SDC-92-381

SDC
SOLENOIDAL DETECTOR NOTES

SDC MUON MEASURMENT SYSTEM
CONCEPTUAL DESIGN OF THE ALIGNMENT SYSTEM

October 1992

Edited by J. Govignon
C.S. Draper Laboratory

Foreword

The following document is a **working** document. It is an attempt to reflect the views of the Committee for the Alignmentof the SDC Muon Measurement System. It is based on the core chapters of the "Alignment Reference Document", SDT-000043 distributed "For Comment" on July 13, 1992. Very few comments were received, but I have presented the material related to the Conceptual Design several times at different meetings since, and feedback received during the presentations has been included. Additional (new) material has also been provided by D. Eartly , S. Behrends/P. Hurst and myself.

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I. INTRODUCTION

First we provide a *vue d'ensemble* of the alignment requirements and concepts. Given the complexity of the alignment task, this introduction should allow the reader to keep in mind a global view of the task, and after consultation of the table of contents, to focus on technical matters of interest with a proper perspective.

1.1 Requirement Overview

The Muon detector is a distributed sensor system, with each sensor being a drift tube. Particle trajectories are derived from hits recorded by the sense wires, which means that the position of the wires must first be known. The purpose of the alignment task is twofold:

1) To ensure that the wires in the drift tubes are positioned close enough from their designed location w/r/t the beam line and Interaction "Point" (IP) so that the Muon System can provide proper trigger information.

2) To measure the actual wires' locations relative to other wires' and also to the accelerator beam and IP while the detector magnet is turned "ON".

For the first part, the required accuracy of positioning has been found to be of the order of 1 to 3 mm with respect to the beam line, and it is felt that this can be achieved with proper conventional surveying augmented by ad hoc procedures. **One caveat is that the Muon System Construction starts before the beam line exists, and the <u>expected</u> position of the beam line carries an uncertainty of the same order of magnitude (i.e. ~ 3 mm).**

For the second part, we notice that the number of sensing elements (the anode wires) is extremely large, and we cannot expect to measure directly during operation the position of each one. The near continuum of the detector sensing elements within the detector volume is discretized by the modules, and it seems logical to divide the alignment measurement process in 2 steps : First, measure the position of the modules, and second to measure the position of the wires within the modules. Therefore we should anticipate an alignment scheme which will reflect the shape and position of the modules.

The muon trajectories emanate from the interaction point (fig 1-1), and what the detector is required to measure accurately (TBD but of the order of 150μm) are the deviations from straight line of those trajectories. The absolute orientation of those trajectories need to be known with a lesser accuracy. Because the shapes of the modules spatially dividing the detector do not follow the overall trajectory lines (fig 1-2), the alignment cannot be divided into projective regions, and therefore we cannot take advantage of the lesser requirement on the absolute orientation of the

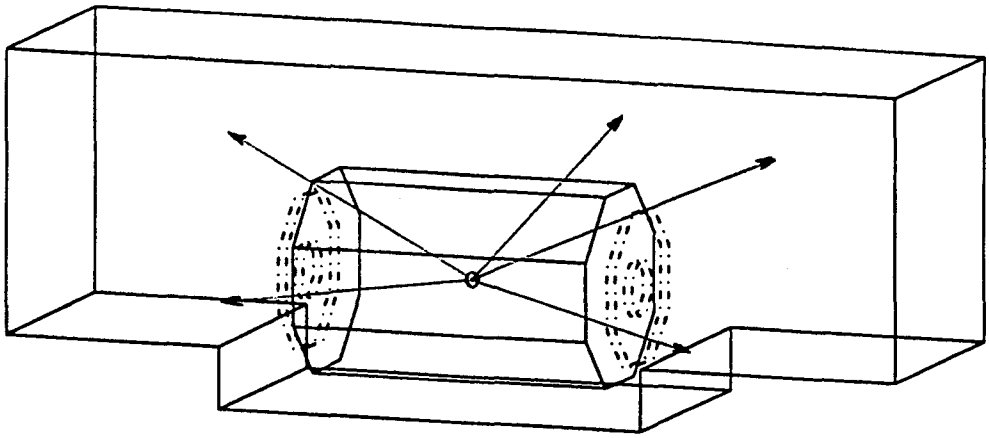


Figure 1.1 Detector and Muon Trajectories

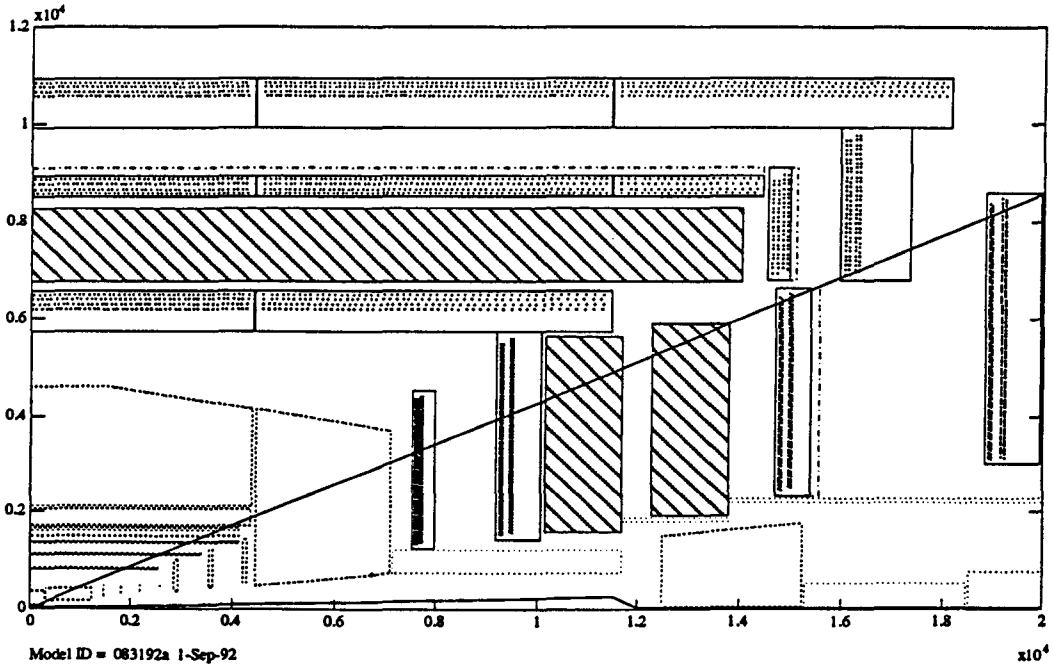


Figure 1.2. Detector Section (one quarter) and Muon Trajectories

trajectories. Most modules have tubes in both ϕ and θ orientations, many trajectories overlap adjacent modules, and many adjacent trajectories cross different modules in different layers of the detector (fig 1-3). **Therefore the argument that only points along a trajectory (or trajectory region) need to be measured accurately leads to the conclusion that all the modules will need to be measured with the same approximate 150 μm mentioned earlier. On the other hand this coupling of the modules will enable a more accurate reconstruction of the geometry of the detector when the actual particles' trajectory have been sorted out and can be used (It would be very convenient to use straight trajectories for this purpose, i.e. with the magnet turned "OFF").**

Due to the relatively high accuracy required, coupled with the long distances involved, monitoring the temperature of critical components and selected structural members is a necessity.

A detail study of the accuracy requirements is in progress, and preliminary results are presented in chapter 3. It should be noted that the requirements are evolving with the maturing of the detector design and analysis. An other aspect of the requirement which has a significant impact on the alignment system design is the range over which the measurements have to be performed. This is largely dictated by the range of deformations of the toroid magnet which is supporting most of the detector components, during and after the construction of the detector.

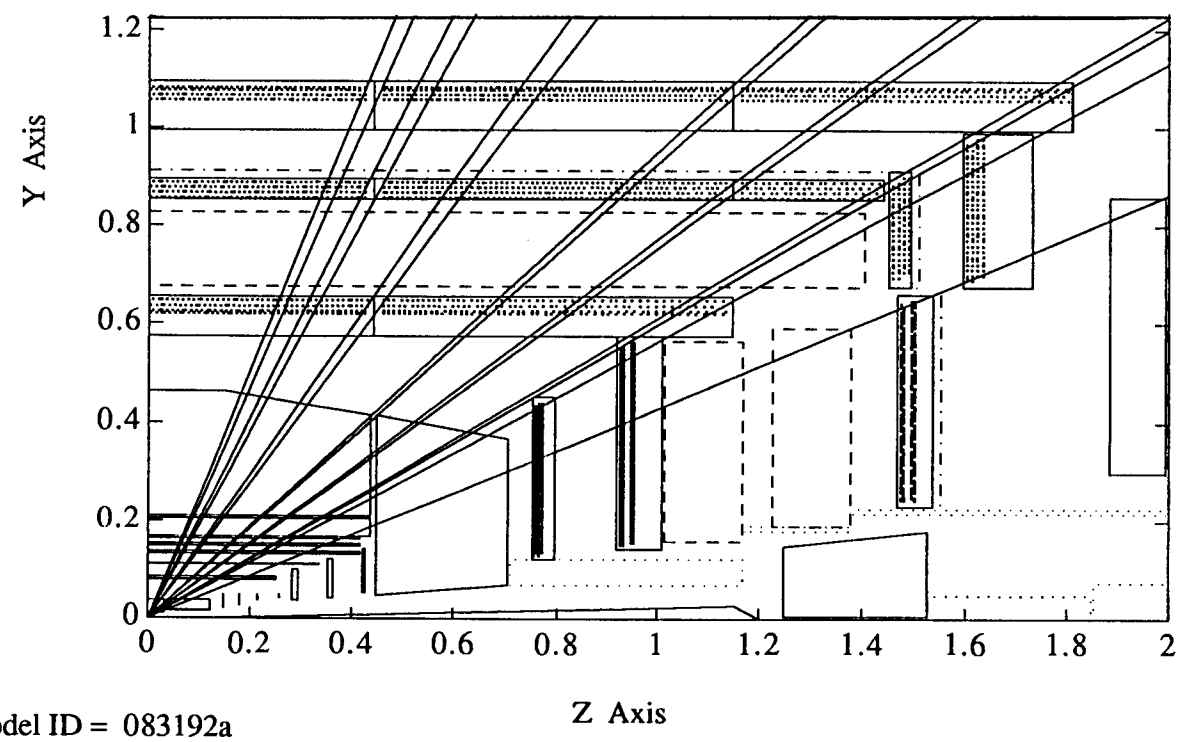


Figure 1-3 Trajectory Regions with Overlap within a Module

1.2 Summary of the Alignment Approach and Concept

The Muon System Alignment approach does not include any adjustment except for the jacking system in the barrel support. After fabrication, the large components of the detector are placed close to their designed location. The accuracy requirement of this positioning is governed by the triggering function of the Muon System, and is ensured by a survey conducted mostly by the Applied Geodesy Group during the detector construction. During operation, an accurate measurement and monitoring system provides the information leading to the precise knowledge of the actual position of the sensing elements.

The accurate measurement and monitoring technique is divided into three main steps:

I) Within each module, a Local Alignment relates the position of the end-wires to some fiducial points located at or near the corners of the modules.

II) A Global Alignment relates the position of the corners of the modules to each others and to the tracker and accelerator beam.

III) The information gathered by the sensors used in these 2 steps along with temperature sensor data and structural distances provided by quality acceptance data gathered during module fabrication and assembly are fed to a computer model of the detector which provides the reconstruction of the actual geometry of the detector.

- I) The local alignment monitors the module deformations at selected points (Figure 1-4) using simple Straight Line Monitors (SLMs) (Figure 1-5). A mathematical model of the module's shape based on a finite element analysis, and including the information of the precision machined (NC) end plates of the modules, relates the wire-ends to fiducial marks located at the module's corners. The SLMs are 3-point optical straight line alignment systems which have been used on L3 and again demonstrated during the muon chamber prototyping activities[1].

- II) The global alignment is itself divided into two parts:

1) Inside the detector, concatenated straight line monitors and proximity sensors located between modules (Figures 1-6,7) relate the relative positions of the corners of the modules to the corners of adjacent modules and modules placed on different layers. At appropriate locations, extensions of the SLMs relate them to the tracker and to alignment targets located outside of the detector.

2) Outside the detector, a network of Range-Only-Measurement (ROM) relates accurately the coordinates of the SLM ends and outside extensions to each other and to the beam via Beam Position Sensor at both ends of the detector. This is achieved by measuring the distances between a network of simple Range-Emitter-Receivers (RERs) and discrete cooperative targets located at the SLM ends, SLM outside extensions and Beam Position Sensor (fig 1-8). The ROM network is self referencing, and provides (after massaging of the data provided in step III) the accurate positioning information in the detector coordinate system, including the

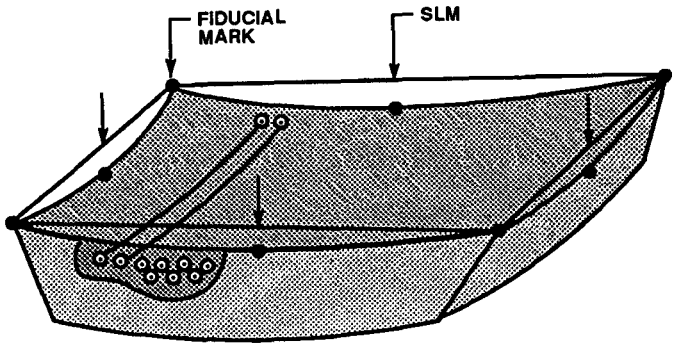


Figure 1-4 Local Alignment (Schematic)

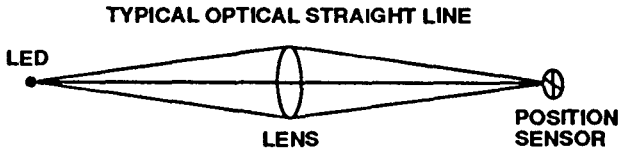


Figure 1-5 Simple Straight Line Monitor (Schematic)

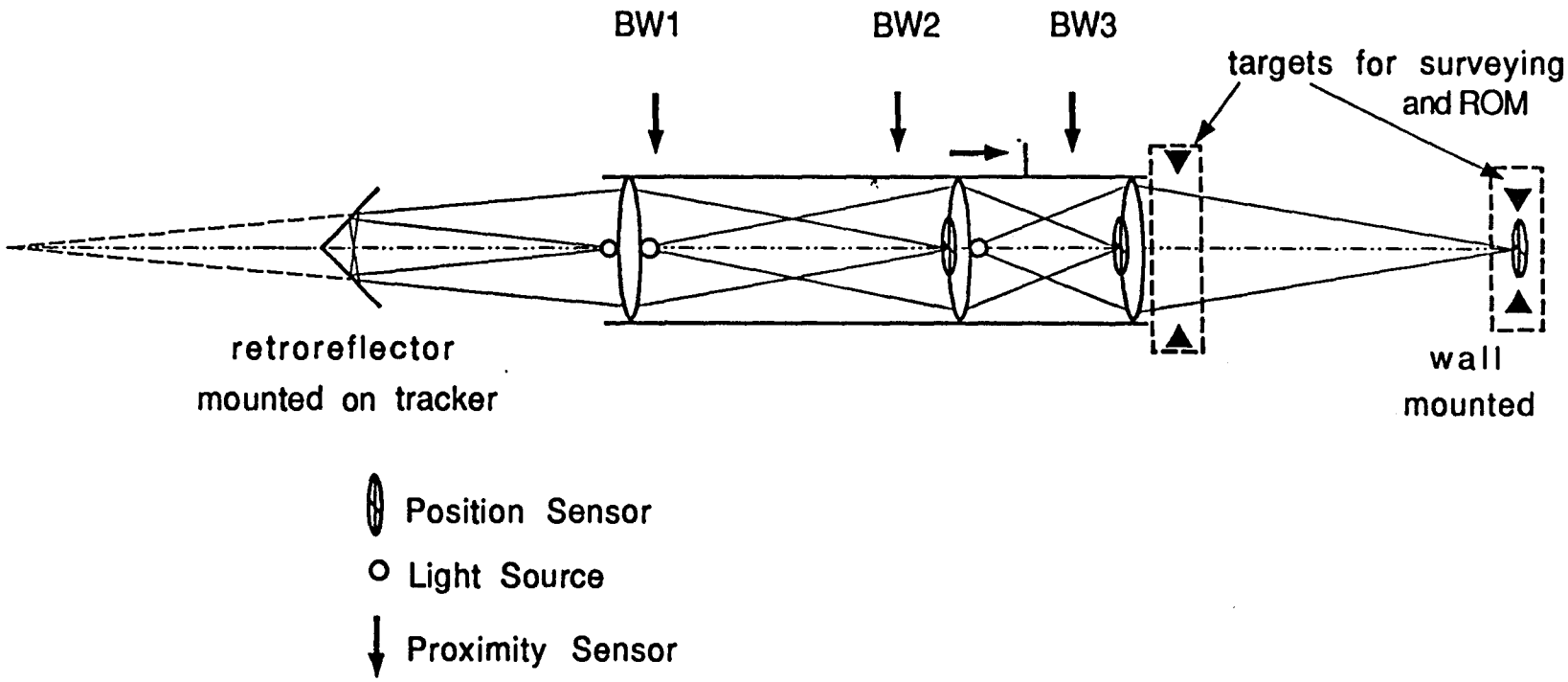


Figure 1-6 Concatenated 3-point Straight Line Monitor

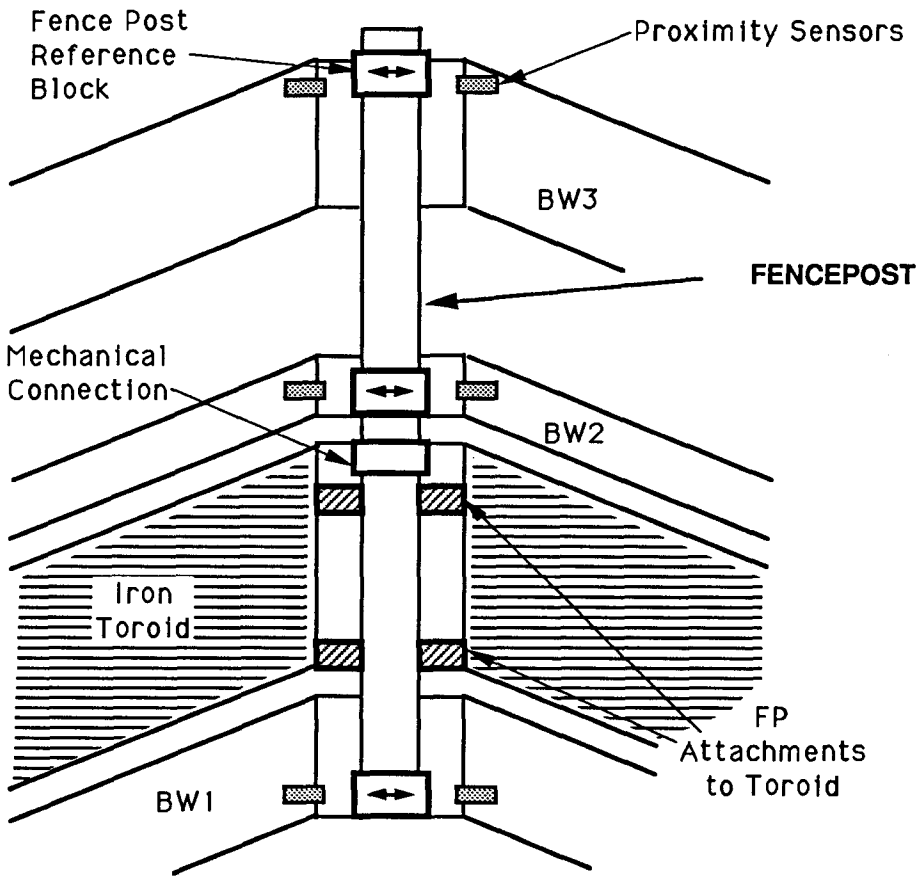


Figure 1-7 Location of Concatenated SLM (Schematic)

