POLARIX: a small mission of x-ray polarimetry

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ABSTRACT

X-Ray Polarimetry can be now performed by using a Micro Pattern Gas Chamber in the focus of a telescope. It requires large area optics for most important scientific targets. But since the technique is additive a dedicated mission with a cluster of small telescopes can perform many important measurements and bridge the 40 year gap between OSO-8 data and future big telescopes such as XEUS. POLARIX has been conceived as such a pathfinder. It is a Small Satellite based on the optics of JET-X. Two telescopes are available in flight configuration and three more can be easily produced starting from the available superpolished mandrels. We show the capabilities of such a cluster of telescopes each equipped with a focal plane photoelectric polarimeter and discuss a few alternative solutions.

Keywords: X-ray Astronomy, Polarimetry, Telescope, Detectors

1. POLARIMETRY: BIG HOPES MEAGRE RESULTS.

A long term theoretical analysis has foreseen the possibility to test models of X-ray sources and to derive relevant parameters of the models themselves by measuring the linear polarization of X-rays. In the first years the polarization deriving from the emission process was outlined. On 1985 Sunyaev and and Titarchuk demonstrated that in a hot accretion disk the scattered photons have an energy much higher than the original photons and thence the Chandrasekhar limit of 11.7 % could be exceeded. In 1988 Meszaros et al. stated "Polarimetry would add to energy and time two further observable quantities (the amount and the angle of polarization) constraining any model and interpretation: a theoretical/observational break-through".

This very attractive perspective pushed some investigators to develop instrumentation aimed to perform this measurements. This was mainly based on Bragg Diffraction at 45° and on Compton/Thomson scattering in a certain range of angles around 90°. Bragg crystal is an excellent analyzer of polarization (100% modulation) but is effective in a very narrow interval around the energy that fulfils the Bragg condition for that particular crystal and that particular angle. A flat Bragg crystal at 45° set before the focal plane of an X-ray telescope acts as a newtonian secondary mirror and a detector in the secondary focal plane detects the source in the thin band defined by the Bragg (plus higher orders if in the band). The whole is rotated and the source brightness is modulated depending on the amount of polarization.

The scattering polarimetry is effective only when scattering exceeds photoabsorption. A well of detectors surrounds the scatterer and the polarization is measured by the angular distribution of the out-coming photons.

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This technique can be used by means of large experiments with a distributed multiplicity of detectors and scatterers and many experiments based on this principle have been proposed and some are on the way.[1] Scattering polarimetry can also be performed in the focus of a telescope with some substantial limitations: even with lithium the method is only effective above 5 keV and this is mismatched with the bandpass of most telescopes; the angular distribution strongly depends on the impact point and the measurement is severely affected by systematics; all the detector set (and not only a few pixels) is involved in the measurement so that the improvement of signal to noise ratio introduced by the use of the telescope is essentially lost.

The pioneering result achieved by the Columbia University team was the measurement of polarization of Crab Nebula first with a rocket[2] then with a Bragg polarimeter on-board OSO-8 satellite.[3] This result was of extreme relevance but the overall throughput of X-ray polarimetry based on conventional techniques was considered too meagre to support the inclusion of a polarimeter onboard further X-ray missions. Moreover theoretical analysis suggested that a polarimeter capable to perform polarimetry at few % level also on relatively faint sources was needed for most of the scientific objectives. The only mission with a focal plane polarimeter (both Bragg and Compton) was the Spectrum X-Gamma[4] that sinked in the general collapse of the soviet system.

A third physical process that can analyze the polarization is photoelectric absorption: s-photoelectrons are ejected according to a $\cos^2$ distribution, with respect to the electric field. This is a potentially ideal analyzer of polarization and many teams tried, also in early times, to build a device based on this effect. The difficulty is that electrons penetrate much less than photons, and a finely subdivided detector is needed. Various attempts arrived to perform this measurement in one dimension[5] or in two dimensions but at higher energies.[6] Eventually the Micropattern Gas Chamber was developed with a full capability to convert photons and image photoelectrons, making possible focal plane photoelectric polarimetry.

