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Activities of the AIDA project Task 8.5.2 revolved around construction and performance tests of a Totally Active Scintillation Detector (TASD) prototype and a Magnetized Iron Neutrino Detector prototype (MIND). The TASD has been operational at the MICE test beam at the Rutherford Appleton Laboratory in Oxfordshire (UK) since October 2013. A complete redesign of the MIND magnet was proposed in order to extend the reach of high charge identification efficiencies for muons below 1 GeV/c. The motivation and status of the magnet redesign are presented, along with selection and procurement of MIND detector module components.
MIND redesign justification and status for deliverable D8.11

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1. Introduction

Activities in the AIDA Task 8.5.2 concern the design and characterisation of a Magnetised Iron Neutrino Detector (MIND) prototype and a Totally Active Scintillator Detector (TASD) prototype to be installed and tested at CERN. The TASD prototype was constructed at the University of Geneva and installed at the MICE facility at the Rutherford Appleton Laboratory for testing, since there were no CERN test beams during 2013 and 2014. The TASD part of milestone MS33 was delivered February 2014.

The AIDA Milestone MS33 was to report on the performance of the MIND in January 2014. But for reasons outlined here, that report was not filed. Instead, a complete redesign of the MIND magnet was carried out. Following the publication of Daya Bay measurements of $\theta_{13}$ in March 2012, it was quickly realised that the original MIND prototype foreseen for the AIDA project was no longer relevant to future neutrino studies. Rather than committing resources to a detector with no future, the AIDA management and steering group chose to go through a redesign phase, affecting the magnet and electronics readout chain. The goal for the MIND prototyping was redefined towards a new design of the magnet, and selection,
procurement and testing of detector elements. The new design is reported in this document, while AIDA Deliverable D8.11 will show preliminary results and measurements of the main components of the revised MIND prototype.

2. Relevance and Design of MIND

Measurements of $\theta_{13}$, one of three mixing angles describing neutrino oscillations, were reported in March 2012 by the Daya Bay collaboration. Assigning a value to this significant parameter in neutrino physics has triggered a re-evaluation of most of the planned future large-scale neutrino facilities. The publication of these results occurred once the AIDA project was underway. We had initially envisaged a relatively straightforward design for the MIND, a prototype for the much larger MIND of a Neutrino Factory, based on previous operational MINDs such as MINOS, and optimised for good muon charge ID efficiencies at muon momenta above 1 GeV/c. The case for a Neutrino Factory has weakened due to the large value of $\theta_{13}$, which opens up possibilities for measurements of mass hierarchy and CP violation in the leptonic sector with other neutrino sources and detectors. During the course of the AIDA project, the importance of water cherenkov (SK, HK, ESS), liquid scintillator and liquid argon detectors (LBNE, LBNO) for future neutrino facilities was re-affirmed. These large-scale detectors are not magnetized and charge identification of outgoing leptons from the interaction vertices of neutrinos contributes to systematic errors. Recently, several studies have been launched to explore how a MIND downstream of a water cherekov (TITUS-HK) or LAr (LBNO) could reduce systematic errors by providing muon charge ID.

With this rapidly changing landscape in neutrino physics over the course of the AIDA project, the community, in agreement with AIDA management, chose to re-assess its original goals, setting requirements to extend the optimisation of charge ID efficiencies below 1 GeV/c. As will be detailed in the following sections, we re-designed the magnet, and brought changes to the electronics and detector elements.

3. Magnet Design

Magnetised Iron Neutrino Detectors are typically built from plates of iron interleaved with detector planes, with regular and identical spacings between iron plates. The main limitation for charge identification comes from multiple scattering of the muon within the iron, which worsens the angular resolution for muons below 1 GeV/c. The motivation for improving muon charge ID efficiencies below 1 GeV/c comes from applications at existing neutrino beamlines such as T2K, where the off-axis oscillation peak occurs for $\nu_e$ around 600 MeV and lower for $\nu_{\mu}$. With respect to traditional MIND designs, we propose:

a) Larger gaps between the first 3 iron plates: We have adopted a design where the gap between the first and second iron plates is 30 cm, i.e. much larger than typical. The gap between the second and third iron plates is 10 cm, also larger than the typical 3-5 cm. With these larger gaps between the first 3 iron plates, the transverse displacement
on a given detector plane is greater, leading to increased angular resolution and therefore better charge ID efficiencies, Figure 1.

b) **Modular approach to the magnetization scheme:** Traditional designs for the magnet adopt conductor ducts threading through all iron plates, with several turns of the conductor coil, Figure 2. This approach turns out to be very inefficient for our application, since the effective permeability of the volume to be magnetized, which contains iron and the air gaps, is low. We collaborated with a team at CERN with extensive experience in magnets and designed a magnet where every individual iron plate has its own coil windings, Figure 3. Because the power supply requirements are relatively modest, air-cooling of the coil is sufficient. The absence of a water cooling channel leads to much smaller coil cross-sections, thicknesses of 1-5 mm, so multiple scattering due to the coil material is negligible.

