A Laue-Pie in the Sky
- is it really worth the hazzle ?

Niels Lund
Danish National Space Center

….. this is not what I promised – but this is what you get!

DANISH NATIONAL SPACE CENTER

Laue-lenses – some basic problems:

- Is the Astrophysics of the 200 keV to 2 MeV energy band exciting? Yes!

  Are there enough point sources within reach? Yes!

- To be interesting for the community (and for a review committee) the lens must cover a wide energy range, and it must be ”affordable”.
  Are our designs realistic?
  Can we live with the constraints of a medium size launcher (Soyuz)?

- Laue-telescopes observes only one object at a time!
  The focal length may be more than 100 m! How do we repoint to a new target?

- Is the effective area of an affordable lens really worth all the hazzle?

Affordability: – take the Soyuz constraints

- Assumption: We take a formation flying concept with a lens spacecraft and a detector spacecraft. The focal length can then be chosen freely.

- However, precision formation flying for hours or even days cannot be done close to the Earth (because of the gravity gradient effects). We shall assume that our Laue-telescope will operate at one of the Lagrange points.

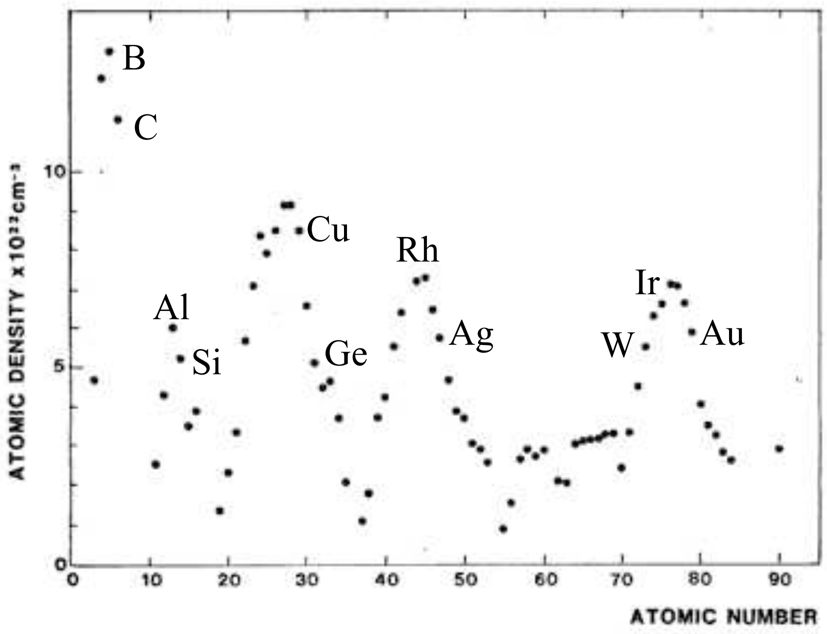
- Soyuz can take about 1700 kg to the L2 point. The Soyuz fairing can accept a spacecraft of maximum 3.8 m diameter (stowed).

- We shall assume a Laue-lens with 150 m focal length. If copper crystals are used for the lens, the crystal ring which focuses 511 keV will be situated at a radius of 174 cm (for the 111-reflection). Once the focal length is chosen Braggs law and the Soyuz constraints drives most of the remaining design.

150 m Laue-Telescope – design options

Energy range: 200 keV to 1000 keV selected initially. Emphasis on 511 keV, but a continous coverage from 200 keV to 1000 keV should be aimed for.

Choice of crystal material: Only pure metal crystals are considered. To achieve the best telescope sensitivity we must emphasize high specific reflectivity. This is correlated with a high atomic density in the material of the crystal. (Lund, 1992 – copies available).



Atomic density of the elements

Note: With the choice of a 150 m focal length the full lens will not fit into the Soyuz shroud. The radius of the ring reflecting at 200 keV will be about 450 cm so a fancy deployment mechanism will be required. I will come back to this.

First try:
A fully filled Laue lens covering 200 to 1000 keV

When the focal length is decided Braggs law specifies precisely the energy for which each crystal ring in the lens must be tuned.

Once we decide on the crystal material we can calculate what thickness will give the highest reflectivity for a given Miller index choice.

We normally get the highest reflectivity for that reflection which give the smallest Bragg angle*).

It is also important to decide on the size of the focal spot. I this study I have assumed the detector to be a conventional high purity Ge detector with 6 cm diameter. 6 cm is then also the goal for the focal spot diameter.

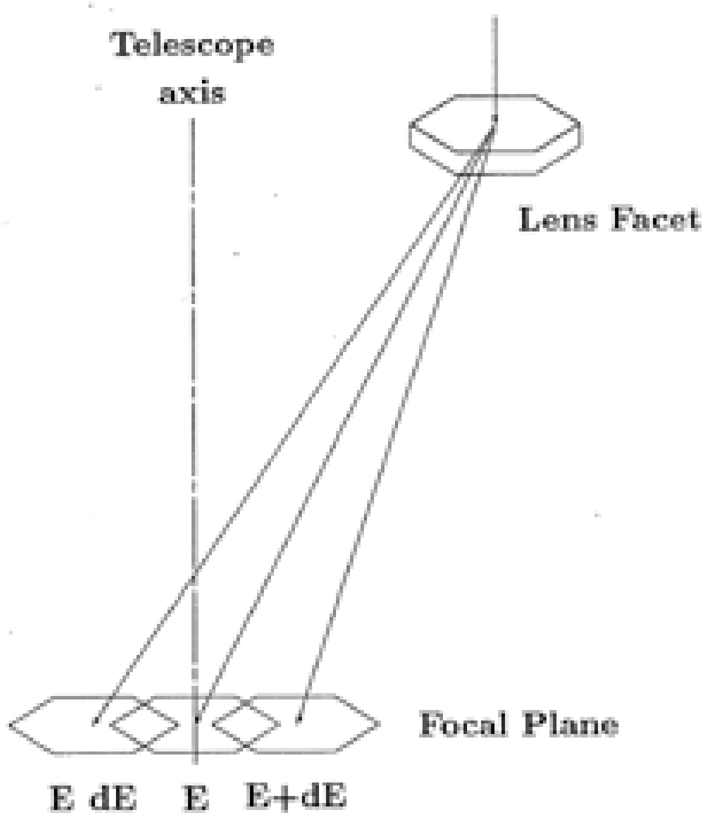
*) The diamond structure is an exception here because only half of the atoms in the crystal contribute at the lowest Bragg angle (the 111-reflection). For the diamond structure the 200-reflection is actually the strongest.

The mosaic width – a key parameter

The mosaic width of the crystals is a critical parameter.

A large mosaicity means a large integrated reflectivity of the crystals.
But a large mosaicity also means a serious mosaic defocusing. This implies a degraded signal to noise ratio at the detector end.

The mosaic width should be chosen as large as possible consistent with the amount of mosaic defocusing we can tolerate! With a focal length of 150 m a mosaic width of 1 arcminute will broaden the exit beams from the crystal by 4 cm at the detector. This is still acceptable, but only just!



