Characterisation of a Condenser Lens for High-Efficiency Light Collection with Photomultiplier Tubes

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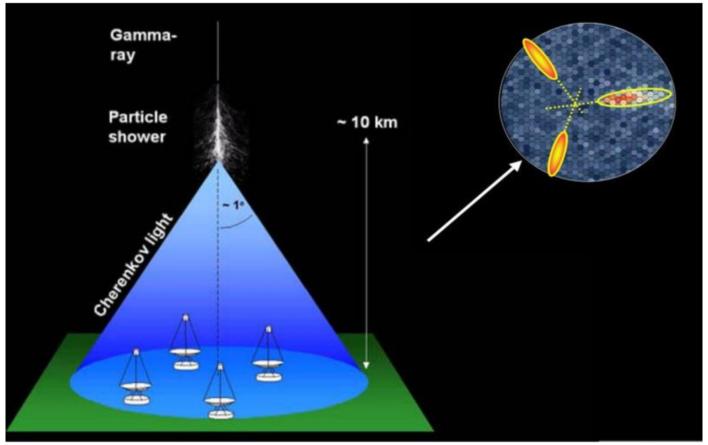
Cherenkov Telescope Array Observatory

- Cherenkov Telescope Array Observatory (CTAO) – next-generation observatory for detection of very high-energy (VHE) photons with Imaging Atmospheric Cherenkov Telescopes (IACTs)
  - Will include more than 70 telescopes at two locations, one in each hemisphere
  - Sensitivities for cosmic VHE photon detection, larger by a factor of 5 – 10 (with respect to present experiments)
- IACTs use atmosphere as a calorimeter → limitations to the accuracy of the shower energy reconstruction
  - Constant monitoring of aerosol extinction in entire calorimeter volume is required! → **LIDAR**

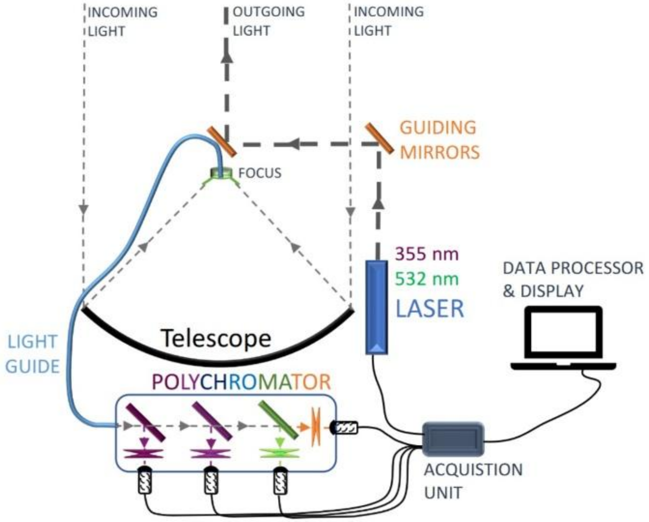


IACTs operation principle.

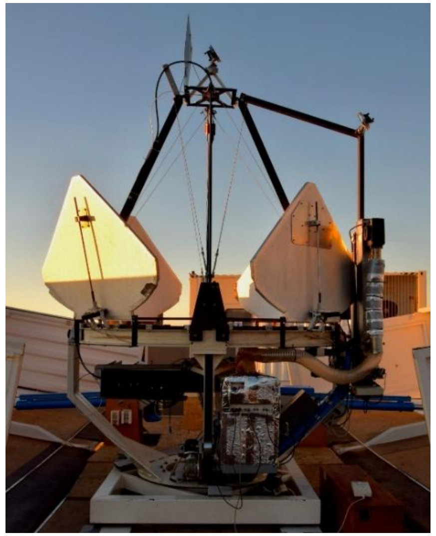
Status of the CTAO-North site at Observatorio del Roque de Los Muchachos (ORM), La Palma, Spain on 28 May 2026.

