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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

The calculations of the magnetic field and forces in the ZEUS detector at HERA

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The finite-element software package TOSCA has been used to perform magnetic field calculations for the ZEUS experiment at HERA Applications and performance are discussed The main ZEUS model is described and the results are compared with field and force measurements.

1. Introduction

Like most of the high-energy experiments, the ZEUS detector at HERA requires a strong magnetic field for tracking the charged particles created in e–p interactions.

The ZEUS detector and its requirements are described in the next section. Section 3 deals with the TOSCA finite-element software package used to solve the Laplace equation in three dimensions. The models built to represent the detector are then presented in section 4. Measurement methods are briefly described in section 5. The final calculation results and their comparisons with measurement data are shown in the last section.

2. The ZEUS detector

The ZEUS detector contains the usual set of components, from tracking devices around the interaction point to surrounding calorimeter layers and muon spectrometers for escaping particles. A perspective view is presented in fig. 1 and a full description can be found in ref. [1]. In the present discussion, only the components actively or passively affecting the magnetic field will be alluded to. These are the coils and the ferromagnetic materials respectively. All others are henceforth neglected.

2.1. The coils and their return yokes

Fig. 2 shows a model view of one half of the ZEUS coil system around the main return yoke. The 1.8 T magnetic field of the central region is generated by a superconducting solenoid oriented along the main axis of the detector. Its windings are distributed radially in two layers. Longitudinally, there are three sections, the outer ones with higher winding densities to ensure a more homogeneous field in the center. The magnet was produced by Ansaldo (Genoa, Italy).

HERA optics require the presence of a second but smaller solenoid on the same axis to suppress adverse effects on the beam and in particular to retain particle polarization. It is called the compensator and is also superconducting and produced by Ansaldo. Its 4.7 T longitudinal field points in a direction opposite to that of the main solenoid. The magnet is tightly enclosed in its own yoke to minimalize the stray fields.

The largest piece of ZEUS is its main return yoke. For particle detection purposes, it is laminated in up to 11 alternating iron/air layers. The main return yoke can be magnetized by means of eight warm coils installed in series, two at each end-cap on each side of the beam pipe holes, and four on the barrel part of the yoke, as illustrated in fig. 2. Fields up to 1.9 T can be generated in the iron, at either polarity.

2.2 The calorimeters

The ZEUS calorimeters are located inside of the main return yoke but outside of the thin main solenoid. Their active regions are made of a very large number (up to 186) of alternating layers of scintillator plates and depleted uranium plates (as absorber) [2]. These plates require an extremely strong steel supporting structure. This in turn has to be made ferromagnetic because the calorimeter readout system uses photomultiplier tubes (PMT) that must be shielded from the very high (≤ 0.3 T) solenoid field otherwise present.

