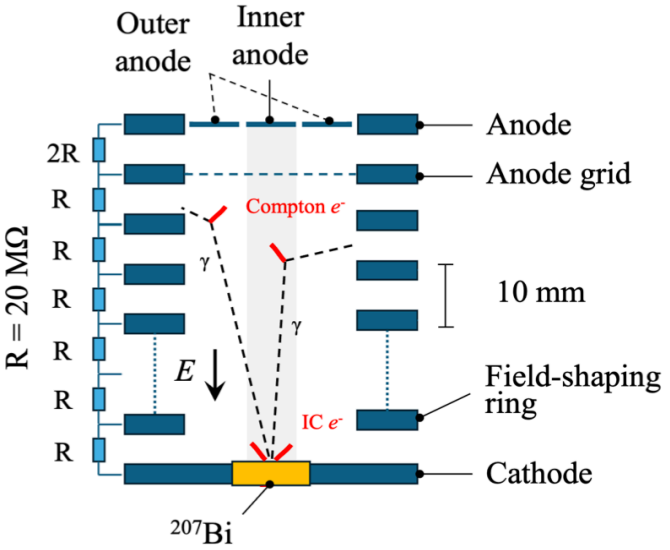
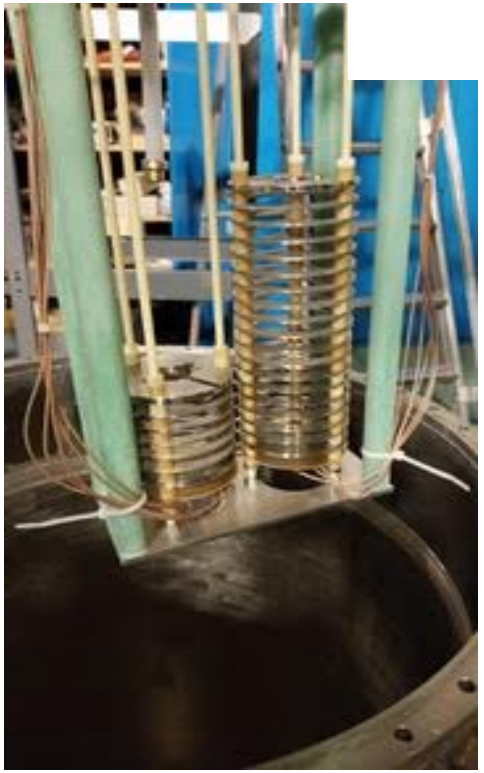
A LAr purity monitor for DUNE

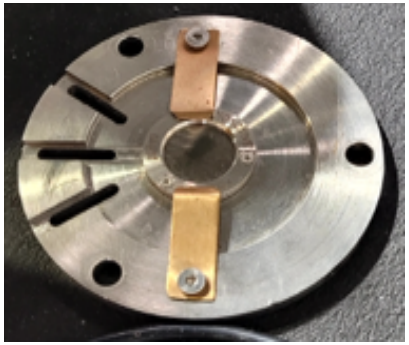
1. LAr purity monitor PrM with ^{207}Bi radioactive source
2. Results of the first prototype, JINST 20P02011
3. Use of Bi-PrM in ProtoDUNE NP02
4. Final optimization of Bi-PrM geometry
5. Plan for the DUNE PrM equipment with UCI Group
6. Funding requests to INFN

New Bi-207 based LAr purity monitor

- Purity monitor PrM is crucial to measure the argon purity and the related attenuation of the ionization e- signal produced by charged particles in LArTPCs.
- A new concept Bi- PrM with a ^{207}Bi radioactive source is proposed, based on collection of ~1 MeV IC e- emitted by the source at cathode and drifted in 500 V/cm to anode.
- The anode is divided into an inner ring reading the IC e- signal and Compton background, and an outer ring reading only the Comptons. The genuine IC e- are determined by subtracting the external ring signal from the inner one.
- 2 Bi-PRMs of different drift length can be used to avoid absolute electronic gain calibration with a sensitivity exceeding 10 ms free e- lifetime in LAr.







