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SEISMIC CONDITIONS IN FINLAND AND STABILITY REQUIREMENTS FOR THE FUTURE LINEAR COLLIDER

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ABSTRACT

We find the natural level of seismic vibrations in Finland to be the same or lower than in other quiet sites of the world. In our investigation we utilize the measured power spectra, correlation spectrum and other characteristics of seismic effects in order to establish their effects on the linear collider techniques. Furthermore, we propose a new concept of two dimensional power spectrum to be used in order to estimate the effects of seismic vibrations. In our studies Finland is found to constitute a suitable location for the next linear collider facility.

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1 Introduction

Further advance in understanding the Nature and creation of the whole physical world requires studies of elementary particles and their interactions. Today sufficient energies for these investigations are most efficiently and conveniently generated by colliding beam machines.

Resolution of a colliding beam machine is inversely proportional to the beam energy, and thus higher resolution requires higher beam energy. The next step in energy increase cannot be achieved with traditional circular storage rings due to energy losses caused by synchrotron radiation. However, the solution for that problem can be found in the form of linear e^+e^- colliders [1].

The worldwide research and development activity on linear colliders centers in a few major laboratories where prototype machines or machine components are being constructed. These laboratories include CERN (Geneva, Switzerland), DESY (Hamburg, Germany), INP (Novosibirsk and Protvino, Russia), KEK (Tsukuba, Japan) and SLAC (Stanford, California, USA). All these laboratories as well as several smaller institutes are members of the international ICFA supervised collaboration coordinating the studies concerning the next linear collider facility. It is very probable that only a single large linear collider will be built and thus one should carefully and objectively study the optimum conditions and cost benefits available through a site selection.

The two main parameters characterizing a linear collider are energy and luminosity. An effective physics program of the next linear collider requires energy of 250 GeV - 1 TeV with luminosity of $10^{33} - 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Linear collider luminosity is given by $L = f_{rep}N^2/(4\pi\sigma_x\sigma_y)$, where f_{rep} is the repetition rate, N the number of particles per bunch and σ_x and σ_y the transverse rms beam sizes. The linear collider will have a relatively slow repetition rate (hundreds of hertz) and for obtaining the required high luminosity beams with large numbers of particles (10^{10} or more) and small sizes (σ_y of the order of nanometers) should be generated and preserved in the machine.

The extremely small beam size results in severe tolerance requirements for the machine components. Vibration and movement of the earth surface would destroy the straight line trajectory represented by the carefully aligned linear collider structure and lead to luminosity losses. It is, therefore, of utmost importance to study the characteristics of seismic vibrations and their possible influence on linear collider operation.

In Finland, as well as in several other countries, careful professional investigations of seismic vibrations have been performed during the past few years (see for example [6]). However, the results of these studies are not sufficient to understand the influence of ground motions on the linear collider operation and thus give an incentive for accelerator physicists to study seismic vibrations. A pioneer work on that field was performed at SLAC over ten years ago [2]. In Protvino (Russia) investigations of different ground motion characteristics were made six years ago [3] and since that studies have been continued in some other sites (see [5] and references therein).

This paper consists of two parts. In the first part we present the results of recent seismic investigations carried out in Finland. Power spectra, correlations and other seismic characteristics are displayed and compared with the results obtained elsewhere in the world. In the second part we summarize the information required for predicting the linear collider behavior in the presence of seismic vibrations. A new approach for calculating the luminosity losses due to vibrations is proposed. Although these two parts differ from each other, a clear understanding of the importance of seismic vibration studies requires the presentation of them both in the same paper.

2 Seismic Noise Description

In order to determine the influence of seismic noise on the linear collider operation one should know the time dependence of displacements, correlation characteristics and relative displacements of distant points. Since different vibration frequencies cause different effects on the linear collider, the spectral characteristics of seismic noise have to be carefully studied. One should note,

however, that seismic noise represents a random process and we can only present its average behavior in stationary conditions.

A random process $x(t)$ can be characterized by the mean value $\langle x \rangle$ and dispersion σ. With assuming $\langle x \rangle = 0$ the square of dispersion is equal to

$$\sigma^2 = \frac{1}{T} \lim_{T \to \infty} \int_{-T/2}^{T/2} x^2(t) dt \tag{1}$$

The main spectral characteristic of a random process is the power spectral density defined as

$$P(f) = \lim_{T \to \infty} \frac{1}{T} \left| \int_{-T/2}^{T/2} x(t) e^{-i\omega t} dt \right|^2 \tag{2}$$

We have to use the power spectral density because the usual Fourier integral of a random process is unlimited.

The power spectrum allows to separate the contributions of different frequencies in the dispersion formula:

$$\sigma^2 = \int_{-\infty}^{\infty} P(f) df \tag{3}$$

Since power spectrum of a real signal is symmetric, it is sufficient to consider only positive frequencies with proper normalization. All the measured spectra presented in this paper are defined for positive values of f in integral (3).

In order to study displacements between distant measurement points a mutual power spectrum

$$P_{12}(f) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} x_1(t) e^{-i\omega t} dt \int_{-T/2}^{T/2} x_2^*(t) e^{i\omega t} dt \tag{4}$$

and a normalized mutual power spectrum

$$N_{12}(f) = \frac{P_{12}}{\sqrt{P_1 P_2}} \tag{5}$$

can be used. The real part of the normalized mutual power spectrum is called 'correlation'. If the seismic signal is comparable with the noise of electronics, the seismic signal can be extracted by averaging the mutual power spectrum of the two probes located together.

In practice the measurement time T is limited and the power spectrum represents a time averaged measurement. The measurement technique (AD converter with discrete sampling frequency) requires that integrals in the above formulas have to be replaced by sums over series. A fast Fourier transformation was used in the calculations and also a cos-like window was applied for the procedure.

The expectation value of displacement after a time period τ can be calculated from the power spectrum:

$$\langle [x(t+\tau) - x(t)]^2 \rangle = \int_{-\infty}^{\infty} P(f)\, 2[1 - \cos(\omega\tau)]\, df \tag{6}$$

Here we take into account the symmetrical characteristics of $P(f)$ and the fact that autocorrelation and power spectrum are connected via Fourier transformation:

$$a(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} x^*(t)x(t+\tau)dt = \int_{-\infty}^{\infty} P(f)e^{i\omega\tau} df \tag{7}$$

Equation (6) shows that the low frequency motion ($f < 1/(2\pi\tau)$) contributes to the integral with an attenuation factor $(\omega\tau)^2$. The modified power spectrum $P(f)2[1-\cos(\omega\tau)]$ can be seen as the power spectrum of a new variable $[x(t+\tau) - x(t)]$.

Assuming that the averaged characteristics of seismic noise do not depend on coordinates, one can write an analogous formula for the variable $[x(s+$

$l) - x(s)]$:

$$\langle [x(s+l) - x(s)]^2 \rangle = \int_{-\infty}^{\infty} P(f)\, 2[1 - \cos(\omega l/v)]\, df \qquad (8)$$

which connects the absolute and relative motions. The value of $v(f)$ is in general unknown and may vary within several orders of magnitudes.

3 Equipment for Seismic Measurements

The results in this paper were recorded with the SM-3KV probes made in Russia [8]. A probe consists of a pendulum with a resonance frequency of 0.5 Hz and three coils fixed to it. The main coil and the damping coil, which are placed in a magnetic system, have sensitivities of 67.5 V* sec/m before amplification. The third coil is placed in a separate magnetic system and it is used for calibration of the probe.

By electronic feedback [8], which transmits the signal from the main coil, amplifies it and feeds it to the damping coil, the frequency of the pendulum itself is eliminated thereby extending the frequency band of the probe down to 0.1 Hz. In the frequency band of 0.1 - 100 Hz the output signal of the probe is proportional to the velocity with the sensitivity of $8 * 10^4$ V*sec/m.

In order to measure the signal to noise ratio the pendulum was fixed mechanically. With this measured data on internal noise reliability of the data in the frequency band of 0.07 - 70 Hz was established. In some very quiet sites in Finland the seismic signal at high frequencies was so small that the upper frequency limit decreased to 50-70 Hz. The proper data region can also be determined by using the correlation function of two probes placed together.

