ALIGNMENT STUDIES FOR THE CERN LINEAR COLLIDER

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Abstract

Transverse alignment tolerances of a few microns are required for the CERN Linear Collider (CLIC) in order to limit the emittance blow-up due to transversely deflecting wakefields to reasonable values. Such tight tolerances over long distances can only be obtained by beam-based active alignment systems using precision micromovers and beam position monitors. Development work being carried out at CERN on closed-loop controlled micron-displacement systems, micron-resolution beam position monitors, active optical pre-alignment schemes and beam blow-up computer simulations for given overall alignment tolerances using both one-to-one and dispersion-free correction algorithms is described.

Introduction

CERN is studying the feasibility of building an e^+e^- linear collider to enable high energy physics experiments to be extended into a range of energies where circular machines would be crippled by synchrotron radiation [1].

The basic idea is to shoot very dense ($5x10^9$) e^- bunches from a high energy (0.25 TeV) e^- linac against equally dense bunches of e^+ from a e^+ linac of the same energy to produce e^- e^+ collisions with centre of mass energies of 0.5 TeV at a repetition rate of 1.7 kHz to achieve luminosities of $3.2x10^{33}$ $cm^{-2}s^{-1}$ with four bunches in a single and unique experimental region.

The machine consists of e^- and e^+ sources, two 3.4 GeV damping rings to reduce the emittance, a small section for bunch compression and pre-acceleration to several GeV, 3.2 km of main linac accelerating sections, and a final focus system to obtain the required 8nm vertical beam sizes at the collision point.

The CERN LInear Collider (CLIC) has an operating frequency of 30 GHz, an audacious choice for two reasons, the first that state-of-the-art technology is required to fabricate the accelerating sections whose dimensions scale as f^{-1}, and the second that the tolerances on the alignment of the linac become extremely tight. The factor linking frequency and alignment tolerances is wakefield generation.

The very small emittances produced in the damping rings ($\gamma\varepsilon$=0.4x10^{-7}rad.m) must be transported along the main linac to the final focus in the presence of transversely deflecting wakefields, with as little blow-up as possible. Transverse wakefields scale as f^3 but are only generated by off-axis particles so although the CLIC frequency is high their effects can be held to reasonable values by imposing stringent alignment tolerances on the quadrupoles and accelerating sections of the main linac, and by applying known stabilization techniques (BNS damping).

The extent of the emittance blow-up has been estimated using beam tracking computer simulation programs. The results show that to limit the blow-up to acceptable values, the two linacs must be aligned and maintained in position in the transverse plane to tolerances of a few microns. An emittance blow-up from $\gamma\varepsilon$=0.5x10^{-7} rad.m to $\gamma\varepsilon$=2.0x10^{-7} rad.m is typical for assumed alignment errors of σ=5μm for the accelerating sections, σ=3μm for the quadrupoles, and a beam position monitor error of σ=2μm.

Since normal ground motion produces displacements which exceed these tolerances, a dynamic alignment system is foreseen using beam-derived signals from beam position monitors to drive precision micro-movers under closed-loop control to maintain the components in position. The best strategy to be adopted for the correction scheme is not yet clear. The simplest approach is a one-to-one correction centering the beam at each monitor, but there is hope that overall tolerances can be relaxed by implementing so-called dispersion-free algorithms to the beam trajectory requiring corrections to be made only at a reduced number of specific locations.

For the active alignment system described above to work it must be demonstrated that

(i) the accelerator can be pre-aligned with respect to an external reference with sufficient precision that the beam can be made to pass through the available aperture and produce a signal in a beam position monitor

(ii) beam position monitors of μm resolution can be built and referenced accurately to the electrical and magnetic axes of the accelerator components

(iii) using the signals from these beam position monitors, the accelerator components can be positioned and maintained in space with micron precision using remote controlled micro-movers.

This paper describes development work being done at CERN to demonstrate the feasibility of these requirements.

General layout of CLIC machine

There are 11450 accelerating sections per linac. Each section is approximately 30cm long with an external diameter of 35mm and a weight of about 4 Kg. The outer diameter of the structure which is machined to ±1μm precision and concentricity with the beam aperture, serves as the external reference for alignment to the beam. To simplify assembly and reduce costs, it is foreseen to mount and pre-align several of these sections on a support girder before installation in the CLIC underground tunnel, and to use micro-movers at the ends of these girders to adjust their position. A conceptual view of a typical section of the CLIC machine showing four accelerating sections of the main linac powered from above by the drive linac is given in Fig.1.

