Chapter 10

POLLUX: European study of a UV spectropolarimeter

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Participating institutes

The Phase 0 study of POLLUX is led by LAM and LESIA with the support of CNES (France), and developed by a consortium of European scientists. The consortium consists of 154 scientists and engineers from 67 institutes in 13 European countries. The main institutes participating in the present document are: Armagh Observatory (Northern Ireland), Bulgarian Academy of Sciences (Bulgaria), CEA (France), Center for Astrobiology (Spain), Complutense University of Madrid (Spain), CNES (France), CSL (Belgium), DESY (Germany), Exeter University (UK), Geneva University (Switzerland), GEPI (France), IAP (France), IMPS (Germany), IPAG (France), IRAP (France), LAM (France), LATMOS (France), LESIA (France), MPS (Germany), Royal Observatory Edinburgh (UK), Space Research Institute (Austria), Stockholm University (Sweden), Strasbourg Observatory (France), Trinity College (Ireland), TU Delft (The Netherlands), UK Astronomy Technology Center (UK), University of Edinburgh (UK), University of Hamburg (Germany), University of Leicester (UK), Catholic University of Leuven (Belgium), University of Liège (Belgium), University of Pisa (Italy), University of Warwick (UK).

10.1 Executive summary

The POLLUX instrument concept study started in January 2017. POLLUX is a high-resolution spectropolarimeter operating at UV wavelengths, designed for the 15-meter LUVOIR-A architecture. The instrument will operate over a broad spectral range (**90 to 390 nm**), at high spectral resolution (**R ≥ 120,000**). These capabilities will permit resolution of narrow UV emission and absorption lines, allowing scientists to follow the baryon cycle over cosmic time, from galaxies forming stars out of interstellar gas and grains, and stars forming planets, to the various forms of feedback into the interstellar and intergalactic medium (ISM and IGM), and active galactic nuclei (AGN).

The most innovative characteristic of POLLUX is its **unique spectropolarimetric capability** that will enable detection of the polarized light reflected from exoplanets or from their circumplanetary material and moons, and characterization of the magnetospheres of stars and planets and their interactions. The magnetospheric properties of planets in the solar system will be accessible at exquisite levels of detail, while the influence of magnetic fields on the Galactic scale and in the IGM will be measured. UV circular and linear polarization will provide a full picture of magnetic field properties and impact for a variety of media and objects, from AGN jets to all types of stars. POLLUX will probe the physics of accretion disks around young stars, white dwarfs, and supermassive black

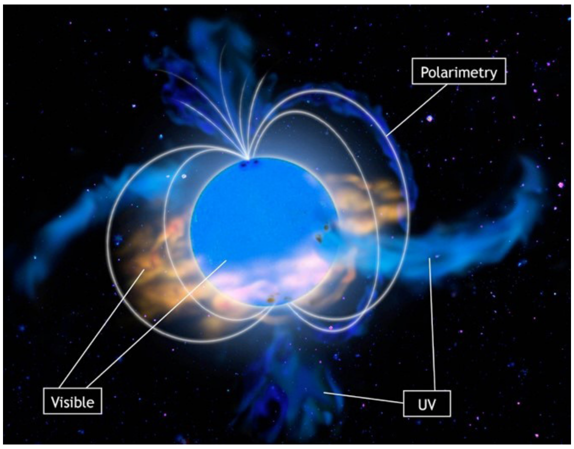

Figure 10.1. *Schematic view of the different features and regions traced by observations at different wavelengths around a hot star. Credit: S. Cnudde.*

holes in AGNs, and constrain the properties, especially sphericity, of stellar ejecta and explosions.

Since the parameter space opened by POLLUX is essentially uncharted territory, its potential for groundbreaking discoveries is tremendous. It will also neatly complement and enrich some of the cases advanced for LUMOS, the multi-object UV spectrograph for LUVOIR. In this chapter we outline a selection of key science topics driving the POLLUX design. We also introduce the current instrument concept and identify technological challenges that we will address in the coming years toward the advanced design and construction of POLLUX.

10.2 Science overview

10.2.1 Stellar magnetic fields across the HR diagram

From the ground in the visible domain, we can obtain sophisticated tomographic mapping of structures on the surfaces of stars and their magnetic fields. However, to understand the formation and evolution of stars and their accompanying planets it is necessary to also explore their circumstellar environments. POLLUX will provide a powerful, high-resolution, full-Stokes (IQUV) spectropolarimetric capability across the ultraviolet domain (90-390 nm) to uniquely trace these structures. When combined with the immense light-gathering power of LUVOIR, it will deliver unprecedented views of the disks, winds, chromospheres and magnetospheres around a broad range of stars, as highlighted below (also see **Figure 10.1**).

Magnetic fields play a significant role in stellar evolution, while also being a key factor in both planet and star formation. We need POLLUX spectropolarimetry to identify and characterize the B-fields across all stellar masses, to address central questions such as:

- How do B-fields develop in the pre-main-sequence (PMS) phase? POLLUX will characterize the strong B-fields arising at the sheared interface between star and disk in the PMS phase (via MgII, FeII, and CII UV lines from the interface region), and will trace the flows via polarization measurements of the nearby continuum.
- How does the stellar dynamo build-up and evolve? As stellar rotation decouples from the young planetary disk, the B-field is predicted to get stronger and more complex (Emeriau-Viard & Brun, 2017). POLLUX will investigate propagation of magnetic energy through the stellar atmosphere into the uppermost coronal layers and stellar wind.
- How do stellar dynamos form and evolve in cool stars? What is their impact on planet formation and evolution? POLLUX will reveal the magnetically mediated interaction between young cool stars and their planetary disks during dynamo formation and stabilization when planets and planetary atmospheres form.
- A small but significant fraction of massive stars have strong B-fields (~10%; e.g.,

Fossati et al. 2015). However, very weak fields could be ubiquitous in massive stars. POLLUX will uniquely detect sub-Gauss B-fields in massive stars, providing a much-needed understanding of weak fields, field-decay mechanisms, and their impact on stellar evolution.
- POLLUX will enable studies of stellar B-fields beyond the Milky Way for the first time. These will open-up observations in the metal-poor Magellanic Clouds (MCs), probing the evolutionary processes linked to B-fields at metallicities equivalent to those at the peak of star-formation in the Universe.

POLLUX will also enable breakthroughs in other areas of contemporary stellar astrophysics, including:

- Jet formation: The mechanism driving the powerful jets from the interaction between disks around PMS stars and their magnetospheres is poorly constrained; POLLUX will transform our understanding of this dramatic part of star formation.
- Winds & Outflows: A large uncertainty in evolutionary models of massive stars is the link between rotation and mass lost via their winds, which limits our understanding of the progenitors of γ-ray bursts, pair-instability SNe, and gravitational-wave sources. POLLUX observations in the Galaxy and MCs will map the density contrasts with stellar latitude required to calibrate these models.
- Novae & SNe: Both classical novae and SNe remnants provide excellent opportunities to learn about the production and lifecycle of dust. POLLUX spectropolarimetry is required to identify sites in the ejecta where dust condenses—allowing us to also infer the effects of kicks imparted by core-collapse SNe—and the shapes/sizes of the grains involved.
- White Dwarfs (WDs): A minority of WDs is strongly (>1MG) magnetic (Ferrario et al. 2015), but little is known of the incidence of weaker fields. POLLUX UV spectropolarimetry will explore this regime for the first time to investigate the ubiquity of B-fields in WDs, as well as the processes generating their fields (e.g., amplification of fossil fields and/or binary mergers?)

A 100-hour POLLUX observing program would be transformational in our understanding of B-fields in stellar evolution. For instance, we could include UV monitoring of two low-mass sources (PMS T Tauri, evolved T Tauri) to directly characterize their B-fields and magnetic-energy transport, combined with observations of a first sample of tens of Galactic massive stars to assess the presence/strength of weak B-fields

10.2.2 What are the characteristics of exoplanet atmospheres and how do planets interact with the host stars?

The characterization of exoplanets is key to our understanding of planets, including those in the Solar System. POLLUX unique, simultaneous, high-resolution and polarimetric capabilities in the UV are essential to unveiling the origins of the huge range of chemical and physical properties found in exoplanetary atmospheres (e.g., Sing et al. 2016), and to understand the interaction between planets and their host stars (e.g., Cuntz et al. 2000).

