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A new tool for MeV astrophysics – the tunable Laue-lens

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ABSTRACT

A novel telescope for astronomy in the MeV energy band is presented. The concept builds on Bragg diffraction in crystals. Such 'Laue-lenses' have been discussed in the past, but so far a design with good sensitivity over a wide energy range seemed out of reach. In the first sections of this paper we shall show that if we find ways to adjust, in orbit, the individual tilt of all the crystals in the lens this would allow one single lens to cover with excellent efficiency the full range of energies from 200 keV to 2.5 MeV in a few observation steps. We also show, that lenses with double crystal layers may significantly increase the photon collection. In the subsequent sections we describe our proposed lens design in more detail and present our first prototype tilt adjustment pedestal for use with the individual lens facets.

Keywords: Gamma-ray astronomy, Telescopes, Laue lenses, Nuclear astrophysics

1. INTRODUCTION

The band of energies between 300 keV and 2 MeV contains the majority of characteristic gamma-ray lines from radioactive nuclei ejected from Supernovae, novae and merging neutron stars. Also, the 511 keV line from astrophysical electron-positron annihilation is found here.

But just this energy band is the most challenging to observe – and in fact very few MeV-sources are known. The detectors are complex and with limited efficiency and poor directionality. And above all – the background both from the sky and generated internally in the instruments is high. The internal background is proportional to the volume of the detector. Shielding is of limited use – the shielding creates background of its own!

1.1 Is focusing of gamma rays possible?

Since the detectors are seriously constrained, many proposals have been made to collect the radiation from a large area on a detector of limited size. This is where the Laue lens comes in.

A Laue lens exploits the Bragg-diffraction of gamma rays by crystals used in the Laue(transmission)-mode to collect radiation from a ring of crystals onto a small detector. Figure 1.

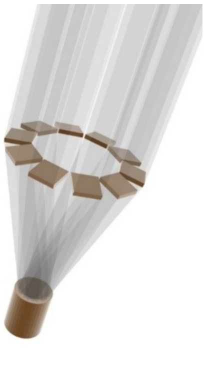

Figure 1. The basic principle of a Laue lens.

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Bragg-diffraction is very selective – only a narrow band of gamma-ray energies will be diffracted from a given crystal. Thus, many thousand crystals are needed to cover a broad range of energies and achieve a high flux concentration.

High density metal crystals - such as Copper or Silver - are most suited for diffracting gamma-rays. We plan to use silver crystals.

Bragg-diffraction is also demanding in terms of the precision of crystal alignment. In our proposed lens the crystals will need to be aligned to better than ±5 arc seconds to achieve the peak diffraction efficiency. The same requirement will apply to the pointing of the whole lens toward the source position in the sky.

1.2 General problems with the classical Laue lens

For a given crystal and a given Bragg-plane d-spacing gamma-photons of a given energy can only be diffracted through a specific angle, Θ_B. Photons of this energy can therefore only reach the detector if they come from a ring-shaped region on the lens, the mean radius of the ring is $2F\tan(\Theta_B)$, where F is the focal length of the Laue lens. The width of the flux collection ring is equal to the diameter of the detector.

The response of a Laue lens is therefore strongly energy dependent. Two factors are important: a) the area of the ring collecting a given energy is inversely proportional to the energy, lower energies are collected to the detector from rings close the outer rim of the lens, higher energies from rings closer to the telescope axis, and b) the diffraction efficiency itself also decreases with energy.