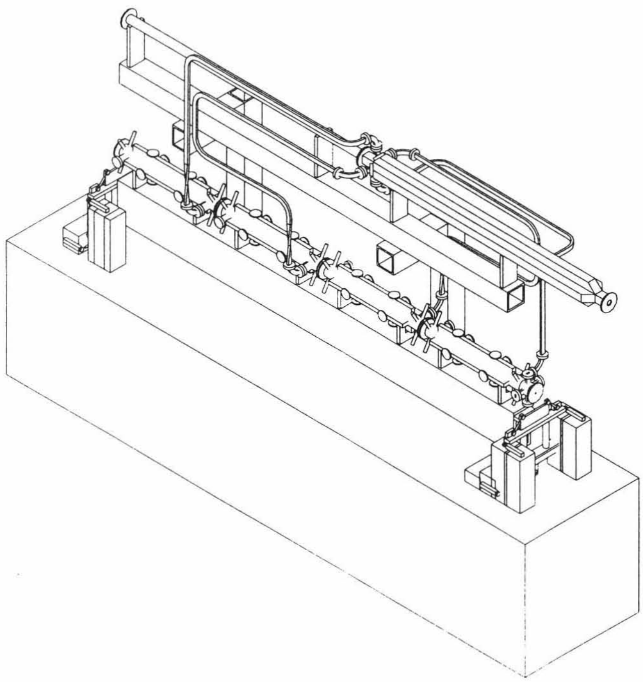


Fig.1 Typical section of CLIC machine

Active alignment test facility

A remote computer-controlled micro-movement test bench permitting controlled submicron displacements, has been built in an unused underground accelerator tunnel to study the problems associated with the support and precise positioning in space of CLIC main linac components (requirement [iii] above). This set-up shown schematically in Fig.2 consisting of two moveable girders and one fixed girder was used to demonstrate the feasibility of controlled sub-micron movement using commercially available components, details of this set-up and the results obtained are given in reference [2]. A second test bench consisting of the same basic elements as the first but with six motorised girders is being built to enable the new CLIC pre-alignment scheme to be studied. Fig.3 shows the basic features of one of these girders.

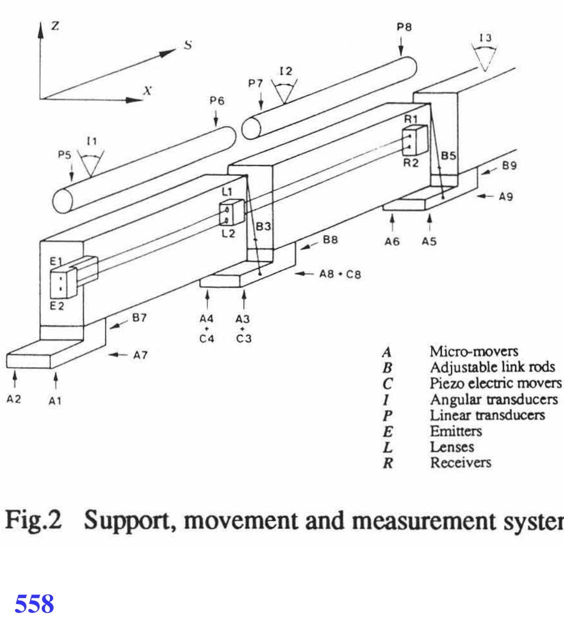


Fig.2 Support, movement and measurement system

Each box-section girder which is made from silicon-carbide because of its high stiffness-to-weight ratio and its low thermal expansion, supports four accelerating sections. The sections are clamped to the girder via INVAR V-block supports which are aligned and fixed with a precision of 3µm in the transverse plane. The ends of two adjacent girders sit on a common platform which assures continuity of position between units. In order to provide independent rotational freedom of each girder, one of the ends is fixed rigidly to the platform whilst the other is connected to it via swivel-joint linking rods. Due to the very small diameter of the ball-joint, displacements are obtained with a minimum of friction by rotations around a point without creating stresses in any of the components.