The line and continuum polarization state of starlight that is reflected by a planet is sensitive to the optical properties of the planetary atmosphere and surface and depends on the star-planet-observer phase angle (**Figure 10.2**). Atmospheric gases are

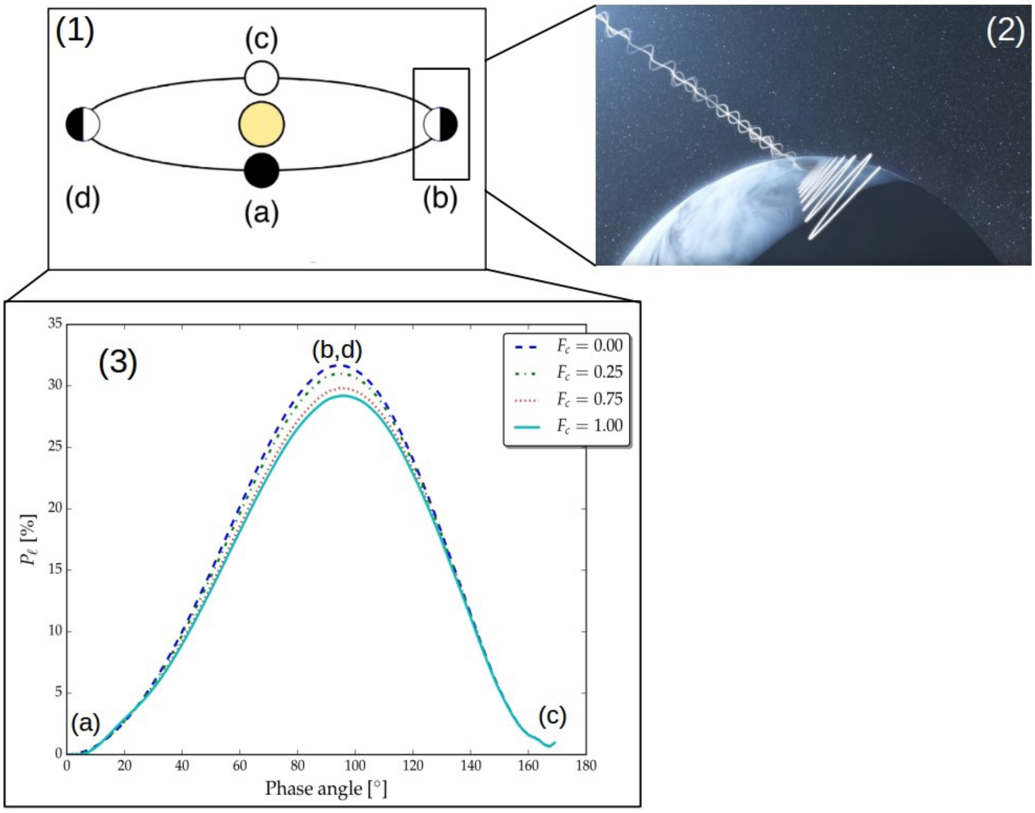

Figure 10.2. *Top panels 1 & 2: Schematic of a planetary system in which the unpolarized stellar light becomes polarized through reflection by a planetary atmosphere. Bottom panel 3: Degree of polarization (in %) as a function of planetary orbital phase, labeled as in panel 1, at 300 nm. The different lines indicate different atmospheric cloud coverages, where zero corresponds to the cloudless condition. POLLUX will measure the degree of polarization as a function of wavelength and planetary orbital phase. Credit: L. Rossi*

efficient scatterers at UV wavelengths and deviations from the expected polarization across the UV would reveal the presence and microphysical properties of aerosol and/or cloud particles. This information is crucial for getting insight into a planet's climate. It would also strongly complement transit observations. POLLUX can significantly detect polarization signatures for close-in gas giants (and brown dwarfs) orbiting stars out to distances of 70 pc, which currently comprises over a dozen targets, two of them transiting.

Star-planet interactions (SPI) could generate detectable signatures in exoplanetary systems. Searching for SPI has developed into a very active field (e.g., Shkolnik et al. 2003; Kashyap et al. 2008; Miller et al. 2015). Evidence of SPI has been observed in UV stellar emission lines (e.g., NV; France et al. 2016). POLLUX will be capable of studying the intensity of UV stellar emission lines forming in a wide range of temperatures as a function of planetary orbital phase, uniquely combining this information with measurements of the magnetic field derived from the Stokes V profiles of these lines. This will allow for the first time to identify the stellar regions mostly affected by SPI and hence to understand their origin.

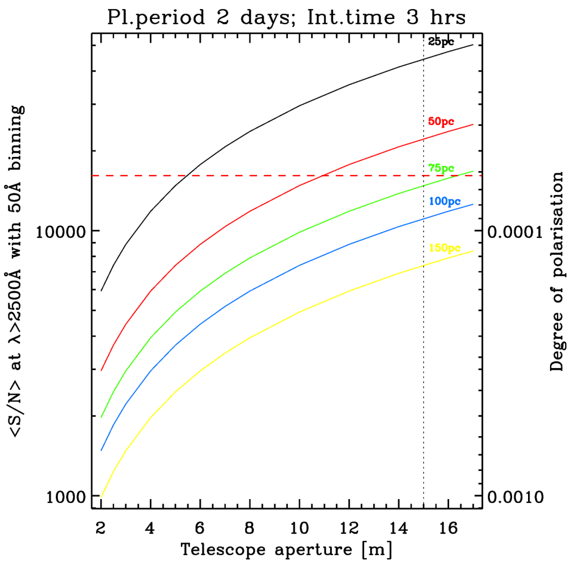

Figure 10.3. *Average S/N in the near-UV obtained with 3 hours of POLLUX shutter time as a function of the distance of the target Sun-like star (line colour) and size of the telescope primary mirror. The red dashed horizontal line indicates the maximum near-UV polarization signal of a hot-Jupiter with a 2 days orbital period. The black dotted vertical line indicates the size of LUVOIR's primary mirror.*

At UV wavelengths, a hot Jupiter orbiting a Sun-like star with a two-day orbital period presents a maximum polarization of ≈30% (**Figure 10.3**), leading to a maximum polarization signal of the order of 7×10^{-5}, when observed unresolved from its star. With POLLUX mounted on a 15-m LUVOIR telescope and a binning size of 50 Å, the signal-to-noise ratio (S/N) necessary to detect such a signal can be obtained in less than 3 hours of shutter time for systems as far as 70 pc (**Figure 10.3**). Measuring and modeling the variation of the polarization signal as a function of the planet's orbital phase requires at least eight measurements spread across the orbit. A POLLUX 100-hour observing program would allow the detection and characterization of the UV polarimetric signature for over a dozen targets.

10.2.3 The various phases of the ISM and extragalactic IGM

Matter in the interstellar space is distributed in diverse, but well-defined phases that consist of (1) the hot, ionized ($T \sim 10^{6-7}$K) ISM that emits soft X-rays, (2) the warm neutral or ionized medium ($6000 < T < 10^4$ K), and (3) the cold (T~10–200 K) neutral medium and molecular star-forming clouds. Boundaries between the different phases play a fundamental role in the cooling of the gas and by consequence in Galactic evolution. However, it is not yet clear how these different phases trade matter and entropy. We need to address the multi-phase aspect of the ISM and the influence of different factors such as magnetic field, thermal/pressure (non-) equilibrium, metallicity, shocks, etc.

Gaining fundamental insights into the processes that influence the different phases requires the wealth of interstellar absorption features appearing in the UV spectra of hot stars, and requires observing them at R ≥ 120,000 to measure individual clouds and disentangle the different phases contributions. POLLUX will, for the first time, give access to all phases at the required high spectral resolution. It will enable simultaneous study of tracers of hot-gas (OVI, CIV.), warm gas (OI, NI, and many singly-ionized species), as well as cold-HI gas like CI, and of the molecular phases through H_2 and CO lines. POLLUX will resolve the velocity profiles of the different H_2 rotational levels, yielding temperature and turbulence, and information on the formation of H_2 and its role as a coolant, e.g., in turbulence dissipation.

ISM studies also need to be generalized to external galaxies. POLLUX will enable tomography of chemical abundances in several hundred nearby galaxies using neutral gas absorption lines toward individual stars across the entire (stellar) body of galaxies or toward background quasars. Abundance

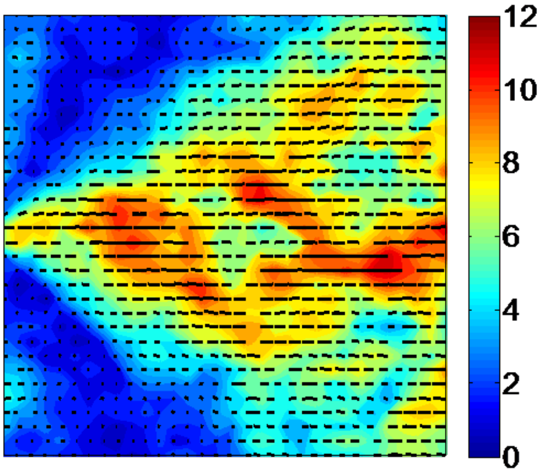

Figure 10.4. *Synthetic polarization (%) map of the simulated diffuse ISM (1 pc²). Contour color: percentage of polarization in the SII 1250 A absorption line. Orientation of the bars: polarization direction. Mean magnetic field=3 μG, oriented along the X-axis. This figure shows that the direction of polarization correctly indicates the magnetic field direction and that the expected polarization is mostly above 5%, within POLLUX capabilities.*

variations across and between galaxies of different types and metallicities will document the dispersal/mixing spatial/time scales of newly produced elements and their nucleosynthetic origin, the role of infalling and outflowing gas in the metallicity build-up, and the dust production/composition through depletion patterns. Furthermore, cooling rates, physical conditions, and the molecular gas content can be determined spatially in the HI reservoir (with implications for the regulation of star formation and for galaxy evolution at large) and in neutral shells of HII regions (with implications for the star-formation process itself).

A huge step forward in the knowledge of the Galactic magnetic field in terms of sensitivity, sky coverage and statistics has been made from recent dust polarization measurements. However, they tell us nothing on the distance of the magnetic field and its distribution in the different components or phases. The POLLUX spectropolarimeter will provide this information by its ability to detect linear polarization in UV absorption lines through Ground State Alignment (GSA, Yan & Lazarian 2012). It will open up access to the magnetic field 3-D, by measuring its orientation in different clouds, on limited distances along sight lines and on small scales (**Figure 10.4**). In a 100-hour program, observing several hundreds of hot stars with a S/N of 500 to measure linear polarization in optically thin absorption lines at a level of a few % will help understand the interplay of magnetic field and the different ISM phases. By discerning magnetic fields in gas with different dynamical properties, POLLUX will allow the first study of interstellar magnetic turbulence (Zhang & Yan 2017).

