WP 8 Cryogenic detectors

Task 8.5 Very High Voltage

S. Murphy, L. Molina Bueno (ETHZ)
VHV in cryogenic detectors needed to separate electrons from ions and drift the electrons over many meters

Charge imaging (readout electrons and perform 3D image of interaction). Neutrino detectors

Light imaging (readout VUV photons compare scintillation profile in gas and liquid). Dark Matter + Neutrino detectors at low (~MeV) energies

VHV in cryogenic detectors needed to separate electrons from ions and drift the electrons over many meters.

**E: 500 V/cm, drift of many meters => need to:**
- safely transport DC VHV of hundreds of kV at the cathode
- ensure stable operation for long periods, no discharges, stable VHV, no noise on the readout, ...

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**Space charge in ionization detectors.** by Sandro Palestini, Kirk T. McDonald, 2007.
VHV in cryogenic detectors needed to separate electrons from ions and drift the electrons over many meters

**Four Main “VHV components” that require extensive R&D and testing.**

1. the VHV power supply
2. the VHV feedthrough
3. the cathode
4. the drift cage

## Very high voltage for cryogenic detectors

<table>
<thead>
<tr>
<th>Detector</th>
<th>Active Lar</th>
<th>drift length</th>
<th>cathode area</th>
<th>design HV (500 V/cm)</th>
<th>Achieved stable operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>MicroBooNE</td>
<td>89t</td>
<td>2.5 m</td>
<td></td>
<td>125 kV</td>
<td>60 kV</td>
</tr>
<tr>
<td>ICARUS T600</td>
<td>476t</td>
<td>1.5 m</td>
<td>9 modules of 2*3.2 m²</td>
<td>75 kV</td>
<td>150 kV</td>
</tr>
<tr>
<td>Dual phase 3x1x1</td>
<td>4 t</td>
<td>1 m</td>
<td>3x1 m²</td>
<td>-56 kV</td>
<td>-56 kV</td>
</tr>
<tr>
<td>ArgonTUBE</td>
<td>~0.8 t</td>
<td>5 m</td>
<td>0.2 m (²π)</td>
<td>0-500 kV</td>
<td>125 kV</td>
</tr>
<tr>
<td>p-DUNE single phase</td>
<td>~300 t</td>
<td>3.6 m</td>
<td>1.16 * 2 m²</td>
<td>-180 kV</td>
<td></td>
</tr>
<tr>
<td>p-DUNE dual phase</td>
<td>~300 t</td>
<td>12 m</td>
<td>6x6 m²</td>
<td>-300 kV</td>
<td></td>
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Sustaining such large voltages is challenging, extensive R&D ongoing in the field. **Huge value of this AIDA202 Networking activity**
Very high voltage for cryogenic detectors

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<th>Detector</th>
<th>Active Lar</th>
<th>drift length</th>
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<td>12 m</td>
<td>6x6 m²</td>
<td>-600 kV</td>
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The R&D of task 8.5 is based on those two detectors. Liquid Argon medium, dual phase TPCs. But all the R&D and results are applicable to all others.
Scope of Task 8.5

1. the VHV power supply  
2. the VHV feedthrough  
3. the cathode  
4. the drift cage

**Design validation on small scale prototypes.**  
Stability, effect on noise, etc..

**Choice of materials.**  
cryogenic and VHV compatibility, surface properties, ..

**Size, layout distance of VHV detector components (FEA simulations)**

- very high voltage feedthrough
- drift cage
- cathode
- meter drifts
- \( e^{-\text{v_drift}} \)
Dielectric rigidity of liquid argon

Fundamental is also the liquid medium temperature and pressure.

Evidence of electric breakdown induced by bubbles in liquid argon

The dielectric rigidity of liquid argon with temperature below the boiling point was found to be larger than 100 kV/cm. The occurrence of breakdowns is significantly sensitive to the presence of bubbles: in boiling liquid argon the breakdown field is as low as 40 kV/cm.

In general the goal is to keep fields in the liquid below 40 kV/cm.

