# Energy (wavelength) selective imaging – Part 2
# Time of Flight (ToF)

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# Energy (wavelength) selective imaging 2

# Reading list & useful references

- **Articles to read** *(in this order is recommended)*
  - Strobl, M. (2009). Future prospects of imaging at spallation neutron sources. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 604(3), 646-652.
    - *Note that this article is from 2009 (the very beginning of ToF imaging), but it summarizes all considerations and the motivations for installating an imaging beamline at a spallation source.*
  - Kockelmann, W., Minniti, T., Pooley, D. E., Burca, G., Ramadhan, R., Akeroyd, F. A., ... & Kabra, S. (2018). Time-of-Flight Neutron Imaging on IMAT@ ISIS: A New User Facility for Materials Science. Journal of Imaging, 4(3), 47.
    - *Description of one of the two ToF imaging beamlines operational worldwide. The article summarizes all important aspects (basics of ToF, basic instrumentation, detectors) as well as a detailed application example.*
  - Woracek, R., Santisteban, J., Fedrigo, A., & Strobl, M. (2018). Diffraction in neutron imaging—A review. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 878, 141-158.
    - *Neutron imaging contrast based on diffraction (often called 'Bragg edge imaging') is the most common application for ToF imaging (as of now). This article gives a comprehensive overview of the principles and shows several examples.*

# Wavelength selective imaging 2 - ToF

## AGENDA

- **Part 1: Introduction to ToF imaging**
  - Basics (neutron energy, wavelength, velocity)
  - The ToF concept
  - ToF vs steady state instruments
- **Part 2: What do we need for a ToF neutron imaging instrument?**
  - ToF Neutron Source
  - Examples of of ToF imaging beamlines
  - ToF Detectors
- **Part 3: ToF Imaging methods**
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  - ‘Attenuation’: Monochromatic, ‘white-beam’ and ‘pink-beam’ (narrow wavelength) applications
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  - Other methods to profit from ToF: Polarized, phase and dark field, 3DND, resonance absorption
- **Part 4:** Hands on example (please install https://imagej.net/Fiji/Downloads or https://imagej.nih.gov/ij/download.html)

# Energy (wavelength) selective imaging 2

## Part 1: Basics

- The neutron can be described as a classical particle with mass m but it shows wave character too, which can be described with the deBroglie wavelength λ.
- neutron energy <-> neutron wavelength <-> neutron velocity

$$E = \frac{mv^2}{2} = \frac{h^2}{2m} \cdot \frac{1}{\lambda^2}$$

$$\lambda[\text{Å}] = \frac{9.045}{\sqrt{E[meV]}}$$

$$E[meV] = \frac{81.82}{(\lambda[\text{Å}])^2}$$

$$v[m/s] = \frac{3956}{\lambda[\text{Å}]} = 437 \cdot \sqrt{E[meV]}$$

- So..... : One can determine the wavelength of neutron by knowing its velocity!
- How can one determine a neutrons velocity?

## Part 1: Basics

- How can one determine a neutrons velocity?
  - By starting a (many) neutron(s) at a time $t_0$ and stop the time it needs to travel a distance L

# Energy (wavelength) selective imaging 2

## Part 1: Basics

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$$t_{ToF} = \frac{\lambda \cdot m \cdot L_{Det}}{h} = \frac{\lambda \cdot L_{Det}}{3956} (\text{Å}m/s)$$

$L_{Det}$ = distance from source to detector
m = mass of the neutron
h = Planck's constant
$\lambda$ = neutron wavelength

- How can one run a ToF experiment?
  - Use a high intensity neutron source with a 'pulsed beam'
  - A reactor is a 'steady state' source, but one can use choppers
  - A spallation source is pulsed be design
- So far, two dedicated neutron time of flight imaging beamlines are in operation:
  - RADEN (J-PARC, Japan) and IMAT (ISIS, UK). Also tof beamlines used for imaging at LANSCE (USA) and ORNL-SNS (USA). ODIN at ESS will start user operation in 2023.
- Wavelength selection allows for maximizing image contrasts…

EUROPEAN SPALLATION SOURCE

# Neutrons have both Particle-like and Wave-like Properties

- Mass: $m_n = 1.675 \times 10^{-27}$ kg
- Charge = 0; Spin = ½
- Magnetic dipole moment: $\mu_n = -1.913\ \mu_N$
- Kinetic energy (E), Velocity (v), Wavelength (λ), Wavevector (k)

$$E = m_n v^2/2 = k_B T = (hk/2\pi)^2/2\ m_n;\ k = 2\pi/\lambda = m_n v/\ (h/2\pi)$$

| | Energy (meV) | Temperature(k) | Wavelength (nm) |
|---|---|---|---|
| Cold | 0.1 – 10 | 1 – 120 | 0.4 – 3 |
| Thermal | 5 – 100 | 60 – 1000 | 0.1 – 0.4 |
| Hot | 100 - 500 | 1000 - 6000 | 0.04 – 0.1 |

Room temperature ~ 25 meV ~ 0.18 nm ~ 2200 m/s

# Energy (wavelength) selective imaging 2

## Part 1: Terminology

Terminology in this quickly developing field is still a source of confusion. Therefore the following terminology is proposed and used herein:

- Because in elastic scattering, and meanwhile also largely in imaging, neutrons are characterized and described with their wavelengths, we predominantly use of **wavelength instead of energy.**

- **Wavelength resolved measurements** are all measurements in which the wavelength of the detected neutron is well defined within the limits of resolution.

- **Wavelength selective** should be the term for monochromatic measurements or series of discrete monochromatic measurements.

- **Wavelength dispersive** should be the term are wavelength resolved measurements that continuously cover a certain wavelength bandwidth.

- **Bragg edge imaging** describes spatially resolved wavelength resolved transmission measurements, which take advantage of the elastic coherent scattering signature of a polycrystalline sample in the attenuation spectrum, i.e. the wavelength dependent cross section.

- While this is clearly an attenuation based approach, due to the nature of the specific exploited contrast originating in diffraction, the term **diffraction contrast** for this kind of wavelength dependent attenuation is certainly eligible.

- For imaging methods working in diffraction instead of transmission geometry we propose the term **diffractive imaging** with potential sub-categories for topology and others.

# Wavelength selective imaging 2 - ToF

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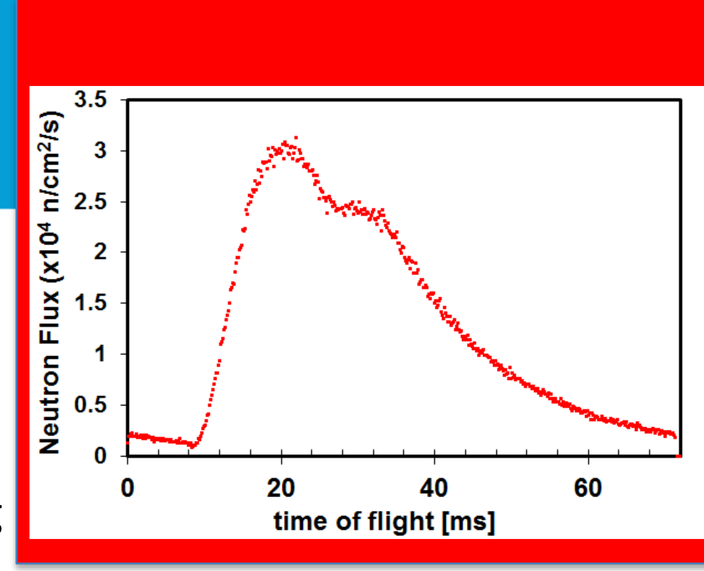
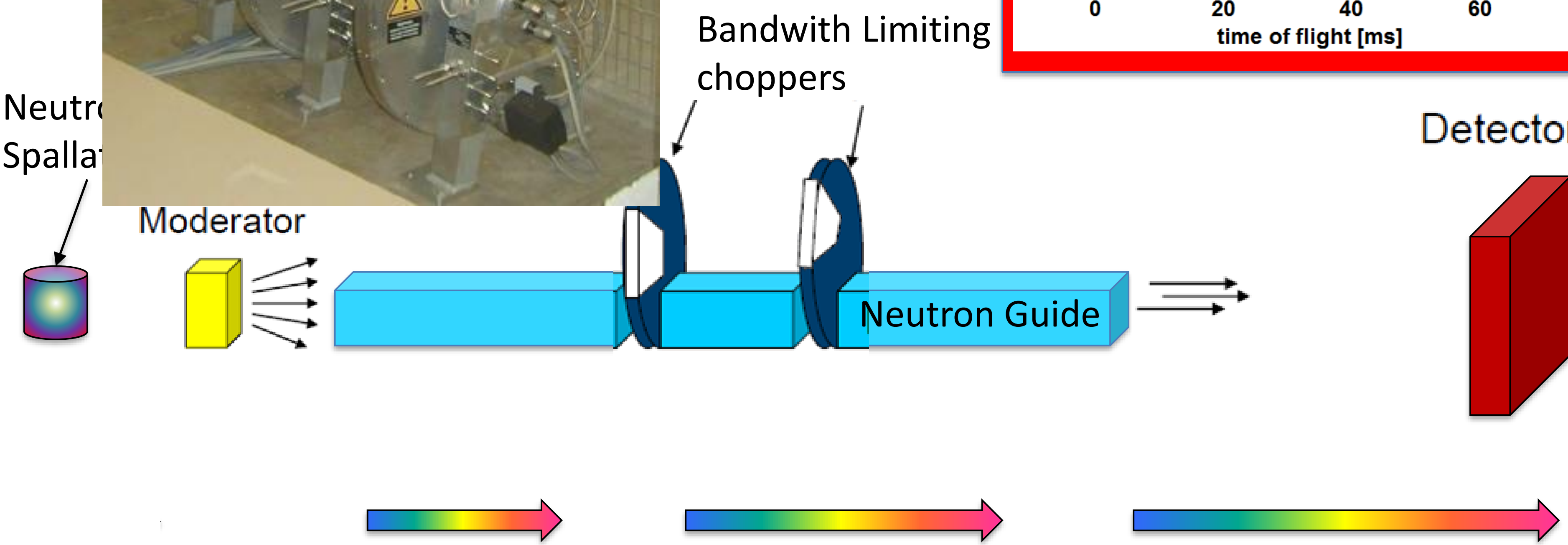
# Wav... ging 2

## Par...

- A... ment
- In...

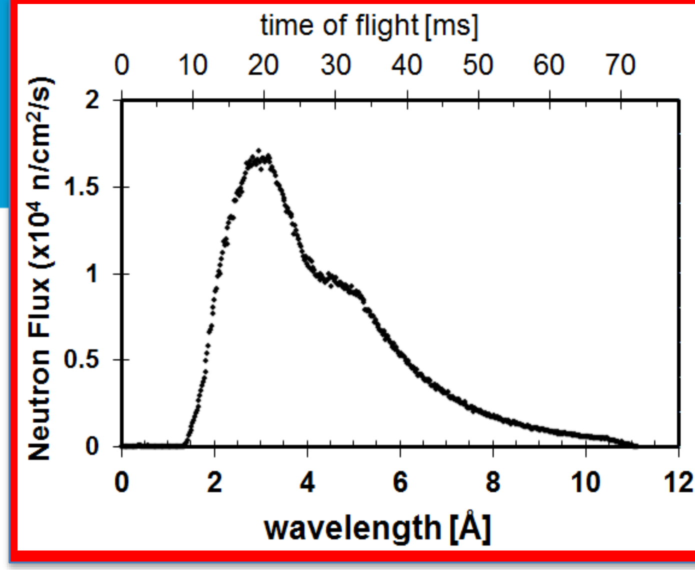


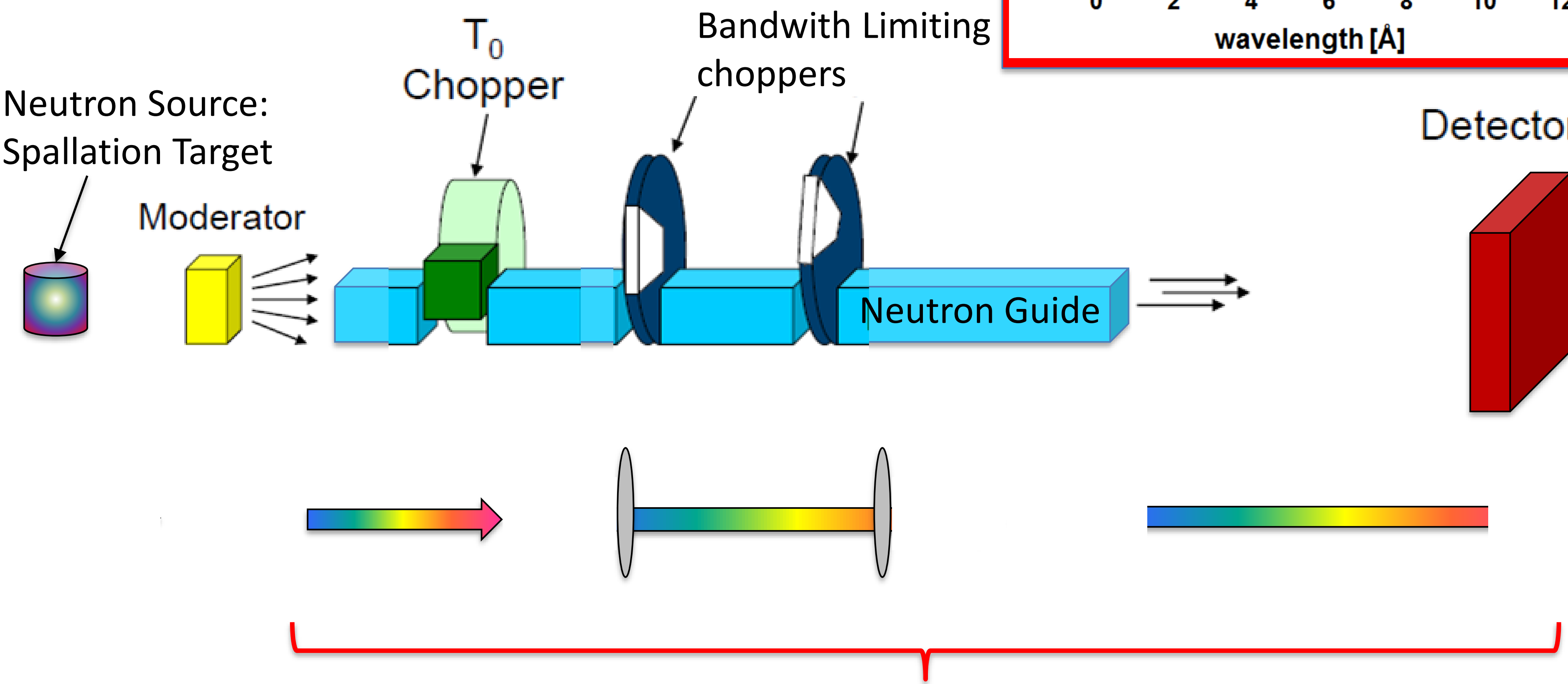



# Wavelength selective imaging 2

## Part 1: The ToF concept

- A generic pulsed source instrument
- Introducing choppers



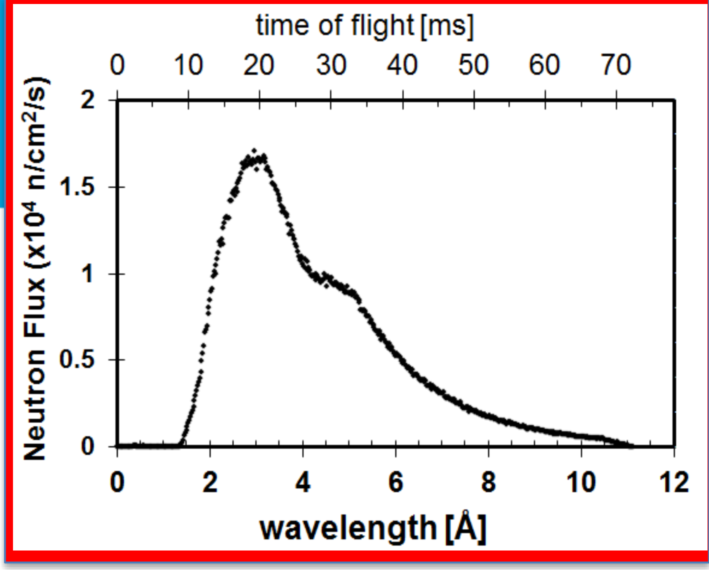



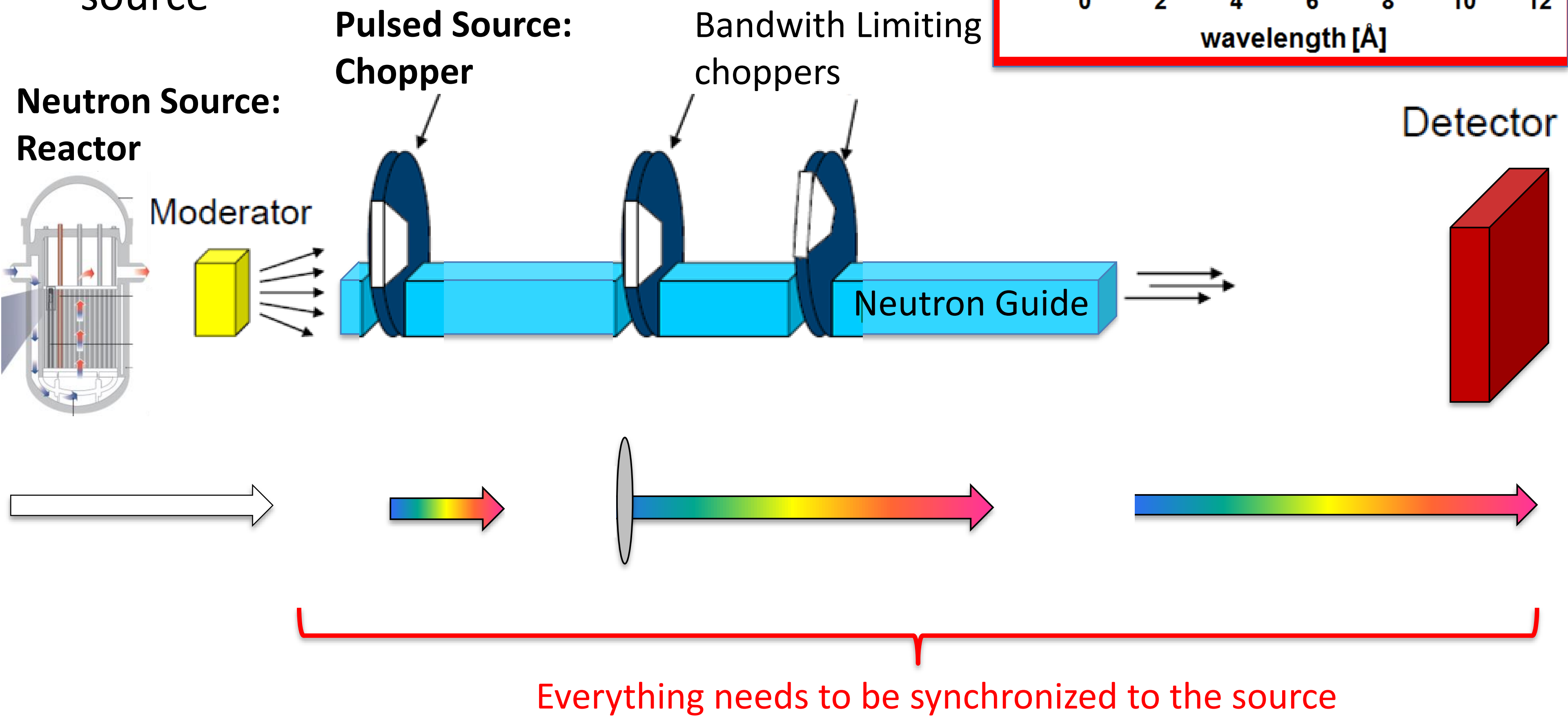

Everything needs to be synchronized to the source

# Wavelength selective imaging 2

## Part 1: The ToF concept

- A generic pulsed source instrument
- Introducing choppers
- Can also be implemented at a steady state source

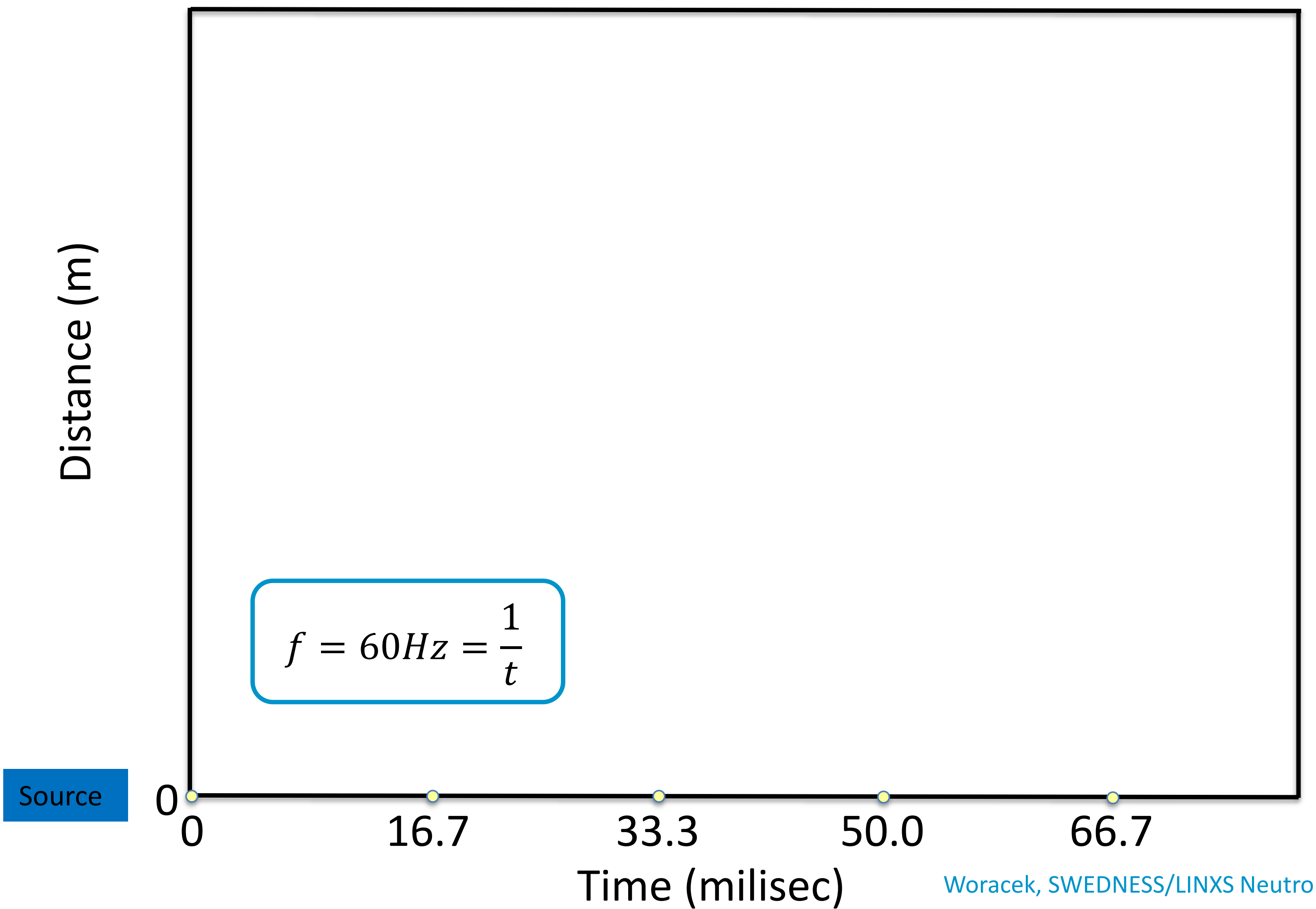


# Wavelength selective imaging 2

## Part 1: The ToF concept

- The ToF diagram



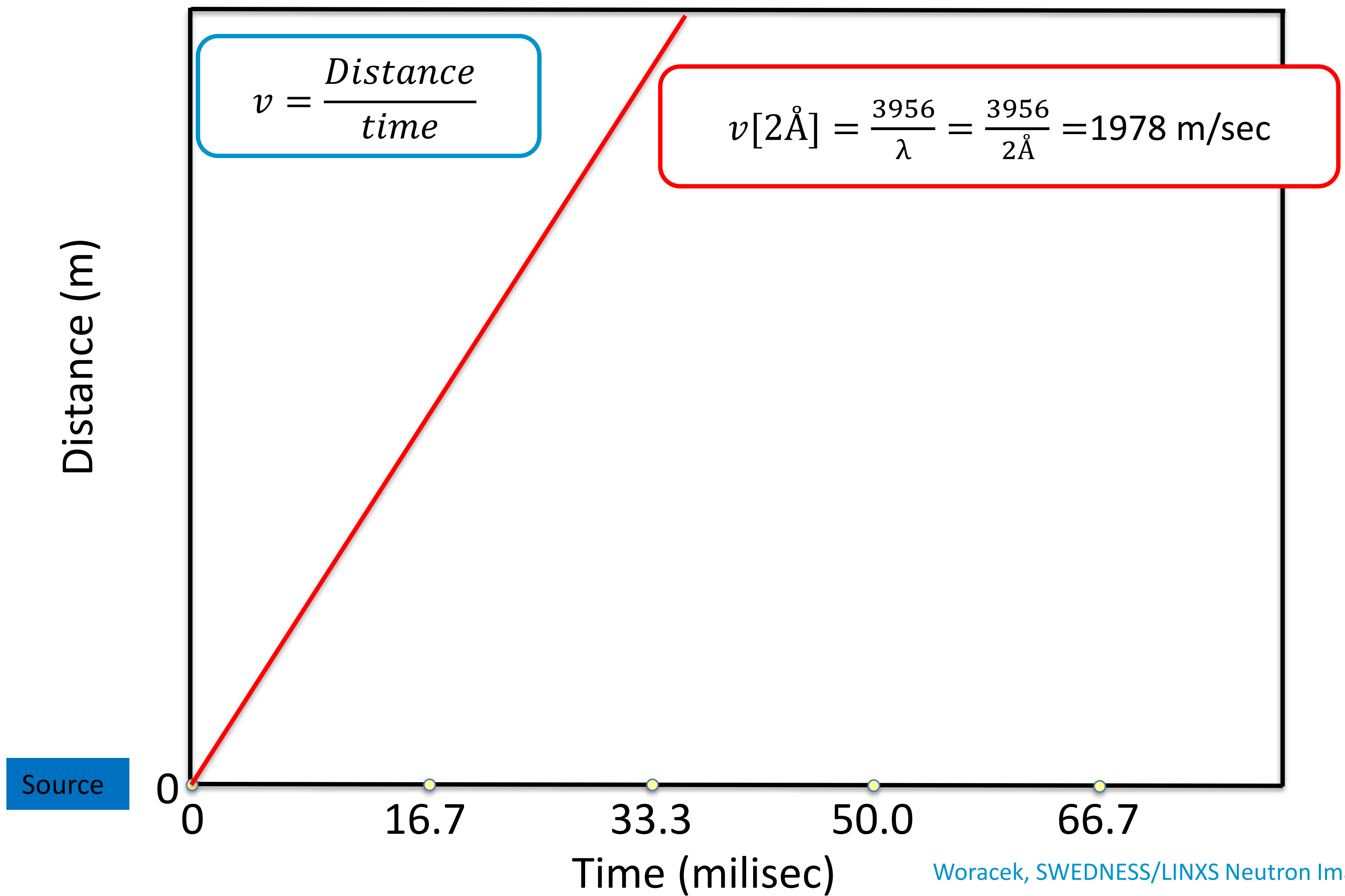

$$f = 60Hz = \frac{1}{t}$$

# Wavelength selective imaging 2

## Part 1: The ToF concept

EUROPEAN SPALLATION SOURCE

- The ToF diagram



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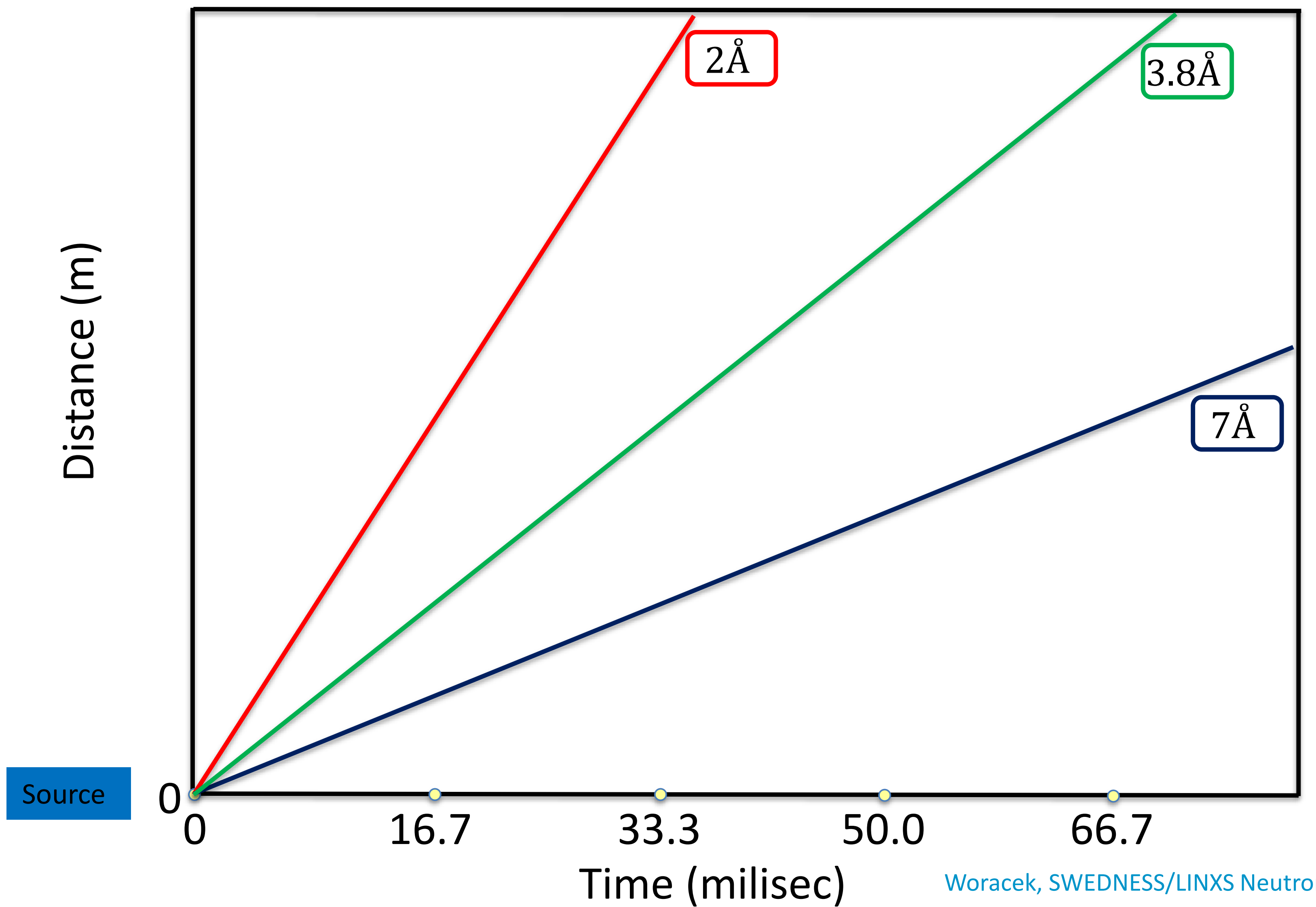

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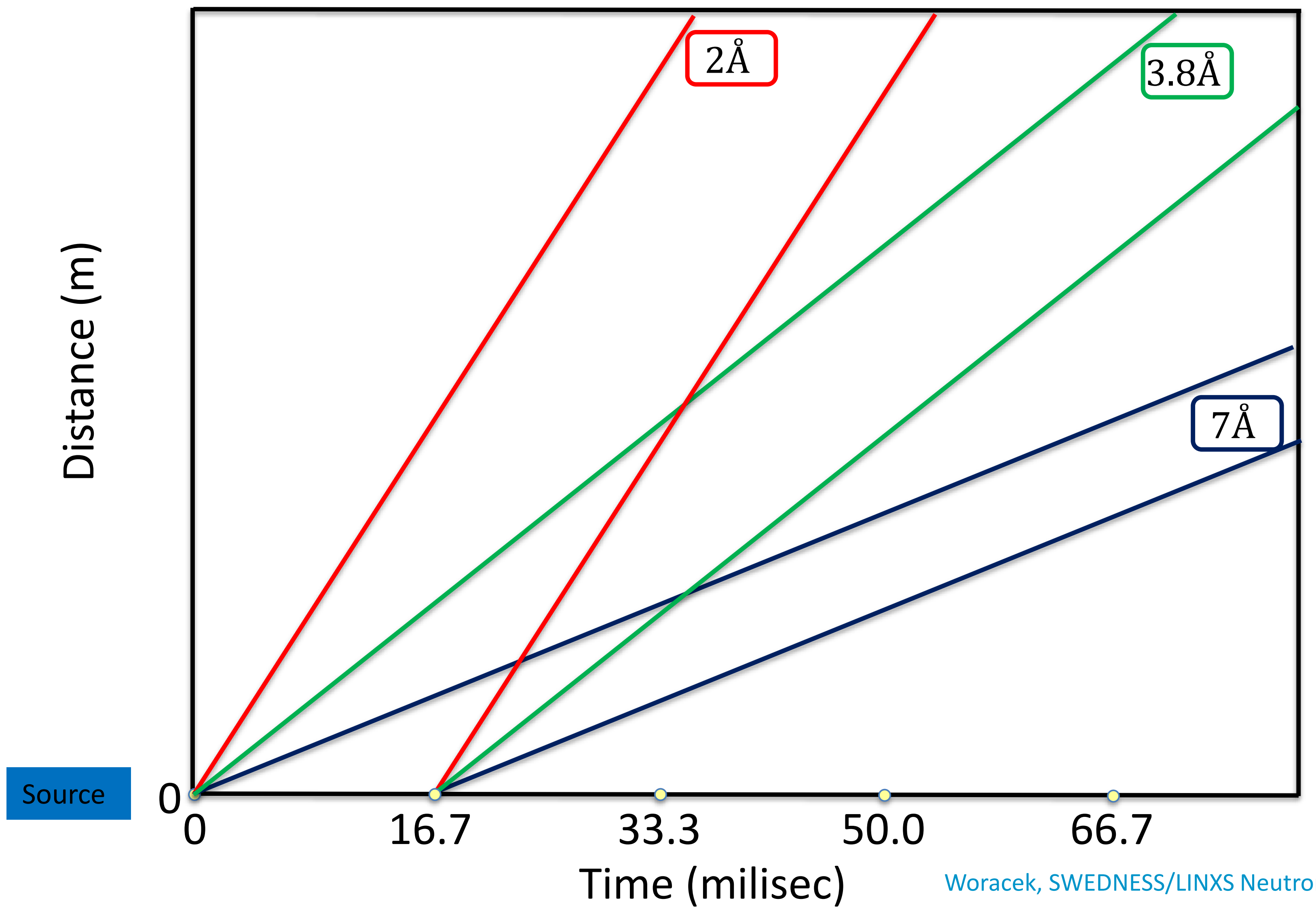

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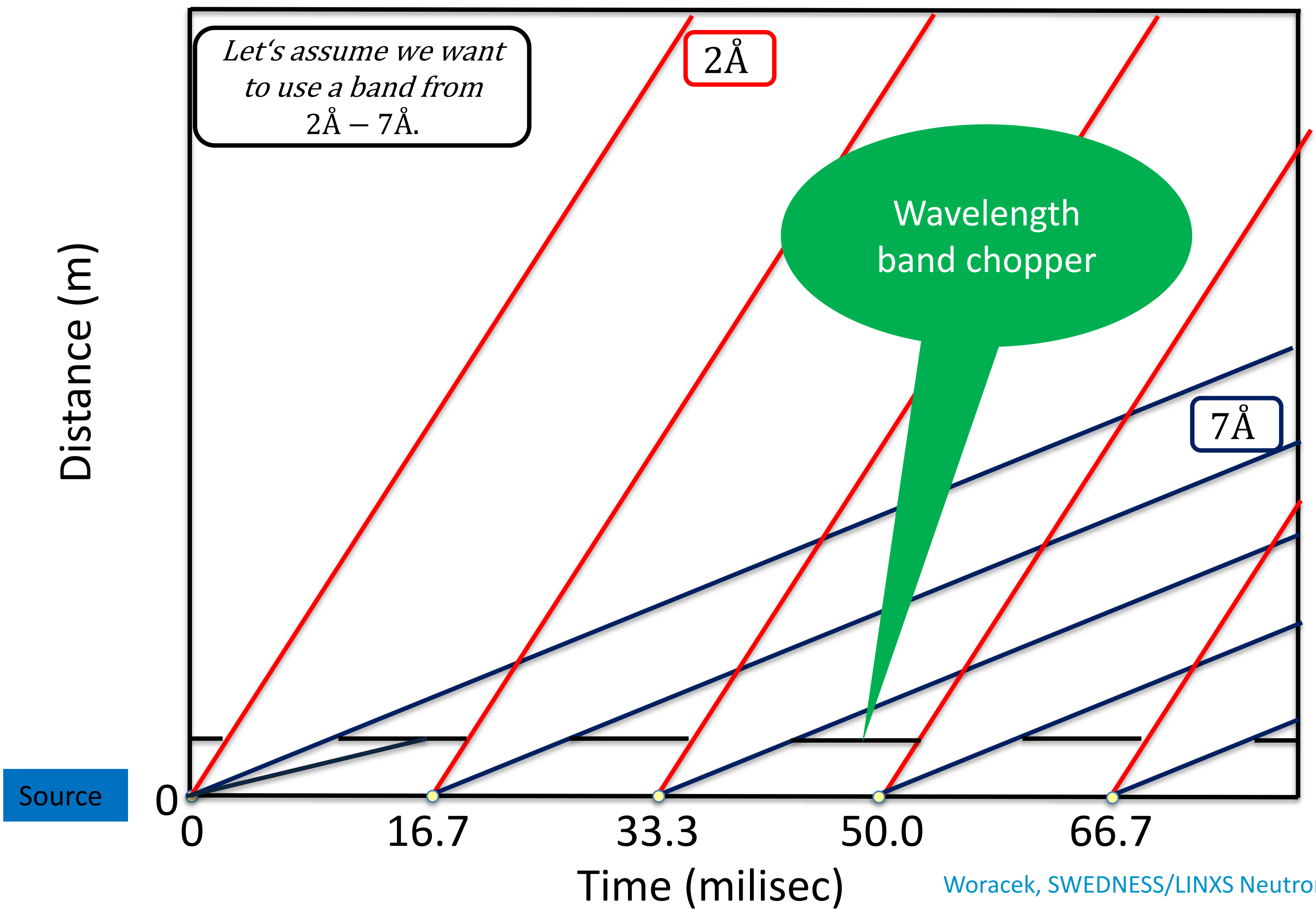

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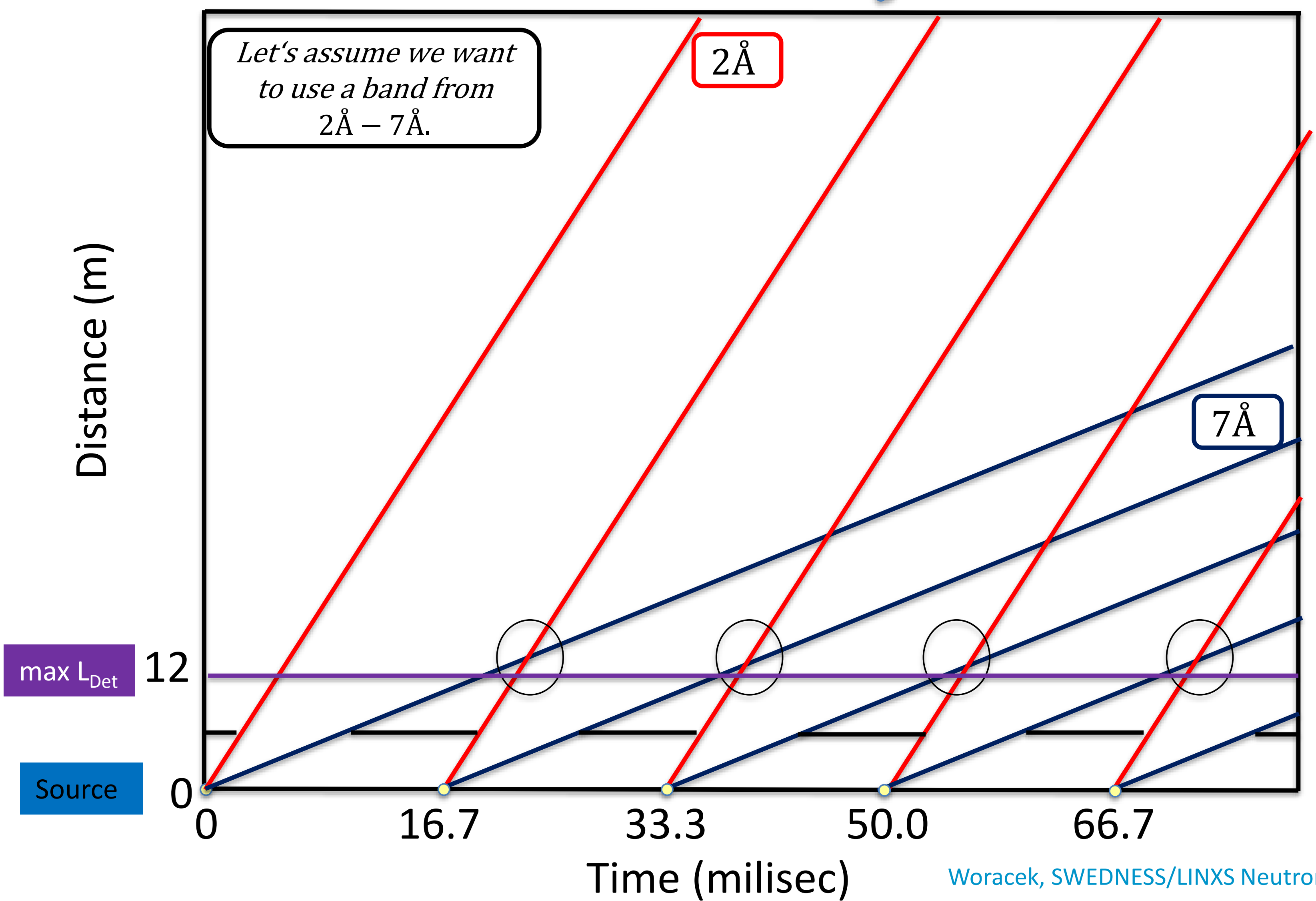

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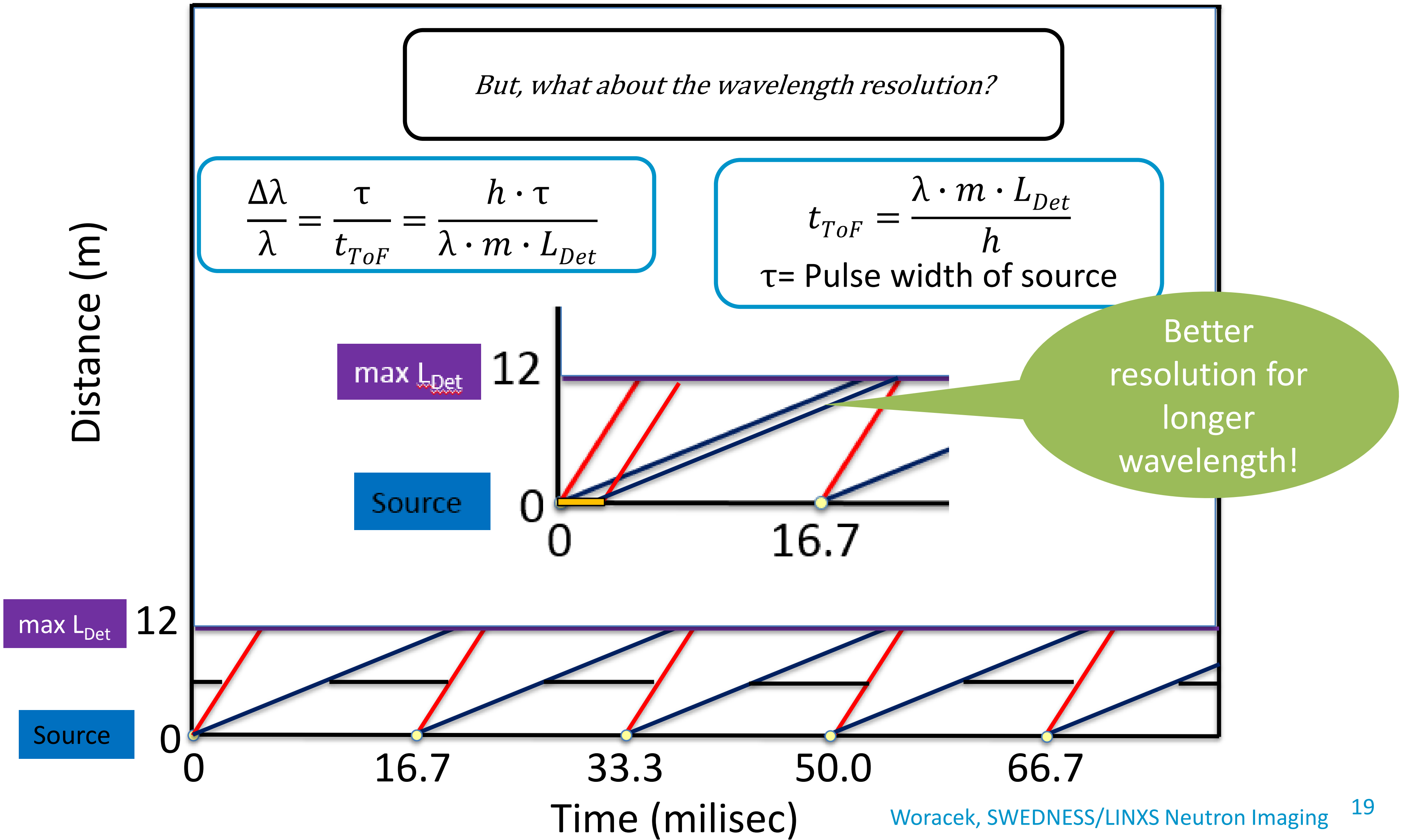