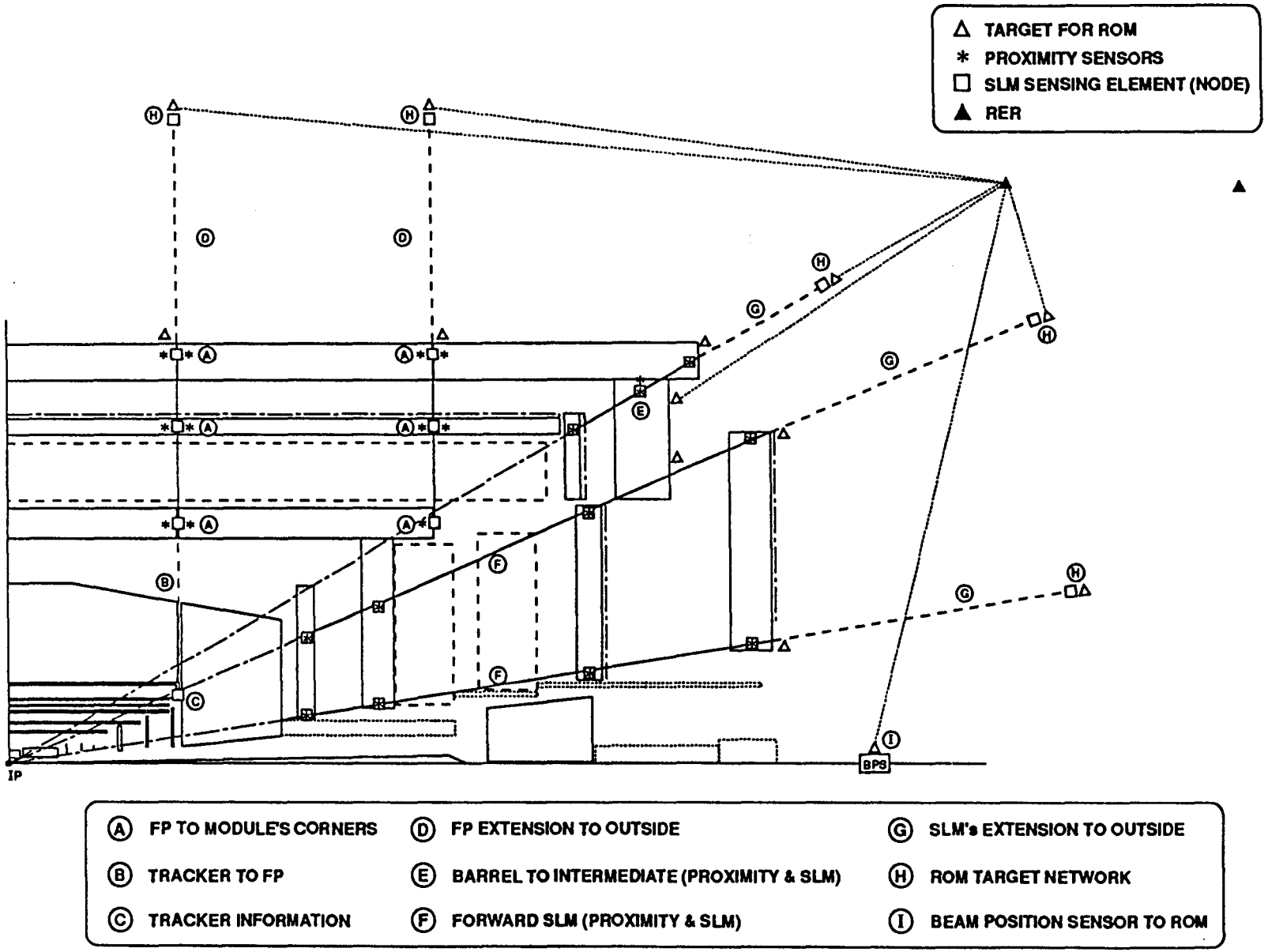


Figure 1-8 Global Alignment Steps and Device Location (Schematic)

orientation and position of the SLMs used in the previous steps. The position of the module corners on the outside of the detector which are not included in the internal system (part 1 above) are also directly measured by the ROM network. The main advantages of the ROM system are its ability to provide accurate closure of the alignment networks automatically under simple computer control while the magnet is "ON", and its flexibility regarding configuration changes or staging.

The network of distance measurements inside and outside the detector is complemented by measurements using Hydrostatic or Liquid Level and Inclinometers in areas of low visibility for the ROM and SLM networks (barrel support, octant 5 and magnet iron). Other important components of the alignment system are a network of temperature sensors to monitor the detector components and the ambient air, and also air pressure sensors for the ROM.

- III) All the data gathered during the steps I and II are fed to a computer where it is integrated within a mathematical model of the detector whose output is the geometrical information about the detector at all time. The errors on the position measurements do not accumulate through transfers, but are distributed through a least square fitting to the model.

The different steps of the alignment system are summarized on figure 1-9 and are fully described in chapter 4.

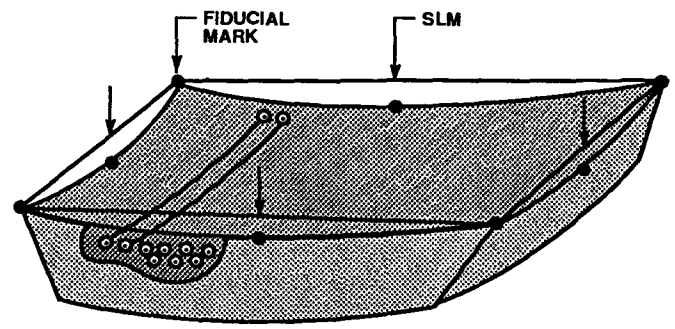
The alignment system will be designed with enough redundancy to provide for graceful degradation of the performance of the alignment monitoring system as the components age and fail, after proper cost trade-off.

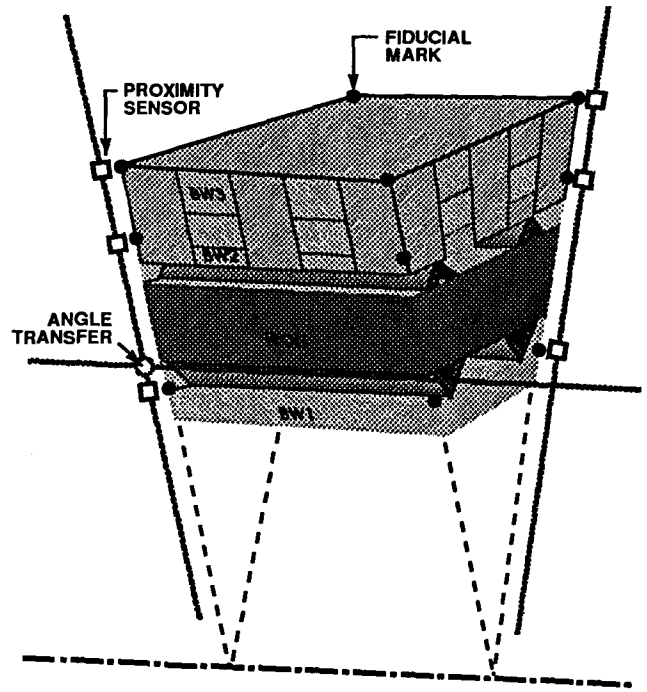
Note : In this document we do not address the possibility of using X-rays to measure directly the position of the wires, or using the background muon radiation for the vertex location.

References

1) "The Engineering Development of an Actively Controlled Precise Muon Chamber for the SDC Detector", F. Ayer and al

- **Alignment During Module Construction**
  - Establish Interpolation Model (Calibration of Relationship between Wires and Fiducials at corners)
- **Alignment During Detector Assembly**
  - Placement of the Modules (Survey by AG)
- **Alignment After Detector Assembly**
  - Position Knowledge and Monitoring Changes with Precision
    - **Local Alignment**
      - Excercising the Interpolation Model (On-Module SLM)
    - **Global Alignment (Baseline)**
      - Relating Module to Module through Fiducials' Position Knowledge
        (1) Limited Network of Straight-Line Monitors (SLMs) and Fenceposts (FPs) Inside the Detector and Extended out
        (2) Range-Only-Measurement (ROM) Network
        (3) Ancilliary Subsystems: Liquid-Level, Temperature Sensors
        (4) Computer Integration of Data





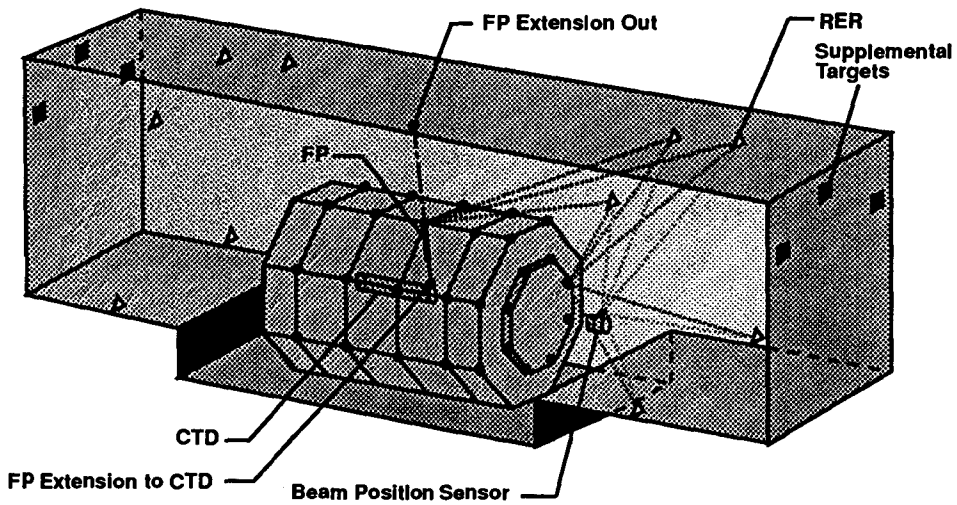


Figure 1-9 Summary of the Alignment Process

2. SUMMARY DESCRIPTION of the MUON DETECTOR, NOMENCLATURE & COORDINATE SYSTEMS

2.0 Muon Detector Description

The SDC muon system consists of three main elements: conventional iron toroids, wire proportional drift chambers, and scintillation trigger counters. The system provides identification and a momentum measurement of muons above a P_t threshold. The system consists of a central region (MBW1, MBW2/MBS2, MBW3 layers), an intermediate region (MIW2, MIW3 layers combined with MBW1 or MFW1) on the barrel toroid MBT plus separate forward systems (MFW1, MFW2, MFW4/MFS4, MFW5/MSF5) on toroids MBT1, MBT2. The system is illustrated in Figure SDC 0131.

The barrel toroid is a steel octagonal cylinder with a diameter from outer flat to outer flat of 16.5 m, a thickness of 1.5 m, a length of 28 m which will be magnetized to 1.8 T. The barrel toroid is the structural base for the detector (including the forward systems) and the mounting reference system for central and intermediate chamber systems. It is assembled of 64 short and 128 long steel blocks as shown in Figure 2-1. Four short blocks plus eight long blocks form one of sixteen vertical rings making up the toroid. The blocks within the rings are held together with corner bolts. The rings are connected together by longitudinal side plates. The central chamber system will be supported from longitudinal rails mounted on the barrel toroid. As the construction sequence of the magnet toroid (figure 2-2) progresses, the straightness of the magnet and its parallelism with the expected beam line will be checked by the Applied Geodesy Group.

Each MBW1 module will be kinematically supported on three bearing assemblies on inner surface rails. Each MBW2-MBW3 tower will be kinematically supported on three bearing assemblies on outer surface rails. Intermediate chamber box assemblies will be mounted on four point supports on the two end faces of the barrel toroid. A cross section of the entire Muon measuring system is shown on Figure 2-3.

To maintain the positions of muon chamber modules and its own mechanical integrity the barrel toroid must behave as a single structural unit under floor motions or position adjustments. A magnet support jacking system will allow local and uniform vertical adjustment (figure 2-4). The local adjustment capability can be used to produce small global tilt and small global roll adjustments (see below for the definition of tilt and roll).

The octagonal forward toroids FT1 and FT2 are located inside both ends of the barrel toroid as shown on Figure 2-3. These will be supported on box stool structures resting on steel tracks in the barrel toroid. The supports will include rollers for moving these systems. The forward chamber module ring assemblies will be supported on three point supports referenced from the forward toroids.