In our measurements two vertical-axis and two horizontal-axis probes were used. The data acquisition system consisted of a CAMAC -crate with a group of electronics modules (ADC, preamplifier, multiplexer, crate-controller), an IBM PC AT computer and a special software (programs for data acquisition

and treatment). This system allows us to measure simultaneously six signals with a sampling frequency up to 4000 Hz. Data treatment was limited to 6*32768 points per measurement. In order to have a lower sampling frequency the average of a small group of neighboring points was used. This procedure simultaneously provides an additional filtering of high frequencies. In order to cover a wide band of spectrum from 0.01 Hz to 100 Hz, we used two measurements with a number of averagings 2 and 50.

Since October 1994 a PC card with 16 bit multichannel AD converter was used in the measurements instead of the CAMAC electronics. The probes were connected to the card via special electronics interface. The maximum sampling frequency of this PC AD card was 500 Hz. The electronics interface had four 'hold and keep' -systems providing simultaneous measurements from the first and second probes and from the third and fourth ones; that was important for the correlation measurements. Due to unremovable internal noise the effective dynamical extent of the PC AD card was 12-13 bits. The DA converter of the PC card was used for an indirect calibration of the probes.

In the long term autonomous operation mode the system measured vibrations continuously and performed only a minor data analysis function. The probability versus amplitude histogram was stored as well as the amplitude information of some selected frequency bands and the data concerning the possible big amplitude events. Every few hours also the power spectrum was stored. A few times per day the system was connected via modem to the SEFT VAX cluster, it then sent the information there and received a file containing instructions to continue the measurements or to change the algorithm of measurements and/or data treatment. Due to a complete remote control system it was possible to measure seismic vibrations automatically over long periods of time.

4 Geological Conditions in Finland

In this paper geological conditions in Finland are not described in detail. More details can be found, for example, in the review by P.Turunen [7].

Finland is situated on the oldest Fennoscandian Shield that is among the stablest places in the world. For example, the probability of earthquakes is extremely low in this region [7].

The Fennoscandian Shield consists mainly of old crystalline rocks. Since dissipation of seismic energy is smaller in hard crystalline bedrock than, for example, in sedimentary rock, the spatial correlation is better in the former thus simplifying the linear collider alignment. The construction of linear collider tunnel into a hard, solid rock is also significantly more economic than construction into a porous sedimentary rock.

A unique feature of earth motion appears in Fennoscandia: a land uplift due to relaxation after the ice age. The amount of the uplift depends on the site and nowadays its maximum value on the Swedish coast is 9 mm/year. The isocurves of this uplift are very smooth and, therefore, this phenomenon does not prevent the linear collider construction.

5 Sites of Measurements

Seismic measurements in Finland were carried out in three selected sites.

The first location was a cave near Hiidenvesi lake about 40 km from the center of Helsinki. In a few kilometers vicinity of the cave there are a number of roads and small company installations. The probes were place about 120 m from the cave entry on a small concrete table connected directly to the rock. Measurements were performed in August 1994 and in October-December 1994.

The second site was a cave near a small town called Petonen about 15 km from the town of Kuopio (400 km to North-East from Helsinki). In its vicinity there are some roads and the Kuopio airport only a few kilometers from the measurement site. These measurements were performed in August 1994.

The measurements both in Hiidenvesi and Petonen were carried out on the level of earth surface (not underground), still there was at least 15 meters of rock above the measurement location.

The third measurement took place in a seismic station situated 10 km from the town of Kuusamo (800 km from Helsinki to North). At that place the probes were placed on a concrete table connected to the surface of the rock. These measurements were made in October 1994.

Locations of the sites on the map of Finland are shown in Fig.1.

6 Results of Measurements

A comparison between the power spectrum of vertical vibrations measured in quiet conditions in Hiidenvesi cave with the spectra measured in CERN LEP tunnel and Protvino UNK tunnel is shown in Fig.2. In Fig.3 the power spectra measured in Hiidenvesi, Petonen and Kuusamo are compared with each others. Almost over the whole frequency band considered the noise level in Finland is lower than in the LEP and UNK tunnels. Only in the range of 0.5-1 Hz the noise in Hiidenvesi is a little larger. One should, however, remember that the measurements in Hiidenvesi were made on the earth surface, while the measurement depths at CERN and in Protvino were 80 m and 25 m, respectively.

The power spectra in Fig.2 and Fig.3 grow very fast with the decreasing frequency. They behave approximately as $P(f) \approx 1/f^4$, and if the behavior were similar at low frequencies, the power spectra would not be integrable and also the value of dispersion would be unlimited. However, the relative displacement calculated from these spectra remains finite (see equations (6)

and (8)).

In the low frequency region (0.07-0.5 Hz) the spectra measured in different places differ significantly from each other. A clear peak can be seen in some of them. The origin of this low frequency vibration (sometimes called as '7-second hum') is due to water motions in the nearest ocean. Vibrations of this band depend only slightly on the local conditions, but they strongly depend on the distance from the ocean and the weather conditions there. The '7-second hum' measured in Hiidenvesi cave was ten times lower in August 1994 than in October 1994. The explanation for that phenomenon is the different weather conditions over the ocean (in August 1994 the ocean was very quiet). The level of low frequency vibrations measured in August 1994 was lower in Petonen than in Hiidenvesi. The longer distance of Petonen from the coast can probably explain this difference. Abrupt changes can happen in the level of low frequency vibrations. For example, in the morning of August 18th the amplitude of low frequency vibrations in Hiidenvesi cave suddenly increased by a factor of ten (see Fig.4). The duration of the event was rather short compared with a typical period of weather changes; it lasted only for two hours. The probable source for it was a strong short storm. Fig.5 shows changes in the lower frequency part of the power spectrum during the measurements in Hiidenvesi cave in August 1994.

The power spectra in Fig.2 and Fig.3 behave in a similar way in the band of 0.5-1 Hz, but at higher frequencies they differ again. In the band of 1-100 Hz human produced noise usually dominate. A clear correlation of vibrations with time can be seen in Fig.6, where the rms amplitude of the different frequency bands is shown. This plot is the result of continuous measurements in the Hiidenvesi cave during a period of one month. The rms amplitude of high frequency part of the spectrum is one order of magnitude larger during the working hours than during the night time and holidays. One could expect [5] that the influence of noise from nearby roads and company installation will be much less at depths of 50 - 100 m. The rms amplitude in the band 1-3 Hz hardly depends on the human activity, and the amplitude in the 0.07-1 Hz band does definitely not depend on it; the variations in these bands correspond to changing of the local weather and the ocean conditions. Increasing amplitudes of slow motions (0.07-0.3 Hz) does not result in increasing of amplitudes in the high frequency bands. Thus dissipation of the large slow

vibrations does not signficantly contribute to the high frequency vibrations. Fig.6 shows also that the rms amplitude of any frequency band in a given time interval can increase an order of magnitude or more. The larger the amplitude increase, the less probable are such events. In Fig.7 one hundred power spectra measured in Hiidenvesi cave are plotted together. The figure shows that the variation of spectra measured at different times is one – two orders of magnitude for the high frequency part of the spectrum and a few orders of magnitude for the lower frequency part.

Fig.8 shows the probability of finding an event with an amplitude within the interval of $A - 1.5 * A$ during the time interval $\Delta T = 10$ sec. It has been evaluated from the data of the long time measurements performed in Hiidenvesi in October - December 1994. The probability decreases fast with the increasing amplitude and detection of a big amplitude event is unlikely. However, events with a big amplitude do happen. For example, on August 22nd the measurement system in Petonen cave detected an event with the maximum amplitude of 4 micrometers (see Fig.9). The amplitude during this event was several times higher than during a period before it. The beginning of the event was very sharp and its duration was long (about 25 min). Although the event mainly consisted of low frequency vibrations with period of about 10 seconds, high frequency harmonics can be found in the first part of it. This kind of behavior can be explained, if the event is understood as a faraway reflection of an earthquake.