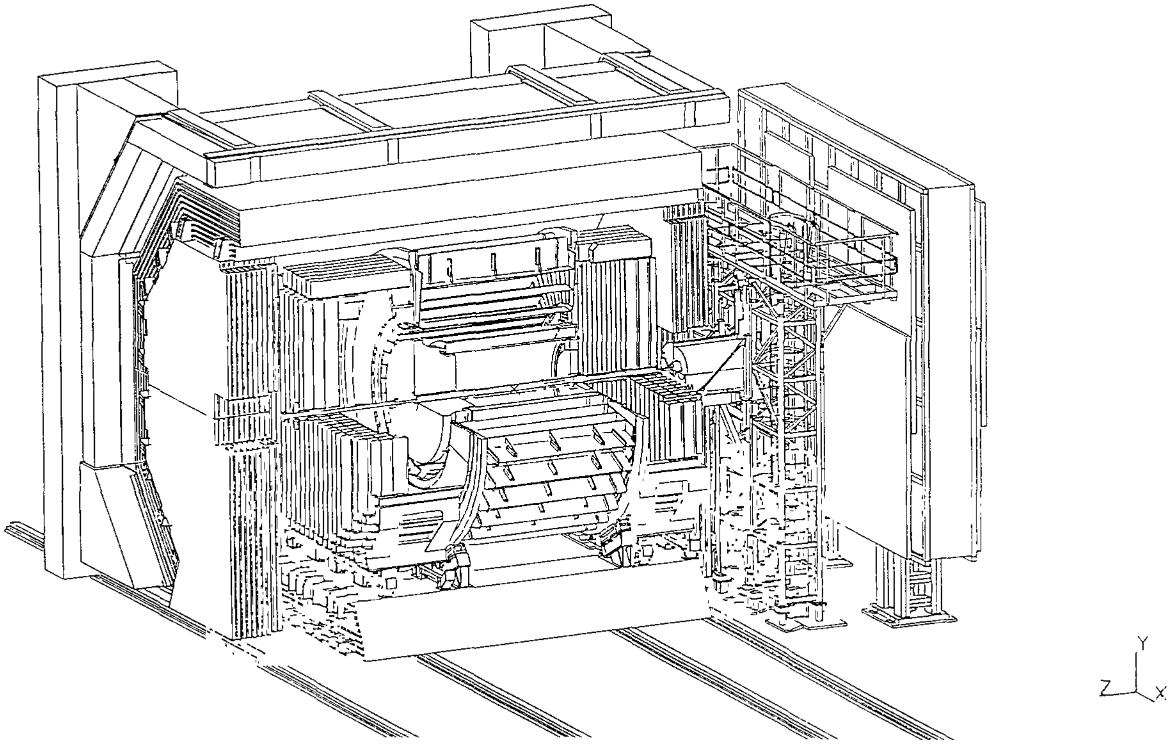

Fig. 1. A perspective view of the ZEUS detector with all its components.

The calorimeter is mechanically subdivided in three units: the barrel calorimeter (BCAL) around the solenoid, the forward and the rear calorimeters (FCAL and RCAL). Each is divided into modules: 32 identical-looking for BCAL and 23 similar-looking for each of FCAL and RCAL. Model examples of the ferromagnetic parts of each module type are shown in fig. 3.

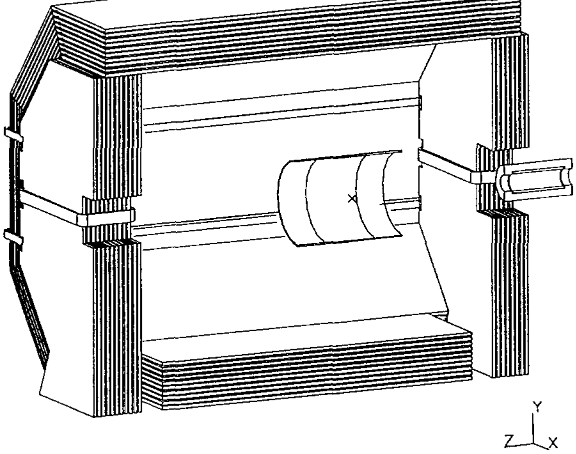

Fig. 2. The ZEUS detector coil system around one yoke half.

Basically, the calorimeter absorber/scintillator layers are attached to a T-shaped backbone structure complemented by perpendicular end supports. The layers closest to the interaction point are called electromagnetic while the deeper ones are called hadronic, according to the kind of energy most likely to be deposited there. The BCAL modules exhibit in addition a ferromagnetic intermediate plate between the two hadronic sections. The FCAL and RCAL modules differ not only by their depths, RCAL needing only one hadronic section, but also by the fact that the inner half of the 0.04 cm thick steel cladding of the 80 depleted uranium plates of the first hadronic section of FCAL also had to be made out of ferromagnetic material, from force equilibrium considerations, as will be explained next.

2.3. Detector design

The large degree of asymmetry between the intersecting proton beams of 820 GeV protons and 30 GeV electrons of the HERA machine leads to a longitudinal asymmetry of the detector: the forward calorimeter is deeper than the rear one, hence the 2.5 m long main solenoid is shifted from the center of the yoke by 0.8 m out of the 8.5 m inner axial dimension. The Helmholtz-like coil configuration is such that the larger