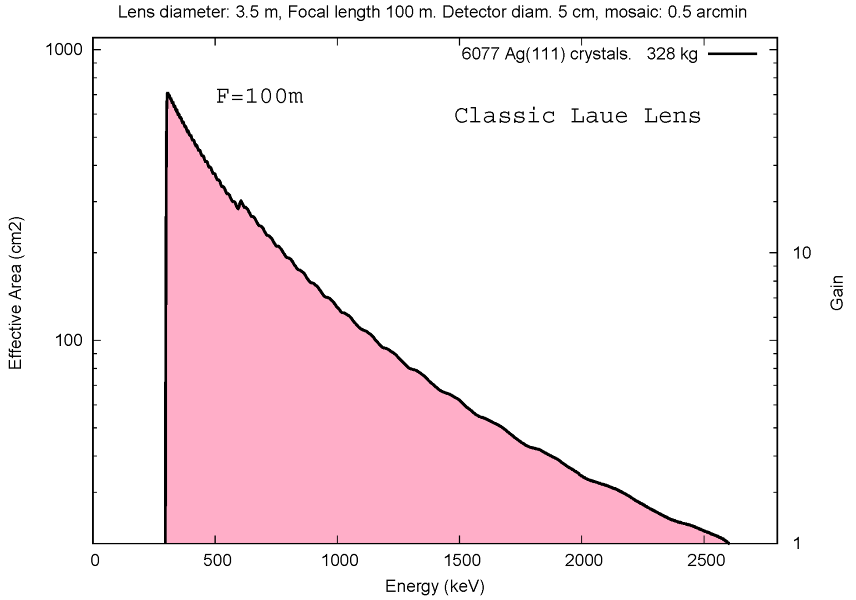

Figure 2. Response of a simple Laue lens as function of energy. The response beyond 1 MeV is too limited.

Figure 2 shows the response of a simple Laue lens using 6077 crystals (Ag(111)) of 4 cm diameter and different thicknesses. The lens is 3.5 m in diameter. The assumed focal length is 100 m. The crystal thickness is smaller (1.7 mm) near the rim of the lens (optimized for lower energies), and higher (12 mm) near the axis. The total weight of the crystals is appreciable, about 325 kg.

Laue lenses of this or similar design have been proposed for flight both to ESA and NASA but never accepted, I believe mainly because the performance – even assuming everything worked as expected was only marginally good enough and the scope of the science too narrow.

A serious technical challenge for the construction have turned out to be the mounting of the crystals on the lens support. Various glues have been tried, but it has turned out to be very difficult to achieve the required arc-second precision due to glue deformation during the setting (hardening) process. Another unsolved problem is the long-term stability of the support platform itself.

2. PROPOSED NEW LENS CONFIGURATION

To solve the problem of precision mounting of the crystals directly on the support panel we proposed some years ago to introduce a tilt adjustable pedestal for each crystal. We wanted a system which could be used in-orbit, after the launch, so we insisted on a system which do not use any power, except during the adjustment phase. In order to reduce the need for recurrent use of gamma ray sources and beams during the lens assembly, we decided to rely primarily on optical alignment techniques and to establish once and for all the relation between the crystal planes and an optical mirror fixed permanently to each crystal. After that, only optical alignment systems should be needed. This will also relieve the stability requirements on the support panel, now the lens stability relies on the stability of the optical system.
Of course, the introduction of a tilt pedestal for every crystal and an external optical system is a major complication, but the possibility of in-flight adjustment of the crystal tilt has opened up a number of new research possibilities which will be described in the following. An overall picture of the lens concept we are working on is shown in Figure 3.

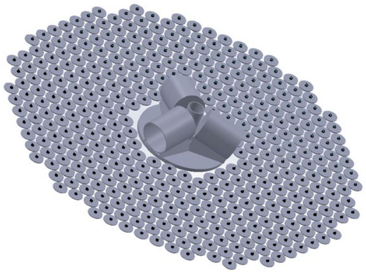

Figure 3. A 3.5 m diameter lens platform with a central hole, 1.3 m in diameter and 4 cm diameter crystals arranged in a hexagonal pattern. (Not to scale).

Each crystal is mounted on a tilt-adjustable pedestal and each crystal carries an optical alignment mirror. The angle between the optical mirror and the Bragg-planes of the crystal is fixed and precisely known!
In the center of the lens is placed three redundant alignment telescopes, they function according to an autocollimator principle. These telescopes can rotate around the Laue lens axis and sequentially scan the alignment mirrors of the 10000 crystals in the lens.

3. THE RESPONSE OF A TRUNCATED, BUT TUNABLE LENS

In Figure 4 is shown the response of a 'truncated' Laue lens – using the identically same crystals as for the classic Laue lens of Figure 2, but eliminating all the inner crystals diffracting energies above 800 keV. This lens now only contains 5300 crystals and we have saved about 100 kg of crystal mass. The response of this truncated lens is the pink area.

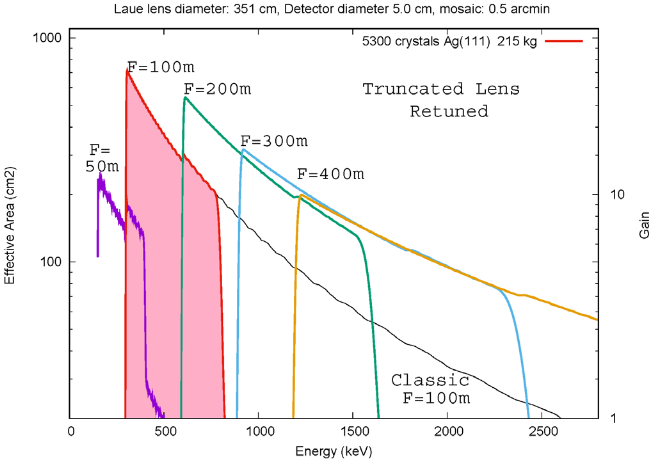

Figure 4. Response of 'truncated' lens, retuned to different focal lengths. Note sensitivity increase at high energies.