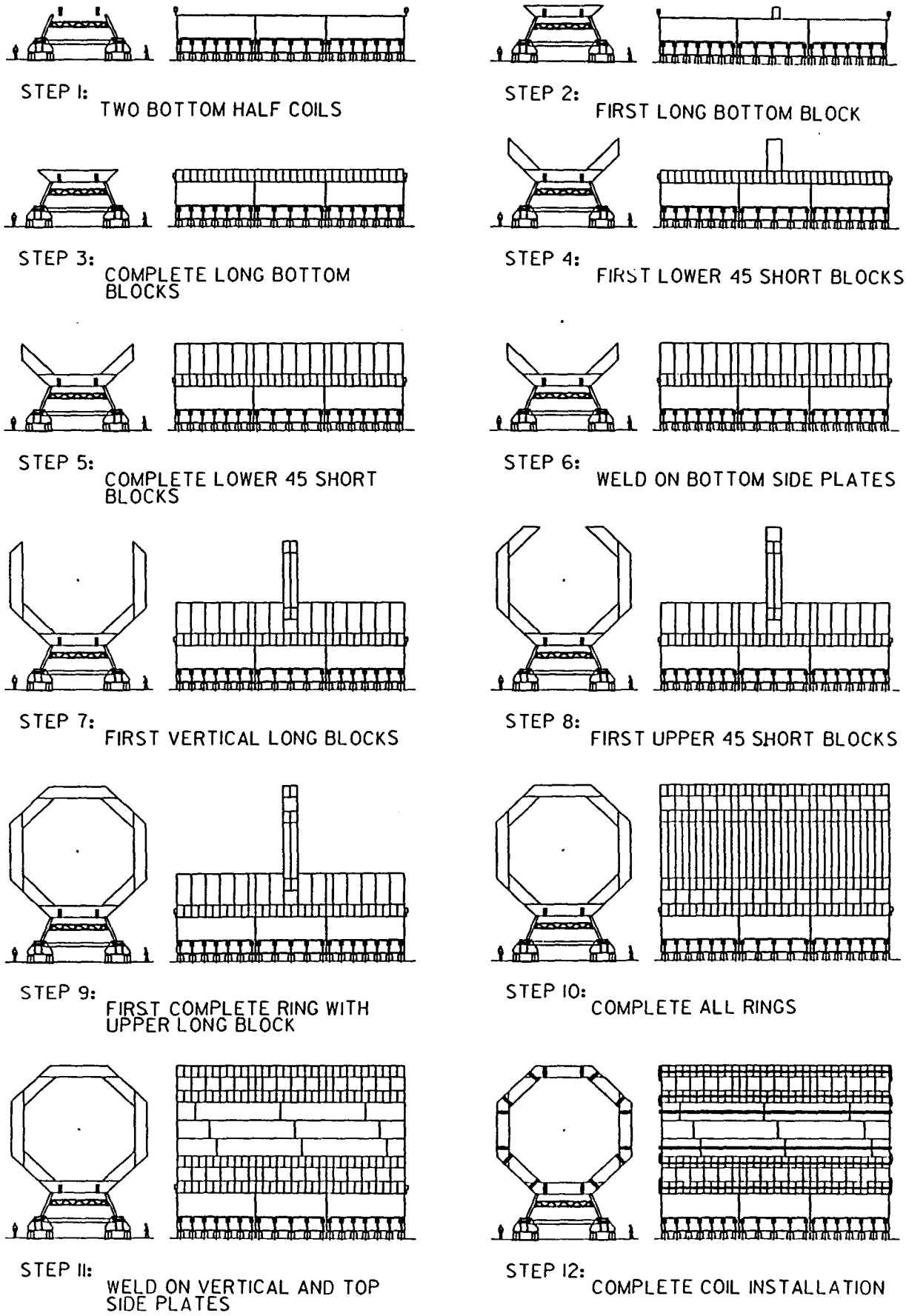


Figure 2-2 Magnet Construction Sequence

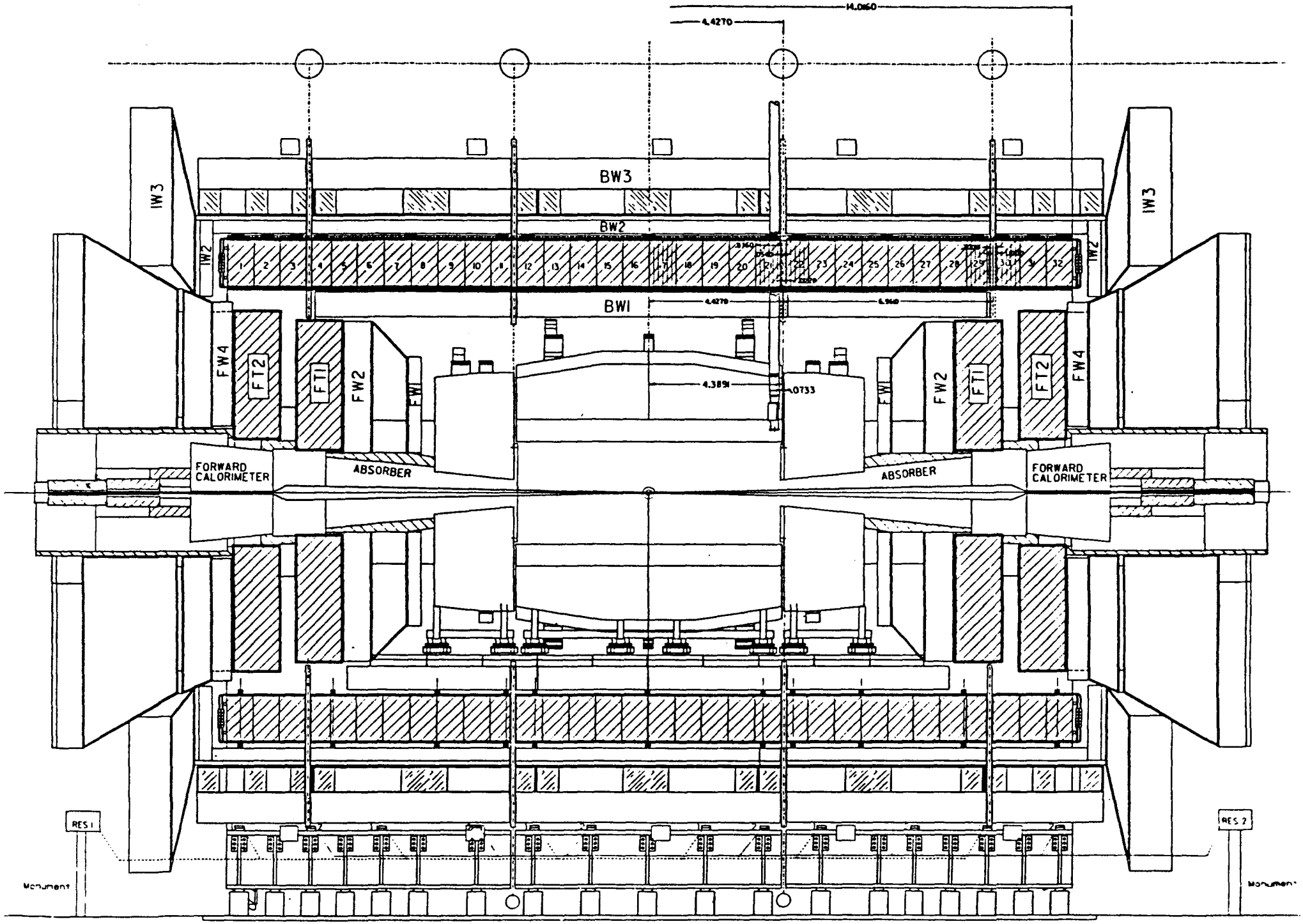


Figure 2-3 Section of the Muon Measurement System

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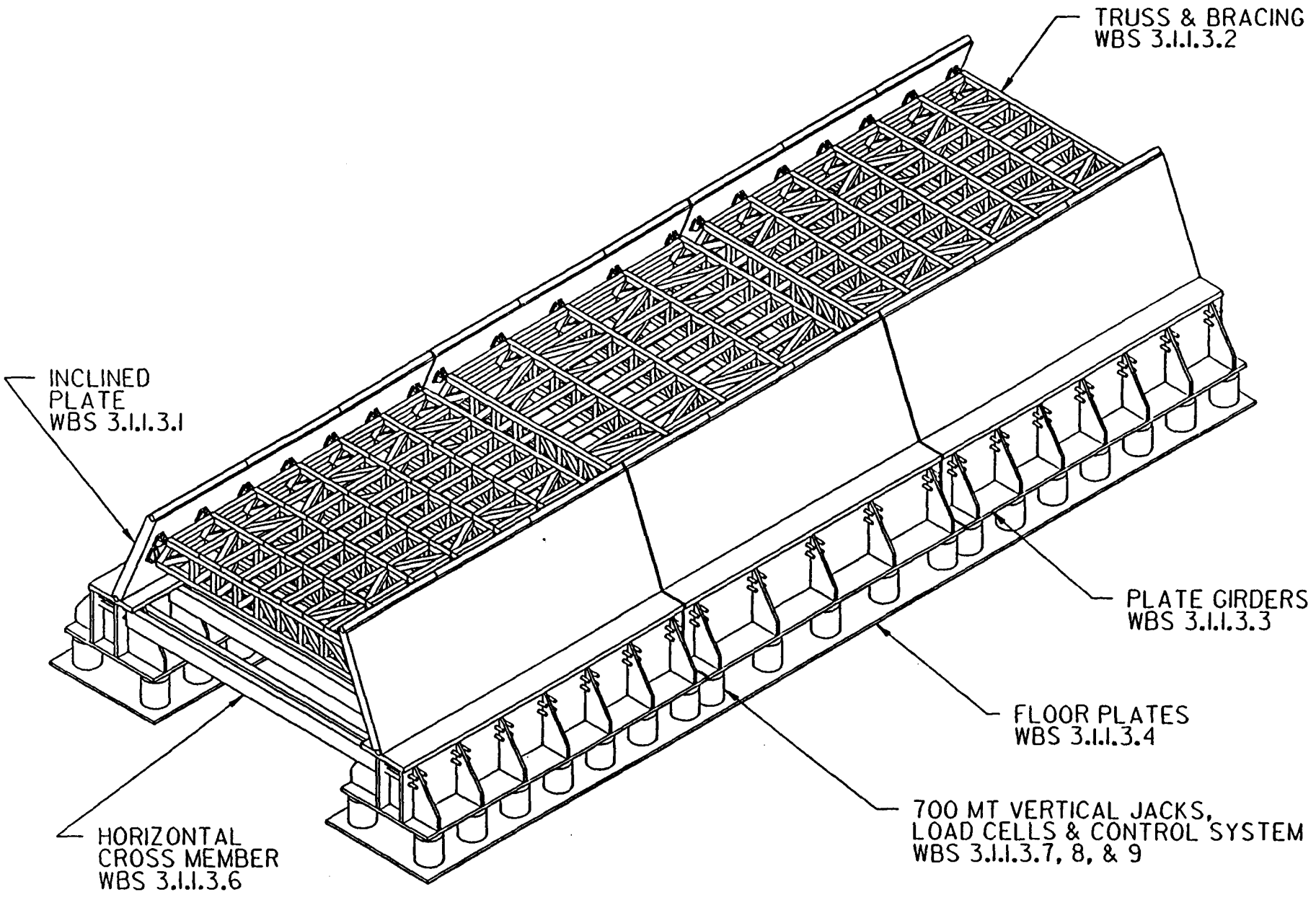


Figure 2-4 Barrel Support System

2.1 Component Identification Nomenclature

Each component of the muon Measuring system has an identification tag number of the type:

ZZZ0.0.0.ZZ.00.00.00

Each entry in the tag number is created using a logic summarized in the table below:

Part	Value	Description
1	Z	A letter designation for the SDC system : Muon
2	Z	A letter designation for region within part 1: Barrel Intermediate Forward
3	Z	A letter designation for subsystem within part 2: Wire Scintillator Toroid Cerenkov Gas Alignment Mechanical Electrical other?
4	0/Z	A letter or number designation for the module location along a track from the IP: 0 signifies that this value does not apply barrel supermodules are 1-3 or T for the 2/3 towers intermediate supermodules are 2-3 or T for the 2/3 towers forward supermodules layers are 1-5 and toroids 1-2
5	.0	A one digit number designation for the supermodule/tower location along the global Z axis, negative to positive: 0 signifies that this value does not apply barrel supertowers 1-5, BW1s 2-4, intermediate supertowers 1-2 forward supermodules and toroids 1-2
6	.0	A one digit number designation for the location in phi: 0 signifies that this value does not apply 1 = global +Y then right hand rotation about global +Z, CW looking global +Z 1-8
7	.ZZ	A two letter designation for the component name: SuperTower Side Panel Drift Tube End Cap Proximity Sensor Top Cover

etc.

8	.00	A two digit number designation for the component location along the local X axis, negative to positive: 00 signifies that this value does not apply 01-99
9	.00	A two digit number designation for the component location along the local Y axis, negative to positive: 00 signifies that this value does not apply 01-99
10	.00	A two digit number designation for the component location along the local Z axis, negative to positive: 00 signifies that this value does not apply 01-99

2.1.1 Example of part identification tag number

The component number of the drift tube end cap on the right hand side of the tube as seen from the IP, in the third tube layer up from the bottom of the module, sixteen tubes from the end of the module closest to the IP, in the BW2 module that's farthest to the south side of the hall, oriented horizontally on the side of the detector away from the ring center is:

MBW2.5.7.EC.01.03.16

2.2 Reference Coordinate Systems.

We define a global cylindrical coordinate system relative to the beam line and interaction point (IP): r, Θ, ϕ where Θ is the angle measured from the beam line at the IP, r is the radial distance from the beamline, and ϕ the azimuthal angle around the beamline.

We also define a Global Cartesian coordinate system (figure 2-5) with its origin at the IP, the Z axis along the beamline ,+Z=south, +Y up, and +X to the east.

We can also define a local Cartesian coordinate system for each module (the same orientation will be used for all the modules in a given octant, therefore the term "local octant coordinate system" will be used) (Figure 2-5,6), with the Z axis paralel to the global Z axis, the +Z still pointing south; the local +Y axis is oriented radially away from the beam, and the X axis complete a right handed Cartesian coordinate system. Whenever it matters, the origin of this local coordinate system will be at the center of the module.

In both Local and Global coordinate systems, rotations around X are defined as pitch, rotations around Y as yaw, and rotations around Z as roll.

Relative positions of chamber modules are described by translations in the Global coordinate system, but tolerance requirements in translation and rotation presented in the next chapter are defined in the local coordinate system of each module, with the origin at the center of the module in its designed location in the Global coordinate system.

Global Coordinate System (figure 2-5):
Cartesian Right Handed XYZ
0,0,0 @ Interaction Point
+X = away from beam ring center, horizontal
+Z = south, in the plane of the machine
+Y = complete the RH coordinate system; close to vertical up

theta = from the + or - Z axis
phi = in the XY plane RH from +X

Local Coordinate System (see figure 2-5,6):
Cartesian RH XYZ
0,0,0 @ Interaction Point
+X = follows from +Y, +Z
+Y = global Y as found in phi = 1 modules, radially out from global Z axis
+Z = away from IP, except Barrel center modules same as global Z

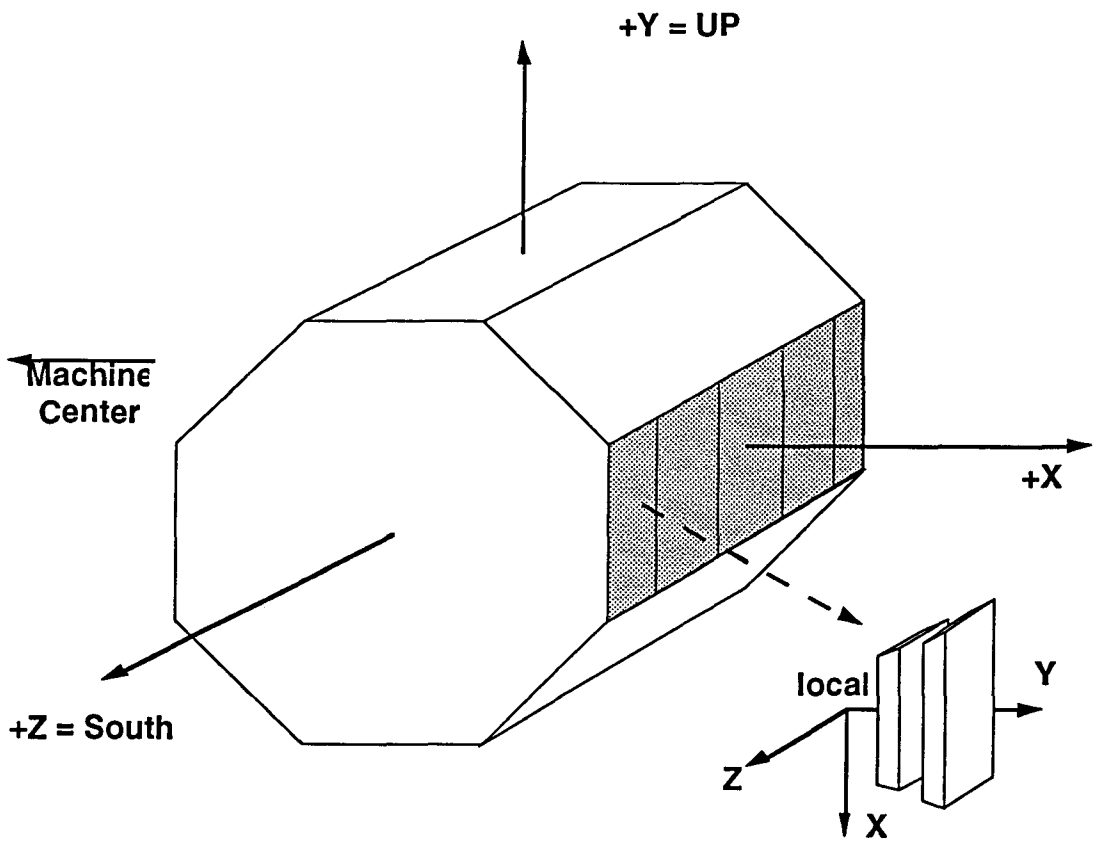


Figure 2-5 Global and Local Cartesian Coordinate Systems

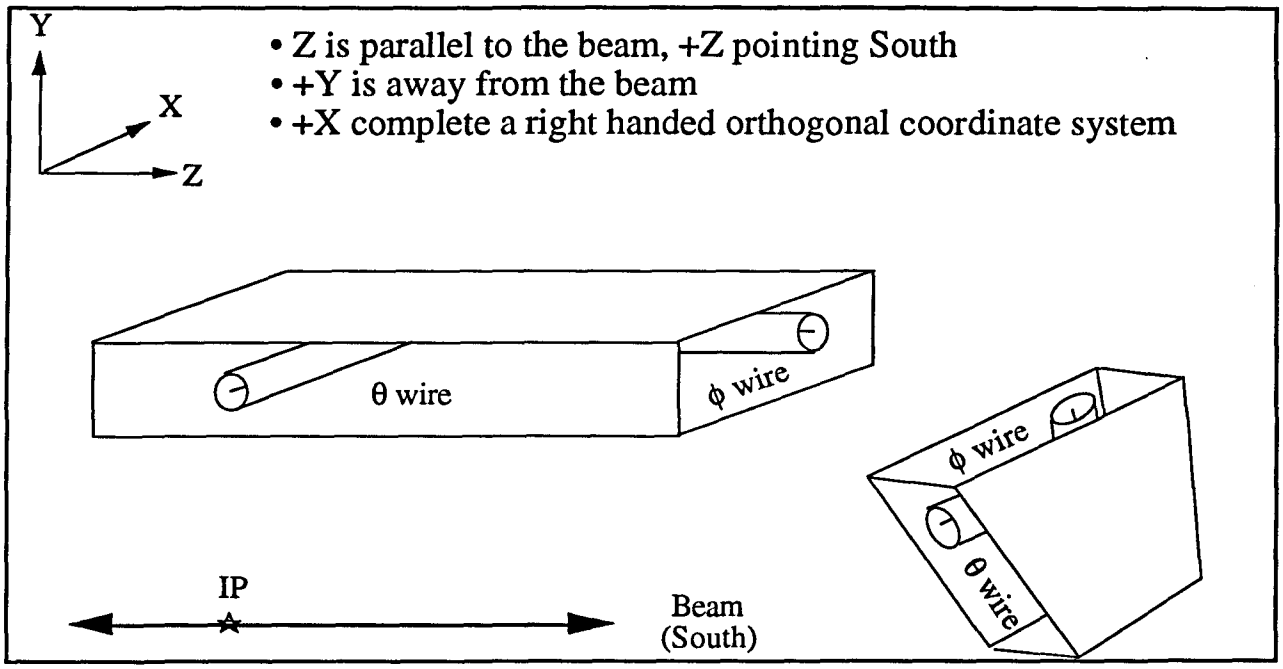


Figure 2-6 Module's Local Coordinate System

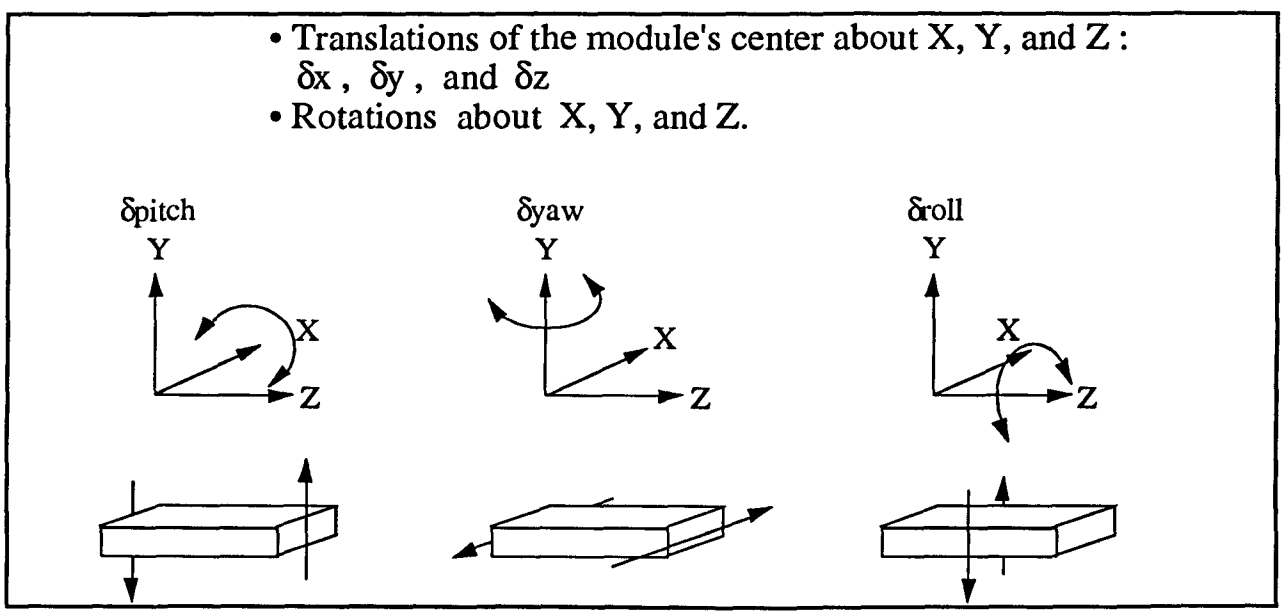


Figure 2.7 Parameters needed to define the position of a module

-References

1) Ch. Grinnell, memo Nomenclature Proposal, 04/03/92 presented also at FNAL on 04/08/92 and incorporated in SDT-000035 Muon Measurement System Engineering Meeting, General Status Review, Fermilab.
2) SDC Technical Design Report, April 1 , 1992. SDC-92-201
3) SDC Detector Parameter book, revision F, September 14,1992. SDT-000010
4) Ch. Grinnell, memo Nomenclature, 8/12/92

3. ALIGNMENT REQUIREMENTS

3.1 Introduction to Alignment Requirement

3.1.1 Alignment Purposes

The purpose of the alignment task is three fold:

1) To ensure that the detector components are located properly during the construction stages. This function is mainly achieved by the static and discrete survey activity.