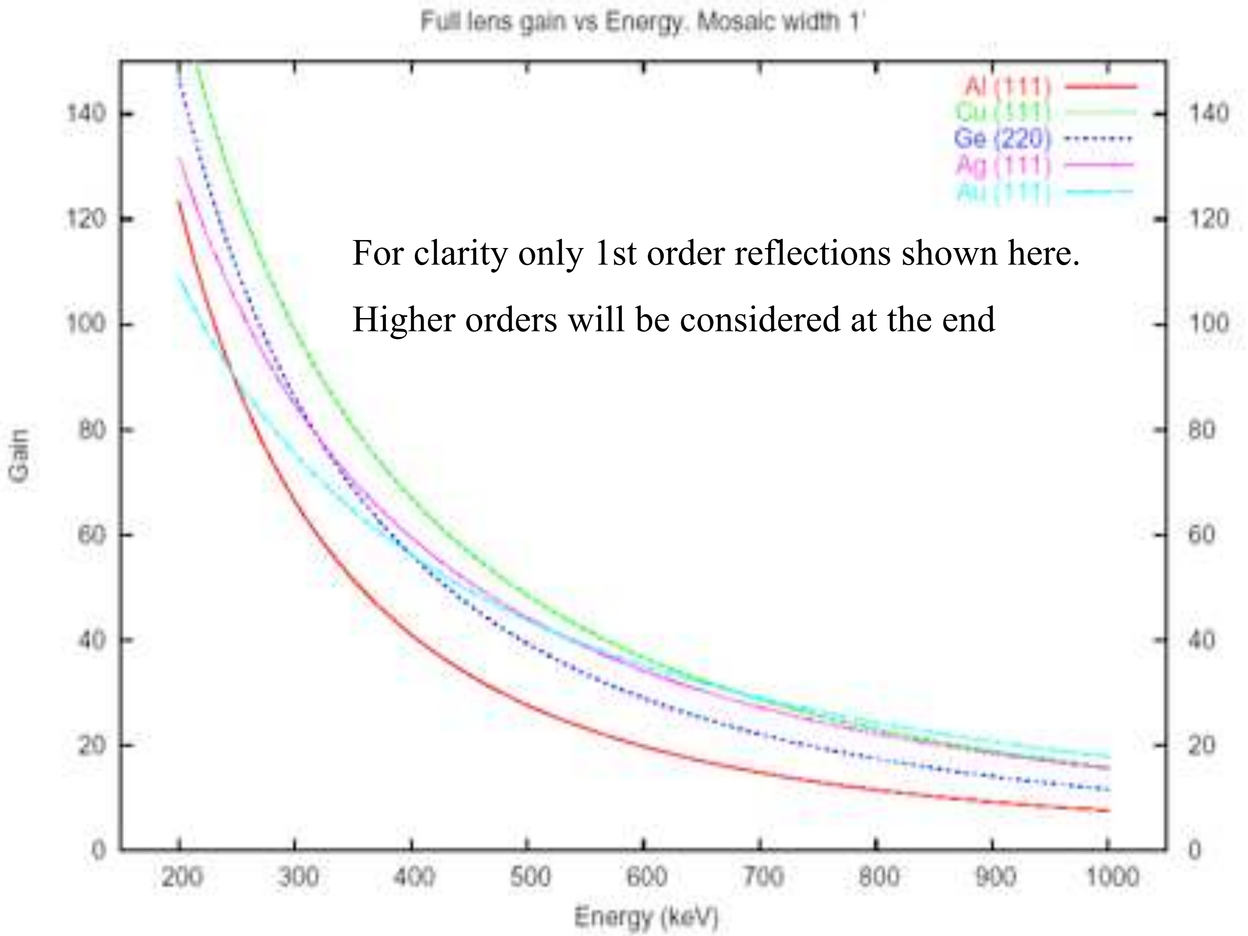
Mosaic defocusing

Lens Reflectivity. Looks good!

All crystal types give enormous gains at 200 keV

The ”gain” is a convenient shorthand for the factor by which the lens amplifies the signal on a ”standard” Ge-detector of 30 cm^2 surface area.

A lens with a gain of 100 (3000 cm^2 effective area) would compete favorably with a SPI type instrument with 10^4 detectors.

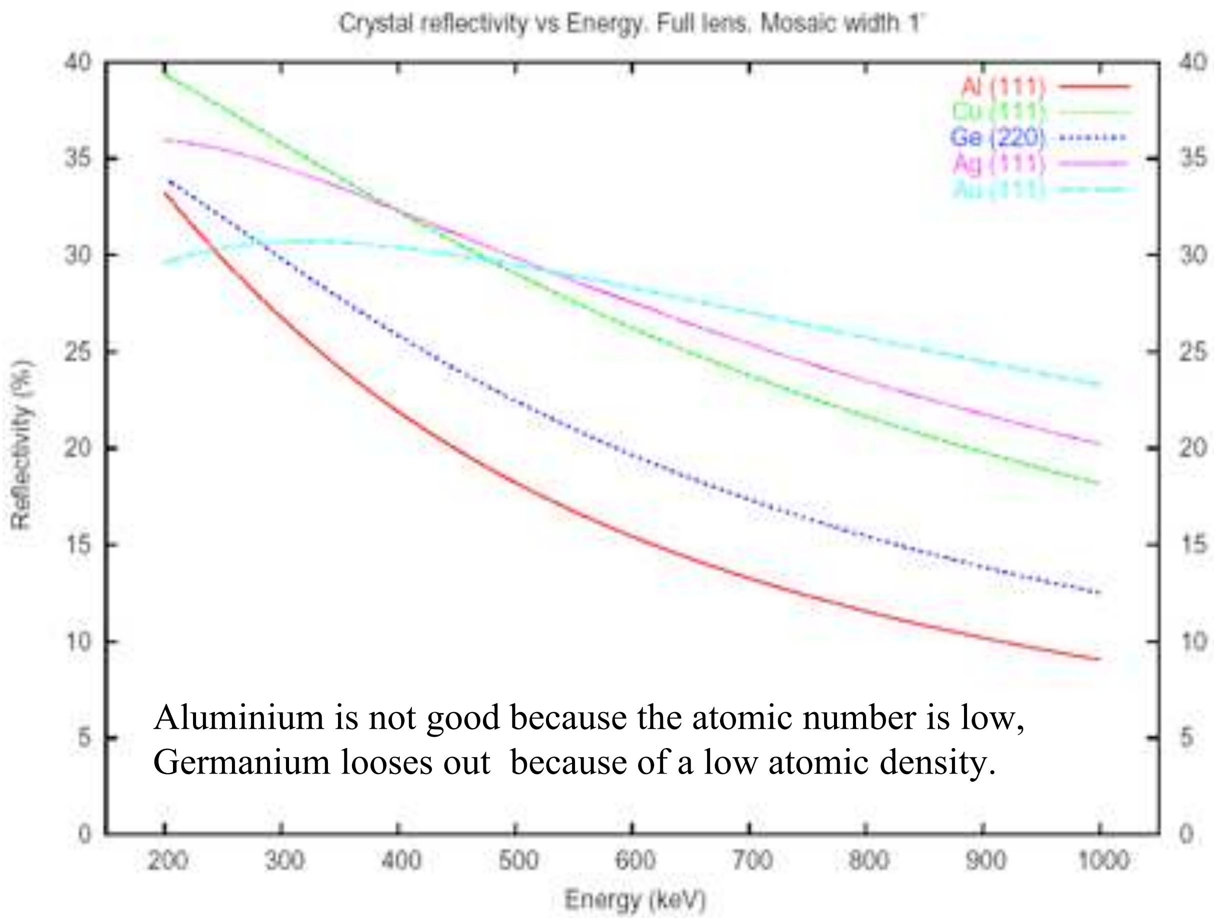


Crystal reflectivity as function of energy

The general rule is that the reflectivity increases with increasing atomic number.

But at low energies the photoelectric absorbtion increases much more rapidly than the reflectivity.

This is why copper is preferable to silver or gold for energies below 400 keV.

