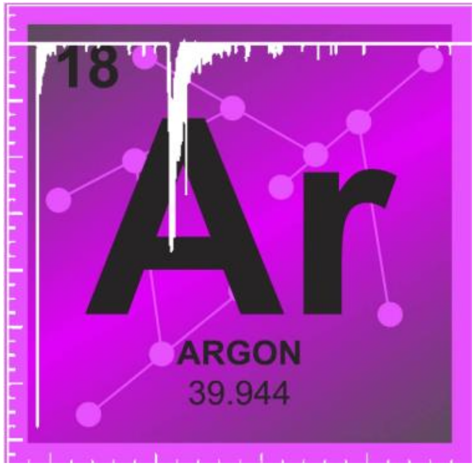
DRD Spanish meeting
Barcelona, 07 March 2023

Dark Matter R&D activities at CIEMAT



Roberto Santorelli
On behalf of the CIEMAT-DM group

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
cfp
CIEMAT
física de partículas

The CIEMAT–DM group

	Name	Position	Projects
	Luciano Romero Barajas	Staff researcher – Contacto	ArDM, CMS
	Pablo García Abia	Staff researcher – Contacto	DarkSide
	Vicente Pesudo Fortes	Postdoc, Research interests – Contacto	ArDM, DarkSide
	Ludovico Luzzi	PhD student – Contacto	DarkSide
	Miguel Cárdenas Montes	Staff researcher – Contacto	Computing
	Juan José Martínez Morales	Technician – Contacto	ArDM, DarkSide
	Ana Isabel Barrado Olmedo	– Contacto	ICPMS
	Marta Fernández Díaz	– Contacto	ICPMS
	Roberto Santorelli	Staff researcher – Contacto	ArDM, DarkSide
	Manuel Daniel Leal	Staff engineer – Contacto	ArDM, DarkSide
	Edgar Sánchez García	PhD student – Contacto	ArDM, DarkSide
	Rodrigo López Manzano	Technician – Contacto	ArDM, DarkSide
	José Manuel Cela Ruiz	Staff researcher – Contacto	LAr R&D
	Antonio Giménez Alcázar	Research assistant – Contacto	DEAP, DarkSide
	Estafanía Conde Vilda	– Contacto	ICPMS

http://darkmatter.ciemat.es/people

General aspects

- The direct search of WIMPs intrinsically requires a constant detector R&D to overcome the current experimental limits
    - *Scale-up*
    - *Lower threshold*
    - *Lower background ….*

- The CIEMAT-DM team has a long time experience in noble elements detector, and **LAr technology** in particular
    - *ICARUS*
    - *WARP-2.3L → WARP-100L*
    - *XENON10 → XENON100*
    - *ArDM, DEAP-3600, DarkSide-50*
    - *GADMC → DarkSide-20k → ARGO*

- The R&D is constant in this field, and it goes in parallel with physics (no sharp separation between experiment activity and R&D)

CIEMAT

Mill: 4×1×1 m in controlled environment

- ***R&D fundamental for CIEMAT***

- Machine shop
  - Laboratorio Nacional de Referencia de Metrología
    - Dosimetria….

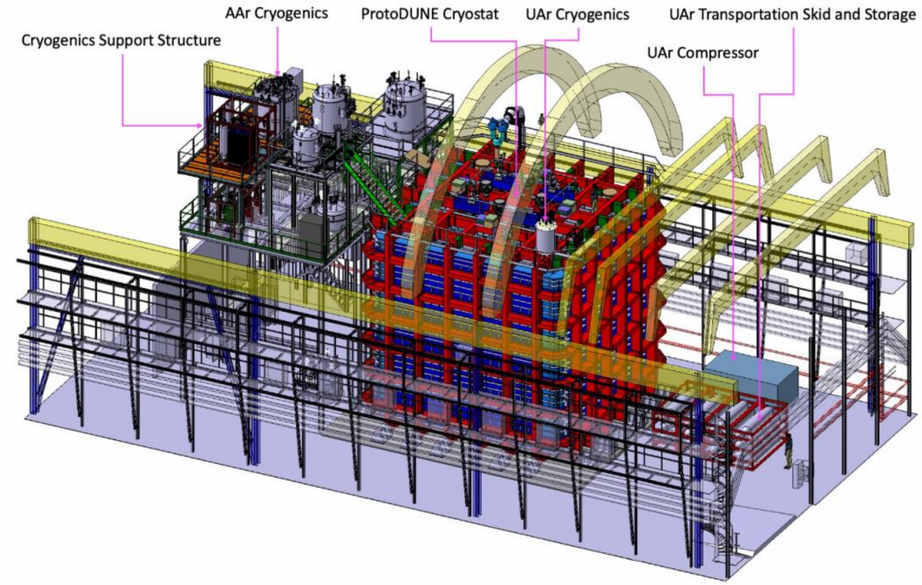
R&D activity @ CIEMAT

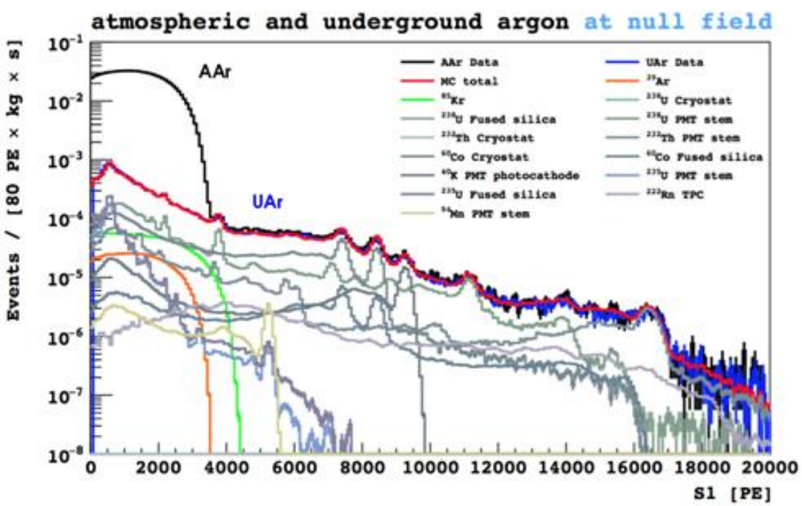
- Radiopurity
- Light emission
- Charge drift

Radiopurity

GADMC: ~500 people, about 100 Institutions

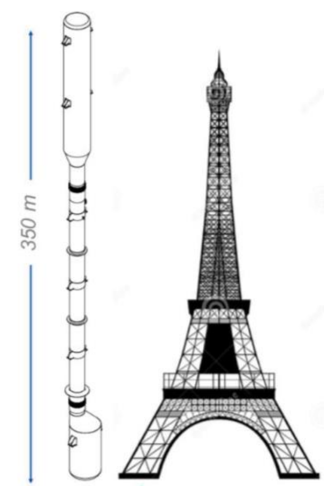
DarkSide-20k





- **URANIA** project: Procurement of UAr extracted from the CO_2 wells in Cortez mine, Colorado (~330 kg/d, 99.99% purity) → Plant in construction

