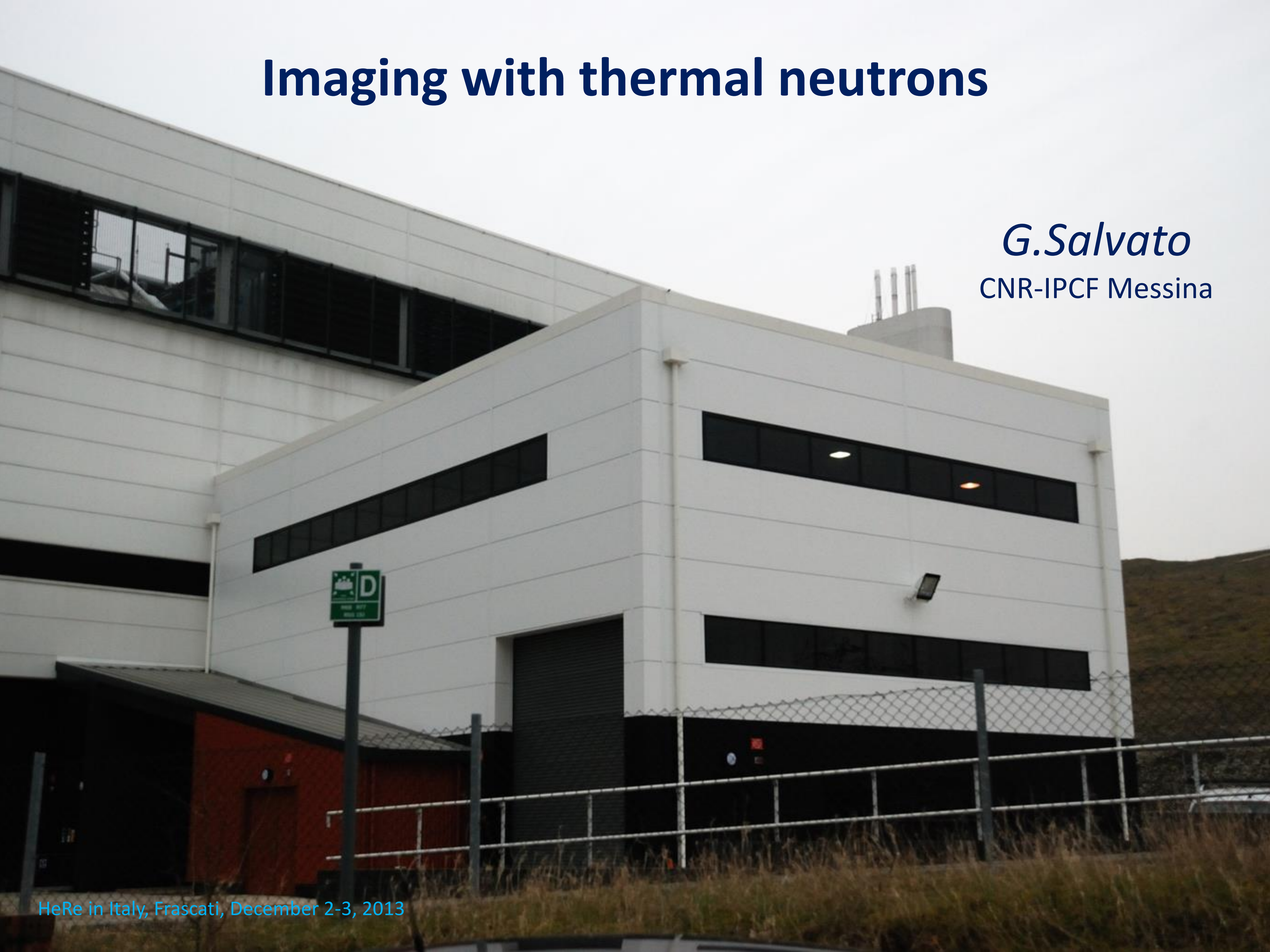
# Imaging with thermal neutrons

*G.Salvato*
CNR-IPCF Messina

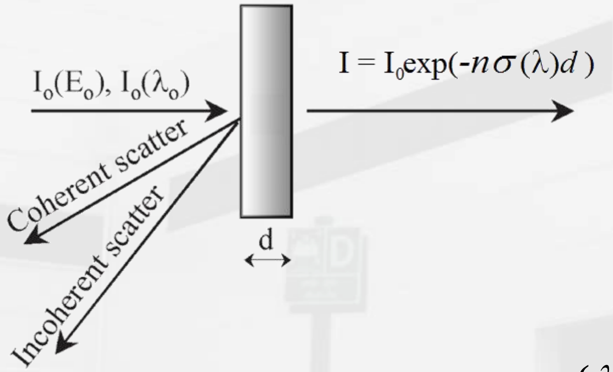


# Why use Neutron Imaging

- ✓ Allows to look, ***non destructively***, inside objects (fundamental for cultural heritage investigations)
- ✓ Gives ***complementary information*** to that obtained from ***X-rays*** (neutrons interact with nuclei instead of electronic shells)
- ✓ ***Deep penetration inside samples*** allows to look past coatings and corrosion layers (neutrons penetrate easily through lead)
- ✓ ***High sensitivity for some light elements*** (e.g. hydrogen)
- ✓ ***Contrast enhancement by means of energy selective imaging*** (Bragg-edge)
- ✓ Of ***aid for the neutron diffraction*** (scattering volume selection)

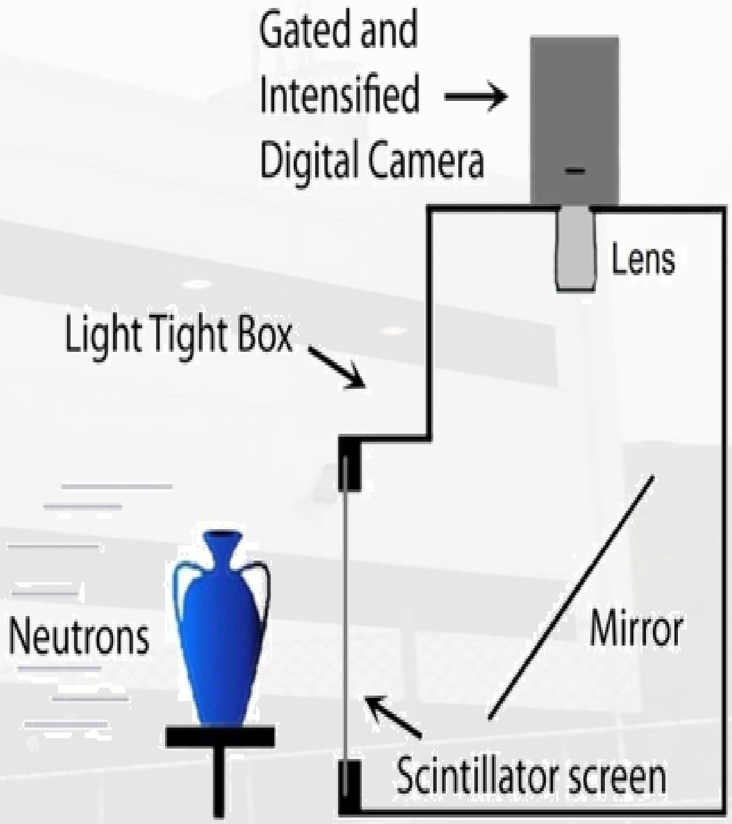
# How Neutron Imaging is done?

The transmission of a **neutron beam** through the matter is described by the ***Lambert-Beer law***:




$$I(\lambda) = I_0(\lambda)e^{-n\sigma(\lambda)d}$$

***n*** *: scattering center number.*
***σ(λ)*** *: total cross-section per scattering center.*



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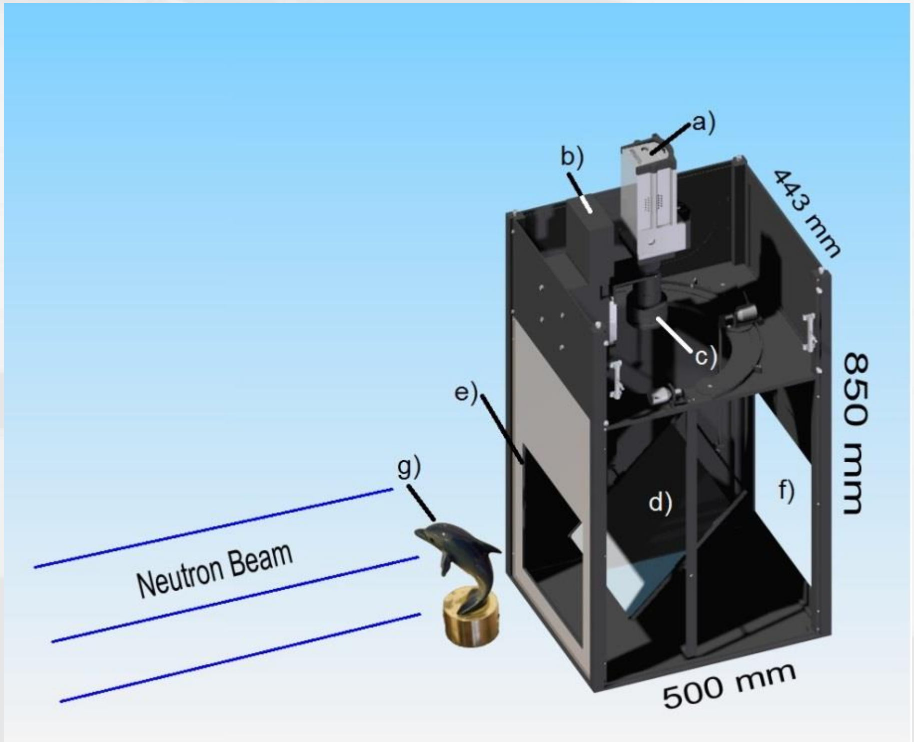
# How Neutron Imaging is done?




a) CCD Camera;
b) Lens positioning linear stage;
c) Lens;
d) Mirror;
e) Front window (for placing scintillator screen, not shown);
f) Rear window (removed);
g) Sample

# From Neutrons to Photons

Most used scintillators are made by a mix of finely grounded powders of ***$^{6}$LiF*** and ***ZnS:Ag*** *or* ***ZnS:Cu*** mixed with an organic binder and deposited on a thin ***Al*** foil.

$$n + {}^{6}\mathbf{Li} \rightarrow {}^{4}He(+2.05MeV) + {}^{3}H(+2.73MeV) \qquad \boxed{\sigma = 520\ \mathrm{b}}$$

The ranges of ***Triton*** and ***α*** particles are about ***30 μm*** and ***5 μm*** respectively[1].

When the particles interact with the ***ZnS*** phosphor produce about ***160.000 photons per neutron*** [2].


