Dynamic alignment in particle accelerators

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Abstract

The problem of dynamic alignment in particle accelerators is introduced. Alignment levels achieved in existing machines are reviewed and compared with typical tolerances of present and future accelerators that require the implementation of dynamic positioning control of accelerator components. Study cases are described to illustrate possible implementations of the active alignment.

1 Introduction

The alignment of accelerator components has always been of primary importance for particle accelerators. Undesired position imperfections of accelerator components such as magnets and accelerating structures determine perturbations of particle motion that can induce limitations on the accelerator performance. The construction of new accelerators has often pushed forward the state of the art of accelerator alignment technology, as required to meet the new challenges of larger and larger underground machines. In most of the particle accelerators built so far, a good static alignment of accelerator magnets to the level of 300–500 micrometres was sufficient to achieve the design performance, as has been proved by the successful operation of many particle accelerators worldwide. Precision in this range was achieved in the 1960s, for example at the CERN Proton Synchrotron [1]. Since then, new developments have focused on adapting the survey technology to larger scales [2] rather than on improving the absolute level of static alignment accuracy.

Continuously higher required machine performance, which often relies on reducing the beam sizes in the accelerator, has caused a reduction of alignment tolerance for accelerator components. This is a common feature of circular colliders, synchrotron light sources, XFELs and linear colliders but the new requirements are particularly stringent for the next generation of linear colliders that aim at colliding nanometre-sized beams. In fact, feasibility studies of the proposed alignment and stabilization techniques have become necessary milestones for approval of the projects. But this is just an extreme example of a general feature of the particle accelerators that have to rely more and more on dynamic alignment, which is becoming an increasingly important domain for particle accelerators.

Various definitions could be formulated for the dynamic alignment domain because it involves a broad spectrum of fields such as accelerator physics, precise position measurements and survey techniques in hostile environments, modelling of ground motion and optimized support design, sub-micrometre actuator technology, feedback theory. Here, the dynamic alignment is defined as an active and remote position control of accelerator components (typically, quadrupole magnets and RF structures). In order to be called ‘dynamic’, the position control should be possible (1) at high frequencies, certainly on time scales below a few hours but most typically below minutes; (2) during the beam operation, i.e., without human intervention in the vicinity of the accelerator.

For example, the yearly re-alignment campaigns routinely carried out in most accelerators (as an example, the case of the CERN Super Proton Synchrotron is shown in Fig. 1) clearly do not fall into the above definition of dynamic alignment. On the other hand, the lattice quadrupoles of present third- and fourth-generation light sources are equipped with active motorization systems that allow the use of the dipole feed-down component of quadrupole fields to steer the beam and optimize the beam trajectory. This is an example of dynamic alignment. Another example is shown in Fig. 2: the quadrupole magnets of the Compact Linear Collider (CLIC) [3] will be equipped with motorized supports that will allow the re-adjustment of the magnet position between consecutive beam pulses, i.e., at a frequency of ≈ 100 Hz.
Fig. 1: Lattice quadrupole of the CERN Super Proton Synchrotron (top) and plot of the alignment offsets applied to the 216 lattice quadrupole during the last three years (bottom, courtesy of C. Arimatea and S. Cave-Cettour). The quadrupole offsets are determined with beam-based measurements performed at 400 GeV.

Fig. 2: Photograph of a prototype of the CLIC linac quadrupole (left) and scheme of the active alignment system that enables adjusting the quadrupole position in 5 degrees of freedom (right) [4].
In this lecture, the alignment tolerances in particle accelerators are reviewed and compared with typical perturbation levels of accelerator components. The concept of beam-based feedback is also briefly introduced. The comparison between alignment tolerance on the one hand and alignment perturbation and effectiveness of feedbacks on the other hand is made in order to identify the accelerators for which a dynamic alignment is required. Three case studies are then considered in detail as an illustration of possible implementations of dynamic alignment techniques and associated high-precision measurement techniques.

2 Alignment requirements in particle accelerators

The main perturbations on the beam dynamics from alignment errors of quadrupole magnets and RF structures are briefly reviewed as an introduction to a general discussion on the alignment tolerance for particles accelerators.

2.1 Perturbations of beam dynamics from quadrupole alignment errors

Quadrupole magnets (Fig. 3, left side) are used in modern particle accelerators to focus the beam particles around the nominal trajectory according to the well-known alternating-gradient scheme [5]. The focusing strength is determined by the field gradient

\[ g = \frac{\partial B_y}{\partial x}, \]

which is often normalized with the beam rigidity \( p_0/e \) (\( p_0 \) and \( e \) are the beam momentum and charge, respectively) to give the normalized quadrupole strength \( k = \frac{g}{p_0/e} \). This is equivalent to an optical lens with focal length \( f \) given by

\[ \frac{1}{f} = kl = \frac{g}{p_0/e} l, \]

where \( l \) is the effective length of the quadrupole. For circular accelerators, the on-momentum particle’s dynamics is described by the equation of motion of the pseudo harmonic oscillator

\[ w'' + K(s)w = 0 \text{ (with } w \equiv x, y), \]

with position-dependent ‘spring constant’ \( K \). Without vertical bending, \( K = -k+1/\rho^2 \) in the horizontal plane and \( K = k \) in the vertical plane. The solution of the unperturbed equation of motion is given by the well-known betatron motion

\[ w(s) = \sqrt{\epsilon} \sqrt{\beta_w(s)} \cos(\psi_w(s) + \psi_w0) \]

Fig. 3: Transverse cross-section of a quadrupole magnet (left) and illustrative view of the feed-down dipole kick experienced by a beam that enters in a quadrupole with an initial vertical offset \( \Delta y \) (right).
Circular accelerators (a)  Linear accelerators (b)

Fig. 4: Illustration of the closed-orbit perturbation in circular accelerators (left) and of the trajectory perturbation in linear accelerators (right) from one single quadrupole alignment error. In reality, the cumulative error from all the lattice components - including non-linear magnetic components - must be taken into account. Analytic expressions can be computed but in practice nowadays various numerical codes exist.

