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ORIGINAL ARTICLE

# MAX, a Laue diffraction lens for nuclear astrophysics

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**Abstract** The next generation of instrumentation for nuclear astrophysics will have to achieve a factor of 10–100 improvement in sensitivity over present technologies. With the focusing gamma-ray telescope MAX we take up this challenge: combining unprecedented sensitivity with high spectral and angular resolution, and the capability of measuring the polarization of the incident photons. The feasibility of such a crystal diffraction gamma-ray lens has recently been demonstrated with the prototype lens CLAIRE. MAX is a proposed

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mission which will make use of satellite formation flight to achieve 86 m focal length, with the Laue lens being carried by one satellite and the detector by the other. In the current design, the Laue diffraction lens of MAX will consist of 13740 copper and germanium ($Ge_{1-x}Si_x$, $x \sim 0.02$) crystal tiles arranged on 36 concentric rings. It simultaneously focuses in two energy bands, each centred on one of the main scientific objectives of the mission: the 800–900 keV band is dedicated to the study of nuclear gamma-ray lines from type Ia supernovae (e.g. $^{56}$Co decay line at 847 keV) while the 450–530 keV band focuses on electron-positron annihilation (511 keV emission) from the Galactic centre region with the aim of resolving potential point sources. MAX promises a breakthrough in the study of point sources at gamma-ray energies by combining high narrow-line sensitivity (better than $10^{-6}$ cm$^{-2}$ s$^{-1}$) and high energy resolution (E/dE $\sim$ 500). The mission has successfully undergone a pre-phase A study with the French Space Agency CNES, and continues to evolve: new diffracting materials such as bent or composite crystals seem very promising.

**Keywords** Instrumentation: Gamma-ray Laue lens · Gamma-ray astrophysics · Mosaic crystals
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## 1. Introduction

Observing gamma-ray lines is first and foremost a matter of extracting a weak signal swamped in an intense and complex instrumental background. This is partly due to the fact that all existing instruments are based on concepts where the collecting area is equal to the sensitive area. Since the instrumental background in a detector operating in space is roughly proportional to its volume, decoupling the instrument effective area from the detector volume would lead to a dramatic improvement of sensitivity. That is why focusing gamma rays appears today as the only way to study point sources with a sufficient sensitivity to further our understanding of explosive nucleosynthesis and compact objects.

MAX is a mission concept for a space-borne gamma-ray telescope using a Laue lens to focus nuclear gamma-ray lines from a large area onto a small detector. The lensing effect is based on Bragg diffraction in the volume of crystalline materials. CLAIRE, a prototype of such a Laue lens has already been realized in a CESR – CNES (the French space Agency) collaboration, and has demonstrated the feasibility of this concept [11, 23].

In this paper we first provide an overview of the MAX mission: its principal scientific objectives, the characteristics of the current instrument design, sensitivity estimates for various crystal types and detector options. We then describe ongoing R&D on new diffracting materials, such as composite crystals or bent crystals.

## 2. Scientific motivations

Gamma-ray astronomy presents an extraordinary scientific potential for the study of the most powerful sources and the most violent events in the Universe. While at lower wavebands the observed emission is generally dominated by thermal processes, the gamma-ray sky provides us with a view of the non-thermal Universe, where particles are accelerated by still poorly understood mechanisms to extremely relativistic energies and nuclear reactions and decays are creating the basic elements that constitute our world (see the first section of this volume).

MAX aims to observe radioisotopes produced in Type Ia supernovae (SN) (see e.g. [19]) and around compact objects through their emitted nuclear lines. Type Ia supernovae (SN), with classical novae [12] and core collapse SN (Type Ib, Ic, II,. . .), are the main contributors to the production of heavy elements, playing a major role in the life cycle of matter in the Universe. The exceptional luminosity of SN Ia has made them a valuable tool for the measurement of extragalactic distances and for determining the metric of the Universe. The optical light produced in Type Ia SN is mostly powered by the decay chain $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$, which is directly observable mainly in two gamma-ray lines at 812 keV and 847 keV.

