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SOLENOIDAL DETECTOR NOTES

THE POSITION OF AN ANODE WIRE RELATIVE TO THE BEAM

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The electrical signal from a given cell in the muon detector provides a measure of the distance between a particle track and the anode wire in that cell. We interpret that information on the basis of a mathematical construct which represents the anode wire as a line in space. There is a design position for each wire, but the actual position of the wire is likely to be displaced from the intended one by an amount too large to be ignored. The design position is defined in a coordinate frame appropriate to the interpretation of the event, that is, in a frame aligned with the beam and centered on the interaction volume.

We speak of aligning the wire, by which we mean placing the wire where it belongs. We speak of measuring the alignment of the wire, by which we mean measuring the position of the wire in a manner which can be related, sooner or later, to the intended position. These two are less ambiguously referred to as placement and measurement. If our placement was known to be very good, and if things stayed put, we could dispense with measurement altogether. If we could not rely on placement at all, the burden of measurement on anything as complex as the muon detector would be intolerable. The real situation is intermediate. We rely very heavily on relative placement within local regions, and then rely on measurement to relate the local regions to one another and to a coordinate frame tied to the beam and the interaction region.

The interaction volume is best revealed by the central tracker. The beam direction is best known in the coordinates of the experimental hall. To find the position of an arbitrary wire segment in those coordinates we must provide survey paths which reach from the wire segment to the central tracker and also to survey monuments in the hall.

There are five major survey segments. The first segment relates the spot on the wire where the avalanche occurred to the endpoints of that wire. The second segment relates those endpoints to specific registration points on the module which serve to define its position. The third segment relates those points to an array of survey devices mounted on the toroid iron which collectively establish a space frame. The final two segments link that space frame to the central tracker and to monuments in the hall.

Segment One: Point on Wire to Wire Ends

More specifically we want the offset between the segment of wire involved in the avalanche and the line through the wire ends. We want the local value of the sag of the wire. To a close approximation the sag of the wire is parabolic, so we need know only the

midspan sag and the position along the wire where the avalanche occurred. The midspan sag depends on the orientation of the tube and on the applied voltages. It is proportional to the square of the length of the tube, the first power of the weight per unit length of the wire and is inverse in the tension on the wire. In the most severe case the midspan sag could amount to about 1500 microns. The most severe slope is about 0.0007.

Because the slopes are always small even a very rough knowledge of the position along the wire will suffice to obtain an accurate measure of the offset. But even that rough knowledge will not be available in time to be used in forming the level-one trigger. For that case we do not correct the offset but rely on cancellation of errors. The input data comes from "hits" at about the same position on nearly identical neighboring tubes. The errors from ignoring the offsets will be nearly the same in each measurement. The trigger algorithm is based on the differences between measurements. In such differences the offset errors cancel.

The midspan sag of the wire can be calculated with great precision given a couple of unrealistic assumptions. The troublesome assumptions are that we know the tension on the wire and that the tube is straight and centered on the wire-ends. Any misplacement of the tube leads to electrostatic forces on the wire. These forces produce displacements, here considered as components of, and errors in, the sag of the wire. The amount of displacement is directly proportional to the placement error of the tube, to the square of the length of the tube, and inversely proportional to the tension. It depends as well in a complicated way on the electrical configuration of the tube. In broad terms the displacement is inverse in the square of the distance between the wire and the closest electrode. The need to keep these unmeasured and unaccounted displacements to the level where they are negligible is reflected in design of the fieldshaping electrodes and in the care to keep the tubes straight.

Since both the known and unknown displacements are inversely proportional to the tension on the wire it behooves us to maximize that tension. At large tension, or more specifically large stress, we encounter the phenomenon called "creep", a gradual inelastic stretching of the wire. The stretching leads to a diminution of the tension and an increase in the sag of the wire. If unaccounted for, the increase in the sag would itself represent an error. The optimum strategy is to use the maximum tension which does not lead to difficulties from creep which are comparable to the other errors already mentioned. Since the effects of creep are cumulative and since we will expect our tubes to operate for ten or twenty years, it is incumbent on us to understand the phenomenon of creep in our application.

Creep is understood to involve the relaxation of stress through the migration of crystal defects. The migration of a defect acts to relieve the stress, but, of course, it also moves the defect through the crystal. A defect cannot move indefinitely. It eventually runs into a grain boundary or something else which immobilizes it. Thereafter it cannot contribute to creep. When we first put a wire under tension we see rapid elongation, but the rate gets lower and lower as more and more of the defects are immobilized. The rate decreases more-or-less exponentially, but not to zero because new defects are always being produced by thermal excitation. There is an equilibrium density of defects at which the rate of production equals the rate of removal. At higher stresses the defects are swept out faster, which would tend to reduce the equilibrium density, but that effect is completely

overwhelmed by the increased rate of production through the lowering of the excitation potentials. The equilibrium density goes up with stress, and of course with temperature.