The purity of the liquid argon plays an important role (dielectric strength decreases with increasing purity).

Experimental study of electric breakdowns in liquid argon at centimeter scale
A. Blatter (U. Bern, AEC) et al.. Jan 26, 2014. 13 pp.
cathode and drift cage

1m drift: goal ~60 kV at the cathode

6 m drift: goal~300 kV at the cathode

1. Common 300 kV rated High voltage Feedthrough + PSU

2. drift cage:
   polished SS pipes, with openings (to avoid trapped air pockets)
   extruded Aluminum profiles

3. cathode:
   cathode: point welded SS pipes
   SS structure with pipes

All with calculated shapes to have < 40 kV/cm liquid
The 300 kV power supply and feedthrough

Generation of voltages at the hundred of kV scale and transport towards the cathode.

**Generation:** Investigated and found a 300 kV PSU, low ripple (1e-5).

**Transport through the cryostat exterior/interior interface:**

- **Length (>2m)** to traverse the thick passive insulation and reach the liquid
- **VHV compatibility:** FEA simulations, shaping of electrodes + surface finish to reduce electric fields
- **“Cryo-compatibility”**:
  - thermal shrinkage, avoid formation of empty volumes where gas may get caught, use material with matching CTE,
  - **UHV rating**. Must not pollute the liquid bulk. Tested down to 1e-9 mbar l.s leak rate
PNChp 300000-05-neg Heinzinger power supply (PSU)

Output voltage: approx. 0 up to 300,000 V DC adjustable
Output current: approx. 0 up to 0.5 mA adjustable
Input voltage: 230V 50Hz

Voltage stabilization
Reproducibility: \( \leq 0.1\% U_{\text{nom}} \)
Stability: \( \leq 0.001\% U_{\text{nom}} \) over 8h
Ripple: \( \leq 0.001\% \text{pp} U_{\text{nom}} \pm 50\text{mV} \)
Temp. Coefficient: \( \leq 0.001\% U_{\text{nom}} /\text{K} \)

Current stabilization
Reproducibility: \( \leq 0.1\% I_{\text{nom}} \)
Stability: \( \leq 0.05\% I_{\text{nom}} \) over 8h
Ripple: \( \leq 0.05\% \text{pp} I_{\text{nom}} \pm 500\mu\text{A} \)
Temp. Coefficient: \( \leq 0.01\% I_{\text{nom}} /\text{K} \)
High voltage feedthrough

- Insulation
- Ultra pure liquid
- Gas

Ground termination in liquid to avoid high fields in gas
• insulation between inner and outer connector: **one continuous 2 meter rod of High Molecular Density Polyethylene** (HMDPE RCH-1000), rated for -269 °C, \( \varepsilon_r \) of 2.3, dielectric rigidity of 900 kV/cm.

• Thin 108 mm outer diameter stainless steel tube **terminated by a Rogowsky shaped electrode**.

• **Assembled by "thermo-fitting" the different pieces together.** Prior to inserting the inner conductor, the HMDPE tube warmed up to about 100 °C. Once the inner conductor is inserted both parts are cooled down to 77 K in a liquid nitrogen bath and introduced in the outer conductor.

manufactured at CINEL (Italy)
The pressure in the LAr was very stable at 1.05 bar.

O₂ impurities measured in the gas were less than 0.1 ppm.

Design successfully tested in dedicated setup up to the end of the scale of the Heinzinger PSU. About 295 kV.
High voltage feedthrough

O$_2$ impurities measured in the gas were less than 0.1 ppm. The pressure in the LAr was very stable at 1.05 bar.

Another exact same feedthrough has been manufactured and is about to be tested in a similar setup.

