Development status of the LAUE project

Vincenzo Liccardo[a,c]

In collaboration with:

F. Frontera[a,b]*, E. Virgilli*[a]*, V. Valsan*[a,c]*, V. Carassiti*[d]*, S. Chiozzi*[d]*, F. Evangelisti*[d]*, S. Squerzanti*[d]*, M. Statera*[a]*, V. Guidi*[a]*, C. Ferrari*[e]*, R.A. Zappettini*[e]*, E. Caroli*[b]*, N. Auricchio*[b]*, S. Silvestri*[b]*, R. Camattari*[a]*, F. Cassese*[f]*, L. Recanatesi*[f]*, M. Pecora*[g]*, S. Mottini*[h]*, P. Attinà*[h] *and B. Negri*[k]

(a) Physics Department, University of Ferrara - Via Saragat, 1, 44100 Ferrara, Italy;
(b) INAF–IASF Bologna, via P. Gobetti 101, Bologna - Italy;
(c) Erasmus Mundus Joint Doctorate IRAP PhD. Student
(d) INFN, Sezione di Ferrara, via Saragat 1, 44100 Ferrara , Italy;
(e) CNR, IMEM, Parco Area delle Scienze 37/A - 43124 Parma, Italy;
(f) DTM, Modena, Via Tacito, I-41100 Modena, Italy;
(g) Thales Alenia SpaceItaly, Milan, Italy;
(h) Thales Alenia SpaceItaly, Turin, Italy;
(k) ASI, Agenzia Spaziale Italiana, Viale Liegi 26, I-00198 Roma, Italy.

Outline

- Introduction;
- Laue Lenses principles;
- The LAUE project;
- The LARIX facility;
- Selected crystals and petal properties;
- Performances simulations;
- Conclusion.

The 80-600 keV range is crucial for several scientific objectives

- Physics of NS in presence of super-strong magnetic fields (Mass accreting X-ray pulsars, Anomalous X-ray Pulsars);
- Nuclear lines (e.g., ^{44}Ti) produced in SN explosions.

Introduction

Many open issues are expected to be solved with focusing telescopes that cover the soft gamma–ray band (> 80 keV)

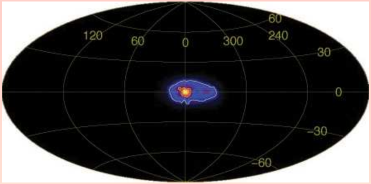


Figure: INTEGRAL map of the glow of 511 keV gamma–rays from electron-positron annihilation (Weidenspointner et al., 2008)

One of the most elusive questions is the origin of positrons in the Galactic Center (CG) region. Is it due to:

– hard low mass X–ray binaries, strong emitters of hard X–rays (>20 keV)?
– extended region of antimatter or dark matter?
– existence of a source of radioactive elements like ^{26}Al, ^{56}Co, ^{44}Ti?
– presence of a gamma–ray source (e.g., gamma–ray pulsar)?

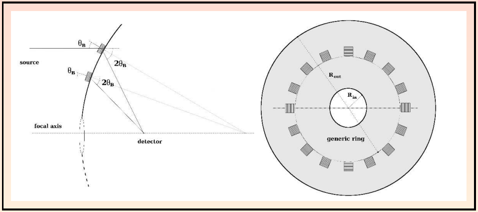
Laue lens principles

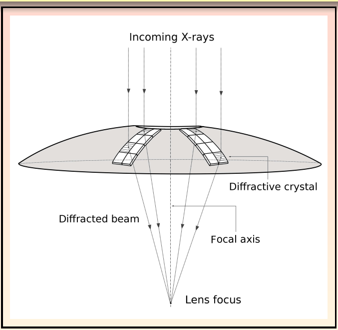
The Bragg Law

$$2d_{hkl}\ \sin\theta_B = n\ \frac{\hbar c}{E_B}$$

Energy–radius relation:

$$E_B \approx \frac{\hbar c\ f}{d_{hkl}\ R_{ring}}$$





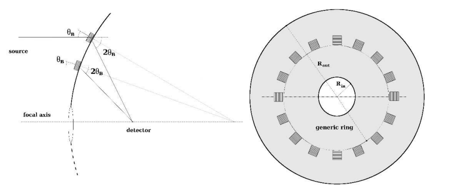
Laue lens principles

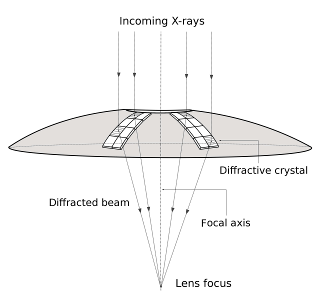
The Bragg Law

$$2d_{hkl}\ sin\theta_B = n\ \frac{\hbar c}{E_B}$$

Energy–radius relation:

$$E_B \approx \frac{\hbar c\ f}{d_{hkl}\ R_{ring}}$$

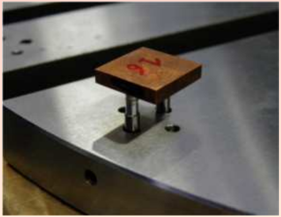




From the HAXTEL to the LAUE project

In the HAXTEL project 3 phases were used for positioning each crystal:

