

SURVEY AND ALIGNMENT OF THE EINSTEIN TELESCOPE PILOT AT CERN

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Abstract

The Einstein Telescope (ET) is a proposed third-generation gravitational-wave observatory requiring an ultra-high-vacuum infrastructure of approximately 120 km, making the achievement of the required alignment tolerances a significant challenge. To validate key engineering and installation procedures, the ET pilot sector has been constructed at CERN as a reduced-scale demonstrator using full-size representative vacuum components in a shortened configuration. Construction is ongoing, with the lower beamline successfully installed and fiducialisation of the upper beamline underway, with its installation envisaged by the end of 2026.

This paper presents the survey and alignment methodology developed for the ET pilot sector, covering beam tube and end-cap fiducialisation, establishment of a high-precision survey network, setting out of vacuum infrastructure supports, pre-weld alignment, and final installation using laser tracker technology. Alignment to the nominal beamline was achieved through iterative adjustments supported by real-time measurement feedback.

The alignment accuracy achieved is reported, highlighting the effects of manufacturing tolerances, welding distortions, structural deformation, and support system limitations. Despite gravitational sag and fabrication-induced offsets, all components of the installed lower beamline were positioned within the required tolerances.

Rather than demonstrating the feasibility of a specific measurement methodology for the full observatory, the study demonstrates the alignment performance achievable with existing adjustment systems. It also highlights the need for more automated survey and alignment workflows for the full-scale Einstein Telescope to achieve the required efficiency, repeatability, and scalability.

EINSTEIN TELESCOPE

The Einstein Telescope (ET) is a proposed third-generation gravitational-wave observatory that aims to increase sensitivity by approximately an order of magnitude compared to existing facilities such as LIGO and Virgo [1,2]. This increase in sensitivity will extend the observable volume of the Universe by several orders of magnitude, enabling precision studies of compact-object mergers, tests of general relativity in the strong-field regime, and observations of astrophysical sources throughout cosmic history [2].

Achieving this performance requires not only advances in detector technology but also the construction of ultra-high vacuum infrastructure.

The final configuration of the observatory has yet to be selected between two alternatives: a triangular layout comprising six interferometers with 10 km-long arms, arranged as three nested pairs within an equilateral triangle; and a two-site layout, with each site hosting an L-shaped detector with two 15 km-long arms. The ET infrastructure is proposed to be located underground with the aim of reducing seismic and Newtonian noise and thereby extending the low-frequency sensitivity [1,3].

Both configurations would have a total beam tube length of approximately 120 km [4]. In the triangular layout, each 10 km side would accommodate two lower and two upper beamlines, whereas each site in the two-site layout would comprise two adjacent 15 km beamlines [5]. The scale of this vacuum system, together with the stringent geometric requirements imposed by the interferometer optics, presents significant challenges in manufacturing, installation, and alignment [3]. Efficient, accurate, and reproducible survey methodologies will therefore be essential for the successful construction of the observatory.

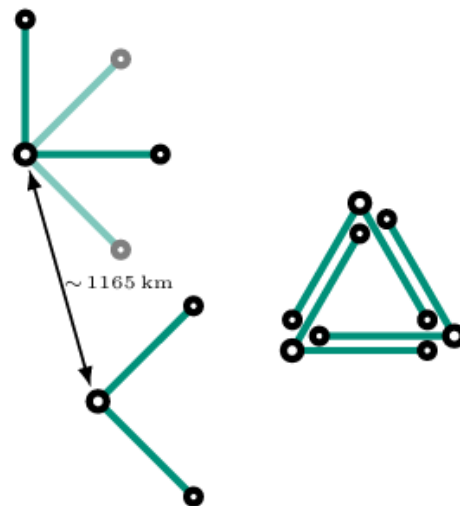


Figure 1: Schematic of ET geometries under consideration: two L-shaped detectors (either parallel or at 45°), or a triangular configuration made of three nested detectors [5].

EINSTEIN TELESCOPE PILOT SECTOR

To validate the proposed engineering solutions, a reduced-scale pilot sector that replicates the ET vacuum infrastructure using full-size components arranged in the same configuration as the final design has been constructed at CERN. The ET pilot serves as an engineering demonstrator for the design, fabrication, installation and commissioning of candidate beam tubes, support structures and vacuum components

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under representative installation conditions. Beyond validating ultra-high vacuum technologies, the ET pilot sector provides an opportunity to evaluate assembly and installation methodologies that must ultimately be deployed over tens of kilometers.