# Wavelength selective imaging 2

## Part 1: The ToF concept

- The ToF diagram

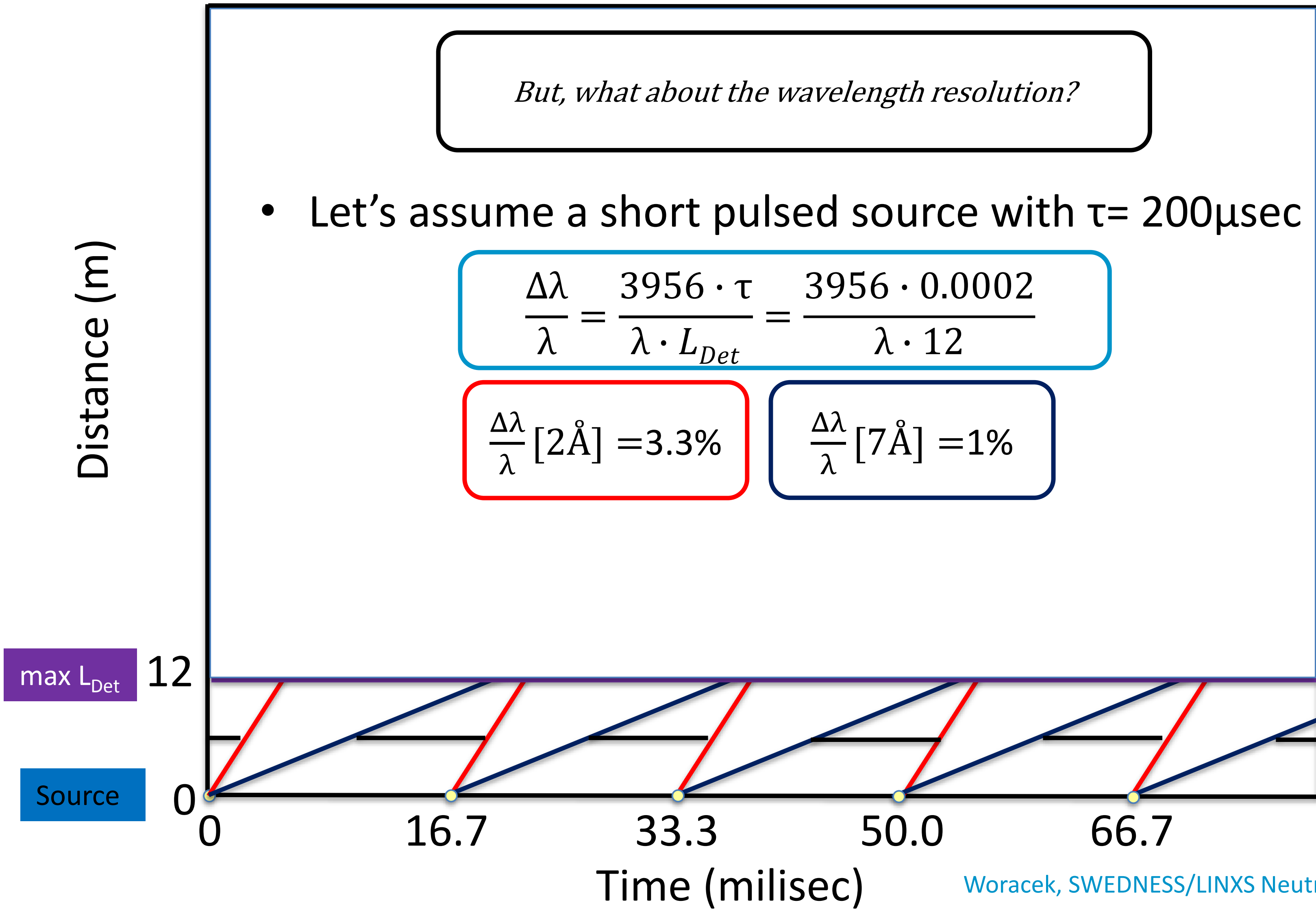
*But, what about the wavelength resolution?*

- Let's assume a short pulsed source with τ= 200µsec

$$\frac{\Delta\lambda}{\lambda} = \frac{3956 \cdot \tau}{\lambda \cdot L_{Det}} = \frac{3956 \cdot 0.0002}{\lambda \cdot 12}$$

$\frac{\Delta\lambda}{\lambda}[2Å]$ =3.3%

$\frac{\Delta\lambda}{\lambda}[7Å]$ =1%



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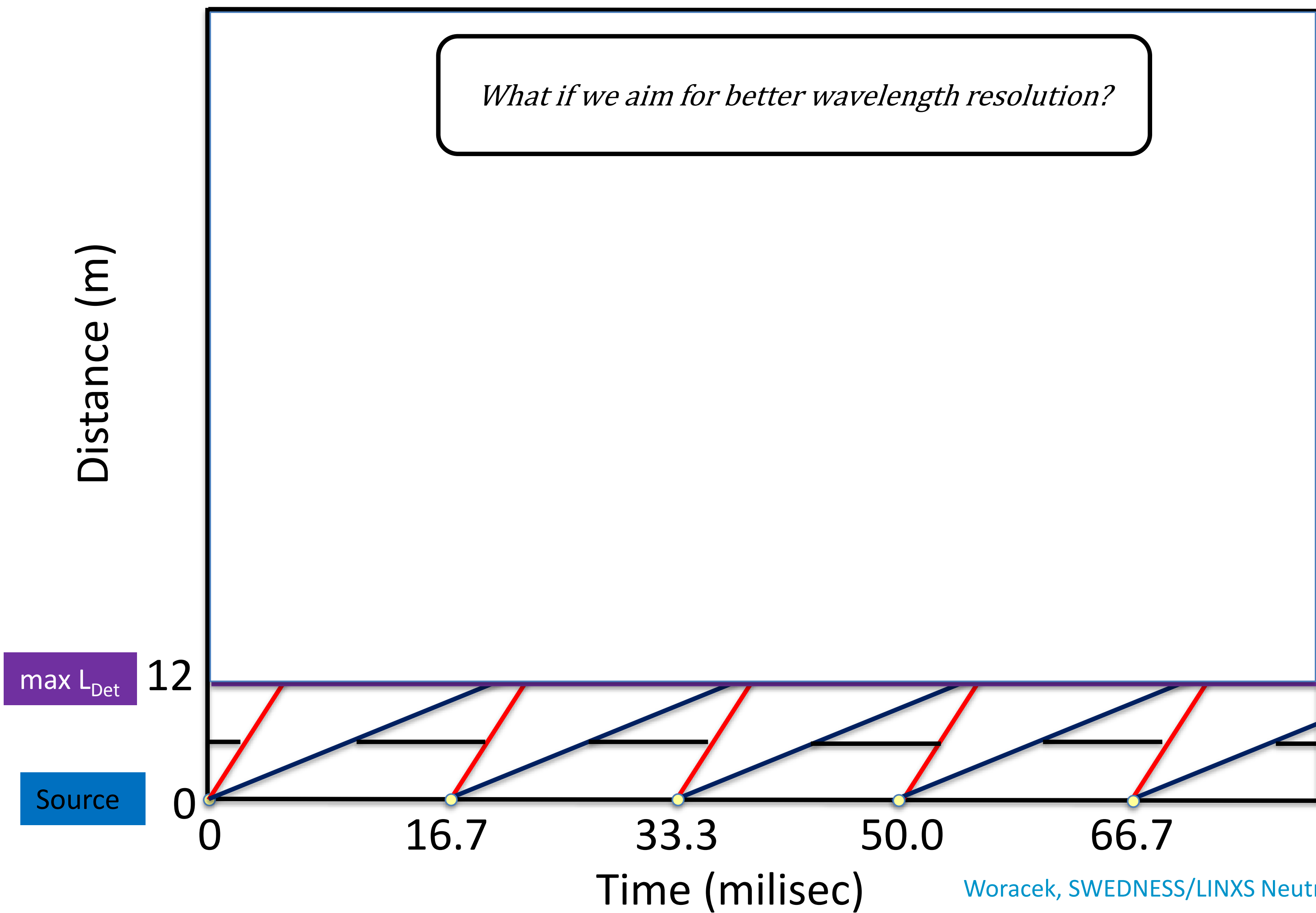

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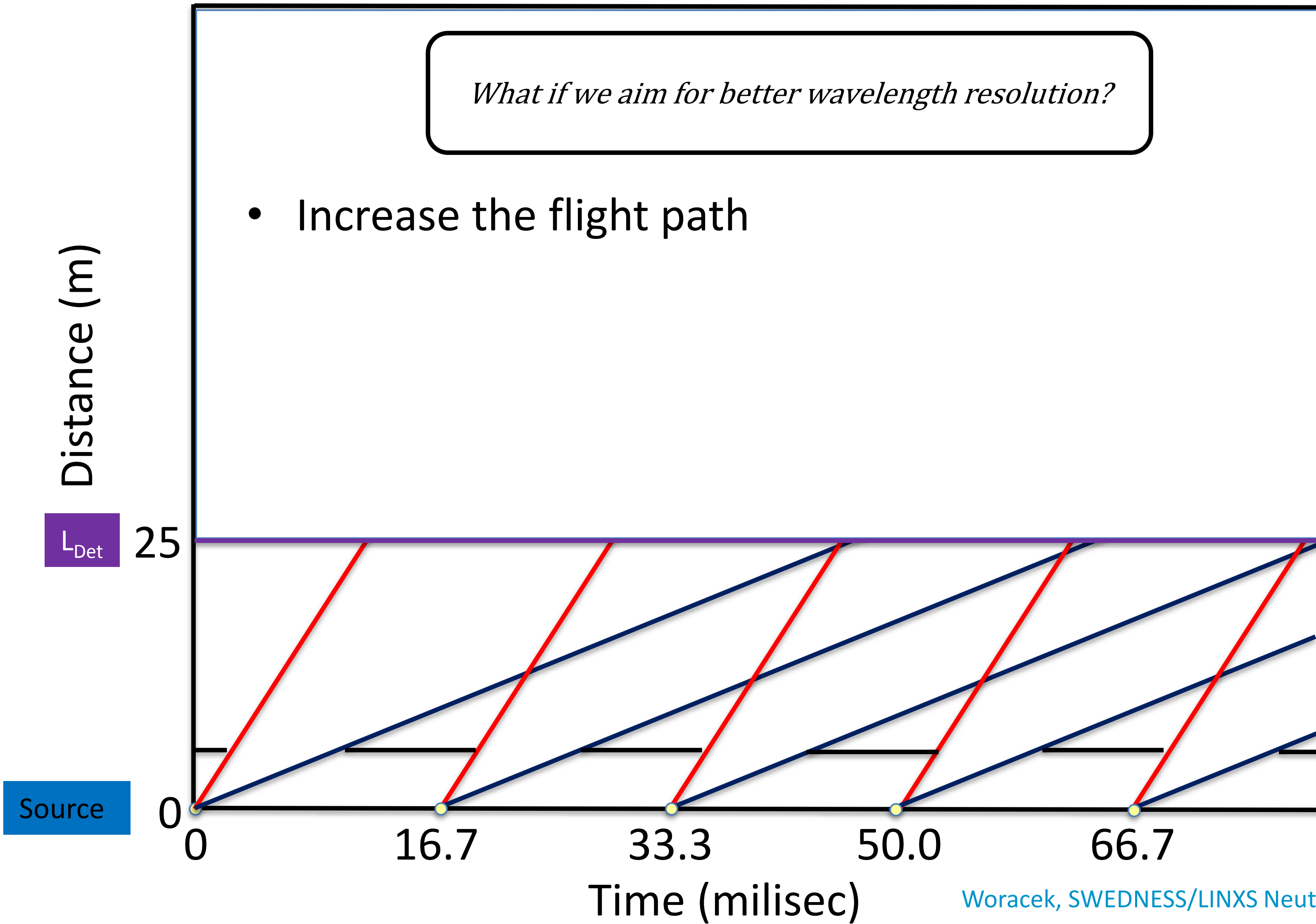


# Part 1: The ToF concept

- The ToF diagram

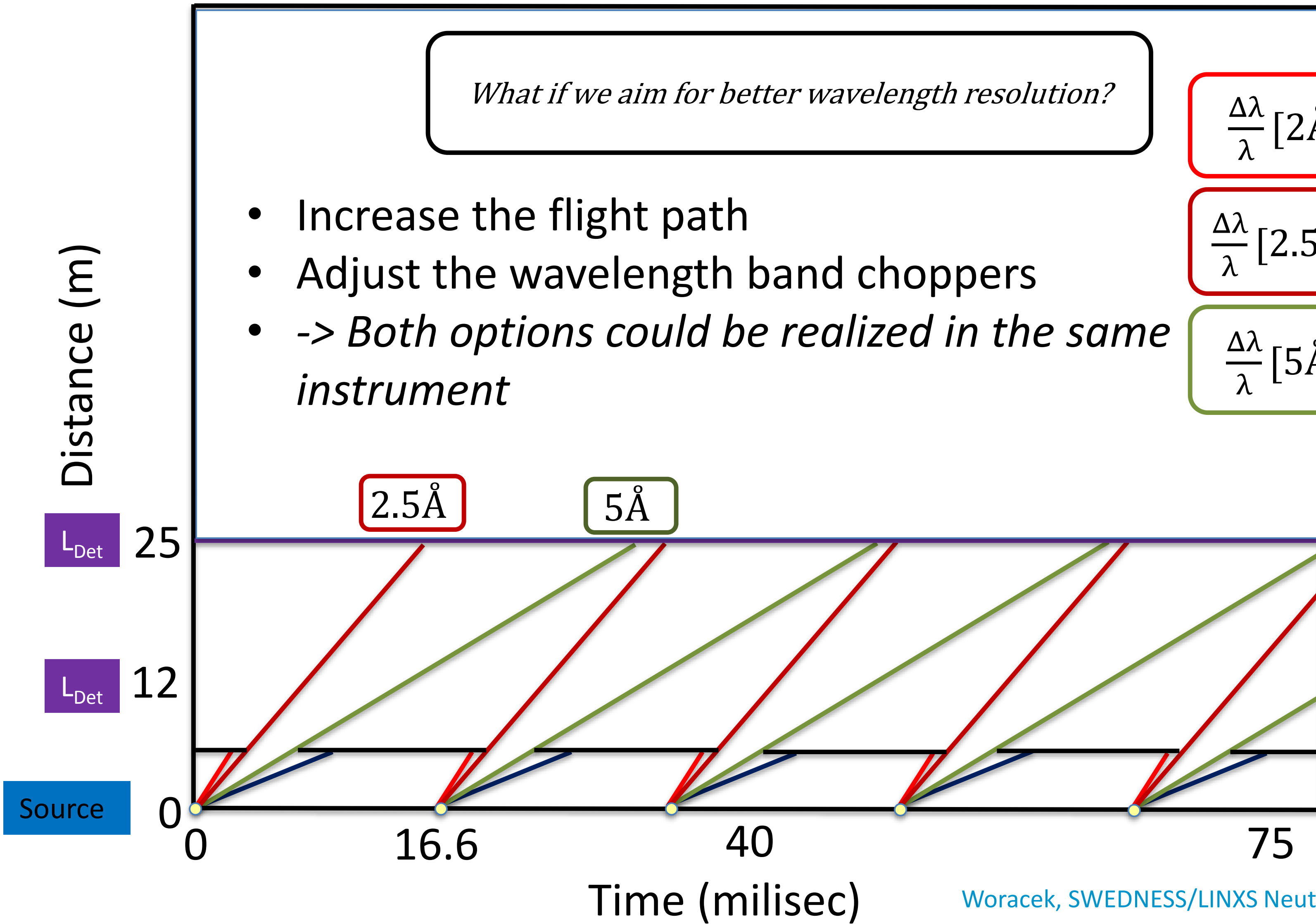
*What if we aim for better wavelength resolution?*

- Increase the flight path
- Adjust the wavelength band choppers
- *-> Both options could be realized in the same instrument*

$$\frac{\Delta\lambda}{\lambda}[2\text{Å}] = 1.6\%$$

$$\frac{\Delta\lambda}{\lambda}[2.5\text{Å}] = 1.3\%$$

$$\frac{\Delta\lambda}{\lambda}[5\text{Å}] = 0.6\%$$



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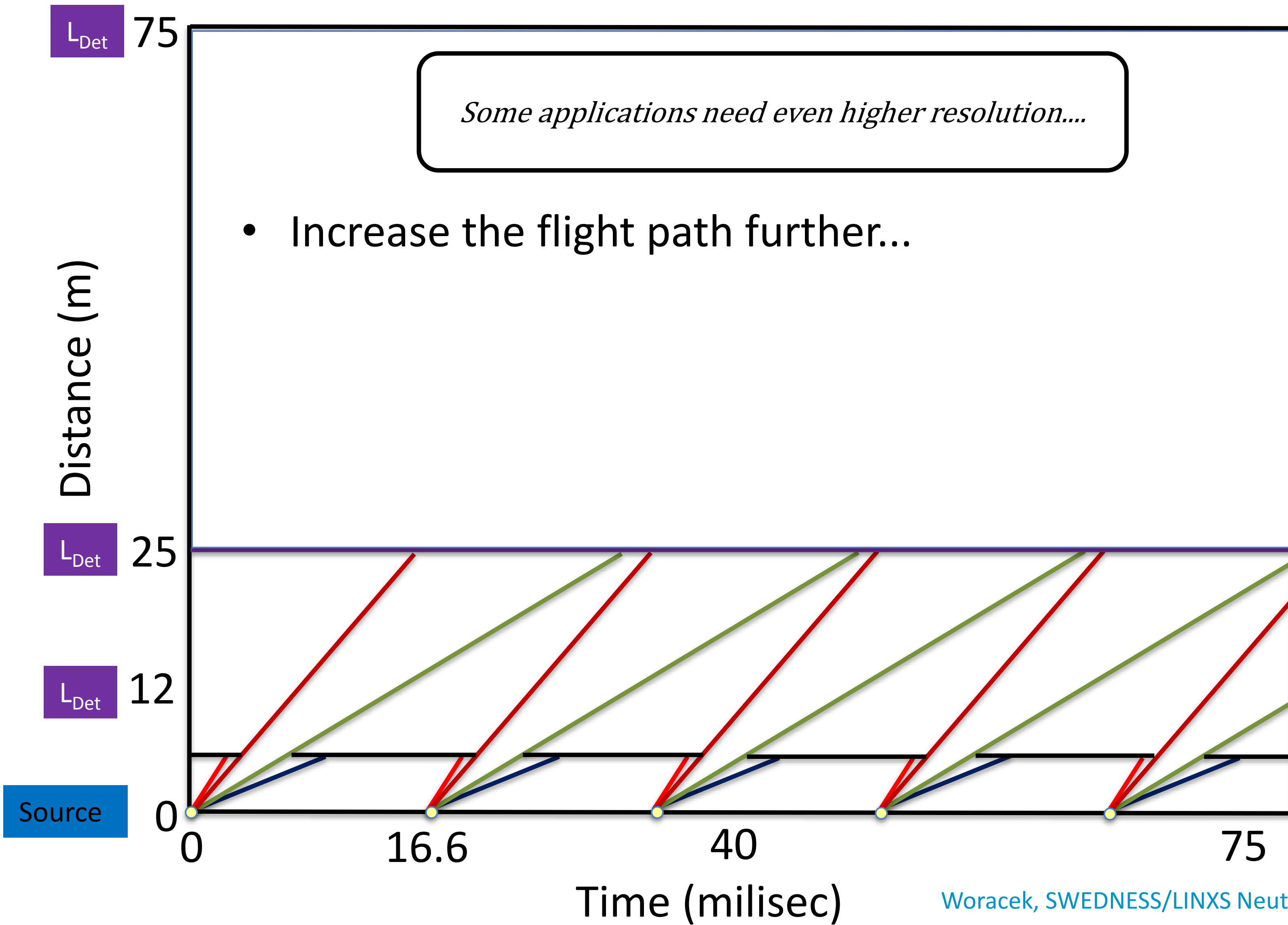

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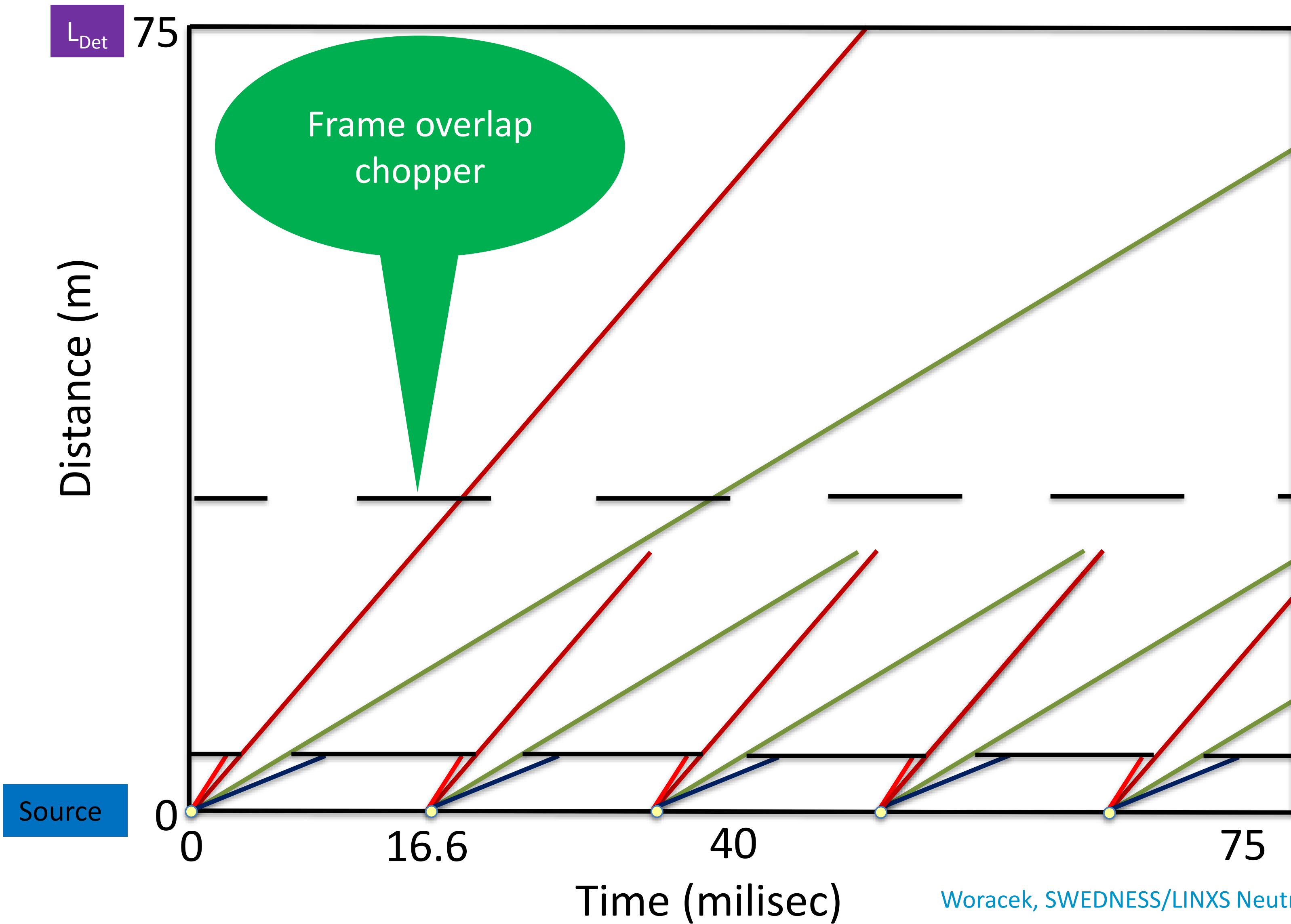

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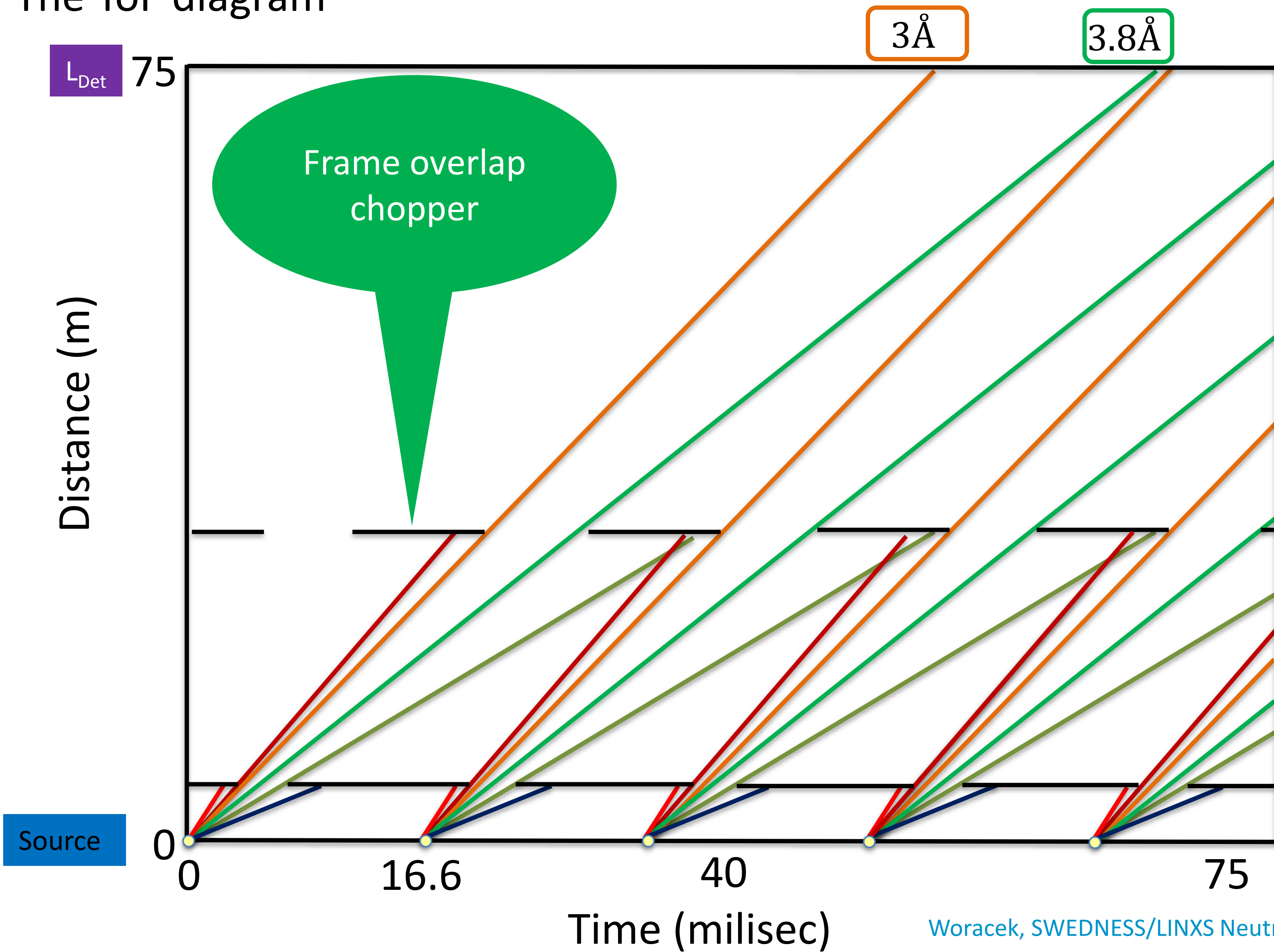

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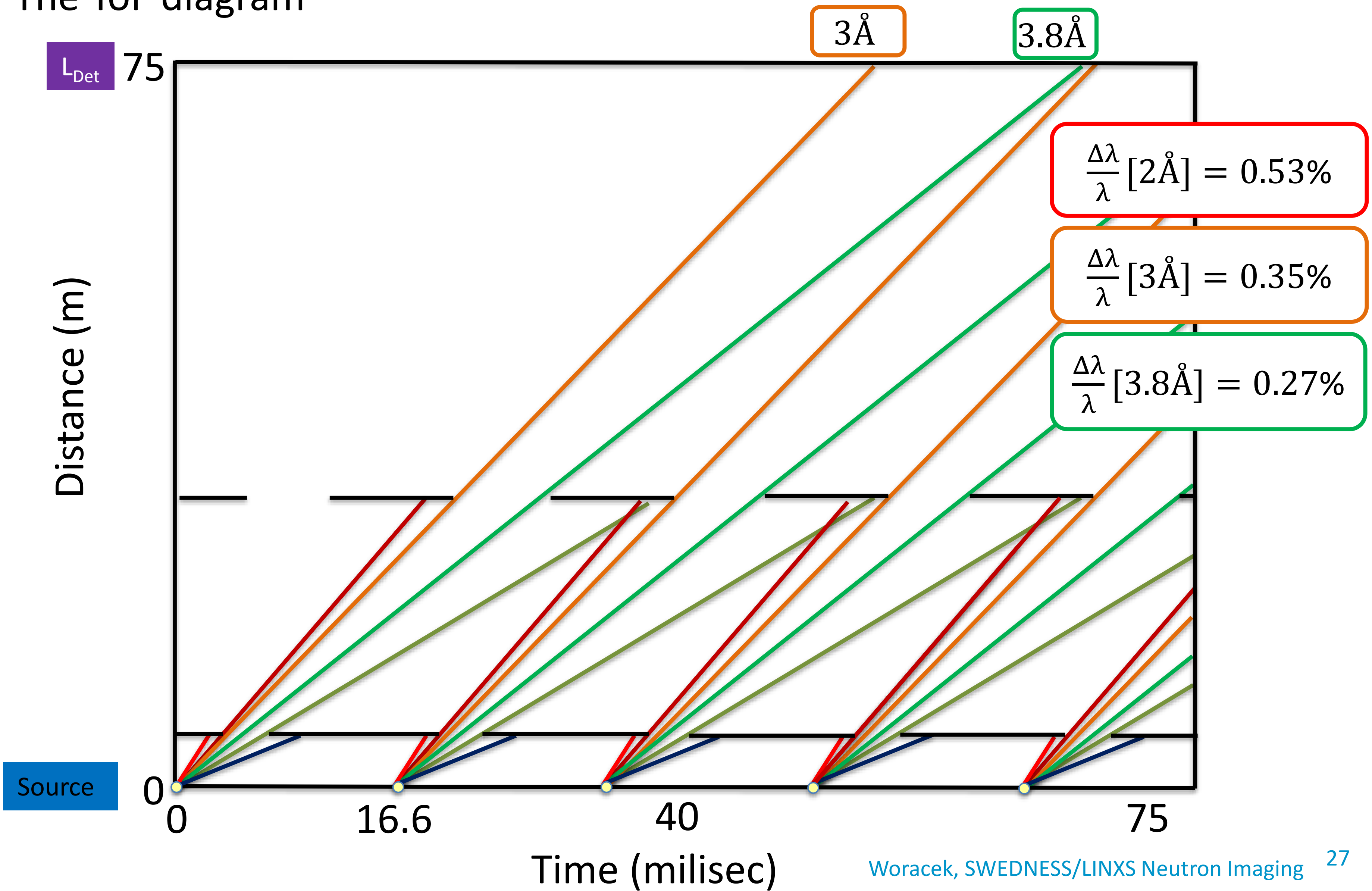
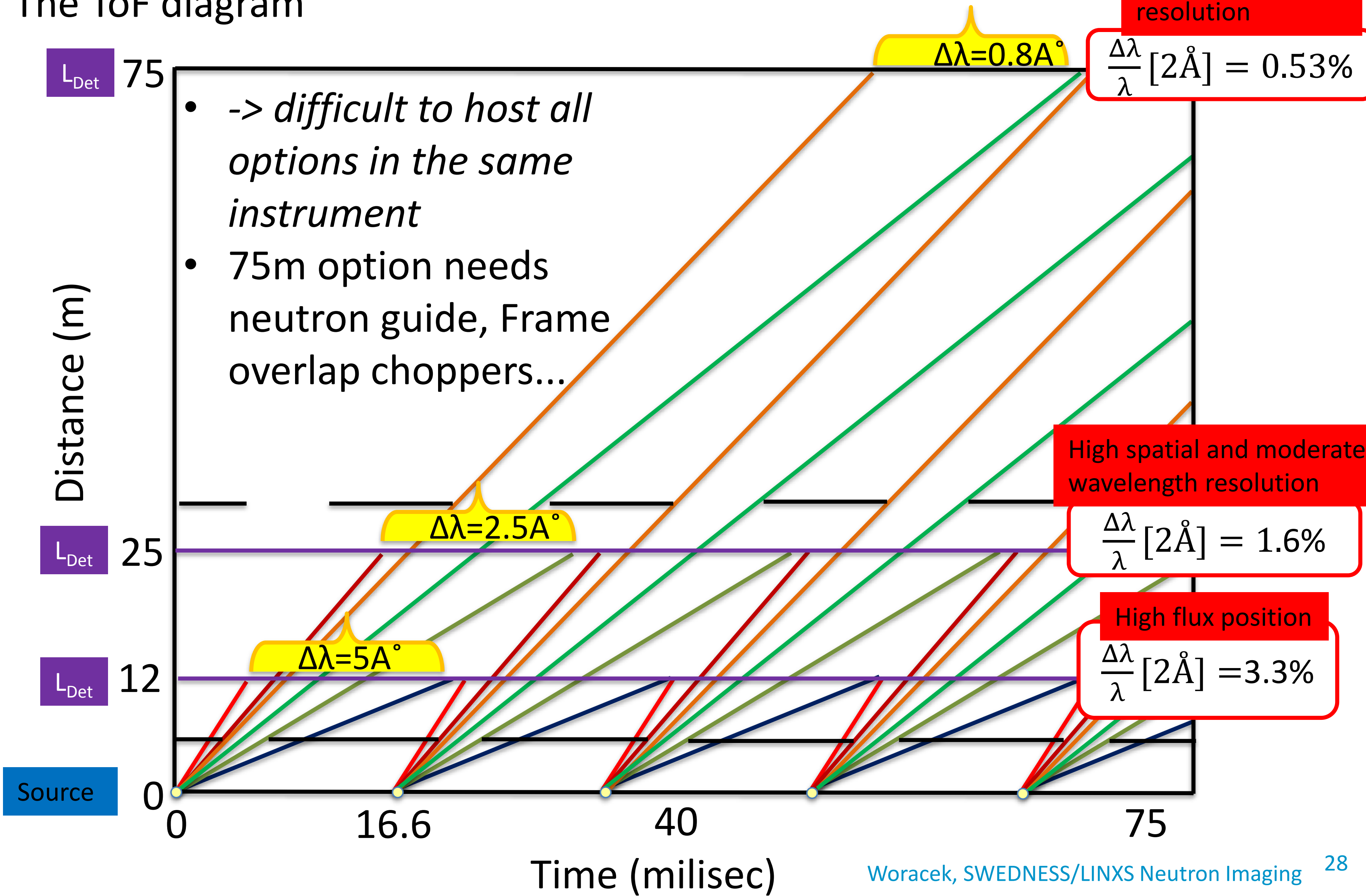


# Wavelength selective imaging 2

## Part 1: The ToF concept

Strobl, M. (2009). Future prospects of imaging at spallation neutron sources. NIMA 604

- The ToF diagram




- *-> difficult to host all options in the same instrument*
- 75m option needs neutron guide, Frame overlap choppers...

# Wavelength selective imaging 2 - ToF

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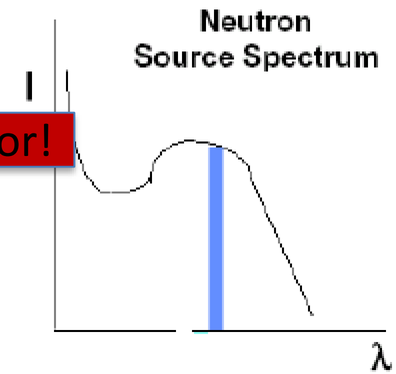
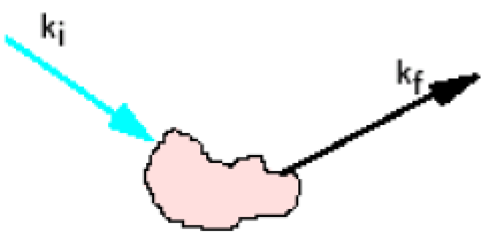
# Differences between TOF and steady-state

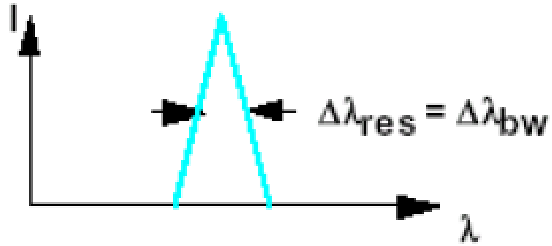
Steady-state

- uses single wavelength
- bandwidth (bw) = resolution width (res)




**Imaging:** We only have one angle! -> need to tune the monochromator!



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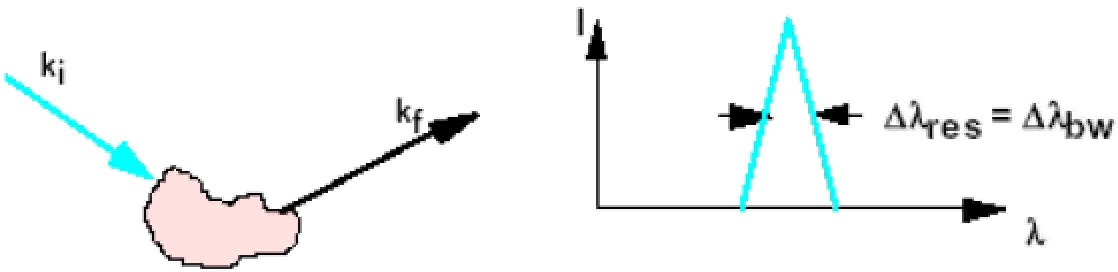
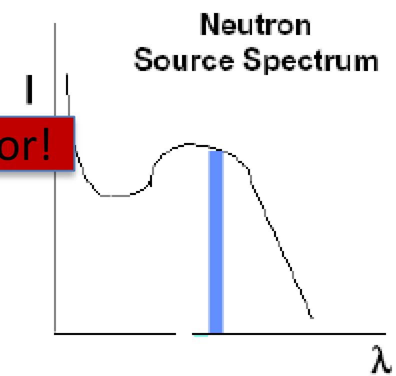
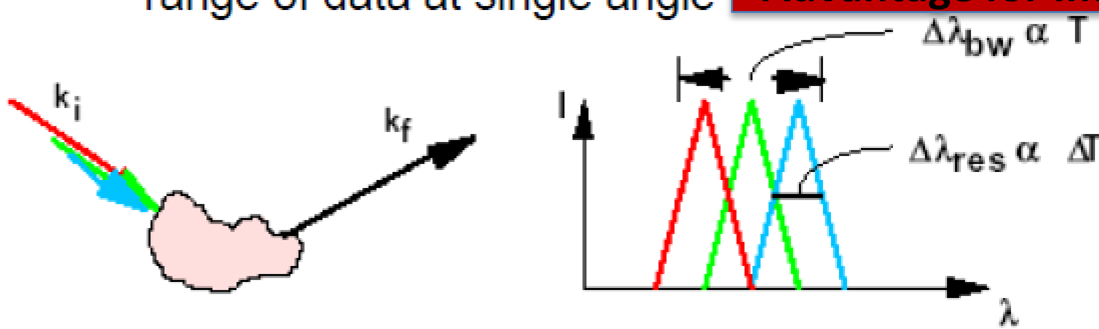
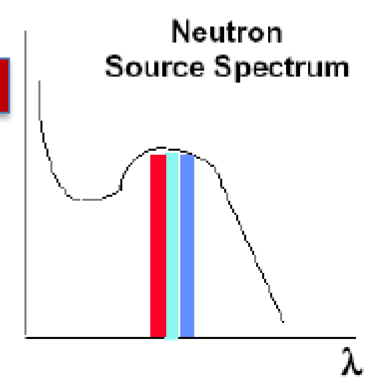



TOF
- uses range of wavelengths
- bandwidth (bw) >> resolution width (res)
- range of data at single angle

**Advantage for Imaging**

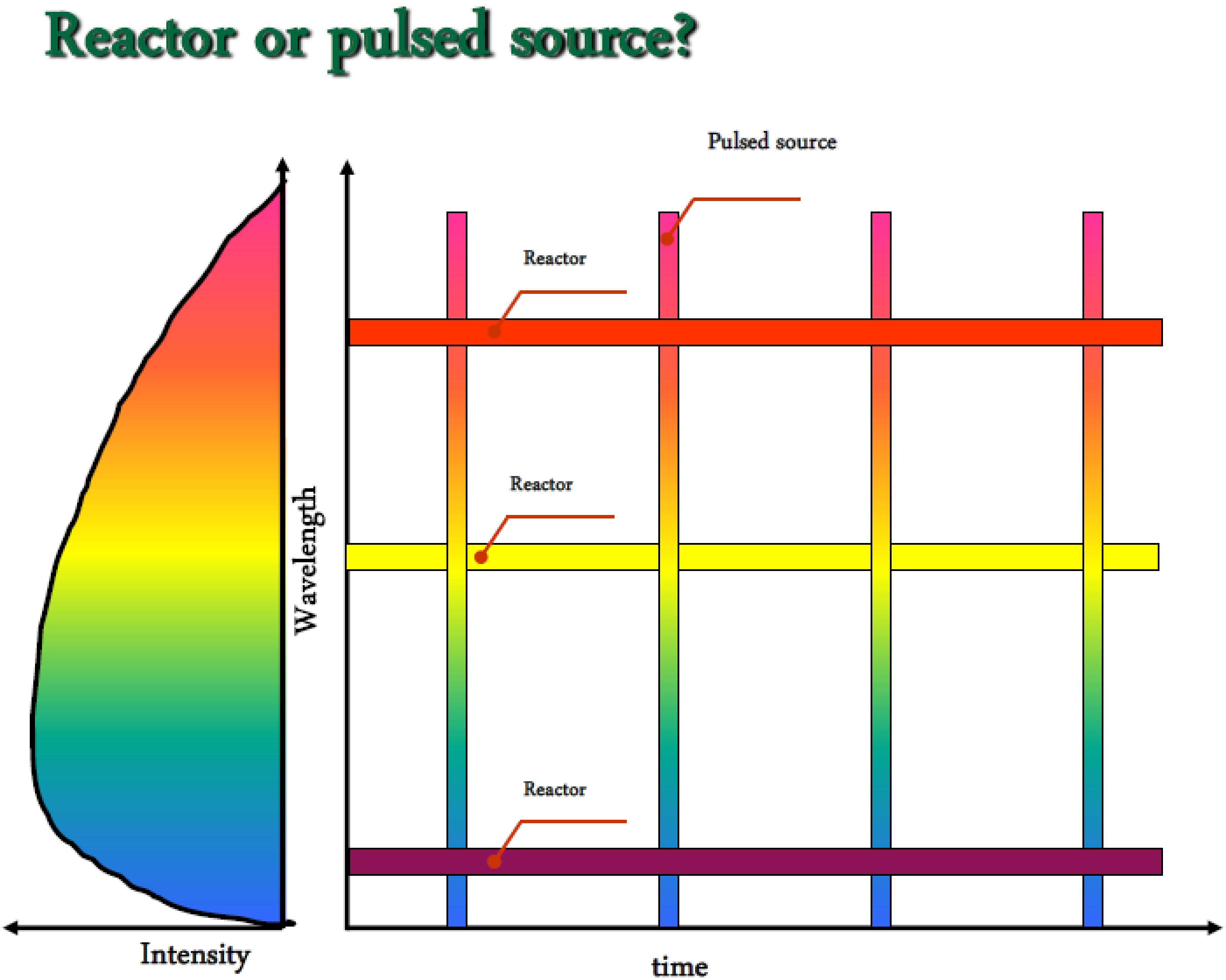


# Wavelength selective imaging 2

## Part 1: ToF vs steady state

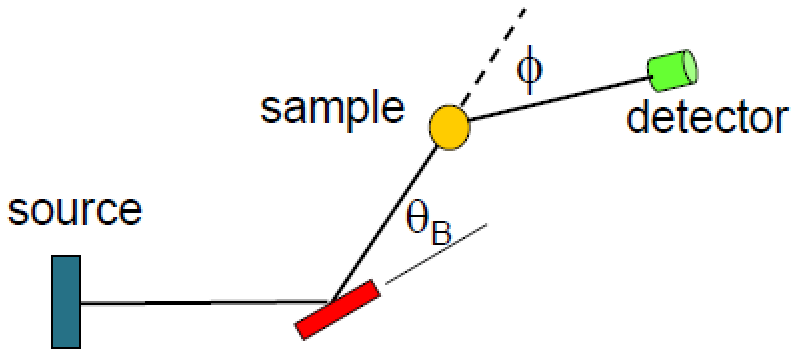
EUROPEAN SPALLATION SOURCE

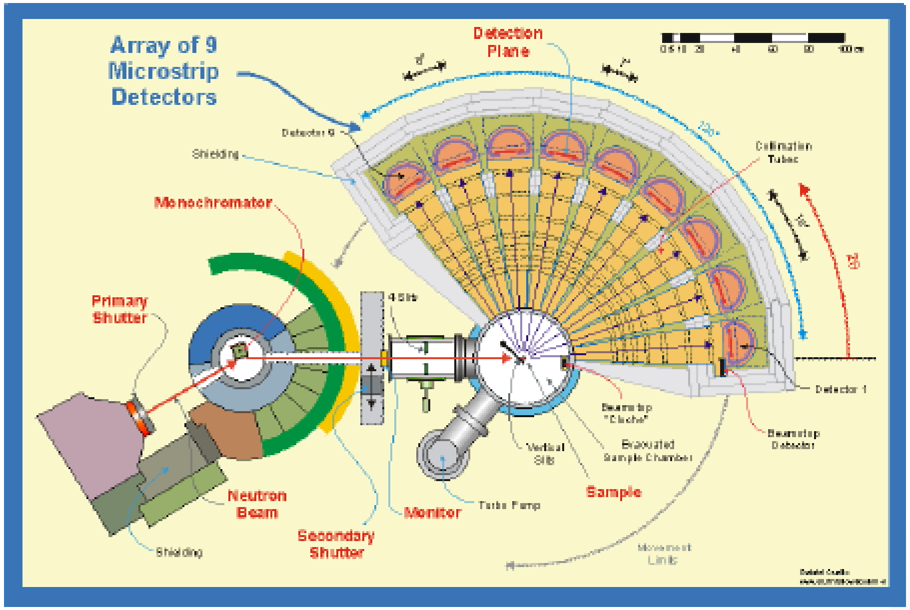


# Determining the Wavelength – reactor (continuous) source

recap

crystal monochromator
(Bragg diffraction)

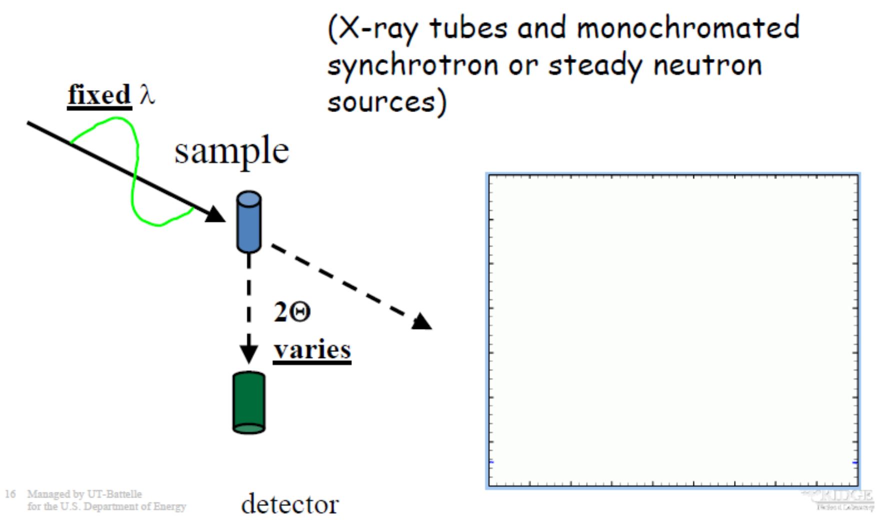


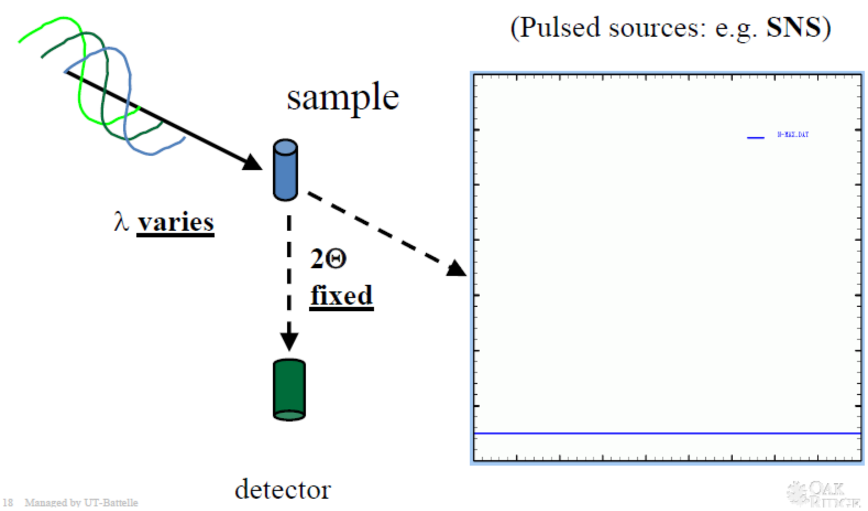

$$\lambda = \frac{2d_c \sin(\theta_B)}{n}$$

$$\Delta\lambda/\lambda \sim \delta d/d + \cot(\theta)\delta\theta$$

Constant wavelength (2dsinΘ=λ)




Time-of-flight (2dsinΘ=λ)



# Wavelength selective imaging 2

## Part 1: ToF vs steady state

EUROPEAN SPALLATION SOURCE

The wavelength resolution

- Remember (for same instrument): Higher resolution <-> lower flux
  Lower resolution <-> higher flux : typically scales with each other

| | • ToF | • Steady state source | | |
|---|---|---|---|---|
| Option | TOF at pulsed source | Velocity selector | Double crystal | Slit method |
| Principle | Time-of-flight | Turbine with tilted blades | Bragg reflection in single crystals | Bragg reflection in single crystals |
| Energy resolution | ~0.2%-3% (short pulse)<br>~0.5%-10% (long pulse) | 10–15% | About 3% | About 2% |
| Beam geometry | Unchanged | Limited by the window | Limited by the crystal size | Limited by setup |
| Detector system | see next chapter | Integrating imaging system | Integrating imaging system | Integrating imaging system |
| Collimation properties | Full performance | Reduced FOV | Given by crystal geometry | Given by the setup |
| Limitations | Frame overlaps, avoidable by choppers or low pulse frequencies | Background at higher energies | Homogeneity across beam | Homogeneity across beam |

**Table 3**
Options for energy selection in neutron imaging.

*E.H. Lehmann et al. / Nuclear Instruments and Methods in Physics Research A 603 (2009) 429–438*

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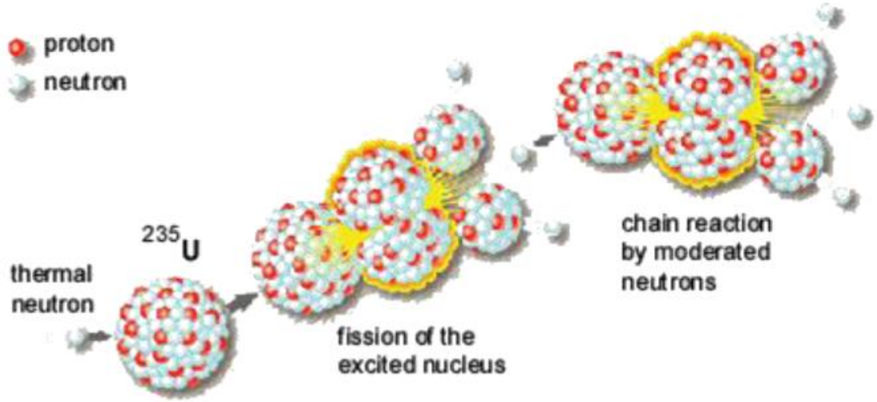
# Wavelength selective imaging 2
## Part 2: ToF neutron sources

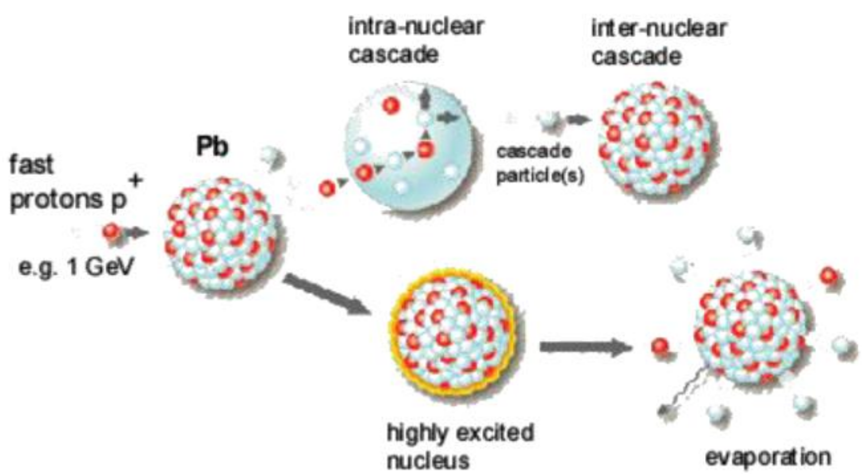
### How do we produce neutrons?