Despite their great interest in many areas of astronomy, fundamental questions remain about all types of SN. Establishing the actual $^{56}$Ni and $^{56}$Co decay line intensities and shapes is a primary goal that will lead to a breakthrough for our understanding of the detailed physics at work in these explosions. A sensitivity of $\sim 10^{-6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ to broadened gamma-ray lines would allow at least one Type Ia SN per year closer than 20 Mpc to be observed with a detection significance of $25\sigma$, which would allow discrimination between various models [16]. Up to 5 $\mathrm{y}^{-1}$ could be detectable with a significance of $3\sigma$, in a radius of 50 Mpc.

The search for potential sources of the positrons whose presence is implied by the 511 keV radiation observed with SPI/INTEGRAL constitutes the other main scientific theme of the MAX mission. Compact objects (microquasars, neutron stars and pulsars, X-ray binaries, . . .), active galactic nuclei, solar flares and the high energy afterglow from gamma-ray bursts may release significant numbers of positrons leading to 511 keV annihilation line emission. The shift and the shape of this line carry a lot of information about the region and conditions where positrons have annihilated [14]. Fine spectroscopy of the annihilation line combined with a good spatial resolution could elucidate the nature of these objects.

## 3. The MAX mission

MAX was proposed in response to an announcement of opportunity issued by the CNES concerning a formation flight demonstrator mission. It consists of a lens spacecraft and a detector spacecraft flying in formation to form a gamma-ray telescope of 86 m focal length. The pre-phase A study led by the CNES/PASO group that ended in November 2005 confirmed the feasibility of the mission, and indicated a mass margin of 400 kg. As a consequence we have updated the MAX design (which becomes MAX 3.0) with an increase of 72% in the focusing area (crystal tiles), resulting in dramatic increases in the effective areas of both bandpasses.

MAX is still under development and so is continuously evolving. The version 3.0 presented here is based on crystals representing the current state of the art and which are relatively conservative compared to new diffracting materials that are highlighted by the current R&D program (see below).

### 3.1. Lens features

In the current MAX design, the lens is made of 13740 crystal tiles of 1.5 cm × 1.5 cm including 90% copper crystals [8] and 10% germanium crystals [1]. The thicknesses, $T_0$, of crystal tiles are optimized for each ring according to the following formula which comes from the maximisation of a mosaic crystal peak diffraction efficiency for a given mosaicity:

$$T_0 = \frac{1}{2\sigma} \ln\left(1 + \frac{2\sigma\cos\theta_B}{\mu}\right).$$

**Table 1** MAX crystals masses and geometrical areas. LE: low energy band; HE: high energy band

| | |
|---|---|
| Focal length $f$ | 86 m |
| Crystal mosaicity | 30 arcsec. |
| Geometrical area | 30915 $\text{cm}^2$ |
| Mass of crystals | 235 kg |
| Number of HE rings | 20 |
| Mass of HE crystals | 172 kg |
| Geometrical area of HE rings | 15966 $\text{cm}^2$ |
| Number of LE rings | 16 |
| Mass of LE crystals | 62 kg |
| Geometrical area of LE rings | 14949 $\text{cm}^2$ |

$\sigma$ is the diffraction coefficient for the crystalline material, $\mu$ is the absorption coefficient (without coherent scattering which is precisely the origin of the Bragg diffraction), and $\theta_B$ is the angle of incidence of rays on the diffracting planes (called Bragg angle when diffraction occurs). The value of $\sigma$ is calculated according to the dynamical theory of diffraction (see Halloin, Bastie [5, 6] for complete treatment). The crystal tiles are arranged on 36 concentric rings with radii ranging from 56.25 to 76.35 cm and from 93.05 to 129.05 cm.