pathfinder Barcelona Raman LIDAR

- Technical design presented in Ballester et al., Remote Sens. 2025, 17, 1074
- Transmitter
  - QUANTEL Brilliant Nd:YAG (10 Hz pulse laser, ~ 100 mJ per pulse)
- Reciever
  - 1.8 m main mirror with focal ratio of 1
  - **Spectroscopic filter with 4 channels**, fed by liquid light guide
    - 2 elastic: 355 and 532 nm
    - 2 Raman: 387 and 607 nm (607 nm not integrated in the pathfinder)
- Data acqusition
  - Commercial Licel Optical Transient Recorders
- Mechanical structure
  - Steerable alt-azimuthal mount
  - Coaxial setup



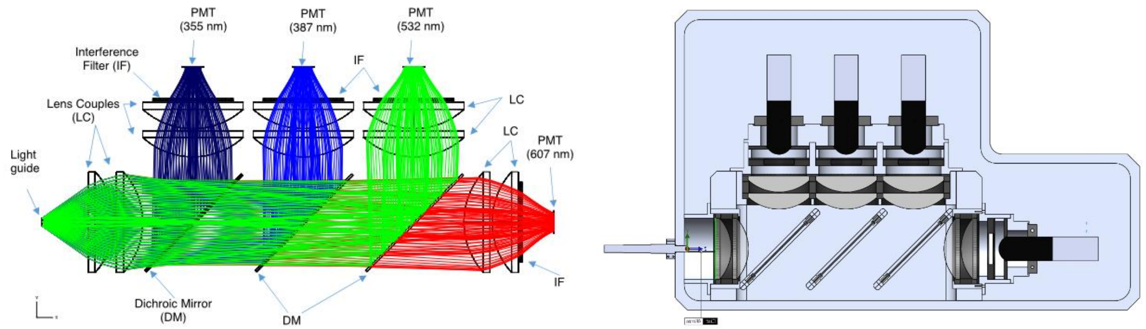
Schematic drawing of the pBRL main components.



pBRL in operation at the ORM in 2021.

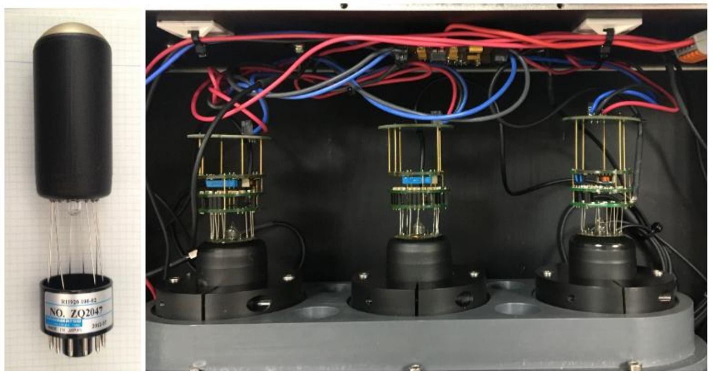
pBRL polychromator design

- Angular distribution of the incoming light (set by the Raman backscattering angle, the NA of the light guide, and the distance to the scattering region) plays a crucial role in the photon detection efficiency
  - Variations in illumination conditions across the detector surface can lead to non-uniform responses, ultimately affecting the accuracy of the reconstructed atmospheric profiles
- PMTs were the preferred choice because of larger sensitive area when compared to silicone photomultipliers since light beam expands along the optical chain
  - 3 identical Hamamatsu R11920-100-20 PMTs used in integrated channels