Correlation spectra of two probes placed together and then separated by 100 m are shown in Fig.10. In the both cases a good correlation can be seen in the low frequency part of the spectrum. At high frequencies the correlation between separated probes should disappear. This cannot, however, be seen from Fig.10, because in Finland the seismic signal of high frequencies is of the same order of magnitude than the internal noise of the data acquisition system electronics. Also for the probes placed together the high frequency part of correlation is well below one. Nevertheless, the measured correlation spectra correspond to their expected behavior and the results obtained earlier [3, 4, 5].

Besides the vibration levels in quiet conditions it is also important to know the spectra containing contribution due to human activity. A comparison

between spectra measured in different sites and different conditions is shown in Fig.11. In order to make the comparison easier the value of $P(f) * f^4$ is presented. As can be seen from Fig.11 the power spectrum can increase by several orders of magnitude during the working hours.

7 Generalization of Information about Seismic Vibrations

Linear collider operation is very sensitive to seismic vibrations. However, the influence of an 'absolute' displacement (the whole collider is displaced by the same value and behaves like a rigid body) is small and a smooth change of the linear collider shape is not dangerous. Only relative displacements are significant. Consequently, vibrations with long spatial period (for example waves from the ocean) have only a small influence on the linear collider in spite of their big amplitudes. Vibrations with short spatial periods can be dangerous, even though their amplitudes are generally small.

In order to determine the influence of different vibrations on the linear collider operation the collider can be considered as a 'two dimensional' body with coordinates time t and longitudinal position s. The most significant movements are transverse, usually vertical, displacements $x(t,s)$. The two dimensional power spectrum of this displacement can be written similar to (2):

$$P(\omega,k) = \lim_{T\to\infty}\lim_{L\to\infty}\frac{1}{T}\frac{1}{L}\left|\int_{-T/2}^{T/2}\int_{-L/2}^{L/2} x(t,s)\,e^{-i\omega t}e^{-iks}dt\,ds\right|^2 \qquad (9)$$

where $k = 2\pi/\lambda$ and λ is the spatial period of displacements. The value of dispersion is

$$\sigma^2 = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P(\omega,k)\,d\omega\,dk/(2\pi)^2 \qquad (10)$$

Generally, this value is unlimited and thus dispersion of another variable

$\xi(\tau, s) = \xi_\tau(s) = [x(t+\tau, s) - x(t, s)]$ is considered:

$$\langle \xi_\tau^2(s) \rangle = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(\omega, k)\, 2[1 - \cos(\omega\tau)]\, d\omega\, dk/(2\pi)^2 \qquad (11)$$

$P_\tau(k) = \int_{-\infty}^{\infty} P(\omega, k) 2[1 - \cos(\omega\tau)] d\omega/(2\pi)$ can be called as a 1-D power spectrum of $\xi_\tau(s)$. In order to determine the change of relative positions of two points, we need to calculate the value of

$$\langle (\xi_\tau(s+L) - \xi_\tau(s))^2 \rangle = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(\omega, k)\, 2[1 - \cos(\omega\tau)]\, 2[1 - \cos(kL)]\, d\omega\, dk/(2\pi)^2 \qquad (12)$$

Any of the usual spectral characteristics can be determined from the two dimensional power spectrum $P(\omega, k)$. For example, a normalized mutual power spectrum (5) can be expressed as

$$N_{12}(\omega) = \frac{\int_0^{\infty} P(\omega, k)\, \cos(kL)\, dk}{\int_0^{\infty} P(\omega, k)\, dk} \qquad (13)$$

The power spectrum $P(\omega, k)$ is unknown and the determination of it requires all the information we have about seismic vibrations. This information consists of results from absolute motion and correlation measurements [3, 5] as well as relative displacement studies (for example [3]) and information about slow relative motion generalized to so-called 'ATL law' [3]. In addition, some reasonable assumptions have to be made.

The 'ATL law' was found during the work described in [3]. The data about slow relative motion measured in different sites of the world can be described by a simple law:

$$\langle \Delta x^2 \rangle = A * T * L \qquad (14)$$

where Δx is the relative displacement after time T of two points separated by distance L. A is a constant whose value is found to be $A \approx 10^{-4}$ μm^2/sec/m

in several sites around the world. A more precise value of A in Finland could be determined by utilizing the data of the land uplift due to post ice age relaxation. The displacement in (14) is proportional to the square root of the time that stresses the random, diffusional character of the motion. The square root dependence on the distance L can be understood by supposing that the number of brakes between two points is proportional to the distance between them.

Assuming for example that $L = 10$ km and $T = 3 * 10^7$ sec (one year) a value of $\langle \Delta x^2 \rangle^{1/2} = 5$ mm is obtained from (14).

The diapasons of the 'ATL law' validity are extensive. The value of T can be from tens of years to some seconds and the value of L from hundreds of kilometers to a few meters. However, one should be careful in extending this law, because the extension should not contradict the other independent measurements. For example, if we calculate the power spectrum (17) for $L =$ 10 m, we obtain an absurd result that the power spectrum of relative motion is four orders of magnitude higher at some frequencies than the measured spectrum of the absolute motion.

Two dimensional power spectrum corresponding to the 'ATL law' can be written as

$$P(\omega, k) = \frac{A}{\omega^2 k^2} \tag{15}$$

which can be shown by substituting (15) to (12).

Formula (15) is used to determine $P(\omega, k)$ in the region of slow motions (i.e. small values of ω). In the case of larger ω $P(\omega, k)$ can be determined from the measured data. The quantity usually measured in experiments is the power spectrum $\rho(\omega, L)$ of the variable $[x(t, s + L) - x(t, s)]$. For $\rho(\omega, L)$ one can write

$$\rho(\omega, L) = \int_{-\infty}^{\infty} P(\omega, k)\, 2[1 - \cos(kL)]\, dk/(2\pi) \tag{16}$$

It can be shown that $\rho(\omega, L)$ for the 'ATL law' equals to

$$\rho(\omega, L) = \frac{A * L}{\omega^2} \tag{17}$$

This formula can be used as an approximation for the small ω part of the spectrum $\rho(\omega, L)$.

The back transformation from $\rho(\omega, L)$ to $P(\omega, k)$ can be expressed as

$$P(\omega, k) = \int_0^\infty \cos(kL)\ [\rho(\omega, \infty) - \rho(\omega, L)]\ dL \tag{18}$$

The approximation of complete $\rho(\omega, L)$ is

$$\begin{aligned} \rho(\omega, L) &= \frac{A * L}{\omega^2} \quad , \quad 0 < \omega < \omega_0 \\ \rho(\omega, L) &= \frac{B}{\omega^4} \quad , \quad \omega_0 < \omega < \infty \end{aligned} \tag{19}$$

where $A = 10^{-4}\ \mu\text{m}^2/\text{sec/m}$, $B = 10^{-3}\ \mu\text{m}^2/\text{sec}^3$ and $\omega_0 = (B/A/L)^{1/2}$.

The second formula in the approximation (19) corresponds to the measured power spectra in quiet conditions (see Fig. 11). We suppose that this term is independent of L and it corresponds to the pure uncorrelated part of vibrations. The horizontal line in Fig.11 corresponds to the second term of (19) and, as can be seen, it sits below the well correlated peak caused by ocean waves. A more sophisticated form for the second term of (19) corresponding to the spectrum distributed by cultural noise can be used, as well.

The generalized power spectrum $P(\omega, k)$ calculated by using (19) can be written as

$$P(\omega, k) = \frac{A}{\omega^2 k^2}(1 - \cos(L_0 k)) \tag{20}$$

where $L_0 = B/A/\omega^2$. In the next chapter this approximation is used to predict the influence of vibrations on the linear collider.

8 Influence of Vibrations on the Linear Collider

The linear collider operates with beams of electrons and positrons. The main beam parameter is emittance (horizontal emittance ϵ_x and vertical emittance ϵ_y). The focussing system of the collider is characterized by the beta-functions $\beta_x(s)$ and $\beta_y(s)$ which depend on the strength and the type of the focussing system. Emittances are invariants, i.e. they do not depend on the focussing, but in the ultrarelativistic case they tend to decrease during the acceleration as $(1/\gamma)$, where γ is the Lorentz factor. Emittance and beta-function determine together the beam size: $\sigma = \sqrt{\beta\epsilon}$.