The resulting lens focuses simultaneously in two broad energy bands corresponding to the previously described scientific objectives (Figure 1): the lower energy band is centred on 500 keV. Its width permits the observation of red-shifted $\text{e}^- - e^+$ annihilation lines from compact objects (e.g. the supermassive black hole in the centre of our Galaxy), as well as the study of the 478 keV decay line from $^7$Be. The bandpasses of the 14 Cu rings and 2 Ge rings combine to cover an energy band from 450 to 530 keV, with a total effective area of 1200 $\text{cm}^2$ at 511 keV. The second energy bandpass is obtained with 18 Cu rings and 2 Ge rings whose responses superimpose to cover an energy band from 800 to 900 keV, with a total effective area of 660 $\text{cm}^2$ at 847 keV. In addition, the second order diffraction of the crystals covering the lower energy bandpass extends this band up to 1050 keV. Details of masses and geometrical areas of both bandpasses are given in Table 1.

### 3.2. Detector features

The baseline detector for MAX is a Compton camera consisting of a stack of planar germanium strip detectors (GeD). The stack is made of 5 GeD modules similar to the ones used in the balloon borne Nuclear Compton Telescope, which was successfully tested in 2005 (NCT, [4]). Each GeD is approximately 8 cm × 8 cm and 1.5 cm thick, and the strips are 2 mm pitch, which ensure a 1 $\text{mm}^3$ 3D-positionning. The design used to estimate sensitivities [24, 25] assumes a gap of 0.7 cm between two GeD. To reduce the background count rate, the detector is separated from the spacecraft by being placed on a 1 m "tower". In addition, the Compton camera is encapsulated in a plastic veto shield, and a 5 cm thick active BGO crystal screens it from the emissions produced in the structure of the spacecraft. It has been established during the MAX pre-phase A study that cooling of the Compton camera can be achieved with a 1 m diameter radiator. Alternative solutions to the above baseline are being considered, including a high sensitivity Si/CdTe narrow field of view Compton camera [17, 22], or Compton CdTe pixel detector [7].

The advantages of using a detector providing localization of the interactions are multiple: besides following any excursions of the focal spot across the detector plane, such a system allows the simultaneous measurement of signal and background. Most importantly, in a system with three-dimensional event localization, a significant background reduction can be achieved by reconstructing the arrival direction of the photons using Compton

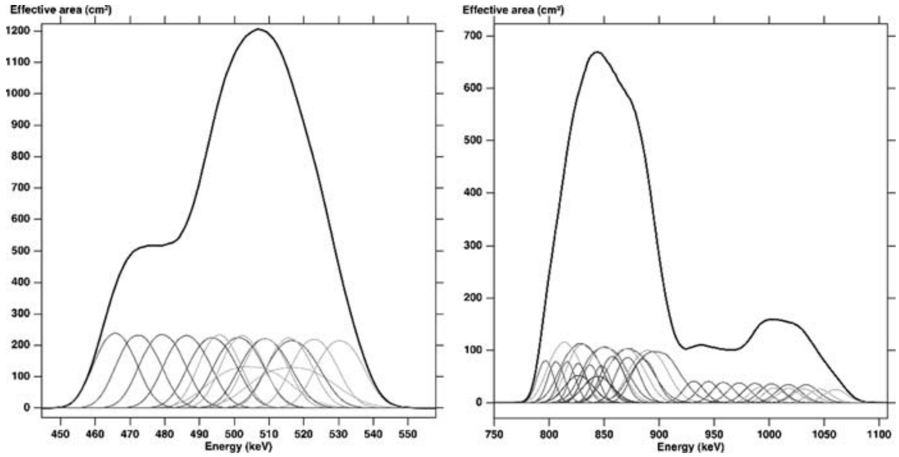

**Fig. 1** Effective area of the lens for a perfect pointing on a point source. Each Gaussian curve is the contribution of a single ring. The second order diffraction of low energy (LE) rings extends the high energy (HE) bandpass up to 1050 keV. Various sets of Bragg planes in copper and germanium at different radii contribute to the two main energy bands: Cu(111), Cu(200) and Ge(111) are used for the LE band, whereas Cu(111), Cu(200), Cu(220), Cu(222) and Ge(311) diffract in the HE band. In this sense, this lens is a hybrid between a broad-band lens and a narrow-band lens

kinematics. This allows the rejection of photons not coming from the lens direction. In addition, a Compton camera is inherently sensitive to gamma-ray polarization. Lastly a fine pixellated focal plane allows the limited imaging capabilities of the lens to be used. One drawback of a Compton camera is at present their low detection efficiency (ranging between 6–7% for a Ge- strip Compton stack). First steps in the optimisation for the particular case of a Laue lens have been performed [25] and this works will continue in the future.

