FERMILAB-Conf-01/440 November 2002

Detailed Summary of the Working Group on Environmental Control (T6)

Wilhelm Bialowons
*DESY**
Chris Laughton
Fermilab†
Andrei Seryi
SLAC‡

1. Charge

For the next generation of large accelerators, the civil engineering of accelerator tunnels and associated underground enclosures will be a major component of the technical challenge of building such machines. Because of the large scale involved, the engineering will be required to be as cost-effective as possible, and issues such as ground motion and artificial sources of vibration in the environment will need to be carefully considered. Installation and alignment of the machine components will be tasks of unprecedented scope, and will require unprecedented precision. Examine in detail the most important and most difficult aspects of these challenges, both from the point of view of performance and cost-effectiveness. In particular, identify what the site requirements are for the different machines under discussion (JLC, NLC, TESLA, VLHC, Muon source), and describe how tunneling methods are affected by them. Identify, for the different types of accelerators, the different length scales that are involved in defining the alignment tolerances, and what are the tolerances over that length scale. Specify the R&D efforts needed to define the scope of the most critical challenges, and prioritize the efforts, in terms of the potential to provide maximal performance and/or cost-effectiveness. Establish a technology-limited time line, and the resource requirements, for the most important of these efforts.

2. Speakers

Fred Asiri, SLAC; Ralph Assmann, CERN; Lars Babendererde, Babendererde Ingenieure GmbH; Robert Bauer, Illinois State Geological Survey; Wilhelm Bialowons, DESY; Reinhard Brinkmann, DESY; Phil Burrows, Oxford; John Cogan, SLAC; Clay Corvin, SLAC; Bill Foster, FNAL; Joe Frisch, SLAC; Peter Garbincius, FNAL; Lindemar Hänisch, DESY; Linda Hendrickson, SLAC; Keith Jobe, SLAC; Vic Kuchler, FNAL; Joe Lach, FNAL; Chris Laughton, FNAL; Catherine LeCocq, SLAC; Tom Mattison, UBC; Rainer Pitthan, SLAC; Johannes Prenting, DESY; Armin Reichold, Oxford; Michael Schmitz, DESY; Andrei Seryi, SLAC; Nick Simos, BNL; Steve Smith, SLAC; Peter Tenenbaum, SLAC; Toby Wightman, American Underground Construction Association.

3. Tunneling experts (attended the workshop during July 9-10)

Robert Bauer,	Illinois State Geological Survey
Lars Babendererde,	Babendererde Ingenieure GmbH
Philip Frame,	Consultant Geologist

*Wilhelm.Bialowons@desy.de
†Laughton@fnal.gov
‡Seryi@slac.stanford.edu

Donald Hilton, Donald Hilton & Associates
Dennis Lachel, LACHEL & Associates, Inc.
Dave Neil, NSA Engineering, Inc.
Toby Wightman, American Underground Construction Association

4. Scope.

For the next generation of large accelerators, the civil engineering of accelerator tunnels and associated underground buildings will be a major component of the technical challenge of constructing such machines. Between a sixth and a half of the total costs for these machines [1] must be used for the civil engineering. Because of the large physical scales of these machines the engineering will be required to be as cost-effective as possible, and because the considered beam sizes are of nanometer scale, issues such as structural and thermal stability, ground motion and artificial sources of vibration in the environment will need to be carefully studied. The working group concentrated on tunneling, ground motion, stability, alignment and environmental issues.

5. Ground motion considerations.

New accelerators to meet the demands of particle physics experiments will have to push both the energy and luminosity frontiers. The technical requirements for these machines are beyond what has typically been achieved. The major candidates for a next generation machine are electron-positron colliders, JLC [1], NLC [2, 3] and TESLA [4] optimized to study the 0.2 - 1.5 TeV energy range, and also a hadron collider VLHC [5] and electron- positron collider CLIC [6] that would probe multi-TeV physics. Ground motion and vibration are of concern for all these machines, but the details of the problems are different. These differences are reflected in the approaches and in the level of detail given to the design of systems to stabilize the beam and the luminosity.

5.1. Effect of ground motion on future colliders.

Ground motion and vibration have two important effects on a collider. They can cause the beams to miss each other at the interaction point (IP), and they can cause beam emittance growth, which reduces the luminosity.

In hadron colliders, such as VLHC, the beam size is still sufficiently large (smallest size 250 nm) compared to the ground motion amplitude at relevant frequencies, that the offset of the beams at the IP is not an issue (all the numbers are for the high field VLHC with 87.5 TeV beam [5]). However, the effects of ground motion can accumulate and result in emittance growth. In the VLHC, the primary issue is that movement of the quadrupoles induces betatron oscillations, which then decohere and turn into emittance growth. The lowest frequency of ground motion contributing to this effect is $f = \Delta\nu f_0$ where f_0 is the revolution frequency (~1.3 kHz) and $f = \Delta\nu$ is the fractional tune (~ 0.18), i.e. the lowest relevant frequency is $f \sim 250$ Hz. The emittance growth rate from white noise quadrupole motion without any feedback is given by $d\varepsilon_n/dt \approx f_0\gamma\langle\beta\rangle N(\sigma/F)^2/2$ [7, 8] where N = 1700 is the number of quads, F = 100 m is their focal length, $\langle\beta\rangle = 230\ m$ is the average beta function, $\gamma = 9.3 \cdot 10^4$ is a relativistic factor and σ is the rms vibration of quadrupoles. For these parameters, the initial emittance of $\varepsilon_n = 1.5$ mm-mrad would double in 2.5 hours with only 0.3 nm of quad vibration (the synchrotron radiation damping time is 2.5 hours for VLHC). This tolerance could be eased by perhaps a factor of 10 with orbit feedback. One should note that for the VLHC the orbit feedbacks may be required not primarily because of vibrations and ground motion, but because of TMCI, resistive wall and other instabilities that may grow quite fast,