2. A NEW PATH TO X-RAY POLARIMETRY

2.1. The Micropattern Gas Chamber

The Micro Pattern Gas Chamber[7,8,9] is a gas detector with a window, a drift region, a plane, finely subdivided, electron multiplier (GEM) and a finely subdivided array of metal pads collecting the charge. Pads are disposed with hexagonal pattern on the top layer of a VLSI chip. Each pad is equipped with a complete analog electronic chain so that the charge collected is measured by a low noise electronics. The track produced by the photoelectron that ionizes the gas are, therefore, imaged by the device. From the analysis of the image the various features of the track are reconstructed and the impact point is determined with a resolution of the order of 150 μm FWHM. The original direction of the photoelectron is reconstructed by fitting the part of the track close to the impact point. The VLSI chip is the core of the device. Three version have been realized in rapid sequence. The last one is extremely evolved[10,11] and can be foreseen, as it is or with minor adjustments, as the core of a detector for a new mission of X-ray Polarimetry. This last version of the device also manages the problems deriving from the very large number of pixels (105600). The original version used the signal from the GEM as a trigger and routed the holded analog signals from each pad to the external A/DC. The advantage with respect to a CCD is a synchronous reading of the device but the time needed to convert the whole image (or a predefined part of it in a segmented configuration) is of the same order. With increasing number of pixels this could result in a large dead time. In the last version this is overcome with a auto-trigger capability and with the routing of only the data within a window defined every time around the pixels that triggered. The device is described in detail in another paper in these same proceedings.[12] Here we want to stress the reasons why this device makes astronomical X-ray polarimetry more attractive than what was possible with the conventional devices.

2.2. Generalities on a measurement of polarization

A polarimeter responds to incoming radiation by assigning out-coming photons to an angular channel. In practice each photon is coming out at a certain azimuth angle and an histogram of events per angular bin is built. In dispersive polarimeters (such as Bragg) one angle is measured at a time. In non dispersive polarimeters (such as a MPGC or a Compton polarimeter) all the output channels are collected simultaneously. When 100% polarized radiation impinges on an ideal polarimeter the histogram of angles can be fitted with a $\cos^2$ law. In a real polarimeter the modulation is lower and a constant term must be added. This defines the modulation factor μ, namely the $(N_{max} - N_{min})/(N_{max} + N_{min})$ in the angle histogram for a 100% polarized beam.

If photons are distributed around the expected value according to Poisson statistics the relevant figure is the Minimum Detectable Polarization (MDP) (at a confidence level of 99 %) :

$$\text{MDP} = \frac{4.29}{\mu S} \left(\frac{S+B}{T}\right)^{0.5}$$

where S is the source counting rate, B is the background, T the observing time and μ is the modulation factor. S is the product of the area A, the efficiency ε, the time and the source flux.

In a focal plane imaging polarimeter the collecting area is provided by the telescope and the background rate is negligible with respect to the source one. This is also true for a focal plane Bragg crystal but with a much larger efficiency due to the larger band. Moreover the rotation needed for the Bragg is a major complexity and requires and independent monitoring for variable sources.

Scattering polarimeters are background dominated and the response is strongly affected by systematics that can only be partially removed with the unavoidable rotation.

MPGC are good imagers and perform simultaneously timing and spectra. They are suitable for energy resolved polarimetry. The response with energy of the photoelectric polarimeter can be tuned with a proper choice of the filling mixture. To do this we must keep in mind that the MDP is proportional to the factor of merit $\varepsilon^{0.5} \times \mu$. The control of systematics seems very good[10] but in general the instrument will be more effective when the modulation factor is high.

3. A PATHFINDER TO POLARIMETRY?

### 3.1. Polarimetry with small telescopes

Since the sensitivity is a matter of number of photons if we want to observe small polarized fractions from faint sources a large collecting area is needed. The optimal application of photoelectric polarimetry is aboard a mission with a large telescope, such as the proposed XEUS, that would access sources down to a fraction of milliCrab. But the last available data were collected 30 years ago. The improvement from OSO-8 to XEUS is several orders of magnitude. There is room for a pathfinder with intermediate sensitivity. In a complex mission the share of time for polarimetry will be necessarily small, while a dedicated mission could invest al the time to this discipline. A peculiarity of polarimetry is that since we must operate in conditions that the counts from the source exceed largely the counts from background in the PSF, the data collected with different telescopes can be added without significant loss with the respect to the same data collected with a single telescope. This allows to achieve a relatively large collecting surface, with no need of a long focal length with the substantial advantage of the use of a much cheaper launcher. Moreover to study a sample of faint sources (mainly extragalactic) or to make detailed studies of brighter sources, a certain number of long pointing can be foreseen.