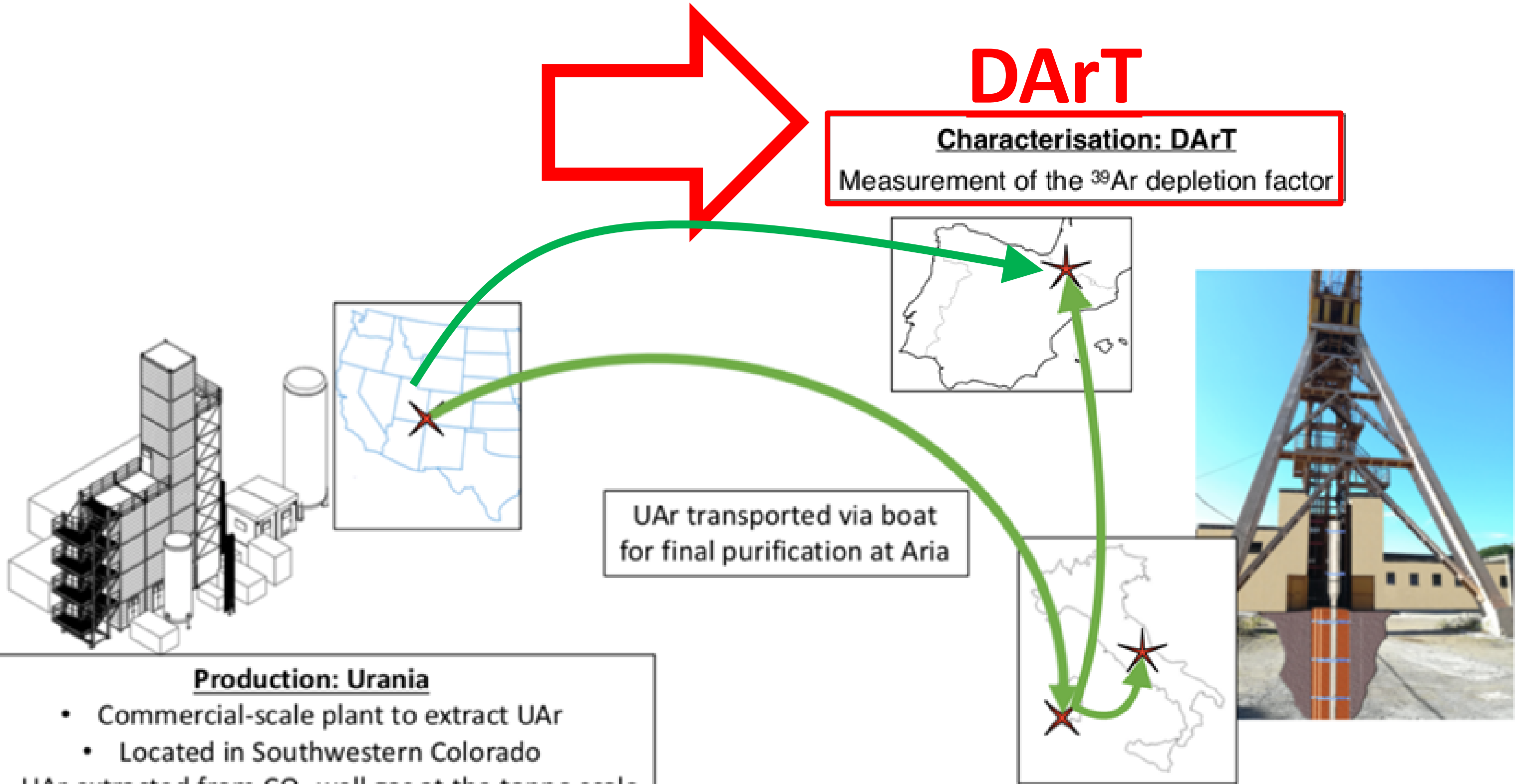
- **ARIA** project: Ar chemical purification and isotopic separation by cryogenic distillation (Sardinia, Italy)



Radiopurity

DArT

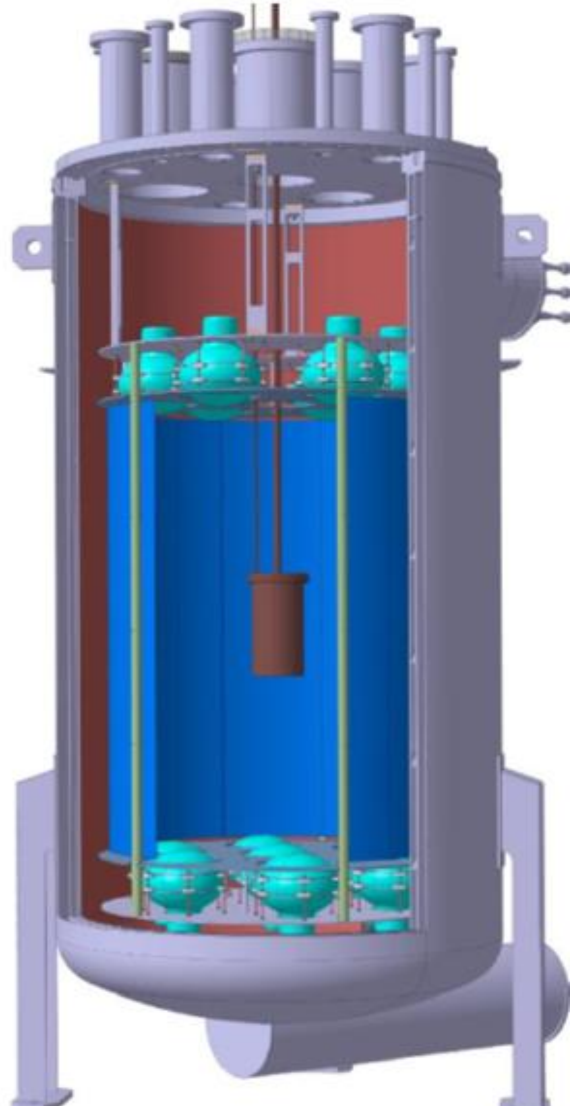
Characterisation: DArT
Measurement of the ^{39}Ar depletion factor

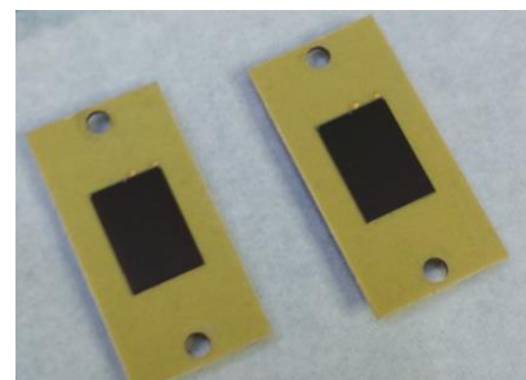


Production: Urania
- Commercial-scale plant to extract UAr
- Located in Southwestern Colorado
- UAr extracted from CO_2 well gas at the tonne scale

Purification: Aria
- 350 m tall cryogenic distillation column to purify UAr and isotopically separate argon and other elements
- Located in refurbished carbon mine shaft in Sardinia, Italy
- Will chemically purify the UAr for DS-20k to detector grade

Radiopurity





1 cm^2 radiopure SiPMs

Radiopurity

- Collaboration **CIEMAT+Unizar** (+Italy+France+Canada)

  CIEMAT: 2.0 FTE Senior + 1.5 FTE PhD + 0.1 Eng + 1 Tech.

  ⮡ (ONLY DETECTOR)

  Unizar: 0.5 FTE Senior + 0.5 FTE PhD + 0.1 Eng

- Clear Spanish leadership:
  - technical coordination of DArT
  - Responsibility for the whole detector’s radiopurity and background of DS-20k

"*Design and Construction of a New Detector to Measure Ultra-Low Radioactive-Isotope Contamination of Argon*"
JINST 15 (2020) 02, P02024

- Coordination of the WG “(a,n) background for rare events searches“

- Funding scheme of the Spanish groups: P.N. (+ DArT international funds)

DArT Collaboration meeting @ LSC. April 2022

Radiopurity

Snowmass2021 White Paper

A Facility for Low-Radioactivity Underground Argon

Henning O. Back[1,*,†,‡], Walter Bonivento[2,§], Mark Boulay[3,‡,**], Eric Church[1,††], Steven R. Elliott[4,‡‡], Federico Gabriele[5,§], Cristiano Galbiati[6,7,§§], Graham K. Giovanetti[8,§§], Christopher Jackson[1,††], Art McDonald[9,§§,**], Andrew Renshaw[10,‡], Roberto Santorelli[11,***], Kate Scholberg[12,††,†††], Marino Simeone[13,‡], Rex Tayloe[14,†††], Richard Van de Water[4,‡‡‡]

1. Pacific Northwest National Laboratory, Richland, Washington 99352, USA
2. INFN Cagliari, Cagliari 09042, Italy
3. Carleton University, Ottawa, Ontario K1S 5B6, Canada
4. Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
5. INFN Laboratori Nazionali del Gran Sasso, Assergi (AQ) 67100, Italy
6. Princeton University, Princeton, NJ 08544, USA
7. Gran Sasso Science Institute, L'Aquila 67100, Italy
8. Williams College, Williamstown, MA 01267 USA
9. Queen's University, Kingston, ON K7L 3N6, Canada
10. University of Houston, Houston, Texas 77204, USA
11. CIEMAT, Madrid 28040, Spain
12. Duke University, Durham, North Carolina 27708, USA
13. Università degli Studi di Napoli "Federico II", Napoli 80125, Italy
14. Indiana University, Bloomington, Indiana 47405, USA

