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Stability and vibration control in synchrotron light source buildings

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1. INTRODUCTION

Synchrotron light sources have undergone three generations of development in the last two decades. The National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory has two "second generation" storage rings that currently provide the world's most intense sources of photons in the VUV and X-ray spectral ranges. There are almost 90 beam lines serving a community of 2600 scientists from 370 institutions. They are engaged in basic and applied research in physics, chemistry, biology, medicine, materials science and various technologies.

When design of the NSLS began in 1977, emphasis was given to the stability of the concrete slab on which the storage rings and experimental beam lines were placed. Stability is the result of controlling:

- vibration from sources internal and external to the building,
- thermal effects of air and water temperature variations,
- foundation settlement and contact between the slab and underlying subsoil.

With the advent of new research where highly focused beams of x-rays must be placed on increasingly smaller targets located 35 meters or more from the source, and the development of x-ray lithography with resolutions approaching 0.1 micron at chip exposure stations, even greater attention to stability is required in building designs.

Worldwide, there are at least 45 synchrotron light sources being designed, under construction, or in operation. First generation facilities operated parasitically at rings used primarily for high energy physics research. Second generation sources, begun in the late 1970's, were dedicated to synchrotron light research and could be scheduled for the needs of their users. Third generation rings in the U.S., such as the Advanced Light Source (ALS) at Berkeley and Advanced Photon Source (APS) at Argonne are optimized for insertion devices to enhance brightness of the light or to shift its wavelength. Similar third generation sources are underway in France, Italy, Japan, Taiwan, Korea and the USSR. There are also a number of special purpose light sources for x-ray lithography such as IBM's HELIOS, BNL'S SXLS and a number of counterparts in Japan. The CAMD ring at Louisiana State University and SRC at the University of Wisconsin, though optimized for lithography, can be used for other research in the soft x-ray regime.

The NSLS rings were designed with unique low-emittance lattices that required stable electron (and photon) beams to utilize their inherent high brightness. Achieving this stability has been an evolving process starting with the building, but requiring innovative measures by accelerator physicists and experimenters. Building stability was achieved on a "best effort" basis by means of a conservative structural design, isolation of the sensitive slab, setting tolerances on water and air temperatures, and good quality control during construction. To keep costs within limits, no aspect of the design or specifications could be so unusual as to scare away competent contractors or force them into adding large contingencies to their bids.

This paper will review the results of the successful NSLS experience and give an integrated design approach that includes elements which contribute to instabilities, and the means available to reduce them to acceptable levels.

2. OPTICAL BENCH CONCEPT

A synchrotron light source with its beam lines and experimental stations is an optical assembly. The platform upon which these elements rest, the concrete slab on grade, is the optical bench. In this frame of reference, we must maintain close tolerances between the slab and key storage ring magnets for periods up to 24 hours for orbital and photon beam stability. Stringent limits of micron or even submicron stability are required between optical elements and the experimental station for each beam line.

The size and shape of optical benches vary. Smaller circumference rings like the NSLS VUV (51m), shown in Figure 1, and many lithography rings rest on rectangular platforms. Most larger and third generation light sources have toroidal-shaped sensitive slabs as shown for the 171m circumference x-ray ring in Figure 1. The width of the slab (O.D. - I.D.) is more dependent upon the length of the beam lines than the circumference of the storage ring. Thus in Figure 2, the section through the 1060m circumference APS, looks very similar to the NSLS section A-A (Figure 1) with respect to the sensitive slab. The same is true for such other third generation rings[1] as the ESRF in Grenoble, the Super Photon ring in Japan, SRRC in Hsinchu, Taiwan, the PLS in Pohang, Korea, and CAMD at Louisiana State University. Note that the slab is structurally independent of the building enclosure except through ground coupling. Lack of isolation of the slab from the building structure and no building insulation gave rise to stability problems[2] at the Photon Factory in Japan which have been subsequently corrected.

