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Laue-telescope construction - a new approach

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Abstract. The feasibility of focusing soft gamma rays (0.1-2 MeV) using Laue diffraction in high quality metal crystals have been studied in many laboratories for over 50 years [1-4]. The manufacture of suitable crystals does not anymore appear as the primary obstacle. But the overall efficiency of Laue lenses still appears marginal, the issue of the precise and stable mounting of thousands of crystal facets has turned out to be very complex, and the design of an efficient detector to be used at the focus of the lens is still largely unproven.

A method to improve the flux collection efficiency of a Laue lens by almost a factor two will be described here. This is possible using double layers of crystals and relying on the fact that the efficiency of a single crystal layer is limited by the coherent primary extinction rather than by incoherent scattering or absorption. If the energy band passes of the two crystal layers do not overlap, each layer can diffract relatively undisturbed by the other.

Two construction aspects concerning the mounting and alignment of the crystals are discussed in this work. Although such very technical issues may seem hardly worth discussing in a scientific paper, the mounting of the crystals and the verification of the critical crystal tilt have turned out to be quite difficult. To get around the problems we propose here some radical departures from the currently employed techniques. The technologies proposed can be readily developed and tested on small-scale experiments.

The last aspect discussed is the problem of increasing the efficiency of detecting the diffracted photons at the telescope focus. In existing wide-field gamma-ray instruments the detection efficiency in the MeV region rarely exceeds 20%. It is disheartening to invest millions in building a complex lens knowing that more than three quarters of the photons focused by the lens will be lost in the detector. Fortunately, in the focus of a Laue lens it is possible to do better, and our conclusion is that with proper design we can approach or even exceed 50% detector efficiency.

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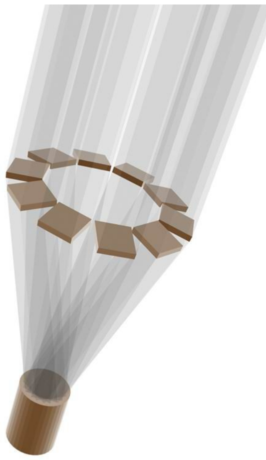
1. Introduction



A Laue lens consists of a large number of crystals arranged on a lens support, and oriented such that all crystals diffract incoming gamma rays from a distant source towards a common focus. Figure 1. The diffraction angles are small, typically less than one degree, so the focal length must be measured in tens or hundreds of meters. Each crystal only diffract over a relatively narrow energy range (a few percent). For a given crystal only specific lattice spacings are available, these are characterized by their 'Miller indices'. The reflectivity decreases rapidly with increasing Miller index values, so in practice only the few lowest Miller sets allowed by the crystal structure can be used. Once the crystal and the Miller index set is chosen there is a strict correlation between the photon energies and the diffraction angles. Bragg's law is very unforgiving: if the crystal is not properly tilted there will be no diffraction at the desired energy. Photons of other energies may be diffracted, but they will most likely miss the detector, as their direction after diffraction will not be as planned.

To cover an extended energy range the crystals must be placed on the lens support at different distances from the axis. The distance to the axis and the focal length defines the diffraction angle, and the angle through Bragg's law defines the photon energy (for a given crystal and Miller index choice). In order to maximize the lens efficiency it is important to pack the lens surface completely with diffracting crystals, leaving only little empty space between the individual facets. Actually, the size of the facets also defines the minimal achievable size of the focal area since diffraction is not focusing in itself, every crystal facet will simply project an image of itself on the focal plane, thus the focal spot will be the combination of thousands of such images. Although it may appear tempting to use small crystals to achieve a small focal spot this has to be weighed against the added work involved in cutting and mounting the increased number of crystals in order to achieve the desired flux collection area. There is also an inherent defocusing effect associated with crystal diffraction, the unavoidable dispersion in diffraction angles coming from the finite energy interval diffracted by a given crystal facet. This dispersion causes a smearing of the focal spot. Taking these factors into account we have settled for circular crystal facets 4 cm in diameter illuminating a detector of 5 cm diameter. For the calculation of the effective flux collection area we assume a circular lens of 3.8 m diameter and a focal length of 120 m.