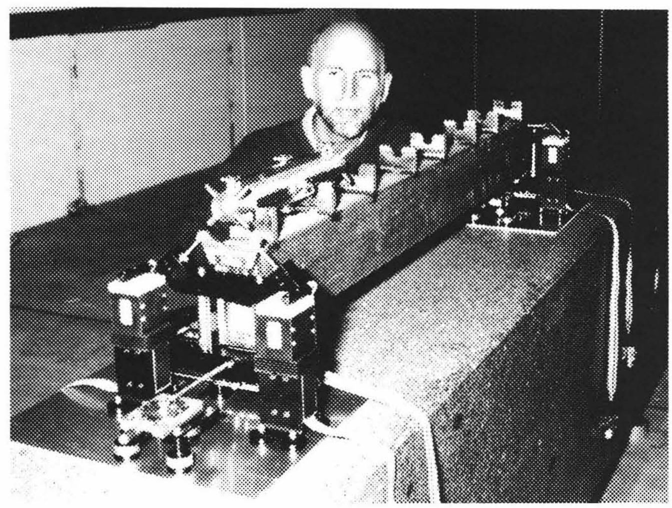


Fig.3 Support girder and displacement system

Each platform is activated via similar link rods by three precision jacks. Two in the vertical plane produce vertical displacements and transverse rotations; the third is situated and acts in the horizontal plane. These stepping motor driven micro-movers with a resolution of 0.1µm and an absolute accuracy of 1µm over ± 4mm provide both large displacements for initial alignment and micron movements for correction of slowly varying perturbations (<1Hz) during CLIC operation. Piezo-electric movers with a stroke of ±3µm have been mounted in series with some of the jacks to provide higher speed response but for the moment this looks unnecessary.

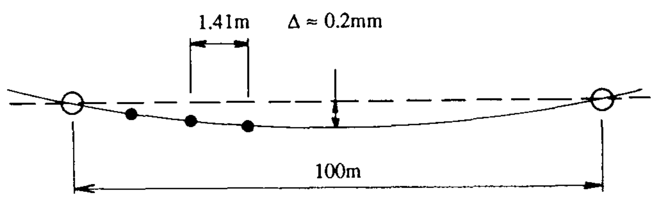
The test facility is piloted remotely from an Olivetti PC and is programmed for automatic alignment with respect to independent transducers monitoring the position of the accelerating sections themselves. After deliberate misalignments (of 1mm say) the system settles back to nominal positions within less than a micron.

The present performance of this micro-movement test device can be summarised as follows.

Smallest step in any one direction = 0.2µm
Hysteresis over ±4mm = 3µm (open loop)
Error over ±4mm in closed loop = 0.2µm
Frequency =1 Hz

Pre-alignment

The accelerator has to be pre-aligned with sufficient precision that the beam can be made to pass through the available aperture and produce a signal in a beam position monitor (requirement (i) above). It is foreseen to do this using the same active micro-movement system described above but using signals from an optical pre-alignment system instead of beam position monitors. The idea [3] is to maintain the relative positions of the far ends of two adjacent support girders to within a few microns in both transverse planes but to allow greater overall excursions from a straight line (say 0.2mm) over longer distances of say 100m between reference pillars as shown below.



The reference pillars are positioned by the stretched-wire technique with respect to master pillars spaced 3km apart which are themselves positioned by the Global Positioning System to an accuracy of ±3mm. The principle of this stretched wire technique is shown schematically in Fig.4. Starting from the master pillar a staight line is defined by a wire stretched between pillars A and C. Pillar B is then positioned by measuring and centering the wire in the capacitive transducer. A second stretched wire between pillars B and D enables D to be positioned by centering the wire in the transducer at C, and the process is repeated.

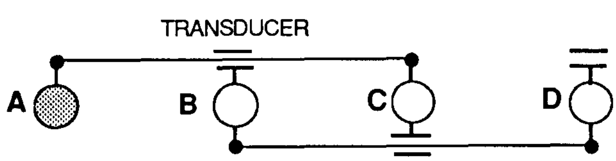


Fig.4 Priciple of stretched-wire alignment system

A typical chain of such a stretched-wire alignment system is shown in Fig.5. By adding additional pillars equipped with two transducers as shown some degree of redundancy is introduced into the measurement system to enable errors to be minimised. The precision of measurement is 10μm over 100m.