Survey and alignment form a key component of this program. The work presented in this paper covers the complete alignment workflow, including the setting out of support frames, fiducialisation of beam tube and end cap assemblies, pre-weld alignment, and final positioning of the installed components with respect to the nominal beamline. The experience gained from the ET pilot sector provides valuable feedback on achievable installation accuracies, alignment strategies and opportunities to improve the efficiency and scalability of future ET construction.

Description and Layout of ET Pilot Sector

The ET pilot sector is installed in Transfer Tunnel 4 at CERN's Meyrin site in Geneva, Switzerland. The facility consists of reinforced concrete floors and walls and provides a mechanically stable environment with limited exposure to seasonal temperature variations, making it suitable for precision survey and alignment activities.

The ET pilot sector is 43 m long, 36 m of which is made up of an assembly of six beam tubes welded together. At either end of the 36 m long beam tube assembly is an end cap, a hydroformed bellows assembly, and a pumping module. Individual beam tubes are welded together and assembled using welded joints and positioned between the pumping modules.

The pilot sector is made up of two beamlines, a lower one and an upper one - see Fig. 3. The distances between the centers of the upper and lower beamline tube centers is 1.79 m. At the date of publication, only the lower beamline had been installed and this will be the scope of this paper.

Beam Tube Description The beam tubes are 6 m long with an internal diameter of 1 m. Each tube has four circumferential stiffeners to impede buckling of the tubes under vacuum - see Fig. 2. Each tube includes an internal baffle ring located 500 mm from one end of the tube. The baffle ring incorporates two precision-machined 6H7 holes designed to receive precision survey target adapters used for measuring the position of the baffle rings. These holes define the reference locations for the accurate installation of baffles within the tubes.

The baffles themselves, which were not installed at the time of the measurement, are precision-shaped, optically coated components positioned within the beam tube to intercept stray light. Their function is to suppress unwanted reflections and scattering by absorbing or redirecting intercepted radiation away from sensitive optical elements [8]. Because the baffle rings are rigidly welded to the beam tube structure, any offset between the baffle ring center and the tube axis is fixed and cannot be corrected during installation.

For alignment purposes, each beam tube is equipped with four 100 mm long extended external fiducials designed to

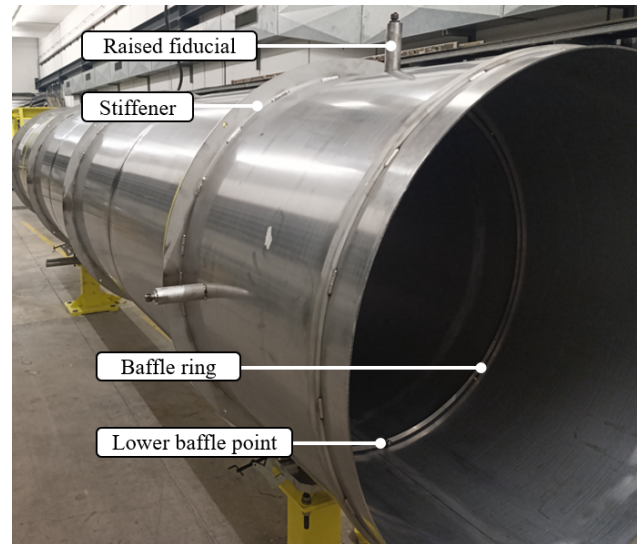


Figure 2: ET pilot sector beam tube

optimise line-of-sight accessibility during laser tracker measurements. These fiducials, which are equipped with 8H7 survey reference holes are located near the ends of the tubes to minimise lever-arm effects during alignment of the tube axis. The beam tubes of the upper beamline includes two fiducials projecting radially outward and two oriented downward for accessibility, while the lower beam tubes have two fiducials projecting radially outward and two oriented upward.

End Cap Description Each end cap is equipped with six external fiducials incorporating 8H7 precision holes. Its reference geometry is defined by a machined cylindrical surface and a reference plane established by four 8H7 holes. The cylinder is measured as a circle and projected onto this plane, with its centre defining the mechanical origin. The nominal beamline direction is given by the normal to the reference plane through this origin, while the midpoint between two 8H7 holes defines the coordinate system orientation. The end caps are connected to the beam tubes by flexible bellows, facilitating assembly and accommodating the small positional adjustments required during installation.

