Stability and Ground Motion Challenges in Linear Colliders

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Abstract

This is a short narrative summary of the review talk given at the Nanobeam 2002 Workshop. Transparencies of the talk are available at [1].

1 SUMMARY OF THE TALK

1.1 Linear collider challenges

Challenges for future linear colliders are the energy and the luminosity. A desirable initial energy reach of a future LC is at least 500 GeV in the center of mass (CM) and at least 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for luminosity. The leaders of the race, which started more than a decade ago, are the JLC and NLC designs, based on normal conducting RF, and the TESLA design, based of superconducting RF.

With respect to the first linear collider SLC, which was based on normal conducting RF and reached about 50 GeV/beam, the JLC and NLC projects must increase their energy by at least a factor of five. The TESLA design would have the world's largest superconducting RF system, by about one hundred times exceeding the one pass energy increase with respect to existing systems (LEP superconducting cavities provided about 3 GeV of acceleration per turn). Providing such high acceleration, reliably and controllably, constitutes the energy challenge.

The 5 times (for warm machines) or 100 times (for SC machines) energy challenge looks modest in comparison with the luminosity challenge – a future LC will aim for luminosity which is 10000 times higher than what was achieved in SLC – the first and the only linear collider so far.

Many technological and scientific improvements make it possible to believe that the 10^4 times luminosity increase would be feasible. Among these improvements are capabilities to generate beams with smaller emittances in modern damping rings, better understanding of wakefields and ways to control them to preserve the small beams, etc. Among the necessary improvements is providing good stability of the collider components i.e. one needs to ensure that ground motion, as well as remotely and locally created vibrations, do not produce intolerable misalignments of the LC elements.

1.2 Effects of ground motion on LC

Ground motion and vibration disturb the alignment of the collider components and therefore may affect luminosity. Properties of ground motion have been intensively studied which allows quantitative estimates of their effects on linear collider performance.

Temporal properties of ground motion and vibration (which are usually studied in terms of spectra of ground motion) should be related to the repetition frequency of the collider f_{rep}, i.e. with the rate with which the beam-based information on misalignments is available to feedback systems for corrections. Accordingly, *fast* ground motion cannot be efficiently suppressed by beam-based feedback, and thus uncorrected misalignments of focusing elements primarily result in errant orbit and beam separation at the IP. On the contrary, *slow* ground motion can be efficiently suppressed by feedback, and the remaining effect would be slowly growing beam emittance if the accumulated misalignments are not corrected by another slow feedback or periodically applied beam-based alignment procedures.

Spatial properties of ground motion (which are usually studied in terms of the correlation of motion of two locations separated in space) should be related to the betatron focusing length of the beamline. Because the motion is correlated, long wavelength ground motion does not affect the beam if this wavelength is much longer than the betatron length.

1.3 Ground motion models

Arbitrarily complex ground motion can be represented by a two-dimensional power spectrum $P(\omega, k)$ which will carry all the necessary information about the spatial and temporal correlations. If known, such a spectrum can be used to evaluate the performance of an LC analytically, provided that the spectral response functions of the beamline and the feedback are available.

Several ground motion models have been built, based on the results of measurements, and parameterized in the form of a $P(\omega, k)$ spectrum. These models include ATL diffusive motion, slow systematic motion, natural microseismic motion, and fast cultural noise. To evaluate the effect of different conditions, and to establish an acceptable range of conditions, three models of ground motion have been created: a low noise model **A**, based on measurements at the LEP deep tunnel; an intermediate noise model **B**, based on measurements at the SLAC shallow tunnel and at the Aurora deep mine near FNAL; and a high noise model **C**, based on measurements in the shallow HERA tunnel located in an urbanized area.

