fly apart are key issues. For small structures, great advances have been made in computer modeling. It would be desirable to extend the models to bulk samples.

X-ray intensity fluctuation spectroscopy is already being pioneered at third generation light sources and its extension to x-ray FELs, in terms of the time-scales and length-scales, were discussed, together with the possibility of studying a broad range of materials.

There were intense discussions trying to define the most important radiation characteristics. This will of course in many cases depend on the specific experiments, but in general terms the following order was established, in de-creasing order of importance:

1. Beam position stability
2. Beam focusing
3. Synchronization for pump-probe
4. Shorter pulses
5. Smoother pulses
6. Reduced pulse to pulse intensity fluctuations

3.3 Workshop on Ground Motion in Future Accelerators

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The 22nd Advanced ICFA Beam Dynamics Workshop on Ground Motion in Future Accelerators was held at Stanford Linear Accelerator Center (SLAC) from November 6 to 9, 2000. The widespread interest in this topic was evident in the 58 participants from 20 laboratories worldwide, as well as universities and companies.

A next-generation linear collider will have tight tolerances on alignment and position jitter, so tight that ground motion and vibration can be limiting factors in the performance. Ground motion and vibration are also important in other areas such as synchrotron light sources, large circular colliders, some fields of industry and non-accelerator experiments requiring high precision such as gravitational wave detection. Teams from many different projects are working on these problems and, in many cases, converging on similar solutions.

The Ground Motion Workshop provided a venue to collect and compare the data, resolve outstanding issues, sharpen the contradictions, outline further studies and, most importantly, unify the worldwide efforts to prepare for the challenges of future machines. Topics discussed included:

- Theoretical considerations of the influence of ground motion on accelerators including proper methods to represent and model the ground motion
- Measurement, interpretation and classification of ground motion
- Fast motion, cultural noise and their correlation properties
- Slow motion and the relation between diffusive and systematic components
- Girder design and tunnel construction techniques and their contribution to vibration and ground motion

- Beam independent methods to ameliorate ground motion effects, including passive damping and active methods of stabilization

The Workshop started with a review of the ground motion and vibration problems in various accelerators, such as large hadron colliders (SSC, VLHC and LHC), linear colliders and synchrotron light sources. Ground motion causes different problems in these machines. For example, the primary effect of fast (second – millisecond time scale) ground motion and vibration in large circular machines is to produce emittance growth, while for light sources the beam stability is an issue, and for linear colliders a bigger concern is beam separation at the interaction point.

In large colliders, for example, when the beam passes through a quadrupole which is moving, it undergoes betatron oscillations which grow in amplitude. Beam decoherence due to the tune spread slowly translates the betatron oscillations into emittance dilution. Detailed analysis has shown that the frequency which contributes most to the dilution is the fractional betatron tune times the revolution frequency which, for large colliders, can be several hundred Hertz. Though the ground motion is quite small at those frequencies, the resulting emittance growth may be noticeable over a typical beam lifetime, and beam orbit feedback may be required to cure the effect.

In the example described above, the motion of neighboring quadrupoles in a large collider can be assumed to be reasonably independent, and therefore uncorrelated. For a linear collider, on the other hand, one typically cannot assume that the motion is uncorrelated. In order to correctly evaluate the effect on the beam, the spectral response function of the optics must be convoluted with the spatial spectrum of motion which properly includes the correlation information.

The analog of revolution frequency of circular machines is repetition frequency in linear colliders. For linear colliders, continuous beam-based feedback operating at the repetition frequency is indispensable. This divides the frequency scale in two ranges:

1. fast motion which cannot be corrected by feedback and produces a relative beam offset at the interaction point

2. slow motion which primarily results in beam emittance growth.

For typical parameters this boundary lies at a scale of about 1 Hertz.

