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LAUE LENS: THE CHALLENGE OF FOCUSING GAMMA RAYS

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ABSTRACT

The development of a Laue lens to focus soft gamma rays appears today as the only solution to improve significantly telescopes' sensitivity and angular resolution in the 100 keV – 1 MeV domain. A Laue lens makes use of diffraction in the volume of a large number of crystal tiles carefully orientated to concentrate incident radiations from a large collecting area in a small focal spot. Various type of crystal have been measured and show excellent results, with angular spread of diffracting planes in the range 15-45 arcsec, and reflectivities up to 31 % at 600 keV. Precision of orientation of crystals is demanding because of the long focal length involved by small angles of diffraction. A prototype currently being built by a French collaboration including the CESR, the CNES and Thales Alenia Space aims to achieve 10 arcsec of tolerance.

Keywords: Soft gamma rays; Focusing telescope; Laue lens; Diffraction; Crystals;

1 INTRODUCTION

In astrophysics, though the sub-Mev domain is very rich in physics, it is not trivial to perform deep and sensitive observations mainly because of the strong background induced in detectors by space environment, as cosmic rays, radiations belts, Earth albedo and sun flares. To detect the extremely low fluxes produced by high energy sources, present-day instruments operating in the soft gamma-ray domain use either aperture modulation (coded mask) or Compton reconstruction to determine the events' direction of origin and hence to rebuilt an image. The common point of these techniques is that the collecting area is coincident with the detector area exposed to a source, which limits strongly the possibilities of sensitivity improvement since the instrumental background scales with the volume of detectors. Knowing that the last generation of coded masks telescopes IBIS and SPI onboard the ESA's International Gamma Ray Laboratory are each weighting about 1 ton, how to improve the sensitivity by a factor 10, or even 100?

A new approach consisting in concentrating gamma rays is being studied since a decade and has proved to be feasible in the ~100 keV - 1 MeV domain. A first lens prototype named CLAIRE demonstrated in 2001 during ground tests and two balloon flights that the principle of the Laue lens is viable [1]. Then, detailed studies started to refine all parameters in order to design lens exploitable for astrophysics. This led to the MAX concept of mission that has been proposed to the CNES in 2005 [2], and more recently to the Gamma Ray Imager mission (GRI) that has been proposed to European Space Agency (ESA) in the frame of Cosmic Vision AO1 [3,4].

In this paper, we will give an overview of technological state of the art of Laue lens. Beforehand, Laue lens principle is described in the next section. Then the state of the art of development of Laue lens elementary constituents - metallic or semiconductor crystals - is given: performance of these crystals has been measured during several runs at the European Synchrotron Radiation Facility (ESRF, Grenoble) and at DIGRA, a new dedicated reactor-beamline at Institute Laue-Langevin (Grenoble). Mechanical issues of a crystals assembly are addressed in the fourth section: the cutting and mounting of the individual crystals on a lens frame and the alignment of their crystalline planes with respect to the optical axis of the lens are particularly challenging given the accuracy required. Finally, performance attainable will be shown through the example of the Gamma Ray Imager (GRI) lens in the last section.

2 LAUE LENS PRINCIPLE

A Laue lens concentrates gamma-rays using Bragg diffraction in the volume of a large number of crystals arranged in concentric rings and accurately orientated in order to diffract radiation coming from infinity towards a common focus. The Bragg's law,

$$2d_{hkl} \sin \theta_B = n\, hc / E, \quad (1)$$

links the ray angle of incidence onto diffracting reticular planes θ_B to the diffracted energy E, through the d-spacing d_{hkl} of the crystal's reticular planes, n being the order of diffraction, h the Planck constant, and c the speed of light in vacuum.

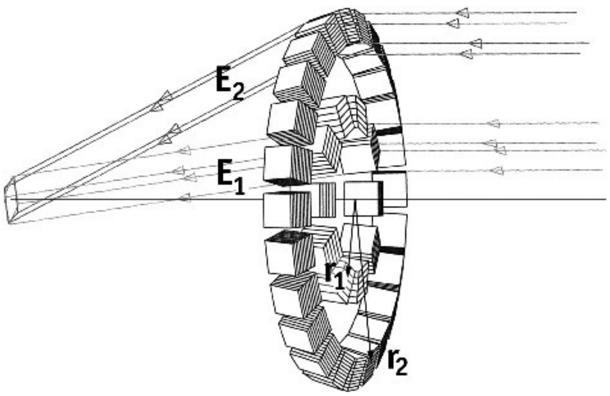

Fig 1 : Principle of a Laue lens : crystals disposed in concentric rings diffracts radiations coming from infinity towards a common focus.