## 3.3. Sensitivity estimates

The modelled narrow line sensitivity of MAX in both energy bandpasses is shown in Figure 2. Lens efficiency estimates are derived from the diffraction efficiency given by the Darwin model, which are in agreement with the diffraction efficiencies measured for the lens prototype CLAIRE [11] and recent measurements made at the European Synchrotron Radiation Facility (ESRF, Grenoble, France) [5, 6]. The upper curve (a) in Figure 2 shows the sensitivity with current technology, based on the lens MAX 3.0 and the baseline Compton camera described in Section 3.2. The lower curve in Figure 2b shows a sensitivity requiring advanced technology: a lens using bent crystals (see below) focusing onto an optimized Compton camera (the “LARGE” geometry in [25]). At this early stage, these estimates are rough but conservative. Numerous optimizations could still be done, as for example, improving the treatment of the Compton-rejected photons (93% of the signal), or the optimization of the detector geometry or the lens efficiency.

## 3.4. Lens PSF – imaging capabilities

Although a crystal lens telescope is not a direct imaging system, the spatial response does depend on the source position in the field of view. For an on-axis point source, the response is a

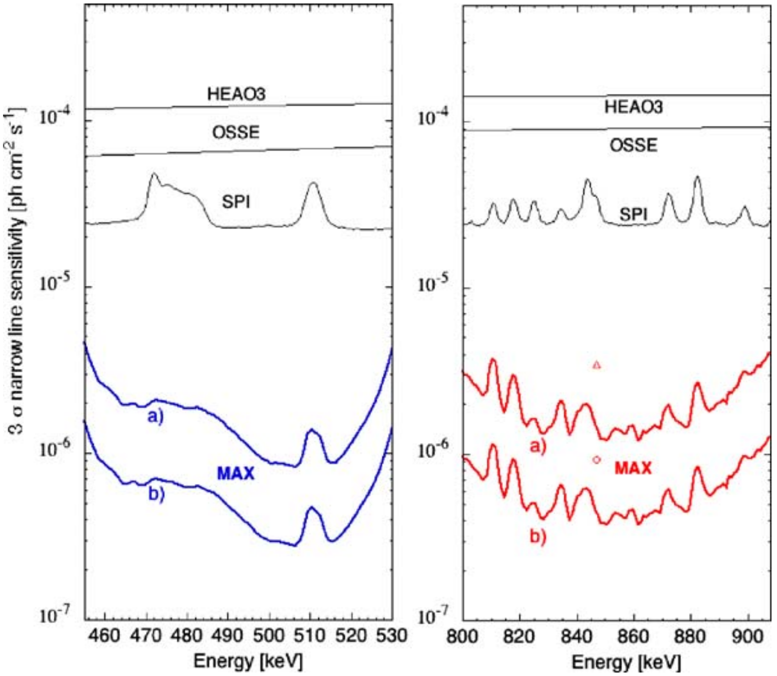

**Fig. 2** The modelled narrow line sensitivity of MAX in both energy bands. Curve (a) is the sensitivity with current technology, using the baseline Compton camera (see above) and the current lens MAX 3.0. Curve (b) is the sensitivity reachable with a lens using bent crystals and an optimized Compton camera. The circle and the triangle are the sensitivities for a broad line (3%) at 847 keV