Although ground motion problems have different effects for each particular accelerator, the phenomena to be understood are similar: ground motion amplitudes and its spatial and temporal correlation properties. For all accelerators, the technical solution for ground motion problems is to first locate the accelerator in a quiet place, if possible, and minimize the generation of additional vibrations, and then typically to use beam-based feedback. For linear colliders, there is an additional problem with the final quadrupoles nearest the Interaction Point. These must be stabilized by a system which is not limited by the repetition frequency and, hence, cannot be beam-based. This requirement creates an interesting connection to developments in the field of gravitational wave detectors.

A highlight of the workshop was the participation of LIGO experimenters who presented ground motion problems for gravitational wave detectors and their solutions. Fast ground motion, in this case, can mimic gravitational waves and therefore the detecting masses must be isolated by many layers of passive and active stabilization. The vibration suppression methods developed for LIGO were very impressive and certainly set a benchmark for what is ultimately possible. The LIGO team also described some of the issues in achieving maximal performance of a stabilization feedback by very careful design, proper combination of sensors, and choice of the right algorithm. Collaboration with the gravitational wave experiments may prove fruitful to future linear collider development.

There have been extensive measurements of the fast ground motion and the correlation functions around the world. Mathematical models of the motion have been created in order to evaluate the effect on an accelerator. One of the outstanding questions is the effect of the “cultural noise” which can be generated in the vicinity of the accelerator and can vary significantly over short distances. This noise has not yet been satisfactorily modelled. The synchrotron light source community worldwide has extensive experience on cultural noise and vibration studies, and their presentations underscored how difficult these problems can be if external and in-tunnel noise sources are not carefully avoided by proper design and site selection. The light sources have also studied in detail the optimal design of support girders, which cannot be perfect and always represent a tradeoff, a fact which tends to be ignored.

A major topic during the Workshop was a discussion of slow motion (minutes – years time scale). Two different models for slow motion have been proposed:

1. a diffusive model governed by the ATL law: $\langle X^2 \rangle = A \cdot T \cdot L$
2. a systematic model which behaves as $\langle X^2 \rangle = A \cdot T \cdot T \cdot L$.

Here, X is the transverse misalignment, A is a coefficient, T is time and L is the distance between two points.

Measurements presented showed evidence for both types of motion where the systematic component seems to dominate on the year time scale, and the diffusive for shorter periods. The difficulty in measuring such motion and the lack of data with sufficiently good statistics both in space and time still allows considerable controversy over the interpretation of existing data. In particular, the evidence for an L dependence in diffusive motion has been questioned. On the other hand, during the Workshop there was significant progress on a systematic approach to the analysis of existing data, including proper decomposition of measurement errors from real motion. Such an approach has been applied to the LEP alignment data (700 quadrupoles measured yearly over 10 years) and plans were made for a collaboration between CERN and SLAC to further analyze the LEP data. In order to understand the region of validity of these models, it is necessary to make thorough studies with better statistics. A collaboration between SLAC, FNAL and BINP plans a series of experiments to measure the dependence of slow motion on temporal and spatial separation and on geological conditions.

A thoughtful review of the implications of geology and tunnel construction techniques returned the discussion to real life as compared to models. The question is how to balance an affordable cost with the requirements for tunnel stability and a specialized tunnel engineering workshop was proposed. It is also clear that not all of the impacts of tunnel engineering on ground motion are understood. For example, there is evidence that bored tunnels may be more stable than those which used blasting. There are also questions about the effect of discontinuities due to the tunnel that modify the external noise and trap the internal noise. Little is known about the hour–day stability of existing tunnels such as LEP and this certainly warrants future measurements.

The Workshop was considered a success by all participants. In addition to the healthy exchange of technical details and solutions, it provided links between groups working on similar problems for different applications. A follow-up Workshop is planned in 1–2 years to keep track of progress in this exciting field of science. For further information, copies of the presentations are available on the Workshop web site:

`http://www-project.slac.stanford.edu/lc/wkshp/GM2000/`

and the Proceedings will be published as a SLAC report.