3.2. A possible solution: JET-X telescopes

Following this concept we made a very preliminary design of a mission, named POLARIX, conceived as a pathfinder of future polarimetry missions following the guidelines:

- Low Costs.

- Established technologies to save development time.

- Re-use of existing hardware.

- Compatibility with a small launcher (but a minimum length is needed).

A possible solution is the use of a cluster of telescopes like those developed for JET-X experiment.[13,14] A twin telescope was built and tested for the Spectrum X-Gamma Mission that was never completed to the launch. The spare unit has been very successfully used for the SWIFT Mission.[15] Each telescope consists of 12 nested double shells, with Wolter-1 geometry with an aperture of 300 mm and a focal length of 3500 mm, manufactured with the electroforming replica process. The measured resolution is better than 15". The effective area of each
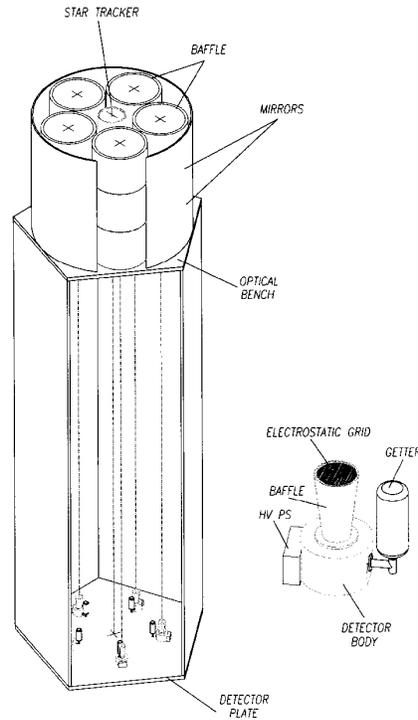
Figure 1. POLARIX.

telescope is around 160 cm^2 at 1.5 keV and has a response relatively flat in energy allowing for good measurement up to 10 keV. The flight units of JET-X could be a part of POLARIX. A relevant part of the production costs of the telescope is the manufacture of superpolished mandrels. Since they are still available we assumed that 3 more telescopes could be built and integrated on POLARIX. The cluster of telescopes would have a total area of 800 cm^2. The total length is below 4 meters, compatible with low cost launchers.

4. EXPECTED PERFORMANCES IN A BASELINE CONFIGURATION

Let us assume to 5 JET-X like telescopes and in the focus of each a MPGC with Ne (40%) DME (60%) filling.

Beryllium is optimal for a sealed cell, without any gas flow system, and can benefit of a long experience for space based proportional counters. We assume to have a beryllium window 50 μm thick. This is the minimum value that does not requires a back-skeleton that would reduce the effective area.

The MPGC beside being a polarimeter is an excellent imaging device. The above mentioned capability to reconstruct the impact point converts into a space resolution of around 150 μm FWHM. This is intrinsically better than the telescope performance. But we must consider another effect: the photons impinge inclined on the detector and they are absorbed at different heights, according to an exponential law. At the higher energies they, in practice, are uniformly distributed, while at lower energies they are absorbed in the majority closer to the window. If we mount the detector in such a position that the focal plane is at half-way from the window to the GEM (roughly a good choice but not necessarily the best), the focal spot will be blurred because of the projection on the detection plane of the interaction points. We evaluate a worsening of the total response from 15 arcseconds due to the telescope alone to $\sim$ 20 arcseconds from the two combined effects.

