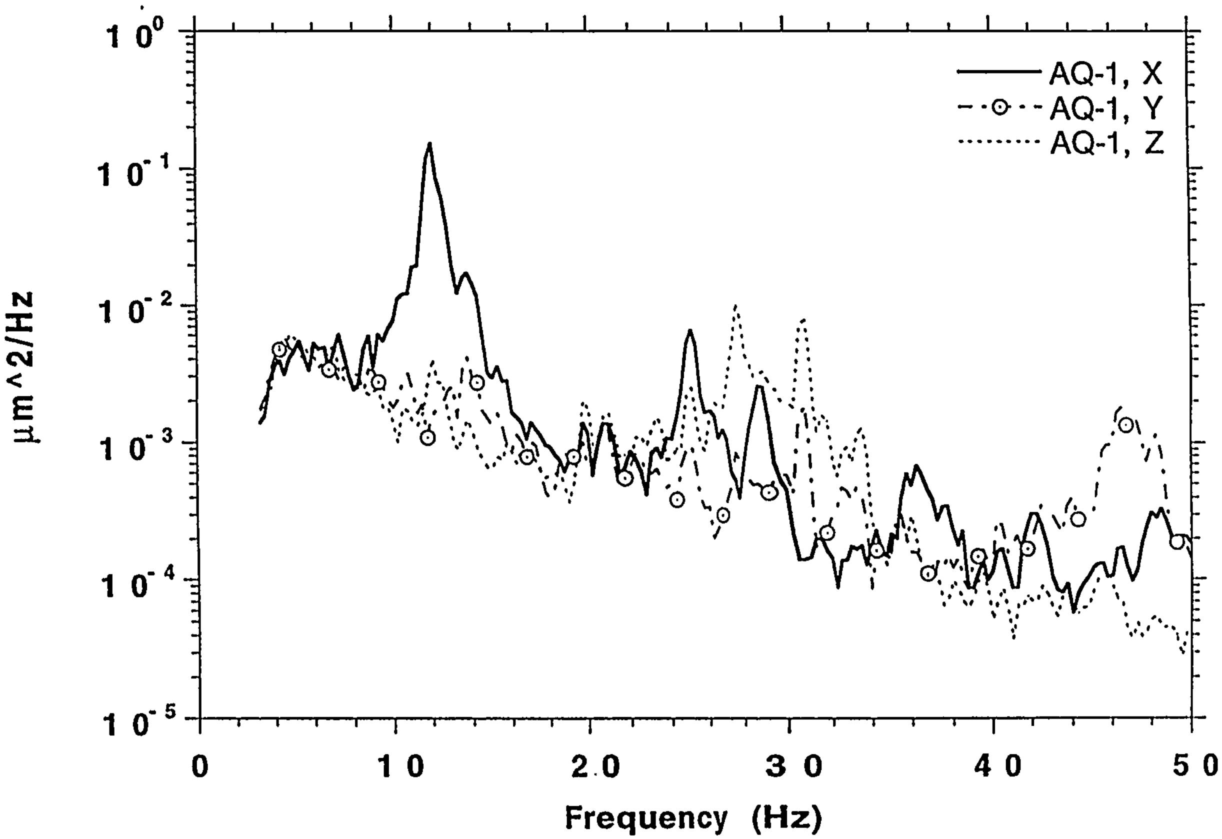

Fig. 6, Measured power spectral density of quadrupole magnet displacements in three orthogonal directions of a typical girder, ambient ground motion excitation, as built configuration.

