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1. Survey Procedure

A procedure is described and methods which yield toward alignment of positions of all CBETA components within their tolerances. Major principles governing survey and alignment measurement space are briefly shown and their relationship to a lattice coordinate system. Then a discussion of the activities involved in a step-by-step sequence from initial layout to final alignment is described. In the vertical plane, the curvature of the earth does not need to be considered as the dimensions of the whole CBETA project are to small. The leveling is done with respect to gravity.

1.1 Network Design Philosophy

A 3-D "free stationing" is chosen, rather than setting up the instrument over a known point. The instrument's position is flexible and chosen only following considerations of geometry, line of sight and convenience. To determine the instrument position, at least three points, whose coordinates are already known or are part of a network solution, need to be included in the measurements. The approach does not require forced centered instrument set-ups, thus eliminating the need for set-up hardware and their systematic error contribution. Removable heavy-duty metal tripods, translation stages, CERN sockets and optical plummets are not needed (see Fig. 16 and Fig. 17). The geometry should also permit observing each target point from at least three different stations. The following sketch (*Fig. 18*) shows a typical section of the layout. A triplet of monuments is always placed in the tunnel cross section containing a corrector magnet. One monument will be placed close to the corrector magnet on the floor, the second one mounted at instrument height to the aisle wall, and the third monument mounted to the back wall also at instrument height.

1.2 Lattice Coordinate System

The LCLS lattice is designed in a right handed beam following coordinate system, where the positive y-axis is perpendicular to the design plane, the z-axis is pointing in the beam direction and perpendicular to the y-axis, and the x-axis is perpendicular to both the y and z-axes.

Figure 1: Sphere mounted theodolite target

Figure 2: Sphere mounted glass and air reflectors

1.3 Tolerance Lists

The relative positioning tolerances σ_x, σ_y, σ_z of the girders, BD's, QFs are listed in the following table:

Table 1: CBETA positioning tolerances

	σ_x [µm]	σ_y [µm]	σ_r [mr]	$\sigma_{x/z}$ [µm/m]
Straightness of girders	15	30	1	n/a
Relative alignment between girders	50	50	1	n/a
Global straightness of CBETA arcs	100	500	2	100/10
Linac straightness	n/a	n/a	n/a	150/15
Quadrupole ab initio	50	50	n/a	n/a