This resolution is suitable for the angular resolved polarimetry of a few but prototypic sources. In the case of Crab POLARIX is capable to perform separate polarimetry of each of the two jets, of inner torus plus the pulsar and of various parts of the outer torus.
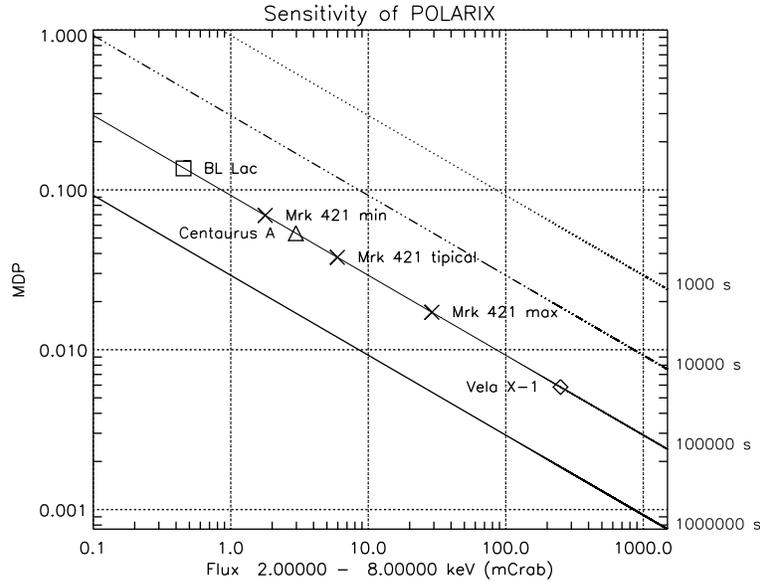
Figure 2. Minimum detectable polarization for POLARIX. A few representative sources are shown on the sensitivity line with a pointing of 10^5sec.

Time resolution can be very high in theory. Without any special provision it can be fixed at 2 to 4 μsec. For a majority of targets this will be redundant, due to the limited photon statistics but for a few targets can be important.

Energy resolution will be that of a good proportional counter. Depending on the mixture it can span from 10 to 14 % at 6 keV, with a $E^{0.5}$ dependence. This is suitable for any reasonable energy resolved measurement on the continua and, also, to separate the unpolarized fluorescence from the partially polarized continuum in reflection spectra.

As POLARIX would be a mission dedicated to the polarimetry in the evaluation of the sensitivity we can also assume long pointing. We stress that for an observation of 10^6 seconds the background counting rate is still negligible even for the faintest sources here considered. This is true for the statistics but, of course, the background, that is mainly generated by gamma rays deriving from an asymmetric source (cosmic, earth albedo, conversion of Cosmic Rays in the spacecraft) could introduce some systematics to be carefully kept under control.

In fig. 2 we show the Minimum Detectable Polarization for various sources of potential interest.

- X-ray binaries can be studied in great details. POLARIX can perform phase and energy resolved polarimetry of pulsators, unveil the nature of the beam (fan or pencil), determine the orientation of the rotation axis projected on the sky and directly measure the angle between this and the magnetic field.

- For Low Mass Binaries the polarization from scattering on the disk can be determined.

- The same for Black Hole Binaries for which the effects of General Relativity should be detectable. As suggested by Stark and Connors 30 years ago[16] photons at different energies are mainly generated at different radii in the disk. In their path to the observer they will therefore be subject to a different rotation of the polarization angle due to the different gravity of the BH according to General Relativity. This has been, for long time, foreseen as the best evidence of the existence of a Black Hole. In fig. 3 we show the results of a simulation of a measurement of 14 days of Cyg X-1 with POLARIX. We plot the expected dependence of the polarization angle on the energy and we show the sensitivity of the measurement to detect such a change in angle for a polarization of 5%. For lower polarization the sensitivity to the angle
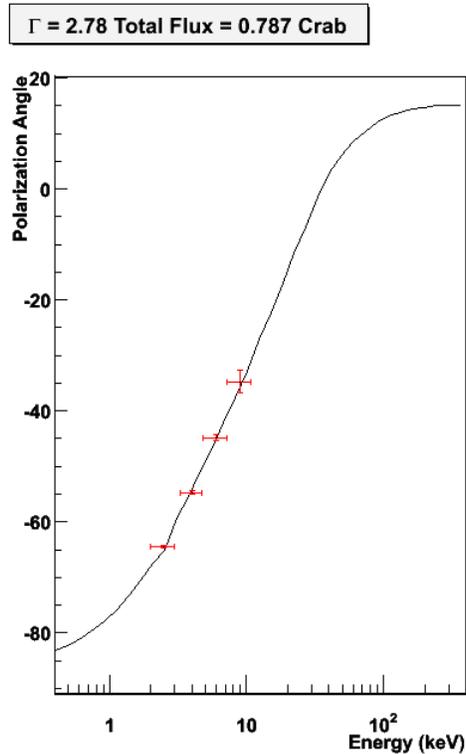
Figure 3. The rotation of the angle of polarization for Cyg X-1 as function of the energy has been proposed for long time as a test of General Relativity effects in the matter around a Black Hole.[16] In this figure we show the results of a simulation of the capability of POLARIX to measure the polarization angle as a function of energy, with a long observation. A polarization of 5% has been assumed.The very long exposure is needed only for the higher energy band

scales as the square root of the polarized fraction. It is evident that even with a polarization of the order of 2% the measurement is feasible.

