Development and performance of high voltage electrodes for the LZ experiment

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Abstract. LZ is a next-generation dark matter search experiment designed to significantly extend our sensitivity to WIMP dark matter candidates. At the core of the LZ detector is a dual-phase xenon time projection chamber (TPC) with a 7-ton active mass. To observe signals from low-energy nuclear recoils, including WIMP-xenon scatters, four custom-woven wire-mesh grids of 1.5m diameter establish strong electric fields in the TPC to drift ionization electrons across the volume and extract them from the liquid surface. As a result of the high electric fields, dielectric breakdown between high voltage surfaces and spurious electron emission from regions of high surface fields are major concerns. To mitigate these risks, an R&D program exploring design geometry in high field regions, cleanliness procedures, and surface treatments has been carried out using a comprehensive suite of three mid-scale dual- and single-phase xenon detectors. These proceedings will summarize the design and construction of the LZ grids, and several aspects of the high voltage performance seen in the testing program.

1. The LZ dark matter detector
A substantial body of evidence suggests that approximately 26% of the energy density of the universe is composed of non-baryonic “dark matter” particles [1]. One historically favored model of dark matter is weakly interacting massive particles, or WIMPs. Despite several decades of searching, there has been no positive detection of dark matter in the lab. LUX-ZEPLIN (LZ) is a next-generation dark matter experiment designed to explore most of the remaining accessible parameter space within the WIMP dark matter paradigm and push the limits of the liquid noble detector technology for dark matter searches [2].

At the core of the LZ detector is a dual-phase xenon time projection chamber (TPC) with a 7-ton active mass. The energy deposited in an interaction within the TPC is reconstructed based on a prompt scintillation signal (S1) and an ionization signal, which occur at the site of the interaction. The ionization signal is drifted to the liquid surface via an electric field in the bulk of the liquid xenon. Surrounding the liquid surface is the “extraction and electroluminescence region” — a higher field region created between two high voltage electrodes. Figure 1 shows a schematic of this region, with the gate electrode below the liquid level and the anode electrode above it in the gas. In this higher field region, the ionization signal is extracted from the liquid surface and drifted through the gas to produce proportional scintillation light (S2). Through this amplification process, single electrons are clearly distinguishable. Light from the S1 and S2 signals is collected by arrays of photomultiplier tubes (PMTs) at the top and bottom of the TPC.
2. Design of the LZ electron extraction and electroluminescence region

The performance of the extraction and electroluminescence region is crucial to the performance of LZ since it is responsible for production of the S2 signal, but its design is a particular challenge due to the competing requirements of high fields and compact geometry. The high field is required for both a high efficiency to extract electrons from the surface of the liquid into the gas, as well as a high scintillation light yield for S2 production. The need for transparency of the electrodes, required for transmission of S1 photons to the PMT arrays and drifting of electrons past the gate to the liquid surface, motivates electrodes made from thin, metallic wires.

Given these considerations, the optimized design for the LZ electrodes is woven meshes of stainless steel wires that are sandwiched between and glued to stainless steel rings approximately 1.5m in diameter. The woven mesh optimizes field uniformity in the extraction and electroluminescence region, limits high surface field points along the wires that could lead to electrical breakdown, and uniformly spreads the mechanical load from the tensioned wires on the supporting rings. The tension on the wires limit electrostatic deflection of the energized meshes to ensure uniformity of the electroluminescence field. In addition to maintaining structural integrity under the load of the wires, the geometry of the rings was designed to limit local high surfaces field regions.

There are four electrodes in the LZ TPC, each with a unique set of design parameters. The gauges of the wires were selected to balance optical transparency with tensile strength and surface fields. The pitch of the anode is twice that of the gate such that there is an anode wire centered between each pair of gate wires, which leads to more uniform drift lines for extracted electrons as they are drifted toward the anode and therefore optimized S2 resolution. Further technical details of the design can be found in Refs. [2], [3] and [4].

3. Production of the LZ electrodes

The LZ electrodes could not be produced commercially because there is no suitable mesh at the correct scale. Instead, a loom was designed and built to weave the wire meshes at SLAC National Accelerator Lab. Production begins with weaving a mesh on the loom and tensioning each wire with a weight. Weaving takes 2-6 days per electrode, depending on the pitch. After careful alignment of the supporting rings, glue is applied via automated dispenser on an XY stage and the tensioned mesh is secured to the rings. Each electrode cures for seven days until the weights are removed. The entire production process takes place in a class 100 cleanroom. Additional diagnostic measurements carried out include assessing the quality of the gate-anode wire alignment over the entire electrode area through optical images, and measuring the electrostatic deflection of the electrodes under realistic electrostatic conditions in order to predict the in situ deflection. Details of LZ electrode production are the subject of a forthcoming paper.
4. Measurement and mitigation of electron emission from the LZ grids

