Space charge effects in liquid argon detectors

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PANIC 2021: Particles and nuclei international conference

(Lisbon, Portugal), 5 September 2021

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MINISTERIO DE CIENCIA E INNOVACIÓN

Ciemat

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

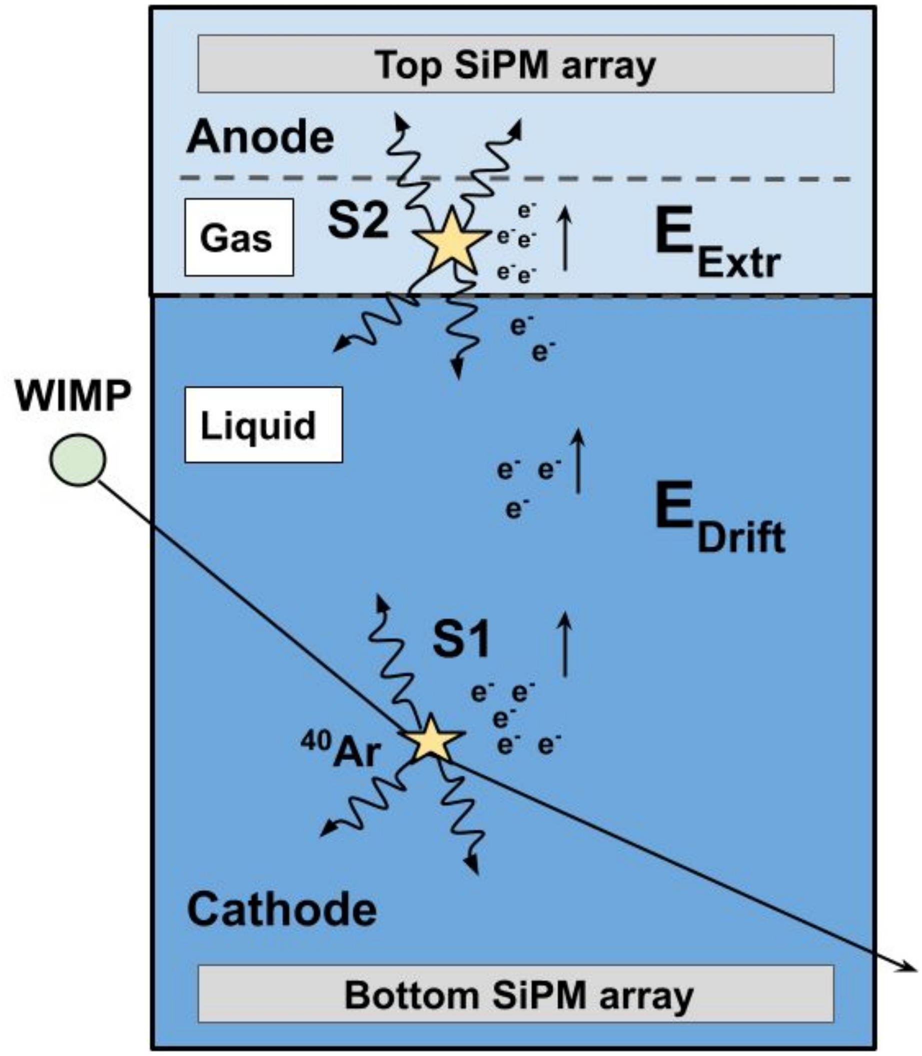
cfp CIEMAT física de partículas

Noble liquid technology

- Noble liquids are good media for rare event searches:
  - Efficient scintillation and ionization medium with high light yields (~10^4 photons/MeV at zero field).
  - Good background suppression (pulse shape discrimination and charge to light ratio).
  - Noble gases do not attach electrons and they can be easily purified (several meters distances for free electrons).
  - Scalable (tonne, Multi-tonne experiments).
  - Available in large quantity (affordable).
  - Safe targets (inert and not flammable).

Time projection chamber

- The primary scintillation produces the S1 signal.
- In a single-phase detectors the electrons are drifted to the anode and collected in wires. This allow a 3D position reconstruction of the event.
- In a dual-phase detectors the electrons are extracted to the gas phase producing an additional charge signal (charge amplification and electroluminescence).



Space charge in large detectors

- Ions have a drift velocity five/six orders of magnitude lower than electrons. At E_d= 1 kV/cm, $v_i \sim 1.6\ 10^{-5}$ mm/μs to be compared to v_e= 2 mm/μs.

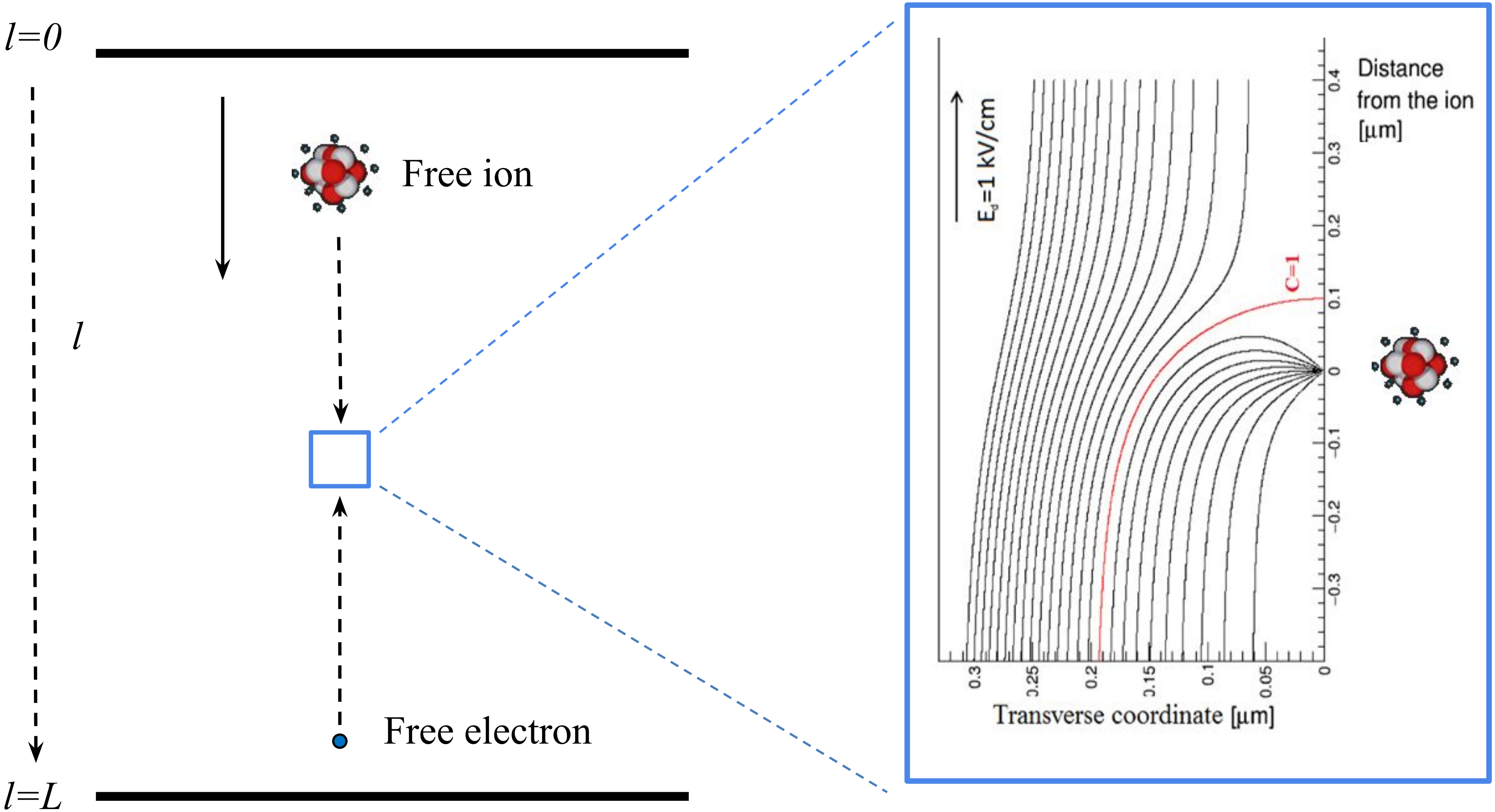
- As consequence, they spend considerably more time than the electrons in the drift region.

