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Searching for trapped magnetic monopoles in LHC accelerator material

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Abstract

We propose to analyse decommissioned parts of the LHC beam-pipe system at the ATLAS, CMS and LHCb/MoEDAL sites with a superconducting magnetometer (induction technique) to search for trapped magnetic monopoles. The MoEDAL experiment is proposed to serve as a formal platform for coordinating machining, scanning and analysis work, in collaboration with interested ATLAS, CMS and LHCb members. Motivation for searching for monopoles is as strong as ever by virtue of Dirac's electric charge quantisation argument and the fact that the LHC allows to probe new mass ranges in the laboratory. The induction technique has been successfully employed at the LHC with the dedicated MoEDAL trapping detector. Additional searches for trapped monopoles in beam-pipe material would access wide windows of magnetic charges and production cross sections to which other LHC experiments are insensitive. The decommissioned central beryllium beam-pipe sections of ATLAS and CMS, with a 4π coverage and exposure to the highest rates of 7 and 8 TeV pp collisions, are by far the most attractive samples to be analysed.

Contents

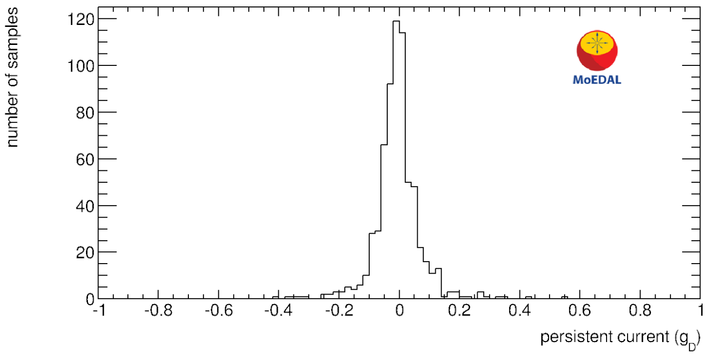

Figure 1: Magnetic charge (in units of the Dirac charge) measured in the forward MoEDAL trapping detector samples exposed to 13 TeV collisions in 2015 in their first passage through the magnetometer [16].

1 Introduction

The possible existence of magnetic monopoles remains an important open question in modern physics, tightly linked with electric charge quantisation and force unification [1, 2, 3, 4]. It follows from Dirac's argument that monopoles would carry a magnetic charge g equal to a *multiple* of a fundamental unit of magnetic charge referred to as the Dirac charge g_D: $g = n \cdot g_D$, where g_D is equivalent (in terms of energy loss for a relativistic particle) to 68.5 times the charge of the electron. The LHC has opened up a new discovery window in mass. Monopoles produced in high-energy pp and heavy-ion collisions would manifest themselves as stable very highly ionising particles which would range out to remain trapped in materials surrounding the interaction points [5].

The search for monopoles trapped in beam pipes provides the only way to discover high magnetic charges or high masses directly [5], while an indirect (and complementary) method for hints of particles which would not reach the sensitive parts of ATLAS and CMS would be through the monojet and monophoton signatures [6]. The most effective trapped monopole search technique is to pass exposed samples through the superconducting coil of a SQUID-based magnetometer and identify the signature of a persistent current. This so-called induction technique was employed for example at HERA [7] and at the Tevatron [8, 9] using obsolete exposed detector and accelerator material. Calibrations, tests and measurements performed since 2011 with two different DC-SQUID rock magnetometers at the ETH Laboratory for Natural Magnetism in Zurich with a variety of material samples – including samples which were exposed to high-energy collisions at the CMS and MoEDAL sites – demonstrate that all the conditions are met for performing efficient trapped monopole searches at the LHC [10, 11, 12, 16].

The work breakdown of this project comprises three main areas: (1) machining of accelerator parts into suitable samples, implying that the original parts are destroyed, and that an agreement needs to be made with the experiments; (2) transport and measurements at the Zurich magnetometer facility; and (3) simulations of monopoles in vacuum chambers and extraction of physics results. To carry out this work in the most efficient way we propose to make use of resources and expertise from the MoEDAL Collaboration.