Spurious emission of light and charge from high voltage wires has been observed at average surfaces fields as low as 10kV/cm, presumably due to significantly higher local fields around sharp imperfections [5]. In a dual-phase TPC, electrons emitted from cathodic surfaces beneath the liquid surface will be drifted to the liquid surface, extracted, and produce S2 light just like an ionization electron. This effect was seen in the LUX experiment and was the main factor that limited the extraction voltage [4]. If emission occurs at a high rate in LZ, it could lead to significant DAQ deadtime. Even at a low rate, emission could mimic a low energy signal, which is concerning for low energy searches like the WIMP search or an ionization-only analysis.

In order to measure emission and develop mitigations for LZ, a System Test platform was built at SLAC. The System Test consists of three separate xenon detectors — a small-scale gas-phase detector to quickly turn around prototype LZ electrode designs; a medium-scale vessel that can be run either as a dual- or gas-phase detector, which has a near clone of the LZ extraction and electroluminescence region profile scaled down to about 20cm; and a large-scale gas-phase detector to validate full-scale LZ electrodes. All three detectors have demonstrated single electron sensitivity, and the mid- and full-scale vessels have PMT arrays to localize electron emission. Details of the System Test platform are the subject of a forthcoming paper.

4.1. Passivation

One method shown to reduce electron emission from stainless steel wires is passivation [5]. The passivation process involves a heated acid bath which preferentially etches away free iron on the surface, leaving a chromium-rich layer. According to our Auger electron microscopy measurements, this increases the thickness of the chromium oxide layer on the outer surface of stainless steel from about 30Å unpassivated to about 70Å after passivation.

In measurements of an untreated 20cm prototype electrode in warm xenon gas, two localized regions of electron emission were seen. In subsequent measurements, despite transportation, exposure, and cleaning of the grid, these regions of emission remained, which indicates that these emission sites were caused by permanent defects on the wires rather than removable defects such as dust. After passivation of the 20cm electrode, the electron emission regions were found to be drastically reduced, even at surface fields much higher than are expected to be achieved in LZ. A before and after comparison of the position and rate of electron-like signals from the passivated grid can bee seen in Fig. 2. The effect of passivation was found to be a clear reduction in emission rate from localized regions of emission.

4.2. Cleanliness

In addition to reproducible electron emission sites similar to those seen on the 20cm prototype electrode, removable electron emission sites were observed in tests of full-scale LZ electrodes. Between two tests of the final LZ gate and anode electrodes in warm xenon gas, the test vessel was opened, the electrodes were exposed to dust, and dust visible under UV light was manually removed. A comparison of the position and rate of electron-like signals before and after dust exposure and removal can be seen in Fig. 3. Regions of electron emission disappeared, and new ones were introduced. This indicates that cleanliness and presence of dust on the electrodes plays a significant role in electron emission.

4.3. Mitigation

Following the results of the tests of the 20cm prototype electrodes, the final LZ gate electrode was passivated to reduce electron emission from reproducible electron emission sites. To reduce emission from removable contaminants like dust, all four LZ electrodes were thoroughly washed in a spray of de-ionized water just prior to integration into the TPC. Visual inspection under UV light showed removal of nearly all visible dust less than 50µm in size.
Figure 2. XY distributions of single electron candidate pulses from two separate tests of a 20cm electrode in warm xenon gas. Before passivation (left), two localized regions of electron emission are visible. After passivation (right), the regions are no longer apparent. The central region of emission is thought to be an artifact of the position reconstruction algorithm.

Figure 3. XY distributions of single electron candidate pulses from two separate tests of the full-scale LZ gate and anode electrodes in warm xenon gas. Between the two tests, the electrodes were exposed to dust and then visible dust was removed under UV inspection. Regions of electron emission are clearly visible, and the positions shifted between tests. No central reconstruction artifact is present due to the scale and spacing of the PMT array in the LZ-scale vessel.

5. Conclusion
The wire mesh electrodes for the LZ experiment were designed to optimize the performance of the extraction and electroluminescence region, which is responsible for the production of the S2 signal. All four final LZ electrodes were produced at SLAC National Lab. It was found that passivation of the stainless steel wires and sufficient cleanliness protocols can reduce electron emission. In order to mitigate emission from the LZ electrodes, the final LZ gate electrode was passivated and all four electrodes were washed in de-ionized water just prior to installation into the TPC. First LZ science can be expected in 2021.

References
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