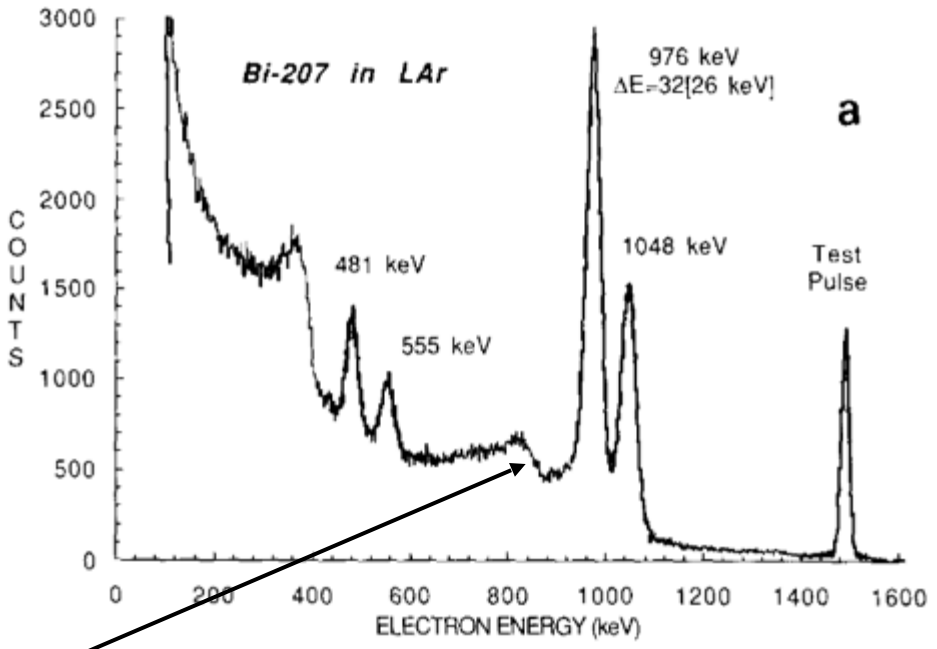
PrM prototype:
L_{DRIFT} = 6, 18 cm

A new LAr purity monitor based on a Bi207 source

- We propose to exploit the Bi207 radioactive source which emits monochromatic IC e- at 976 keV to build a new PM concept.

Decay Mode: EC, β^+		Half-Life: (11523 ± 1) d			[1]
Radiation Type		Energy (keV)	Intensity (%)		Ref.
Auger-L		5.2 - 15.7	53.8	14	[5]
Auger-K		56.0 - 88.0	2.8	3	[5]
ec-K-1		481.7	1.52	2	[5]
ec-L-1		553.8 - 557.7	0.440	6	[5]
ec-M-1		565.8 - 567.2	0.15	2	[5]
ec-K-2		809.8	0.003	1	[5]
ec-K-3		975.7	7.03	13	[5]
ec-L-3		1047 - 1051	1.84	5	[5]
ec-M-3		1059 - 1061	0.54	7	[5]
ec-K-4		1682	0.02	1	[5]
β+max		806.5	0.012	2	[5]
β+av		383.4			[5]
X-ray L	Σ	9.18 - 15.8	33.2	14	[5]
X-ray Kα	Σ	74.2	58.19	24	[5]
X-ray Kβ	Σ	84.4 - 87.6	16.22	25	[5]
γ		328.11	0.00076	8	[5]
γ	Annih	511.0	0.0024	4	[5]
γ		569.70	97.76	3	[5]
γ		897.8	0.131	6	[5]
γ		1063.7	74.58	49	[5]
γ		1442.2	0.131	2	[5]
γ		1770.2	6.87	3	[5]

Common used source for calibration (intense monochromatic IC peak)



Pulse height spectrum of Bismuth source in LAr, at E=10.9 kV/cm. The 976 keV IC e- peak is visible with a 32 keV (fwhm) total energy resolution.

