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Simulation of the MoEDAL experiment

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Abstract

The MoEDAL experiment (Monopole and Exotics Detector at the LHC) is designed to directly search for magnetic monopoles and other highly ionising stable or meta-stable particles at the LHC. The MoEDAL detector comprises an array of plastic track detectors and aluminium trapping volumes around the P8 intersection region, opposite from the LHCb detector. TimePix devices are also installed for monitoring of the experiment. As MoEDAL mostly employs passive detectors the software development focusses on particle simulation, rather than digitisation or reconstruction. Here, we present the current status of the MoEDAL simulation software. Specifically, the development of a material description of the detector and simulations of monopole production and propagation at MoEDAL.

Keywords:
MoEDAL, Monopole, Geant4, Simulation

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1. Introduction

MoEDAL is a new detector being installed at the LHC for Run-2 to search for magnetic monopoles and other long-lived exotic particles.

Simulation of the MoEDAL detector is necessary in order to estimate its performance in different physics scenarios. A simulation of the detector is being developed inside the LHCb Gauss framework [1] in order to perform these estimates.

This paper provides a brief outline of the theoretical motivations for MoEDAL and an overview of the detector systems, followed by a description of the current status of the simulation development.

2. Theoretical motivations

MoEDAL searches primarily for magnetic monopoles, but is also sensitive to other highly ionising particles. This section provides a brief summary of the theoretical motivations for such searches.

The existence of magnetic charge has been hinted at for over a century by the fact that it would make Maxwell's equations of electromagnetism symmetric. Dirac showed in 1931 that magnetic monopoles are consistent with electromagnetic theory and that the existence of magnetic charge would explain electric charge quantization [2].

Long-lived massive particles (LLPs) are predicted by a number of proposed extensions to the Standard Model [3]. Due to their mass, these particles are likely to travel at velocities far below $\beta \approx 1$ and, if charged, would highly ionise due to their low velocity. Several other proposed extensions to the Standard Model also predict long-lived highly ionising particles, such as: multiply charged particles; Q-balls; micro black holes; and others.

There have previously been many for searches magnetic monopoles and other LLPs, both in cosmic ray and collider experiments [4, 5, 6]. However, no evidence for these particles has yet been discovered. If they exist, they must either couple very weakly to the Standard Model, or have masses that have thus-far prohibited sufficient production.

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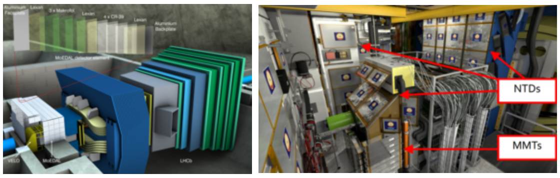
3. The MoEDAL detector

The MoEDAL experiment consists of three detector systems installed around the P8 intersection of the LHC: the Nuclear Track Detectors, Magnetic Monopole Trappers and TimePix pixel detectors. The LHCb detector occupies the cavern on one side of the interaction point (IP), MoEDAL is mainly installed on the opposite side (fig. 1).



(a) (b)

Figure 1: Visualisation of the MoEDAL detector installation (a) wide view, showing LHCb, (b) closer view of NTDs and MMTs.

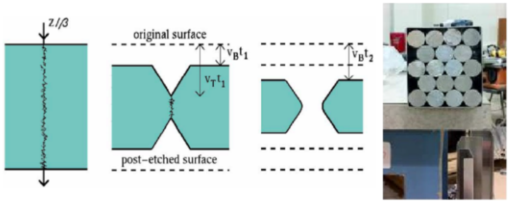
Test detectors were installed in 2012 during the 8 TeV collisions, and lead to the first physics result produced by MoEDAL[7]. The full detector arrays will be deployed over the coming years to take data in 14 TeV collisions[8].

3.1. Nuclear Track Detectors (NTDs)

The NTDs are passive detectors, designed to track highly ionising particles such as monopoles. They consist of several layers of plastic, the molecular chains of which can be disrupted by sufficiently highly ionising particles. The disrupted plastic is then chemically etched at a separate facility and results in observable holes at the locations where highly ionising particles had passed through (fig. 2a). Different plastic sheets have different thresholds for disruption against the particle ionisation potential, which can typically be characterized as charge divided by velocity ($\frac{Z}{\beta}$).

3.2. Magnetic Monopole Trappers (MMTs)

The MMTs are passive detectors, designed to trap magnetic monopoles inside their volume. A single MMT unit consists of 2.5 cm diameter aluminium rods packed into an aluminium box (fig. 2b). The high nuclear magnetic moment of aluminium makes it especially effective at trapping magnetically charged particles. The trapper rods are then analysed at a separate facility, using a specialised magnetometer, to search for any trapped monopoles.



(a) (b)

Figure 2: (a) The NTD etching process. (b) Cross section of a single MMT unit.

