



# **Energy-resolved neutron imaging with MCP/Medipx technology**

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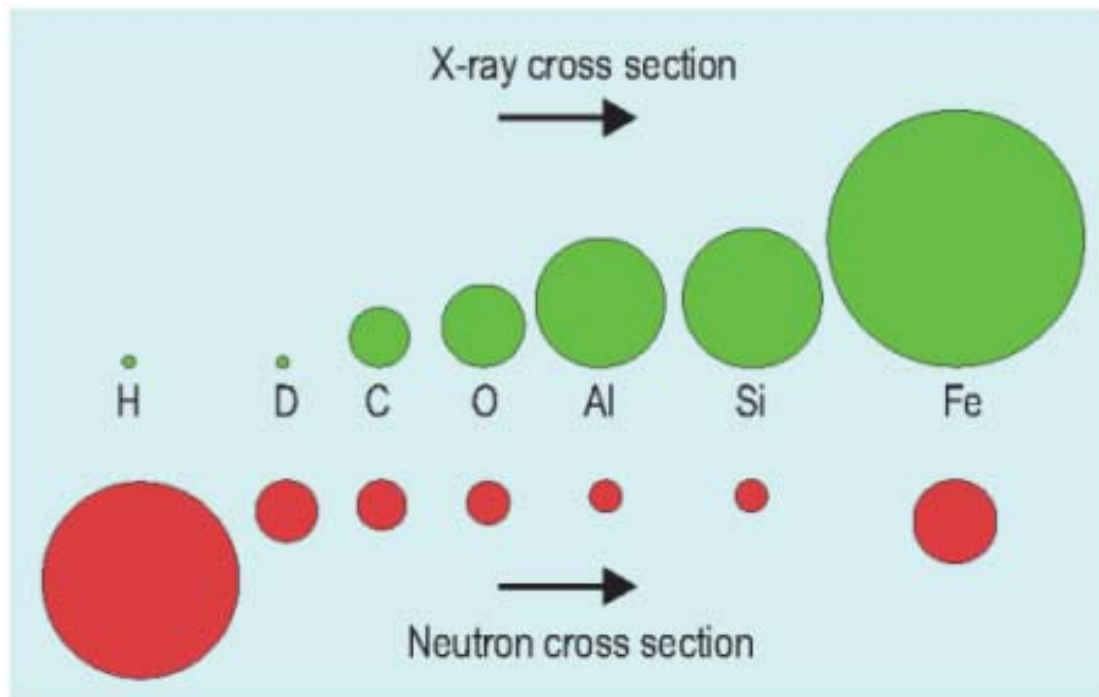
# Unique capabilities of neutron imaging



# X-rays versus neutrons

- X-rays interact with **electrons in the atoms**.

The heavier is the atom – the larger is absorption of X-rays.



- Neutrons interact with **nucleus** and have very different absorption contrast.

NIST annual report 2003, D. Jacobson, M. Arif, and P. Huffman  
Physics Laboratory Ionizing Radiation Division



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New detector technology we use  
in neutron imaging was partially  
developed for astrophysical applications:

- Event counting
- UV, soft X-ray sensitive
- High dynamic range
- Low noise/background
- Good spatial resolution

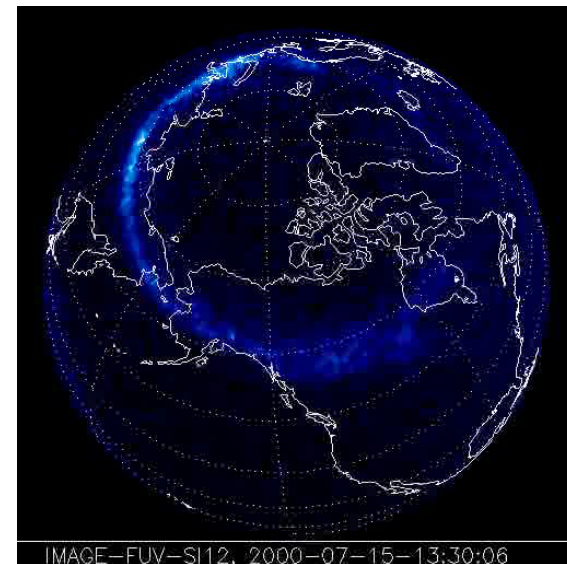


# Detectors developed at Berkeley for NASA applications



NASA Image satellite

MCP detector technology  
developed for astrophysical  
applications





# Mdipix/Timepix neutron imaging was pioneered by Institute of Experimental and Applied Physics, Czech Technical University in Prague



Available online at [www.sciencedirect.com](http://www.sciencedirect.com)

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Nuclear Instruments and Methods in Physics Research A 560 (2006) 143–147

NUCLEAR  
INSTRUMENTS  
& METHODS  
IN PHYSICS  
RESEARCH  
Section A

[www.elsevier.com/locate/nima](http://www.elsevier.com/locate/nima)

## Neutron imaging with Medipix-2 chip and a coated sensor

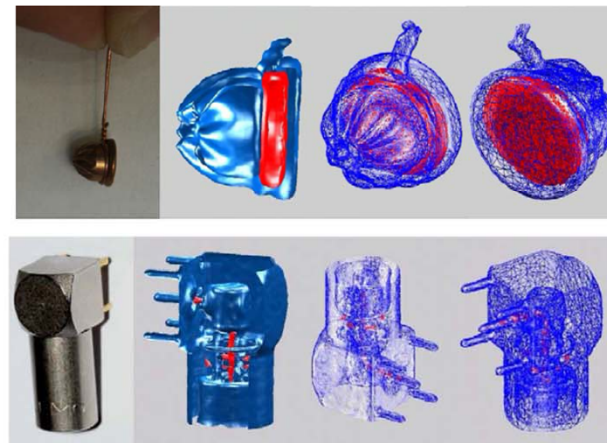
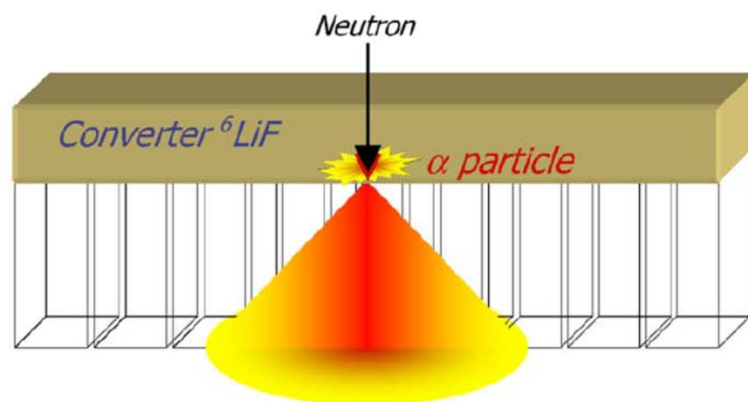
J. Jakubek<sup>a,\*</sup>, T. Holy<sup>a</sup>, E. Lehmann<sup>b</sup>, S. Pospisil<sup>a</sup>, J. Uher<sup>a</sup>, J. Vacik<sup>c</sup>, D. Vavrik<sup>a</sup>