  A positive volume region is created by the accumulated ions (space charge).

- The space charge can locally modify the electric field, the drift lines and the velocity of the electrons.

- Electrons can recombine with the accumulated ions (secondary electron-ion recombination), eventually producing the loss of the electronic signal and a production of photons shifted in position and time relative to the primary interaction.

Secondary electron-ion recombination



- $S_{CS} \rightarrow$ transverse are whose crossing field lines end on one ion.

$$S_{cs} = \frac{q}{\varepsilon_{LAr} E_d} \quad \rightarrow \quad S_{cs} = 1.2 \cdot 10^{-7} mm^2 \quad \text{with } E_d = 1 \text{ kV/cm}$$

[1] Dynamics of the ions in Liquid Argon Detectors and electron signal quenching, Astropart.Phys. 92 (2017) 11-20

Space charge calculation

Drift velocity

$v_i \sim 1.6\ 10^{-5}$ mm/μs and $v_e \sim 2$ mm/μs with E_d = 1 kV/cm.

Drift distance

… up to 12 m!!!

"Ion yield"

- **Surface**:

  Dominant contribution from muons (168 muons/m^2/s).

  Minimum ionizing energy: $dE/dl \approx 1.5\ MeV cm^2/g$.

  Mean deposited energy 35 GeV/m^3/s → 1.5×10^9 pairs/m^3/s.

- **Underground**:

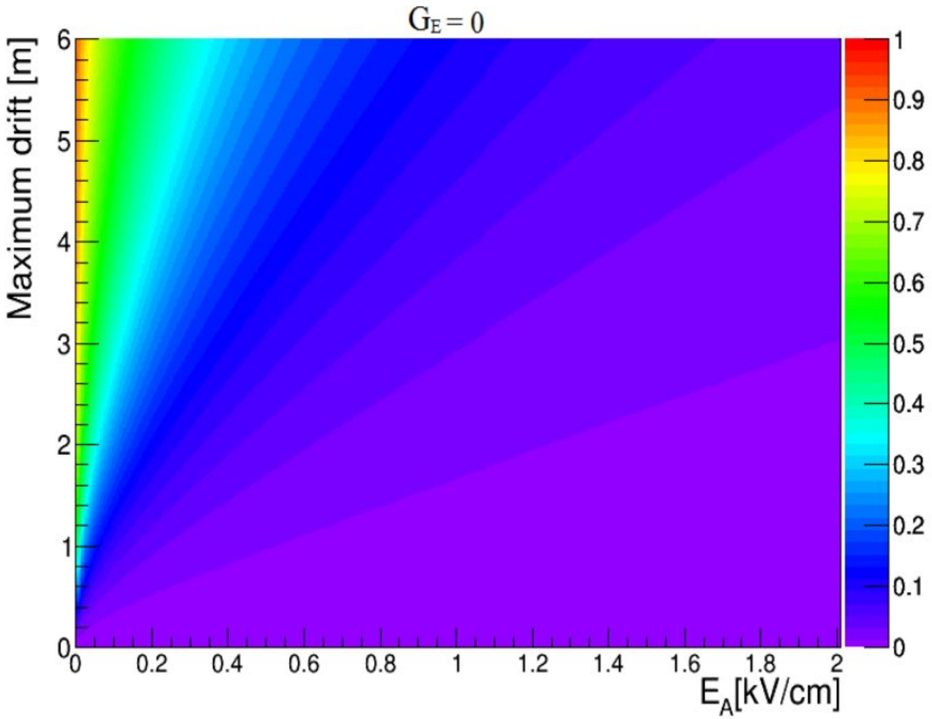
  Dominant" contribution from ^{39}Ar (~1 Bq/kg).

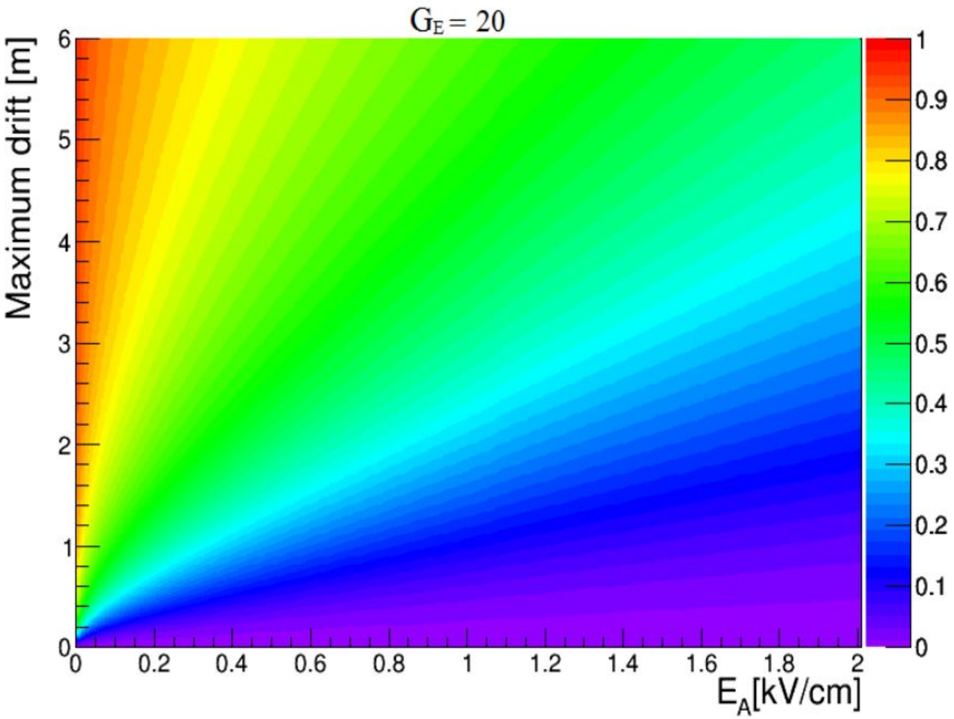
  Q-value of 565 keV, 1/3 mean energy→ One decay 8×10^3 pairs.

  Mean deposited energy 263 MeV/m^3/s → ~ 1.1×10^7 pairs/m^3/s.

Surface detectors

- Dominant contribution in surface detector from cosmic-rays (168 muons/m^2/s) producing 1.5x10^9 pairs/m^3/s.
- Ion gain = positive ions injected for each electron extracted in the gas-liquid interface.



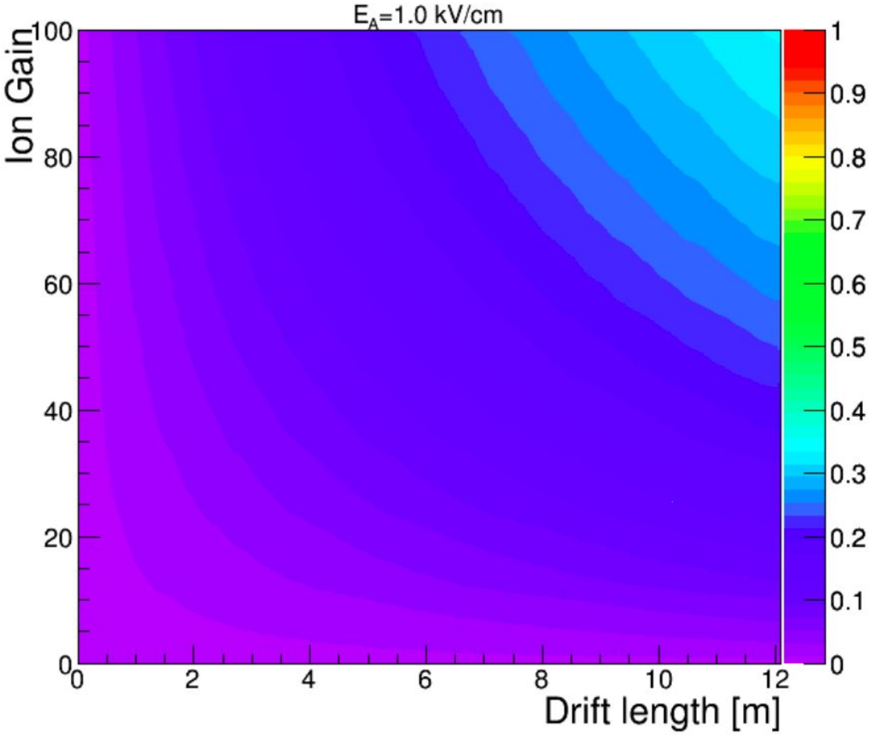


[1] Dynamics of the ions in Liquid Argon Detectors and electron signal quenching, Astropart.Phys. 92 (2017) 11-20

[2] Impact of the positive ion current on large size neutrino detectors and delayed photon emission, JINST

Underground detectors

- Dominant contribution in underground detectors from ^{39}Ar isotope (1 Bq/kg) producing 1.1×10^7 pairs/m^3/s.
- Space charge effects worsened by ion feedback from the gas phase in case of charge amplification.