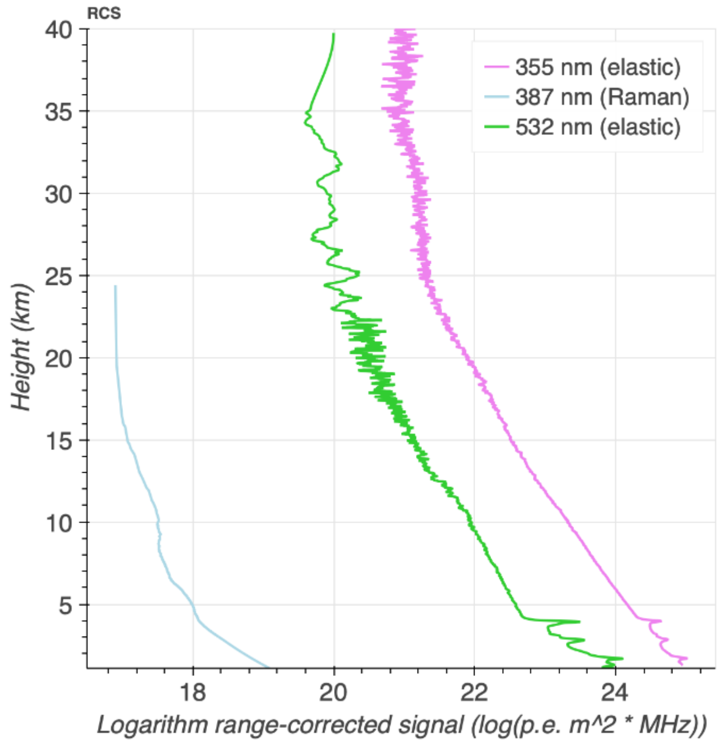
Polychromator design and sketch of the optical bench.


Light concentrated onto the PMTs photocathodes.


Single Hamamatsu R11920-100 and their placements inside the polychromator.

pBRL performance

- pBRL performance presented in Bauzá-Ruiz et al., Remote Sens. 2025, 17, 1815, was assessed using datasets from its initial tests at Universitat Autonòma de Barcelona (UAB) between 2017 and 2019
  - The maximal detectable range with a SNR greater than 1 only around 20 km in the Raman channel
  - Signal saturation observed in the near range (up to 2 km) in both elastic channels
- Used PMTs not sensitive to all the required wavelength channels, additional need for gated versions



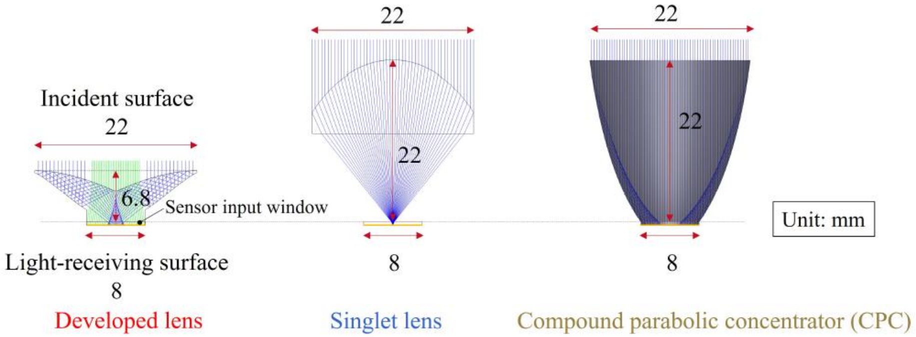
Example of range-corrected signals (RCS) as obtained at UAB on 5 July 2018 during nighttime.

Condenser optics

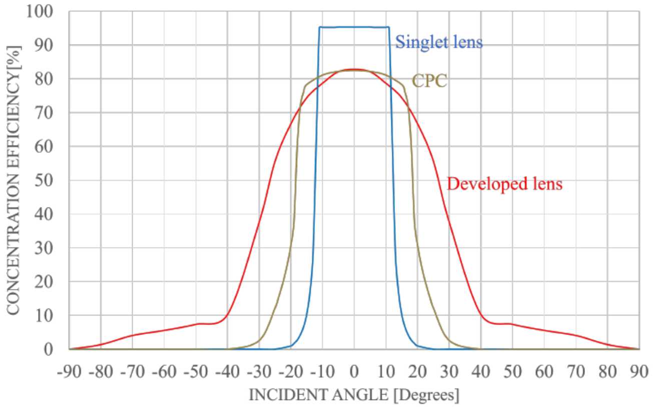
- To fully exploit the effective area of a PMT, it is necessary to efficiently guide incoming photons onto the photocathode (relevant in the BRL system, where the detected light spans a wide angular distribution)
  - Larger PMTs (>1.5″) are not compatible with the existing polychromator design without substantial modifications
  - Smaller PMTs are compatible, but would have significant signal losses due to their reduced active area