The wire we use has been drawn through dies. As it passes through the die it is subject to enormous stresses. The crystals become densely populated with defects. Depending on how it was handled between drawing and crimping a greater or lesser number of these defects will still be present when the wire is crimped into the tube at some carefully controlled tension. The subsequent decrease in that tension from creep will depend on the number of defects and so can, if no precautions are taken, vary from tube to tube.

We do not intend to make provision for in-situ monitoring of all of the wire tensions once the tubes are in the modules. We do plan to measure the mechanical oscillation period of each anode before the tube is installed in a module. Any showing anomalous behavior will be culled. We will arrange to make in-situ measurements on a few of the tubes and will presume that they speak for all.

Segment Two: Wire End to Module

So far as alignment is concerned the module design seeks to put the greatest burden on the strongest shoulders, the placement accuracy of a computer controlled mill, and to arrange everything else to preserve that accuracy. All proposed designs rely on the precision of NC milled panels for the relative placement of neighboring detectors. The Washington design is distinct in using single large panels rather than multiple small panels across the width of a module. This extends the placing accuracy across the whole module uncorrupted by errors in the alignment of the subpanels. The ultimate placement accuracy of an NC mill is on the order of ten microns.

There is, of course, a penalty. The bending of the panel becomes a significant consideration for a long panel, but not for a short one. The displacements from bending scale as length squared for fabrication tolerances and for most thermal effects, and as length to the fourth for gravitational distortion. This bending, like the sag of a wire, is very orderly. A very few parameters suffice for its description. These few parameters will be continuously monitored by a combination of thermometers and "optical straightedges". The optical straightedge is simply a light, a lens, and an image position detector all in line. More about that later!

The module is built in an unstressed condition on an assembly table. During fabrication the straightness and alignment of the endplates will be established and maintained by jigs to close tolerances, about 20 microns. At that time optical straightedges will be installed and zeroed in. Once the module is away from the assembly table it will flex and bend from applied stresses. The monolithic module construction provides great rigidity which insures that the distortions are both small and orderly. Though the distortions are calculable we do not rely on the calculations alone. We continuously monitor the deflections with the optical straightedges.

The distortions of interest are, first, the overall linear scale change due to the thermal expansion of the aluminum of which everything is made. The thermometers, and the thermometers alone, tell us this. Next are distortions from thermal gradients in the plane

of the module. These, as well, fail to report themselves to our straightedges and must be inferred from the temperature measurements. The coefficient of thermal expansion of aluminum is twenty four microns per meter per Kelvin. The extent of a module is about ten meters so temperature measurements to a tenth degree are appropriate.

Temperature gradients normal to the plane will induce bending or twisting of the module. These distortions, in company with like distortions from mechanical stresses, will be monitored by the optical straightedges. Those devices will be mounted along all four edges and across the diagonals of each module. The former monitor bending, the latter skew.

Segment Three: The Module in the Grand Scheme

Once we get to the placement of the module or supermodule on the iron toroid we have run out of placement precision, so everything has to be measured. The position of each module, and of all of the other detectors which together form THE DETECTOR, must be established by survey. That survey must be made after everything is put together with layer over layer like a giant onion. It must be made with the field on and the beams colliding, and it must be made again and again to track any shifting which may occur. This cannot be your standard survey. It must be made with special survey instruments which remain in place throughout the run and are read out remotely. A large part, but certainly not all, of the arsenal of instruments which serve this role derive from the optical straightedge already mentioned. We now describe these instruments.

The Optical Straightedge

The "optical straightedge" alluded to above is the primitive member of a class of instruments which form the space frame which tie all of the individual detectors together. In this form the device consists of a light, a lens, and an image position sensor arranged along a line, not necessarily evenly spaced. In the conceptually simplest case the light is a laser diode and the image sensor a quadrant photodiode. As a representative example, the lens for an eight-meter span with even spacing would have a focal length of 2000 mm. It could reasonably have a diameter of 50 mm. With a focal ratio of 40 and monochromatic illumination that does not strain the lens designer's art!

If the three components are spaced so the image of the light is focused upon the quadrant detector, and if indeed the optical centers of the three lie along a line, then the photocurrents will balance across both cuts of the detector. If the three are slightly out of line then the currents will be unbalanced in ways which indicate the sense of the misalignment. The device in this form is a null detector.

The laser diode is effectively a point source. The diameter of the diffraction image at the quadrant detector is 50 to 100 microns depending on how you choose to define "diameter". The intrinsic resolution is way down at the micron level.

To make use of a null detector one must have some means of adjusting to null. That

may not be practical, in which case one would want to measure how far the image was from the center. To do this properly one would substitute a video CCD for the quadrant detector and some extended structured source for the laser; this along with some associated electronics.

Alternatively one can use the proportional response of the quadrant detector to obtain a position measurement, but that would work only over a very short range. That range can be extended in a variety of ways, but always at the expense of resolution and accuracy.

A more detailed analysis of the relative virtues of the various approaches is deferred because it does not alter the principle of what one does. One chooses from among the alternatives in each application on the basis of cost and need. Regardless of the choice, the device defines three points in a line. They are logically equivalent; however, we find that the descriptions based on the use of null detectors and servo loops are less tortured than the others.