1.4 Damping ring to IP integrated simulations

Integrated tools have been developed in the NLC Accelerator Physics Group to allow complete simulation of a linear collider, starting from the exit of the damping ring to the IP. These tools are based on the LIAR [2] program for calculation of the beam acceleration and transport in the linac including single and multi-bunch wakefields, various

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errors and misalignments, on the DIMAD [3] program for calculation of beam transport in the bunch compressor and beam delivery system, where proper calculation of higher order aberrations and longitudinal beam dynamics is essential, on the Guinea-Pig [4] program for complete simulation of beam-beam collisions including generation of beamstrahlung photons or other background, on a ground motion modeling program [5] which can represent correctly the correlated motion of both electron and positron beamlines and also model higher vibration at the IP due to detector, and finally on the Matlab [6] program which encompasses all the above mentioned pieces and also allows realistic representation of the feedback systems [7]. This tool has been dubbed MATLIAR [8] and it was extensively used for performance comparison of three 500 GeV CM linear collider designs (TESLA, JLC/NLC and CLIC) within the framework of the Technical Review Committee (TRC) [9].

1.5 DR => IP <= DR *simulations for NLC*

The newly developed MATLIAR tools have been used to verify the performance of the NLC. Results presented during this talk show that the NLC performance is satisfactory with the ground motion models **A** and **B**, where luminosity reduction is negligible (A) or amounts to several percent (B). With the high noise model **C** almost half of the luminosity was lost and the pulse-to-pulse luminosity jitter was significant. These results confirm the necessity for NLC to be sited in a stable environment, approximately corresponding to the model **B**.

These simulations of the effects of ground motion have been performed assuming that the LC is already tuned and rather well aligned. In the simulations, the linac was first misaligned, then orbit correction was applied to bring the luminosity back to nominal, and only after that ground motion was applied. The next question to study is to confirm that the tuning and correction methods will be able to converge in the presence of ground motion, with beam orbit and luminosity jitter. Such simulations will be performed in the near future.

Other very important tasks are to verify that the assumptions included in the simulations are correct, and to develop the design and hardware that would meet the stability requirements.

1.6 Ongoing and planned R&D aimed for NLC stability

Stability studies at NLC representative sites have been performed in several locations in California and Illinois. All the CA sites considered as well as the deep tunnel site in IL were found to be acceptable. Slow motion studies are ongoing at SLAC and FNAL (in the shallow MI8 tunnel and in the deep Aurora mine) to characterize the dependence of slow motion on geological conditions [10]. These studies (performed in collaboration of FNAL, SLAC and BINP and using a hydrostatic level system developed by BINP) will help to clarify results of preliminary investigations [11] which show that a shallow tunnel in IL is much less stable than a deep tunnel.

Studies of near-tunnel noise and vibration transfer from the surface will help to determine the necessary depth of the tunnel or set limits on surface activity. Studies of vibration transfer from the surface to the SLC tunnel have been performed at SLAC [12]. Fast motion studies are also planned at the NUMI tunnel at FNAL (this slightly inclined tunnel goes from the surface to about 100 m depth), to determine the dependence of cultural noise on tunnel depth (this will be studied in collaboration with FNAL and Northwestern University).

Studies of in-tunnel noises, including vibration transfer from the parallel tunnel are considered to be quite important since they will determine the vibration suppression requirements and techniques to be applied for a large number of noise sources located near the beamline, such as klystrons and their modulators. These noise sources will be located in the utility tunnel which is parallel to the main beamline tunnel. Vibration transfer between tunnels will be studied experimentally in a similar tunnel and geological configuration near Los Angeles [12].

Studies of on-girder noise are considered, perhaps, the most important, since in this case the noise sources are closest to the elements which need to be stable. One of the noise sources characterized so far is the vibration of accelerating structures induced by cooling water [13]. (Studies of cooling water induced vibrations are also being done at CERN [14]). This vibration can transfer (via bellows or via supports) to linac quadrupoles which have much tighter stability requirements than the accelerating structures themselves. Studies have shown that vibrational coupling is small and acceptable, confirming the feasibility of NLC linac quad stability.

1.7 Quadrupole stability in TESLA linac

Among the LC linac components, the quadrupoles have the tightest vibrational stability requirements. However, the linacs have the highest concentration of noise sources due primarily to the accelerating structures. In a warm LC, vibration of accelerating structures can be caused by cooling water. In a superconducting LC, the vibrations may be caused by cryogenic equipment (mechanical coupling to pumps, etc.), by imperfections in the supports (which may amplify ground motion), and by Lorenz forces (associated with RF pulse).