- Condenser optics provide means to effectively extend optical collection area beyond physical size of the photocathode
  - The freeform-based RXI (reflection, refraction, and total internal reflection) concentrator presented in Suzuki et al., Optical Components and Materials XXI 12882, SPIE, 2024, were considered, where the **lens optimization matches the requirements of the BRL system (Hamamatsu PMT Module H10721)**
  - Unlike conventional concentrators, this design incorporates two spatially overlapping optical paths

Fabricated sample of developed lens and a PMT model having it mounted on.



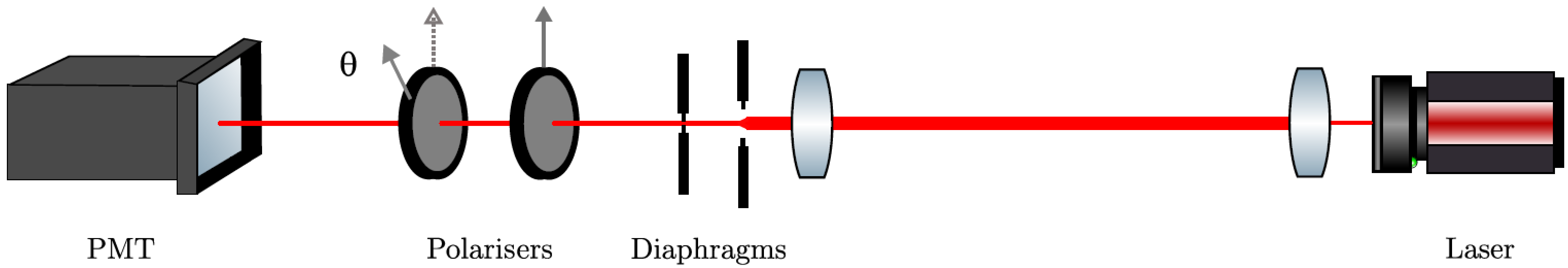
Cross-sectional dimensions comparissons of three types of models with the developed freeform lens having the most compact structure while maintaining high efficiency.



Angular response of each model.

Experimental setup

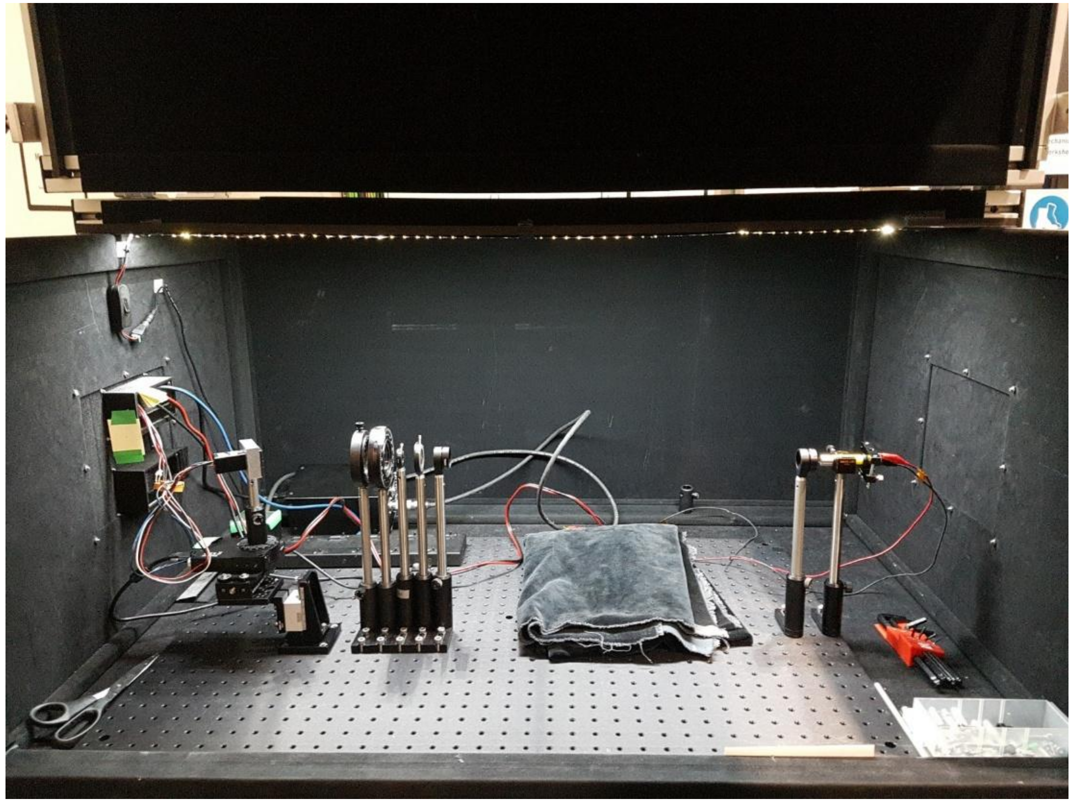
- A dedicated experimental setup was developed to illuminate the PMT and quantify its performance in terms of light collection efficiency, angular acceptance, and response uniformity to evaluate the suitability of this optical design for the BRL application