Fig 1 shows a sketch of a Laue lens constituted of 2 rings of crystals, which radii are r_1 and r_2. The angle of incidence of radiations onto reticular planes depends on the radius of the crystal ring. From there two possibilities arise: Either the d-spacing of crystals is identical on both rings (meaning that same crystals and same reflection is used) and consequently the energy diffracted is slightly shifted with $E_1 > E_2$. Or the d-spacing is different, and if the condition $d_{hkl} \,.\, r_1 = d_{hkl} \,.\, r_2$ is satisfied then the diffracted energy from both rings is equal $E_1 = E_2$.

Combining both effects is a way to get an efficient coverage on an energy band larger than the one produced by a single ring; several radii ranges on the lens can diffract in the same energy band, adding up to produce an high effective area.

As we can see from Bragg's law (1), a perfect single crystal that presents only a single angle of incidence to the incoming radiations will behaves as a monochromator, diffracting a very narrow line. Instead, suitable crystals must have an angular spread in their diffracting planes such that neighbouring rings create bandpass-overlaps resulting in continuous energy coverage over a specified band (angular acceptance, energy bandpass and profile of the diffracted beam are directly related [4]). This limits the choice to crystals having either a mosaic structure or curved diffracting planes (a complete description of Laue lenses can be found in [5]).

3 STATUS OF CRYSTALS STUDY AND DEVELOPMENT

CLAIRE lens was made of 556 germanium mosaic crystals arranged in 8 concentric rings [1]. Since then, several different type of crystals have been investigated to improve the 12% overall reflectivity which was achieved. Quality criterions are the angular spread, which should range between 10 and 60 arcsec, the diffraction efficiency, the homogeneity and the reproducibility.

So far, two kind of crystals have been extensively studied (added to germanium crystals that were made for CLAIRE lens [6]): Copper mosaic crystals (Cu) and an alloy of silicon and germanium Si(Ge) featuring a gradient of concentration along the crystal's growth axis that have the property to create crystals with curved diffracting planes. Latterly, high diffraction efficiency crystals such as gold have been measured for the first time at high energies. Properties of crystals are investigated by recording rocking curves, i.e. a plot of the diffracted intensity as the crystal is rotated in a high-monochromaticity and low-divergency beam (Fig 2). Two complementary curves can be recorded, in the transmitted beam or in the diffracted beam, both curves being complementary since the intensity removed from the direct beam is sent in the diffracted one (geometry of diffraction used for crystals characterization is the same as shown in Fig 3).

Copper mosaic crystals produced at ILL (Grenoble, France) [7] have been extensively studied and are now showing very satisfactory results. Very low mosaicity has been measured with performance reaching the theoretical maximum. Fig 2 shows as an example a rocking curve (RC) of a Cu sample of 8.6 mm of thickness measured at 489 keV, which reflectivity is as high as 24 % despite the fact that the 220 reflection is used (less efficient that 111 reflection). The main problem of copper has long been the mosaicity that was too large for our application, but this is no longer the case.

An alloy of silicon and germanium with a varying relative concentration (inducing a curvature in diffracting planes) has been developed in cooperation with IKZ (Berlin, Germany) [6]. Added to the fact that this kind of crystals can reach twice higher diffraction efficiency than mosaic crystals, they produce a square-shaped bandpass [8], which limits the spread of photons over the focal plane. The RC shown on Fig 2 comes from a 23 mm thick sample measured at 300 keV attaining a reflectivity of 26%. Our last measurements indicates that the mosaicity achieved with SiGe alloy crystals seem perfectly controlled and hence very reproducible.