**Fission**

- chain reaction
- continuous flow
- 1 excess neutron/fission
- 180 MeV/neutron

Time of flight can be achieved by choppers

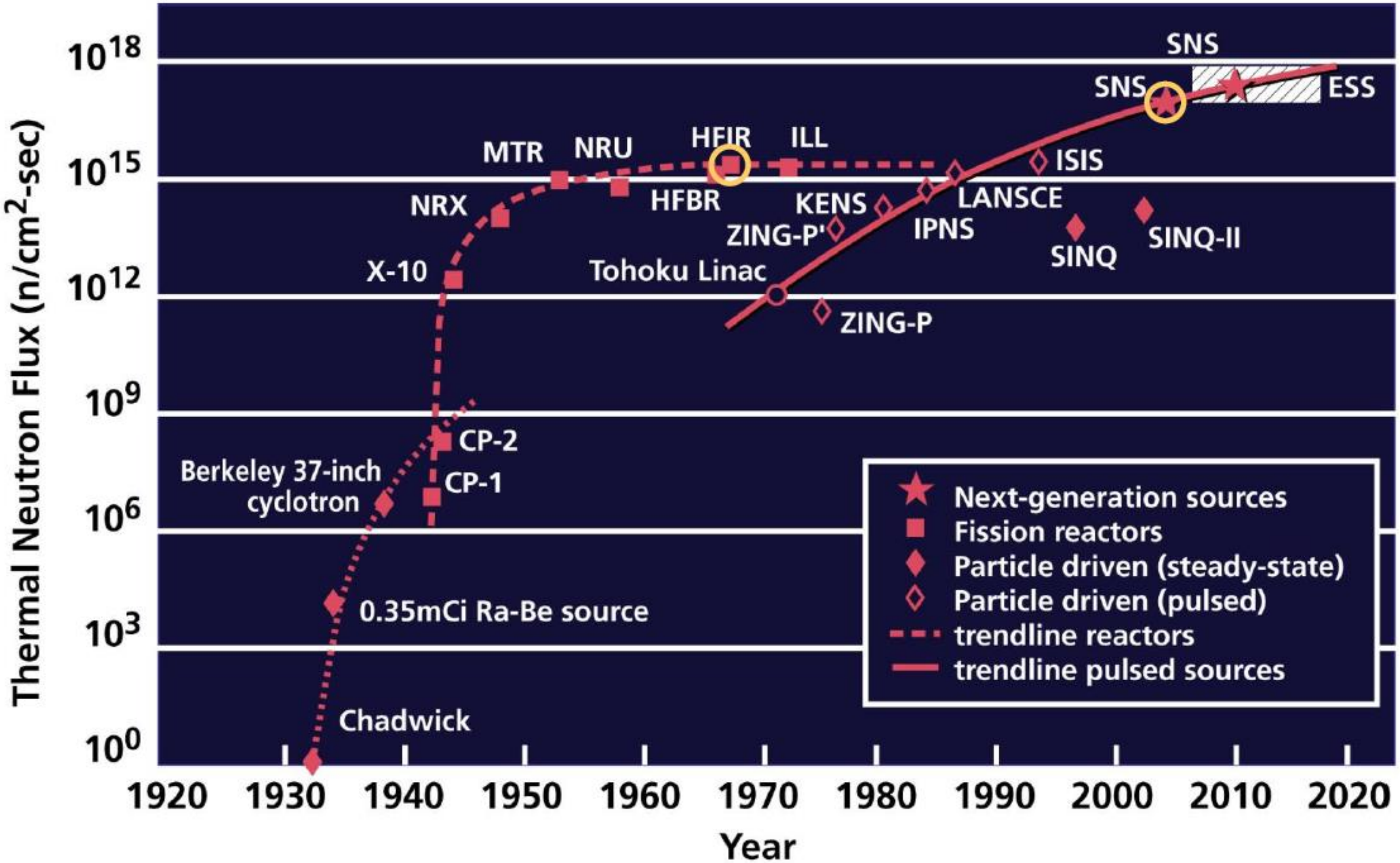



**Spallation**

- no chain reaction
- pulsed operation
- 40 neutrons/proton
- 30 MeV/neutron

Time of flight concept inherent *(Exception: SINQ at PSI is a continous spallation source)*

# Neutron Source Trends

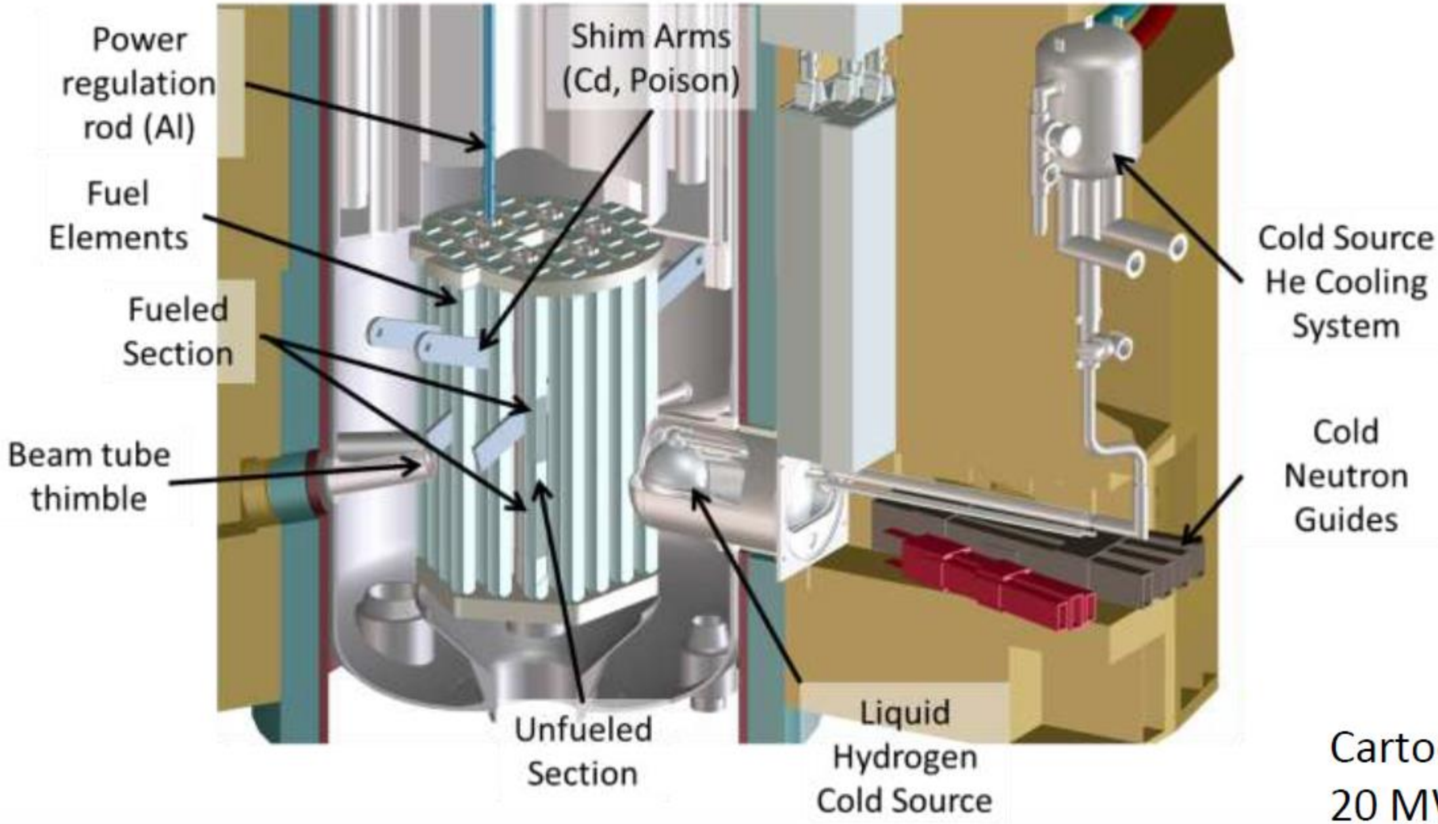



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

# Neutron Sources: Uranium Fission Reactors

Time of flight can be achieved by choppers

- "Large" (~$10^{14}$ $cm^{-2}$ $s^{-1}$) flux of neutrons at the core
- Continuous spectrum or one wavelength for a long time
- Generally more stable operation than an accelerator-based source

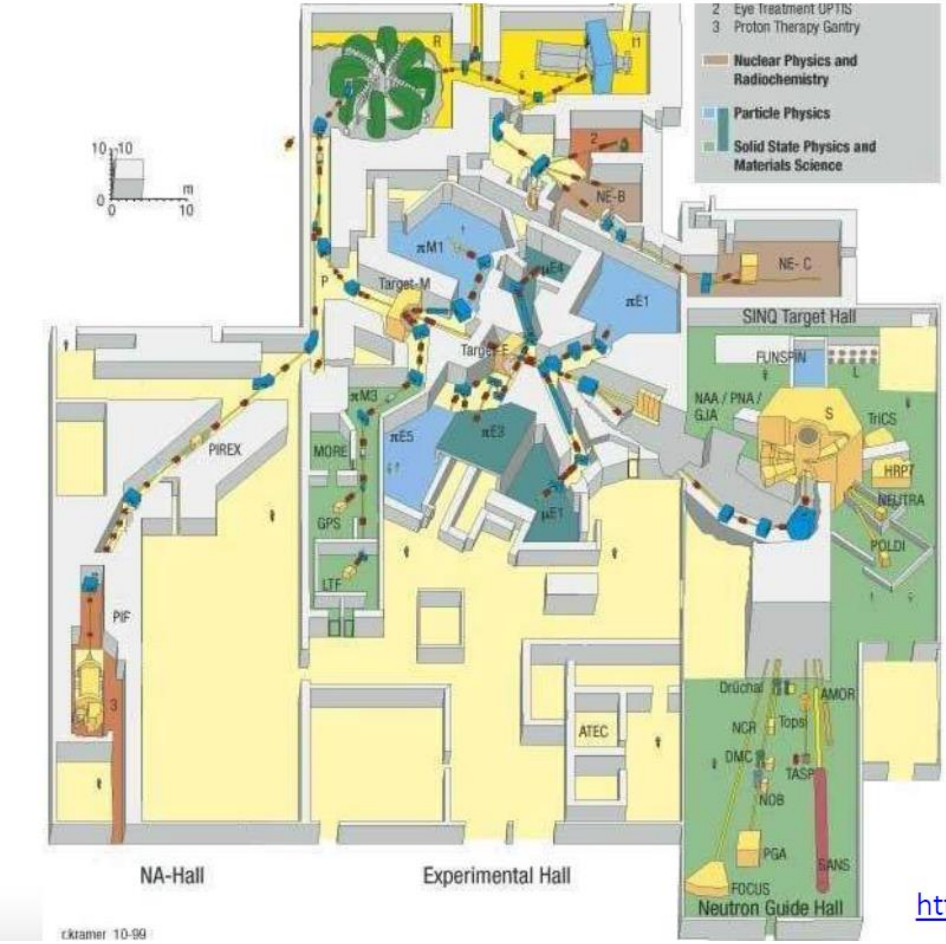



Cartoon of the NIST 20 MW reactor

# Neutron Sources: Pulsed Spallation

- High energy (1 GeV) proton beam smashes into a heavy nucleus
- Historically lower integrated neutron flux than reactor (SNS x3 lower than NIST)
- ESS will change that, having similar integrated flux to a 60 MW research reactor
- Short pulsed proton beam, choppers, and time-of-flight yields energy information
- Can resolve all wavelengths within a large range in each pulse

## Neutron Sources: Continuous Spallation




- SINQ at the Paul Scherrer Institute is the only major facility
- 3 accelerators feed a multi-use facility and direct a 570 MeV continuous proton beam with thermal power of ~0.75 MW onto SINQ's lead spallation target
- Neutrons are produced "continuously", no intrinsic time of flight information
- Comparable to a medium power reactor source in flux, but without the societal concerns of a fission reactor

http://aea.web.psi.ch/Urs_Rohrer/MyWeb/weha.htm

# Wavelength selective imaging 2

## Part 2: ToF neutron sources

**Table 2.2** Past, existing, and future spallation source and their respective parameters

| Country | United States | United States | United States | U.K. | Switzerland | China | Europe | Japan | Japan |
|---|---|---|---|---|---|---|---|---|---|
| Neutron source | IPNS | LANSCE | SNS | ISIS | SINQ | CSNS | ESS | KENS | JSNS |
| Organization | Argonne National Laboratory | Los Alamos National Laboratory | Oak Ridge National Laboratory | Rutherford Appleton Laboratory | Paul Scherrer Institute | Institute of High Energy Physics | Undecided | High Energy Accelerator Research Organization | Japan Atomic Energy Agency |
| Proton energy (MeV)/ Current (μA) | 450/15 | 800/70 | 1000/1400 | 800/200 | 590/1500 | 1600 | 1333/7500 | 500/9 | 3000/333 |
| Proton beam power | 7 kW | 56 kW | 1.4 MW | 160 kW | 1 MW | 100 kW | 5 MW | 4.5 kW | 1 MW |
| Repetition rate (Hz) | 30 | 20 | 60 | 50/10 (2 targets) | Continuous | 25 | 14 long pulse) | 20 | 25 |
| Target material | Depleted Uranium | Tungsten | Mercury | Tantalum | Zircaloy | Tungsten | Rotating tungsten | Tungsten | Mercury |
| Moderator | S-$CH_4$/L-$CH_4$ | L-$H_2$/$H_2O$ | L-$H_2$/$H_2O$ | L-$H_2$/L-$CH_4$/ $H_2O$ | L-$D_2$/$D_2O$ | $H_2O$L-$CH_4$L-$H_2$ | L-$H_2$ | S-$CH_4$/$H_2O$ | L-$H_2$ |
| Number of instruments | 12 | 7 | 24 (beam ports) | 22 (TS1) 7 (TS2) | 15 | | 20 (beam ports) | 15 | 23 (beam ports) |
| Existing neutron imaging instrument | | | Venus PLANNING | IMAT | NEUTRA [30] and ICON [31] | | ODIN contruction | | RADEN |
| Facility operating since or planned to operate in | 1981 (closed 2008) | 1983 | 2006 | 1985 (TS1) 2008 (TS2) | 1996 | 2014 | Under planning | 1980 (closed 2005) | 2008 |

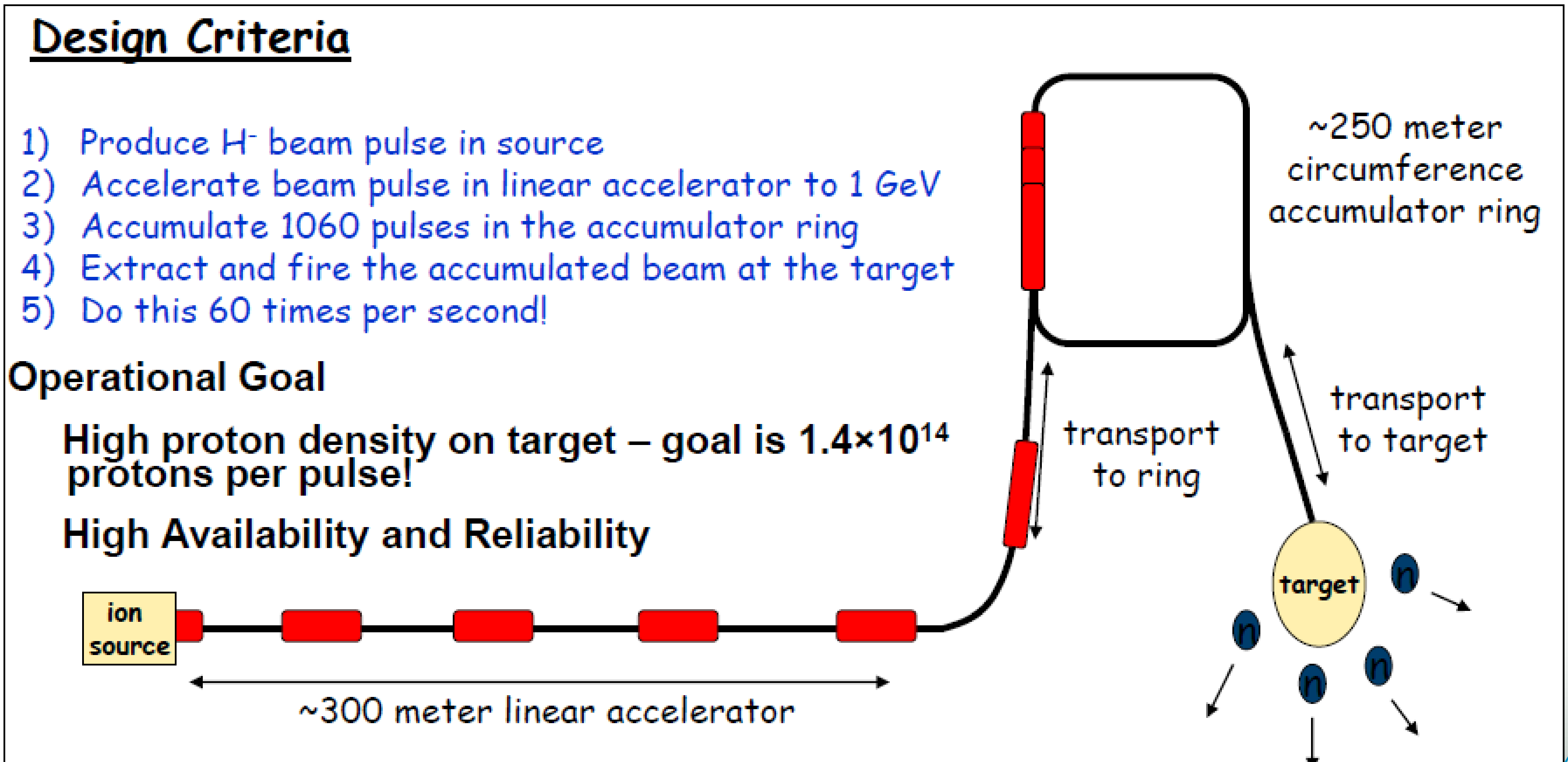
IPNS: Intense Pulsed Neutron Source [32]; LANSCE: Los Alamos Neutron Science Center [33]; SNS: Spallation Neutron Source [8, 9]; ISIS: [34, 35]; SINQ: Swiss Spallation Neutron Source [36, 37]; CSNS: Chinese Spallation Neutron Source [10, 11]; ESS: European Spallation Source [38, 39]; KENS: Koh-Energy-ken Neutron Source [40, 41]; JSNS: Japanese Spallation Neutron Source [8, 9]. Consult the websites for these facilities to obtain additional information and current details.

# Wavelength selective imaging 2
## Part 2: ToF neutron sources



- Example of a Spallation Source: SNS

# Full Energy linac and Accumulator Ring

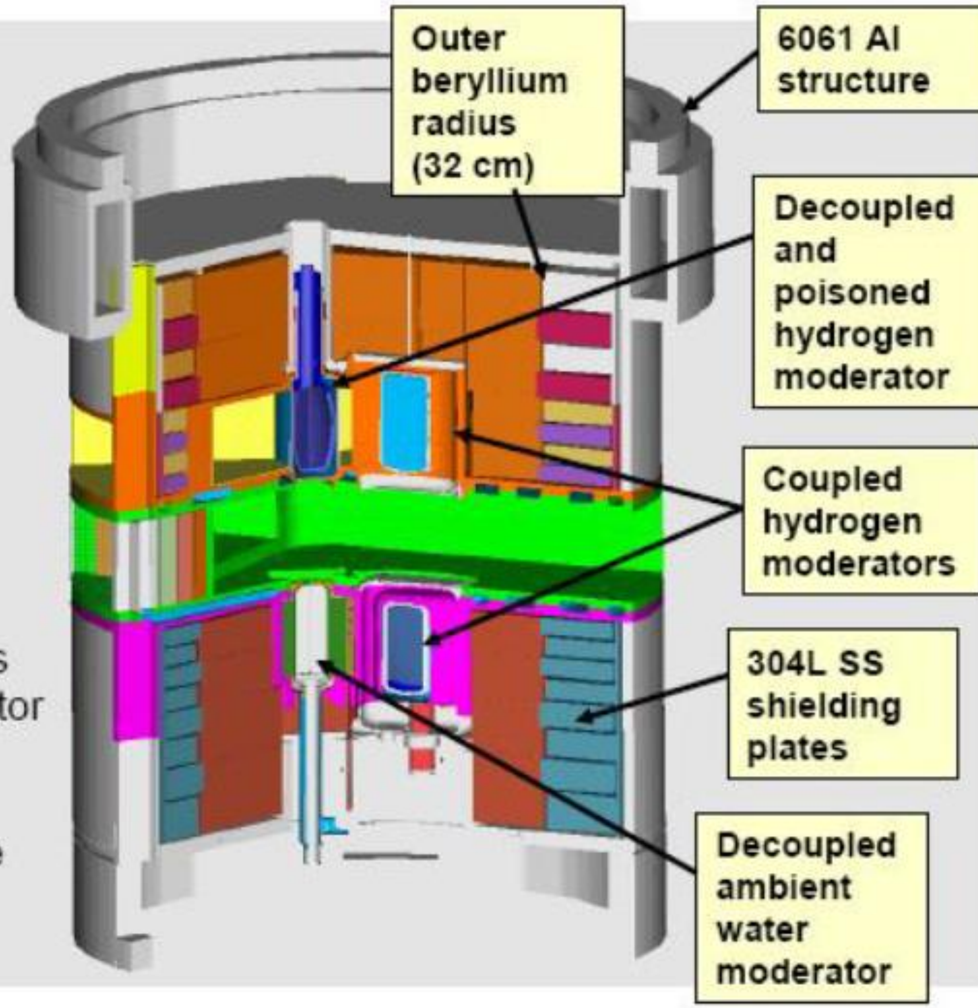


- Example of a Spallation Source: SNS

Mercury Target

# Wavelength selective imaging 2
## Part 2: ToF neutron sources

- Example of a Spallation Source: SNS

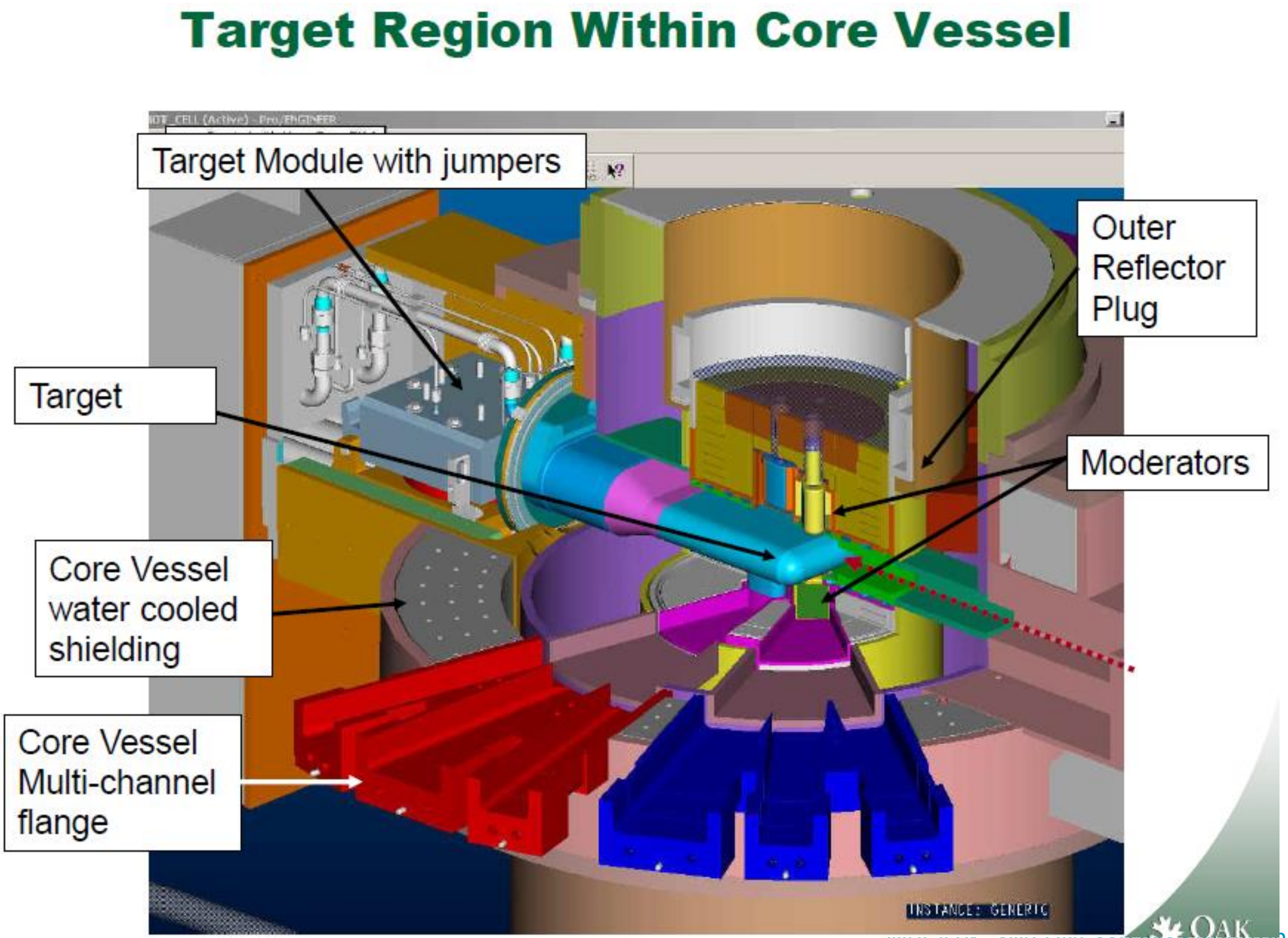



**Inner Reflector Plug**

- Contains moderators and reflectors around the target. Three H moderators running at ~20K and one $H_2O$ moderator running at 290K
- Neutrons produced by spallation in the Hg are high energy, ~1GeV, must be cooled to 1meV → 1eV range for use in thermal neutron scattering

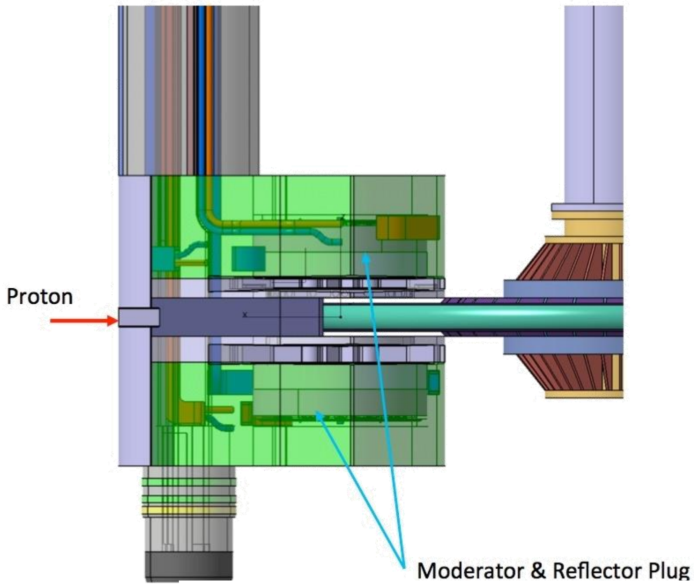
# Wavelength selective imaging 2
## Part 2: ToF neutron sources

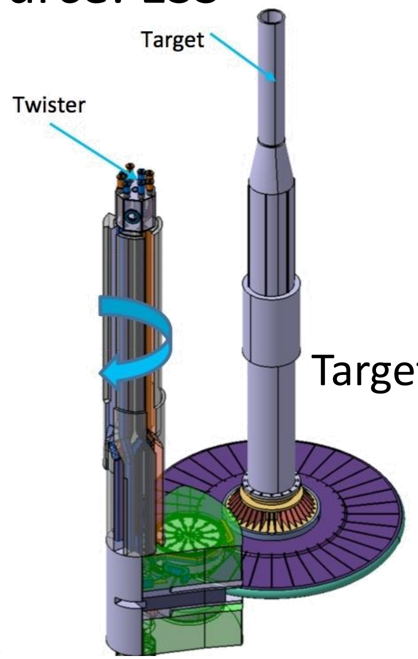
- Example of a Spallation Source: SNS



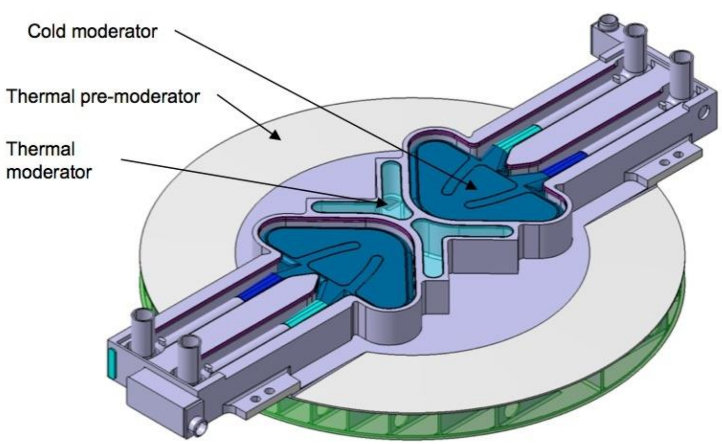
# Part 2: ToF neutron sources

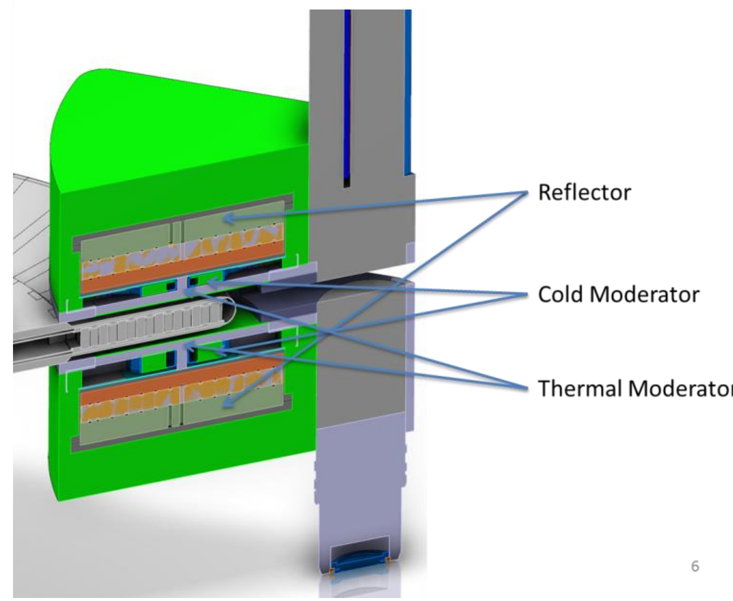
- Example of a Spallation Source: ESS



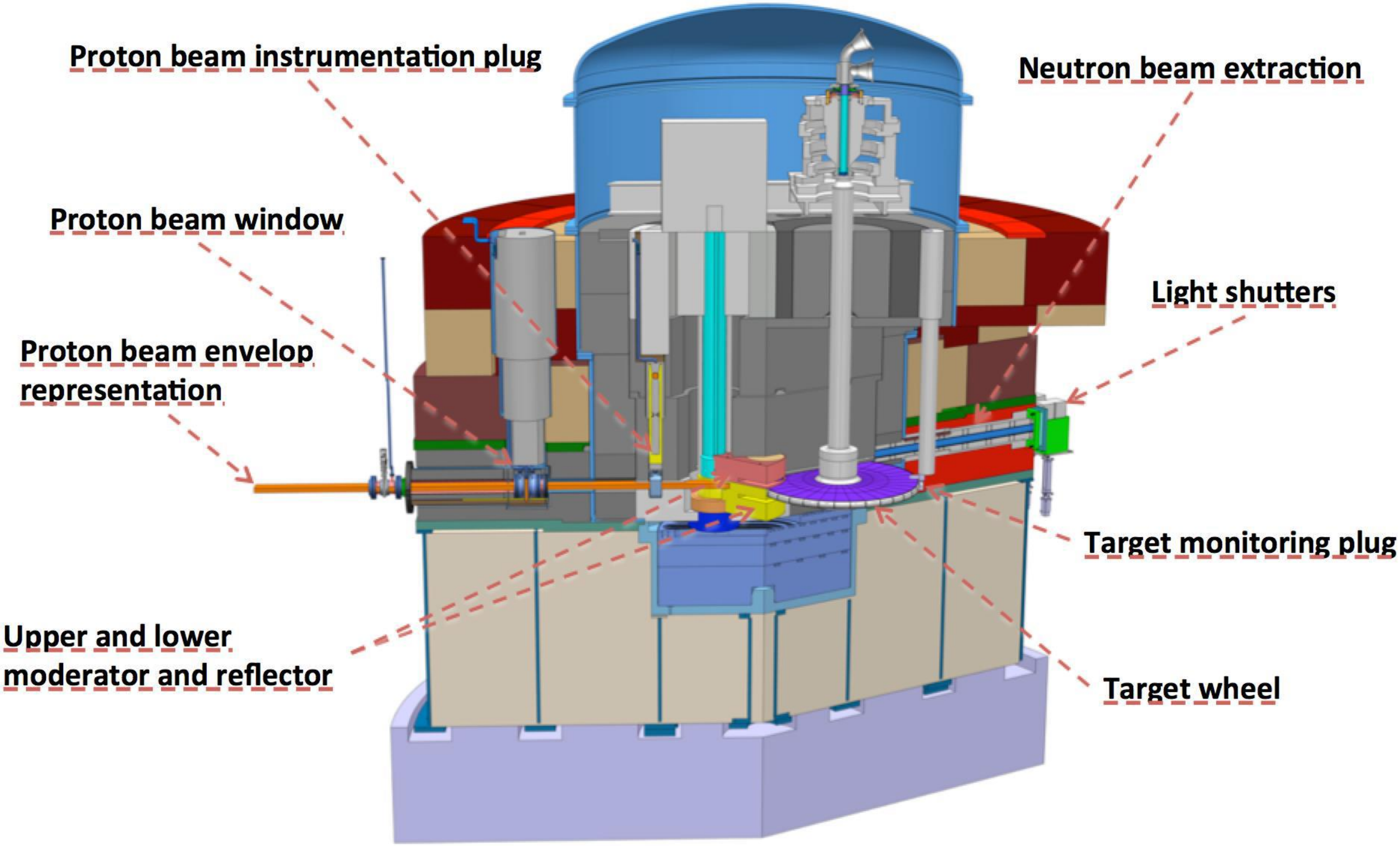

Target Wheel



# Wavelength selective imaging 2
## Part 2: ToF neutron sources

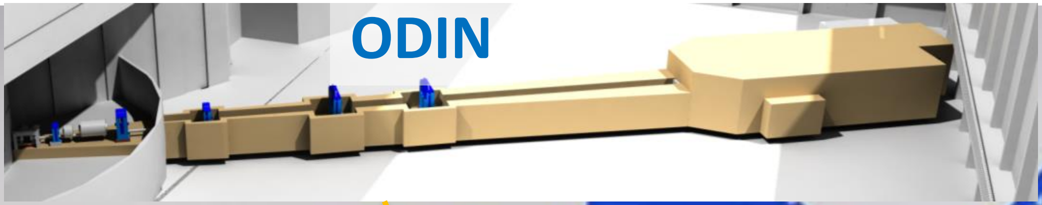
- Example of a Spallation Source: ESS

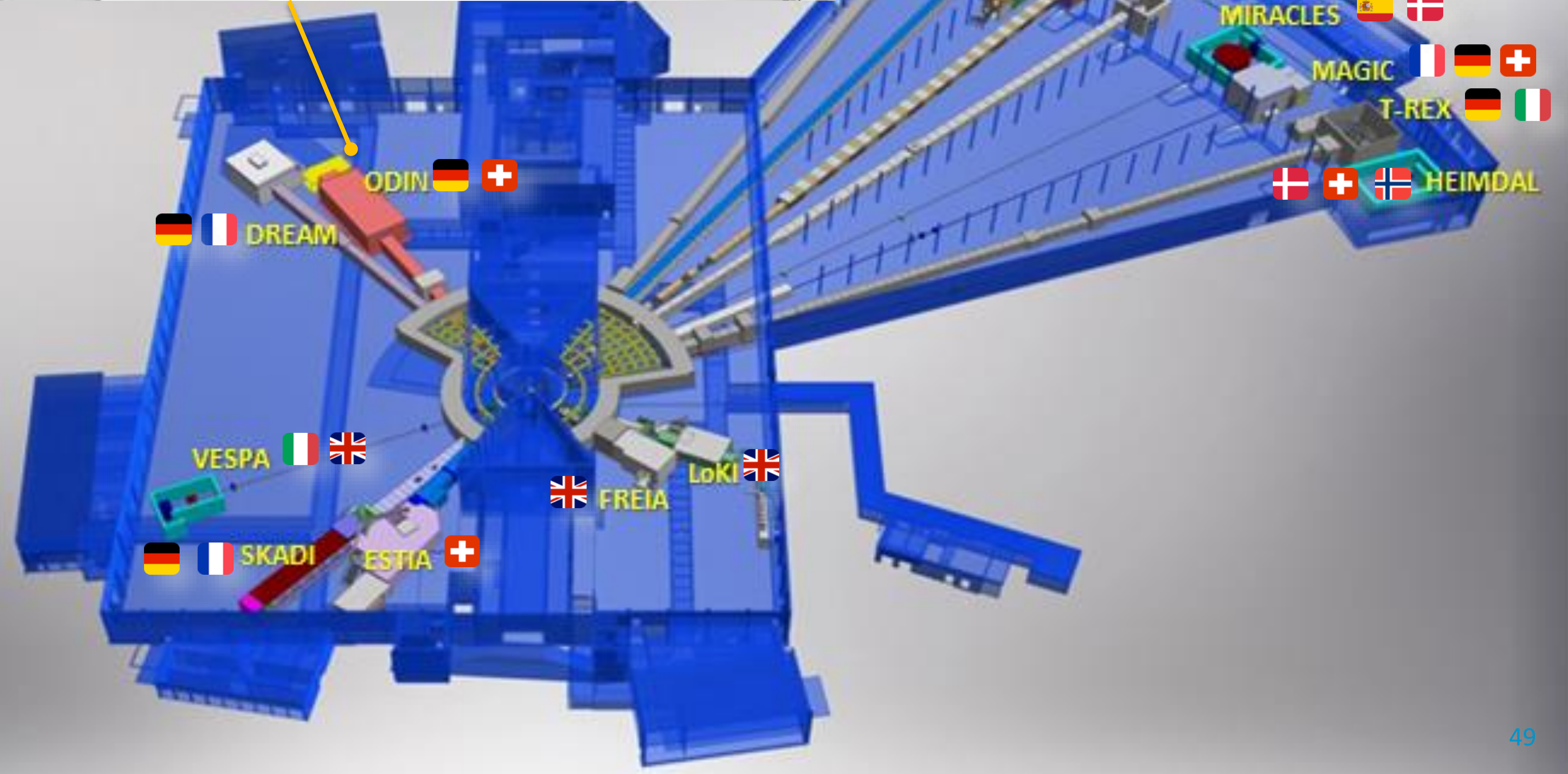


# Wavelength selective imaging 2

## Part 2: ToF neutron sources

- Example of a Spallation Source: ESS



# Wavelength selective imaging 2

## Part 2: ToF neutron sources

Let‘s go back to the pulse width

- The ToF diagram

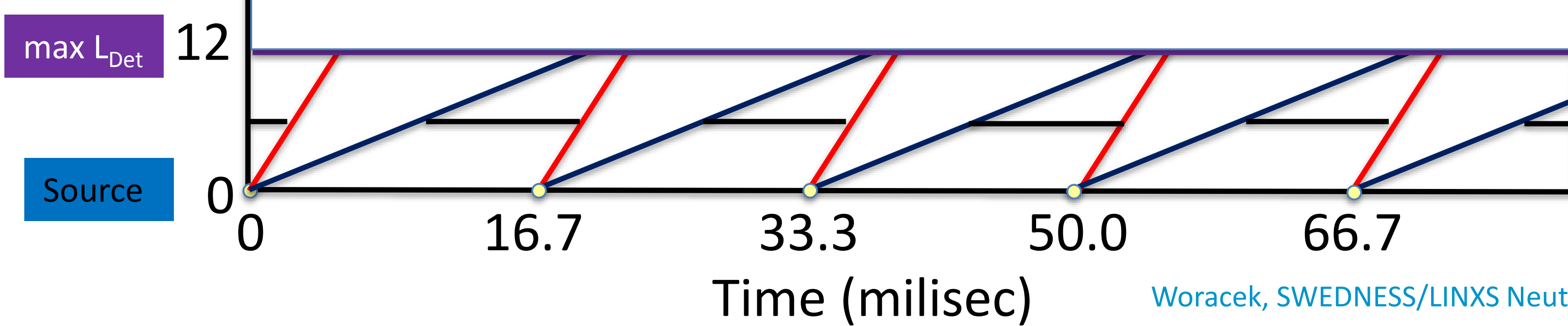
*But, what about the wavelength resolution?*

- Let’s assume a short pulsed source with τ= 200µsec

$$\frac{\Delta\lambda}{\lambda} = \frac{3956 \cdot \tau}{\lambda \cdot L_{Det}} = \frac{3956 \cdot 0.0002}{\lambda \cdot 12}$$

$$\frac{\Delta\lambda}{\lambda}[2\text{Å}] = 3.3\%$$

$$\frac{\Delta\lambda}{\lambda}[7\text{Å}] = 1\%$$

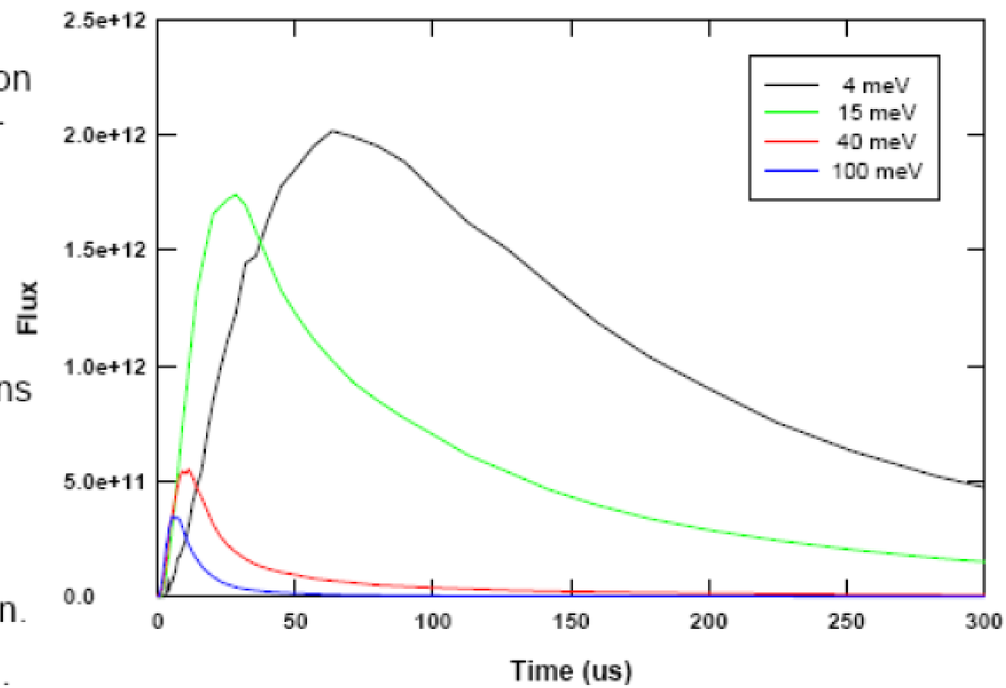


- **At short pulsed spallation source, the pulse width depends stronly on the moderator and wavelength.**

## Slowing down time or T0(λ) or T0(E)

Page 142 will have an example from IMAT

- Neutrons emerging from moderators have a distribution of energies = a Maxwellian + a 1/E (epithermal) tail.
- But different neutron energies (wavelengths) emerge from the moderator with different time distributions (see example on right).
- Need to calibrate a T0(E) function for each moderator and use this in data reduction.
- Now the neutrons are emerging out of the monolith and into the beamlines for the neutron scattering instruments.....