[1] T.K. McKnight Master Thesis - Dep. Of Physics and Astronomy – Brigham Young University (2005)
[2] C.W.E. van Eijk Nucl. Instr. And Meth. A **477** 383 (2002)

# From Neutrons to Photons

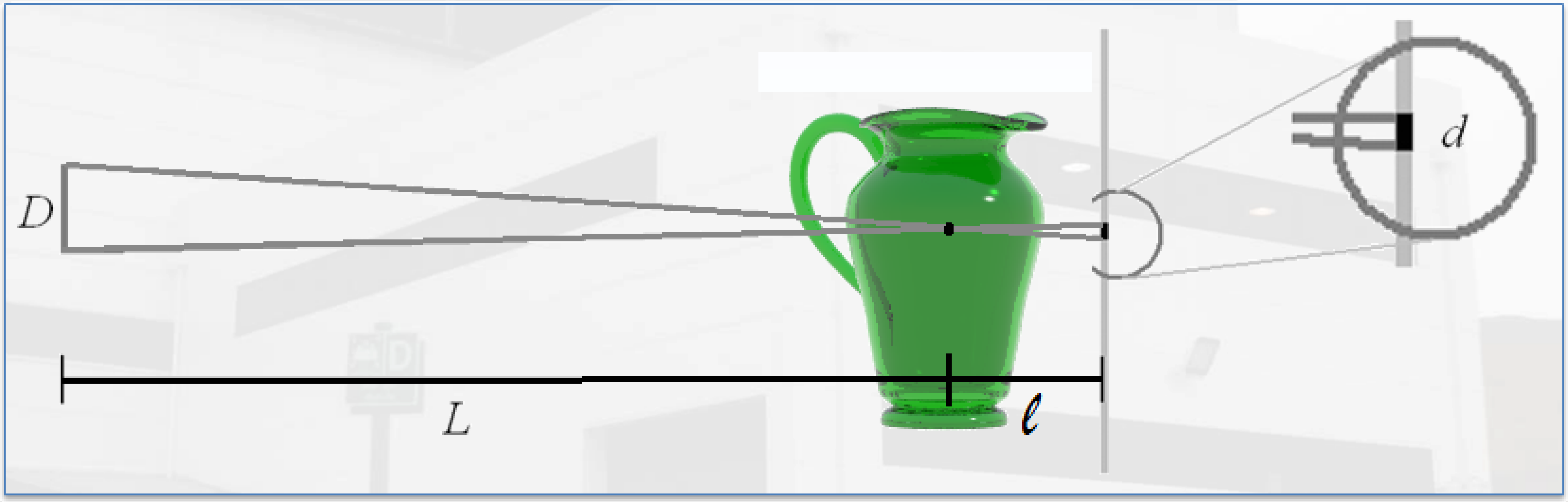
Because of the interaction range of the secondary particles within the scintillator, the light can be produced in a position different from the point of the neutron interaction ***limiting the spatial resolution***.

**The thinner is the scintillator the better is the spatial resolution.**

**But...**

**The thinner is the scintillator the lesser is the light emitted.**

# Neutron sources are NOT point-like ones




$$d = \ell \frac{D}{L} = \frac{\ell}{L/D}$$

D = neutron source dimension

L = source-sample distance

$\ell$ = sample-scintillator distance

# Progetto PANAREA

***P*** *rogetto per l'*
***A*** *pplicazione dei*
***N*** *eutroni*
***A*** *lla*
***R*** *icerca in*
***E*** *lettronica e*
***A*** *rcheometria*

***Italian Institutions Involved:***

- **UNIMIB** Prof. ***G. Gorini***
- **CNR-IPCF** Ing. ***G. Salvato***
- **CNR-ISC** Dr. ***M. Zoppi***
- **UNITOV** Prof. ***C. Andreani***

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# Imaging and MATerials

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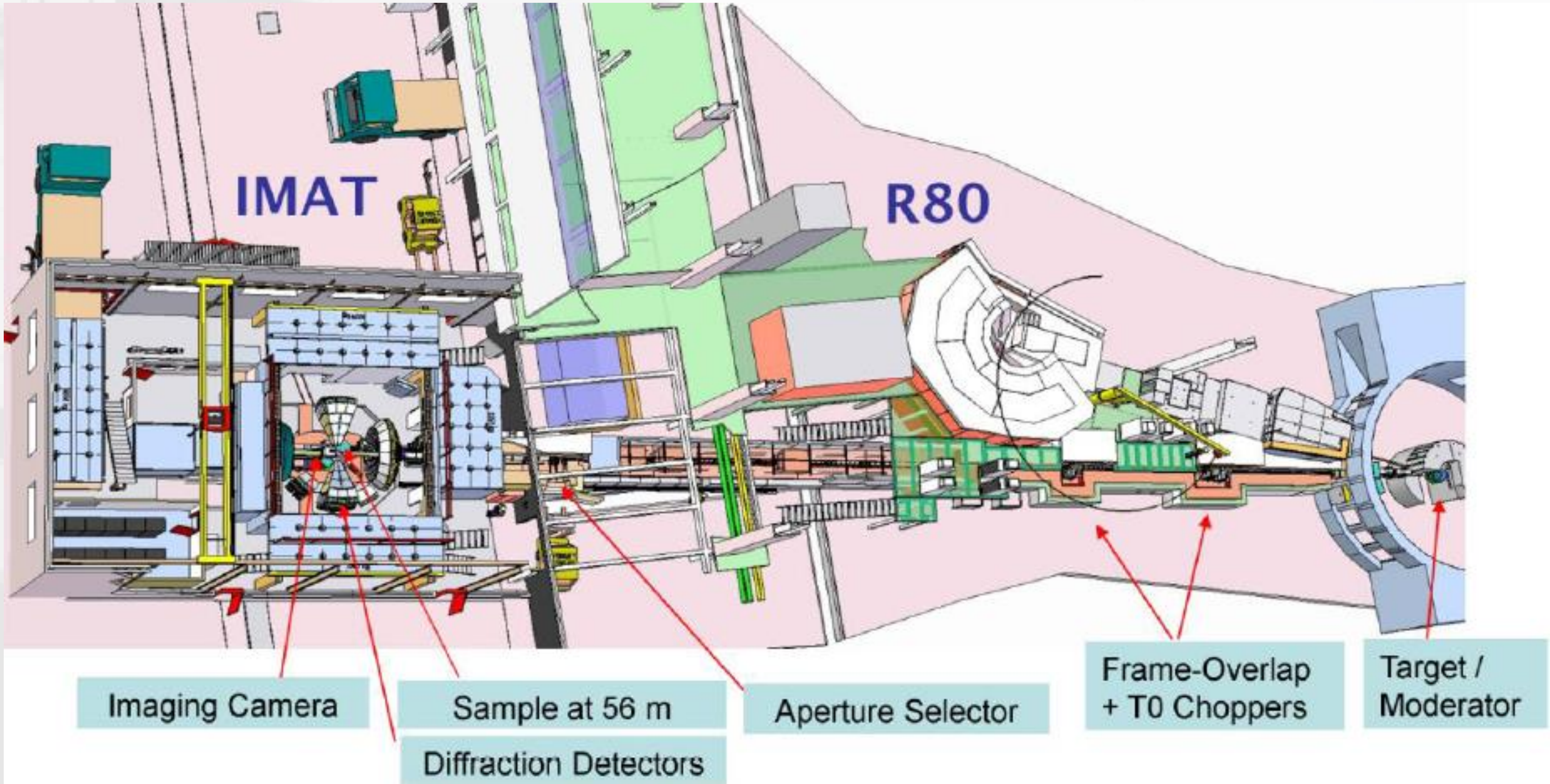