When the NSLS building was designed, the optical bench concept was understood and means were undertaken to control thermal stability and reduce vibration. The approach has been successful and cost-effective but in itself could not keep pace with stability requirements of increasingly sophisticated experiments. It has taken feedback systems on the storage rings and experimental beam lines to achieve the micron and submicron stability now required for some experiments. This paper approaches building stability by dividing it into two related subsystems. The first is the interface between the building and storage ring. Here, a stable electron (or positron) orbit and source of photons must be achieved. The second subsystem is the interface between building and beam lines in which differential movement between beam line optical components must be limited.

3. BUILDING-STORAGE RING INTERFACE

The concrete slab under the storage ring is subject to vibration and movements from several sources. These factors, and others intrinsic to the storage ring, contribute to the movement of magnets, causing error fields that distort the electron orbit. In a low emittance storage ring, the strong focusing quadrupole magnets are the most sensitive to movement. Because vertical emittance is about

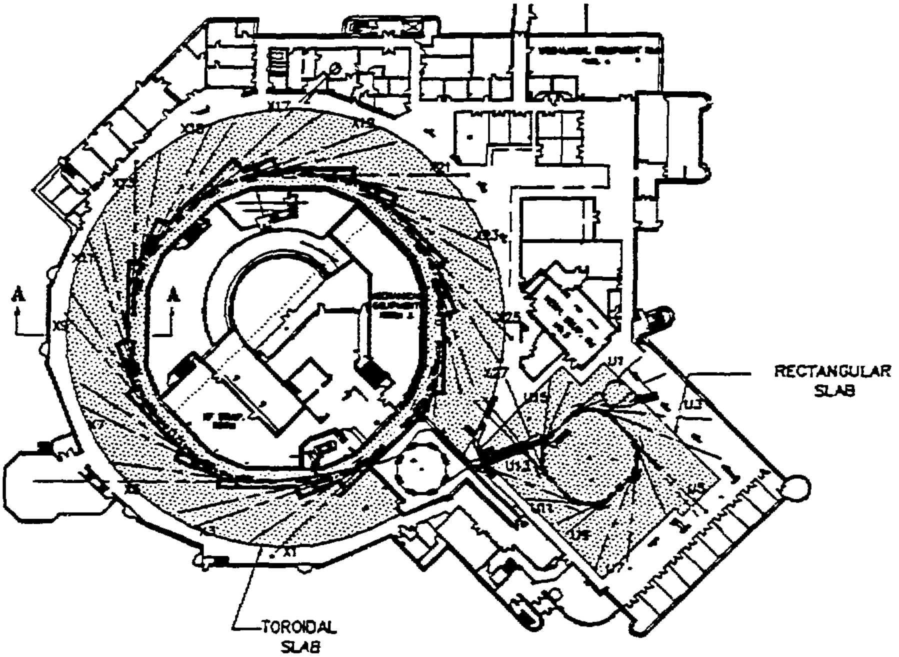


FIGURE 1

NSLS SENSITIVE SLABS

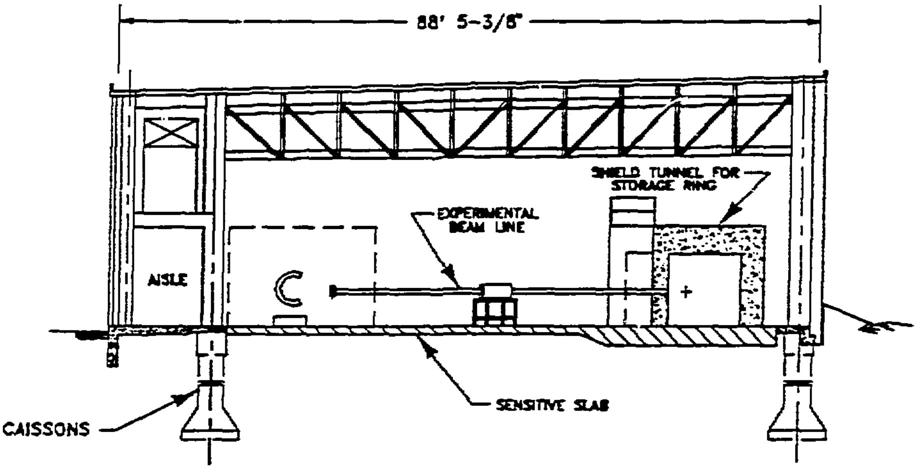


FIGURE 2

CROSS SECTION OF APS EXPERIMENTAL HALL

GODEL

an order of magnitude smaller than horizontal, the vertical movement of the quadrupole is more detrimental. Unfortunately, there is a multiplication effect where the orbit error can be considerably greater than the actual displacement of a single quadrupole. This closed orbit amplification factor is different for each lattice, but a guideline is to limit emittance growth to 10 percent.