E. Aprile et al, NIM 261 3 (1987) 519-526

Several advantages of a Bi-PrM

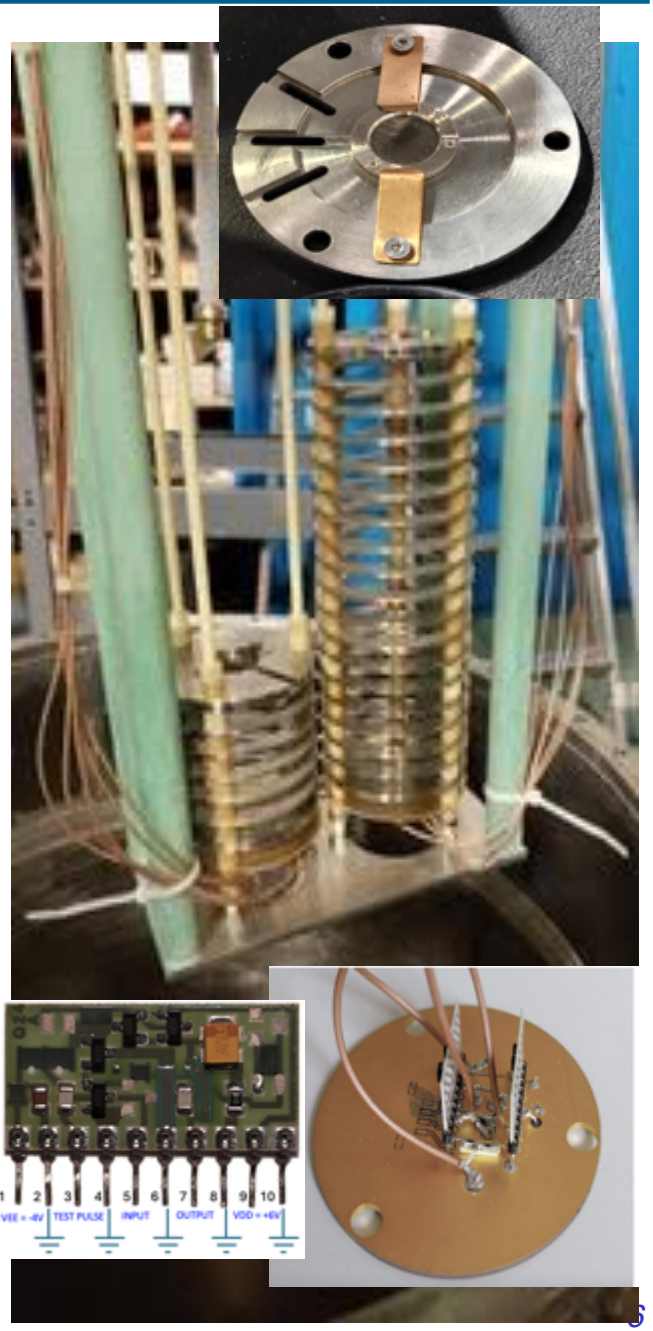
- The proposed Bi-PrM concept presents several advantages with respect to the traditional UV light-based purity monitors:
  - The Bi207 source can be obtained with activities up to 400 kBq and can be easily shielded during the detector assembly and installation;
  - The half-lifetime of Bi207 (31 ys) is well in excess of the expected time exposures of any future detectors (also DUNE);
  - The monitor can be operated continuously without interferring with the main LArTPC operation (both charge and light readout) and also during LAr filling;
  - It can be operated at same E_{DRIFT} as the main LArTPC for a direct e- lifetime measurement;
  - Different PrM lengths can be assembled to further reduce systematic errors due to the calibration of the front-end electronics;
  - The energy of IC e- is similar to a typical MIP on a 5 mm anode readout channel: the same front-end electronics of the LArTPC charge readout can be used.