- gluing pins as references for the diffractive planes;
- positioning in a drilled countermask;
- gluing the set of crystals on the carbon fiber support.



Limitations

– Time consuming;
– Limited accuracy due to the multi-phase process;
– Satisfactory for short focal length Laue lenses ($<$10 m).

The LAUE project

The main objective: a focusing lens for hard X-/soft γ-rays 80 – 600 keV

Goals of the LAUE project

- Massive production of crystals for diffraction, in a relatively short time, with high efficiency and desired spread (15÷25 arcsec);
- Technology for assembly a large number of crystals: accuracy better than 10 arcsec;
- Facility for assembling the crystals on a petal with the required accuracy and for the performance tests;
- Realization of a petal using the selected crystals.

The LAUE project

The main objective: a focusing lens for hard X-/soft γ-rays 80 – 600 keV

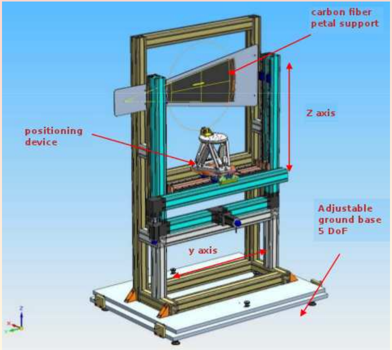
Goals of the LAUE project

- Massive production of crystals for diffraction, in a relatively short time, with high efficiency and desired spread (15÷25 arcsec);
- Technology for assembly a large number of crystals: accuracy better than 10 arcsec;
- Facility for assembling the crystals on a petal with the required accuracy and for the performance tests;
- Realization of a petal using the selected crystals.

The LAUE project: a lens for X and γ-rays

How to assemble hundreds of crystals?

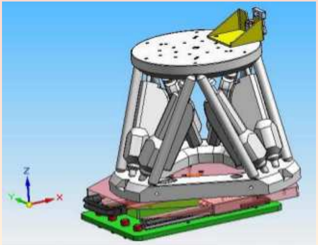
In the LAUE project the crystals will be directly placed on a carbon fiber support using a mechanical device (**DTM Technologies – Modena (Italy)**)



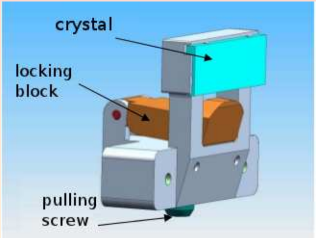
The LAUE project: a lens for X and γ-rays

How to assemble hundreds of crystals?

Two positioner were developed to set each crystal on the petal frame.
A **coarse positioner** made of two perpendicular y/z translation stages.
A **fine positioner** (**esapod**) accurately control the crystal tilting around two perpendicular axes and its motion toward the frame.



Esapod

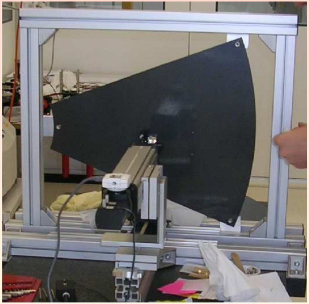


Crystal holder

A crystal holder holds the crystal in such a way that four out of six faces are kept free (for the beam incidence and for positioning the tiles side by side).

Advantages

– Faster alignment;
– Expected accuracy 10 times better than in the HAXTEL method ($\sim$ 10 arcsec).



The LAUE project

A focusing lens for hard X-/soft γ-rays 70 – 600 keV

Goals of the LAUE project

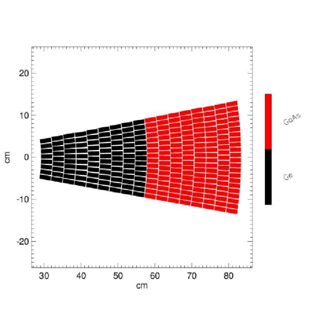
- Massive production of crystals for diffraction, in a relatively short time, with high efficiency and desired spread (15÷25 arcsec);
- Technology for assembly a large number of crystals: accuracy better than 10 arcsec;
- Facility for assembling the crystals on a petal with the required accuracy and for the performance tests;
- Realization of a petal using the selected crystals;
- Feasibility study for assembling an entire lens made of petals, for space application.