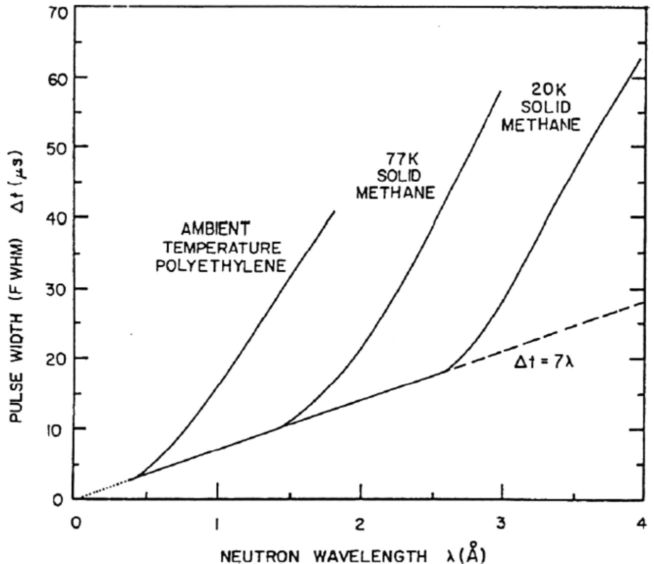



Example: MCNPX results for coupled cryogenic $H_2$ moderator on SNS target station 1

# Wavelength selective imaging 2

## Part 2: ToF neutron sources

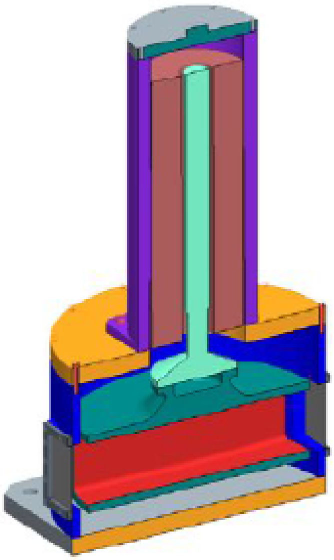
- **At short pulsed spallation source, the pulse width depends stronly on the moderator and wavelength.**
- The pulse width is a **key parameter** for short-pulse spallation sources and is directly influential on neutron beam instrument performance.
- It is almost proportional to the neutron wavelength in the 1/E region of flux, is broadened in the thermal equilibrium region, and then saturates in the very low-energy region.
- The broadening starts to occur at about 300 meV (neutron wavelength of 0.5A˚) for an ambient-temperature moderator and at about 15 meV (2.5A˚) for a methane moderator at 20 K (see figure).
- In the 1/E region for each moderator, the pulse width is proportional to wavelength.

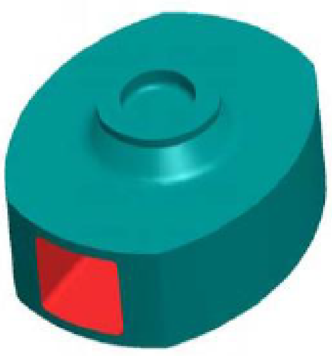



$$\Delta t[\mu s] \sim \frac{2}{\sqrt{E[eV]}} \sim 7\lambda[\AA]$$

# Beam Selection/conditioning
# T0 Choppers and Curved Guides

- When the proton beam strikes the target (time T0) a burst of ~1GeV neutrons and a flash of gamma rays are produced. Some are neutrons are moderated but some emerge into the beamlineat time T0. Have to get rid of the fast neutrons and gamma rays.
- Two methods -T0 chopper or curved guide
- T0 chopper –rotating plug of Inconel(200 →300mm) that blocks the beam at time T0.
- Curved guide, low energy neutrons are reflected but not higher energies. The guide is curved so that final sample position does nothave a line of sight to the source and fast neutrons must collide/be absorbed in, shielding around beamline. BASIS, CNCS and HYSPEC have curved guides.
- Note T0 choppers are phased (electronically) to the source“T0”signal.





# Wavelength selective imaging 2 - ToF

## AGENDA

- **Part 1: Introduction to ToF imaging**
  - Basics (neutron energy, wavelength, velocity)
  - The ToF concept
  - ToF vs steady state instruments
- **Part 2: What do we need for a ToF neutron imaging instrument?**
  - ToF Neutron Source
  - Examples of of ToF imaging beamlines
  - ToF Detectors
- **Part 3: ToF Imaging methods**
  - The bigger picture: overview and comparison to other neutron techniques
  - ‘Attenuation’: Monochromatic, ‘white-beam’ and ‘pink-beam’ (narrow wavelength) applications
  - Diffraction Contrast / Bragg edge imaging (including diffraction basics)
  - Other methods to profit from ToF: Polarized, phase and dark field, 3DND, resonance absorption
- **Part 4:** Hands on example (please install https://imagej.net/Fiji/Downloads or https://imagej.nih.gov/ij/download.html)

# Wavelength selective imaging 2

## Part 2: Overview of ToF imaging beamlines

EUROPEAN SPALLATION SOURCE

RADEN

**J-PARC** -Japan Proton Accelerator Research Complex-


3 proton accelerators

RADEN

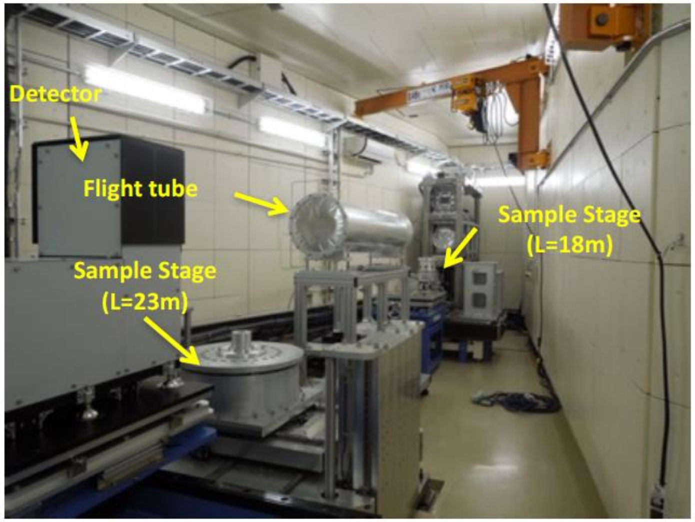
# RADEN -Energy-Resolved Neutron Imaging System-

**The first instrument dedicated to Energy-Resolved Neutron Imaging**

- ✓ Energy-resolved neutron imaging fully using the short pulsed neutron nature
  - Bragg edge, Resonance absorption, Polarization analysis -
- ✓ Conventional neutron radiography & tomography
  - Various L/D, Large FOV, Dynamic Imaging-
- ✓ New neutron imaging technique development

"RADEN"（螺鈿）
Mother-of-pearl work

**On beam commissioning and user programs started from 2015.**



# Wavelength selective imaging 2

## Part 2: Overview of ToF imaging beamlines

RADEN

Table 1. Basic parameters of RADEN.

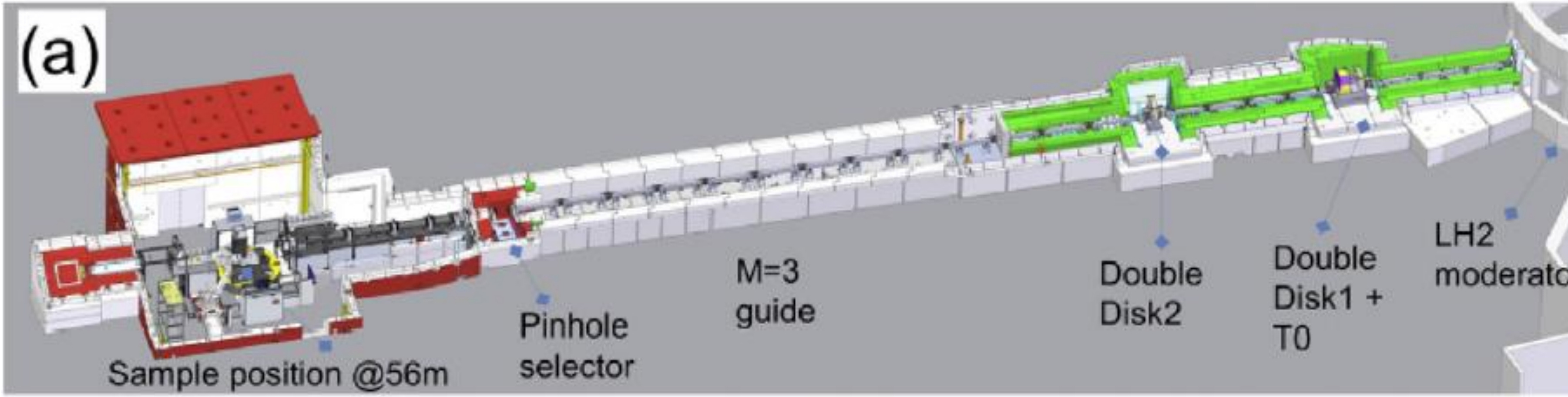
| | | |
|---|---|---|
| Beam line | BL22 | |
| Moderator type | Supercritical hydrogen decoupled moderator | |
| Sample position | 18 m | 23 m |
| Beam Size | < 221 x 221 $mm^2$ | < 300 x 300 $mm^2$ |
| L/D ratio | 180 ~ 5000 | 230 ~ 7500 |
| Wavelength resolution (cold) | 0.26% | 0.20% |
| Energy resolution (epithermal) | 1.6% | 1.2% |
| Longest wavelength (first frame) | 8.8 Å | 6.9 Å |

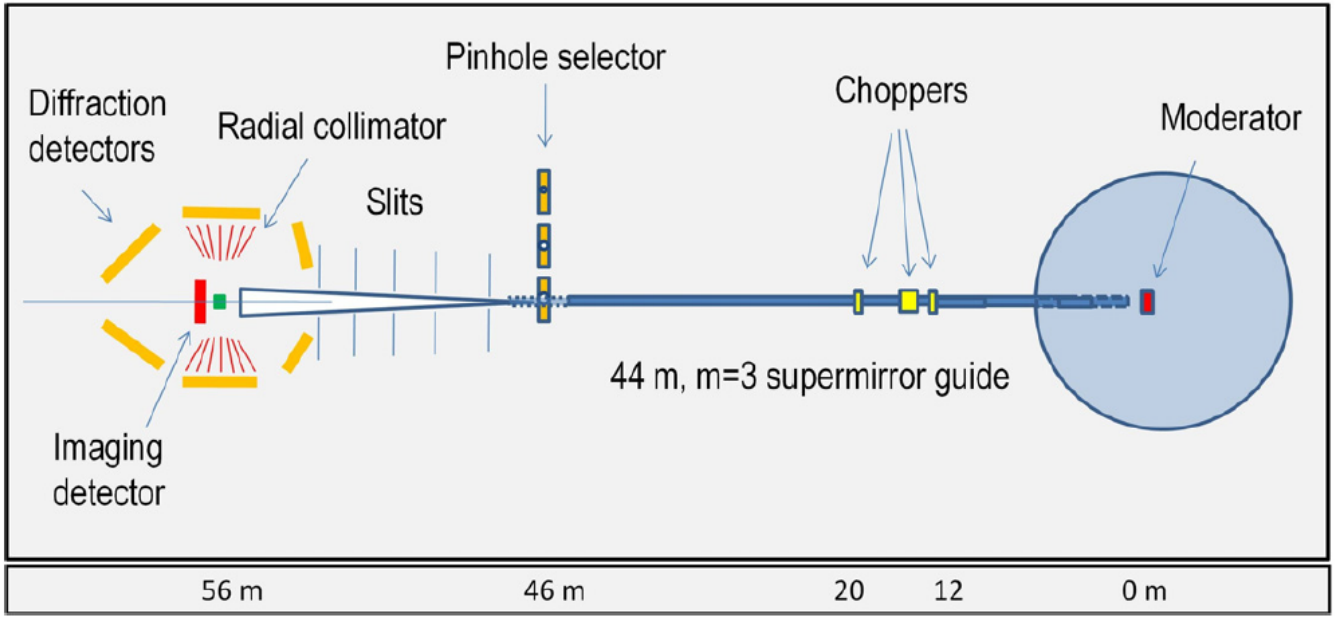
# Wavelength selective imaging 2

## Part 2: Overview of ToF imaging beamlines

EUROPEAN SPALLATION SOURCE

IMAT

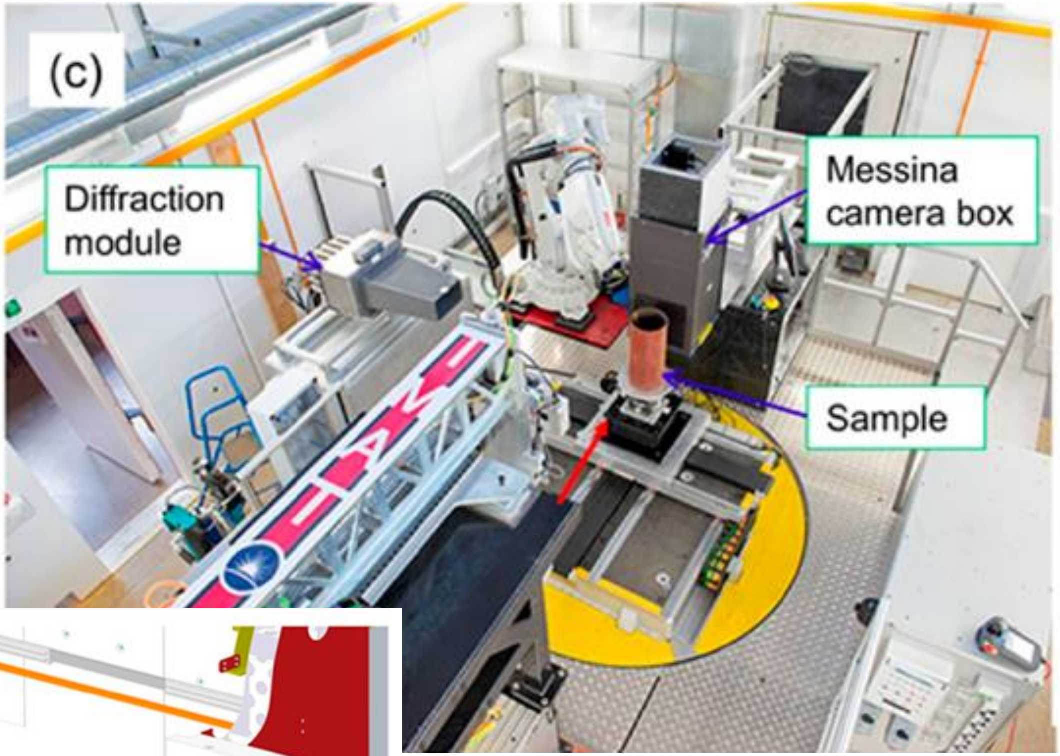


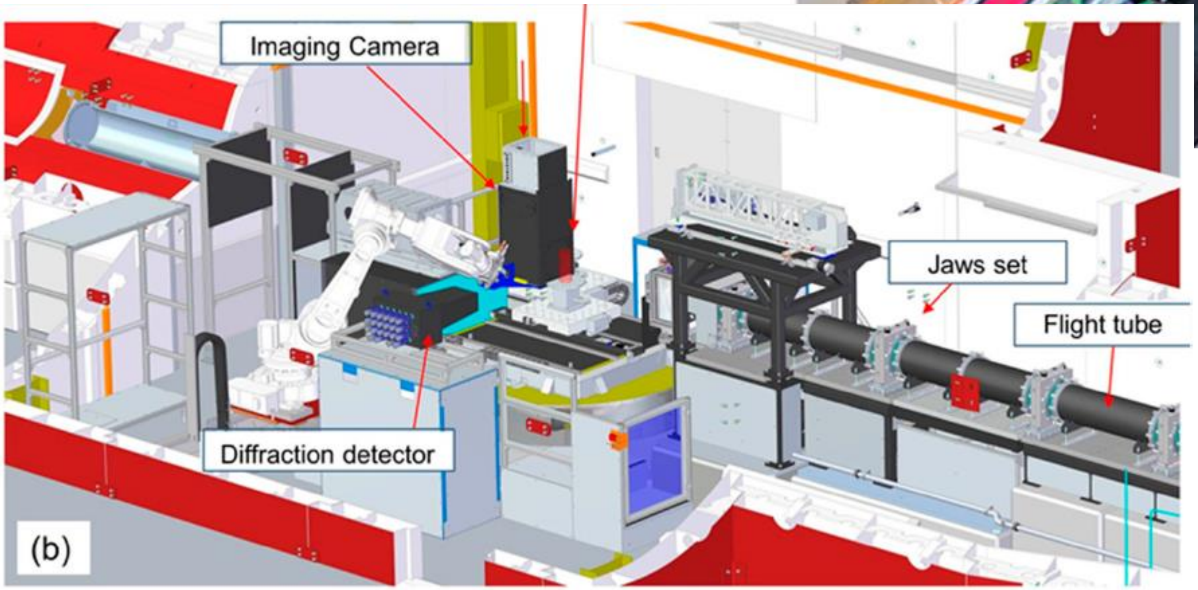



# Wavelength selective imaging 2

## Part 2: Overview of ToF imaging beamlines

IMAT



# Wavelength selective imaging 2

## Part 2: Overview of ToF imaging beamlines



**IMAT**

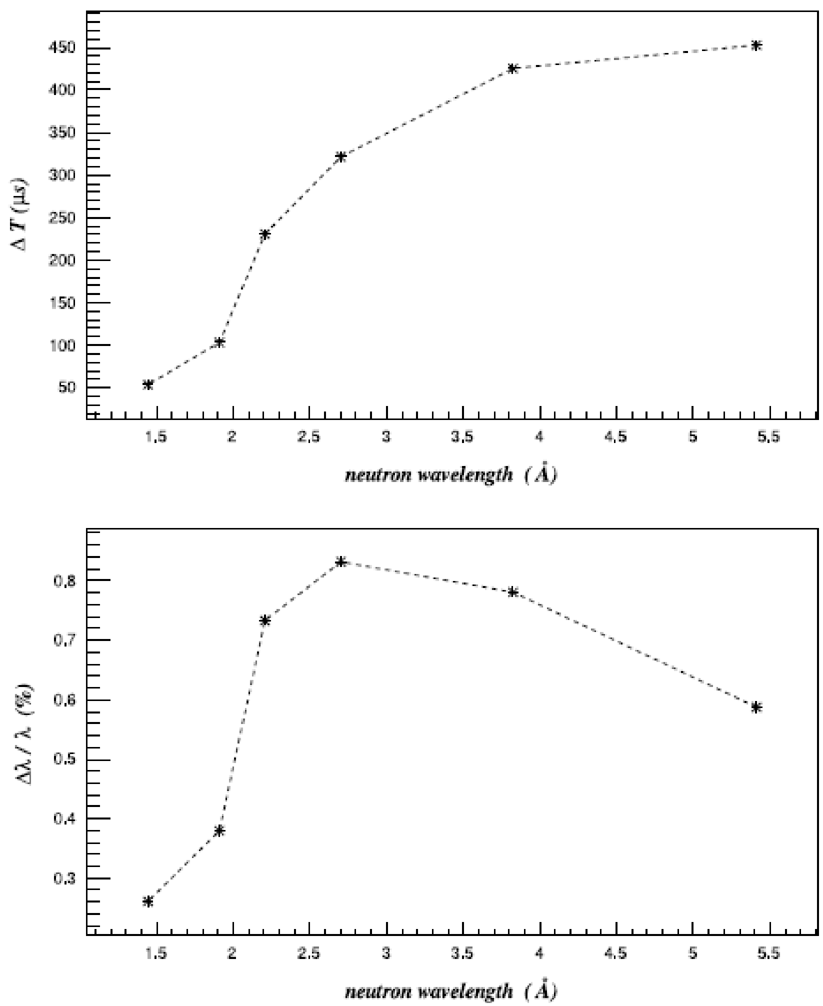
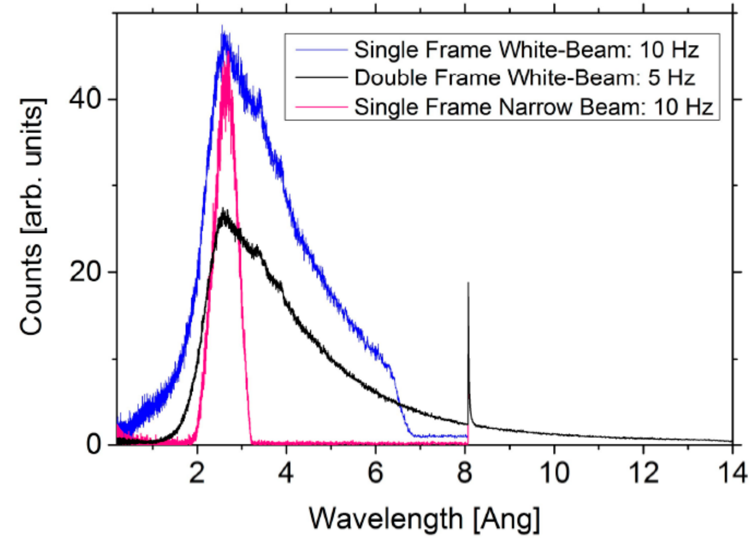



Fig. 16. Neutron pulse width $\Delta t$ (μs) (top panel), resolution $\Delta\lambda/\lambda$(%) as a function of the neutron wavelength (bottom panel).



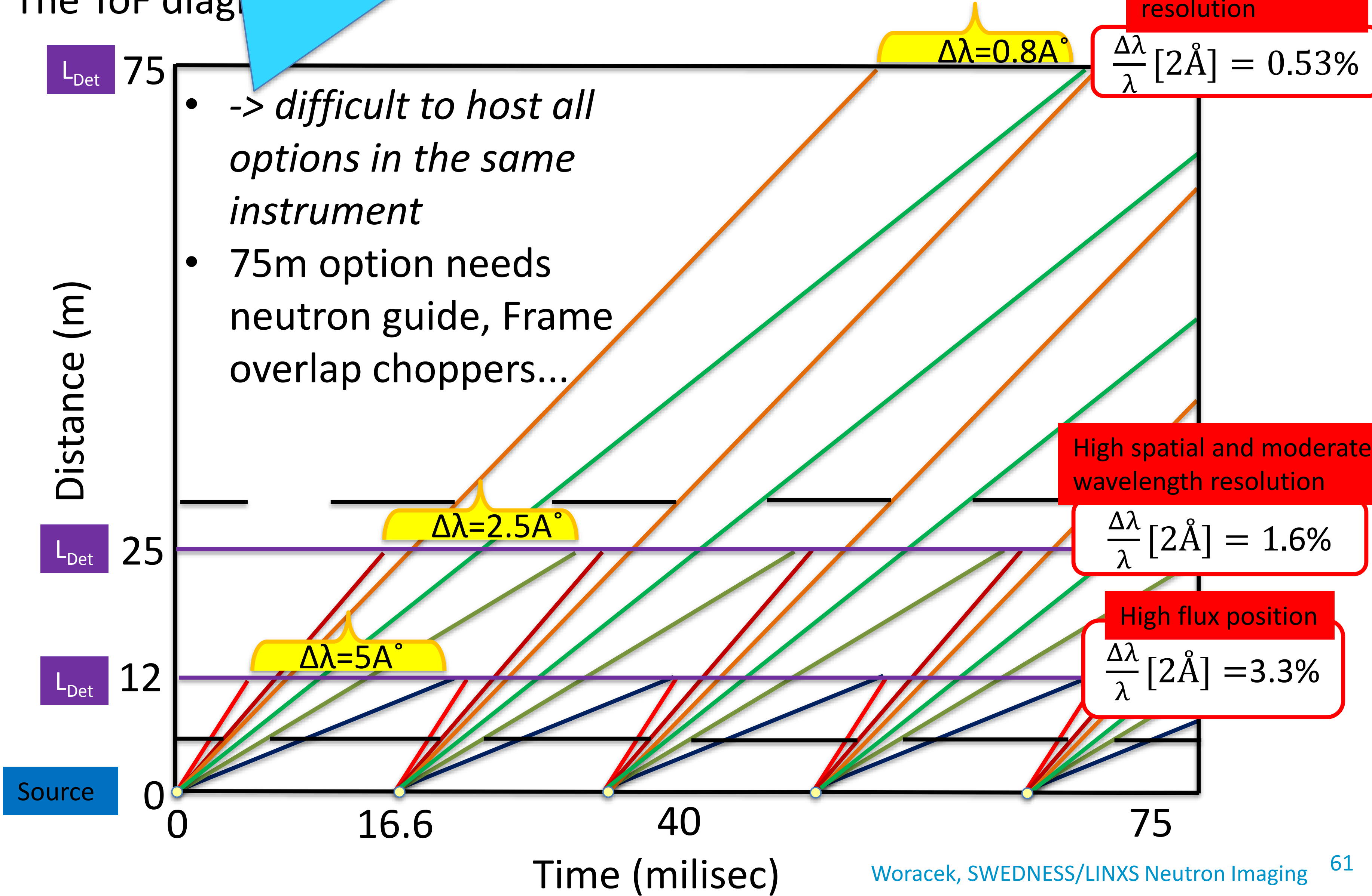

| | |
|---|---|
| Neutron source | TS-2; 10 Hz pulsed; tungsten target<br>Coupled liquid H-moderator at 18 K |
| Single frame bandwidth | 6 Å (measured) |
| Flight path to sample | 56 m (measured) |
| L: Distance pinhole – sample<br>D: Aperture diameter | 10 m<br>5, 10, 20, 40, 80 mm<br>L/D: 2000, 1000, 500, 250, 125 (nominal)<br>L/D: 2000, 1150, 510, 245, 125 (measured) |
| Maximum neutron flux | 3.8 $10^7$ n/cm^2/s (measured) |
| Maximum Field of View | 211×211 $mm^2$ (measured) |
| Wavelength resolution | $\Delta\lambda/\lambda < 0.4$ % (< 2 Å) (measured)<br>$\Delta\lambda/\lambda < 0.8$ % (> 2 Å) (measured) |

# Wavel... ing 2

Remember form earlier:
At short pulsed source....

...re prospects of imaging
...tron sources. NIMA 604

- The ToF diag...

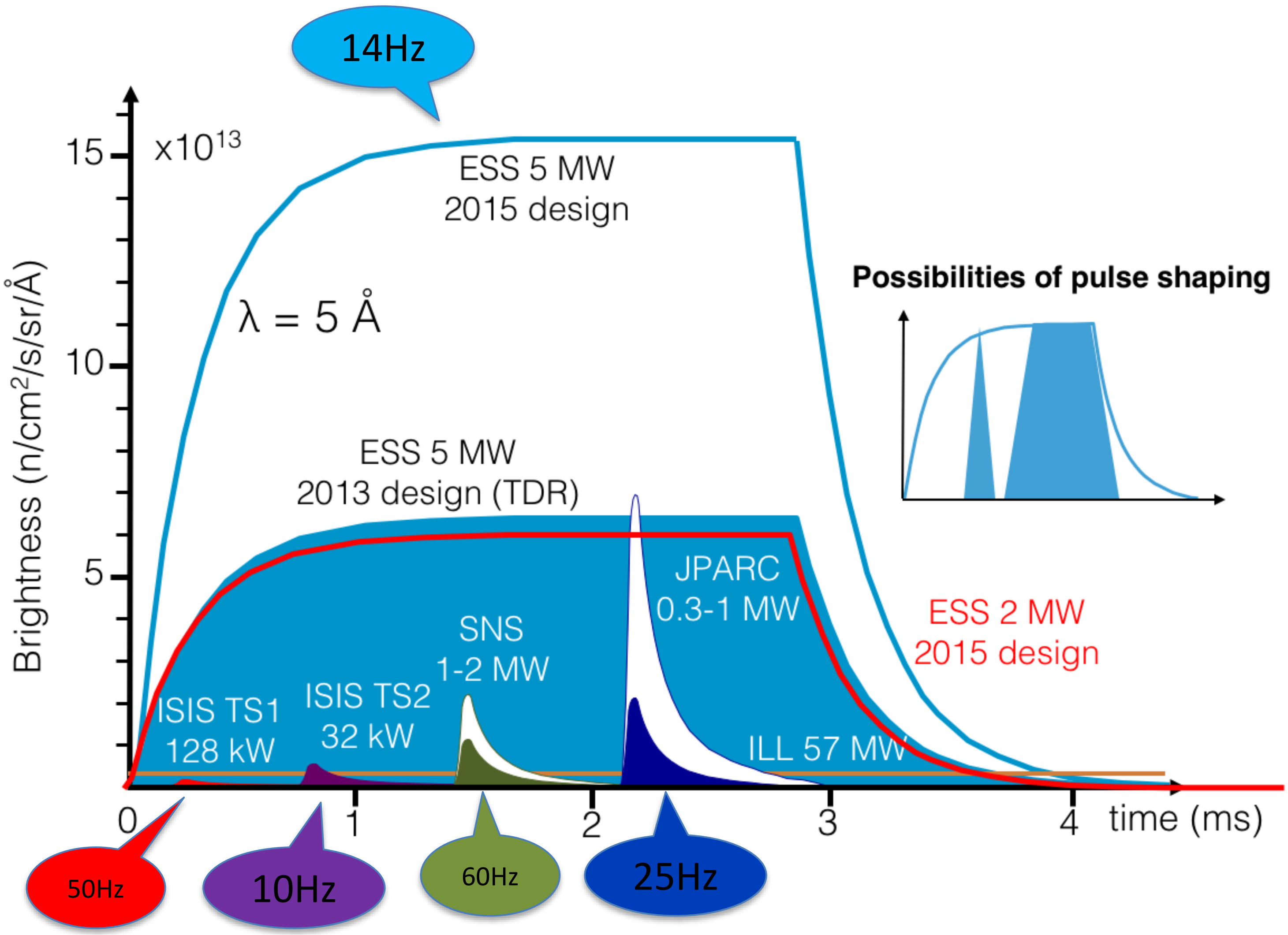



- *-> difficult to host all options in the same instrument*
- 75m option needs neutron guide, Frame overlap choppers...

# Wavelength selective imaging 2

## Part 2: Overview of ToF imaging beamlines

- ESS will be the first Long Pulse Spallation Source



# Wavelength selective imaging 2

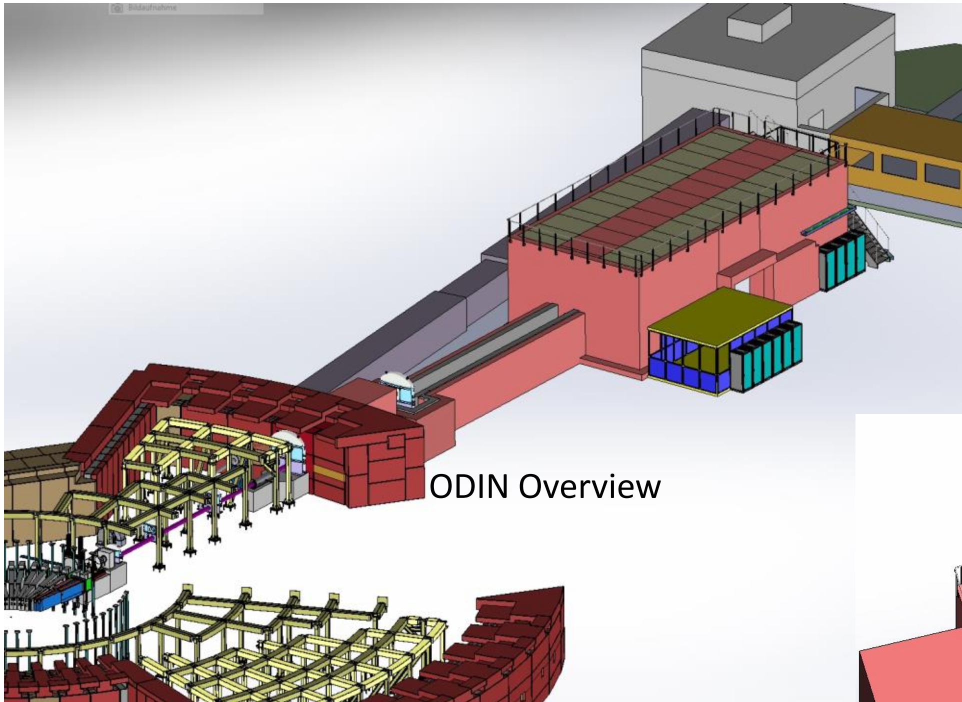
## Part 2: Overview of ToF imaging beamlines

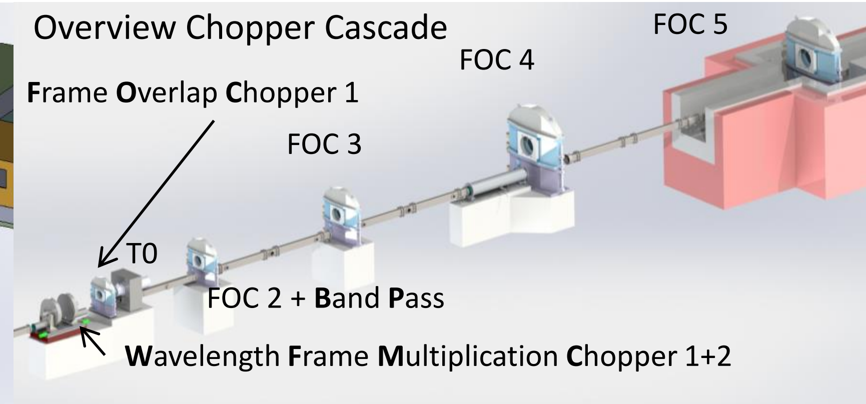
TECHNISCHE UNIVERSITÄT MÜNCHEN

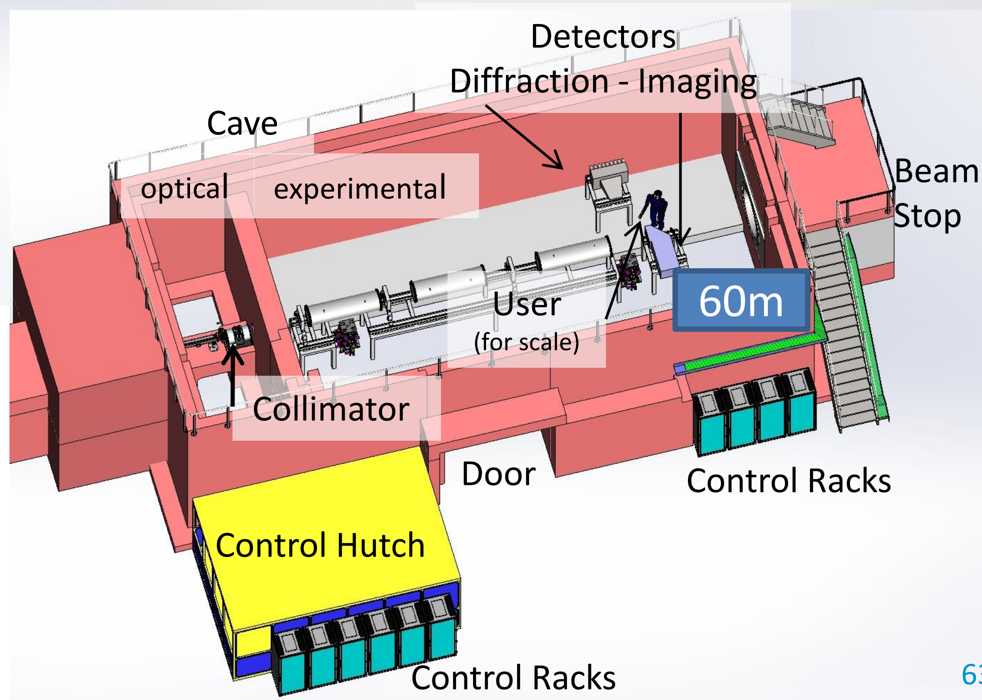
PAUL SCHERRER INSTITUT PSI

EUROPEAN SPALLATION SOURCE

### ODIN




- source-sample distance of 60m will give a natural resolution of 10%
- complex chopper system will provide wavelength resolution of 0.3-1%
- large experimental station this will offer unprecedented versatility

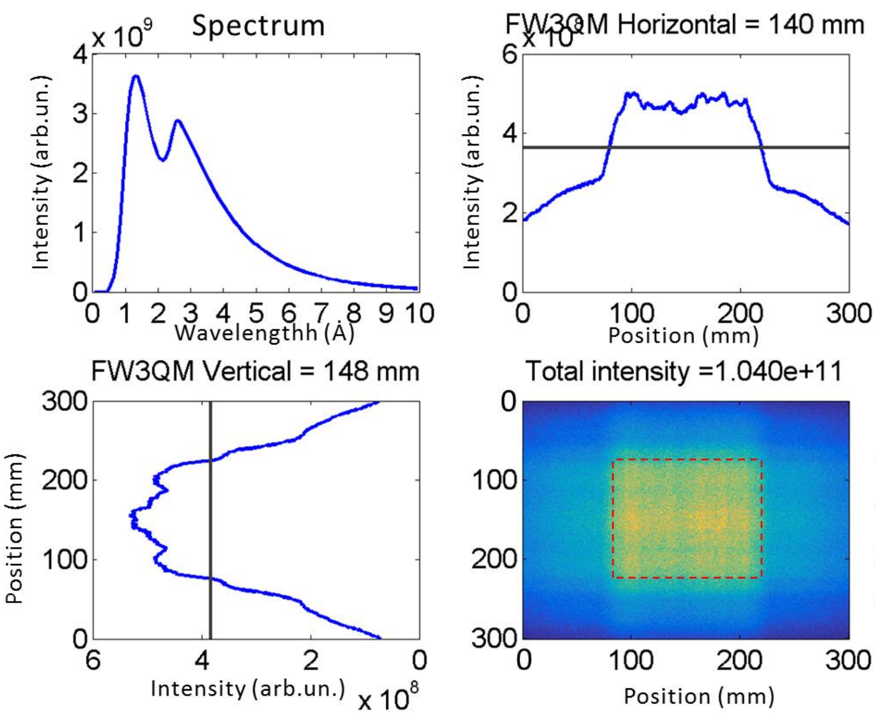
# Wavelength selective imaging 2

## Part 2: Overview of ToF imaging beamlines

ODIN

### Spectrum and Field of View

**FoV at 10m position**

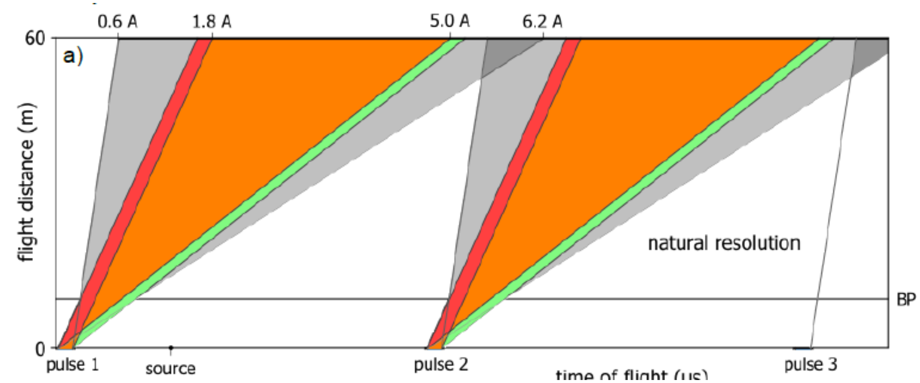



Large, homogenous FoV for large samples in e.g. Geology and Engineering.

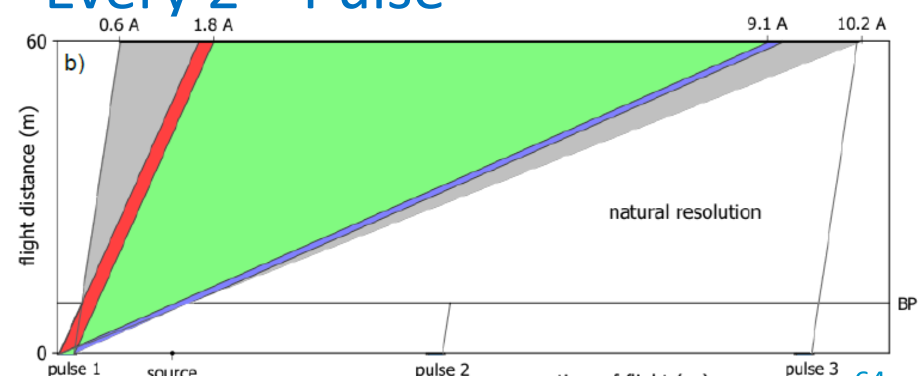
Credit: M. Lerche, M. Morgano

### Chopper System: flexible resolution

Every Pulse



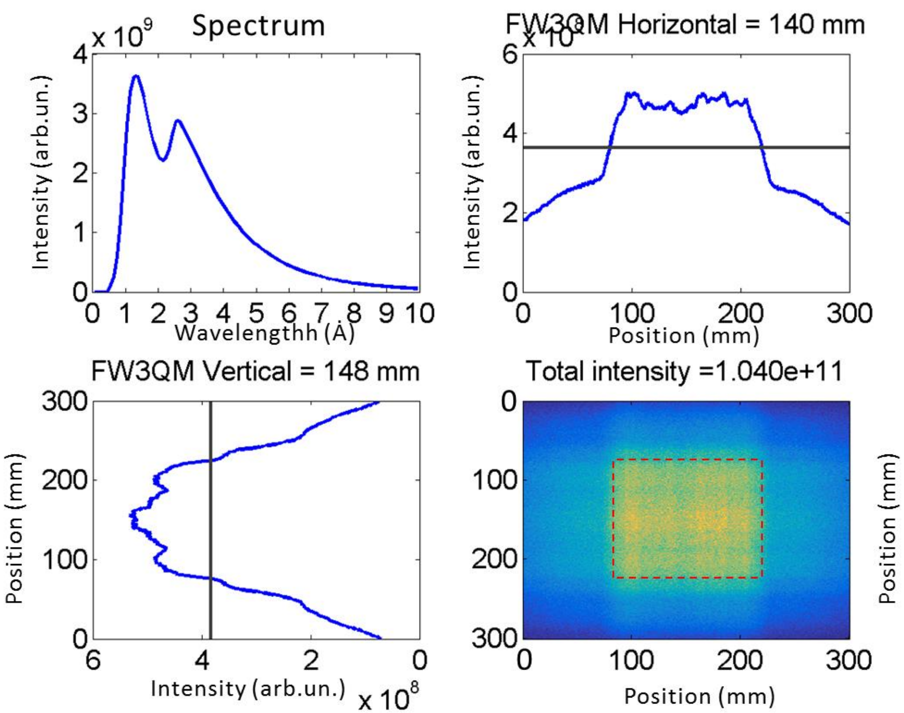

Every 2nd Pulse



ODIN

## Spectrum and Field of View

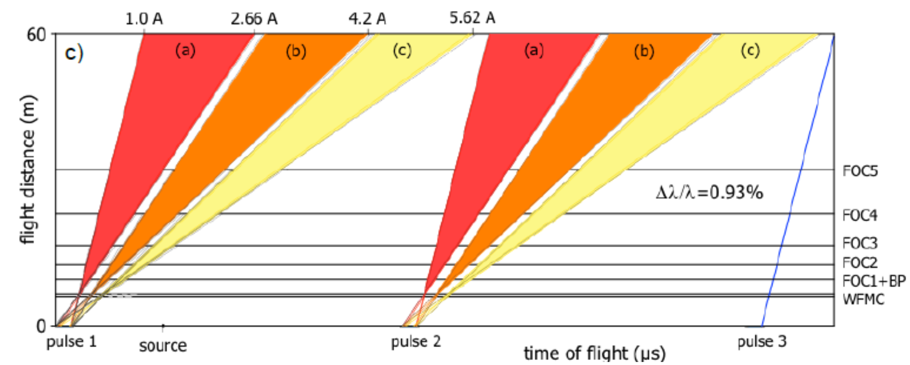
### FoV at 10m position



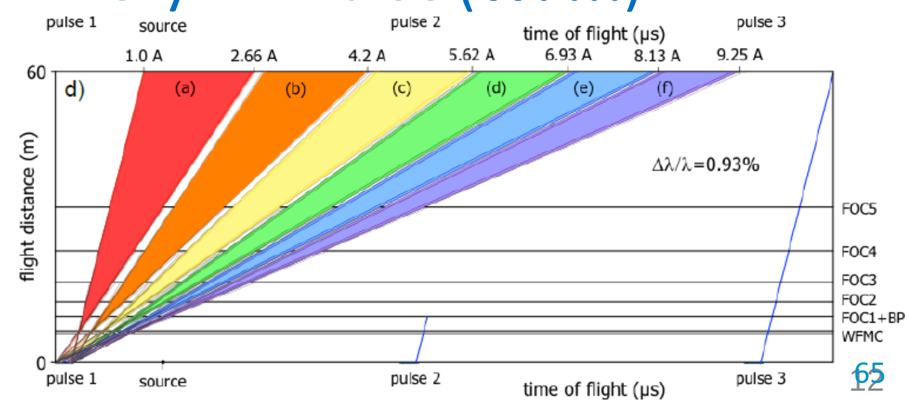

Large, homogenous FoV for large samples in e.g. Geology and Engineering.