10.2.4 Beyond the unresolvable regions of active galactic nuclei: revealing accretion disk physics, dust composition and magnetic field strength with UV polarimetry

POLLUX will offer unique insight into the still largely unknown physics of Active Galactic Nuclei (AGNs), which are believed to arise from accretion of matter by supermassive black holes in the central regions of galaxies. Some key signatures of accretion disks can be revealed only in polarized light, and with higher contrast at ultraviolet than at longer wavelengths. Specifically, high-resolution UV polarimetry will provide geometric, chemical and thermodynamic measurements of accretion disks in unprecedented detail. By probing the ubiquitous magnetic fields expected to align small, non-spherical dust grains on scales from the accretion disk out to the extended dust torus, POLLUX will be able to reveal the mechanisms structuring the multi-scale AGN medium. The key information encoded into the polarized light will allow determinations of the mineralogy, structure

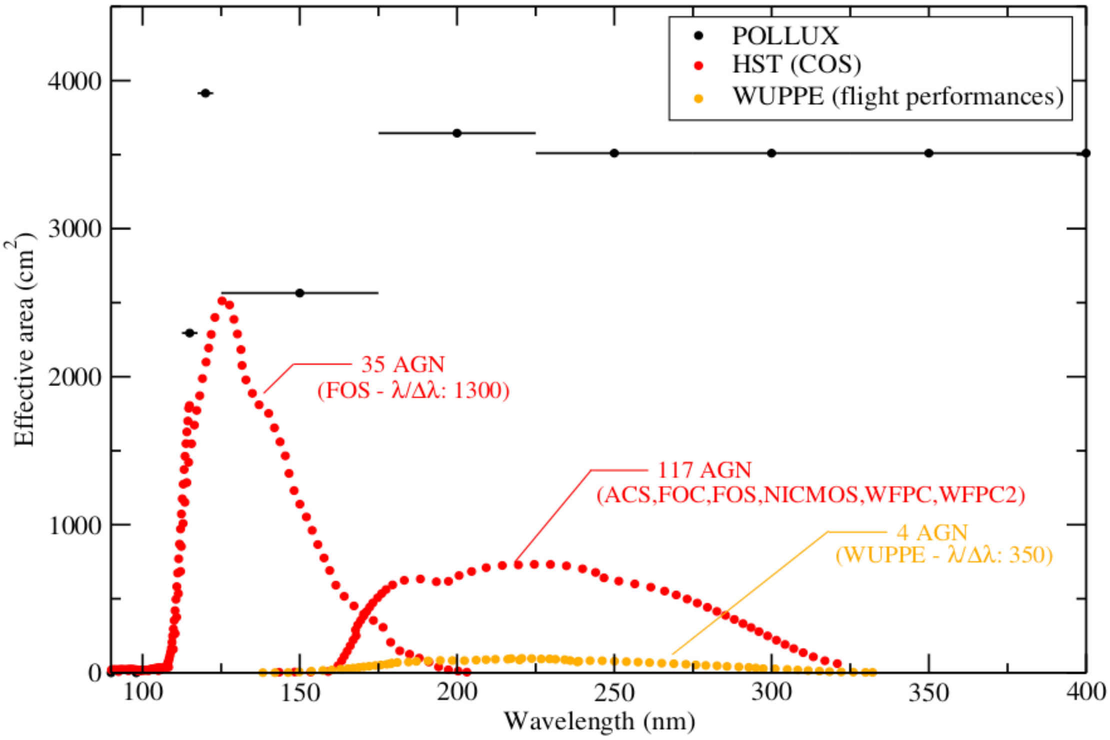

Figure 10.5. *Effective area of POLLUX (in black; assuming 135 m² for LUVOIR with a RC telescope), compared to those of previous space-based UV spectrographs, as indicated. Only 4 AGN were observed with WUPPE. A total of 117 were observed with different polarimetric instruments on board HST, out of which only 35 in the UV with HST/FOS (for which an effective area similar to that of HST/COS was adopted). POLLUX will enable observations of hundreds of AGN over a wide UV spectral domain, and with much larger spectral resolution than ever achieved.*

and alignment of the smallest dust grains, together with on-line-of-sight magnetic-field strengths. Measurements of magnetic field strengths will also make constraints on the structure of magneto-hydrodynamic winds in nearby, broad absorption-lines systems accessible to the instrument. On larger scales, UV polarimetric studies of young star-forming regions will provide unprecedented insight into the enigmatic relation between onset of star formation and triggering of nuclear activity. Once activated, an AGN is expected to feed vast amounts of energy back into the interstellar medium of its host galaxy through radiation and shocks. This feedback can decrease or increase the star formation activity of the host, the physical conditions of which observational constraints from UV polarization with POLLUX will greatly help understand. In addition to the extended environment of AGNs, POLLUX will provide insight into the nature and lifetime of particles in relativistic jets, which are other key factors to fully understand AGN feedback on star formation in galaxies. By focusing on bright, low-redshift galaxies, it will be possible to obtain, for the first time, high-resolution spectra providing striking details on the structure and physics of AGNs. Complemented with the optical and infrared instruments on board LUVOIR, POLLUX will constitute a groundbreaking means of assessing the important role played by AGNs on galaxy evolution (**Figure 10.5**).

10.2.5 Testing fundamental physics and cosmology using absorption lines towards quasars

Physics and cosmology as we know today have been remarkably successful in reproducing most of the available observations with only a small number of parameters. However, it also requires that 96% of mass-energy content of the Universe is in mysterious forms (dark energy and dark matter) that has never been seen in the laboratory. This shows that our canonical theories of gravitation and particle physics may be incomplete, if not incorrect. Improving the sensitivity of current observational constraints is therefore of utmost importance, irrespective of whether it is consistent with the current standard physics—in which case it will reject other scenarios—or whether it will instead favor new physics.

Absorption-line systems produced by intervening gas in the spectra of background sources provide original sensitive probes of fundamental physics and cosmology. The high UV spectral resolution of POLLUX on LUVOIR will open a unique window on such probes, in particular (1) the measurement of the primordial abundance of deuterium, (2) the stability of fundamental constants over time and space and (3) the redshift evolution of the cosmic microwave background (CMB) temperature. The D/H ratio can be estimated from the DI and HI Lyman series lines. Any change in the proton-to-electron mass ratio ($\mu=m_p/m_e$) translates into a relative wavelength change of the H_2 Lyman and Werner lines. Finally, the CMB radiation excites the CO molecules so that the relative population in different rotational levels (measured through the electronic bands in the UV) is an excellent thermometer for the CMB temperature.

We remark that, while these are independent probes, they are intimately related by the underneath physics. For example, models involving varying scalar-photon couplings (e.g., Avgoustidis et al. 2014) also affect the temperature-redshift relation so that constraining this relation is complementary to a search for varying fundamental constants. The Big Bang nucleosynthesis calculations of the D/H ratio are also dependent on the fundamental constants and can be altered if new physics is at play (e.g., Olive et al. 2012).

The baseline specifications of LUVOIR/POLLUX are S/N~100 per resolution element in 1h for $F\lambda=10^{-14}$ erg s^{-1} cm^{-2} $Å^{-1}$. This means that for known quasars with low-z H_2 absorbers as observed by HST/COS (Muzahid et al. 2015), we can reach a precision of a $\Delta\mu/\mu$ ~ a few 10^{-7} in 20–30h (**Figure 10.6**). This is about an order of magnitude better than the current best limits in less observing time than typical used to achieve those (around 5 x 10^{-6} with UVES on the Very Large Telescope). Similarly, the achieved precision on TCMB scales directly with the S/N ratio (0.1 K at S/N~100 and R~100,000 when current limits are ΔT~1K). The same is again true with the D/H ratio, although a very high resolution is less critical since the corresponding lines are typically thermally broadened above 10 km s^{-1}.

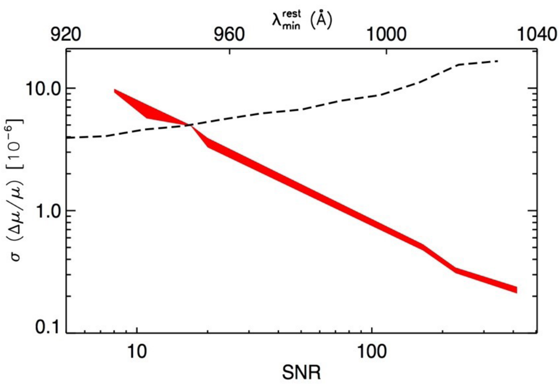

Figure 10.6. *Expected error on $\Delta\mu/\mu$ as a function of signal-to noise ratio (red band, abscissa scale) and minimum wavelength (dashed line, absorber's rest-frame, top axis) covered by a R=120,000 spectrum.*

10.2.6 *Solar System: Surfaces, dust scattering, and auroral emissions*

UV observations uniquely probe the surface of telluric bodies of the solar system. They diagnose their volcanic and plume activity, their interaction with the solar wind and their composition in the frame of space weather and exobiology/habitability fields. Very few UV polarimetric observations were obtained so far with WUPPE (e.g., Fox et al. 1997), revealing in particular the Io surface as spatially covered by 25% SO_2 frost with polarization variations associated to different volcanic regions. POLLUX will primarily characterize volcanism and/or plume activity of icy moons from polarized solar continuum reflected light and spectral UV albedo. Its high sensitivity is necessary to track any organic and ice composition of the crust of comets and Kuiper Belt objects from their UV spectrum.