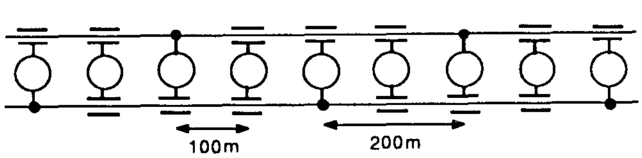
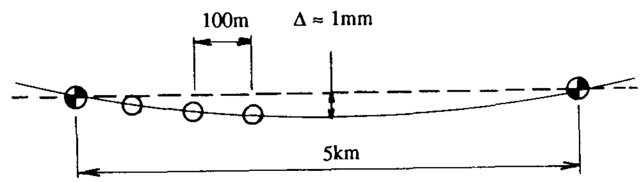
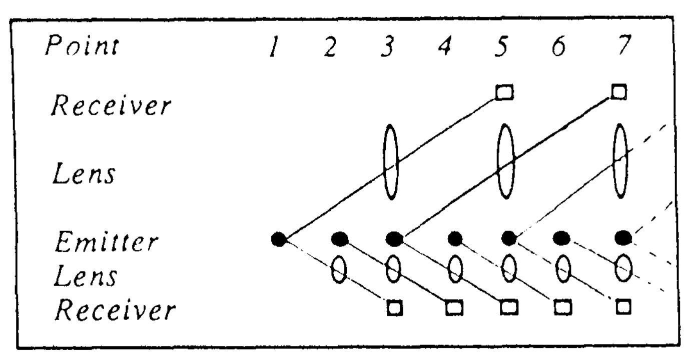


Fig.5 Stretched-wire alignment chain for CLIC

A statistical analysis of this redundant set of transducer readings has been simulated and the results indicate a positional accuracy of the reference pillars with respect to the ideal straight line as shown below. Over 3km the maximum deviation is about 1mm.



Since the linac components are aligned accurately with respect to the support girders, and the fixation of the girders is such that they only articulate about a common moveable point (like a universal joint), it is only necessary to align the string of common points to align the linac between reference pillars. It is planned to do this by means of an improved version of the RASNIK optical displacement measuring system first used at CERN to align physics detectors in LEP [4]. The operating principle is simple - the image of a square object illuminated by a red light source is focused on a light detecting four quadrant cell by a thin lens. Displacements of the object (emitter), the lens or the four quadrant cell (receiver) out of the axis of the instrument produce an imbalance at the detector. Each articulated point of the support girders will be equipped with an emitter and a lens at the ends of the first or reference girder, and a receiver at the far end of the second girder as shown in Fig.2.
Initial tests with this system on the micro-movement test bench indicate that the relative positions of the ends of the two girders can be determined to better than 2μm.
Such a system alone however does not provide sufficient information to enable the inevitable errors in the string of articulated points to be identified and minimised. To be able to do this some redundancy is required, this is provided by a second set of overlapping measurements obtained from a parallel optical system monitoring twice the span of the first. The overall system therefore requires the two types of optical component combinations indicated below.



A statistical analysis of this redundant set of measurements enables the absolute displacements of the articulated points in space with respect to the ideal straight line to be determined and the necessary movements of the jacks to be calculated to minimise the excursions. Such a system would necessarily be connected to a computer so that the "measurement-calculation-correction" operation could be automated and if necessary reiterated.

Computer simulations of this pre-alignment scheme indicate that over a 100m length maximum typical excursions of less than 0.2mm are obtained if the precision of the optical measurement system is 2µm.

The reference line for the machine is therefore not straight, it is obtained by superimposing the gently undulating "snakes" resulting from the alignment accuracy of the reference pillars on the one hand and the interconnecting support girders on the other.

Beam position monitor

The feasibility of obtaining micron precision BPMs using an E_{11} resonant cavity has already been demonstrated theoretically [5]. Recent experimental results using a single cell 33 GHz cavity have now substantiated this claim [6] and are described briefly below.

To simulate the passage of an e^- bunch (no suitable bunched beam at the time being available) the clamped copper cavity shown in Fig.6 was excited by a network analyser using the central conductor of a piece of co-axial line as an antenna.

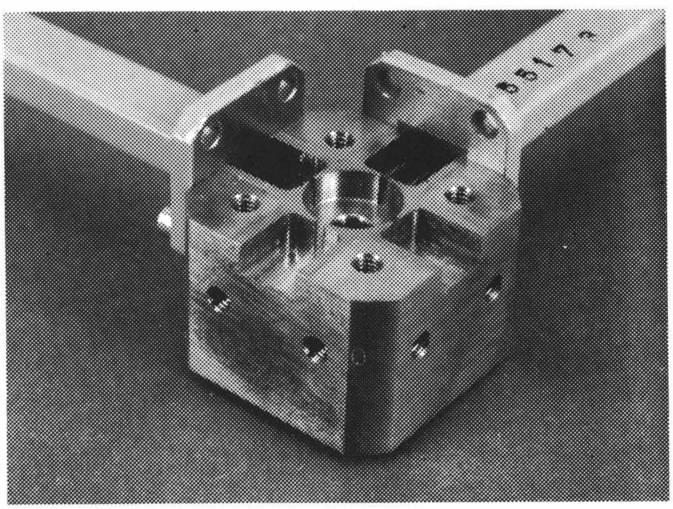


Fig. 6 CLIC prototype beam position monitor

The experimental set-up is shown in Fig.7. A precision translator having a nominal resolution of 0.1 micron moves the antenna with respect to the cavity.