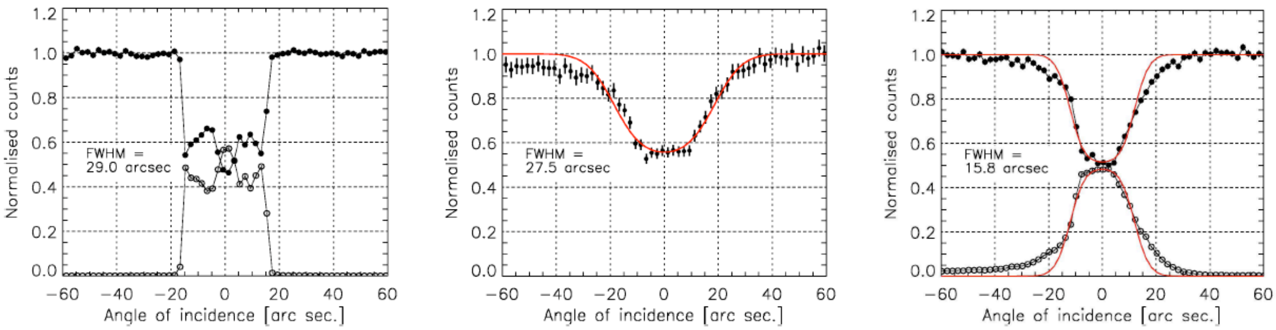

Fig 2 : Left: RC of a 23 mm thick SiGe gradient crystal measured at 300 keV (reflection 111). Center: RC of a 8.6 mm thick Cu crystal (220 reflection) realized at 489 keV. Right: RC of a 2 mm thick Au crystal (reflection 111) realized at 588 keV. Applying the transmission coefficient due to the absorption through the crystal, the achieved reflectivities are respectively: 0.26, 0.24 and 0.31. All these measurements have been performed at ESRF (Grenoble France) on beamline ID15A.

Now that Ge (as used on CLAIRE lens), Cu, SiGe crystals are ready, our endeavour turns towards crystals for high energies. Latterly, three samples of gold mosaic crystals (produced by the Mateck company) have been measured, showing that this crystal can be produced with the right mosaicity range, which is truly the most critical constraint. Fig 2 shows performances of a 2 mm thick sample reaching the theoretical maximum at almost 600 keV, giving an excellent reflectivity of 31%. Gold but also, silver, tantalum, tungsten and even platinum are currently under study at CESR, IASF, and ILL, opening the path to lenses really efficient and lightweight at energies up to 1 MeV.

4 LENS ASSEMBLY: CRYSTALS FIXATION

MAX and GRI, the two latter projects of soft gamma ray telescopes featuring a Laue lens have in common a focal distance of several tens of meters (86 m for MAX, 100 m for GRI), involving a formation flying of two satellites, the one carrying the focal plane and the other carrying the lens. Crystals foreseen to realize these lenses have dimensions of 15 x 15 mm, with thicknesses ranging between 2 and 30 mm (optimized according the material, the reflection, the mosaic spread and the energy diffracted). MAX was constituted of more than 13500 elements, while GRI was made of 28000 elements.

The first difficulty for the mounting of crystals is related to the long focal length. Indeed, at 100m the disorientation of a crystal of 10 arcsec engenders a displacement of its diffracted print by 1 cm, which is detrimental for the focusing. The second difficulty comes from the fact that crystals that we use do not cleave; faces of crystal tiles are not related to the orientation of diffracting planes. It means that the use of X-rays is mandatory in the orientation process.

Basically, there are two methods to orientate crystals on the lens: The first one consists in tuning every crystal directly on the lens. This implies to have tuneable fixations, as had CLAIRE (CLAIRE's fixations of crystals were tuneable only along one axis, which was enough for its 2.76 m focal length. Longer focal distances require a two axis tuning). The advantage is obvious; each crystal is manipulated only once and is not touched any more after. The drawback is the space taken by fixation device on the lens frame, which decreases the collecting area. A compromise could be to put the orienting device under each crystal in order to recover a full packing factor, but it would increase the absorption of diffracted radiations, since in a Laue lens radiations pass through the crystals and consequently through their supports (Fig 3).

The second way to orientate crystals on the lens is indirect; it consists in dividing the process in two phases. The first one uses X-rays to determine the orientation of diffracting planes with respect to a reference, and the second one is the actual fixation of the crystal on the lens frame. This implies to have a reference that will be kept between these two phases, which is not undemanding. This procedure is currently being investigated in two institutes in Europe, however with a difference in the choice of the orientation reference;

Thales Alenia Space, in collaboration with the CESR (Toulouse, France) in the framework of an R&D financed by the CNES, have proposed a method that consists in determining the asymmetry angle with respect to the back-face of crystals, and then in transmitting this information in order that the site of each crystal is machined to set diffracting planes at the Bragg angle from the line of sight. Thus each crystal has a dedicated site specifically machined to correct his cut defect. Each site is constituted of 3 pins that will be directly in contact with the crystal in order to support and orientate it, while it will be maintained in position by glue disposed between pins (see Fig 4).