- The X-ray emission of most Blazars has been characterized by various X-ray missions and is assumed to be well understood when combined with observations at shorter and longer wavelengths. If in the X-ray band the synchrotron is dominant a very high polarization is expected. If the blazar is in such a state that inverse Compton is the main source of the radiation the polarization should be much lower or even null if the target photons have a wide angular distribution (e.g. if they come from the disk or from cosmic background). A few measurements from POLARIX can test the unified model of blazars and enlighten the physics of the jet.

- In a few cases (at least in the subsystems of the Crab Nebula but, likely, also in the brightest shell-like SNR) the amount and orientation of regions of non thermal emission can unveil the sites of acceleration of cosmic rays.

5. POSSIBLE IMPROVEMENTS AND TRADE-OFF.

5.1. Optics

Relax the resolution of the telescopes to save weight. The JET-X telescopes are based on the nickel replica technology and have been designed to provide the excellent resolution of 15", needed for the original application to imaging. They are relatively heavy: each modulus weights 70 kg. For polarimetry sensitivity the only requirement is that the background within the PSF is (quadratically) negligible with respect to the source. This
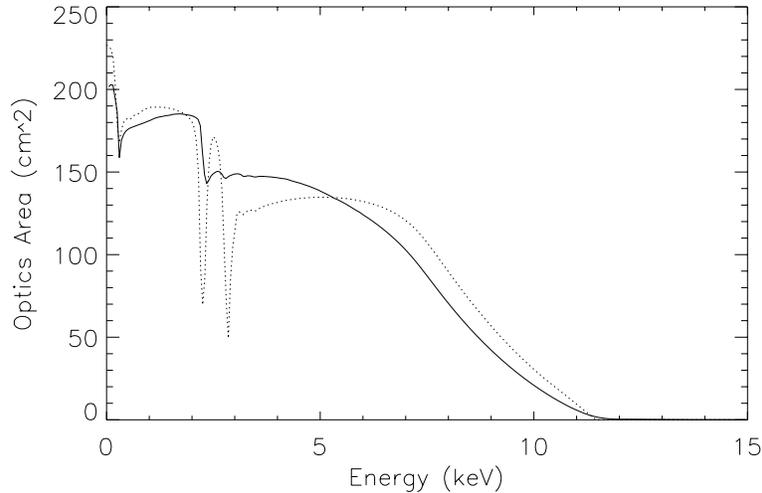
Figure 4. Effective Area of one JET-X modulus without the carbon coating and with carbon coating.
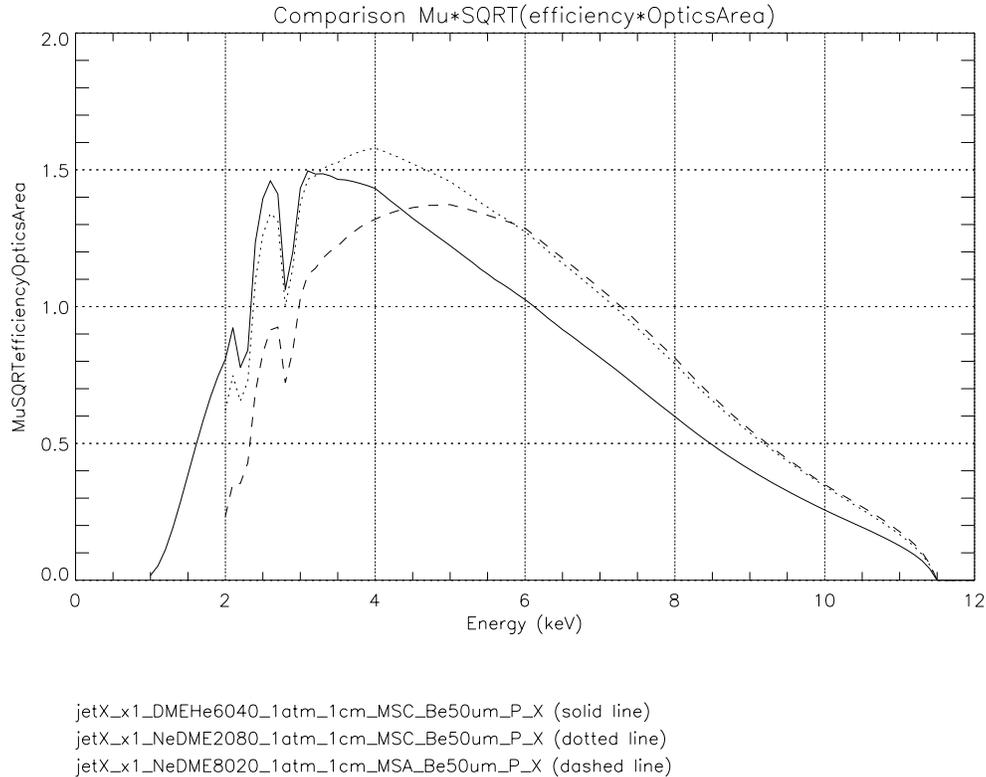
situation will hold also if we relax the angular resolution. With thinner nickel shells the resolution will degrade from 15" to 30" and the total weight will decrease of more than 50%. This could be a good solution, at least for the telescopes which are still to be manufactured. The only degradation of performances would be in the domain of angular resolved polarimetry (where already a degradation to 20" was expected due to inclined penetration of photons), especially on Crab, but the trade-off could be acceptable if it increases the feasibility of the mission.