The Adjustment Systems

The vacuum components are supported by a gantry-based suspension system - see Fig. 4. The 36 m beam tube assembly is supported by four cradles suspended by steel cables from overhead gantry frames, enabling controlled vertical and horizontal adjustment. The entire 36 m beam tube assembly was supported by four positions i.e., two positions for each 18 m section of the assembly - see Fig. 5. The fact that the tube assembly was non-rigid affected how well the sections of the that were far away from the adjustment points could be adjusted.

The end caps are mounted on adjustable supports equipped with push-pull screw mechanisms, allowing posi-

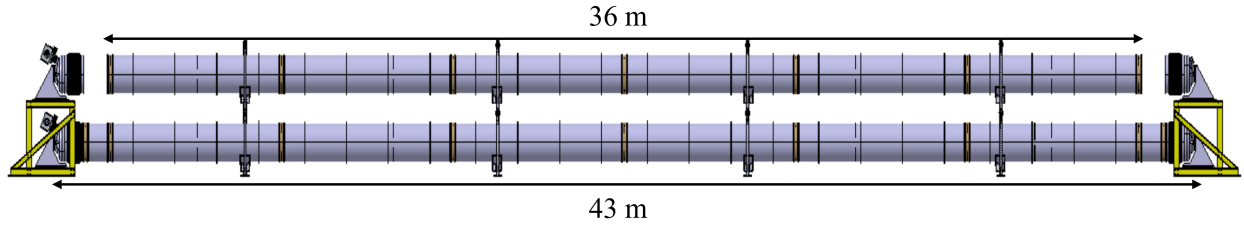


Figure 3: Full length configuration of the ET pilot sector at CERN showing lower and upper beamlines.

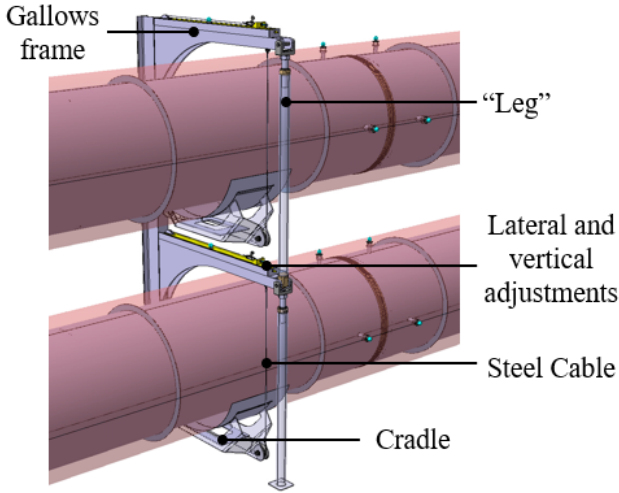


Figure 4: Adjustment system of the ET pilot sector

tioning in horizontal and vertical directions but with shimming being the only means of controlling pitch.

SURVEY AND ALIGNMENT PROCEDURE

All the survey and alignment was conducted with a laser tracker and Spatial Analyzer software.

Beam Tube Fiducialisation

Fiducialisation is the process of transferring the position of functionally significant internal features to a set of accessible external reference points (fiducials). This enables components to be accurately aligned during installation when the critical internal geometry is inaccessible or obscured. For the beam tubes, the fiducialisation process established the relationship between the external fiducials and the internal beamline geometry. The centers of both tube ends were measured to define the tube axis, while two additional points located on a baffle mounting ring were measured to provide references for the subsequent positioning of the internal baffles. Four fiducial points located on the exterior of each beam tube were then measured, creating a rigid link between the internal geometry and the external alignment references used during installation.

Beam Tube Coordinate System The origin of the beam tube coordinate system used for fiducialisation is the center of the circle at the end of the beam tube closest to the baffle

ring. The Z axis (primary axis) is along the axis of the cylinder, positive towards the non-baffle end. The X axis (secondary axis) is defined by the line connecting the origin and the baffle point closest to the top external fiducial and is positive towards this baffle point. The Y axis is perpendicular to Y and Z completing a right handed coordinate system.

End Cap Fiducialisation

For the end caps, the mechanical center of each assembly was measured together with offset points defining the nominal beamline position. These features provided the primary references for establishing the correct position and orientation of the end caps within the ET pilot sector. In addition, six external fiducial points were measured on each end cap, allowing the internal reference geometry to be transferred to accessible locations for installation and verification measurements. The resulting fiducialisation data provided a rigid geometrical link between the external fiducials and the functional internal geometry, enabling alignment of the beam tubes and end caps throughout the installation process.