The NSLS had no standard for maximum allowable vertical vibration amplitude to limit emittance growth at the time of its design. To meet the needs of third generation rings, methods[3, 4] were developed to calculate emittance growth from static effects (errors in magnetic fields or quadrupole placement) and from dynamic effects (ground vibrations, magnet supports, or fluctuations in coolant flow and magnet power supplies). From these magnification factors, the vibration criteria for the APS were developed[5] and are part of the paper in this session by Jendrzejczyk and Wambsganss. Allowable vertical amplitude of a single quad is given as 1.29 μm and random vibration of all quads is 0.12 μm. To achieve these criteria, ground vibrations are limited to 0.28 μm at frequencies over 4.4 Hz. For the SPring-8 project[6] the maximum vertical amplitude for a single quad is 1.2 μm which is very close to the APS criteria.

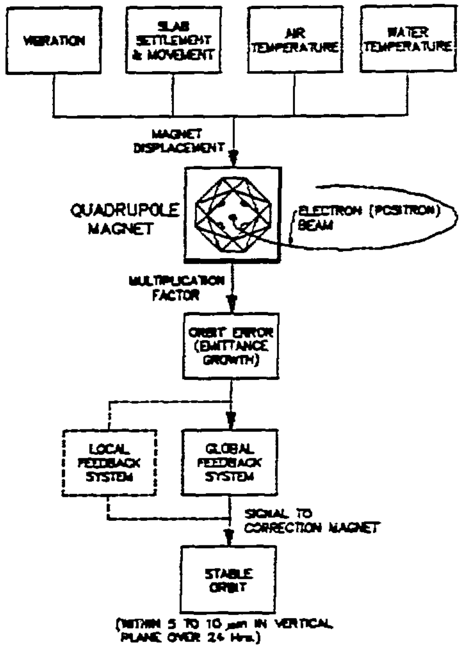


FIGURE 3
BUILDING–STORAGE RING INTERFACE

Figure 3 is a schematic of the building-storage ring interface. Ground motion from external sources and traffic plus excitation from pumps and compressors will transmit vibrations to the sensitive slab. The magnet support structure must be free of resonances that amplify slab vibrations at the center line of the electron orbit. Accelerator component designers must also reduce vibration from water cooling of magnet coils and the vacuum chamber. Slab settlement and movement over a 24 hour period should not be a problem for a properly designed system. A large initial settlement will take place during construction and secondary settlement after one year will be very small since heavy weights will not be routinely shifted. Slab movement can also occur from improper contact with the underlying subsoil. Large temperature swings in the air-conditioning system can affect the growth of magnet supports and cause thermal deflections in the concrete slab. Thermal effects can also occur at outer edges of uninsulated slabs from diurnal changes in outdoor temperatures. Cooling water temperature stability is required to prevent unwanted movements in the storage ring vacuum chamber and magnets.

