CLIC ACTIVE PRE-ALIGNMENT SYSTEM: PROPOSAL FOR CDR AND PROGRAM FOR TDR

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Abstract

The active pre-alignment of the Compact Linear Collider (CLIC) is one of the key points of the project: its feasibility will be demonstrated in the Conceptual Design Report (CDR), end of 2010. The components must be pre-aligned with respect to a straight line within a few microns over a sliding window of 200 m, along the two linacs of 20 km each. The proposed solution is the outcome of 20 years of R&D. Stretched wires of more than 200 m, overlapping over half of their length, will be the reference of alignment. WPS sensors, coupled to the components to be pre-aligned, will perform precise and accurate measurements within a few microns, with respect to these wires.

In this paper, the global strategy of active pre-alignment is detailed, taking into account both the determination of the position and the re-adjustment. This presentation will be completed by results demonstrating the feasibility of the proposed solution. The validation of such a solution will be confirmed on real size mock-ups, in laboratory and in an accelerator environment. These tests, foreseen during the Technical Design (TDR) phase, will be completed by R&D on alternative alignment and re-adjustment solutions.

INTRODUCTION

The Compact Linear Collider (CLIC) study is a site independent feasibility study in order to develop an electron-positron linear collider for physics up to the multi-TeV center of mass colliding beam energy range (nominal 3 TeV). The solution proposed must be of a realistic technology at an affordable cost [1]. The next milestone of this project is a Conceptual Design Report (CDR) that must be ready mid of 2011. In this report, the feasibility of CLIC technology will be demonstrated, a design of a linear collider based on CLIC technology will be proposed and an estimation of its cost will be given.

The required luminosity of 2.10^{34} $cm^{-2}s^{-1}$ will be reached with powerful beams (14 MW each) colliding with extremely small dimensions (1 nm in the vertical plane) and high beam stability [2]. Such small dimensions can only be obtained with extremely small emittances: the limitation of the total emittance growth is one of the technical challenges of the CLIC technology. As a consequence, pre-alignment tolerances are far tighter than in other accelerators.

Pre-alignment will take place when the beam is off, with the aim of supplying a proper pre-alignment of the components within a few microns over several hundred meters, in order to minimize the emittance growth or beam losses. This first step of alignment will allow the implementation of beam based alignment and beam-based feedbacks. It will be performed remotely, taking into account the precision and accuracy needed and the number of components to be pre-aligned. The determination of the position of the components will be performed thanks to alignment systems and their associated sensors, while the re-adjustment will be carried out thanks to actuators.

Since 1990, the hypothesis considered as target for research and development (R&D) is the following: after computation, for a sliding window of 200 m, the standard deviations of the transverse position of each component with respect to the straight fitting line must be inferior to 3 microns rms. In 2007, after discussion with physicists in charge of the beam dynamics, this value was set at 14 microns rms for CDR [3].

The state of the art concerning the determination of the position of the components is about 0.1 mm rms over 100 m (case of the cryo-magnets of the LHC) [4]. Alignment systems have been developed for monitoring applications, where micrometric precision is needed. In LCLS, a combination of WPM sensors and HLS provides a monitoring of the stability of the components below 5 microns, during one week, along 140 m [5]. In the case of the CLIC pre-alignment, precision and accuracy of a few microns are needed, and an accuracy of such a value is far more difficult to reach. Concerning re-adjustment, only solutions providing a precision of displacements of a few microns exist, while the requirements are sub-micrometric for CLIC.

The solution of active pre-alignment (determination of the position and re-adjustment) chosen for the CDR will be detailed, as the mock-ups being built for its validation. Then, the paper will introduce the perspectives concerning the TDR phase.