Dilution of the emittance due to vibration of focussing elements is one of the main sources of luminosity losses in a linear collider. Vibrations can lead to uncontrolled emittance growth via different phenomena which strongly depend on the linear collider parameters [1]. Emittance growth due to instabilities caused by wake fields, for example, depends on the number of bunches and the number of particles per bunch. In this paper, in order to illustrate how the $P(\omega, k)$ spectrum can be utilized we consider only one source for a loss of luminosity: displacement of beam position at the interaction point (IP). This phenomenon can not be avoided in any of the linear collider designs.

The change of beam position due to seismic vibrations results in a mismatch of electron and positron beams at the interaction point thus leading to a loss of luminosity. Here we assume that the change of the beam position at the IP is due to changes of transverse positions of the focussing elements. At the moment $t = 0$ all the focussing elements are assumed to be aligned and during the next collider pulse they are displaced. The change of the beam position at the IP can be written as

$$\langle x_{IP}^2 \rangle = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(\omega, k)\, 2[1 - \cos(\omega T_{rep})]\, G(k)\, \frac{d\omega}{2\pi}\, \frac{dk}{2\pi} \qquad (21)$$

where $T_{rep} = 1/F_{rep}$ and F_{rep} is the repetition rate of the collider.

The function $G(k)$ characterizes contributions of harmonics with spatial period of $2\pi/k$ to the change of beam position at the IP. $G(k)$ depends on the type of focussing and it is different for different linear collider designs. A rough estimate for it is

$$G(k) \approx N\frac{\beta_{IP}}{\beta_0}(1 - \cos(k\beta_0)) \tag{22}$$

where N is the number of focussing lenses and β_{IP} and β_0 the beta-functions at the interaction point and in the linac, respectively. The $(1 - \cos)$ term in this formula exhibits less contribution of the harmonics with long spatial periods. An alignment procedure applied to the collider structure can be taken into account by inserting an alignment function $Q(\omega, k)$ into (21). This function includes attenuation of different harmonics due to the alignment.

As an example, we consider a hypothetical linear collider with parameters $N = 1000$, $\beta_{IP} = 10^{-3}$ m, $\beta_0 = 10$ m, $T_{rep} = 10^{-2}$ sec and $\sigma^* = 5$ nm. This set of parameters is close to the choice of NLC, JLC, CLIC and VLEPP designs. Using the formulas (20) and (21) a value of $\langle x_{IP}^2 \rangle^{1/2} \approx 0.05$ nm is obtained. (The pure ATL spectrum overestimates this value by more than one order of magnitude.) Thus the displacement at the IP is 1% of the beam size only. In all the three measurement sites (Hiidenvesi, Petonen and Kuusamo in quiet conditions) the calculated value of the beam displacement at the IP is of the same order of magnitude (within a factor of two). Stronger influence is caused by the cultural noise: for the noisy conditions displayed in Fig.11 (except the HERA tunnel) we obtain $\langle x_{IP}^2 \rangle^{1/2} \approx 0.4$ nm. This is almost 10% of the beam rms size and will result in measurable luminosity losses. With the data from the HERA tunnel [9] we get 4 nm of displacement.

For a set of parameters close to TESLA choice ($N = 2000$, $\beta_{IP} = 5 * 10^{-3}$ m, $\beta_0 = 10$ m, $T_{rep} = 0.1$ sec, $\sigma^* = 50$ nm) the displacement of beam position at the IP in quiet conditions is 2 nm. For the noisy conditions (Fig.11) the displacement is three times larger (6 nm) and in the HERA tunnel this value is approximately 15 nm. In the HERA tunnel the noise caused by the adjacent urban area and the usual accelerator equipment (designed without consideration of the produced vibrations) is significant and thus the conditions there do not seem to fit the linear collider requirements.

The investigations above show that in relatively quiet conditions a displacement of the beam position at the interaction point does not result in dramatic luminosity losses. However, in order to determine the acceptable vibration levels also emittance dilutions due to vibrations and misalignments should be considered. The method proposed in this paper will be used for this purpose in our further studies.

9 Conclusions

The on-surface measurements carried out in some selected sites in Finland show that the natural level of seismic vibrations in Finland in the band of 0.1 – 100 Hz is of the same or lower level ($f > 10$ Hz) than in other measured quiet sites of the world (underground LEP tunnel at CERN and UNK tunnel in Protvino).

Seismic vibrations in Finland are characterized by the relatively high level of low frequency vibrations due to activity of the ocean. These vibrations are, however, not harmful for the linear collider operation, since they are well correlated. Due to the solid crystalline structure of the Finnish bedrock they do not cause any noticeable contribution to the high frequency uncorrelated vibrations.

In Finland the lowest natural level of seismic vibrations does not considerably depend on the geographical site. If the site of the underground collider tunnel is chosen carefully, the internal noise of the collider components is more significant than the external cultural noise. Consequently, if the collider site with a low natural level of seismic vibrations is chosen, other factors (traffic connections, communication capacity, availability of labor force etc.) should have a significant influence on the site selection.

Studying and reducing the internal noise of the linear collider devices is important both for the cost and technical feasibility of the next linear collider. The acceptable collider noise levels should be determined for the different collider designs. We propose that the two dimensional power spectrum to be

used for this evaluation.

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Figure Captions

Fig.1. Locations of measurement sites on the map of Finland.

Fig.2. Power spectra of vertical seismic vibrations measured in Russia (UNK tunnel, Protvino), in Switzerland (LEP tunnel, CERN) [4] and in Finland (Hiidenvesi cave) in quiet conditions.

Fig.3. Power spectra of vertical seismic vibrations measured in Finland (Hiidenvesi cave, Petonen cave and Kuusamo station) in quiet conditions.

Fig.4. Low frequency horizontal vibrations measured in Hiidenvesi cave in different days of August 1994.

Fig.5. Low frequency part of the power spectrum measured in Hiidenvesi cave in different days of August 1994.

Fig.6. Dependence of rms amplitude on time in different frequency bands; measured in Hiidenvesi cave.