Survey Reference Network

A dedicated survey reference network was established to provide a stable reference frame for the alignment of the ET pilot sector components. The network was realised using permanently bonded drift nests designed to accommodate 1.5-inch diameter spherically mounted retroreflectors (SMRs).

A total of 32 drift nests were installed on the walls of the experimental hall. Their distribution was optimised to ensure homogeneous spatial coverage of the measurement volume and to mitigate line-of-sight limitations during laser tracker observations. Particular attention was given to maintaining visibility in regions constrained by the presence of two vertically separated 1 m diameter beam tubes, which could significantly restrict direct observation paths.

The network geometry was designed to maximise redundancy and measurement strength across the full installation volume, ensuring robust connections between all survey stations and reference points. A network adjustment of eight laser tracker stations was performed using the Unified Spatial Metrology Network (USMN) algorithm in SpatialAnalyzer software to determine the final coordinates of the drift nests.

The resulting network had a root mean square (RMS) residual of 0.03 mm, with a maximum residual of 0.13 mm,

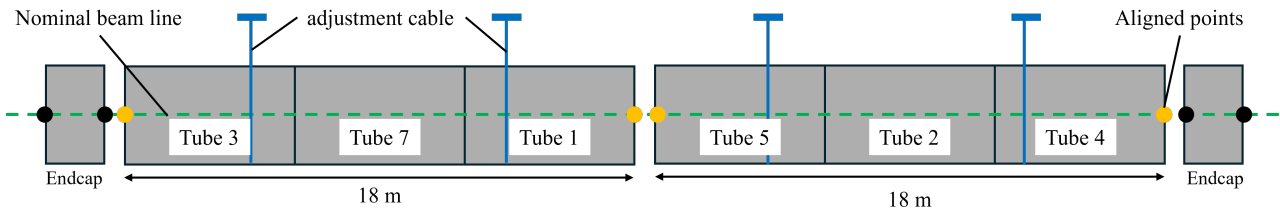


Figure 5: Schematic of the 18 m long beam tube sections used to position the beam tubes on the nominal beamline.

demonstrating a high level of internal consistency and suitability for the alignment tasks within the experimental environment.

Installation Coordinate Systems

Three coordinate systems were established for the setting out and alignment activities associated with the ET Pilot sector installation: a tracing coordinate system used for marking reference lines on the floor, and dedicated installation coordinate systems for the lower and upper beamlines.

Setting Out Coordinate System The tracing coordinate system was defined to facilitate the transfer of the design geometry onto the experimental hall floor, enabling the accurate positioning of the mounting frames. The coordinate system was established using existing civil engineering features identified in the facility drawings, namely the longitudinal wall running parallel to the pilot sector axis, the rear wall, and the floor surface. The origin was defined as the intersection of the planes fitted to the longitudinal wall, rear wall, and floor. The coordinate axes were defined as follows:

- Z-axis (primary): Defined by the normal vector of the local gravity plane, with the positive direction pointing upwards towards the roof of the experimental hall.
- X-axis (secondary): Defined by the normal vector of the longitudinal wall, with the positive direction pointing away from the wall towards the interior of the experimental hall.
- Y-axis (tertiary): Defined as the vector orthogonal to both the X- and Z-axes, with the positive direction towards the inside of the experimental hall.

Lower Beamline Installation Coordinate System The lower beamline installation coordinate system was derived from the tracing coordinate system through a translation and axis rotation. The origin was offset by 2477.50 mm from the longitudinal wall and 908.50 mm above the floor. The axes were then rotated such that:

- Z-axis: Along the nominal lower beamline, positive towards the interior of the experimental hall.
- Y-axis: Aligned with the local vertical direction, positive towards the roof.
- X-axis: Perpendicular to Z and Y completing a right-handed coordinate system.

This coordinate system was used as the reference frame for the installation and verification of the lower beamline components.

Upper Beamline Installation Coordinate System The upper beamline installation coordinate system maintains the same orientation as the lower beamline installation coordinate system. Its origin is translated vertically by 1790 mm relative to the lower beamline coordinate system, corresponding to the nominal separation between the two telescope beamlines. This coordinate system will serve as the reference frame for the installation of the upper beamline components.