## Chopper System: flexible resolution

### Every Pulse (WFM)



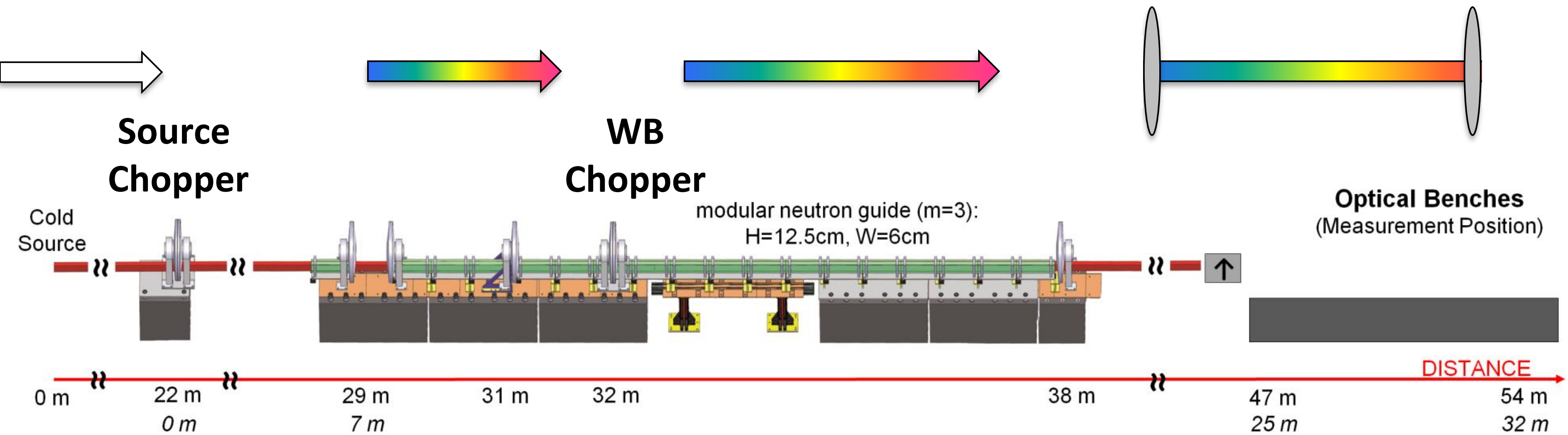

### Every 2nd Pulse (WFM)

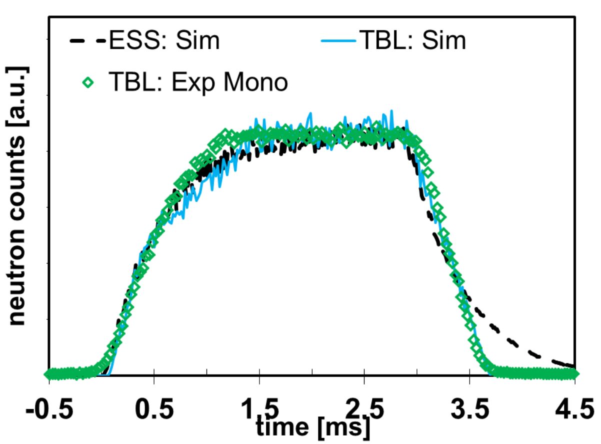



Credit: M. Lerche, M. Morgano

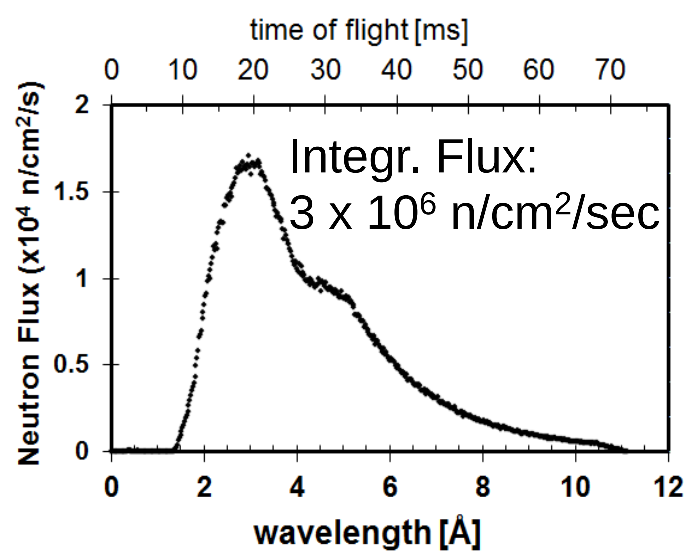
# WAVELENGTH SELECTIVE IMAGING 2

## Example ESS testbeamline: ESS mockup



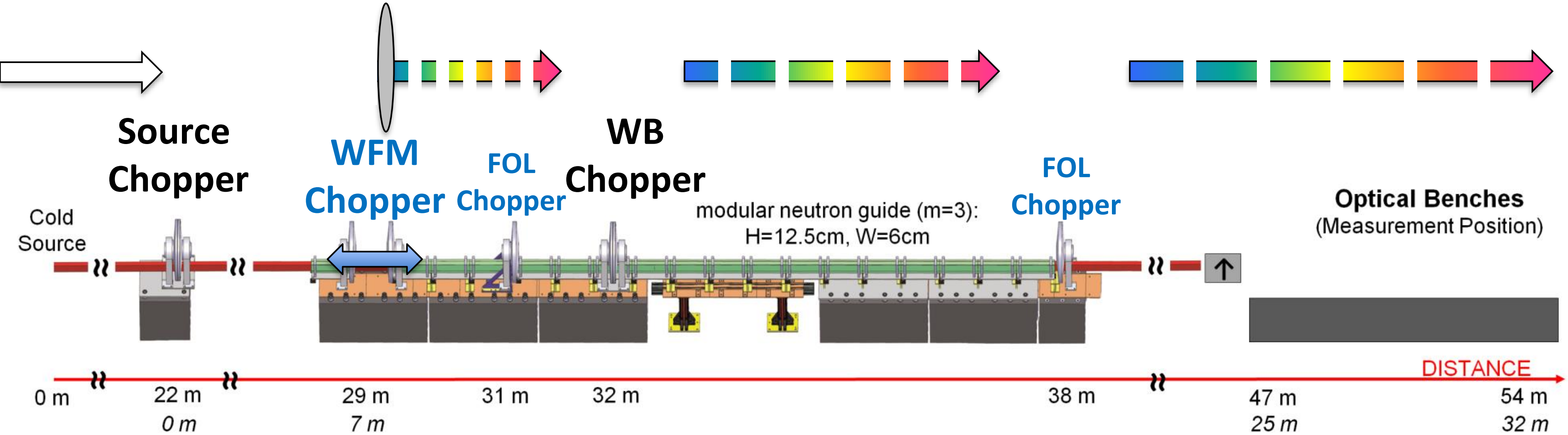

**Repetition: 14 Hz**

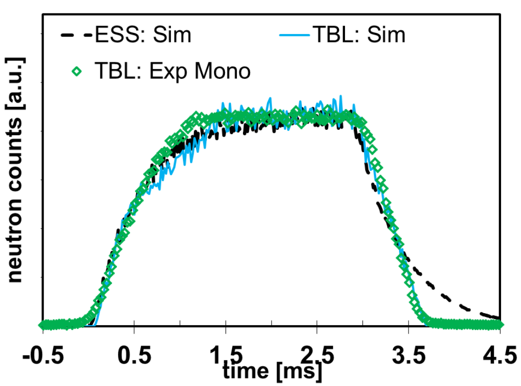


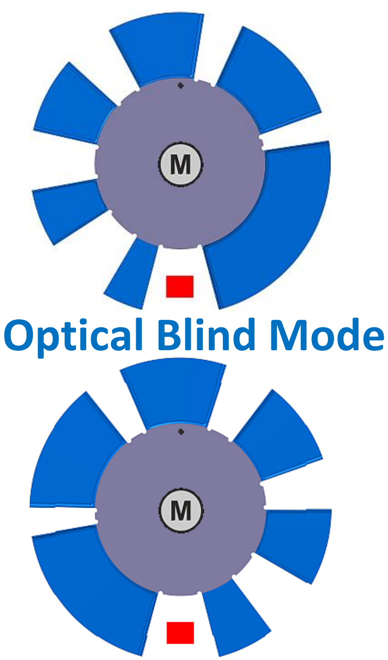

Wavelength resolutions: 4%-23%

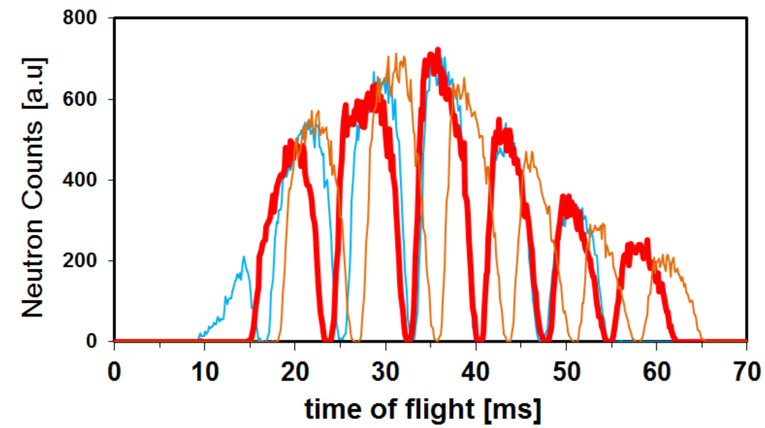
# WAVELENGTH SELECTIVE IMAGING 2

## Example ESS testbeamline: WFM




Tunable (but constant)
Wavelength resolutions: 0.5%-2%

# Wavelength selective imaging 2

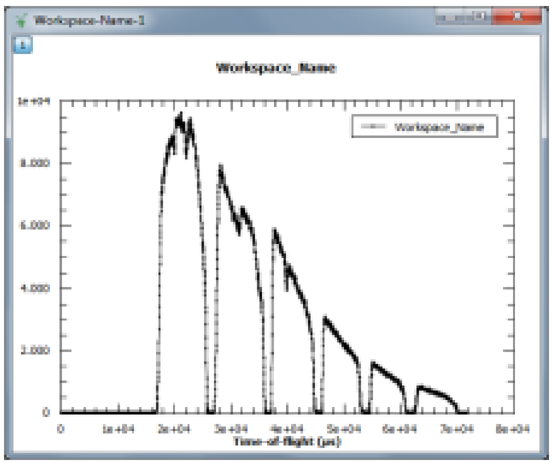
## Example ESS testbeamline: WFM

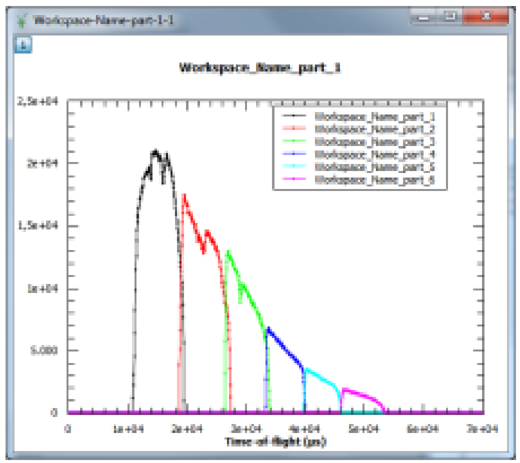
EUROPEAN SPALLATION SOURCE

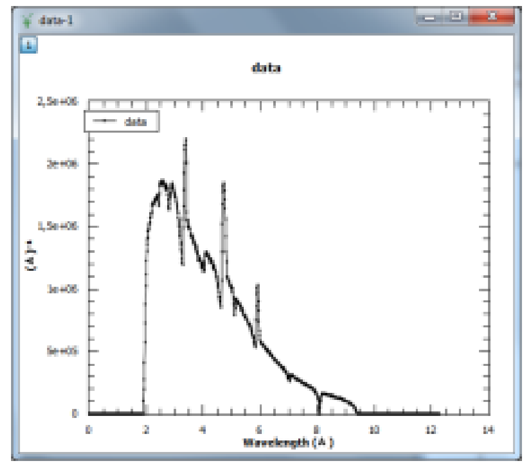
- WFM data reduction in NOW implemented in MANTID
- Data reudction of 1 image stack requires >20GB RAM

Offset frames

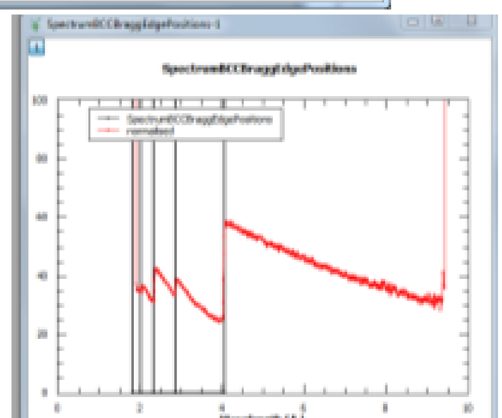
Stitch & Convert to λ







T = Sample/OpenBeam



# Energy (wavelength) selective imaging 2

## Part 2: Overview of ToF imaging beamlines

EUROPEAN SPALLATION SOURCE

SUMMARY

| | IMAT | | RADEN | | ODIN | |
|---|---|---|---|---|---|---|
| Repition | 10Hz | 5Hz (skipping) | 25Hz (12.5Hz possible) | | 14Hz | 7Hz (skipping) |
| Bandwith | 6A | 14A | 8.8A | 6.9A | 4.5A | 9A |
| Flightpath | 56m | | 18m | 23m | 60m | |
| Max flux [n/cm2/sec] | 3.8x10^7 | | 9.8x10^7 | 5.8x10^7 | 1.2x10^9 (at 2MW, no WFM) | |
| Resolution (at 2A) | 0.5%-0.8% | | 0.26 | 0.2 | No WFM: 10%<br>WFM: 0.3-0.8 | |
| L/D ratios | 245 - 1150 | | 180-5000 | 230-7500 | | Up to 10000 |

# Wavelength selective imaging 2 - ToF

## AGENDA

- **Part 1: Introduction to ToF imaging**
  - Basics (neutron energy, wavelength, velocity)
  - The ToF concept
  - ToF vs steady state instruments
- **Part 2: What do we need for a ToF neutron imaging instrument?**
  - ToF Neutron Source
  - Examples of of ToF imaging beamlines
  - ToF Detectors
- **Part 3: ToF Imaging methods**
  - The bigger picture: overview and comparison to other neutron techniques
  - ‘Attenuation’: Monochromatic, ‘white-beam’ and ‘pink-beam’ (narrow wavelength) applications
  - Diffraction Contrast / Bragg edge imaging (including diffraction basics)
  - Other methods to profit from ToF: Polarized, phase and dark field, 3DND, resonance absorption
- **Part 4:** Hands on example (please install https://imagej.net/Fiji/Downloads or https://imagej.nih.gov/ij/download.html)

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## Neutron Detectors

- How does one “detect” a neutron?
  - Can’t directly detect slow neutrons (neutrons relevant to materials science, that is)—they carry too little energy
  - Need to produce some sort of measurable quantitative (countable) electrical signal
- Need to use nuclear reactions to convert neutrons into charged particles
- Then one can use some of the many types of charged particle detectors
  - Gas proportional counters and ionization chambers
  - Scintillation detectors
  - Semiconductor detectors

# Energy (wavelength) selective imaging 2

## Part 2: Detectors

A common method for detecting neutrons involves converting the energy released from neutron capture reactions into electrical signals. Certain nuclides have a high neutron capture cross section, which is the probability of absorbing a neutron. Upon neutron capture, the compound nucleus emits more easily detectable radiation, for example an alpha particle, which is then detected.

- **Since neutrons have zero charge they cannot be detected directly, instead a charge particle needs to be produced and then detected.**
- Counters:
  - $BF_3$ $\quad {}^{10}B_5 + {}^{1}n_0 \rightarrow {}^{7}Li_3 + {}^{4}He_2 + 2.7\ \text{MeV}$
  - ${}^{3}He$ $\quad {}^{3}He_2 + {}^{1}n_0 \rightarrow {}^{3}He_1 + {}^{1}H_1$
- Film/scintillators:
  - ${}^{6}Li_3 + {}^{1}n_0 \rightarrow {}^{3}H_1 + {}^{4}He_2$
- Most detectors need bulky shielding as they are sensitive also to γ-rays

EUROPEAN SPALLATION SOURCE

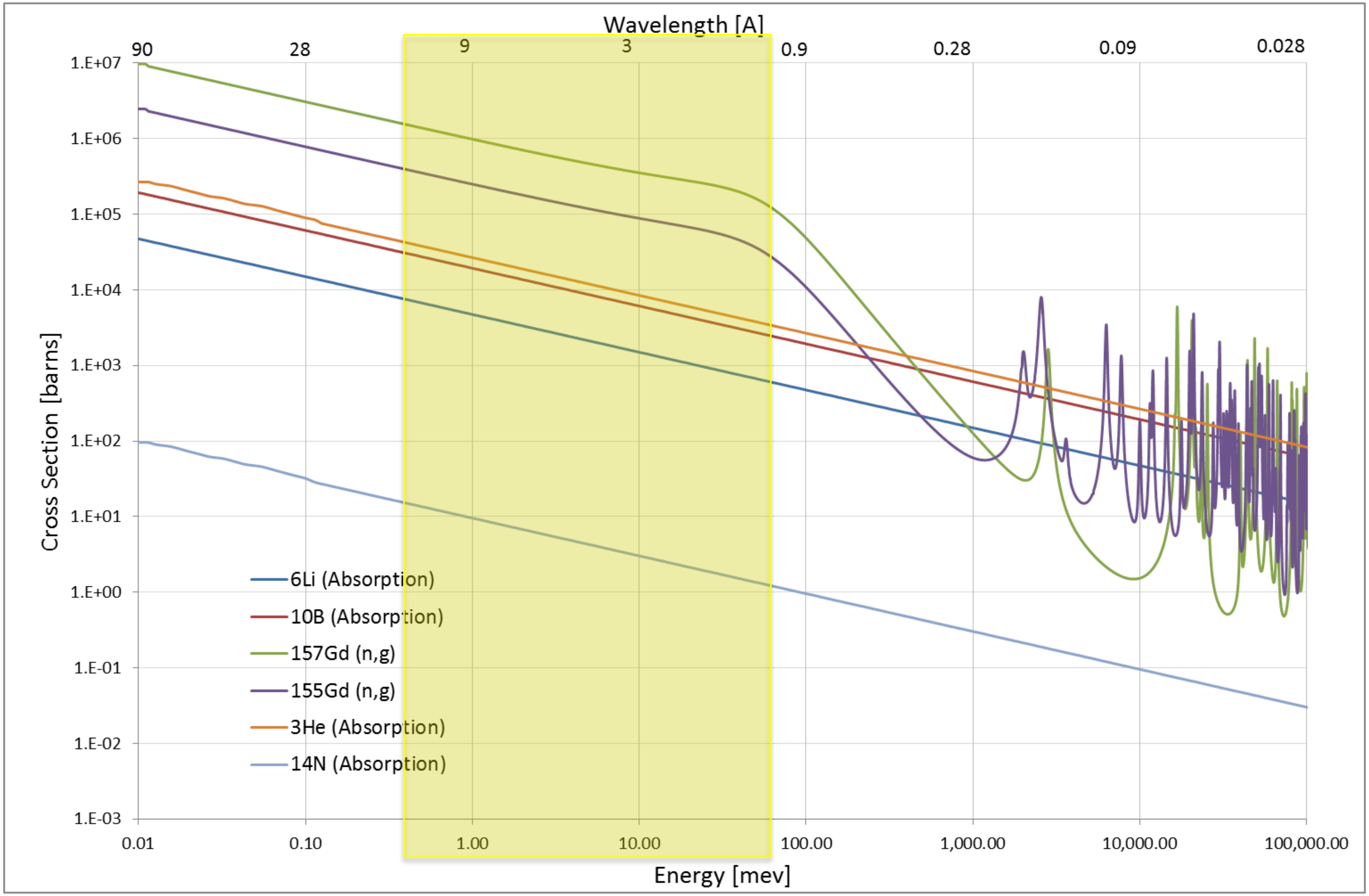
## *Nuclear Reactions for Neutron Detectors*

- n + $^{3}$He → $^{3}$H + $^{1}$H + 0.764 MeV
- n + $^{6}$Li → $^{4}$He + $^{3}$H + 4.79 MeV
- n + $^{10}$B → $^{7}$Li* + $^{4}$He→$^{7}$Li + $^{4}$He +2.31 MeV+ gamma (0.48 MeV) (93%)
  → $^{7}$Li + $^{4}$He +2.79 MeV ( 7%)
- n + $^{14}$N → $^{14}$C + $^{1}$H + 0.626 MeV
- n + $^{155}$Gd → Gd* → gamma-ray spectrum + conversion electron spectrum (~70 keV)
- n + $^{157}$Gd → Gd* → gamma-ray spectrum + conversion electron spectrum (~70 keV)
- n + $^{235}$U → xn + fission fragments + ~160 MeV (<x> ~ 2.5)
- n + $^{239}$Pu → xn + fission fragments + ~160 MeV (<x> ~ 2.5)
- $^{197}$Au(4.906 eV), 115In( 1.46 eV), $^{181}$Ta(4.28 eV), $^{238}$U(6.67, 10.25 eV); energy-selective detectors, narrow resonances, prompt capture gamma rays

# Energy (wavelength) selective imaging 2

## Part 2: Detectors

# Cross Sections for Neutron Detection

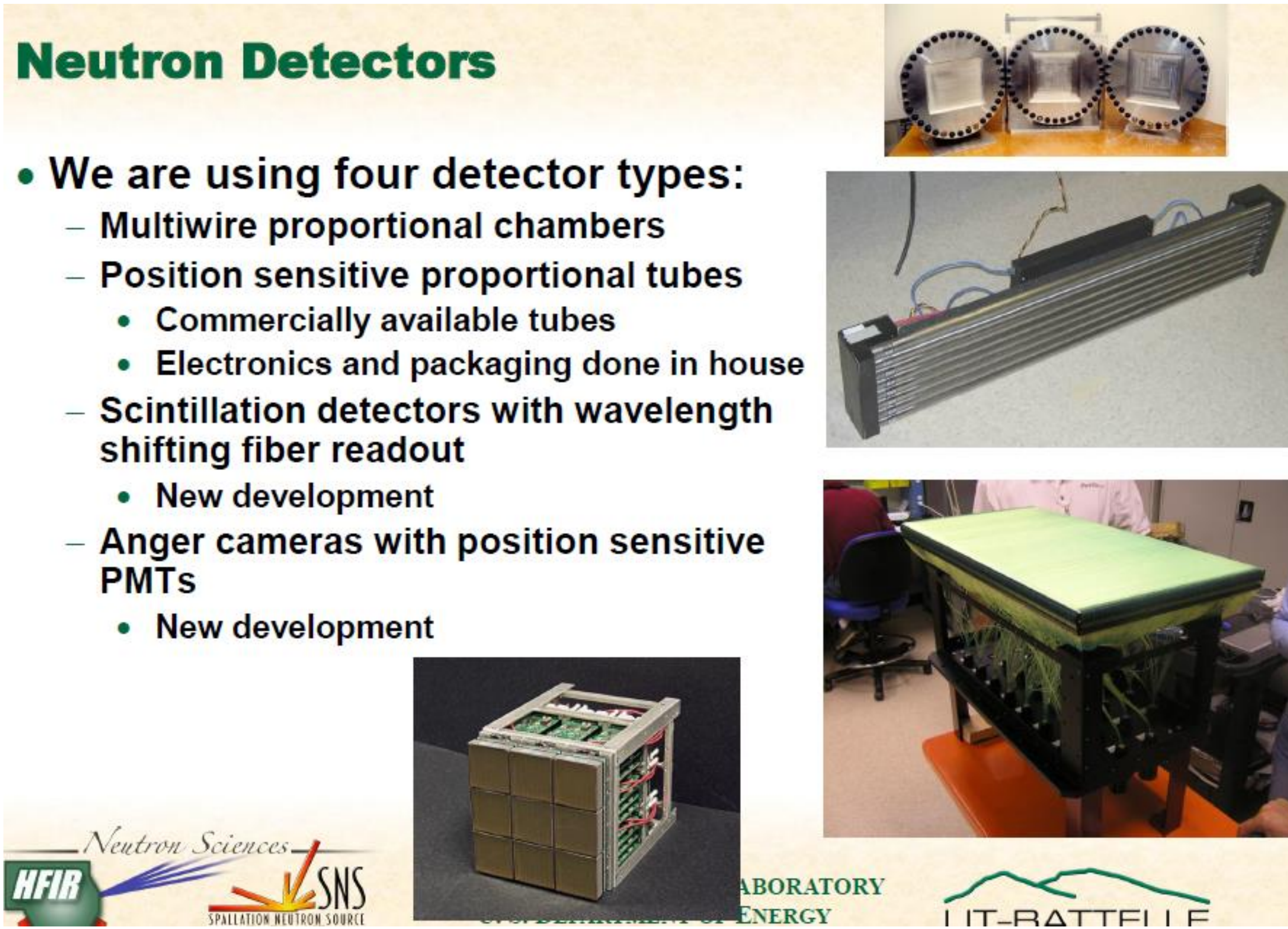



Courtesy: D. Pooley

# Energy (wavelength) selective imaging 2

## Part 2: Detectors

### Common ToF detectors for scattering instruments



# Energy (wavelength) selective imaging 2

## Part 2: Detectors

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**Common ToF detectors for scattering instruments**

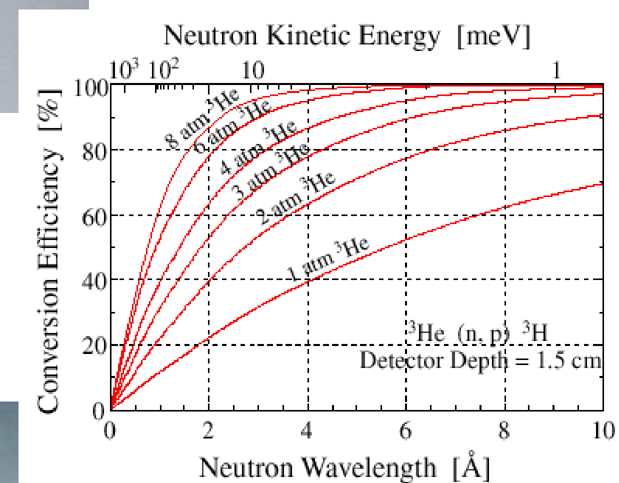
### Gas Detectors

n + $^3$He → $^3$H + p + 0.764 MeV

Ionization of gas

$e^-$ drift to high voltage anode

High efficiency




Also used at imaging beamlines

### Beam monitors

Low efficiency detectors for measuring beam flux

## Common ToF detectors for scattering instruments

### *Gas Detectors – cont'd*

- Ionization Mode
  - Electrons drift to anode, producing a charge pulse with no gas multiplication.
  - Typically employed in low-efficiency beam-monitor detectors.

- Proportional Mode
  - If voltage is high enough, electron collisions ionize gas atoms producing even more electrons.
    - *Gas amplification increases the collected charge proportional to the initial charge produced.*
    - *Gas gains of up to a few thousand are possible, above which proportionality is lost.*

## Common ToF detectors for scattering instruments

### *Spatial Resolution of Proportional Counters*

Spatial resolution (how well the detector tells the location of an event) is always limited by the charged-particle range and by the range of neutrons in the fill gas, which depend on the pressure and composition of the fill gas.

And by the geometry:

Simple PCs: $\delta z$ ~ diameter; 6 mm - 50 m*m.*
*LPSDs:* $\delta z$ *~ diameter,* $\delta y$ ~ diameter ; 6 mm - 50 mm.
MWPC: $\delta z$ and $\delta y$ ~ wire spacing; 1 mm - 10 mm.

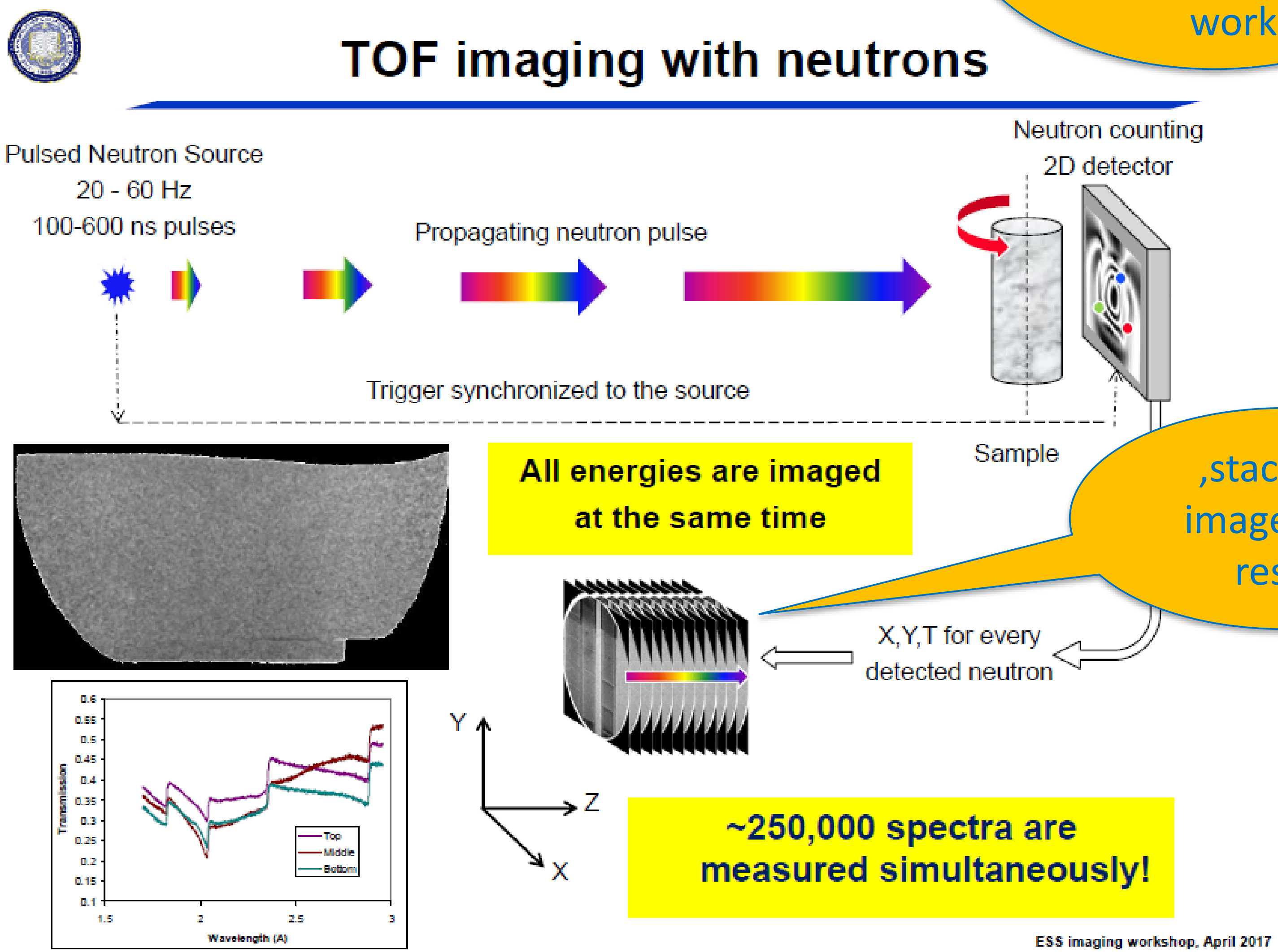
- Very coarse resolution for imaging
- Also: count rates for imaging different than for scattering

# Energy (wavelength) selective imaging 2

## Part 2: Detectors

### ToF detectors for imaging: developing field

- Let us briefly remind ourselves how a ToF imaging experiment works



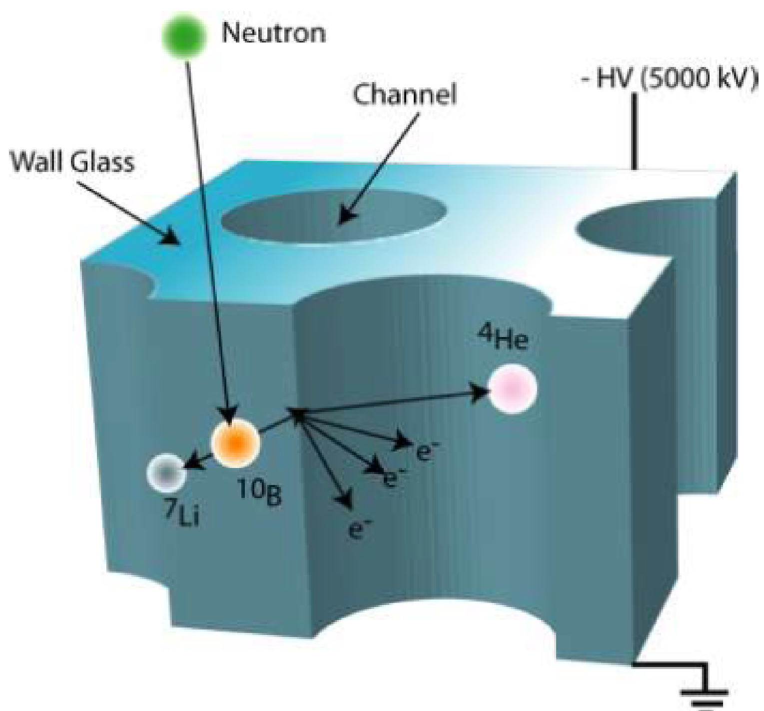

‚stacks' of images as a result

Courtesy: A. Tremsin

Different readouts can be used, optimized for particular application

**ToF detectors for imaging: developing field**

MicroChannel Plates (MCP's)




- Similar principle of photo-multiplier tube
- $^{10}B$ or $^{nat}Gd$ in wall glass absorbs neutron
- Reaction particles and high electric field create an electron avalanche
- Charge cloud detected with position sensitive anode
- No read noise due to large amplification, but small gamma-ray sensitivity
- Spatial resolution limited by channel separation and range of charged particle
- Ultimate resolution of ~**10 µm**
- Each detected neutron event is reconstructed, which introduces a deadtime
- Deadtime limits useable field of view to about 1-2 cm$^2$, which is OK for PEMFCs

Courtesy: D. Hussey

# Wavelength selective imaging 2 - ToF

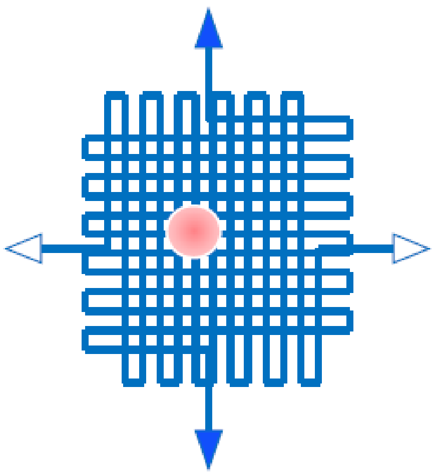
## Part 2: Detectors

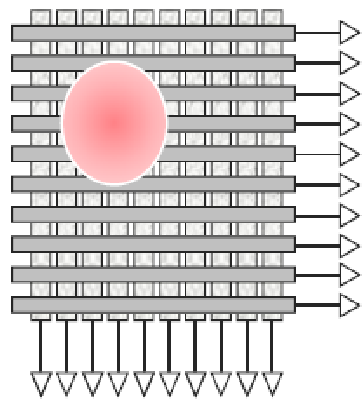
EUROPEAN SPALLATION SOURCE

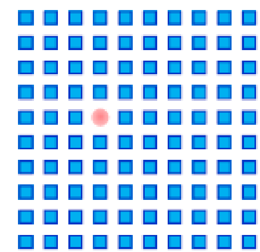
**ToF detectors for imaging: developing field**

<u>MicroChannel Plates (MCP's)</u>

Readout types







but events (not neutrons)

| Cross Delayline (XDL) | Cross Strip (XS) | Medipix/Timepix ASIC |
|---|---|---|
| 4 amps | 2 x N amps | N x N amps |
| Gain ~ $10^7$ | Gain ~ $10^6$ | Gain ~ $10^4$-$10^5$ |
| Rate < 1MHz | Rate < 5MHz | Rate > 200MHz |
| $\Delta t$ ~ 50 ps rms | $\Delta t$ ~ 100 ps rms | $\Delta t$ ~ 10 ns - 1 ms |

1x10^6

5x10^6

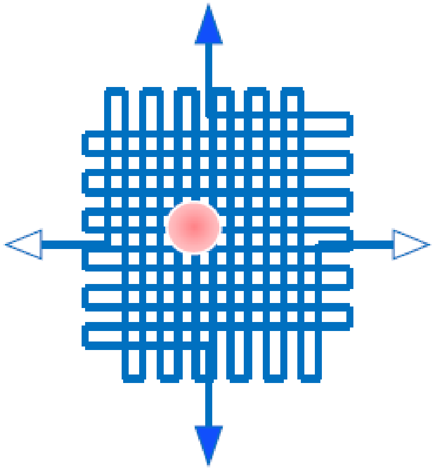
2x10^8

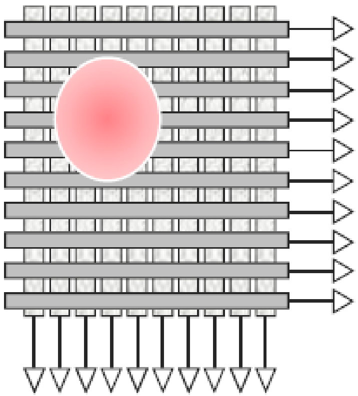
Courtesy: A. Tremsin

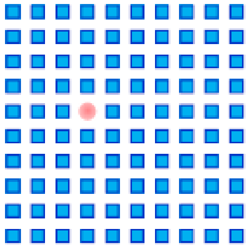
# ToF detectors for imaging: developing field

## MicroChannel Plates (MCP's)

Readout types





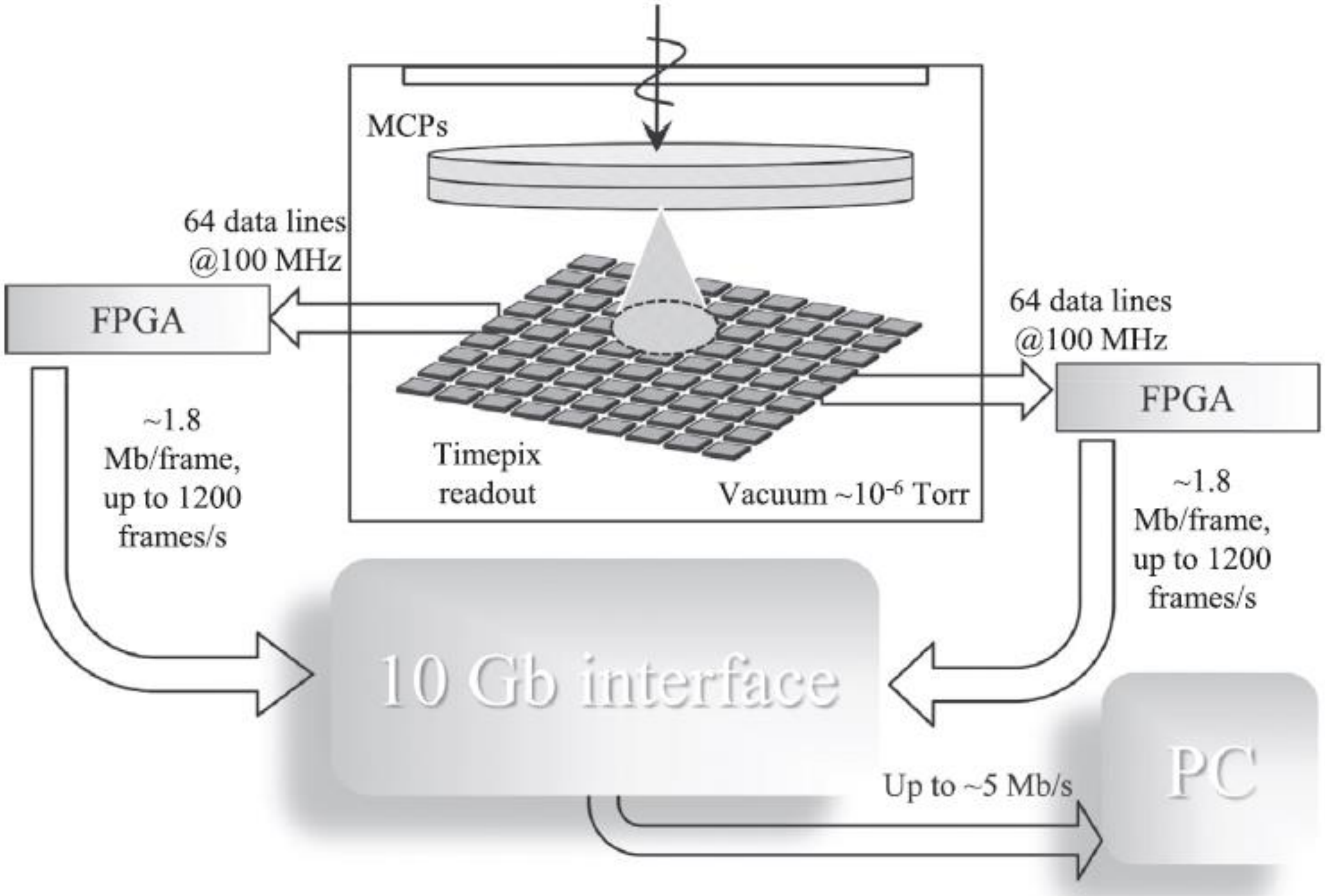


| Cross Delayline (XDL) | Cross Strip (XS) | Medipix/Timepix ASIC |
|---|---|---|
| Single particle processed<br>Dead time 200-300 ns | Single particle processed<br>Dead time ~300ns<br>**only for active fingers** | Multiple events detected (up to 25000)<br>1200 frames/s<br>Timepix3 – 80 MHz per chip |

Courtesy: A. Tremsin

# ToF detectors for imaging: developing field

MicroChannel Plates (MCP's): Timepix readout

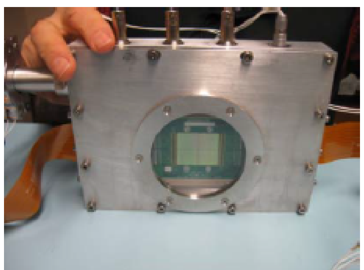


EUROPEAN SPALLATION SOURCE

# ToF detectors for imaging: developing field

## MicroChannel Plates (MCP's): Timepix readout

### Detector configuration and performance



- Detection of photons, ions, neutrons, alphas, high energy electrons, atoms.
- Up to ~25000 simultaneous events can be detected.
- Active area 28x28 mm$^2$ (2x2 Timepix chips).
- Fast parallel readout (x32) allowing ~1200 frames per second with ~320 μs readout time
- Event centroiding (~12 μm resolution, at ~5x10$^6$ events/s) or 55 μm resolution at >5x10$^8$ events/s.
- Time resolution can be ~20 ns at ~2.5x10$^7$ events/s rates with 55 μm resolution.
- Timing within frames – TOF(energy) or dynamic processes can be studied. Wide energy range or most phases measured in one experiment.

High count rate

Small FoV

Leads to gaps

Best spatial resultion of any ToF detector

Better than needed for most applications

Courtesy: A. Tremsin

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# ToF detectors for imaging: developing field

## MicroChannel Plates (MCP's): Timepix readout

### 3 modes of event counting/imaging

1. **Event counting in each pixel**
   - up to 11800 events per pixel/frame
   - ~10 kHz rate/pix
   - detector global rate >100 MHz with no resolution degradation
   - local counting rate ~100 kHz
   - spatial resolution = 55 μm pixel
   - time resolution = shutter length (1μs-seconds)
   - can be synchronized to external trigger (stroboscopic imaging)

2. **Time of event : internal clock or relative to external trigger**
   - 1 event per pixel/frame (~25K events/frame)
   - time bin from 10 ns
   - time range = 11800 x time bin
   - spatial resolution = 55 μm pixel
   - multiple shutters per trigger

3. **Charge in pixel**
   - 1 event per pixel/frame (~25K events/frame)
   - spatial resolution = 55 μm pixel
   - time resolution = shutter length (1 μs to secondss)
   - can be synchronized to external trigger
   - multiple shutters per external trigger

Courtesy: A. Tremsin

Present status of neutron imaging detector development at RADEN

Joe Parker
CROSS
BL22 Group

NEUWAVE-9 NIST 13 June 2017

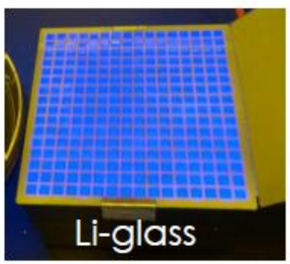
# ToF detectors for imaging: developing field

## Detectors at RADEN

### Counting type



- nGEM (boron)
- μNID ($^3$He)
- Li-glass scintillator
- Anton's MCP also available




### Counting-type detectors at RADEN

| Detector | Type | Performance | Primary imaging methods |
|---|---|---|---|
| μNID | Micropattern, $^3$He converter | • Area: 10 x 10 cm$^2$<br>• Spatial resolution: 0.2 mm<br>• Time resolution: 0.25 μs<br>• Efficiency: 25% (thermal)<br>• Count rate: 100~300 kcps | • Resonance absorption<br>• Bragg-edge<br>• Magnetic imaging<br>• Phase-contrast imaging |
| nGEM | Micropattern, $^{10}$B converter | • Area: 10 x 10 cm$^2$<br>• Spatial resolution: 1 mm<br>• Time resolution: 10 ns<br>• Efficiency: 10% (thermal)<br>• Count rate: 200~400 kcps | • Resonance absorption<br>• Bragg-edge |
| Li-glass | GS20 scintillator pixels with $^6$Li | • Area: 5 x 5 cm$^2$<br>• Spatial resolution: 3 mm<br>• Time resolution: >40 ns<br>• Efficiency: 25% (thermal)<br>• Count rate: 6 Mcps | • Resonance absorption<br>• Bragg-edge |

Courtesy: J. Parker

Present status of neutron imaging detector development at RADEN

Joe Parker
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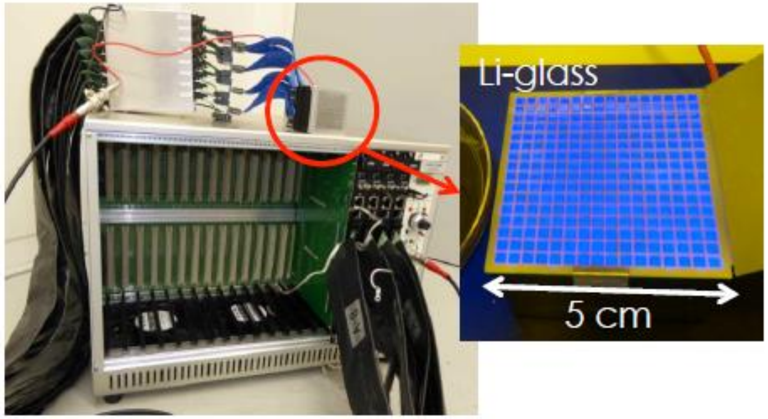
# ToF detectors for imaging: developing field

## Detectors at RADEN

## Li-glass scintillator detector (LiTA12)

- Li-glass scintillator with Ce activator (GS20) (2.1 x 2.1 x 1mm$^3$ x 256)
- Hamamatsu H9500 multi-anode PMT
- 3.4% efficiency at 4 eV for t=1mm
- Improvements for resonance absorption imaging
  - < 1mm spatial resolution with flat-panel scintillator and charge centroiding
  - Increase efficiency with 3~4 mm thick scintillator




| Li-glass detector parameters | |
|---|---|
| Area | 5 x 5 cm$^2$ |
| Spatial resolution | 3 mm |
| Time resolution | 40 ns ~ |
| Efficiency (thermal) | 20~25% |
| Count rate | 6 Mcps |

Courtesy: J. Parker

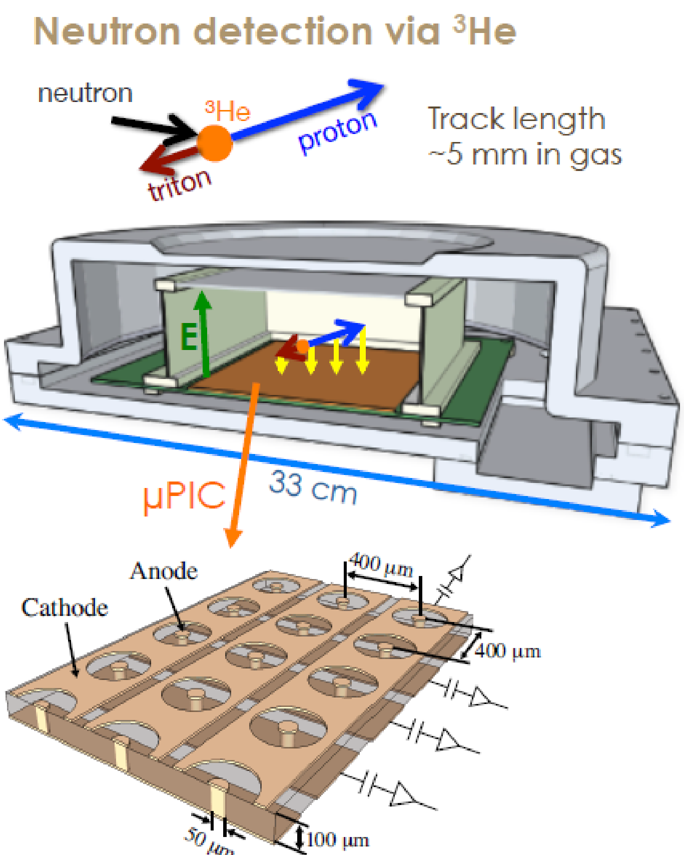
# Wavelength selective imaging 2 - ToF

## Part 2: Detectors


**ToF detectors for imaging: developing field**

Detectors at RADEN

### μPIC-based neutron imaging detector (μNID)




- $CF_4$-isobutane-$^3He$ (45:5:50) gas mixture at 2 atm
- 3-dimensional tracking of decay pattern
- Energy via time-over-threshold
- Compact ASIC+FPGA data encoder

| μNID performance characteristics | |
|---|---|
| Area | 10 x 10 $cm^2$ |
| Spatial res. | <0.2 mm |
| Time res. | 0.25 μs |
| $\gamma$-sensitivity | < $10^{-12}$ |
| Efficiency @25.3 meV | Up to 26% |
| Count rate capacity | 8 Mcps |

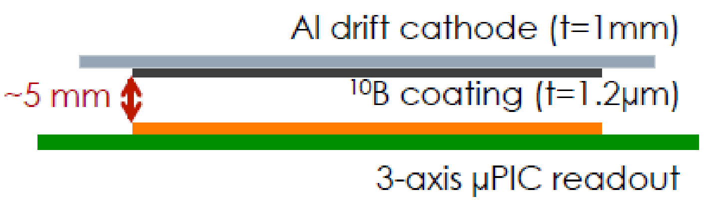
Courtesy: J. Parker


# ToF detectors for imaging: developing field

## Detectors at RADEN

### μNID with boron converter

- $^{10}B$-coated drift cathode (t=1μm) for initial test
- $CF_4$-isobutane(10%) at 1.2~1.6 atm
  - 3x smaller event size compared to $^{3}He$
- Testing at RADEN started in February
- Considering how to improve efficiency




| Expected performance | |
|---|---|
| Efficiency@25.3meV | 3~5% |
| Time resolution | 10 ns |
| Spatial resolution | 0.4~0.5 mm |
| Peak count rate | 20~30 Mcps |

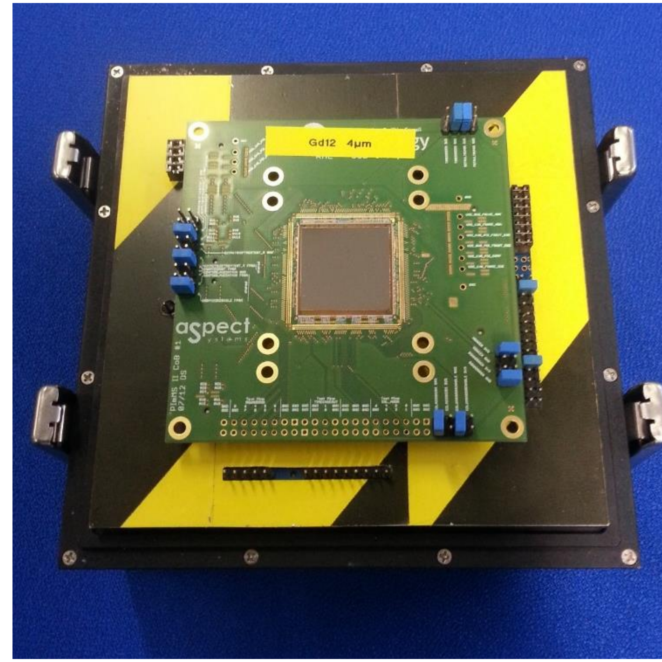
Courtesy: J. Parker

# ToF detectors for imaging: developing field

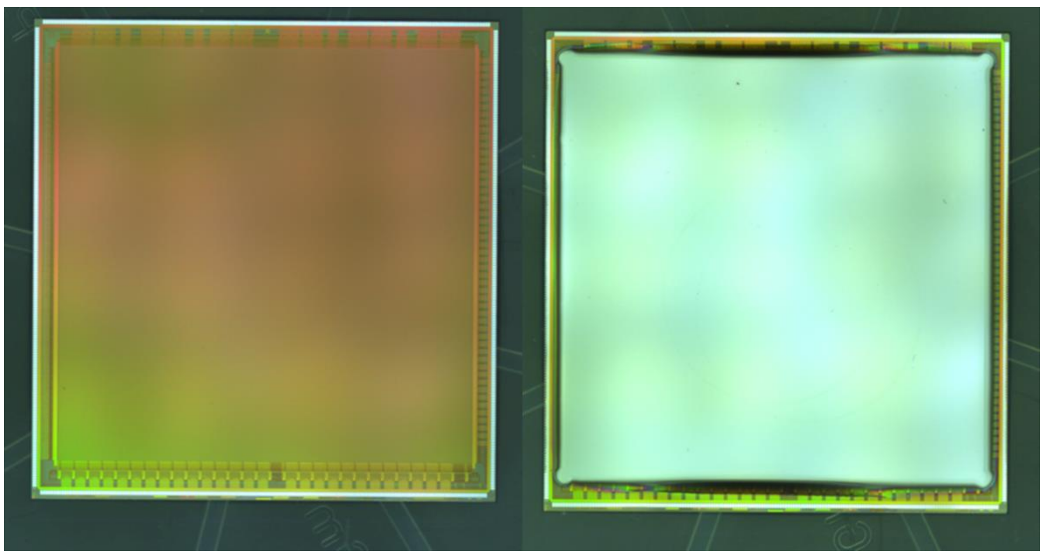
## Detectors at IMAT

## GP2

GP2 [1] is a 100k pixel time-of-flight neutron camera,




which combines a gadolinium converter film and a CMOS readout sensor [2].