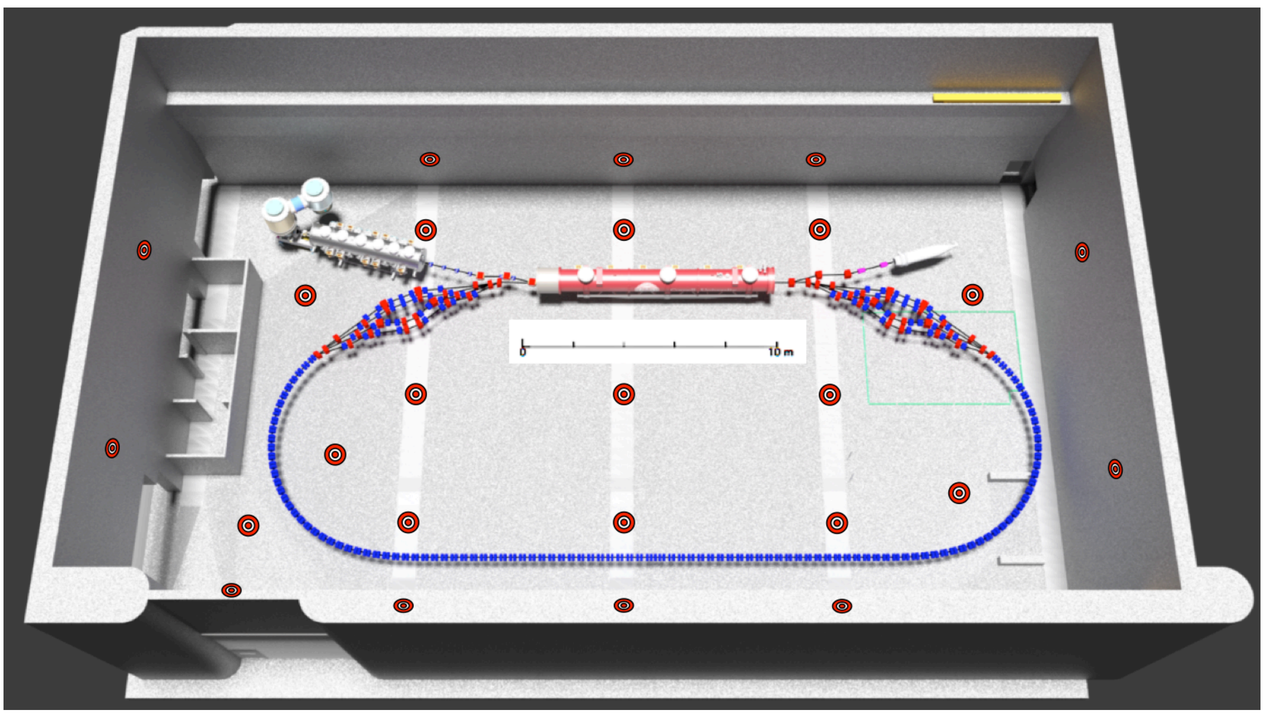

Figure 3: CBETA network layout

7.2.3 Relationship between Coordinate Systems

The relationship between the surveying and lattice coordinate systems is given by the building design and machine lay-out parameters. The result is a transformation matrix (rotations and translations).

1.2 Fiducializing the CBETA Magnets

The correct fiducialization of magnets is as important as their correct alignment since an error in either task will affect the particles' trajectory and cannot be distinguished from each other. Fiducialization can be accomplished either through opto-mechanical and opto-electrical measurements or by using fixtures, which refer to a magnet's reference features. The opto-electrical measurements are the "Harmonic coil" measurement preformed together with the survey measurements of the magnetic field center, magnet fiducials with respect to the harmonic coil center as shown in *Fig. 4.*