1.1 Trapped monopoles at the LHC

If produced in LHC collisions, monopoles would quickly come to rest inside exposed material around the interaction points. They would generally be expected to remain trapped in the material owing to a high binding energy between monopoles and nuclei with non-zero magnetic

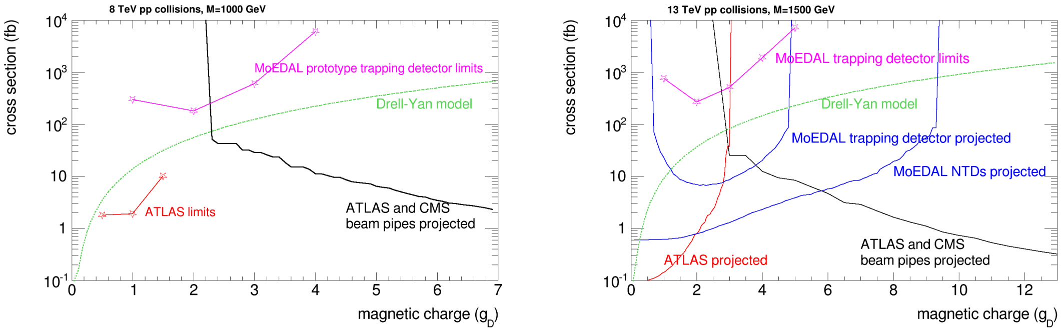

Figure 2: Projected cross sections for observing an average of 3 monopole events in existing data in a given LHC experiment as a function of magnetic charge, assuming a spin-1/2 Drell-Yan production mechanism, in 8 TeV pp collisions for $M = 1000$ GeV (left) and in 13 TeV pp collisions for $M = 1500$ GeV (right). Existing 95% confidence level limits from ATLAS and MoEDAL [15, 12, 16] are indicated as stars. The Drell-Yan cross section prediction is shown as a dashed curve, although it should not be taken at face value due to the non-perturbative nature of the process.

moments [13]. Since there are untested assumptions behind predictions of monopole binding to a given nucleus, it is preferable to use a variety of different materials in a search. The presence of a monopole in a sample can be unambiguously revealed using the induction technique [7, 8, 9, 10, 12, 16].

A successful collaboration was established with the Laboratory for Natural Magnetism at ETH Zurich, which possesses two DC-SQUID rock magnetometers suitable for monopole searches (the only ones available in Switzerland). In 2012, superconducting magnetometer tests and measurements with calibration coils and rock samples demonstrated that such a search is indeed feasible with the necessary magnetic charge resolution [10, 11]. The principle of using obsolete LHC accelerator material for such purposes was also demonstrated in a run where small parts of a plug-in module near the CMS interaction region were cut, transported to Zurich, and analysed with the magnetometer [10].

A dedicated aluminium absorbing array — the monopole trapping detector — was designed as a MoEDAL subdetector. A prototype was installed in the LHCb VELO cavern in 2012 and exposed to 0.75 fb^{-1} of 8 TeV pp collisions and analysed [12]. Following the success of this initial test, a full-scale MoEDAL trapping detector was deployed and exposed in 2015 and 2016. It consists of three arrays placed at approximately 1.5 m from the LHCb interaction point, each of 14 boxes stacked in two columns, with each box containing 48 samples of solid aluminium with dimensions $19\times2.5\times2.5$ cm^3 disposed in four rows, three columns and four layers in depth. Each of the three arrays totals 672 samples for 222 kg of aluminium. One of these array was analysed after 2015 exposure with the Zurich superconducting magnetometer during a two-week campaign. The measured magnetic charge in these samples is shown in Fig. 1. These pioneering runs demonstrate the effectiveness of the concept and probe magnetic charges higher than the fundamental Dirac charge (up to $n = 6$) for the first time at the LHC, setting the best constraints to date for $n \geq 2$ [12, 16], while the best limits for $n \leq 1.5$ were set by ATLAS [14, 15].

