MoEDAL-MAPP – Detectors specialised in LLP searches

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MoEDAL – Monopole & Exotics Detector At LHC

Optimised for anomalously ionising (meta)stable particles

LHC’s first dedicated search experiment
(approved 2010)
MoEDAL physics goals

• MoEDAL baseline detector optimised for the detection of (meta)stable highly ionising particles
  ▫ high charges (high $z$)
    – magnetic $\rightarrow$ monopoles!
    – electric $\rightarrow$ Highly Electrically Charged particles (HECOs)
  ▫ slow moving (low $\beta$) $\Rightarrow$ massive

• MAPP upgrade designed for minimally ionising particles

MoEDAL physics program
Baseline MoEDAL detector

- Mostly **passive detectors**; no trigger; no readout
- Permanent physical record of new physics
- No SM physics backgrounds

DETECTOR SYSTEMS

1. Nuclear Track Detectors (**NTD**)  
2. Monopole Trapping detector (**MMT**) – aluminum bars  
3. **TimePix** radiation background monitor
Magnetic monopole limits

- Novelties in models: $\beta$-dependent coupling, spin-1 monopoles, $\gamma\gamma$ fusion
- MoEDAL set world-best collider limits for $|g| > 2g_D$
- Overall, MoEDAL achieved extended reach by combining Drell-Yan and $\gamma$-fusion mechanisms


Monopoles via thermal Schwinger mechanism

- First limits based on non-perturbative calculation of monopole production cross section
- First direct search sensitive to finite-size monopoles

Monopole-antimonopole pairs may be produced in strong magnetic fields present in heavy-ion collisions

Limits on monopoles of $1 - 3 \, g_D$ and masses up to 75 GeV

MoEDAL, *Nature 602 (2022) 7895, 63-67*
High Electric Charge Objects (HECOs)

- First NTD analysis for MoEDAL
- Prototype NTD array of 125 stacks (7.8 m²) in Run-1
- NTDs etched and scanned

No HIP candidates found in the NTDs stacks

HECOs results

- Limits on HECOs with electric charges in the range $15e - 175e$ and masses from $110 - 1020$ GeV
- Upper limits on production cross section $\sim 30 - 70$ pb
- Better sensitivity expected in ongoing Run 2 analysis
  - higher c.m.s. energy: 13 TeV
  - larger integrated luminosity
  - larger exposed NTD surface
  - lower CR39 $Z/\beta$ threshold than Macrofol

MoEDAL HECOs limits are the strongest to date, in terms of charge, at any collider experiment

Non-perturbativity of large coupling can be tackled by appropriate resummation [Alexandre, Mavromatos, Musumeci, VAM]
"Low" electric charges

- Supersymmetric singly charged LLPs: sleptons, R-hadrons, charginos
- Generic multiply charged particles
- Also, models of $\nu$ masses $\rightarrow$ 2-, 3-, 4-ply charged [Hirsch et al, EPJC 81 (2021) 697]

MoEDAL has the best sensitivity at intermediate electric charges at HL-LHC
Upgraded MoEDAL installed for Run-3

- Upgrades to Run-2 MoEDAL
- Completed in March 2023

- Forward MMT box reconfigured
- VELO-top NTD array installed
- NTD stacks point to IP
- TimePix3 chips connected to LHC clock
MAPP – MoEDAL Apparatus for Penetrating Particles

**MAPP-mQP:** sensitive to low ionisation induced by *millicharged* particles (mCPs), i.e. particles with charges $\ll 1e$

**MAPP-LLP:** sensitive to very long-lived weakly interacting neutral particles through visible decay products $\rightarrow$ displaced vertices

- **Phase-1 approved by CERN Research Board** in 2021
- **Phase-1 for Run-3 (2022–2025):** MAPP-mQP installation in UA83 is underway
- **Phase-2 HL-LHC (2029 –):** Reinstall Phase-1 in UA83 and add MAPP-LLP in UGC1


Talk by [Hualin Mei](http://www.physixel.com/JLP_MAPP/MAPP_FlyOver1.mp4) in BSM2 FIPs session

MAPP location(s)

- MAPP-1 mQP UA83
- MAPP-2 LLP UGC1

- At forward region w.r.t. beam axis
- Protected by ~100 m of rock overburden
MAPP-mQP Phase-1 detector concept

- 400 scintillator bars (10×10×75 cm³) in 4 sections readout by PMTs
- Protected by a hermetic VETO counter system

Prototype mQP in 2017 in UGC1 gallery
MAPP-mQP Phase-1 installation

- Next installation period during Technical Stop in June 2023
- Data taking expected to start in July 2023
Millicharged particles

- mCP generated by massless dark photon, kinetically mixed with SM, that couples to millicharged $\chi$
- Production through meson decays also possible
  - only Drell-Yan production shown here
- MAPP sensitive to heavy neutrino with large electric dipole moment, experimentally similar to mCP [Frank et al, Phys.Lett.B 802 (2020) 135204]
- Millicharged strongly interacting DM (mSIDM)
  - mCPs can account for a fraction of DM abundance
  - can escape from underground direct-detection detectors
  - MAPP mCP results can be recasted to mSIDM