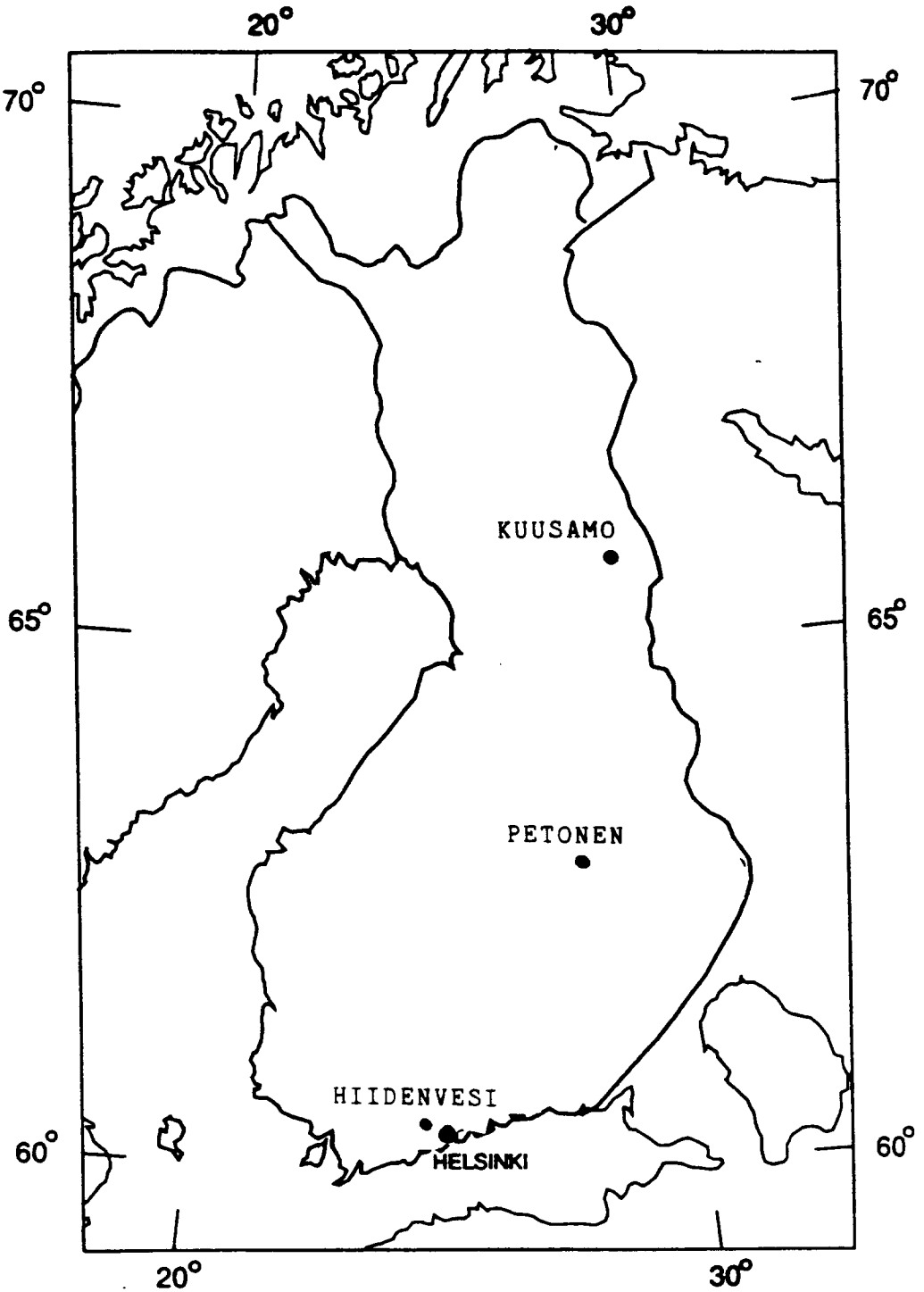
Fig.7. Variation of the power spectrum measured in Hiidenvesi in August 12-19, 1994.

Fig.8. Probability to find an event with an amplitude within the interval A - $1.5 * A$ during the time interval $\Delta T = 10$ sec; measured in Hiidenvesi cave.

Fig.9. Displacement versus time during a rare faraway event detected in Petonen cave.

Fig.10. Correlation of two vertical probes placed together and separated by 100 m; measured in Hiidenvesi cave.

Fig.11. Power spectra multiplied by f^4 measured in different conditions and sites (Hiidenvesi in quiet time, Petonen during the working hours, center of Helsinki city in night time, CERN TT2A tunnel in day time and DESY HERA tunnel [9]).



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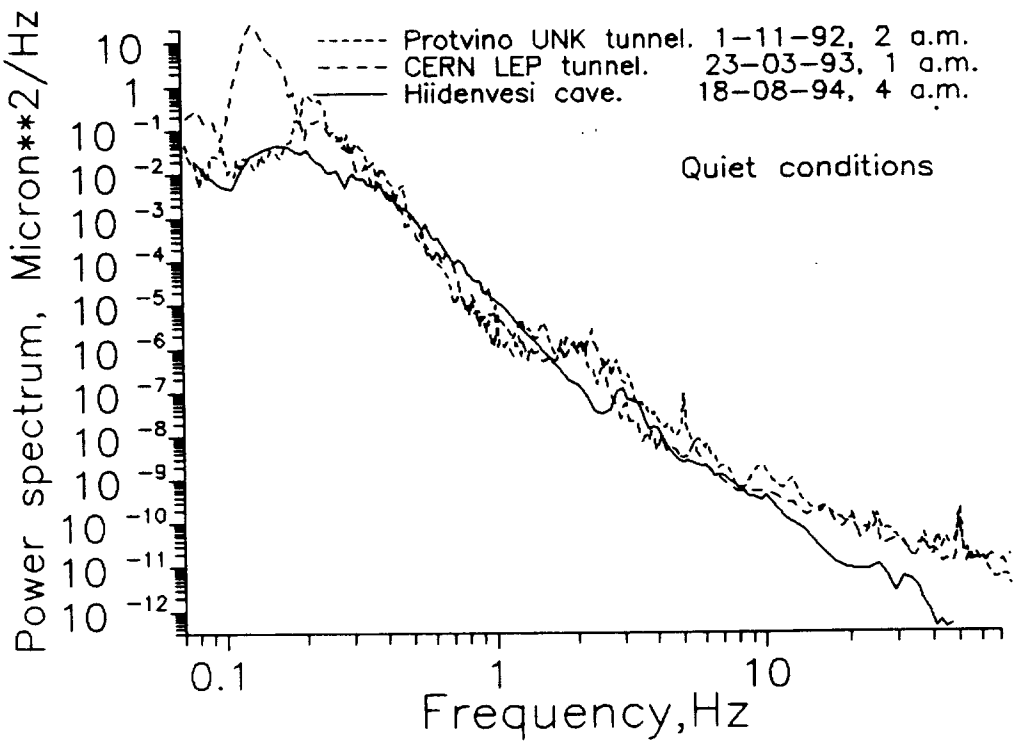

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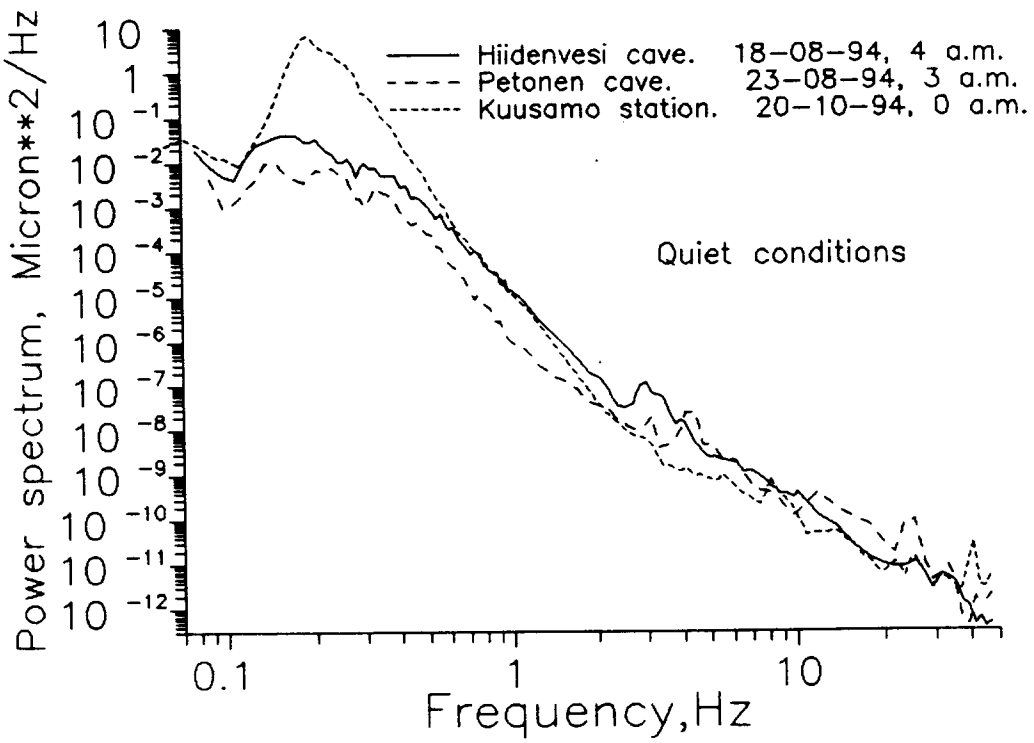