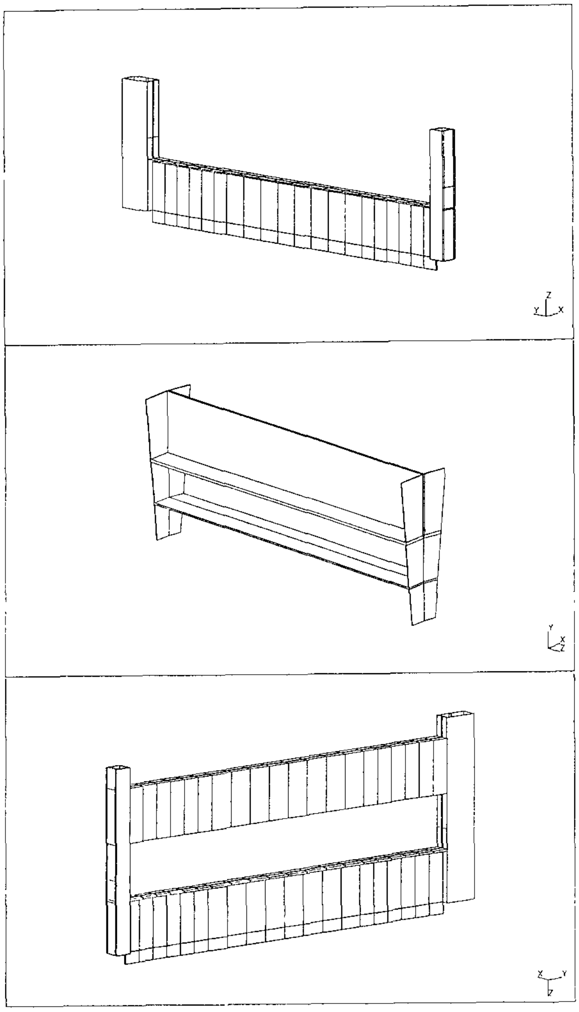

Fig. 3. The ZEUS calorimeter ferromagnetic supporting structures for the three types of modules: (top) RCAL, (middle) BCAL and (bottom) FCAL.

part of the magnetic flux is returning in the air. Without ferromagnetic calorimeter support, an axial force of −45 kN (in the rear direction) would already be exerted on the solenoid support. Because the coil and its anchor are located between the interaction point and the calorimeters, both must also be as thin as possible (typically less than 0.1–0.2 interaction length) but still guarantee a −50 kN standard safety limit.

Preliminary calculations and symmetry arguments had shown that the introduction of the asymmetric calorimeter structure of the original design would more than double the force to −106 kN, hence the addition of the ferromagnetic cladding in the forward region. They also demonstrated that two-dimensional Laplace equation solvers, in their assumption of cylindrical symmetry, could not yield accurate enough predictions. Indeed, the interplay between all relevant components sets very stringent conditions on the detector design.

In summary, the major requirements of the ZEUS detector in terms of magnetic field are:

1) on the field:
   - high, homogeneous and accurate (< 1%) in the tracking regions;
   - as low as possible in the calorimeter photomultiplier regions;
   - known in the calorimeter sensitive regions, as it affects the scintillator light output and therefore the calibration of the calorimeter typically at the 1–2% level [3];
2) on the forces:
   - within safety limits for the main solenoid and its support;
   - idem for the stability of the calorimeter carriages;
   - also when the forward and rear calorimeter halves are opened laterally at beam injection time (to avoid possible higher exposures to beam radiations);
3) on the measurements:
   - precise mapping in the central regions;
   - this must be accomplished with a provisional iron configuration as close as possible to the final one;
   - sample field and forces must be monitored in the whole ZEUS volume;
   - quench tests and checks that generated eddy current effects are small;
4) on the calculations:
   - predictive power for most of the above field and force requirements, as they influenced the design;
   - three-dimensional modellization of the detector and its components;
   - knowledge from permeability measurements of the magnetic properties of both yoke irons;
   - knowledge of the field where not mapped, especially inside the iron structures, provided the corresponding magnetization curves are known;
   - highest possible accuracy (typically 2–3%);
   - cross-checks with measurements;
   - upon agreement with the measurements, extrapolations to the final calorimeter iron configuration.

3. The TOSCA software finite-element package

TOSCA is a commercial software package from Vector Field Ltd., Kidlington, England [4,5]. Its purpose is the general solution of three-dimensional magnetostatics equations. The code is distributed among three parts: a preprocessor to define the problem, a processor to solve it and a postprocessor to extract and interpret the results.

Calculations were performed at the Rutherford Appleton Laboratory in England. The version used on the IBM-3090 was 5.4. The largest processor module required 12 Mbytes of computer central memory. TOSCA was also run on the Cray X-MP/48 and /416 with partly vectorized versions 5.0 and 5.5, respectively.