[1] Dynamics of the ions in Liquid Argon Detectors and electron signal quenching, Astropart.Phys. 92 (2017) 11-20

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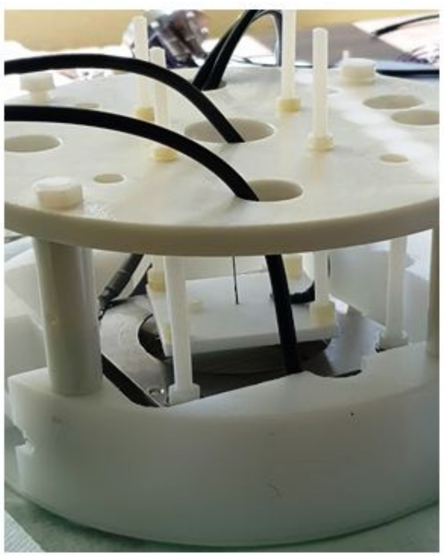
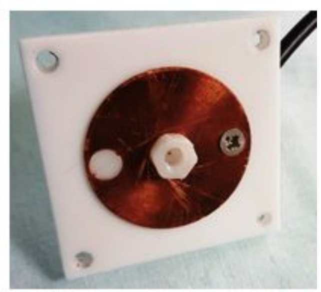
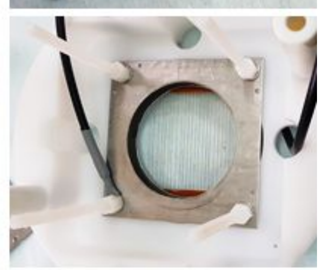
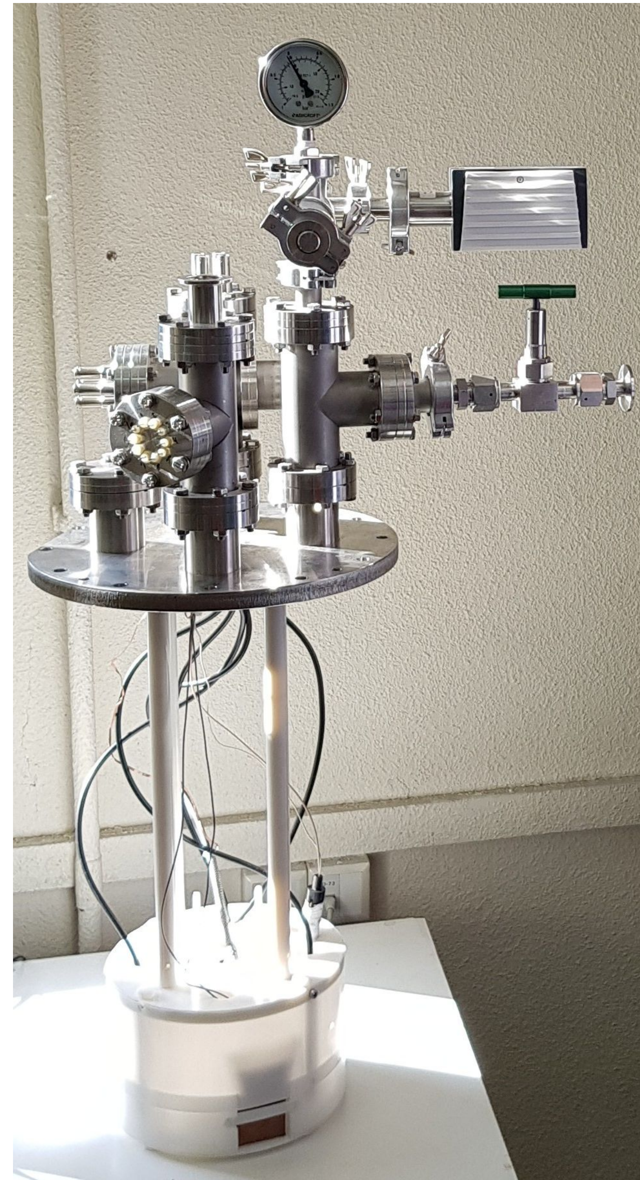
ARgon Ion Experiment: ARION at CIEMAT

- Teflon support structure.
- Tungsten needle to produce ions in the anode. Maximum voltage 5kV.
- Two stainless steel shaping rings to have an uniform electric field.
- Cathode made from stainless steel wires at bottom.

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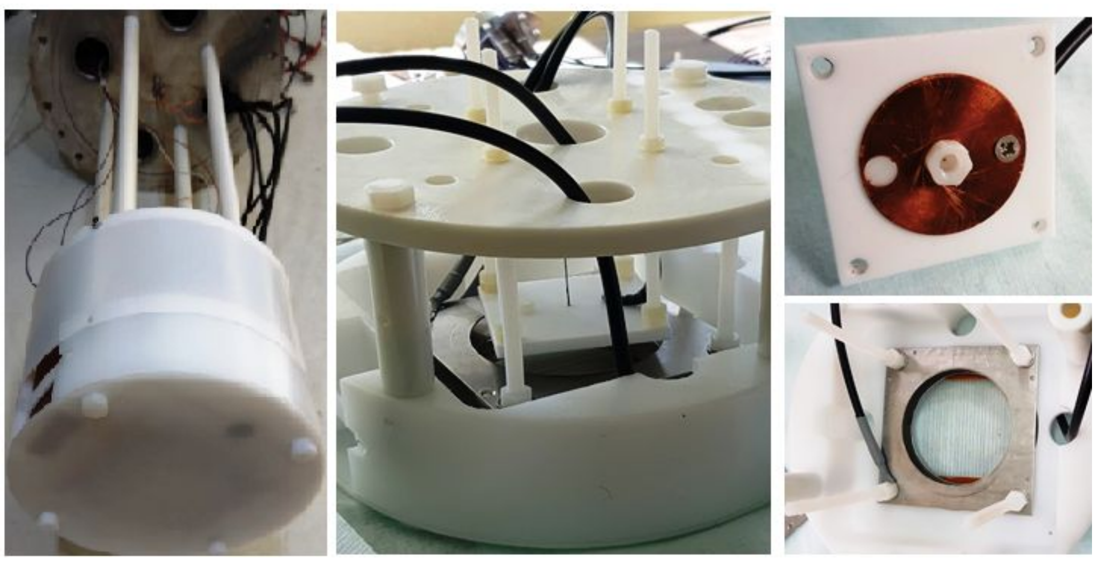