The output signal from the cavity is composed of an unwanted symmetrical signal produced at all antenna positions, and a wanted asymmetric signal which is proportional to the antenna offset from the electrical centre of the cavity. By feeding a magic tee with the output signals from two diametrically opposed coupling ports, a 30dB reduction in the unwanted signal (see Fig.8) was obtained. Having minimised this symmetric signal in this way, the precision of the device is essentially determined by the accuracy with which it can be made. As opposed to this clamped cavity which has been made with conventional machine tools to an accuracy of the order of 0.01mm, CLIC BPM cavities would be brazed and diamond machined to a precision and concentricity of 1 micron.

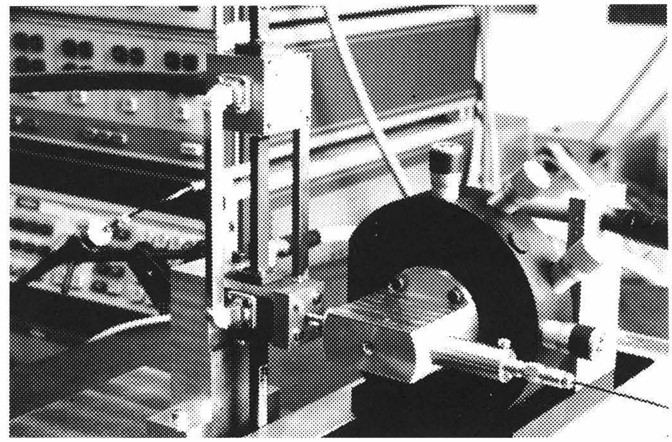


Fig.7 Experimental test set-up

A plot of output voltage versus antenna position in the range ± 5 microns is shown in Fig.9. The output is linear down to displacements of ±0.5 microns. Clearly the BPM cavity is capable of measuring positions accurately to below a micron.

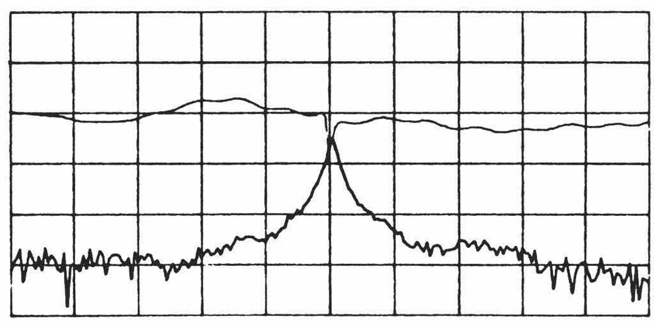


Fig.8 Transmission through cavity.
Upper trace without magic tee, lower trace with tee.
Scales vertical 10dB/div, horizontal 100 MHz/div.

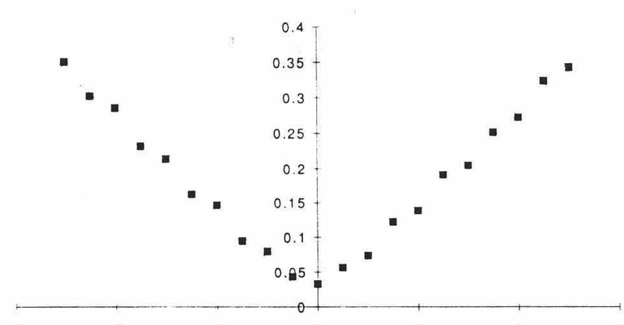


Fig.9 BPM output voltage versus nominal antenna position (microns)

Prototype electronics for signal processing with a bunched beam has been developed and is operational and plans are underway to build precision BPMs and test them in the CLIC Test Facility (CTF).

Ground motion measurements

It is of course important in the face of such tight alignment tolerances to build the linear collider on a quiet site. Ground motion measurements shown in Fig.10 were made in an unused underground accelerator tunnel at CERN using a three axis Mark Products geophone having a calibrated frequency range of 1-30Hz.