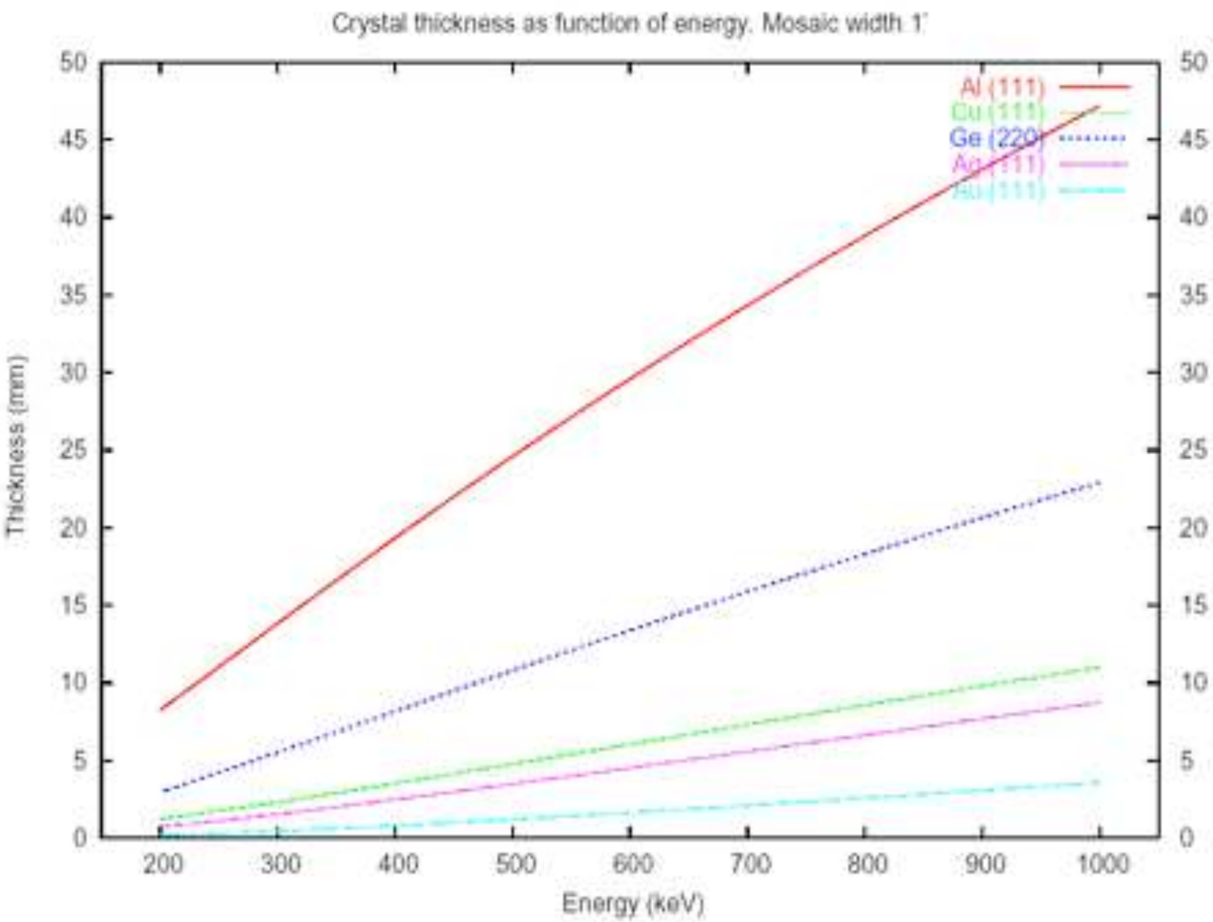


Optimal crystal thickness vs. Energy

The crystal thickness which maximizes the reflectivity is roughly proportional to the energy and inversely proportional to the density of the crystal.

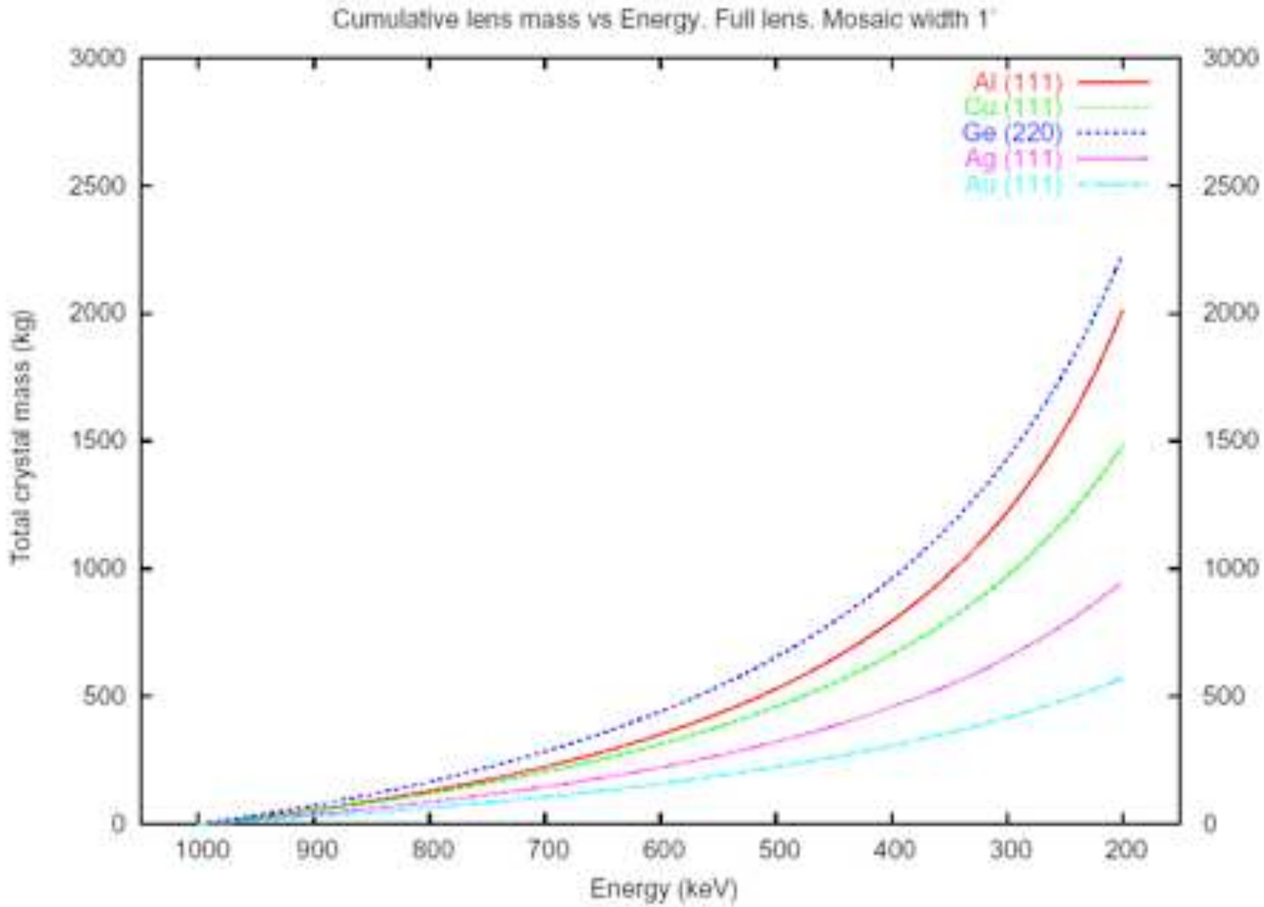
The optimal crystal thickness also depends on the width of the mosaic distribution.

In this study we have fixed the width to 1 arcminute.



But: bad luck! All the lenses are much too heavy!