3.3. TimePix Pixel Detectors

TimePix units are silicon pixel detectors that can measure the duration that current in each triggered pixel remained above the threshold value. This allows for estimates of energy deposition to be taken, making the detectors especially useful for detecting highly ionising particles. The TimePix units are the only “active” detectors deployed at MoEDAL, but occupy an extremely small solid angle and are mainly used for monitoring.

4. MoEDAL Simulation

Simulation of monopole and exotic particle behaviour is necessary in the interpretation of experimental results, and is also useful in development of the detector. As MoEDAL occupies the same cavern as LHCb, we utilise the LHCb collaboration’s simulation framework, Gauss, in developing a simulation of MoEDAL. The development efforts comprise three main areas: simulation of monopole production; description of additional material; and development of Gauss to simulate monopole propagation. As the main MoEDAL detector systems are passive, the digitisation and reconstruction steps typically employed at LHC experiments are not required.

4.1. Simulation of monopole production

Previous searches for monopoles at colliders have mainly been interpreted using a leading order Drell-Yan production model. Figure 3 compares the acceptance of the MMT detectors installed during 2012 with that of the 2011 ATLAS monopole search. It is clear that the production distribution of monopoles will greatly affect the acceptance of the MMTs, due to the relatively small solid angle that they occupy.

Various theoretical approaches to monopole production are currently being considered. Some of these models allow for the production of monopolium, a monopole to anti-monopole bound state that may lead to especially interesting effects in the NTD detectors.

4.2. Description of additional material

The standard geometry used in Gauss has been developed for the simulation of LHCb and, as such, does not include some infrastructure elements on the opposite side of the IP. These elements represent significant radiation lengths and must be included in any simulation of MoEDAL. Additionally, the detectors themselves must be added to the simulation as sensitive detectors, producing hit collections.

Figure 4b shows the new material added to the simulation thus far, specifically the LHCb VELO upstream tank cap and the MoEDAL MMT detector array. Photos of the actual VELO cap and the MMT arrays are shown in figures 4c and 4d for comparison.

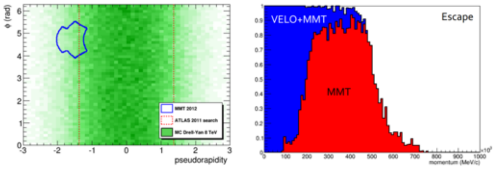
Development of the material description to include all relevant infrastructure, and the MoEDAL detector elements, is ongoing.

4.3. Simulation of monopole propagation

Gauss uses Geant4 as its simulation engine, providing access through an interface system called GiGa (Geant4 in Gauss). A “physics constructor” class was written for GiGa which simulates monopole propagation processes when included in Gauss’ modular physics list. Specifically, the class: adds a new particle definition to Gauss that describes the monopole particle; applies existing Geant4 monopole ionisation processes to the monopole definition; and modifies the particle transportation processes to include magnetic charge in the Lorentz equation definition.

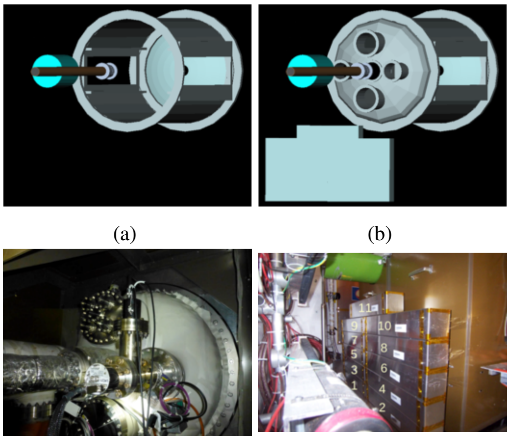
Figure 3b shows the fraction of benchmark 1 TeV monopoles, produced using a “particle-gun” generator, trapped by the MMT in simulations.

Further development of the energy loss processes, beyond the existing Geant4 ionisation model are likely to become necessary. Particularly, we require a more accurate description of monopoles with very low velocities.



(a) (b)

Figure 3: (a) Comparison of the acceptance regions of the MoEDAL MMTs and ATLAS over a Drell-Yan monopole production distribution (b) Fractions of monopoles, produced inside the MMTs geometric acceptance, stopped in the VELO cap and MMT array.



(a) (b)

(c) (d)

Figure 4: Visualisations of the geometry (a) before and (b) after inclusion of the new material description. Photos of the (c) VELO tank cap and (d) MMT array.

5. Summary

The full MoEDAL experiment will take data during Run-2 with the primary aim of observing magnetic monopoles. A simulation of the experiment is being developed inside the Gauss framework to accurately describe the detector and allow for the simulation of monopoles.

Work on all areas of the software is ongoing. Monopole production scenarios beyond the typical Drell-Yan process are being considered. The remaining material in the P8 cavern is being added to the simulation geometry. Simulation of monopole propagation is being developed, with a special focus on potential new energy loss process implementations.

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