The giant planets' UV aurorae are mainly radiated from H and H_2 atmospheric species, collisionally excited by accelerated charged particles precipitating along the auroral magnetic field lines. Aurorae thus directly probe complex interactions between the ionosphere, the magnetosphere, the moons and the solar wind. Precipitation of auroral particles is additionally a major source of atmospheric heating, whose knowledge is needed to assess the energy budget, the dynamics and the chemical balance of the atmosphere. The narrow FOV of POLLUX will measure the bright complex aurorae of

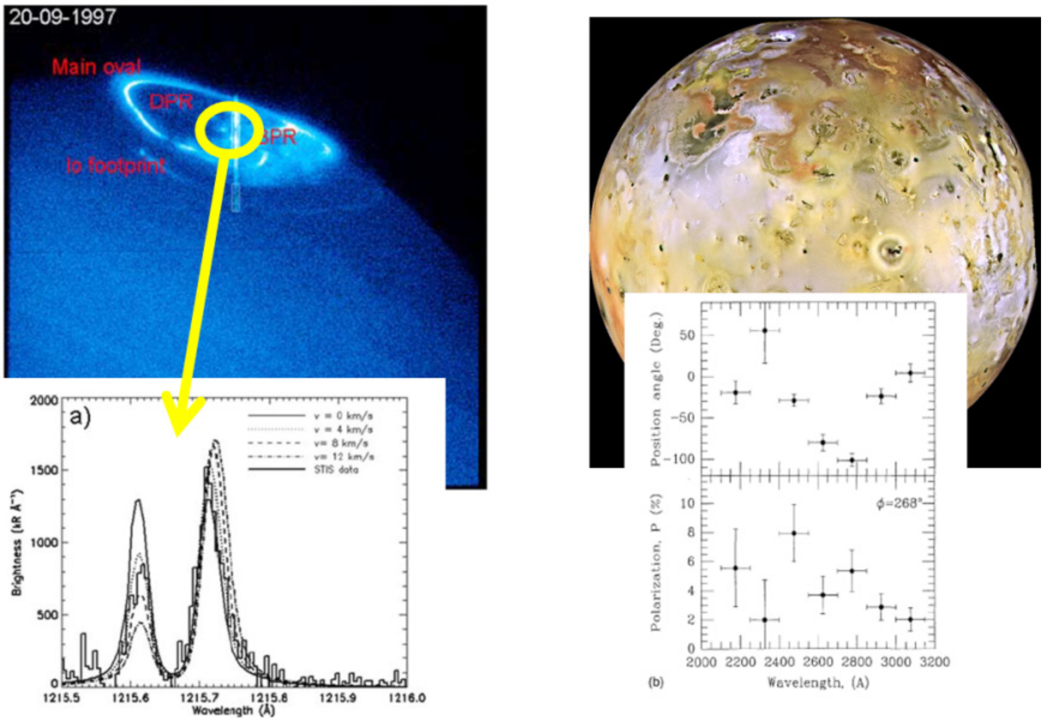

Figure 10.7. *Left: auroral emissions observed on Jupiter by HST. The Ly-alpha emission spectrum in the polar auroral region was obtained with STIS. Its strong asymmetry can be reproduced with a wind shear reaching 4-8 km/s. Credit: Chaufray et al. (2010). Right: Io observed by Galileo. The linear polarisation of the surface measured by WUPPE between 220–320 nm presents complex variations with wavelength and provide information on the volcanic activity on the surface of Io. Credit: Galileo Project / JPL / NASA / Fox et al. (1997)*

Jupiter and Saturn, the fainter ones of Uranus and catch those of Neptune, only seen by Voyager 2 (Lamy et al., 2017). The high spectral resolution will be used to finely map the energy of precipitating electrons from partial spectral absorption of H_2 by hydrocarbons (Ménager et al. 2010, Gustin et al., 2017) and the thermospheric wind shear from the H Ly–α line (**Figure 10.7**, left panels; Chaufray et al. 2010).

The asymmetric profile of the H Ly-α line in the Jovian auroral region (**Figure 10.7**, left panels) should be resolved by POLLUX: for an exposure time of 10 minutes, and considering the brightness of the wings of the Ly-α line measured by HST/STIS, the two wings should produce 68±8 cts/px and 34±6 cts/px respectively, implying a velocity larger than 4 km/s which can be measured precisely by POLLUX.

The albedo of a region of 100 km^2 can be derived with an accuracy of 0.1% with a spectral resolution of 1 nm with a 5-min exposure only near 320 nm. The linear polarization of Io surface varies between 1 and -10% between 220 and 320 nm; near 320 nm, the linear polarized signal observed by POLLUX for a binning size of 1 nm in 5 minutes should have a S/N~10, which is better than WUPPE (**Figure 10.7**, right panels).

10.3 Design drivers

The science goals described in the previous section lead to the technical requirements for POLLUX presented in **Table 10.1**, with comments in the last column.

10.4 Design overview & implementation

The baseline configuration of POLLUX that we will now present allows fulfillment of all the requirements for the instrument performance.

Table 10.1. *High-level requirements*

Parameter	Requirement	Goal	Reasons for requirement
Wavelength range	97–390 nm	90–650 nm	97 nm to reach Lyγ line. 390 nm to reach CN line at 388 nm in comets
Spectral resolving power	120,000	200,000	Resolve line profiles for ISM, solar system, and cosmology science cases
Spectral length of the order	6 nm	≥6 nm	To avoid having broad spectral lines spread over multiple orders
Polarization mode	Circular + linear (= IQUV)		
Polarization precision	10^{-6}	Detect polarization of hot Jupiters	
Aperture size	0.03"	0.01"	Avoid contamination by background stars in Local Group galaxies
Observing modes	spectropolarimetry and pure spectroscopy		
Radial velocity stability	Absolute = 1 km/s and relative = 1/10 pixel		Avoid spurious polarization signature
Flux stability	0.1%		Probe flux and polarization correlation in WDs
Limiting Magnitude	V=17		To reach individual stars in MCs
Calibration	Dark, bias, flat-field, polarization, and wavelength calibration	+ Flux calibration	

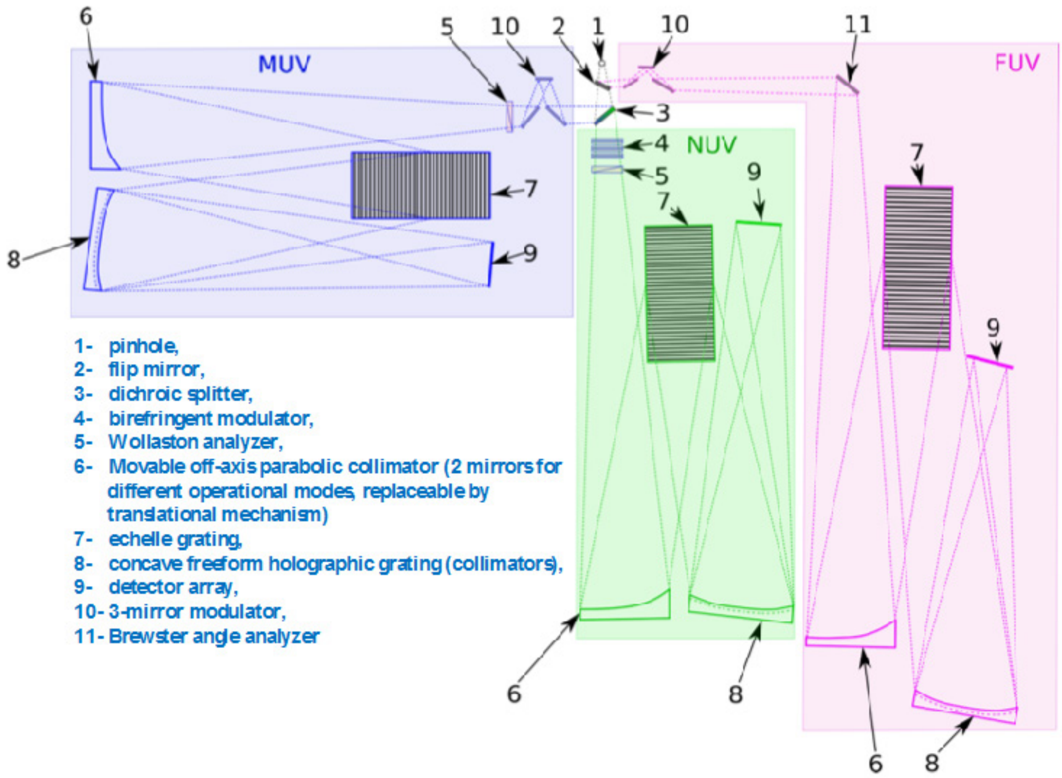

Figure 10.8. *POLLUX instrument baseline architecture schematic diagram*

Most of the technologies required for a complete implementation present TRLs compatible with a Phase 0 study. We did not find fundamental restrictions or physical limitations preventing its implementation. We will discuss what research and development is needed to allow us to realize the baseline configuration by the time of LUVOIR implementation.

10.4.1 Baseline optical architecture and specifications

In the baseline configuration of POLLUX, we adopted the telescope parameters provided by the LUVOIR study. POLLUX is a spectropolarimeter working in three channels. For practical reasons we refer to these as NUV (19–390 nm), MUV (118.5–195 nm), FUV (90–124.5 nm). Each is equipped with its own dedicated polarimeter followed by a high-resolution spectrograph. The spectra are recorded on δ-doped EMCCD detectors. MUV+NUV channels are recorded simultaneously, while the FUV is recorded separately. POLLUX can be operated in pure spectroscopy mode or in spectropolarimetric mode. POLLUX can be fed by the light coming from the telescope or from sources in the calibration unit. We anticipate that POLLUX can operate with a 270 K housing, in line with the requirement of LUVOIR.