Thus, if the vertical position of the APS quads could be limited to 0.12 μm, the orbit would be stable to within 5 to 10 μm or 10 percent of its beam height (using a multiplication factor in the order of 40 to 100) without a global feedback system. In practice, this stability is difficult to achieve. At the NSLS it was essential to correct orbit instabilities, and the first dynamic (real time) global feedback system for synchrotron light sources was developed[7] using pick-up electrode (PUE) beam position monitors. Orbit error signals from the PUE's are analyzed and a compensating input made to correcting magnets. The result is shown in Figure 4 in which the feedback system was turned on and off every 30 minutes in a test. The orbit deviation was significantly reduced from 20 μm to 1 or 2 μm at PUE 31, which corresponds to the stability of the photons in the beam line immediately downstream of the PUE.

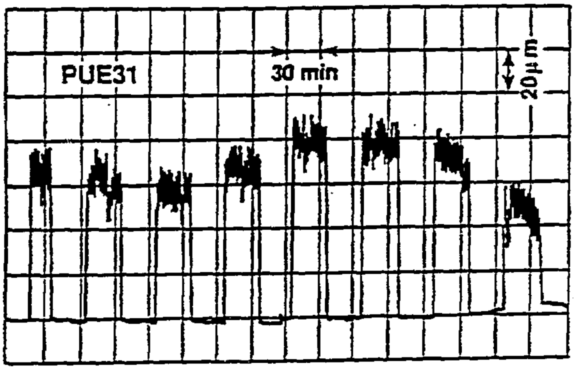


FIGURE 4

ORBIT CORRECTION WITH GLOBAL FEEDBACK SYSTEM

4. BUILDING-BEAMLINE-EXPERIMENT INTERFACE

Given a stable source of photons from the storage ring, the objective for each beam line is to limit differential motion between optical elements and the experiment. This requires thermal and mechanical stability in a number of building-related systems. In a forthcoming paper[5] the stability requirements for a range of experiments at the NSLS were classified based on the typical time for gathering data. Figure 5 from this paper, shows that for experiments taking one hour, the accepted motion at the sample is between 10 and 200 μm. However, in several areas of research, micro-focusing as one example, there are more stringent requirements of micron and submicron stability. Longer, third generation beam lines with bright, compact x-ray beams, will also require micron stability between optical elements and the experiment.

Figure 6 is a schematic of the building-beamline-experiment interface. The same vibration and slab settlement effects as were described for the building-storage ring system will apply here. There is no multiplication factor per se, but care must be taken in the design of optical support systems to prevent motion at the floor from increasing at the center of the photon beam 1.4 meters above the floor. Air or water temperature fluctuations affect the movement of supports and water cooled components.

The schematic shows two methods to reduce excessive motion. The first isolates floor vibrations from optical elements by means of an active or passive device such as a pneumatic table