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# IMAT

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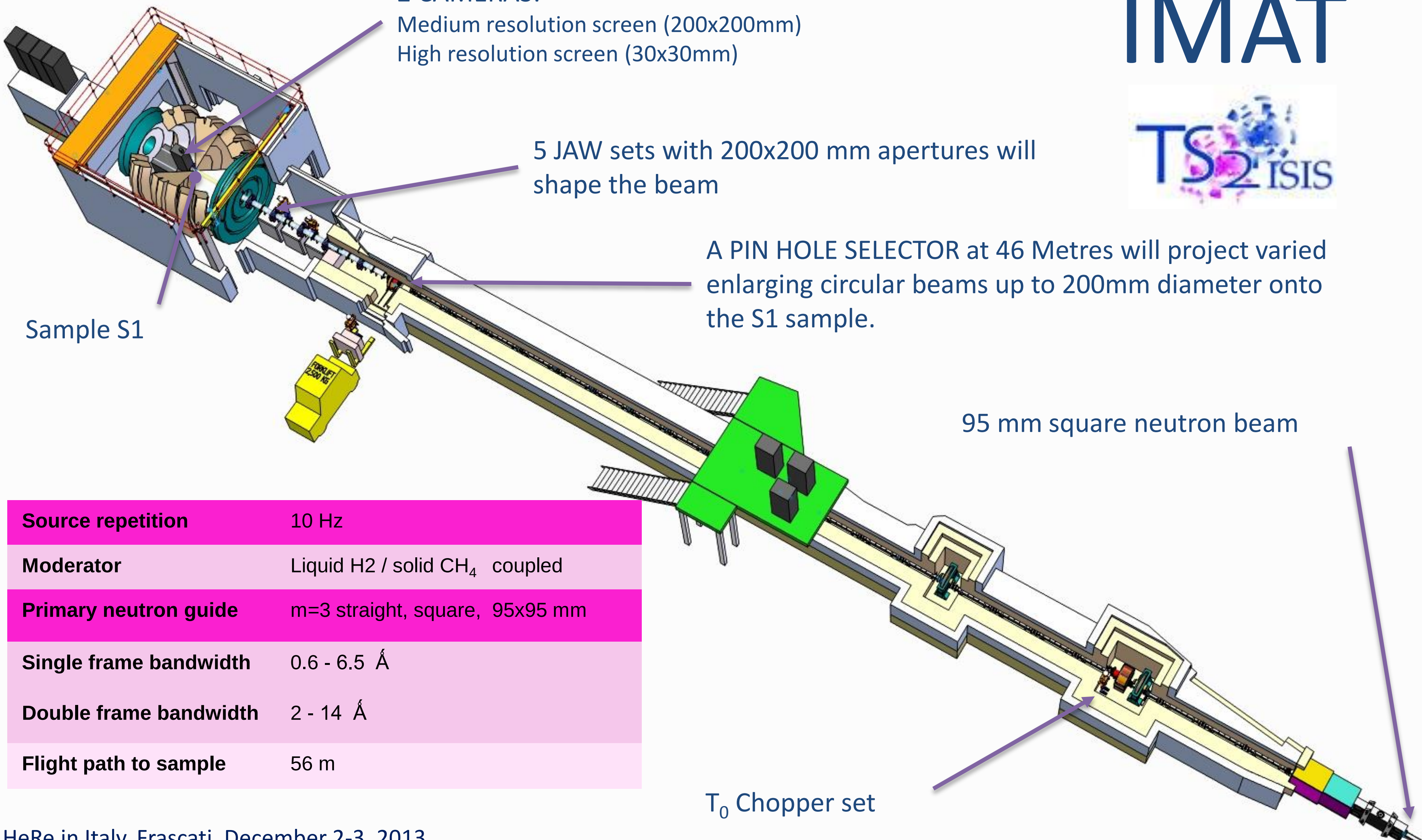
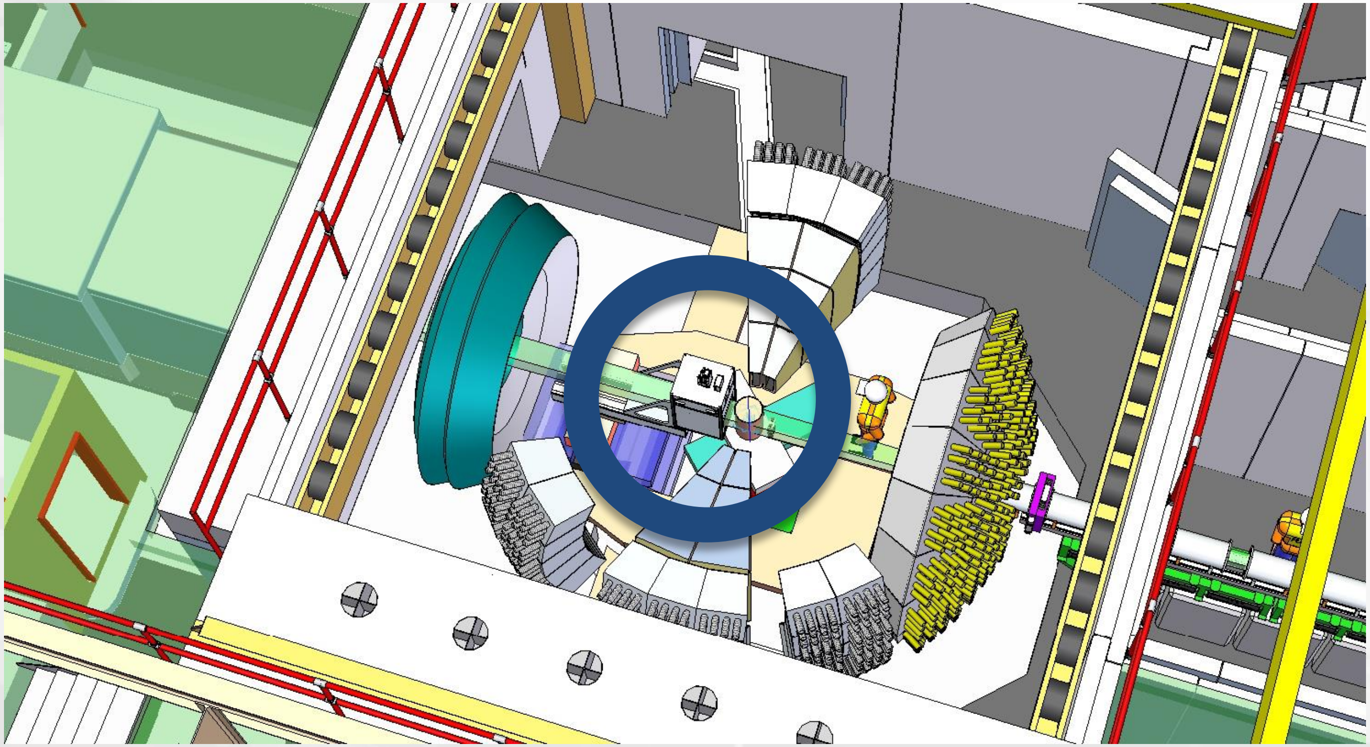


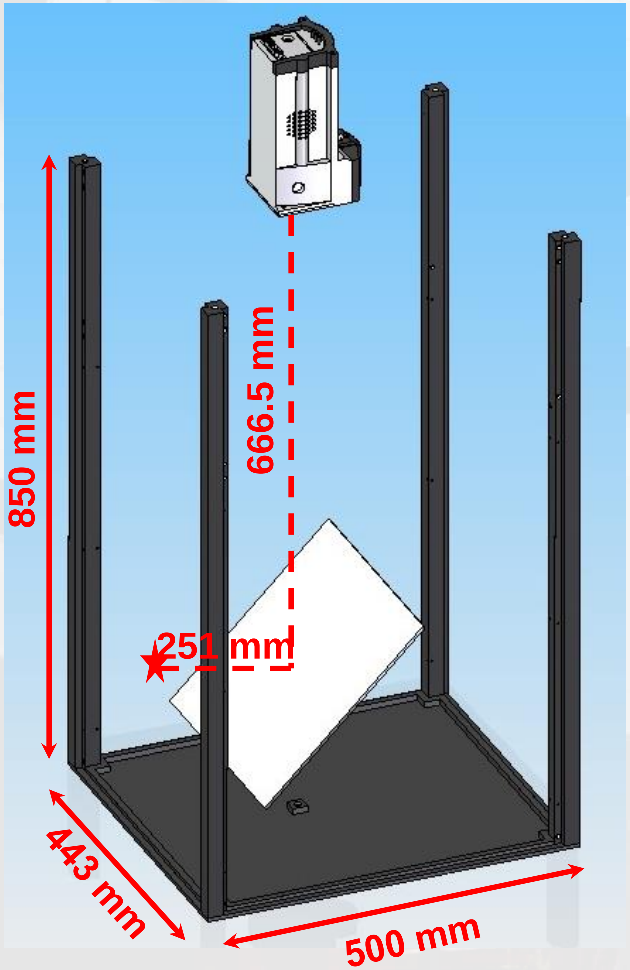

| | |
|---|---|
| **Source repetition** | 10 Hz |
| **Moderator** | Liquid H2 / solid $CH_4$ coupled |
| **Primary neutron guide** | m=3 straight, square, 95x95 mm |
| **Single frame bandwidth** | 0.6 - 6.5 Å |
| **Double frame bandwidth** | 2 - 14 Å |
| **Flight path to sample** | 56 m |



**IMAGING MODE**

| IMAT CCD neutron camera specifications | |
|---|---|
| Flight path | 56 m to sample |
| Max. Effective detector area | 200x200 $mm^2$ |
| Variable field of view | Down to 55x55 $mm^2$ |
| Resolution for full field | 0.2x0.2 $mm^2$ |
| Resolution for reduced field | 50x50 $\mu m^2$ |
| Estimated flux (L/D=125) | Up to $2 \times 10^8$ $n \cdot s^{-1} \cdot cm^{-2}$ |
| Maximum L/D | 2000 |
| Wavelength range | 0.68÷6.8 Å in full-frame 2-14 Å in double-frame |
| Timing resolution | For energy-resolving applications Timing better than $\Delta T/T<1\%$. |

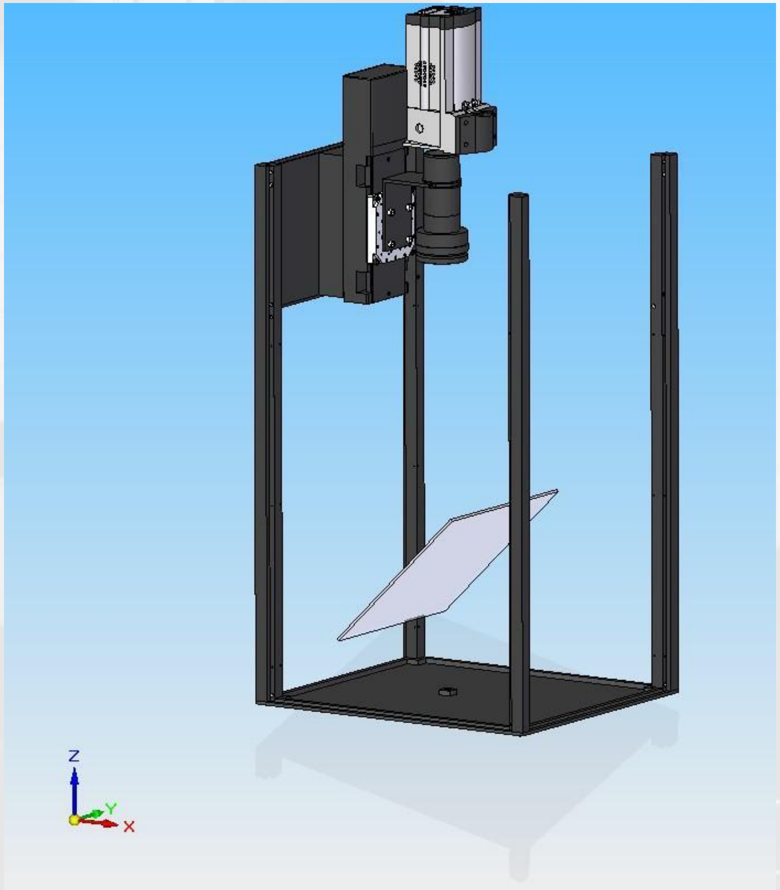
# OPTICAL DESIGN

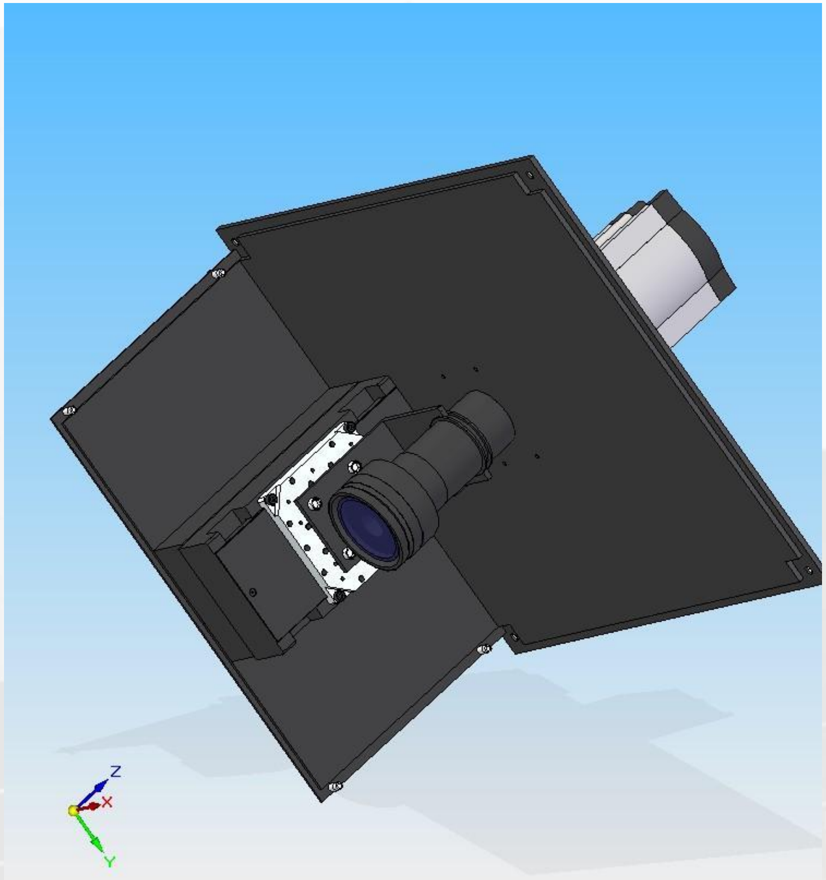



Optical path = 917.5 mm

| Lens | Field of View $mm^2$ | Pixel resolution |
|---|---|---|
| 50mm f/1.2 | 211.5x211.5 | 0.20 mm |
| 85mm f/1.4 | 112.7x112.7 | 0.11 mm |
| 105mm f/2.5 | 85.5x85.5 | 0.08 mm |
| 135mm f/2.0 | 59.5x59.5 | 0.06 mm |