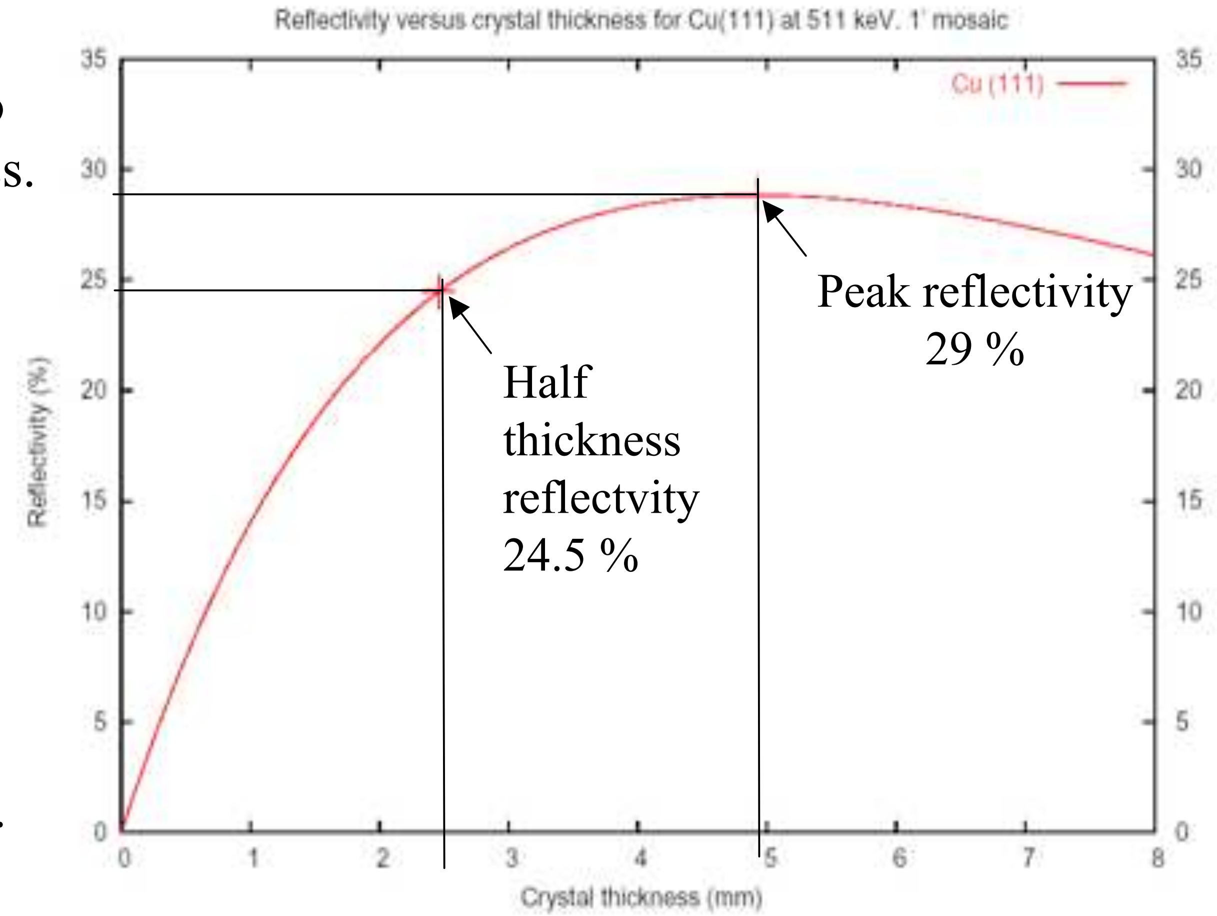
The model lenses does not fit within the Soyuz mass constraint. We must find ways to reduce the weight.



What is the ”optimal” crystal thickness ?

The first lens design used the maximum reflectivity to define an optimum thickness. But that is very costly regarding the mass of the crystals.

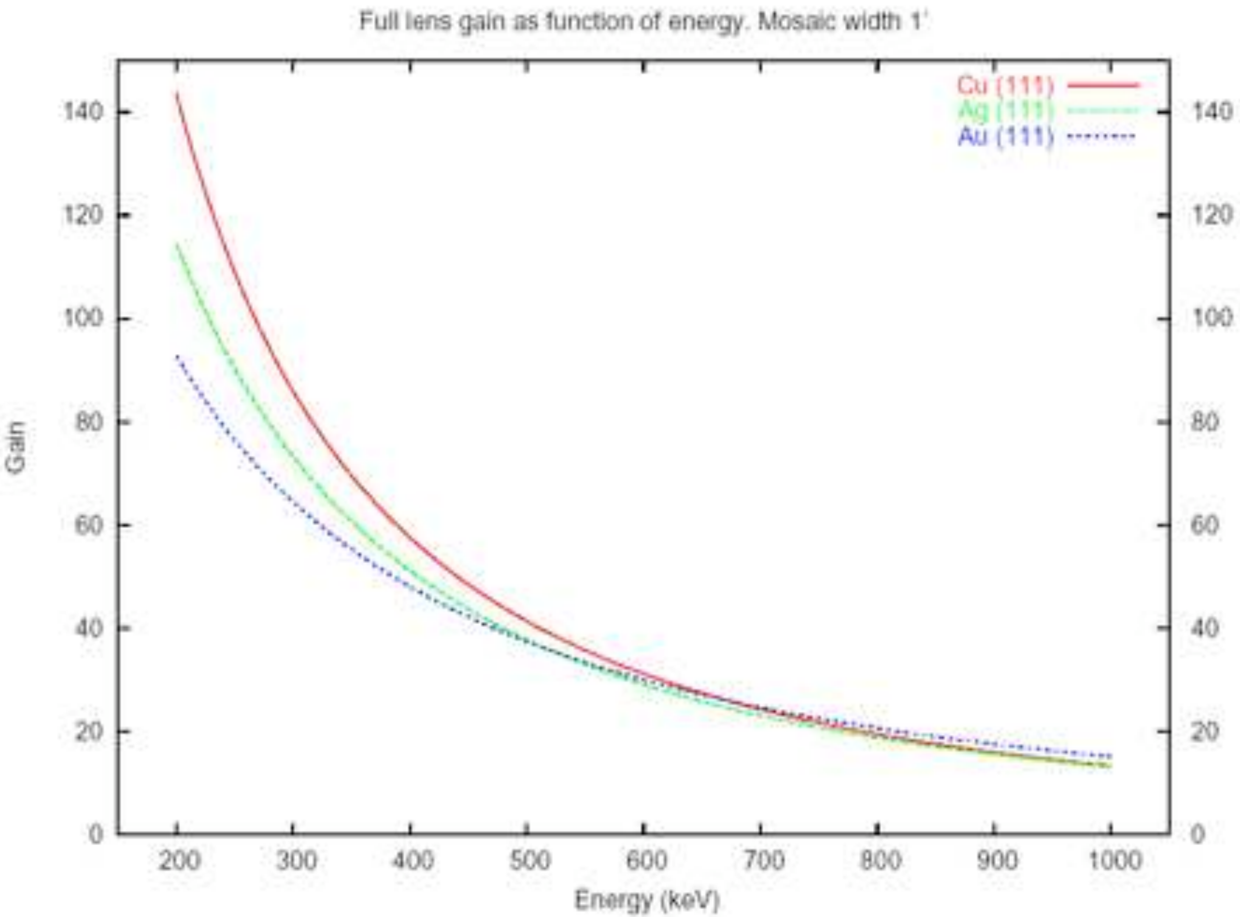
Reducing the thickness by a factor two from the peak reflectivity value only reduces the reflectivity by about 15%. We accept this loss in order to save weight.



Gain of lens with all crystal thicknesses cut into half

The gain is still very impressive at low energies.

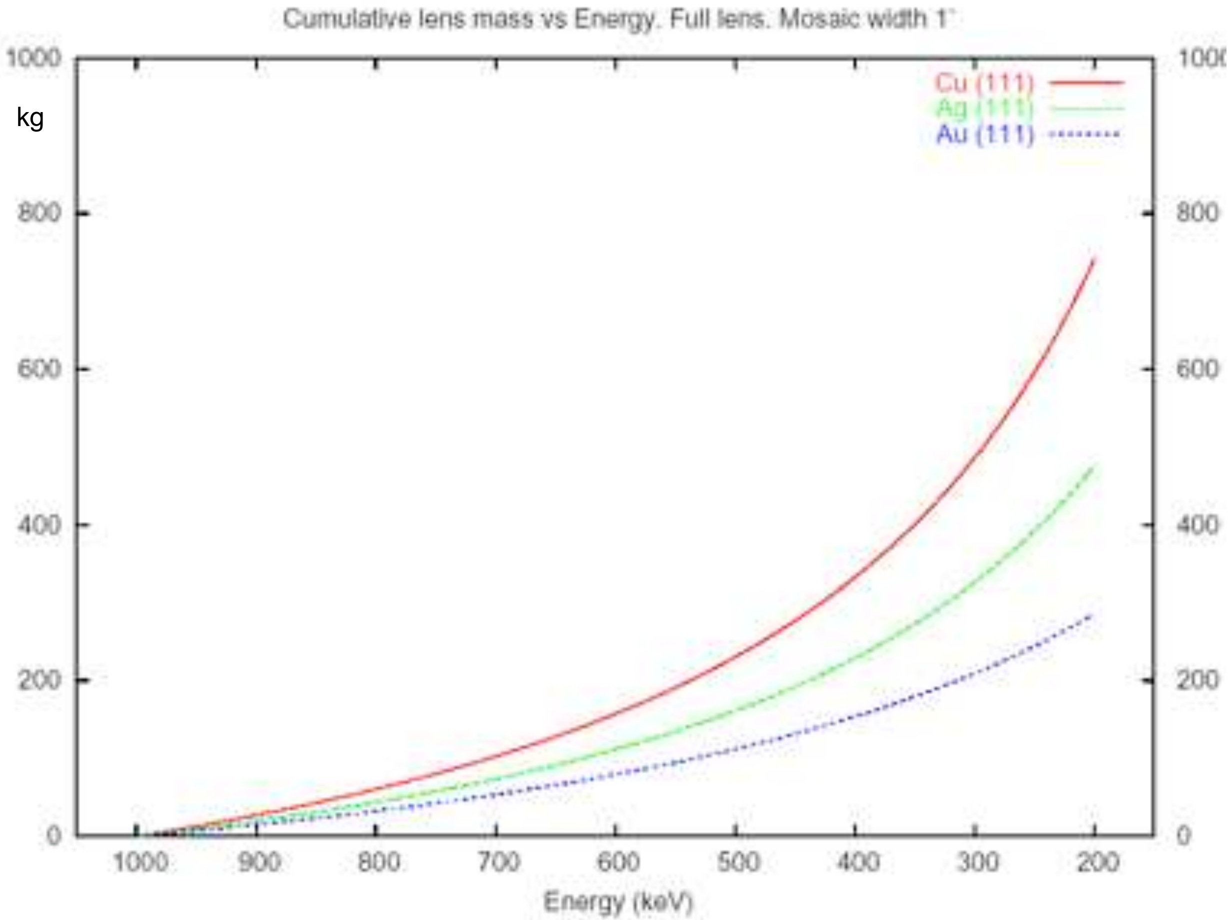
Copper is the best choice up to 650 keV!