2) To provide geometrical information on the difference between "as built" and "theoretical or designed", with a better accuracy than provided by the survey during construction, when necessary.

3) To monitor the detector deformations with the same fine accuracyas in 2) above

3.1.2 Requirement Overview

The Muon detector is a multisensor system, each sensor being a drift tube or a scintillator. The main purpose of the alignment task is to provide the wire-ends' locations relative to other wires' and to the accelerator beam and interaction "point" while the detector magnet is turned "ON".

There are two types of requirements for the alignment: 1) Accuracy and 2) Range over which this accuracy has to be achieved. The ratio of Range to Accuracy is called the dynamic range, and the larger this ratio, the harder the difficulty of the task. Dynamic range above 10^5 are difficult to achieve, unless a priori knowledge effectively reduces the range to a region around an expected value.

The accuracy requirement can be divided into Placement and Knowledge type of accuracy. Most of the accuracy requirements are driven by "Physics", and are treated in § 3.2. The Range requirements are dictated by engineering problems such as the size of the initial error in positioning the modules, the ability to "zero" the measuring devices at installation time, and the expected deformation of the Muon Measurement Detector over its lifetime. This second set of requirement is treated in § 3.3.

The muon trajectories emanate from the interaction point (fig 1.1), and the trajectories are detected by the Central Tracker, and by the scintillators and the wires in the drift tubes located in the Muon System. The Tracker alignment is described in a separate document (reference: chapter 4 in the SDC TDR). The alignment interaction between the Muon system and the Tracker is briefly described in chapter 4 of this document. There is no tolerance requirement on the positioning of the scintillators due to the very low geometric resolution of these devices. The Muon Measurement System, is required to measure accurately the deviations from straight line of the particles' tracks. The absolute orientation of those trajectories need to be known with a lesser accuracy. The measurement of deviation from straight line of the tracks has to be done with an error smaller or comparable to the drift tube intrinsic error (150 to 200 μm). We adopted an initial goal of 150 μm for the accuracy of measurement of deviation from straight line.

The continuum of the detector sensing points is discretized by the modules. Because the shapes of the modules spatially dividing the detector do not follow the overall trajectory lines (fig 1.2), except for points along trajectories with $\theta = 90°$ and because most of the modules have tubes in both the ϕ and θ orientation, in the Introduction (§ 1.1) we have adopted as a first approximation of the accuracy requirement, the same 150 μm on the 3 coordinates of all the points measured by the alignment system. Obviously this is a simplification as the accuracy requirements change with the location of those points, and in this chapter we look at the geographical differences.

3.1.3 Design Drivers

The requirements are dictated by:

- The Detector Configuration

- The System Function and Module(s) Function
  Trigger level 1-2, Stand-Alone Pt measurement, Off-Line ϕ and θ measurements.

- The expected range of deformations from "as built"
  A. Ground Movements :
    - Ground heaving
    - Displacement of heavy components (Calorimeter, Forward / Intermediate)

  B. Structural Deformations without ground movements :
    - Displacement of heavy components
    - Thermal changes (changes in power load)
    - Magnet "ON" / "OFF"
    - Hydraulic leaks

3.2 Accuracy Requirement Analysis

The accuracy requirements from the "physics" point of view can themselves be divided into two tolerancing requirements: 1) Acceptable wire position knowledge uncertainty, and 2) Acceptable chamber placement error. Uncertainty on the knowledge of the actual wire positions affects the momentum measurement and resolution of the muons in the Off-Line data analysis and in the Stand-Alone. For a perfect momentum measurement, the positions of the muon track within the chambers, and therefore the positions of the wires, must be known with infinite precision. There are, however, limits to which the position of the muon track can be measured; effects like electron diffusion in the gas filling of the drift tubes limit the position resolution of each tube to a random error of approximately 250 microns (or approximately 125 microns for four layers of tubes). The knowledge requirement for the wire positions, then, can be relaxed, and need only be somewhat less than the inherent measurement resolution of the tubes themselves.

3.2.1 Accuracy of Wire Position Knowledge

The data presented here is derived from e-mail from S. Behrends and P. Hurst, and more details should be available in reference 6. Two different scenarios were used to estimate the position knowledge uncertainty tolerances on translations and rotations of various modules. First, an Off-Line measurement which is a weighted average of Tracker, Mu-Theta, and Mu-Phi measurement, and second a Stand-Alone measurement using a vertex position and measurements by the Muon Measurement System alone. For example in the Barrel section, the Stand-Alone measurement uses two line segments, one formed from the vertex and the BW1 positions and a second formed from the BW2 and BW3 positions to measure the theta bend as the muon traverses the toroid. For low momentum muons, the momentum resolution is dominated by multiple scattering in the toroid and calorimeter. As momentum increases, however, the relative effect of multiple scattering decreases, and at momenta near 2 TeV/c the multiple scattering and chamber measurement contributions to the resolution are approximately equal.

The knowledge tolerances derived for the Off-Line case are defined as module displacement that worsen Off-Line resolution by 10% at 2 Tev P_t. Stand-Alone tolerances were taken to be the module displacement that worsen the Stand-Alone (theta) resolution by 10% at 2 Tev P_t, with the event vertex location in z assumed to be known. The knowledge tolerances derived in this way are given in Table 1. These tolerances are expressed in a local module coordinate system defined in the previous chapter: the Z axis is oriented along the beam direction and the X axis is oriented along the theta wire direction. Pitch is a rotation around the X axis, yaw a rotation around Y and roll a rotation around Z. Note that there is no tolerance on the X position for the Stand-Alone case; this corresponds to movemement along the theta wire direction, where there is no sensitivity. Note, too, that the **tolerances listed** here are exclusive in nature - they **assume that position knowledge is perfect except for the displacement in question**. In the future, a more realistic scenario will be studied to reflect the fact that some modules invoved in the same momentum measurement are attached together, for example in the Barrel and in the Intermediate region, and there is a correlation in the uncertainty on the position of these modules.

Module dimension/locations were taken from the SDC Parameter Book revision E.

Table 1

SUPERMODULE KNOWLEDGE TOLERANCES

MBW13

	x	y	z	pitch	yaw	roll	
Offline	0.804	1.555	1.116	1.555	1.560	1.548	mm
				0.352	0.306	0.609	mrad
Standalone	--	0.701	0.397	0.701	1.003	0.698	mm
				0.159	0.197	0.275	mrad

MBW14

	x	y	z	pitch	yaw	roll	
Offline	1.355	0.773	1.122	0.774	1.674	0.770	mm
				0.221	0.387	0.303	mrad
Standalone	--	0.515	0.504	0.516	0.854	0.513	mm
				0.147	0.197	0.202	mrad

MBW23

	x	y	z	pitch	yaw	roll	
Offline	--	0.610	0.309	0.609	0.488	0.608	mm
				0.138	0.086	0.169	mrad
Standalone	--	0.250	0.111	0.250	0.200	0.249	mm
				0.057	0.035	0.069	mrad

MBW24

	x	y	z	pitch	yaw	roll	
Offline	--	0.258	0.309	0.258	0.430	0.257	mm
				0.074	0.086	0.071	mrad
Standalone	--	0.152	0.125	0.152	0.176	0.151	mm
				0.043	0.035	0.042	mrad

MBW25

	x	y	z	pitch	yaw	roll	
Offline	--	0.228	0.338	0.227	0.365	0.226	mm
				0.154	0.094	0.063	mrad
Standalone	--	0.146	0.200	0.145	0.214	0.145	mm
				0.098	0.055	0.040	mrad

MBW33

	x	y	z	pitch	yaw	roll	
Offline	0.942	0.727	0.308	0.726	0.440	0.725	mm
				0.164	0.071	0.168	mrad
Standalone	--	0.289	0.111	0.288	0.175	0.287	mm
				0.065	0.028	0.067	mrad

MBW34

	x	y	z	pitch	yaw	roll	
Offline	1.130	0.297	0.304	0.298	0.396	0.297	mm
				0.085	0.071	0.069	mrad
Standalone	--	0.159	0.122	0.158	0.157	0.159	mm
				0.045	0.028	0.037	mrad

MBW35

	x	y	z	pitch	yaw	roll	
Offline	3.137	0.221	0.326	0.221	0.412	0.220	mm
				0.066	0.076	0.051	mrad
Standalone	--	0.145	0.175	0.145	0.222	0.144	mm
				0.044	0.041	0.033	mrad

MIW2

	x	y	z	pitch	yaw	roll	
Offline	--	0.196	0.321	0.321	0.098	0.172	mm
				0.278	0.085	0.053	mrad
Standalone	--	0.107	0.206	0.206	0.063	0.111	mm
				0.179	0.055	0.034	mrad

MIW3

	x	y	z	pitch	yaw	roll	
Offline	1.109	0.196	0.331	0.330	0.125	0.172	mm
				0.211	0.080	0.050	mrad
Standalone	--	0.102	0.210	0.209	0.079	0.104	mm
				0.134	0.051	0.030	mrad

MFW1

	x	y	z	pitch	yaw	roll	
Offline	--	0.180	0.810	0.809	0.715	0.298	mm
				0.486	0.429	0.252	mrad
Standalone	--	0.178	0.680	0.696	0.615	0.256	mm
				0.418	0.369	0.216	mrad

MFW2

	x	y	z	pitch	yaw	roll	
Offline	--	0.213	0.956	0.955	0.869	0.353	mm
				0.442	0.402	0.240	mrad
Standalone	--	0.212	0.810	0.819	0.745	0.302	mm
				0.379	0.345	0.206	mrad

MFW4

	x	y	z	pitch	yaw	roll	
Offline	--	0.096	0.442	0.442	0.347	0.131	mm
				0.206	0.161	0.071	mrad
Standalone	--	0.095	0.370	0.370	0.290	0.110	mm
				0.172	0.135	0.059	mrad

MFW5

	x	y	z	pitch	yaw	roll	
Offline	--	0.097	0.441	0.442	0.345	0.131	mm
				0.159	0.124	0.055	mrad
Standalone	--	0.095	0.370	0.370	0.289	0.108	mm
				0.133	0.104	0.045	mrad

3.2.2 Accuracy of Chamber Placement

The placement tolerances give the accuracy with which the modules must be positioned. Small misplacements can be corrected in the offline analysis, but the trigger assumes that all modules are correctly positioned on the detector. The trigger measures momentum by measuring the angle of a muon track within single modules, not by measuring the absolute trajectory of the muon track. The short lever arm (approximately 20 cm) of an angle measurement internal to a single module, coupled with the smeared event vertex and the physical width of a trigger tower, degrade the trigger's momentum resolution. The placement tolerances derived from the trigger resolutions, therefore, are significantly less stringent than those derived for wire position knowledge.

Momentum resolutions for Level 1 and a particular Level 2 trigger have been derived from the ISAJET Monte-Carlo and the BOSSIM detector simulation[6]. The Level 1 trigger measures the momentum of a muon by measuring the angle of its track in BW2, while the Level 2 trigger measures the difference of angles measured in BW1 and BW2. Placement tolerances for the Level 1 trigger were taken to be the module displacement that worsen L1 resolution by 10% at 20 GeV/c P_t, while the Level 2 tolerances are defined as misalignment that worsen L2 resolution by 10% at 100 GeV/c P_t.

Table 2 gives these placement tolerances for various types of modules. Note, too, that the tolerances listed here are exclusive in nature - they **assume that only one module is displaced at a time, with only one degree of freedom being considered.** In the future, a more realistic scenario will be studied to reflect the fact that some modules involved in the same momentum measurement are attached together, for example in the Barrel and in the Intermediate region.

Module dimensions/locations were taken from the SDC Parameter Book revision E.

Table 2

SUPERMODULE PLACEMENT TOLERANCES

MBW13

	x	y	z	pitch	yaw	roll	
Level1	--	--	--	--	--	--	mm
				--	--	--	mrad
Level2	--	14.906	6.863	4.795	20.150	13.957	mm
				1.085	3.953	5.491	mrad

MBW14

	x	y	z	pitch	yaw	roll	
Level1	--	--	--	--	--	--	mm
				--	--	--	mrad
Level2	--	14.169	9.902	3.671	17.170	13.923	mm
				1.048	3.968	5.477	mrad

MBW23

	x	y	z	pitch	yaw	roll	
Level1	--	126.327	48.527	24.234	93.672	112.616	mm
				5.484	16.436	31.293	mrad
Level2	--	25.265	9.705	4.839	18.916	23.383	mm
				1.095	3.319	6.496	mrad

MBW24

	x	y	z	pitch	yaw	roll	
Level1	--	97.475	59.272	18.564	82.664	92.373	mm
				5.301	16.462	25.667	mrad
Level2	--	19.495	11.854	3.706	16.709	18.990	mm
				1.058	3.327	5.276	mrad

MBW25

	x	y	z	pitch	yaw	roll	
Level1	--	98.902	120.177	7.761	128.290	92.358	mm
				5.257	32.982	25.663	mrad
Level2	--	19.780	24.035	1.551	26.845	18.968	mm
				1.050	6.900	5.270	mrad

MBW33

	x	y	z	pitch	yaw	roll	
Level1	--	170.917	58.039	24.325	95.705	150.865	mm
				5.505	15.510	35.036	mrad
Level2	--	34.183	11.608	4.844	19.260	31.481	mm
				1.096	3.121	7.310	mrad

MBW34

	x	y	z	pitch	yaw	roll	
Level1	--	116.089	67.022	18.709	86.212	107.707	mm
				5.342	15.532	25.011	mrad
Level2	--	23.218	13.404	3.753	17.343	22.103	mm
				1.072	3.124	5.132	mrad

MBW35

	x	y	z	pitch	yaw	roll	
Level1	--	116.092	117.947	17.496	148.723	107.805	mm
				5.253	27.320	25.034	mrad
Level2	--	23.218	23.589	3.492	30.749	22.190	mm
				1.048	5.648	5.152	mrad

MIW2

	x	y	z	pitch	yaw	roll	
Level1	--	79.390	159.435	5.050	50.708	88.148	mm
				4.383	44.030	26.931	mrad
Level2	--	19.406	38.973	1.233	13.263	22.071	mm
				1.070	11.513	6.742	mrad

MIW3

	x	y	z	pitch	yaw	roll	
Level1	--	77.673	176.101	6.183	70.237	91.054	mm
				3.958	44.980	26.446	mrad
Level2	--	18.987	43.047	1.512	18.369	22.876	mm
				0.968	11.760	6.643	mrad

MFW1

	x	y	z	pitch	yaw	roll	
Level1	--	--	--	--	--	--	mm
				--	--	--	mrad
Level2	--	3.531	20.752	0.738	25.604	8.178	mm
				0.443	15.373	6.904	mrad

MFW2

	x	y	z	pitch	yaw	roll	
Level1	--	--	--	--	--	--	mm
				--	--	--	mrad
Level2	--	4.092	25.652	0.894	32.960	10.141	mm
				0.414	15.270	6.894	mrad

MFW4

	x	y	z	pitch	yaw	roll	
Level1	--	23.088	137.740	3.218	118.261	42.832	mm
				1.497	55.039	23.226	mrad
Level2	--	6.734	40.174	0.937	38.075	12.768	mm
				0.436	17.712	6.923	mrad

MFW5

	x	y	z	pitch	yaw	roll	
Level1	--	29.845	177.478	4.178	153.061	55.512	mm
				1.500	54.965	23.229	mrad
Level2	--	8.705	51.764	1.217	49.296	16.511	mm
				0.437	17.695	6.909	mrad

3.3 Analysis of Alignment Range Requirement

Each Alignment measurement has a required accuracy, and a range over which this accuracy has to be achieved. The Range requirements are dictated by engineering problems such as the size of the initial error in positioning the modules, the ability to "zero" the measuring devices at installation time, and the expected deformation of the Muon Measurement Detector over its lifetime. Only a very limited amount of information regarding the Alignment Range Requirements has been gathered so far:

- The largest amount of deformation of the magnet structure occurs at the time of the magnet construction, due to its own weight.
- The effect of the magnetic forces on the magnet structure is negligible (less than a micrometer).
- The maximum module deformation under gravity is of the order of 1 millimeter for the Barrel modules.

- References

1. A. Seiden. Systematic Errors and Alignment for Barrel Detectors, SCIPP 91/20, March 1991
2. J. Chapman & R. Thun. SDC Muon Trigger Preliminary Conceptual Design, (8/27/91)
3. S. Behrends, J. Bensinger. Trigger Resolution Issues for the SDC Muon System, (11/07/91)
4. S. Errede, R. Gardner, J. Wiss. Muon Matching Studies, SDC-91-156 (11/11/91) SDC Collaboration. SDC TDR April 92
5. S. Errede, R. Gardner, J. Wiss. More on Muon Matching, presented FNAL 4/10/92
6. S. Behrends, P. Hurst, J. Bensinger. Performance-Based Tolerances For Muon Module Alignment (Draft) October 8, 1992.
7. Muon Detector Alignment System, Reference Document and Conceptual Design Report. Version 2 For Comment. SDT-000043, July 13, 1992.
8. SDC Detector Parameters, SDT-000010, Rev. F September 14, 1992.

4. ALIGNMENT SYSTEM DESCRIPTION

4.1. Introduction and Summary of Alignment Approach and Baseline Concept

The Muon detector is a multisensor system, each sensor being a drift tube or a scintillator panel. The critical components are the anode wires within the drift tubes, and the main purpose of the alignment task is to provide the wires' locations relative to other wires' and also to the accelerator beam and interaction "point", while the detector magnet is turned "ON".

The alignment requirements have been studied in chapter 3.