The principle of the model design is to define a so-called base plane containing in three- or four-corner facet patterns the approximate profiles of all objects to be represented. The plane is then extruded towards the third dimension in successive layers. The volume elements thus defined can then be modified to their final shape and assigned air or any magnetic material as content. The coils are included separately and in first approximation they only require to be located within air regions. Symmetries, boundary conditions, eventual periodicity conditions and further modifications can then be defined before the model is submitted to the solver.

In the TOSCA algorithm [4], the potential is splitted in two parts, called "reduced" and "total". Reduced potential regions will comprise flowing currents, e.g. from coils, while total potential regions, which obey simpler equations, will cover the rest of the model space. By thus splitting the scalar potential, most of the cancellation problems are avoided and both calculation speed and accuracy are enhanced.

Upon field retrieval, two interpolation methods are available, depending on the type of potential of the region. Furthermore, forces can be evaluated in two different ways: $\boldsymbol{J} \times \boldsymbol{B}$ for coils and Maxwell stress tensor integration over predefined object surfaces or fractional volumes of space.

The current TOSCA version can accommodate up to 50 000 model nodes. As the model nodes need not be defined on a regular grid, models of high complexity and mixed shapes can easily be achieved. Alternatively, increasing the number of subdivisions in the model will improve granularity, hence the local field accuracy. As can be seen in fig. 4, the computer time consumption rises linearly with the number of nodes for the most simple models, where only the number of subdivisions is increased. In practice however, additional nodes are mostly used to increase the model complexity. The CPU time demand for such applications rises almost exponentially and 25 000–30 000 nodes turned out to be the real limit on the available computers. Adding to that the fact that a minimum of two layers, in any dimension for a transition from iron to air are needed, one quickly reaches this limit for model design.

Disk space requirements are also large. Typically, the TOSCA database containing the whole of the geometrical information and the field solution requires ~ 500 bytes per node. Disk files are then usually in the 12–15 Mbyte range. The additional temporary files needed for storing of intermediate information amount to 1.5 times the main database size.

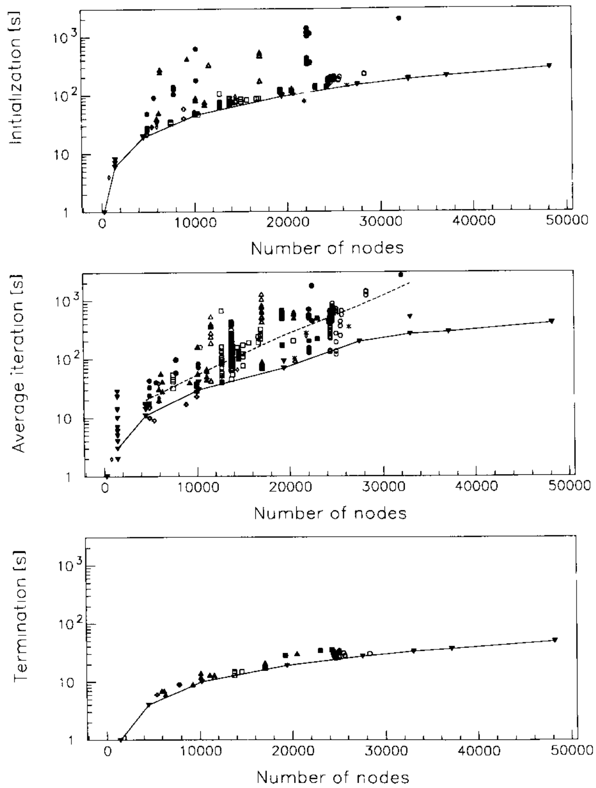

Fig. 4. The TOSCA solver relative CPU-time requirements as function of the model's number of nodes. The solid lines identify models where granularity increases, while the dashed line shows the trend for models where complexity increases.

Both pre- and postprocessors rely heavily on graphics for the convenient handling of the model and its solution. For extensive use, however, as for the fine tuning of e.g. thickness and dimension parameters, both had to be adapted to batch submission and equipped with their own pre- and postprocessors. Finally, the complexity of the ZEUS models was such that it was four times larger than what the preprocessor could handle. They then had to be artificially cut into four distinct parts, each fed separately to the preprocessor before being put back together for the solver processor.