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<sup>b</sup>*Paul Scherrer Institute, CH-5232 Villigen, Switzerland*

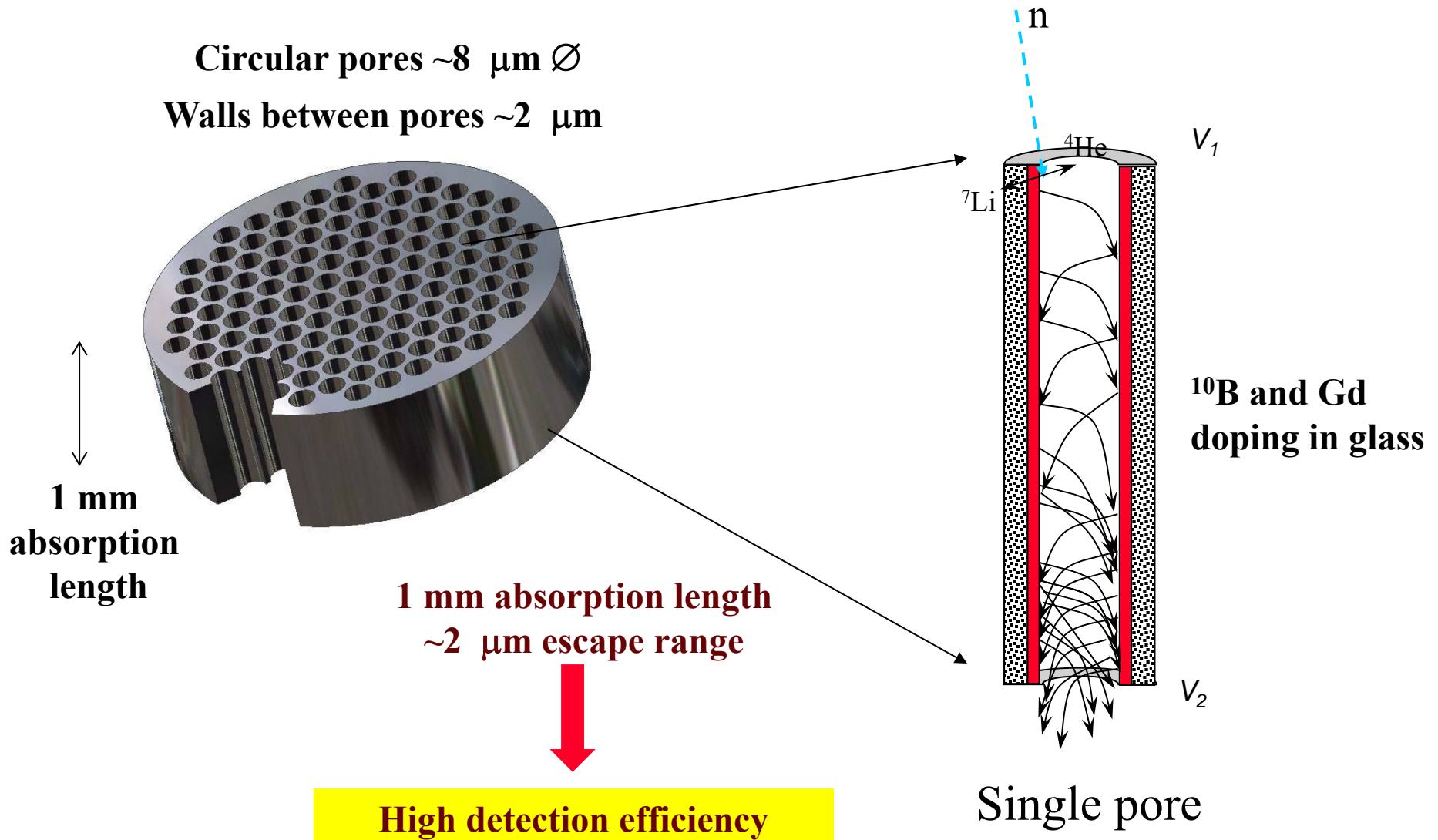
<sup>c</sup>*Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Rez near Prague CZ-25068, Czech Republic*

Available online 29 December 2005





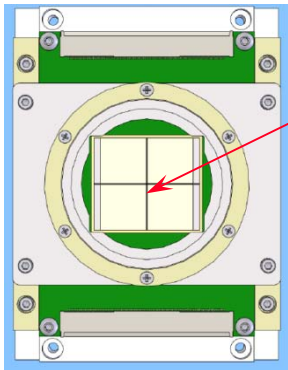
# MCP electron amplifier for UV/neutron detection



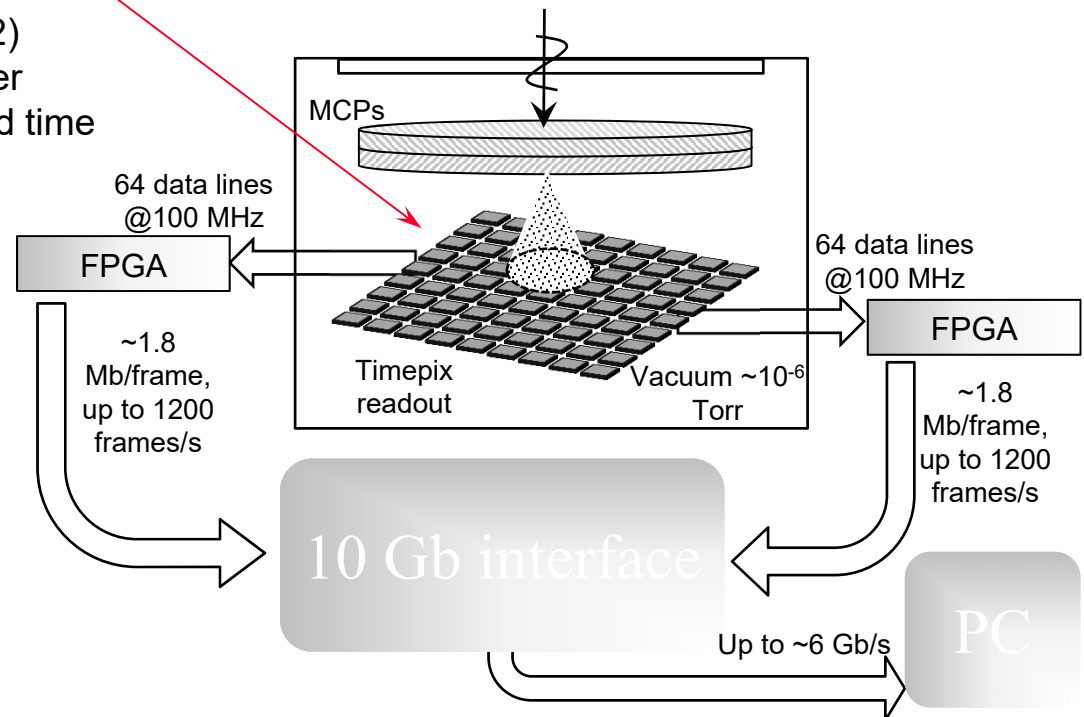


# Enabling technology: MCP/Timepix detectors

- **Bright** pulsed neutron beams
- New **neutron counting detectors** with high timing and spatial resolution @ high count rates



- Active area with **2x2 Timepix chips** (28x28 mm<sup>2</sup>)
- Fast parallel readout (x32) allowing ~1200 frames per second and ~300  $\mu$ s dead time
- Wide transmission spectrum measured at the same time.