The LAUE project

Building a petal

Petal properties

On the basis of:
– Available X-ray source (< 320 keV);
– Beam-line dimension.



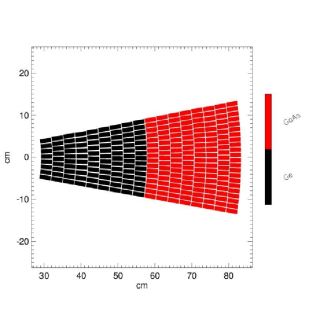
Petal properties	
Materials	Germanium (111)
	Gallium Arsenide (111)
Passband	80–300 keV
Focal Length	20 m
Crystal size	$30 \times 10 \times 2$ mm^3
N^o crystals	$\sim$ 300
	(aperture angle 18^o)
N^o rings	18

The LAUE project

Building a petal

Petal properties

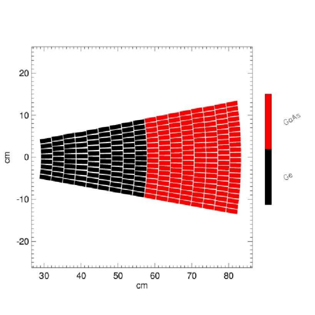
On the basis of:
– Available X-ray source (< 320 keV);
– Beam-line dimension.



Petal properties	
Materials	Germanium (111)
	Gallium Arsenide (111)
Passband	80–300 keV
Focal Length	20 m
Crystal size	$30 \times 10 \times 2$ mm^3
N^o crystals	~ 300
	(aperture angle 18^o)
N^o rings	18

Petal properties

On the basis of:
– Available X-ray source (< 320 keV);
– Beam-line dimension.



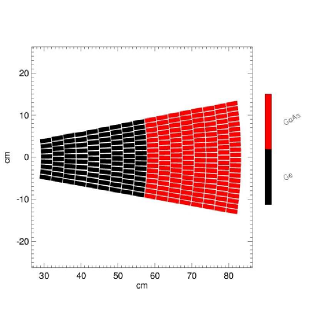
Petal properties	
Materials	Germanium (111)
	Gallium Arsenide (111)
Passband	80–300 keV
Focal Length	20 m
Crystal size	$30 \times 10 \times 2$ mm^3
N^o crystals	~ 300
	(aperture angle 18^o)
N^o rings	18

The LAUE project

Building a petal

Petal properties

On the basis of:
– Available X-ray source (< 320 keV);
– Beam-line dimension.



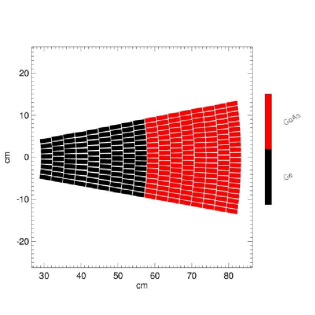
Petal properties	
Materials	Germanium (111)
	Gallium Arsenide (111)
Passband	80–300 keV
Focal Length	20 m
Crystal size	$30 \times 10 \times 2$ mm^3
N^o crystals	~ 300
	(aperture angle 18^o)
N^o rings	18

The LAUE project

Building a petal

Petal properties

On the basis of:
– Available X-ray source (< 320 keV);
– Beam-line dimension.



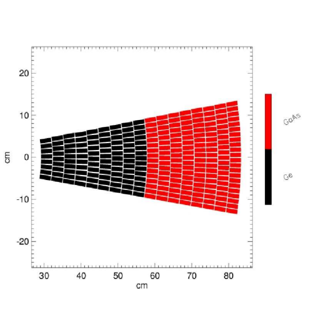
Petal properties	
Materials	Germanium (111)
	Gallium Arsenide (111)
Passband	80–300 keV
Focal Length	20 m
Crystal size	$30 \times 10 \times 2$ mm^3
N^o crystals	$\sim$ 300
	(aperture angle 18^o)
N^o rings	18

The LAUE project

Building a petal

Petal properties

On the basis of:
– Available X-ray source (< 320 keV);
– Beam-line dimension.

