R2D2 project

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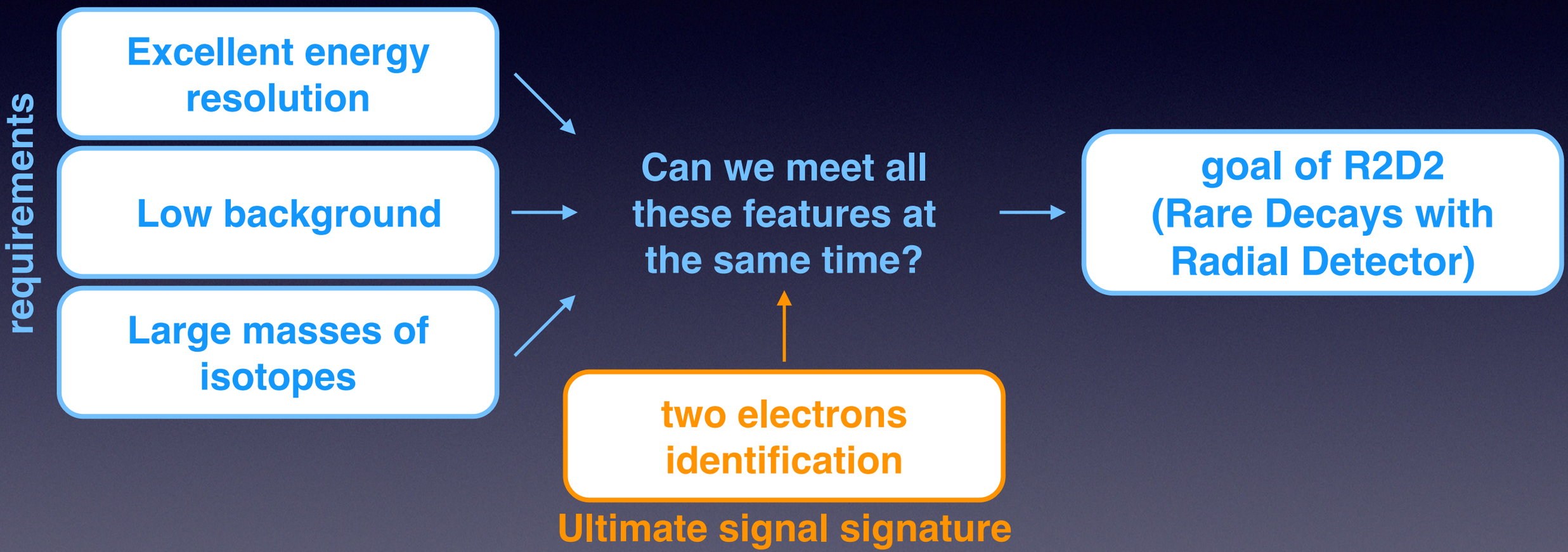
on behalf of
the R2D2 collaboration

Journées R&T IN2P3 - Lyon - 17-19/10/2022

Scientific context

- To demonstrate the Majorana nature of neutrino the most sensitive experimental way is an observation of the so called **0νββ decay**.
- To search for such a rare phenomenon there are three **main requirements** and a **ultimate signal signature**:



- R2D2 is an **R&D program** aiming at the development of a **low background large scale detector** to search for the neutrinoless double beta decay. → How? → **Using a radial high pressure xenon TPC**

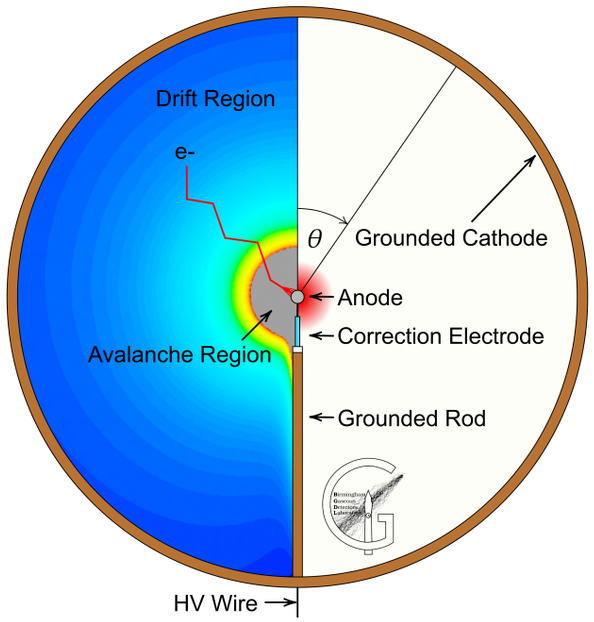
The detector

- **Two options** are considered in the R&D: a spherical Xenon gas proportional counter (SPC) as proposed by Giomataris et al. and used today in the NEWS-G collaboration for the search of dark matter, and a cylindrical proportional counter (CPC).
- Both setup have the critical feature for the search of $\beta\beta0\nu$.

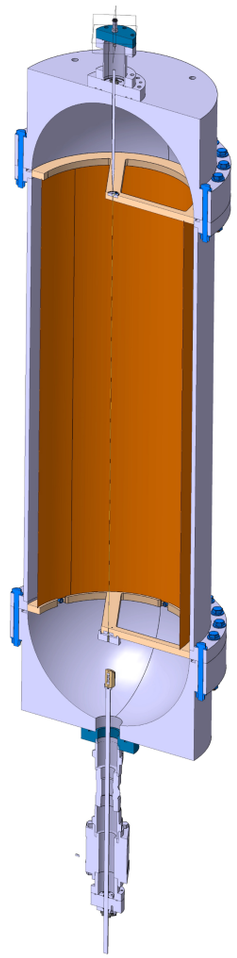
To be validated
Main goal of R2D2 R&D

Detector features

- High energy resolution (goal of 1% FWHM at ^{136}Xe $Q_{\beta\beta}$)
- Extremely low background due to the very low material budget.
- Scalability to large isotope masses.
- Low detection threshold at the level of 30 eV i.e. single electron signal.
- Simplicity of the detector readout with only one (or few in the upgraded version) readout channels.



SPC



CPC

R2D2 collaboration

- A proto-collaboration has been formed.
- R2D2 is today approved as IN2P3 R&D to assess in particular the possibility to reach the desired energy resolution which is the major showstopper.