4. The ZEUS models

Symmetries play an important role in the building of the models. For example, mirror quadrant symmetry can be assumed in ZEUS if only the main solenoid is on and if one neglects top–bottom and top–side differences in the yoke and the calorimeters. The addition of the yoke coils breaks this symmetry and requires a minimum of 180° rotation symmetry around the main axis. This means that, under the same detector assumptions, one needs already twice the number of nodes, not counting the ones necessary to allow the coils themselves in.

Given the minimum geometrical description of ZEUS (section 2) and the properties of TOSCA (section 3), it can be shown already by simple counting arguments that no single model can simultaneously contain all coils and all ferromagnetic materials. Several parallel models had to be designed depending on the issue to be resolved, each addressing a set of issues as uncorrelated as possible with what had been further neglected.

In the course of the calculations, more than 500 models and their variations have been created, run and their results analyzed. Some tested the code itself for self-consistency or against analytical calculations in ZEUS-like conditions. Others were used for actual magnets where magnetic field effects were investigated or devoted to study photomultiplier shielding, etc.

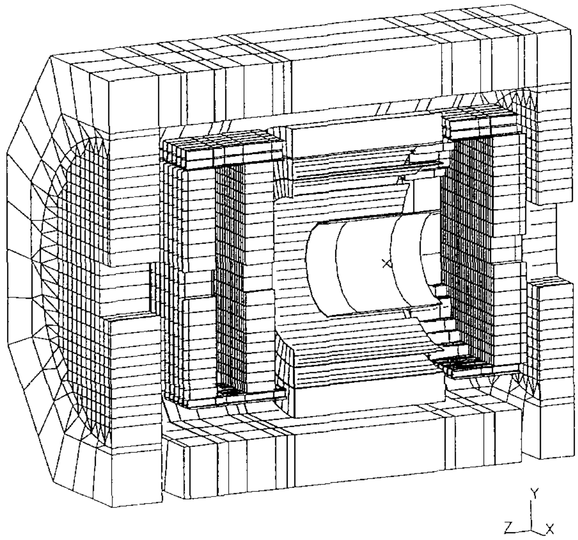

Fig. 6. One half of the ZEUS detector as in the global model.

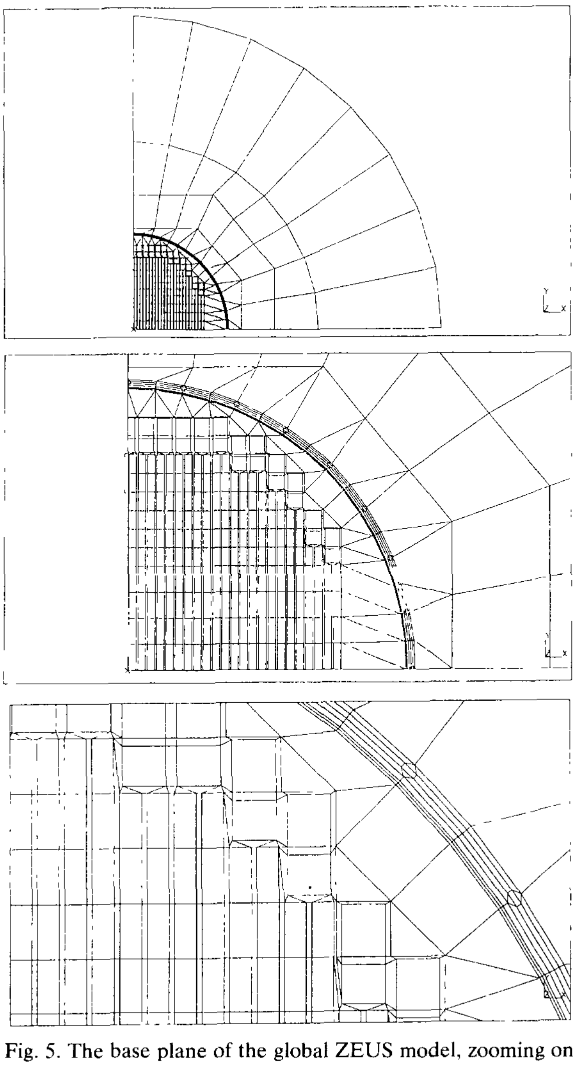
Fig. 5. The base plane of the global ZEUS model, zooming on its details.