Extensions

It may be vainglorious to refer to three points in a line as a straightedge, but consider: if we put points 1, 2, and 3 in line and then put points 2, 3, and 4 in line we will have put all four in line. If we can iterate this process we can put any number in line. That approaches a straightedge.

With our four points in a line, points 2 and 3 each must contain the optical centers of both a lens and an electrical thing, either a light or a photodetector. This is all right because we don't need the central portion of the lens and the lights and photodetectors are small compared to the lens. With five points in a line, point 3 contains the optical centers of one lens and two electrical things mounted back-to-back, one is at 3 and facing toward 4, which we designate by 3 <. the other is also at 3 but facing 2, which we indicate by > 3. The number of objects at any point does not increase beyond three no matter how many points there are in the line.

We appear to have a physical interference problem! We have three objects with optical centers at 3. Seemingly they should properly all be at the same physical location. It's all right; in optics it is appearances, and not reality, which counts! When viewed through lenses or mirrors things appear to be where they are not, but we don't really need to go to that trouble. If they are close together and arranged along the presumed line it will be good enough.

Endgames

Start with a quadrant detector at 1 <, a lens at 2, and a laser diode at > 3. Put a corner reflector half way between points 1 and 2 and move the quadrant detector to > 2. The image will center on the detector when the corner of the corner reflector is in line with points 2 and 3. If the corner is displaced by some amount, delta, the image will be displaced by two delta. This arrangement has the distinction, which may on occasion be

an advantage, that the terminal point requires no electrical service.

We can go directly from a line of points to an orientation by using a plane mirror in place of the corner reflector above. If the mirror is normal to the line 2,3 the image will be centered. Translating the mirror in its own plane has no effect but tilting it through the angle theta displaces the image by two theta times the distance between the mirror and point 2.

An edge reflector gives a mixed case. The image is centered when the edge intersects the extended line 2,3 at right angles. Translating the reflector along, or rotating it about, the edge has no effect. Translating the reflector in the direction normal to both edge and line translates the image by twice the distance. Tilting it from the perpendicular moves the image double the angle times the distance.

Parallels

Somewhere along our string of points, at position N, we have a lens which images (N-1)< onto >(N+1). The lens equation tells us that the reciprocal of its focal length equals the sum of the reciprocals of the distances between (N-1) and N, and N and (N+1). That lens could be, and let us presume that it is, replaced by a close pair of lenses with focal lengths equal to those two distances, placed in the obvious order. The light which passes between those lenses is focused at infinity. If we take everything on one side, say the high-side lens and all beyond, and move it as a block without rotation there will be no optical consequence, beyond some possible vignetting. Now we have the points from N< up in a line and the points from >N down in a line. The two lines are parallel, but not necessarily co-linear. This allows us to transfera direction without having to bring points into coincidence.

Angles and Branches

Suppose we leave the low index, i.e., from N down, stuff in place and move the rest, in block, straight out along the line a short distance, opening up a gap. Into that gap we introduce a plane mirror at 45 degrees. We then move the high index stuff to its mirror-image position, that is, we swing it around through 90 degrees. This preserves the optical alignment. We have a way of defining a deflected direction. The practical difficulty with this scheme is that the deflection angle is sensitive to the angular position of the mirror. We overcome that fault by replacing the mirror with a pentaprism or its equivalent.

There is nothing sacred about 90 degrees. We can make pentaprisms for other deflection angles, most notably for our purposes, for 112.5 degrees.

There is a tacit assumption in this that the prism is large enough to intercept the whole beam. It need not be so. We will not be straining for light. For best resolution, best definition of the angle, we should span the whole aperture in the plane of deflection, but in the other direction it doesn't matter. We need only a thin slice. We can take one thin slice to deflect 112.5 degrees one way, another to deflect 112.5 degrees the other way

and still have light going forward to continue the original line of points.

Uses: Creating a Space Frame

Euclid used a straightedge and a compass and could put things whereever he wanted. We don't have a compass yet and there's all kinds of stuff in our way. In the space between the BW2 and BW3 modules we can open line-of-sight paths running the full length of the toroid and beyond. We can also open paths from one octant to the next in that same region. Dave Eartly's wormholes provide paths which penetrate through the various layers all of the way from the central tracker to the walls of the experimental hall. We can put straightedges in these places. Euclid did not have a pentaprism. We do and can use it to interrelate the directions of our straightedges. We can create a three-dimension mesh of lines which we survey in during the construction phase and to which we relate all of the modules and other detectors. The position of the central tracker relative to the mesh can be well monitored as can the relation of the mesh to the hall. That is fine so long as everything remains stable.

Everything is tied to the iron, all of the detectors and all of the physical objects which define our straightedges. The iron squirms, particularly when the magnetic field is turned on or off, and everything moves and all of the images in our straightedges move in relation to the detectors. From these shifts we can redefine the structure providing we have some invariant base to start from. Perhaps the central tracker is stable as a unit. You could work out from there assuming it remained fixed and then rotate the whole coordinate system if you found it didn't match with the hall definition of the beam direction.