[1] The fraction for the civil engineering of the total costs is approximately one sixth for TESLA [4] and is greater than one third for NLC [3].

over several turns. Suppression of these instabilities will require sophisticated feedback systems to be developed and tested [9]. Assuming that proper feedbacks to suppress instabilities are developed, one can conclude that in a quiet location (see the Fig.1 and, for example, Figs.1-3 in [40] and Fig.14, 18 in [7]), ground motion is sufficiently small for the VLHC. A more real concern for VLHC may be not the ground motion itself, but vibrations produced by equipment, for example by cryogenic systems. Design of VLHC girders and cryostats is another issue requiring attention since the amplification of ground vibrations by girder and cryostat and in-cryostat generated vibrations need to be minimized.

In current linear collider designs (CLIC, JLC, NLC, TESLA), the beam size at the interaction point is nanometer scale (2-5 nm). Ground motion can produce not only the emittance growth, as for circular machines, but also may cause the beams to be offset at the IP. The relevant frequencies are determined by the repetition rate of collisions frep. The SLC experience has shown that frequencies higher than about $f_c = f_{rep}/20$ cannot be adequately corrected by a pulse-to-pulse feedback operating at the repetition rate. Therefore, it is these frequencies that are the source of beam offsets at the IP. Slower motion can be compensated by feedback and thus only causes beam emittance growth.

The superconductive and normal conductive linear collider projects differ significantly in terms of their repetition rate. The f_{rep} for bunch trains at TESLA is 3-5 Hz, so that $f_c \sim 0.2$ Hz while, for example, the NLC with a repetition rate 120 Hz has feedback cutoff frequency around $f_c = 6$ Hz. The sensitivity for uncorrelated motion of linac quadrupoles above cut-off frequency is roughly 10 nm for both TESLA and NLC [3, 4]. Such motion would produce approximately equal effect on the luminosity (still tolerable) corresponded to the beam offset at the IP about $0.25\sigma_y$ for NLC and $0.1\sigma_y$ for TESLA (higher precision of collision is needed for TESLA because of higher beam-beam disruption with the present set of TESLA beam parameters).

Spatial properties of the focusing structure is another factor that influence sensitivity of colliders to misalignment. Typically, normal conducting machines require stronger focusing, or, equivalently, shorter betatron wavelength – a paramter which define the scale at which misalignments become sufficiently smooth. The betatron wavelength in TESLA linac is about 360 m, about 80 m in NLC or JLC linacs and 40 m in CLIC. Considering that the uncorrelated motion above 0.2 Hz for spatial separation $\Delta L = 50$ m is roughly 4 nm in a quiet place (see Fig.3 in [40] or, for example, Fig.4 in [40]), one can see that this motion, even in a quiet place, can reach or be slightly above the tolerable level for the superconducting design. Ground motion similar to that in the LEP tunnel would be barely acceptable for TESLA, provided that any additional motion of the quadrupoles, which are located inside cryostats, is sufficiently small.

The small repetition rate and softer focusing are the two reason which makes it impractical for the superconducting linear collider design to rely on quietness of a site. However, in spite of the small repetition rate of the bunch trains, the large number of bunches within a single train may prove to be advantageous in terms of vibrational stability. Indeed, for collision stabilization, TESLA may implement a fast intratrain correction [4], so that the correction would be based on 3 MHz repetition rate of the bunch collisions. The proposed design uses the first hundred or so bunches in the train (train duration is about 1 msec) to correct the offset for the rest of the train. It is essential for this correction that the transverse position of the bunches in the train do not fluctuate significantly, or at least that such fluctuations are static in time, i.e. they do not fluctuate from train to train so that prediction can improve the response latency. Any phenomena that may spoil this static picture, must be controlled.

The repetition rate of normal conducting linear colliders (CLIC, JLC, NLC) is typically above hundred Hertz. For instance, the NLC linear collider has a high repetition rate 120 Hz, and therefore the feedback cutoff frequency is $f_c = 6$ Hz. Natural ground motion is quite low at these frequencies, as low as 0.1 nm. Even in the SLAC linac, which is a shallow, cut-and-cover tunnel sitting on sandstone, the ground motion above 6 Hz is only about a nanometer. This is already stable enough for NLC or JLC. For collision stabilization, NLC can rely on the quietness of a tunnel built in favorable geology together with required careful engineering control of possible vibration sources in the tunnel. The linac quadrupole girders should be sufficiently rigid so that they do not amplify ground motion. Vibrations produced by the cooling flow should be tolerable as well. It was demonstrated at FFTB [13] that differential motion with respect to ground of a quad sitting on an anocast girder with cooling water was about 2 nm above several Hertz that would be tolerable. Further improvements would include, for example, use of permanent quadrupoles.