Setting Out

To facilitate the installation of the support frames for the end caps and beam tubes, a series of points were set out on the floor along the beamline together with additional points defining perpendicular directions. These points were used to establish reference lines on the floor, providing a geometric framework for the positioning of the supports. Custom installation templates incorporating alignment notches and precision-machined mounting holes were then aligned to the surveyed reference lines. Once correctly positioned, the mounting hole locations were transferred directly onto the floor by the installation technicians. The use of these templates significantly reduced the number of individual points that required direct survey marking, thereby improving installation efficiency and reducing the time required for survey support activities while maintaining the required positioning accuracy.

Pre-Weld Alignment

To facilitate welding and minimise geometric deviations at the joints, the beam tube segments were pre-aligned prior to welding. For each assembly, three supported beam tubes were positioned with the central tube serving as the reference element. The adjacent tubes were aligned such that the centre points defining their axes coincided with the axis of the central tube within the specified tolerances. Following alignment, the tubes were displaced to accommodate a welding sleeve, assuming that the radial positions could be reproduced.

The three-tube assemblies, each approximately 18 m long, were then welded in situ. This procedure was performed for two assemblies, which were subsequently installed in the lower beamline of the telescope pilot.

End Cap Alignment

The initial positioning of the end caps was established by the support frames, which has been installed using the survey set-out measurements described previously. Final alignment was then performed through an iterative adjustment process using the push–pull screw mechanisms integrated into the end-cap supports.

Alignment measurements were carried out by measuring the end-cap fiducials in the installation coordinate system. A 3D Helmert best-fit transformation of the fiducialisation coordinates to the measured fiducial coordinates was used to determine the position and orientation of each end cap within the lower beamline installation reference frame. This transformation enabled the coordinates of the end-cap center and the beamline reference points to be computed and compared with their nominal positions. Successive adjustments were applied until the specified alignment criteria were satisfied.

To improve the efficiency of the adjustment process, a set of monitored points located close to the adjustment mechanisms were measured in near real time. The live coordinate updates provided immediate feedback to the installation team, allowing corrective actions to be applied between successive best-fit computations and thereby reducing the number of adjustment iterations required.

Beam Tube Alignment

Following fabrication and pre-weld alignment, the two 18 m long welded beam tube assemblies were installed on their final support and adjustment systems. Alignment was performed by measuring the external fiducials of the two end tubes of each assembly in the installation coordinate system and relating these measurements to the fiducialisation data. The adjustment system was such that it could only control the points closest to the ends.

A best-fit 3D Helmert transformation of the fiducialisation data to the measured fiducials was performed, allowing the positions of the beam tube axis points and baffle-ring reference features to be determined within the installation reference frame. These calculated positions were then compared with their nominal coordinates to quantify alignment deviations.

The beam tube assemblies were adjusted iteratively using the cable-supported suspension system described previously. Following each adjustment step, the fiducials were remeasured and the transformation recomputed until all monitored points were positioned within ± 0.5 mm of their nominal locations relative to the beamline. As with the end-cap alignment, selected points located close to the support and adjustment system were monitored in real time to guide the installation team during the adjustment process. Once the alignment requirements had been achieved, the assemblies were secured in their final positions and prepared for subsequent installation and commissioning activities see Fig. 6.



Figure 6: The lower beamline of the pilot sector after final alignment.

ALIGNMENT RESULTS

End Cap Position

The final positions of the end caps after alignment are shown in Fig. 7. The origins of both the upstream and downstream end caps were positioned to within ± 0.2 mm horizontally and vertically relative to the nominal beamline. The offset points placed along the beamline to help control pitch and yaw exhibit deviations of less than ± 0.5 mm horizontally for both end caps and with larger deviations of up to 2 mm vertically. While this level of alignment is acceptable for the ET pilot, a clear lever-arm effect is observed, particularly in the vertical direction. Over longer distances, such behavior would lead to rapidly increasing deviations from the nominal beamline. A finer adjustment system would therefore be required to adequately control pitch and yaw over extended baselines.

Beam Tube Position

The centers of the beam tube ends at the extremities of each 18 m welded section were aligned to the nominal beamline axis to facilitate welding between adjacent assemblies. The remaining individual beam tube end centers were not independently adjustable and therefore assumed positions dictated by the alignment of the controlled end points.

Figure 8 presents the final positions of the beam tube axis points relative to the nominal beamline. The thicker gray vertical lines indicate the approximate locations of the suspension cables used to support and adjust the beam tube assemblies. The black markers represent the centers of the beam tube ends at the extremities of the 18 m welded sections that were monitored and actively adjusted during the alignment process. The orange and blue markers denote the centers in the vertical and horizontal directions of the individual ends of the beam tube that were not directly monitored or adjusted. The orange and blue lines connecting adjacent beam tube ends are included to aid visualization of the beamline geometry.