A.S. Tremsin, et al., NIM A **787** (2015) 20–25.



# Neutron cross sections vs. energy

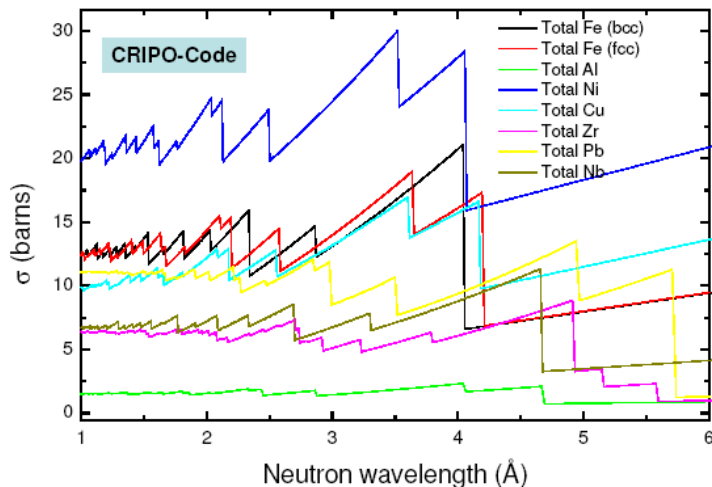
**Thermal range**  
**1-5 Å (~4-100meV)**

**Epithermal range**  
**1eV-10 keV (~2-300 mÅ)**

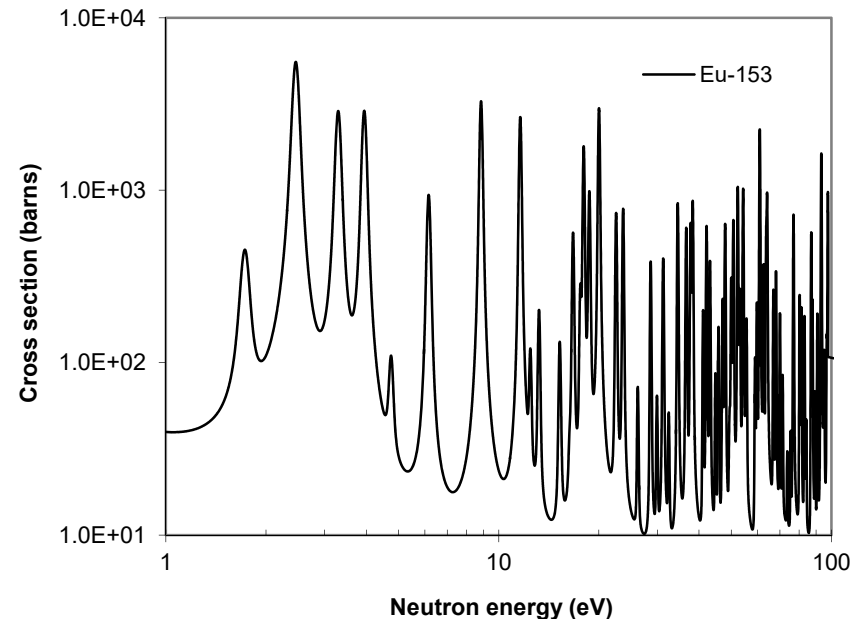
**Bragg edges**

**Resonance attenuation**

Energy selective radiography with cold neutrons  
for crystalline materials



Ref.: Javier Santisteban, Dept. Materials Engineering, The Open University, UK



**Crystallographic parameters extracted**

**Phase**  
**Texture**  
**Lattice parameter**

**Elemental/isotopic composition**  
**Temperature map**



# From radiography to energy resolved imaging



Images are taken from google images website



# Energy-resolved neutron imaging: time of flight

## Pulsed Neutron Source

20 - 60 Hz

~100 ns pulses

## Propagating neutron pulse

Neutron counting  
2D detector

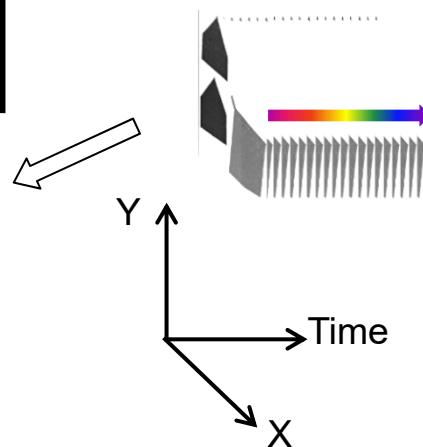
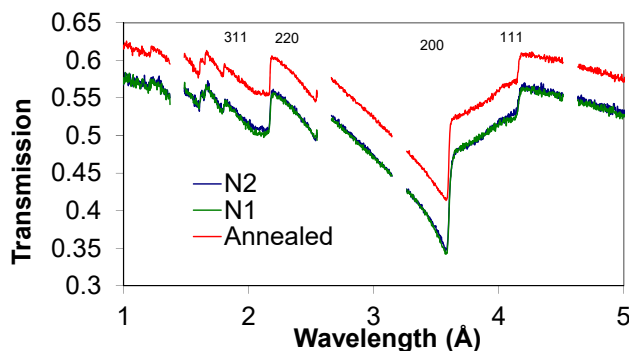
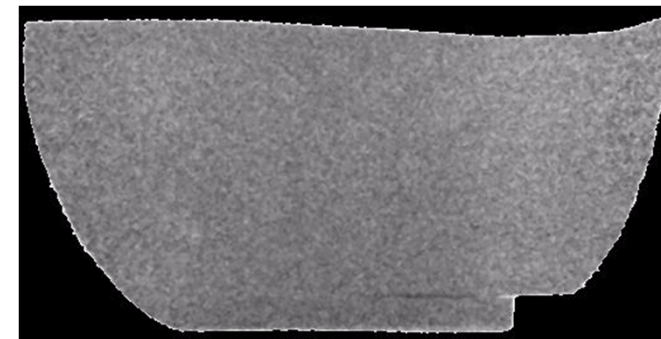
## Sample