Mass of lenses with reduced thickness

The lenses with gold and silver crystals are now in the acceptable weight range.

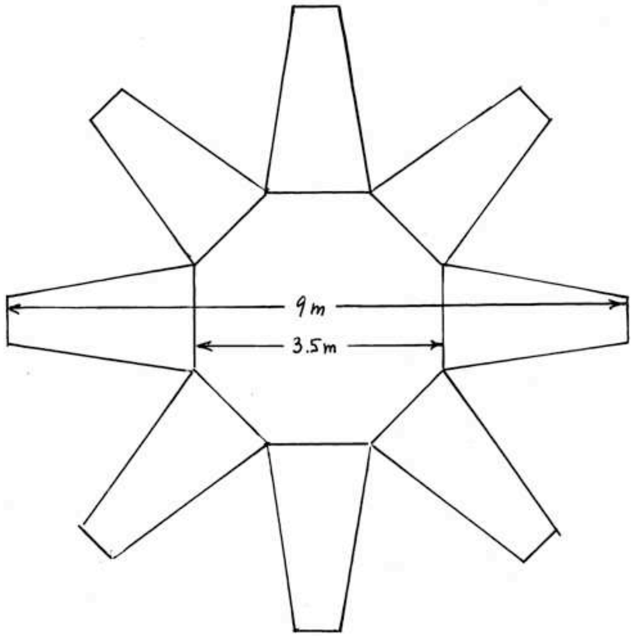
But since copper is a lot less expensive and also very efficient at low energies we shall pursue further the weight saving attempts on the copper lens.



How to save weight and to make lens easy to deploy ?

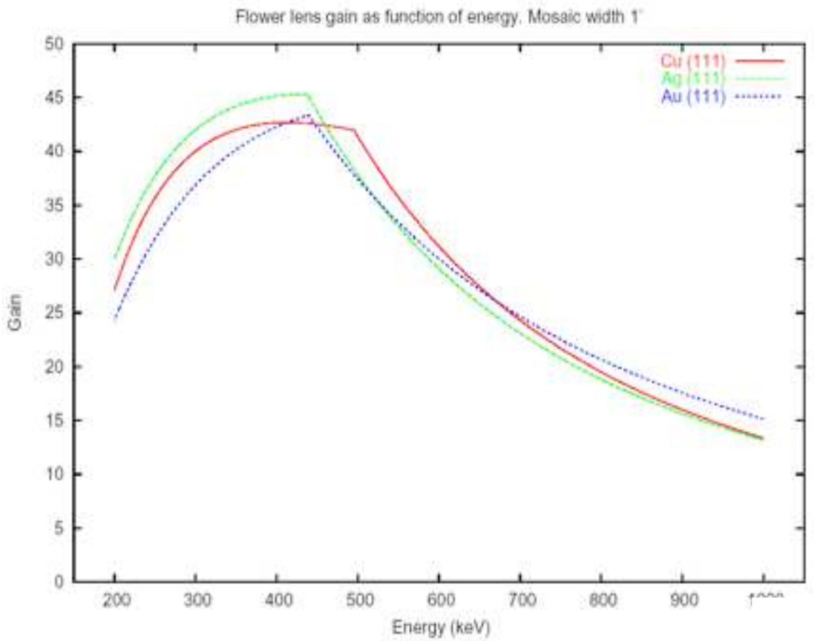
The lens simulations with a full, circular lens have resulted in lenses with a collection power which rises sharply at the lowest energies. But the prime scientific interest lies in the energy range upwards of 500 keV.

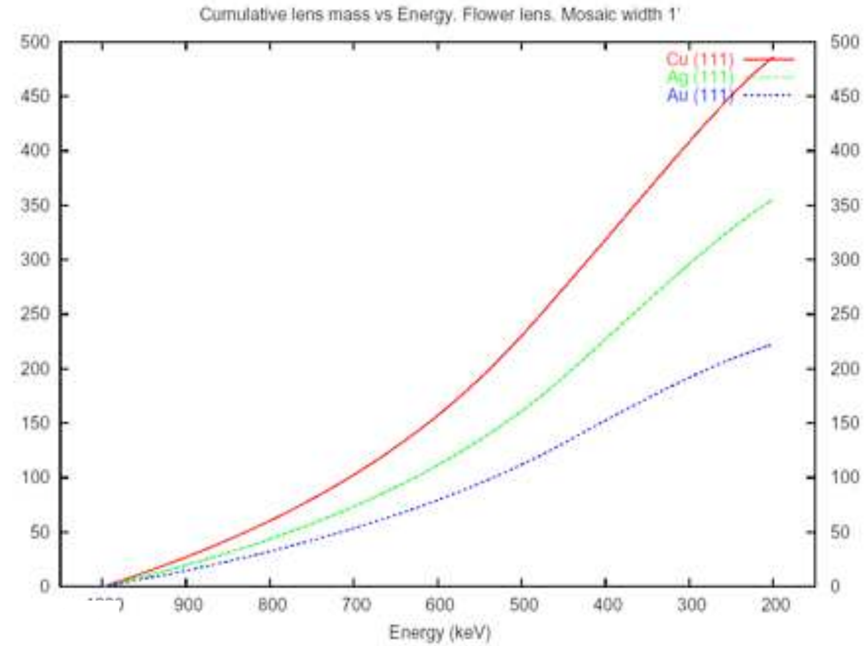
In order to save weight we must reduce the surface area of the lens at radii beyond that corresponding to 511 keV. The lens then take the shape of a ”flower” with triangular petals. During launch the flower petals can simply be folded up to fit inside the rocket fairing. The flower will be launched as a ”bud” and blossom in space!