The most surprising effect illustrated in Figure 4 is the increase (by about a factor two) of the response at the higher energies. Three effects conspire to produce this gain:

a) The diffracting rings moves outward on the lens. (positive effect)

b) The diffraction efficiency for each crystal is reduced (negative)

c) The angular separation of the crystals seen from the detector diminishes (positive). This crystals contributing at a specific energy, but slightly off the ideal distance from the axis will contribute more efficiently at long focal lengths than at shorter lengths.

4. USING DOUBLE LAYERS OF CRYSTALS

Having the crystals mounted on pedestals makes it relatively easy to accommodate double layers of crystals. The two layers will use different crystals, tuned to diffract different gamma-energies through the same angle. Both gamma energies will aim correctly for the detector, but each layer will only absorb to a limited extent the rays diffracted by the other layer. Overall this will improve the photon collection by about 65 %. Figure 5 illustrates the gain in sensitivity resulting from the use of a double-layer lens.

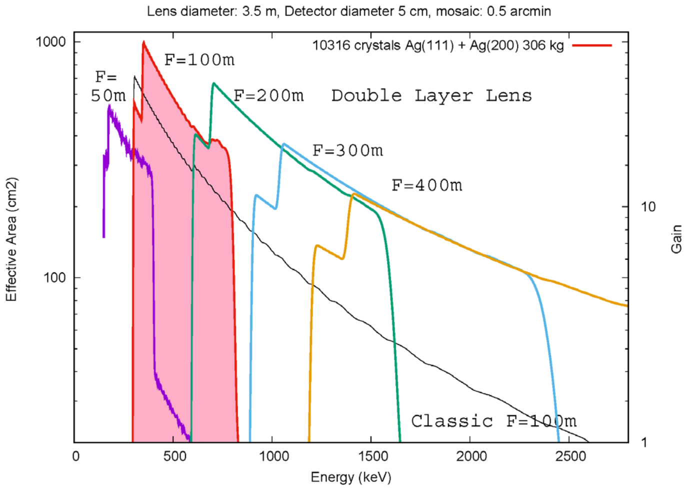

Figure 5. Using double crystal layer (Ag(111) and Ag(200)) increases the photon collection efficiency by about 65%.

5. TUNING FOR SPECIFIC ENERGIES

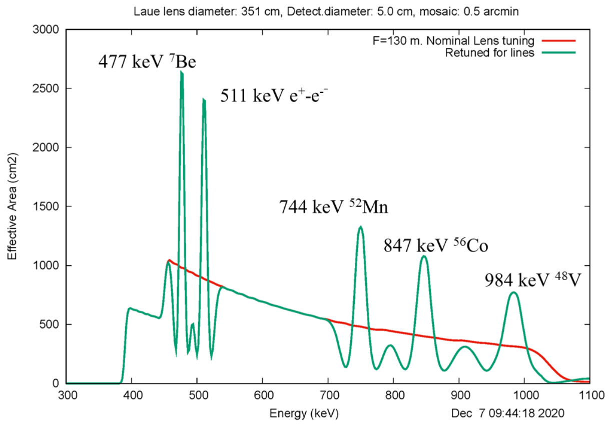

Figure 6. Response of the lens when tuning for an (arbitrary) selection of astrophysically interesting line energies.

We can enhance the lens performance for point sources emitting narrow lines. Even slightly extended sources (on the few-arc-minute scale) may be observed. We can implement such a tuning by identifying all crystals in the lens which contribute to the photon collection of the desired energy. In the standard lens tuning each crystal is tuned according to its distance from the lens axis, i.e. each crystal is set to provide peak reflectivity for that outgoing ray which traverse the center of the detector. In this tuning each crystal is tuned optimally for its own energy. But if we want to enhance the sensitivity for a specific energy we start by identifying all the crystals which contribute at a that energy, say 511 keV. Now we can retune this subset of crystals so they all diffract with peak efficiency our chosen energy. Only a limited fraction of the diffracted photons will hit the detector, but we have increased significantly the mean diffraction efficiency for many of the contributing crystals.

