

The XMASS 800kg Dark Matter Detector in Kamioka, Japan

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Abstract: XMASS 800kg is a single phase liquid xenon scintillation light detector. The total liquid xenon mass read out by its photomultipliers is 835 kg. It is shielded against neutrons by a 10 m diameter, active muon-veto, water Cherenkov detector in its underground location at the Kamioka Observatory in Japan. We discuss the design and calibration of our detector as well as improvements being made in its current refurbishment. A brief outlook on the future of the XMASS experimental program is also included.

Keywords: dark matter, xenon, Xe, Kamioka, XMASS, experiment, detector

1 Introduction

The XMASS experimental program has several stages. Using liquid xenon (LXe) in a single phase scintillation detector of approximately spherical shape it aims at the detection of Dark Matter (DM) and in later stages also solar neutrinos (pp and ⁷Be) as well as neutrinoless double-beta decay.

LXe recommends itself as a detector medium by its large scintillation yield and an absence of long-lived radioactive isotopes. Its high atomic number allows the construction of self-shielding detectors like XMASS. The original idea for this experiment was presented in [1].

With a total mass of 835 kg of LXe inside its instrumented volume the current XMASS 800kg detector is aiming to detect Dark Matter down to cross sections below 10^{-44} cm² for a 100 GeV WIMP in the innermost (shielded) 100kg of LXe. Active planning has started for a next DM phase of the experiment with a total LXe mass of 5 tons, out of which 1 ton would be the shielded fiducial volume. In the final stage we envision a 20 ton (10 ton fiducial) volume detector to cover the whole experimental program indicated above.

Here we report on the design and current refurbishment effort for the 800kg detector. Results from its commissioning phase [2] [3] will be presented in a separate contribution at this conference.

2 Detector Design

The idea of a self-shielding inner volume in the detector suggest a spherical design. In XMASS this is approximated by a pentakis-dodecahedral shape for the inner LXe volume. The inner surface of the active detector volume therefore consists of isosceles triangles. Scintillation light from this active inner volume is detected by 642 inward looking Hamamatsu R10789-11 photomultiplier tubes (PMTs). 630 of these PMTs have a hexagonal shape; to achieve optimal photocathode coverage on the inner surface 12 PMTs were modified to have a smaller, round entrance window. These round PMTs each sit at the center of one of the twelve pentagons that constitute the fundamental dodecahedron. Each of the pentagons consists of five isosceles triangles. Figure 1 shows the schematic of the XMASS inner detector (ID) and its two containment vessels that hold the LXe and provide thermal insulation.

The PMTs in the ID are supported by an OFHC copper structure that delimits the active volume of the inner detector. More than 62% of the ID surface is covered by their photocathodes. The quantum efficiency of the ID PMTs at the Xe scintillation wavelength (≈ 175 nm) is 28%.

At the current stage XMASS contains a total mass of 835 kg of LXe in the ID, which has a radius of roughly 40 cm. If the outer 20 cm of that LXe volume are used as a gamma ray shield for the inner 20 cm of the ID, this inner 20 cm volume contains a fiducial mass of 100 kg that is well shielded against external gamma rays with energies in the range of DM nuclear recoils.

The LXe that the ID is immersed in is held in an inner OFHC copper vessel. OFHC copper “fillers” are used inside this inner vessel around the PMT holder structure to reduce the volume of LXe needed in the experiment. The inner vessel is housed in an outer vessel also made from OFHC copper. The space between inner and outer vessel is evacuated for thermal insulation. The whole assembly is suspended at the center of a water Cherenkov counter, the outer detector (OD).

2.1 Location and Outer Detector

The detector is located underground at the Kamioka Observatory in Japan, where the overburden is 2700 mwe. A new experimental hall was excavated for the experiment. It is lined with radon retardant and supplied with outside air to minimize the radon intake of the experiment.

The water Cherenkov OD also shields the experiment from fast neutrons as well as external gamma rays and is used to veto muon induced activity. The experiment is located at the center of its free-standing, cylindrical, 10.5 m high and 10 m diameter stainless steel water tank. Muon induced Cherenkov light emitted in the ultra-pure water circulated through that tank is detected by 72 Hamamatsu 20-inch PMTs (R3600), the same as used in Super-Kamiokande (SK). Especially prepared radon-free air is supplied to the air volume above the water in the tank, and the ultra-pure water is constantly recirculated through a dedicated water purification system.