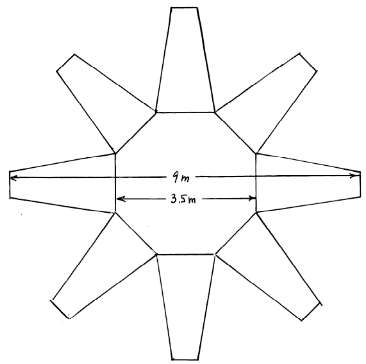


DANISH NATIONAL SPACE CENTER

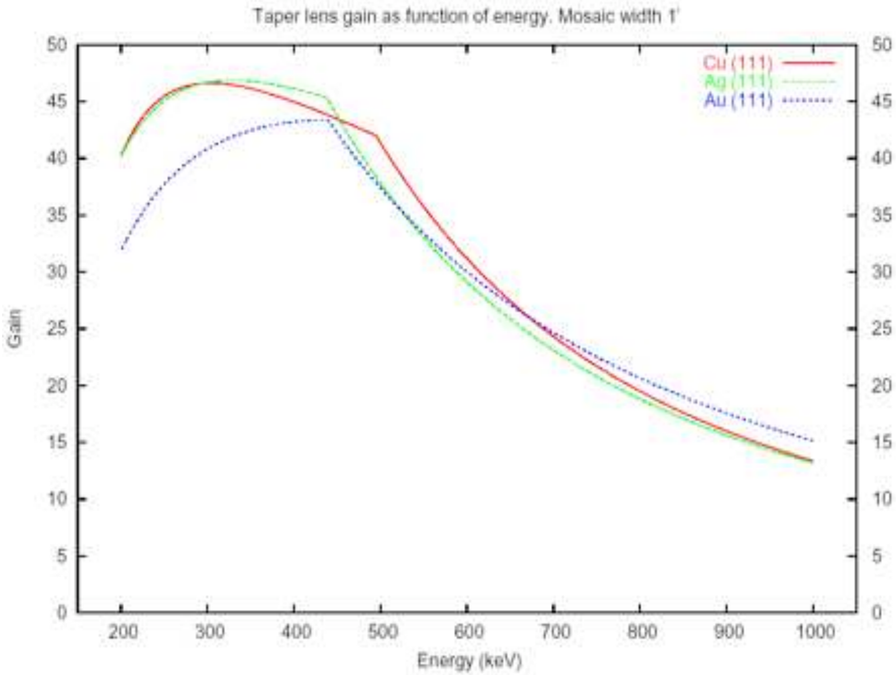
Gain vs Energy and Weight of a flower lens

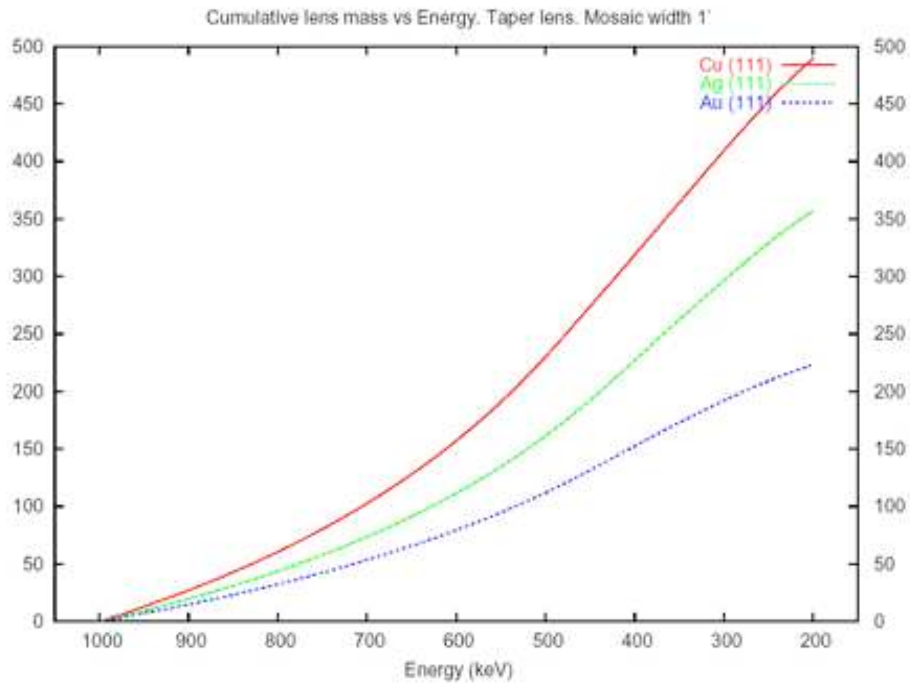


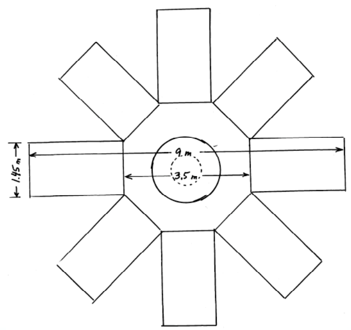




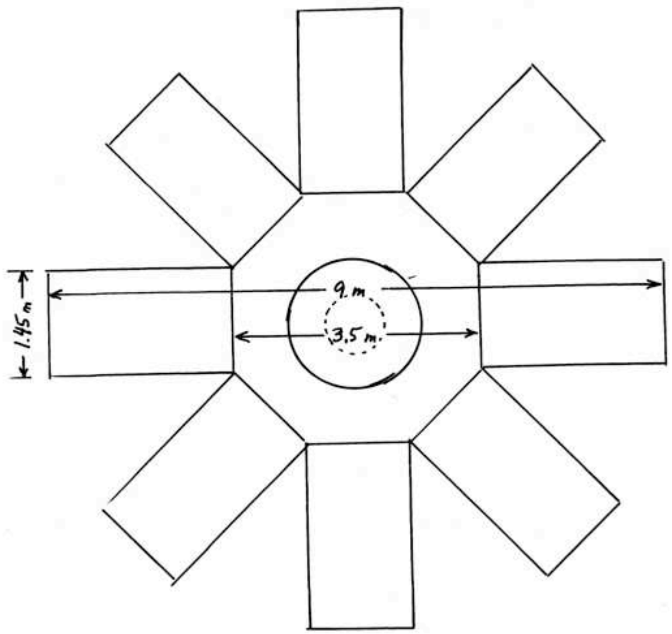
A better design: Rectangular petals with tapered thickness