R&D and testing for Bi-PrM validation

- The Bi-PrM concept was successfully developed in the past two years into two phases:
  1. Laboratory tests (Padova and CERN) focusing on the mechanics, electronics and DAQ and proof of concept as described in JINST 20P02011.
  2. Construction and operation of a quasi-final double PrM layout installed at CERN in ProtoDUNE NP-02 detector for long term performance, sensitivity validation and comparison with UV-based PrMs.
- Following the obtained positive results, the DUNE Collaboration is planning to adopt this new concept Bi-PrM to be installed in several locations within the two 17 kton Far Detector modules.
- The conclusion of the Bi-PrM R&D before starting the monitor production for DUNE includes the final optimization of specific design features such as the best drift-length and the electronic response to 1 MeV e- signals.
- Final Bi-PrM optimization is under way with a 3 detector set-up to define the best drift length of the 2 detectors and reach a pre-Amps cross calibration better than 0.5%:
  - ✓ Short, Intermediate, Long PrM : 6, 18, 54 cm
  - ✓ One single HV FT (one resistor chain)
  - ✓ Modular construction, as for "classic" PrM: flexible arrangements of drift lengths.

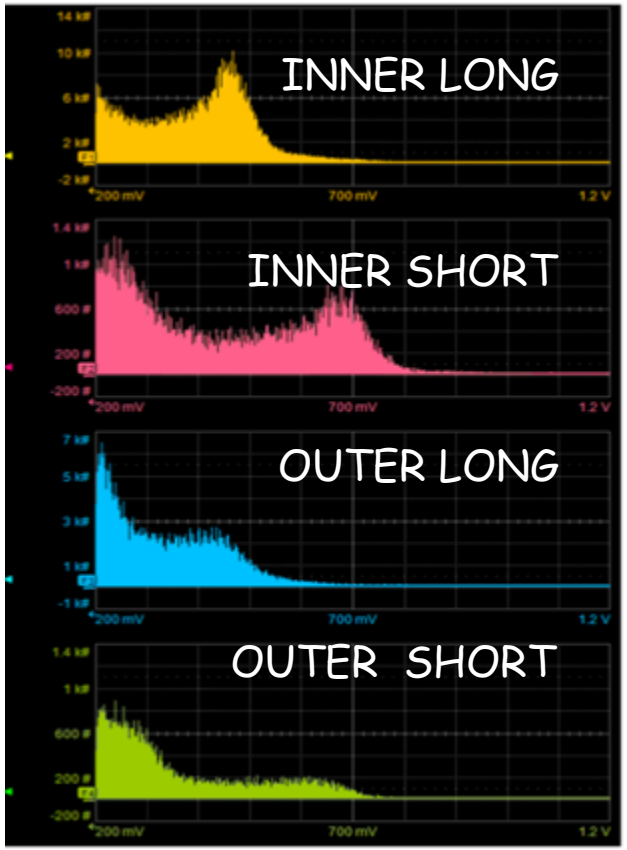
1. Laboratory Tests, Bi-PrM layout

- 2 Bi-PrM built at CERN / INFN-Padova, L_{DRIFT} = 6, 18 cm used simultaneously, to remove absolute calibration requirements.
  - Exactly same layout/E-field to minimize systematics: HV applied only on cathode of long PrM, short PrM rings voltage taken from long one
- Cryogenic J-fet pre-Amplifiers with equal response/gain developed for ICARUS in the '90:
  - Directly mounted on the back of anode: < 1000 e- ENC
  - Gain calibration accuracy $\delta \sim 1$ % achieved
  - Able to drive long output cable without losses
  - High reliability: no dead ch. after numerous cryogenic cycles for 30 years.
- Dedicated feedthrough flange and warm receivers/shapers. DAQ based on 4 ch scope or Multi Channel Analyzers.
- HV cable and feedthrough for > 20 KV (industrial version also available).