The "global" ZEUS model contains a rudimentary version of the yoke but the full calorimeter support description. It describes best the field and forces in all the tracking regions and in the rest of the detector within the main yoke. Its base plane is displayed in fig. 5. The final model appearance, extended to mirror half symmetry, is as in fig. 6. Nodes total 26 000.

Starting from generic files and commands, a few CPU minutes were needed to build up the 115 000-line (9 Mbytes) input to the TOSCA processor. A typical run requesting 15 iterations consumed a few CPU hours. The output database was 13 Mb large. The following large map productions for the central field needed 50% of the running time, while force calculations on the main solenoid and on the calorimeter structures were achieved in respectively 10% and 75% of the running time.

5. Field and force measurements

At the time of the ZEUS central field mapping, the detector was still empty but for the main solenoid. In order to perform the measurements, a provisional iron structure was proposed and implemented inside the main yoke. Its shapes and complexity were very similar to those of the calorimeter backbone structure. Its purpose was thus to imitate to a large extent the final operating conditions and to insure in the tracking regions a magnetic field extremely close to the final one. The structure enabled moreover the installation of hundreds of strain gauges and Hall probe units at strategic locations to monitor forces and field during the commissioning of the solenoid [6,7].

The field mapping of the tracking regions was done using a windmill-like device running on rails along the axis of the main solenoid. A large number of Hall probes were distributed on each of the two arms. The ~ 1.8 T field was measured at intervals of 5 cm axially, 10 cm radially and 45° azimuthally [8].

From the point of view of the calculations, both detector configurations, being so similar, could be accommodated in the same global model, with suitable switches to go from one to the other. This procedure considerably increased the efficiency of the model design. It also reduced to a minimum any calculational systematics when the relative results from both configurations were used to extrapolate the field measurements to the final field map.

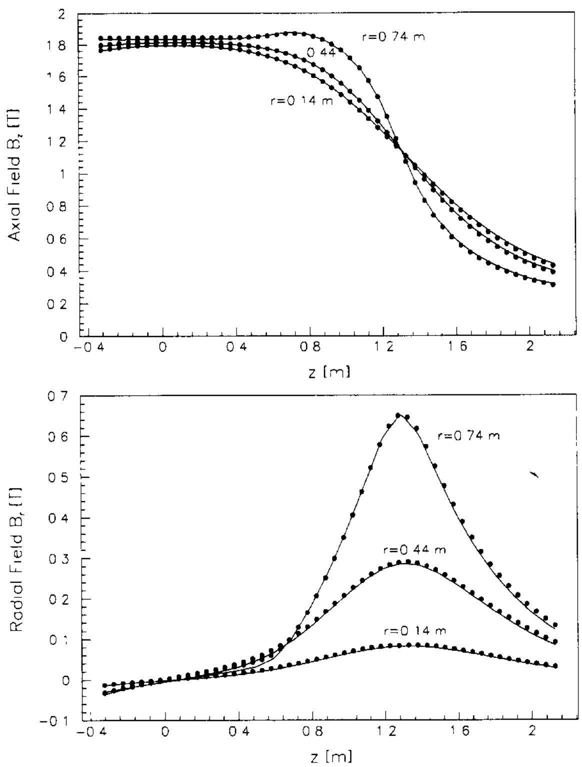

Fig. 7. Comparison of field calculations (lines) and measurements (points) in the central tracking region along the main axis for three different values of radius.