The magnetization scheme enables MINDs with much larger acceptances, by covering the sides of vertexing detectors, as well as their downstream areas.

![MIND Detector modules](image)

Figure 1: Variable gaps in the MIND between iron plates in the first few layers, to increase charge ID efficiencies for lower momentum muons. With the magnetization scheme proposed here, where each iron plate has its own coil windings, it is possible to envisage instrumenting the sides of a vertexing detector with MINDs.
4. Detector Module Design

A custom design of plastic scintillator bars, wavelength shifting (WLS) optical fibers and optical connectors was completed. In order to validate the design, we performed extensive measurements of the most critical components. This section on detector module design reports on:

1. plastic scintillator geometry,
2. choice of WLS fiber,
3. choice of optical glue,
4. custom optical connectors design,
5. module support frame design,
6. module assembly,
7. choice of silicon photomultipliers.
Having tested extensively the light yield from several thicknesses of scintillator, we decided to go for 1 cm bars, with a length of 90 cm and depth of 0.7 cm. Light yields for 1, 2 and 3 cm-wide bars readout from both ends were measured to be 83, 61 and 58 photo-electrons respectively. We compared different WLS fibers, observing that the light yield with our choice of fiber supplied by Kuraray was 36% higher than an alternative supplied by St. Gobain. Tests of light transmission efficiencies were carried out for different optical glues (Bicron BC600, Eljen EJ500, Aqua E30) required to embed the WLS fiber into the scintillator bar. They all show light transmission efficiencies close to 90% for wavelengths between 400 and 600 nm. We selected Eljen EJ500 due to lower costs, straightforward shipping and better handling characteristics during assembly compared with Bicron BC600.

Custom optical connectors were designed to couple the silicon photomultipliers as efficiently as possible, limiting light losses between these and the ends of the WLS fibers, Figure 4. During the design phase, several iterations were made, with prototypes produced through 3D lithography before the final injection-moulded production runs were launched. In total 8400 scintillator bars have been produced at the Institute for Nuclear Research in Russia.

![Figure 4](image.png)

*Figure 4: a) Custom optical connector designed for the AIDA MIND. b) Photo showing the end of an AIDA scintillator bar equipped with a black connector designed to guide and center the WLS fiber end with respect to the photo-sensor sensitive surface housed in the matching connector (not shown).*

Light emission from the WLS fiber was measured to determine requirements for the surface area of the silicon photomultiplier and also assess requirements on the coupling quality between WLS fiber and photo-sensor. The measurement was performed with a digital silicon photomultiplier, with results showing light emission from the WLS fiber over an area of $1.22 \times 1.27$ mm$^2$, Figure 5. The high intensity area with counts above the dark count level of the digital SiPM is roughly $1.00 \times 1.02$ mm$^2$. This information is crucial when choosing between $1.00 \times 1.00$ mm$^2$ and $1.3 \times 1.3$ mm$^2$ photo-sensors, given the factor $\times 1.5$ higher cost of the
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second option.

Figure 5:  a) Mapping of the light emission from the WLS fiber embedded in the scintillator bar. b) Philips digital SiPM used in dark count mode to measure the light emission at CERN.

The detector module design integrates the individual scintillator bars into one assembly that also includes support mechanics for the electronics, Figures 6-7. An assembly procedure was established to mount the individual plastic scintillator bars onto detector modules, Figure 8.

Figure 6: CAD drawing of the AIDA MIND detector module, showing single-ended readout for each of two planes, one of which can be seen here. The plane beneath is perpendicular to the visible plane.
Figure 7: Main elements of the detector modules. Not shown here are the cabling to/from the electronics cards and to/from the silicon photomultipliers.
The selection of silicon photomultipliers was carried out in two steps:

1) Comparison of devices from different manufacturers and selection of a manufacturer.
2) Evaluation of different variants from the chosen manufacturer.