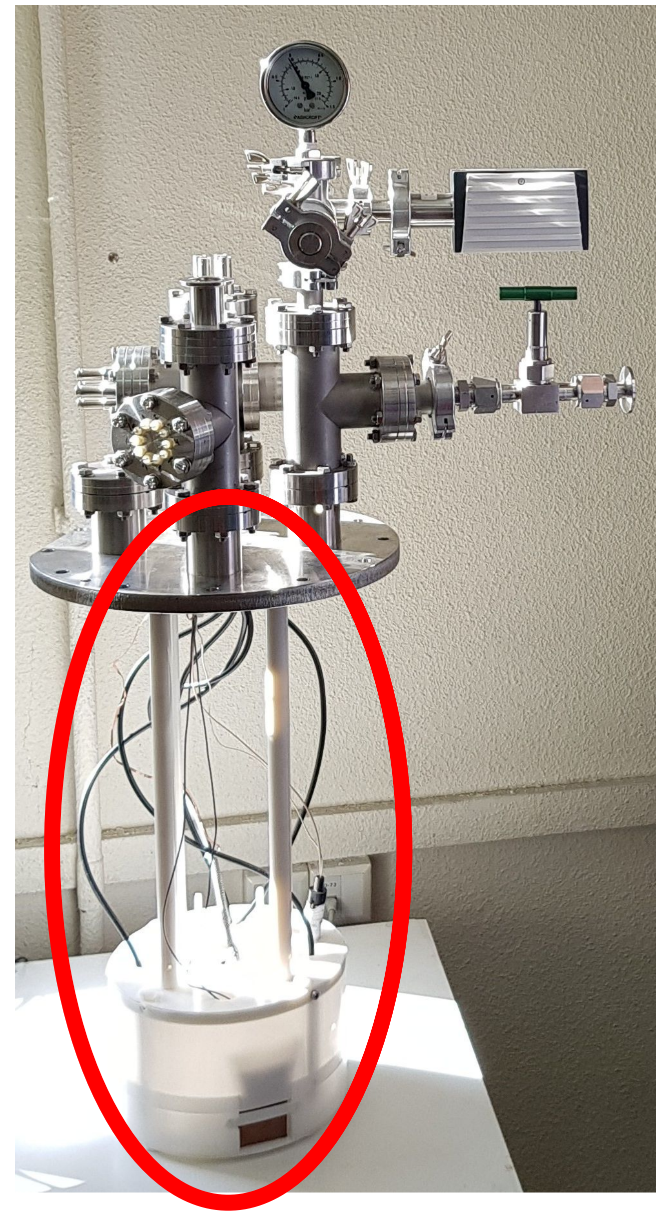

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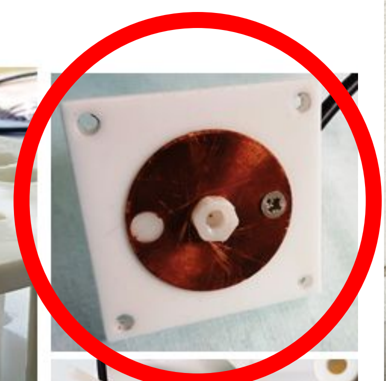

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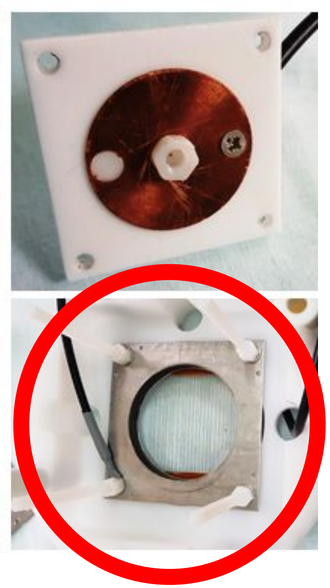
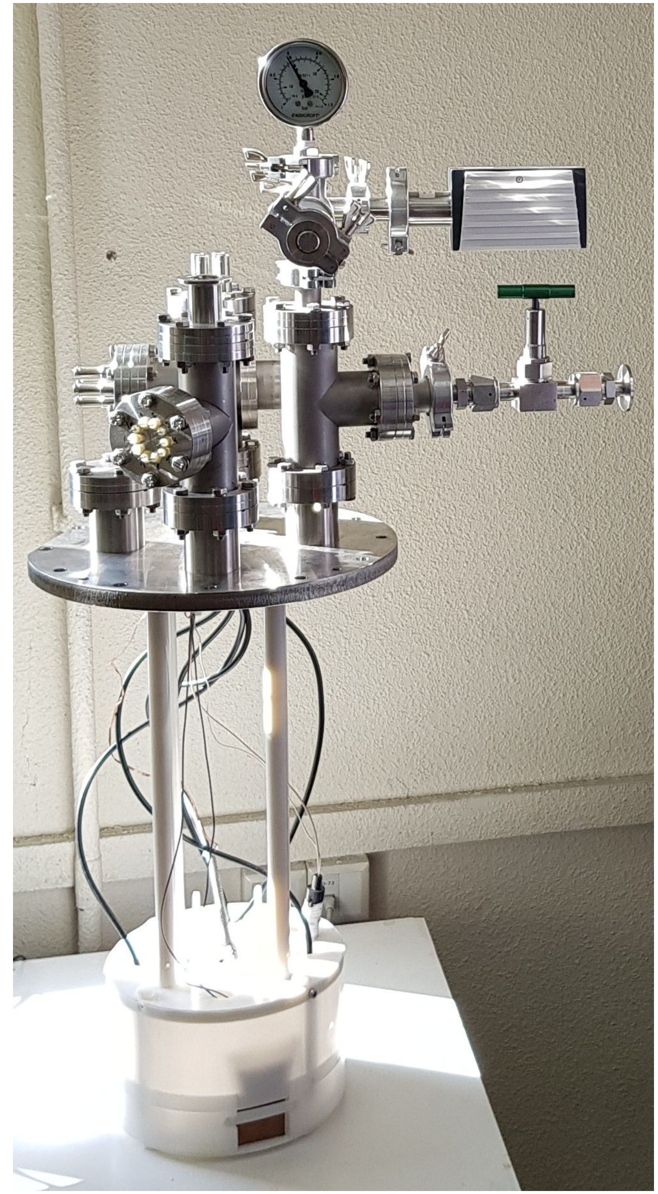
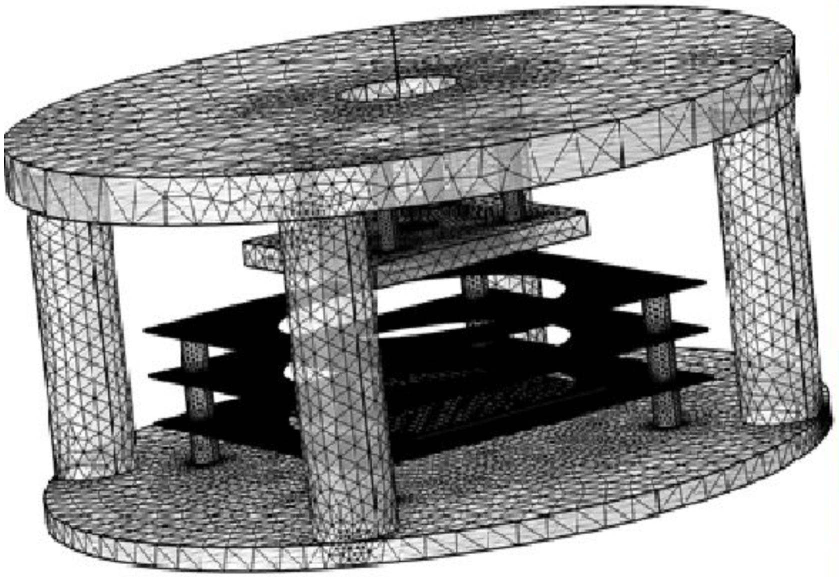
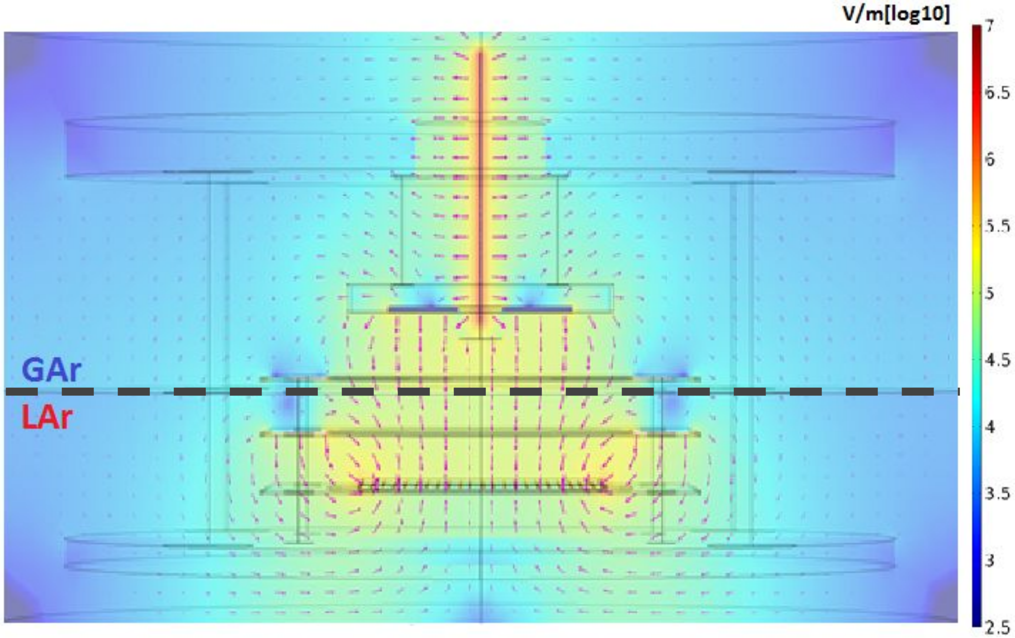