These results pave the way for searches for monopoles trapped in beam pipes exposed to 7 and 8 TeV collisions in run-1. Since a particle needs only to traverse vacuum before it reaches the beam pipe, this provides a probe of monopoles with high magnetic charges or low energies, which would not penetrate into detectors and could not be directly observed by experiments in any other way [7, 5]. Monopoles which carry a single Dirac charge will almost always punch through the pipe material, while a significant fraction of monopoles with $n = 4$ or higher will stop in the beam pipe [5].

experiment	$\mathcal{L}$ (fb^{-1})	type	material	length	distance	pseudorapidity	$\Delta\Omega$ (sr)
ATLAS	28.9	pipes	steel	8 m	±8 m	$5.3 < \lvert\eta\rvert < 6.4$	$5.6 \cdot 10^{-4}$
ATLAS	28.9	pipe	beryllium	6 m	0 m	$\lvert\eta\rvert < 5.3$	4π
CMS	29.4	rings	steel	2 cm	±1.5 m	$\lvert\eta\rvert \sim 4.3$	$1.1 \cdot 10^{-4}$
CMS	29.4	pipe	beryllium	6 m	0 m	$\lvert\eta\rvert < 5.3$	4π
LHCb	2.2	bellow	aluminium	40 cm	3 m	$\eta \sim 5.3$	$0.7 \cdot 10^{-4}$
LHCb	2.2	bellow	steel	1 m	13 m	$\eta \sim 6.5$	$4.1 \cdot 10^{-6}$
LHCb	2.2	pipe	beryllium	6 m	3.5 m	$6.1 < \eta < 6.8$	$0.4 \cdot 10^{-4}$

Table 1: Summary of relevant LHC accelerator components replaced after LS1 near the interaction points. The integrated luminosity corresponds to exposure to 7 and 8 TeV *pp* collisions. The distance is measured from the interaction point to the center of the considered section. The ATLAS and CMS beryllium pipes, kept as spares until now, offer the best sensitivity with a high integrated luminosity and full angular coverage.

Cross-section limits and expected sensitivities of various LHC experiments as a function of monopole charge using existing data with 8 and 13 TeV *pp* collisions are shown in Fig. 2. It is clearly visible in the figures that the various techniques are complementary: a combination of experiments which use active in-flight detection in ATLAS and CMS, passive in-flight detection and trapping in MoEDAL, and trapping in beam pipes is needed to thoroughly explore the whole range of possible magnetic charges. ATLAS and CMS are sensitive only to $n \leq 2$ due to the need to trigger with calorimeter signals [14, 5]. Even MoEDAL has a limited charge range due to the stopping of monopoles in the material of the VELO vacuum chamber. Therefore, searches in beam pipes are essential for the coverage of $n \geq 5$. Also in the ranges where the various experiments overlap, the use of complementary detection techniques which make very different assumptions (energy loss measurements and magnetic pole measurements after trapping) allows for an all-embracing investigation.

2 Requirements

2.1 Available material

Parts of the vacuum chambers near the ATLAS, CMS and LHCb and ALICE interaction points (IPs) were replaced during LHC long-shutdown 1 (LS1). These include aluminium beam pipes several meters long and several meters away from the ATLAS IP, rings a few cm long and about 1.5 m from the CMS IP, aluminium, steel and beryllium parts several meters from the LHCb IP, and beryllium central beam pipes right around the ATLAS and CMS IPs. There may also be parts near the ALICE IP, a priori less interesting because of the ~ 1000 times lower integrated luminosity for *pp* collisions. The characteristics of relevant samples identified by the authors are summarised in Table 1. The search sensitivity depends mainly on the angular coverage; in models of monopole production (although these models have large uncertainties), the vast majority of monopoles appear in the central regions ($|\eta| < 3$) [5].