Abstract/Executive summary

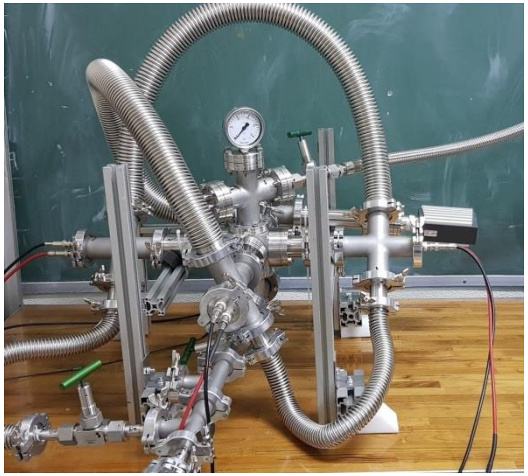
The DarkSide-50 experiment demonstrated the ability to extract and purify argon from deep underground sources and showed that the concentration of ^{39}Ar in that argon was greatly reduced from the level found in argon derived from the atmosphere. That discovery broadened the physics reach of argon-based detector and created a demand for low-radioactivity underground argon (UAr) in high-energy physics, nuclear physics, and in environmental and allied sciences. The Global Argon Dark Matter Collaboration (GADMC) is preparing to produce UAr for DarkSide-20k, but a general UAr supply for the community does not exist. With the proper resources, those plants could be operated as a facility to supply UAr for most of the experiments after the DarkSide-20k production. However, if the current source becomes unavailable, or UAr masses greater than what is available from the current source is needed, then a new source must be found. To find a new source will require understanding the production of the radioactive argon isotopes underground in a gas field, and the ability to measure ^{37}Ar, ^{39}Ar, and ^{42}Ar to ultra-low levels. The operation of a facility creates a need for ancillary systems to monitor for ^{37}Ar, ^{39}Ar, or ^{42}Ar infiltration either directly or indirectly, which can also be used to vet the ^{37}Ar, ^{39}Ar, and ^{42}Ar levels in a new UAr source, but requires the ability to separate UAr from the matrix well gas. Finding methods to work with industry to find gas streams enriched in UAr, or to commercialize a UAr facility, are highly desirable.

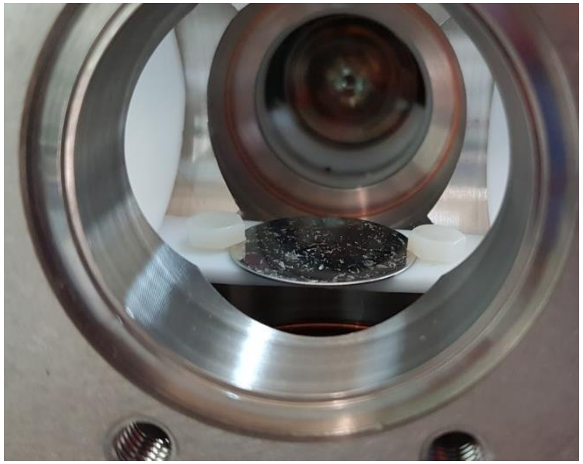
* *Corresponding author. PNNL, 902 Battelle blvd., P.O. Box 999, MSIN J4-65, Richland, WA 99352 Email:henning.back@pnnl.gov*

† Representing environment and applied sciences
‡ Representing the Urania portion of GADMC/Darkside-20k
§ Representing the Aria portion of GADMC/Darkside-20k
** Representing the DEAP-3600 collaboration
†† Representing the DUNE-like detector
‡‡ Representing the LEGEND collaboration
§§ Representing the GADMC/Darkside-20k collaboration
*** Representing the DART portion of GADMC/Darkside-20k
††† Representing the COHERENT collaboration
‡‡‡ Representing the Coherent Captain-Mills (CCM) collaboration

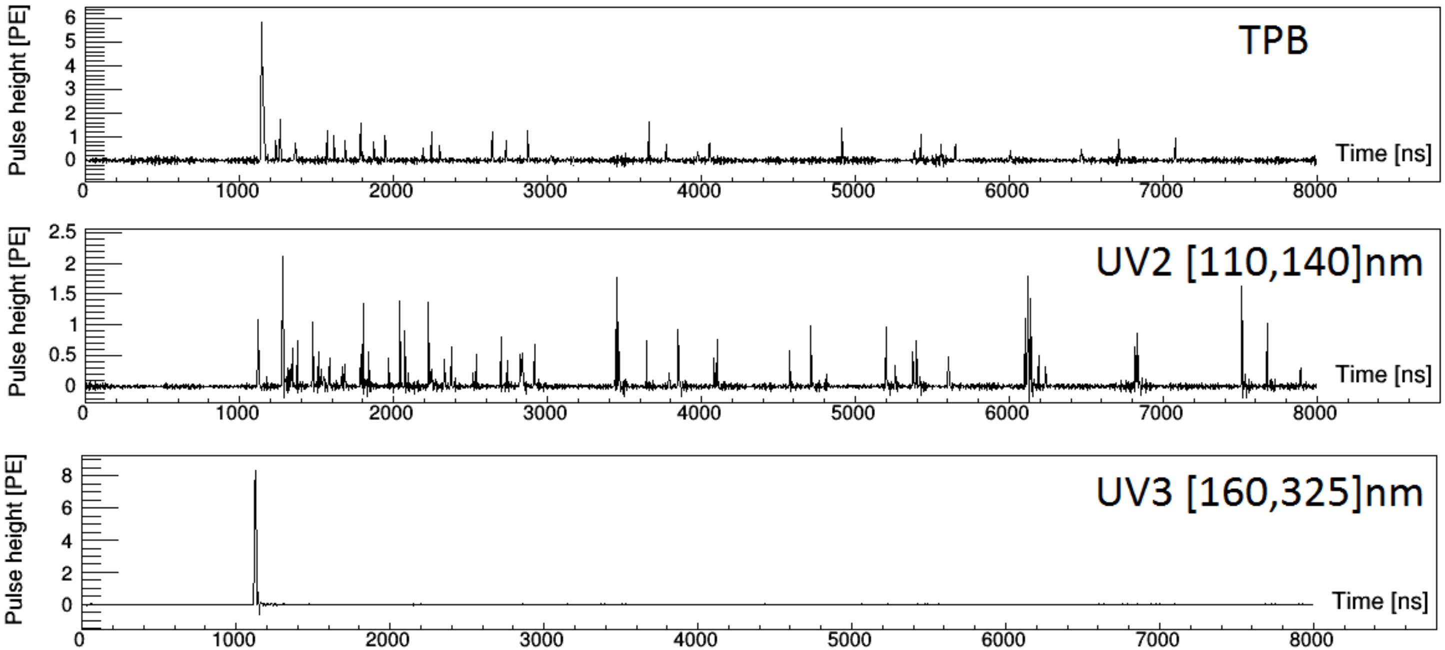
LEGEND + DUNE + GADMC + COHERENT

Ar-light emission





ArDis: Proposal funded through the EXPLORA project **FPA2017-92505-EXP**
LArDis: ERC starting grant **A+A**



Mechanisms leading to scintillation mainly in the region 180-300 nm grouped under the generic denomination of

"3rd continuum"

Ar-light emission

Eur. Phys. J. C (2021) 81:622
https://doi.org/10.1140/epjc/s10052-021-09375-3
The European Physical Journal C

Regular Article - Experimental Physics

Spectroscopic analysis of the gaseous argon scintillation with a wavelength sensitive particle detector

R. Santorelli[1,a], E. Sanchez Garcia[1,b], P. Garcia Abia[1], D. González-Díaz[2], R. Lopez Manzano[1], J. J. Martinez Morales[1], V. Pesudo[1], L. Romero[1]
[1] CIEMAT, Division de Física de Particulas, Avda. Complutense, 40, Madrid, Spain
[2] IGFAE, Campus Vida, Rúa Xosé María Suárez Núñez, s/n, Santiago de Compostela, Spain

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Abstract We performed a time-resolved spectroscopic study of the VUV/UV scintillation of gaseous argon as a function of pressure and electric field, by means of a wavelength sensitive detector operated with different radioactive sources. Our work conveys new evidence of distinctive features of the argon light which are in contrast with the general assumption that, for particle detection purposes, the scintillation can be considered to be largely monochromatic at 128 nm (second continuum). The wavelength and time-resolved analysis of the photon emission reveal that the dominant component of the argon scintillation during the first tens of ns is in the range [160, 325] nm. This light is consistent with the third continuum emission from highly charged argon ions/molecules. This component of the scintillation is field-independent up to 25 V/cm/bar and shows a very mild dependence with pressure in the range [1, 16] bar. The dynamics of the second continuum emission is dominated by the excimer formation time, whose variation as a function of pressure has been measured. Additionally, the time and pressure-dependent features of electron-ion recombination, in the second continuum band, have been measured. This study opens new paths toward a novel particle identification technique based on the spectral information of the noble-elements scintillation light.