Electric field simulation

- Simulated static electric field using finite element analysis in COMSOL and a simplified version of as-built geometry.



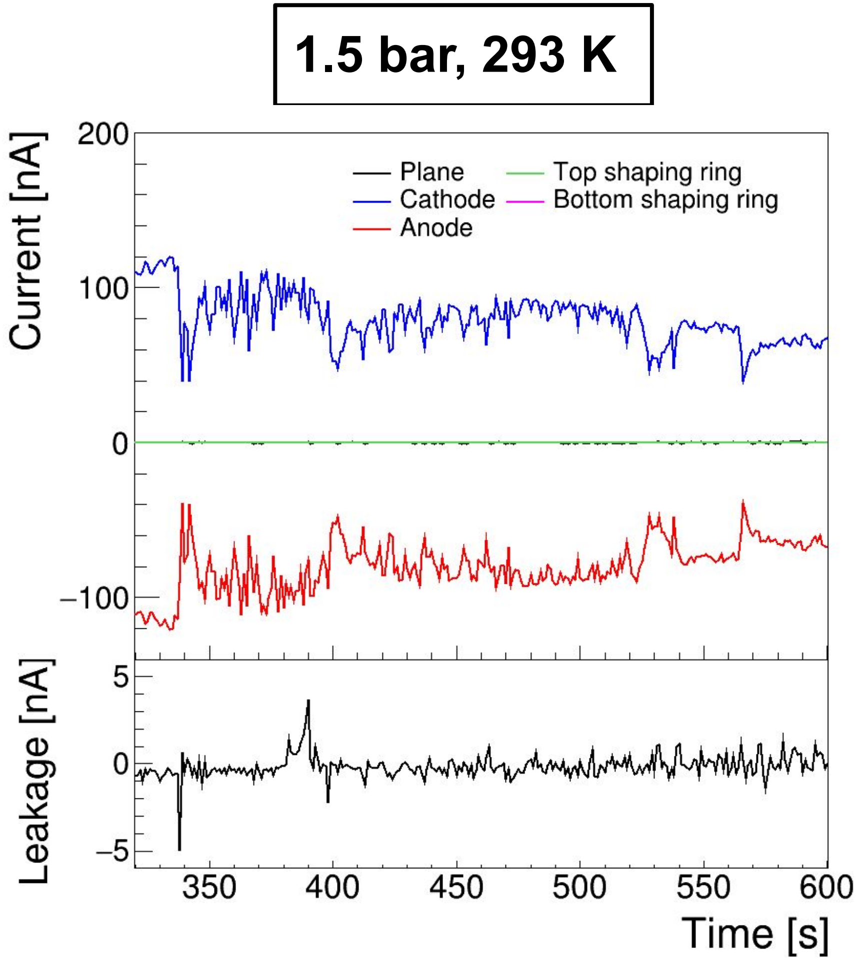


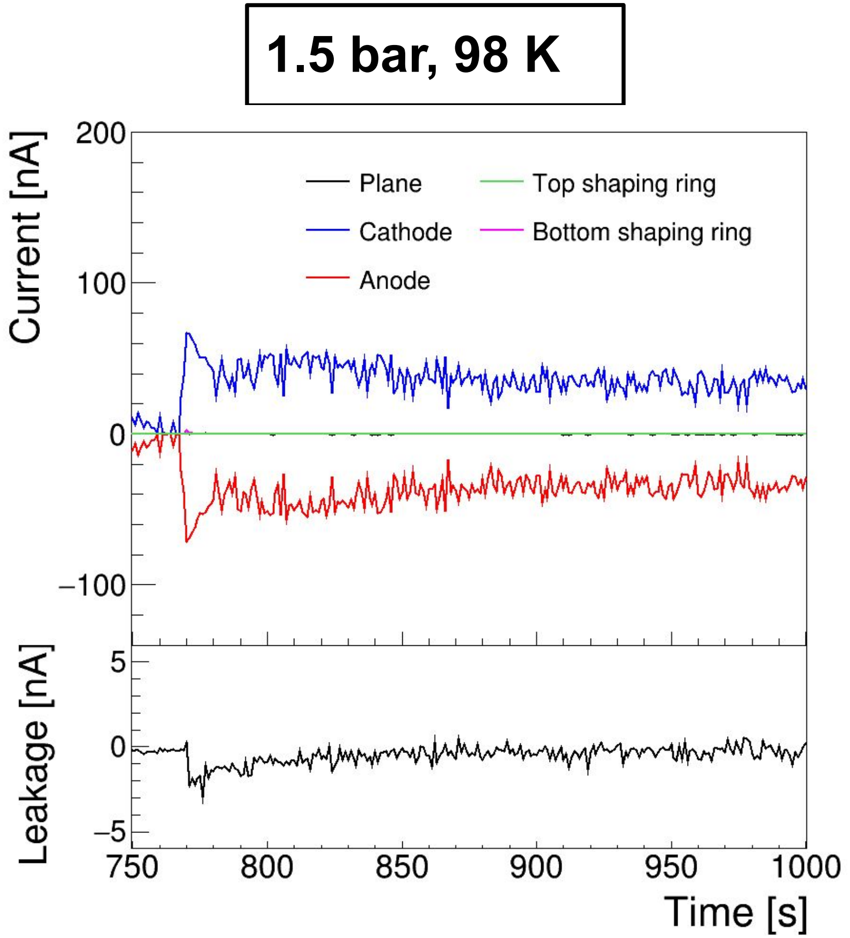
	Ar gas (293 K)	Ar gas (98 K)	Ar liquid (87.3 K)
ε_r	1.000516	1.00155	1.49545

- Needle at 3.1 kV, plane 0.95 kV, shaping rings grounded and cathode at -3 kV.

Commissioning with gas argon

- Collection efficiency defined as the ratio of the ion current produced in the anode and collected in the cathode, close to 100%.