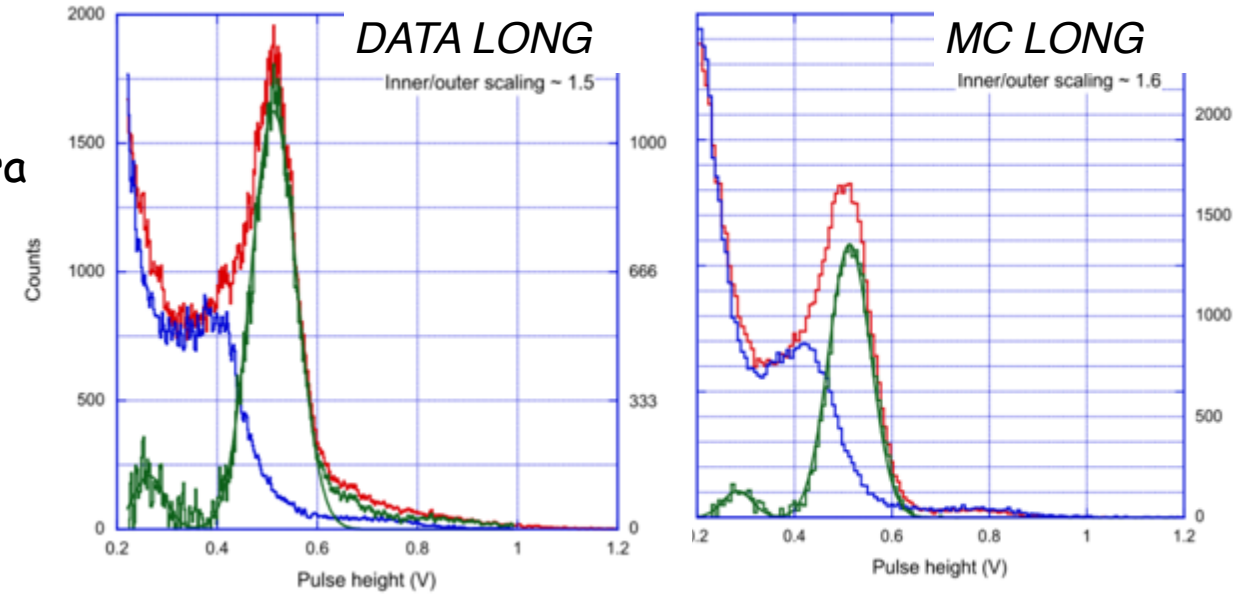


Bi-PrM operation in LAr

- Oscilloscope based DAQ
  - Event by event online charge measurement and spectra
  - The different ranges of the INNER, OUTER charge spectra due to free e- attenuation in LAr are visible.



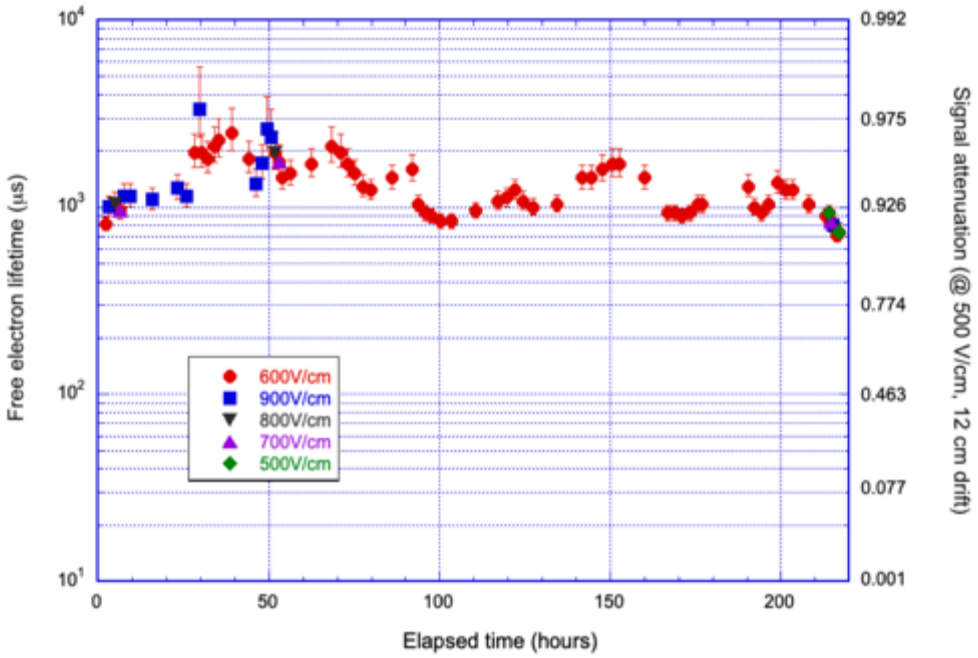
Example of MC vs DATA comparison for 18 cm PrM



- Green spectra: pure IC peaks subtracting OUTER spectra (Compton, blue) from INNER ones (IC + Compton, red)
- LONG/ SHORT IC peak value ratio used to evaluate the free e- lifetime over the drift length of the PrM
- MC including all source decays and detector response, reproduces DATA accurately for all drift lengths and wide range of LAr purity.