($\beta_w(s)$ is the periodic betatron function and $\psi_w(s)$ is the betatron phase advance). The same formalism can be used for linear accelerators and transfer lines even though in these cases the betatron functions are not a periodic solution of the equation of motion but rather depend on the initial beam conditions.

As schematically illustrated in Fig. 3 (right side), if there is a relative offset between the quadrupole centre and the beam position, the beam experiences a net feed-down dipole field $B_{qd}$ proportional to the offset ($\Delta_{qd}$) and to the quadrupole gradient: $B_{qd} = g\Delta_{qd}$. The particle’s motion in case of errors is described by the equation

$$w'' + K(s)w = G(s).$$  \hfill (5)

For example, in case of a single quadrupole alignment error, $G(s) = \delta(s - s_0) \times k(s_0)\Delta_{qd}(s_0)$ ($\delta$ is the Dirac function). The effects of linear imperfections are treated in detail in the literature (see for example Ref. [6]). Illustrative examples are shown schematically in Fig. 4 for the simple case of one quadrupole error. For circular accelerators, quadrupole alignment errors determine, at the first order, a distortion of the closed orbit that can be calculated as

$$w(s) = \frac{\sqrt{\beta_w(s)}}{2\sin(\pi Q_w)} \times \int \sqrt{\beta_w(t)}G(t)\cos[|\psi_w(t) - \psi_w(s)| - \pi Q_w]dt \ (w \equiv x, y),$$  \hfill (6)

where $Q_w$ is the betatron tune. In linear accelerators the perturbation of the trajectory is calculated in a similar way by adding the transverse kicks from all the quadrupoles. For example, considering only the contribution of quadrupole offsets one gets

$$\Delta w^* = \sum_{i=1}^{N_{qd}} \sqrt{\beta_w(s_i)\beta_w(s_j)} \sin[\psi^* - \psi(s_i)]k_{qd}^{(i)}\Delta_{qd,w}^{(i)} \ (w \equiv x, y),$$  \hfill (7)

where $\Delta w^*$ is the offset at the observation (typically the vertical offset at the interaction point (IP) is relevant for the performance of a linear collider, Fig. 4). The integral and the sum in the equations above are referred to as lattice response functions. Note that in both cases the effect of the error depends on the beta functions at the locations of the error source as well as at the observation points.

Equations (6) and (7) give only the first-order effect from quadrupole alignment errors. The proper calculation of lattice response functions must take into account in addition all the non-linear elements of the lattice. A complete treatment shows that at higher order the errors also induce variation of the beam size and reduction of the beam lifetime (circular accelerators). A variety of semi-analytical [7] or numerical [8] simulation tools are available nowadays to compute in detail the perturbations from the various error sources and to infer the corresponding alignment tolerance for each magnet.

2.2 Perturbations of beam dynamics from RF alignment errors

Radio-frequency cavities are used to accelerate the particle beams by generating resonant electromagnetic fields at an optimized phase with respect to the beam. If there is a transverse offset between the
Fig. 5: Illustration of the various modes of the wake-field excited in a CLIC-like RF cavity by a bunch with an offset with respect to the cavity’s mechanical centre (top). All frequencies are excited and, depending on the cavity design and on the beam parameters, various high-order modes can perturb the tail of the bunch or the next bunches. The occurrence of single bunch, head-tail perturbations is also schematically shown (bottom).

beam position and the centre of the RF cavity, undesired high-order modes are induced (see Fig. 5, top graph), which can perturb the beam dynamics by exciting single-bunch (head–tail) and/or multibunch effects, detrimental to the performance of the accelerator. The relevance of one effect or of the other depends on the beam parameters such as bunch intensity, bunch spacing, bunch length. Alignment of RF structures is a primary concern for linear accelerators. Even with single passage of the beams, alignment errors can sum-up due to the large number of RF structures (that typically fill most of the available space in order to optimize the beam energy for a given machine length) and perturb the bunch as illustrated in Fig. 5 (bottom graph). The result is an effective emittance blow-up that must be kept under control.

The key parameter to quantify the perturbations from RF alignment error is the so-called transfer wake-fields, which can be calculated as the sum of all high-order modes of the cavities [9]:

$$W_\perp(t) = \sum_n \frac{2k_n c}{\omega_n} e^{-\frac{\chi_{n}}{\lambda_n}} \sin \omega_n t.$$  (8)

A detailed estimate of the perturbation from wake-fields must rely on finite-element electromagnetic tools to compute the RF modes. The tolerance for beam dynamics can be determined accurately only with dedicated tracking simulation tools of the full linear accelerator.

2.3 Static alignment tolerances

A clear definition of ‘alignment tolerance’ is not always straightforward. Clearly the operation of particle accelerators does not rely only on the bare alignment of components but also on a number of correction algorithms based on beam measurements, which are extensively used to optimize the machine performance in presence of alignment errors and other imperfections. The topic of beam-based correction was covered extensively in this school [10–12]. In some cases the border between ‘acceptable’ and ‘unacceptable’ performance limitations from alignment errors is not well defined.