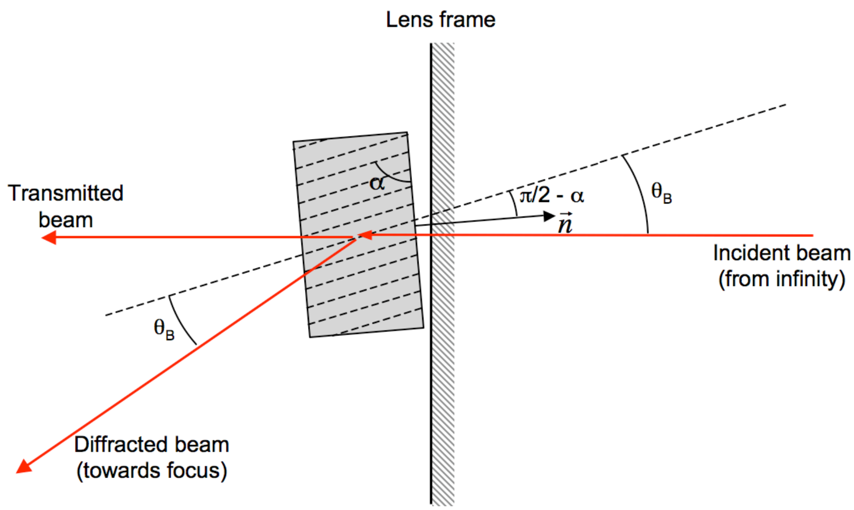

Fig 3 : Sketch of the positioning of a crystal having an asymmetry angle (named α) on a Laue lens. Dashed lines represents diffracting planes. The aim of the orientation is to bring the diffracting planes at the Bragg angle θ_B with respect to the optical axis (here shown as the normal of the lens frame). If the crystal cleaved, or was perfectly cut, α would be equal to π/2 and the normal of the crystal's back-face $\vec{n}$ would be at the Bragg angle from the optical axis.

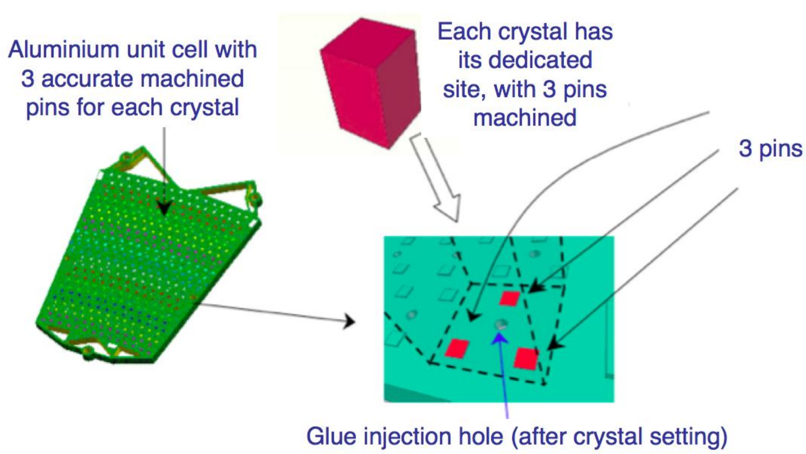

Fig 4 : Method of crystals' fixation proposed by Thales Alenia Space of Cannes for the R&D initiated by the CESR and financed by the CNES. (See text for more details).

For a large scale lens (GRI lens sized 1.8 m of radius), a modular architecture is more suitable in terms of constraints repartition. Moreover, it allows the parallelisation of the second part of the assembly process, the fixation. Such elementary cell is represented in Fig 4. A small prototype containing a handful of crystals should be ready by the end of 2008, and will permit to evaluate this method. An orientation tolerance lower than 10 arcsec around the nominal angle is aimed.

Another strategy has been chosen by the team of the University of Ferrara (Italy), as detailed in ref. [9]. The idea is to orientate each crystal in an X-ray beam, and then to keep trace of this orientation by gluing a pin (of a few centimetre long) on the front-face of the crystal, the pin being precisely set parallel to the incident