[1] D. E. Pooley, et al., IEEE TNS, vol. 64, no. 12, p. 2970, 2017
[2] I. Sedgwick, et al., IEEE NEWCAS, 2012

Courtesy: D. Pooley

# Wavelength selective imaging 2 - ToF

## Part 2: Detectors

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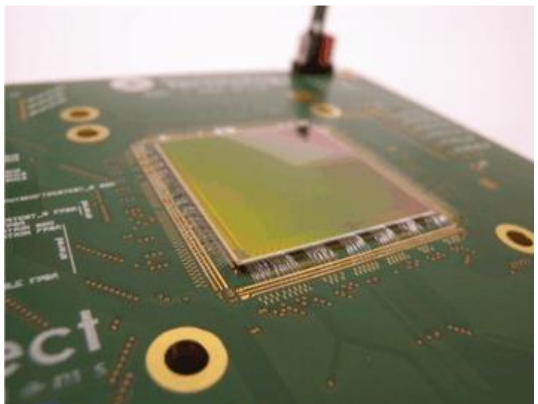
## ToF detectors for imaging: developing field

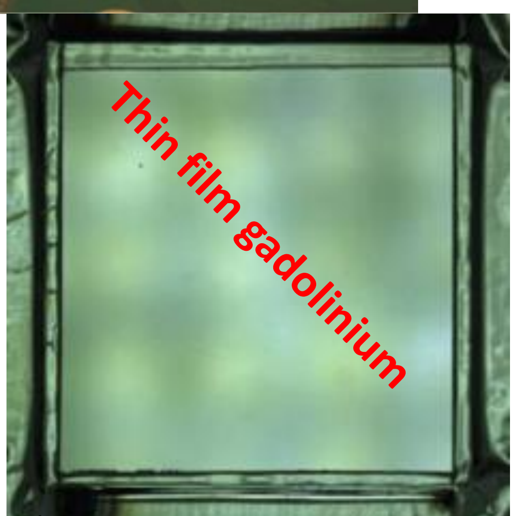
<u>Detectors at IMAT</u>

**Philosophy: Provide an independent solution for the requirements of ToF imaging**

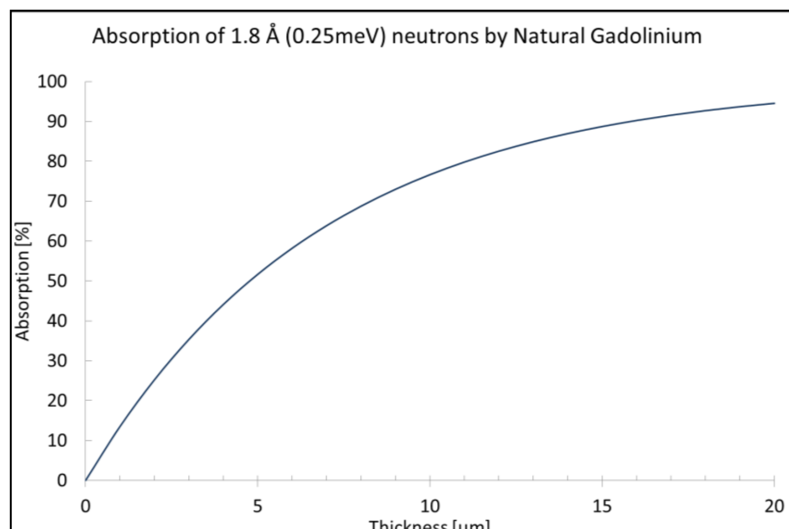
1. Active Area: Continuous, without gaps.
2. Compact, robust & free of moving parts.
3. Standardized and reliable connectivity.

| | | | Cross Section |
|---|---|---|---|
| $^{3}He$ | → | $^{3}H$ + p | 3000 |
| $^{157}Gd$ | → | γ + Conversion electrons | 74000 |
| $^{nat}Gd$ | → | γ + Conversion electrons | 17000 |

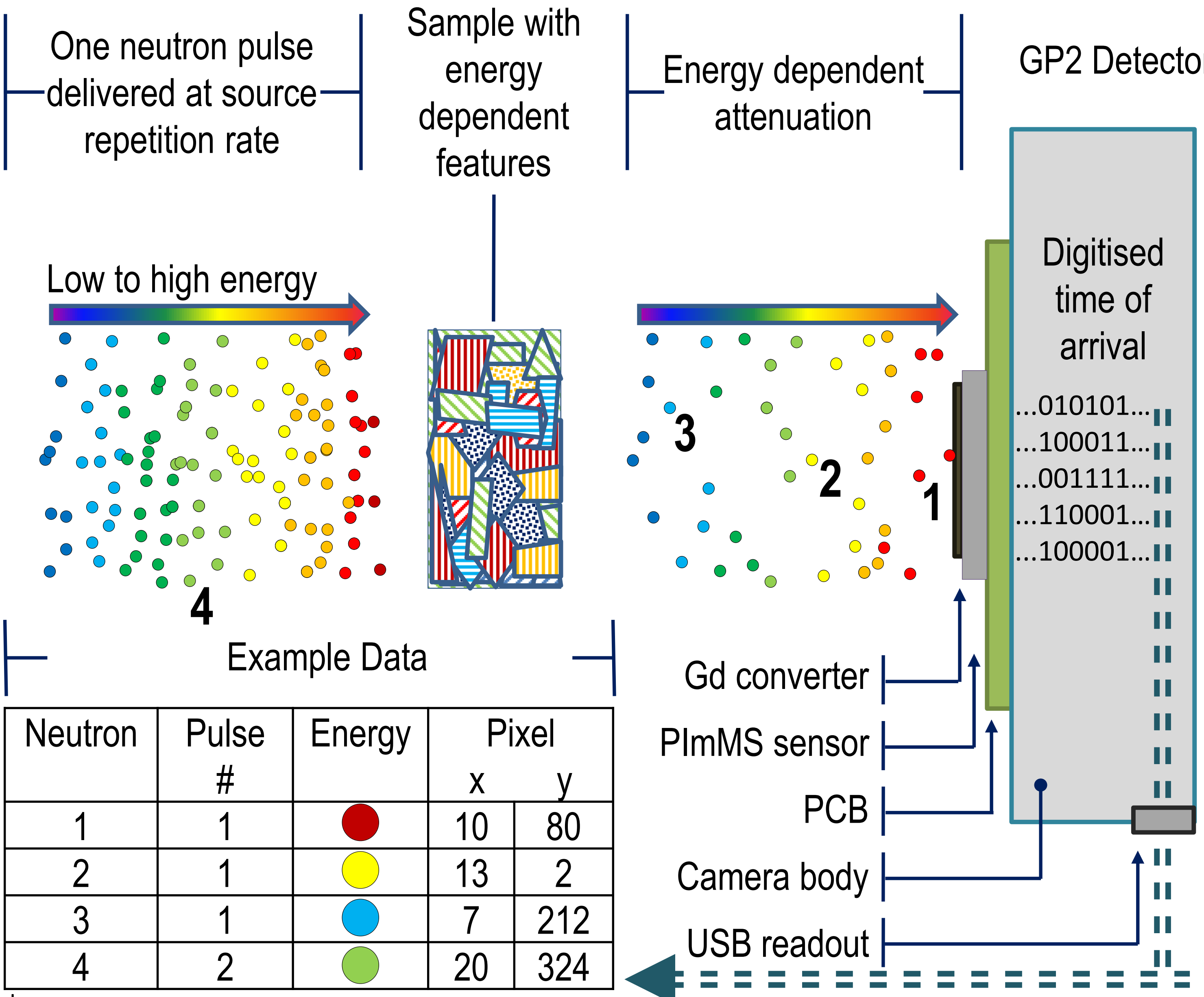





Courtesy: D. Pooley



# GP2 RUNS IN EVENT MODE




| Neutron | Pulse # | Energy | Pixel x | Pixel y |
|---|---|---|---|---|
| 1 | 1 | (red) | 10 | 80 |
| 2 | 1 | (yellow) | 13 | 2 |
| 3 | 1 | (blue) | 7 | 212 |
| 4 | 2 | (green) | 20 | 324 |

Courtesy: D. Pooley

# Wavelength selective imaging 2 - ToF

## Part 2: Detectors

512x512 pixels 16-bit images per time/wavelength bin. The time bin position and width can be freely chosen (to a certain extent) with a small text configuration file that has to be included in the data folder for reference purposes.

| Step | Measurement | Raw data produced (GB) | exposure time (h) | average data rate (GB/h) | Resulting 'raw' data after detector 'correction' (GB) |
|---|---|---|---|---|---|
| 1 | Test Radiographs of a few samples (overnight run after initial setup) | 22.0 | 14.5 | 1.5 | 65.9 |
| 2 | In-situ Furnace test | 5.2 | 1 | 5.2 | 15.6 |
| 3 | Sample alignment | 0.5 | 0.5 | 1.0 | 1.5 |
| 4 | Measurement sample 1-3 | 33.0 | 17 | 1.9 | 99.0 |
| 5 | Radiographs | 20.0 | 8 | 2.5 | 60.0 |
| 6 | Alignment | 1.0 | 0.5 | 2.0 | 3.0 |
| 7 | Tomography ( | 63.0 | 24 | 2.6 | 189.0 |
| 8 | Measurement sample 4-6 | 49.0 | 14.5 | 3.4 | 147.0 |
| 9 | Calibration sample | 0.5 | 0.5 | 1.0 | 1.5 |
| | total | 194.1 | 80.5 | 2.4 | 582.4 |

Courtesy: M. Morgano

# Wavelength selective imaging 2 - ToF

## AGENDA

- **Part 1: Introduction to ToF imaging**
  - Basics (neutron energy, wavelength, velocity)
  - The ToF concept
  - ToF vs steady state instruments
- **Part 2: What do we need for a ToF neutron imaging instrument?**
  - ToF Neutron Source
  - Examples of of ToF imaging beamlines
  - ToF Detectors
- **Part 3: ToF Imaging methods**
  - The bigger picture: overview and comparison to other neutron techniques
  - ‘Attenuation’: Monochromatic, ‘white-beam’ and ‘pink-beam’ (narrow wavelength) applications
  - Diffraction Contrast / Bragg edge imaging (including diffraction basics)
  - Other methods to profit from ToF: Polarized, phase and dark field, 3DND, resonance absorption
- **Part 4:** Hands on example (please install https://imagej.net/Fiji/Downloads or https://imagej.nih.gov/ij/download.html)

# Part 3: ToF Imaging methods

**Essentially, there were 2 types of neutron instruments:**

**Diffractometers: -measure Elastic Scattering**

**Structure**

Neutrons as waves
Based on Bragg's Law
No change of energy detected

**Spectrometers: -measure Inelastic Scattering**

**Dynamics**

Neutrons as particles
Based upon Newton's laws
Change of energy detected

# Part 3: ToF Imaging methods

**Essentially, there are 3 types of neutron instruments:**

**Diffractometers: -measure Elastic Scattering**

**Structure**

Neutrons as waves
Based on Bragg's Law
No change of energy detected

**Spectrometers: -measure Inelastic Scattering**

**Dynamics**

Neutrons as particles
Based upon Newton's laws
Change of energy detected

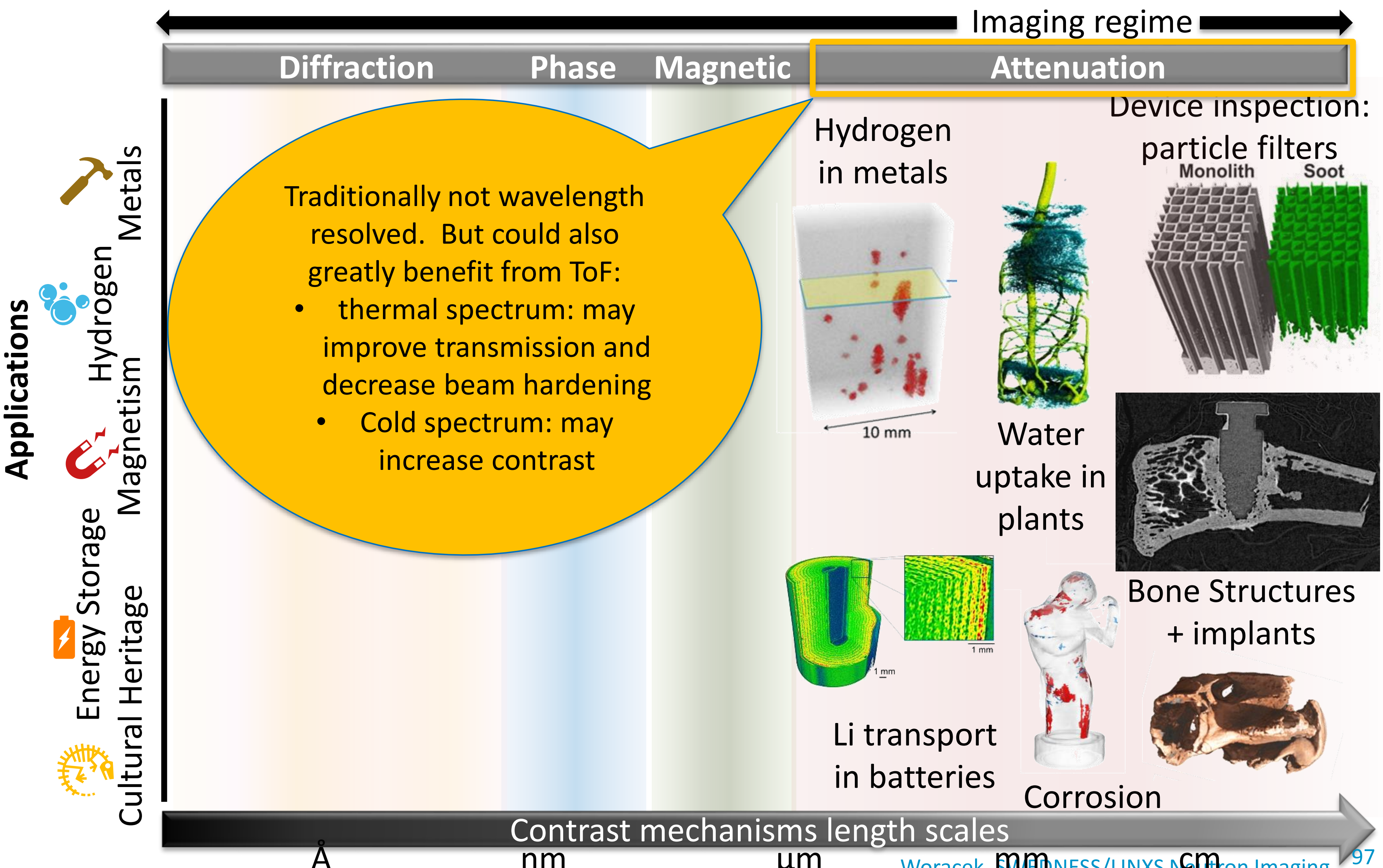
**Imaging –measure the overall attenuation**

**Structure**

The total cross section is essentially probed
Based on Lambert Beer law
*Novel methods exploit a lot more…*

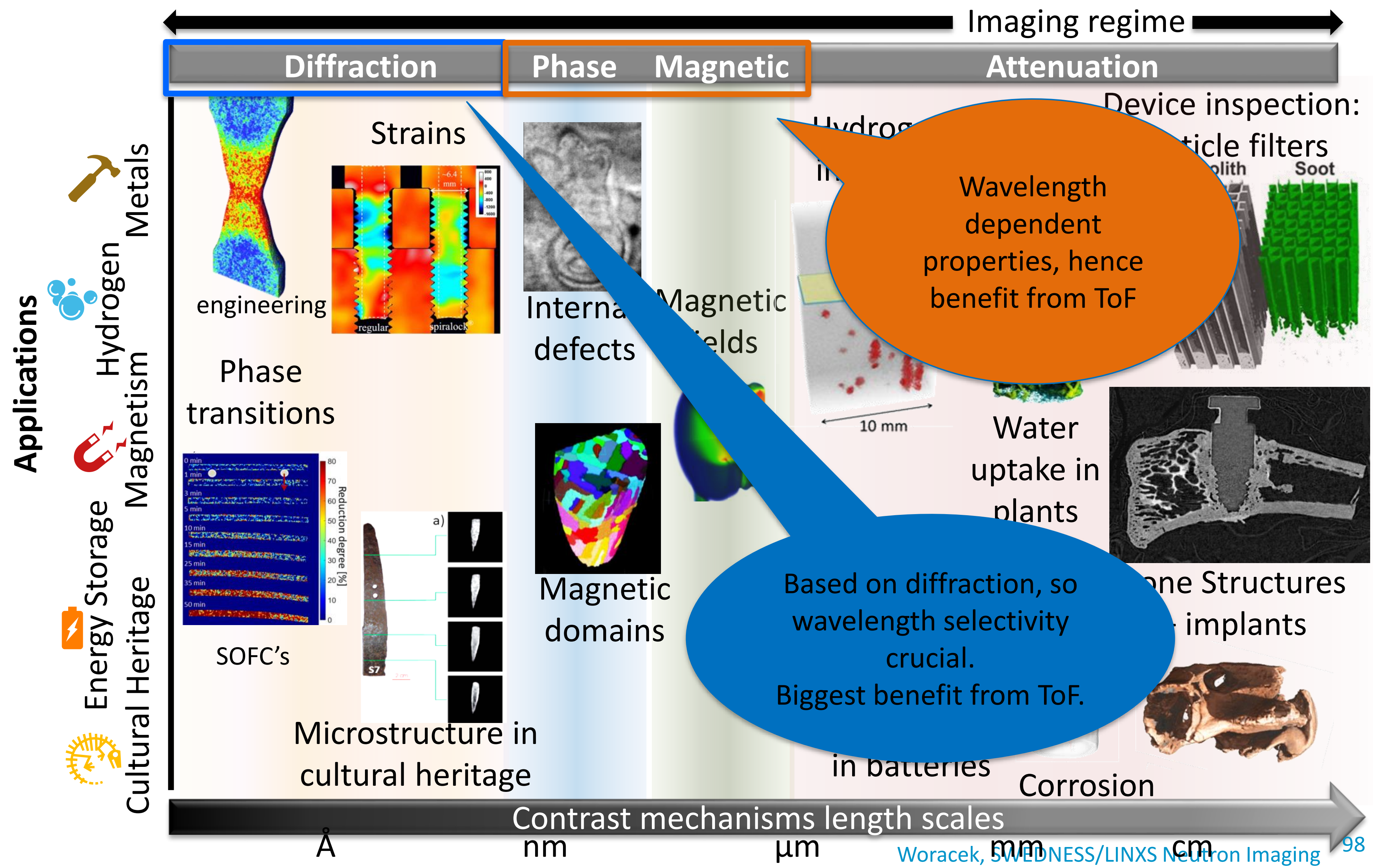
# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods



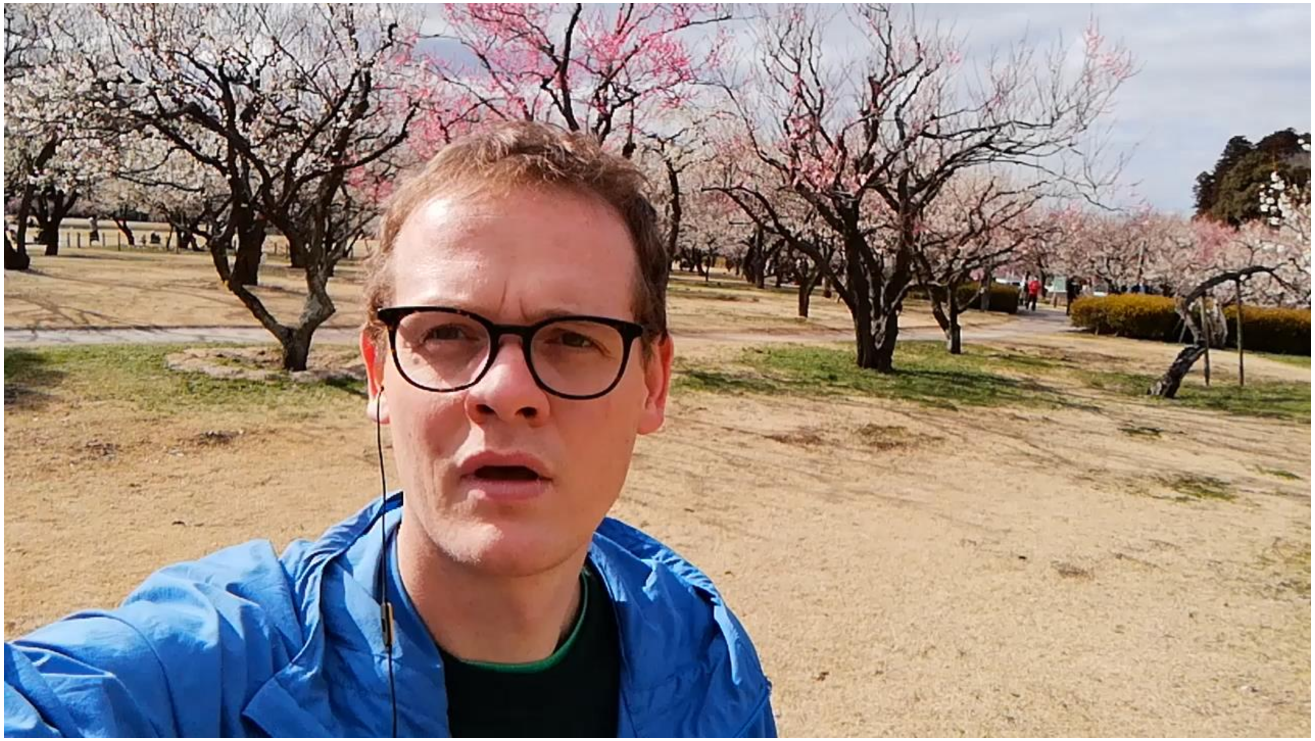
# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods



# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods



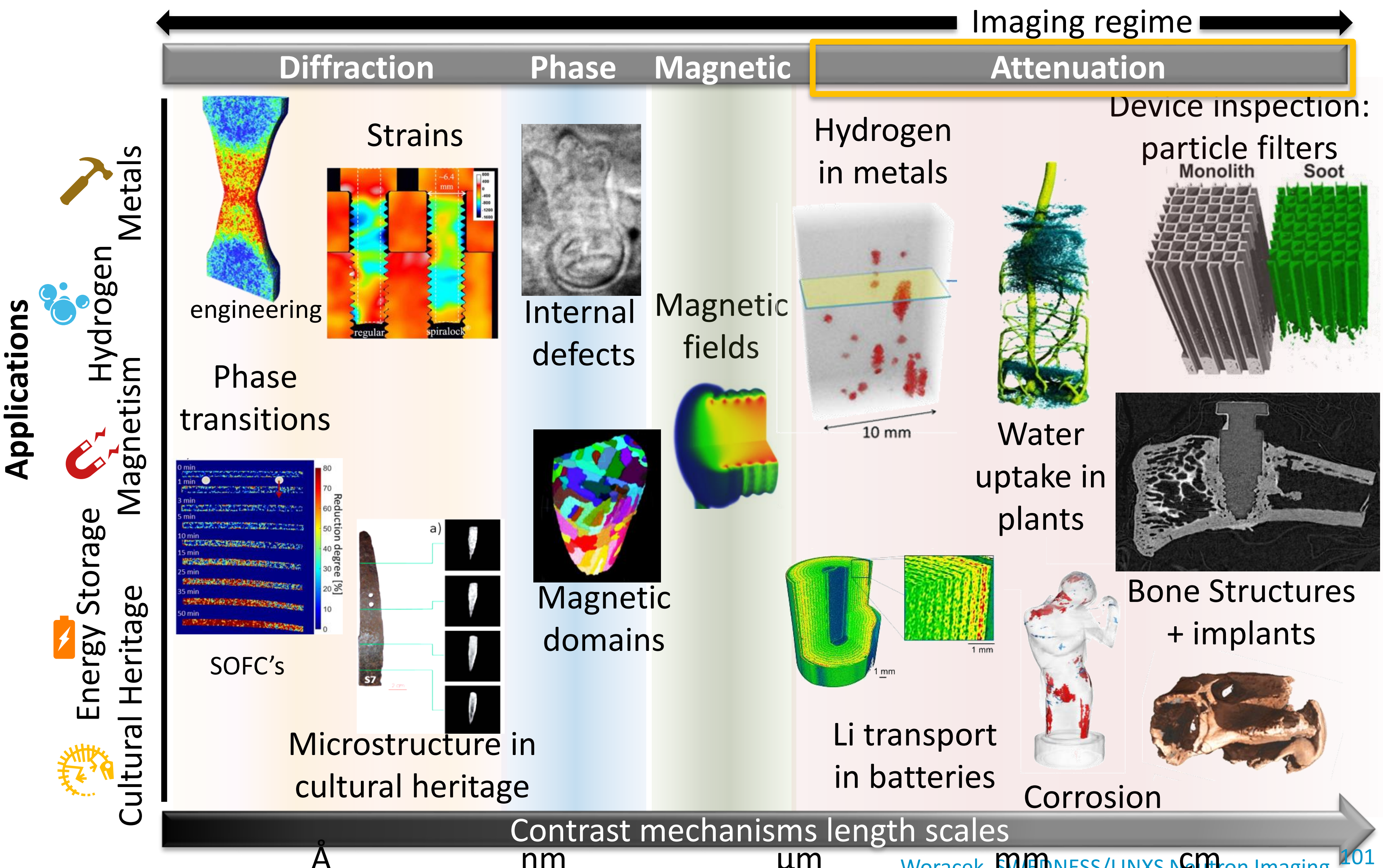
Credit: M. Sales and all….

# AGENDA

- **Part 1: Introduction to ToF imaging**
  - Basics (neutron energy, wavelength, velocity)
  - The ToF concept
  - ToF vs steady state instruments
- **Part 2: What do we need for a ToF neutron imaging instrument?**
  - ToF Neutron Source
  - Examples of of ToF imaging beamlines
  - ToF Detectors
- **Part 3: ToF Imaging methods**
  - The bigger picture: overview and comparison to other neutron techniques
  - 'Attenuation': Monochromatic, 'white-beam' and 'pink-beam' (narrow wavelength) applications
  - Diffraction Contrast / Bragg edge imaging (including diffraction basics)
  - Other methods to profit from ToF: Polarized, phase and dark field, 3DND, resonance absorption
- **Part 4:** Hands on example (please install https://imagej.net/Fiji/Downloads or https://imagej.nih.gov/ij/download.html)

# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods **Attenuation**



# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods **Attenuation**

EUROPEAN SPALLATION SOURCE

## Attenuation of different materials (at one wavelength)

Attenuation coefficients with neutrons [cm?$^{1}$ ]

| 1a | 2a | 3b | 4b | 5b | 6b | 7b | 8 | | | 1b | 2b | 3a | 4a | 5a | 6a | 7a | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H 3.44 | | | | | | | | | | | | | | | | | He 0.02 |
| Li 3.30 | Be 0.79 | | | | | | | | | | | B 101.60 | C 0.56 | N 0.43 | O 0.17 | F 0.20 | Ne 0.10 |
| Na 0.09 | Mg 0.15 | | | | | | | | | | | Al 0.10 | Si 0.11 | P 0.12 | S 0.06 | Cl 1.33 | Ar 0.03 |
| K 0.06 | Ca 0.08 | Sc 2.00 | Ti 0.60 | V 0.72 | Cr 0.54 | Mn 1.21 | Fe 1.19 | Co 3.92 | Ni 2.05 | Cu 1.07 | Zn 0.35 | Ga 0.49 | Ge 0.47 | As 0.67 | Se 0.73 | Br 0.24 | Kr 0.61 |
| Rb 0.08 | Sr 0.14 | Y 0.27 | Zr 0.29 | Nb 0.40 | Mo 0.52 | Tc 1.76 | Ru 0.58 | Rh 10.88 | Pd 0.78 | Ag 4.04 | Cd 115.11 | In 7.58 | Sn 0.21 | Sb 0.30 | Te 0.25 | I 0.23 | Xe 0.43 |
| Cs 0.29 | Ba 0.07 | La 0.52 | Hf 4.99 | Ta 1.49 | W 1.47 | Re 6.85 | Os 2.24 | Ir 30.46 | Pt 1.46 | Au 6.23 | Hg 16.21 | Tl 0.47 | Pb 0.38 | Bi 0.27 | Po | At | Rn |
| Fr | Ra 0.34 | Ac | Rf | Ha | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| *Lanthanides | Ce 0.14 | Pr 0.41 | Nd 1.87 | Pm 5.72 | Sm 171.47 | Eu 94.58 | Gd 1479.04 | Tb 0.93 | Dy 32.42 | Ho 2.25 | Er 5.48 | Tm 3.53 | Yb 1.40 | Lu 2.75 | | | |
| **Actinides | Th 0.59 | Pa 8.46 | U 0.82 | Np 9.80 | Pu 50.20 | Am 2.86 | Cm | Bk | Cf | Es | Fm | Md | No | Lr neut. | | | |

See also: https://www.ncnr.nist.gov/instruments/bt1/neutron.html

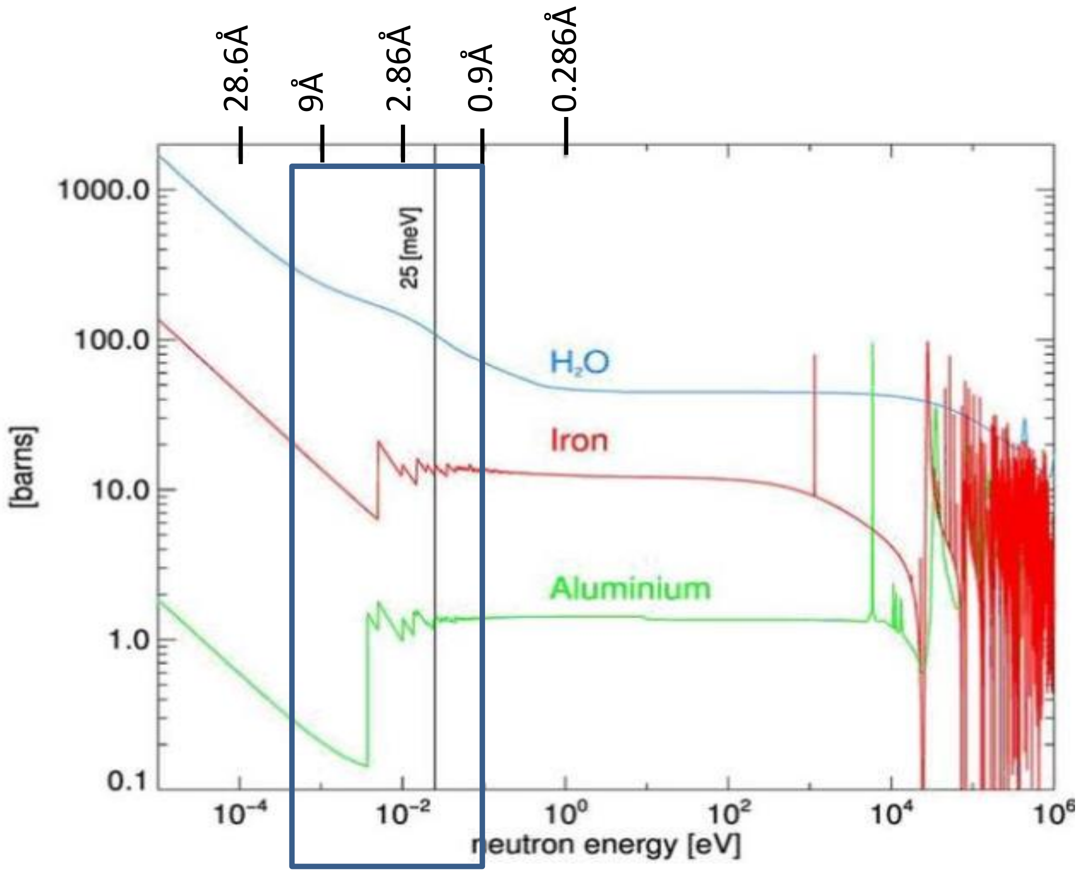


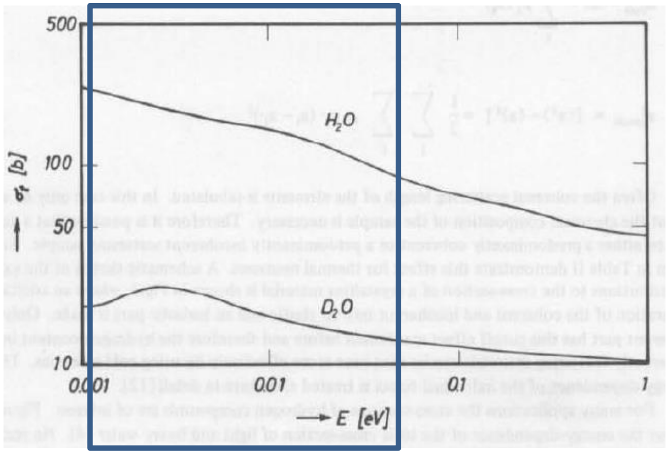
REF

# Part 3: ToF Imaging methods **Attenuation**

EUROPEAN SPALLATION SOURCE

## Cross section (attenuation) is wavelength dependent



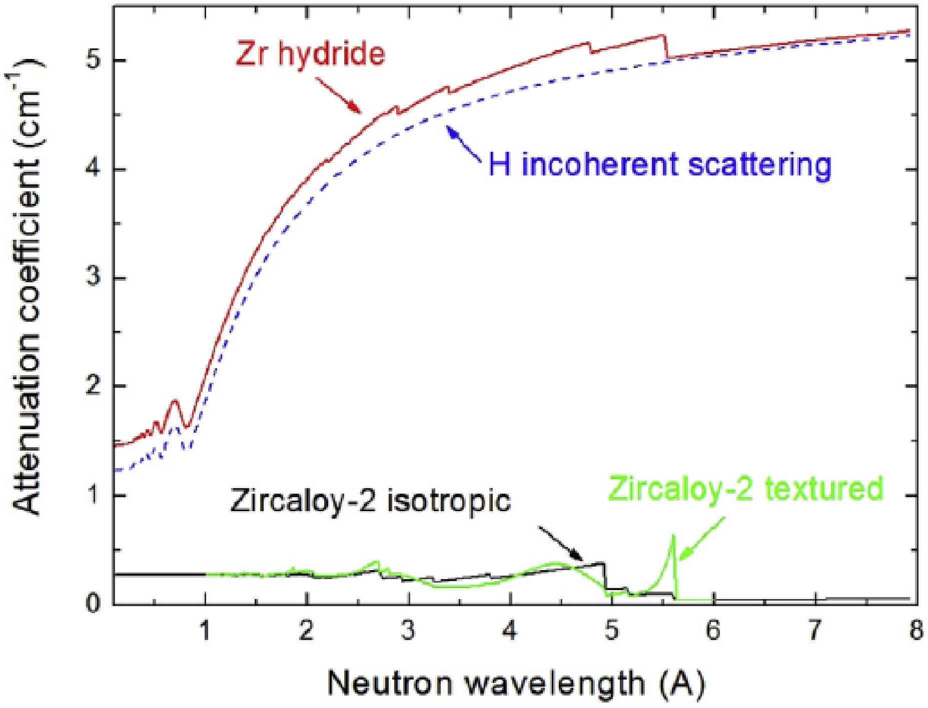



# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods

**Example:** Determination of very low concentrations of Hydrogen in Zirconium alloys


Wavelength dependent attenuation coefficients:
- Zirconium alloy
- Zirconium hydride




Buitrago, N. L., Santisteban, J. R., Tartaglione, A., Marín, J., Barrow, L., Daymond, M. R., ... & Kaestner, A. (2018). Determination of very low concentrations of hydrogen in zirconium alloys by neutron imaging. Journal of Nuclear Materials, 503, 98-109.

**Example:** Determination of very low concentrations of Hydrogen in Zirconium alloys

3 samples
- 11 wt ppm H
- 166 wt ppm H
- 366 wt ppm H

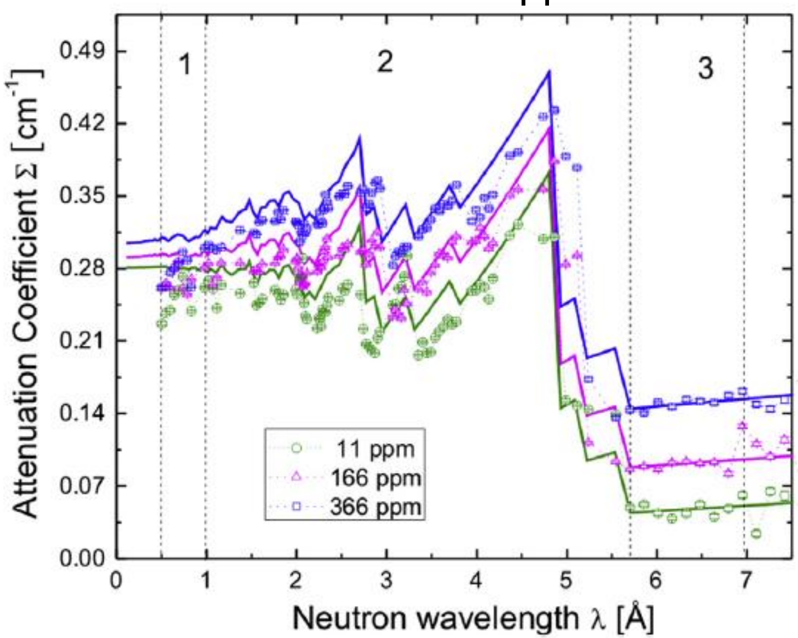



**Fig. 10.** Attenuation coefficient of three Zircaloy-2 calibration specimens measured on the Engin-X beamline with the MCP detector.

1sample with 130 wt ppm H
- 2 orientations

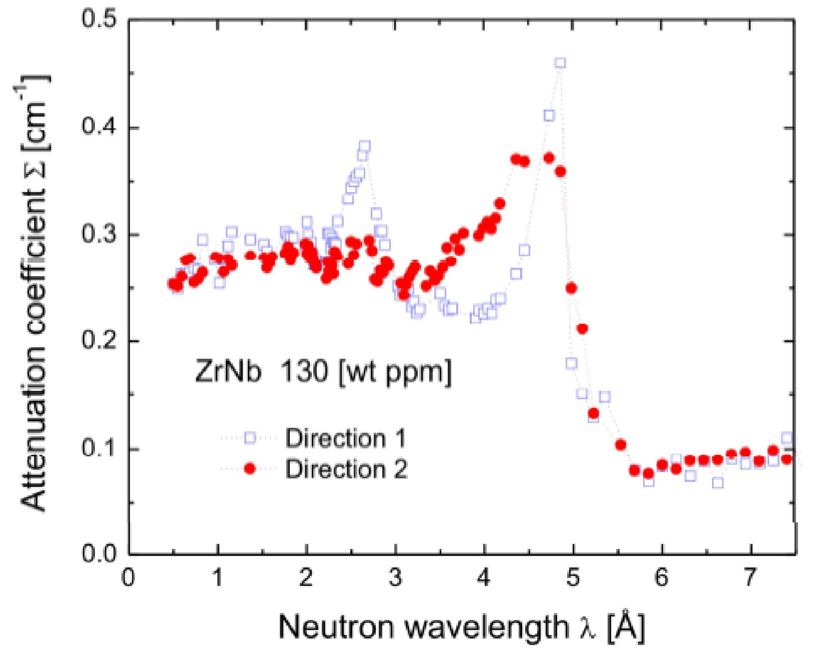



**Figure 8:** Attenuation coefficient of the Zr2.5%Nb calibration specimen containing a homogeneous content of 130 wt ppm H measured along two perpendicular directions on Engin-X. The differences observed between 2Å and 5.5Å are due to the crystallographic texture.

Buitrago, N. L., Santisteban, J. R., Tartaglione, A., Marín, J., Barrow, L., Daymond, M. R., ... & Kaestner, A. (2018). Determination of very low concentrations of hydrogen in zirconium alloys by neutron imaging. Journal of Nuclear Materials, 503, 98-109.

# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods **Attenuation**

**Example:** Determination of very low concentrations of Hydrogen in Zirconium alloys

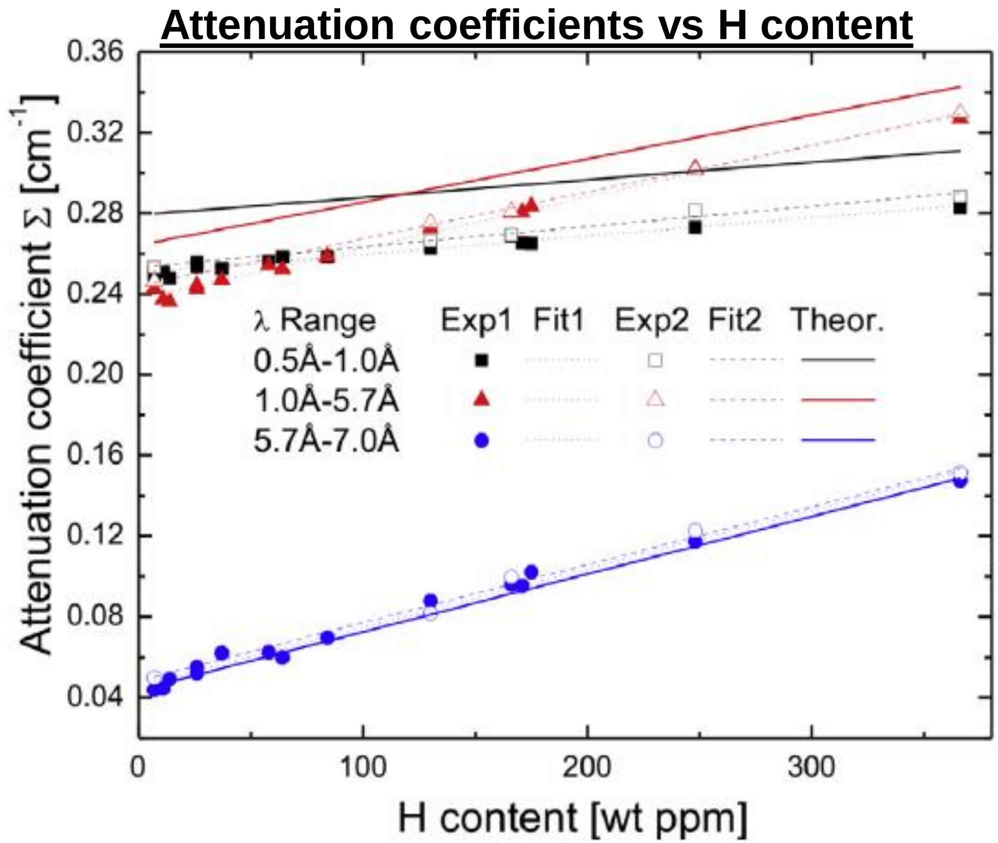



**Fig. 11.** Calibration lines for wavelength-resolved attenuation coefficients of Zircaloy-2 calibration specimens measured on the Engin-X beamline with the MCP detector.


Buitrago, N. L., Santisteban, J. R., Tartaglione, A., Marín, J., Barrow, L., Daymond, M. R., ... & Kaestner, A. (2018). Determination of very low concentrations of hydrogen in zirconium alloys by neutron imaging. Journal of Nuclear Materials, 503, 98-109.