The combination of these measures alone reduces the Rn concentration in the LXe in the inner detector to 8.2 ± 0.5 mBq for the whole volume (see below). No further measures for Rn reduction in the ID were deemed nec-

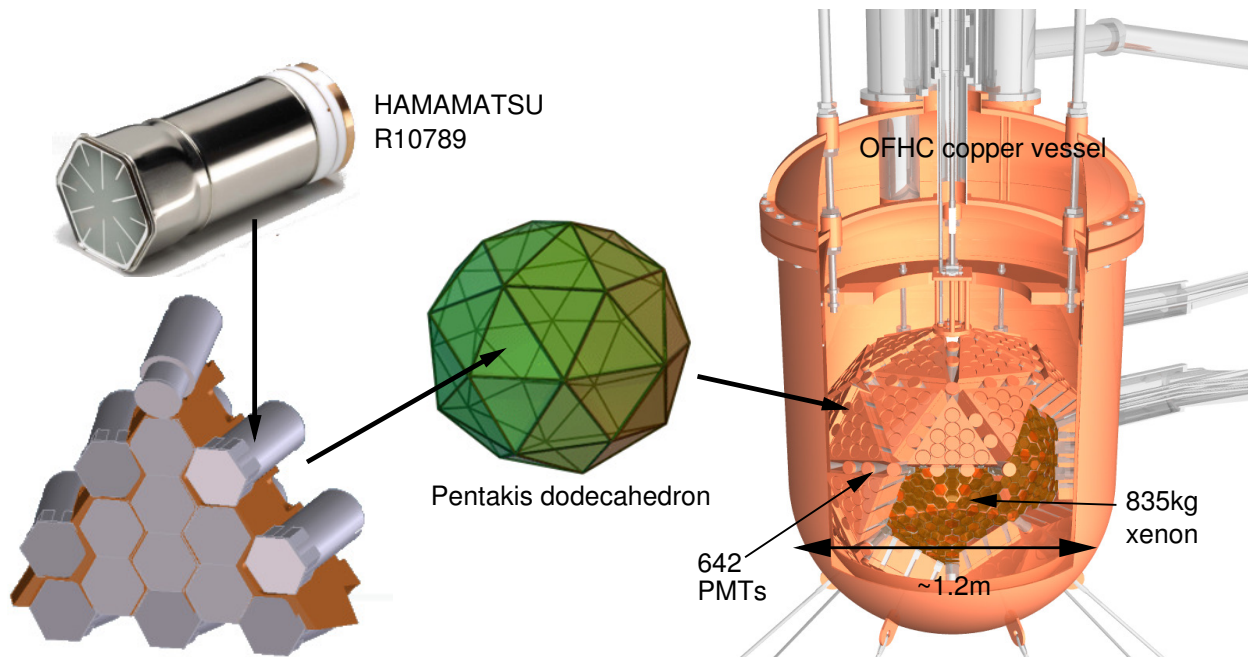


Figure 1: Schematic of the XMASS detector:

The lower left corner of this figure shows the fundamental triangle that the pentakis-dodecahedral approximation to a spherical surface for the ID is tiled with. Within a pentagon 5 triangles share a common round PMT at the center of the pentagon, and two hexagonal PMTs with each of its neighbors. At a pentagon boundary three PMTs are shared with the adjacent triangle in the next pentagon.

essary. The water tank itself is big enough to eventually house the final XMASS 20 ton detector.

2.2 Xe Circulation and Getter Use

The heat introduced to the ID mainly by the PMTs leads to a natural rate of evaporation from the liquid surface in the ID. A gas line allows this gas to flow to a pulse refrigerator cooled condensation site where it is returned to the liquid phase, keeping the liquid level in the detector stable. The gas line between the volume above the ID and the cooled condensation site also contains a hot getter, but after the (twice repeated) initial filling through two hot getters we did not find it necessary to pass the gas through this getter any more.

We also had prepared for additional heating to force increased gas circulation and a liquid circulation system. Both systems ended up not being used in normal operation, as after the two initial filling and Xe recovery cycles (during which the Xe gas was passed through two hot getters in series) the detector proved to be superbly stable without any further dedicated effort. Details can be found in [4].

