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Calculation of the Potentials and 3D Electric Fields in a Proton Decay Detector.*

Robert J. Lari, John W. Dawson, Larry R. Turner
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439-4814, USA

Abstract: An electrostatic detector for measuring the lifetime of the proton has been modeled in three dimensions. Linear hexahedral finite elements were used and the potential obtained at all nodes. The three components of the electric field were calculated and used to determine field lines, calculate drift fields and drift times. Effective aperture calculations agreed with the measurements.

Overview of Project

A worldwide collaboration¹ is studying the decay of the proton. This experiment involves building 256 electrostatic detectors each 100-cm wide, 100-cm deep, and 260-cm high. These are attacked in the Soudan iron mine in Minnesota at a depth of 732 m in an array 2H by 8W by 16L.

Detector Geometry

A small section of a honeycomb detector is shown in Fig. 1. A complete cell and parts of

Figure 1. Honeycomb Detector.

adjoining cells is shown in Fig. 2. Potentials are applied to the outer surface of the hytrel² tube by narrow bands of copper between the insulation and tube. This produces a gradient of 20 V/mm along the tube axis. A honeycomb of tubes, steel, and insulation are formed 100-cm wide by 260-cm high with a tube length of 100 cm. This two dimensional cross-section is changed to a 3D geometry at the end of the tube where small vertical wires at 2200 V are placed intersecting the tube centerlines at 1 cm from the steel end as shown in Fig. 2. The end configuration is shown more clearly in Fig. 3.

Figure 2. A Single Detector Cell.

Figure 3. End Configuration.

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In the actual construction of these large detectors the nominal distance between the wires and the face of the steel may vary by ± 0.5 cm. The hytrel tube may also extend from the steel by a varying amount. The effect of these geometry variations on the electric field and electric field was studied.

Modeling the Geometry

The smallest possible section of the detector that has symmetric boundaries is shown in Fig. 4. The

Figure 4. Smallest Symmetrical Section.

right boundary is symmetric to the left boundary if it is rotated 180 degrees, translated horizontally 1.468 cm, and vertically 1.088 cm. Similarly the top boundary is symmetric to the bottom boundary. This base plane of quadrilaterals was projected out of the paper 0.15 cm to form block layer 1 containing 154 hexahedral blocks. Some of these hexahedrons were further subdivided so that there were 400 finite elements in the block layer. The nominal z coordinate of each of the planes is given below.

Plane	z (cm)	Potential (V)	Comment
1	0.00	-270.	Base plane.
2	0.15	-240.	
3	0.30	-210.	
4	0.45	-180.	
5	0.60	-150.	
6	0.75	-120.	
7	0.90	-90.	
8	1.05	-60.	
9	1.20	-30.	
10	1.35	0.0	
11	1.60	0.0	End of steel
12	1.65	-	
13	1.70	-	End of hytrel
14	2.50	-	
15	2.60	-	
16	2.70	-	
17	3.10	-	

Notice that the first 10 planes have a potential gradient of 20 V/mm and are all identical in geometry. The quadrilaterals in the hytrel regions are set at these potentials and are shown in Fig. 5. Plane 11 has the steel region set at 0 V with the hytrel region not set at any potential. Block layer 10 between planes 10 and 11 is subdivided into two layers, block layer 13 has 4 and block layer 16 has 2 subdivisions. The geometry changes from plane 13, to the wire planes 14, 15, and 16 and the cathode plane 17.

Figure 5. Planes with Applied Potentials.

The size of the wire, 0.005 cm diameter, is much smaller than the size of the finite elements that have been used, ~ 0.150 cm. To avoid this mismatch of finite element size, the wire has been modeled as an octagon of diameter 0.100 cm with a smaller potential on the surface. To obtain the correct potential for the octagon, a 2D calculation was made of the 0.005 cm wire in the x - z plane with a potential of 2200 V. Equipotential curves were plotted and the cylinder of diameter 0.100 cm had a potential of 1050 V. This half cylinder was approximated with a half octagon. One side lies in plane 14, one in plane 16, and the other two sides formed by planes between planes 14-15 and 15-16.