# Changing lenses

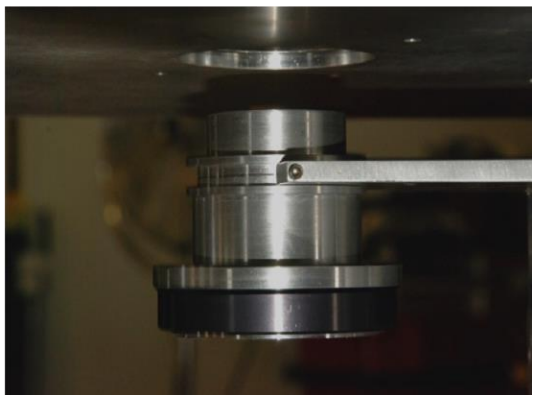


# Changing lenses

Extension tubes

Fast mount and release (ball-spring mechanism)



Lens in ***mounting*** position

Lens in ***focused*** position

**The fast**
**lens mounting and releasing mechanics**

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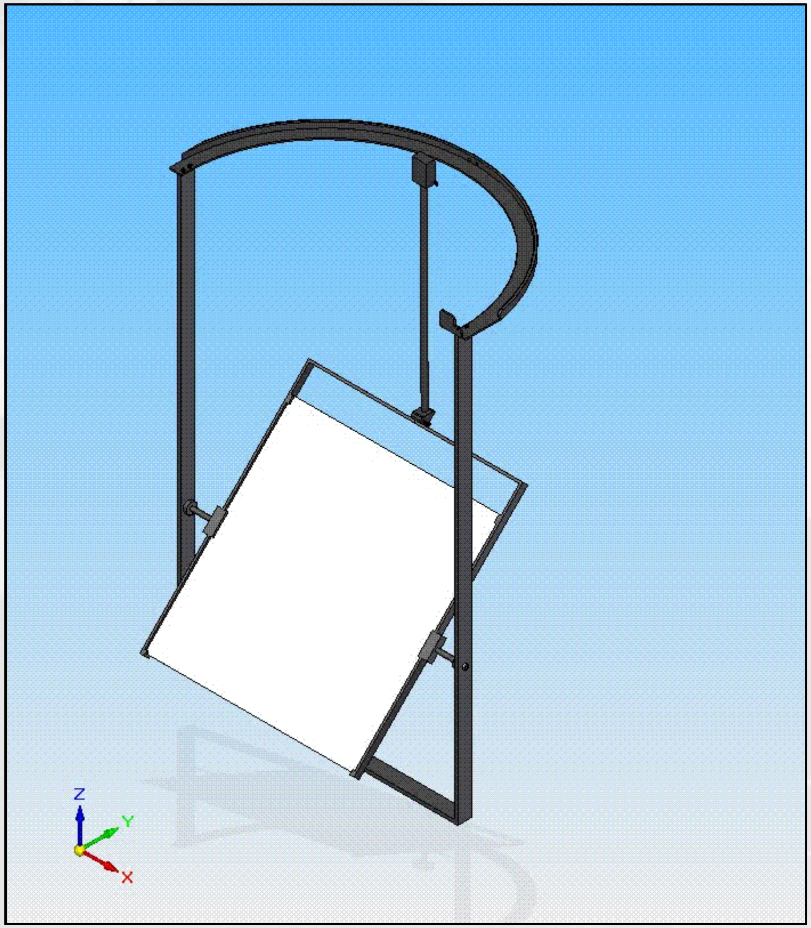
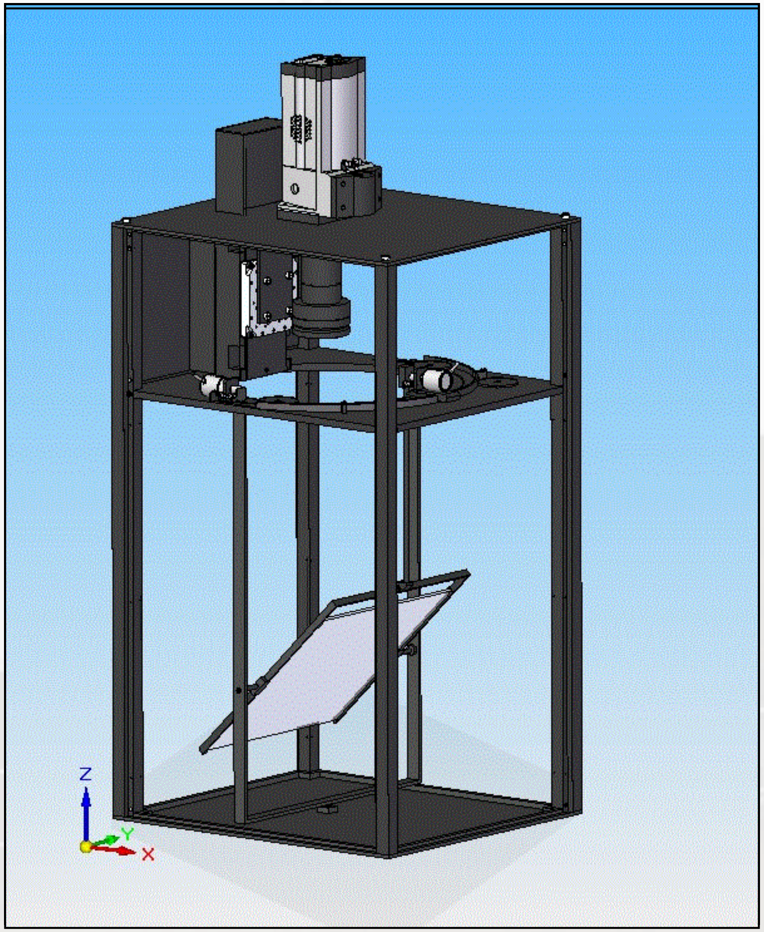
# Aligning mirror



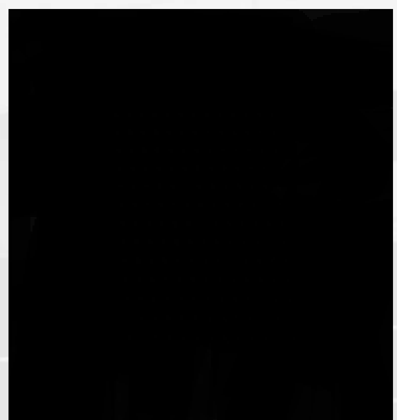



# Auto Focusing

V.Finocchiaro et al. *"The autofocusing system of the IMAT Neutron Camera"* Rev. Sci. Instrum. 84, 093701 (2013)

Laser pointer (Global Laser Ltd. mod. Cameo)
\+ Diffracting lens

$^{6}$***LiF/ZnS*** scintillator
(in the dark)



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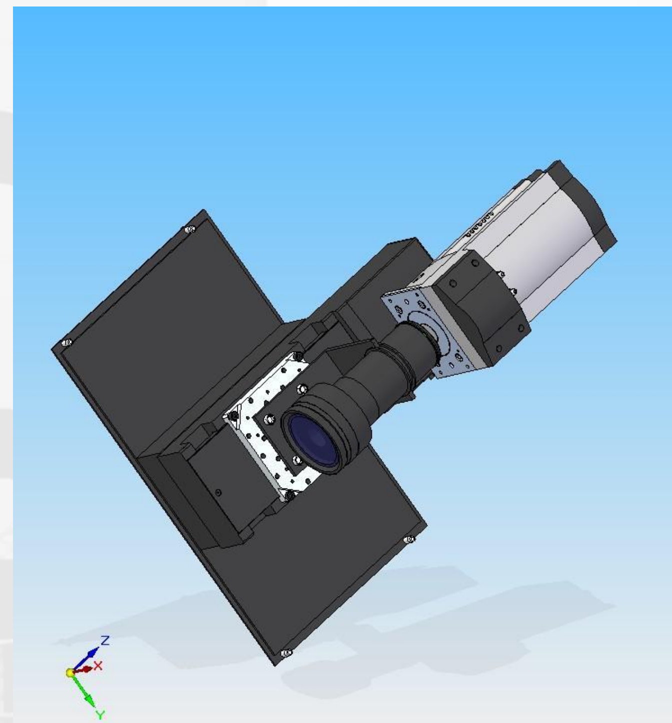
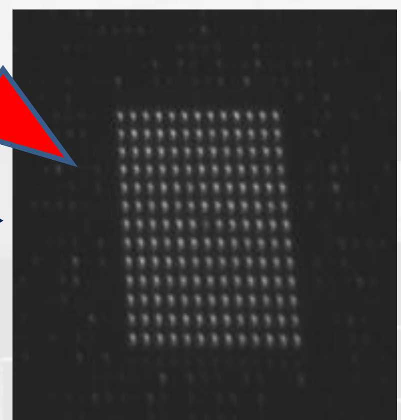


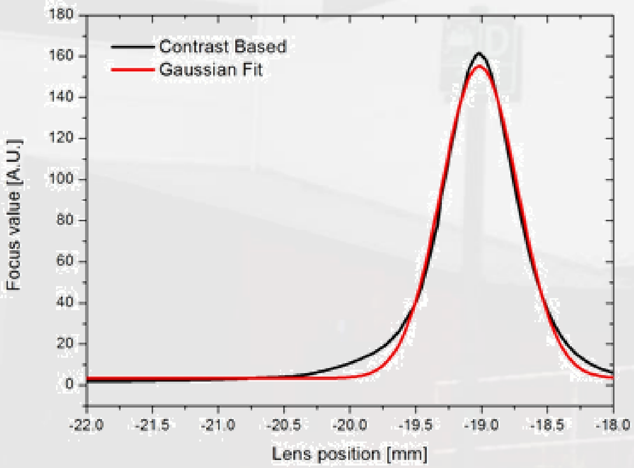

$^{6}$***LiF/ZnS*** scintillator
(in the dark)



# Auto Focusing

The **Contrast Based** algorithm calculates the absolute value of the difference between the brightness value of each pixel, $i(x, y)$, and that of first neighbours along the $x$ and $y$ axis.

$$G(x,y) = \sum_{j=x-1}^{x+1} |i(x,y) - i(j,y)| + \sum_{k=y-1}^{y+1} |i(x,y) - i(x,k)|$$




The ***Focus value*** is given by the sum of the square of $G(x, y)$.

