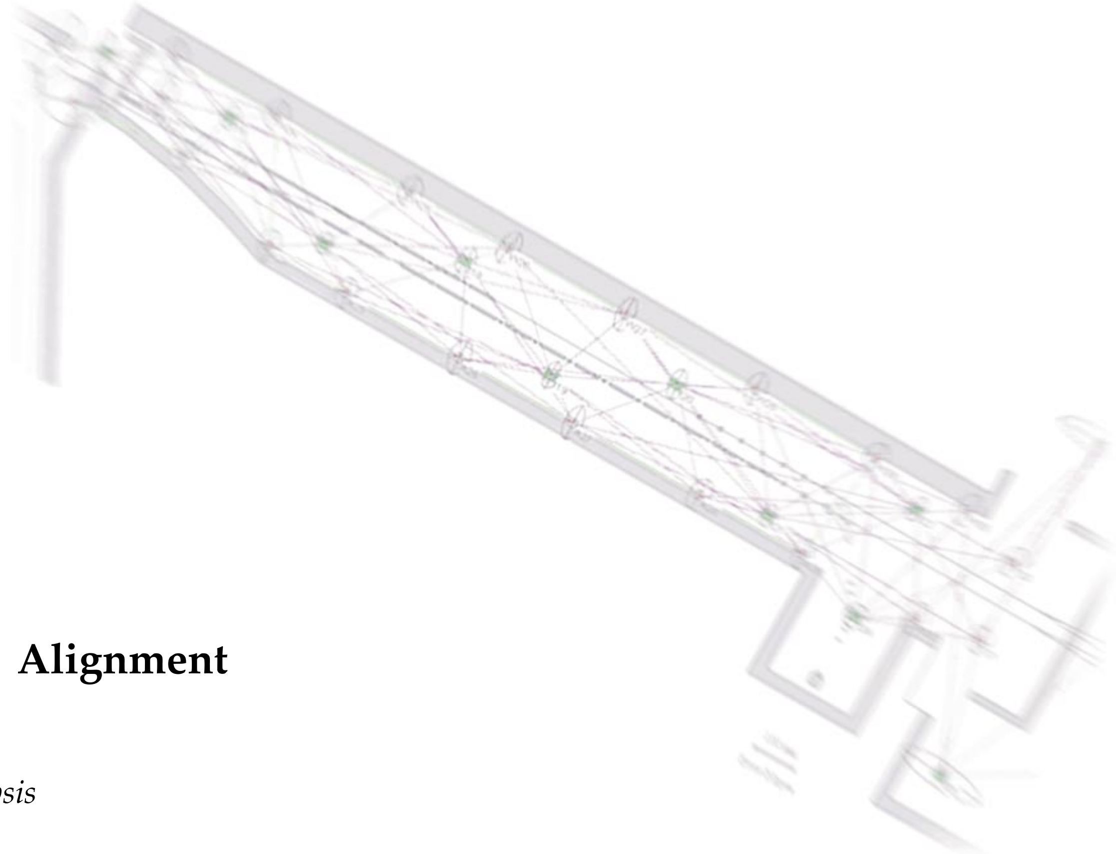

13 Alignment

Synopsis

In order to ensure that the machine components are placed according to the physics requirements, FERMI needs well defined survey and alignment procedures and techniques. Surveys are necessary for placement of components and for support of conventional facilities. ELETTRA has a solid history of quality surveying and engineering. The needs of FERMI will be well served by building on the available infrastructure of reference points and the current observation techniques. All surveys will be based on a single coordinate system integrating the existing surface network and storage ring surveys. Components that have been carefully fiducialized can then be installed and aligned using a series of steps from the ground up and later checked with a survey map. The linac area needs special attention, both for the quality control of the accelerator sections and for the alignment methods to be applied in the field.

The alignment coordinate system is a Cartesian right-handed system, with the origin placed at a particular point in the beamline. A three-dimensional network methodology is proposed, with the FERMI network integrated with that of the existing ELETTRA storage ring. The instrumentation will include theodolites, total stations, laser trackers and precise levels.