To be sure that the hytrel tube of 1.35-cm length was long enough so as not to be perturbed deep inside by the high potential on the wire, a 2D axisymmetric calculation was made on the end of the tube in an r - z plane extending a distance $z = 4.5$ cm into the tube. This showed only a 0.2 percent change in the potential at 1.35 cm from the tube end when the wire was at 2200 volts. The same number of finite elements were used in the 2D and 3D calculations.

The total number of finite elements was 8400 and the number of nodes was 9724 in the 3D model of the geometry. The preprocessor program SCARPIA² was used to set-up this geometry and prepare the input data for the solver program, TOSCA.² All of the 2D calculations were made using PE2D.²

Solving the Problem

The problem was solved on a VAX 11/780 computer and the three components of the electric field were calculated on a fine grid and written to a results file. The solution consisting of the potentials at the nodes was saved as a separate file so that the electric fields could be calculated at other points without solving the problem again.

Objectives of the Analysis

There were two basic objectives in this simulation program. The first was to understand the effects of mechanical tolerances in the module manufacturing process on the data acquisition performance of the modules. The second was to predict the variation in gain of the proportional wire caused by variation of charge per unit length, q/λ . To examine the

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effects of mechanical variations, several perturbations on the nominal geometry were defined. This geometry as set forth in figures 2, 3, 4, and 5 was originally specified by L. E. Price⁴, and accordingly was referenced during the analysis phase as LEP nominal geometry. Variations were viewed as perturbations to the LEP nominal geometry, and the input data was formulated, as far as possible, to facilitate these perturbations. Approximately 150 simulations were done on the following:

- PDK04 LEP Nominal Geometry
- PDK05 LEP Nominal Geometry with the hytrel tube extended .5 mm
- PDK06 LEP Nominal Geometry with the hytrel tube extended 1.0 mm
- PDK07 LEP Nominal Geometry with the hytrel tube extended 1.5 mm
- PDK10 LEP Nominal Geometry with the ground potential moved 3 mm down the hytrel tube
- PDK11 LEP Nominal Geometry with the ground equipotential moved 1.5 mm down the hytrel tube
- PDK12 LEP nominal geometry with the face of the hytrel tube moved flush with the steel

Analysis Procedure

Generally speaking, the routine followed was to create a new perturbation to the nominal geometry by editing a `pdxxx.scarpia` file. The preprocessor was then run using the edited file as input. The preprocessor created a `pdxxx.tosca` file, which then was used as input to the solver. In executing the solver a `pdxxx.drop` file is created. Subsequent solutions for this perturbation to the nominal geometry were accomplished by using a `pdxxx.cont` file in association with the `pdxxx.drop` file as input for the solver. This is clearly expedient if some number of solutions are done on a particular geometry. The output of a solver run was a `pdxxx.res` file, which consists of a header, trailer, and data elements. The data elements were electric field values, coordinate positions, and potential values. The `pdxxx.res` files were edited to remove the header and trailer, and the substitution was made in the data elements of "-0." for "-0.". The reason for this is that the edited `pdxxx.res` files were read with a list directed format by the analysis programs, and the formatting of the solver sometimes leaves no space between data elements when they are in E format and have negative values. The edited `pdxxx.res` files were appended onto `pdxxx.dat` files, which then serve as input for analysis programs. The grid which has been used for the output field values from the solver is .06, .06, .025 cm for the data from which field lines were traced, and .005, .005, .005 for the data used to obtain q/l on the wire. Three analysis programs were written to process the field values generated by the solver. The first of these, `ev.for`, follows field lines, calculates drift fields, and traces drifting electrons. The second, `fv.for`, follows drifting electrons, continually calculating their velocity, and from this obtains the drift time as well as drift velocity as a function of position. The other program, `eq.for`, calculates q/l on the wire by evaluating an integral form of Gauss's law around the wire in cylindrical coordinates. In a proportional wire system, the avalanche gain of a wire is nominally an exponential function of the charge per unit length on the wire⁵. In the Soudan 2 detector, dE/dx information is obtained from pulse amplitude,