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The R2D2 Roadmap

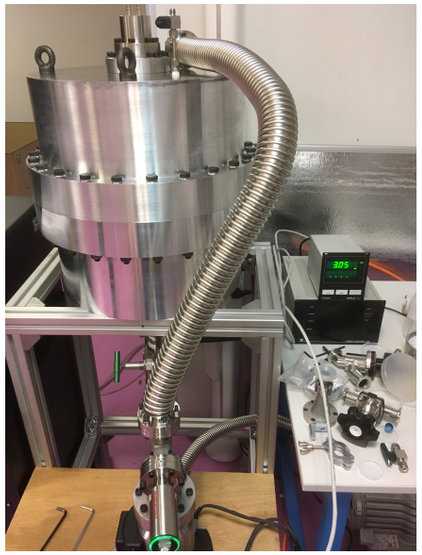
Prototype 1

Running - Funded by IN2P3 R&D

Up to 10 kg (40 bars) Xenon prototype (no low radioactivity) to demonstrate the detector capability in particular on the energy resolution

Demonstrator

If prototype 1 successful and prototype 2 funded



Prototype 2

Sensitivity studies carried out

50 kg Xenon detector (low radioactivity) with LS veto for first physics results to demonstrate the almost zero background

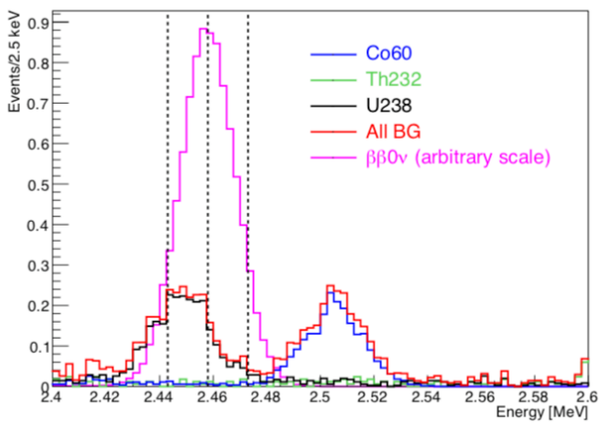
$m_{\beta\beta}$ < 160 - 330 meV

Depending on the results and fundings

Experiment

Going towards a 1 ton background free detector

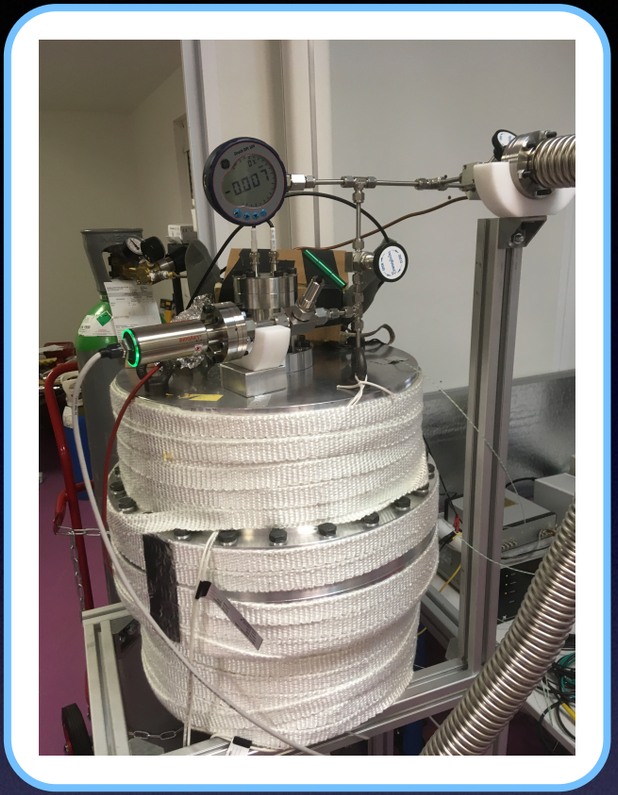
$m_{\beta\beta}$ < 10 meV (I.H. covered)



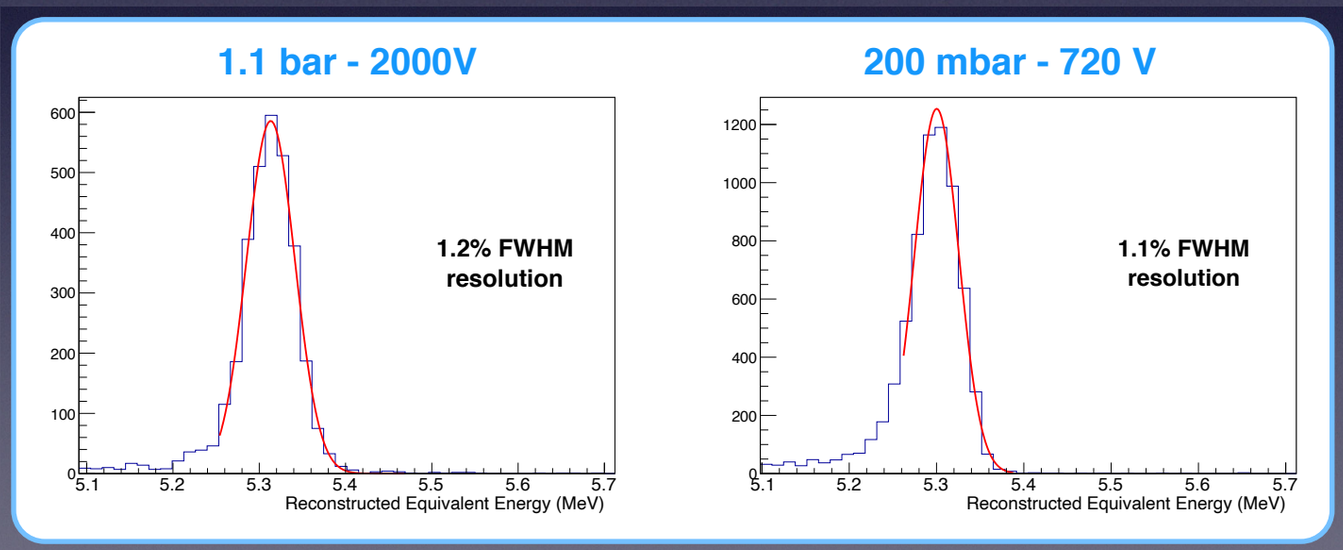
JINST 13 (2018) no.01, P01009

Milestones: Prototype S1.0

- In 2018 the R2D2 was funded as R&D by the IN2P3: **prototype S1.0 for a SPC was built**.
- A 20 cm radius sphere made of Aluminium (i.e. no low background but much cheaper) was built at LP2IB and a custom made low noise electronics (OWEN project) was developed.
- The detector was commissioned and was **operated with Ar (98%) + CH_4 (2%)** at LP2IB at **pressures up to 1.1 bar**. First resolution results were published (*JINST* 16 (2021) 03, P03012).