R&D PROGRAM

Taking into account the tight requirements for pre-alignment, the studies concerning pre-alignment started 20 years ago. Several successive mock-ups demonstrated that sub-micrometric active alignment is possible [6]. Alignment methods using overlapping stretched wires were proposed, with their associated WPS, and validated in the accelerator environment of CLIC Test Facility 2 (CTF2) [7]. But only the precision of this alignment system was demonstrated and not its accuracy. Then, due to the increase in size of the components, the complete solution of interlinking their supports needed to be reviewed, as well as the solution concerning the support of the Main Beam quadrupole, that has to be compatible with the stabilization requirements (nanometer level in the vertical direction) [8]. So, the following R&D program was set up to address the issues:

- Concerning the re-adjustment: to upgrade the existing solutions of supporting and adjustment, allowing sub-micrometric displacements over 3 and 5 degrees of freedom.
- Concerning the determination of the position of the components: to improve the stretched wire solution and to develop a laser based solution as B-plan, allowing validating the first solution through an inter-comparison

Solutions coming out this R&D program are detailed in the two next chapters.

SOLUTION CONCERNING RE-ADJUSTMENT

In order to simplify the re-adjustment, several components will be pre-aligned on supports. Along the Main Beam (MB), RF structures will be pre-aligned on girders, and MB quad of 4 different lengths will be coupled with BPM on an interface plate. Along the Drive Beam (DB), PETS and DB quadrupoles will be pre-aligned on the same girders. So, two types of supports are foreseen: DB and MB girders on one hand and interface plates for MB quadrupole on the other hand. DB and MB girders will be interlinked with their extremities, based on so-called cradle. This allows a movement in the transverse girder interlink plane within 3 degrees of freedom ("articulation point" between girders), the longitudinal direction being adjusted thanks to a micrometric mechanical guiding. MB quad is mounted on an interface plate allowing an adjustment along 5 degrees of freedom (the longitudinal axis will be blocked longitudinally after the initial alignment).

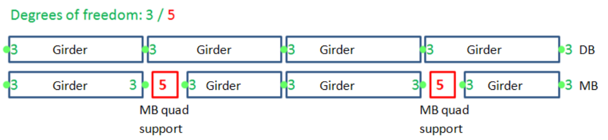

Figure 1: degrees of freedom of supports

Cam movers are proposed for 5 DOF re-adjustment of the MB quad interface plate and linear actuators are proposed for the re-adjustment of the DB and MB girders.

Case of the cam movers

CTF2 solution being not compatible with stabilization requirements, the new re-adjustment system must fulfill the following requirements:

- Providing rigid support, low vertical dimension
- High first Eigen frequency of supporting structure
- Low friction in contact points
- Simple kinematics

Three solutions were considered: hexapod structures, wedge systems and cam-based repositioning systems. Hexapod structures are based on linear actuation: they provide low rigidity and low Eigen Frequency. Wedge systems provide larger contact surface which leads to higher contact friction, which is not recommended in CLIC case. That is why a cam-based alignment systems was chosen. It is a 3 points alignment system, with 4 interfaces with the ground settlement, providing 5 Degrees of Freedom (DOF). This system, which supports the girders of the Swiss Light Source (SLS) at PSI and the undulators of the XFEL at SLAC, is used in several other synchrotrons, but not with the sub-micrometric displacements required. Therefore, an improved 1 DOF cam-based system from SLS is being studied on a dedicated mock-up, and more particularly the sine wave response and the repeatability in short and long range alignment. The cam based system was tested with three different bearing and outer rink configurations. Sub-micron repeatability on full stroke (10 mm) was achieved with every configuration. The best repeatability, 0.3 micron on full stroke, was attained with a cylindrical roller bearing and a cylindrical outer rink [9]. A validation of 5 high resolution cam movers is foreseen mid November 2010 on a 5 DOF mock-up, with an interface plate designed to provide stiffness and to deform on self weight less than one micron in the center.

Case of the linear actuators

The re-adjustment concept, using linear actuators and cradles linking two adjacent girders as an articulation point was validated in CTF2. But due to the modification of the size of the components and to a considerable increase of load, some questions were raised concerning the clearances and kinematics of such a solution. Consequently, a new design is being studied concerning the cradles. The proposed solution will be validated on a mock-up consisting of two girders and three cradles, which will be ready mid November 2010. This mock-up will allow:

- The determination of the impact of millimetric displacements on one cradle with respect to the others
- The evaluation of the impact of such displacements on the extremities of girders
- A better understanding of the girder behavior.