For example, let us consider a circular machine well aligned with an accuracy of 300 µm except for one quadrupole magnet that shows an error of several millimetres. This is not ideal, however, one
cannot argue that the machine cannot operate under these conditions: based on orbit measurements, one can infer the quadrupole errors (see Fig. 1) and set up an orbit bump [10] to properly cancel the resulting dipole kick. This argument works for a number of isolated alignment errors but, on the other hand, if too many magnets have such a large error, the machine operation becomes difficult or even impossible. For example, if the alignment errors are too large, one can run out of corrector strength (e.g., at larger energies), or big bumps would be needed which could introduce aperture bottlenecks in the lattice elements close to the location of the error.

In a sense one should distinguish between (1) the alignment requirements that have to be achieved as a zeroth-order machine alignment prior to the beam commissioning, and (2) the requirements that have to be ensured during standard machine operation. The latter requirements can only be fully specified by taking into account the correction algorithms that are available to counteract perturbations from alignment errors. In the last 50 year alignment accuracies of the order of a few hundred micrometres have been achieved in particle accelerators and these have typically been sufficient for machine commissioning. Improvements to the alignment, based on beam measurements, have been pursued to improve the machine performance. This is obviously coupled to the operational range of beam-based corrections as well as to the frequency of the motion, as discussed in the next section.

In this respect, the new frontier for alignment requirements is represented by the Compact Linear Collider: the machine pre-alignment tolerance — as well as the stability requirements, see later — are so critical for the machine performance that their feasibility studies have become essential milestones for the approval of the project.

In Table 1 the alignment levels achieved or targeted are listed for a number of existing and future particle accelerators. As mentioned above, since the 1960s alignment accuracy of a fraction of a millimetre (expressed for RMS value around the nominal position) has been routinely achieved. It is interesting to note that the developments in terms of alignment technology have rather been focused on getting this good level of accuracy transposed along longer and longer machines [1]. The alignment levels quoted in Table 1 are considered as ‘static’ values. In the next section we shall see the role of the frequency content to justify which machines require dynamic alignment.

Table 1: Typical alignment requirements for various particle accelerators

<table>
<thead>
<tr>
<th>Year</th>
<th>( E_{\text{max}} ) [GeV]</th>
<th>( L ) [km]</th>
<th>( \sigma ) [( \mu \text{m} )]</th>
<th>Align. target</th>
<th>Need active alignment?</th>
<th>Required accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS (p)</td>
<td>1959</td>
<td>26</td>
<td>0.6</td>
<td>( \approx 3000 ) (h)/300(v)</td>
<td>No</td>
<td>–</td>
</tr>
<tr>
<td>SPS (p)</td>
<td>1972</td>
<td>450</td>
<td>6.9</td>
<td>( \approx 1000 )</td>
<td>No</td>
<td>–</td>
</tr>
<tr>
<td>LHC (pp)</td>
<td>2008</td>
<td>7000</td>
<td>27</td>
<td>17</td>
<td>( 300/100 ) (MQX)</td>
<td>Yes</td>
</tr>
<tr>
<td>Light sources</td>
<td>now</td>
<td>( \approx 3 )</td>
<td>( \approx 0.2 )</td>
<td>( \approx 50 )</td>
<td>Yes</td>
<td>10 ( \mu \text{m} )</td>
</tr>
<tr>
<td>ILC (e(^+)e(^-))</td>
<td>&gt;2010</td>
<td>500</td>
<td>35</td>
<td>0.005</td>
<td>Yes</td>
<td>10 ( \mu \text{m} )</td>
</tr>
<tr>
<td>CLIC(e(^+)e(^-))</td>
<td>&gt;2010</td>
<td>3000</td>
<td>50</td>
<td>0.0007</td>
<td>Yes</td>
<td>1 ( \mu \text{m} )</td>
</tr>
</tbody>
</table>

2.4 Frequency content of motion: ‘slow’ and ‘fast’ perturbations and feedback response

The perturbations from alignment errors depend not only on the amplitude of motion but also — and to some extent mainly — on the frequency at which the motion occurs. Slow modulations of the magnet positions with peak-to-peak amplitudes of micrometres, e.g., due to tidal motion of the Earth’s surface, can easily be compensated by manual steering based on orbit measurements. However, vibrations more than 1000 times smaller can prevent collisions in a linear collider if they occur at frequencies slightly above what can be compensated by pulse-to-pulse orbit feedbacks. In a circular machine, kicks equivalent to one millionth of the tidal motion, e.g., caused by a tiny ripple of the power converters, can induce
significant beam losses if they are close in frequency to a betatron tune.

It appears clear that the key parameter that enables the distinction between ‘slow’ and ‘fast’ motions is the characteristic response frequency of corrector algorithms (manual or automated) that are put in place to counteract the effect of alignment errors. As far as alignment is concerned, the relevant parameter is the effectiveness of orbit correction. For a circular machine [10] this is determined by the orbit acquisition chain and by the rapidity of the correcting algorithms. For linear colliders, the primary intrinsic limitation comes from the repetition rate of bunch trains. In either case one can define a characteristic feedback cut-off frequency $f_{\text{cut}}$ above which the correction becomes ineffective (or even detrimental). Based on the experience with the feedback systems used so far, one expects typically

$$f_{\text{cut}} \approx \frac{1}{20} f_{\text{acq}},$$

where $f_{\text{acq}}$ is the acquisition frequency of orbit measurements. The latest generation of light sources aims at $f_{\text{cut}}$ values up to 100–300 Hz whereas for linear accelerators typical values are of the order of a few Hz.