As can be seen in the table, the CMS and ATLAS central beryllium pipes provide full coverage of the relevant angular range at the highest luminosities and are clearly the most interesting for a search (see also the black lines in Fig. 2). However, they are also the most precious components for the experiments. Replacements have been installed in 2013 and successfully operated in 2015 and 2016, so that the destructive analysis of the decommissioned pipes used in run-1 can now be envisaged. Among the other parts, despite the much smaller angular coverage, the CMS steel rings and the LHCb aluminium bellows are of interest because they are not too large and sit not too far from the IPs. For a relatively small extra effort, they will allow to test materials different from beryllium to which monopoles could possibly bind.

2.2 Machining

Handling beryllium and/or slightly radioactive material requires specific safety measures to be taken. Beryllium causes health hazards and CERN does not possess the facilities and expertise for the machining of beryllium components. We have identified the mechanical engineering shop at U. Alberta as a suitable place for shaping the beryllium beam pipes into samples of a size and shape suitable for magnetometer measurements. Sample dimensions must fulfil the requirements mentioned in Subsection 2.4 (less than 3.5 cm diameter and less than 20 cm long) and can be optimised for each component. Sample size reduction can be achieved using cutting and compressing techniques. The means of cutting must be chosen such as not to contaminate samples with ferromagnetic material which would impair the magnetometer resolution.

2.3 Transport

Our proposal is to ship the beam pipes whole to U. Alberta for machining, and then back to CERN in small packaged samples. The U. Alberta machine shop is already routinely receiving irradiated samples from CERN and the shipping request will be greatly facilitated if it is made as part of MoEDAL, a project which is recognised by the U. Alberta Physics department.

Then the samples will need to be sent from CERN to Zurich for magnetometer measurements, and back for storage at CERN (a measurement campaign takes of the order of a few days to a few weeks). This procedure was already followed by us using activated material near CMS [10], and to a lesser extent with the MoEDAL trapping detector near LHCb (whose radioactivity level was negligible) [12, 16]. In this case, the fact that the samples stay in Switzerland simplifies the tracking procedure.

2.4 Magnetometer measurements

A 2G Enterprises DC-SQUID rock magnetometer (model 755) installed at the Laboratory for Natural Magnetism at ETH Zurich was used to search for the signature of monopoles in various samples, including samples from the vicinity of the CMS and LHCb interaction points [10, 11, 17]. A DC-SQUID long-core magnetometer of similar type but with the convenience of a conveyor tray was recently installed and used for monopoles searches with the MoEDAL trapping detector [12, 16]. The magnetometer flux sensing system comprises two pick-up coils of radius 4 cm along the longitudinal z-axis of the magnetometer, which are coupled to a SQUID device. Samples are transported along the axis in the $+z$ direction through an access shaft with diameter $\sim$3.5 cm. The sensing region is surrounded by superconducting shielding. The access shaft size and mode of sample transport through the magnetometer set constraints on the sample shape and weight and on the measurement speed. With the new instrument, samples with diameter up to 3.5 cm, length up to 20 cm, and weight up to 500 g can be transported and measured at a rate of one sample every three minutes.

The relevant quantity measured by the magnetometer is the persistent current, defined as the difference between the SQUID output after and before passage of a sample through the sensing region. The persistent current is directly proportional to the magnetic charge contained in a sample, and a consistent non-zero persistent current for multiple passages is an unmistakable signature of a monopole. The calibration constant translating persistent current into magnetic charge (in units of g_D) is determined using either a convolution method with a sample of well-known dipole magnetic moment or a long thin solenoid that mimics a magnetic pole [10]. Samples for which the persistent current shows a significant deviation from zero in the first measurement are measured multiple time. The consistency of multiple measurements provides an unambiguous test of the presence of a genuine monopole.

The minimum magnetic charge that can be resolved depends on the intrinsic magnetisation of the samples, as magnetised samples are more likely to provoke flux jumps [10, 11, 12, 16]. Fig. 1 gives the resolution obtained with aluminium samples. A resolution well below the Dirac charge is achieved even with highly-magnetised samples after demagnetisation or crushing [10, 11].