Bi-PrM performance from the collected data

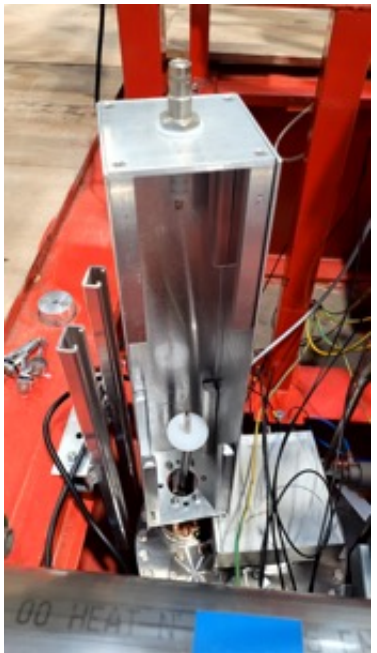
- Runs were taken at different E_{DRIFT} in the 500-900 V/cm, lasting ~ 1 week each.
- Free e- lifetime τ is evaluated simply comparing the pulse height of the two different PrMs, 6 and 18 cm long, removing the need for absolute calibration:
  - $Pulseheight_{LONG}/Pulseheight_{SHORT} = \exp(-(18\ cm - 6\ cm) / v_{drift} / \tau)$
- The PrM detector sensitivity to LAr purity depends on ΔL_{DRIFT} = 18 – 6 cm =12 cm, the e- drift velocity V_{DRIFT} and the relative accuracy of electronic gain calibration, δ ~1 %:
  - $\tau_{MAX} \sim \Delta L_{DRIFT} / V_{DRIFT} / \ln(1-\delta) \sim 8$ ms @ 500 V/cm



- ✓ Continuous data taking allows to follow e- lifetime evolution in detail.
- ✓ The equivalent signal attenuation between Short and Long PrM is shown on the right axis for E_{DRIFT} = 500 V/cm.
- ✓ Errors are dominated by the cross gain calibration of pre-Amps δ