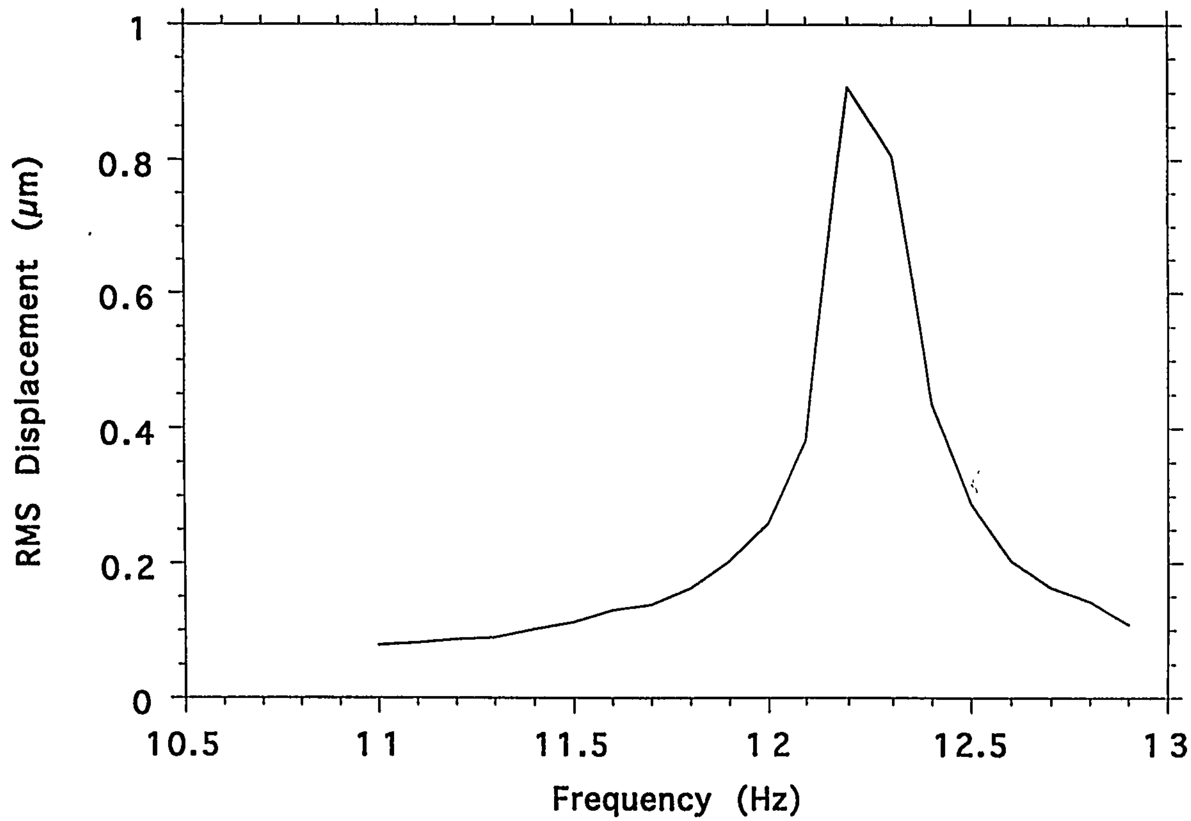

Fig. 7, Typical forced excitation response of a quadrupole magnet, magnification factor = 61, modal damping factor = 0.82%.