There are three main Alignment functions:

I. Alignment during module construction, testing and calibration.
I. Alignment during detector construction (modules' positioning)
III. Alignment after detector construction presently divided in 3 parts:
- A Local Alignment
- B Global Alignment
- C Computer integration of the data

I. During the module construction the Alignment group will provide support to the construction teams. The alignment procedures for each type of module will be described in the documents describing the modules. Dimensional data gathered during the construction phases will be made available for later use in the mathematical model of each module which will be used as an interpolation function.

II. As the construction sequence of the magnet toroid progresses, the position and straightness of the magnet and its parallelism with the expected beam line will be checked by survey measurements carried out by the Applied Geodesy Group. After completion of the Barrel Magnet (and any adjustment to "best shape"), the detector base liquid level system will be recalibrated. All octant support rails will be installed on the statically deflected toroid within ± 1 mm in x and y (in the local coordinate system of each octant) of the designed values. Also a system of opto-mechanical straight line monitors ("Fencepost", see § 4.4.2.2) oriented along the local y axis of each octant, and penetrating through the magnet iron, will be installed, checked and removed.

Once fabricated and calibrated, the modules will be properly positioned with respect to each other and to the beam. It is expected that given the tolerance requirements on positioning described in chapter 3, this can be

accomplished by the Survey team of the DAG. The survey reference targets located at the reference points of the modules will be installed, and the modules will be placed within the required position tolerances from the theoretical design positions. Preliminary procedures are described in § 4.3 . After installing the BW1 modules, the part of the Fencepost penetrating the iron magnet will be reinstalled. The BW2-BW3 Supermodules (or Boxes) will be installed, and the second half of the Fencepost will be reinstalled and initially checked.

III. The final alignment task is to obtain a more precise knowledge of the position of the sensing wires within the detector than provided by the installation survey, so that all the necessary dimensional information enabling the proper trigger functions and the reconstruction of trajectories before the final Image Processing is obtained. This task builds upon the two previous tasks. Because the near continuum of detector sensing points (the anode-wires) is discretized by the modules whose shape does not lend itself to direct measurement of the position of the sensing wires perpendicular to the particles' tracks, the task is divided into three main steps:

A) a Local sensing providing data about the position of the wire-ends within a module relative to the position of fiducial or reference points at the corners of the same module,
B) a Global sensing providing data about the position of the corners of the modules relative to each others and to the tracker and accelerator beam. This step used a technique which provides at the same time precise global dimensional information about the sensing alignment devices.
C) finally the data gathered by the sensors used in the Local and Global alignment steps, along with temperature and pressure sensor data, are fed to a computer model of the detector. The model includes calibration curves of the sensors, structural information of the detector and alignment devices etc... The execution of the model will provide the relative position of the wire-ends from one chamber to an other and to the IP at any required time.

The complete alignment tasks can be summarized in four steps as presented in the table below:

STEP 1
• Measure precisely the location of the sensor end-wires w/r/t fiducials located at or near the module's corners during the module fabrication. This is the calibration of the interpolation function.
STEP 1
• Place the modules within the placement tolerances (1 to 3 mm) from the expected (at the time of construction) Beam-Line.
STEP 3
• Measure continuously (or as required) while the Detector is operating:
a) The deformation of the modules with the On-Module SLMs (Local Alignment) and use the interpolation function to find the position of the wires w/r/t the fiducials.
b) A set of relative distances between fiducials of different modules, and also between fiducials located on Beam Position Sensors and the Central Tracker using a variety of devices.
c) The temperature distribution
STEP 4
• Feed the distance measurements and the temperature readings into a computer model to reconstruct the precise actual wire locations.

Besides the division in local and global functions, the alignment system can also be logically divided by the detector functions that it is supporting (i.e. trigger 1,2 ..., momentum measurement, etc..), by regions within the detector (Barrel, Intermediate, Forward, Magnet Support, etc..), by regions dictated by trajectory lines, or by devices used in the alignment process. The preferred way of presenting this material varies with the interest of the reader, and in the following paragraphs we have attempted to present a coherent view of the alignment system from which an understanding from another point of view could be extracted. Later on, alignment of specific subsystems based on division dictated by schedule or important difference of approach are addressed: Alignment of the Barrel Tower in § 4.4.2.2, and Alignment of the Support System in § 4.5.2.

A summary of Alternate Alignment System Concepts which have been considered is finally presented for completeness in § 4.6

4.2 Alignment during Module Construction, Testing and Calibration

The goal is to achieve a representation of each module such that later by measuring the actual relative displacements of a few points (the middle element or node of the Straight Line Monitors), and given the position of a few reference points (the module's corners), the position of the wire-anode of each drift tube in the detector be known with the desired accuracy set forth in the Requirement chapter.

During the module construction, quality acceptance (QA) data will be gathered for dimensions involved in relating the positions of the drift tube wire-ends to the positions of the fiducial points at the corners of each module. Because of the tight manufacturing tolerance obtained with Numerically Controlled machines, only a few points need to be checked on each end-plate. The fiducial points are attachment points for alignment devices which can be surveying targets, proximity sensors, element of multi-node straight line monitors or hydrostatic levels. In the text, the expressions fiducial points, module corners and alignment reference points will often be used interchangeably. It will be shown in the paragraph addressing the error budget, that this QA data gathering will require the use of very precise tooling equipment (Laser Tracker) for measuring and surveying the position of the fiducials on the modules.

Through finite element analysis (FEA), the expected static deformational mode shapes of each modules will have been calculated. As the expected deformations are well within the elastic limits of the modules, all the points of an end-plate follow an affine transformation when the end-plate is deformed. By monitoring the deformation of a properly selected reference line on the end-plate, the position of all the points of the end-plate relative to the reference points can be known. The modules' mode shapes and by extension the shape of the reference lines are dependent upon the known gravity loading, the number and location of the module's support points and the construction of each module. Due to the structural continuity of the plates, the deformation of these reference lines can be approximated by low order polynomials. The reference lines selected are one long edge of each end-plate. During the module testing, the validity of the polynomial approximations* will be verified using surveying and other optical measuring tools. Depending upon the mode shape, a number of simple 3-point Straight Line Monitors (SLMs) will have been installed at selected points inside or on the surface of the modules and near the edges, and these On-Module SLMs will be calibrated. The performance of 3-point SLMs have been demonstrated during the muon chamber prototyping activities (ref xx). The quality acceptance data and calibration data will be recorded along with the temperature provided by the temperature sensors, and this information will be used in the Local Alignment after detector assembly (§ 4.4.1). The finite element model of each module will be the starting point for the creation of a mathematical model of the module. This model will incorporate material

* There are two reasons for using a polynomial approximation. First as a didactic device to convey the idea that only a few points need to be monitored in order to reconstruct the useful shape of the module. The only requirements are that the alignment sensors be placed at the "antinodes" of the mode shape. It must be remembered that the deformation of interest are only at the end plates supporting end-wires. Second, the polynomial approximation is useful in order to reduce the computational load in the use of the mathematical model of the detector. The finite element model can always be used if needed.

data, position of sensors (temperature and position sensors) and calibration curves.

The number of temperature sensors has been estimated at 8 per module (14 for the prototype modules). Figure 4-1 illustrates the process used in reconstructing the position of an end-wire from the measurement provided by the SLMs. Figure 4.1a) shows a barrel module with the global coordinates of the corners obtained through the global alignment. Figure 4-1b) shows the in-plane deformation of an end-plate. On this figure it is assumed that a second degree polynomial is adequate to represent the in-plane deformation of the long edge of an end-plate. Z_0, z_l, z_w, y_w are dimensional data provided by Quality Acceptance (QA) and measurements obtained during construction of the module. The local alignment sensor provides d_l. The value of y_w under deformation, in this sub-local coordinate is y_w' :

$$y_w' = y_w + a \times z \times (z - z_0) \quad \text{with} \quad a = \frac{d_l}{z_l \times (z_l - z_0)}$$

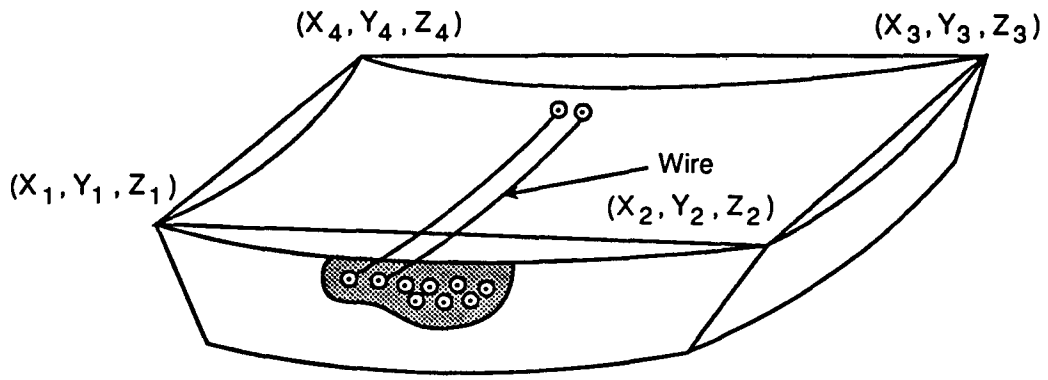
Table xx presents the different components of the local uncertainty i.e. the uncertainty on the knowledge of the position of a wire w/r/t the fiducial points on the same module. It must be remembered that because the wires are under tension, the <u>change</u> in wire sag due to the deformation of the module is negligible compared to the sag in the edge of the end-plates (and the tubes) which are sensed by the local alignment.

4.3. Alignment During Detector Assembly

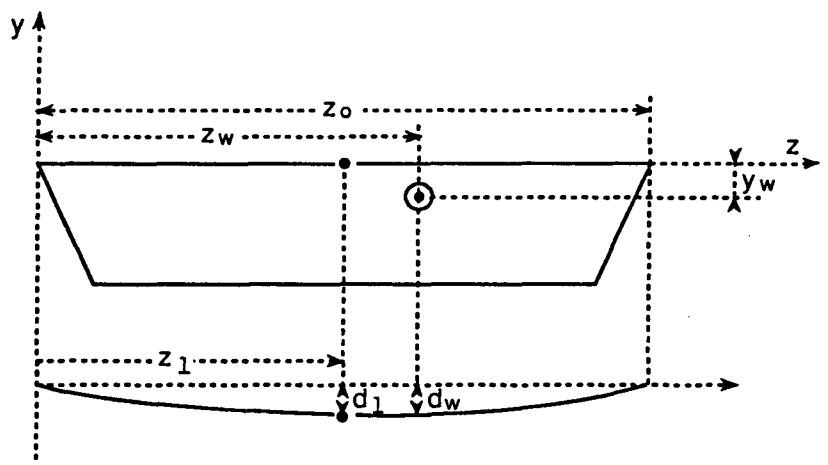
This activity consists in ensuring the correct placement of the modules within the placement envelope calculated in the Requirement chapter. If the anticipated displacements of some modules between their position at installation time and during operation are larger than the *Placement* tolerances (due to magnet ON/OFF, or thermal expansion for example), measured offset will have to be established. Also the position of the alignment components will be initially surveyed; this activity automatically provides the starting values for the global alignment process. The major Alignment activity during the Detector Assembly is the Survey carried out by the Department of Applied Geodesy, but other Alignment activities will take place, for example:

- Installation and calibration of the Liquid level network for the magnet base.
- Fixture Alignment in the Surface Assembly Facility.
- Module Alignment and QA in the Surface Assembly Facility.
- Measurement of the module deformation in their final orientation on the
- Calibration work: Proximity Sensors, Fencepost, ROM Targets, etc...

An other important task will be the interaction with the Installation and Survey personel. This interaction must start at the design stage because



(a) - X, Y, and Z are global coordinates.



(b) - y and z are sub-local coordinates defined by the line joining the two ends of the long edge of an end-plate.

Figure 4-1 Illustration of the Local Alignment Steps

the Alignment performances during the detector Assembly will depend upon the methods used and the order of installation. In order to anticipate the Placement accuracy and compare it with the requirements, the procedures for Installation and Surveying must be described:

- Initial Survey of the Experimental Hall w/r/t expected Beam Line. Definition and budgeting of the possible errors.
- Installation Plan for the Support System
- Plan for Survey and Alignment of the Support System. Definition and budgeting of the possible errors.
- Installation Plan for the Barrel Magnet.
- Plan for Survey and Alignment of the Magnet.
- Installation Plan of the Rails on the Magnet.
- Plan for Survey and Alignment of the Rails on the Magnet.
- Integrated Installation Plan for the Tracker and the Calorimeter.
- Installation Plan for the Muon System.
- Plan for Survey and Alignment of the Muon System.

In the list above, the word Alignment refers to the verification that the placement tolerances have not been exceeded.

For example, with the information already available, we can anticipate difficulties in achieving some module's angular placement tolerance because the current plan for the installation of the Barrel modules does not have provision for adjustment (it is claimed that there is no access to the mounting points after the modules have been installed): The modules are installed on rails and the precision with which the placement is achieved is limited by the future deformation of the Barrel magnet which support the Muon Measurement System, the uncertainty on the placement of the rails on the magnet, the placement of the mounting supports on the modules at the time of module fabrication, the knowledge of the barrel iron deformation through the assembly and the module's deformation. Fortunately, the tightest tolerances (in local pitch ~ 0.44 mr) are for the forward modules which are adjustable.

4.3.1 Work performed mostly by the Department of Applied Geodesy

The principal tasks of the Department of Applied Geodesy (AG) Detector Alignment group at the SSCL are defined as part of the AG alignment plan. A document detailing the conceptual plan for the survey alignment of the SDC experiment should be available around October 1992, and a preliminary outline follows.

Applied Geodesy (AG) global survey goals for the SDC experiment would seem to be to:

a) realize the theoretical parameters of the detector to tolerances required by trigger

b) produce as built parameters of the detector

c) assure the alignment interface between the machine and the detector.

The base of all survey alignment for accelerators is the surface geodetic network. This assures the finished geometry of the machine, the relationship between associated accelerators and the homogeneity between the machine and the experimental apparatus. The surface coordinates are transmitted to the subterranean works and are used as known coordinates for the propagation of relationship throughout the the subsurface installation networks.

The process of propagation and the smoothing criteria on the completed accelerator means that the axis for installation of the detector and the local axis for alignment of the accelerator will be to a first approximation parallel but not coincident. An educated guess would be that the shifts should not exceed ±3mm in X and Y. The shifts will be known just prior to the final "smoothing" of the collider. If the mismatch between alignment axes is unacceptable for trigger purposes this must be stated clearly and early as the effect of a local distortion (over several kilometers) of the machine and the impact on machine installation schedules must be assessed.

The experimental cavern installation reference system will be materialized by survey brackets whose approximate positions will be established as part of the civil engineering design. A major survey task will be to maintain a consistent reference system throughout the installation period of 39 months. The internal consistency of the network will be maintained by conventional survey measurement procedures. The external consistency will be maintained by stable points linked with geotechnical measurement devices anchored in undisturbed bedrock. The driver for a redetermination of relation will be the alignment needs of the installation process. The survey brackets will not be sufficient for a comprehensive coverage of the SDC detector, the basic network will be densified by stations on the floor of the cavern and points on the more stable parts of the experimental apparatus such as the barrel toroid, forward toroid, absorber and calorimeter. The stationable points on the detector will require bolt holes to secure fixtures and will only be temporary.

Survey is dependent on the optical line of sight(s), and a detector is materialized from an alignment point of view by a series of external fiducials known to an appropriate accuracy with respect to the internal physics fiducials of the detector element. The use of fiducial sockets is recommended as they allow flexibility of method. A typical fiducial socket is given in Figure 1. A line of sight is considered acceptable if it is within a right-angled cone with the apex at the reference socket. This cone should be kept clear of obstruction at all times.

A collider experiment's structure resembles a set of "Russian dolls". The only way survey can handle "Russian doll geometry" is by transmission of relationship using 6 parameter transformation. That is the whole object is measured before insertion into the detector, after installation the coordinates of non-visible fiducials can then be deduced from measurements on visible fiducials. This of course assumes the object behaves as a rigid body, or that its shape is modeled and/or monitored appropriately.

Survey information on experimental apparatus in working conditions is limited by the hermetic condition of the detector and the magnetic fringe fields. Survey however will provide coordinates for fiducial marks on the outer "layers" of the detector as well as zero condition for relative measurement systems such as fence posts.

It is unreasonable to quote expected accuracy out of context because of the overriding influence of environmental conditions and the geometry of determination. As a general rule, work of the highest accuracy should be performed during assembly whether this be on the surface or in the cavern, before insertion of the subsystem into the detector. The last generation of collider experiments at Fermilab,SLAC and CERN relied very heavily on industrial triangulation for coordinate determination because of the versatility of this method. This will undoubtedly also be true for the SSC experiments. Industrial triangulation in good conditions yields coordinates of an accuracy of 0.1mm (1σ) on a reasonable sized object (5m*5m*5m). The recent developments in the field of industrial measurements namely laser tracking and industrial photogrammetry would seem to offer a significant gain in accuracy. The former technique will undoubtedly be on site and used extensively at the SSC.

4.4. Alignment After Detector Assembly

4.4.1. Local Alignment(Figure 4.1 and 4.2)

The local alignment provides the positions of the end-wires relative to the reference points on the same module. This step is simply the execution of the program described in § 4.2 under the actual load, i.e. during the Module construction and checking, the interpolation functions have been established, and now they are used. The output of the 3-point SLMs along with the output from the temperature sensors are fed into the mathematical model which has been created and verified during the module construction (see § 4.2).

4.4.2. Global Alignment

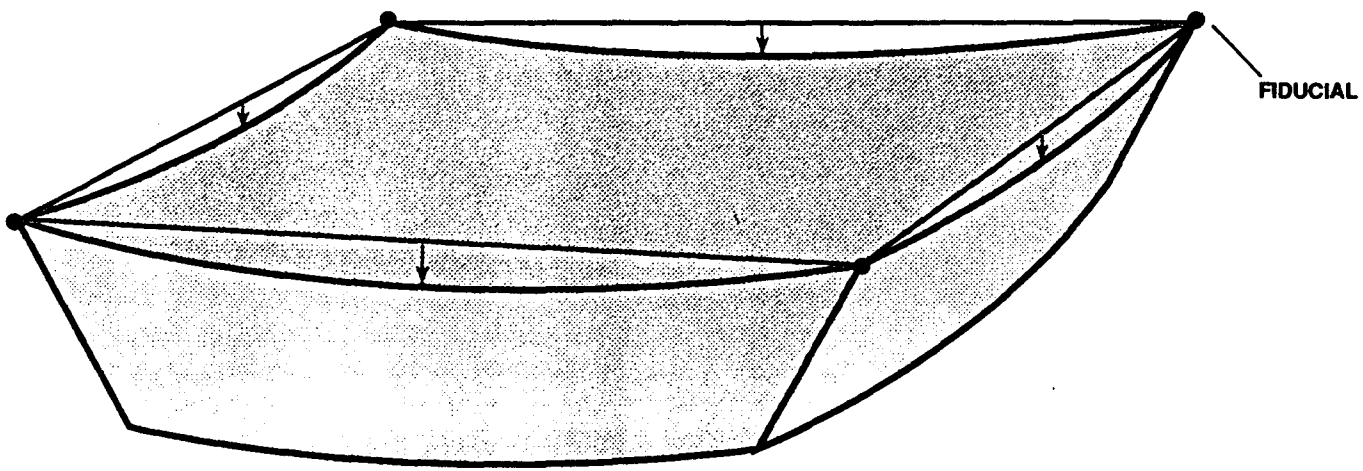
4.4.2.1 Overview

The total alignment must provide the knowledge of the relative position of the drift wires, and eventually their positions relative to the beam.