2.5 Simulations

Monopole generation and simulation using frameworks such as MadGraph, Pythia and Geant4 will be performed to estimate monopole trapping acceptances for various accelerator parts in various physics scenarios (the main parameters being the particle mass and magnetic charge). Special care and effort needs to be invested into implementing an accurate geometry description of the vacuum chambers and understanding the behaviour of monopoles in the strong magnetic fields of ATLAS and CMS, especially while stopping. Acceleration along magnetic fields can affect the acceptance only for monopoles with very high charges and kinetic energies below 100 GeV [5].

3 Structure

3.1 Work breakdown

The authors of this proposal will coordinate the search team, in collaboration with MoEDAL. Several of us have been at the forefront of a variety of standalone monopole search experiments of the same ilk as what is proposed here [18, 19, 7, 11, 12, 16].

The approach to the Collaborations for use of their discarded beam pipes should be made by the Spokesperson of MoEDAL partnered by P. Mermod in the case of ATLAS and A. De Roeck in the case of CMS.

Material transport, sample machining, and magnetometer run campaigns will be organised by the authors. Shifters for the magnetometer runs will be recruited from the pool of MoEDAL collaborators.

The analysis team will take advantage of existing MoEDAL software infrastructure to perform the necessary simulation work. It will also ensure that the results are assessed, interpreted and summarised in publications.

3.2 Formal approval of physics results and authorship

Internal review and approval of the results would then be the responsibility of the MoEDAL collaboration.

Interested members of ATLAS and CMS will be invited to join the MoEDAL author list of the paper resulting from the search for monopoles trapped in the ATLAS and CMS beam pipes as long as they made a definite contribution to the analysis.

In the case of a discovery, MoEDAL would offer to publish a joint discovery paper with ATLAS and CMS. However, if one or both of these collaborations decides not to join the discovery publication it will go ahead anyway – providing that publication is approved by MoEDAL and, of course, the CERN physics division.

3.3 Budget and manpower

Costs to process, analyse and dispose of analysed beam-pipe elements will be born by the MoEDAL Collaboration.

The cost of cutting beryllium beam pipes is non-negligible due to the need for special safety procedures to mitigate poisoning hazards. A cost estimate for cutting a beryllium beam pipe — based on precedent at the Tevatron [9] — amounts to $\mathcal{O}$ 50000 CHF. As a part of a grant from the Swiss National Science Foundation obtained by P. Mermod, a budget of 60000 CHF is allocated to the present project, to be used for covering machining costs as well as costs related to transport and magnetometer measurements.

The authors of this document and members of the MoEDAL collaboration will make appropriate contributions to this work and will have access to students and postdocs for performing magnetometer measurements, simulations, and data analysis.

3.4 Timeline

Access to the central beryllium beam pipes of the ATLAS and CMS experiments as well as rings and bellows from CMS and LHCb is desired by Summer 2017. These parts will be destroyed as they are machined into monopole search samples. These will be analysed with the magnetometer during a $1-2$ week run campaign in Zurich. Provided that the samples can be cut during Summer 2017 and scanned during the Fall, results can be obtained by the end of 2017, probing high-charged monopoles in 7 and 8 TeV *pp* collisions for the first time, as shown in Fig. 2 (left panel, black line). Searches with the induction technique have the advantage to be simple and provide results very quickly, as exemplified by the MoEDAL trapping detector results which probed monopoles for the first time in 13 TeV collisions [16].

4 Summary

Searches for trapped magnetic monopoles in beam pipes are essential to ensure full coverage of the parameter space. We outline a work plan to exploit fully the potential for searches for monopole produced in LHC run-1. This project is proposed to become a part of the MoEDAL experiment since the MoEDAL collaboration possesses the required infrastructure and expertise for the machining, scanning and analysis work to be performed. On the basis of this document, the authors hope to reach an agreement to access and shape the obsolete beryllium beam pipes of ATLAS and CMS, to be formalised in an MoU between the involved collaborations.

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