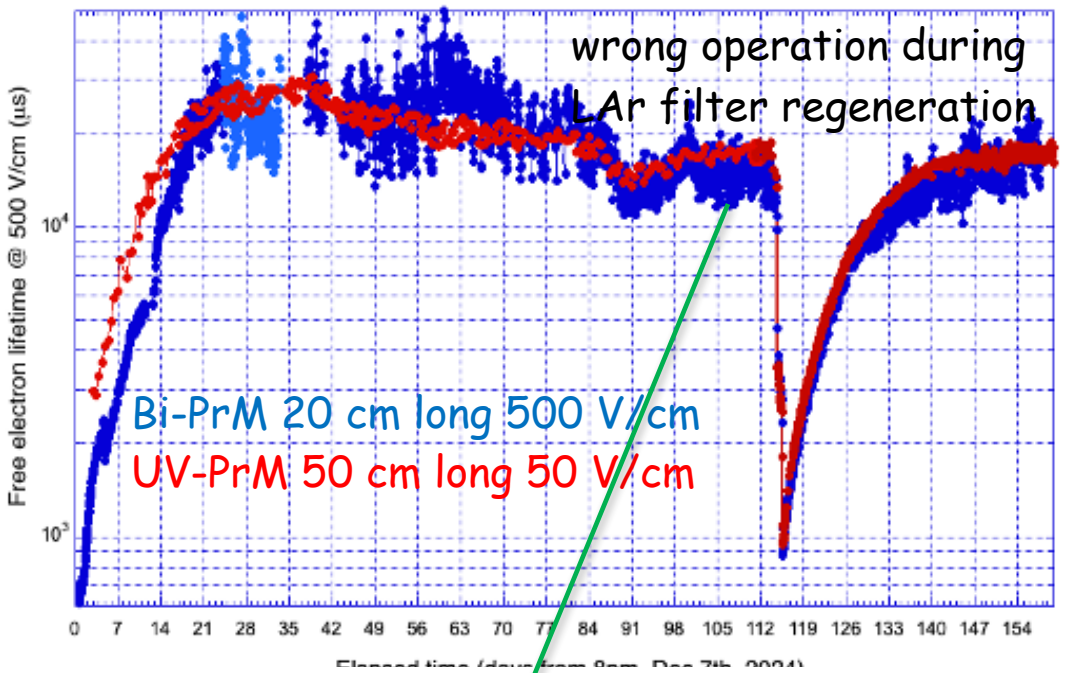
2. Bi207 PrM in ProtoDUNE NP02

- A double PrM with 6 and 18 cm drift was installed in NP02 in Nov. '24 in a corner on the cryostat floor
  - Inserted in a faraday cage with 50% opening to allow efficient LAr circulation while shielding from external noise sources
  - 10 m HV, signal and bias cables routed to cryostat roof on a dedicated flange hosting HV feed through, warm receiver buffer amplifiers and bias voltage supply for cold electronics.
  - HV power supply (12 kV @500 V/cm E-field) located in NP02 slow controls racks with additional ripple filter box.
- A classical 50 cm long UV based PrM is installed at mid height (5 m), ~ 6 m away from the Bi207 PrM:
  - generally operated twice a day to avoid fiber and photocathode degradation and interference with DUNE photon detectors.

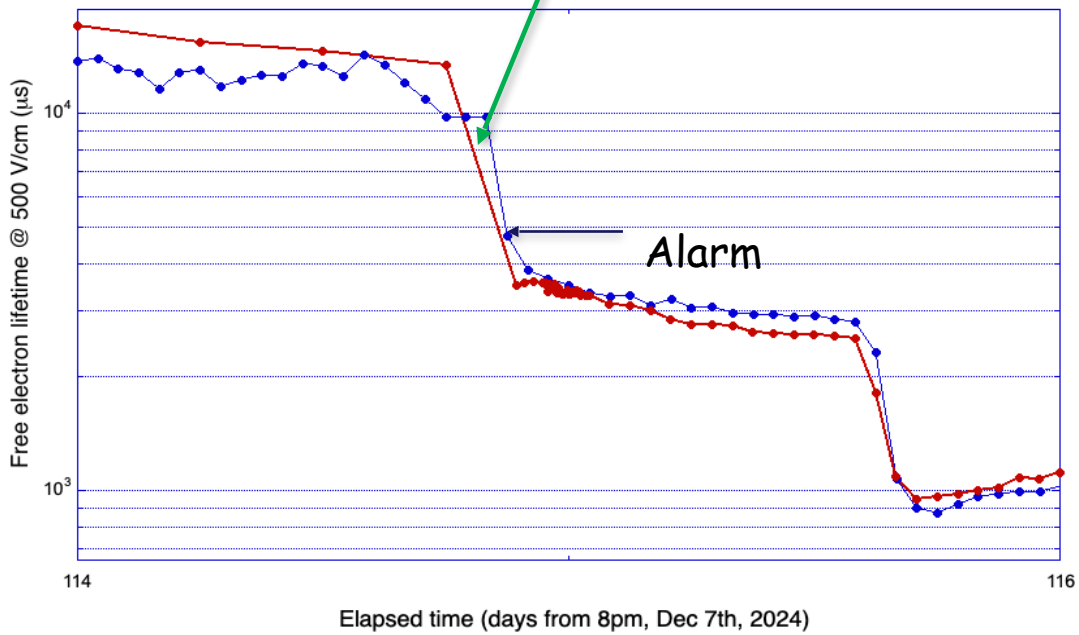


LAr purity measurement in NP02

- e- attenuation evaluated on the ratio of IC peaks of long and short PrM.
- Long term operation since Dec '24 and comparison with UV based PrM validate:
  - performance and sensitivity,
  - electronics stability with time and ambient temperature,
  - DAQ efficiency and data analysis.