We now describe the major assumptions that we adopted to design the optical architecture of this configuration. They are illustrated on **Figure 10.8**:

- The instrument entrance is a pinhole, rather than a slit, for simpler aberration correction.
- The working spectral range is 300 nm. It is split into three channels: far ultraviolet (FUV), medium ultraviolet (MUV) and near ultraviolet (NUV). This allows POLLUX to achieve high spectral resolving power with

feasible values of the detector length, the camera optics field of view and the overall size of the instrument. It also allows to use dedicated optical elements, coatings and detectors and polarimeter for each band, hence obtain a gain in efficiency.

- The FUV and MUV boundaries are set relative to the Lyman-α line. The lower limit for the MUV band is set at Lyman-α minus roughly 3 nm, that is 118.5 nm, while the upper one for the FUV is Lyman-α + roughly 3 nm, i.e., 124.5 nm.
- The shortest wavelength for the FUV strongly depends on the main telescope throughput and may be reconsidered in the future.
- The MUV and NUV channel are separated by means of a dichroic splitter. Such splitters can have a high efficiency (e.g., a mean reflectance of 61% over the 140–170 nm i.e., most of the MUV band, and a mean transmittance of 83% over the 180–275 nm, i.e., most of the NUV band, see **http://www.galex.caltech.edu/researcher/techdoc-ch1.html**). A dichroic splitter allows the instrument to work in two bands simultaneously and use the full aperture thus achieving the high resolving power with relatively small collimator focal length. In the present design, we set the MUV/NUV boundary at 195 nm, to have a maximum of one full octave in each channel (here the NUV).
- Currently there are no dichroic splitters operating in the FUV below the Ly-α line and there is no evidence that such an element will become possible in the future. We have decided to use a flip mirror to feed the FUV channel. The flip mirror is located immediately before the dichroic splitter.
- The splitters are placed as close to the focal point as possible in order to decrease their size and the size of the polarimeters. Currently the flip mirror is located 20 mm away from the focus and the distance from focus to dichroic is 35 mm.
- In each channel, the beam is collimated by an ordinary off-axis parabolic (OAP) mirror. The off-axis shift and the corresponding ray deviation angle are chosen in such a way that the distance between the entrance pinhole and the echelle grating is large enough to place the polarimeter and corresponding mechanical parts. The MUV and NUV mirrors have identical geometry, though they may have different coatings and have slightly different operation mode due to the difference in each polarimeter's design.
- Echelle grating works in a quasi-Littrow mounting. The exact values of the groove frequency and the blaze angle are computed to obtain the target dispersion and subsequently the spectral resolving power.
- The cross-disperser in each channel operates also as a camera mirror, so it is a concave reflection grating. This approach allows minimization of the number of optical components and increases the throughput. In order to correct the aberrations, the cross-disperser's surface is a freeform and has a complex pattern of grooves formed by holographic recording.
- Adopted coatings on the optical elements of POLLUX are those used for the telescope, except for the polarimeters. In the future, they will be optimized for each element of each channel (see **Section 10.5**).
- Polarimeters are located immediately after the splitters in each channel to avoid instrumental polarization by the spectrograph elements. The polarimeters are retractable in the MUV and NUV to allow the pure spectroscopic mode. In the FUV only the modulator is retractable.

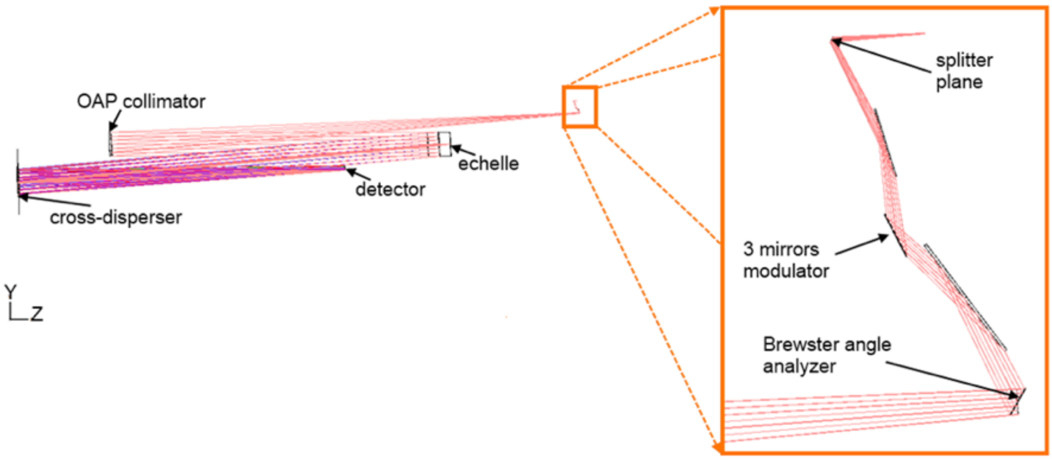

Figure 10.9. *An example of a schematic optical scheme, here for the FUV channel, including a zoom on the FUV polarimeter unit.*

The analyzer is kept in the optical path to direct the beam towards the collimator.

- Change of the optical path caused by removing the polarimeter from the beam is compensated by translating the OAP mirror for the three channels.
- The polarimeter design was optimized for each channel accounting for the technological feasibility (see **Section 10.4.2**). The polarimeters should have minimal size in order to decrease their influence on the image quality. Firstly, transparent plates introduce some aberrations. Secondly, due to polarization ray splitting the collimator may operate in an unusual mode and have considerable aberrations. Thirdly, the shorter the optical path inside the polarimeter, the smaller the difference between the spectropolarimetric and the pure spectral observation modes.

It is necessary to switch beams in POLLUX in order to feed the detectors with light coming from the telescope, or from sources in the calibration unit. Furthermore, in order to compensate the optical path difference and maintain the same beam position and the angle of incidence at the echelle when switching from the spectropolarimetric mode to the spectroscopic mode (done by removing the polarimeters from the optical train), it is necessary to change the collimator mirror (see #6 in **Figure 10.8**). Due to the focal length change, the collimated beam and therefore the theoretical resolution limit are also changed. On the other hand, the pinhole projection size is also changed, so the resolution values found with account for the aberrations should be re-scaled.

The optical design is optimized for the conditions described above. In order to account for possible misalignments due to switching from the pure spectroscopic mode to the spectropolarimetric one, the target spectral resolving power was set to 130 000 (i.e., 110% of the requirement).

10.4.2 Polarimeters

Below 120 nm, MgF_2 is opaque. Above this wavelength, both the birefringence and transparency of MgF_2 recover quickly. In order to optimize the throughput in particular below 150 nm, we explored modulation based on reflection rather than transmission for the FUV and MUV modulators.

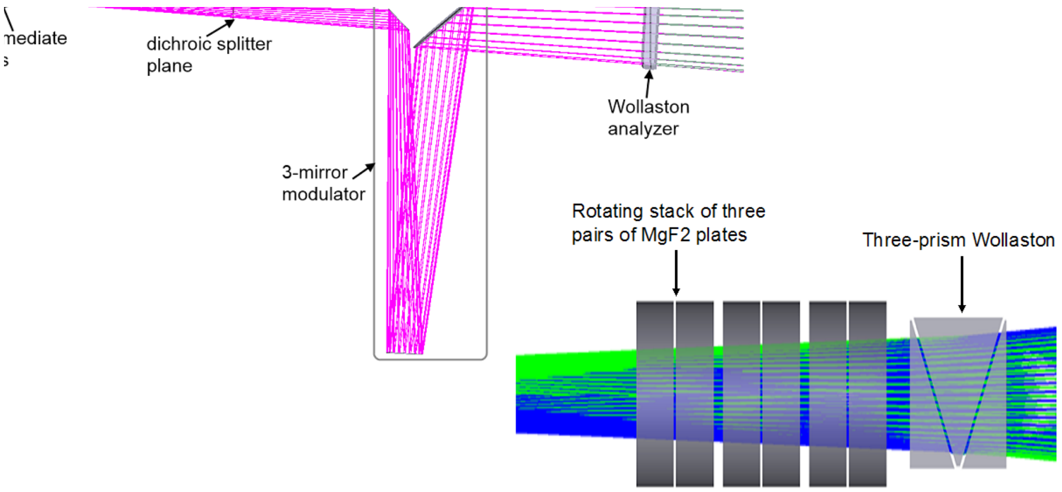

Figure 10.10. *Optical schemes for the polarimeter units of MUV (left) and NUV (right) channels.*

- The FUV polarimeter has a three-mirrors modulator with SiC mirrors with high incidence Brewster angle (close to 80 degrees) to record polarization. Only the reflected P beam can be recovered with this technique, hence we cannot use two-beam polarimetry to reduce systematics.
- The MUV polarimeter (see **Figure 10.10**) has a three-mirror modulator coated with Al+LiF. The three mirrors rotate as a whole around the optical axis of the instrument. The first and third mirrors work at an incidence angle close to 47 degrees and the second mirror at the complementary of twice this angle. The choice of three mirrors ensures that the output beam is in the same axis as the entrance beam. A Wollaston prism made of MgF_2 is the current baseline solution for the analyzer, but other options will be studied.
- The NUV polarimeter is completely adapted from the ARAGO design (Pertenais et al. 2016), that is a birefringent modulator made of three pairs of MgF_2 plates, and a Wollaston prism of MgF_2 for the analyzer. However, thanks to its reduced operational range with respect to ARAGO, it will be simplified for POLLUX.