The areas to be aligned are the injector, linac, undulator, photon beamlines and experimental hall. The tolerances for the injector, linac and undulator components, 100 μm rms, are achievable with established techniques. The fine adjustment to the BPM and quadrupole positions in the undulator will be done via the beam-based alignment technique described in Chapter 7. The components of the experimental hall have relatively loose alignment requirements, and traditional measuring techniques like those currently in practice at ELETTRA can be used for the placement of components.

13.1 Introduction

Survey and alignment related tasks are found at all stages of a project like FERMI and the purpose of this chapter is to present them in a concise manner. There are often several approaches for solving a particular alignment request and it is important at the design stage to allow provision for flexibility in instrumentation and tooling. For example, in the paragraphs for the specific sections of the project, one observation scheme is presented in depth and alternative methods are mentioned in reference. Where possible, the method reusing existing ELETTRA data or techniques was preferred.

The primary purpose of alignment is to ensure the placement of all machine components within the tolerances set by the physics requirements. The procedure is split into well defined tasks: component fiducialization, assembly control, tunnel survey, floor marking, alignment and the final adjustments based on the results of Beam Based Alignment (BBA) computations. The other purpose of alignment is of a more general nature for the surveyor community and can be considered as support for conventional facilities. It starts by providing accessible and well understood references on site for all construction purposes. Often it also encompasses control measurements for building acceptance.

It is proposed to achieve both goals by designing a geodetic network that is based on the machine layout and to build references with flexible instrument and target mounts. This is presented in the next two sections.

13.2 Geodetic Network

One single coordinate system will be used for the FERMI project. The size of the project is large enough that an understanding of some basic geodetic principles is needed. Conversely, it is small enough that common approximations are possible. This section gives its formal definition and describes the principles to be used in order to first realize it and then subsequently to use it. A technical note [1] states the specific details and presents the numbers to be used.

The FERMI coordinate system will be a three dimensional Cartesian system (O, x, y, z). Its origin O will be chosen at one particular point in the beamline, such as the center of a quadrupole. Its x-axis will follow the beam-direction. Its z-axis will be opposite to the gravity vector at the origin. The y-axis will complete the triad and make it right-handed. This definition implicitly assumes that the beam direction is normal to the gravity vector at the origin which is a factor to be taken into account at the time of the construction. It is completely sufficient to represent the machine layout and also to model all geometric measurements. To take care of gravity based measurements it is also necessary to add a model of the gravity field for the area.

Because the knowledge of the Earth's density distribution is not sufficiently well known, it is not possible to compute the gravity field directly from its defining formula. Recently, with the development of satellite observations, there have been major advances at the global level and in the handling of the temporal fluctuations. For local studies, the common procedure to determine the gravity field is carried out in three steps. First, a global geo-potential model (such as EGM96) is used for the long-wavelength contribution. Secondly, the medium wavelength component is derived from all the available field observations (such as free-air gravity anomalies and differences between GPS and leveling data). Finally, the short-wavelength is inferred from a digital terrain model [2]; this part, which deals with the topographic effects, is a limiting factor for accurate and high-resolution models. For the alignment of an accelerator one must ask if such a specialized procedure is necessary and possible or if a simplified model is sufficient. In fact, what is really important for the alignment of a machine is just the understanding of the variations of the gravity vector within the site and with respect to the value at the origin. Placing the origin in the middle of the machine limits the range for possible variations. For all these reasons, a simpler spherical model can be chosen. This sphere will act as a local approximation of the geoid (the equipotential surface of the gravity field which coincides on average with mean sea level). In practice, this means selecting a radius (R) and a distance from the origin along the z-axis (the height of the origin H_O) [3].