1 Introduction

Over the last decade, argon and xenon detectors have attracted a lot of interest for their use in direct dark matter search [1–5] and neutrino experiments [6–8], given their unique ionization and scintillation properties. These experiments use high-purity noble elements as both interaction target and tracking medium for particles, attaining overall performances better than the ones reachable with other technologies. In gas phase, their exceptional calorimetric properties are used for instance in [9,10].

A central aspect of either single or dual phase (gas-liquid) noble element detectors is their efficient collection and detection of the vacuum ultraviolet (VUV) scintillation photons, which provides calorimetric data, event time for the 3D event reconstruction, and particle identification capability [11,12]. Experimental information, obtained largely from the closely related fields of photo-chemistry, plasma and laser physics, allows attributing this characteristic scintillation to the bond created between excited and ground state atoms through 3-body collisions (see, e.g., [13]). The resulting singlet and triplet excimer states (Rydberg states with a dimer core and a binding electron) undergo radiative de-excitation, giving rise to the so-called *second excimer continuum*. It is typically assumed that this feature dominates the scintillation spectrum for gas pressures above 100 mbar, and results in relatively narrow emission bands (≈ 10 nm wide) at 128 nm (argon) and 172 nm (xenon) [10,14].

Under the above paradigm, there has been so far little motivation towards exploiting spectroscopic information in this kind of particle detectors. As a consequence, the light detection systems of argon and xenon chambers are based on broad-band optical sensors, possibly coupled to photon wavelength-shifters, that effectively integrate the light signal over a wide spectral range, missing the potential information provided by the scintillation wavelength.

Indeed, studies were carried out (mostly prior to the 00's) to investigate the temporal evolution of characteristic spectral components of argon and xenon scintillation with strong X-ray [15], electron [16–18], proton [19] or heavy ion [20,21] beams. Although a high intensity beam is a simple way to produce the photon yields required to study scintillation with high spectroscopic detail, it is known to potentially introduce spurious effects such as heating, volume recombination,

[a] e-mail: r.santorelli@ciemat.es (corresponding author)
[b] e-mail: edgar.sanchez@ciemat.es (corresponding author)

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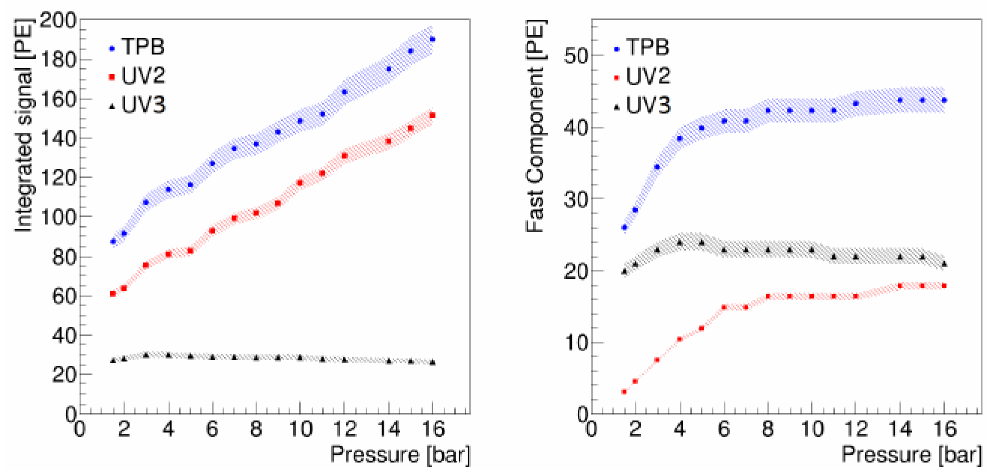
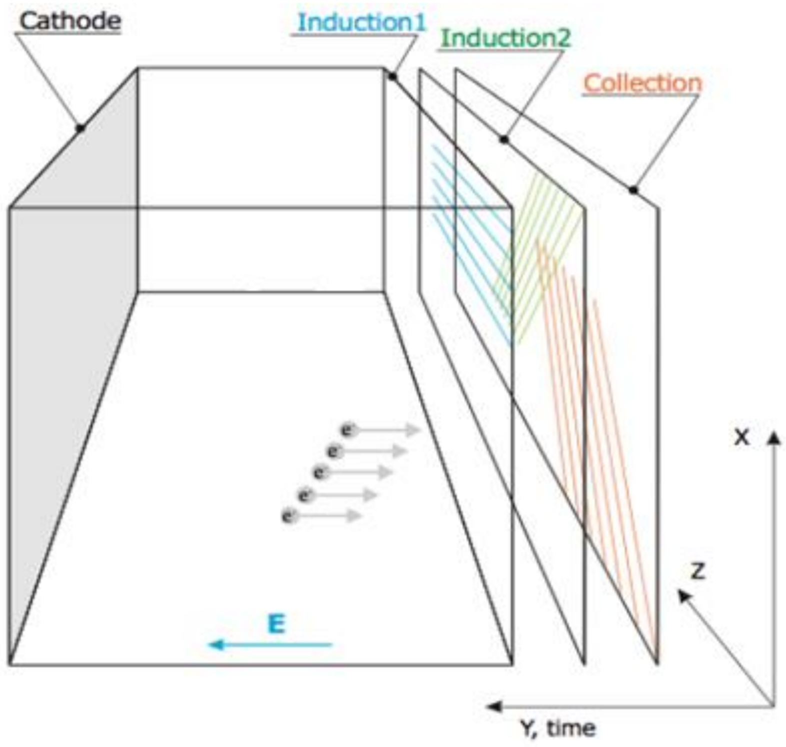


“This study opens new paths toward a novel particle identification technique based on the spectral information of the noble-elements scintillation light”

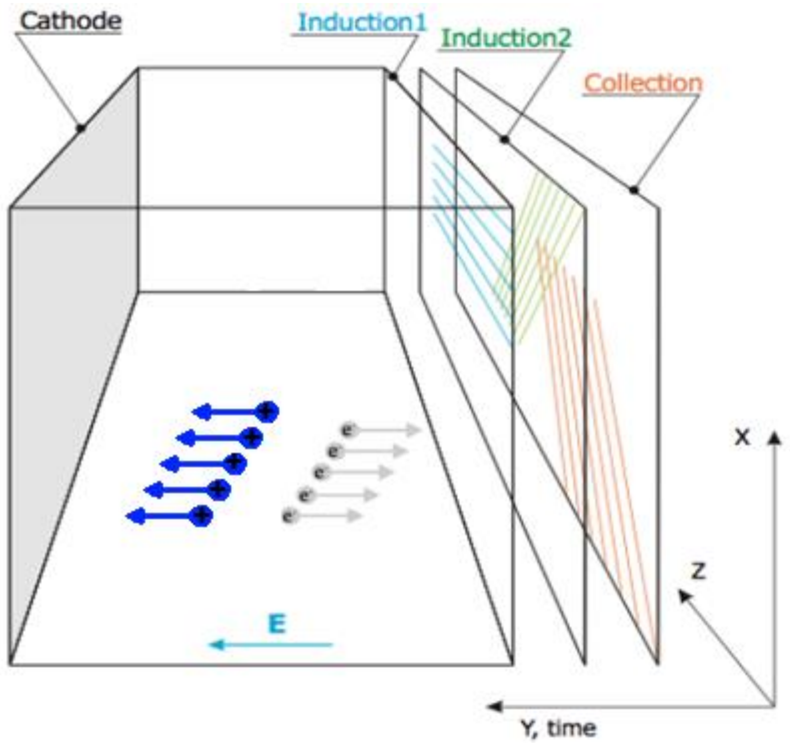
CIEMAT: 0.5 FTE Senior
0.5 FTE PhD
0.1 FTE Eng
0.5 FTE Tech.