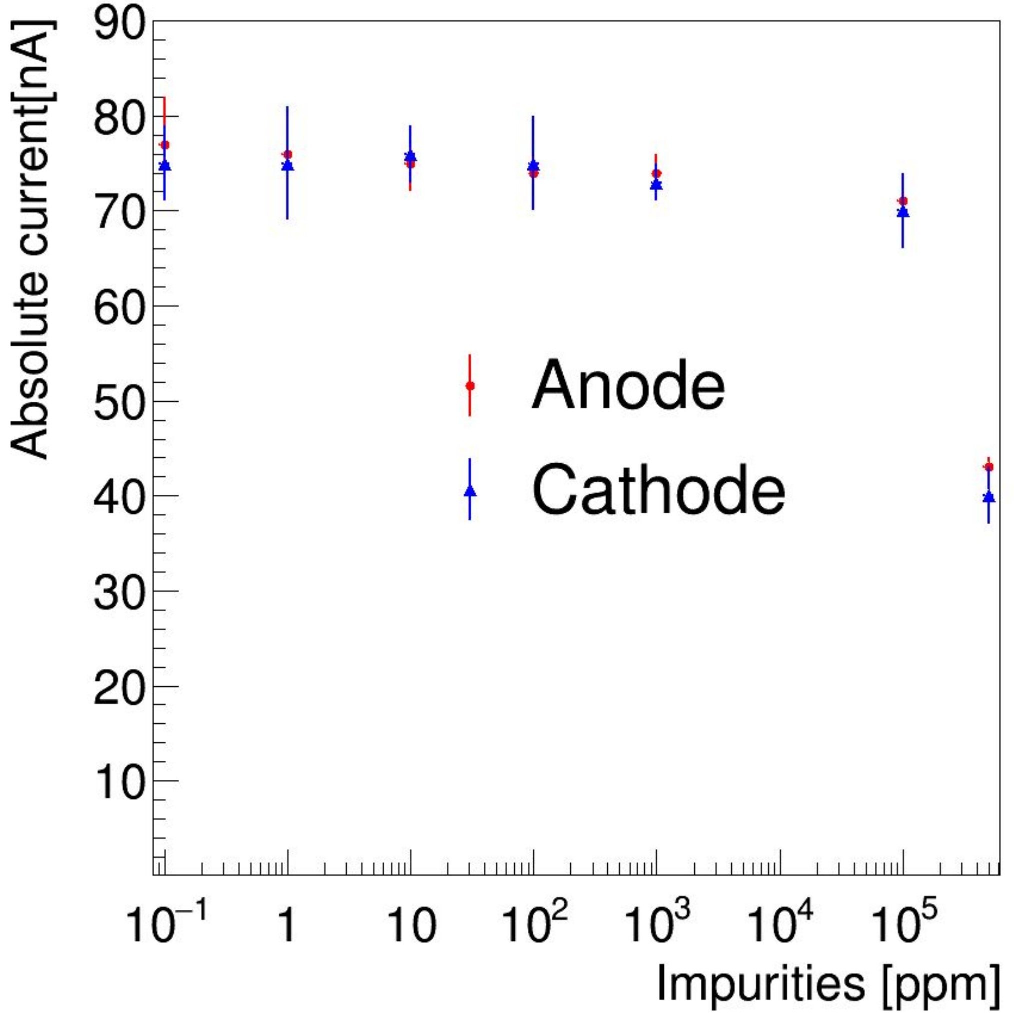




Impact of impurities in gas

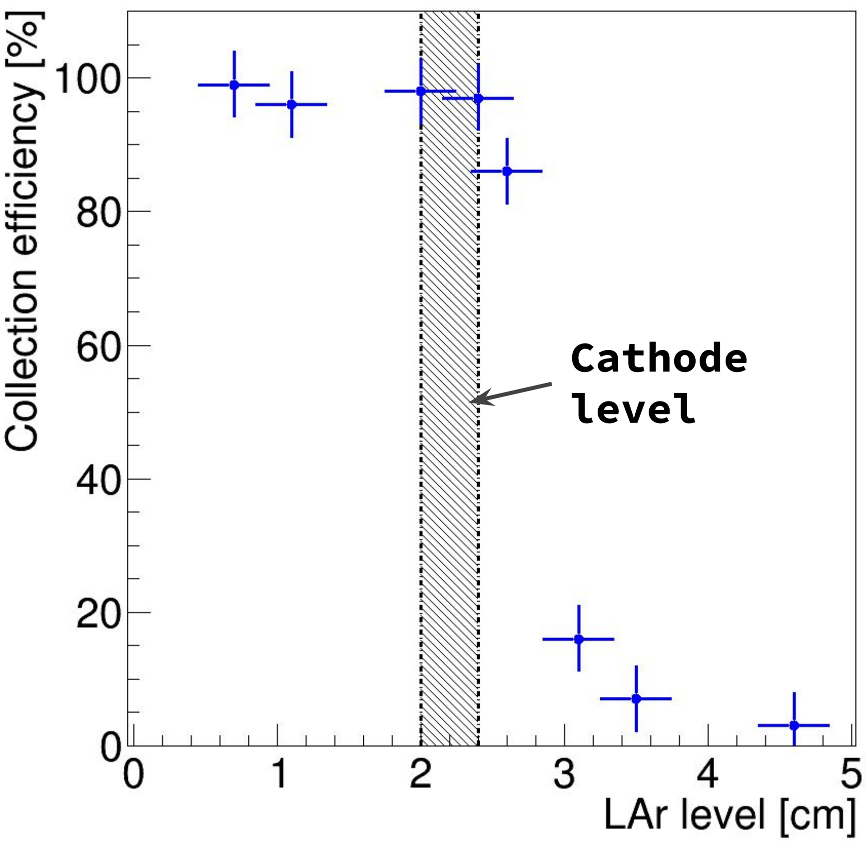
- The current at anode and cathode is measured with the same field and pressure conditions, but increasing the previous air level in the detector.

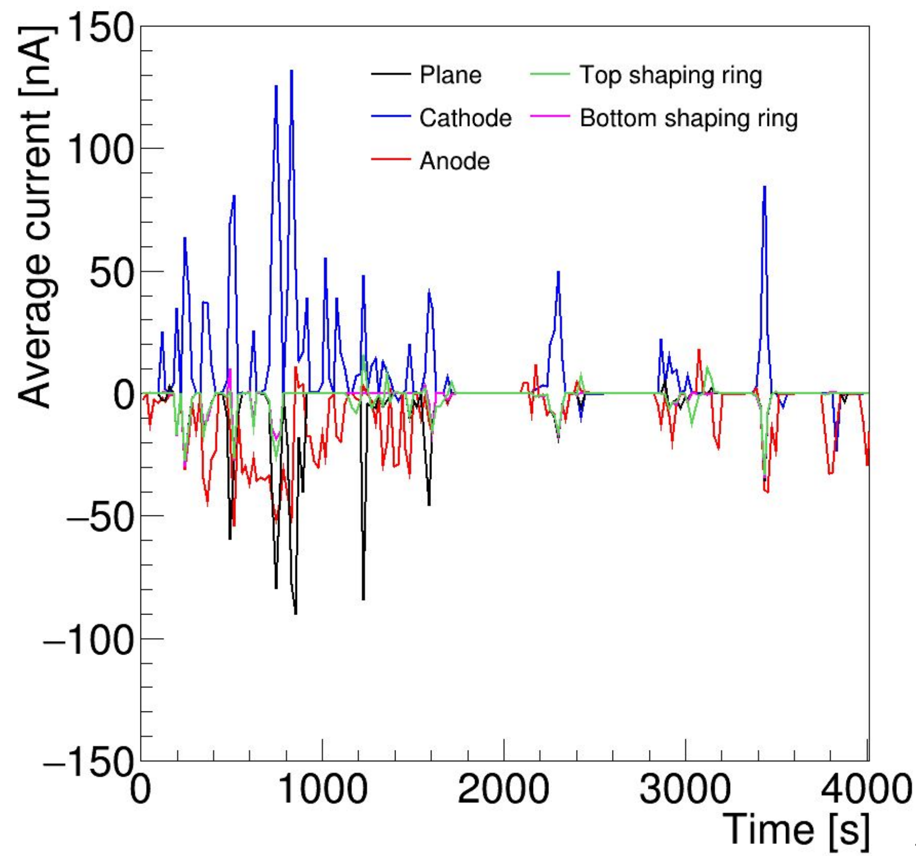
- The collection efficiency is independent of the initial vacuum level, thus the ion drift is not affected by impurities.



Liquid argon run

- The cathode is covered when liquid argon level is at 2 cm.
- A 15% collection efficiency is obtained with the cathode under 1 cm of liquid argon.