2.3 Radiopurity

Together with Hamamatsu XMASS developed the new R10789 PMTs, which are designed to have very low radioactivity: roughly a factor 100 better than traditional PMTs. Table 1 summarizes the relevant HPGc measurements done in Kamioka.

Care was taken to avoid cosmogenic activation of the OFHC copper used in the experiment. After electrorefining the material its underground storage at the Kamioka Observatory kept above-ground exposure to cosmogenic activation below 130 days and its ^{60}Co activity below 0.25 mBq/kg. After manufacture the surfaces of the parts

Isotopes	Activity [mBq/PMT]
U-chain	0.70 ± 0.28
Th-chain	1.5 ± 0.31
K	5.1
Co	2.9 ± 0.16

Table 1: Radioisotopes in the PMTs.

holding the PMTs were chemically etched to remove surface contamination.

Commercially available Xe contains traces of Kr and its radioactive isotope ^{85}Kr . We established that the $^{85}\text{Kr}/\text{Kr}$ ratio in the original XMASS Xe was $(0.6 \pm 0.2) \times 10^{-11}$ in a 360 ppb contamination with Kr. To reduce the Kr concentration in the Xe used in XMASS we built a distillation system that achieved a 10^{-5} reduction in one pass. This represents an improvement over its prototype for which results had been reported in [5]. An atmospheric pressure ionization mass spectroscopy (API-MS) measurement at the Kamioka Observatory found the remaining Kr concentration in our Xe to be smaller than 2.7 ppt.

Radon decays in the fiducial mass of the detector were measured in situ through appropriate coincidences in the respective radon decay chains and yielded a value of (8.2 ± 0.5) mBq for ^{222}Rn and an upper limit of 0.28 mBq for ^{220}Rn . While this is not yet limiting our measurements, systems are still being developed to further reduce this contamination [6].

All other materials like for example the stainless steel bolts that hold together the triangles of the copper ID PMT holder structure were carefully vetted for optimal radiopurity. More than 250 samples of various detector

