Dead zone analysis of ECAL barrel modules under static and dynamic load

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Abstract

In the context of ILD project, impact studies of environmental loads on the Electromagnetic CALorimeter (ECAL) have been initiated. The ECAL part considered is the barrel and it consists of several independent modules which are mounted on the Hadronic CALorimeter barrel (HCAL) itself mounted on the cryostat coil and the yoke. The estimate of the gap required between each ECAL modules is fundamental to define the assembly step and avoid mechanical contacts over the barrel lifetime. In the meantime, it has to be done in consideration to the dead spaces reduction and detector hermeticity optimization. Several Finite Element Analysis (FEA) with static and dynamic loads have been performed in order to define correctly the minimum values for those gaps. Due to the implantation site of the whole project in Japan, seismic analysis were carried out in addition to the static ones. This article shows results of these analysis done with the Finite Element Method (FEM) in ANSYS. First results show the impact of HCAL design on the ECAL modules motion in static load. The second study dedicated to seismic approach on a larger model (including yoke and cryostat) gives additional results on earthquake consequences.

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ABSTRACT:

In the context of ILD project, impact studies of environmental loads on the Electromagnetic CALorimeter (ECAL) have been initiated. The ECAL part considered is the barrel and it consists of several independent modules which are mounted on the Hadronic CALorimeter barrel (HCAL) itself mounted on the cryostat coil and the yoke. The estimate of the gap required between each ECAL modules is fundamental to define the assembly step and avoid mechanical contacts over the barrel lifetime. In the meantime, it has to be done in consideration to the dead spaces reduction and detector hermiticity optimization. Several Finite Element Analysis (FEA) with static and dynamic loads have been performed in order to define correctly the minimum values for those gaps. Due to the implantation site of the whole project in Japan, seismic analysis were carried out in addition to the static ones. This article shows results of these analysis done with the Finite Element Method (FEM) in ANSYS. First results show the impact of HCAL design on the ECAL modules motion in static load. The second study dedicated to seismic approach on a larger model (including yoke and cryostat) gives additional results on earthquake consequences.

KEYWORDS: ILD, FEA, ANSYS, seismic, earthquake.

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1. Introduction

The International Large Detector (ILD) represents the conceptual design of a high performance detector [3] which should be a part of the International Linear Collider (ILC). This installation for high-precision physics [1] will complete and push forward the analysis done at the Large Hadron Collider (LHC) in Geneva. Analysis carried at ILC will essentially involve electrons and positrons collisions at 500 GeV [5] with the use of particle flow algorithm [2]. Calorimetry for ILD is based on high granularity calorimeters as dense as possible (minimal dead zones) [4].

![Figure 1: ILD within ILC](a) picture of ILC installation; (b) ILD concept from CAD model.)
Construction of this gigantic program in Japan requires a large international effort. This report, dedicated to mechanics of the ECAL structure in its environment, represents only a small part of the work done and to be done.

2. ECAL barrel module: preliminary approach

2.1 ECAL barrel modules presentation

This study focuses on the ECAL barrel relative motion with regard to its environment. The ECAL barrel is composed of 40 modules (eight staves of five modules). Each module is a trapezoidal alveolar structure made of tungsten embedded into carbon fiber composite. Every alveoli are filled with sensor layers called slab. Thanks to rail systems, modules can be slide into the HCAL barrel (adjacent detector which hold the ECAL). Two kind of clearances (i.e. gap\(\text{(1)}\) and gap\(\text{(2)}\)) can be defined to avoid module contacts over the detector lifetime.

![Figure 2: Picture of the ECAL barrel and clearances considered in the analysis.](image)

First part of this study consisted of modelling the ECAL module under its own weight.

2.2 ECAL geometry used for FEA

Initially, shell model was used with ANSYS ACP (ANSYS Composite Pre-Post module). This method turned out to be time consuming for one module. Knowing that the ECAL barrel is made of 40 modules, solving time (time spent by the computer for solving) would increase dramatically with larger model. It has been decided to use a simplified model to deal with this. Shell elements are replaced by 3D solid ones with equivalent material to obtain the comparable results. The geometry is made of two stiff flanges and a rather soft core material.