Alignment is often seen as ‘zero frequency’ positioning of the accelerator components. Indeed, for machines built up to a few years ago, the achieved positioning was sufficiently large for the motion of perturbing sources to be considered small. The new requirements for dynamic alignment are motivated by the fact that this assumption is no longer correct due to the reduction of the alignment tolerance. Basically, the dynamic alignment becomes a requirement when the perturbations that cannot be compensated by beam-based techniques (i.e., which occur at frequencies larger than $f_{\text{acq}}$) are large compared to the tolerance table. In other words, dynamic alignment is required when the amplitude of motion left uncompensated exceeds the operational tolerances. In the next section various sources of alignment errors are reviewed to justify the dynamic alignment requirements as listed in the last column of Table 1.

3 Sources of alignment errors

At the micrometre and nanometre scales, nothing is perfectly stable but everything moves without rest. The primary source of motion is the underlying ground motion, however, other perturbations, such as human activity (cultural noise), acoustic noise, temperature variations, mechanical resonances and noise from various accelerator components, can enhance significantly the natural ground motion. In this section the basics of vibration analysis are introduced and typical sources of perturbation for accelerator components are discussed.

3.1 Fourier analysis of magnet motion

As discussed above, it is important to understand the frequency content of magnet motion and therefore a Fourier analysis is often used to process the position measurements of the accelerator components. If $y(n) \equiv y(n\Delta t)$ is the (vertical) displacement measured at a sampling time $\Delta t$ during a total time $T = N\Delta t$, the power spectral density of the displacement $P(f_k)$ is defined for the discrete frequency $f_k = \frac{k}{N\Delta t}$ as

$$P(f_k) = \frac{2\Delta t}{N} \left| \sum_{n=1}^{N} y(n)e^{-2\pi i \frac{kn}{N}} \right|^2 = \frac{2\Delta t}{N} |\tilde{y}(f_k)|^2 (k = 1, 2, ..., N/2 - 1).$$

Here, $|\tilde{y}(f_k)|$ is the discrete Fourier transform of the measured signal. The integral of $P(f_k)$ in a given frequency range gives the RMS motion induced by the vibrations in the range. In particular, what is relevant for particle accelerators is the integration of all the frequencies above a given minimum frequency
For \( f_{\text{min}} = f_{\text{cut}} \), \( I(f_{\text{min}}) \) gives the residual vibrational motion left uncompensated by the feedback algorithm.

Like the importance of time structure of magnet vibrations, the spatial distribution along the accelerator is also important. For example, the specific spatial profiles of the ground motion can possibly enter in resonance with the lattice response function of the accelerator, resulting in a worsening of the effect of magnet alignment errors. Proper treatment of such effects can be taken into account by considering the correlation of motion and the two-dimensional power spectral density [13]. These aspects will not be treated further here.

### 3.2 Sources of perturbation of magnet motion and example of measurements

The primary source of motion for the accelerator component is the motion of the underlying ground. Figure 6 shows the results of vibration measurements carried out in various locations around the world [14,15]. However, it is important to stress that even very quiet ground motion conditions are not necessarily sufficient to ensure a good position accuracy of accelerator components because the natural vibrations can be enhanced by effects such as (1) cultural noise from human activities; (2) mechanical resonance of the magnets and their supporting structures; (3) cooling water; (4) acoustic noise. The importance of the noise from the accelerator environment is proved by the measurement carried out in the LEP tunnel in the 1990s (Fig. 7) [16]: the natural ground vibration was increased by about a factor 100 (from a fraction of a nanometre to 20 nanometres) when the accelerator was turned on. In Figs. 7–10, various examples of the perturbing effects listed above are presented.

It is very difficult to provide precise and generic enough estimates of the amplitude of motion.
Fig. 7: Spectrum of ground motion in the underground tunnel of the CERN Large Electron–Positron collider (LEP) measured with accelerator ON and OFF [16]

Fig. 8: Effect of daily temperature variations on the alignment of the CLIC quadrupoles as measured on the test stand of Fig. 15 [17]

Fig. 9: Vibration level of a CLIC prototype quadrupole measured with different speeds of cooling water: power spectral density (left) and total RMS motion versus water flow [17]
for the various effects described above because the effects of various contributions are very strongly dependent on the specific features of the site (see Fig. 6), of the machine, of the environment, etc. An attempt is nevertheless given in Table 2 where typical vibration amplitudes and frequencies are listed for the most relevant sources of alignment perturbations. Clearly the choice of the site and the design of the accelerator cavern infrastructures must be aimed at minimizing these effects in order to achieve values much smaller than the figures given in Table 2, which should be considered as worst-case values for unoptimized designs (for example, one would expect to control the tunnel temperature in order to minimize variations of magnet positions induced by thermal effects).