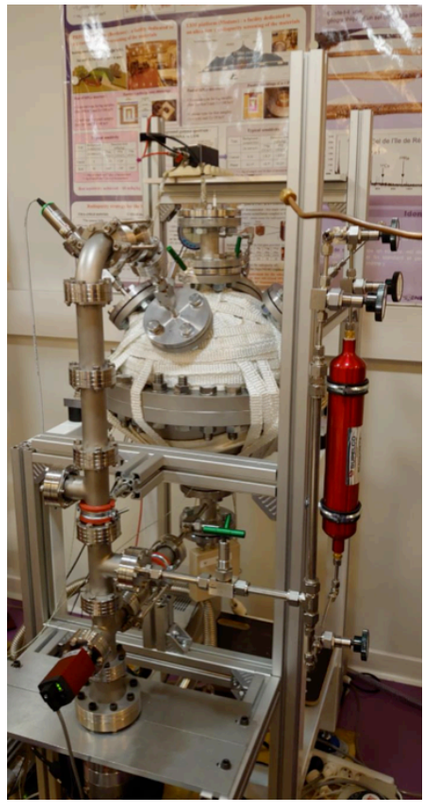
- A detailed simulation was setup to confirm our detector understanding: the **agreement between data and simulation is very good** and the detector behaviour is well understood.
- The resolution was computed at 200 mbar and 1.1 bar: we obtained a similar resolution showing **no impact due to the length of the tracks** (from 3-4 cm at 1.1 bar to 15-20 cm at 200 mbar).

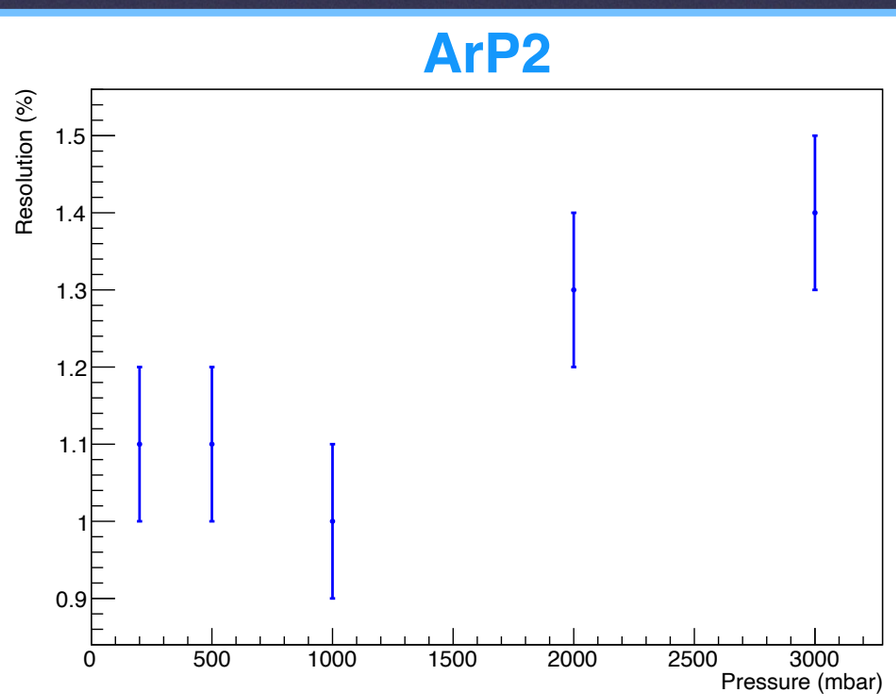


JINST 16 (2021) 03, P03012

Milestones: Prototype S2.0

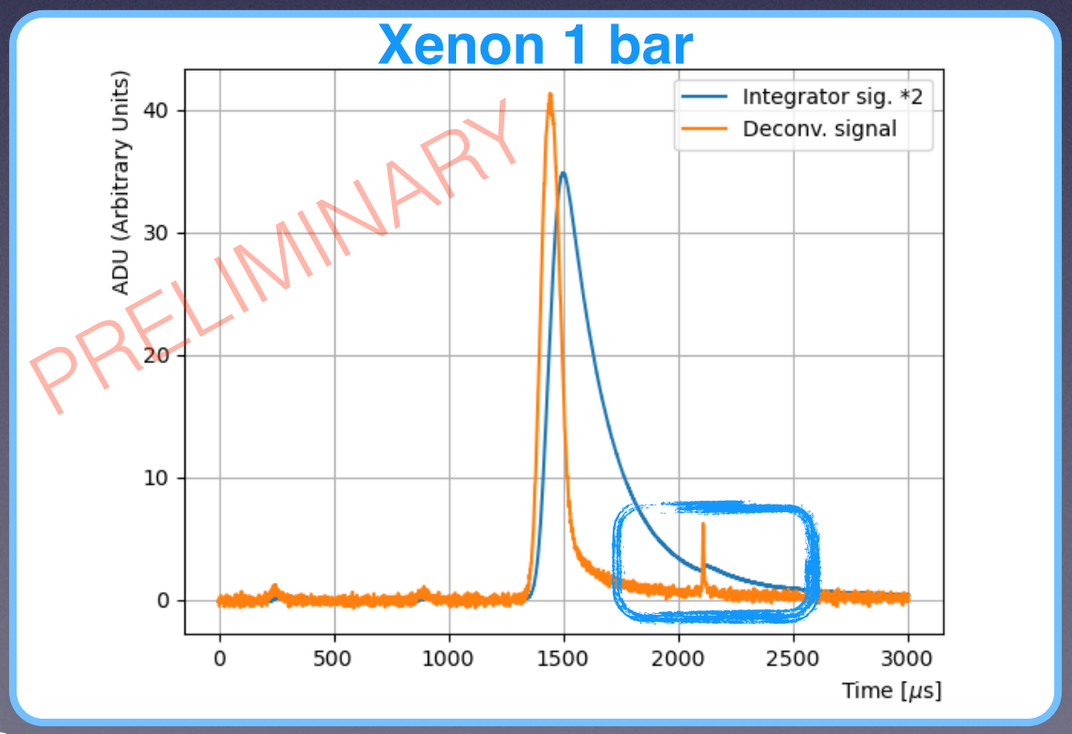
- In 2021 the second prototype (**prototype S2.0 for SPC**) certified to be operated up to 40 bar was built by RAVANAT company.
- In the meantime the xenon recirculation and recuperation system was finalized and commissioned.
- In 2022 the detector was **operated with Ar (98%) + CH_4 (2%)** at LP2IB at **pressures up to 3 bar**. A set of measurement was carried out with a **resolution below 1.4% up to 3 bar**.
- The limit of 3 bar is given by the actual limit on the HV of 5 kV (power supply, filters and central sensor).
- First **signals were also observed in xenon up to 1 bar**.
- Gas purity is still an issue (no hot getter) and larger anode is needed however this limits the SPC to work in ionization mode and resolution is limited by the noise.