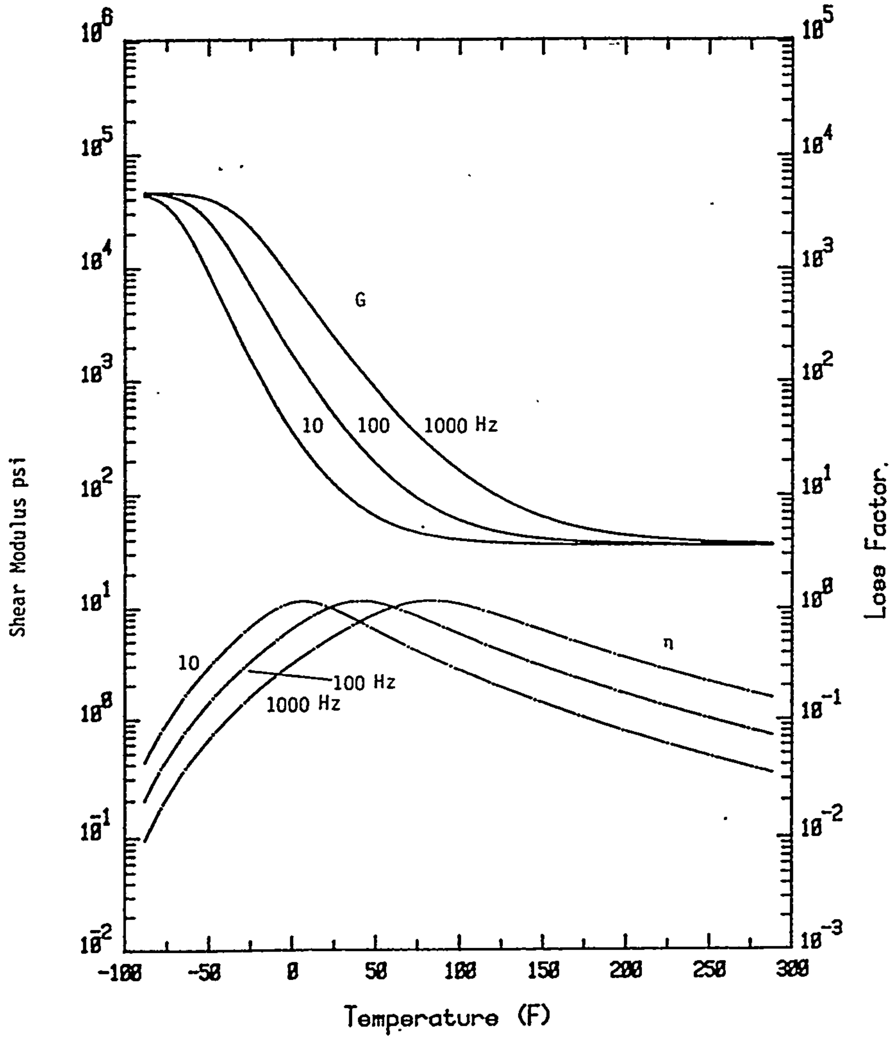

Fig. 8, Damping properties of ISD-112.