Schematic representation of the experimental setup. From right to left: laser source of wavelength λ = 635 nm; pair of biconvex lenses (f_1 = 75.0 mm and f_2 = 400.0 mm); pair of diaphragms (D_1 = 3 mm and D_2 = 1 mm); pair of polarisers with relative angle θ for intensity control; Hamamatsu PMT Module H10721 equipped with the condenser lens, mounted on a motorized stage allowing translation and rotation.

Automation and data taking

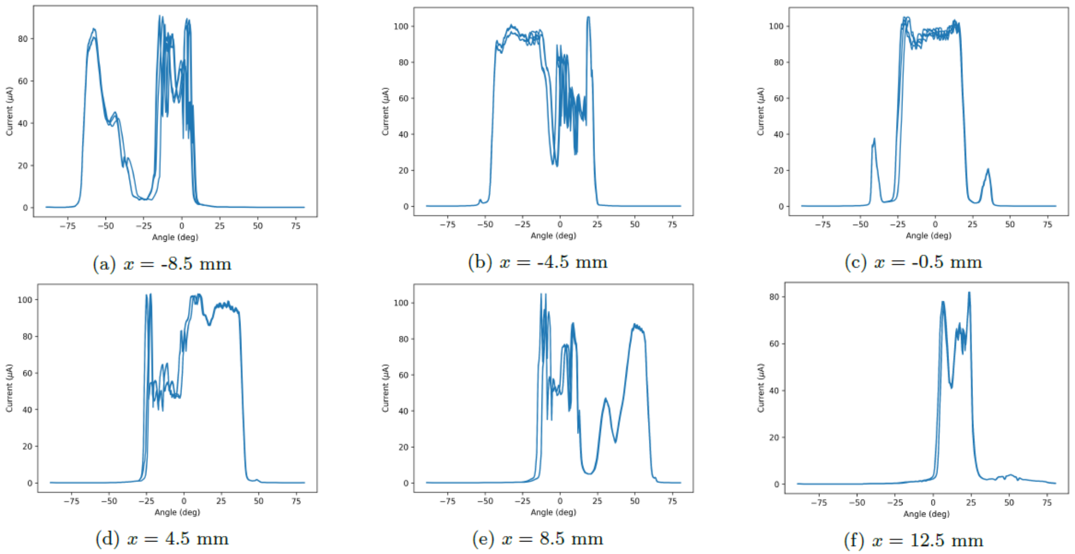
- To obtain a statistically significant dataset, the measurement procedure was **automated**
- PMT output current as a function of position and incident angle was measured using the following procedure
  - Set PMT height from −11 to +11 mm (1 mm steps)
  - Scan horizontal position from −12.5 to +12.5 mm (1 mm steps)
  - Rotate PMT from −80° to +80° (0.5° steps)
  - Record current, position, and angle for every configuration
  - Perform forward and backward scans to verify reproducibility