2. Improving flux collection efficiency

We have realized that it is possible to improve the flux collection efficiency of a Laue lens by almost a factor two by the use of double layers of crystals - for instance by putting crystals on both sides of the lens platform. The reason for the additional gain is that the optimal reflectivity for a single layer of Laue crystals is set, not by the incoherent absorption of the radiation in the

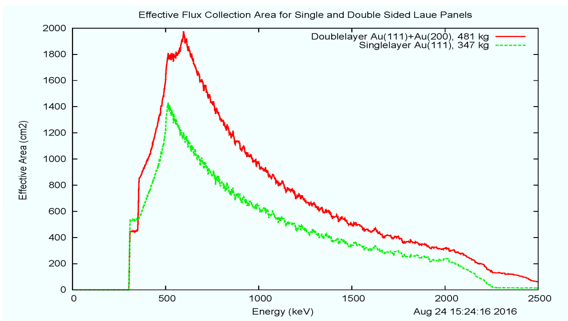


Figure 2. Single/Double layer efficiency

bulk material, but by the coherent 'extinction' of the diffracted beam, i.e. the switching of the already diffracted photons back to the direction of the incoming beam. Therefore, if we use different crystals (or different Miller index sets) in the two layers the photons diffracted in layer 1 are only affected by the (limited) incoherent absorption in layer 2 and vice versa. In principle this idea can be extended to multiple layers, but of course, the incoherent absorbtion by all the layers will quickly reduce the benefit of adding more layers. Figure 2 illustrates the advantage of using a combination of Au(111) and Au(200) layers rather than a single layer with Au(111).

The crystal facets are placed in a close packing hexagonal scheme on the lens support, the hexagonal patterns on the two sides of the support platform are offset with respect to each other such that the central area of the top side facets cover the triangular gap between three underside crystals. Figure 3. The total covering factor of the double layer is almost 90%, even allowing for our special mounting system described below.

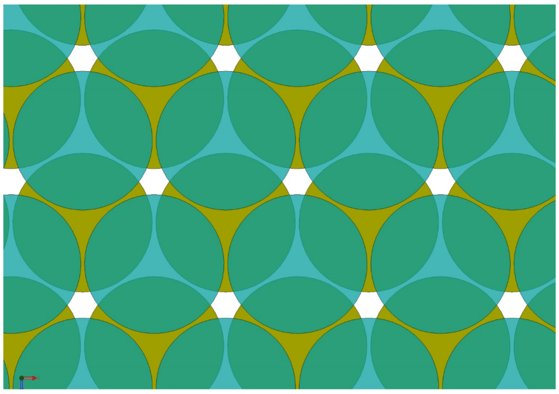


Figure 3. Double layer configuration

3. Lens assembly issues

It has become increasingly clear that the actual assembly of a large scale lens containing tens of thousands of crystal elements will be a formidable technological task when each crystal must be aligned to the lens structure with arcsecond precision using a beam of hard X-rays and working sequentially with individual crystals. It is therefore proposed to equip each crystal disc with an optical reference mirror. The reference mirror must be fixed approximately parallel to the diffracting crystal planes (within degrees), and the precise deviation between the crystal planes and the mirror surface should be determined (with arc-second precision) after assembling the two surfaces. The mirror-crystal alignment can be done on the small single crystal units. All further alignment work when working on the complete Laue lens or segments of this lens can then rely on fast and proven optical technology without concerns for the occupational hazards of ionizing radiation.

One thing is to verify the orientation of the crystal prior to its fixation to the support structure, another is the actual fixation process itself, which has also turned out to be quite problematic. It has proven difficult to find an adhesive which is stable enough during the curing process. Moreover, the thermal expansion and contraction of the adhesive after curing may cause alignment shifts on individual crystals and large scale support structure distortions. Glue forces may even damage the metal crystals, which are quite soft. All these issues indicate that we should look for crystal fixation techniques which do not load the crystals or the support structure with uncontrolled forces.

4. Crystal alignment issues

The crystals need to be aligned in two directions: in 'tilt' where the requirements are in the arc-second range, and in azimuth where the requirements are in the arc-minute range. The azimuth adjustment is needed to ensure that the diffracted beams all cross the telescope axis within a few mm, for the outermost crystals this corresponds to about 10^{-3} radians. We believe that the azimuth alignment can be achieved with conventional machining accuracy. We are sceptical however, whether the tilt alignment can really be achieved during the assembly phase using conventional techniques, and maintained through the launch and extended operational phase.