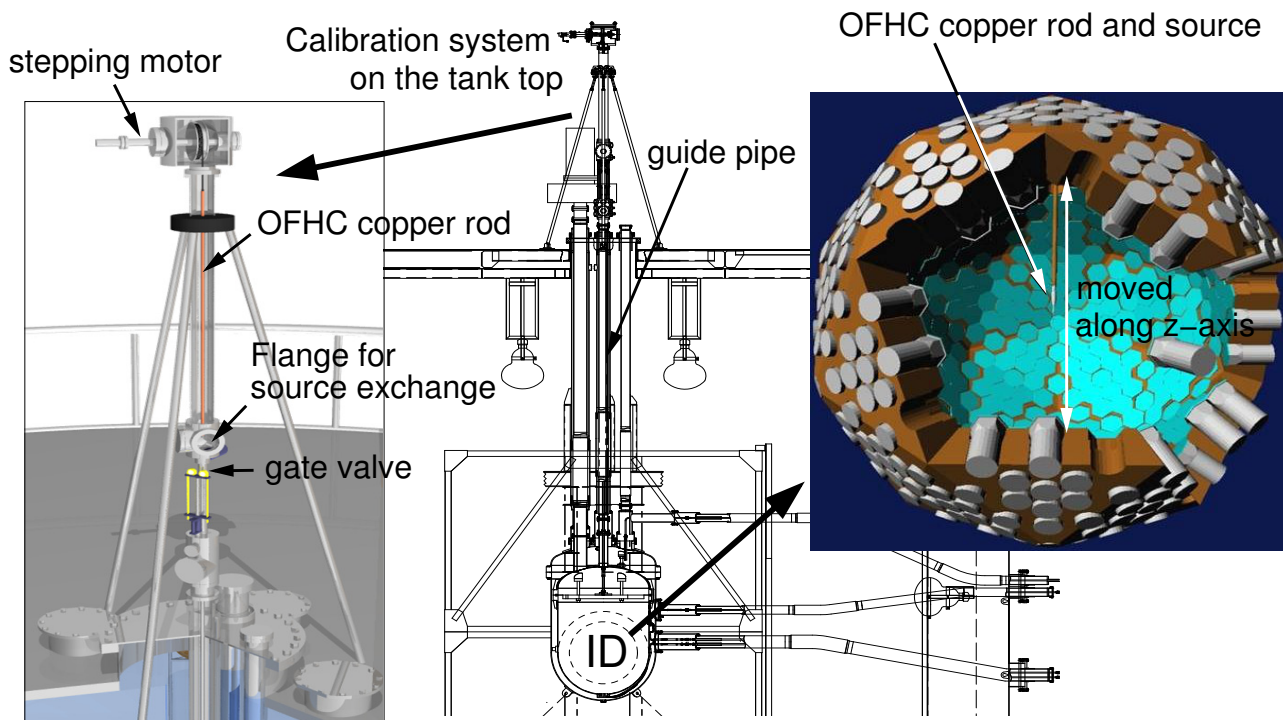


Figure 2: The XMASS calibration system:

The round PMT at the center of the top pentagon, the entrance window of which is horizontal and at the top of the ID, can be pulled back (up) and swiveled sideways to open up the ID for the perfectly vertical and central insertion of calibration sources on one of the detector's symmetry axes. On this axis the position of the source can be adjusted to within 1 mm.

components were studied in HPGe detectors at Kamioka to identify the best materials.

2.4 Electronics

PMT signals are amplified 11-fold before they are fed into the DAQ electronics. From the beginning these amplifiers were designed to feed each channels output into two different digitization channels: An older system inherited from SK that records one hit per channel, and a new 1 GHz FADC system.

During most of the commissioning phase only the analog timing modules (ATMs) that had previously been used in SK were available. The ATMs provide a threshold crossing time with 0.4 ns resolution and a charge integral that saturates at roughly 120 photoelectron (PE) equivalent and is measured with 0.05 PE resolution. Pedestal data are taken every 5 minutes, which accounts for most of the total dead time of 1-2%.

Like previously in SK the trigger is formed from an analog sum of a digital hitsum output that each of the ATM boards provides. Each individual hit or channel on the ATM contributes a 15 mV high and 200 ns wide input to the digital hitsum output of the board; each ATM board has 12 electronics channels. An ID trigger or an OD trigger (or both) are generated and a detector readout initiated if the total hitsums for ID and/or OD pass their respective thresholds. In normal data taking the ID threshold was initially set to the equivalent of 9 ID hits, but later lowered to 3 hits. The OD trigger threshold is set at 7 hits. Trigger rates are ~ 4 Hz for the ID and ~ 7 Hz for the OD. Each ID trigger is followed by a 6 μ s veto to suppress the recording of afterpulses.

A second output that the ATM boards provide is an analog sum of the input signals on all their 12 input channels. Also available from the old SK electronics were some older CAEN V1721 500 MHz FADCs boards that were used to individually record these analog sum outputs of the 60 ATM modules, roughly representing the 60 triangles. These FADC traces were used in some of our background studies.

In December of 2011 new CAEN V1751 FADC modules were installed. In the future they will allow for an improved analysis as photon counting can now be done at the individual channel level. This system will provide the detailed timing structure of events and can be used for pulse shape analysis and to better incorporate the timing information into the event reconstruction.

3 Detector Operation

A slow control system continuously monitors the whole detector for any irregularities. Detector operation as monitored by this system was found to be very stable.

In the interest of understanding the detector and its performance data were also taken with non-standard operating parameters. The temperature (and anti-correlated with it the pressure) in the ID were both lowered and raised to optimize the detector response. After careful evaluation of the data the ID temperature was kept at -99°C and the absolute pressure in the gas above the LXe at 0.165 MPa. We also separately injected (and later removed) both O_2 and heat into the LXe to evaluate their impact.

The detector was also run with Xe gas instead of LXe in the ID; this data was used to investigate surface background.

Published results are based on data taken under the standard operating conditions for the detector though.

4 Calibration System

Designed for maximum reliability the internal XMASS calibration system allows us to place calibration sources along the central vertical axis in the detector. Along that axis sources can be positioned with 1 mm accuracy. Available sources include ^{55}Fe , ^{109}Cd , ^{241}Am , ^{57}Co , and ^{137}Cs . To minimize shadowing effects the sources are sealed into thin cylinders that are mounted at the top of a straight OFHC Cu rod that holds them on the axis. The different sources can be exchanged without affecting ID operation. After exchange the source can then carefully be introduced into the ID. A typical source exchange operation takes one night as the air introduced to the source exchange volume needs to be completely removed in order to prevent contamination of the Xe in the detector. Using the accepted standard of ^{57}Co calibration we established a yield of (14.7 ± 1.2) PE/keV at 122 keV. Our Geant4 based detector Monte Carlo simulation (MC) is tuned on various calibration data sets with different sources.