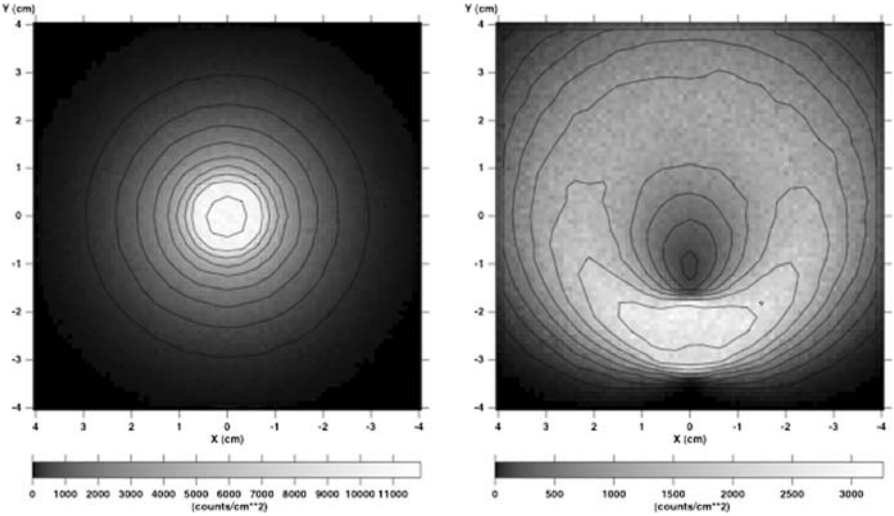

**Fig. 3** MAX baseline detection plane (8 cm × 8 cm, 1 mm$^2$ pixels) response for a point source. Flux is coded both by a grey square root scale and by square root contours. Left: image of an on-axis point source. Right: image of an off-axis point source when the lens is pointing 60 arcsec away from the source. The Monte-Carlo code used for these simulations was developed by Halloin [11]

Gaussian-like spot centred on the optical axis of the lens (Figure 3, right). For an off-axis point source, the focal spot becomes a donut shape (centred on the lens optical axis) presenting an azimuthal intensity modulation [18]. The average radius $r_a$ of the focal ring and the angular position of the maximum intensity $\varphi_m$ give the zenithal (off-axis) ($\theta_s$) and the azimuthal ($\varphi_s$) angles of the source through the very simple relations:

$$\theta_S = a\tan\left({}^{r_a}/_f\right),$$
$$\varphi_S = \varphi_m + \pi$$

where *f* is the focal distance of the lens for a source at infinity.

The minimum thickness of the focal ring (where the intensity is maximal) approaches the radial size of the crystals with increasing zenith angle of the source (individual square crystals are arranged on rings such that one side is tangential). Thus, mosaicity and crystal sizes dictate the angular resolution of the instrument.

The field of view of MAX is limited by two parameters: firstly, the size of the detection plane (8 cm × 8 cm) limits the radius of the recorded focal ring to 4 cm. Taking into account crystals radial size, the maximum radius of observable focal ring is 3.25 cm. The field of view of MAX is therefore ±78 arcsec. The second limiting parameter is the decrease of the lens effective area when the zenithal angle of the source increases (Figure 4). For an angle of 60 arcsec, the effective area goes down by 45% and 40% at 511 keV and 847 keV respectively.