It can be observed that the beam tube end centers located at the extremities of the 18 m sections exhibit the smallest deviations from the nominal beamline, with maximum residuals of approximately 0.25 mm vertically and 0.5 mm horizontally. This behavior is expected, as these points were actively monitored and controlled throughout the iterative

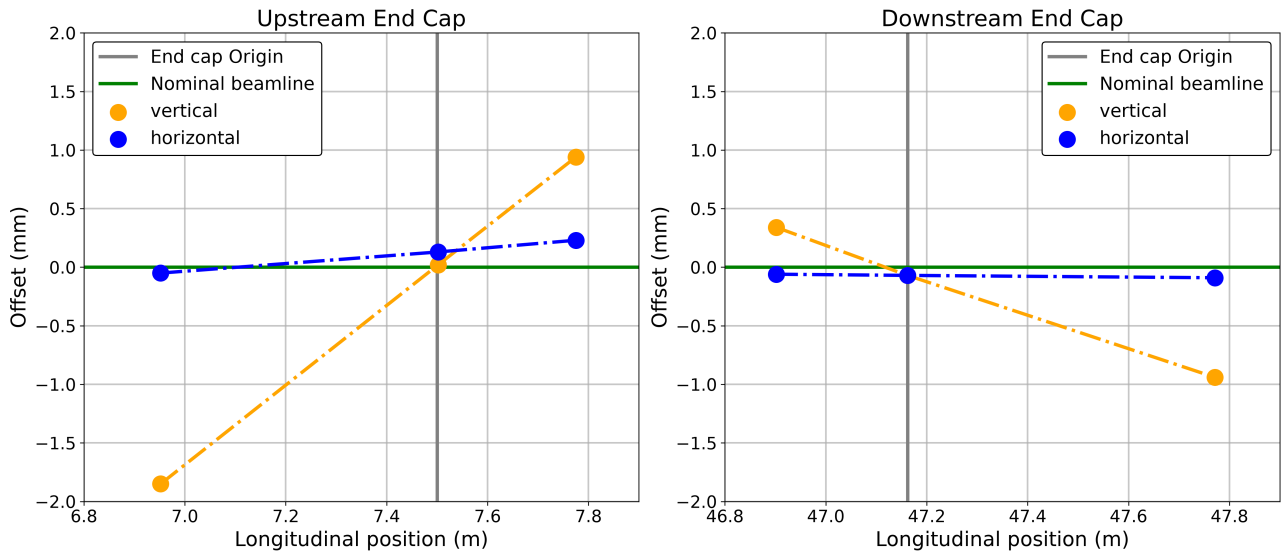


Figure 7: Vertical and horizontal deviations of end cap origins and offset points (defined along the nominal end cap axis) from the nominal beamline after alignment.