# Wavelength selective imaging 2 - ToF

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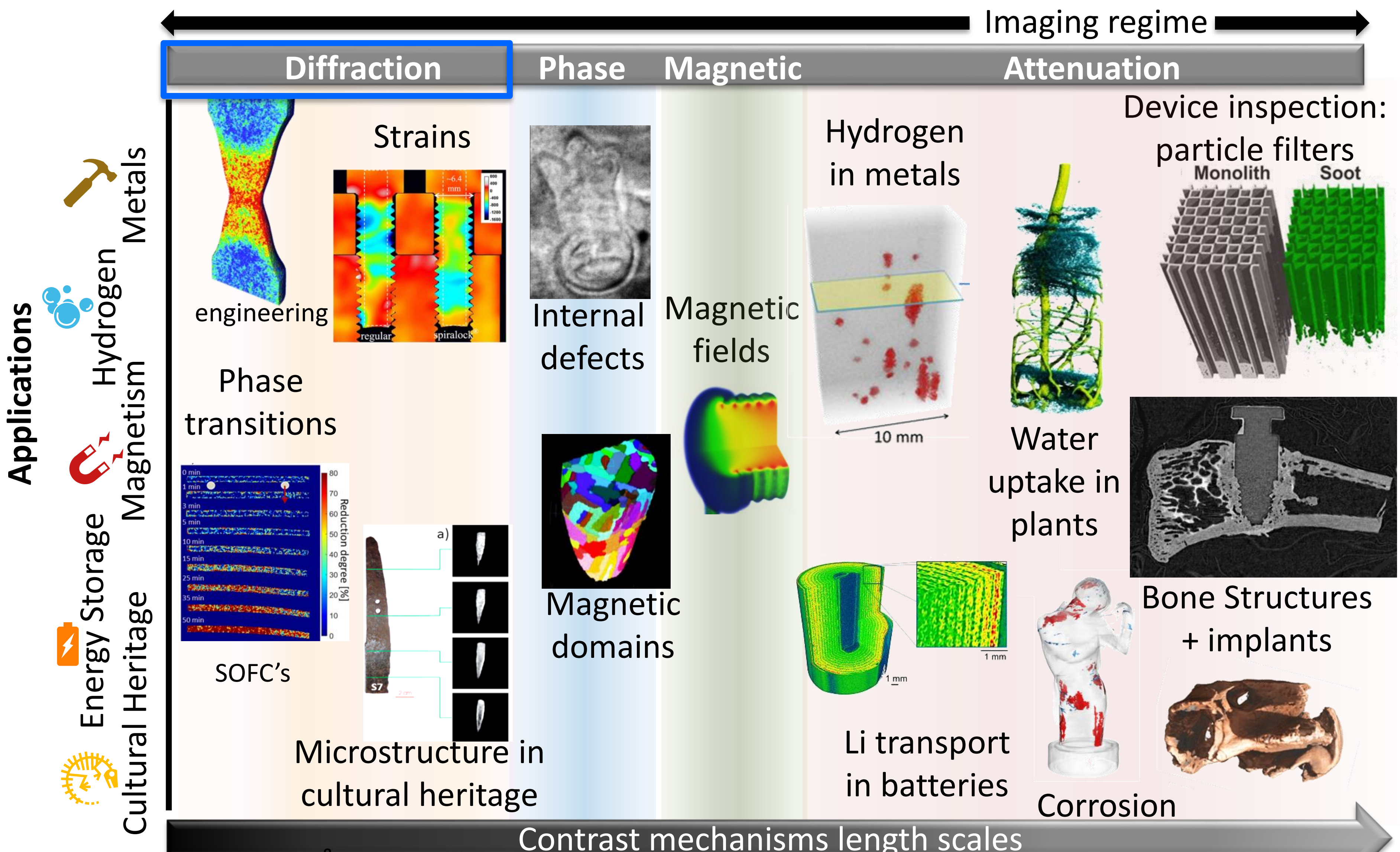
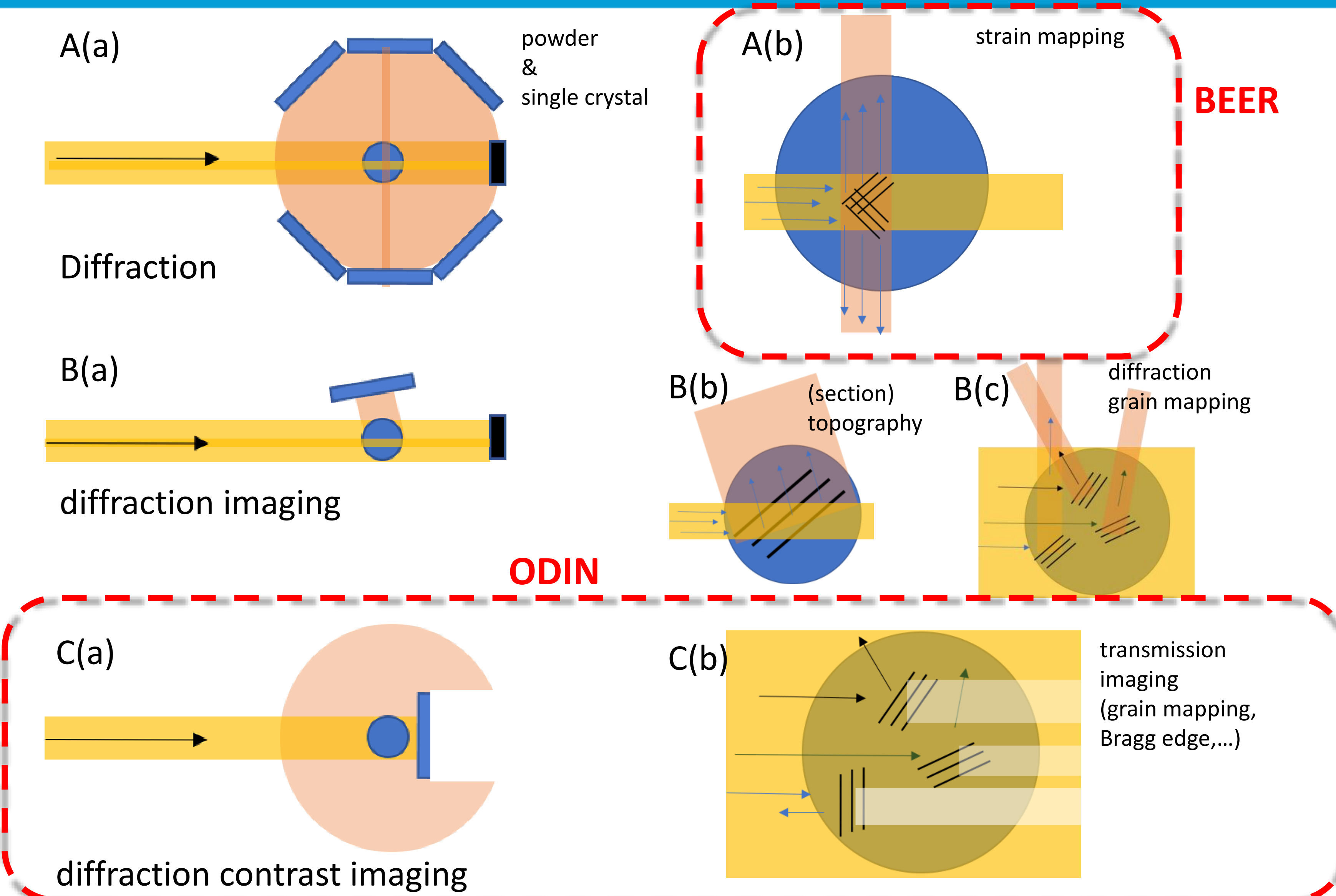
# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods



# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods **Diffraction Contrast**

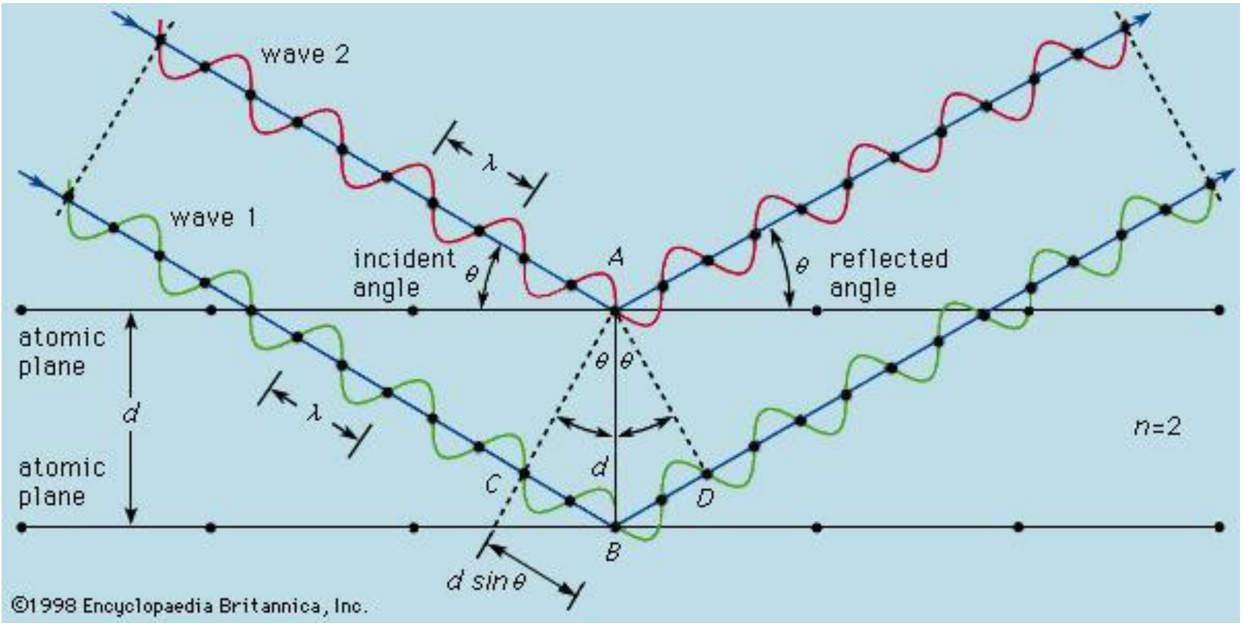



R. Woracek, J. Santisteban, A. Fedrigo, M. Strobl, M. *Diffraction in neutron imaging—A review*. NIMA (2018)

## Diffraction Contract

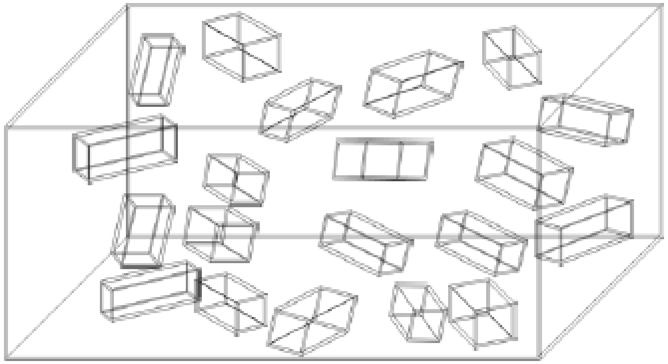
Based on Bragg's law

$$n\lambda = 2d_{hkl}\sin\theta^{B}$$




Constructive interference only occurs for certain $\theta$'s correlating to a (*hkl*) plane, specifically when the path difference is equal to n wavelengths.

## Powder – A Polycrystalline Mass



**All orientations of crystallites possible**

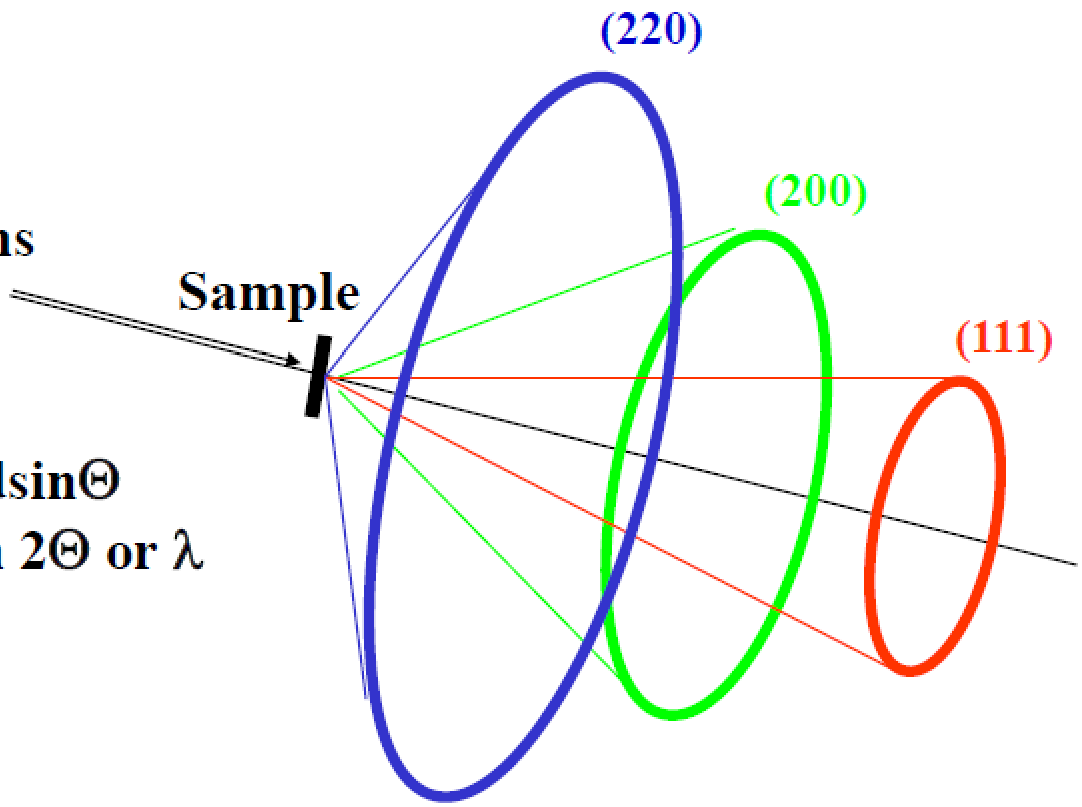
**Typical Sample: 1cc powder of 10μm crystallites - $10^9$ particles if 1μm crystallites - $10^{12}$ particles**

# Part 3: ToF Imaging methods **Diffraction Contrast**

EUROPEAN SPALLATION SOURCE

## Powder Diffraction gives Scattering on Debye-Scherrer Cones

**Incident beam**
**x-rays or neutrons**




**Bragg's Law** $\lambda = 2d\sin\Theta$

**Powder pattern – scan $2\Theta$ or $\lambda$**

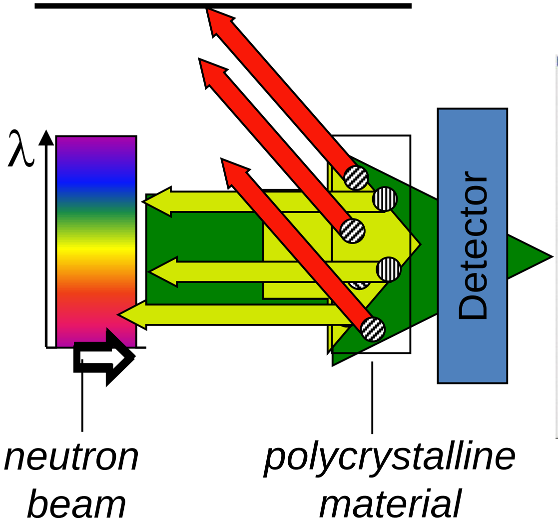
# Wavelength selective imaging 2 - ToF

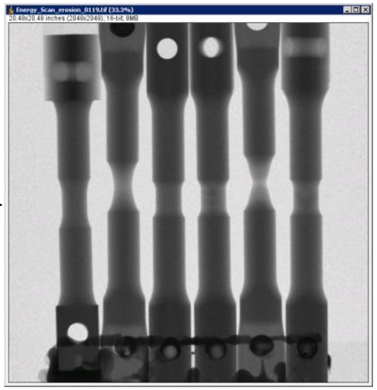
## Part 3: ToF Imaging methods **Diffraction Contrast**

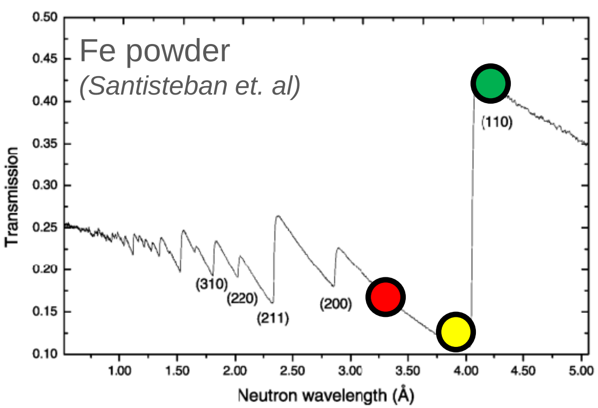
EUROPEAN SPALLATION SOURCE

- Coh. elastic scattering $\sigma_T(\lambda) = \sigma_{el.coh.}(\lambda) + \sigma_{el.inc.}(\lambda) + \sigma_{inel.coh.}(\lambda) + \sigma_{inel.incoh.}(\lambda) + \sigma_{abs}(\lambda)$
- *hkl* spacing probed in beam direction (“averaged” through thickness)

**Monochromatic**





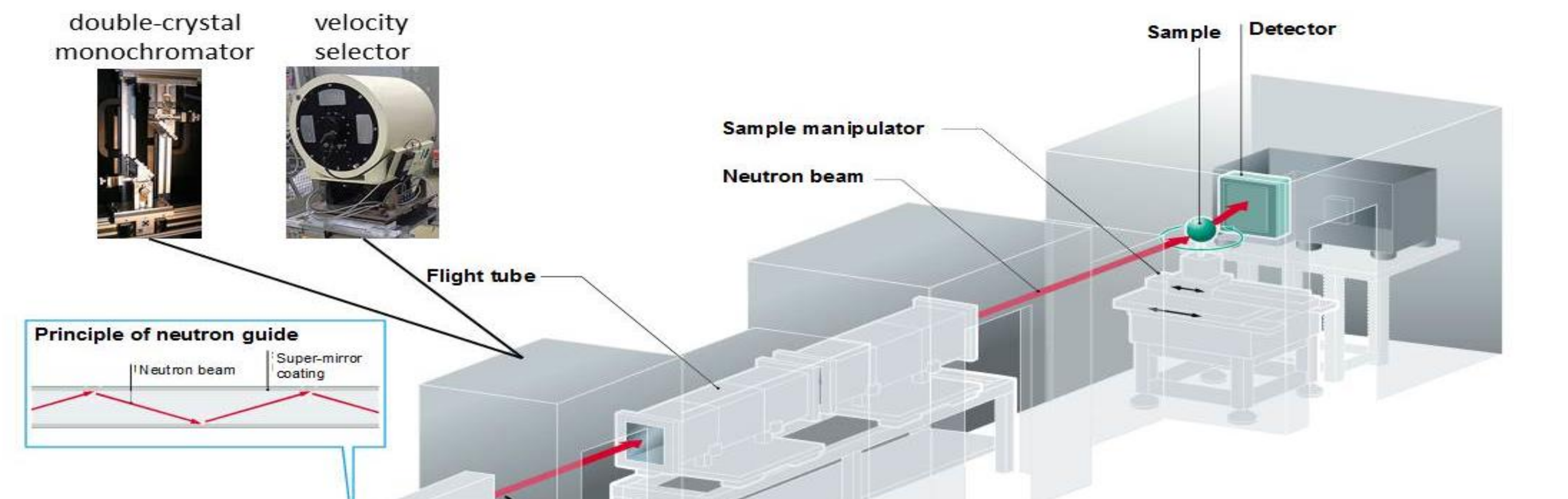

$2d_{hkl}\sin\theta=\lambda$

$2d_{hkl}\sin 90°=\lambda$

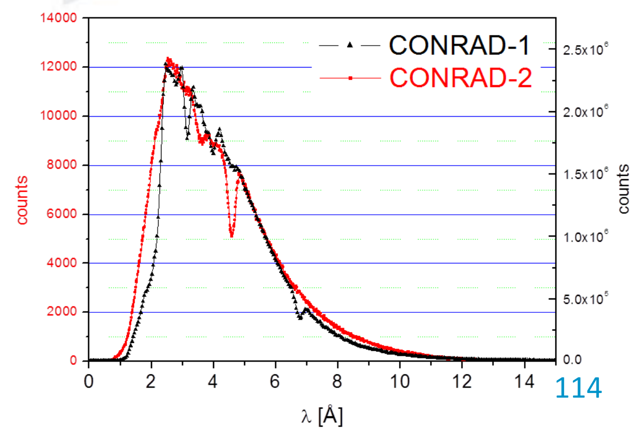
$2d_{hkl}\sin\theta<\lambda$

# Diffraction Contrast

- Coh. elastic scattering $\sigma_T(\lambda) = \sigma_{el.coh.}(\lambda) + \sigma_{el.inc.}(\lambda) + \sigma_{inel.coh.}(\lambda) + \sigma_{inel.incoh.}(\lambda) + \sigma_{abs}(\lambda)$
- *hkl* spacing probed in beam direction ("averaged" through thickness)




Guide system: super-mirror coated neutron guide (M=3) with a curvature of 750 m and length of 15 m followed by linear guide section (M=2) with a length of 10 m.

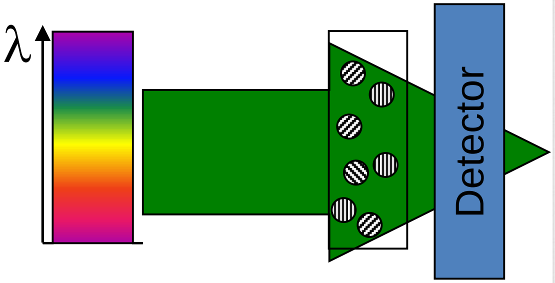


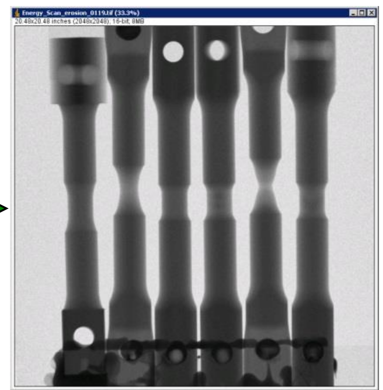
# Wavelength selective imaging 2 - ToF

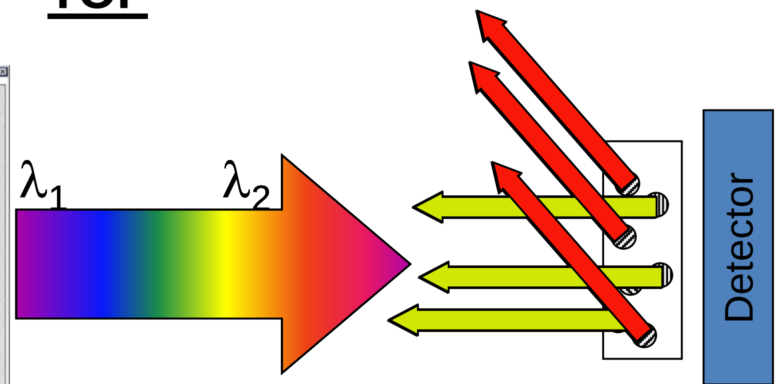
## Part 3: ToF Imaging methods **Diffraction Contrast**

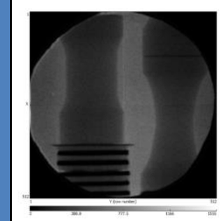
- Coh. elastic scattering $\sigma_T(\lambda) = \sigma_{el.coh.}(\lambda) + \sigma_{el.inc.}(\lambda) + \sigma_{inel.coh.}(\lambda) + \sigma_{inel.incoh.}(\lambda) + \sigma_{abs}(\lambda)$
- *hkl* spacing probed in beam direction ("averaged" through thickness)

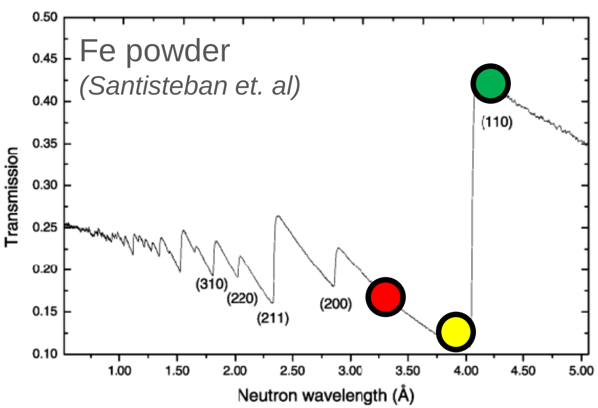
**Monochromatic** **TOF**





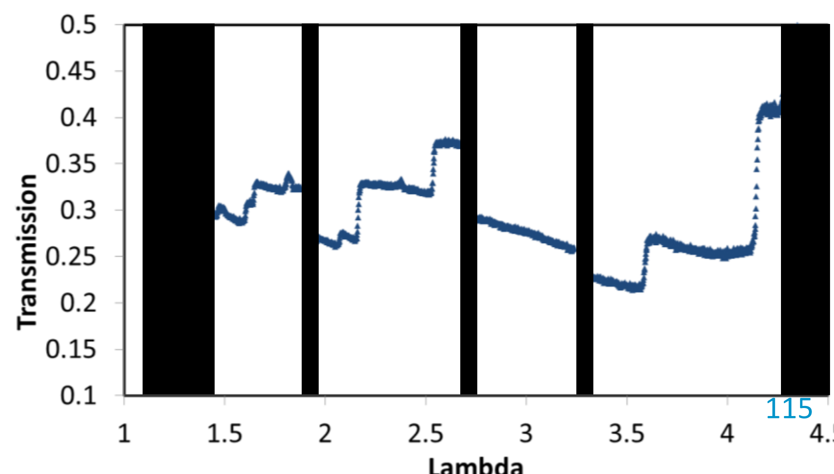





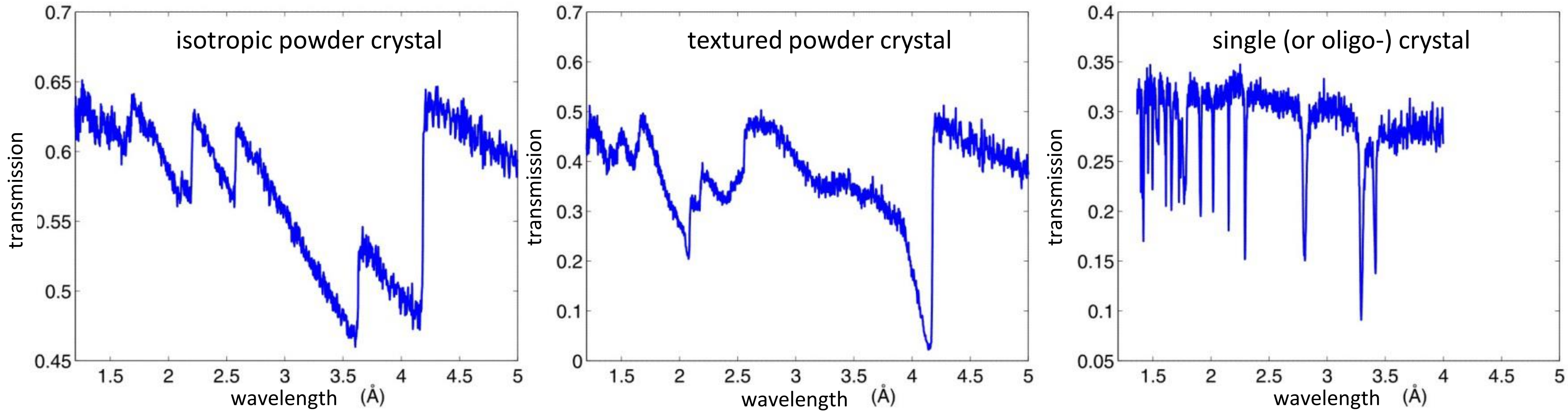

$2d_{hkl}\sin\theta=\lambda$

$2d_{hkl}\sin 90°=\lambda$

$2d_{hkl}\sin\theta<\lambda$



- Transmission though crystalline samples

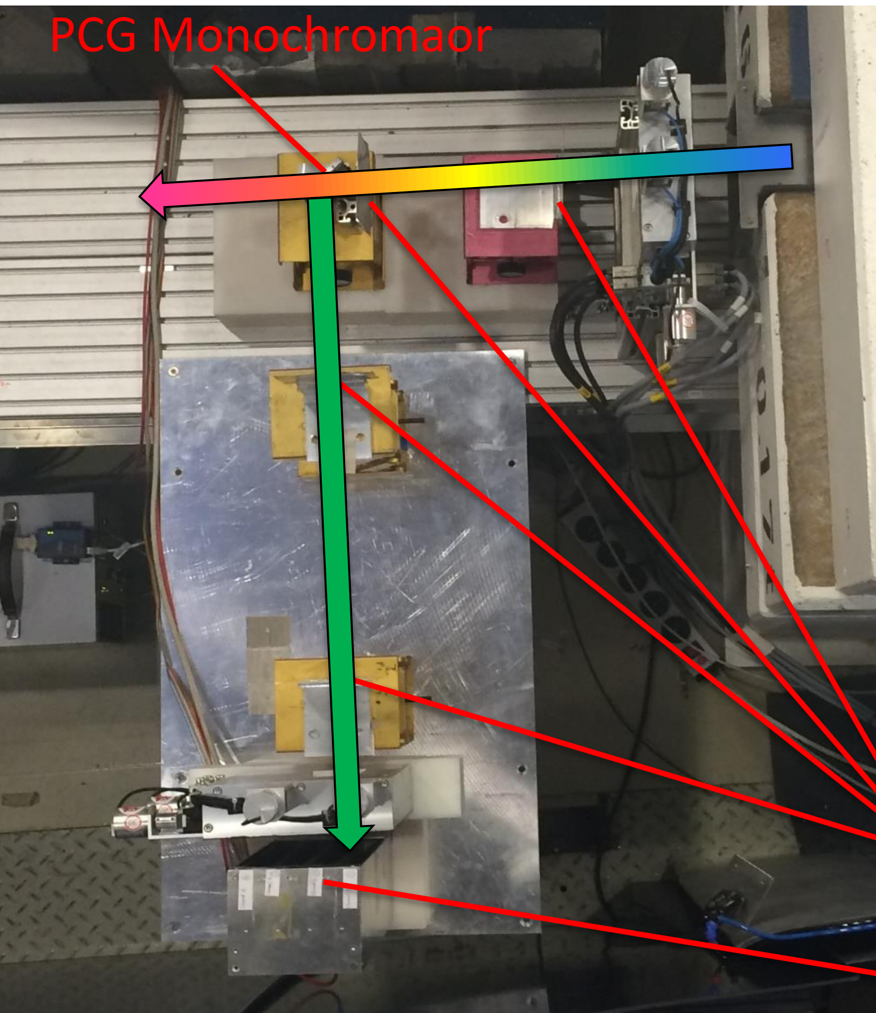


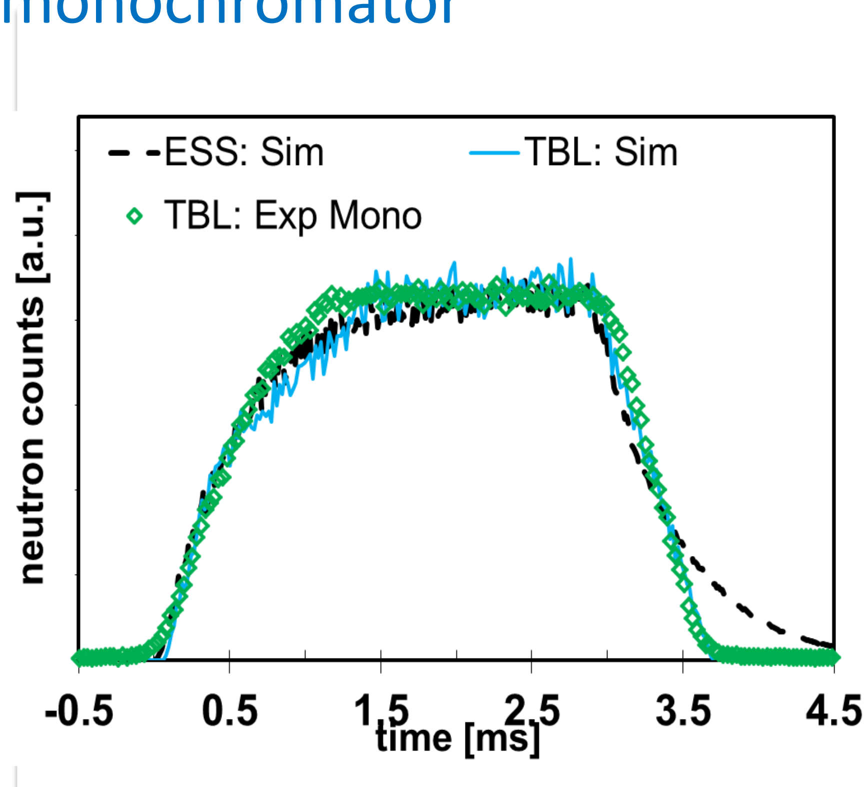
# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods

Let‘s go back a bit...
What about the pulse shape of the source?

- Measure the pulse shape at a beamline
- Use a diffraction set-up with a monochromator




Gd Pinholes (10mm)

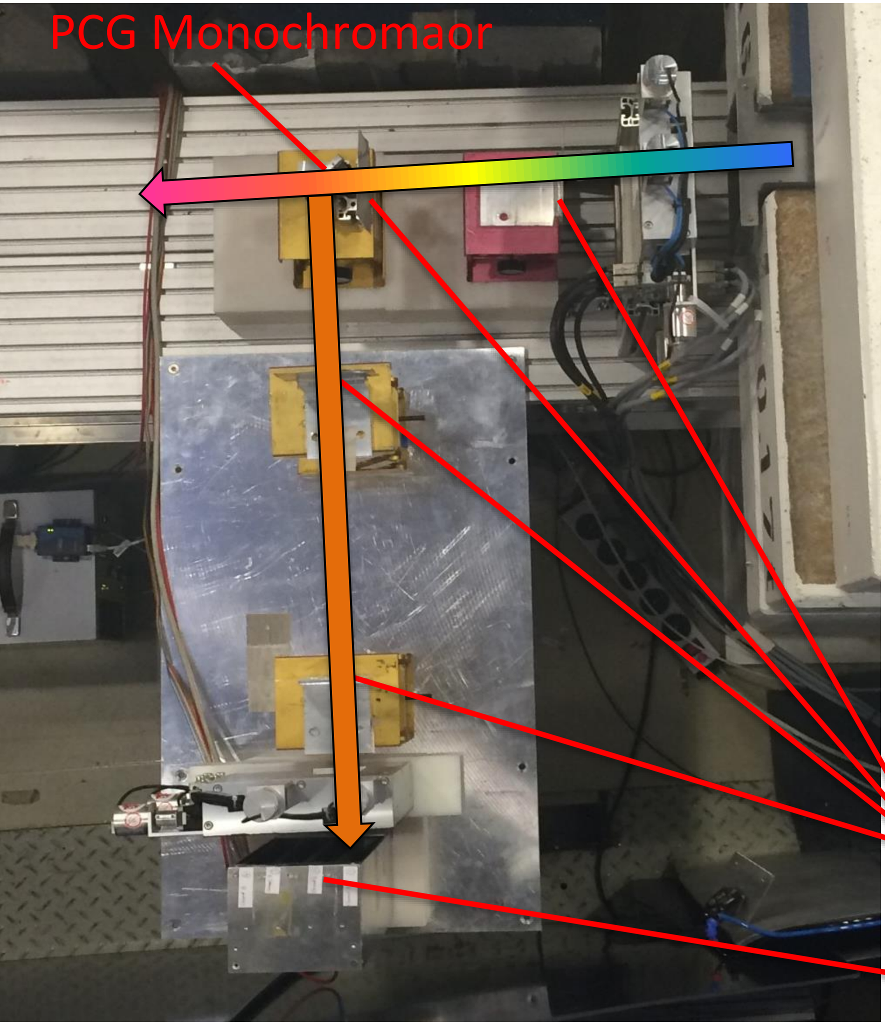
$^3$He Detector (4tubes)

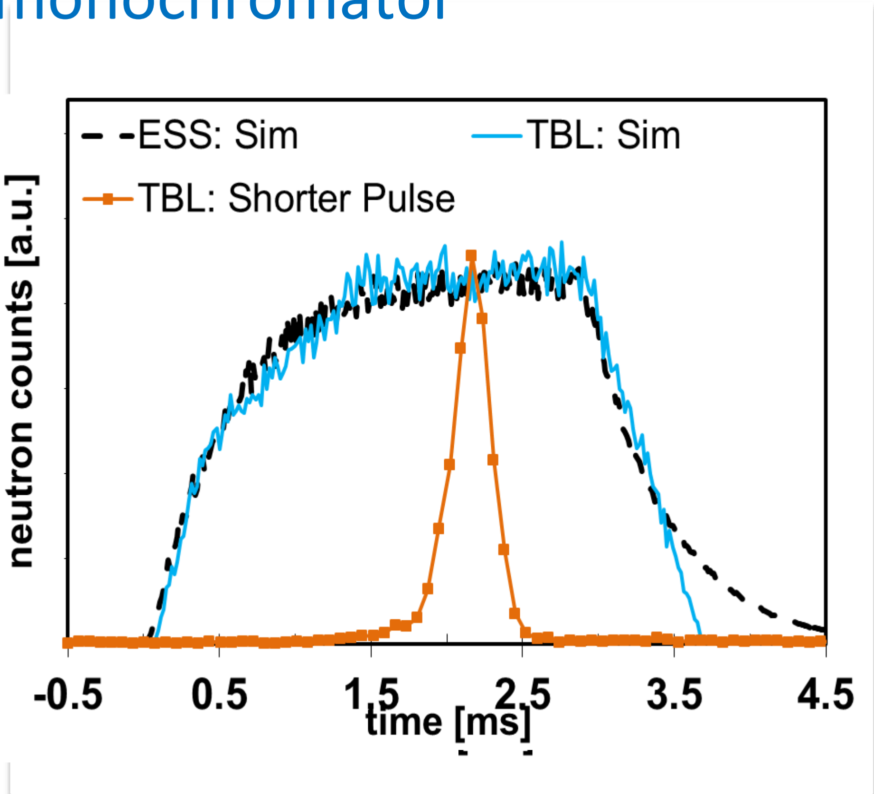
# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods

Let's go back a bit...
What about the pulse shape of the source?

- Measure the pulse shape at a beamline
- Use a diffraction set-up with a monochromator



# Part 3: ToF Imaging methods **Diffraction Contrast**

The short pulsed neutron source leads to specific Bragg peak shapes (due to the moderator properties; non-Gaussian)

Bragg edges of course also influenced

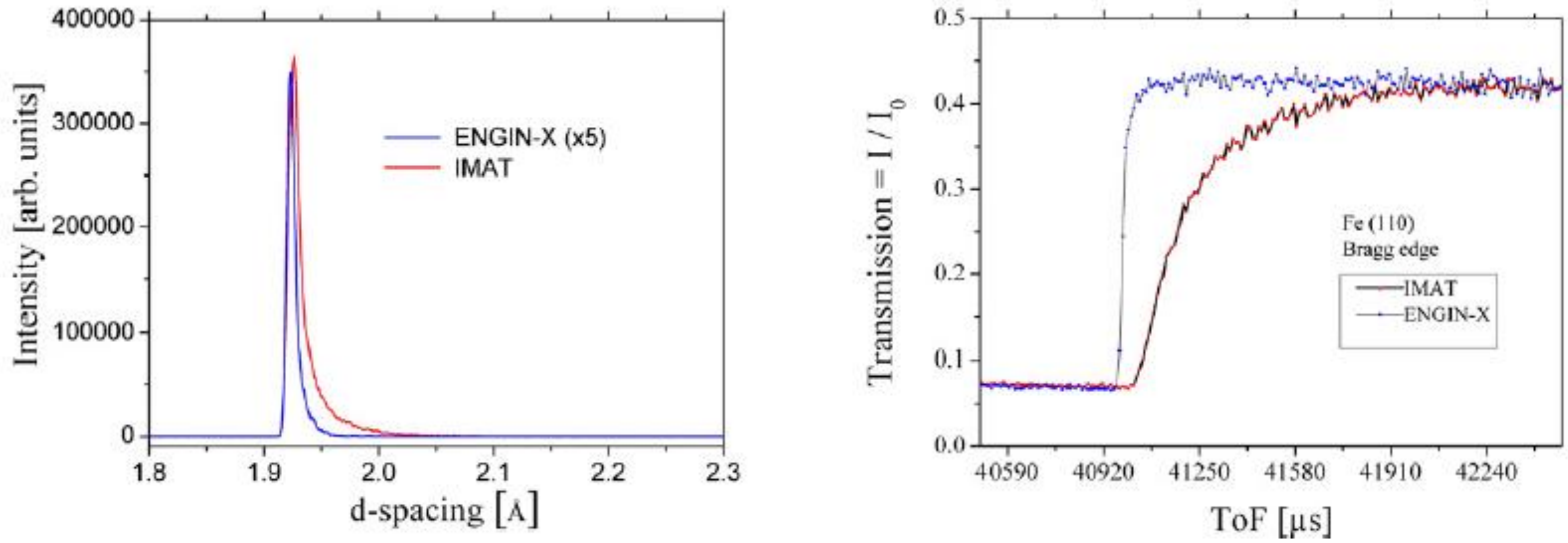
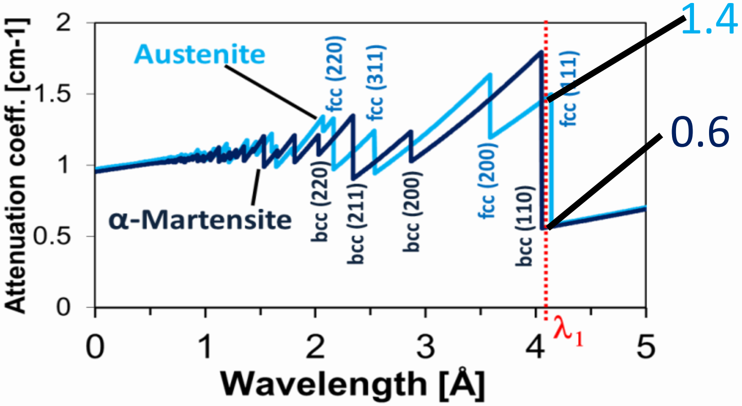
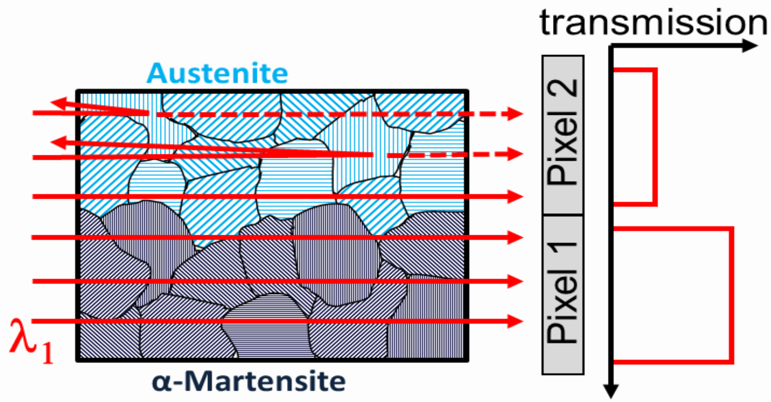


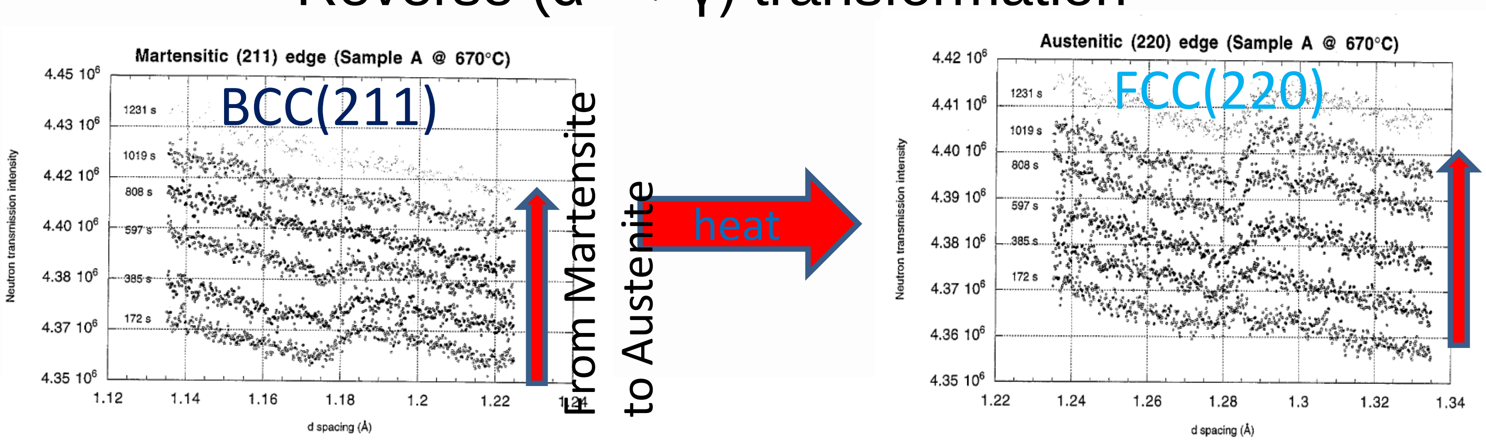

Fig. 3. Comparison of Bragg peak shape (left) and Bragg edge shape (right) of IMAT (red) and ENGIN-X (blue). The Bragg peak intensity for ENGIN-X is multiplied by 5 for better comparison.

- Phase imaging: Austenite vs Martensite




Reverse (α′ → γ) transformation



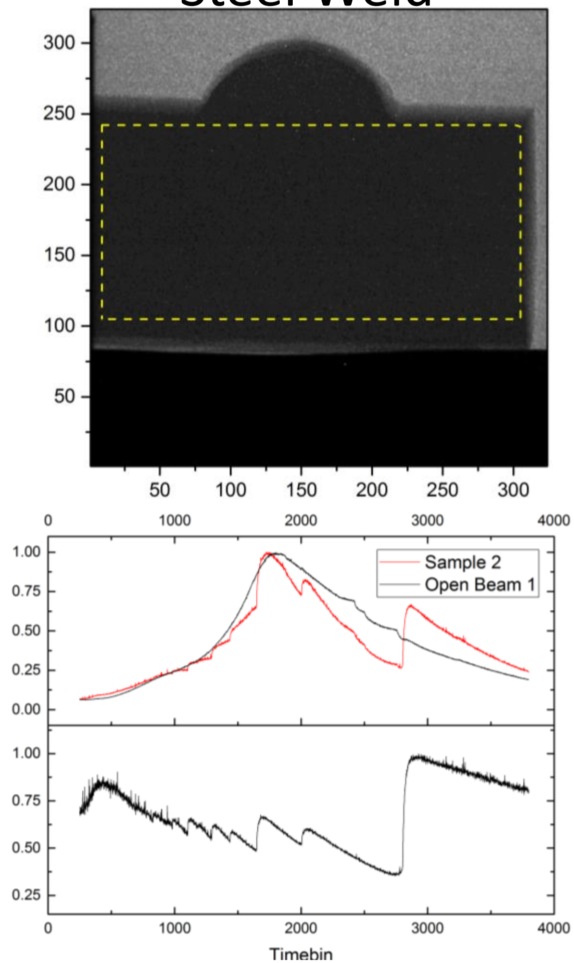

- M.A.M. Bourke, J.G. Maldonado, D. Masters, K. Meggers, H.G. Priesmeyer, “Real time measurement by Bragg edge diffraction of the reverse (α′ → γ) transformation in a deformed 304 stainless steel”, Materials Science and Engineering: A, Vol 221 (1996).