SOLUTION CONCERNING THE DETERMINATION OF THE POSITION OF THE COMPONENTS

Before adjusting, the position of the components has to be determined. The general philosophy of pre-alignment consists of two metrology networks:

- A primary network: the Metrologic Reference Network (MRN), made of overlapping alignment references of at least 200 m. It propagates the precision of alignment needed: a few microns over more than 200 m. As it is not possible to implement a straight alignment reference over 20 km, this last one is determined from parallel wires, linked in at least three points (for redundancy) by WPS sensors fastened on a common metrological plate. The mechanical interfaces of the sensors have been determined from a Coordinate Measuring Machine (CMM) with a sub-micrometric uncertainty of measurement (±0.3 µm +1 ppm).

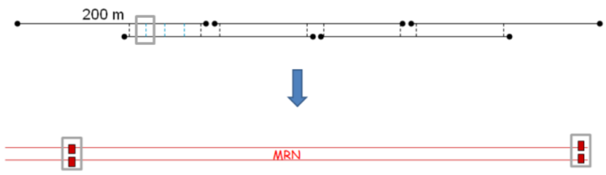

Figure 2: Metrological Reference Network (MRN)

- A secondary network: the Support Pre-alignment Network (SPN), framed by the MRN, associates sensors to each support to be aligned, providing a few microns precision and accuracy over 10 m.

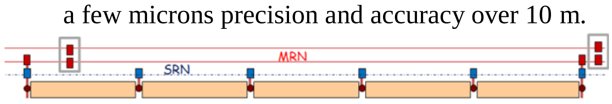

Figure 3: Support Pre-alignment Network (SPN)

A third step is required: AFC (Alignment and Fiducialisation of each component on the supports). Indeed, this pre-alignment strategy is effective only if as a preliminary the components could be pre-aligned accurately and precisely on the supports, and that the mean axis of the zero of components of the same support is perfectly known with respect to the mechanical interfaces of sensors from SPN network. This step of fiducialisation will be performed with tri-dimensional CMM machines with an uncertainty of measurement below the micron.

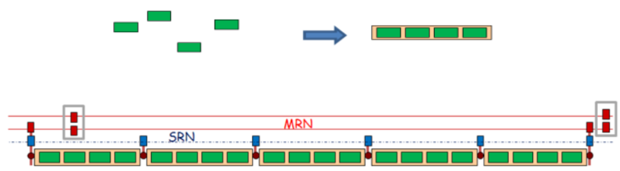

Figure 4: Alignment and Fiducialisation of Component (AFC)

Solution for MRN

A new concept of a 3 points alignment system was proposed and tested over 140 m through an informal collaboration with NIKHEF. This system consists of a laser beam under vacuum, illuminating a diffraction hole and a CCD camera measuring the offset of the center of the created diffraction pattern, w.r.t the axis formed by the two first components. This alignment system showed a resolution below 0.1 micron [10], but its adaptation to the CLIC configuration, and more particularly its calibration will not be ready for the CDR.

So, a solution of overlapping stretched wires of at least 200 m is proposed for the CDR. The main issue concerning the stretched wire as reference for alignment is its long term stability (w.r.t to perturbations like effects of temperature, humidity, creeping effects, air currents). HLS system coupled to WPS allows a continuous modelling of the catenary, following the minimal configuration shown below.