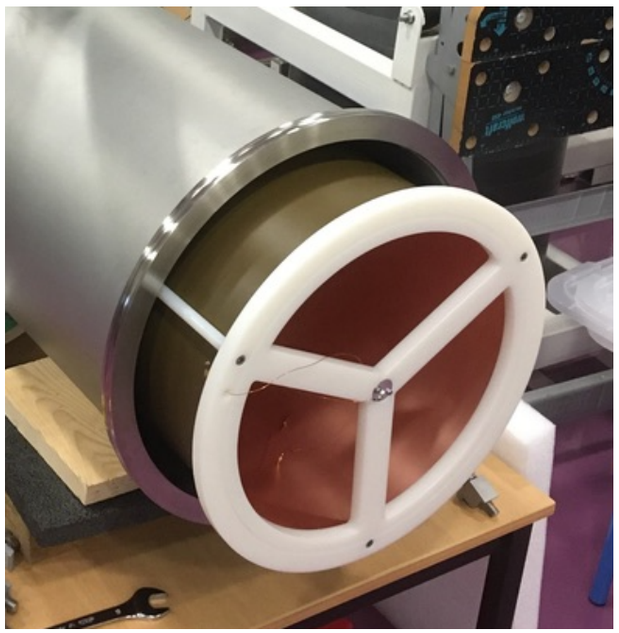




Milestones: Prototype C1.0

- In 2021 the first prototype for CPC was conceived and built at SUBATECH (**prototype C1.0 for CPC**).
- A 10μm radius grounded wire is in the middle and the cathode is set to negative HV.
- First validation in ArP2 showed a **resolution comparable with SPC (1.2% at 1 bar)** at lower voltage.
- The setup was filled with **xenon** at 1 bar and clean signals were observed. **A resolution of 1.8% was achieved** dominated by gas purity and the presence of cosmic muons creating pile up (1.4% in a sample cleaned from cosmics).

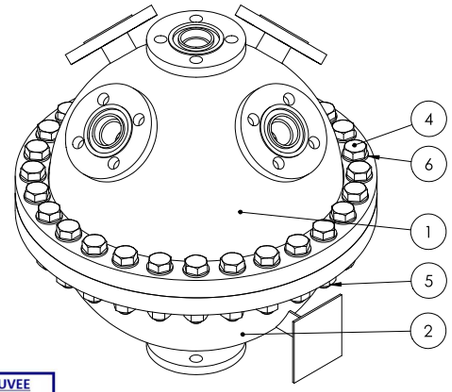




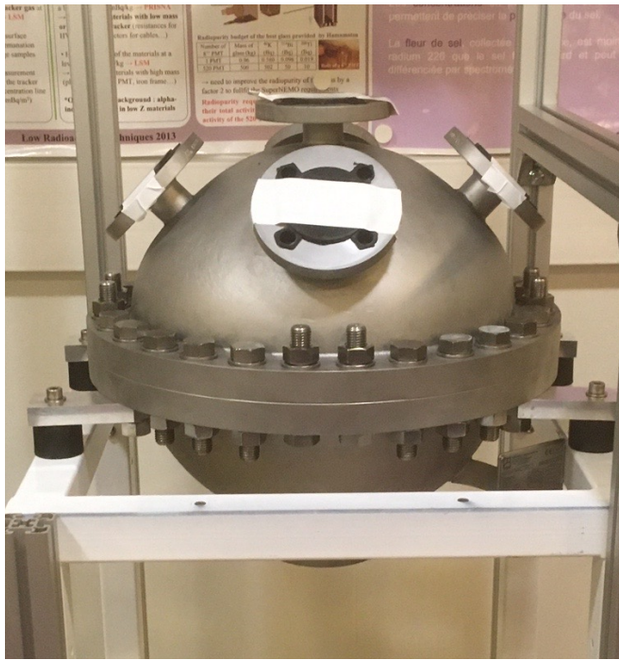
Technical developments

Mechanics

- The main issue on the mechanics are:
  - Need of vacuum at the level of 10^{-8} mbar.
  - Certification to operate at 40 bars.
- "vacuum" and "high pressure" are expertises quite different and our mechanic pool struggled to have this two domains talking to each other.
- **Certification is extremely expensive** for relatively easy task. Any additional piece added to the detector (flange, tube, etc.) has to be certified and no in-house welding is allowed which makes the evolution of the setup slower and more expensive. **Is there a solution at IN2P3?** Just a few examples:
  - The S2.0 Prototype costed 15keuro.
  - A quotation for a cylinder certified was 25keuro.
  - A welding of a tube on a bottle costed 2keuro.



CONCEPTION APPROUVEE
Suivant DESP 2014/68/UE
N° E-F-20-09-RAVANAT-10545
Les remarques indiquées sur le courrier d'accompagnement sont à prendre en compte.
Metz, le 17 SEPTEMBRE 2020
TÜV SÜD Industrie Service GmbH
Organisme Notifié n°0036