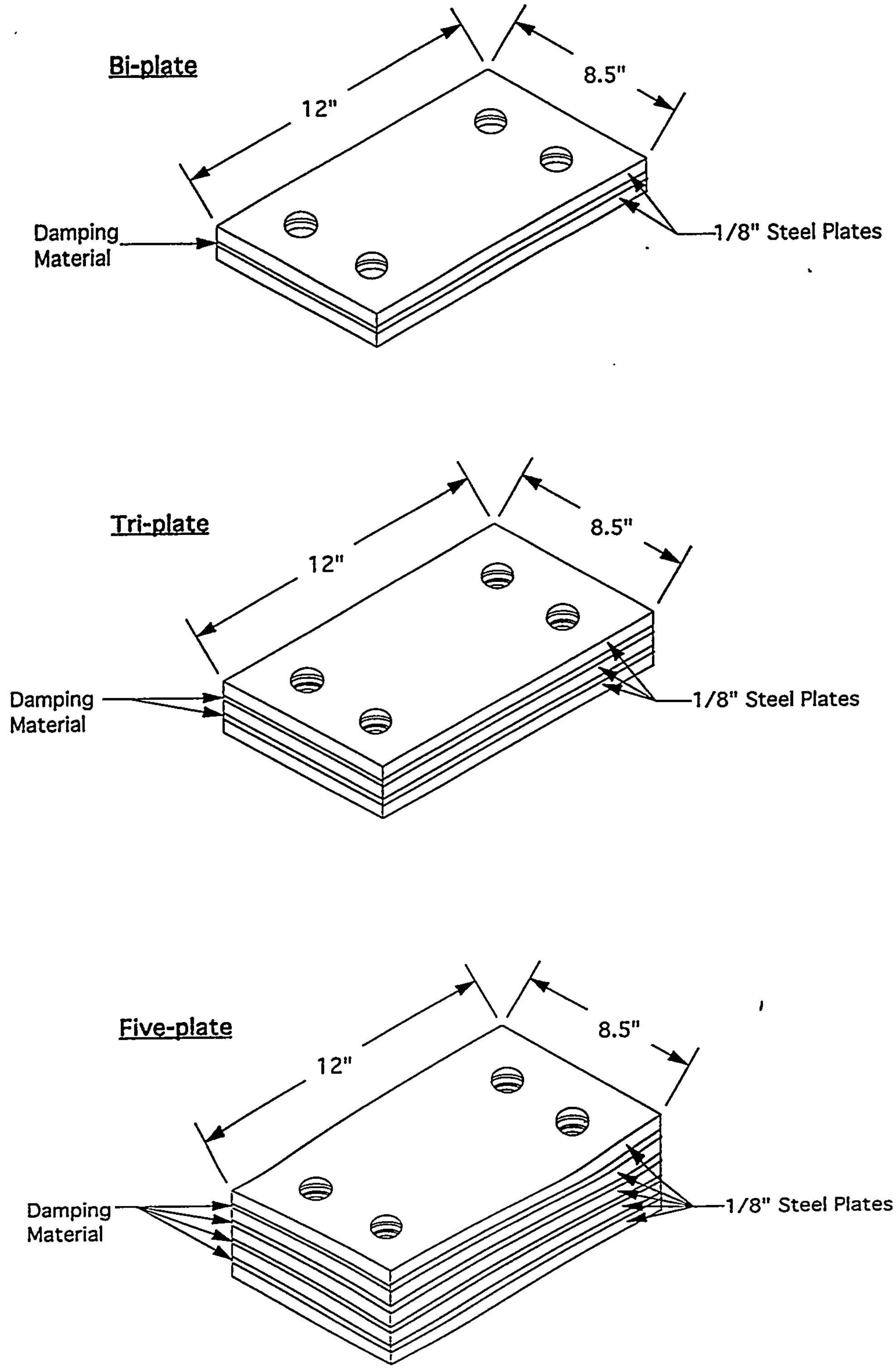

Fig. 9, Configuration of the three types of damping plate arrangements used in this study.

