Considering the current CLIC SiD detector design and the machine parameter $L^*$, the final focus quadrupole QD0 will be placed inside the experiment itself. This configuration is very challenging from an integration point of view. Among several other aspects, the iron-dominated QD0 will need an active magnetic shielding to avoid undesired interactions with the magnetic field generated by the main solenoid of the detector. This shielding will be provided by a superconducting anti-solenoid, and this paper aims to describe the method used to design such device, the results obtained and the issues still to be solved.

1 Introduction

There are two proposed detectors for CLIC: the SiD and the ILD designs, both represented in figure 1. The SiD is considered to be the most challenging one, due to its higher magnetic field of 5 T at the Interaction Point (IP), therefore the following study focuses on the SiD design only.

![Figure 1: The SiD and ILD designs overview](image)

With an $L^*$ value of 3.5 m, the normal conducting final focus lies inside the boundaries...
of the detector as shown in figure 2. In such a compact configuration, QD0 needs to be magnetically shielded, so it was proposed since 2009 [2] a superconducting anti-solenoid to expel the magnetic field from the region reserved to the final focus. This anti-solenoid must then be dimensioned and integrated in the compact layout of the SiD detector: in this paper the process followed to design the anti-solenoid, the results obtained and the issues still open are illustrated.

1.1 The CLiC SiD experiment and the MDI

In the SiD MDI region many components are required for the most different reasons, and figure 2 shows the most relevant to this study. In the magnetic simulations, the following items were always modelled: the main solenoid, the flux-return yoke and the anti-solenoid. QD0 was included only in 3D analyses, while any other element was considered as non magnetic and not included in the simulations, just considered for the integration check.

1.2 Starting point and objectives of the analysis

Figure 3a shows the first anti-solenoid layout proposed for the ILD detector [2], while figure 3b illustrates the flux lines for the first version of the SiD detector with its anti-solenoid. Such configurations were used as concepts for this analysis, since shape and currents of the new anti-solenoid were redefined from scratch. Summarising, the requirements for the anti-solenoid are:

1. To provide the correct magnetic shielding to the final focus.

2. To be magnetically compatible with the beam dynamics.
3. To be integrated in the Machine Detector Interface (MDI) region.

The number of coils, their dimensions and currents were set as the output of this study.

2 The two-dimensional model

As a first approximation, a 2D axial-symmetric FEM model was considered the best choice to represent the MDI region. In fact, even if QD0 could not be included in this kind of simulation, it was possible to use such model to reduce the magnetic field in the final focus region and evaluate both the forces and the stresses acting on the anti-solenoid. However, since a 3D simulation was considered fundamental, it was planned and performed later.

The first model was set up using Ansys by Ansol, mainly to evaluate forces and stresses after performing a magnetic simulation. Once found out that magnetic precision was more relevant than stress calculation, that software was abandoned in favour of Opera2D by Vector Fields. Figure 4 shows the very first and the very last designs proposed.

The first anti-solenoid was designed for an $L^*$ of 3.8 m, and consisted in 3 superconducting coils, the current densities were $1.14 \times 10^8$ A/m$^2$, $3.67 \times 10^7$ A/m$^2$ and $6.00 \times 10^6$ A/m$^2$ for coil 1, 2 and 3 respectively. Results in terms of magnetic field along the beam line are shown in figures 5a and 5b while the maximum axial force was $7.0 \times 10^6$ N, on coil 1.

2.1 Design evolution of the 2D model

The first magnetic results obtained were satisfying, but many integration issues still needed a solution. The most important changes that occurred in the evolution of the MDI were the setting of $L^*$ to 3.5 m with the consequent detector re-dimensioning; the necessity to reserve a space of at least 40 mm around the anti-solenoid coils for their cryostat, and finally the setting of the maximum current density for the anti-solenoid to $8 \times 10^7$ A/m$^2$. 

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To improve the shielding, anti-solenoids made by different numbers of coils were studied, and also the coils shapes were continuously changed. At some point, it was introduced a ferromagnetic disc to be placed in front of the QD0 region, as shown in figure 4b, and it was also defined a numeric routine to iteratively find the coil currents which minimize the remaining magnetic field in the QD0 region and on the beam axis.

2.2 Results of the 2D models and conclusions

Figures 5c and 5d show the best results ever obtained in terms of magnetic field with a 2D model. However, due to integration issues, that design was discarded in favour of a less performing one, which gave the results represented in figures 5e and 5f. Once reached this stage, the integration issues were considered solved, the remaining magnetic field minimized and the forces under control. It was then clear that only a 3D simulation could add some more information, and in particular a 3D simulation was the only way to introduce the QD0 magnet in the analysis and study its magnetic interactions with both the detector main solenoid and the anti-solenoid.

3 The three-dimensional model

The main challenge of the 3D model is the scale difference of the various components (Figure 6a). In the same model there are in fact objects as big as the iron end-cap, with a radius of 7 m, and object as detailed as the final focus, with an aperture radius of just 4.125 mm. Furthermore, it was possible to use only one plane of symmetry to simplify the model, which consisted in a half of the detector plus a full QD0 and an anti-solenoid (Figure 6b). The magnetic simulation included non linear iron regions, coils and even the permanent magnets blocks which are proposed in the QD0 hybrid design [3].
Figure 5: Axial, radial and overall magnetic field on the beamline
3.1 Design evolution of the 3D model

The anti-solenoid defined during the previous 2D analyses didn’t perform as before once QD0 was introduced, and too much magnetic field was attracted by its poles and yokes. Then it was necessary to adapt the currents and also reposition slightly some of the anti-solenoid coils, to shield the magnet properly. This was done with a trial and error procedure, since the routine that was set up for the 2D model was based on the superposition of effects and became unusable due to the non linear behaviour of QD0. Finally, the ferromagnetic disc effect was overcome by the presence of the magnet, so it was removed.

3.2 Results of the 3D model

Magnetic field on the beam axis was highly reduced as the ferromagnetic QD0 shielded the beam line. Figures 7a and 7b show the remaining field on the beam line. However, since QD0 was simulated, it was also possible to evaluate directly its performance in terms of gradient developed. Figure 7c shows the gradient calculated at 1 mm from the magnetic axis in four different directions, labelled coherently with the beam coordinate system. Some losses are present in the first part (the expected gradient was 535 T/m). Forces on the anti-solenoid were the same as the first 2D analysis and forces on the QD0 were present and highly related to the shielding efficiency. With the best integrated design the maximum force on the QD0 was roughly 5 KN, in the axial direction towards the IP.

3.3 A last non integrated version

Since the QD0 performance was still not satisfying, it was decided to put aside integration and try to define a better anti-solenoid. The latest design investigated was not compatible with the pre-alignment system [4], since the first coil was closer to the IP, but it was not interfering with the Hadronic Calorimeter or any other system. Figure 7d shows the improvements in terms of gradient. Losses were reduced, as the first part (about 30 cm) of QD0 worked at 95%. The only solution found so far to achieve 100% of the QD0 gradient was to increase $L^*$ by 30 cm.
3.4 Conclusions and next steps

This study points out that the anti-solenoid can shield the QD0, even if this will require some additional space, or a slightly bigger $L^\ast$. This will also reduce the forces acting on the magnet, while in the anti-solenoid forces are still relevant and instability issues may occur. As next steps, transient analyses, further integration and better FEM models are foreseen.

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