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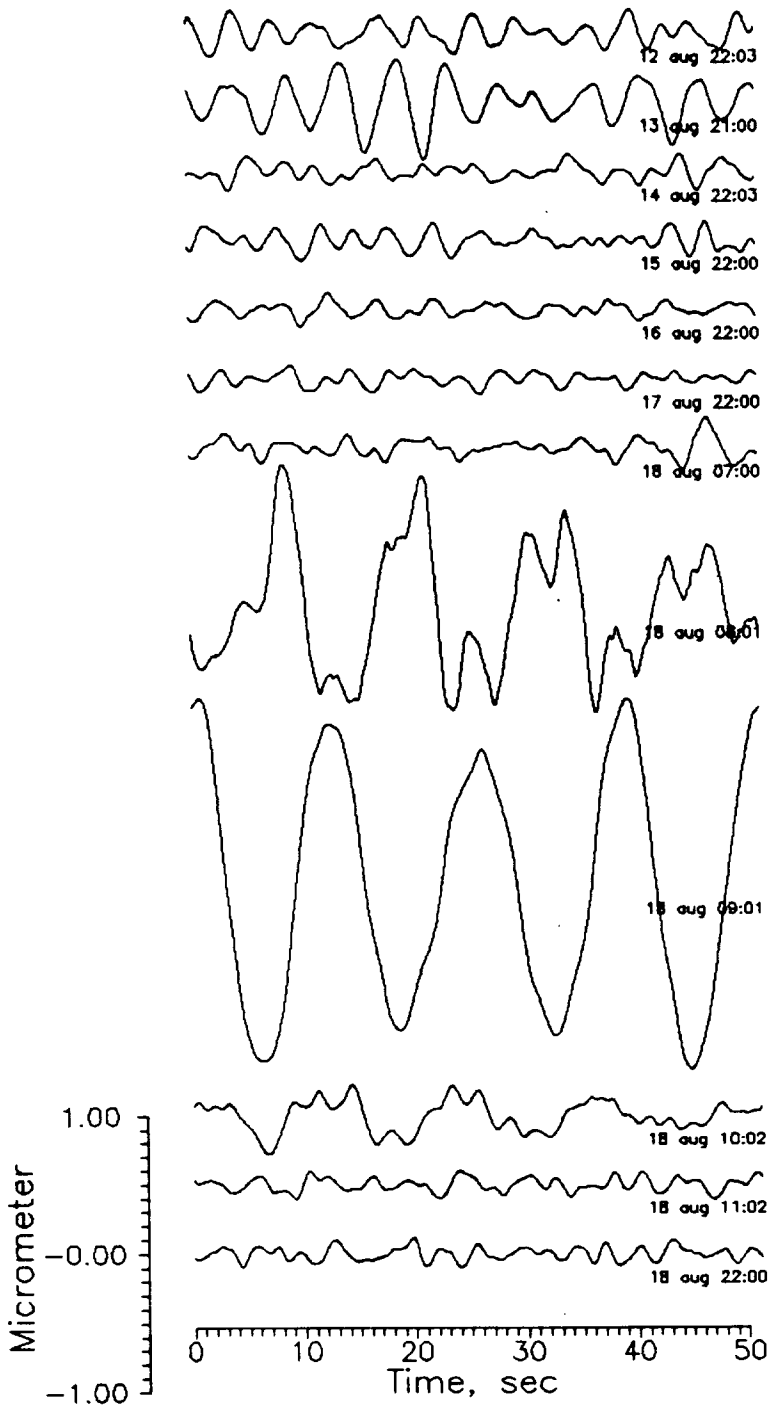

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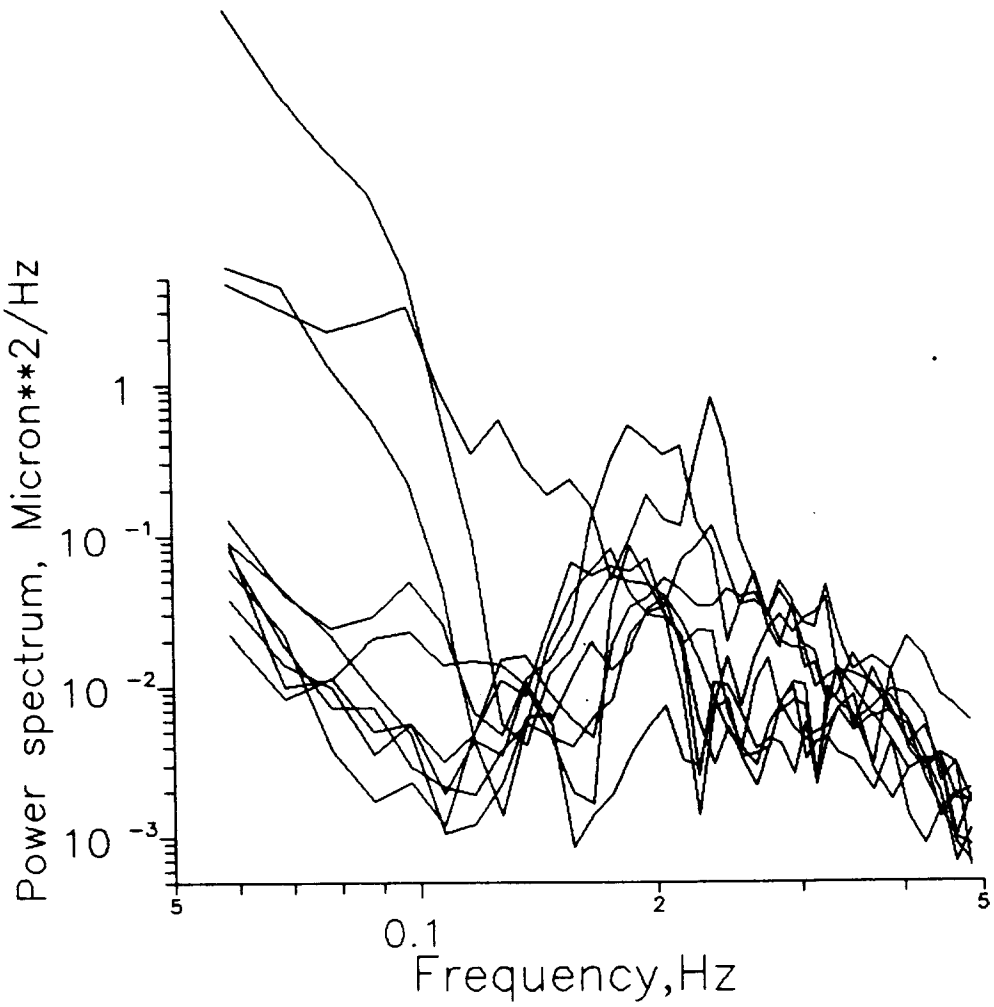