### Table 2: Approximate figures of vibration amplitudes and frequencies of various sources of magnet movements

<table>
<thead>
<tr>
<th>Source</th>
<th>Amplitude [µm]</th>
<th>Frequency [Hz]</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerator noise</td>
<td>≈ 0.05–0.10</td>
<td>&gt;1</td>
<td>poor</td>
</tr>
<tr>
<td>Cultural noise</td>
<td>≈ 0.02–0.10</td>
<td>&gt;1</td>
<td>poor</td>
</tr>
<tr>
<td>Acoustical noise</td>
<td>≈ 0.02</td>
<td>&gt; 100</td>
<td>poor</td>
</tr>
<tr>
<td>Cooling water</td>
<td>a few 0.001</td>
<td>&gt;1</td>
<td>poor</td>
</tr>
<tr>
<td>Structural resonances</td>
<td>&lt; 0.01</td>
<td>&gt; 0.1</td>
<td>poor</td>
</tr>
<tr>
<td>Ocean waves</td>
<td>≈ 10</td>
<td>≈ 0.2</td>
<td>good</td>
</tr>
<tr>
<td>Tidal motion</td>
<td>several µm</td>
<td>2×10^{-5}</td>
<td>good</td>
</tr>
<tr>
<td>Thermal deformations</td>
<td>10–50</td>
<td>10^{-3}</td>
<td>poor</td>
</tr>
</tbody>
</table>

### 4 Examples of dynamic alignment in particle accelerators

In this section some detailed examples of implementations — or proposed implementations — of active alignment systems are discussed. As case studies, the alignment and stability requirements for the Compact Linear Collider (CLIC) [3] and the dynamic positioning control of the inner triplet of the Larger Hadron Collider (LHC) [18] are considered. The most recent set of CLIC parameters is given for reference in Table 3 [19].

With the reduction of the beam size of electron beams in light sources, the dynamic alignment of lattice quadrupoles has become more and more important for these machines in recent years. Though
Table 3: The main parameters of CLIC (3 TeV) [19]

<table>
<thead>
<tr>
<th>Main CLIC parameters</th>
<th></th>
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<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>3 TeV</td>
</tr>
<tr>
<td>Design luminosity</td>
<td>$6.0 \times 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>RF frequency of main linac</td>
<td>11.994 GHz</td>
</tr>
<tr>
<td>Bunch train repetition frequency</td>
<td>150 Hz</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$0.4 \times 10^{10}$</td>
</tr>
<tr>
<td>Number of bunches per train</td>
<td>312</td>
</tr>
<tr>
<td>Unloaded/loaded gradient</td>
<td>100 MV/m</td>
</tr>
<tr>
<td>Colliding beam size, $\sigma_x \times \sigma_y$</td>
<td>$40 \times 0.7$ nm$^2$</td>
</tr>
</tbody>
</table>

Fig. 11: Illustration of the straight line of the CLIC machine compared to the surface of the Earth (left). The level with respect to the ground changes by approximately 13 m per 10 km and this requires a special ‘stair’ structure to be implemented for the water levelling system (right). Courtesy of H. Mainaud-Durand.

not covered in this short paper, the topic was treated by other lecturers [10]. See also Ref. [20].

4.1 Linac alignment for Compact LInear Collider (CLIC)

The alignment requirements for the Compact LInear Collider (CLIC) are defined for three distinct operational phases [4,21,22]:

(1) During machine set-up prior to operation for physics production, a good relative alignment of accelerator structures and quadrupoles shall be ensured over the typical length of a few betatron oscillations, i.e., over about 200 m. This is necessary to successfully send probe beams through the linac.

Tolerances for RMS alignment over a sliding window of 200 m: 10 µm for RF structures and 50 µm for quadrupoles.

(2) After a probe beam is successfully sent along the whole linac, beam-based methods that involve beam measurements and quadrupole position tuning are used to optimize the machine and to determine a ‘golden’ orbit for the physics runs.

Requirements: remote control of quadrupole position with a resolution of 10 µm (requiring precision of $\approx 10$ µm for the minimum position step).

(3) Optimization of the luminosity performance during standard operation.

Requirements: orbit feedback will be active at frequencies below 4 Hz. The total RMS motion of quadrupoles above 4 Hz must be below 1.3 nm (linac) and 0.1 nm (final focus quadrupole).

All these operational cases require an active alignment system as well as an active stabilization of fast mechanical vibrations (item (3) is discussed in the next section). It is also noted that the CLIC alignment has to be performed with respect to a straight line that does not follow the shape of the Earth (which minimized vertical dispersion). This is schematically shown in Fig. 11. In addition, remote controls and radiation hardness are also clearly required.
It is basically impossible to find a single device that covers all the requirements listed above. In particular, a straight line must be transported over distances of $2 \times 25$ km while ensuring a micrometre accuracy. In order to achieve that, for CLIC it has been proposed to combine different technologies that are optimized for different measurement ranges:

- The straight reference over long distances is built using a hydrostatic levelling system (HLS).
- The precise reference for intermediate ranges of $\approx 200$ m is constructed with a stretched wire system (wire positioning system, WPS)
- The micrometre accuracy over short distances of 2–3 m is achieved with optical measurements.

All the proposed technologies have been extensively and successfully used in accelerator environments \cite{23,24}. Along with this network of measurement systems, quadrupole magnets and RF structures must be installed on a sequence of girders approximately $2$ m long and connected by articulation points shared by two consecutive girders in order to minimize the relative offsets on short distances.

The proposed implementation for CLIC is shown in Fig. 12. A ‘propagation network’ is built with the HLS system and is used to construct the straight line (red line of Fig. 12). This reference is transported along the linac by the stretched wire system that is used to build a ‘proximity network’ (blue line). At least three HLS measurement points are used to determine the sag of the wire. On shorter scales, the relative offsets of two adjacent girders are controlled with a RASNIK optical system \cite{25}: the three alignment points for this system are illustrated by the blue boxes in Fig. 12. In order to achieve that, the measurements from the various sensor types must be precisely linked to each other. This is achieved by mounting all of them on dedicated motorized support plates, as shown in Fig. 12 (top-right corner). WPS pick-up sensors are also mounted on the motorized quadrupole supports (see Fig. 2) that are used to adjust the magnet position with respect to the reference wire of the proximity network.