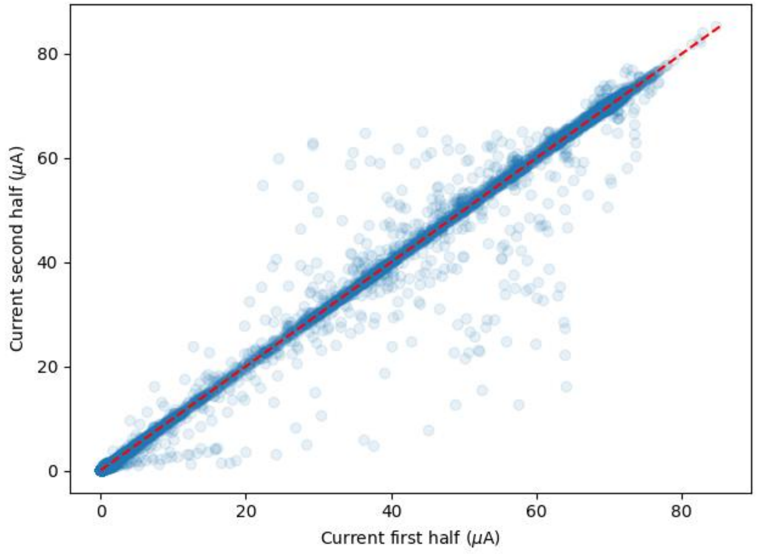
Experimental setup, fixed on optical table inside a dark box.

Short-term stability

- The analysis focuses on evaluating the stability and reproducibility of the measurements, as well as characterising the system response as a function of incident position and angle
  - Short-term stability verified using four repeated scans (forward and backward translations/rotations)
  - Overall, the setup demonstrates **good short-term repeatability**



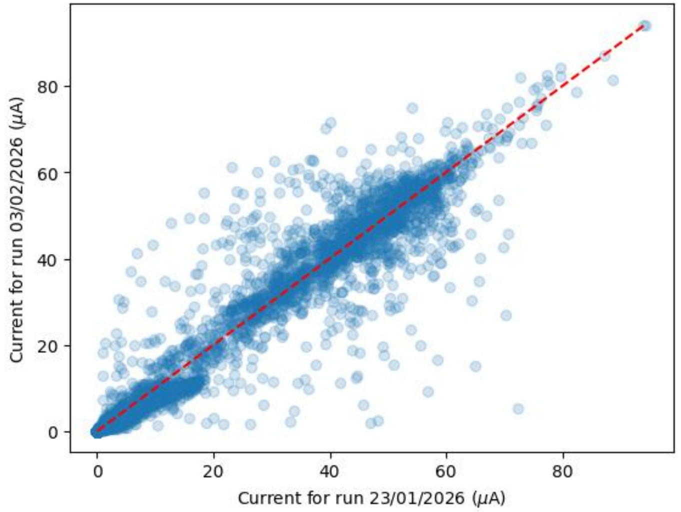
PMT current as a function of incident angle for several translation positions, measured at same height.



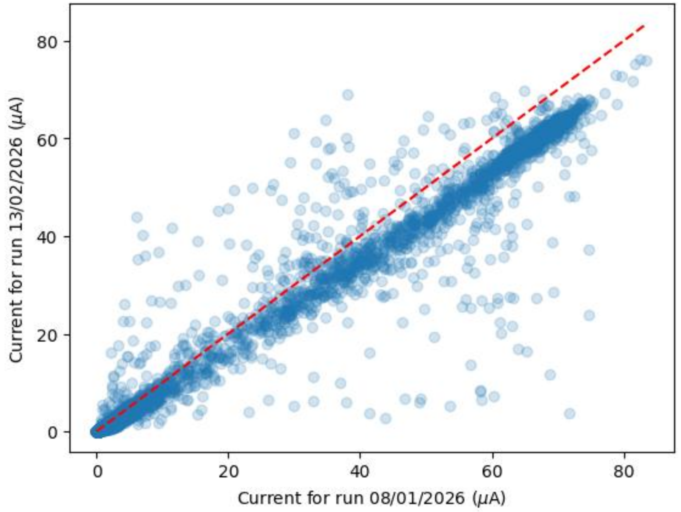
Point-by-point comparison between forward and backward scans in the same run.