LOCAL ALIGNMENT

Monitor module deformations and, through a mathematical model, relate wire-ends to fiducial marks at module's corners (tied to Global Alignment)

- Straight line monitors measure the deflection of the module at the end-plates
- Module shape ascertained by finite-element analysis and prototyping
- Module shape is determined by:
  - Fabrication errors
  - Thermal & gravity loadings
  - Mounting conditions (# and location of support points)
- Length calculated from data recorded during quality control of parts, mechanical and gravity loading, and temperature sensing



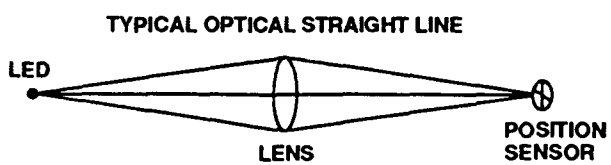


Figure 4-2 Summary of the Local Alignment Procedures

The transfer of position information from the wires to the fiducial points at the corners of the modules has been established by the local alignment. The global alignment is therefore concerned with the knowledge of the position of the fiducial points in relation to each others and to the beam.

The global alignment is divided into two parts:

1) Inside the detector, straight line monitors (SLMs) and proximity sensors located between modules (fig 4.3) measure the relative positions of the corners of a module to the corners of the adjacent modules. At appropriate locations, extensions of the SLMs relate the SLMs to the tracker and to alignment targets on the walls of the cavern. The present SLM design concept, based on an extension to multi-point of the 3-point SLM used in the local alignment, is described in § 4.4.2.2.1 .

2) Outside the detector (Figure 4.4), a network of Range-Only-Measurement (ROM) provides absolute accurate information regarding the orientation and position of the SLMs, and also provides direct positional information of the modules which are not included in the internal network of SLMs. This is achieved by measuring the distances between Range-Emitter-Receivers (RERs) devices and discrete cooperative targets located at the nominal SLM ends, at extensions of the SLM toward the wall of the cavern, and at the beam position sensors (fig 4.4 and 4.5). The network of RERs is organized in clusters and is self-referencing by using redundant measurements. The main advantages of this ROM system are its ability to provide accurate closure of the network of SLMs automatically under simple computer control while the magnet is "ON", its flexibility regarding configuration changes, and the easiness of providing redundancy necessary for graceful degradation of the alignment system under failure of some of the devices. The use of the ROM network is described in § 4.4.2.3.

The networks of SLMs and ROMs are complemented by a liquid level measurement network in areas of low visibility for the ROM network (barrel support and octant 5). This network is described in § 4.4.2.4.

Other important components of the alignment system are a network of temperature sensors, and the computer model of the detector which is updated by the sensors output, therefore providing geometrical information about the detector at all time. The alignment system will be designed with enough redundancy to provide for graceful degradation with component aging and failures after a proper cost trade-off.

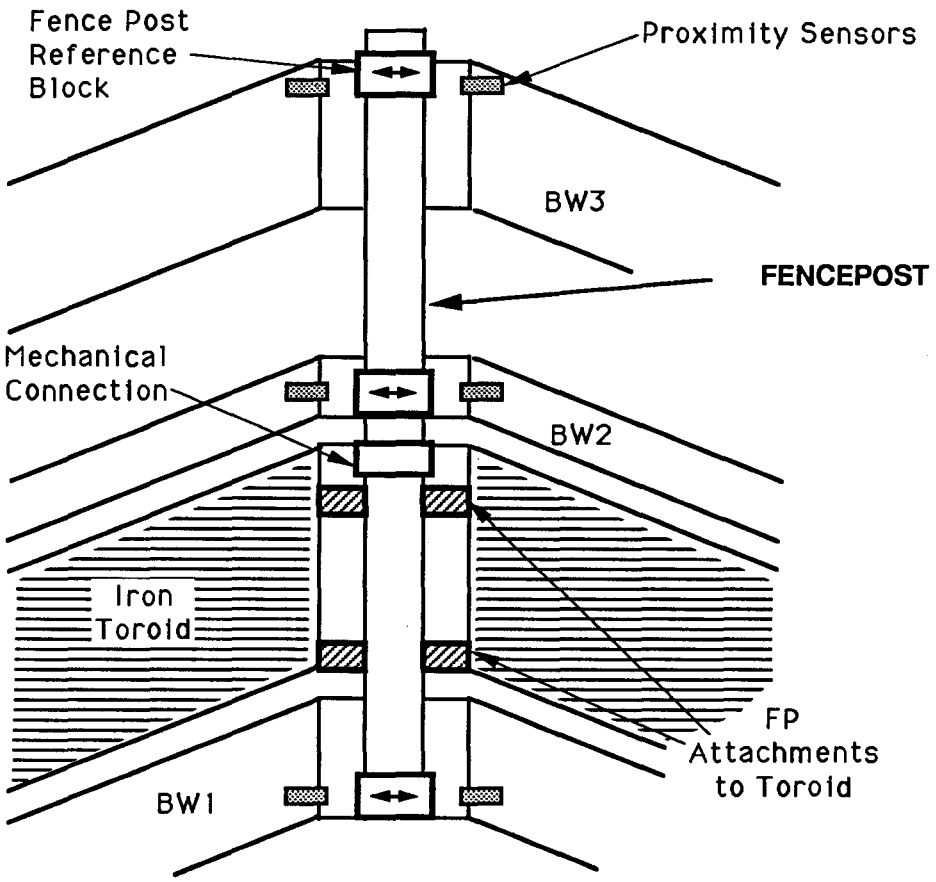


Figure 4-3 SLM for Global Alignment in the Barrel Region (Schematic)

Baseline Global Alignment Part 2

- To provide accurate closure of the network of optical straight lines and relate it to the beam line via beam position sensors or survey network.
- Based on a system of automated distance-only-measuring devices using laser diode ranging, organized in clusters providing self alignment capability.

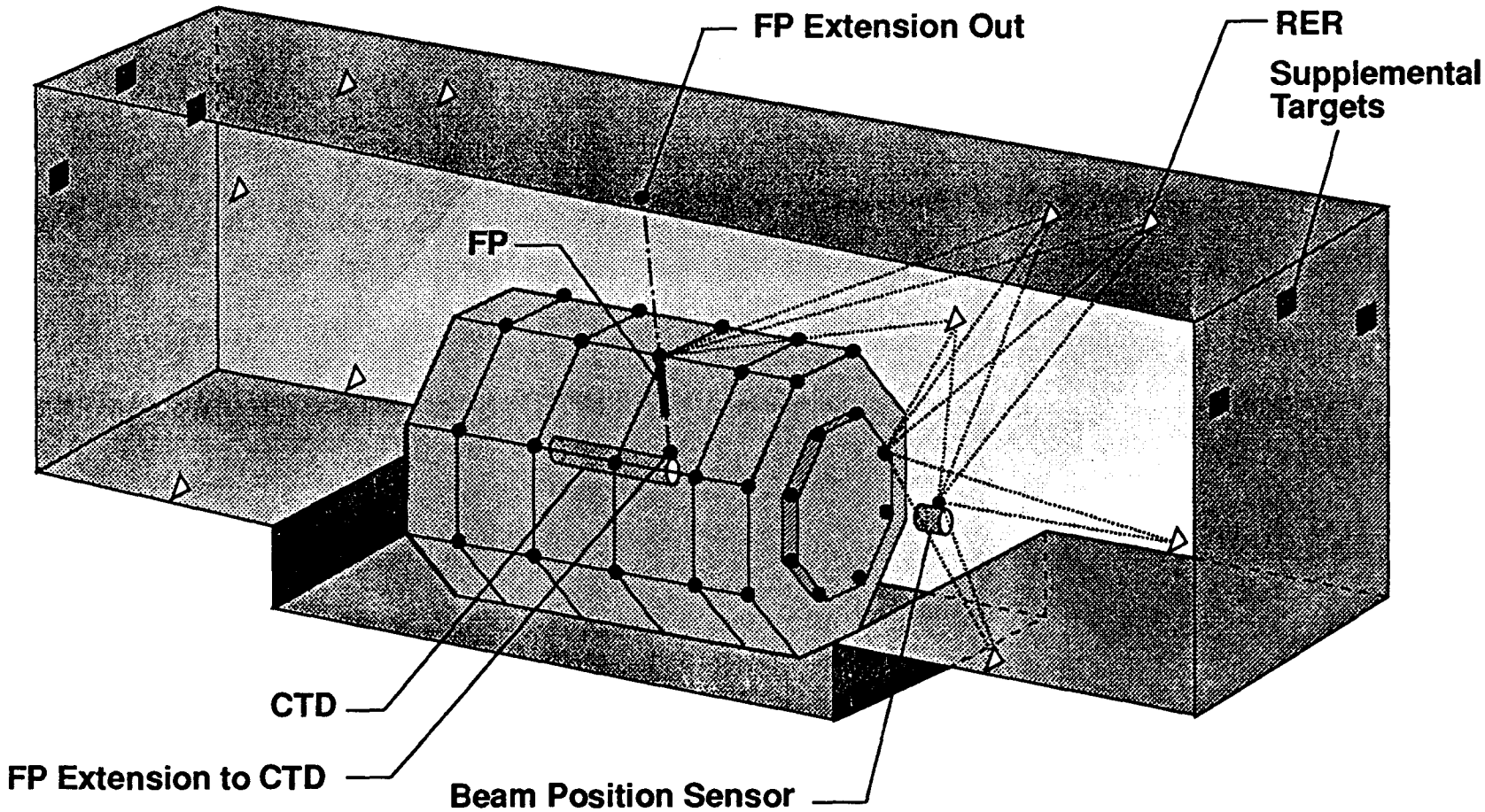


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Figure 4-4 Global Alignment

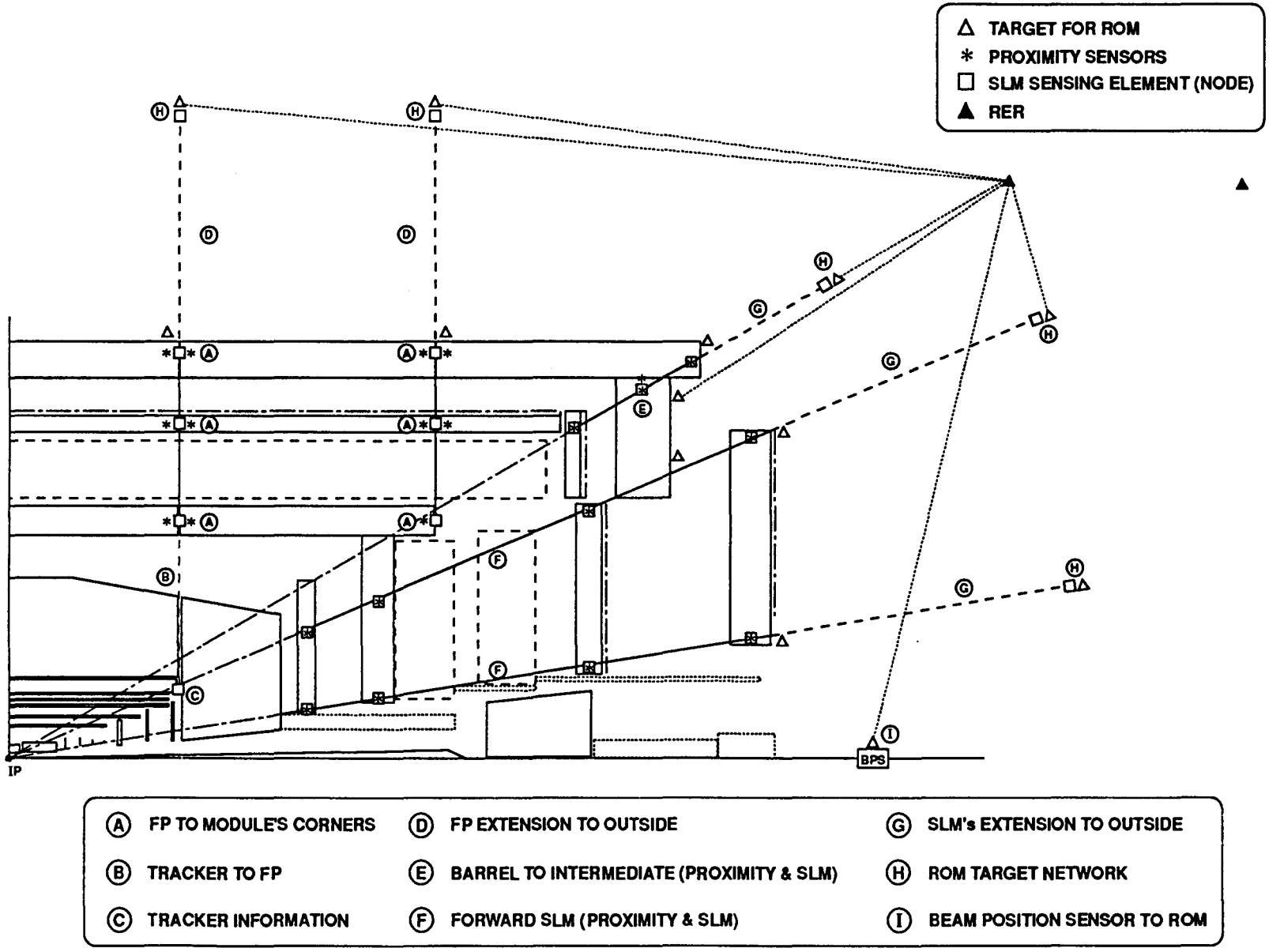

Figure 4-5 Global Alignment Steps and Device Locations

4.4.2.2 Straight-Line-Monitor (SLM) Network

By design, the module corners of different modules are forming straight lines, and the approach to global alignment is first to try as much as possible to use this information by measuring the actual deviation from those straight lines. This is accomplished by using multipoint straight line monitors (SLMs). Whenever the line defined by a SLM follows approximately a possible muon trajectory, it is only necessary to measure accurately the positions transverse to the line, i.e. the deformation of the line; constructional data provide enough information about the overall position of the line. When the SLM does not follow approximately a possible muon trajectory, the SLM must also measure the distance along the line.

The selected (present baseline) network of SLMs is shown on figure 4-5 for a quarter of the section of the detector in one of the eight planes defined by $\phi_i = 22°5 + i \times 45°$. Two SLMs monitor the deformation of the line defined by the gaps between the Barrel modules, perpendicular to the beam-line. As explained above, because they do not follow possible trajectories, these SLMs must provide dimensional information transverse and along the line. This is achieved by using a SLM configuration that we call Fencepost (FP).

Essentially a Fencepost is a SLM with a continuous structural support. This configuration has two purposes, one just mentionned which is to use the structure as a ruler to measure along the line, the other purpose is to increase the dynamic range of the measurable transverse deformations. The Fencepost structure has its own measuring device to measure its shape accurately , but with a limited dynamic range corresponding to the possible transverse deformations of the Fencepost from its calibrated shape. The measurement of the line of fiducials is done by one-dimensional proximity sensors attached to the modules and related to the fiducials (in some cases the sensor head could be the fiducial). This 2-step approach extends the dynamic range in 2 ways. One because it is easier (and cheaper) to have a large dynamic range in a one-dimensional sensor compared to a two-dimensional one. Second, the proximity sensors can be mounted on brackets which can be selected during final assembly to bring the sensor within its range. This 2-step approach does not decrease the accuracy, and we feel it is less expensive and ultimately more accurate to use one dimensional proximity sensors when the accuracy required is of the order of 25 μm and the dynamic range is at least ± 5 mm. Even if we did not want to use this 2-step approach, we would still be forced to use it, because if one node of the SLM was attached directly to a module, the three adjacent modules at the level of this node would still require proximity sensors. This approach also keeps the design symmetric, and leaves the Fencepost totally independant of the modules.

On figure 4-5, the line defined by the FP closer to the center of the detector goes through the crack in the calorimeter, and this provides the ability to relate the position of fiducial points on the tracker (or on a calibrated bracket attached to the tracker) to the muon barrel system by optically extending the FP. A schematic of an optical Fencepost with the optical extensions is shown on figure 4-6. The FPs are also optically extended outside the detector to provide a reference for the ROM

network described in § 4.4.2.3 .

In the Forward Region, two 5-point SLMs are located in the same planes ϕ_i = 22°5 + i x 45° . These SLMs are nearly projectives, and they need to provide transverse information only. Therefore the multipoint alignment devices need not be mounted on the same structural component. These multipoint SLMs are also optically extended outside. A similar but shorter type of SLM is also used in the Intermediate Region.

4.4.2.2.1 SLM for the Barrel Tower Alignment

To link the fiducials from one module to another, it is necessary to measure the relative positions of the module corners in all layers (BW1 to BW2 to BW3, FW2 to IW2 to IW3, FW1 to FW2 to FW4 to FW5 etc) from tower to tower, octant to octant, and finally to corner positions of intermediate and forward chamber modules.

To achieve this relative position measurement, we have studied in R&D both optical straight line monitor (OSLM) schemes[1] and mechanical ruler (fencepost) schemes. The former scheme measures only relative transverse displacement of one item in a source-lens-detector triplet with light spot position sensitive photodiodes. By installing stainless steel tube structures through the barrel magnet iron which extend from BW1 to BW3 at the corners of towers on the octant boundaries as rulers (Figure 4-3), we can in principle measure the X, Y, Z positions of the corner fiducials on all layers of the four adjacent towers simultaneously on the same line, and thus to each other by using proximity sensors. With reference lines at all octant boundaries, the system links the complete azimuth. Thermal sensors would be embedded in the system to allow for corrections of the sensors and the tube lengths. The tubes would be supported from the magnet.