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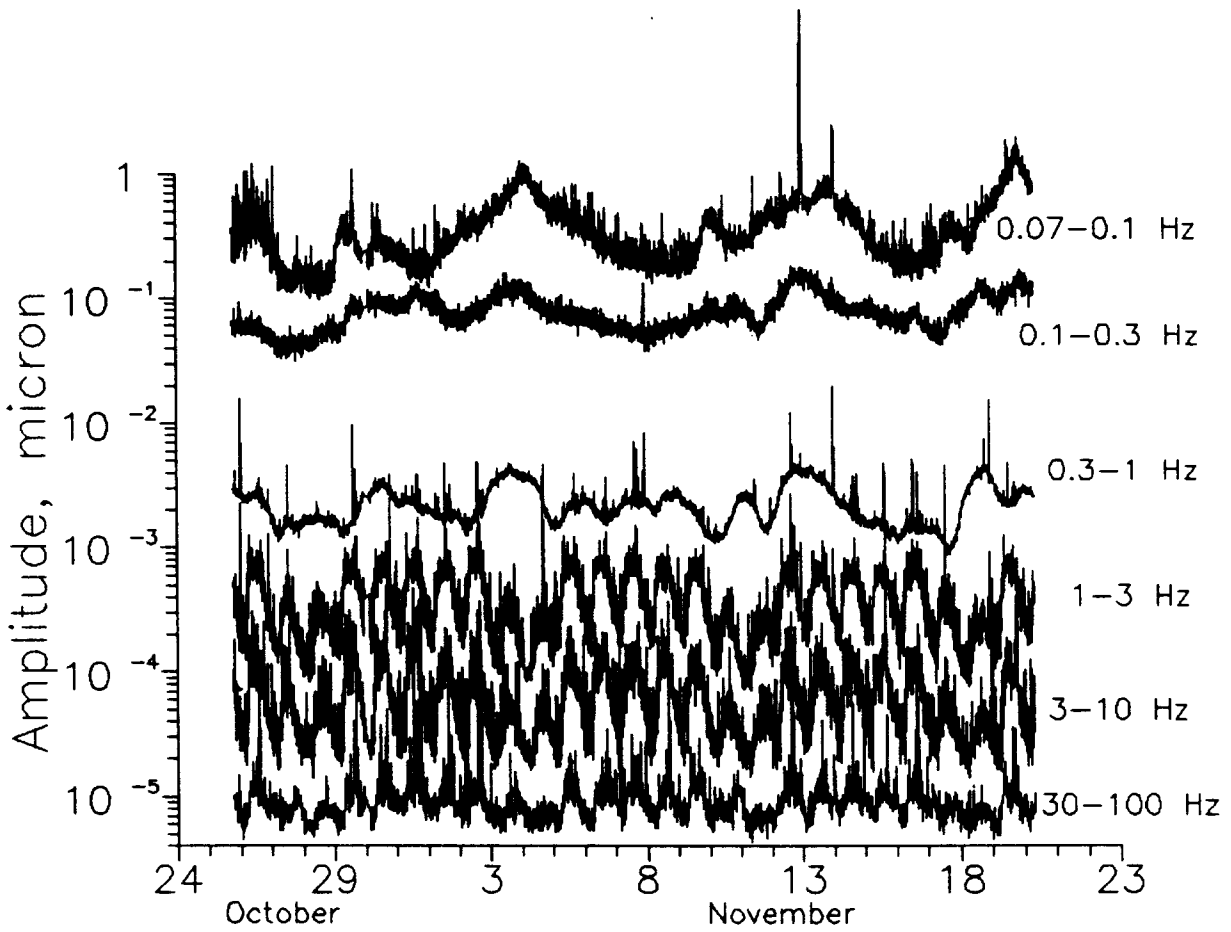

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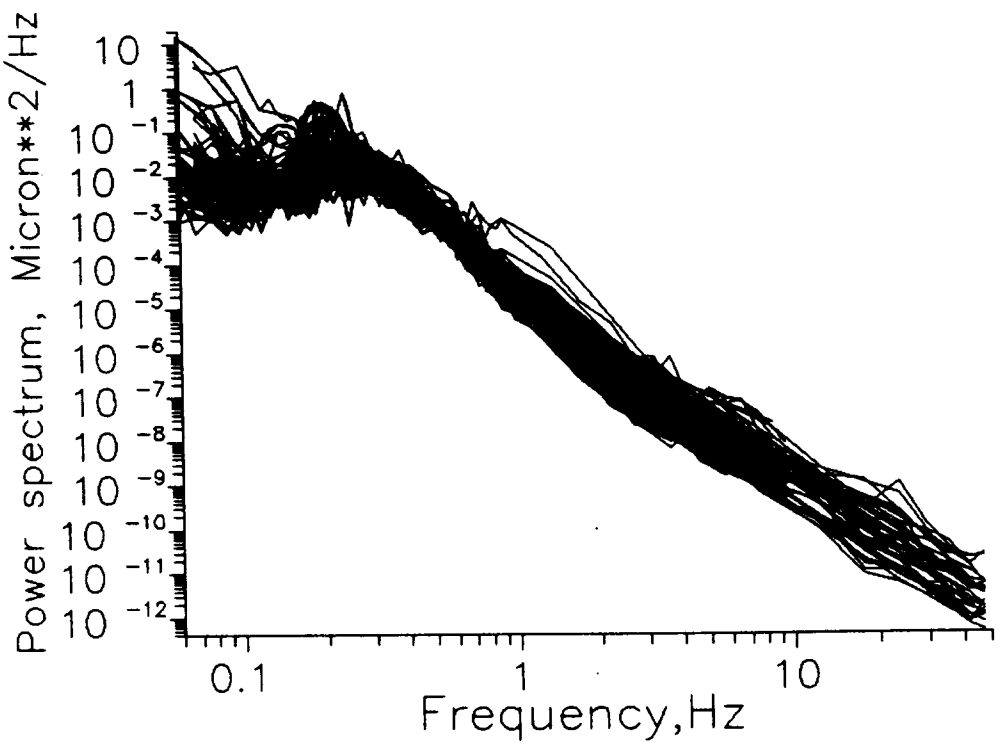
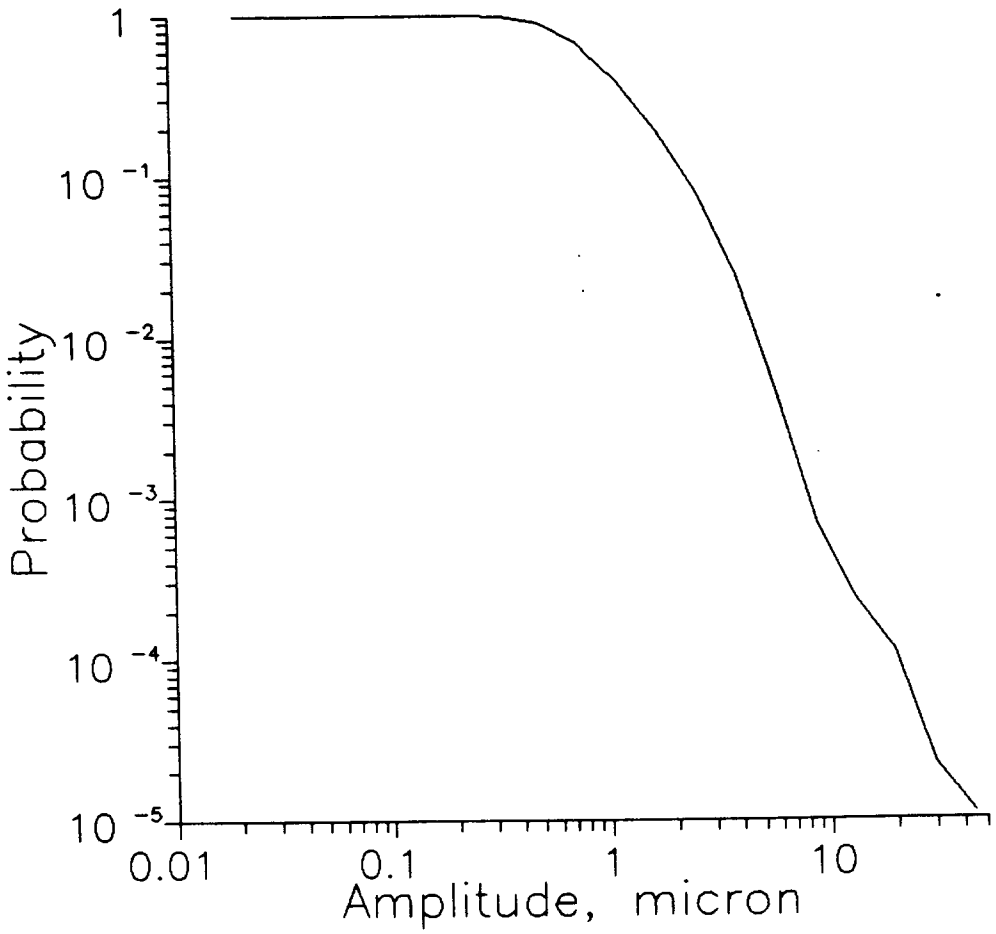


Fig.7. Variation of the power spectrum measured in Hiidenvesi in August 12-19, 1994.