MoEDAL contribution to Snowmass, arXiv:2209.03988

Talk by Hualin Mei in BSM2 FIPs session
Phase-2: MAPP-2 upgrade for HL-LHC

- The UGC1 gallery will be prepared during Long Shutdown 3 prior to HL-LHC
- MAPP-2 detector extends to the full length of the UGC1 gallery
- Detector technology: large scintillator tiles with optical fibre readout
- Tracking detectors formed by 3 or 4 hermetic containers – one within the other – lining UGC1 walls
MAPP-LLP – dark matter & heavy neutrinos

Dark Higgs scenario

Dark Higgs $\phi$ mixes with SM $H^0$ (mixing angle $\theta \ll 1$), leading to exotic $B \rightarrow X_s \phi$ decays with $\phi \rightarrow \ell^+\ell^-$

MoEDAL contribution to Snowmass, arXiv:2209.03988

Heavy neutrino via $Z'$ production

Pair production of RH neutrinos from the decay of a $Z'$ boson in the gauged $B-L$ model
Summary & outlook

- **Exciting results by MoEDAL**
  - sole contender in **high magnetic charges**
  - sole **dyon** search in accelerator experiment
  - first search for monopoles produced via **Schwinger mechanism**
  - entered the arena of **electrically charged particles**

- **Upcoming results**
  - CMS beam pipe analysis → constrain very high magnetic charges
  - Second NTD analysis → improved sensitivity to electric charges

- **Future perspectives**
  - MoEDAL baseline redeployed for **Run-3** with improved geometry
    - planned to operate during **HL-LHC**
  - MAPP will extend reach to **millicharged** particles and **neutral long-lived particles**
    - Phase-1 MAPP installation ongoing
    - expected to start data-taking in 2023

MoEDAL web page:
https://moedal.web.cern.ch/
Spares
Results

• 2016 – First monopole results @ 8 TeV ☛ CERN Press Release

• 2017 – First monopole results @ 13 TeV

• 2018 – MMT results
  ▫ spin-1 monopoles ← FIRST in colliders
  ▫ β-dependent coupling

• 2019 – MMT results
  ▫ photon fusion interpretation ← FIRST at LHC

• 2020 – MMT search for Dyons ← FIRST in colliders

• 2021 – Schwinger thermal production ← FIRST
  Nature 602 (2022) 7895, 63 [arXiv:2106.11933]

• 2021 – NTD & MMT ← FIRST NTD analysis [arXiv:2112.05806]
  ▫ First limits in highly electrically charged objects
# LHC & High Luminosity LHC (HL-LHC)

## LHC / HL-LHC Plan

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4 - 5...</th>
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<tr>
<td>LS1</td>
<td>EYETS</td>
<td>LS2</td>
<td>EYETS</td>
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**LHC Plan**
- **LS1**
  - splice consolidation button collimators R2E project
- **EYETS**
  - cryolimit interaction regions
- **LS2**
  - Diodes Consolidation L1U Installation
  - Civil Eng. P1-P5
  - ATLAS - CMS upgrade phase 1
  - ALICE - LHCb upgrade
  - 2 x nominal Lumi
- **EYETS**
  - pilot beam
- **LS3**
  - HL-LHC installation
  - ATLAS - CMS HL upgrade
  - 2 x nominal Lumi
  - 450 fb^{-1}

**HL-LHC Technical Equipment**
- Integrated luminosity: 3000 fb^{-1}
- 4000 fb^{-1}
- 5 to 7.5 x nominal Lumi

**HL-LHC Civil Engineering**
- Definition
- Excavation
- Buildings

**LHC Technical Equipment**
- Design Study
- Prototypes
- Construction
- Installation & Comm.
- Physics
Run-2 NTD deployment

Low-threshold NTD
NTDs sheets kept in boxes mounted onto cavern walls

Low-threshold NTD
• Top of VELO cover
• Closest possible location to IP

HCC-NTD
Installed in LHCb acceptance between RICH1 and Trigger Tracker
MMTs deployment

2012
11 boxes each containing 18 Al rods of 60 cm length and 2.54 cm diameter (160 kg)

2015-2018
- Installed in forward region under beam pipe & in sides A & C
- Approximately 800 kg of aluminium
- Total 2400 aluminum bars
**MMT scanning**

- Monopoles can bind to nuclei and get trapped
- MMTs analysed in superconducting quantum interference device (SQUID) at ETH Zurich
- **Persistent current**: difference between resulting current after and before
- Outliers are **scanned several times** further

**Calibration:**
Typical sample & pseudo-monopole curves

**SQUID analysis** – Persistent current after first two passages for all samples

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*MoEDAL, PRL 123 (2019) 021802*
Magnetic monopoles in a nutshell