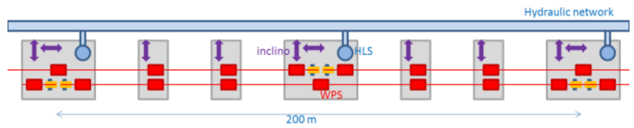

Figure 5: MRN configuration for CDR

Solution for SPN

In order to perform sub-micrometric measurements, stability and knowledge of reference are important, as well as sensors carrying out 'absolute' measurements, e.g. with a zero of sensor determined with respect to its mechanical interface fastened on the support to be aligned. Two types of WPS can be considered: the capacitive based WPS (cWPS) and the optical based WPS (oWPS). Both sensors have been equipped with a flat, cone, chamfer, conical type interface capable of an installation to the micron repeatability. cWPS sensor, at that stage of "on the shelf product", can be used in radioactive environments, which is not the case of the oWPS stage prototype [11], where optimization with rad-hard components has not been done yet. In addition to its cost, the oWPS has a second advantage: any type of wire can be used and not necessarily a conductive one, which opens up opportunities in terms of linear mass and applied load. As an example, a non-conductive wire as the Vectran, a liquid crystal polymer fiber [12], will have a sag two times smaller than a carbon peek wire used with the cWPS if stretched on 200 m.

Using the same system alignment for the SPN and MNR simplifies configuration: the stretched wire reference will be used for both networks. Taking into account the two parallel beams, the same reference installed between the two beams can be used, which leads to the configuration below.

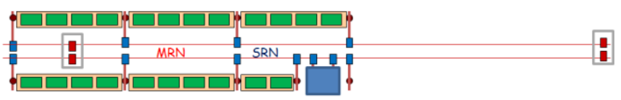

Figure 6: Configuration of the metrological networks for CDR

Feasibility of the solution proposed

The following points are required to demonstrate the feasibility of the pre-alignment solution proposed for the CDR:

- A stable and known alignment reference
- Sensors accurate and precise
- Objects with a length of 2 m can be measured with a precision and accuracy better than a few microns.
- The solution is compatible with other systems and environment.

Short distance precision was achieved in CTF2, where a few microns precision was demonstrated, but there was no relevant value at that time concerning accuracy.

The two first points are being validated on a 140 m facility located in TT1 tunnel, on old tunnel from Inter Section Region (ISR). The precision of such a solution was shown to be better than 2 microns over 33 days on a 140 m long facility [13]. Some first results were obtained concerning the accuracy of such a solution: 11 microns rms in vertical and 17 microns rms in radial. Following these measurements, some faults were detected and are being corrected: the accuracy should soon stand below 10 microns rms [14].

The dynamic and static effects of gravity on these alignment systems are the subject of the two theses. [15]

With regard to sensors, inter-comparison measurements between these two types of sensors, as well as the RF Peters WPM are under way in order to conclude concerning the performance of sensors [16].

As mentioned, fiducialisation stage will be carried out with a tri-dimensional CMM machine with an uncertainty of measurement below the micron. Other methods are being investigated in order to achieve such measurements on the field: micro-triangulation, new generation laser tracker and photogrammetry.

Concerning the compatibility of the alignment solution with the other systems (vacuum, RF, powering, stabilization, clip art magnets, BPM), all systems and components are now integrated into CAD 3D models. Real size mock-ups with real components (or false components with equal functionalities) will allow the testing and validation of the pre-alignment strategy on short range [17].

VALIDATION ON TWO BEAM PROTOTYPE MODULES

Description

The CLIC linac will consist of more than 20,000 modules. These are sets of 2 m length, including the components of the two beams DB and MB, knowing that there are 5 types of different modules (depending on the length of the quad MB component). In order to validate technical components that are part of these modules and their integration, two CLIC module prototypes are in preparation: one for laboratory environment, one for operation in the real environment of an accelerator of particles with beam: CLEX (Experimental Area CLIC) [18].

Validation of pre-alignment on these two beam prototype modules

A test program has been set on the pre-alignment and these mock-ups. First, the concept of re-adjustment will be validated, with the ability to perform sub-micrometric displacements. A comparison of performance will be carried out before and after the installation of systems that can create mechanical stresses such as wave guides or vacuum. Measurement of the Eigen Frequencies of the supports will be then performed. These prototypes will help validate fiducialisation strategy then check the stability of the position of components on girders, through different sequences: the impact of transport on a micrometric pre-alignment, then the impact of variations in temperature. Finally, thanks to these prototypes, the costs will be better apprehended, as well as schedule data.

Sensor interfaces will be doubled on the laboratory mock-up, in order to achieve inter-comparisons between different SPN type systems.