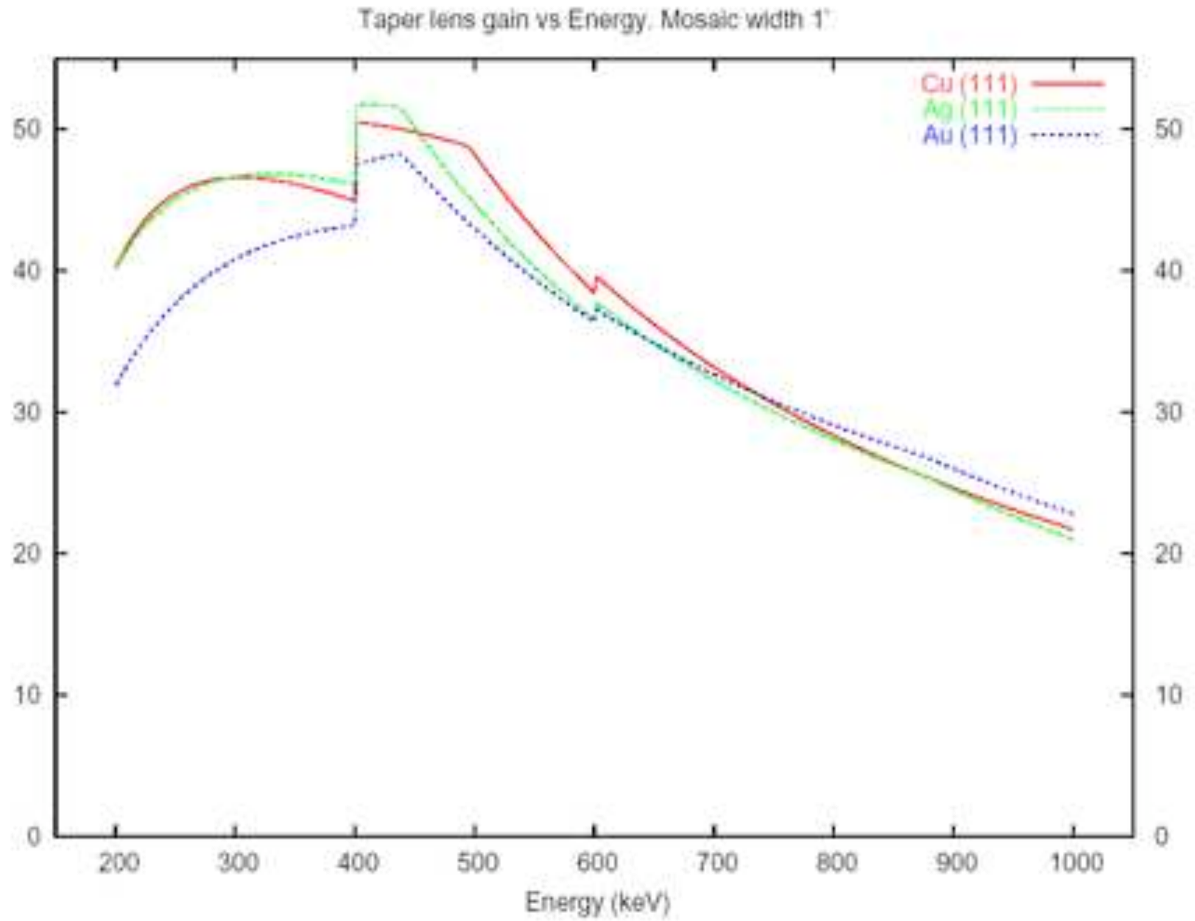






Gain vs Energy for a thickness tapered lens,
2.nd and 3.rd order included

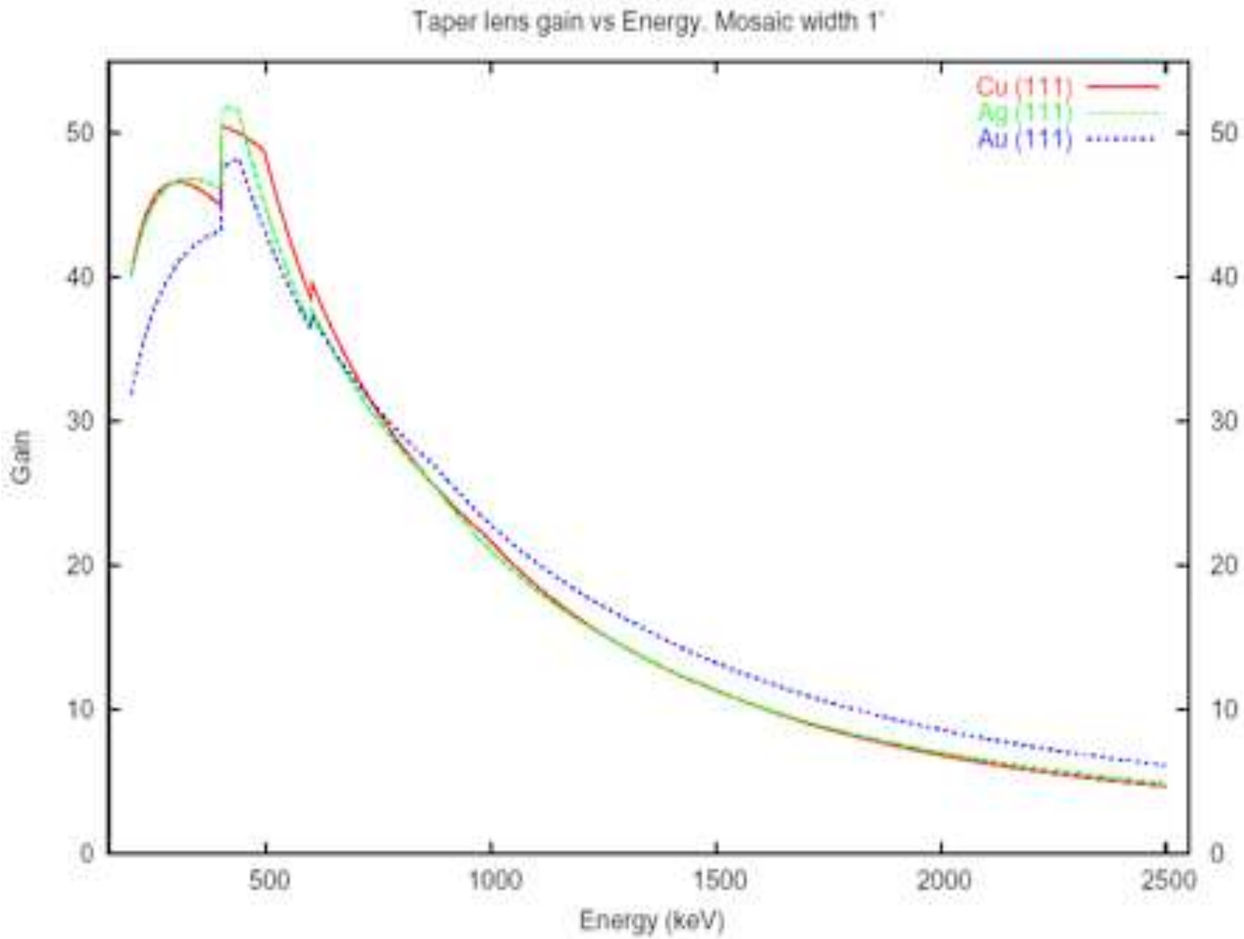




Can we extend the energy range to higher energies?

It is tempting to see how far up in energy we can push a Laue lens of these geometric dimensions.

The figure shows the response of a lens with crystal rings at small radii corresponding to energies up to 2.5 MeV.

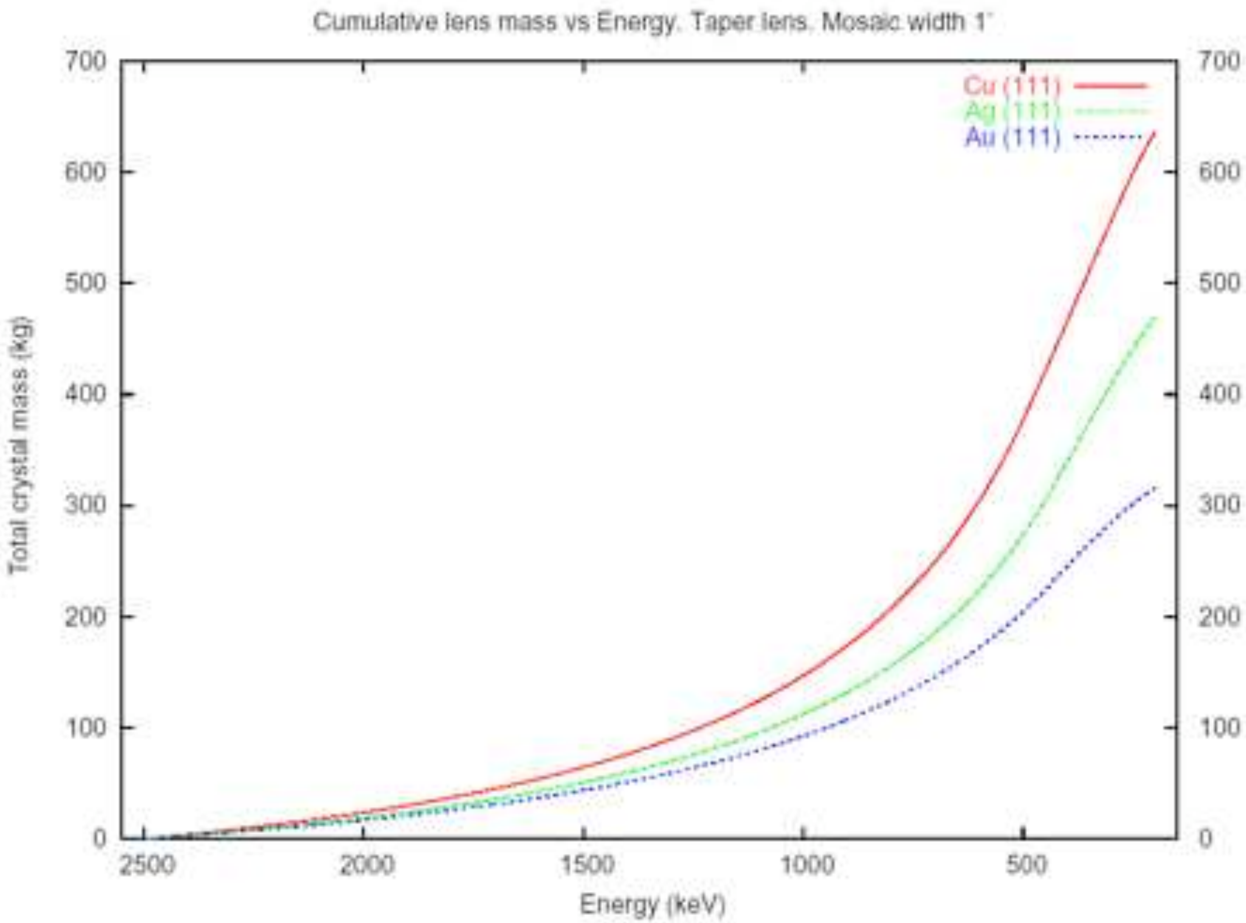


Mass penalty for the high energy response

The mass penalty for a copper lens is 150 kg which may be acceptable with an upgraded Soyuz which is already under development.