## Trigger synchronized to the source

**All energies are imaged  
at the same time!**

X,Y,T for every  
detected neutron

**~250,000 spectra is measured simultaneously!**





# **Application examples.**

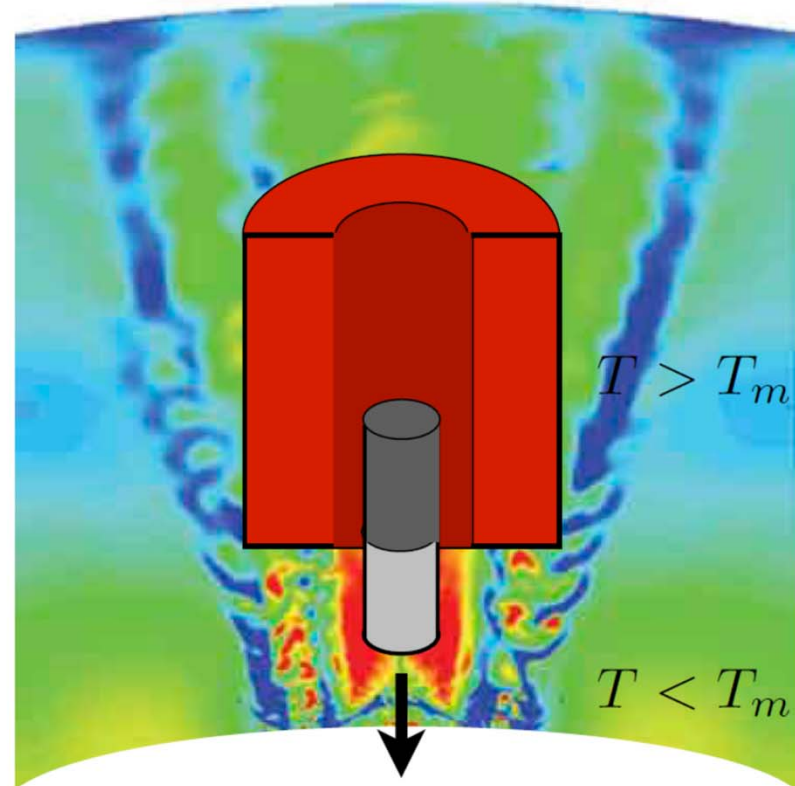
## **Optimization of crystal growth: In-situ imaging**

# Historically, the Bridgman crystal growth process has been simple, relatively uncontrolled, ...



P. W. Bridgman

- “The general method is that of slow solidification from the melt...The metal in the molten condition in a suitable mold of glass or quartz tubing is slowly lowered through the bottom of the furnace into the air of the room or into a cooling bath of oil”
- “It is important that air drafts be kept from the emerging mold, as otherwise new centers of solidification may be started.”



# Industrial Bridgman furnace: RMD



**A two-zone furnace, which allows 2" growth.  
Theoretically it can be used in neutron imaging experiments,  
although our 5-zone furnace is better suited for it.**

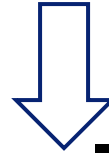
Proc. of SPIE Vol. 8507 850716-1,  
Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XIV



# **Crystal growth: In-situ measurement**

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**Understand and optimize growth process for single crystal materials.**



**Transfer that knowledge to industrial scale production.**

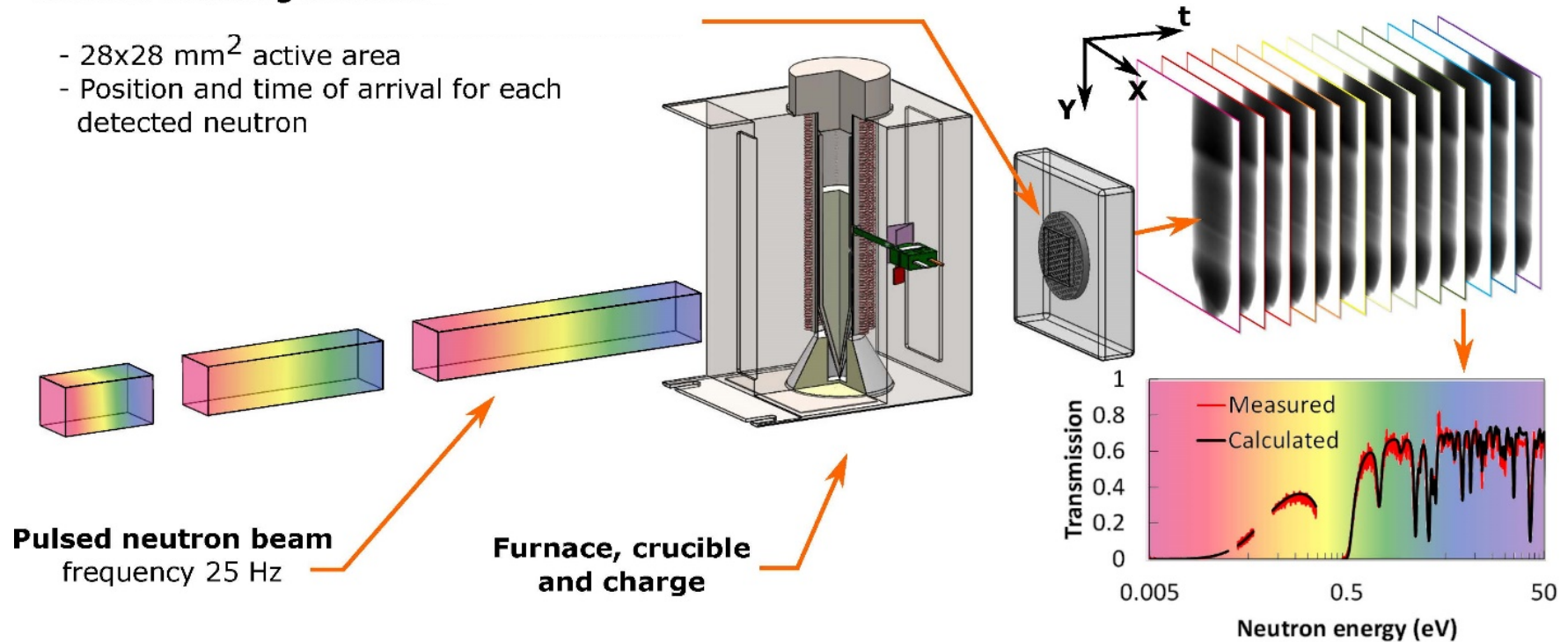
Dedicated furnaces optimized for neutron imaging were developed.