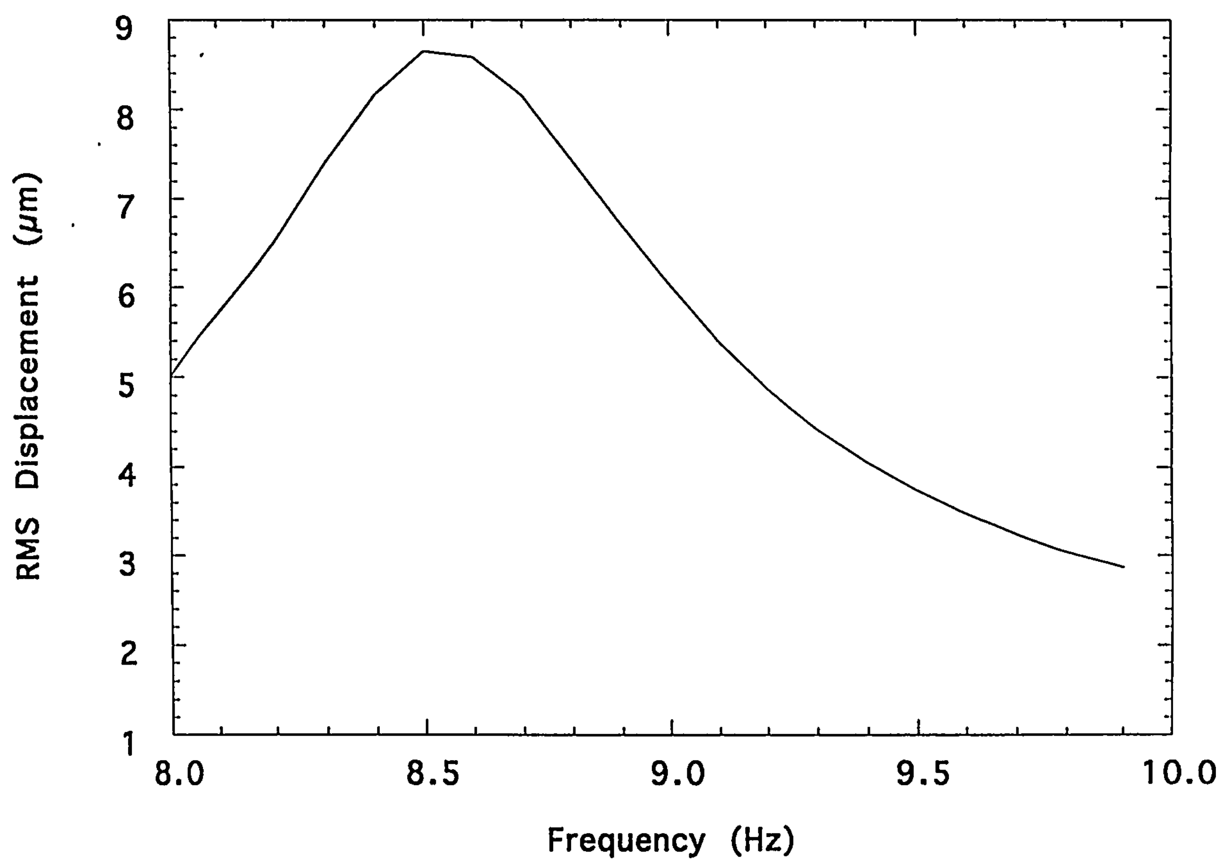

Fig. 10, Typical forced excitation response of a quadrupole magnet using a tri-plate of damping material in the jack/pedestal interface, magnification factor = 10.2, modal damping factor = 4.88%.

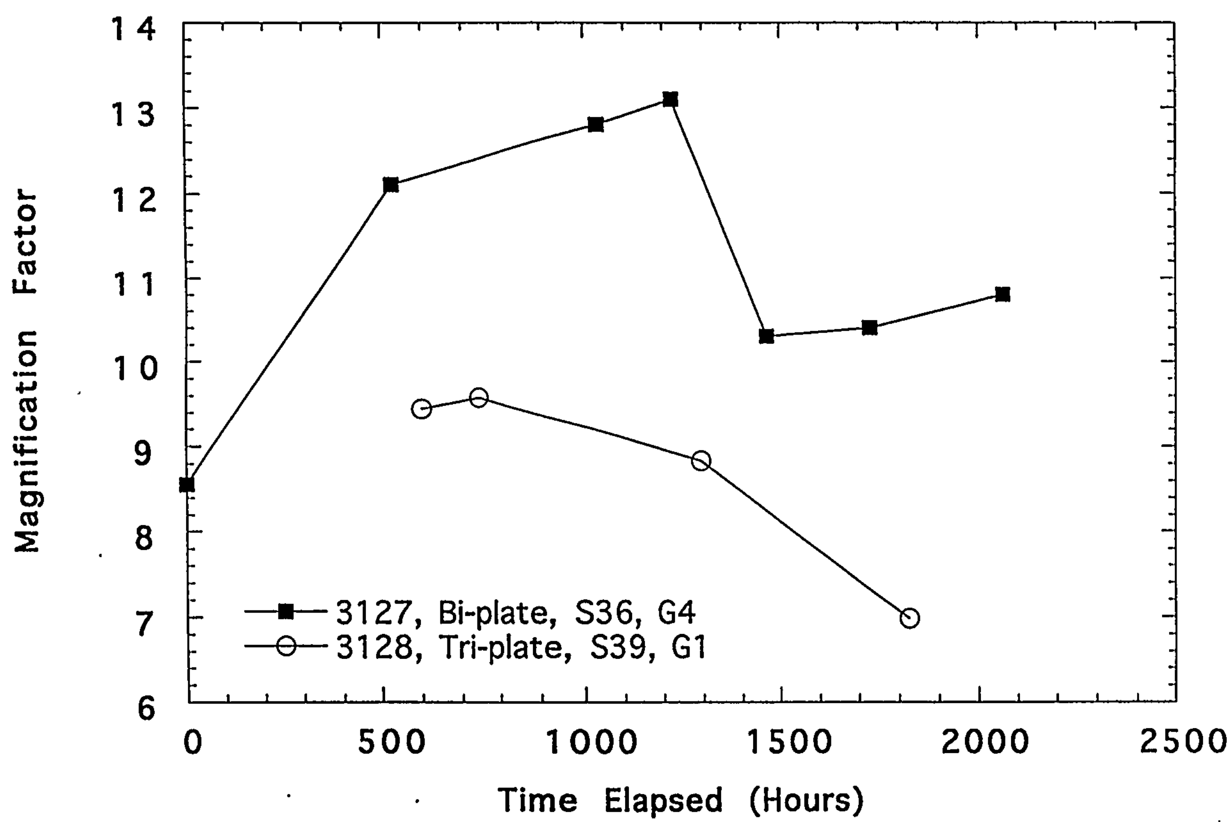

Fig. 11, Effect of creep on magnification factor as a function of time.