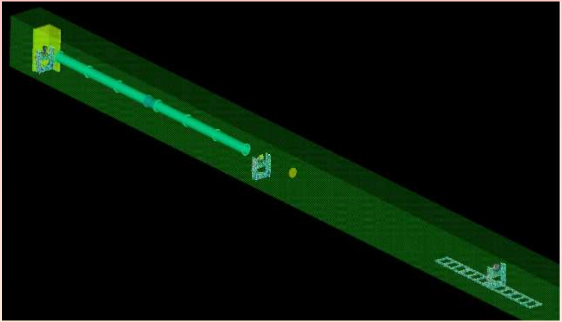


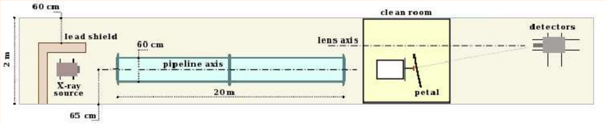
Petal properties	
Materials	Germanium (111)
	Gallium Arsenide (111)
Passband	80–300 keV
Focal Length	20 m
Crystal size	$30 \times 10 \times 2$ mm^3
N^o crystals	~ 300
	(aperture angle 18^o)
N^o rings	18

Goals of the LAUE project

- Development of a technology for a massive production of crystals for diffraction, with high efficiency and desired spread ($20 \div 30$ arcsec);
- Development of a technology to assemble a large number of crystals with a positioning accuracy better than 10 arcsec;
- Development of a facility for assembling the crystals on a petal with the required accuracy and for the performance tests;
- Realization of a petal using the selected crystals;
- Feasibility study for assembling an entire lens made of petals, for space application.

The LARIX facility



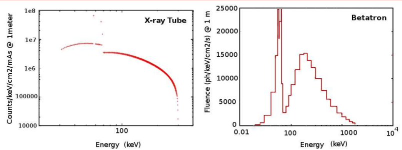


Source and Collimator are moved together along Y and Z axis providing a parallel X-ray beam to the target with a precision of ± 0.1 mm (few arcsec @ 20 m).

The LARIX facility

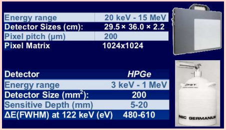
Photon source

X-ray tube up to $\sim$ 320 keV (for building)
Bethatron source up to 2.5 MeV (for testing)



Detectors

– Cooled HPGe (2.5 cm diameter) spectral resolution: 500 eV @ 122keV
– Imager (20×20 cm^2) spatial resolution: 200 μm

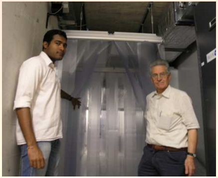


Energy range	20 keV - 15 MeV
Detector Sizes (cm):	29.5 × 36.0 × 2.2
Pixel pitch (µm)	200
Pixel Matrix	1024x1024

Detector	HPGe
Energy range	3 keV - 1 MeV
Detector Size (mm^2):	200
Sensitive Depth (mm)	5-20
ΔE(FWHM) at 122 keV (eV)	480-610

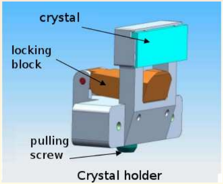
Clean room

Class 10^5, humidity stable 50%, temperature $\pm 1\ ^\circ\mathrm{C}$



Robotic device

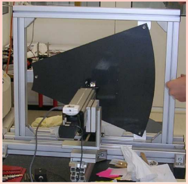
Mechanical holder for crystals alignment



The LARIX facility

Assembled/tested petal

Defined properties



Collimator

Slit collimator with four independent blades of W (20 mm thick), variable aperture and remote control

Beam-line

Vacuum environment (1–10 mbar)

Input–Output windows

Transparency: >90% @ 80 keV

The LAUE project

A focusing lens for hard X-/soft γ-rays 70 – 600 keV

Goals of the LAUE project

- Development of a technology for a massive production of crystals for diffraction, with high efficiency and desired spread ($20 \div 30$ arcsec);
- Development of a technology to assemble a large number of crystals with a positioning accuracy better than 10 arcsec;
- Development of a facility for assembling the crystals on a petal with the required accuracy and for the performance tests;
- Realization of a petal using the selected crystals;
- Feasibility study for assembling an entire lens made of petals, for space application.

Crystal selection

Selected materials

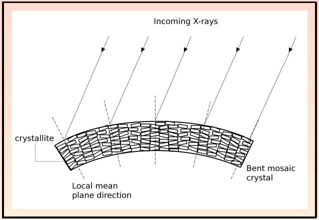
- Ge(111) perfect (bent)
- GaAs(111) mosaic (bent)

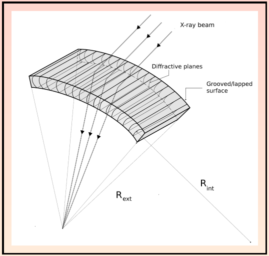
Provided by:
– Sensors and Semiconductors Laboratory (**LSS Ferrara**)
– Istituto dei Materiali per l' Elettronica ed il Magnetismo (**IMEM Parma**)

Crystals structure

Bent mosaic and bent perfect crystals

The advantages of the bent crystals with respect to the flat ones lies in the focusing capability of each single tile. The PSF of flat mosaic crystals are limited by the dimension of the tiles.