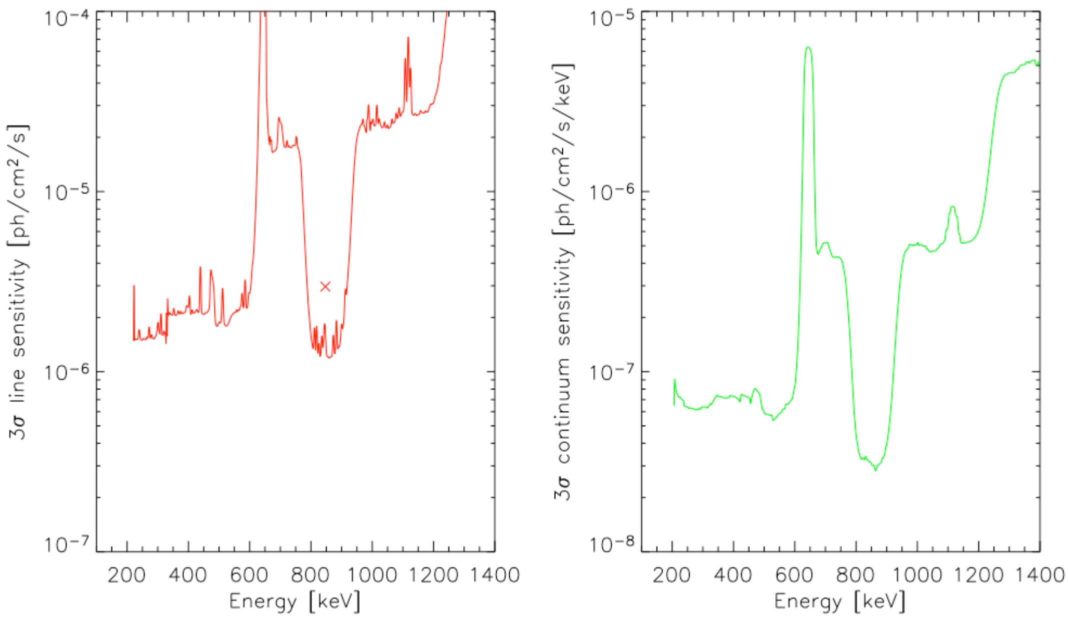

Figure 5 : Narrow line (left panel) and continuum (right panel) sensitivity of GRI telescope in the energy band covered by the Laue lens. These calculations assume 100 ks of exposure time, and an energy bin of E/2 for the continuum sensitivity. On the left panel, the cross shows the sensitivity for the 847 keV broadened line.

beam. Then pins are put in a counter mask, in which holes welcoming them are accurately drilled at the angle making crystals oriented at the Bragg angle with respect to the line of sight. In the following step, while the counter-mask is filled with all the crystals the frame of the lens is approached and glued to the back-face of crystals. Finally the basis of pins is cut by chemical treatment allowing to remove the counter mask. As reported in [9], a first prototype has already been built with this method, giving an orientation precision of about 2 arcmin. This first trial permitted above all to identify the weaker points of the method, which will be improved for the next time.

5 EXPECTED PERFORMANCES

Performance in the soft gamma ray domain given by a telescope featuring a Laue lens is worth the difficulty it represents to build it. For an exposure time of 100 ks, a mission like GRI would be able to achieve a continuum sensitivity of 8.10^{-8} ph/s/cm^2/keV ($\Delta E = E/2$) over the range 220 keV – 620 keV, a broadened line (3%) sensitivity of 2.10^{-6} ph/s/cm^2 for the 847 keV line emitted by ^{56}Co decay in Type 1A supernova, and a narrow line sensitivity of 3.10^{-6} ph/s/cm^2 at 511 keV to look for the e^+ - e^- annihilation line in compact objects (Figure 5), a factor 50 better than past and present missions.With its 100 m focal length, and a focal plane of 15 cm wide, GRI has a field of view of 5 arcmin, with an angular resolution of 30 arcsec.

The design of the GRI lens was done about one year ago, before the investigation of new high diffraction-power crystals as gold. The availability of these new materials allows now making new design that combines various materials in order to use the best ones for each energy band. In consequences, the lens could become 20% lighter and 20% more powerful.
GRI mission was not selected in cosmic vision AO1, however the development of a focusing telescope remains the only option to increase significantly the sensitivity in soft gamma ray domain. New projects are currently being studied, especially with shorter focal length that would allow for a valuable instrument without formation flying of two satellites. For example, a focal length of the order of 20 m would permit to cover efficiently energies from 150 keV up to 600 keV.

6 CONCLUSION

Main difficulties for the realisation of a Laue lens are about to be overcome. Crystals available are always more efficient and show now very good diffraction efficiencies up to high energies, as illustrated by our last gold sample that reached a reflectivity of 31% at 600 keV. The high number of crystals will require a selection process to insure a constant quality. But since crystals must be put in an X-ray beam to be orientated, their diffraction power can be derived at the same time.

Two mounting processes are currently investigated in Europe. The prototype financed by the CNES aims to reach an orientation accuracy compatible with a long focal of the order of 100 m. It should be ready in a few months, and will permit to evaluate the method.

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