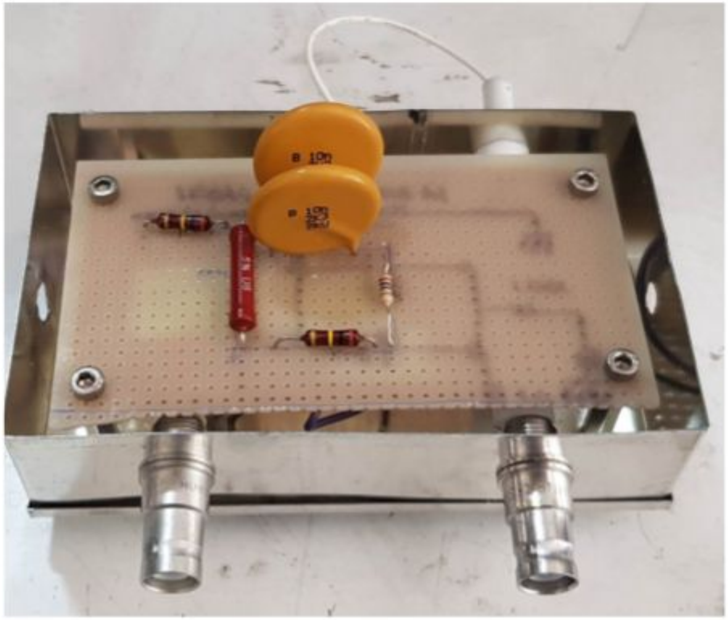


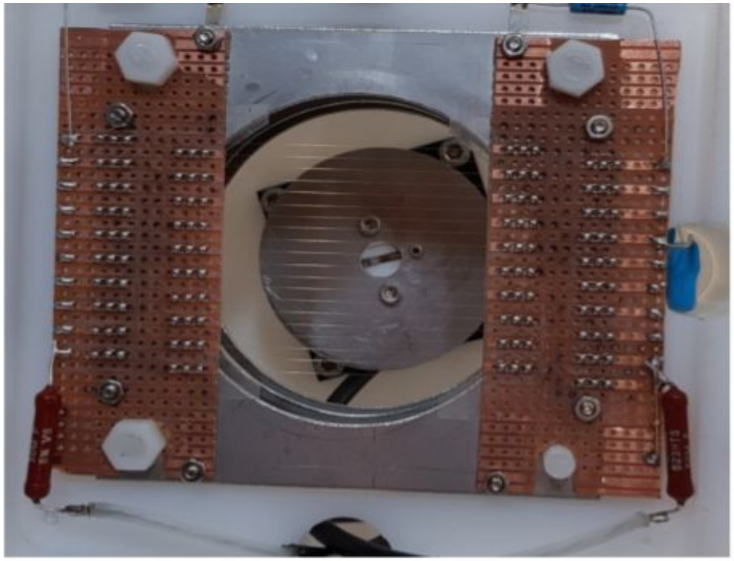
Results from liquid argon operation

- The ions are passing from the gas to the liquid phase.
- The ions accumulate in the liquid argon in front of the cathode due to its small mobility, producing a distortion of the electric field.
- Space charge effects generated in a small liquid argon detector.
- The operation with a continuous ion current has some limitations. For this reason, the setup has been modified in order to generate ion pulses in a controlled way.

Experimental upgrade

- The setup has been modified in order to generate ion pulses in a controlled way.
- An external circuit is designed to generate the ion pulses with in a controlled way. This signal is acquired with a 1 MHz oscilloscope.
- The wire plane is replaced by a double coplanar grid, in which each one of the two grids are at different potentials

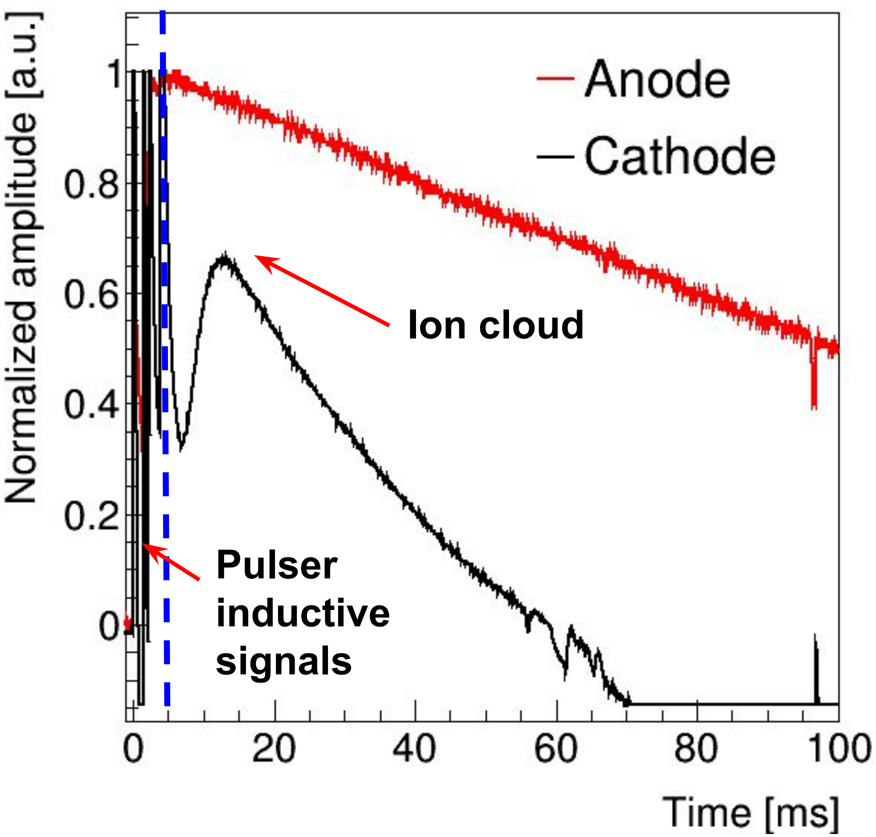


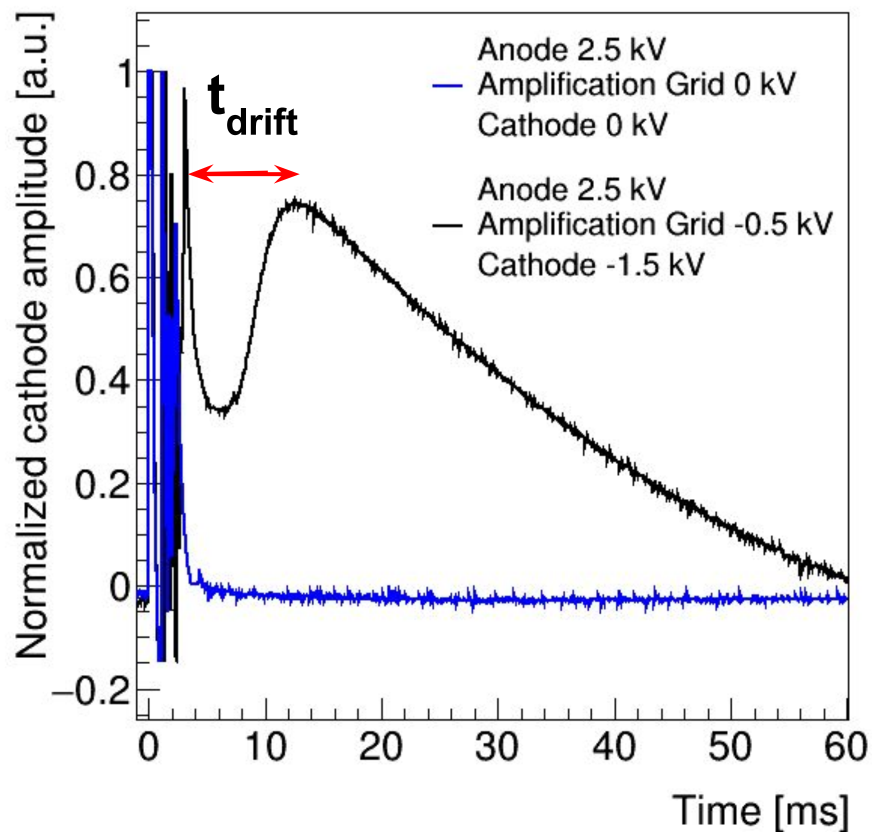


Operation with ion pulses

- Average signal detected at the cathode with a drift field of 200 V/cm and without it.