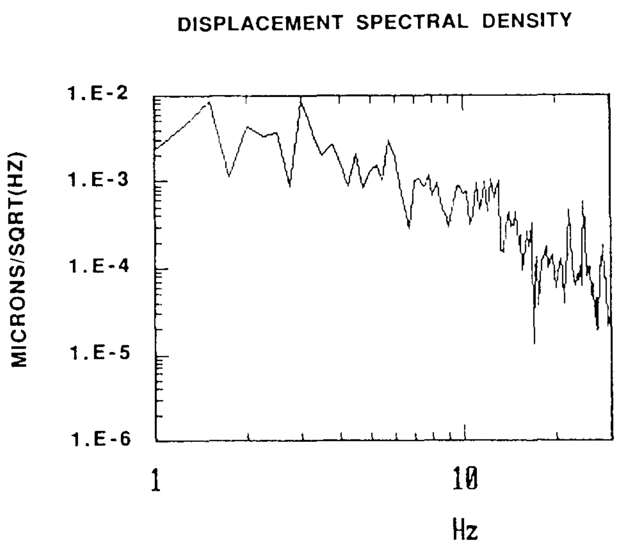


Fig.10 Ground motion

Emittance blow-up simulation results

Reduction of beam emittance blow-up is being attacked on two fronts. The first, described in detail above, aims at reducing the physical misalignment of the linac, the second aims to find alignment strategies which minimise the effects of the misalignments. Two different trajectory correction schemes are being investigated, the so-called "one-to-one" and the "dispersion-free" schemes. Both assume that the necessary dipole correcting kicks will be produced by transverse off-sets of the quadrupoles, and that there is a BPM very close to every quadrupole. The quadrupoles are supported and moved independently of the main support girders and will be pre-aligned with respect to the BPMs either via the stretched wires (a difference measurement) or by special purpose transducers. The one-to-one scheme simply uses the quadrupole to centre the beam at the local BPM. The second scheme recognises that the contribution of dispersion to the overall emittance can be significant and that both the trajectory and dispersive terms should carry some sort of weighted importance. It relies on quadrupole corrections to minimise the overall emittance without necessarily centering the beam at every BPM. The basic idea comes from SLAC [7] and involves an on-line analysis of all BPM readings for small excursions of quadrupole settings around the nominal values to establish the overall transport matrix of the linac which is then used to predict corrections that minimise both the trajectory and the dispersion. Beam trajectory simulations made at CERN using this scheme have shown that more accuracy and better convergence can be obtained by modulating the relative weights of the dispersive and trajectory terms in the algorithm during the iterative calculation/correction process [8].

A typical result obtained from simulations of the emittance blow-up along the CLIC linac is shown in Fig.11 for the one-to-one correction scheme.

It appears from the results of many simulations of various CLIC machines for different tolerances that using the dispersion-free correction the emittance blow-up is relatively insensitive to the mis-alignment of the accelerating sections (σ=5μm and 10μm give little change), since however the BPMs are integrated into the first accelerating section of each girder the tolerances from girder to girder at this particular location are more severe.

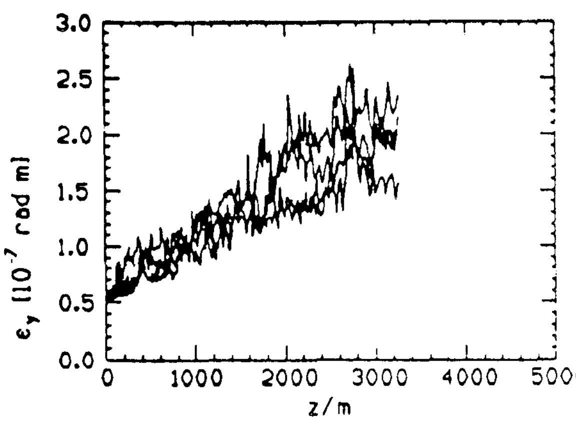


Fig.11 Vertical emittance blow-up along the CLIC linac for the one-to-one correction scheme (500 GeV c.m.)

Assumed mis-alignments for results in Fig.11:
Quadrupoles σ_q=3μm
BPMs σ_b=2μm
Accelerating structure σ_a=5μm

References

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Acknowledgement

Most of the work and many of the original ideas on micromovement and alignment are due to W. Coosemans.