![Figure 3: (a) Shell analysis of the 12 o'clock ECAL module under gravity; (b) simplified ECAL model with hard flanges and soft core; (c) 3D solid analysis of the 12 o'clock ECAL.](image)
Thanks to this choice, similar results were obtained between (a) and (c) but solving time was considerably reduced (~70%). The following table and bar charts illustrate this improvement.

<table>
<thead>
<tr>
<th>Model</th>
<th>Max disp. (mm)</th>
<th>Disp. corner (mm)</th>
<th>Solving time (s)</th>
<th>Time saving (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell</td>
<td>0.430</td>
<td>0.057</td>
<td>116.642</td>
<td>N/A</td>
</tr>
<tr>
<td>Solid 3D</td>
<td>0.433</td>
<td>0.056</td>
<td>36.177</td>
<td>69.0</td>
</tr>
</tbody>
</table>

3. Static analysis: HCAL + ECAL

3.1 Designs used

For the purpose of this analysis, two HCAL structure designs were used, the Semi Digital Hadronic CALorimeter (SDHCAL design) and the Analog Hadronic CALorimeter (AHCAL design).

3.1.1 SDHCAL barrel

The HCAL is also an alveolar based structure which hosts sensor layers. The structure is mainly made of stainless steel plates which account for both weight and stiffness. The SDHCAL design (see next figure) is made of stainless steel layers called absorbers (15 mm thick) reassembled by two side flanges (10 mm thick). Five wheels are stacked to produce the full barrel. Each wheel has the same width as the ECAL modules.

![SDHCAL Sketch](image)

Figure 4: Sketch of SDHCAL individual module (left), ring (middle) and finally full barrel (right). Absorbers are 15 mm thick in yellow and flanges are 10 mm thick in grey.

This empty structure (i.e. without sensor layers) represents a total mass of about 460 t. Electronic and sensor layers represent about 184 t.

3.1.2 AHCAL barrel

As for the SDHCAL, the AHCAL is an alternative hollow structure which hosts sensor layers with a different insertion principle. Sensor layers are slide in along the beam axis. This
version of HCAL is based on 2 symmetrical modules which are duplicated to produce a wheel. Two wheels are needed to get the full barrel. This is illustrated in Figure 5.

![Figure 5: Sketch of two symmetrical AHCAL modules which produce a "super module" (left), ring (middle) and full barrel (right). Absorbers 16 mm thick are in yellow and flanges are in grey.](image)

With absorber thickness of 16 mm the total mass for the HCAL barrel is approximately 470 t, without additional 142 t for the sensor layers.

### 3.2 Boundary conditions and results

For both designs the HCAL is supposed to be held at 3 and 9 o’clock. However kinematics is slightly different. This is illustrated in Figures 6. The SDHCAL is fixed at 9 o’clock and free to move on a horizontal plane at 3o’clock whereas the AHCAL is assumed to be mounted on a cylindrical pad at both 9 and 3 o’clock which allow one degree of freedom in rotation. Moreover, the cylindrical pad at 9 o’clock is mounted on a “V” shaped rail and the one at 3 o’clock is free to move on a horizontal plane.

![Figure 6: Mechanical linkage used as boundary conditions for (a) SDHCAL and (b) AHCAL.](image)

![Figure 7: Displacement field obtained for SDHCAL (a) and AHCAL (b) designs, under its own weight with electronic considered as a point mass.](image)
For the SDHCAL, the maximum total displacement is 0.9 mm. The smallest gap between ECAL modules in phi (azimuthal gap) is reduced from 2.5 mm to 2.31 mm. On the other hand, the total displacement for AHCAL is estimated to be 6 mm with a reduction of gap from 2.5 mm down to 0.95 mm. Hence, the SDHCAL design is stiffer than the AHCAL which would help minimizing gap.

4. Earthquake analysis

4.1 Context and Specifications used (ISO 3010)

This section focuses on preliminary studies of the structure response in case of earthquakes. The Kitakami site (in Japan) foreseen for ILD installation is known for its seismic activity. Response spectrum analysis was done with AHCAL design as a starting point. This design was chosen as it is revealed to be the least stiff. Several specifications for civil engineering can be used. The EUROCODE 8 [6] and ISO 3010 [7] are one of them. This latter (ISO 3010) is used by Architectural Institute of Japan and therefore also used here. As illustrated in figure 8, this method gives the acceleration response spectrum as a function of frequency, exhibiting a maximum in the frequency range between 3 Hz and 7 Hz.