The CLIC linear collider, aiming to higher energy and smaller beam dimensions at the IP, re-

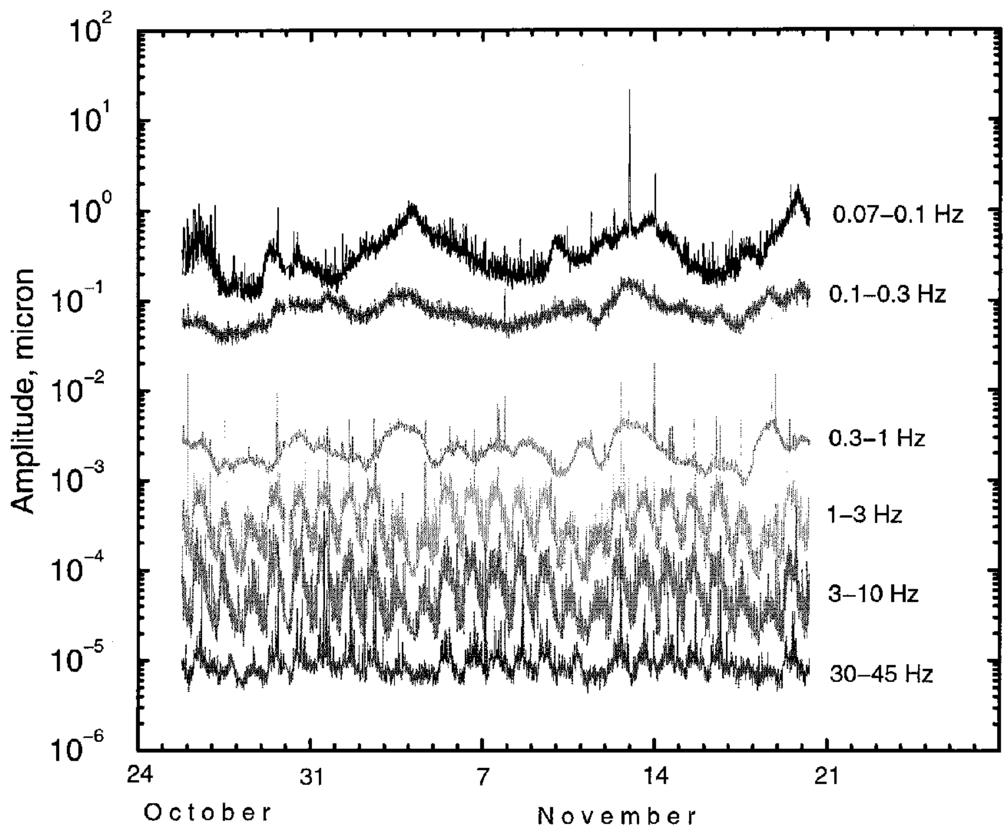

Figure 1: Rms amplitude in different frequency bands for a typical quiet location (Hiidenvesi cave in Finland) [40]. The picture shows that the natural ground motion is very low at high frequencies.

quires the linac quadrupoles to be stable to about 1 nm above several Hertz. Practically, this may require stabilization of the linac quadrupoles (either the quadrupoles themselves or their magnetic center by a dipole coil).

The superconductive and normal-conductive linear colliders also differ in the sensitivity of the beam emittance to quadrupole offsets caused by slow ground motion or inaccuracies of alignment. TESLA's large superconducting cavities with low wakefields and small beam energy spread make the quad alignment tolerances rather loose. For example, the misalignment of quadrupoles tolerable before a beam-based alignment would be needed, is about 25 μm over 50 m for TESLA [4] and about 1 μm over 50 m for NLC. Therefore, TESLA can tolerate larger diffusive ground motion and less comfortable geological conditions. On the other hand, a quiet tunnel built in good geology, as suggested for normal conductive designs, would also reduce the amount of slow motion to tolerable values. Regardless of this, in both approaches, the girders would need to be carefully designed to minimize any additional drifts of quadrupoles with respect to ground. In the TESLA design, where the quadrupoles are located inside the cryostat, a careful engineering balance is required between the mechanical stability and minimization of the heat loss in cryostats. In normal conducting designs, good temperature stability of the tunnel is also needed to minimize additional drifts of the girders. The experience of existing tunnels have shown that the temperature of underground tunnels can be very stable provided that the heat losses are constant. It was also observed that ground water and water conducting soils may help the temperature stability as they effectively increase the heat capacity of the tunnel surrounding.

5.2. Ground motion studies

Ground motion studies are essential for the accurate evaluation and optimization of the performance of future colliders to be possible. In this section, the present status of understanding is briefly described as was presented in the talks by Fred Asiri (SLAC), Ralph Assmann (CERN), Joe Lach (FNAL), Rainer Pitthan (SLAC) and Andrei Seryi (SLAC).