Long-term stability

- Long-term stability evaluated by comparing measurements from different dates at identical system heights
  - Over ~10 days, results are reproducible within measurement uncertainties
  - Over ~1 month, systematic deviations become apparent
- Overall, the system shows good short-term repeatability with limited temporal drift, while **long-term reproducibility gradually decreases**



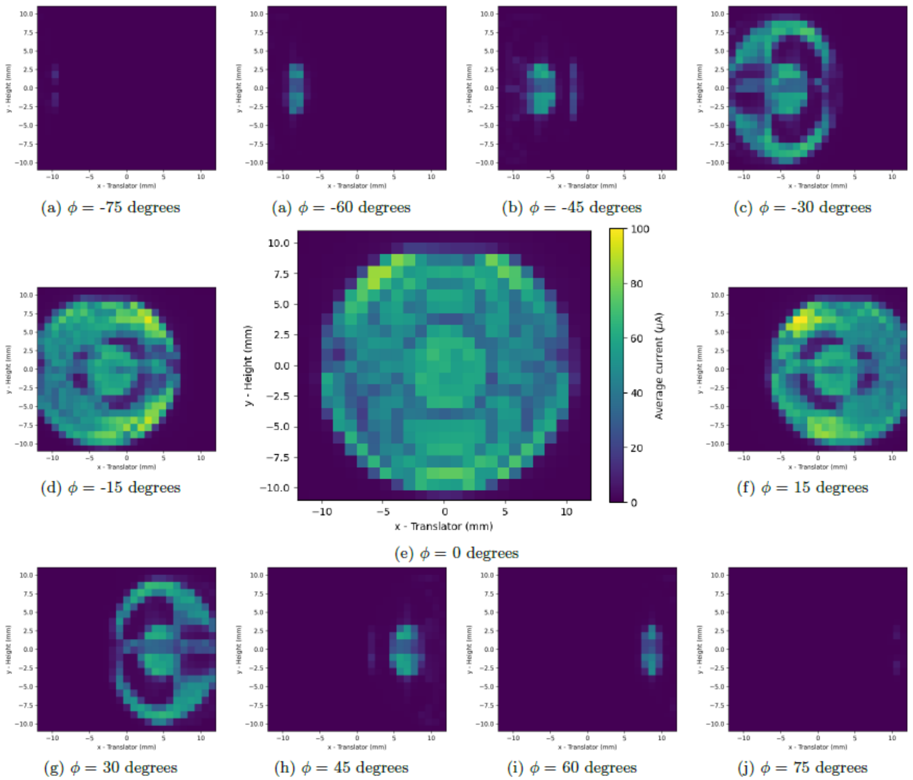
Point-by-point comparison of the measured current for two runs taken on different dates with a 11-day interval.



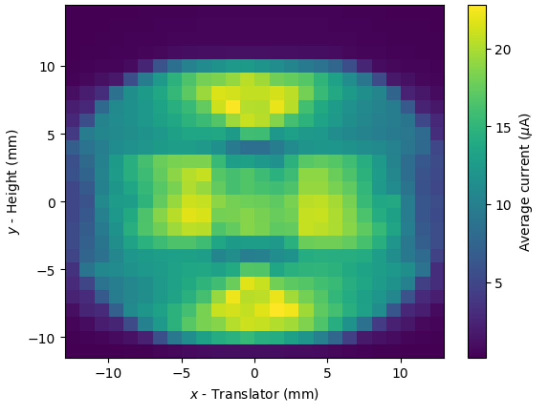
Point-by-point comparison of the measured current for two runs taken on different dates with a 36-day interval.