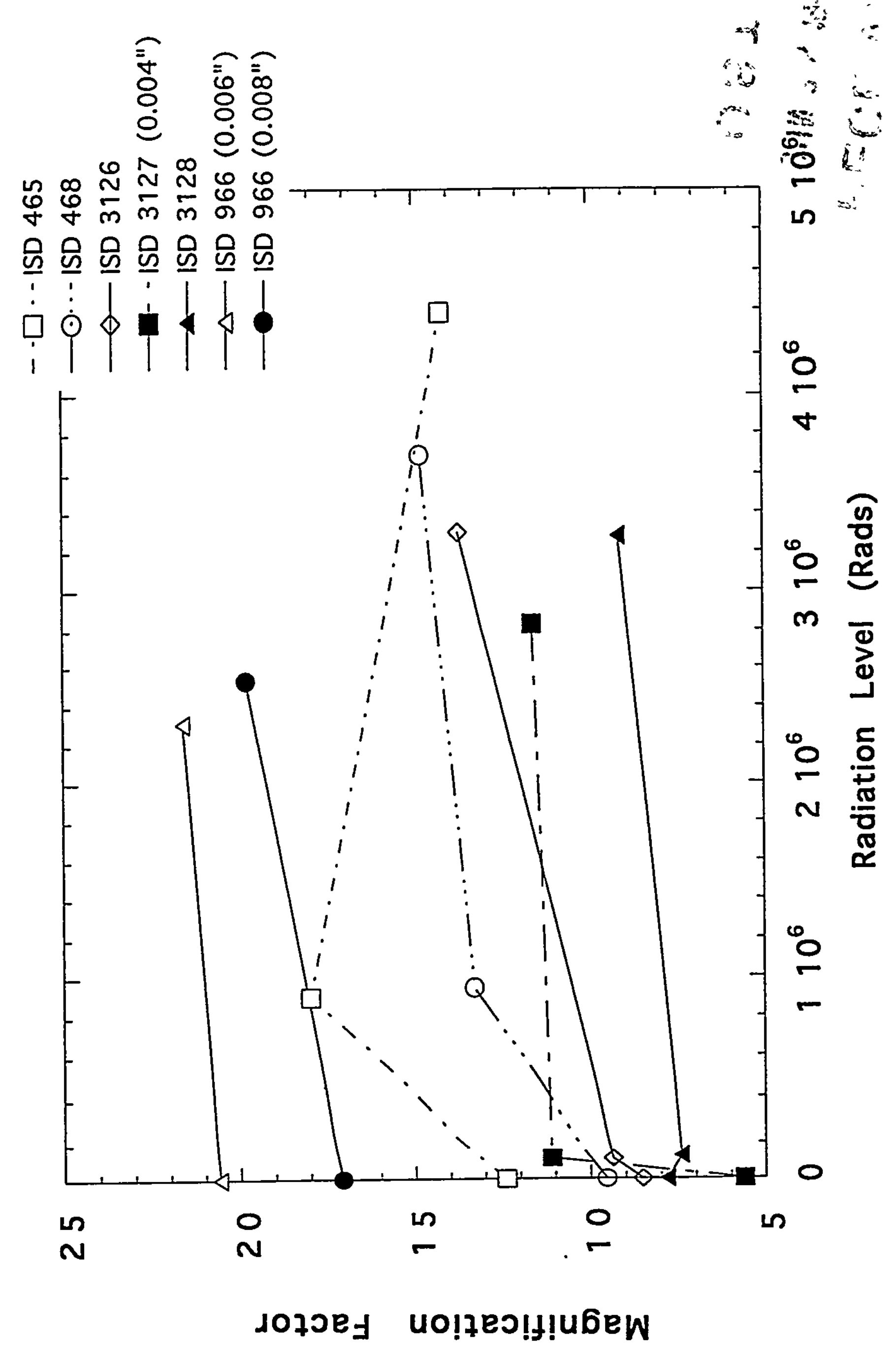

Fig. 12, Effect of radiation on magnification factor on selected viscoelastic damping materials.

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