Ground motion can be divided into 'fast' and 'slow'. The beam offset at the IP caused by slow motion can be corrected using beam-based information arriving with repetition rate of the collisions, in contrast to the fast motion, which require additional information to be corrected. For example, for the NLC parameters, the boundary between 'fast' and 'slow' motion is in the region of a few Hz. Ground motion, being random process from a mathematical point of view, is typically represented by a power spectrum. An integrated spectrum over a particular frequency band gives the corresponding RMS motion. See, for example, [40] and [7] for the typical spectra. The natural ground motion is quite small, as low as a fraction of a nanometer, for frequencies higher than several Hz (see Fig.1). The motion in the low frequency bands is much larger, on the order of a micrometer. However, it is important to emphasize that the amplitude shown is absolute, i.e. it is the motion of a single point with respect to an inertial reference frame. What is important for a linear collider is the relative motion of two quadrupoles separated by distances less than the betatron wavelength. Correlation measurements have shown [2, 10, 15, 16] that natural fast ground motion consists mostly of elastic waves with a wavelength given by the phase velocity in the media. The low frequency portion of the 'fast' motion has quite a long wavelength and is therefore highly correlated. Thus, this motion is not harmful for a linear collider assuming that low frequency girder resonances do not degrade the correlation.

In a linear collider, the tolerance on jitter in the position of an element depends on its location. The tolerance for the Final Doublet (FD) is a fraction of the beam size at the IP, around 1 nm for NLC. Some of the quadrupoles in the beam delivery system have tolerances roughly 5–10 nm. The jitter tolerance for the NLC main linac quadrupoles is 10 nm. The relevant frequency range for these tolerances is $f_c > 6$ Hz. For comparison, the motion of an FFTB quadrupole mounted on NLC-like movers and sitting on an Anocast girder, with water flowing in the quadrupole, differs from the floor motion by only 2 nm in the relevant frequency band [13]. This is sufficient for NLC requirements even though the environment was relatively noisy. Further improvements, such as slower water flow and improved girders, can also be envisaged.

From these considerations, one can conclude that natural fast ground motion does not represent a limitation for a normal conducting linear collider. The real concern is cultural noise produced in the vicinity of the accelerator, whether external or internal to the tunnel, and vibrations produced on the accelerator girder themselves. It is clear that the accelerator equipment and the detector must be carefully designed with a goal of minimizing vibration. All of the conventional facilities support equipment for the accelerator will have to satisfy strict vibration criteria or additional measured should be taken to minimize transmission of the noise from equipment to sensitive elements of the collider. This may seem to be a new or unusual constraint for accelerator designers, but is standard practice in some areas of engineering. For example, the LIGO project [17] successfully applied various methods of passive vibration isolation to noise sources in order to achieve a sufficiently quiet environment in a noise area. Developments of such methods is one of the tasks for normal conductive linear collider designs, and, in particular, for NLC, as was reported in the talk of Fred Asiri (SLAC).

One need to note that the high level of noise measured at HERA site, apparent in the spectra (see Fig.2 in [40]), may be caused not only by cultural noises, but also by resonances of clay/sandy site itself (resonances exhibit as a minimum of vibration attenuation with distance at certain frequencies). For example, preliminary studies at two LIGO sites indicated [19] that the Livingston LIGO site, which is based on water logged clay, exhibit resonances at 1–5 Hz, while the Hanford LIGO site built on dry sand appears to have resonances at 5-12 Hz. This phenomenon, in particular the role of water and geology in it, deserves further attention. Additional studies at DESY site (located in glacial morains, as reported in the talk by Lindemar Hänisch, DESY) may prove to be necessary in this respect. The layout of the TESLA in Hamburg area, for about one third of its length, is placed in populated area and the electron collider also in vicinity of a highway. Another part of the collider is placed in more rural area. The average depth of the TESLA tunnel is 12 m (see TESLA TDR [4]). Low attenuation of cultural noises (from highways, etc.) may be an issue in this case.

The fast motion and vibration discussed above is not the only issue for a linear collider. Ground motion below 0.01 Hz or so, in spite of being very slow, can have a rather short wavelength, causing misalignments of the collider and producing emittance growth. This motion is not wave-like and can be inelastic. There are two types of motion – one is diffusive and another is systematic (described in the talk by Rainer Pitthan, SLAC). The model for the diffusive motion parameterizes the RMS relative misalignment as an ATL law [7, 20]: $\langle X^2 \rangle = ATL$ where T is the time since perfect alignment and L is the distance between points. The word "law" should not be taken literatim in this case. This formula is an approximation which is known to have limited applicability.

The parameter A varies by a few orders of magnitude when measured in different locations and is clearly site and geology dependent. For example, measurements at the DESY site gave a value of $A \approx 4 \cdot 10^{-6} \mu m^2/(m * s)$ [21] while in a tunnel built in Japan, $A \approx 2 * 10^{-9} \mu m^2/(m * s)$ was observed [22]. In this example, in the measurements at DESY the coefficient of diffusive motion was extracted from the drift of the HERA closed orbit while in the measurements in Japan a hydrostatic level system was used. It is important to note, that comparison of such numbers should be done cautiously, since not only the ground conditions may differ, but different measuring methods may contain contributions from effects that not always can be completely identified or disentangled.

Recent measurements at SLAC have shown that the value of A can depend on changes in atmospheric pressure acting on the ground [18]. These observations are explained by a variation of the ground properties along the linac. This variation can be due to changes in the Young's modulus E, changes in the topology of the surface, or changes in the characteristic depth of the softer surface layers. In this case the atmosphere-driven contribution to A scales as $1/E^2$ and, therefore, depends strongly on geology. This may be partly responsible for the large variation of A observed at different sites.