Status

Design of technical components is in progress as well as their integration. The two first modules of the laboratory mock-up will be installed before the end of the year, including girders, linear actuators and associated cradles, loads simulating components. Cradles will be equipped with WPS sensors and inclinometers to perform the pre-alignment of the girders.

TOWARDS TDR

At the end of this CDR period, the preparation of the Technical Design phase is in progress. In addition to the mock-ups, which will ensure a transition between the two phases, other developments are planned: alternative solutions concerning re-adjustment and determination of position. Indeed, even if the technical feasibility for the pre-alignment proves to be settled, the cost of the entire solution must be realistic and as low as possible. With the proposed configuration, a very large number of components are implemented (more than 120 000 actuators, 20,000 cam movers, 90,000 WPS) and various optimization solutions need to be considered.

One of the first ideas to decrease the number of actuators and sensors would be to reduce the number of supports to be aligned. The length of a module is currently 2 m, and one of the first studies to be launched will be looking at the possibility to extend this module, or group DB and MB components of the same module on a single support. Although this idea of lengthening the girders is initially appealing, this increases the volume in which components will have to be pre-aligned and dimensionally controlled to a few microns. Similarly, long term stability (temperature dilatation) will still be more difficult to achieve.

The coupling of DB and MB components on the same girder must also be assessed. In this case, the loads applied on a support would be doubled and a new concept of re-adjustment should be proposed. One solution would be to keep the articulation point concept, using a special configuration of cam movers instead of linear actuators [19]. However, to implement such a solution some experience must have been acquired on the cam movers.

One other solution to decrease the number of WPS would be to use one WPS sensor for two wires. This possibility has to be studied with oWPS type sensors. A mechanical procedure was found to stretch efficiently two wires in the same protection and sensor.

At present, the only solution to validate stretched wire solution on long range is to cross-check with other stretched wire solutions (sometimes with sensors of different technologies). The development of an alternative optical solution would allow a real comparison and validation of alignment systems in term of performance, integration and cost.

A new formal collaboration with NIKHEF will deal with:

- The design of short range (SPN type) / long range (MRN type) solutions adapted for the CLIC requirements.
- The integration of a short range alignment solution (SPN type) on the two beam module prototype
- The inter-comparison of a long range solution in TT1/TZ32 tunnels.

An alternative solution was also proposed on CERN side, named LAMBDA for Laser Alignment Multipoint Based – Design Approach [20]. The concept is based on the use of a laser beam under vacuum, considered as the reference of alignment and sensors distributed along the beam, coupled to the support to be aligned and determining their offset with respect to the beam. The originality of the proposal stands in two points:

- Each sensor consists of three parts: a measurement surface, a convergent lens and a CCD camera; thus the observation of the speckles on the surface is performed indirectly by the CCD, which reduces the angular sensitivity of the system. According to a first simulation study [20], an angular orientation better than 0.2 mrad is sufficient for micrometric movements.
- Mechanical or optical shutters as measurement surface will not alter the beam and keep the straightness of the reference of alignment. Each shutter should have repeatability better than 12 microns to ensure a sub-micrometric measurement uncertainty.

In addition to these developments of alternative solutions, an optimization of the systems proposed for the CDR is underway: development of low cost capacitive sensors with firm FOGALE Nanotech, development of a more robust oWPS with Brandeis University, development of wires with high rupture force, low linear mass, no creep effect and rad-hard.

CONCLUSION

Thanks to 20 years of R&D and several mock-ups, a solution fulfilling the CLIC pre-alignment requirements is proposed for CDR. The preferred with regard to the determination of the position is to use parallel wires of at least 200 m covering about half their length. Concerning the determination of position of components, stretched wires overlapping over half of their length are proposed. These wires will provide a stable and perfectly determined reference of alignment for sub-micrometric measurements. WPS sensors and inclinometers, coupled to the support to be aligned will determine the position of supports with respect to the alignment references. Re-adjustment of these supports will be carried out thanks to linear actuators for DB and MB beams actuators or cam movers for the MB quad interfaces. The feasibility of the proposed solutions will be endorsed on the CLIC module prototype mock-ups.

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