The realization of the coordinate system is the process of building reference marks and assigning coordinates to them. In turn, it is this set of coordinates that implicitly define the coordinate system. This process has occurred during the construction of the storage ring [4]. The ELETTRA surface network can be integrated into the FERMI network. It was designed with a two-dimensional approach and a forced-centering technology. It consisted of five monuments embedded in the rock and one monument M9 placed on top of a building near the linac entrance. M1 marked the center of the Storage Ring. The Y-axis was materialized with M1 and M0. The two markers M3 and M6 indicated the direction of the accelerator, which is parallel to the X axis. With the construction of the new booster, one point M2 had to be destroyed. Monument M3 is at the current limit of the construction for the linac extension. In the eventuality of an extension, a replacement needs to be installed and a local survey performed before removal. This network was observed by a combination of theodolite and distance measurements. A re-iteration of the observation scheme is not directly possible because most of the original lines of sight

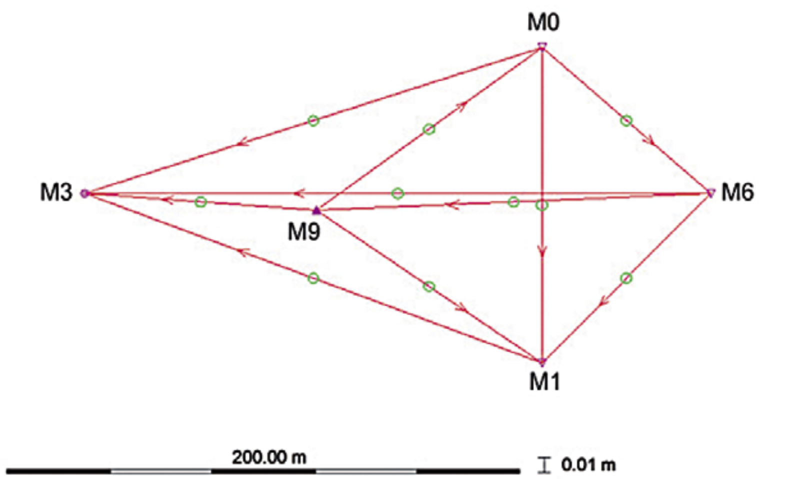

Figure 13.2.1:
GPS Network Simulation using Ski-Pro Software.

were lost with time and development. Fortunately a simple GPS network could easily be surveyed and computed within the Italian GPS Fiducial Network (IGFN) [5]. Figure 13.2.1 shows one possible baseline arrangement over the remaining pillars.

By adding a couple of points during the construction, this process accomplishes several goals at the same time. It ties the site to a known global coordinate system, provides references to the tunnel and enables a transformation formula to the Storage Ring system if needed.

13.3 Method and Instrumentation

Within the accelerator alignment community there are two different philosophies for surveying positions of monuments and machine components. They are known as the two-dimensional plus one-dimensional approach (2D+1D) and the three-dimensional approach (3D). The 3D methodology is often associated with the free-stationing of the instrumentation, such as laser trackers. On the other hand, the 2D+1D methodology is associated to the forced-centering of instruments and targets. Just as in any classification, it is somewhat arbitrary and a practical approach is to be able to use a combination of both scenarios when needed. To achieve this, it is necessary to adopt a versatile mounting system for targets and references. It is also important to verify that the data processing software selected for the reduction and adjustment of the observations is based on a general mathematical model [6].

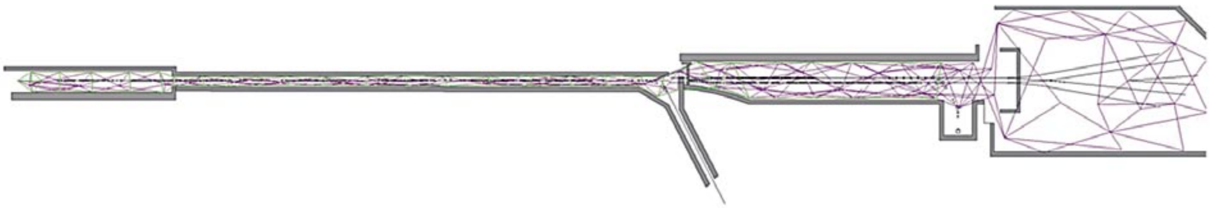

Figure 13.3.1:
Tunnel Network Simulation using SIMS Software.