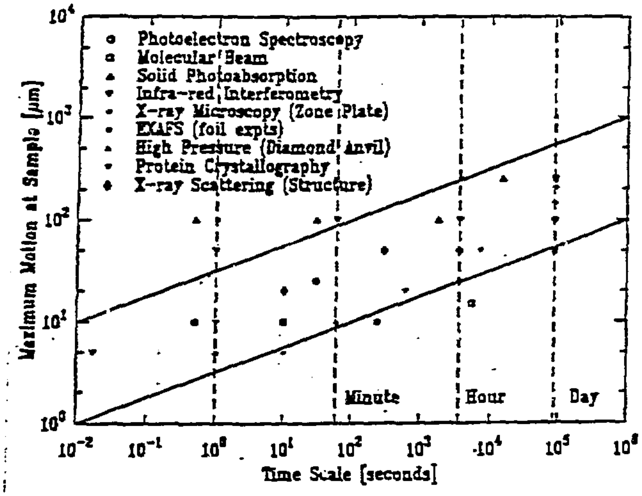


FIGURE 5
USER BEAM STABILITY REQUIREMENTS

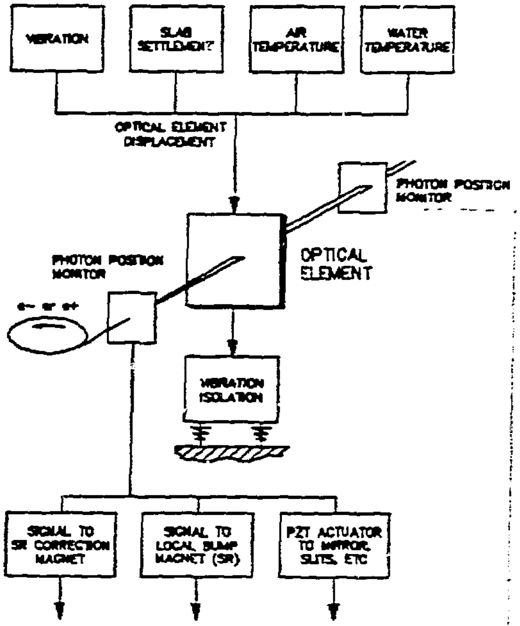


FIGURE 6
BUILDING-BEAMLINE-EXPERIMENT INTERFACE

which is effective between 2 and 30 Hz, or a control system[9] which generates a reverse-phase signal which drives a force transducer to attenuate table motion. The second method, currently under development at several laboratories,[10] detects photon beam position errors. Error signals may be used for

- Global orbit feedback of storage ring,
- control of local bump magnet in storage ring specific to one beam line, or
- active feedback to move mirror or slits to compensate for error.

At the EXXON Beam Line X10C at the NSLS, M. Sansone[11] and colleagues have developed a split ion chamber feedback system in which the vertical position error is fed to a PZT actuator on the mirror. Figure 7 is a plot of displacement vs. time with the system "on" (top) and "off". Errors of up to 50 μm are stabilized to within submicron limits, and 500 μm steps to within 1 to 2 microns.

The NSLS Experimental Hall HVAC control system is specified to tolerances of +/- 1°F. Tight limits have been set at other facilities since even small changes in air temperature can impact the stability of optical supports. Thermal insulation of the building envelope, including foundations, is also necessary to prevent sudden changes in outdoor temperatures from overloading the HVAC control system. Despite the tight design tolerances and insulation, it is difficult to maintain such small temperature differences in a large, open building. For example, opening an overhead door can change local temperatures by 10°C[12]. Bakeout of vacuum equipment can also perturb local air temperatures. Several remedies have been proposed to control expansion or contraction of optical supports. Hollow tubular support legs for a large monochromator at the ALS[13] are filled with water and insulated to provide thermal ballast. This technique has been calculated to limit motion to 1 μm after six hours.

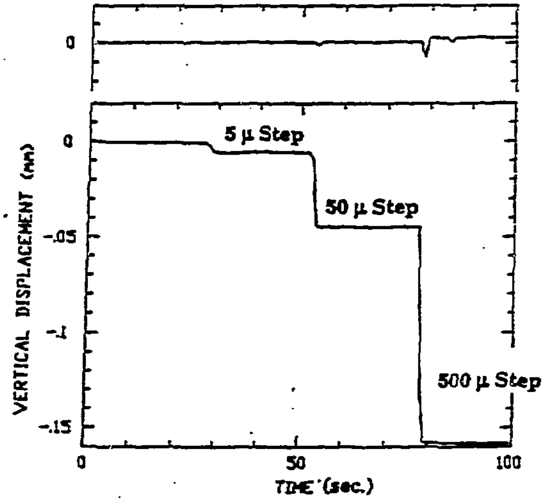


FIGURE 7
MIRROR FEEDBACK
FOR VERTICAL POSITION STABILIZATION
EXXON BEAMLINE X10C AT NSLS

R. Hewett of EXXON has suggested thermostatically controlled heating tapes on support legs.

It is difficult to accurately predict how small air temperature variations will affect local changes in slab elevation. A. Seifert[14] has calculated that the top surface of a 1 ft. thick x 56 ft. long slab on-grade could bow more than one micron per degree F change. Similarly, Warwick[15] has shown that a 1°C change in 24 hours will result in less than one micron movement. It would be useful to verify these calculations with field measurements.