- Continuous operation of Bi PrM in NP02 allowed to set an ~ real time alarm:
  - In NP02 when purity rapidly dropping alarm given within 1 h .
    Monitor also activated with UV PrM



Planned optimal layout of the PrM in DUNE

- Based on the present Bi-PrM performance which will be further validated with 3-detectors prototype, each Bi-PrM should be composed by either 1 or 2 detectors of different L_{DRIFT}.6 Bi-PrMs would be installed in each of 2 DUNE Far modules:
  - ✓ 1 Bi-PrM with 1 single detector inline with the ultrapure LAr injection;
  - ✓ 3 Bi-PrM double detectors on the cryostat floor distributed along the 60 m length
  - ✓ 2 Bi-PrM single detector on two opposite cryostat corner coupled to UV Light-PrM
- Proposed sharing of deliverable between US-DOE and INFN (1 Far Site DUNE Module):
  - ➢ IRVINE Group with DOE funding contributes with:
    - ✓ 2 UV light complete PrMs; 3 single-detector Bi-PrM without electronics and HV FT
    - ✓ Bi sources for all Bi-PrMs
  - ➢ INFN would contribute with:
    - ✓ 3 double detectors PrMs but without the source procurement
    - ✓ Full electronic chains for the additional 3 US-built single detector Bi-PrM and HV feed-through

Financial plan submitted to INFN

- R&D and first Bi-PrM prototype have been successfully performed with the available material from ICARUS and CERN, without additional support to INFN.
- According to the proposed plan, INFN funding for construction of PrM for each DUNE Far detector module would require ~ 81 k euro (NO TVA: delivering at CERN)
  - ✓ 3 double detectors Bi-PrMs but without the source procurement ~ 65 k euro
  - ✓ Full electronic chains + FT for the additional 3 single detector Bi-PrM ~ 16 k euro
- About 160 k euro are requested in total (2 DUNE Far Detector modules), to be shared in 4 fiscal years, 2026-2029.
- In addition we would ask support for testing activity and precise pre-Amps calibration with already existing instrumentation at CERN, where the Bi sources certified for cryogenic use are available, i.e. 10 k euro/year for LAr procurement and ~ 3 MU/year for missions.
- The PrM installation in the first DUNE Far detector module is expected in three years from now, the 2nd in the 2 successive years. As a first rough estimation, 2 MU would be necessary for the Bi-PrM installation in each module at the DUNE Far site.
- Requests to INFN for 2026:
  - ✓ 42 k euro for construction with priority on front-end electronics and DAQ
  - ✓ 10 k euro for consumable (test , LAr, 1 test-pulse generator, storage …)
  - ✓ 15 k euro for mission/tests at CERN

Construction funding for 2026

- In 2026 we need produce and test 2 definitive double detectors Bi-PrM (INFN built) and the electronics for 2 single detector Bi-PrM (US built):
  - ✓ 2 Bi-PrM mechanics (2 x 4.5 k euro) 9 k euro
  - ✓ Front-end electronics:, cryogenic preamplifiers, warm buffer/shaper/stabilized Power Supply mounted on UHV flanges for 2 double detectors Bi-PrM (6 k euro) and for 2 single detector Bi-PrM (2x 2 k euro = 4 k euro): 10 k euro
  - ✓ Cryogenic HV cables, cryo-fitted HV feedthrough in UHV flange for 2 double detectors Bi-PrM (7 k euro) and for 2 single detector Bi-PrM (2x 3.5 k euro = 7 k euro): 14 k euro
  - ✓ Warm HV cables filter resistor box, HV power supply for 2 double detectors Bi-PrM (2 x 4.5 k euro) 9 k euro

  Total: 42 k euro

- The 3 detector Bi-PrM tests will be performed with the already available power supply and DAQ at CERN, shared with NP02 long term run.
- Procurement of DAQ multichannel analyzers CAEN N6781 is planned just before installation in DUNE Far site. The validation of first 2 Bi-PrM will be performed with the existing setup.
- The calibration set-up for the frontend electronics will be realized with the requested consumable funding