10.4.3 Mechanical architecture

The mechanical layout is based on the optical design discussed above (cf. **Figure 10.11**). It is intended to illustrate a feasible structural design concept including the necessary mechanisms, which fit within the available space envelope.

The major points of this layout can be summarized as:

- The central support structure of POLLUX consists of a central chassis, which provides mechanical interfaces for the MUV, FUV, NUV arms, calibration unit, polarimetry and beam switching mechanisms. This will also provide the mechanical interface to the telescope but has not been represented at this time.
- MUV, FUV, NUV arms are generically similar optical benches constructed of rectangular or triangular box sections. They provide flat mounting interfaces for the collimator, disperser, camera and detector subassemblies. The benches are connected to the central support via box section brackets with angled bolted flanges (**Figure 10.12**).
- The collimator exchange mechanism is implemented by linear slides using

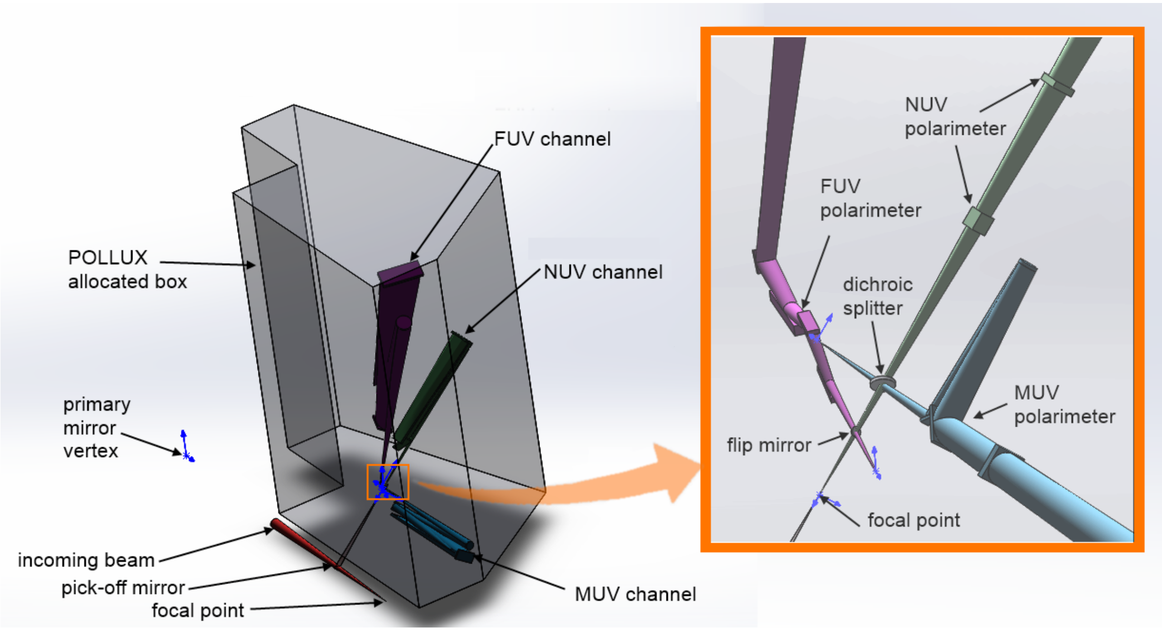

Figure 10.11. *Optical system of POLLUX arranged inside the dedicated volume.*

recirculating ball bearing carriages. Two slides are used to better control tilt error and for robustness. The slides are positioned via a leadscrew driven by a stepper motor.

- The calibration insert mechanism rotates a fold mirror into the beam. The mirror is mounted on a radius arm attached directly to the motor shaft. To achieve the repeatability required the mirror position should be compliantly mounted and the position defined kinematically against a stop.
- The polarimetry insert mechanisms for the three channels are implemented by linear slides using recirculating ball bearing carriages. Two slides are used to better control tilt error and for robustness. The slides are positioned via a leadscrew driven by a stepper motor.
- The polarimetry rotation mechanisms are implemented by worm and gear

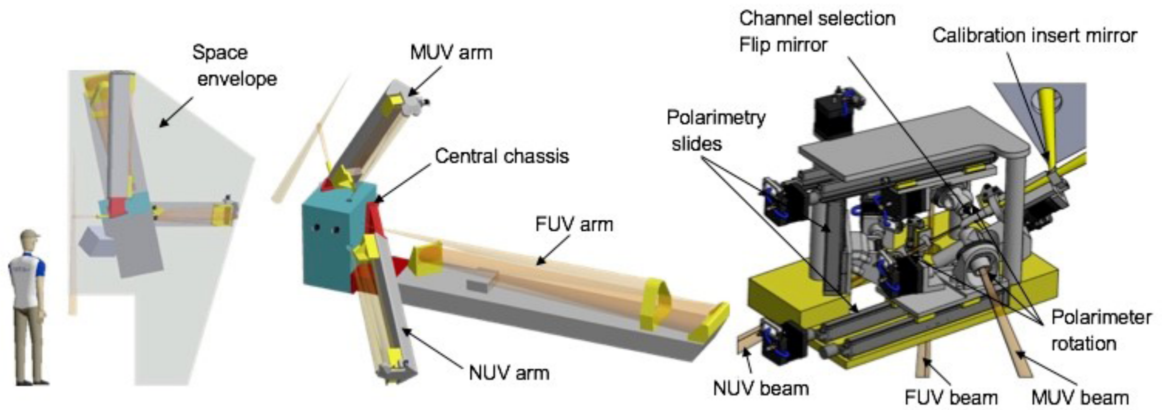

Figure 10.12. *Rendering of POLLUX within the allocated volume (left); Opto-mechanical layout (center); Beam switching and polarimetry mechanisms (right).*

mechanism driven by a stepper motor. The axis is defined by a pre-loaded angular contact bearing pair. For the FUV and MUV, the polarimeters are rotated to four positions, while for the NUV the modulator is rotated to six positions.

10.4.4 Detectors

The detectors of POLLUX are based on the technology of surface processing of thinned, back-side illuminated EMCCDs (e.g., "δ-doping"). These have now become competitive with MCPs in the FUV to NUV range. They combine the linearity of CCDs with the photon-counting ability, which is a key capability enabling detection of faint UV signals. Furthermore, these detectors now deliver high quantum efficiency (e.g., in band QE > 60%, see http://www.mdpi.com/1424-8220/16/6/927), thus offering the possibility to reach very high signal-to-noise ratios.

Recent developments show that visible-blindness can be achieved with proper treatment (e.g., anti-reflection coatings). Detectors with 13µm pixels will be used for POLLUX. They may be passively cooled to ~ 120K (to reduce dark current level etc.). In the FUV channel, the detector active area is 203 mm x 19 mm, while for MUV and NUV, the active areas are 131 mm x 19 mm and 131 mm x 24 mm, respectively.

10.4.5 Operation modes

POLLUX is designed to work in two science modes, a pure spectroscopic mode and spectropolarimetric mode.

- In pure spectroscopy mode, one measurement produces either one spectrum in the FUV, or two spectra, one in the MUV and one in the NUV. It is expected that in a majority of cases, two measurements (one in the FUV and one in the MUV+NUV) will be obtained for a target.
- In spectropolarimetric mode, one full-Stokes polarimetric measurement requires four spectra in the FUV, or ten spectra in the MUV+NUV channels (six spectra in the NUV and four spectra in the MUV. Here again, we anticipate that in most cases two measurements (one in the FUV and one in the MUV+NUV) will be obtained for a target.

When switching to the spectroscopic mode, the full polarimetric unit for MUV and NUV, or the polarimetric modulator for the FUV, is removed from the optical train. The optical path length and the beam position are then maintained by translating the collimator mirrors (see **Section 10.4.1**).

In addition to the science modes, POLLUX can work in calibration mode. This consists of inserting one of the calibration lamps in the light path, blocking the stellar light, to acquire calibration images.

The calibration unit (CU, **Figure 10.13**) groups the necessary light sources, including a cold redundancy. In order to minimize the impact of the instrumental polarization

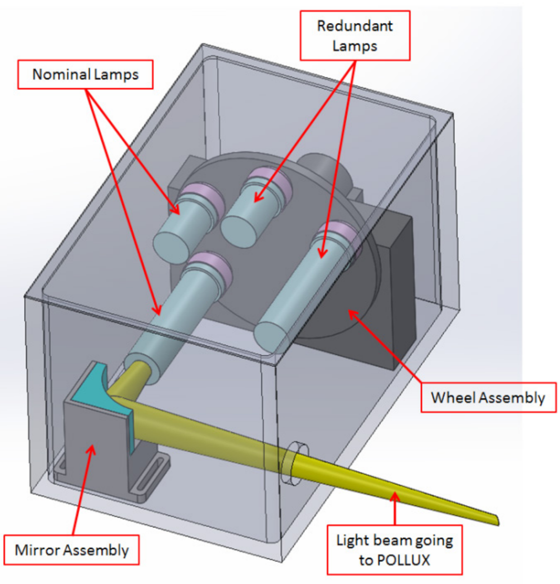

Figure 10.13. *Schematic rendering of a possible calibration unit of POLLUX.*

on the final calibration, the light from the calibration sources will be injected before the polarimeters of each channel as early as possible in the optical chain, i.e., at the level of the flip-mirror mechanism directing the light towards the FUV or MUV+NUV channels.