# Experimental setup pulsed beam: energy resolved imaging

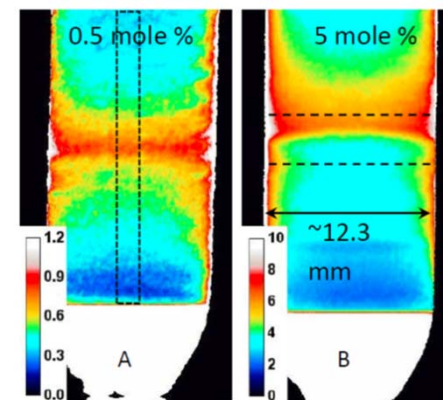
## Neutron counting detector

- 28x28 mm<sup>2</sup> active area
- Position and time of arrival for each detected neutron



**~250000 spectra are measured at the same time, each within 55  $\mu\text{m}$  pixel!**

Map of Eu concentration



A.S. Tremsin, et al., Scientific Reports 7 (2017) 46275

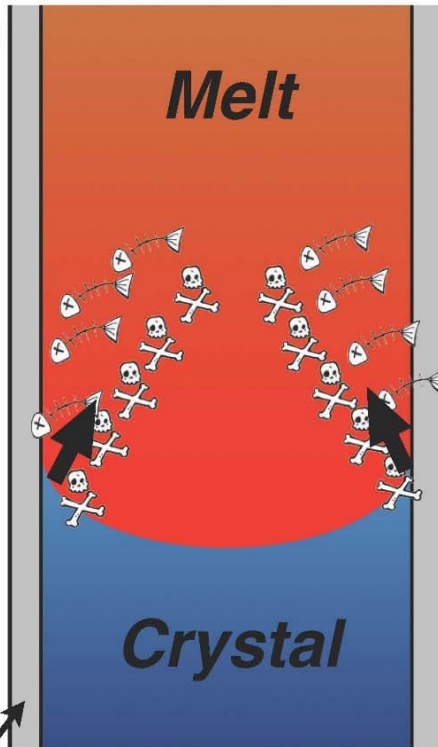
# One objective of furnace design is to tailor the shape of the melt-solid interface to minimize deleterious interactions with ampoule wall



Concave interface  
moves defects  
toward center

*Interface  
Motion*

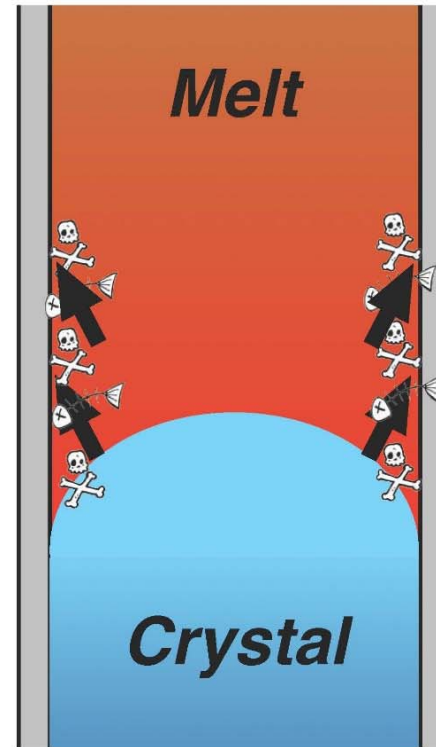
*Ampoule  
Wall*



Concave interface



Convex interface  
keeps defects  
at periphery

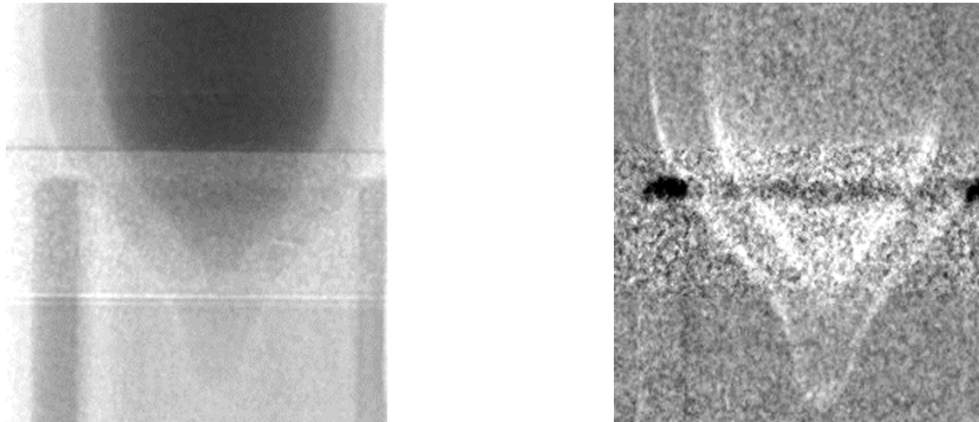


Convex interface



# Crystal growth – in situ diagnostics

Initially 1 mm/hr pull speed. Increased to 2 mm/hr.  
Strong asymmetry of interface seen at high speed.



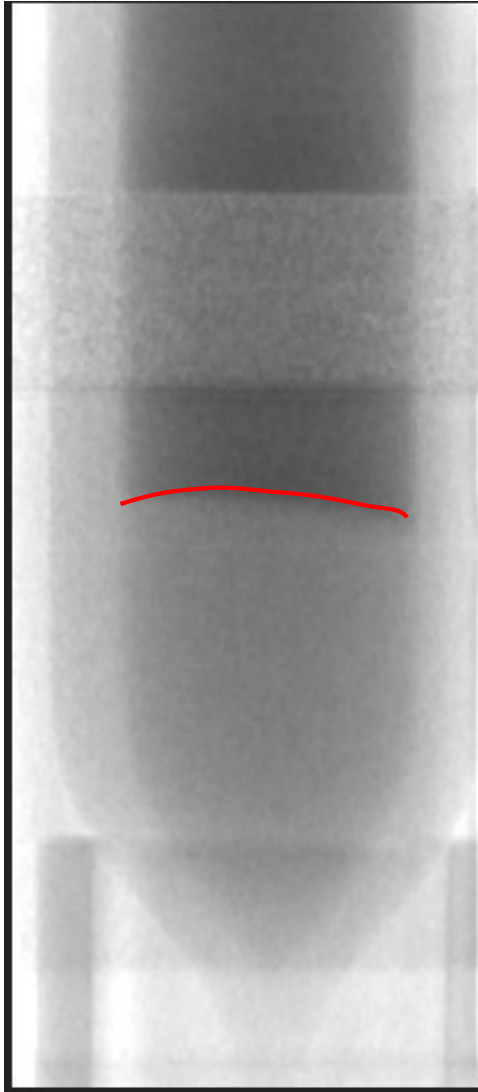
1. Interface is convex, as desired.
2. Interface remains at the same position/moves slowly during regular growth.