At present, we envision a concatenated optical straight line monitor system (Figures 4-6 and 4-7) inside the tubes to measure the real shape of the tubes. These tube systems can be calibrated in an alignment fixture and premeasured in the varying octant orientations. The calibrated proximity sensor assemblies can be transferred to module assemblies and automatically referenced to fiducials on the module's end plates, via CNC prelocated mounting pins. Adjustable mounting bushings at the magnet surfaces will allow measurement and pre-positioning of these line references to a theoretical matrix for correct placement of chamber modules in the measured detector coordinate system. There would be four rings of mechanical rulers at the Z boundaries of modules and towers. The lines of the inner two rings would correspond to the center of the gap of the Central and End calorimeters. Optical extensions of these inner lines to target retroreflectors mounted on the Outer tracking system would provide relative position measurements between the two systems using position sensitive photodetectors in the tubes. This has been shown on figures 4.5 and 4.6. Optical extensions to external targets would allow measurement of these line references as vectors in the detector coordinate system using a system like the Range-Only cluster scheme to be described in 4.4.2.3. The calorimeter inclined support plates and rails as well as the barrel magnet inclined plates and support base will be used as references for octant 5 modules. For Octant 4-5 and octant 5-6 connections at the inner two rings, the

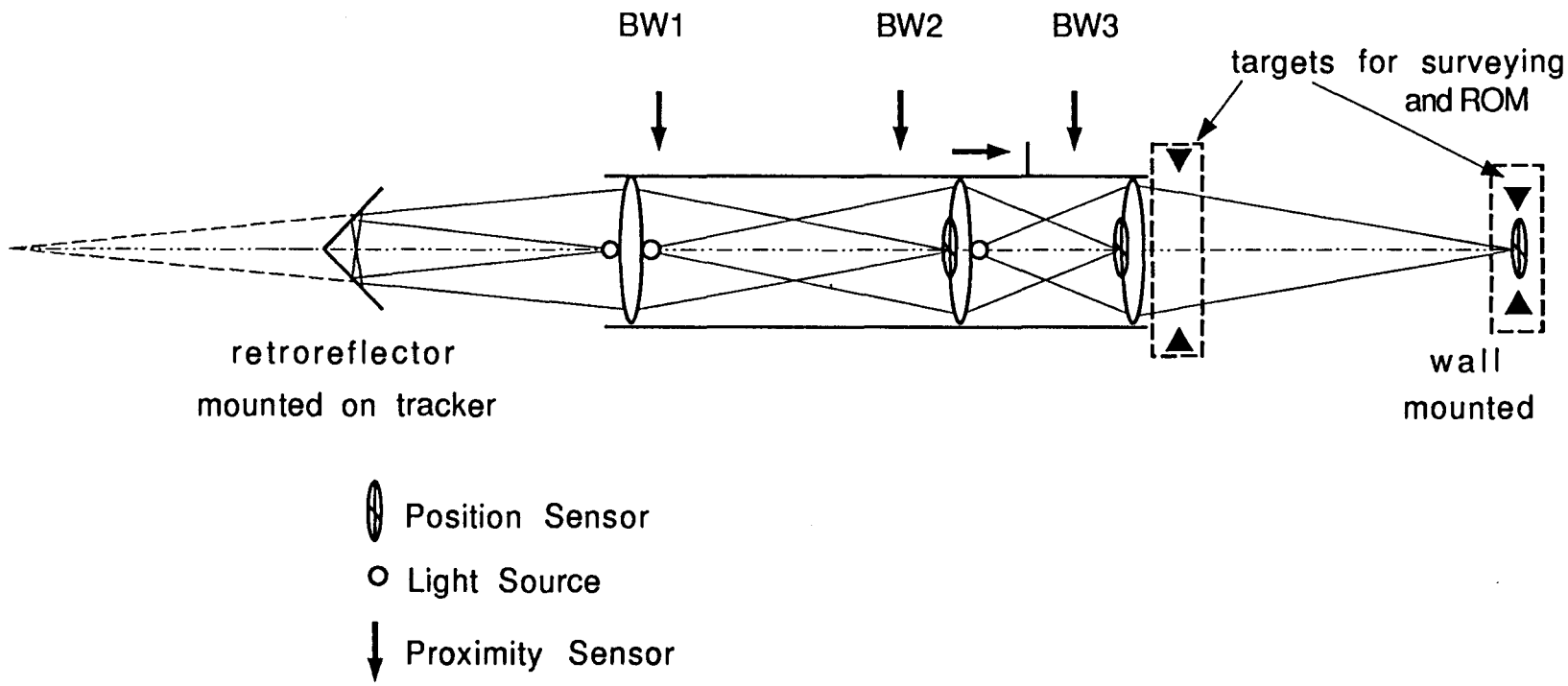

Figure 4-6 Schematic of an Optical Fencepost with Optical Extensions

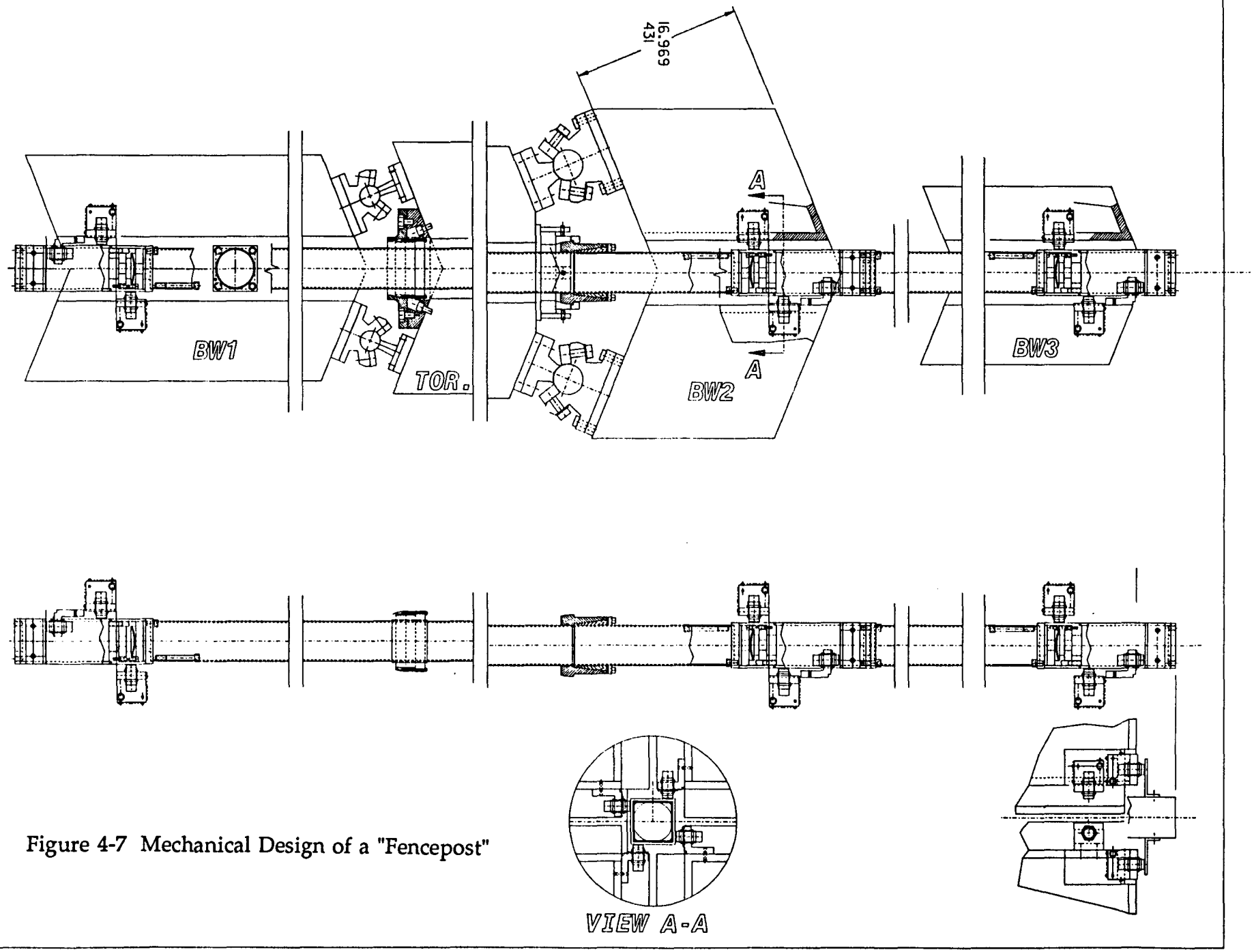

Figure 4-7 Mechanical Design of a "Fencepost"

calorimeter and magnet support plates will be cut to allow penetration of the mechanical posts. For the octant 4-5 and octant 5-6 connections at the outer two rings, the magnet and calorimeter inclined support plates would function as the rulers. This may apply to the inner lines if optical extensions from six other octant boundaries prove adequate, and this would avoid cuts in the support structure.

Intermediate Region

In the Intermediate region, where physical fenceposts are difficult to implement and we can have projective paths, we propose to use projective optical straight line monitors (OSLMs) through the octant gaps between modules coupled with relative position linear proximity sensing between BW2-IW2 and BW3-IW3 modules. With projective lines, transverse position measurements are adequate. These lines would be measured by Range only survey of their extensions from the outside of the IW3 to external endpoint position sensing photodiodes mounted on Range only survey targets. This has been illustrated in Figure 4.5

Forward Region

In the forward systems, we propose to establish a set of projective OSLMs between supermodule rings which also couple to the Intermediate region. These lines will require holes through the FW2 ring, and FT1, FT2 toroids. Octant corner notches would be required in FW4 and FW5. Details of these lines will be dependent on the choices made on an an evolving forward system configuration. There are configurations which allow linking IW2 and IW3 on these lines. Detailed position monitoring will require two sets of these lines. One set would project along the outer octant boundaries of FW4 and FW5. The inner set would prject along the inner boundaries of all layers. Again these lines would be determined from the range only survey of their extensions from FW5 to endpoint sensor-targets.

Each of the forward system detector layers MFW1, MFW2, MFW4, and MFW5 consist of eight octant module assemblies located and supported on an octant ring assembly. The ring-chamber assembly is mounted on a three point inner radius support located on the absorber tube assembly in the forward toroids. Outer perimeter Z position constraints will limit the out of plane distortion of these assemblies. The octant modules of every layer will be assembled in precision fixtures in the SDC surface assembly facility. In this assembly, using a combination of fixture references and optical survey, OSLM elements will be located on the theoretical four projective lines.

4.4.2.2.2 SLM Network Preliminary Composition

The entire network of SLMs consists of:

- 2 x 8 FPs with extension toward the tracker and extension outside in the middle of the barrel
- 2 x 8 FPs with extension outside in between the modules MBW and MBW
- 2 x 2 x 8 long SLMs with extension outside in the Forward Region
- 2 x 8 short SLMs with extension outside in the Intermediate Region.

This network of SLMs is very sparse, and by itself does not provide the necessary information for global alignment, because it does not provide any direct information about the relative orientation between the different SLMs (although known structural information such as the length of the modules do provide some information which is used in reconstructing the shape of the detector as explained in section 4.4.3.3) and only a very loose relationship to the interaction point through the tracker.

The relative orientations and positions are provided by the next step in the global alignment process, the use of distance-only or Range-Only-Measurements (ROMs) outside the detector. This is the step which makes use of the outside extension of the FPs and SLMs.

4.4.2.3 Range-Only-Measurement Network

Principle of operation

Let us take 3 reference points forming a triangle (i.e. not in straight line), and assume we know their positions. If we measure their distances to a 4th point, we can calculate the position of this 4th point from the measured distances. There are two solutions, one on each side of the plane defined by the 3 reference points, and in general a priori approximate knowledge of the geometry remove the ambiguity. We can do that for any point in space. Therefore by measuring distances only, we can in principle reconstruct the geometry of any point system in space given 3 reference points. This can be explained easily by expliciting the calculation process:

For each measured distance we have one equation with 3 unknowns (the 3 coordinates of the point), and with 3 measured distances, we have a solvable system.

If the positions of the so-called reference points are not known, we have now 3 equations and 12 unknowns and the system is indeterminate. If without changing the geometry, we measure the distances from those 3 "references" to a large number of points, say N, we have 3N equations and 3N + 9 unknowns. The ratio of the number of equations to the number of unknowns is getting closer to 1, but the system is still indeterminate.

What happens now if we add one "reference" point from which we measure the distances to the same N points: we get one more equation for each point measured, but only a total of 3 more unknowns, because the coordinates of the N points have already been counted. Therefore now we have 4N equations, and 3N + (3x4) unknowns. We see that for N = 12 we have 48 equations and 36 + 12 = 48 unknowns, and the system is solvable. For N > 12, we will have more equations than unknowns, but we know there is one solution, so it means that we have just added redundancy, and the problem is solvable in a least square sense for example. In this mini-analysis, we have implicitly assumed that the equations were linear which they are not. But if we know the approximate position of each points (reference included), we can linearize the problem and proceed by iteration. An other assumption is that the system under measurement does not change during

the time of the measurements.

Implementation

This technique is applied to the SDC global alignment, where the reference points are Range-Emitter-Receivers (RERs), and the measured points are targets located at the corners of modules visible from the RERs, at the nominal end of fenceposts (FPs), at the extensions of FPs, and at the beam position sensors on the north and south sides of the detector (see figures 4-4 & 4-5). The RERs (Figure 4-8) are small laser rangers emitting a collimated beam of light. The RERs also have 2 detectors to sense the return beam from some targets. One for alignment of the beam with the target, the other for the distance measurement. The targets are passive retroreflectors sending back the light to the RERs. The RERs measure the distances to the targets by measuring the time of flight of repetitive pulses of light, or the phase of the return signal if a continuously modulated beam is emitted [6-9]. It should be noted that in the proposed method, the distance measurements are not based on interferometry, which, although providing a very accurate distance measurement capability, suffer from the inability to measure absolute distance after the beam has been interrupted (unless sophisticated and expensive techniques are applied).

Operation

A summary of the operation follows:

The approximate position of the targets and RERs are established by the initial survey during construction. Each RER is mounted on a motorized gimbal with low precision angle readout, and is addressed to each visible target in succession, using the a priori position information. When the beam come close to the addressed target, a strong return signal is received, and the optical position sensor in the RER provides the error signal to the gimbal drive so that the beam is oriented in the exact line of sight to the target. This is a very simple and precise positioning because the error signal is driven to zero. At this time the distance is measured. Many measurements are obtained in less than a second due to the high modulation frequency of the laser, thereby providing a large signal to noise ratio, and also integrating the effects of air turbulence. The RER's line of sight is driven to address the next target and so on. After all the targets have been addressed by the RERs according to a set plan, a computer solve the system of equations created by the distance measurements, for the coordinates of the targets.

4.4.2.3.1 Advantages of Range-Only-Measurement

The advantages of this technique are multiple:

- The fenceposts are being measured at 2 points (one at the nominal end and one at the extended point), thereby establishing the FPs direction and position in a global coordinate system.

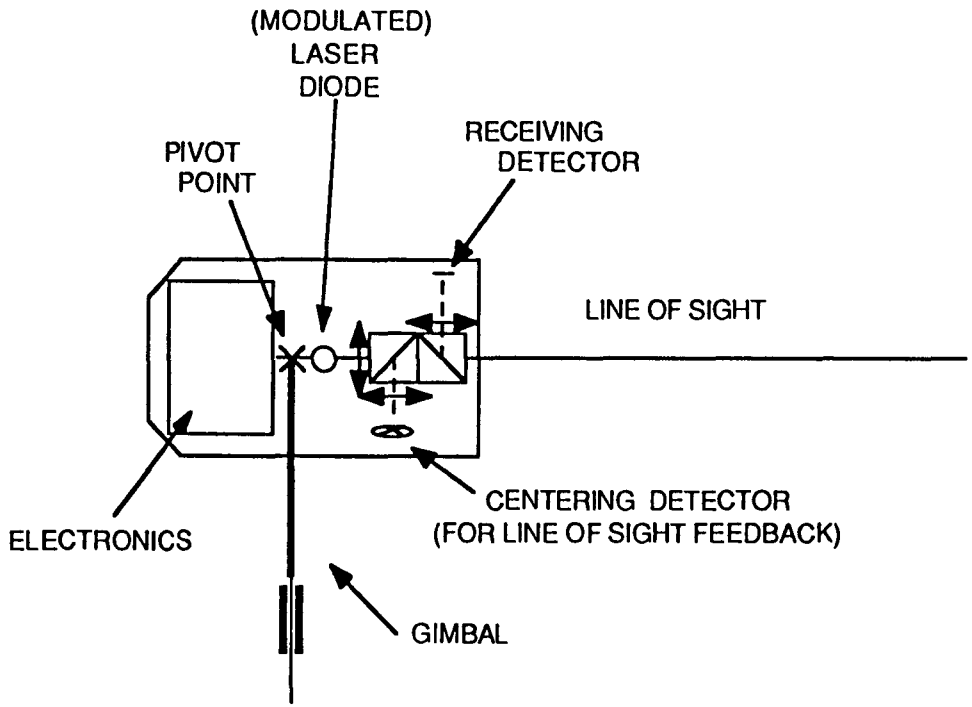

Figure 4-8 Schematic of a Range-Emitter-Receiver (RER)

- Targets can be installed on the Beam Position Sensors at the North and South ends of the detector thereby tying up the alignment network of the detector with the beam.
- It is possible to measure directly targets placed at reference points on modules which are located on the surface of the detector (barrel) and in the forward end without tying up excessive space for alignment components.
- The network is easily adaptable to change in detector configuration or staging.
- The distance measurements are independent of the orientation (local tilt) of the components (within limits) and the system is self calibrated (assuming the approximate position knowledge that is furnished by the survey during the detector installation). Therefore the measurements can be done with the magnet "ON", or immediately after heavy components have been moved.
- In a distance measurement based system as opposed to an angle measurement based system, the accuracy load is being transferred from expensive precision mechanical components (as theodolite) to inexpensive electronic components.

Performance Expectation:

The ranging technology to be used, can draw from several existing technologies: Imaging laser radar; Robotic; Electronic Distance Measurement in Surveying and Sensing; Alignment of Aircraft structures, Ship Structures, Radar Antennas; Fast events measurements in High Energy Physics; High Speed Communication (modulated laser diodes). Of particular interest is the fast pace of development of very reliable and inexpensive laser sources which can be modulated at high frequency. A preliminary comparison of the ranging measurement situation in this application vs other published [6-9] ranging results (and fast electronics applications) let us expect an accuracy in individual distance measurement of the order of 100 microns or less for the following reasons:

- Retroreflector target can be used, therefore the return signal is strong compared to the background. A laser radar imager must measure the scene as it is viewed, without cooperative targets.
- Due to the stable (short term) structure, long measurement (integration) time is allowed, as opposed to ranging system mounted on a moving platform, or imaging laser radar which requires a short measurement time for each point in the picture. If time of flight measurement is used, many measurements are possible and also the start pulse is under control, as opposed to single pulse physics events which may also have a random start.
- The approximate knowledge of the geometry lend itself to automated measurement system, and the ambiguity which usually complicates the distance measurement is easily removed.
- For the same reason, the amplitude of the return signal is under control, allowing stable return signal level and minimizing phase delay error in the electronics.
- The air temperature and pressure can be monitored for speed of light correction.
- The distances to be measured are much shorter than those measured with Electronic Distance Measurement (EDM) system in outdoor surveying.