- Why? Because they symmetrise Maxwell’s equations
  - electric ↔ magnetic charge duality
- Single magnetic charge (Dirac charge): \( g_D = 68.5e \)
  - higher charges are integer multiples of Dirac charge:
    \( g = ng_D, \quad n = 1, 2, ... \)
  - if carries electric charge as well, is called Dyon
- Photon-monopole coupling constant
  - large: \( \frac{g}{\hbar c} \sim 20 \) (precise value depends on units)
- Dirac monopole is a point-like particle; GUT monopoles are extended objects
  - production of composite monopoles exponentially suppressed by \( e^{-4/\alpha} \)
- Monopole spin & mass is not determined by theory → free parameters

Dyons: electric & magnetic charge

- MMT scanning searching for captured dyons
- Mass limits 750-1910 GeV set for dyons with
  - up to 5 Dirac magnetic charges (5g_D)
  - electric charge 1e – 200e
- Excluded cross sections as low as 30 fb
- Previous searches for highly ionising particles would, in principle, also have sensitivity to dyons
  - caution on behaviour under magnetic field

First explicit accelerator search for direct dyon production!

Monopoles in Schwinger mechanism – Future

- Run-1 CMS beam pipe analysis in heavy-ion run
- HL-LHC projection for MoEDAL’s MMTs
  - Conservative theoretical assumptions
  - Nuclear track detectors not included in projection
  - Assuming 2.5 nb⁻¹ Pb-Pb collisions at $\sqrt{s_{NN}} = 5.52$ TeV

Opportunities for new physics searches with heavy ions at colliders, Snowmass 2021 white paper, arXiv:2203.05939

For FCC : $\sqrt{s_{NN}} \sim 40$ TeV
\[ \Rightarrow M \gtrsim 600 \text{ GeV} \]

Theoretical improvements in semiclassical and fully classical approaches
CMS beam pipe

Beam pipe
- most directly exposed piece of material
- covers very high magnetic charges

- **1990’s**: materials from CDF, D0 (Tevatron) and H1 (HERA) subject to SQUID scans for trapped monopoles
- **2012**: first pieces of CMS beam pipe tested [EPJC72 (2012) 2212]; far from collision point
- **Feb 2019**: CMS officially transfers ownership of the Run-1 CMS beam pipe to MoEDAL

- Beam pipe scanned with SQUID at ETH Zurich
- Analysis for Pb-Pb collision data ongoing
- Results to be released soon
Multiply charged quasi-stable particles

- Highly Electrically Charged Objects (HECOs) predicted in many scenarios of physics beyond the SM
  - finite-sized objects (Q-balls)
  - condensed states (strangelets)
  - microscopic black holes (through their remnants)
  - ...
- They eventually decay into other particles
- Detected by **high ionisation**
NTD results on HECOs

- Drell-Yan production
  - $Z$ exchange is also taken into account for fermions [Song & Taylor, J.Phys.G 49 (2022) 045002]
  - non-perturbativity of large coupling can be tackled by appropriate resummation [Alexandre, Mavromatos, Musumeci, VAM, in progress]

- Limits set on HECO pair production with cross section $\sim 30 – 70$ pb

MoEDAL, EPJC 82 (2022) 694
Hidden sector – Feebly Interacting Particles (FIPs)

**Dark vectors ("Dark Photons")**
- adding U(1) gauge group to SM, kinetic mixing with γ/Z
- light neutral meson decays, millicharged particles

**Dark scalars ("Dark Higgs")**
- neutral singlet scalers that couple to the SM Higgs field
- produced in penguin decays of K, D, B mesons

**Heavy neutral leptons ("sterile neutrinos")**
- explain SM ν masses (seesaw), DM, BAU
- weak semi-leptonic decays of hadrons, W, Z

**Axion-like particles ("ALPs")**
- solution of the strong CP problem
- generalisation of the axion model in MeV-GeV mass range

For a review on LLP experiments, see: VAM, MG16 procs.

arXiv:2111.03036
Different angle w.r.t. beam axis, detector volume and distance from IP probe different range of lifetime, coupling to SM and boost (mass)
The MAPP-1 Outrigger Detector

- To increase the acceptance of MAPP-1 at higher mass & larger fractional charge
- Size of the scintillator “planks” $6 \times 0.6 \times 5$ cm, inclined at 45 deg.
- Covers from $\sim 1.7 - 5.3$ deg.
R-parity violating supersymmetry

If RPV coupling, $\lambda$, $\lambda'$, $\lambda''$ small enough, the (N)LSP may be long lived

\[ \tilde{\chi}_1^0 \rightarrow \text{charged} \]

Dreiner, Günther, Wang,
PRD 103 (2021) 075013
mCPs – Heavy neutrino with large EDM

Limits that MAPP can place on heavy neutrino production with large EDM at Run-3 and HL-LHC at IP8

Axion-like particles (ALPs)

- ALPs produced via rare decays of $\pi$ and $\eta$ mesons
- Light ALPs with mass of $10$ MeV – $1$ GeV with suppressed couplings can be long lived
- They can be detected in MAPP-LLP