Heinzinger PSU. About 295 kV.
High voltage feedthrough

- The VHV system (PSU+feedthrough+ cathode + drift cage) has operated **stably** for month scale periods on a 3m³ LAr TPC
- **No degradation of performance**, no visible noise on the charge or light readout system when operating at -56 kV.
- Validation of the PSU, FT, cathode and DC design at this scale and voltage

~100 Mohm Ceramic resistors for voltage divider
Next steps: large area cathodes and 6 m long drift cages

Extensive FEA field simulations to guide the design

modular components of 3x3 m² for installation. Electrically connected together

All electric fields below 30 kV/cm
Drift cages

Cost effective and modular design.

FIELD CAGE

- HV divider Column
- M4 Nuts inserted in the profile
- Alu Profiles fixed at corner side with M4 screws (reduce shrinking)

SS Hanging System

PCB divider board

- Sub-module 1
  - 3 profiles
- Sub-module 2
  - 3 profiles
- Sub-module 3
  - 3 profiles + contacts

Cathode Connection

All connections:
- G10 inserts
- FRP Rod and Nuts

- Divider board is 3 mm thick - to have strong mechanical connection.
- Each stage will be electrically connected through copper tap, screws and metal washer.
• Passivated Al profiles (SurTec coating) to avoid formation of Alumina oxyde.
• Tested and inspected (HV rigidity, noise,..) for long durations on small LAr setups.
• shape provides a uniform drift field inside the fiducial volume. The part of the profile facing the cryostat (the ground potential) is rounded.
• For a cathode at 300 kV, maximal E fields between drift cage and cryostat GND are below 40 kV/cm even in corners (3D simulation)
Fully assembled and first successful test of the entire drift cage + divider at 150 kV in air. Test ongoing
Very high voltage (VHV)

Generation and transport of very high voltage (O(100) kV) in pure cryogenic liquid and gases has always been a rich source of R&D. Indeed, cryogenic detectors have the huge advantage of generating a complete 3-D image of all particles from an interaction and reconstruct the particles’ energies well while sorting event from background. However, because of the dense media (compared to gas) they require high drift fields of 500 V/cm. This kind of experiments aiming at a maximum drift of several meters require bias voltages at their cathode in the hundreds of kilovolt range. The problem is to be able to generate this extremely high voltages and to get the voltage to the cathode over an unusually large distance without compromising the purity of the argon inside the detector by letting heat or air inside. Nonetheless there is a huge worldwide effort to tackle those issues.

The components

The very high voltage system consists of:

- **Generation**: The power supply should be able to provide the maximal operation high voltage (HV) and the power cable should be rated for this voltage.
- **Transmission**: The HV feedthrough (HVFT) should be designed to sustain this maximal operation HV.
- **Design**: The shape of all the elements of the TPC should be carefully designed to avoid critical field regions (maximal electric field above 40 kV/cm).
- **Electrostatic simulations**: The whole detector including the cathode, the field cage and the feedthrough has been simulated using the COMSOL multiphysics software. This work was done inside the WP8 and the results have been summarised in [refThesisPin]. We optimised the design of the feedthrough through simulations and we studied the influence of the different parameters of the HVFT design in the computed electric field along the whole TPC. The results are important also for future R&D on HVFT, cathode and field cage design.

Long-term operation tested inside the 3x1x1 m3 dual phase LAr TPC prototype

- HVFT inside the 3x1x1 m3 detector:
Conclusions

Task 8.5 on very high voltage is a crucial aspect for large cryogenic detectors and englobes a large number of fundamental deliverables for the field:

- The design, manufacture and test of a feedthrough that can be operated near 300 kV.
- The test in terms of monitoring, current and voltage stability of a 300 kV power supply over long periods.
- The necessary 2D and 3D FEA simulations to optimise the design of large cryogenic detector components which are biased at very high voltages.
- The QA of VHV components before and during installation.
- Validation of part of the design at the multi 10 kV scale (done) and multi 100 kV scale (to be tested in protoDUNE-DP).

Next step is a full scale test with the 300t and 6 meter drift.
Very high voltage

Fig. 3. Recombination factors as a function of the electric field, for 364 keV electrons [1], 976 KeV electrons [2], and minimum ionizing particles (ICARUS, this work). Errors on the Scattlar et al. data are smaller than the symbol size.