To avoid the problematic glue-interface directly between the crystals and the support we want to investigate the feasibility of designing an active, piezoelectric support unit for each crystal with the capability to provide one-axis tilt adjustment within a ±1° range. Such a unit together with the optical alignment system described below would significantly simplify the lens assembly, and may even allow to re-tune the lens after launch. Tilt mechanisms of this type has been discussed previously for Laue lenses [5], but with a different purpose in mind.

The addition of a tilt adjustment stage for every crystal may seem to be a major complication for the lens construction. However, we believe that it can be built as a self contained, cylindrical unit, 8 mm in diameter and weighing less than 4 g. It is an important element of our proposal, that the development of this critical unit is a small scale undertaking which can be done independent of other developments needed before deciding to go ahead with a full scale lens project. If our mass and dimension estimates holds true, the support units would obscure less than 5 % of the crystal area and would add less than 100 kg to the mass of the full lens. The consequent simplification of the lens assembly process would be very significant.

5. Optical alignment system

The optical alignment system is based on an autocollimation scheme where the autocollimation telescope (ACT) defines the optical axis of the Laue lens. Conceptually the ACT is located on the lens axis and can rotate around this axis, sequentially scanning crystals on the platform. The alignment mirrors on the crystals must be tilted up relative to the plane of the lens platform by about 10° so the mirror on one crystal does not shadow the mirrors on crystals lying immediately behind as seen from the ACT. The development of the ACT is, like the development of the tilt adjustment system, something which can be done indepently of the other preparations of the Laue lens project. Since the ACT wil be essentially for the success of the mission it will be necessary to plan for two redundant units.

6. Detector simulations

The energy range in which the Laue lens will be efficient is precisely the energy range where it is most difficult to detect the photons: 300 to 1500 keV. This is also the range where the background photons are most penetrating and most difficult to shield against. Only detectors based on the Compton telescope concept [6] seems to be able to offer adequate background rejection. So far Compton telescopes has been applied only as large-area wide-field instruments and the detection afficiencies have beed quite moderate, 20% or less. We have performed simulations using GEANT4 to ascertain the detection efficiency which is achievable when exploiting the well focused and well collimated beam from a Laue lens.

First we must realize that in order to keep the background down we cannot accept into the analysis photons which are absorbed in their first interaction ('one hit' photons). We need the Compton analysis to suppress the isotropic background. This implies that the first interaction must take place in a material where the photo-absorption cross section is much smaller than the cross section for Compton scattering.

The second realization is that for those events which are fully absorbed in the detector (so we know the total energy) all we can know about the direction of the incoming ray is derived from the first Compton scatter. There is no extra information coming from an extended sequence of Compton scatterings. So our logic must be: Get the first scatter in a light medium, and absorb the photon as quickly as possible after that in a heavy medium with maximal photo-absorption.

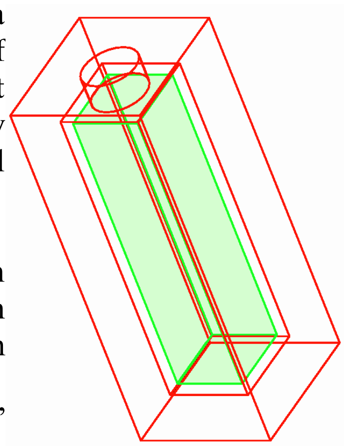


Figure 4. Focal detector

Our first concern has been to optimize the detection efficiency, so we use a stack of Silicon detectors with an affective thickness of 10 cm to minimize photon penetration of the Silicon stack.

Secondly, we must minimize the loss of 'telescope photons' during event reconstruction. Thus we surround the scattering detector with an absorbing detector realized a s 2 cm thick box using CZT detectors with 3D-reconstruction of the interaction points [7]. The spatial resolution for both the Si-stack and for the CZT-detectors is 1 mm^3.