This versatility already exists at ELETTRA. The surface network and the original alignment of the storage ring were realized around forced-centering techniques. The Taylor-Hobson system was adopted for both the surface network and the component fiducialization of the whole machine. In this method, good mechanical fit and proper use of the instrument tribrach guarantee that the center of any 3.5″ diameter sphere-target lies on the local vertical used for the instrument set-up. The net advantage of such a scenario is the reduced number of unknowns in the adjustment while its major drawback is the dependence on hardware arrangement and repeatability. It is also worth noting that, because the positions of the instruments (theodolites and total stations) are linked to the positions of the targets, lines of sight need to be preserved, otherwise the network has to be modified. The latest surveys of the storage ring magnets were performed with laser trackers. New references were installed and special adapters were used in order to place the 1.5″ SMR (Sphere Mounted Retroreflector) in the 3.5″ receptacles.

13.4 Component Placement

Once the monument network is processed, the placement of components in the tunnel can start. All critical components need to be fiducialized in advance. Fiducialization is the process of defining a local coordinate system specific to the component and assigning coordinates to external references that will be used later for the alignment process. The coordinate system can either be built from geometrical features or from a materialization of the magnetic field. In all cases, it is important to evaluate the quality of the fiducialization step, as this is the first contribution in the tolerance budget. Next, the decision has to be made as to whether to place the components on a girder outside the tunnel or in an assembly area in order to ensure the relative alignment and to speed up the installation process. In either case, the alignment of individual components or the pre-assembled girders, the placement process in the tunnel follows the same successive steps.

The position of the anchors securing the supports needs to be marked on the floor. This step can be carried out with the help of templates in the case of repetitive patterns. The templates need to be surveyed for control and marked clearly to identify their position and orientation. The quality of the marking should be consistent with the chosen drilling technique: a reasonable goal is between 0.5 and 1 mm. After the installation of the supports, another round of alignment checks is advisable. The specifics of this survey depend on the mechanical arrangement of the interface between support and component. This may be as simple as reading some identified features on the support to confirm the installation or, when movers are used, an opportunity to set the movers to preserve the maximum range of movement. The quality of this survey should match the type of hardware involved at this stage. In case of mechanical registration for the component set-up, a reasonable goal is 0.25 mm; otherwise it can remain at 0.5 mm.

Next, the components are installed; this can be done without the help of a surveyor in the first case, otherwise a local set-up will be needed with a reasonable goal of 0.25 mm. All these installation surveys can be performed by local set-ups of total stations. The recommended procedure is a free stationing approach based on a solid resection. A minimum of four monuments (preferably more) are observed in both faces of the instrument and with two iterations. The quality of the position and orientation of the instrument is verified in the field, after which the observations controlling the placement can be made in one face only. The final position is recorded after two iterations per instrument face.

At this point, it is time to perform a global survey of the monuments and of all the installed components. This process is generally referred to as the mapping stage and the recommended procedure is a combination of laser tracker and precise leveling observations. The laser tracker set-ups are performed in both faces and two iterations. All the component points have at least double coverage. A double run of leveling observations connects all the floor monuments. Depending on the size and shape of the area, height differences between components and reference points are observed with precision levels. These leveling data are reduced first to correct any naming or rod calibration mistakes. Then the set of cleaned height differences is entered in the adjustment of the laser tracker data. A free datum approach based on the monument coordinates is recommended and can provide an indication of the stability of new construction. After a statistical analysis of all the residuals and a verification of the a-posteriori standard deviation of all the unknowns, the coordinates of all the points are available.

For further analysis, depending on the location of the fiducials with respect to the component, an additional step may be necessary to estimate the position and the orientation of the component. Graphical outputs are welcome at this stage to verify that the adjustment results are within the required tolerances. Then a list of the required moves is established and local set-ups are performed. Unless there are very few moves to be made and they are well distributed, it is necessary to repeat the mapping process before publishing the observed positions of the components.

The next four sections discuss the alignment of the major sections of the FERMI system.

13.4.1 Injector

This is the first part of the machine that reaches to the end of the accelerating section SØB. It is about 5 meters long and is presented in Chapter 5 of this CDR. There are two distinct tasks as far as alignment is concerned: the control of the assembly on the common table and the placement of individual components.