**Should allow real-time adjustment of T profile  
to keep the interface convex and at the desired location.**

20 min image acquisition per step



# Controlled interface shape



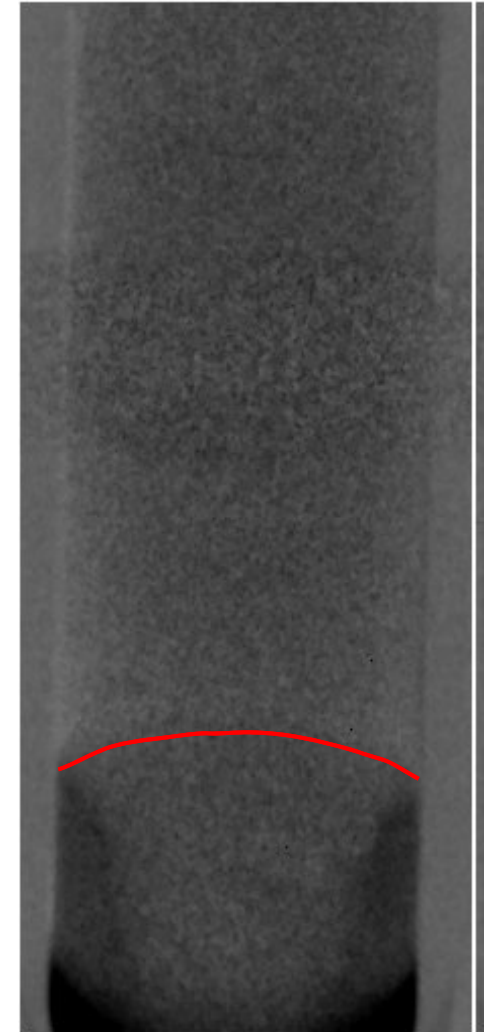
(CsI:0.5%Eu)

Sample width ~11 mm

Booster heater area. Neutron scattering distorts the image.

**Interface between the liquid and solid phases is convex.**

Contrast is due to segregation of Eu (CsI:Eu) and Li (in TLYC) between the liquid and solid phases.