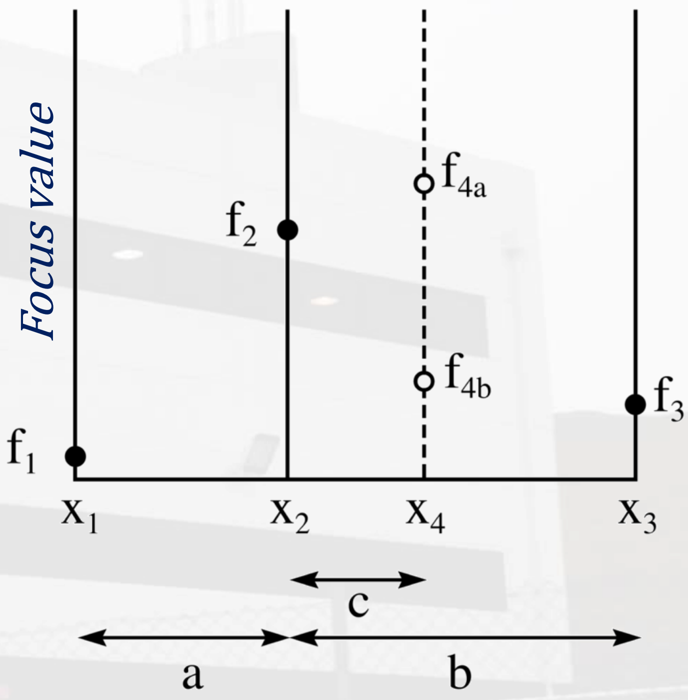
$$Focus\ value = \sum_{H}\sum_{W} G(x,y)^2$$

# Auto Focusing

## Finding the focus with the *Golden section search strategy*

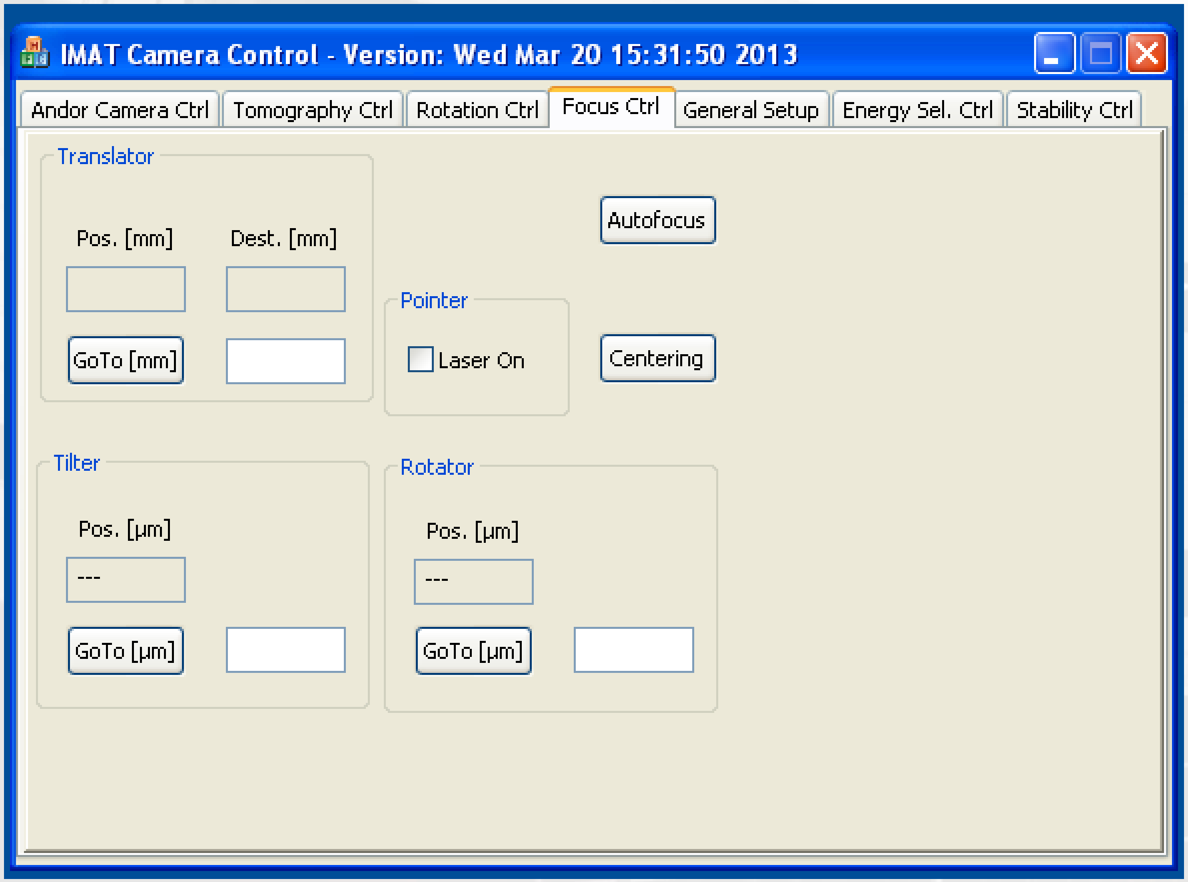
The **golden section search** is a technique for finding the extremum of a ***strictly unimodal*** function by successively narrowing the range inside which the extremum is known to exist.

$$\frac{a}{c} = \frac{b}{a} = \varphi = \frac{1+\sqrt{5}}{2}$$ = ***golden ratio***




http://en.wikipedia.org/wiki/Golden_section_search

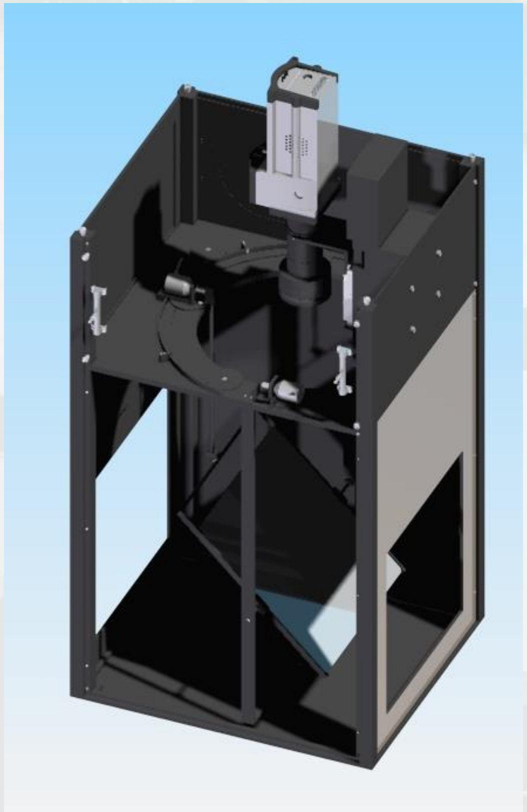
# Auto Focusing




Camera control software has been developed in C++ using Microsoft Visual Studio.

**Next step:**
Converting the control software to run in *EPICS*

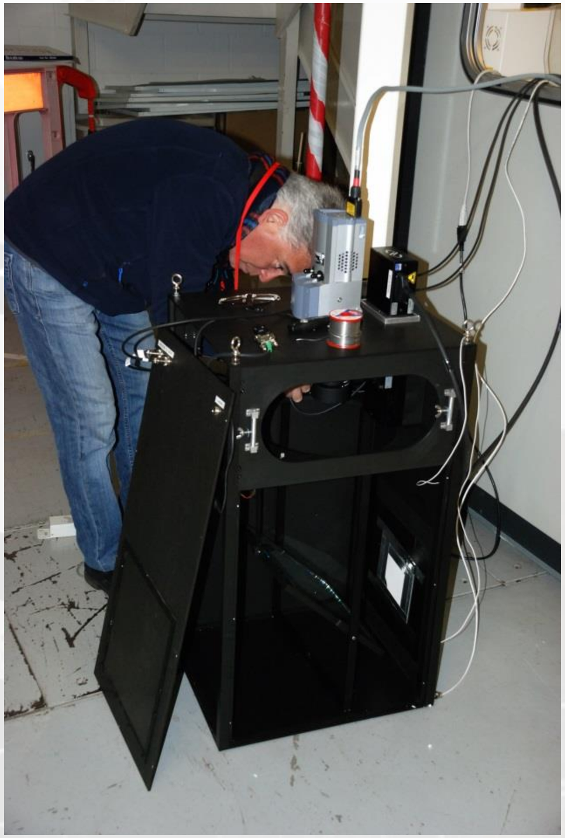
# From Theory to Practice



In October 2012 the completed camera box has been moved from IPCF-Messina to ISIS (UK).

An *Andor* Camera mod. *iStar* DH712 (512x512 pixel) has been mounted as the imaging device and the first test of the camera box has been performed in December 2012.

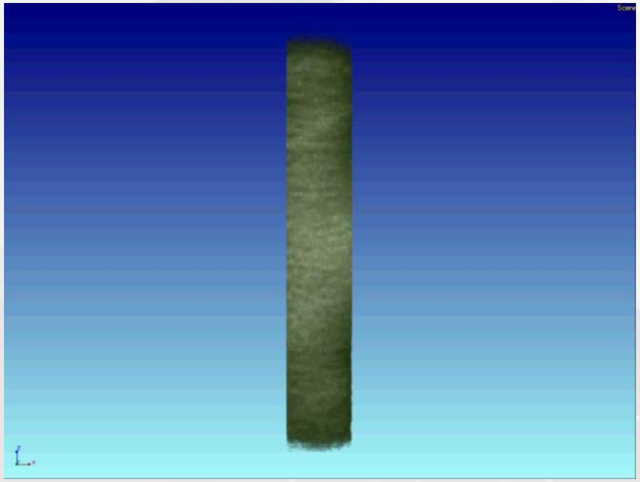
The Camera works as expected from the day one.