The injection of the calibration beams requires an additional mechanism inside the CU, for the selection of the calibration sources. A wheel, bearing the calibration lamps, is placed facing a mirror assembly that is used to redirect the light from the lamps to POLLUX while reproducing the f-number of the LUVOIR telescope. This way, we avoid any systematic effect resulting from different illumination patterns between the scientific and calibration beams within the instrument. Such wheel mechanisms are usually used as filter wheels inside optical instruments and therefore they have a long flight heritage.

The main calibration purposes for POLLUX internal calibration sources are the wavelength calibration and the flat field. The optical stimulus for the wavelength calibration is a Pt/Ne Hollow Cathode Lamp (HCL), covering the entire wavelength range of the MUV+NUV channel. The flat-field (FF) source is used to calibrate the pixel-to-pixel response variations and to monitor the blaze function and/or the evolution of the relative spectral response function (which will be tied to celestial calibrators at sparser time intervals). The optical stimulus for the FF is a deuterium arc lamp. Given that the FF will not be acquired with every observation, the impact on the overall mission efficiency is marginal. A power supply box will be placed next to the CU and will include a high voltage supply, which is required for the HCL.

The error matrix of polarization will be calibrated on the ground. Any possible evolution or aging will be monitored in flight by regular observations of a set of celestial calibrators, used as reproducibility sources.

We have currently not identified calibration sources covering the full FUV channel. Consequently, in this channel, the ground-based and onboard calibrations will be completed with observations of celestial standards, essentially white dwarfs.

Standard calibration images will be collected once per day for each detector through a fixed sequence: 10 flat-field images, 5 bias images, and 1 dark image. In addition, wavelength calibration should be obtained. In pure spectroscopy mode: 2 wavelength calibration images will be downloaded at each new pointing of the telescope, one once the telescope is pointed and before the science acquisition start, and the other after the science acquisition is finished and the telescope moves away. In spectropolarimetric mode: 1 wavelength calibration image would be obtained not only before and after the acquisition but also between each spectropolarimetric measurement.

10.4.6 Performance evaluation

The overall efficiency of POLLUX was computed under the following set of assumptions:

- The pick-off mirror is assumed to be covered with the same broadband coating as the telescope mirrors (Al+MgF_2+SiC).
- The dichroic is taken to be identical to that used in GALEX, but its efficiency curves are shifted by 17.1 nm to the red.
- The coatings of the flip mirror is single-layer SiC. The coating of the collimators and the cross-dispersers are single layer SiC in the FUV, and Al+LiF+AlF_3 in the MUV and NUV.
- The 3-mirror modulator and analyzer of the polarimeter in the FUV are in SiC. For the MUV, the 3-mirror modulator is coated with Al+LiF, while the analyzer is in MgF_2. For the NUV, both the plates and analyzers are in MgF_2.

- For each channel, the echelle gratings work under pure Littrow mounting. They are etched into Si substrate, and their profiles are not fully optimized at this stage of the proposal. The echelle coating is taken to be Al+LiF for all the channels.
- Efficiency of the cross-disperser grooves is that for an ideal blazed profile in Al multiplied by the coating reflectivity.
- The detector quantum efficiency assumes an uncoated δ-doped EMCCD. In the future it will be optimized for each of the channels separately.

The total efficiency (**Figure 10.14**) is the product of efficiencies of all the elements. The result was also converted into the effective area (adopting a geometrical coefficient A_{geom}=135 x 10^4 cm^2 for LUVOIR).

In the final design of POLLUX, we expect that using specifically tailored coatings for each channel will improve the throughput of POLLUX. We also intend to investigate alternative designs reducing the number of reflections. However, the current baseline already shows that POLLUX is feasible and its science goals reachable.

10.4.7 Future developments for POLLUX

In 2018, we will continue to improve the optical and mechanical design. We will also study the thermal architecture, the thermo-mechanical stability, the main electronic hardware and software, the data telemetry, the power and mass budget, the AIT/AIV model philosophy, the contamination and cleanliness issues, and the radiation impact.

10.5 Engineering and technology challenges

Table 10.2 presents the current TRLs and heritage of the main components of POLLUX. Here we present the development plan we have prepared for key elements in **Table 10.2**. Two of the elements have low TRLs, namely the cross-dispersers and polarimeters:

Cross-dispersers. Each of the cross-dispersers of the present design is a concave freeform holographic grating. This is a novel type of optical elements having high aberration correction capabilities. For the cross-dispersers, computation show that a sufficient aberration correction is possible only if the spectral components at the cross-disperser's surface are separated, although it leads to the grating's aperture increase.

A R&D program has been set up in collaboration with Jobin-Yvon HORIBA (France) to study the feasibility of the required holographic recording geometry parameters, develop and test prototypes. According to current technology, no showstoppers have been identified.

Examples of clear apertures and asphericities of the cross-dispersers used in the present design are shown on **Figure 10.15**.

Polarimeters. An existing R&D program funded by CNES started four years ago on the development of new concepts of UV polarimeters. It has been extended for three more years in the fall of 2017. In this frame, a first prototype of the concept proposed for the NUV channel has been built and tested in the visible, and is now being tested in the UV. The prototype was optimized for the ARAGO project and will be specifically tailored for POLLUX in 2018.

Furthermore, the concept with three mirrors proposed for FUV and MUV will be further studied and prototypes will be developed and tested in the framework of the CNES R&D. A PhD student has already been hired to work on this specific point.

The performance of the polarimeters strongly depends on the properties of the material and coatings to be used. Measurements to characterize them

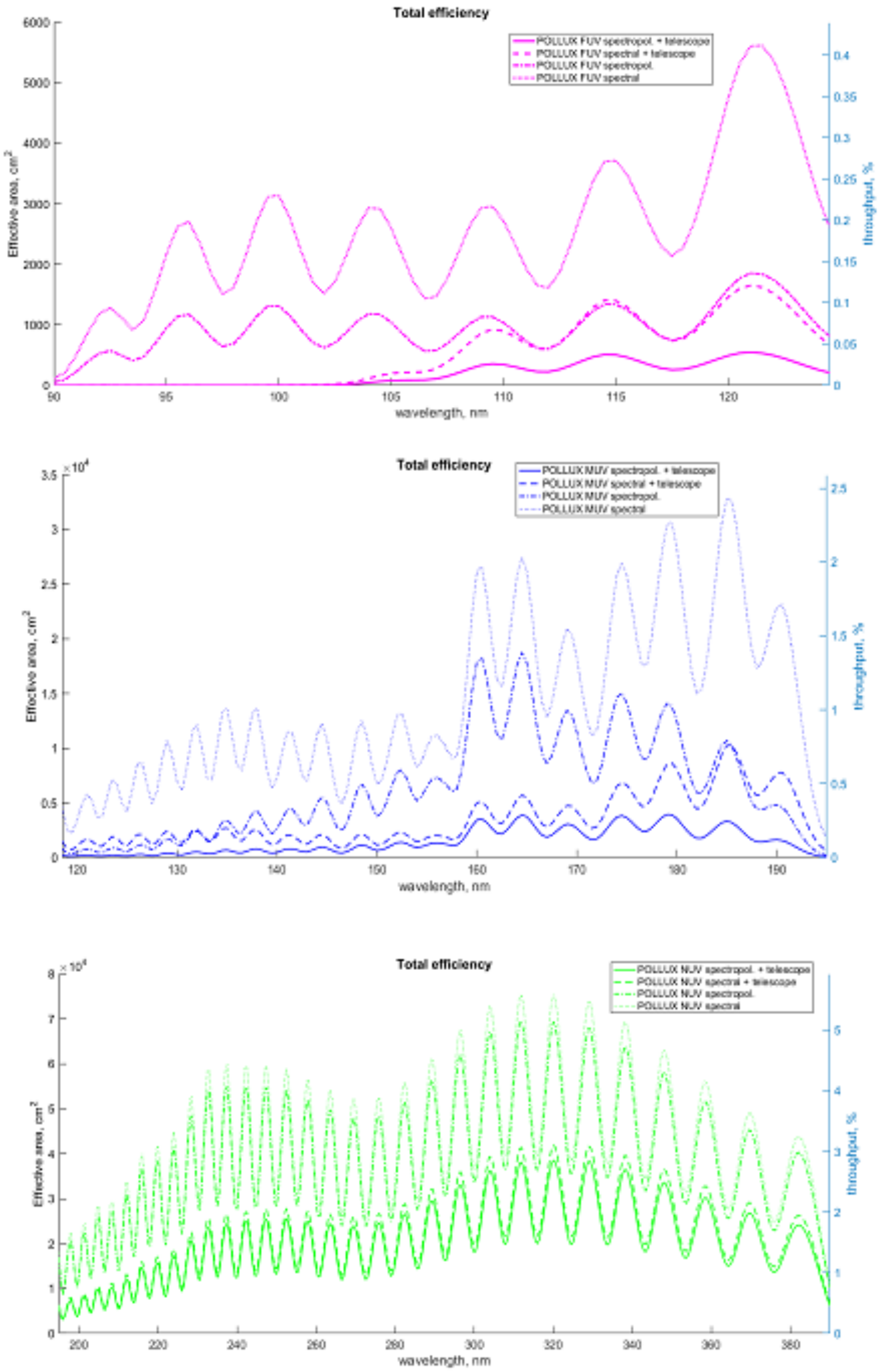

Figure 10.14. *Throughput for POLLUX and effective area. For the MUV and NUV, they have been computed with and without the polarimeters. See text for underlying assumptions.*