Very slow ground motion can also be systematic in time over periods of months to years. Such motion has been observed at SLAC, CERN as well as other places [24, 25]. For example, the Fig.17 in [25] shows differential motion of neighboring quadrupoles in LEP, measured over several years. One can clearly see that this motion exhibit unidirectional, systematic character. In some cases such motion can be described by a simple rule for its RMS relative misalignment [14]: $\langle X^2 \rangle = A_S T^2 L$ with another site-specific coefficient A_S. Immediately after construction of SLAC, it appears that the systematic motion dominated on a time scale greater than a day however it is significantly reduced nowadays. It is important to note that earlier studies of slow motion suggested higher values of the parameter A. One reason for this, especially for the SLAC data, was a misinterpretation of year-to-year systematic motion as diffusive motion. This confusion resulted in the overestimation of A by more than two orders of magnitude. Studies to investigate slow ground motion in more detail are in progress at many different laboratories (see, e.g. [26]). An important relation between slow ground motion and effects of underground water for the case of LEP tunnel has been reported by Rainer Pitthan, SLAC. These issues deserve further attention and investigations.

Modeling the ground motion is an important step towards accurately characterizing the influence of ground motion on a linear collider. The model should include an understanding of the temporal and spatial properties of the motion and of the driving mechanisms. In most cases, an adequate representation for such a model consists of the 2-D power spectrum $P(\omega, k)$ based on measured spectra of absolute motion and correlation. Recently, several models representing different conditions have been developed and used to evaluate NLC performance. They represent quiet, moderate and noisy sites and are described in details in [14]. Such models can be incorporated into simulation programs such as, for example, the LIAR code [41] allowing to evaluate performance of a particular linear collider design.

5.3. Active stabilization.

As became clear from the previous sections, active feedback systems are essential for the future linear collider to be able to deal with ground motion and other disturbances. The stabilization studies have been described in the talks by Ralph Assmann (CERN), Reinhard Brinkmann (DESY), Phil Burrows (Oxford), Joe Frisch (SLAC), Linda Hendrickson (SLAC), Tom Mattison (UBC), Johannes Prenting (DESY), Armin Reichold (Oxford), Steve Smith (SLAC), Peter Tenenbaum (SLAC). The issues presented are covered in more detail in the summary of T1 and M3 working groups. Here we just briefly highlight the topics discussed.

For superconducting linear collider design, the ground motion and vibration issues are addressed by application of the fast correction within bunch train and by trajectory correction in the linac. For the normal conductive linear collider, the ground motion and vibration issues are addressed by careful consideration of sites and geology, application of orbit feedbacks and fast intratrain feedback and by development of appropriate stabilization methods.

The fast intratrain feedback is an essential part of the TESLA design. It allows the collider to be insensitive to quite large amount of ground motion and vibration. The IP beam separation of hundred of beam sizes can be corrected. This system is described in more details in the summary of T1 working group and the implications for the beam size stability are described in the summary of M3 working group.

Feedback systems are an essential component of normal conducting linear collider designs. For the NLC and for the SLAC ground motion model, simulations show that the linac orbit feedback can suppress the beam motion at the end of the linac to less than 4 % of the beam size, while it can be as much as 30 % of the beam size without feedback [27].

For diffusive motion with a value of $A = 5 * 10^{-7} \mu m^2/(m * s)$, similar to observations at SLAC in the SLC and FFTB tunnels [18, 28, 29], the NLC linac feedback can maintain the orbit for several hours before steering (a non-disruptive procedure) is required to restore the smoothness of the beam line [27]. For the Beam Delivery System, feedback to correct the trajectory and to optimize the luminosity together with first order aberration knobs can maintain optimal performance of the system for nearly one year [30]. Eventually, a beam-based quadrupole alignment must be reapplied.

The site location is clearly an important issue for the normal conductive linear collider such as CLIC, JLC or NLC designs. An ideal site should have little external cultural noise, now and in the future. Solid rock is the preferred surrounding media since fast motion will be better correlated and slow motion will be reduced. In real life, proximity to an existing major laboratory would also be a great advantage. This proximity would not necessarily mean compromising the other requirements since a deep tunnel could have good geology and low noise and still be located near an existing laboratory. As was reported in the talk of Joe Lach (FNAL), the measurements in the existing Aurora mine show quite small level of noise in spite that this mine is located under the interstate highway [7]. This is explained by the fact that most of the cultural noises propagate near surface but attenuate exponentially into the depth. Therefore sufficient depth (about 100 m in the case of Aurora mine) provides much more efficient attenuation than spatial longitudinal separation. The layered structure of ground, with top layers being more soft than deeper layers, provides additional attenuation due to reflection of the waves from layer interfaces (disscussed in talks by Nick Simos, BNL and Andrei Seryi, SLAC).

Certainly, a good and quiet site alone is not sufficient. Noise generated by the linear collider equipment itself and by conventional facilities equipment must be appropriately controlled and minimized (by design and by further passive or active damping), as described in the talks by Clay Corvin and Fred Asiri, SLAC. This should allow the tolerances to be met for all of the JLC or NLC focusing and accelerating elements, except for the final doublet (FD), without any additional active stabilization or correction. An additional stabilization (correction) for the CLIC linac quadrupoles may be required.