Similar study in XENON with *USC*

Ar-charge drift



Ar-charge drift



Space charge

- ρ_i depends on:
  - ➢ Amount of ionization (event energy and rate)
  - ➢ Total drift length
  - ➢ Ion velocity (E_d and mobility)

➢ ***Drift velocity:***

$v_i \sim 10\ mm/s$ to be compared to $v_e \sim 2\ m/ms$ (E_d=1 kV/cm)

➢ ***Drift distance:***

…up to 12 m !

➢ ***"Ion yield":***

❖ Underground:

- "Dominant" contribution from ^{39}Ar (~1 Bq/kg or ~1.4 kBq/m3)
- Q-value of 565 keV, 1/3 mean energy, One decay 8e3 pairs,
- Mean deposited energy **263 MeV/m³/s**, h_0 ~ 1.1e7 pairs/m³/s

❖ Surface:

- Dominant contribution from muons (≈168 muons/m²/s)
- Minimum ionizing energy: $\frac{dE}{dl} \approx 1.5\ \frac{MeV\ cm^2}{g}$
- Mean deposited energy ≈ **35 GeV/m³/s,** $h_0 \approx$ 1.5e9 pairs/m³/s

Ar-charge drift

Electron and ion fluxes as $j_{i,e}(l) = v_{i,e}(l)\rho_{i,e}(l)$ $\quad v_{i,e}(l) = \mu_{i,e} E_d(l)$

The recombination rate is given by $r(l) = j_e(l)\rho_i(l)S_{cs}(l) \Rightarrow r(l) = j_e(l)j_i(l)\frac{q}{\mu_i \varepsilon E_d^2(l)}$

We can determine the recombination rate in LAr knowing the currents and the drift field.
In a stationary state the density variation is null at any l:

$$\mathrm{h} - \mathrm{r(l)} - \frac{dj_i(l)}{dl} = 0 \qquad \frac{dj_i(l)}{dl} + j_e(l)j_i(l)\frac{q}{\mu_i \varepsilon E_d^2(l)} = \mathrm{h}$$

(h constant ionization rate)

$$\mathrm{h} - \mathrm{r(l)} + \frac{dj_e(l)}{dl} = 0 \qquad \frac{dj_e(l)}{dl} - j_e(l)j_i(l)\frac{q}{\mu_i \varepsilon E_d^2(l)} = -\mathrm{h}$$

At the same time the variation of the drift field is determined by
the charge density: $\varepsilon\frac{dE_d(l)}{dl} = q \cdot \rho_i\,(l) - q \cdot \rho_e\,(l)$ $\quad \rho_i \gg \rho_e \quad \frac{dE_d^2(l)}{dl} = \frac{2q}{\mu_i \varepsilon} j_i$

These are three coupled differential equations with three functions (j_e, j_i, E_d) and a variable l

Boundary conditions

- $E_d(0) = E_A$
- $j_e(L) = 0$
- $j_i(0) = G_I \cdot j_e(0)$

Ar-charge drift

The field variation is a function of l

$$E_d(l) = \sqrt{\frac{q}{\varepsilon\mu_i}\left(hl^2 + 2j_i(0)l\right) + E_A^2}$$

The field is minimum at 0 ($E_d(L) = E_A$) and maximum at the cathode

The cathode voltage necessary to obtain a given field can be calculated integrating the drift field

$$V(l) = \int_0^L E_d(l)dl$$

The secondary recombination probability is equal to the fraction of the surface S(l) spanned the filed lines ending on the anode with respect to the total anode (cathode) area.

$$P(l) = \frac{S(l)}{S(0)} = \frac{E(0)}{E(l)} = \frac{E_A}{\sqrt{\frac{q}{\varepsilon\mu_i}\left(hl^2 + 2j_i(0)l\right) + E_A^2}}$$

Field variation, cathode voltage and secondary recombination probability can be calculated knowing the constant ionization rate, the field at the anode and ion gain G_i

Ar-charge drift

Astroparticle Physics 92 (2017) 11–20

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journal homepage: www.elsevier.com/locate/astropartphys

Dynamics of the ions in liquid argon detectors and electron signal quenching

Luciano Romero, Roberto Santorelli*, Bárbara Montes

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Av. Complutense 40, Madrid 28040, Spain

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Neutrino
Dark matter

A B S T R A C T

A study of the dynamics of the positive charges in liquid argon has been carried out in the context of the future massive time projection chambers proposed for dark matter and neutrino physics. Given their small mobility coefficient in liquid argon, the ions spend a considerably longer time in the active volume with respect to the electrons. The positive charge density can be additionally increased by the injection, in the liquid volume, of the ions produced by the electron multiplying devices located in gas argon. The impact of the ion current on the uniformity of the field has been evaluated as well as the probability of the charge signal quenching due to the electron–ion recombination along the drift. The study results show some potential concerns for massive detectors with drift of many meters operated on surface.

1. Introduction

Liquid argon (LAr) detectors have been widely used during recent years in several fields ranging from neutrino physics [1–3] to direct dark matter searches [4–6], given their particle identification and low energy threshold capabilities in large active volumes [7]. In particular a massive liquid argon time projection chamber (LAr-TPC) is the chosen design for the next generation of underground neutrino observatories recently proposed [8].

Particle interactions in argon produce simultaneous excitation and ionization of the atoms, generating VUV photons and ion/electron pairs. In a typical LAr-TPC, photon sensors are used to detect the scintillation light, while a constant electric field $\vec{E}_d$ drifts the electrons to the anode. The charge readout can be carried out through the collection of the electrons on thin wires placed directly in the liquid [9] or, for double phase liquid–vapor detectors, through their extraction to a gas region placed above the sensitive volume [10]. In this case, a Townsend avalanche can be induced through high electric fields, producing an amplified signal proportional to the number of primary electrons extracted from the liquid phase.

Both single and double phase options are presently investigated for the DUNE experiment [8], with maximum electron drifts of 3.6 m and 12 m, respectively. Other experiments foreseeing drift up to 20 m have been recently proposed [11–14], which require a considerable technological effort to maintain a level of contamination less than 60 ppt of O_2 equivalent [15] (electron half life > 5 ms [16]), in order to reduce the impact of the electron quenching by electronegative impurities contaminating the LAr bulk. A direct charge readout with the wires in a single phase chamber has the advantage of an overall simplified detector design, while the amplification in the gas phase makes it possible to detect smaller charge signals, thus allowing it to reach a lower energy threshold, or to exploit longer drift distances with respect to the single phase design.

The positive and negative charges, produced by the particle interactions in the liquid, drift to the cathode and the anode following the same field lines, although the former have a drift speed which is six orders of magnitude lower than the latter ($v_i \ll v_e$) [17,18]. As a consequence, the positive ions spend more time in the liquid before they get collected on the cathode and neutralized, and the ion charge density is much larger than that of the electrons ($\rho_i \gg \rho_e$). This effect can be particularly relevant for double phase detectors foreseeing large charge amplification factors, where the ions, created in the vapor volume, may drift back to the cathode crossing the gas–liquid interface and further increase the ρ_i in the active volume. The space charge can locally modify the amplitude of the electric field, the drift lines and the velocity of the electrons produced in the liquid, leading to a displacement in the reconstructed position of the ionization signal. Additionally, the positive density ρ_i can be sizable such that the probability of a "secondary electron/ion recombination", different than the primary electron/parent-ion columnar recombination

* Corresponding author.
E-mail address: roberto.santorelli@ciemat.es (R. Santorelli).