A minor mismatching of MPGC with gold coated optics is the fact that due to the M absorption edges of Au there is a drop in reflectivity at energies where the polarimeter is particularly sensitive. Pareschi et al[17] have recently shown that a thin Coating of Carbon, overimposed to the gold coating, can fill this gap and increase the effective area in the 2 - 3 keV band.[17,18] This possibility will be seriously considered.

5.2. Detectors

In a MPGC the main trade-off is that on the gas mixture and on the absorption gap thickness. Increasing the thickness or the pressure, the efficiency increases and the modulation factor decreases. This is further complicated by the fact that the effective area of the telescope is another relevant parameter with a fast dependence on the energy. Last but not least the fluxes from the sources are usually decreasing with energy with a fast law (power law or exponential). In practice even though the polarimeter has a bandwidth much larger than a Bragg polarimeter, the band is limited by these trade-offs. The choice of the optimal band is not only a matter of technology but also a matter of scientific preferences. Some targets, such as isolated pulsars or Blazars in the synchrotron regime can be studied better at energies as low as possible because of their spectrum. Sources for which the polarization is expected to come from scattering, such as low mass binaries, Seyfert Galaxies and QSOs, could be studied much better at higher energies, where the scattering prevails on photoabsorption. Also the phenomenology of X-ray pulsators is expected to be more significant closer to resonance frequencies. In some cases the dependence of polarization on energy is the most valuable information, as in Black Hole binaries or blazars in the transition from synchrotron to inverse Compton.

This opens the possibility that instead of having the same detector in the focus of all telescopes we can use different detectors, each tuned to a specific energy band. In fig. 5 we show the $\mu \times \sqrt{\epsilon \times Area}$ which is the factor of merit as a function of the energy for three mixtures. The He/DME mixture optimizes the low energy performance. This could be further stressed by using a filling gas at a pressure below one atmosphere and a thin plastic window. The Ne/DME (80%-20%) is more sensitive to higher energies. This could be stressed with an overpressure or with a thicker absorption gap, losing something at the low energy side, where the modulation factor would decrease. A systematic study with a set of benchmark sources is required to find the optimal configuration.

Comparison Mu*SQRT(efficiency*OpticsArea)

jetX_x1_DMEHe6040_1atm_1cm_MSC_Be50um_P_X (solid line)
jetX_x1_NeDME2080_1atm_1cm_MSC_Be50um_P_X (dotted line)
jetX_x1_NeDME8020_1atm_1cm_MSA_Be50um_P_X (dashed line)

Figure 5. The factor of merit for three different mixtures tuned on different bands.

6. CONCLUSIONS

POLARIX is a based on a new but already reliable technology and is capable to perform a set of measurements of high astrophysic interest and open the path to polarimetry with future large aperture telescopes. An advanced study to evolve this concept to a better defined design is about to start under ASI contract.

7. ACKNOWLEDGMENTS

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