# From Theory to Practice

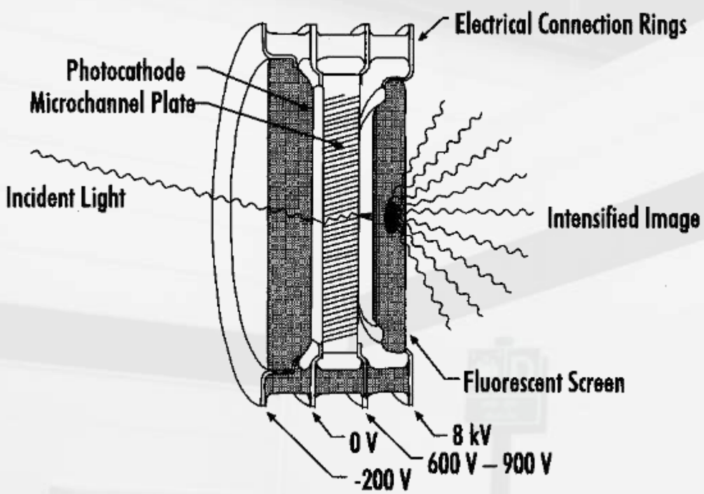
The first test of the camera box has been performed at the ROTAX beamline of ISIS.

The available neutron beam has a size of ~30x30mm$^2$, a flux of ~10$^6$n/cm$^2$ and wavelengths in the range 0.6-5.2 Å.

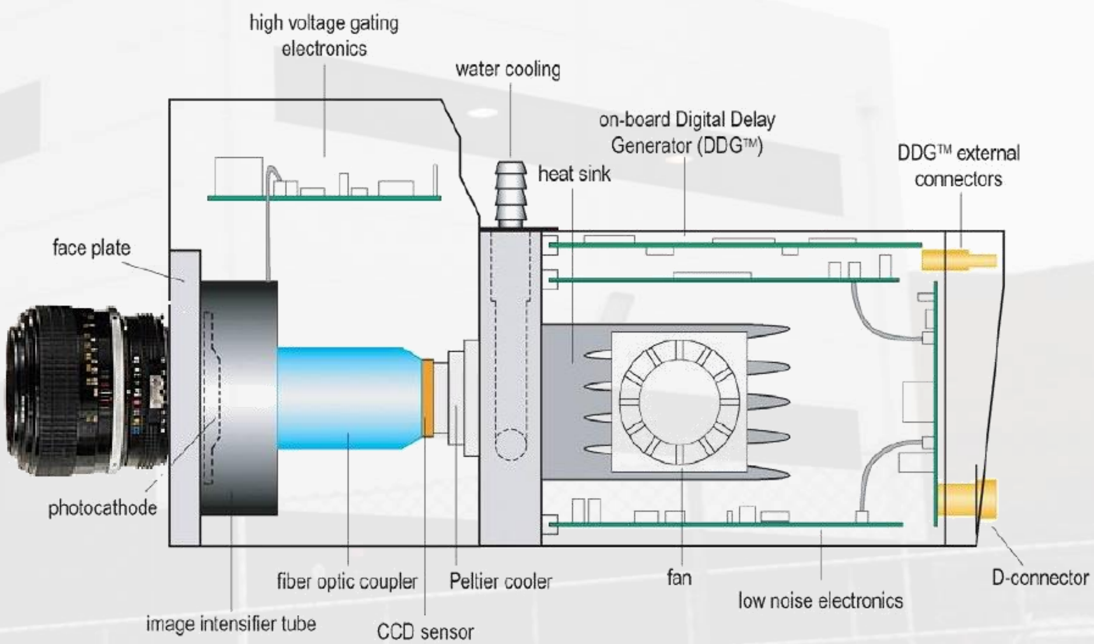


# Energy selective Imaging

Gated Image Intensifier




Andor *iStar* DH712




Energy-selective imaging is obtained by synchronizing the voltage at the image intensifier with the source $\boldsymbol{T_0}$

# Energy selective Imaging

The main amplification of an image intensifier is due to the electron cascade in the channel plate. ***Varying the voltage across the channel plate will control the gain***.

Changing the ***voltage across the microchannel plate it is possible to completely stop the light*** that reach the CCD sensor. Typically ***the on/off ratio of the intensifier is 1:10$^{8}$*** in the visible region

In this way ***you may control the exposure time by applying voltage pulses across the microchannel plate.***

# Energy selective Imaging

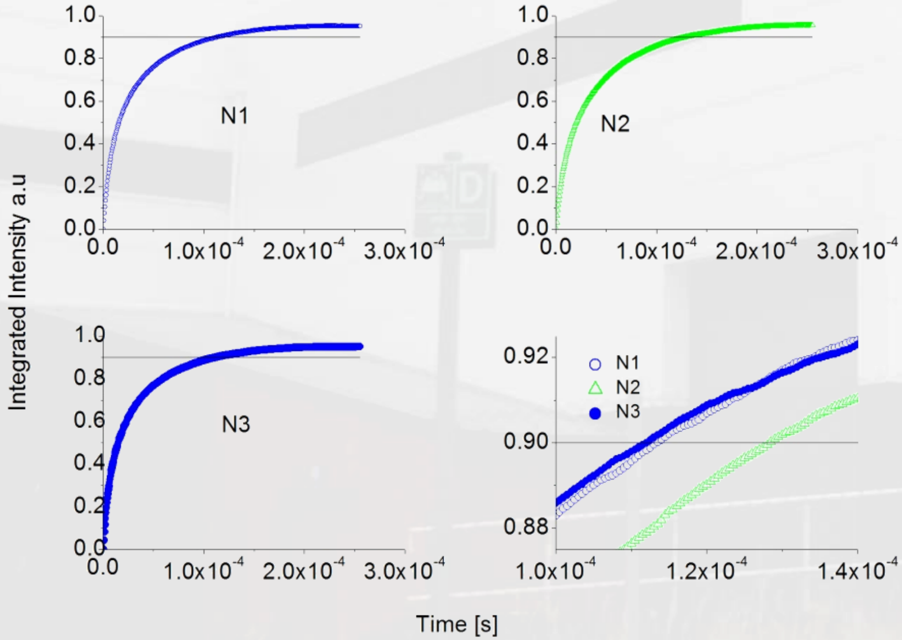
Since the intrinsic noise of the ***CCD*** can be made very low by cooling the sensor, ***it is possible to make very long exposures and turn on, repetitively, for short time periods the intensifier.***

The obtained image is a sum of many partial images without the need to transfer each single image outside the chip (with the associated readout noise).

This procedure is called ***"Integrate on Chip"***.

# Energy selective Imaging

While *iCCD*s gate times are well below the requested time resolution the common used scintillator screens ($^{6}$***LiF/ZnS*** based) have not equally satisfactory timing characteristics.

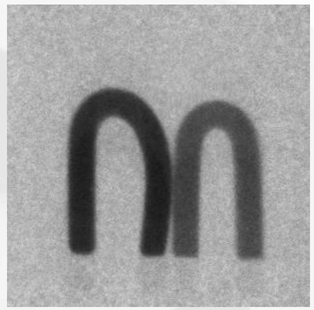



The intensity of the light produced by a neutron hitting the scintillator decays rather slowly.

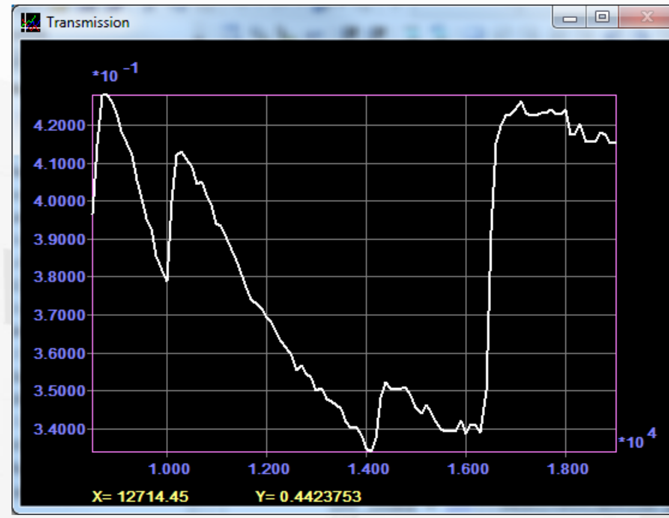
G. Salvato et al. *Nucl. Instr. and Meth.* A **621** 489–492 (2010)

# Energy selective Imaging

Bended ***Cu*** samples



TOF = 8500***μs***
λ= 2.1691**Å**
ΔT=100***μs***
Exposure Time=250***s***




Measured TOFs (8500-19000)***μs*** in 100***μs*** steps corresponding to a wavelength range (2.17-4.85)**Å**

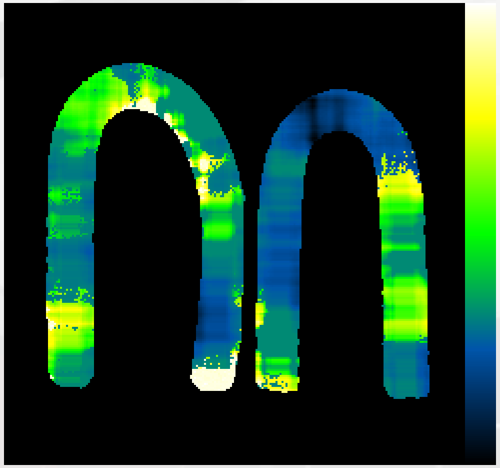
**The camera system is able to identify both the <u>presence</u> of *Bragg Edges* and their approximate <u>positions</u>.**

# Energy selective Imaging

To check further the capabilities of the camera system we have selected the edge at TOF~ 10000***μs*** (where the ROTAX beam intensity is near to its maximum) and we have fitted the data in order to verify point by point the edge position.

To obtain reasonable ***Signal/Noise*** ratios we need a consistent binning of the image (***30x30 pixels***).

λ=2.5774 **Å**

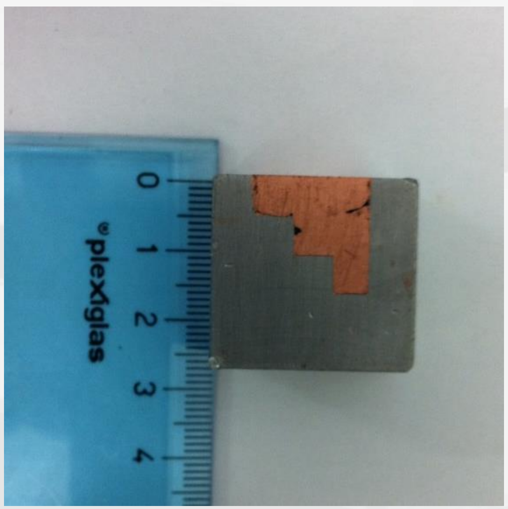


λ=2.5391 **Å**

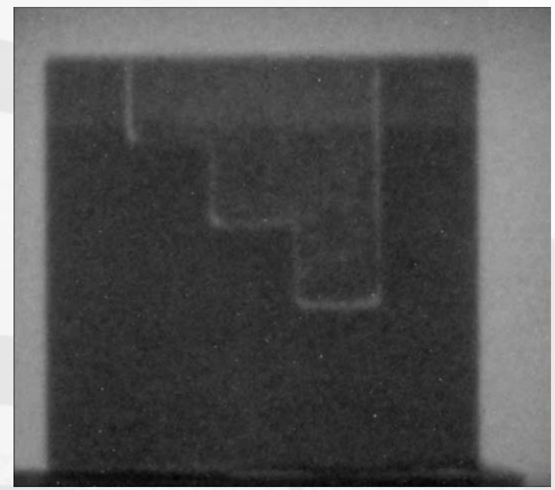
# Energy selective Imaging

## Energy selective imaging for contrast enhancement

***Cu*-*Fe*** Cube




**Contrast Inversion**



From left to right:

- Roberto Caruso
- Giuseppe Spinella
- Vincenzo Finocchiaro
- Gabriele Salvato
- Francesco Aliotta
- Rosa Ponterio
- Cirino Vasi
- Domenico Arigò
- Dario Tresoldi
- Giuseppe Lupò

# Energy selective Imaging

***TOF*** technique for energy resolved imaging **with a CCD's based system** has ***two major drawbacks***:

- timing characteristics of the $^6$LiF ZnS scintillators
- ***the needed acquisition time***.