An outer calibration system allows to move sources along a fixed tube that runs in the water on the outside of the outer copper vessel, the one that contains the vacuum to thermally isolates the inner detector from the surrounding water. This "external" calibration system has been used to study the effects of both, external gamma and neutron sources.

5 Refurbishment Effort

An unexpected background problem arose from the PMTs: Re-checking samples of the aluminum material used to seal the PMTs' entrance windows against their Kovar bodies was confirmed to contain high concentrations of ^{210}Pb and ^{238}U . The problem is that scintillation light from their (subsequent) β^- decays at the side of the PMT entrance window typically passes through the entrance window without impinging on the photocathode - thus avoiding detection in the PMTs immediately surrounding the decay position. This identified weakness of our original design is addressed in the current refurbishment effort. Three steps are taken to alleviate it:

- 1.) surface cleaning is improved,
- 2.) the surface structure is improved, and
- 3.) cleanliness during assembly is improved.

The surface of the copper PMT holder has now been electropolished rather than chemically etched. New copper parts are designed to provide a smooth ID inner surface that now is raised above the entrance windows of the PMTs and prevents scintillation light from the aluminum seal to reach and spread in the ID's active volume. In general and on top of this MC studies show that the avoidance of cracks and crevices on the Cu surface (from which light can emerge without being registered on the nearest PMTs) will significantly reduce the background at the lowest energies. Last but not least we dramatically improved the clean room environment for the re-assembly of our refurbished detector. New and better air filters were installed both in the experimental hall, which for the first time now itself is treated as a clean room, the water tank, and the clean booth used for assembly inside it. This layered defense against dust and Radon together with careful evaluation

of packing materials and anti-static measures constitutes a concerted effort to prevent new surface contaminations on the carefully cleaned and treated surfaces. We expect the combined effect of these three steps to yield about two orders of magnitude in background reduction.

6 Towards XMASS 1.5

This 5 ton total LXe mass detector will use ~ 1800 PMTs. Apart from further efforts to reduce the residual radioisotope loading of the new ID's components one of the main improvements anticipated for the XMASS 1 ton stage is related to these PMTs. With Hamamatsu we are developing a version of our PMT where the photocathode on the inside of the flat entrance window is dome shaped rather than flat. This geometry will allow a part of the scintillation light entering the entrance window from the side to still strike the photocathode and thus give us a direct light signal also in PMTs that are immediate neighbors to a surface event. MC simulations of this next detector incorporating the new photocathode geometry and incorporating all our experience with the current 800kg detector let us expect residual background at low energies to be of order 10^{-2} /ton/day/keV.

We hope to begin construction of this new detector already in 2014, although no money has been allocated yet. The aim is to get it operational as soon as possible.

7 Conclusions

The current incarnation of XMASS is proven to have excellent operational stability and a very high light yield during its first commissioning runs between Nov. 2010 and Jun. 2012. It is currently undergoing refurbishment to further reduce the surface background sources identified in its commissioning phase. The improved ID surface structure combined with the new FADC electronics now available to the experiment will provide significant improvements for both, event reconstruction and classification.

XMASS 800kg is expected to take data again this fall, aiming for DM detection at cross sections of a few 10^{-45} cm² for a 100 GeV WIMP. Our conceptually simple, easily scalable, and operationally extremely stable detector technology is proving to be a valuable tool in our quest to uncover the nature of Dark Matter.

In parallel preparations are being made for the next stage of the XMASS program: XMASS 1.5, a LXe detector containing a fiducial mass of 1 ton and a total mass of 5 ton of LXe in its inner detector. It will incorporate lessons learned on XMASS 800kg, as well as further improvements brought about by e.g. newly optimized PMTs.

In the final 10 ton fiducial mass stage the experimental program will include neutrinoless double beta decay and the measurement of pp solar neutrinos, which at that scale will become an irreducible background to DM detection.

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