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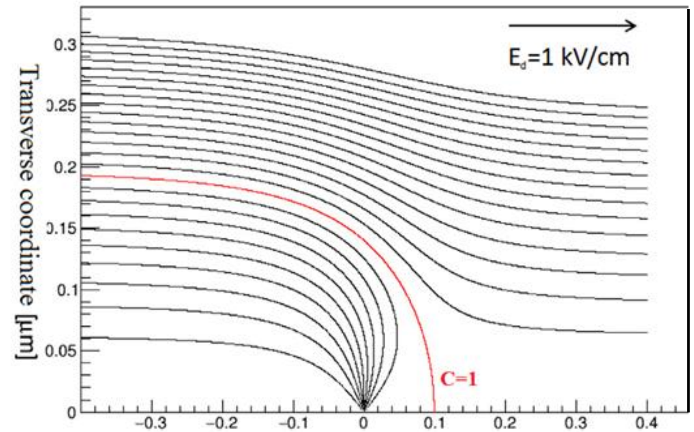
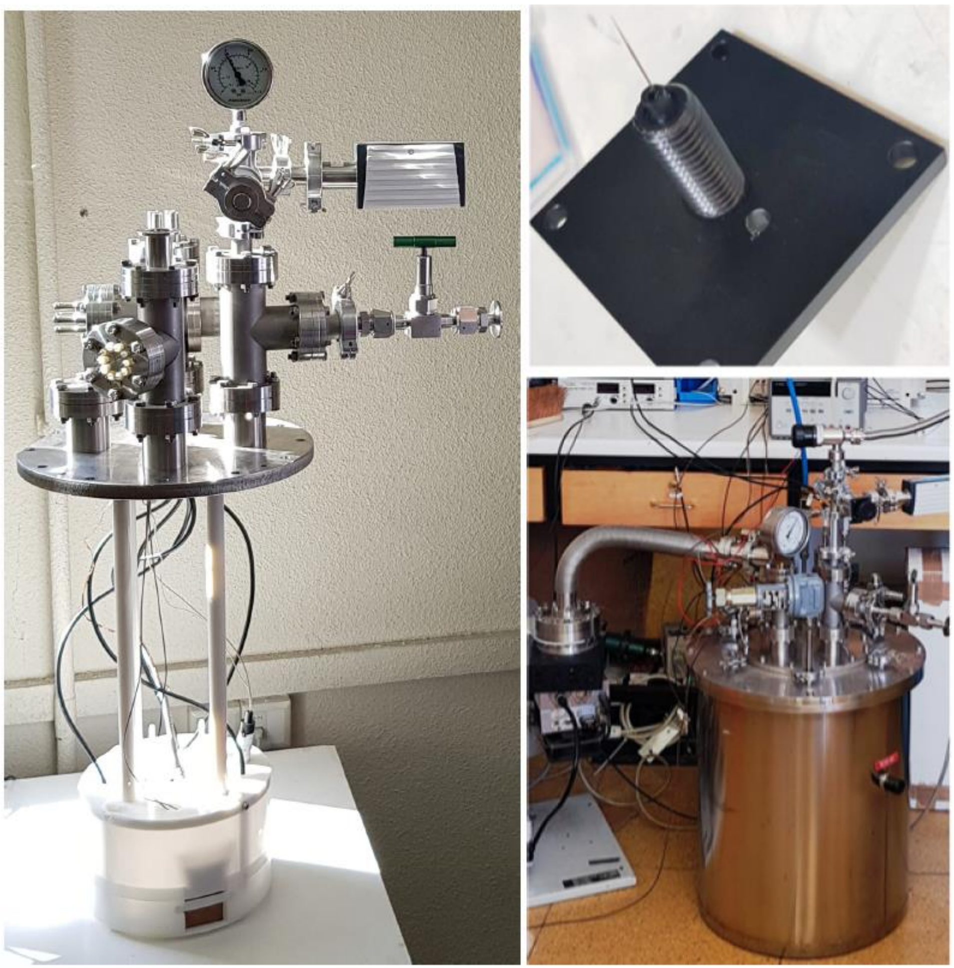


- Quantitative evaluation of the charge signal quenching as a function of the drift field and ionization rate
- Prediction of a constant light emission in argon by secondary electron/ion recombination
- *"To the best of our knowledge, the study evidences, for the first time, an intrinsic limit for the maximum practical drift obtainable with a TPC operated with natural argon, even in case of a null electronegative impurities concentration."*

Ar-charge drift

ArIon



CIEMAT + IFAE

- *"Impact of the positive ion current on large size neutrino detectors and delayed photon emission"* JINST 13 (2018) 04
- *"Experimental Study of the Positive Ion Feedback from Gas to Liquid in a Dual-Phase Argon Chamber and Measurement of the Ion Mobility in Argon Gas"* Universe 8 (2022) 2, 134

➢ Local funds, expertise fundamental

➢ **CIEMAT:** **0.5 FTE Senior**
0.1 FTE Eng
0.2 FTE Tech.

Summary

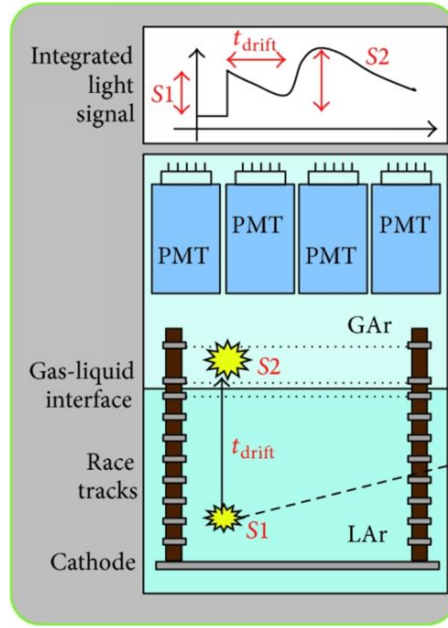
- *"Measurement of the Argon Purity by ICP-MS and Results of the Analysis of the Gas Used for the MicroBooNE Experiment"*, arXiv:2303.00816
- *"Experimental Study of the Positive Ion Feedback from Gas to Liquid in a Dual-Phase Argon Chamber and Measurement of the Ion Mobility in Argon Gas"*, **Universe** 8 (2022) 2, 134
- *"Time and band-resolved scintillation in time projection chambers based on gaseous xenon"*, **Eur.Phys.J.C** 82 (2022) 5, 425
- *"Spectroscopic analysis of the gaseous argon scintillation with a wavelength sensitive particle detector"*, **Eur.Phys.J.C** 81 (2021) 7, 622
- *"Design and Construction of a New Detector to Measure Ultra-Low Radioactive-Isotope Contamination of Argon"*, **JINST** 15 (2020) 02, P02024
- *"Impact of the positive ion current on large size neutrino detectors and delayed photon emission"*, **JINST** 13 (2018) 04, C04015
- *"Characterization of a CLYC detector for underground experiments"*, **Nucl.Instrum.Meth.A** 906 (2018) 150-158
- "Dynamics of the ions in Liquid Argon Detectors and electron signal quenching", **Astropart.Phys.** 92 (2017) 11-20

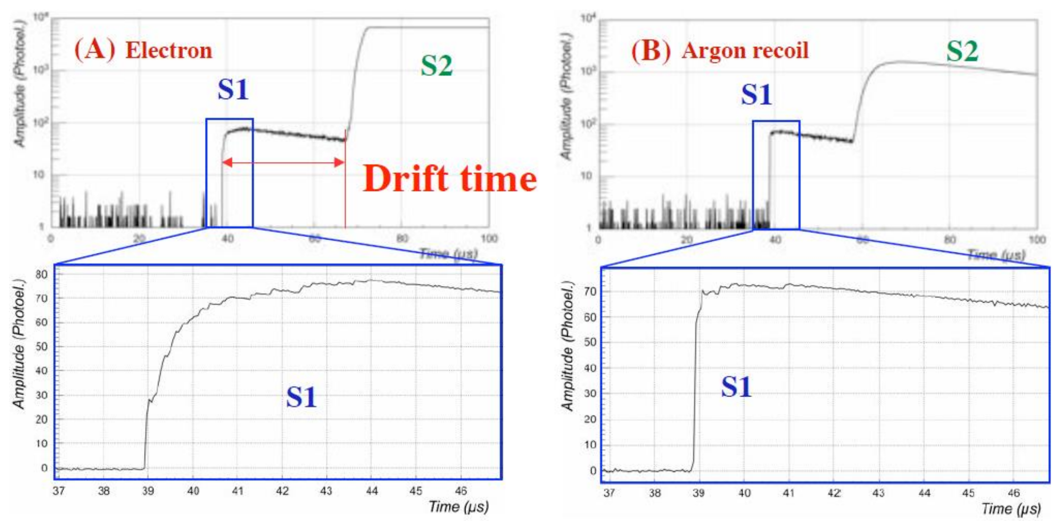
Conclusions

- R&D vital for dark matter direct searches with LAr-TPCs: constant and steady progress in this field
- CIEMAT group more than 20y experience in LAr technology
- Recognized expertise at international level
- Solid scientific production
- Coherent R&D on several fronts
- Funding scheme…?