Although the linear collider detector must be designed to minimize vibrations, it is unlikely that the FD mounted on the detector can meet the position stability tolerances without additional active measures. Several methods are being developed to provide the necessary relative stability between the FDs for the NLC. These include position stabilization via feedback, and correction of the magnetic center position with dipole coils via feedforward. Both methods would rely on either inertial measurements of the motion by seismometers or on optical interferometric measurements of their position with respect to each other or to stable ground under the detector (with an 'Optical anchor'). A prototype optical anchor has demonstrated a resolution of about 0.2 nm [31] that would be sufficient for measuring the position of the FD. It is now being used for stabilization tests in the University of British Columbia, as reported by Tom Mattison (UBC) [32].

An attempt to stabilize the position of a quadrupole was made at DESY as part of the S-Band linear collider project [33]. A single seismometer and a single piezo-mover were used to stabilize the effective position of the quadrupole center. A reduction of RMS motion by a factor of 3 was achieved (from 100 nm to about 30 nm for frequencies higher than a few Hz). Another attempt of inertial stabilization was performed at SLAC using three commercial STACIS insulation stands

[34] to stabilize a 1500 kg PEP-II quadrupole [35, 36]. In this test, the floor motion was reduced by about a factor of 20 (from 40 nm to 2 nm for $f > 2$ Hz). However, additional slow noise of the order of 200 nm was introduced and the performance in the horizontal plane was not as satisfactory. These first examples of inertial stabilization (or inertial sensing for feedforward) do not yet satisfy NLC requirements. In a real collider, the system must detect and minimize motion of two extended and separated FDs without disturbing the correlation with the rest of machine; it must work in an external magnetic field, be compact and reliable. Ongoing work (described in the talks by Ralph Assmann (CERN), Joe Frisch (SLAC), Tom Mattison (UBC), see also [32, 37, 38]) will address these issues. At SLAC, preliminary tests of the recently developed inertial stabilization system with digital feedback in 6D resulted in more than an order of magnitude reduction of motion of a test object [37].

In addition to these methods of stabilization, a fast correction within the bunch train is being developed for NLC (similar to TESLA). The intratrain feedback uses a position monitor (BPM) near the IP to detect the offset of the first bunches of the train. The signal is the beam-beam deflection due to the relative offset of the beams and fast kickers are then used to correct the rest of the bunch train. Recent preliminary evaluation indicates that such a system is technically feasible with available components and could provide efficient capture of beams with several sigma offset [39]. For example, with a 10 nm beam offset essentially full luminosity would be restored after roughly 15 % of the bunch train. This would significantly reduce the requirements on incoming beam jitter and on stabilization of the FD. These developments have been reported in the talks by Steve Smith (SLAC) and Phil Burrows (Oxford) and should certainly be continued.

5.4. Ground Motion Transfer into an Accelerator

The problem of ground motion–accelerator tunnel interaction is by nature complex and cumbersome. As was already mentioned before, attenuation of vibration is quite different for spatial horizontal or vertical separation (deep or shallow tunnel). The tunnel itself may serve as waveguide for certain modes of vibration. The typical layered structure of ground adds complexity to this picture.

However, by understanding these features and phenomena, the collider builders may gain additional significant advantages for their future machines. For example, proper choice of depth of the tunnels, conscious use of layered geology to get additional attenuation for the surface noises, understanding the behavior of different waves that impinge on the accelerator tunnel, combined with source identification, proper location of facilities, etc., will be the factors essential for achieving required performance of the future colliders.

An approach to investigation of these issues was described in the talk by Nick Simos (BNL). The approach allows generating a complete transfer function from the source to the subsystem, thus allowing for the best possible estimate of critical subsystem response. The analytical and simulation tools exist that allow such evaluation and should be applied for a future linear collider design.

5.5. Alignment issues

Alignment of the collider components will be an essential step of construction and commissioning. For the future machines, the task usually cannot be performed with just conventional tools. After initial conventional alignment, a beam-based alignment should take over. An approach to conventional alignment has been presented in the talks of Catherine LeCocq (SLAC) and Johannes Prenting (DESY) which is briefly summarized below. An alternative approach to alignment, based on the frequency scanning interferometry, has been presented by Armin Reichold (Oxford). The beam-based alignment and its interaction with conventional alignment are discussed in more details in the M3 working group summary.

The positioning of a new particle accelerator machine may be organized into 4 steps: surface network, tunnel network, transfer between these 2 networks and component placement. The goal of the surface network is to establish a global system of pillars and benchmarks to control the positioning, orientation and scale of the entire accelerator project. A combination of GPS and leveling observations is a reasonable and efficient strategy for any possible size and shape of any machine. There are several manufacturers of geodetic GPS receivers to choose from as well as commercial and scientific software packages. By using precise satellite orbits, such as those computed by the International GPS Service (IGS), the coordinates of the surface points will be in a realization of a Conventional Terrestrial Reference System. This means a geocentric datum with an orientation consistent with the International Earth Rotation Service (IERS). Unlike GPS observations, which are geometric in nature, leveling observations refer to the Earth's gravity field, most often to a particular equipotential surface called the geoid. Combining both types of measurements for the surface network will require knowing the relationship between the 2 systems, i.e. the determination of a local geoid. The goal of the tunnel network is to establish a system of combined wall and floor monuments. This network will be used in the placement of machine components. The datum of the surface network is transferred into the tunnel through penetrations or shafts. The instrumentation used for the transfer depends greatly on the depth of the tunnel. A traditional approach for tunnel networking is a combination of total stations and leveling observations with occasional gyro-theodolite stations. A possible alternative is the use of specialized alignment systems such as the Rapid Tunnel Reference Survey System (RTRSS) under development for the TESLA project. In this case, a combination of wire and hydrostatic level observations will produce a network of equidistant points on the aisle side of the tunnel. The final step is to lay out, install, map and monitor the accelerator components both locally and globally to the given tolerances. Laser trackers may be a viable option for these tasks. In conclusion, the above discussion is a possible scenario based on available technology. Future efforts should be directed both towards more efficient instrumentation development, modeling analysis and towards better understanding and optimization of the interaction between conventional and beam-based alignment.