Preliminary tests and detailed simulations of the system performance \cite{4} suggest that the proposed solution can provide the required alignment accuracy. This project remains nevertheless very challenging because on the scale of the full CLIC length various perturbations of the measurement systems must be precisely quantified. This includes (1) local variations of the gravitation field; (2) tidal motion; (3) effects from wire sag; (4) electromagnetic perturbations from the accelerator environment. Effects (1) and (2) are relevant for the propagation network that relies on the water levelling system. Studies are ongoing in order to address all the open points.
The dependence of the luminosity on the colliding beam offset. The instantaneous luminosity produced by two colliding beams depends on the area where the two beams overlap (left graph). For Gaussian beams, one can show that the luminosity depends exponentially on the relative beam–beam offset. A 2% luminosity reduction is induced for an offset of 30% of the beam size, which corresponds to approximately 0.2 nm for CLIC. Detailed calculations from beam–beam simulation codes basically confirm this conclusion.

4.2 Active stabilization of final focus magnets in linear colliders

One of the most extreme and challenging examples of dynamic positioning control in particle accelerators is certainly given by the sub-nanometre stability requirements of the final focus systems of future linear colliders [26]. The driving motivation to investigate magnet stability to the nanometre and sub-nanometre level came from the feasibility studies for linear colliders based on warm RF acceleration, such as the Next Linear Collider (JLC/NLC) [27] and the Compact Linear Collider (CLIC) [3]. A rich literature is available to document the studies carried out within these feasibility studies [17, 27, 28]. Since 2004, after the superconducting accelerator technology was recommended by the International Technology Recommendation Panel [29], sub-nanometre stability has remained an issue primarily for CLIC. On the other hand, stability concerns are still an issue also for the International Linear Collider (ILC) [30] even though the requirements are significantly relaxed with respect to the CLIC case that is considered here.

The luminosity in a linear collider, $L$, is given by the well-known formula:

$$L = F(\theta_c) \frac{N_e^2 N_p f_{\text{rep}}}{4\pi \sigma_x^* \sigma_y^*} H_d \propto \frac{P_b}{\sigma_x^* \sigma_y^*},$$  \hspace{1cm} (12)$$

where $N_e$ is the bunch population, $N_p$ the number of bunches per beam train, $f_{\text{rep}}$ the train repetition frequency, $\sigma_x^*$ and $\sigma_y^*$ the colliding beam sizes at the interaction point and $P_b$ the total beam power. The luminosity enhancement factor $H_d$ describes the luminosity increase due to the mutual attraction of the colliding beam of opposite charge (disruption). The geometrical luminosity factor $F(\theta_c)$ expresses the luminosity reduction from the crossing angle $\theta_c$. The relevant design parameters for the 3 TeV CLIC option are listed in Table 3.\(^1\) Since the factor $N_e N_p f_{\text{rep}}$ that appears in Eq. (12) is proportional to the total beam power, an optimization of the peak luminosity in a linear accelerator while keeping the power consumption under a reasonable limit can only be achieved by reducing the colliding beam size. Single-pass collisions are optimized by colliding flat beams [27], with horizontal spot size approximately 100 times larger than the vertical size. CLIC aims at colliding beams of 0.7 nm.

The problem with reducing the beam sizes is that the peak luminosity becomes more and more sensitive on relative beam–beam offsets. It can be shown that for rigid Gaussian beams colliding head-on

\(^1\)The CLIC parameters are being reviewed and finalized. Latest values are available in Ref. [19].
the luminosity depends exponentially on the transverse beam–beam offset at the interaction point, $\Delta y^*$:

$$L = L_0 e^{-\frac{(\Delta y^*)^2}{(2\sigma y^*)^2}}.$$ (13)

This is illustrated schematically in Fig. 13. The vertical case is considered because it is more critical. Equation (14) is not accurate for beam offsets larger than approximately $1\sigma_y^*$ because the detailed beam–beam dynamics can no longer be neglected: the mutual attraction of the beams deforms the particle distributions as well as the transverse position while the beams cross each other. In fact, for large offsets Eq. (14) is a pessimistic estimate of the luminosity. On the other hand, Eq. (14) can be used to estimate tolerances on small offsets. A 2% luminosity reduction is achieved from an offset that equals 30% of the vertical beam size, i.e., 0.2 nm for CLIC (which is compatible with the findings of detailed simulation codes).

In order to understand how the tolerance on relative beam–beam offsets translates into a position tolerance for the bulk magnets, Eq. (7) can be used to calculate the beam offset induced by a vertical shift of the final focus quadrupole, $\Delta y^{ff}$. Since the focal point of the doublet by design coincides with the position of the interaction point ($f = l^*$, i.e., $\Delta \psi = \pi/2$), we can easily calculate that

$$\Delta y^* \approx \Delta y^{ff}.$$ (14)

The offset of the quadrupole doublet is approximately equal to the induced beam offset at the IP. The quadrupole doublet behaves like a focusing lens that acts on a parallel incoming beam of light: the focal point moves with the lens. This has important implications on the stability requirements because the sub-nanometre tolerances for the small beams are directly translated into macroscopic tolerances for the stability of the bulk magnets: the relative offsets of the final doublets at either side of the IP must be stabilized to about 0.2 nm in order to ensure stable luminosity production. This tolerance is set for ‘fast’, uncorrelated vibrations above 4–6 Hz.