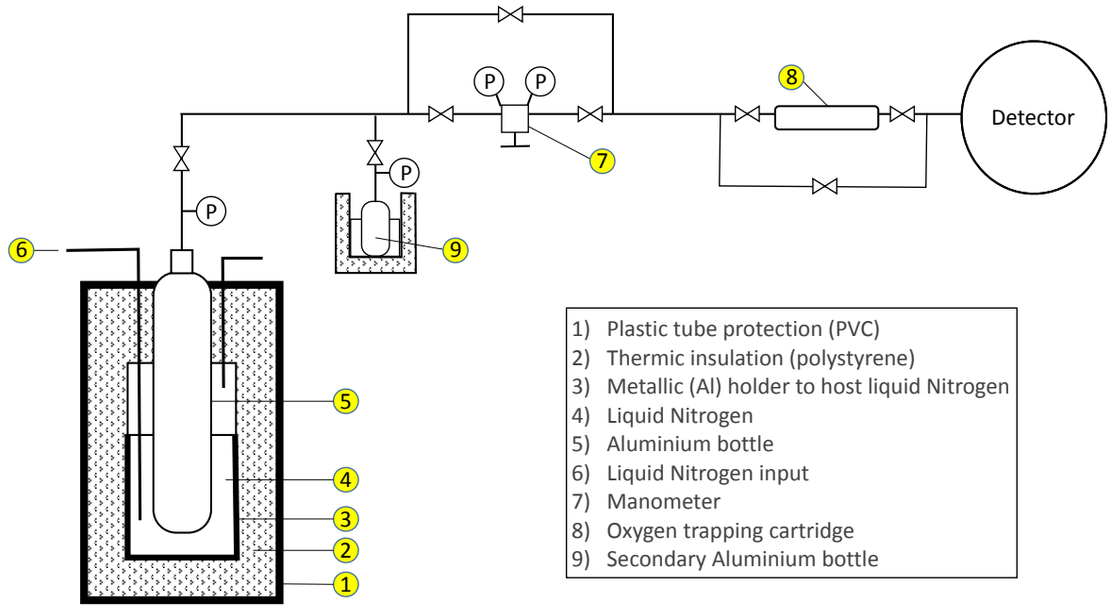


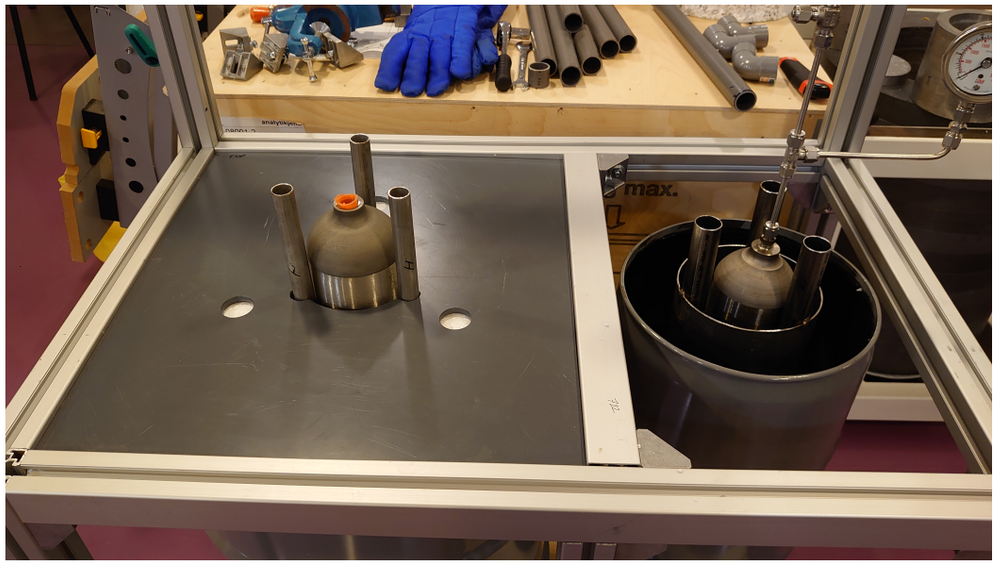
Technical developments

Gas system (1)

- Operating the detector with xenon need a **very high gas purity** (sub-ppm?) and an **efficient recuperation and recirculation system**.
- The recuperation system is based on cryogenic pumping and the know how is well established (in particular we rely on CPPM).
- The purification relies on commercial cartridge (such as cold getter oxysorb) and the use of hot getter (not present today in our setup) should improve the purification.
- **The issue is the recirculation of the gas at high pressure**. The actual pump works up to a few bars and cartridges can be operated up to 17 bars.
- Expertise exist in the international community (XENON, PANDA-X, etc.) and we hope to profit from the SUBATECH expertise of the XENON group.