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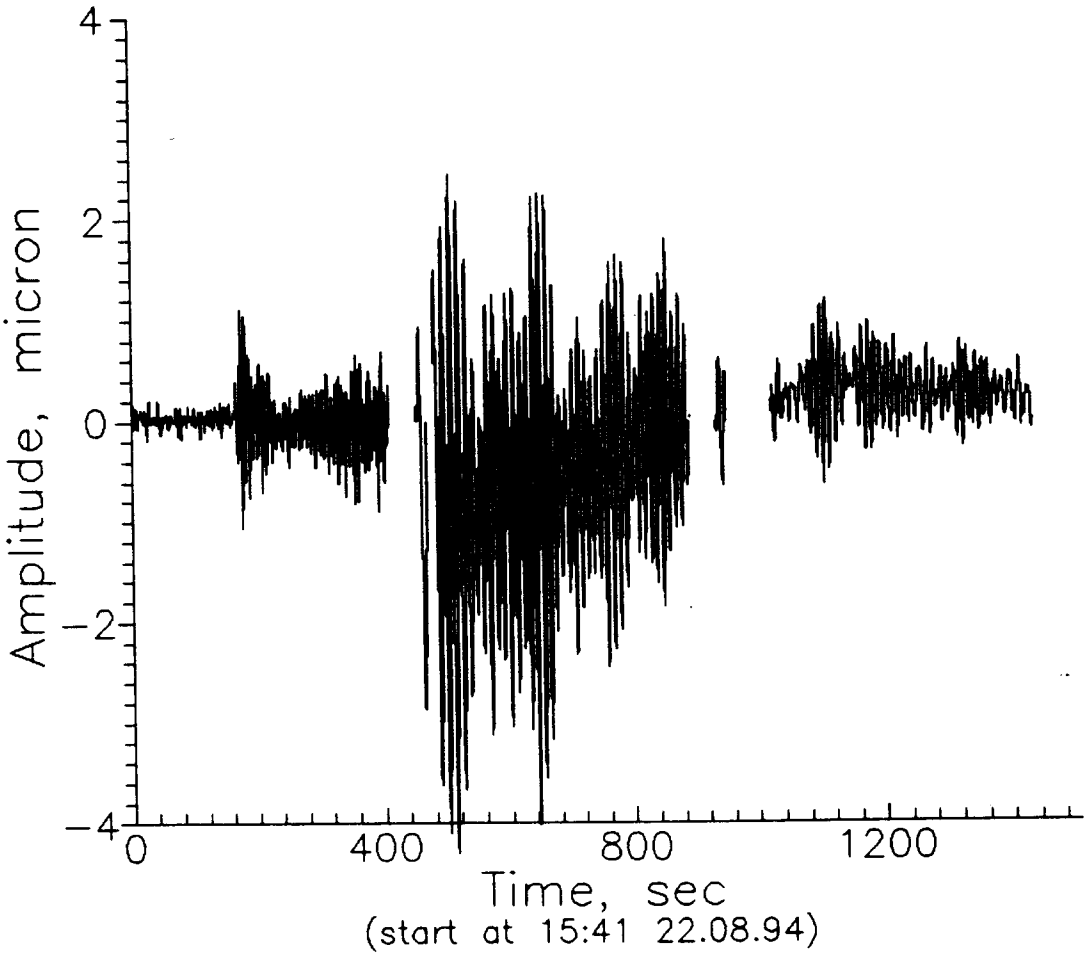

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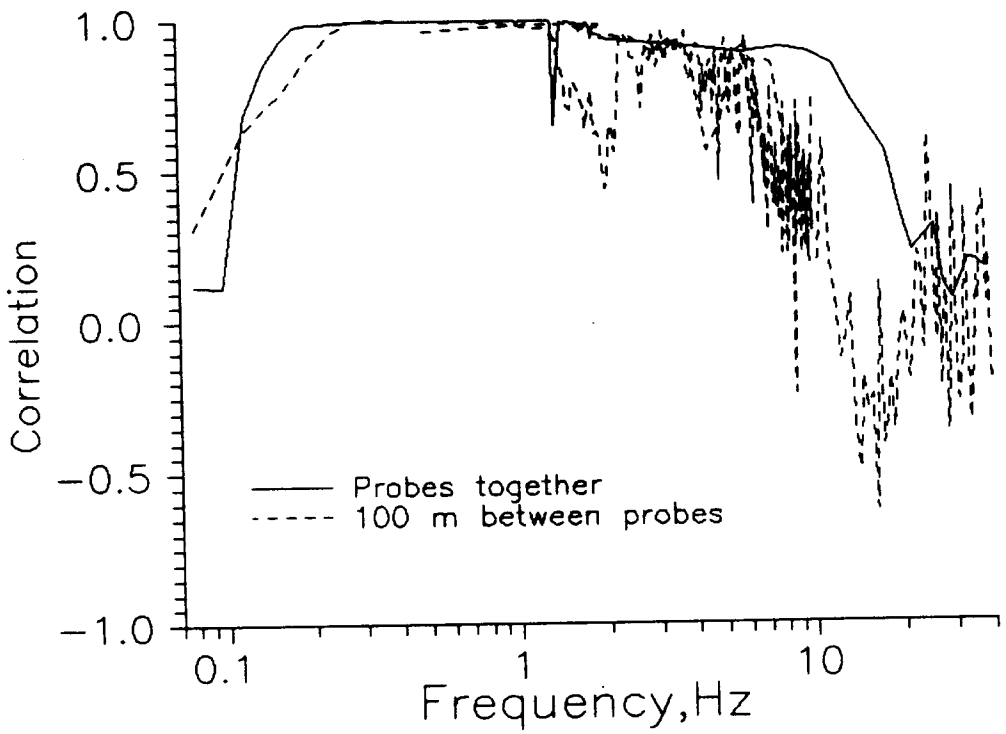

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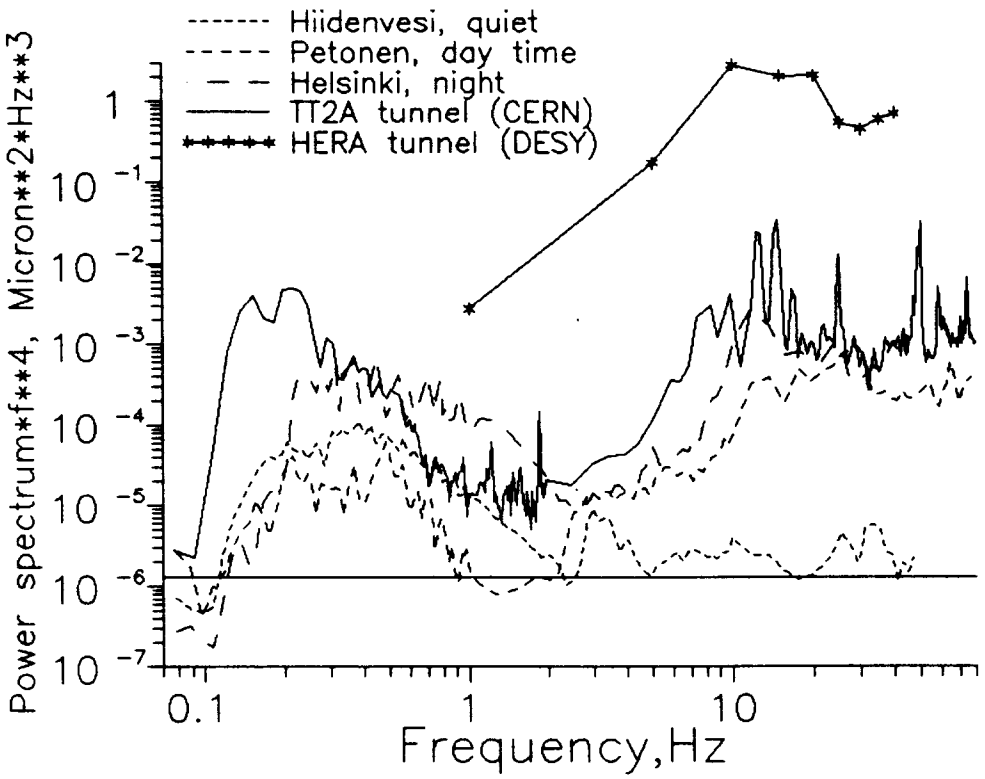

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