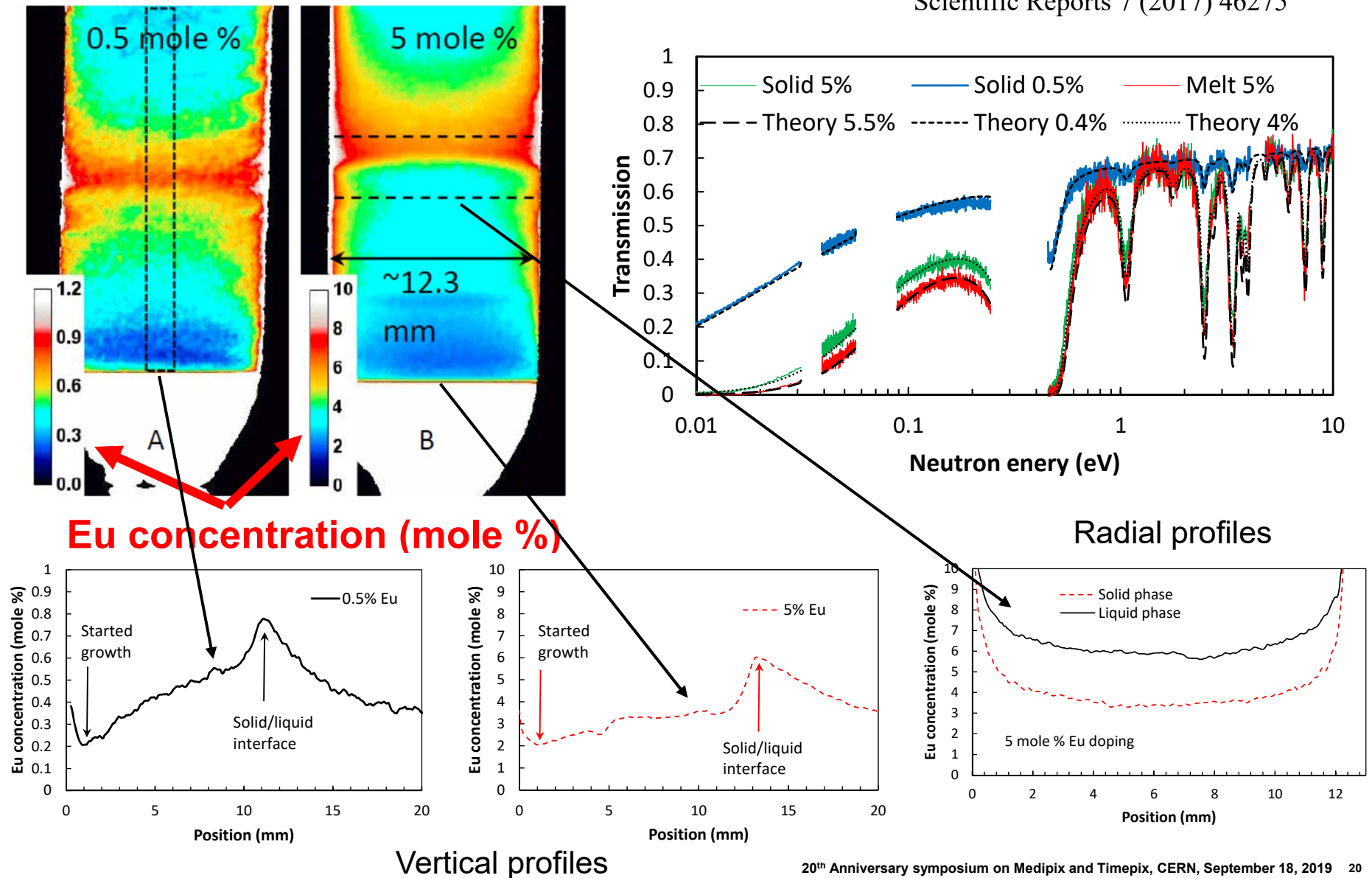


$\text{Tl}_2\text{LiYCl}_6\text{:Ce}$



# In-situ Eu distribution quantification

Scientific Reports 7 (2017) 46275

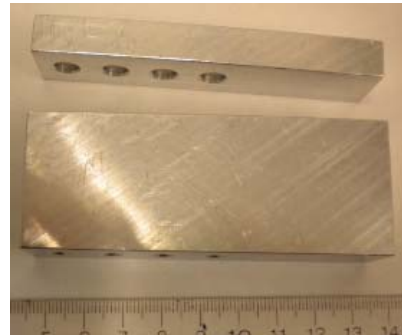
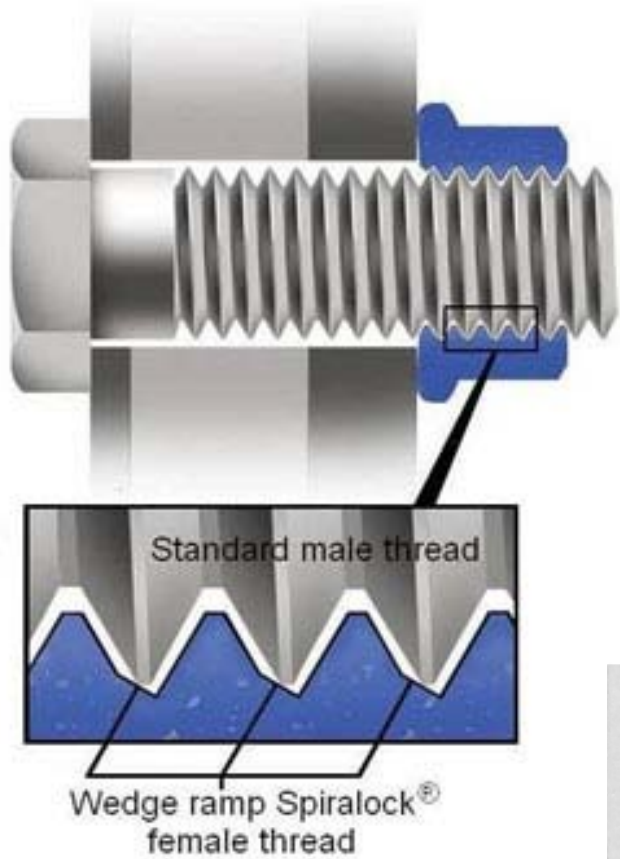




# In-situ measurement of strain



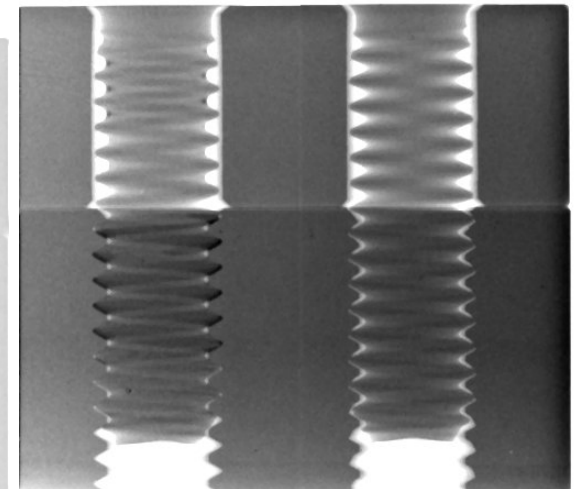
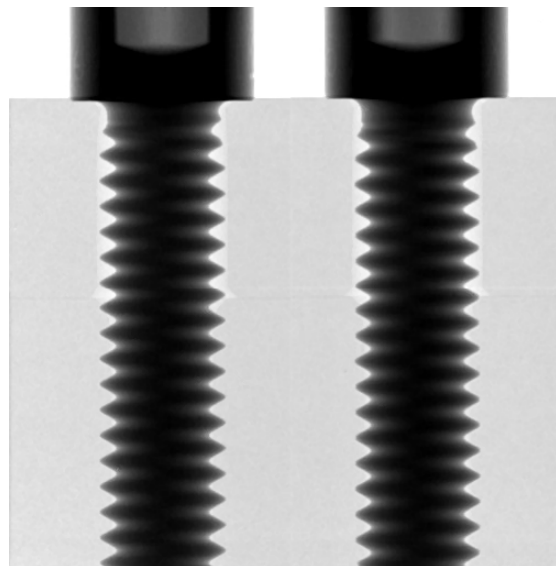
# Load in Spirallock threads: vibrational stability



Steel screws in Al base

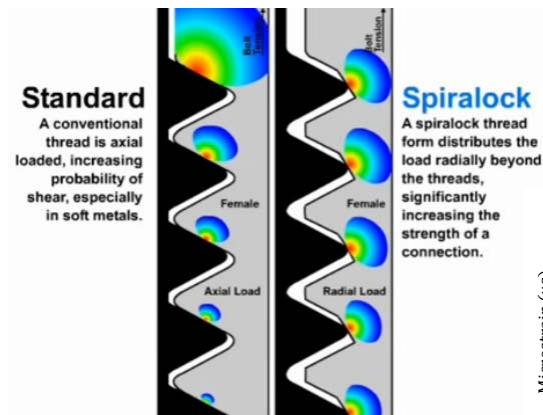
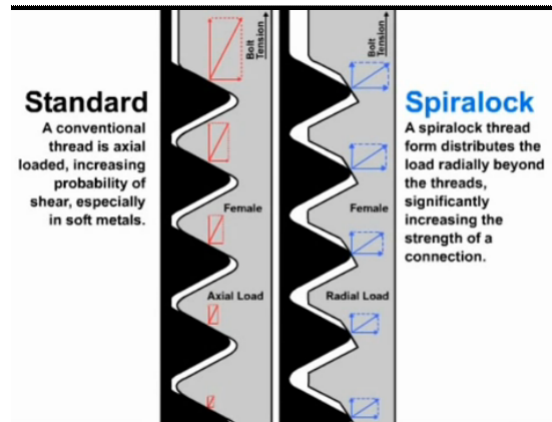