The silver and gold lenses are still under our tentative 500 kg mass limit.

A combined copper-gold lens (500 kg Cu + 80 kg Au) would be ideal.



Summary of the lens study

- We have shown that the laws of physics allows to build a Laue-lens which geometrically can be fitted inside a Soyuz fairing and which theoretically could provide a lens gain of about 50 (1500 cm^2 effective area) around 511 keV and a gain of more than 20 (600 cm^2) over the energy range between 200 keV and 1 MeV.
- Even allowing for the losses inevitably involved when going from a theoretical design to a practical design the prospects for dong competitive science with a Laue lens look very promising.

What is needed to move forward?

- We need to move the production of high quality copper crystals from a research laboratory phase to an ”industrial” phase.
- Correspondingly we need to develop mass production techniques for the crystal characterization and quality control.
- Mounting and handling of thousands of thin (0.5 mm) Copper crystals will be difficult process which also need tecnical development.

- There is quite some work ahead!

DANISH NATIONAL SPACE CENTER

– and now to something entirely different:

How to repoint a 150 m telescope ?

Observation times will typically be a day or two.

The repointing a two satellite formation to a new target will be slow – or it will require a lot of fuel.

A three satellite configuration with one heavy lens spacecraft containing most of the support systems and two (very!) light detector spacecraft may solve that bottleneck which otherwise may result in a loss of a substatial fraction of the observation time.

One detector spacecraft can be slowly maneuvered to prepare for the next observation while the current observation is ongoing.

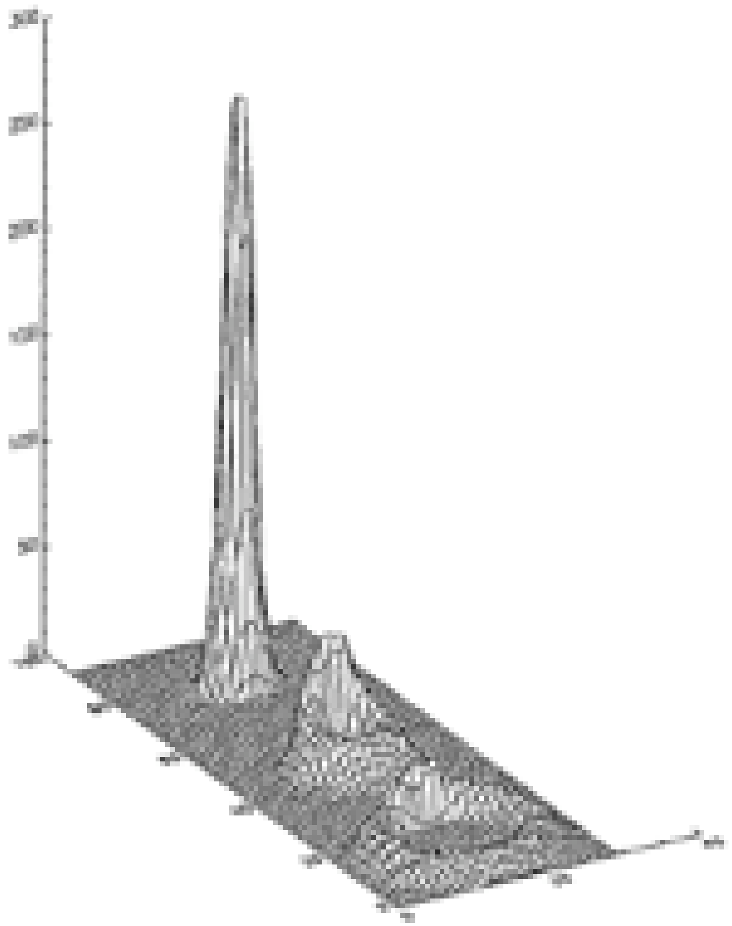
It is then only required to reorient the lens spacecraft to commence a new observation.

In addition to increase significantly the efficiency of the operations and providing redundancy in the detector element of the mission the second detector spacecraft may provide additional information on background variations.

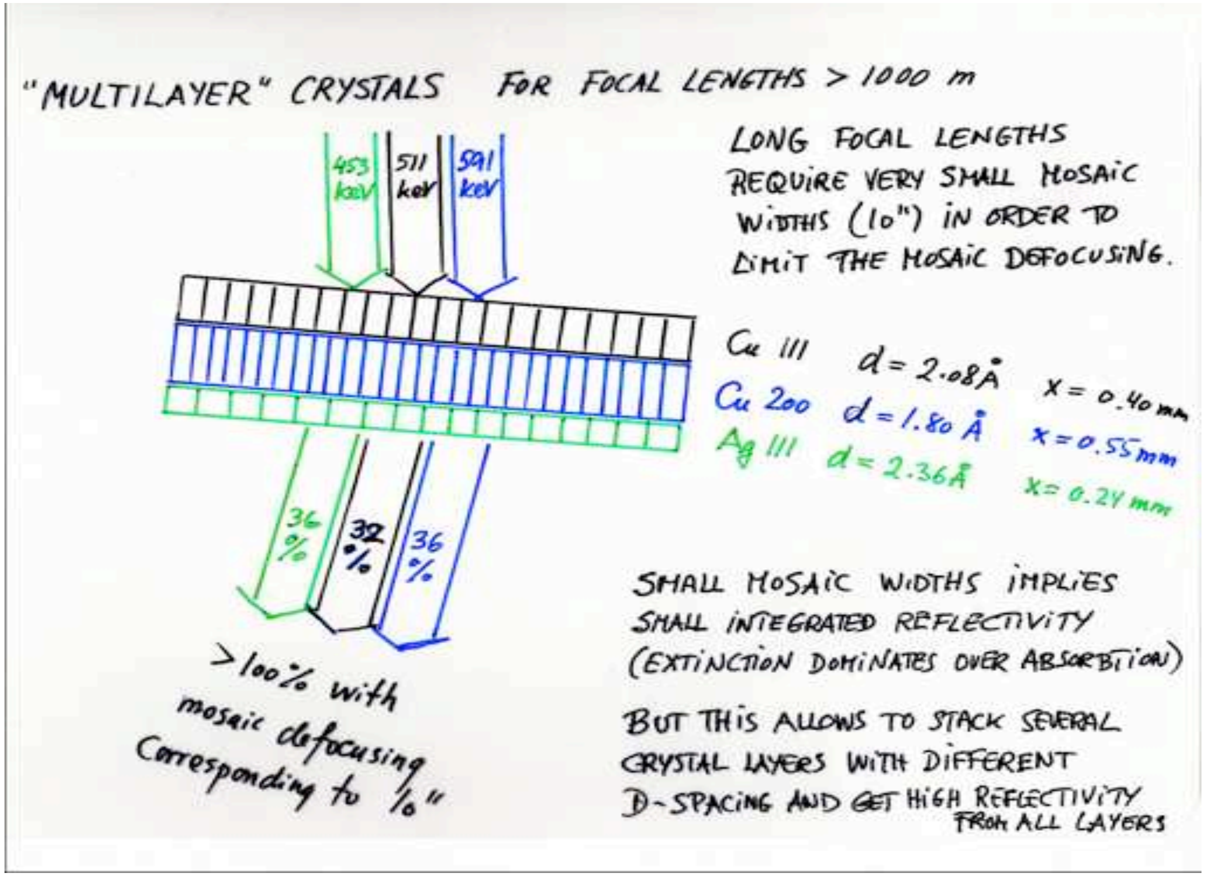
Finally: my 2 cents on imaging:

Imaging using a Laue lens is possible using the off-axis response described in previous lectures. However, since all off-axis sources are imaged as rings around a common center the ”contrast” between sources in different positions is rather low.

I suspect that a 1-dimensional Laue lens could do better over a limited field, but this idea will need to be worked on – for the next wokshop maybe?



How to fight mosaic defocusing for >1000 m focal lengths



Obviously, this is an expensive way to go !

But the laws of physics allow it !