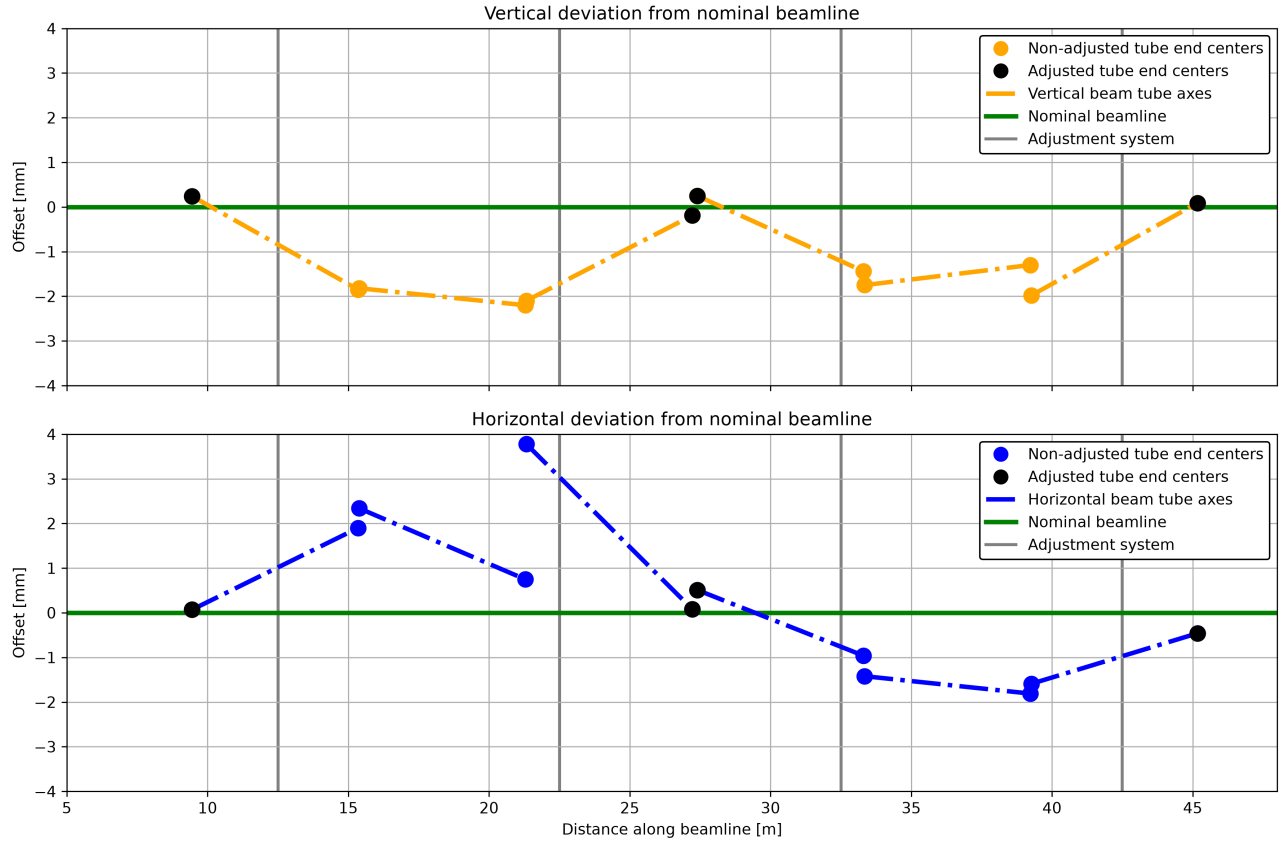


Figure 8: Horizontal and vertical deviations of beam tube end centers relative to the nominal beamline.

alignment process. In contrast, points located further from the section extremities exhibit larger residual deviations, reflecting the limited capability to independently control the geometry of the entire 18 m beam tube assembly.

The vertical deviation plot shows a clear sagging behavior within the central regions of the two 18 m beam tube

assemblies. This deformation is attributed to gravitational loading acting on the beam tubes between the suspension points. The observed profile is consistent with expected elastic deflection of the unsupported spans and highlights the influence of the support configuration on the final beamline geometry.

Despite the observed sagging of the beam tube assemblies, the overall variation in vertical position remained acceptable for the ET pilot sector. The difference between the highest and lowest measured points was less than 2.5 mm across the full installation. This demonstrates that, although gravitational deflection was evident between the support locations, the beam tubes remained well constrained within the specified alignment envelope over their entire length for purposes of this pilot.

The horizontal deviations were generally well controlled, with most measured points lying within ± 2 mm of the nominal beamline, reflecting the positioning achievable with the adjustment system. The exception of a single point exhibiting a deviation of 3.8 mm. This single larger residual offset is believed to be primarily attributable to manufacturing and assembly effects rather than limitations of the alignment procedure itself. In particular, measurements performed during fiducialisation revealed tube-end circularity of a few millimetres. The average beam tube diameter was 1001 mm with a diameter range of 0.88 mm.

Furthermore, additional geometric distortions may have been introduced during the welding process used to join the beam tube sections. The magnitude of the observed horizontal deviations is therefore consistent with the combined influence of these fabrication and assembly tolerances.

Baffle Position

Figure 9 illustrates the positions of the baffle center points (mid point of the two 6H7 baffle points) for each of the six tubes in two reference frames. In the fiducialisation coordinate system, the points are expressed relative to each tube's local axis (green markers), while in the alignment coordinate system they are referenced to the nominal beamline in the experimental hall after alignment (yellow markers).

When evaluated in the local tube frame, the baffle centers lie within a circle of radius 1.3 mm about the tube axis, indicating the welding quality and concentricity of the baffle ring with respect to the beam tube axis. After transformation to correspond to the position of the beam tubes relative to the nominal beamline, the same points are contained within a circle of radius 3 mm about the nominal axis. This larger dispersion reflects the cumulative effects of several contributions, including the positioning accuracy of individual baffle ring welds, assembly and welding of adjacent tubes, and the intrinsic precision limits of the alignment and adjustment system.