During the time interval (***~500s*** at ROTAX) needed to acquire an image, ***only a single wavelength band*** can be explored.

For a true strain analysis by neutron imaging we need a

***different image detector !***

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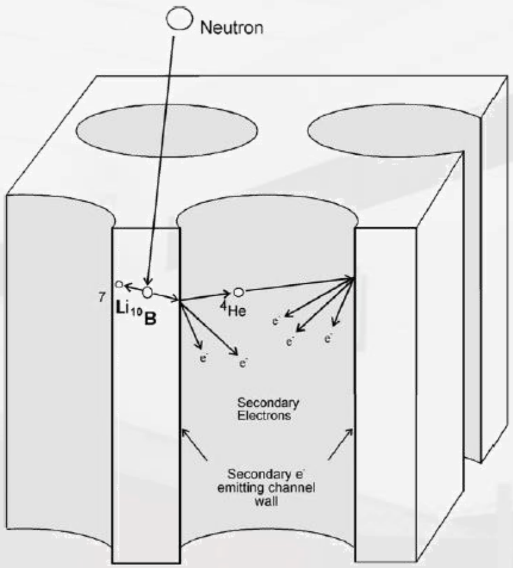
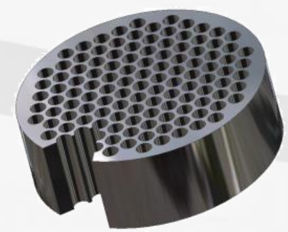
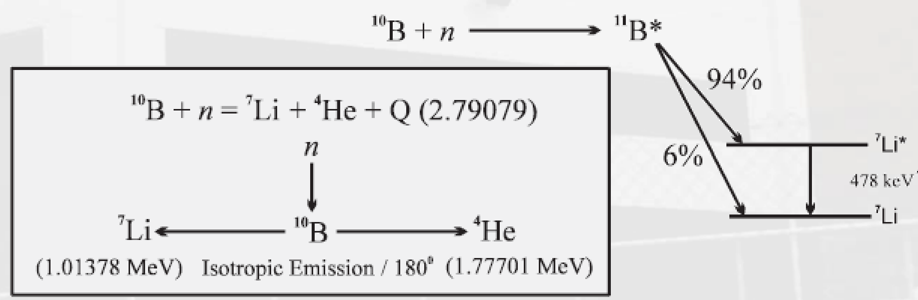
# Energy selective Imaging

A new image sensor, based on a $^{10}$***B-doped*** microchannel plate, has been developed by *A. Tremsin* et coworkers. The neutron detection exploits the $^{10}$**B(n, α)** $^{7}$***Li*** reaction.



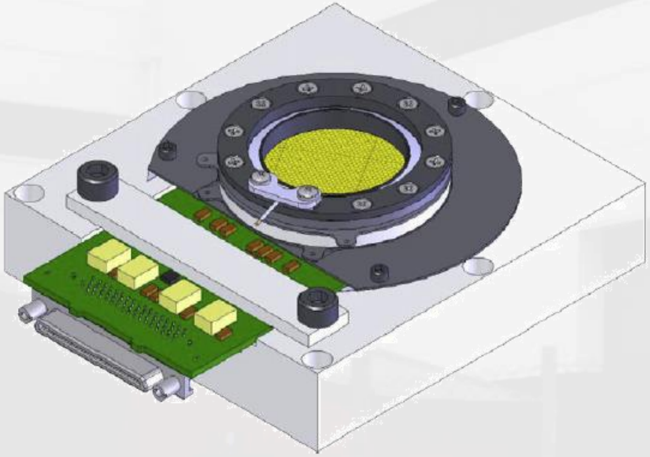



A.S. Tremsin et al. *Nucl. Instr. and Meth.* A **539** 278–311 (2005)

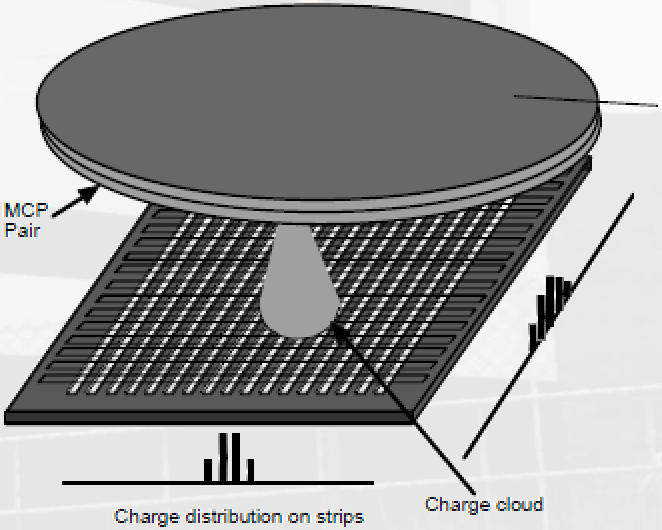
# Energy selective Imaging

The neutron sensing ***MCP*** is combined with a fast readout device originally developed at CERN for high energy particles: ***Medipix***.

***Medipix*** is realized in CMOS technology and has a spatial resolution of ***~55μm***. It has 256x256 pixels and an active area of $14x14mm^2$.



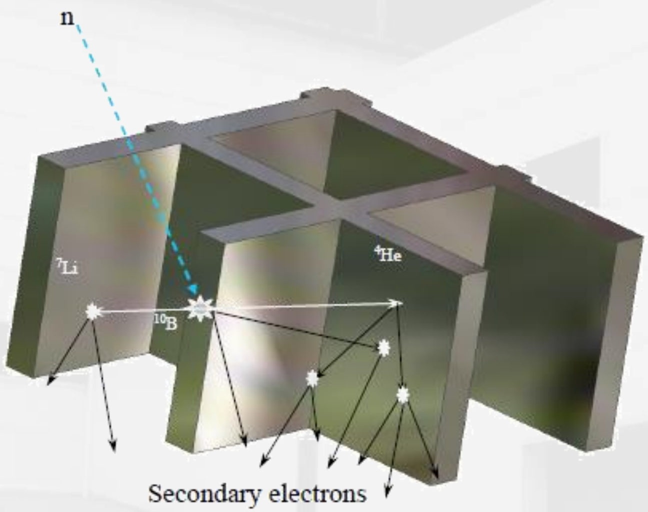
A.S. Tremsin et al. *Nucl. Instr. and Meth. A* 592 374–384 (2008)

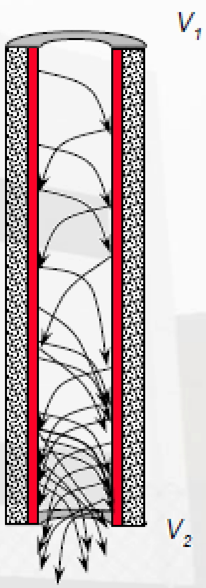



A.S. Tremsin et al. IEEE NSS 2007, October 2007

# Energy selective Imaging

The ***alpha*** and $^{7}$***Li*** charged particle reaction products emerge from the channel wall surfaces into an open channel.




As these heavy particles cross the surface, a relatively large number of secondary electrons (and other species) are liberated to ***generate a strong electron avalanche*** and an output pulse.

A.S. Tremsin et al. IEEE NSS 2007, October 2007

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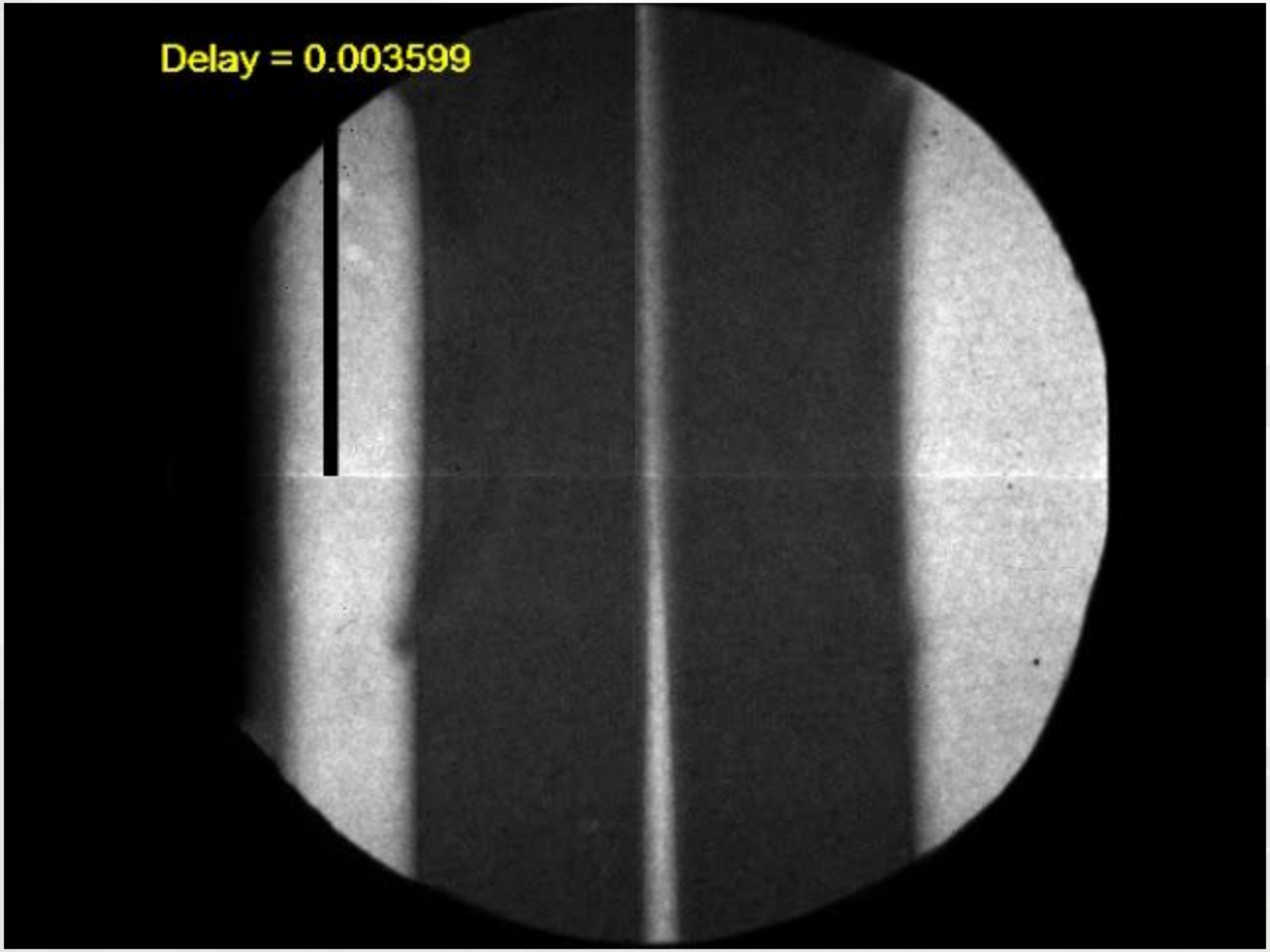
# Energy selective Imaging