Bent mosaic crystals

The direction of the mean plane of the crystallite gaussian distribution continuously changes along the crystal.

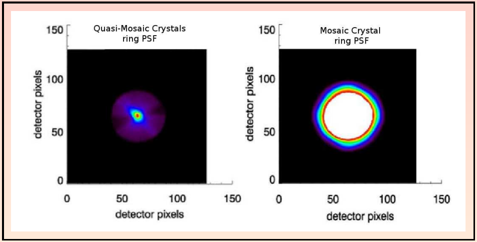
Bent perfect crystals

Surface indentations bending the tile under a certain R_{ext}, creates an internal secondary curvature, (R_{int}), which enhances the diffraction (**quasi-mosaic configuration**).

PSF simulation of a ring of crystals: ideal alignment

Quasi-mosaic crystals vs. flat mosaic crystals

Simulations with an uniform distribution of photons over each crystal in **one single ring** of the Lens @ 100 keV
Crystal size: 1.5 $\times$ 1.5 cm^2
Thickness: 0.2 cm



Quasi-mosaic crystals

peak value $\sim 1.5 \times 10^5$

Flat mosaic crystals

peak value $\sim 1.2 \times 10^4$

Enclosed photons

50% @ 5.8 mm radius from the center of the PSF for mosaic crystals
50% @ 2.2 mm for quasi-mosaic crystals

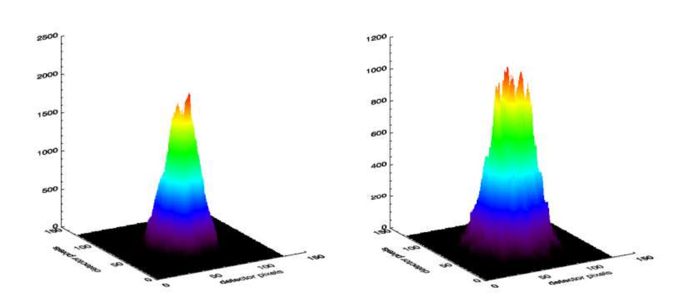
Misalignment effects

Crystal size: 1.5×1.5 cm^2

With a gaussian distribution for the misalignments:

30 arcsec $\rightarrow$ 1.3%

60 arcsec $\rightarrow$ 0.8%



Conclusions I

Technology for $>$ 15 m FL is in the final developing stage (LAUE project):

- Defined a technology for a fast and accurate alignment of the crystals;
- Assembled a facility for build/test a petal;
- Aquired the know-how to align the crystals and build a petal;
- Performed a feasibility study for assembling a Laue lens made of petals.

Conclusions II

Crystal properties

- **Developed technology for the production of a large number of crystals suitable for Laue lenses**;
- Indented (bent) Germanium can be produced with the requested curvature radius (40 m);
- **Bent crystals improve angular resolution by an order of magnitude with respect to flat crystals**;
- Bent GaAs mosaic tiles can be produced with a mosaicity as defined by the project (20 – 30 arcsec) and with the requested reflectivity.

Bibliography

- E. Virgilli, F. Frontera, V. Valsan, V. Liccardo. (Proc. SPIE 8147, 81471C (2011); doi:10.1117/12.895236);
- E. Virgilli, F. Frontera, V. Valsan, V. Liccardo. (Proc. SPIE 8147, 81471B (2011); doi:10.1117/12.895233);
- F. Frontera, G. Risaliti, E. Virgilli, V. Liccardo, V. Valsan. (Journal of Physics: Conference Series 355 (2012) 012005; doi:10.1088/1742-6596/355/1/012005);
- V. Liccardo, F. Frontera, E. Virgilli, V. Valsan. [SPIE Conference Series], Proc. SPIE 8443, (2012);
- F. Frontera, V. Liccardo, E. Virgilli, V. Valsan, V. Carassiti, S. Chiozzi, F. Evangelisti, S. Sqerzanti, M. Statera [SPIE Conference Series], Proc. SPIE 8443, (2012);
- V. Valsan, E. Virgilli, V. Liccardo, F. Frontera. [SPIE Conference Series], Proc. SPIE 8443, (2012)

Profound and heartfelt thanks to all.