- The drift time of the ion cloud, t_{drift}, is estimated as the time difference between the maximum of the signal introduced in the anode and the average value of the bump detected in the cathode.





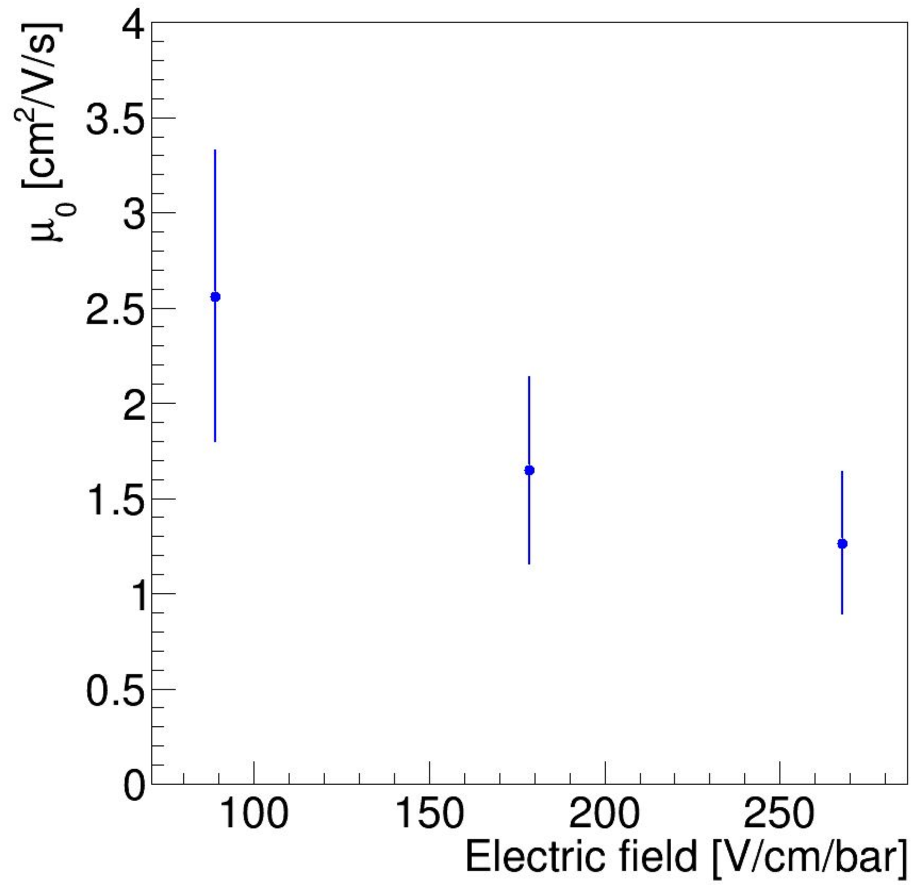
Ion mobility in gas argon

- Assuming that the field is uniform in the drift region, the ion drift mobility is:

$$\mu_0 = v_{drift} / E_{drift}$$

- Ion mobility values in the range [2.5-1.1] cm^2/V/bar are measured for drift fields between 80 and 280 V/cm/bar.

- These values are in good agreement with [3,4], confirming the capability of the setup to measure the ion drift velocity.



[3] Ion mobility measurements in Ar-CO_2 , Ne-CO2, and Ne-CO_2-N_2 mixtures, and the effect of water contents, Nucl. Instrum. Meth. A 904 (2018), 1-8

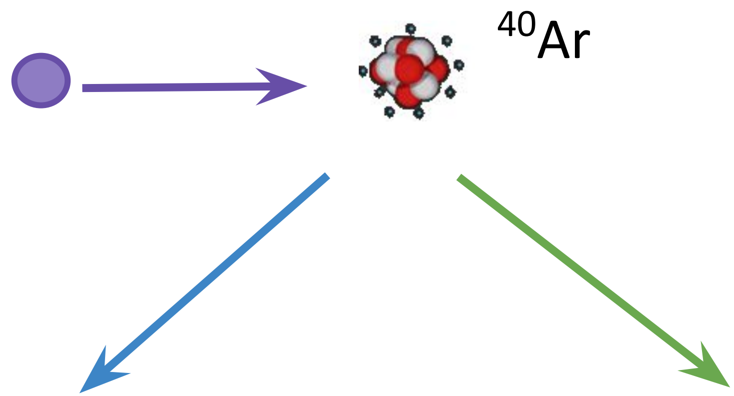
[4] Mobility of Argon ions in argon, Physics Letters A, Volume 25 (1967), 407-408

Conclusions

- We designed and constructed a small detector able to reproduce space charge effects typically produced in large liquid argon TPCs.
- A first evidence of ion feedback from the gas into the liquid phase is presented.
- The detector has been upgraded to operate with ion pulses generated in a controlled way. It has been commissioned with argon gas successfully. More detailed liquid argon operations are planned for 2021.
- A paper reporting the results presented in this talk is in preparation.

Thanks for your attention

Ar "Second continuum"



Excitation

$$e^- + Ar \rightarrow Ar^* + e^-$$

$Ar^* + Ar \rightarrow Ar^{v*}_2$ Excimer formation

$Ar^{v*}_2 + Ar \rightarrow Ar_2^* + Ar$ Relaxation

$Ar_2^* \rightarrow Ar + Ar + h\nu$ 128 nm

Radiative de-excitation and dissociation

Ionization

$$e^- + Ar \rightarrow Ar^+ + 2e^-$$

$Ar^+ + Ar \rightarrow Ar^+_2$ Molecular ion

$Ar^+_2 + e^- \rightarrow Ar^{**} + Ar$ Recombination

$Ar^{**} + Ar \rightarrow Ar^* + Ar + heat$ Excimer

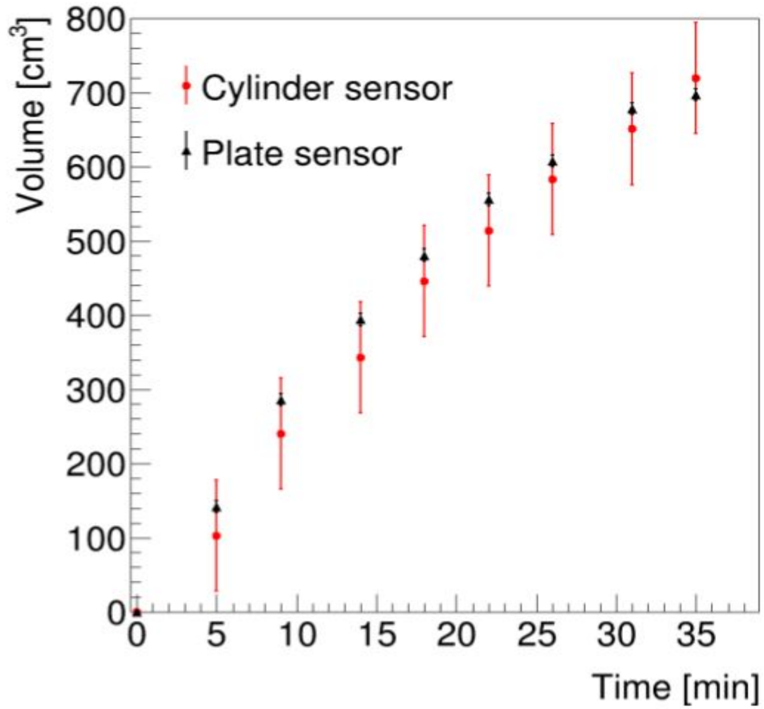
↓

Excitation process

↓

$h\nu$ 128 nm

Liquid argon level



- Two level sensors are installed inside the detector. They are fixed at vertical position with the bottom part at 0.5 cm under the cathode.
- The capacity without LN_2 and with the sensor totally covered are found in a specific test. The liquid argon level is estimated from:

$$C_{LAr} = \varepsilon_{LAr} / \varepsilon_{LN2} * C_{LN2}$$