Backup

General aspects

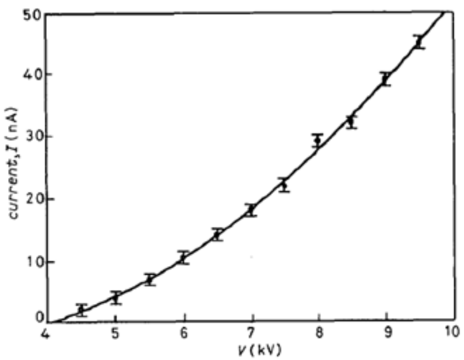


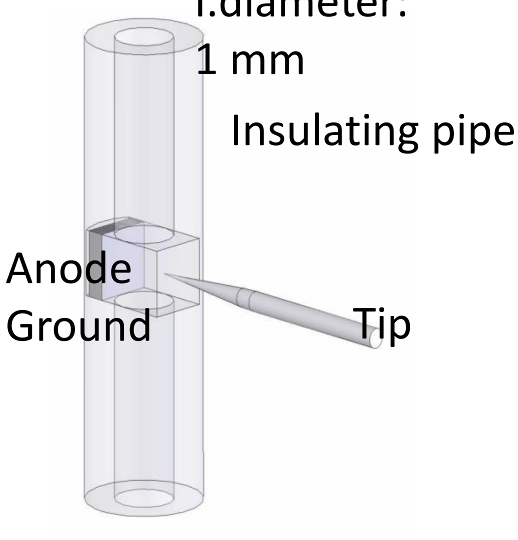


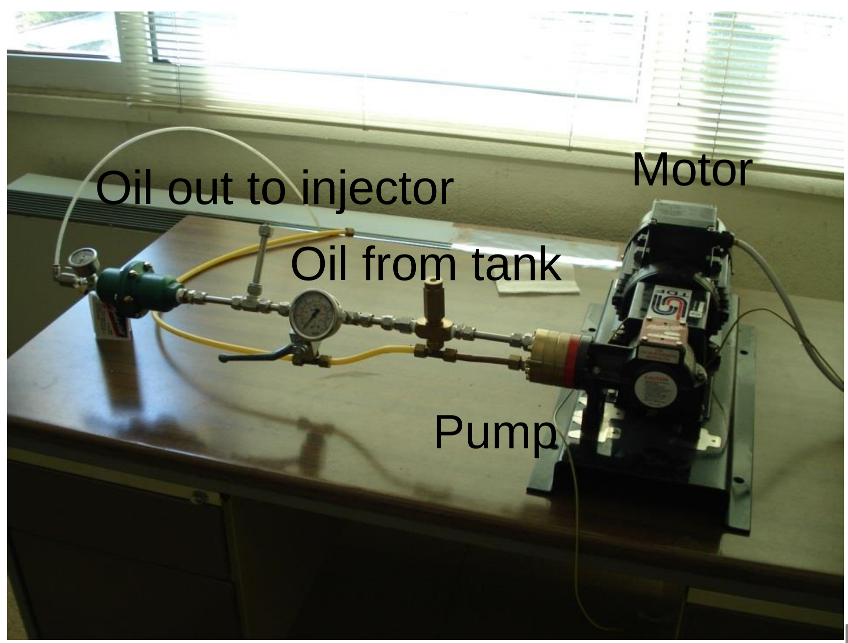
R&D on a novel high voltage system

- Megavolts ranges HV sources required by the future detectors, with several meters drifts
- Efficient removal of the positive charge cloud
- Novel approach: to generate the HV directly inside the detector

Il Nuovo Cimento Vol.13 D, N.8 (1991)







Tests already carried out with dielectric mineral oil:

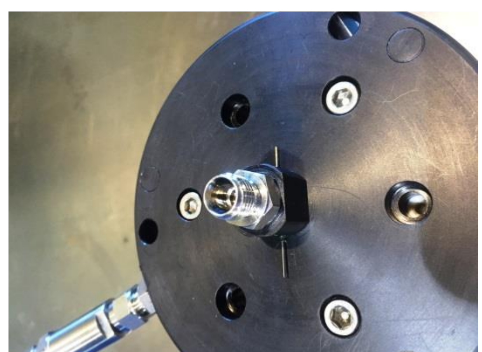
- High voltage measured at the cathode≈30 KV.
- Current ≈100nA

R&D on a novel high voltage system: setup at CIEMAT(in preparation)

Pressure Drop Online-Calculator

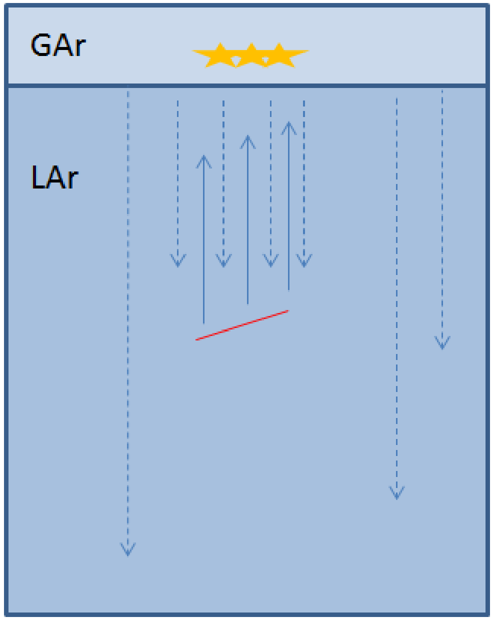
Calculation output

Flow medium:	Argon / liquid
Volume flow::	0.02 l/s
Weight density:	1400 kg/m³
Dynamic Viscosity:	300 10-6 kg/ms
Element of pipe:	circular
Dimensions of element:	Diameter of pipe D: 4 mm
	Length of pipe L: 10 m
Velocity of flow:	1.59 m/s
Reynolds number:	29709
Velocity of flow 2:	-
Reynolds number 2:	-
Flow:	turbulent
Absolute roughness:	0.005 mm
Pipe friction number:	0.03
Resistance coefficient:	66.39
Resist.coeff.branching pipe:	-
Press.drop branch.pipe:	-
Pressure drop:	1177.21 mbar
	1.18 bar

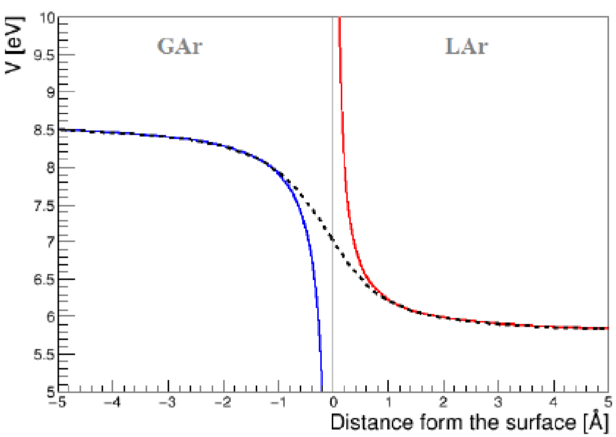


To be operative in 2017!