Opportunities and Lessons Learned

Setting Out The installation process benefited significantly from the use of multi-hole drilling templates, which accelerated the setting out of support locations. For future large-scale implementations, additional gains in efficiency could be achieved through robotic setting-out technologies, such as those developed for tracing installation points and reference lines during the High Luminosity Large Hadron Collider upgrade [6]. Although the benefits are modest for a pilot installation, they become increasingly significant when

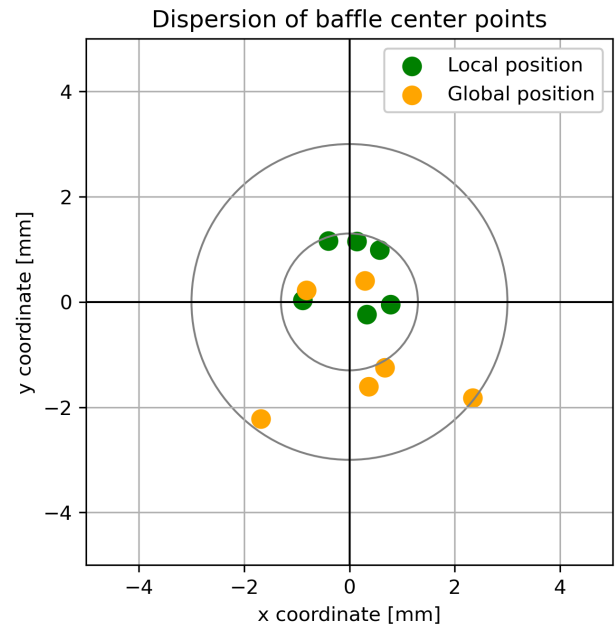


Figure 9: Transverse view of local positioning of baffle centers within individual beam tubes (green markers) and relative to the nominal beamline after alignment (yellow markers).

extrapolated to the approximately 120 km of beam tube infrastructure planned for the ET, where the reductions in installation time and labor would translate into substantial cost savings.

Pre-Weld Alignment The pre-weld alignment procedure was intended to establish the correct relative positions of adjacent beam tube segments and thereby facilitate the insertion of the welding sleeve. The adopted approach assumed that, after temporarily displacing the tubes to accommodate the sleeve, the support adjustment system would allow the assemblies to be returned to their pre-aligned positions with sufficient repeatability.

However, Figure 8 shows a relative horizontal deviation of up to 3 mm between two adjacent beam tube segments, indicating that the pre-aligned geometry was not fully preserved during the welding preparation stage. Several factors may have contributed to this discrepancy, including departures of the tube ends from perfect circularity and limitations in the repeatability of the support adjustment system.

These observations suggest that introducing an additional alignment verification step after sleeve installation and immediately before welding would reduce the risk of residual misalignment and improve geometric continuity across welded joints.

Fiducialisation and Alignment The ET will comprise approximately 120 km of beam tubes, each 15 m long, resulting in around 8000 individual beam tube sections [7]. During the ET pilot project, the fiducialisation of each beam

Baffle Ring Positioning The final positioning accuracy of the baffle rings was primarily determined by the manufacturing, welding and assembly tolerances of the beam tube sections. As the pilot installation did not incorporate an adjustment mechanism for the baffle rings, no post-installation correction was possible. Future installations could further improve positioning accuracy through tighter manufacturing tolerances or by integrating adjustable mounting systems, allowing fine alignment following assembly.

CONCLUSION AND OUTLOOK

of existing survey and alignment techniques to support the installation of ET infrastructure in a representative environment.

Moreover, achieving the tighter alignment tolerances anticipated for ET will require metrology, adjustment mechanisms, and installation procedures to be considered as an integrated system. High-precision measurement alone cannot guarantee the final alignment performance; the adjustment and installation systems must provide sufficient resolution, stability, and repeatability to translate measurement information into the required physical positions.

The procedures demonstrated by the pilot should be considered a proof of technical capability and a foundation for the development of scalable ET survey and alignment workflows, rather than a direct template for full-scale deployment. Future work will focus on increasing automation of the measurement and alignment processes, with the aim of reducing manual intervention, increasing throughput, and maintaining accurate, repeatable, and traceable alignment quality across the ET infrastructure.

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