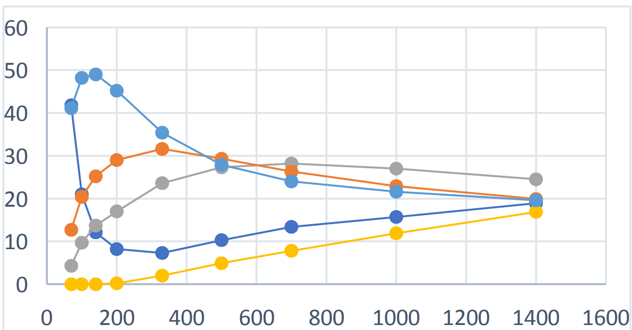
An acceptable 'telescope consistent photon' must have its first scattering interaction inside the 'focal volume' of the detector and the first Compton scatter angle must be 'telescope consistent'. The 'focal volume' is in our case defined as a 50 mm diameter cylinder extending from the top to the bottom of the scattering detector.

The definition of 'telescope consistent' is a bit more complex. The Compton scatter angles are not precisely related to the observed energy deposits, there is an uncertainty in the scatter angle caused by the (unknown) momentum of the atomic electron involved in the scattering process. This 'Doppler uncertainty' depends on both the photon energy and on the ratio of the local energy deposit to the maximum energy deposit (backscatter energy). We map and fit these dependencies based on our GEANT results, and use the fits to derive the relevant consistency criterion for each scatter situation. The Doppler uncertainty increases at low energy, and also depends on the atomic number of the scattering material, so also in this respect Silicon is better as the first scatter material than CZT or Germanium.

The complexity of the Compton analysis depends on the number of scattering events, 'hits', involved in the absorbtion of the photon energy. The major problem is to arrange the observed scatterings in the correct time order.

Figure 5. Number of 'hits' before full absorption in the proposed detector. Dark blue: 1 hit, Light blue: 2 hits, Red, grey, yellow: 3, 4, and >4 hits.

The fraction of 'one hit' events increases at the higher energies due to escape. Abcissa in keV.



In the sub-MeV range the majority of the events have 2 or 3 hits, but the fraction of events with more than 3 hits increases with energy. This illustrated in Figure 5.

We have tried two different logics to select the finally accepted events: Our ‘Method 1’ put the same constraints on the complete sequence of hits, whereas ‘Method 2’ accept the event as ‘telescope consistent’ if just the three ‘first’ hits are consistent with the telescope geometry.

The final results of our simulations are shown in Figure 6. It will be seen that with Method 2 (red curve) it is possible to have efficiencies of more than 60% at 300 keV, 55% at 500 keV and 30% at 1500 keV. Naturally the final background will also depend on our selection criteria, so the final data selection logic will have to be optimized for the real project.

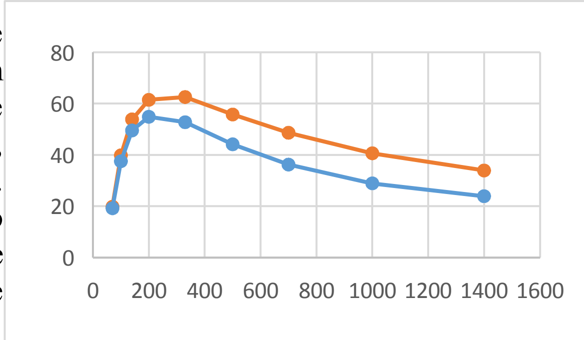


Figure 6. Detector efficiency vs energy

7. Discussion

There are many issues to be solved before a major Laue lens project can be proposed in earnest for a satellite flight. In this paper we have adressed a few of them. We have argued, that we can avoid many of the problems related to the precise mounting of the many thousand crystals on the lens if we accept the complication of mounting each crystal on a tunable pedestal. We propose to align the crystas using an optical system for which we suggest a specific design. Relying on optical technology would serve to eliminate cumbersome gamma-ray sources from the work on the complete lens or segments of the lens. The gamma-rays will still be needed, but now only during the preparatory work on the crystal units, which anyway ought to be mass produced and primarily handled remotely by robotic systems.
Finally we have investigated the efficiency limits for the focal plane detector. We are sure, that in the energy range around one MeV a Compton scattering detector is needed in order to suppress the background from particles and the diffuse gamma-rays. We conclude that with this type of detector we can obtain efficiencies of more than 50% at 511 keV – this is an encouraging result considering the much lower efficiencies obtained for Compton detectors previously developed for wide field instruments.

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