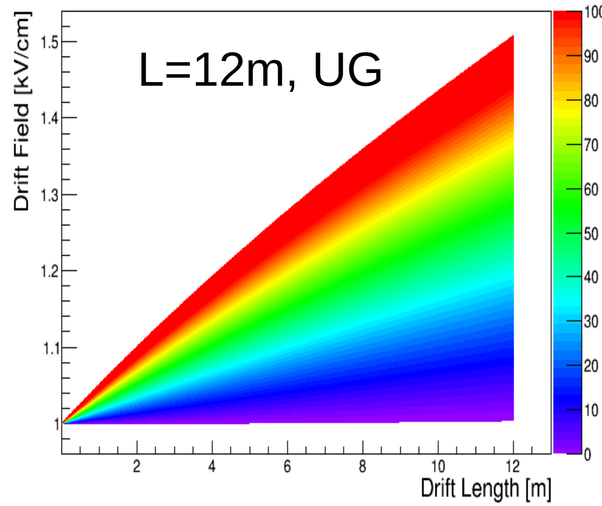
Study of the dynamics of the ions in LAr

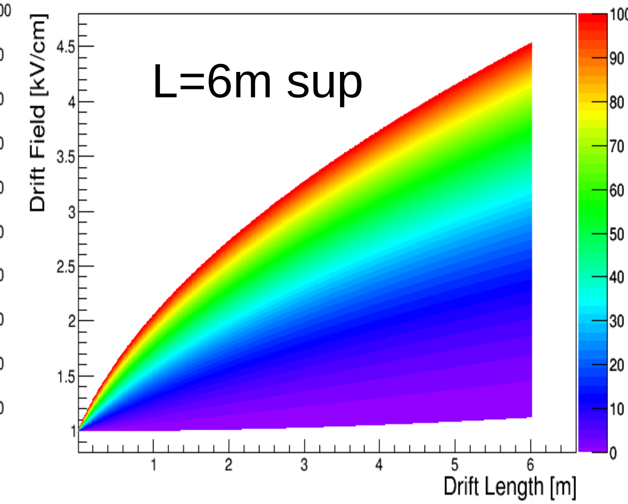


E_d= 0.5-1 kV/cm
$v_e \approx$ 2 mm/μs
$v_i \approx 1.6 \cdot 10^{-5}$ mm/μs

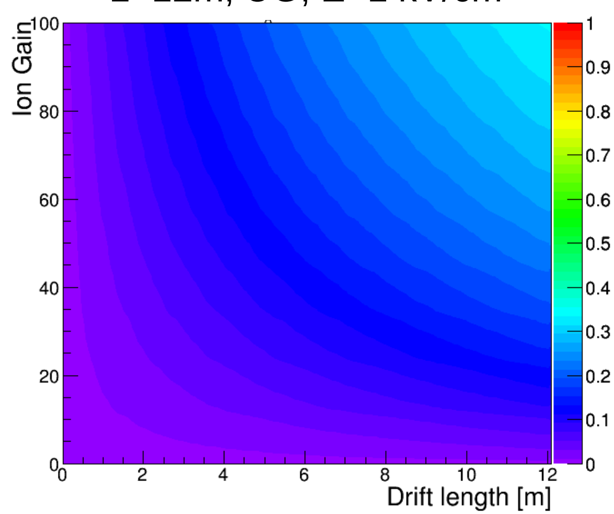


L. Romero, R. Santorelli, B. Montes:" Dynamics of the ions in Liquid Argon Detectors and electron signal quenching"
Astropart.Phys. 92 (2017) 11-20
https://arxiv.org/pdf/1609.08984v2.pdf

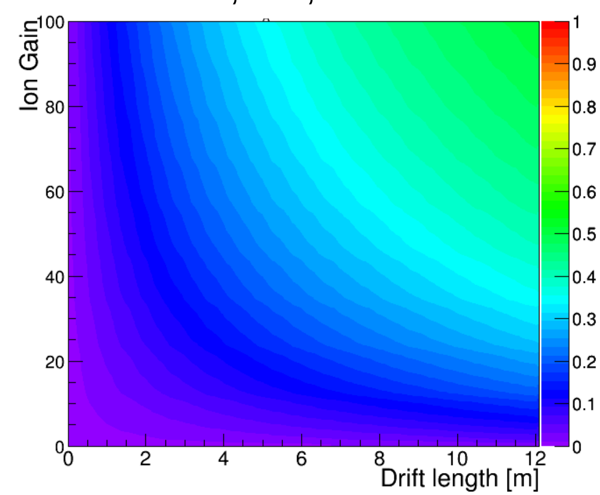




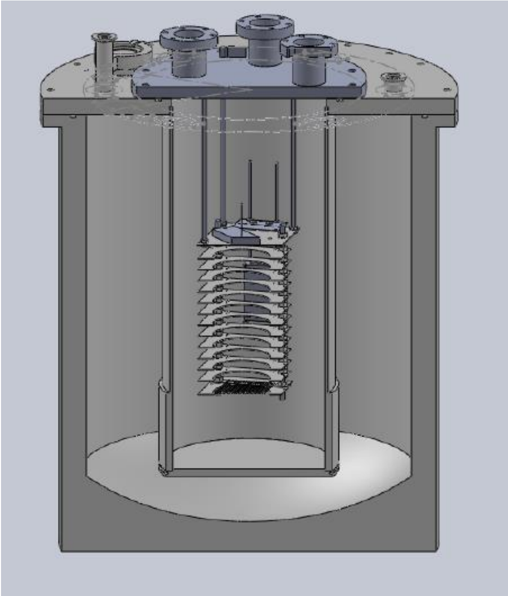
L=12m, UG, E=1 kV/cm



L=12m, UG, E=0.5 kV/cm

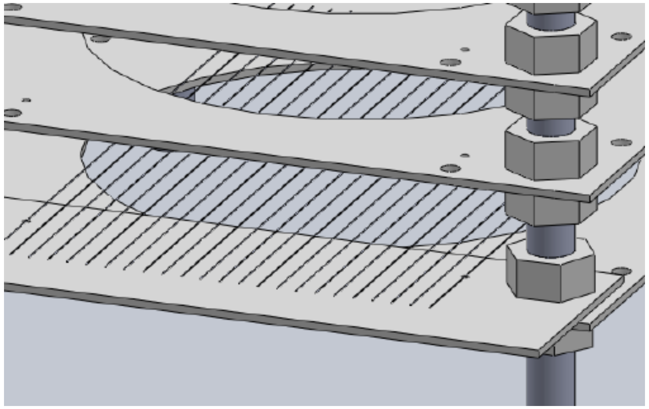


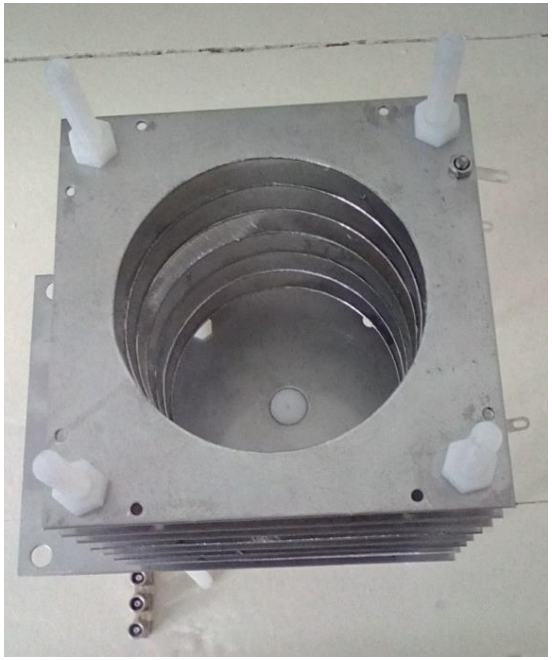
Ions in LAr: Setup at CIEMAT (in preparation)



Goals:

- Measurement of the ions drift velocity
- Study of the dynamics of the ions at interface Gar/LAr
- Study of uniformity of the drift field
- Electron signal quenching





Collaboration with IFAE

To be operative in 2017!

TPCs