Steel screws in stainless steel

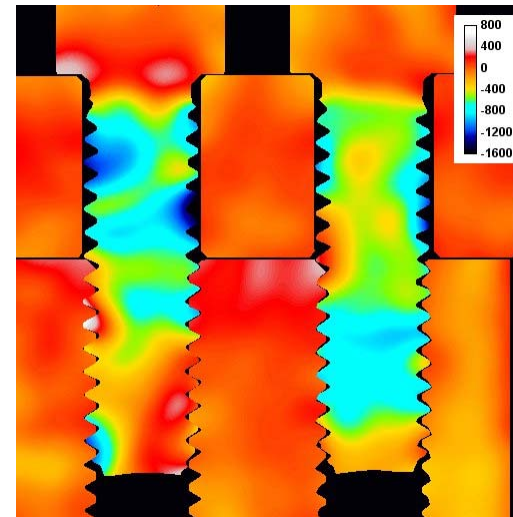




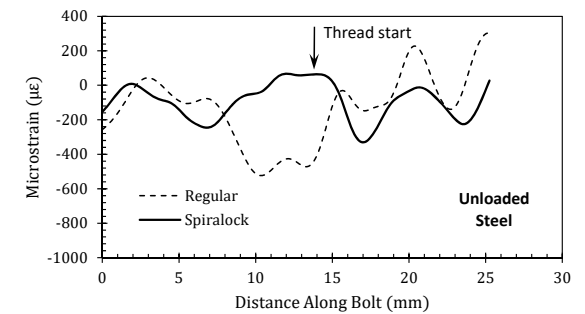
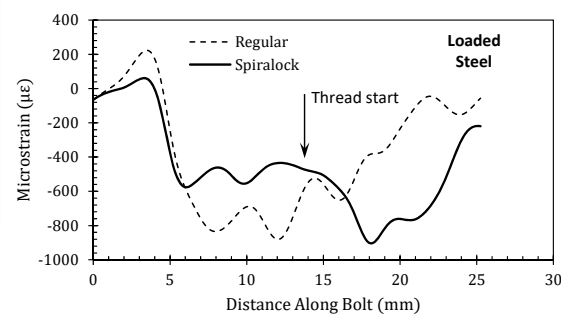
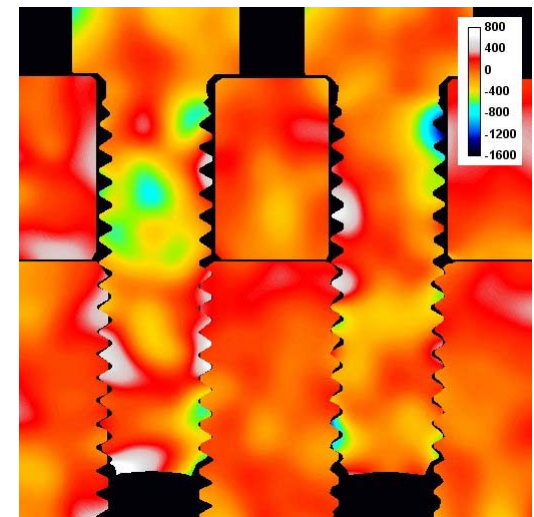
# Load in Spirallock threads: vibrational stability



Torqued to 185 lb-in



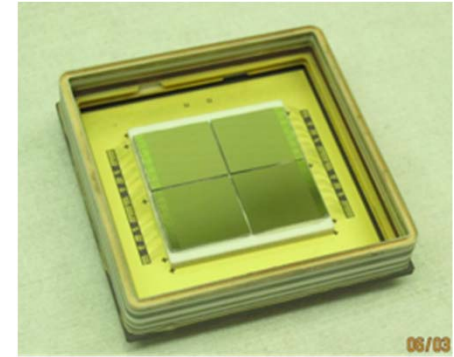
Not torqued



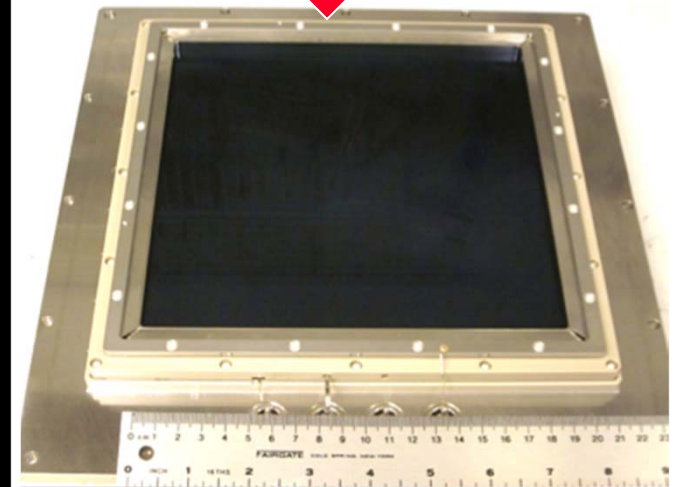


# Future capabilities enabled by Timepix4

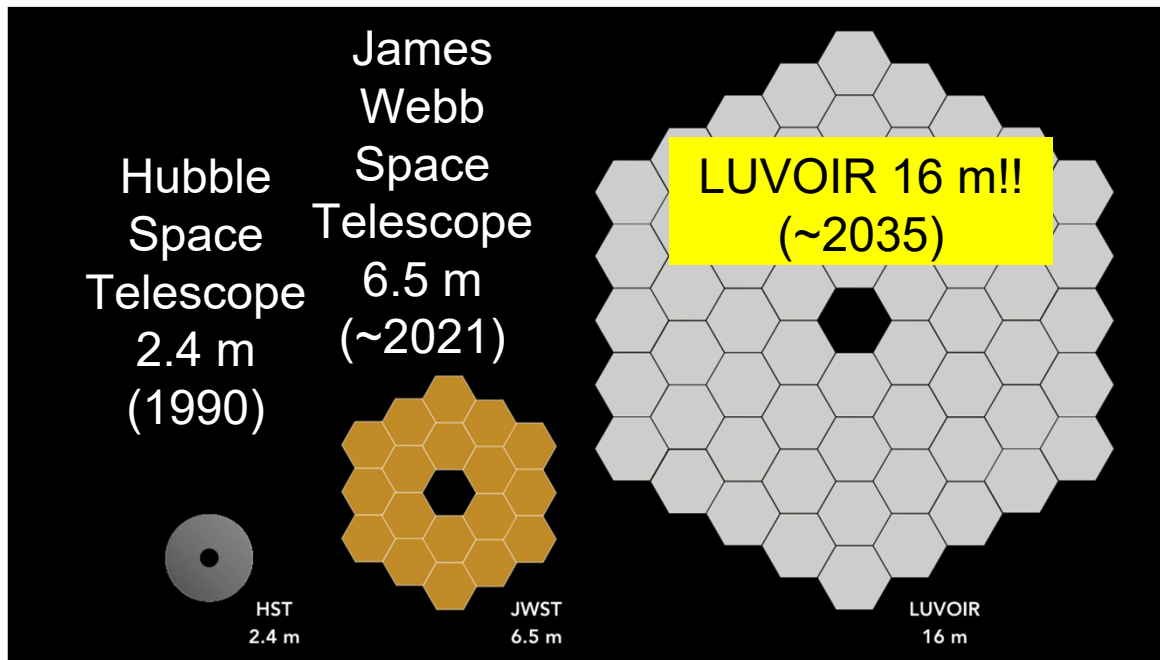
Larger contiguous MxN area (TSVs)  
Better timing resolution  
Huge dynamic range  
Photon/particle counting



28x28 mm  
(2x2 Timepix)



200x200 mm  
(7x7 Timepix4)





## The work done in collaboration

**CERN Medipix team**

**Advacam**

**NIKHEF, Amsterdam**

**IEAP, Prague**

**University of California at Berkeley, CA, USA**

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**Nova Scientific, Inc, Sturbridge, USA (manufacturer of neutron sensitive MCPs)**

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**Rutherford Appleton Laboratory, ISIS Facility, UK**

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*M. Strobl, R. Woracek*

**Technical University of Denmark**

*S. Schmidt*

**Open University, Coventry University, UK**

*M. Fitzpatrick, R. Ramadhan*

**General Electric Global Research**

*Yan Gao*

...and many others!

apologies for missed names



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# Thank you for your attention!

This work was done within the Medipix collaboration.

We would like to thank Medipix collaboration for the readout electronics and data acquisition software (Advacam, Prague and Espoo, NIKHEF, Amsterdam and IEAP, Prague).

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