In order to calculate the luminosity performance in the presence of magnet motion, the time-dependent beam–beam offset has to be calculated as

$$\langle \Delta y^2 \rangle_t = \int_0^\infty \int_0^\infty GM(\omega, \kappa) \times TR(\omega, \kappa) \times R(\kappa) \times FB(\omega) \frac{d\omega}{2\pi} \frac{d\kappa}{2\pi},$$ (15)

where

- $GM(\omega, \kappa)$ is the 2D spectrum of motion of the underlying ground (that mainly depends on the site location and on the tunnel depth);
Fig. 15: Scheme with the overall set-up of the CLIC test stand for vibration measurements and magnet stabilization. A honeycomb support structure provides a flat and stiff surface to test measurement devices and to install objects needing to be stabilized, e.g., CLIC prototype quadrupoles. Two different stabilization systems can be used to damp the table vibrations. Several geophones and a capacitive stretched-wire system (WPS) are used to monitor the vibrations and the alignment of the quadrupoles with respect to the ground. Ground vibrations are always monitored as a reference. Quadrupole prototypes can be connected to cooling water channels.

- $TR(\omega, \kappa)$ is the transfer function between ground and magnet centre, which is used to model support transmission functions and mechanical internal resonances of the structures;
- $FB(\omega)$ is the transfer function of beam-based feedback for the on-line correction of the IP beam offset;
- $R(\kappa)$ is the lattice response function.

Plugging $(\Delta y^2)_t$ into Eq. (13) gives the time-dependent luminosity performance. In reality the luminosity reduction is not determined only by the beam–beam offset in Eq. (15). Similar expressions can be worked out for time variation of the beam size. We have been focusing on the offset because this represents the leading order for performance reduction of a linear collider. In practice, simulation codes exist to evaluate numerically the integrals such as the one of Eq. (15), taking into account accurate treatments of the various contributions (the so-called integrated simulations [31, 32]).

This stability problem is a very good example of the required synergy between different domains such as accelerator physics, magnet and support design, ground motion measurements and modelling, feedback designs. All these aspects have to be taken into proper account in order to achieve a sub-nanometre control of the magnetic centre of the CLIC final focus quadrupole.

For the scope of this lecture, what is relevant is the transfer function $TR(\omega, \kappa)$ because it basically summarizes the result of active mechanical stabilization applied to dump the magnet vibrations in the frequency range that is above the active range of beam-based feedbacks. In the following we shall focus on the CLIC stabilization study. It is nevertheless worth mentioning how the beam-based feedbacks are implemented because this is a critical aspect of the problem. In Fig. 14 the working principle of the IP feedback is illustrated. If the opposing beams collide with an offset, their mutual electromagnetic
Fig. 16: Vertical cross-section of one isolator of the Stacis2000 stabilization system. Four feet were used to stabilize the table housing the CLIC prototype quadrupoles (Fig. 15). A passive damping is provided by stiff rubber (grey area that surrounds the foot leg) with a natural resonance of about 15 Hz depending upon the load. This vibration is damped with an active system based on a closed-loop feedback between geophones (boxes with arrows), which measure the load motion, and piezoelectric actuators, which counteract the measured vibrations. The geophones are fixed to the load and hence table vibrations within the active bandwidth can also be damped.

attraction causes a deflection of the beam trajectory that can be detected with a dedicated beam position monitor (BPM) located downstream of the IP. The BPM reading is the input for a closed-loop feedback that uses a dipole orbit corrector, located at a $\pi/2$ betatron phase advance upstream of the IP to steer the trajectory of the incoming beam. The same scheme is used for the correction of subsequent bunch trains (intra-pulse feedback) as well as for the correction of single bunches within the same train (intra-train feedback). In the latter case, the first bunches of the train are used to steer the rest of the train to collision. The ILC relies on this scheme because of the large number of bunches per train ($\approx 3000$) but this is not the case for CLIC where there is a much smaller number of bunches. As already mentioned, the cut-off frequency for such a feedback is of the order of 1/20 of the repetition frequency.
The CLIC stability study has been focused on demonstrating the feasibility of colliding nanometre-sized beams in CLIC. The goal of the study was to provide an experimental demonstration of the feasibility of stabilizing CLIC prototype quadrupoles to the required sub-nanometre level in a realistic accelerator environment. The tolerances of the final focus doublet are the tightest and therefore feasibility studies have been targeted to meet the tolerance of 0.2 nm above 4 Hz. This was done by building a dedicated test stand for vibration and stabilization studies, as shown in Fig. 15, that included [17]:

1) a honeycomb structure (table) to support the objects being stabilized, e.g., the CLIC prototype quadrupoles;
2) some CLIC prototype quadrupoles;
3) two different stabilization devices to isolate the ground motion and possibly to damp also vibrations of the support structure or of the quadrupoles themselves;
4) several sensors to measure the vibrations of ground, table, and quadrupole prototypes and the alignment of the whole system.

A stabilization system is used to support the honeycomb structure, on top of which quadrupole prototypes are mounted. Several sensors allow simultaneous monitoring of the vibration level of ground, table, and quadrupoles. Quadrupoles can be connected to incoming and outgoing channels for the cooling water. Details of the complete system are available in Ref. [17].

The active stabilization system is an industrial system that combines passive and active stabilization. Passive stabilization alone would not be sufficient because it is only effective at low frequencies (typically below a fraction of a Hz) where correlation of ground motion and beam-based feedbacks effectively reduce the relative beam–beam offsets. The key for the mechanical stabilization for particle accelerators is an active damping of vibrations in the range of frequencies between approximately 1 Hz and 250 Hz, where the mechanical resonances and cultural environmental noise are important — and typically not correlated — and the beam-based feedback is not effective. Active mechanical stability in this case is achieved by piezo-electric crystals as actuators and geophones as vibration measurements. A scheme of the stabilizer feet is given in Fig. 16. Clearly this is just an example of a possible implementation that was used because it proved to work effectively in the range of interest for CLIC.