Recuperation system from CPPM

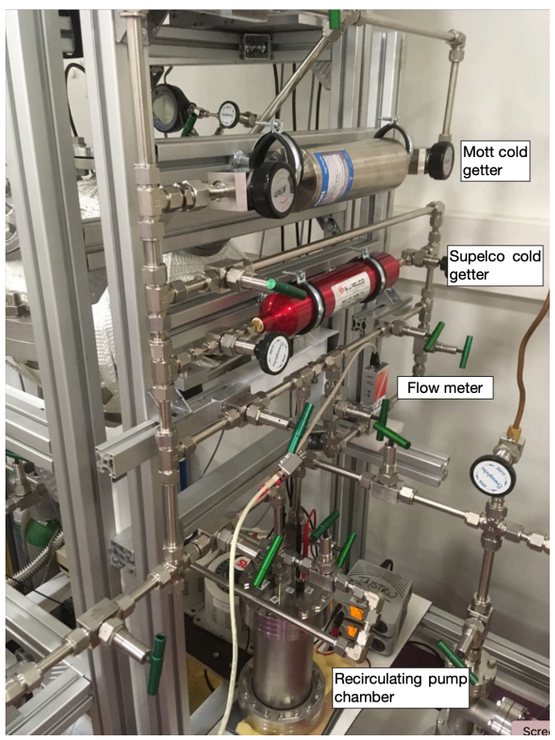


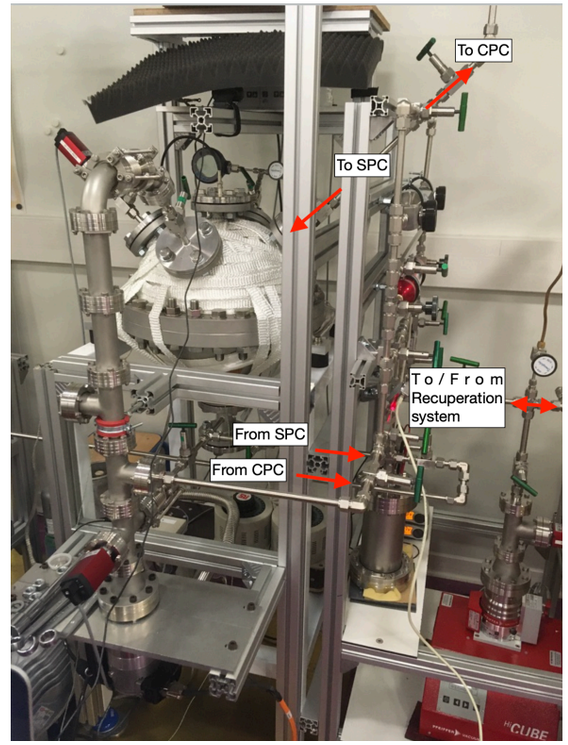


Technical developments

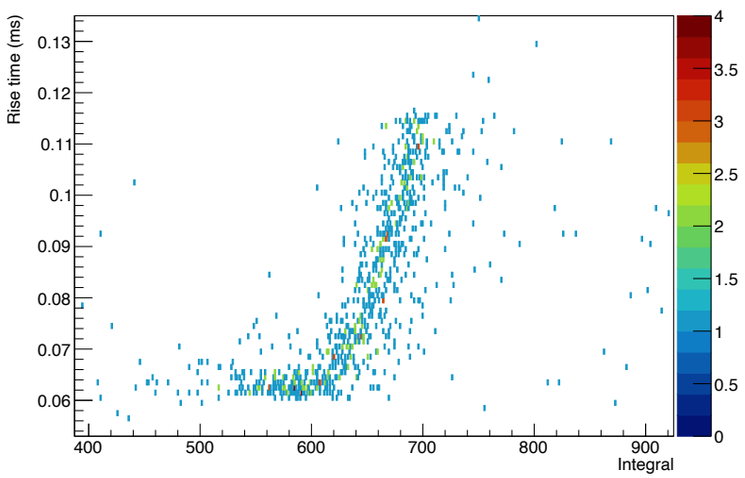
Gas system (2)

- **Full system commissioned in 2022**.
- Flowmeters showed a recirculation at the level of 1.5 liter per minute depending on the gas pressure.
- **Impact of the recirculation clearly seen in data.**

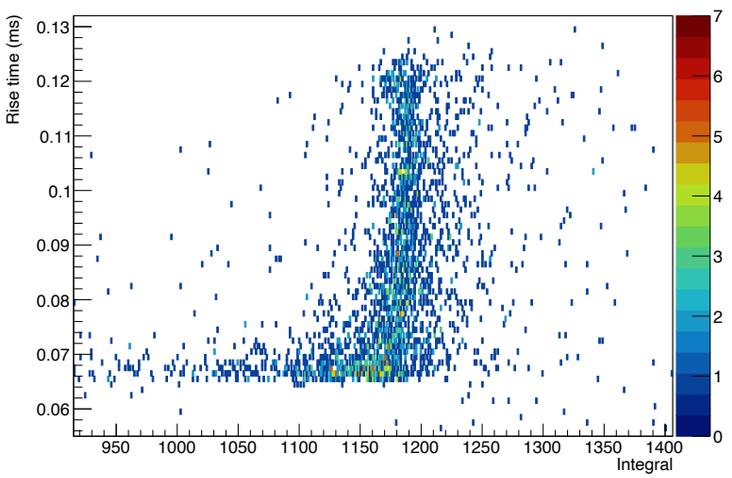




24h



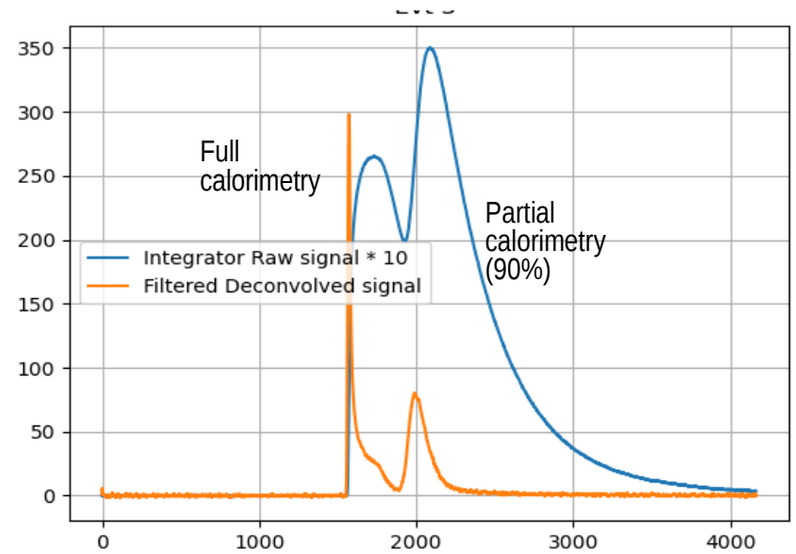
48h



Technical developments

Electronics and DAQ

- The electronics is a hot point of the project since a dedicated low noise electronics chain is foreseen to obtain an excellent energy resolution.
- In particular a **low noise preamplifier** was developed and a DAQ chain is under development (foreseen for end-2022) while we use in the meantime the CALI card developed for EDELWEISS and used today in NEWS-G.
- This work is carried out in the framework of the **OWEN project** (IdEX Emergence Université Bordeaux) which includes a dedicated development of **onboard technology** for a fast data processing.
- A specific work related to **Artificial Intelligence** is also ongoing in synergy with the **THINK** project of IN2P3 both for the final onboard technology and for the offline waveform processing in order to analyse signal and possibly reconstruct two-electrons tracks signature in the signal.
- Indeed a **signal treatment** is a hot point of the project to achieve ultimate energy resolution and have multit-tracks recognition for 2β event selection.