and accordingly the constancy of wire gain is critical. To determine the effective aperture, the solver solutions were obtained over a mesh of 50,000 points by merging a number of `pdxxx.res` files with a grid spacing of (0.06, 0.06, 0.025)cm. The program `ev.for` was then used to propagate field lines from plane 0 to the wire. The program looked for field lines, and drifting electrons which follow field lines, to hit the inner surface of the hytrel as a function of starting coordinates. Other results relating to the drift time, drift fields, trajectories, and charge per unit length on the wire were obtained from the same data files.

Results of the Analysis

Figures 6 and 7 present some typical field lines obtained from the analysis programs. The field lines were obtained by starting at $z = 0$, $(x,y) = (0.1, 0.1), (0.2, 0.2), (0.3, 0.3), (0.4, 0.4), (0.5, 0.5), (0.53, 0.53)$, and the values of drift field are

Figure 6. Field Lines in the x-z Plane.

Figure 7. Field Lines in the y-z Plane.

for these field lines. For the perturbed geometries, the field lines bow out so that they intersect the walls of the drift tube, thereby reducing the effective aperture. If efficiency is defined as the ratio of the area of the effective aperture as a per cent of the physical aperture defined by the hytrel tube, then some typical efficiencies are as follows:

Geometry	Efficiency
PDK04	99%
PDK07	91%
PDK10	60%
PDK11	81%

Figure 8 presents q/l on the wire as a function of the dimension y along the wire transverse to

Figure 8. Variation of q/l Along the Wire.

the drift tube axis, obtained by evaluating the surface integral around the wire at a radius of 0.06 cm. Although the variation does not seem large, q/l enters into the expression for wire gain as an exponential function, so this level of variation is significant. Figure 9 presents the drift field experienced by the drifting electron as a function of the drift coordinate, z . The family of curves has as a parameter the starting position of the drift electron transverse to the tube axis. Those electrons which start nearer the wall experience a section of reduced drift field, which for a perturbed geometry becomes progressively more stagnating. At some point as the perturbations become more severe, the field lines run into the wall of the tube. The region of near stagnation then becomes a region where drifting electrons are lost. Some conclusions drawn from these results are as follows:

- 1) There is an aperture loss on the order of 13%/mm as the ground equipotential is allowed to move down the hytrel tube from the LEP nominal position.
- 2) The LEP nominal geometry appears to transport electrons through this region with very little loss.
- 3) Allowing the hytrel tube to stick out into the drift region seems to give an aperture loss of about 6%/mm.

These results agreed with measurements⁶ made on the detector modules.

Figure 9. Drift field vs z .

References

- [1] "The Soudan 2 Nucleon Decay Experiment." Soudan 2 Collaboration (Univ. of Minnesota, Argonne National Laboratory, Oxford University, Rutherford-Appleton Laboratory, Tufts University), 7th Workshop on Grand Unification/ICOBAN 86, Toyama University, Japan, April 16-18, 1986, pp. 106-117, Jiro Arafune, Editor, World Scientific Publishing Co., Singapore.
- [2] Hytrel Polyester Elastimer is a trademark of the E. I. DuPont Co.
- [3] Available from Vector Fields Limited, 24 Bankside, Kidlington, Oxford, OX5 1JE, England; Infolytica Corp., 1500 Stanley St., Montreal, Canada, H3A 1R3.
- [4] L. E. Price, private communication.
- [5] F. Sauli, "Principles of Operation of Multiwire Proportional and Drift Chambers," CERN 77-09, Geneva, 1977
- [6] J. Thron, private communication.