5.6. Summary of the ground motion considerations

Known information on ground motion (spectral, correlation) suggests that the considered machines (NLC, TESLA, VLHC, Muon source) are feasible. Particular concerns for each of the machine are summarized below.

In the VLHC the main effect of ground motion is emittance growth; for the high energy stage, the rms uncorrelated motion of 0.3 nm above ~250 Hz would result in doubling the emittance in ~2.5 hours. This is still a modest growth rate in comparison with the one for TMCI and resistive wall instabilities that would need to be cured by feedbacks. The natural ground motion in deep tunnels is much smaller than 0.3 nm above ~250 Hz, the concern for VLHC is not the natural ground motion, but vibrations that may be created by equipment installed in the tunnels, the enhancement of vibrations by girders and internal mechanics of cryostats. These issues need to be addressed in design and further engineering tests.

In linear colliders the primary concern is beam offset at the IP induced by ground motion. In the TESLA and NLC designs, the tolerance for uncorrelated motion of quadrupoles is about 10 nm, though the relevant frequency range roughly defined as $f_c > f_{rep}/20$ is different ($f_c > 0.2$ Hz for TESLA and $f_c > 6$ Hz for NLC). For the NLC case, even in modestly quiet sites, the motion is below these tolerances. For TESLA, due to low repetition rate of collisions, the motion, even in quiet sites, may reach the tolerance limit. However, due to large separation between bunches, a correction within a bunch train is possible for TESLA.

An issue of concern and for further R&D for NLC, and to a lesser extent for TESLA, is cultural noise that may greatly increase vibration in the tunnel. In an urban area, a deep tunnel solution appears to be the best alternative. Local geologic factors (soil and rock stiffness, structure and water table) will strongly influence the in-tunnel vibration characteristics. Site-specific models of vibration propagation need to be studied in more detail. In terms of slow ground motion (minutes to months), the impact on NLC performance is more serious than on TESLA due to higher RF-frequency. Nevertheless, measured amplitudes are tolerable for NLC with a shallow site in glacial till being the most critical case. Studies are planned that would clarify this conclusion. Active methods of stabilization, feedback systems, beam-based alignment, passive methods of noise reduction, will all be essential components of the future linear collider. R&D need to be continued to further improve the performance of the systems being developed and to optimize their interference.

6. Tunneling considerations

During the Snowmass Meeting a two-day tunnel workshop was held (9th and 10th of July) to review the design concepts and layouts of the underground housings for four major particle physics projects that are currently on the drawing board. The Projects reviewed at the workshop were: a) The Muon Source (Neutrino Factory); b) The Next Linear Collider (NLC), c) The Tera Electron-Volt Superconducting Linear Accelerator (TESLA), and d) The Very Large Hadron Collider (VLHC). A number of tunneling professionals (7) attended the workshop to provide industry perspective on the current plans for subsurface construction. The projects, their construction, geological and other issues have been presented in the talks by Wilhelm Bialowons (DESY), John Cogan (SLAC), Clay Corvin (SLAC), Peter Garbincius (FNAL), Lindemar Hänisch (DESY), Vic Kuchler (FNAL), Chris Laughton (FNAL). The tunneling experts provided feedback in their various areas of expertise, specifically: geology, tunnel design and construction.

6.1. Tunneling Workshop Agenda Items

The following items were discussed in detail for each project:

a) Technical Requirements of the underground housings;

b) Subsurface Ground Conditions along the tunnel alignments;

c) Construction Issues associated with the current design and layout concepts; and

d) Tunneling Research and Development that could result in cheaper excavations.

These four items are discussed in the next sections.

6.2. Site criteria and technical requirements.

High Energy Physics frontier accelerators are large and complex. Ideally, they should be constructed close to an existing laboratory site. The environmental impact of the project is minimized for a tunnel solution rather than a cut and cover that would involve greater surface disruption. In many respects, the tunnel design requirements for the beamline housings are not unlike the requirements for underground rail or metro tunnels. However, some key requirements, related to stability and watertightness, are more stringent than those normally associated with underground design. Meeting such criteria could be difficult to achieve in some ground units and may require design and construction mitigation measures that are not currently accounted for within in the framework of the pre-project plans. Better knowledge of key design parameters of certain ground units is necessary in order to be able to evaluate, with some confidence, the types of design mitigation measures that will be needed to meet stability and watertightness requirements.