On the table, the critical parts are the RF gun and its solenoid with their tight relative alignment. To achieve this, the two are mounted on a common plate after independent fiducialization steps. The placement of the table and the other components such as the two accelerating sections, the spectrometer and quadrupole magnets will be completed by traditional survey techniques as described above.

13.4.2 Linac

The linac section starts at the end of the accelerator section SØB and extends to the end of the spreader. It is about 150 meters long and is presented in chapter 6 of this CDR. Two types of components need special attention as far as alignment is concerned: the accelerating sections and the quadrupoles. The BPMs will be secured to the quads.

There are two types of accelerating sections but there is no real conceptual difference in the alignment procedure. The transversal alignment requirement is identical: 100 µm rms (horizontal and vertical). The existing ELETTRA sections, S1 to S7, are $3\pi/4$ BTW units. They are 6.15 meters long and the iris radius is 5 mm. They have three fiducials distributed along the length of the vacuum vessel. They were used to set the sections at the time of their installation and have not been re-observed since. Because of the alignment requirement, it is recommended to perform a map of the seven sections as they are currently in the tunnel. This will confirm the inner relationships of the fiducials. It is also recommended to plan a fiducialization check for the sections that will be displaced [7]. This will ensure the quality level of the nominal values of the fiducials. The new accelerating sections coming from CERN are $2\pi/3$ TW units. They are 4.5 meters long and the iris diameter is 10.75 mm. They have two fiducials, one at each end. These fiducials were set to a nominal position (-25.00 cm off axis horizontally and 40.00 cm up) at the time of their first evaluation. Because most of these sections have been displaced and recently transported, it is recommended to perform a new fiducialization of all the CERN sections [8]. After all the quality inspections of the sections are completed, it will be possible to evaluate the contributions of the fiducialization to the global error budget and to derive the necessary placement tolerances.

Most of the quadrupoles in the linac have an alignment tolerance of 100 μm rms transversally. Eight magnets in the BC1 region have a tighter tolerance: 50 µm rms. All the quadrupoles have a longitudinal position tolerance of 150 µm rms. It is recommended to perform the fiducialization of these magnets in close conjunction with the magnetic field map in order to produce ideal values referenced to the magnetic axis and to minimize the contribution of the fiducialization step to the error budget.

Given the geometry of the linac tunnel, long and narrow, it is difficult to build a network more accurate than 100 µm rms in all directions with total stations, laser trackers and precision levels. Because of the limited width of the tunnel, the most difficult direction to be determined is the one transverse to the beam. The relatively large spacing between components prevents an efficient use of optical tooling methods to derive horizontal offsets. A possible solution to improve the initial placement is to introduce a combination of portable HLS (Hydrostatic Level System) and portable wire measurements. This is the concept that is being applied to the alignment of the LCLS undulator "loose end" [9]. Another alternative is to set up a straightness interferometer along the beam.

13.4.3 Undulator

The 60 meter long undulator section starts at the end of the spreader and goes up to the beginning of the beamlines and the experimental stations. It contains the beam dumps and is presented in Chapter 7 of this CDR. Three types of components need special attention as far as alignment is concerned: the undulators, the quadrupoles and the BPMs. The transversal alignment requirement for the quadrupoles and the undulators is 100 μm rms (horizontal and vertical). The BPMs will be set relative to the quadrupoles before the installation in the tunnel. Assuming an error budget of 50 μm rms for the fiducialization of the quadrupoles and the undulators, the fiducials need to be aligned to 85 μm rms to meet the required placement tolerance. This can be achieved by a combination of laser trackers and digital level observations. Figure 13.4.1 shows a plan view of a network simulation for a monument network scheme across the undulator hall. Points on the wall and aisle are laid out regularly (10 meter spacing). The approach chosen is a free net (no parameters are fixed or weighted), and the adjustment solves for the datum parameters. The a-priori standard deviations are given in the table below.

Table 13.4.1: Input to the Simulation.