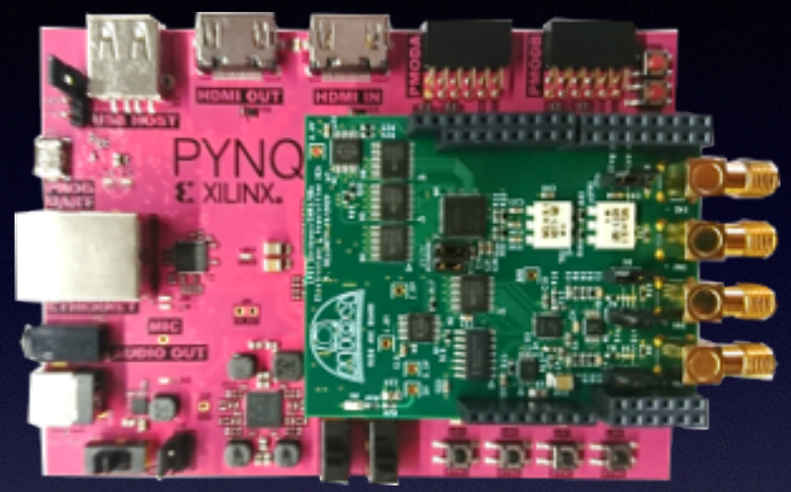


2 alphas reconstruction

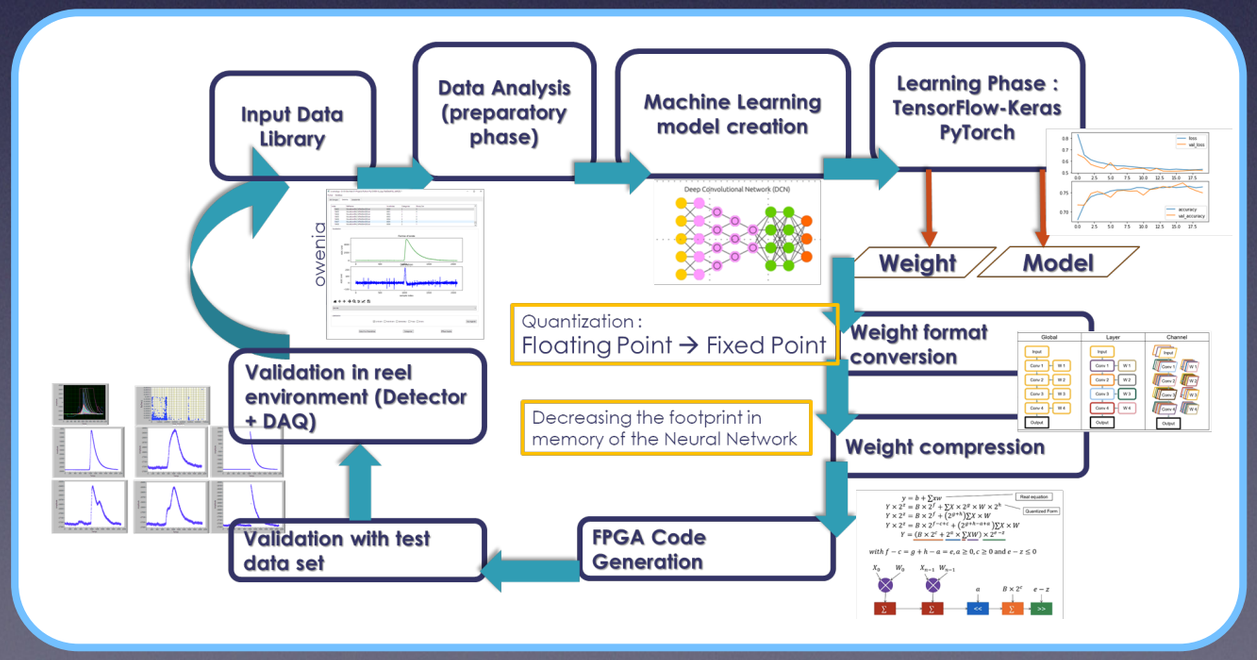
OWEN

Optimal Waveform recognition Electronic Node

- **Hardware developments**:
  - Very low noise front end
  - Optimized waveform digitization with High resolution (18 bits)
  - Embedded processor in integrated shape @ 1Gb/s



- **On-Line Embedded Artificial Intelligence:**
  - Offline classification waveform (classic AI) to possibly reconstruct two-electrons track signature
  - Research of a good neural network architecture to fulfill R2D2 needs
  - Research of a process to integrate AI algorithm in embedded system
  - Digital signal processing to tag events online (with embedded AI)

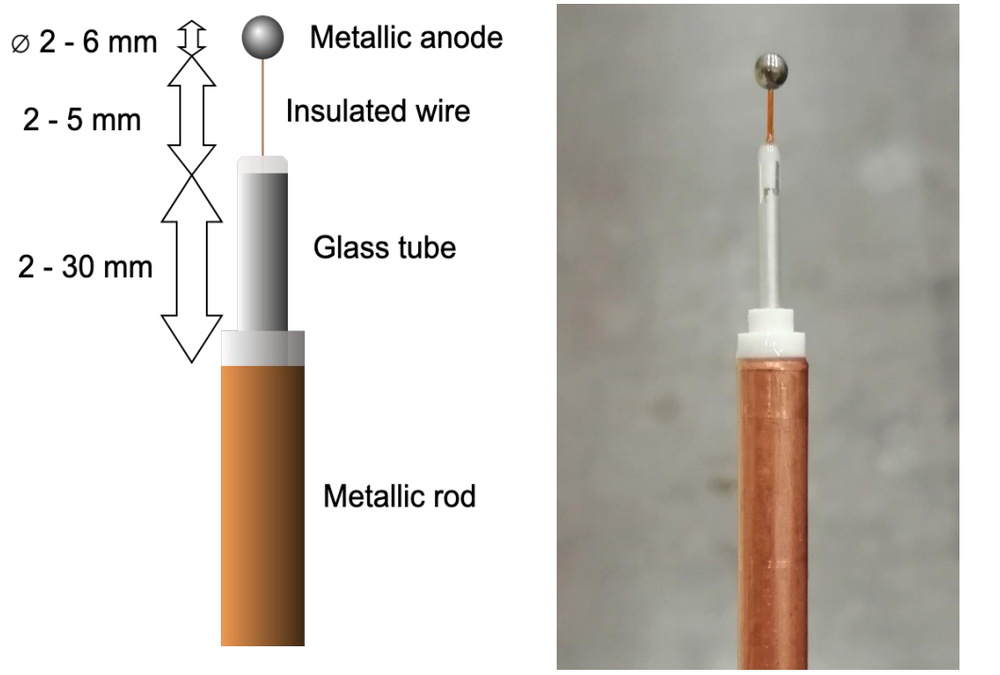


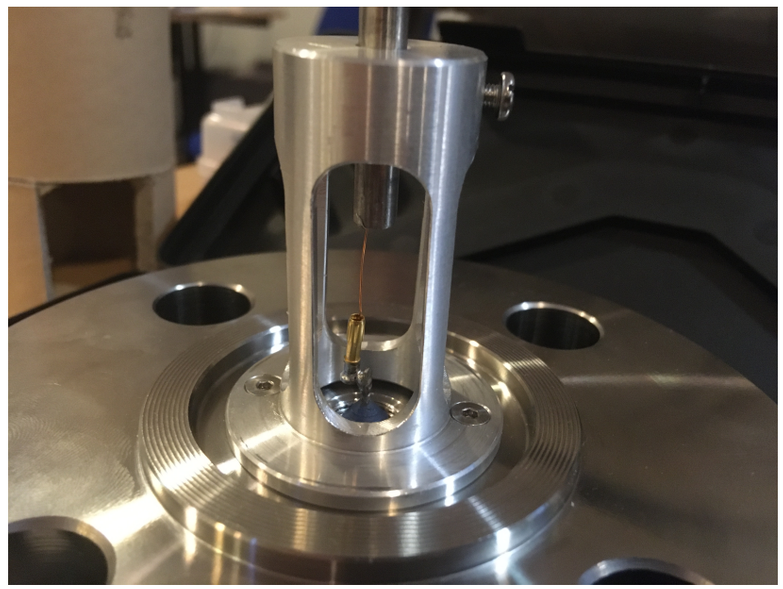
Full system expected to be ready for experiments use at the beginning of 2023

Technical developments

Sensor

- The sensor is the key point of the SPC detector.
- With the ongoing R&D we learned a lot from the detector functioning and we tested different option modifying the distance between the anode and the supporting rod.
- The anode soldering to the wire is still a critical point since **any imperfection results into a field distortion**. We are in discussion with AXON to perform micro soldering without drilling the anode and compromise its sphericity.
- Multi channel sensor was also tested but channel equalisation is currently an issue for resolution.