Present day x-ray optics need effective cooling of heat densities of 150w/mm^2 within acceptable limits of thermal distortion and vibration. This is the domain of the optical equipment designer. The building designer must provide stabilized cooling water systems to experiments in the range of +/- 1°F. At the NSLS, this was specified but not achieved and may contribute to a problem of long-term drift in the electron orbit. The matter is now under study by E. Johnson[16] and others who have identified the problem as a malfunctioning control valve.

Third generation building designers have specified cooling water tolerances of +/- 1°C over a 24 hour period, which is achievable. It is probable however, that for future state-of-the-art optics even more stringent tolerances will be required and individual, small volume closed systems will be used.

5. BUILDING DESIGN

The building design approach at the NSLS has been to

- Identify critical systems, components, and areas,
- set attainable performance requirements, and
- apply best available design standards and construction practices without resorting to heroic (and expensive) methods.

Recommendations for specific critical systems and areas follow below.

5.1 Site

Undertake the following studies before final site selection:

- Geotechnical: soil bearing properties, settlement, ground water, seismic faults
- Vibration: ambient, traffic, other buildings
- Soil-foundation interaction: seismic analysis

5.2 Foundation & Slab

The salient design features are shown in Figure 8. At Brookhaven we are particularly fortunate to have very stable, high bearing capacity, undisturbed glacial sand less than two meters below grade. The NSLS sensitive slab was placed directly upon the undisturbed sand. Great care was taken to minimize distortion from initial shrinkage, moisture changes and temperature gradients during curing. The concrete mix was well proportioned to minimize cement content (low slump) and poured after the roof was erected to protect it from direct sunlight. Initial shrinkage was controlled by placing the concrete in a checkerboard pattern. Wet curing was specified for 14 days.

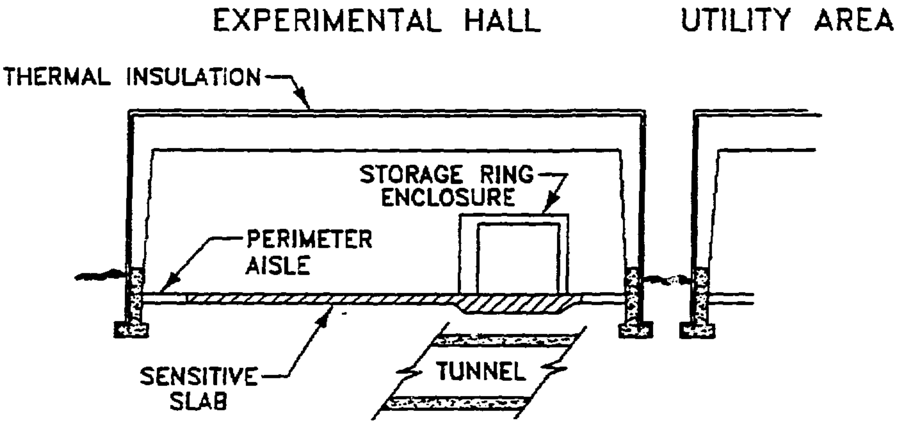
The toroidal slab was divided into three concentric rings and each subdivided into large plates with controlled contraction and expansion joints. Vertical alignment was maintained across expansion joints by means of smooth steel dowels with one end lubricated. Designers at the APS may eliminate all expansion joints to ensure that the slab is monolithic. Their rationale is that initial shrinkage and settlement will take place well before operations begin and temperature changes in the building will be carefully regulated thereafter. Microcracking of the concrete will be random and well distributed so is not expected to be a problem.