The stability performance achieved with the stabilization system described above is shown in Fig. 17 [33]. After tuning, the system was used to stabilize a prototype quadrupole to the sub-nm level for the first time: the integrated vertical RMS motion above 4 Hz was 0.4 nm. Integrated simulations of CLIC luminosity performance [17] show that, correspondingly, 70% of the nominal performance can be
achieved (see Fig. 18. Stability in the horizontal plane was also acceptable [17].

The results described above have to be considered as a principle of demonstration of the feasibility of colliding nanobeams. On the other hand, it is clear that the proposed solution cannot be implemented in the real CLIC layout and a mechanical design has to be worked out in detail [34]. It is also worth mentioning that tight tolerance of the order of 1 nm are imposed on the \( \approx 2600 \) quadrupoles of the CLIC linac for preserving small emittances. A cost-effective solution needs to be implemented in the whole machine.

4.3 Remote alignment of the LHC superconducting triplet quadrupoles

The superconducting quadrupole triplets of the Large Hadron Collider (LHC) [18] are the machine components with the tightest alignment tolerance. In order to achieve the nominal colliding beam sizes of 16.7 \( \mu \)m at the interaction point, betatron functions larger than 4000 m are required at the location of the quadrupole triplet. As shown in Eq. (6), larger values of the betatron function amplify the effect of the perturbation from quadrupole alignment errors. In order to optimize the LHC performance, the magnetic centre of these quadrupoles should be centred around the beam trajectory to within better than 0.1 mm, which is at the limit of typical noise levels that can be found in an accelerator environment.

In addition, the LHC experimental insertions will be highly activated by radiation products from the collisions. Thus, after a few years of operation, any human intervention close to the magnets must be minimized. It was decided to equip the superconducting triplet of the LHC with an active alignment system that will allow a fully remote positioning control of these critical magnets during beam operation.

Another critical aspect is that superconducting magnets are inserted into a cryostat and their position cannot be measured directly. The determination of the position of the magnetic centre with respect to reference targets outside the cryostat (sometimes referred to as fiducialization) is a critical procedure that involves many steps throughout the magnet production, cryostating, and installation. This is beyond the scope of this contribution and interested readers should look into the dedicated literature [35].

A schematic view of an LHC experimental insertion region is shown in Fig. 19. The cavern around the interaction point (IP) houses the particle detector (not shown in this scheme). Four experiments will be installed in the LHC and all their triplets are equipped with an active alignment system. A detailed description of them can be found in Refs. [38, 39]. The survey of the quadrupole position relies on a redundant set of high-precision sensors, and stepping motors mounted on the jacks are used to change the cryostat positions. In particular, the system includes

- 68 WPS (wire positioning system) sensors (two axes each for horizontal and vertical position measurements);
- 100 HLS (hydrostatic levelling system) sensors (vertical measurements only);
- 24 DOMS (differential offset measurement system) (horizontal measurements only);
- 128 stepping motors for motorized jacks (16 \( \times \) 2 per 4 interaction points);

The layout of the sensor installation onto each magnet cryostat is shown in Fig. 20 and photographs of the tunnel installations are given in Fig. 21. In addition, 128 temperature sensors are installed in order to monitor the temperature of key components of the system. The relevant statuses and configuration parameters are also accessible remotely. It should be noted that the application software that controls this system is connected to the alignment survey database and can access the ‘as-installed’ position of the magnets. This allows the calculation of the magnet positions with respect to the nominal beam trajectory (according to the latest alignment survey) and will be a crucial tool for LHC operation.

Clearly, a precise survey of the magnet positions is of primary importance in order to achieve an accurate alignment. Therefore, high-precision HLS and WPS systems, which have proved their reliability in real accelerator environments during several years of operation worldwide, have been chosen. It is expected that these systems will allow measuring the position of the triplet quadrupole with an accuracy...
below 10 µm. In order to achieve this level of accuracy a number of systematic effects must be taken into account and compensated. These include

- electronics noise on the capacitive sensors, possibly induced by the circulating beam or by the near-by equipment;
- effect of the wire sag;
- effect of tidal motion that modifies the water level;
- local variations/perturbations of the gravitational field.

Algorithms have been developed to take into account all these effects [4, 23]. Unfortunately, the system could not be tested extensively with beam in the machine in 2008 because of the short LHC run with beam. Commissioning without beam suggests that the accuracy of 10 µm set as a goal is within reach.

The differential offset measurement system (DOMS) is only used in the high-luminosity experiments in IP1 and IP5 where an additional stretched-wire system is installed in a dedicated by-pass gallery along the experimental areas in order to monitor relative offsets of the two triplets at either side of the interaction point. This parameter will be of primary importance during operation at small beam sizes. The DOMS are used to measure the horizontal distance between the reference wire in the by-pass gallery and the two wires stretched along each triplet.

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Fig. 20: Installation layout of the hydrostatic levelling system (HLS, blue circles) and wire positioning system (WPS, black boxes) on the LHC triplet magnet cryostats (light blue boxes). The Q1, Q2 and Q3 magnets at the right side of the IP are shown. A symmetric layout is used on the IP left side, in all four experimental regions.

Fig. 21: Photographs of the stepping motors that are used for the remote alignment of the LHC triplets (left) and of the sensor installation mounted on the upper part of the magnet cryostats (right).
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