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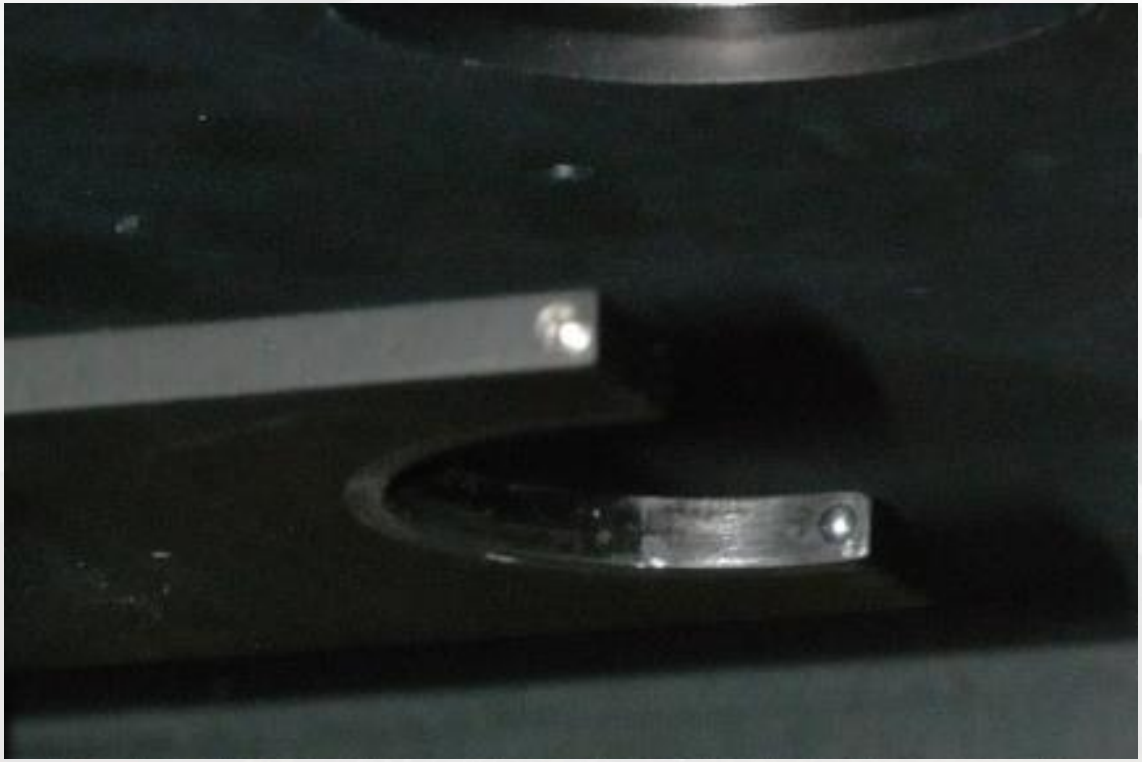
# Changing lenses

**The fast**
***lens mounting and releasing* mechanics**



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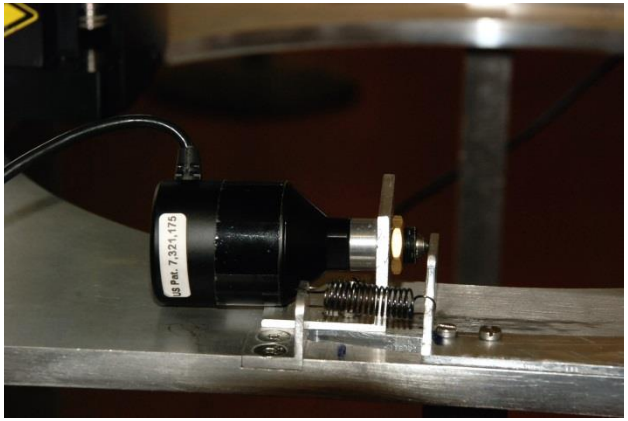
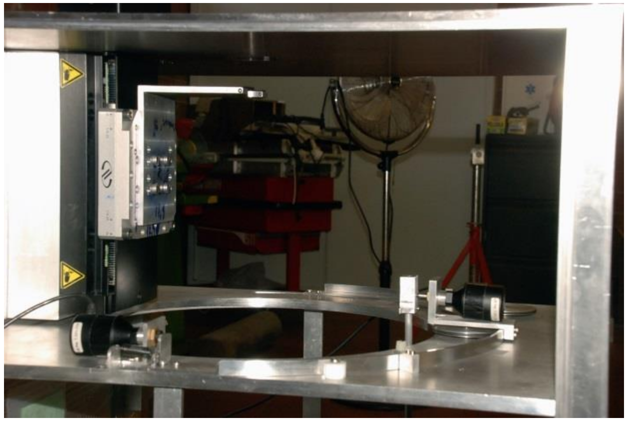
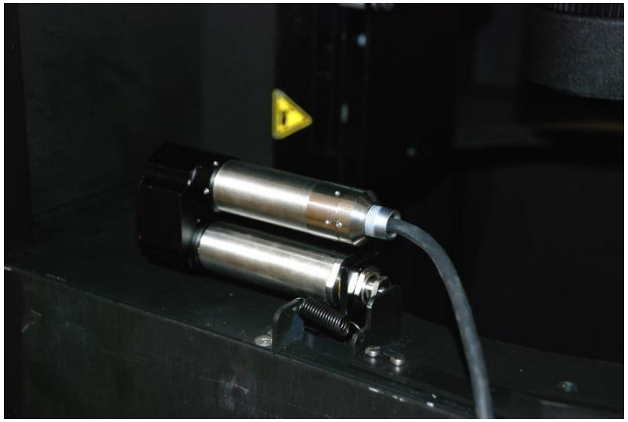
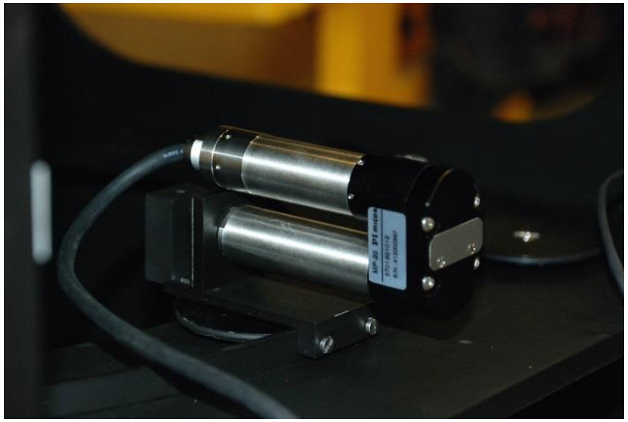
# From Theory to Practice



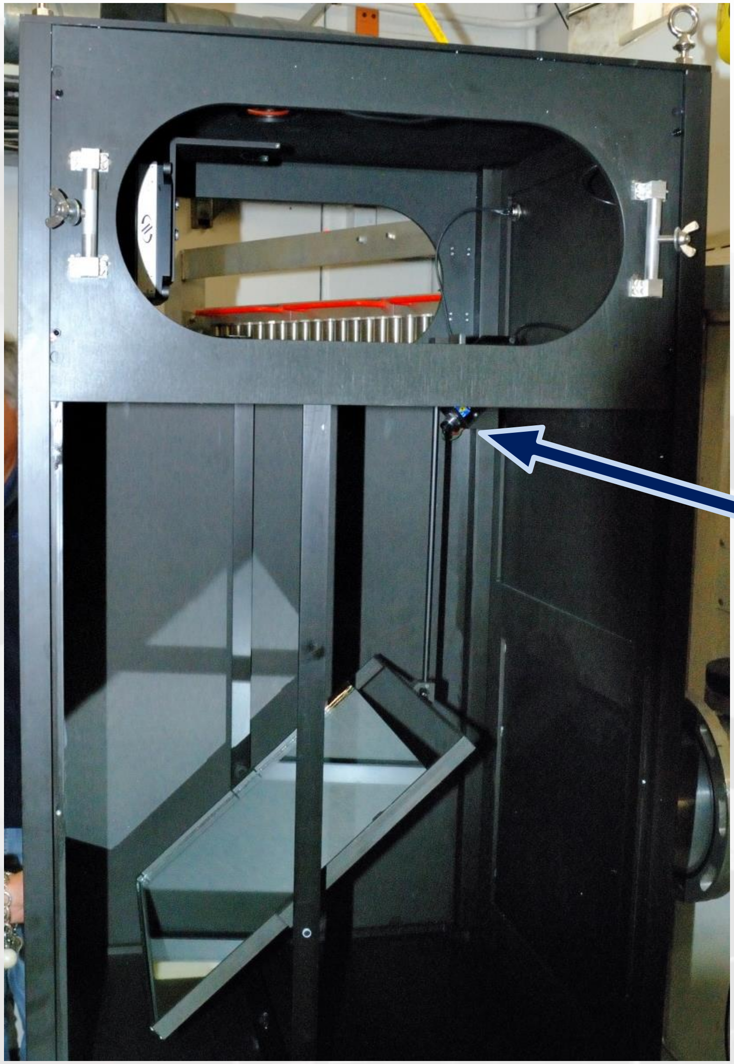







We decided to change the mounted micro pushers with others more robust and endowed with two *end-run* detectors.

National Research Council of Italy



Laser diode

# From Theory to Practice


The Box of the camera box

What will we found inside ?

Surprise ! The camera is Intact !