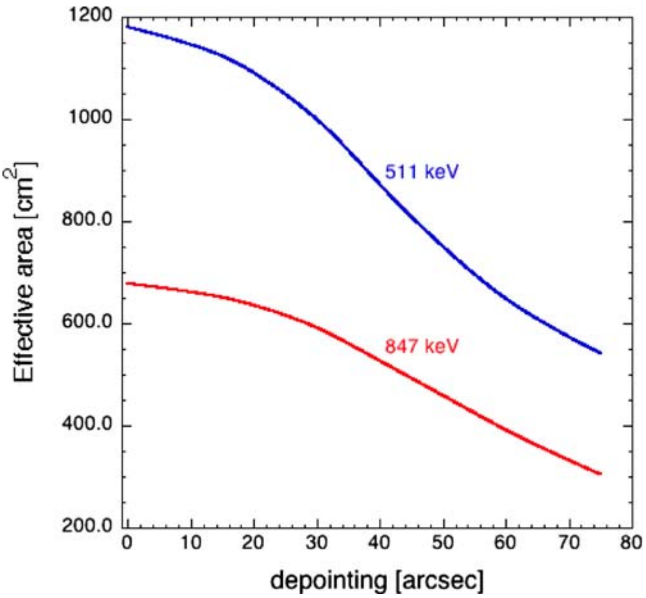

**Fig. 4** Effective area as a function of position in the field of view at 511 keV and 847 keV

## 4. The R&D towards a spaceborne Laue lens

### 4.1. Lens structure

A first design of the structure of the lens has been made in order to study its thermo-elastic deformations. The design is based on the ALCATEL structural concept [10, 13]: a main circular carrier structure supports 32 independent modules onto which the individual crystals are attached. The central carrier structure homogenizes the temperature and transmits mechanical forces to the satellite structure through four titanium links. Due to the penetrating nature of gamma rays it is possible to put the lens in a multilayers insulator (MLI) cocoon to ensure sufficient thermal stability. Even with such a passive system the temperature would already be within ±3 K of the nominal temperature, whatever the orientation of the sun.

For a 86 m focal distance, the diffracting planes of a crystal have to be oriented within $\sim$10 arcsec with respect to the lens line of sight to keep the position of the crystal footprint within ±1 cm of its nominal position. This value dictates the specification for the lens out of plane deformation: modules have to keep their nominal orientation within ±10 arcsec. It has been shown in the MAX pre-phase A study that a ±2 K active thermal control around the nominal temperature (ambient) is sufficient to satisfy this deformation specification, a requirement that seems easily attainable [13].

### 4.2. Diffracting materials

#### *4.2.1. Lessons from the CLAIRE lens*

The CLAIRE lens was made of 556 crystals mounted on eight rings (see [11, 23] for an in-depth description of the CLAIRE project). These crystals, that are actually a solid solution of silicon in germanium ($Ge_{1-x}Si_x$, $x < 0.1$), were grown using a modified Czochralski technique at the Institute of Kristalzüchtung (IKZ, Berlin, Germany) by [1]. CLAIRE was a narrow bandpass Laue lens, it focused radiation centered on 170 keV (for rays coming from infinity) using a different family of crystalline planes for each ring. The overall diffraction efficiency of the lens was found to be about 10%, though some of the best crystals had a peak reflectivity of 25%.

There are two reasons to explain the relatively low efficiency of the entire lens compared to that of the best crystals. Firstly, the theoretical diffraction efficiency decreases with increasing Miller index. For example, the eighth ring used the [440] reflection that has a theoretical integrated reflectivity 7.5 times lower than that of the (111) planes. Secondly, even on a given ring where all crystals are supposed to be identical, differences do exist. These differences that translate into differences in absolute reflectivity and energy bandpass, are due to mosaicity and crystallites length variation. Basically, the larger the crystallites, the worse is the reflectivity. A larger mosaicity offers a larger energy bandpass, but it, too, decreases the reflectivity.

The CLAIRE project has emphasized the need to use preferentially sets of crystalline planes of lower Miller index, and to ensure that the quality of the crystals grown can be maintained consistently during the production of a large number of boules.

#### *4.2.2. Existing crystals*

MAX lens would be mainly made with copper crystals, with 10% germanium-silicon crystals to provide enhanced collecting area in the energy bands of interest. Copper crystals combine high theoretical diffraction efficiency (higher than germanium) with inherent mosaic structure. The challenge was to grow crystals with a mosaicity of about 30 arcsec, a value which is very small for this material. In 2005, this goal was achieved for the very first time by [8] at ILL. Such a low mosaicity copper crystal have shown a peak reflectivity reaching 30%.

Concerning germanium crystals, since the time when CLAIRE's crystals were grown the quality of crystals obtained by the modified Czochralski technique has been improved. Using only the most efficient reflections (low Miller index), we can count on peak diffraction efficiencies exceeding 25%.

Nevertheless, the only way to completely avoid variation of the crystalline parameters, such as those noted in the CLAIRE lens, would be to characterize every crystal and to select only the best.