Distance (D)	40 μm
Horizontal Angle	60 μm / D
Vertical Angle	70 μm / D
Height Difference	80 μm

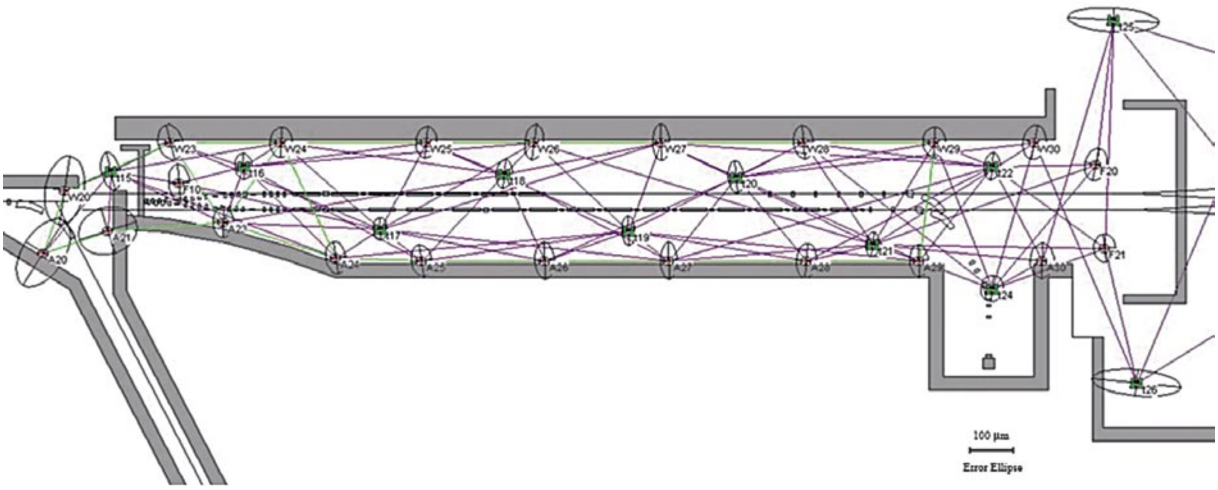

Figure 13.4.1:
Undulator Hall Network Simulation using SIMS Software.

The a posteriori standard deviations for the monuments are under the required 85 μm limit. For example, the characteristics of point W28 in the middle of the tunnel are given in the table below.

Table 13.4.2 Output Example of the Simulation.

Name	σ_x (μm)	σ_y (μm)	σ_z (μm)
W28	22	32	55

This network can serve as a basis for component placement. The mapping of the components will produce a denser network and the addition of level observations between components and monuments will produce an even stronger network.

13.4.4 Experimental Hall

This is the last part of the machine, starting at the end of the undulator. It is presented in chapter 8 of this CDR. There are two favorable factors that contribute to the relative ease of alignment for the Experimental Hall. Firstly, the components have relatively loose tolerance requirements for their initial positioning. Secondly, the overall wider dimensions of the building allow greater flexibility in the design of the network. For these reasons combined, traditional measuring techniques such as the ones currently in practice at ELETTRA can be used for component placement.

13.6 References

[1] Technical Note on the FERMI Coordinate System.

[2] "The GeoAdria project – the geoid of the Adratic See" by A. Borghi found at: http://bgi.cnes.fr:8110/The-GeoAdria-project.pdf

[3] ibid [1].

[4] "Alignment for the Synchrotron Light Source ELETTRA" by F. Wei, A. Bergamo, P. Furlan Radivo, J. Grgic, D. Vivoda and A. Wrulich presented at EPAC 94.

[5] "The Italian GPS Fiducial Network: Services and Products" by F. Vespe, G. Bianco, M. Fermi, C. Ferraro, A. Nardi and C. Sciarretta found at: http://geodaf.mt.asi.it/html_old/gps/product_services.pdf

[6] "LEGO: A Modular Approach to Accelerator Alignment Data Analysis" by C. LeCocq presented at IWAA97.

[7] Technical Note on the Metrology of the ELETTRA Accelerator Sections.

[8] Technical Note on the Metrology of the CERN Accelerator Sections.

[9] "Proposal for the Alignment of the Loose End" by G. Gassner (LCLS-TN-06-11).

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