4.4.2.3.2 Referencing the Detector to the Beam

In order to provide a closure of the alignment system including the orientation of the detector relative to the beam line, targets for ROM will be installed on the Beam Position Sensors (BPS) at both ends of the detector (see Figure 4-5). These targets will be carefully calibrated by measuring their position relative to the beam position sensors reference points at installation time. Short term accurate BPS have been developed at Fermi Lab, but for the present application long term stability is required. If long term stability cannot be achieved, a calibration method for these BPS will have to be incorporated, and such a possibility has been discussed[6].

4.4.2.4. Ancillary Subsystems: Liquid-Level Network

In Octant 5, the FPs cannot be extended outside because of obstruction created by the magnet base, and anyway the ROM network has a very limited view under the detector. For these reasons, a different approach to global alignment based on a network of Hydrostatic Levels is used in this region, and this is described in paragraph 4.5.2.

4.4.3. Alignment Computer Model, Database, Error Budget and Data Acquisition

4.4.3.1 Mathematical Model and Database

TBD. Work is in progress.

4.4.3.2 Summary of the steps involved in the Alignment: Error Path

There are several sub-models describing the passage of information within the main model: a) one sub-model describing the wire-to-fiducial relationships for each module, b) for each "physics" region, a model describing the relationship between fiducial points belonging to different modules. These relationships *create an error path* described by the steps involved in the alignment, and are summarized in the table 4-1.

The SLM extensions to the outside *of the Detector* are used only to tie up the SLMs together in a global coordinate system. This is done by the ROM network. This network of RERs and targets, need to be stationary only during the ROM measurements. Therefore it can be displaced in between two complete set of measurements, as long as it is repositionned in a satisfactory manner for RER-to-target visibility, and at locations which are approximately known for removing any ambiguity in the distance measurements.

0) From wire-ends to corner of modules (Local Alignment)
A) BW1/2/3 corners x,y,z relative position to calibrated FPs (active SLM inside)
B) Projection from FPs transverse to axis to tracker references (8)

C) From References on Outer Tracker to IP (Tracker Information)
D) FPs extension to outside point (wall)
E) Proximity Sensors Intermediate-to-Barrel and also short SLM
F) SLM (Concatenated LED-Lens-Qcell)
G) SLMs extended outside
H) RER/ROM relating SLM extensions (and also outside modules)
I) Beam Position Sensor (Both ends) tied to ROM network

Table 4-1 Error Path

4.4.3.3 Error Budget and Error Estimate

For each function of the detector, and for each "physics" region a position error budget can be established using the mathematical model describing the detector, *the Error Path* for the region under consideration, and the expected accuracy of the sensors. A preliminary typical "bottom up"estimate (see figure 4-9) has been established by analysis and limited simulation. The error propagation factor in the "Global" uncertainty is the ratio between the position uncertainty obtained by reconstruction, and the measurement uncertainty of the sensors. In the case presented, this number is an average, and has been extrapolated from the results of limited simulations. The weighted average measurement uncertainty has been obtained with a spreadsheet shown on figure 4-10. In real operation, the reconstruction of the geometry of the detector from the alignment devices' measurements will provide a different uncertainty for every region of the detector, and these numbers will have to be compared to the requirements set on the tables in chapter 3.

On figure 4-10, it is shown that each module has 7 degree of freedom (DOF), because we expect the modules to deform in a limited way. To the first order, we assume that the distances between the corners will not change under module deformation (except for the thermal expansion which is treated separetely). There are 6 DOF for a rigid body, and in our case we locate each module in space by locating 3 out of the 4 fiducials placed at the corners. We need an extra degree of freedon to account for the twist of the modules which can be quantified by the distance from the fourth fiducial to the plane defined by the three others for each module. The out-of-straightness of the edges of the modules are measured by the On-Module SLM, and because they are small effects, the changes in length which are second order effects can be neglected; this allow for the de coupling of the local and global positioning.

4.4.3.4 Data Acquisition

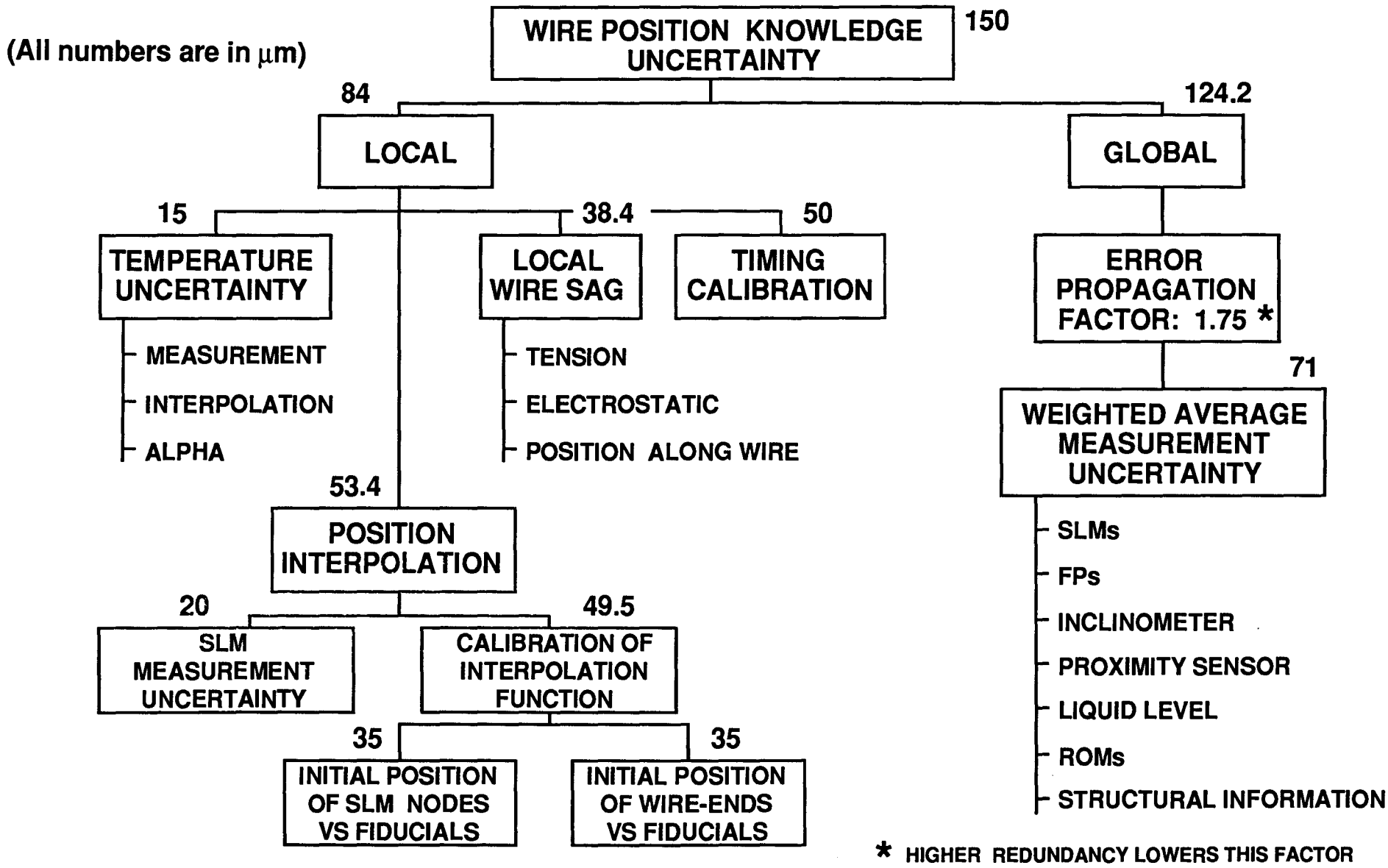

Figure 4-9 Typical Error Budget (Bottom up)

GLOBAL ALIGNMENT SYSTEM

Device Quantity	Device or Measurement Type	number of measurements	Total Measrmt. Uncertainty (micrometer)	Measurement Uncertainty (micrometer)	Temperature Effect (micrometer)	Transfer to Fiducials (micrometer)
48	SLM	96	43.0	20	15	35
32	Indpndt. FP Measrmnt. (extension)	64	68.2	55	20	35
20	Inclinometer	20	60.4	45	20	35
160	Independant Proximity Sensors	160	43.0	20	15	35
768	FP's Prox. Sensor (lateral)	768	80.6			
384	FP's Prox. Sensor (length)	384	49.7			25
2	Beam Position Sensor (BPS)	2	66.0	50	25	35
20	Liquid_Level	20	58.7	40	25	35
26	Range-Emitter-Receiver (RER)*	0	83.8	80	25	0
220	ROM_Target*	0	38.1	0	15	35
0	Range-Only-Measurement (ROM)*	2288	92.1			
0	Structural Knowledge**	1200	38.1	35	15	
Total		Total				
1680		5002				
Measurement Uncertainty (Weighted Average):			71.0			
* 40% of the number of RERs times the number of targets						
** 6 lengths per Module (the distances between the fiducials)						
200 modules, 7 DOF. 1400 unknown. Redundancy factor=5002/1400						

• This spreadsheet is still incomplete. SLM-4 and SLM-5 shown on figure 4-5 for the alignment of the Forward System have not been included.

Figure 4-10 Weighted Average Measurement Uncertainty of the Global Alignment System

TBD

4.5. Alignment of Specific Subsystems

4.5.1 Alignment of Prototype Supermodules (or Towers)

4.5.1.1 Introduction

The alignment and testing of the Prototype towers has to be provided early in the schedule, but some elements of the global alignment may not be available in time because of scheduling bottleneck. The SLMs and Fenceposts have to be available because they are an integral part of the module alignment. The range only measuring devices could be temporarily replaced by an angle only (i.e. theodolite) type of measuring system, as the devices used are off-the-shelf, and will be already in the hands of the Survey team. This replacement is feasible because there is no issue of high magnetic field and restricted access for the alignment team around the tower prototype, and it is needed anyway as it provides the "truth test" . It also allows for the validation of the local alignment concept as early as possible. When the ROM devices become available, most of the early learning about and debugging of the tower structure will have been done, and the testing of the ROMs will blend gracefully in the schedule.

4.5.1.2 Description of Prototype Barrel Tower Alignment

TBD

4.5.1.3 Description of the alignment of the Prototype Forward Tower

TBD. The state of development of the Forward System precludes the description of a credible Alignment Concept.

4.5.2 Alignment of Barrel Magnet & Support base

The shape and elevation of the Barrel magnet and its support base must be monitored in order to limit mechanical stresses in the iron plate assembly at all times, in all configurations of the detector. A good monitoring system must be simple, passive, continuously sensing, and reliable. It must provide integrated analog information for monitoring, control, and processing.

Non contact Hydrostatic leveling systems have been demonstrated at the European Synchrotron Radiation Ring ESRF (2) (Fogale-Nanotech) and at Fermilab for the B0, D0 low beta quadrupole and detector systems. These systems continuously measure (without contact) the vertical positions of each capacitive proximity sensor in the system with respect to a local conductive water surface in a vessel. The vessels are communicating and linked to a reference reservoir. The water levels in local vessels are equal because the air pressure is the same in all vessels. They are sealed and linked to the reference reservoir vent. The sensors are water proofed and the vessel connections are designed to prevent water and air bubble trapping. The Fermilab system includes heaters on the sensors to eliminate condensation problems and to maintain a constant temperature. Local temperatures are measured to provide a correction for local water column height.

For the SDC detector Barrel magnet and support base design, a uniform Z distribution of level sensors provides the best information on magnet shape and stress distributions, as well as local support loads. From the mechanical Finite Element Analysis of the magnet and support structure, a single horizontal string of level detectors at the base of each inclined support plate provides the necessary position-displacement information for both the magnet and the base. We plan to provide twelve vertical position measurements along each side of the support, and there will be two interleaved leveling systems with separate reference reservoirs located on vertical monuments. These monuments can be near the center (in Z) of the detector. Each system will be distributed to both sides of the detector base. Alternate (in Z) vessels/sensors are connected in a star (branch) configuration to the alternate system reference reservoirs. This will provide redundancy and consistency measurements.

The two systems will be installed during the construction of the magnet base in the collision hall. They will measure the base and magnet shapes through the magnet construction and installation of the Z plates. The rapid response and settling times of these systems allows for repeated adjustment of the magnet during major internal component installation-motion if that proves necessary. They can be maintained under all conditions in real time with a very simple battery backup system.

4.6 Summary of Alternate Alignment System Concepts and Comments

4.6.0 General Comments about Alignment Concepts

At least three types of Alignment Concepts have been considered (see below). All of them includes three major steps as described earlier in the baseline concept: Local Alignment step, Global Alignment step, and finally computer integration of the data in a Model of the Detector. The concepts differ from each other only in their approach and implementation of the Global Alignment step.

What was not clear a priori, or at least not explicated in the early work on Alignment, is that in all cases, the Global Alignment step includes gathering relative position information between fiducial points on the modules through sensors because the shape of the modules precludes a direct measurement of what is required, i.e. the cross position along the particles' trajectories in order to measure accurately the bend in the trajectories. Therefore the information will need to be processed on a computer platform. This is done first to correct the sensor outputs for thermal effect, and second, to transform the sensed relative position measurements into either an other set of relative position appropriate to the Muon System, or into a global coordinate system related to the beam line and interaction point.

Because of the difficulty to achieve the desired "knowledge" position accuracy in some zones of the Muon System, and in order to provide a soft degradation in alignment performance as the alignment devices age of fail, redundancy is built in. This requires that the transformation of the sensed relative position measurements into another set of relative position appropriate to the Muon System must be done in a least square sense. Therefore the assessment of the "quality of the alignment" can be done only after the

complete set of alignment information has been introduced into the mathematical representation of the Alignment System and the Muon System.

In other words the alignment problem is: Given a set of measurements relating the coordinates of some reference points (the fiducial points) in space, find the most likely distribution of these points in space satisfying the set of measurements; This operation can be thought as being similar to the inversion of a matrix relating the measurements to the coordinate positions, and this inversion process can be evaluated only after the whole matrix has been specified. The different concepts vary in the selection of the devices which produce the measurements.

4.6.1 Summary of the Alternate Concepts

4.6.1.1 Concept # 1

This is the original concept described in the SDC TDR (Reference):

A **Local Alignment**: - On-Module SLMs

B **Global Alignment**:
1) Limited Network of SLMs and FPs inside the Detector
2) Dense Network of Proximity Sensors between the Modules
3) Ancillary Subsystems: Liquid-Level, Inclinometers and Temperature Sensors

C **Computer Integration of Local and Global Data**

4.6.1.2 Concept # 2

This is the present baseline previously described in this chapter.

A **Local Alignment**: - On-Module SLMs

B **Global Alignment**:
1) Limited Network of SLMs, Proximity Sensors and FPs inside the Detector and extended outside
2) Range-Only-Measurement (ROM) Network
3) Ancillary Subsystems: Liquid-Level, Inclinometers and Temperature Sensors

C **Computer Integration of Local and Global Data**

4.6.1.3 Concept # 3

This concept is described in a memo by R. Davison (Reference)

A Local Alignment: - On-Module SLMs

B Global Alignment:
1) Limited Network of Proximity Sensors inside the Detector
2) Systematic Lattice of FPs with Angle Transfer, surrounding the module's layers and penetrating the Magnet.
3) Ancillary Subsystems: Liquid-Level, Inclinometers and Temperature Sensors

C Computer Integration of Local and Global Data

4.6.2 Brief Comparison of Advantages and Drawbacks

The first concept relies heavily on the proximity sensors between the modules, therefore it relies nearly uniquely on the structural knowledge of each modules. High redundancy is harder to achieve than in the other concepts.

The second concept (Baseline) is easily adaptable to staging or late change in Detector configuration; the technology used may be very useful also during the installation; It provides an easy tie between the different regions of the detector and the Beam-Line via the Beam Position Sensors at both ends of the Detector; the Fenceposts required are simple therefore easy to fabricate and align; the critical components are easily accessible for repairs; It has movable parts (but again easily accessible); it employs existing concepts but with recent technology that needs to be adapted to achieve the desired cost.

The third concept stresses the design of the Fenceposts in several aspects: complexity of the design of the lens/prism blocks, dynamic range due to the length and the angle transfers (twist in the modules, lack of symmetry of revolution of the magnet due to gravity), amount of light due to the obscurations, complexity of the alignment /calibration of the FPs themselves; it requires clear paths along the diagonals of many modules and in general more clear paths inside the Detector than the two other concepts; It has an obvious advantage which is that if you can obtain the necessary clear paths, it can be demonstrated that all the required measurements are included in the system (systematic approach), although this still does not allow the evaluation of how well it performs these measurements, as this still require the design of a redundant system (with more required clear paths) and the "inversion" of the matrix of measurement.

4.6.3 Conclusions

It is clear that all the concepts considered differ only to the extant they rely more specifically on one technology, and the best concept may be a blend of these three concepts, starting with the baseline (concept # 2) and incorporating:
- a larger use of proximity sensors but not as extensive as in concept #1;
- a few more concatenated SLMs and a few Fenceposts with Angle Transfer, but without the multiple Angle Transfer required in concept #3, especially the diagonal one's;

- a lower reliance on ROM. The ROM could be limited to the direct links between the end of the Barrel, the Intermediate Regions, and the Forwards with the Beam Position Sensors.

The Alignment activities during the construction of the Prototype Modules will be very important in shaping the details of the Alignment strategy.

References

1) "Alignment for SDC; Optical Sighting", R. Davisson, July 1992
2) "A Solution to the Global Alignment of the SDC Muon Detector", J. Govignon, July 1992. SDC-92-296
3) Prototype SDC Muon Alignment-Position Monitoring Concepts, D. Eartly and P. Johnson, SDC-92-195, March 1991
4) The Hydrostatic Levelling System: D, Martin and D. Roux, ESFR Newsletter No. 8, April 1991
5) SDC Technical Design Report, April 1 , 1992. SDC-92-201
6) Discussion with T. Pal, SSCL.