4.2 Design used and simplifications

Generally, seismic measurements are provided from the ground and structures analyzed must touch it. In ILD, several components separate the HCAL from the ground. It is mounted inside a cryostat itself inserted inside the central yoke supported by two air pads. Here, both air pads are supposed to be perfectly fixed to the ground. The cryostat cryogenic fluid and copper coil mass are not taken into account. Sensor layers inside the HCAL and the yoke are not taken into account. This gives an iron based structure of 2% damping with a total detector mass of about 3100 t.

To be able to model this large assembly, additional simplifications were done. Relative motion of fixations have been removed. Moreover, adjacent plates within the HCAL were merged and considered as one single thicker plate for seismic analysis.

Figure 8: Acceleration Response Spectrum at the Kitakami site (ISO 3010).

Figure 9: Full structure used for earthquake analysis: air pads (green); central yoke + cryostat (blue); AHCAL barrel (orange); ECAL barrel (grey).
Figure 10: (a) Kinematic chain simplifications of the HCAL; (b) HCAL adjacent plates merging.

Table 1: Simplifications consequences on FEA estimates

<table>
<thead>
<tr>
<th></th>
<th>Case1: Static FEA in section 3.2</th>
<th>Case2 = Case1 without sensor layers</th>
<th>Case3 = Case2 + changes (a) and (b) from (Figure 10)</th>
<th>Case4 = Case3 + cryostat + Yoke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total displ (mm)</td>
<td>6.04</td>
<td>5.04</td>
<td>4.09</td>
<td>5.62</td>
</tr>
<tr>
<td>Min gap (mm)</td>
<td>0.95</td>
<td>1.27</td>
<td>1.31</td>
<td>1.98</td>
</tr>
</tbody>
</table>

Frirst step from case 1 to case 2 shows that by removing sensor layers weight the total deformation is underestimated and ECAL gap is overestimated. The second step from case 2 to case 3 shows that stiffening boundary conditions and merging 2 adjacent plates into a thicker one also reduce the total displacement. However gap value remains quite stable after those simplifications. Finally, by introducing surrounding elements from case 3 to case 4, the total displacement increases showing the elasticity of supporting structure. Considering the gap value it also increases. This might be due to the HCAL supports which are following the cryostat deformation instead of being perfectly fixed. In other words, the HCAL surrounding elements doesn’t seem to be infinitely rigid and the ECAL tends to follow their general motion. In general, one can say that case 4 used for seismic analysis tends underestimate to the total deformation and overestimate ECAL gap value. Further studies might help in understanding these results.

4.3 Earthquake results and discussions

4.3.1 Eigenvalue analysis

Eigenvalues have been determined filtering the most participating modes between 0 Hz and 50 Hz. 42 modes were found. They account for about 90% of the total mass (3100 t). 4 dominating modes in term of mass involved are shown here. Those modes are more prone to drive the detector motion. This doesn’t mean that other modes can be disregarded.
Figure 11: (a) Mode 1 at 2.3 Hz; (b) Mode 2 at 3.0 Hz; (c) Mode 6 at 7.0 Hz; (d) Mode 9 at 8.6 Hz with 68%, 68%, 88% and 35% of the total mass (3100 t) involved respectively.

Eigenvalues estimated for this cantilever structure are in the range of the earthquake peak frequency (Figure 8). Low frequency values with significant amount of mass involved are found for horizontal ground motion, whereas the structure is stiffer along the vertical direction. Therefore horizontal accelerations are foreseen to have a bigger impact than the vertical ones.

4.3.2 Displacement analysis

Acceleration spectrum calculated from ISO3010 was used in 3 different directions. The first approach considers that ground acceleration is unidirectional (acceleration combination being harder to estimate). One also has to know that no recombination with gravity load was done here. Only acceleration impact is studied (i.e. gravity is not considered). Results are illustrated in Figure 12.