### *4.2.3. New generation of crystals*

Alternative crystalline materials are also being considered. One possibility is germanium 'composite crystals', made of perfect single-crystal germanium wafers that are stacked with a slight mis-oriention from one to the next (like the crystallites in a mosaic crystal). This kind of crystal presents potentially advantages with respect to mosaic crystals: single crystal wafers are easily reproducible and it is possible to optimize the wafer thickness according to the energy that the stack will have to diffract. Since wafers are perfect single crystals, the formulae given in subsection 3.1 do not apply any more, the optimal thickness of a wafer equals half of the Pendellösung period (the period of the oscillations of the diffracted intensity as a function of the thickness of the crystal; [3]). Of course the key point is to manage to build the stack properly. Indeed, a recent measurement run at the ESRF [5, 6] on a prototype composite crystal showed that the angular separation between wafers was greater than their angular bandpass[1], leading to an undesirable comb-like response. This still-evolving technique, especially the surface treatment of the wafers, has yet to be optimised.

Bent crystals are another alternative that seem very promising. Smither [21] have already measured Si crystals with efficiency close to 100% (disregarding absorption[2]) in an angular bandpass of 30 arcsec. Bent diffracting planes can be obtained in 3 ways: by applying a thermal gradient to a crystal, by elastically bending a crystal, or by growing a composition-gradient crystal ($Ge_{1-x}Si_x$) [2]. In the latter case, a spherical curvature of atomic planes perpendicular to the gradient direction appears, due to the fact that Ge atoms are larger than Si atoms [21].

Bent crystals present two main advantages with respect to mosaic crystals: their peak diffraction efficiencies are not limited to 50% as is the case for mosaic crystals (see for instance Halloin, Bastie [5, 6]), and their rocking curves (curves representing the range of angles through which an incident beam can be diffracted) can have a square shape. As a comparison, mosaic crystals exhibit a Gaussian-like rocking curve, which is good for the lens field of view, but degrades the focusing on the detector (since each crystal diffracts a diverging beam whose spatial distribution is Gaussian). Preliminary estimates of the sensitivity achievable with a lens made of bent crystals show a gain of a factor 2 with respect to the current version of MAX.

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[1] Even a perfect single crystal has an angular bandpass that is called the Darwin width. In addition, the cutting process induces deformations that increase the angular bandpass.

[2] If we do not consider the absorption, when a beam goes through a crystal, it is shared in two complementary parts: the diffracted beam and the transmitted beam. In the case of a mosaic crystal, these two parts tend to be equal if the crystal is thick enough: the maximum diffraction efficiency without absorption is 50%.

## 5. Summary

With its Laue lens consisting of Cu and Ge crystals rings MAX promises a breakthrough for the study of point sources at gamma-ray energies by combining narrow line sensitivities better than $10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and high energy resolution (E/dE $\sim$ 500). MAX features a Laue lens consisting of rings of Cu and Ge crystals, covering simultaneously two broad energy ranges: 800–900 keV and 450–540 keV. A small detector, maintained at a distance of 86 m by a second spacecraft flying in formation, collects the focused radiation. A pre-phase A study of the French Space Agency CNES has established the feasibility of the mission with present technologies [10].

The performance of a future Laue lens depends mainly on the diffraction properties of its individual crystals. Despite the fact that mosaic crystals produce a focal spot not ideally concentrated on the detection plane, the copper crystals grown at ILL show peak reflectivities up to 30%. The growth of copper crystals can be fairly well controlled at present, with mosaicities ranging from a few minutes down to 30 arcsec. It is hence already possible to build an efficient gamma-ray Laue lens using a combination of copper and germanium mosaic crystals.

We have shown that Laue lenses can benefit either from crystals having a composition gradient (causing curvature of the crystalline planes) or from “composite crystals” (having an “artificial mosaic structure” produced by assembling wafers with slightly different alignments). In either case, the efficiency-limitation, which prevents Laue mosaic crystals of having a reflectivity higher than 50%, can be exceeded. We also show the importance of improving the crystals point spread function to obtain a compact focal spot and thus a enhanced signal/noise ratio.

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