6.3. Subsurface ground conditions.

None of the projects have performed site investigations of the subsurface conditions (borings, seismic work or laboratory testing) along a specific tunnel alignment. At present, TESLA is the only project that has selected a tunnel alignment. Site-specific investigation of this alignment is scheduled to start soon. Confidence in ground conditions along the TESLA tunnel route is already fairly high given the relatively large amount of existing geologic, geotechnical and construction reference data available in the Hamburg area. Based on this data, site conditions along the alignment are projected to be similar to those encountered during the construction of HERA. There is only a limited amount of geological, geotechnical and construction data available to describe some of the ground units in which the proposed NLC and VLHC tunnels will be sited. For these ground units there is a need for additional geotechnical data to be gathered before realistic plans and costs for excavation and tunnel construction can be developed with confidence. Geotechnical data and design studies are needed in the following key areas: For the California and Illinois Tunnels sited in Expansive Shales: The impact of swelling pressures and/or displacement on the excavation, arch support and foundations of beamline housings needs to be studied. For the VLHC tunnels sited in St. Peter Sandstone: The impact of groundwater, in situ stresses and presence of abrasive minerals on the excavation and support of beamline housings needs to be studied. For California sites: geologic and geotechnical properties related to tunneling and cut and cover excavation and long term facility stability; and groundwater conditions. For the Illinois Tunnels and Halls: The impact of high horizontal in situ stresses on the excavation and support of tunnels and, in particular, any large span openings (e.g. Interaction Regions), needs to be studied further. The Muon Source facility sited at Fermilab (the only site presented) benefits from geotechnical data archived from other projects, most recently the Main Injector and NuMI. Geotechnical parameters are anticipated to be similar with those collected for other local projects.

6.4. Construction issues.

The layout and construction concepts being developed for TESLA will be largely consistent with those of the HERA Project. The design concepts for VLHC and NLC are still evolving. VLHC is looking at two representative sites in northern Illinois. NLC has identified a number of representative sites in California and Illinois. Cut and cover, cut and cover-tunnel combinations and various tunnel layout options are being studied. To date, none of these layouts has been subject to either "constructability" or value engineering reviews. Constructability reviews are designed to ensure that the layouts being developed to satisfy end-user requirements could actually be built cost-effectively using standard industry equipment and materials. Value Engineering reviews would enable technical and conventional designers to perform trade-off studies in the different areas of the project with the aim of identifying lower cost solutions that still respect the functional requirements of the project.

6.5. Tunnel Research and Development

Although several key tunnel design criteria need further definition, it is clear that the viability of these accelerator projects could be enhanced if the cost of tunnel excavation can be reduced. The Working Group spent time reviewing the current status of R&D in the mining and tunneling industries. R&D areas reviewed focused on:

a) Improving the performance and longevity of existing tunneling sub-systems (rock breakage, broken rock evacuation, ground support installation, etc.) by increasing the penetration rate of the machine, eliminating cyclic stoppages in the penetration process and improving the reliability of critical equipment components;

b) Reducing labor requirements of existing tunneling sub-systems by increasing the use of remote operations, automation and multi-tasking of underground personnel;

c) Improving tunneling management by enhancing communications, real-time data analysis and the adoption of improved ground prediction practices; and

d) Replacing existing tunneling sub-systems with other more cost-effective systems.

On-going R&D projects in tunneling and mining in Japan, Canada, Australia, Europe and the United States of America were reviewed. The tunneling professionals, most have participated or are participating in tunnel R&D projects, were rather skeptical of the value of active involvement in a specific tunnel R&D program at this time. They noted that the tunneling environment requires a level of robustness and reliability that is often lacking from R&D products. Practical problems that arise underground are rarely planned for during design and laboratory testing. Risks in the implementation of new technology underground are particularly high because of the low tolerance of tunnel constructors for teething problems and extended learning curves! Historically, few tunneling innovations have proven successful. Those that have been implemented have tended to be evolutionary in nature and have taken a long time to become standard practice (at least ten years). The tunneling professionals thought that there might be some interesting systems that would become economically attractive in the next few years (for example, new mechanical excavation techniques). Such R&D products could be beneficial to one or more of the projects under review. The tunneling professionals recommended that the physics community continue to actively monitor the development of tunneling R&D products. If at some stage in the future, a product is considered to be technically feasible and economically advantageous to a project an effort should be made to familiarize all bidding contractors (prequalification recommended for tunnel contracts) with its use before bidding. Only if bidding contractors are convinced that such a product will work underground will cost economy actually be realized by the project.

6.6. Conclusions and recommendations in terms of tunneling.

For the VLHC and NLC sites, it is important that a scope be developed for preliminary site investigation requirements. The Scope of the investigation of proposed sites should identify key design issues. For the VLHC and NLC sites, it is important that a process be established for reducing the number of potential sites and selecting a single site as soon as possible. A prioritized list of site selection criteria should be developed that can be used to help select specific sites. All the projects would benefit from constructability and value engineering reviews. These reviews should be undertaken with the participation of industry professionals at key moments in the design process. In the future there may be potential for the use of R&D products on one or several of the proposed projects. However, cost benefits are only likely to be achieved if bidding contractors have seen such products successfully applied underground and such products are stated to be acceptable within the construction contract. It is recommended that on-going R&D projects continue to be actively monitored and periodic assessments made to evaluate if cost savings can be achieved through the adoption of a R&D product on a given site. To date, project plans for underground work have largely been developed in-house, at individual laboratories, with indirect input from the underground industry. The formation of an underground advisory panel is recommended to improve access to tunneling expertise and help develop and coordinate plans for site investigations, designs and technical reviews for all the projects. It is recommended that the panel include international members who can relate recent underground construction experience from overseas locations, such as the Australia, Europe and the Far East.

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