While warm LCs can place the quadrupoles on separate supports, and therefore provide good vibrational decoupling from the accelerating structure girders, this is more difficult in the SC design.

For example, in the present TESLA design the helium return pipe serves as a common “girder” for all the accelerating structures and also for the quadrupoles which are located in the same cryostat. Studies of longitudinal mechanical oscillations of the RF cavities (measured cavity detuning was converted to changes in the longitudinal dimension) have shown that the measured spectrum contains peaks associated with mechanical resonances of the cavities as well as with the helium system and pumps [15], exhibiting mechanical coupling to these systems. To prevent transmission of these vibrations to the quadrupoles, they need to be accurately decoupled from vibration sources by design.

Mechanical and vibrational properties of the TESLA cavities have been a design optimization criteria from the very beginning to ensure the energy performance. There is a lot of experience with analysis and successful optimization of vibration properties of RF structures – to stiffen, optimize positions of supports, etc., so that the Lorenz force deformations and detuning during the RF pulse would be acceptable. (See an example of consideration of vibration modes of different SC cavities for SNS and their optimization in [16].) Similar techniques could be extended to optimize the SC design to minimize quad vibration as well.

1.8 IP stability

If we assume now that we understand the linac stability we can move our attention to the IP. What are the stability concerns in the detector region? The final doublets (FD) are the strongest lenses (typical focal length is about 3-4 meters, $\sim L^*$) which focus a large and almost parallel beam coming into the FD down to the nanometer-scale beam at the IP. A transverse displacement of the FD translates almost one to one into displacement of the beam at IP. The FD has therefore the tightest vibrational tolerances. The situation is complicated by the fact that the FD has to be located partially inside of the detector, which may be a "noisy support".

Although every possible effort must be used to make the future LC detector vibrationally stable, the expected level of vibration is still not known. Measurements at the SLD detector have shown that differential motion of the south and north superconducting final triplets is approximately 30 nm [17] (in these studies the detector doors were closed, cooling water was flowing, but the magnetic field was switched off that would otherwise stiffen the detector and possibly make the vibration smaller). If one assumes that additional vibration of the FD in NLC will be similar to that measured at SLD and include such additional vibration in the ground motion model, then the integrated $\mathrm{DR} => \mathrm{IP} <= \mathrm{DR}$ simulations show that the luminosity would drop to about one third of nominal.

It is certainly possible to make a quieter detector than SLD, where minimal vibration was not a design criteria, however it is not likely that the detector will be sufficiently stable to support the FDs without any additional active measures. Several techniques are being developed to actively counteract FD vibrations: an "optical anchor" where the FDs are actively "locked" to more stable ground under the detector using interferometric measurements [18]; inertial stabilization where signals of seismometers attached to the FD are used to stabilize the FD position [19, 20]; and feedforward correction, where either optical or inertial signals are used to correct the position of the FD magnetic center using nearby dipole correctors.

With reasonable assumptions about the transfer function of such stabilization or correction techniques, simulations show that the devastating effect of detector vibration can be eliminated almost entirely. The task is to develop appropriate stabilization hardware and to test it in a realistic detector environment.

An IR test facility would serve as a test bed for various IR stabilization ideas. The idea of the LINX test facility (based on SLD and SLC final focus), if realized, would help in developing stabilization techniques. It could also test various final focus ideas as well as possibly become a test area for a gamma-gamma collider [21, 22]. The usefulness of such facilities and their benefits for our community in comparison to available resources was discussed during the Workshop.

1.9 Conclusion

There is already a good understanding of ground motion and vibration, and it is constantly improving. Although there may always be surprises, it seems possible that the LC luminosity stability can be achieved provided that important issues are not forgotten and are vigilantly pursued. A lot of important details and particular concerns were discussed during the Workshop.

2 REFERENCES

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