5.3 Vibration Control

Guidelines consistent with good design practice include:

- Building equipment (pumps, chillers, compressors) should be on an independent slab and be located as far as economically feasible from the sensitive slab to maximized attenuation.
- No reciprocating compressors permitted.
- Provide vibration isolation for all rotating equipment with efficiencies greater than 99 percent.
- Rotating equipment should operate at less than 80 percent of critical speed.
- Pumps, compressors, and fans to be factory and field tested to meet vibration (and noise) specifications. Larger fans to be statically and dynamically balanced in the factory and balanced in the field.
- Piping and ducting systems to be isolated from the building via spring supports, guides, etc., and connected to vibration-isolated equipment via flexible connections.

Vibration from outside the building is seismic or stems from traffic or large machinery nearby which is transmitted through the ground. An excellent tutorial on ground motion and its effects on accelerators is given in reference[17]. Little can be done about seismic noise, whereas traffic can be slowed down and the road surface improved to mitigate the problem. It is useful to know of the existence of pre-existing machinery nearby since it might affect site selection.



SENSITIVE SLAB

- Sensitive slab to be isolated from foundation and superstructure
- Movement of equipment via perimeter aisle or overhead crane
- No internal columns on sensitive slab
- Monolithic design with or without control joints in slab
- High density compaction of structural fill under slab
- Tunnels, if required, should be isolated from and not undermine sensitive slab

EXPERIMENTAL HALL

- Thermal insulation of enclosure
- Control air & water temperatures to +/- 1°F

UTILITY AREA

- Independent slab, foundation & columns
- Maximum distance from sensitive slab

FIGURE 8

DESIGN FEATURES FOR STABILITY OF LIGHT SOURCE BUILDING

5.4 Thermal Issues

- Design for air temperature control in the Experimental Hall and Storage Ring Tunnel to be in the range of +/- 1°F with emphasis on the space between the floor and the center of the electron or photon beams. The tolerance and actual temperature may vary at different heights in the building without adverse effects.
- Overhead and personnel doors for entry to the Experimental Hall should be "airlocked" if connected to unconditioned space. Both overhead doors in the airlock should be prevented from being open simultaneously.
- Thermal insulation is required for the building envelope and may be needed for foundation walls and under the sensitive slab if near the building perimeter. Pipe insulation is mandatory for energy conservation but may also be needed to maintain temperature tolerances for water cooling supply manifolds.

6. RESULTS & COMMENTS

6.1 Vibrations

In June 1989, vibration (and acoustic) measurements were made at the *NSLS* by Acentech, Inc. as part of a study[18] for the design of the Advanced Photon Source. Figure 9, taken from this study, shows the range of vertical vibration measurements (3rd octave band) on the sensitive slab taken under a number of beam lines. The maximum velocity was measured at 80 microinch/sec. in the 63 Hz band. The maximum rms displacement ranged from 0.016 μm at 20 Hz to 0.028 μm at 3.15 Hz. The maximum horizontal amplitude was 0.003 μm above 20 Hz. In terms of peak-to-peak displacements, the vertical was .045 μm at 20 Hz. The maximum vertical displacement at any frequency was 0.08 μm. These are well below the APS and SPring-8 criteria.