Table 10.2. *TRL and heritage of main POLLUX components*

	Element	Est. TRL	Status	Comment
	Flip-Mirror mechanism	9	Exist	Similar mechanism has already flown (e.g., HST)
	Dichroic	5	To be tailored	Heritage from GALEX and ARAGO study
	FUV polarimeter	2	Concept defined	New concept
	MUV polarimeter	2	Concept defined	New concept - Analyzer exists and has been tested
	NUV polarimeter	4	Proven concept	Based on HINODE and CLASP heritage, and ARAGO study
	FUV, MUV and NUV collimator translation	9	Exist	Similar mechanism has already flown (e.g., CHEMCAM)
	FUV, MUV, NUV collimator	8	To be tailored	OAP mirror
	FUV echelle grating	4	To be studied	Manufacturer identified. Size exceeds what is presently doable. Prospects are encouraging
	MUV and NUV echelle grating	7	To be tailored	Manufacturer identified. Similar gratings flew on sound rockets
	FUV Cross-disperser	2	Concept defined	To be studied. On-going contact with Jobin-Yvon Horiba.
	MUV, NUV Cross-disperser	2	Concept defined	On-going contact with Jobin-Yvon Horiba. Preliminary studies are encouraging
	FUV, MUV, NUV detectors	6	To be studied and tailored	δ-doped EMCCDs; will rely on heritage from recent or soon to be flown missions (e.g., CHESS, LIDOS, FIREball-2)
	FUV coating	5	To be studied	Choice will depend on the cut-off wavelength of the telescope.
	MUV, NUV coatings	5	To be studied	Several options are identified and will be compared
	Calibration lamps	9	Exist	Heritage from SCIAMACHY, IUE, HST...

(e.g., refractive index) will be performed in collaboration with the Max-Planck institute in Göttingen and the Metrology Light Source of PTB in Berlin (Germany).

Other elements of POLLUX have higher TRLs but require further development and tailoring:

Detectors. The technology of δ-doped EMCCDs is not fully mature yet. More R&D is required to further demonstrate the dynamic range and how low spurious noise is, in a realistic, end-to-end environment for spectroscopy. We need to assess how the detectors behave around and below Lyman-α for instance. Implementation of antireflection coatings, or of metal-dielectric stacks as visible rejection filters must be improved. A last point will be to demonstrate feasibility of detector wafers large enough to accommodate our needs (typical detector size is 15k x 2k for POLLUX). This size appears achievable in the coming years (communication from Dr. Shouleh Nikzad, JPL). In case tiling detectors would be needed, test on the impact of the science

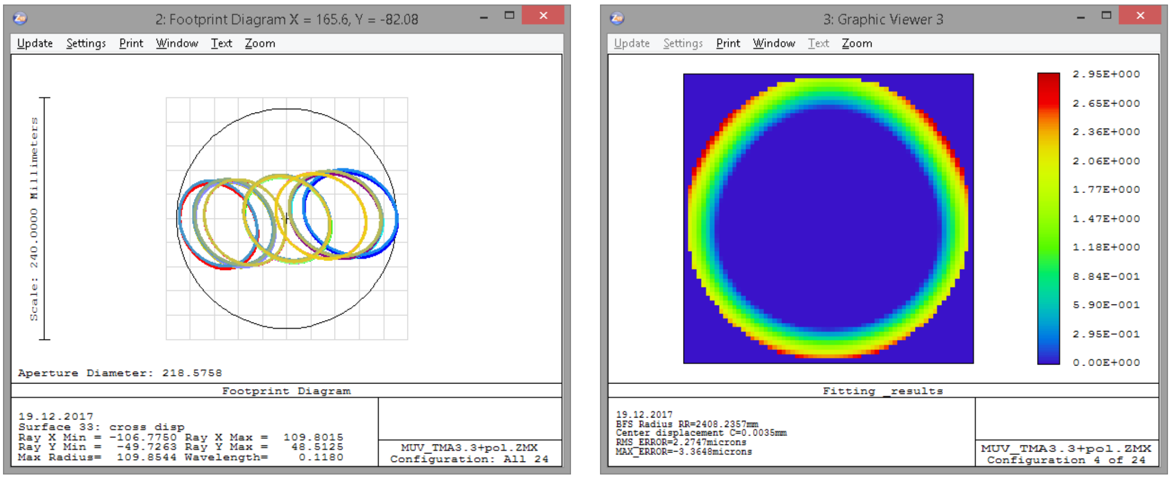

Figure 10.15. *MUV cross-disperser. (Left) Footprint diagram. (Right) Asphericity map in microns.*

cases will be done. These are specific studies that will be led by Leicester University (UK).

Echelle gratings. In the current design, the MUV and NUV echelle gratings have almost identical sizes and blazing angles. The groove frequencies differ approximately by a factor of two. Both the groove frequencies and the angles are non-standard. For the FUV echelle grating, the groove frequency and blazing angle are even more unusual. We have no evidence that such a grating has been ever produced before for the UV domain. For the three channels however, feasibility is in the range of today's technological limits (communication from Dr. Randall McEntaffer, Penn State University).

Open issues include the accuracy of the groove profiles and the coatings optimization for each of the channels. Another high technological risk is the clear aperture of the gratings. Today's process tools are limited to 200 mm diameter wafers (~140 x 140 mm clear aperture), so at least one of the dimensions on each of these gratings is a challenge (e.g., McEntaffer et al. 2013). These points will be addressed in the framework of R&D plan between Penn State and University of Colorado, and the POLLUX consortium.

Coatings. A CNES R&D program to obtain and select coatings with excellent UV and FUV efficiency, particularly in the 90 nm to 390 nm range, started in October 2017. The goal is to reach above 90% for as much as possible of this spectral range, high-uniformity coatings (< 1%), over a large spectral range with low polarization (< 1%) for high-contrast imaging, and pre-launch stability of ultra-thin coatings.

Materials with best perspectives are MgF_2, LiF, and AlF_3. Single and double layers of these materials have been investigated, e.g., Al/LiF, Al/AlF_3, Al/LiF/MgF_2, Al/LiF/AlF_3, and combinations with different process conditions. At the short wavelength edge, presently a top coating with AlF_3 gives the best reflectance results, as has been published most recently by Del Hoya and Quijada (NASA GSFC). A reflectance of more than 30% above 100 nm and more than 90% from 120 nm to 130 nm has been reported (see **Figure 10.16**).

Members of our consortium have investigated in the past protective coatings of MgF_2, LiF, and AlF_3 for mirrors at 120 nm and studied also the environmental stability and durability. To optimize these coatings at the short wavelength cutoff it is necessary to investigate further the dependence on coating thickness and substrate temperature during the deposition process. We propose

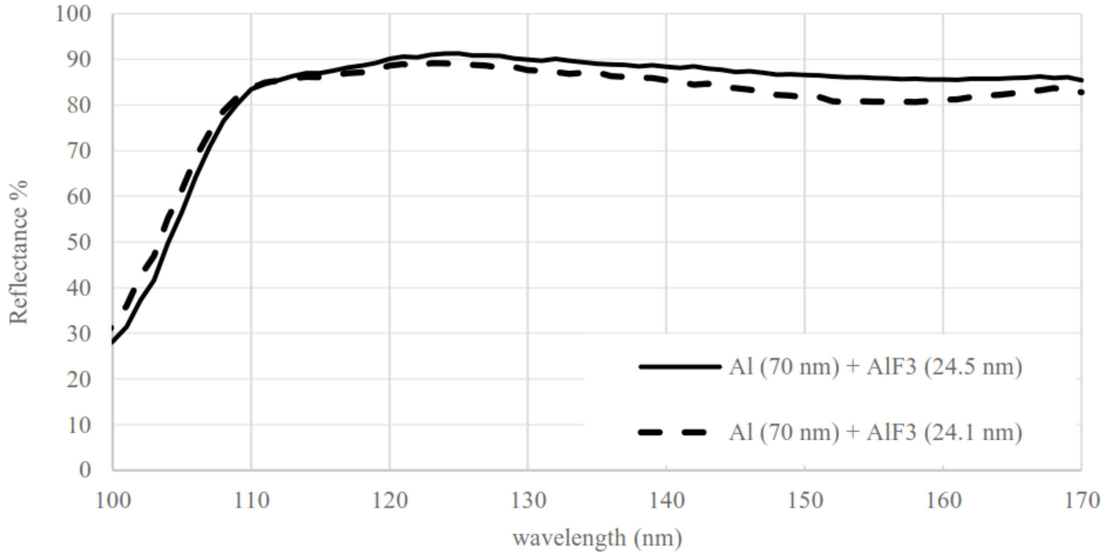

Figure 10.16. *Reflectance of Al protected with AlF_3 coatings. Credit: Quijada et al. (2017).*

to investigate protected aluminum coatings in collaboration between MPS (Göttingen, Germany) and OptiXfab (Jena, Germany). Experimental studies with mirror samples will start in 2018.

Dichroic. The dichroic filter used for beam separation of the MUV and the NUV is based on the GALEX heritage. It provides a mean reflectance of 61% over the 140–170 nm band and a mean transmittance of 83% over the 180–275 nm band. The reflectance was extrapolated down to 118.5 nm, the transmittance up to 390 nm, for the computation of the efficiency calculations presented in **Section 10.4.6**. A study by REOSC performed for ARAGO has demonstrated feasibility down to 119nm. Our development plan is to tailor a dichroic beam splitter to the MUV and NUV, and further increase the efficiency in both channels of POLLUX. This will be done in partnership with the REOSC Company.

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