Technical developments

High Voltage

- High voltages at the level of more than 20 kV might be needed when working at 40 bars (a possible back up option is to work in ionisation mode).
- At the moment we need however a feed through with several features:

  - Good for vacuum and high pressure
  - Good up to 10 kV (possibly more in the future)
  - Good for temperatures up to 100 degrees for detector heating.
  - Low noise

Leakage current

Not shielded (noise)

Not certified for HP

- We tested several commercial options but **each feed through has to be welded by a certified company and the behavior in terms of noise is not guarantee to be the same after and before**.
- Discussion ongoing with AXON company (already collaborating in JUNO) and prototype expected in 2023.

Note: This is an issue only for SPC

Technical developments

Geometry

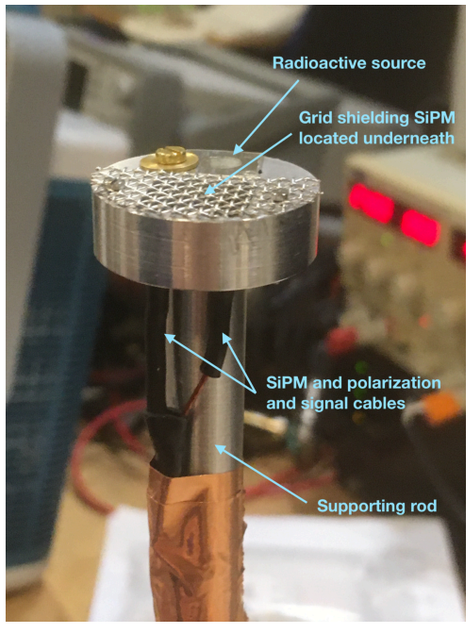
- One of the question we ask ourselves since the beginning (and many people ask us) is: **sphere or cylinder**? Based on the acquired knowhow here is a summary of pro and cons.

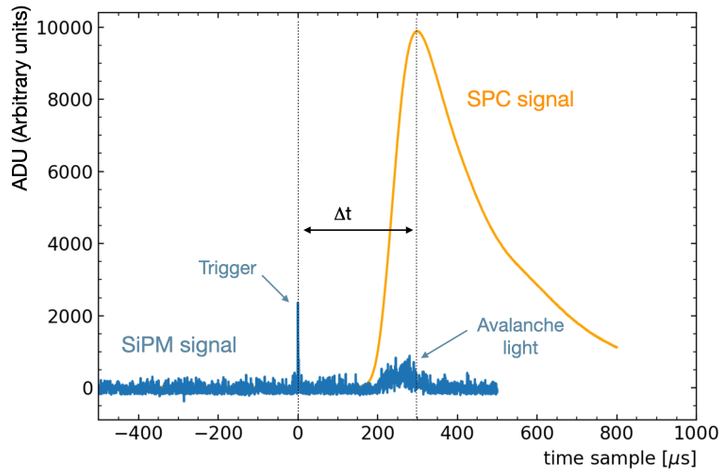
	SPC	CPC
Field distortion	Field issues around the supporting rod	Edge effects at endcap
Field strength	Weak at cathode ($1/R^2$)	Stronger at cathode ($1/R$)
Xenon volume	Optimal	Volume over surface not maximized
Noise	HV dependent	HV independent with grounded wire
Operation mode	Ionisation only at high pressure	Ionisation or proportional

Technical developments

Light readout

- So far spherical TPC (NEWS-G or SEDINE detectors) used the waveform rise time to reconstruct the radial position of the deposited energy with a precision of the order of few cm.
- Having an event trigger (T_0) and knowing the drift velocity a sub-cm precision can be reached which is important for any fiducialization of the volume or to identify multiple energy depositions (electron/gamma rejection).
- We run the detector in pure argon to observe the scintillation light and use it as trigger for the first time in a SPC detector.
- We used a 6x6 mm^2 SiPM from Hamamatsu with a 15% QE at 128 nm.
- We observed two signals on the SiPM: a trigger given by the scintillation light (S1) and a second signal on time with the SPC signal due to the light emitted in the avalanche (S2).
- The time between the S1 and S2 gives the electrons drift time and can be used to validate the Garfield++ simulation. An **excellent agreement is found for alphas emitted at about 19 cm** from the anode as expected.





***Nucl.Instrum.Meth.A* 1028 (2022) 166382**

Next steps

- Huge improvements were carried out since last year namely measurements in argon up to 3 bars and first measurements in xenon. We need now to confirm the results:

  - Higher pressure → Small cylinder could be operated within the sphere (10 cm drift) up to 40 bars. Larger cylinder certified would be needed in the future but expensive…

  - With electrons → ^{207}Bi source available but more than 10 bars needed to contain electron tracks

  - With a diffuse source → Clean radon source yet to be found (problem with electronegative impurities)

- Further gas quality is needed in order to increase pressure and hot getter should be used (recently funded and ordered but delivery time of 6 months).
- We need to demonstrate the two tracks reconstruction in the cylindrical geometry (ongoing).
- Further developments are ongoing on the DAQ to have a faster readout.

Move on to a real project and international collaboration

Conclusions

- The R2D2 R&D has been funded by IN2P3 since 2018.
- A lot of work was done in terms of **sensor development**, **gas purification and handling** and **electronics development**.
- Different geometries were tested in order to optimize the detector and the cylindrical TPC seems easier to operate.
- A good detector understanding was demonstrated and a **resolution at the level of 1.4% was achieved** with alphas at 5.3 MeV in xenon.
- We need to confirm the results at higher pressure but the limits is given just by the gas purity which not a show stopper considering the know-how existing in the community if the needed fundings are secured.
- We are working on the tracks identification.
- We are ready to move on to a project phase for a first low background prototype if we manage to establish a real international collaboration and secure the needed fundings (warning: xenon gas price increased by a factor of 8 in the last year…).