In Figure 6 we illustrate this type of tuning for a selection of astrophysically relevant line energies. Note that the ordinate scale is linear in this plot!) The advantage of this type of tuning is the largest for the lower energies (shorter focal lengths). For the long focal lengths there is not so much to gain, because the mean diffraction efficiency of the contributing crystals is already near the peak value. To quantify this, we may note that we have gained a factor 3 for 511 keV, but our calculations show that we only gain a factor 2 at 1809 keV.

6. IS IT REALISTIC TO BUILD A TUNABLE LENS?

A miniature piezo-motor has been constructed which can move in sub-micron steps and which do not require any power when not moving. The motor is based on the slip-stick concept, where a small permanent magnet will stick to a surface when the piezo expands or contracts slowly, but the magnet will ‘slip’ and move relative to the surface when the piezo expands or contracts very fast. The slip-movements are very small – less than 1 micron, corresponding to arc-second angular rotations of the Bragg-crystals. The step size of this type of motor is not repeatable, so an external reference is required for precise crystal tuning.

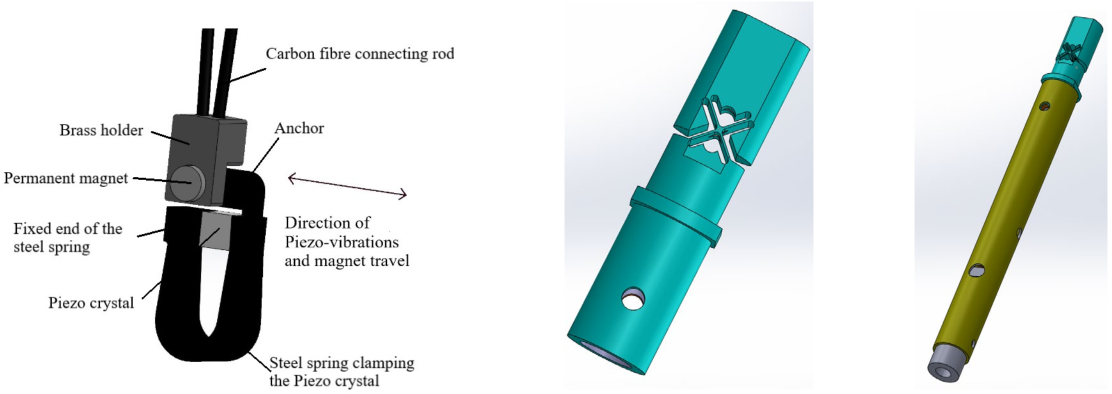

Figure 7. The key elements of the miniature tilt pedestal now being manufactured. Left is the piezo motor, center the flexible pivot and right the completed pedestal. The external tube is 7 mm in diameter and protrude through the lens panel, fixed at both ends.

The other essential element of the tilt pedestal is the flexible pivot. It is an old invention, its main advantage is that it has no slip and no stick, even the smallest movement of the sliding magnet in the piezo motor is immediately felt in the crystal tilt. The complete pedestal will be enclosed in a 7 mm diameter tube. Less than 5 % of the area of the 40 mm diameter crystals will be blocked by the pedestals. Based on a successful first prototype employing these two elements we are now manufacturing 10 second generation prototypes for more extensive testing.

The last element we need to design in detail is the top crystal holder. We need circular crystals of 40 mm outside diameter and with a central hole of 8 mm diameter. We need to place the center of gravity of the crystal precisely of the turning axis of the flexible pivot, otherwise the dynamic forces during launch may overfload the pivot. The crystal holder must be a rigid unit keeping the crystal and the alignment mirror solidly fixed to each other. Only this unit need to go through a gamma-ray alignment process. All later alignments will rely on well-known optical techniques. Also for the optical alignment system we have a working prototype and have proven the performance of the autocollimator principle

7. CONCLUSIONS AND FUTURE WORK

We have shown how a tunable Laue lens is an extremely versatile and flexible tool for MeV astrophysics. It can expand the useful energy band of a moderate size lens from a factor of less than three to a factor more than ten and even allow narrow line studies with lens gains of more than 10 up well beyond 2 MeV.

We will continue the development work now concentrating on the crystal holder and in particular on the methods needed to cut and machine our non-trivial crystal shape in the very soft and fragile material in the as-grown crystal ingots.

Further details and references can be found the two recent papers[1,2].

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