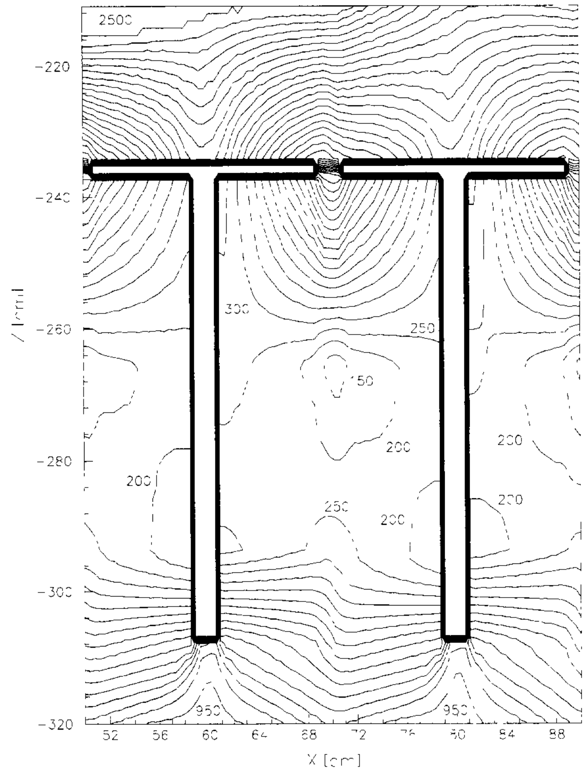

Fig. 8. Cross section of the field predictions between two T-beams of the rear calorimeter supporting structure. Sample contour line values are given in Gauss. Photomultipliers are located in the lower-field regions.

6. Calculation results and comparison with measurements

6.1. The field

Roughly based on the number of available model nodes n, an absolute ~3% field accuracy ($n^{-1/3}$) could easily be reached with TOSCA. It worsened up to 10–20% in regions very close to ferromagnetic materials, while far from them, as in the central tracking regions, better than 1% was achieved. Comparisons between predictions and measurement results are presented in fig. 7 [8]. The agreement is shown to be of the order of 120 G or better over the tracking detector volumes. Fig. 8 shows the expectations in the regions where the calorimeter photomultipliers are located. One of the main outcomes is that local segmentations down to the 1 cm level could be reliably accommodated in a detector spanning 10 m.

6.2. The forces

Given the percent-level accuracy of the field and very large cancelling terms, force predictions were dif-

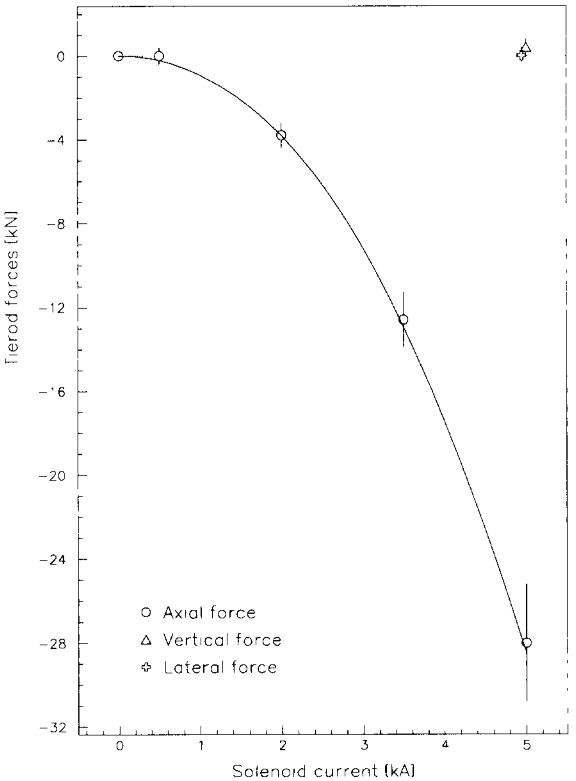

Fig. 9. Comparison of force calculations and measurements on the main solenoid support.

ficult and very sensitive to details of the model definitions. For example, considering the coil as two half-coils along the main z-axis, the pulls in the $+z$ and $-z$ directions are of the order of 3000 and 3050 kN respectively, with their difference as the quantity of interest. In the provisional calorimeter configuration, the estimated axial force on the solenoid of -28 ± 12 kN was matched by a measurement of -28 ± 3 kN (fig. 9). In the final configuration at 80% of the maximum solenoid current, the numbers similarly agreed within 3 kN at 48 kN. Such measurements therefore provided a reliable absolute scale for the calculations and their errors.

7. Conclusions

TOSCA and its processors were an appropriate, flexible and very efficient tool for the field calculations in ZEUS. TOSCA's limitations in terms of model nodes or available CPU time were largely compensated by its versatility and reliability. Calculations provided many insights in the understanding of the field in all regions and forces on all components, thus assuming an important role in the detector design and particle tracking algorithm. Since the TOSCA calculations were very precisely confirmed by the measured field and force values in the provisional detector configuration, further predictions were made for the final configuration and checked with similar accuracy against new sets of measurements.

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