PMT study

- The average PMT current over all rotation angles for each translation position was evaluated
  - At small angles, the response is broad and nearly centered, with a ring-like structure
  - Increasing angle causes the response to become asymmetric and shift laterally
  - Average current map shows a four-lobed pattern with enhanced signal regions
    - Pattern indicates **non-uniform detector response**, likely due to geometrical or optical effects
    - Spatial variations should be considered in calibration and data analysis



Average current measured over different rotation angles as a function of translation and height values.

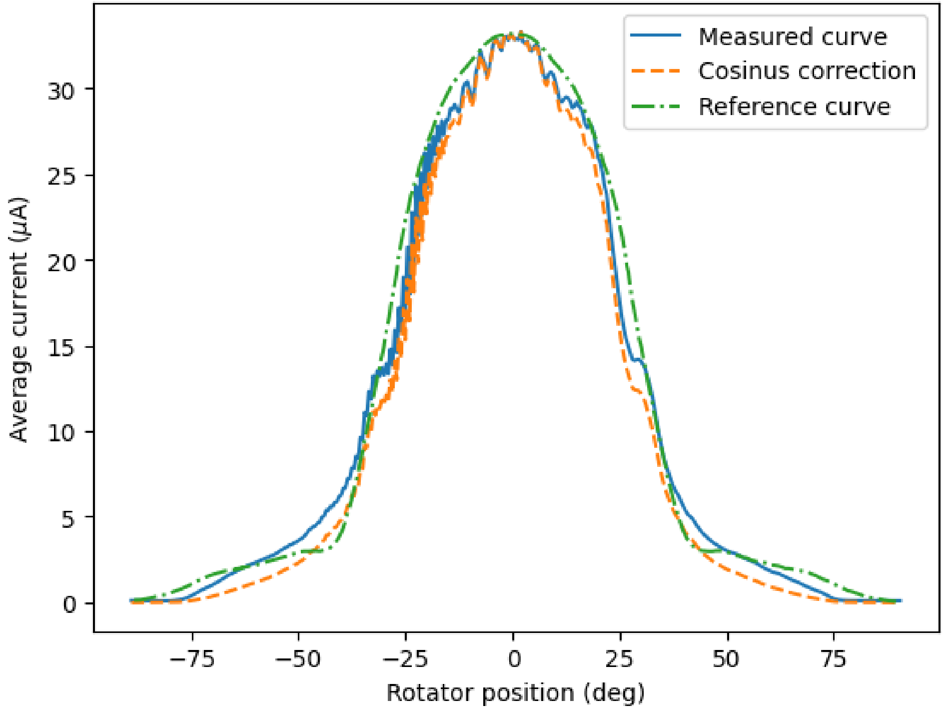


Average current measured over all rotation angles as a function of translation and height values.

Rotation correction

- Geometrical effects associated with the projection of the incoming beam onto the photocathode were also considered
  - Rotating the system increases the illuminated area by 1/cos(θ)

    → reduction in the light intensity per unit area (decrease in measured current)
  - Geometrical correction has **only a small effect** on the angular distribution
  - Corrected and uncorrected data both agree well with the Hamamatsu reference



Average PMT current as a function of incident angle, PMT current corrected for cosine effect, and the curve from Hamamatsu.

Conclusions

- A dedicated setup was developed to characterize the angular and spatial response of a Hamamatsu H10721 PMT with a mounted freeform condenser lens
  - Measurements show good short-term stability and reproducibility
  - Long-term measurements remain stable over $\sim$ 10 days, with systematic deviations appearing after $\sim$ 1 month
  - A non-uniform spatial response (four-lobed pattern) was observed, indicating geometrical/optical effects
  - The PMT response agrees well with the Hamamatsu reference
- These results provide a solid basis for calibration and optimization of the PMT system for the BRL application