Figure 12: Total displacement without recombination for three different acceleration directions: parallel to the beam-pipe (a); perpendicular to the beam pipe (b); vertical acceleration (c).

Acceleration parallel to the ground are the most damaging for the structure. The same set of analysis was done with gravity recombination according to the following principle:

\[ F_{\text{static+spectral}} = F_{\text{static}} + \sqrt{F_{RX}^2 + F_{RY}^2 + F_{RZ}^2} \]

\[ F_{\text{static-spectral}} = F_{\text{static}} - \sqrt{F_{RX}^2 + F_{RY}^2 + F_{RZ}^2} \]

With the following matrices:

- \( F_{\text{static+spectral}} \) is the combined responses with positive summation
- \( F_{\text{static-spectral}} \) is the combined responses with negative summation
- \( F_{\text{static}} \) is the static responses of the structure
- \( F_{RX}, F_{RY} \) and \( F_{RZ} \) are the dynamic response to the acceleration spectrum
Figure 13 illustrates the same results as for figure 12, assuming gravity recombination according to equation (1).

Figure 13: Total displacement with recombination for three different acceleration directions: parallel to the beam-pipe (a); perpendicular to the beam pipe (b); vertical acceleration (c).

Results from Figure 12 and Figure 13 are summarized in tables 2 and 3.

**Table 2: Results for ECAL response without mass recombination.**

<table>
<thead>
<tr>
<th>Without recombination</th>
<th>Static case (own weight)</th>
<th>Acceleration along beam axis</th>
<th>Acceleration perpendicular to beam pipe</th>
<th>Acceleration vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max displ (mm)</td>
<td>5.62</td>
<td>24.88</td>
<td>17.25</td>
<td>2.84</td>
</tr>
<tr>
<td>Gap&lt;sub&gt;1&lt;/sub&gt; (mm)</td>
<td>1.98</td>
<td>2.29</td>
<td>1.89</td>
<td>2.05</td>
</tr>
<tr>
<td>Gap&lt;sub&gt;2&lt;/sub&gt; (mm)</td>
<td>1.98</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
</tr>
</tbody>
</table>

**Table 3: Results for ECAL response with mass recombination.**

<table>
<thead>
<tr>
<th>With recombination</th>
<th>Acceleration along beam axis</th>
<th>Acceleration perpendicular to beam pipe</th>
<th>Acceleration vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max displ (mm)</td>
<td>26.25</td>
<td>18.22</td>
<td>8.42</td>
</tr>
<tr>
<td>Gap&lt;sub&gt;1&lt;/sub&gt; (mm)</td>
<td>1.98</td>
<td>1.74</td>
<td>1.92</td>
</tr>
<tr>
<td>Gap&lt;sub&gt;2&lt;/sub&gt; (mm)</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
</tr>
</tbody>
</table>

On one hand, it is clearly seen that the gap<sub>2</sub> along the beam axis is almost unaffected by the study cases, provided that ECAL modules are not allowed to rail relatively to the HCAL after insertion. On the other hand, one can notice that even if sensor layers are not taken into account yet, mass recombination affects mainly vertical motion as expected. Finally, gap<sub>1</sub> as well as the full structure is the most affected by ground horizontal motion. In general, the ECAL modules tend to follow general structure motion despite some gap<sub>1</sub> reduction.

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1 Results extracted from case4 in Section 4.2
5. Conclusion

In this report it has been shown that the ECAL barrel motion is linked to the surrounding elements and their designs. Among the two investigated HCAL designs, the AHCAL introduces the biggest deformations under static load. Using this conservative candidate for further investigation with seismic load, it is shown that simplifications and boundary conditions choices affect significantly the total deformation and more importantly the gap between ECAL modules in the azimuthal angle. The first normal modes for this large and heavy structure are inevitably within peak range of a Japan earthquake spectrum. On the one hand, initial guess for the gaps values seems to be in the right order of magnitude compared with the calculated deformation field. On the other hand simplifications and dynamic component should be kept in mind for the gap size optimizing especially in the azimuthal angle. Further studies by introducing virtual masses and comparison with the SDHCAL design will help in getting a better understanding of ECAL barrel module relative motion.

References