We tested devices from Advansid, Ketek, Hamamatsu and SensL. It should be mentioned that the field of photo-sensor development based on silicon photomultipliers is in rapid expansion, with manufacturers regularly announcing new and improved processes. At the time the measurements were made, the Hamamatsu devices exhibited the best combination of PDE, pulse shape and peak separation. Hamamatsu supplied over 50'000 photo-sensors (Multi-Pixel Photon Counter - MPPC - in Hamamatsu terminology) for the T2K ND280 detector, with excellent feedback from their use, which provides further confidence in long term reliability.

Five variants of the MPPC were further tested before the final selection was made. The new generation "Low Afterpulse" devices with/without "Low CrossTalk (LCT)" in two different geometries ($1.0 \times 1.0 \text{ mm}^2$ and $1.3 \times 1.3 \text{ mm}^2$), and two different cell sizes (25 and 50 microns) were compared to the older generation S10363-050C. Measured light yields were 5% higher for the $1.3 \times 1.3 \text{ mm}^2$ devices compared to the $1.0 \times 1.0 \text{ mm}^2$ devices of the same generation, consistent with the mapping of light emission from the WLS fiber reported earlier. We therefore opted for the $1.0 \times 1.0 \text{ mm}^2$ devices, given their lower cost, with the assumption that good alignment within $\pm 100 \mu\text{m}$ could be guaranteed by the optical connector.

Over the testing period 2013/2014, there was a jump in LCT generations from LCT2 to LCT4. Although we obtained some LCT4 test devices, uncertainties in the availability and lead times for large quantities led us to choose a new generation device without LCT features, the
S12571-025C, of which we purchased 3000. Tests carried out at the INR showed high light yields for this device, 58.5 photo-electrons/MIP compared to 50 photo-electrons/MIP for the older generation S10363-050C, later confirmed at CERN with the CITIROC readout chain described in the next section.

5. Electronics

The initial proposal for this AIDA Task 8.5.2 was to assemble an electronic readout system based on the Trip-t readout chip designed over a decade ago at Fermilab for the Tevatron D0 experiment, and used to readout scintillator bars of the T2K ND280 detector. Limitations with the architecture of the Trip-t chip and uncertainties about the availability of back-end components led us to study recently developed alternatives, the DRS4 chip and the EASIROC/CITIROC family of chips. The latter was chosen due to the relatively high cost, 50 CHF/channel, of the DRS4 chip. We therefore embarked on an additional development of a new readout chain with requirements for additional resources, but with much brighter prospects for compatibility with future sensors.

The schematic layout for the electronics front-end board (FEB) is shown in Figure 9. Each 84-channel scintillator plane is readout by one FEB equipped with three EASIROC\(^1\) (or CITIROC) readout chips, Figure 10.

We installed two separate readout chains at CERN to compare the EASIROC and CITIROC chips, using prototype readout boards supplied by OMEGA microelectronics of the French IN2P3, Figure 11. Results of these tests are detailed in the Deliverable D8.11 report.

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1 These chips are based on a larger family of chips designed and developed in the AIDA WP9 for the read-out of calorimeters.
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Figure 9: *AIDA Baby-MIND* electronics front-end board architecture.

Figure 10: Front-end board layout with the three readout chips (*EASIROC/CITIROC*) mounted along the lower edge, close to the SiPM co-axial inputs.
6. Conclusion

A complete redesign of the MIND was carried out within Task 8.5.2, compared to the original AIDA proposal, which had been rendered less relevant for future facilities due to a significant shift in the neutrino physics landscape in 2012.

With decisive inputs from magnet experts at CERN, a new magnet design was proposed, based on individually coiled iron plates and the possibility to tune gaps between plates. This enables further optimisation of the detector beyond the reach of more traditional MIND detectors, with high charge reconstruction efficiencies for low energy muons well below 1 GeV/c.

Resources allocated in AIDA have been used to finalize the new design of the magnet and carry out the procurement and testing of detector elements, with additional external resources. Experience gained in the construction of the TASD detector was very valuable in designing and constructing detector elements for the MIND. In particular silicon photomultipliers were adopted instead of PMTs, optical connector design was improved, and assembly procedures were simplified.

AIDA MIND R&D reported in this document is leading to the construction of a MIND prototype to be fully characterized at a beamline at CERN in 2016. Experience and results from these tests are expected to confirm its potential usefulness downstream of the water and carbon targets of the Wagasci detector on the operational neutrino beamline of the T2K experiment. Preliminary estimations show MIND charge reconstruction efficiencies of 94% in the T2K oscillation region. This additional positive outlook was not originally foreseen in the AIDA project.

Figure 11: a) EASIROC prototype board, and b) readout of a scintillator bar equipped with photo-sensors on both ends.