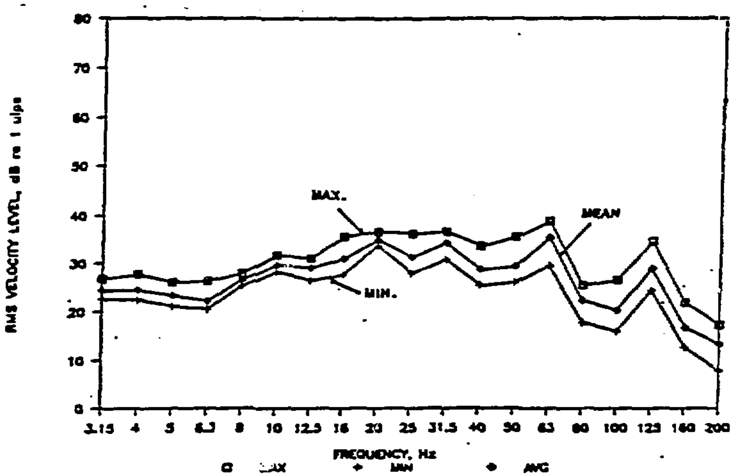


FIGURE 9
RANGE OF VIBRATION MEASUREMENTS, ALL LOCATIONS

We learned, to our chagrin, that there is a 600 HP reciprocating helium compressor about 1000 feet from the *NSLS*. It operated only very intermittently between 1981 and 1988 and we were not aware of its existence at the time the NSLS was designed in 1978. It was not operating at the time of the Acentech survey. Although the data has to be verified, it appears from measurements taken under storage ring magnets, that peak-to-peak vertical displacement increases to a maximum of 0.4 to 0.6 μm at 12 Hz in several locations with the compressor on. The displacement falls off sharply at higher and lower frequencies but there are peaks in the 2 Hz range which are lower than at 12 Hz.

Up to now, this has been acceptable in the building-beam line interface but unfortunately, the 12 Hz ground waves from the compressor matched the resonance in several magnet support stands and resulted in unacceptable movement of the quadrupoles. A study[19] recommended methods to correct the stands, which were easily implemented. The study also suggested means to isolate vibrations at the compressor which would reduce the peak-to-peak vertical displacement by 90 percent. This option may be necessary in the future.

6.2 Slab Settlement & Stability

Short-term (24 hours) settlement of the NSLS slab is negligible. This can be attributed to the excellent bearing and stability of the subsoil and that heavy loads are not required to be routinely shifted. We believe that the total secondary settlement of the slab under the storage ring has been 1.5mm over 10 years of which 90 percent occurred in the first two years. At other sites where deeper soil layers contain silt or where ground water may affect bearing properties, short term settlement may be a problem.

No measurements of differential vertical motion or movement from thermal effects have been made at expansion joints on the sensitive slab. Nor have we received complaints from researchers that they suspect such instabilities have occurred. We intend to make a survey in the future of slab movement using a laser interferometer.

6.3 General

(a) The NSLS is a valuable research tool in part because of the ability of its staff and users to improve beam stability at the experiment. In 1982, vertical photon beam stability was limited to ~ 125 μm. By 1988 storage ring improvements reduced instabilities to ~ 10 μm. After global feedback was implemented in 1990, it was further reduced to the range of 1 to 3 μm. As noted above, feedback circuits on beam lines can correct vertical beam movements to 0.1 to 1 μm, the current state-of-the-art. It has been possible to accept a vibration of the sensitive slab with a vertical amplitude of more than 0.4 μm and mitigate the adverse multiplication (~70), resonance and thermal effects to achieve submicron stability at certain experiments. The building design and construction was well within accepted industry standards and the building is probably less than 5 percent more expensive for its vibration, settlement and thermal control features.

(b) In the category of "what would we do differently today", the response is "not too much", but four points could be made.

- Discovery of the helium compressor before site selection would probably not have changed the NSLS location, but we could have dealt with the design of magnet supports and vibration isolation more effectively.
- If more space or funds were available (they were not), it would have been more prudent to move several of the mechanical equipment rooms further away from the sensitive slab to increase vibration attenuation through the ground.
- Use specialists in the design phase for an integrated structural, vibration and acoustic analysis of the building and related equipment.
- Vibration, stability and acoustic records should be as important a part of facility design and operations as surveying and alignment of accelerator and beam line components. Lack of this information makes it difficult to fully understand the effects of adding new

or maintaining existing equipment.

7. ACKNOWLEDGMENTS

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