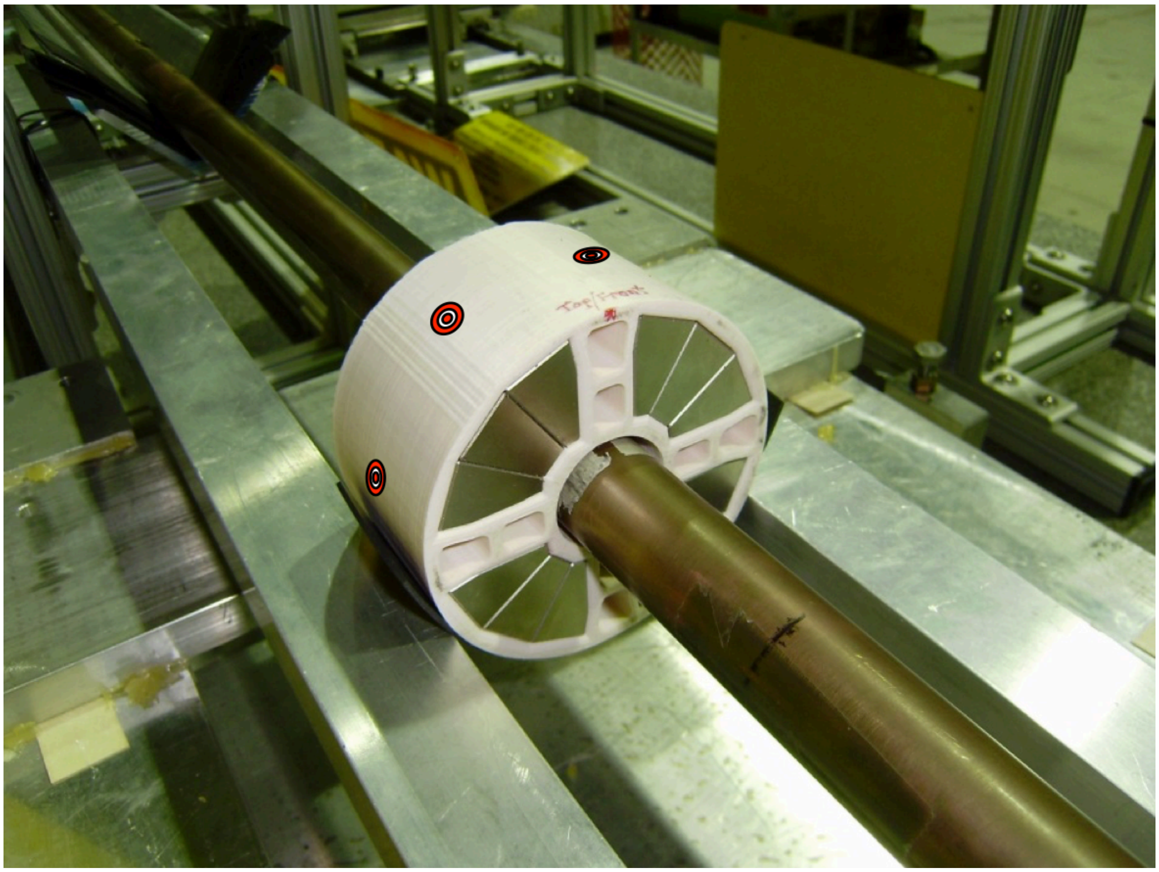

Figure 4: Harmonic coil measurements and magnet fiducialization.

1.3 *CBETA Absolute Positioning*

Common to all parts of the machine, free-stationed laser trackers, oriented to at least four neighboring points, are used for the absolute positioning measurements. The tracking capabilities of these instruments will significantly facilitate the control of any alignment operation (moving components into position).

1.3.1 Pre-alignment of Girder Supports and Magnet Movers The girders will be supported by adjustment systems sitting directly on top of concrete piers. The adjustment systems are based on the Bowden camshaft design. Two individually controlled camshaft pairs and two single camshafts provide five degrees of freedom per girder. The camshaft design doesn't compromise the rigidity of the supports and, consequently, doesn't show a resonance in an undesirable frequency range. This mover system comes in two horizontal slices. The bottom piece consists of a mounting plate, which holds the shafts. The top part is integrated into the girder by mounting the kinematic cams to the girder. The girder is held onto the shafts by gravity.

To accommodate easy installation, the bottom parts of the movers, set to mid range, have to be aligned relative to each other. The required relative position tolerance of these, however, is fairly loose, since the two axes cams are only paired with a single axis cam. On the other hand, to retain as much magnet mover range as possible, the bottom part of the magnet movers should be within 0.5mm of their nominal positions.

To facilitate placing a pedestal such that its top is within 0.5 mm of its nominal position, a widely used method can be used. Here, the base plate of the bottom part of a mover is mounted to the pier by four standoff screws, which are grouted/epoxied into the concrete. The vertical/horizontal pre-alignment of the base plate is accomplished by the following sequence of steps: After the four bolts are epoxied into the concrete, a nut with a washer on top is screwed onto each bolt. These nuts are set to their nominal heights by a simple level operation. Next the base plate is set on the nuts, and a set of washers and nuts is then screwed on the bolts to fasten it down. However, the top nuts remain only hand tight at this point. Next, the elevation and tilts of the base plate are set by adjusting the position of the lower nuts, and subsequently checked with a level with respect to local benchmarks. Then a total station with a "free station Bundle" software package is used to determine the horizontal offset and to simultaneously double-check the vertical offset of the base plate from its nominal position. Finally, the base plate is moved into horizontal alignment using a clamp-on adjustment fixture (push - push screw arrangement), and the nuts are tightened to the prescribed torque. To vibrationally stiffen the set-up, the space between the pier and the base plate should be filled with non-shrinking grout after the alignment has been confirmed.

1.3.2 Quality Control Survey Once the above step is completed, the mover positions will be mapped. If the positional residuals exceed the tolerance, a second iteration can be "jump started" by using the quality control map to quantify the position corrections, which need to be applied. Should a second iteration be necessitated, a new quality control survey is required after completion of the alignment process.