# Wavelength selective imaging 2 - ToF

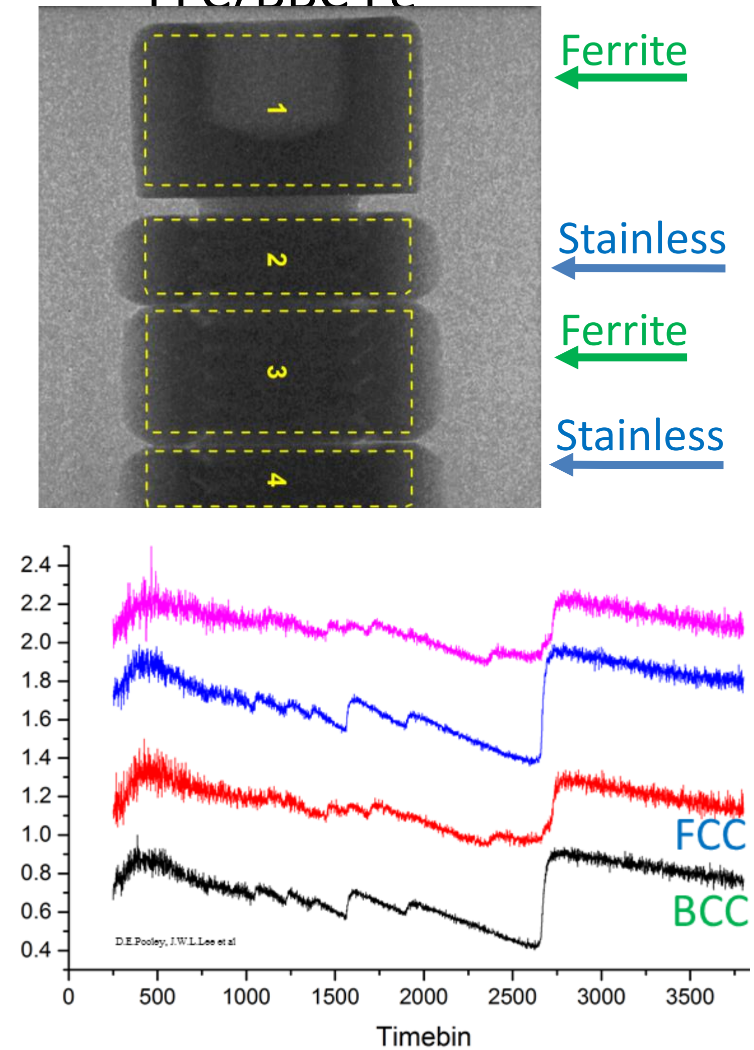
## Part 3: ToF Imaging methods **Diffraction Contrast**

Example from IMAT: Acquire a spectrum
- with sample
- without sample (Open Beam)

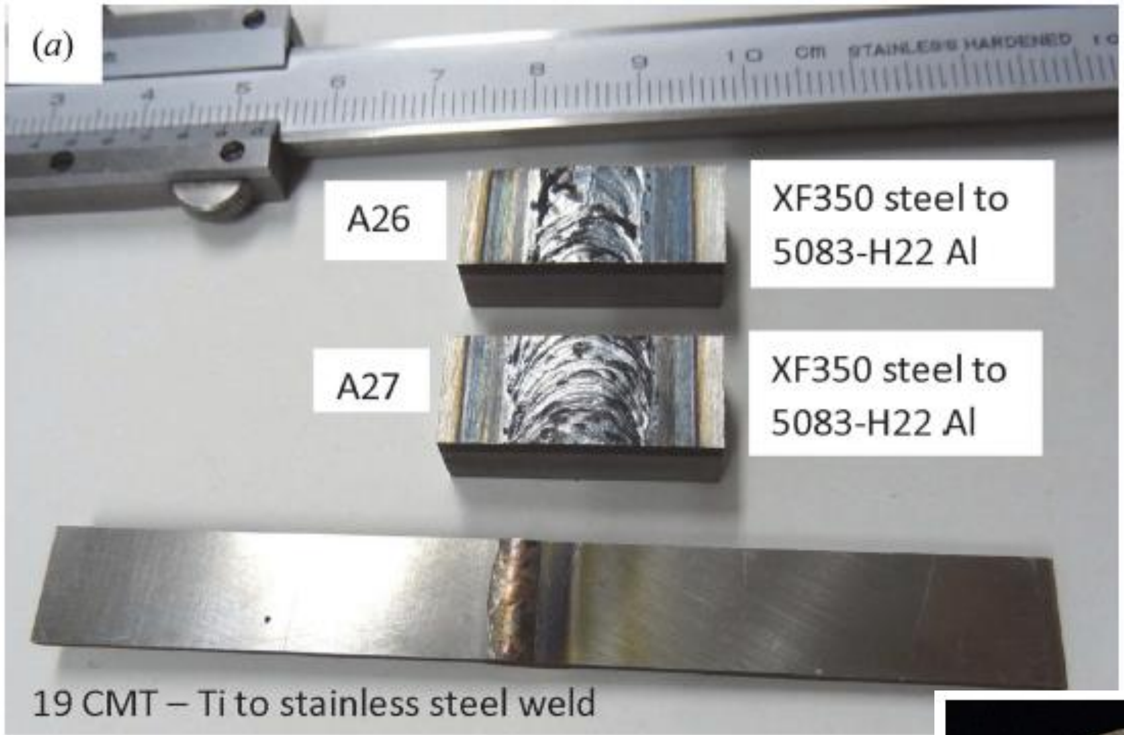
Steel Weld

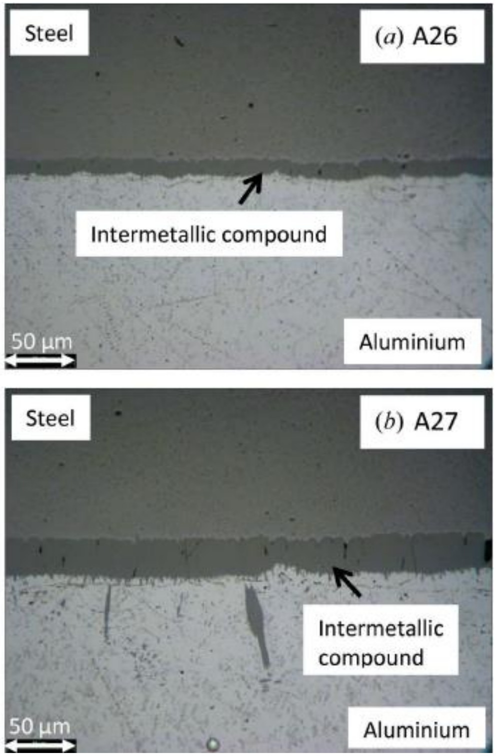



Nuts on a bold
FFC/BBC Fe



Example: Dissimilar welds investigated at RADEN



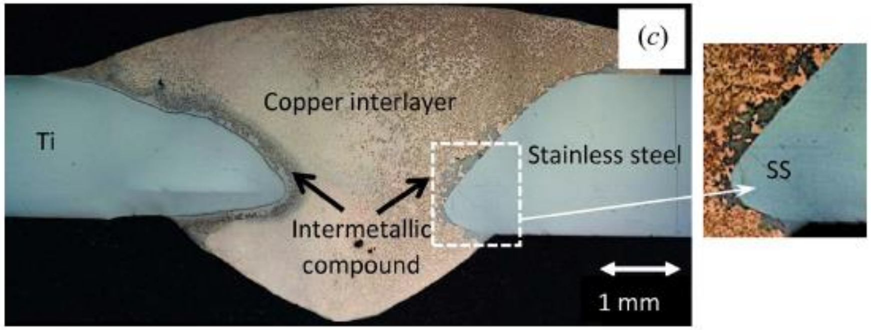




Aluminium to steel alloy.

| | Elements (wt%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Al | Fe | C | Si | Mn | P + S | N | Ti | Cu | Mg | Zn | Cr |
| XF350 (steel) | 0.045 | Balance | 0.0002 | 0.015 | 0.613 | 0.024 | 0.017 | 0.002 | | | | |
| 5083-H22 (aluminium) | Balance | 0.4 | | 0.4 | 0.5 | | | 0.15 | 0.1 | 2.6–3.6 | 0.2 | 0.3 |

Titanium to stainless steel alloy.

| | Elements (wt% maximum) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Si | Fe | Mo | Mn | Ni | Cr | C | P | S | Ti | N | Al | V | O | H | Y |
| AISI 316 L (stainless steel) | 0.45 | Balance | 2.07 | 1.73 | 10 | 17.2 | 0.02 | 0.032 | 0.01 | | 0.054 | | | | | |
| Ti-6Al-4V (titanium) | | 0.3 | | | | | 0.08 | | | Balance | 0.05 | 6.75 | 4.5 | 0.2 | 0.15 | 0.05 |

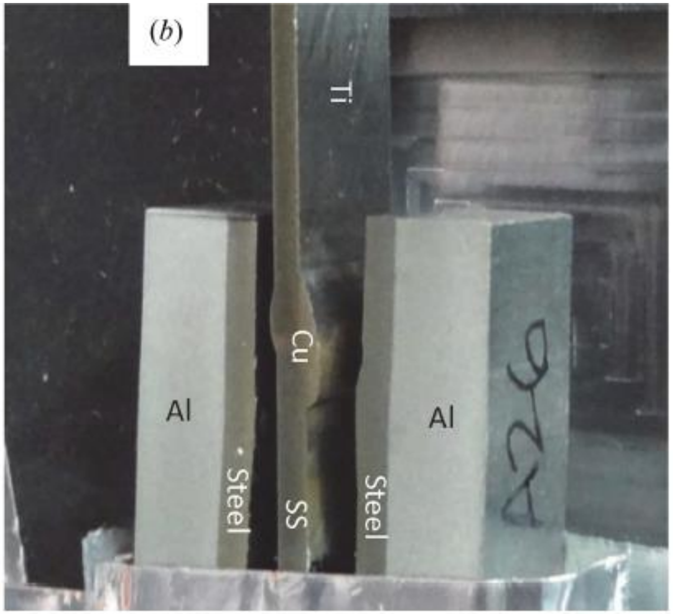


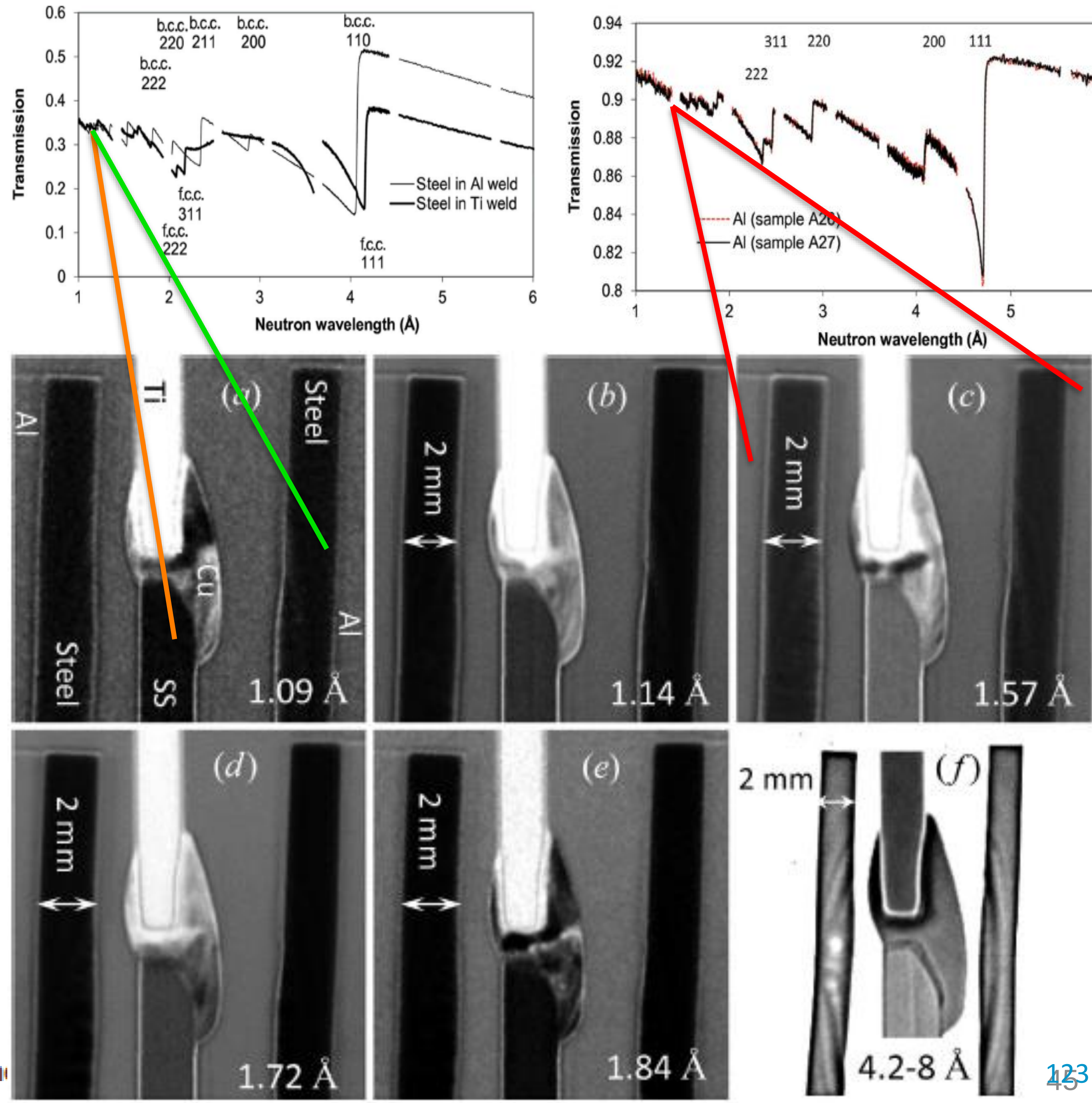

Anton S. Tremsin et al. • Investigation of metal welds by neutron imaging J. Appl. Cryst. (2016). 49, 1130–1140

# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods  Diffraction Contrast

Diffraction Contrast

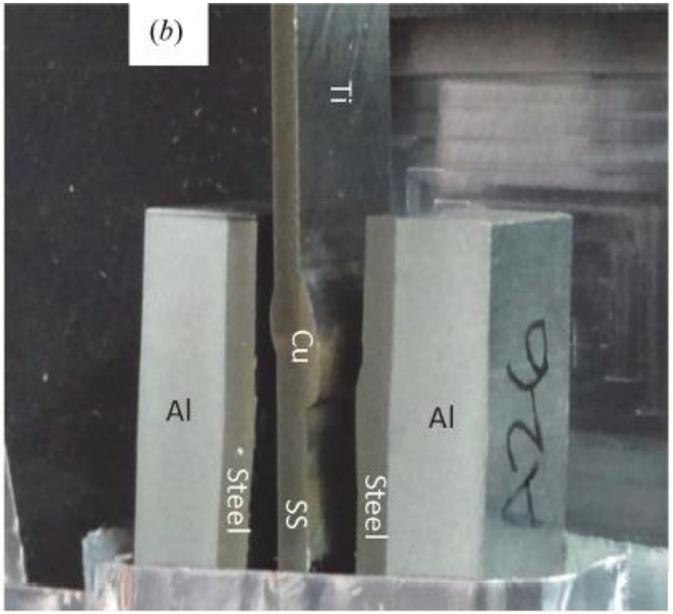


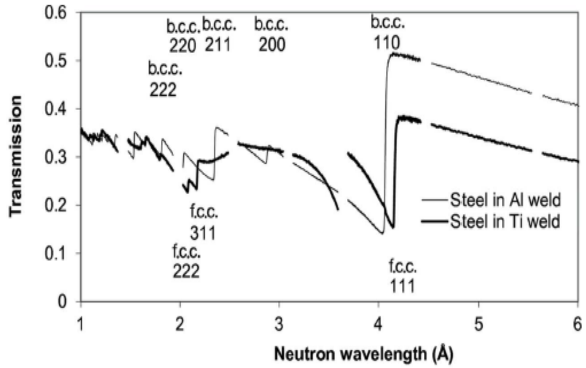



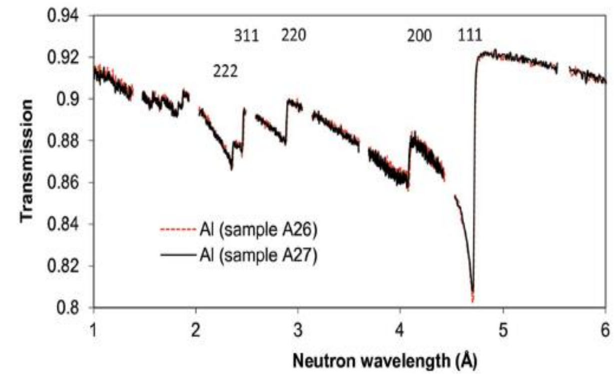

Anton S. Tremsin et al. • Investigation of m

# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods **Diffraction Contrast**



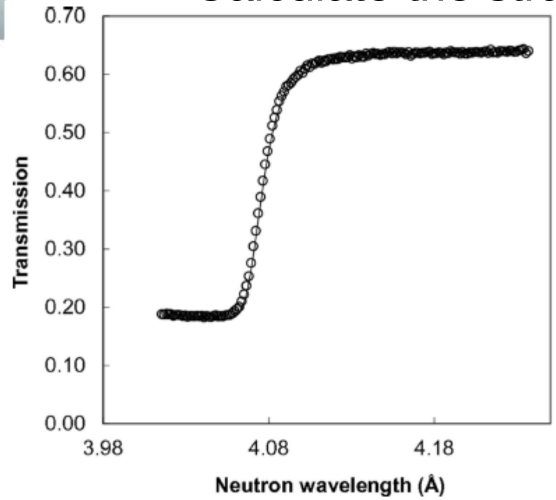



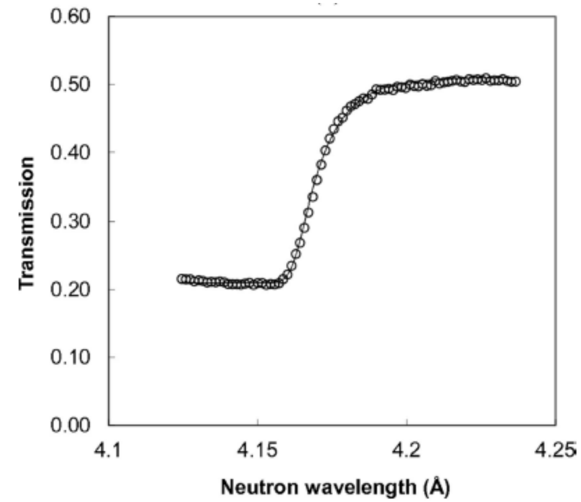




**Spatially resolved strain maps**

- Fit the Bragg edge position
- Calculate the strain

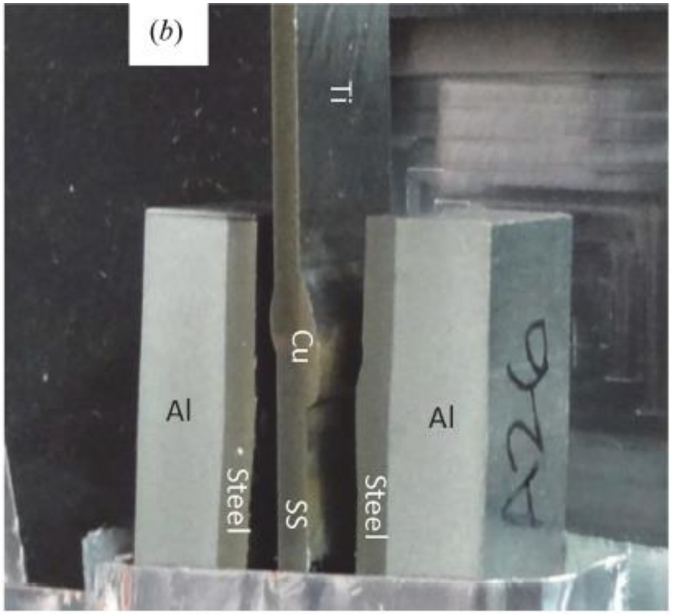
$$\varepsilon = \frac{\Delta d_{hkl}}{d_{hkl}} = \frac{d_{hkl} - d0_{hkl}}{d_{hkl}}$$

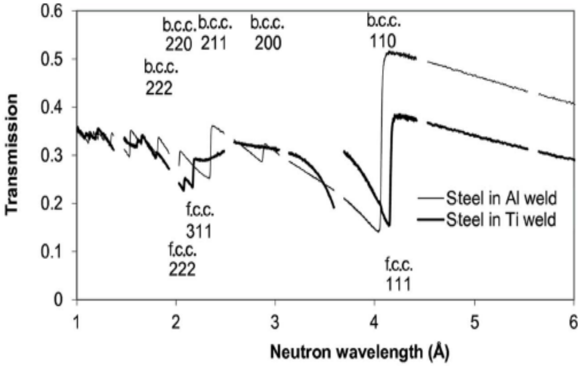


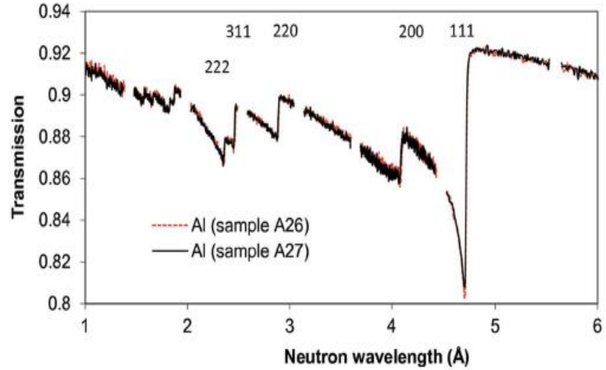




Anton S. Tremsin *et al.* • Investigation of metal welds by neutron imaging *J. Appl. Cryst.* (2016). **49**, 1130–1140

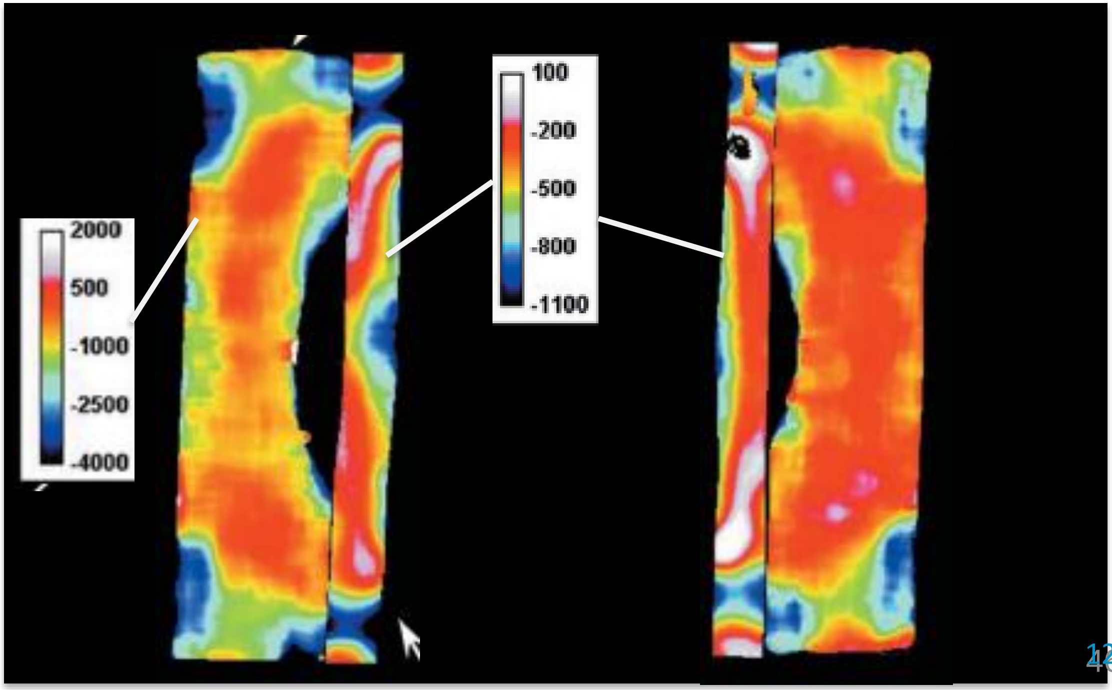
## Part 3: ToF Imaging methods **Diffraction Contrast**



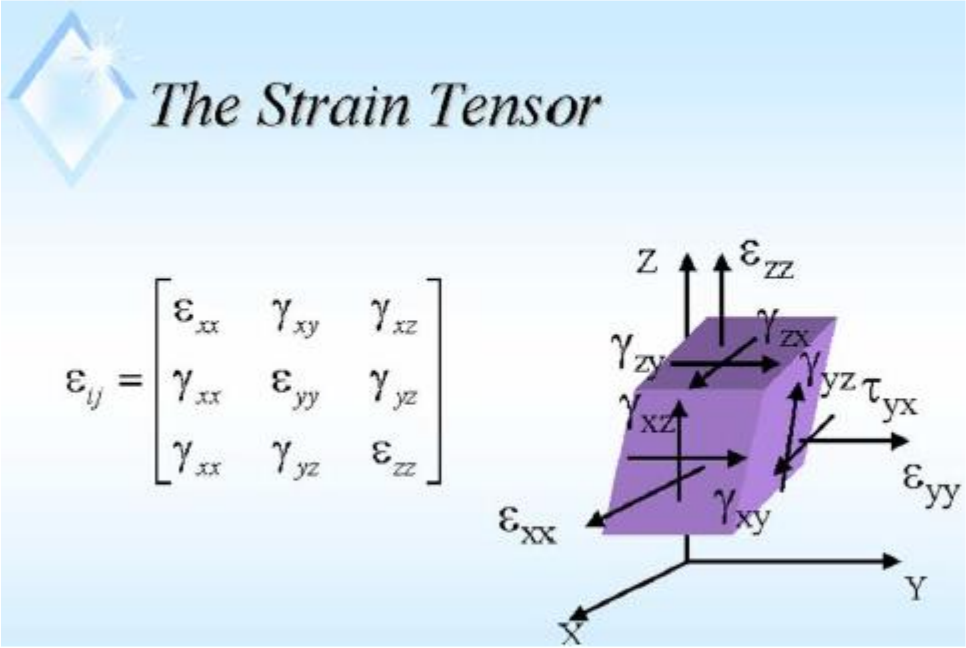




Spatially resolved strain maps




Anton S. Tremsin *et al.* • Investigation of metal

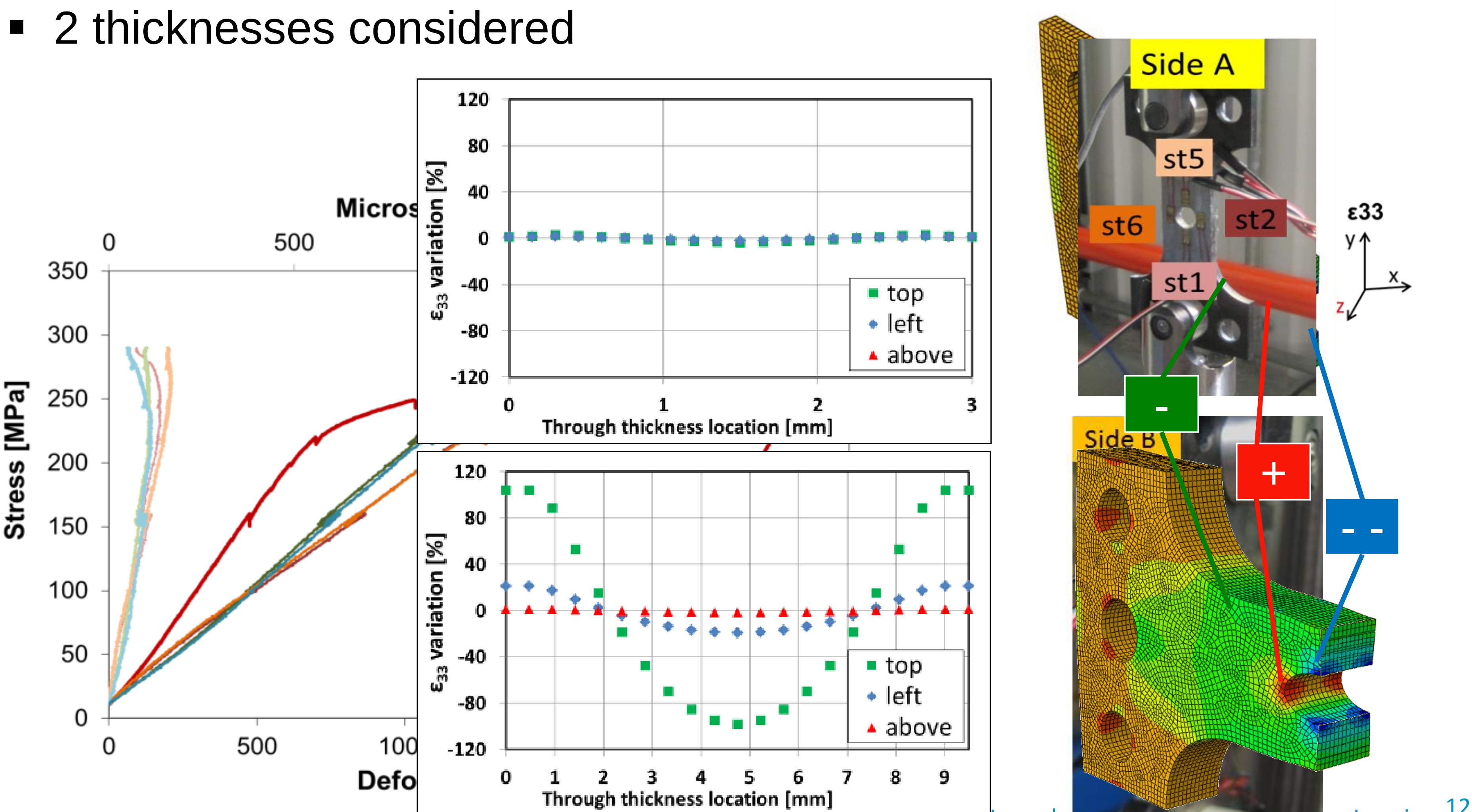
A few words about strain....



# Wavelength selective imaging 2 - ToF

## Bragg Edge Imaging: Strain Radiography

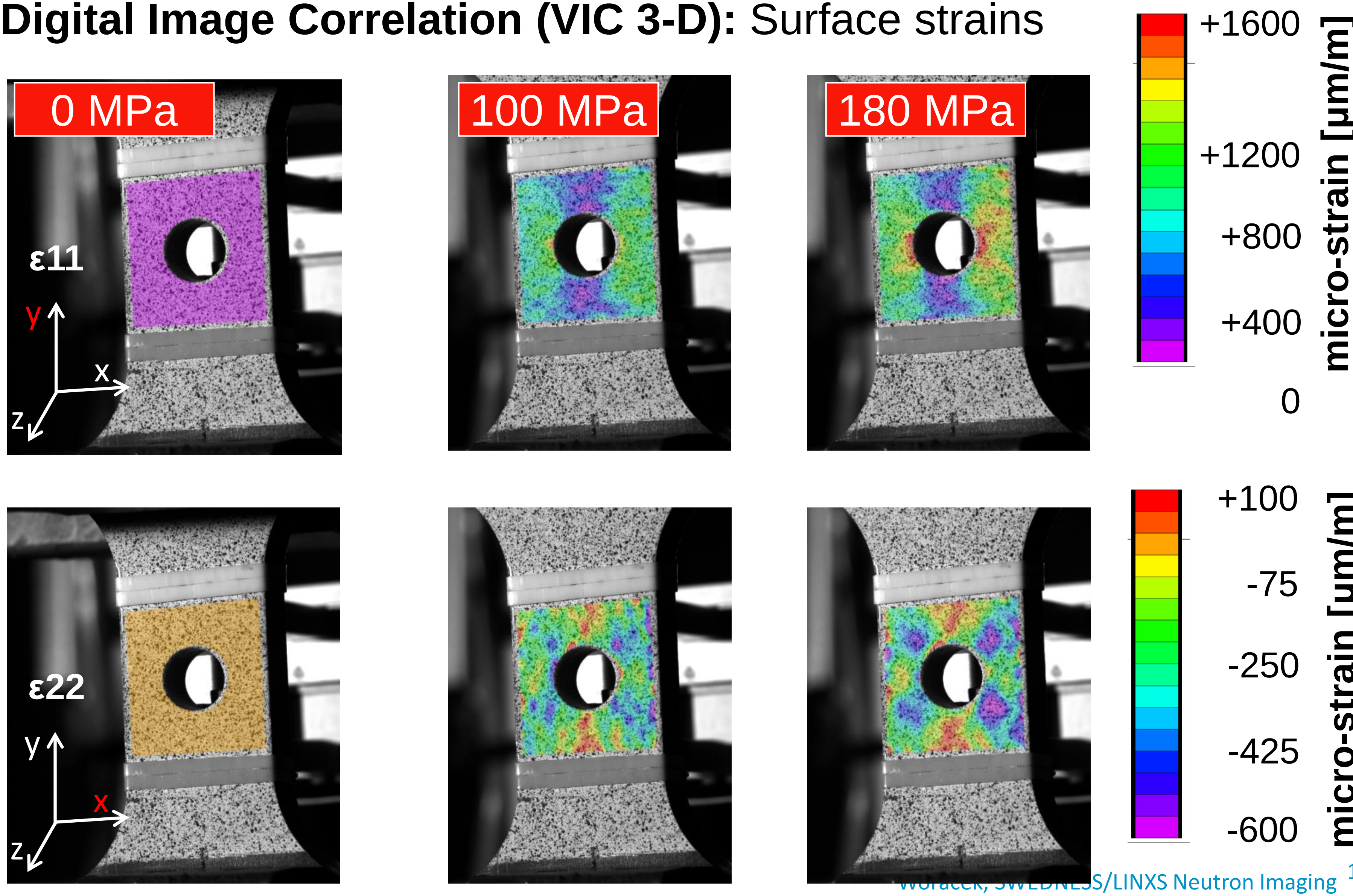
- Sample (low carb steel) with stress concentration: Demonstrate high spatial resolution at TOF source using novel Imaging detector
- 2 thicknesses considered



# Wavelength selective imaging 2 - ToF

## Bragg Edge Imaging: Strain Radiography

**Digital Image Correlation (VIC 3-D):** Surface strains

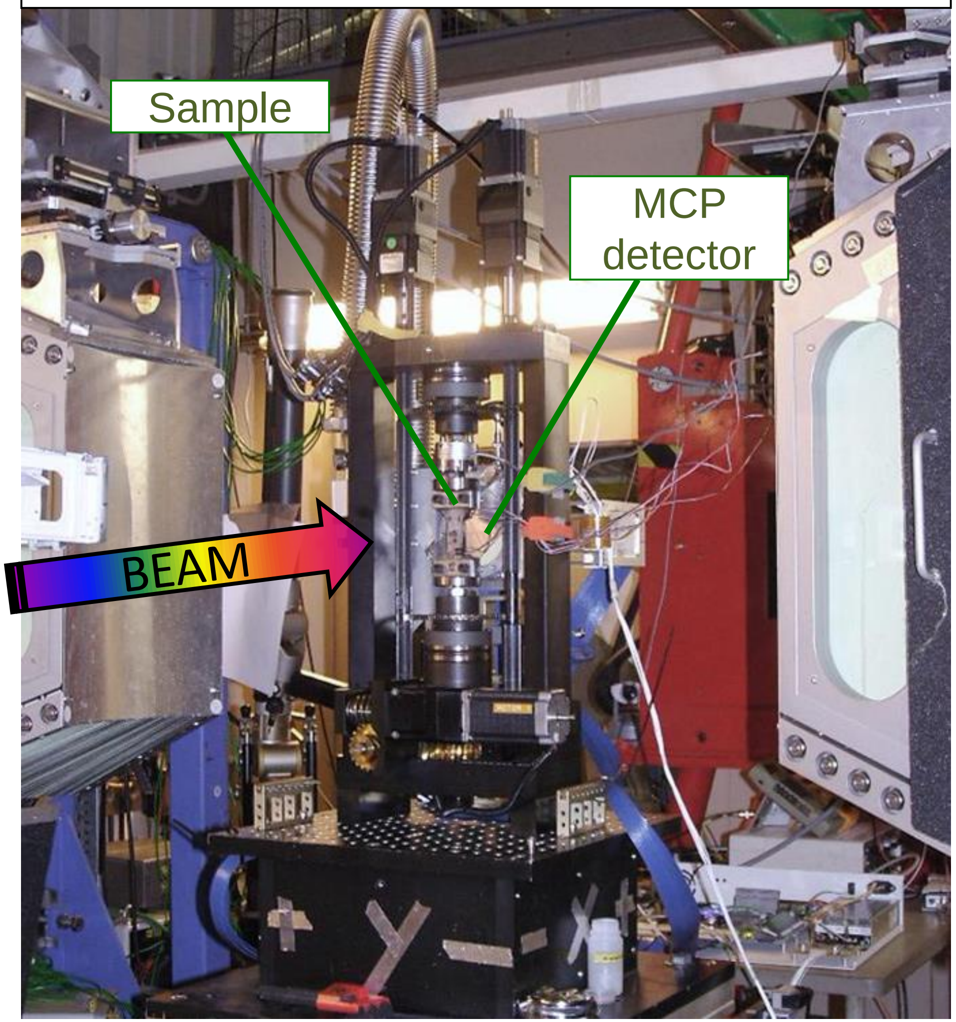


# Wavelength selective imaging 2 - ToF

## Bragg Edge Imaging: Strain Radiography

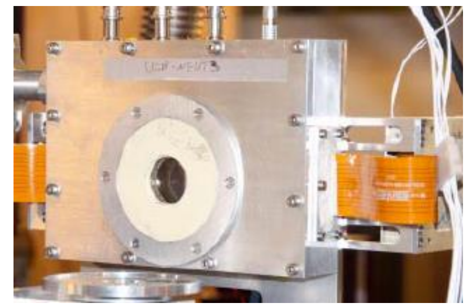


Transmission Measurements at ENGIN-X

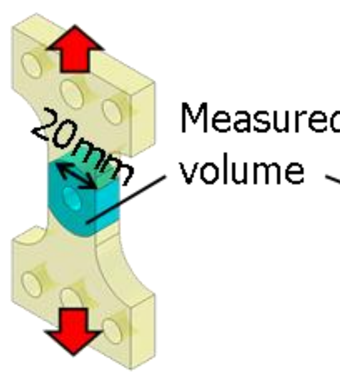


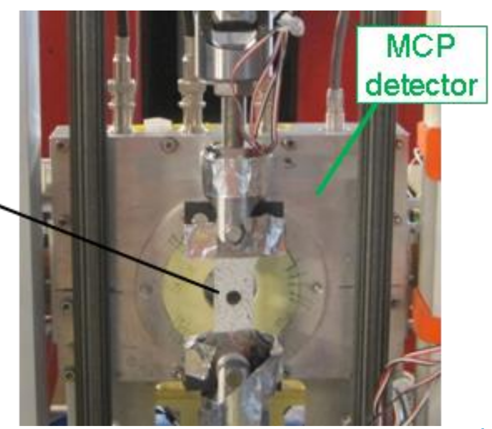

MCP detector (UC Berkeley)

- 28mm FOV, 55um pixels,



(i) A. Tremsin, UC Berkeley

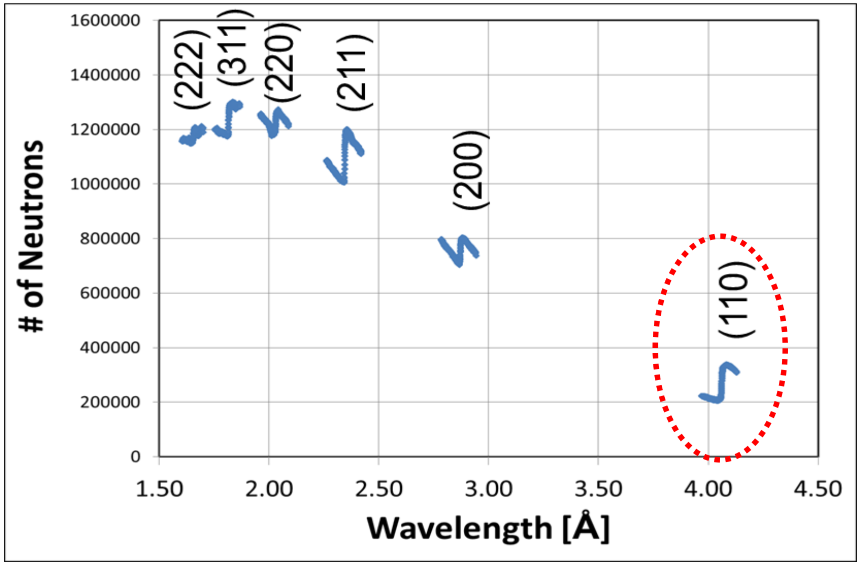


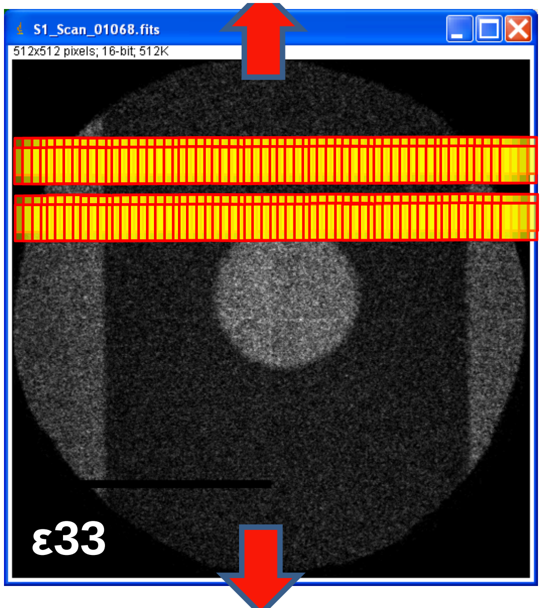



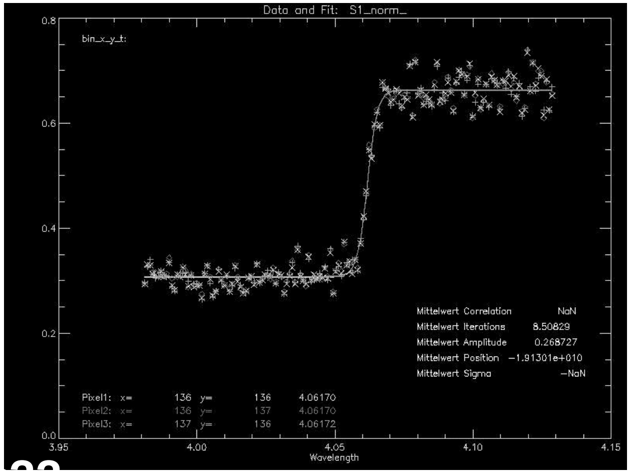
# Bragg Edge Imaging: Strain Radiography

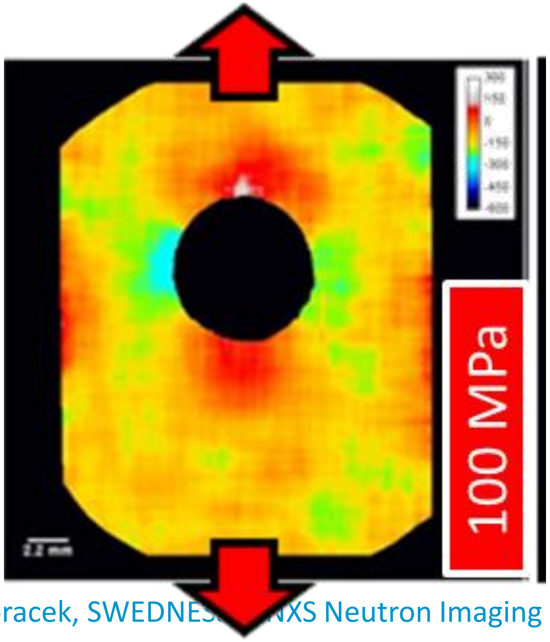
- Record data at few loads
- Pixels are spatially grouped (box 2.1mm) and TOF channel binned (3x15ms; ≈0.001Å)
- Fit is performed for individual edge:

$$f(x) = \frac{1}{A_0 e^{-\left(\frac{x-A_1}{A_2}\right)} + 1} + A_3$$



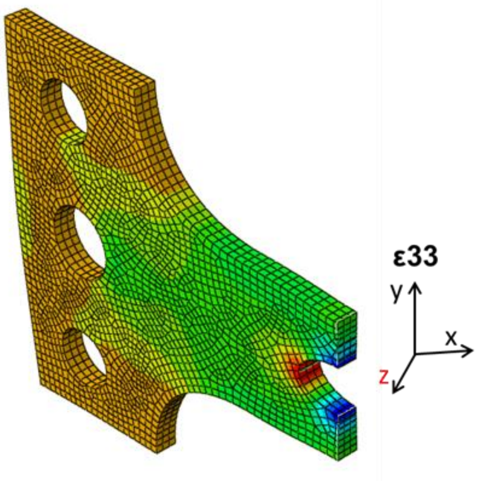



# Wavelength selective imaging 2 - ToF

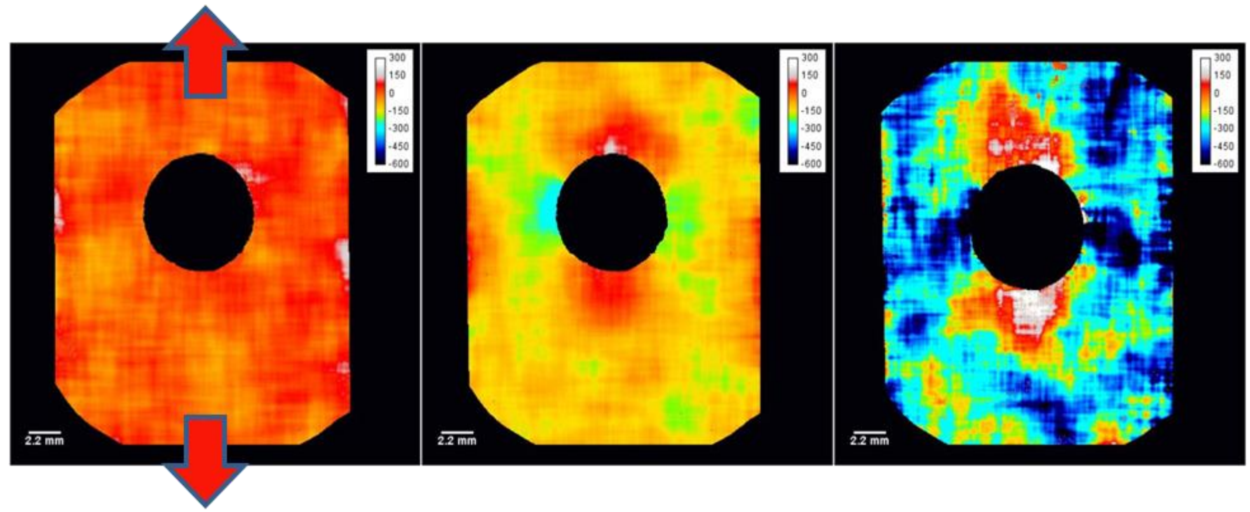
## Bragg Edge Imaging: Strain Radiography

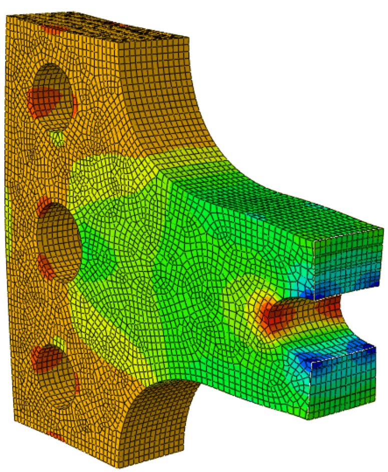
EUROPEAN SPALLATION SOURCE

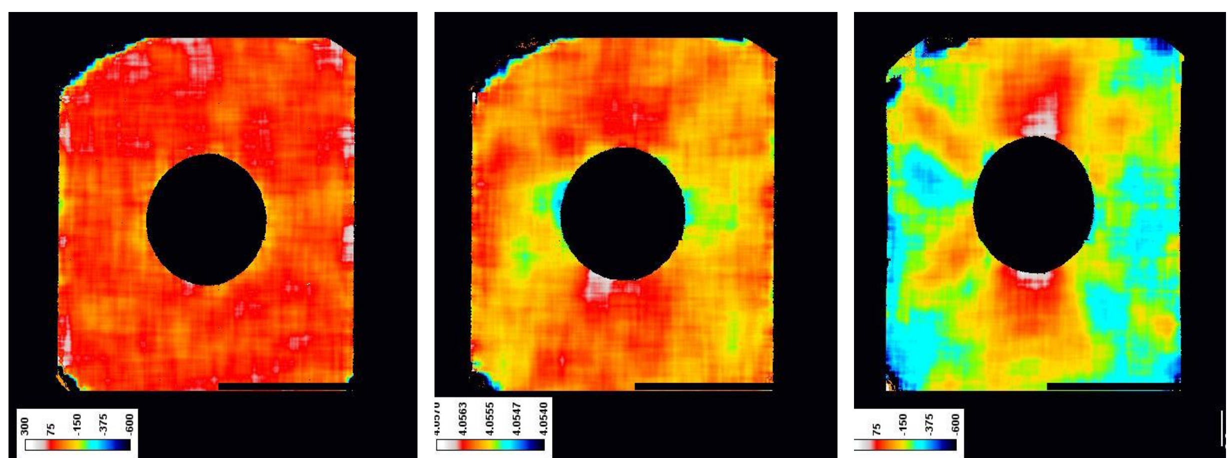
**Edge position (strain) parameter for the (110) lattice**




10 MPa | 160 MPa | 300 MPa





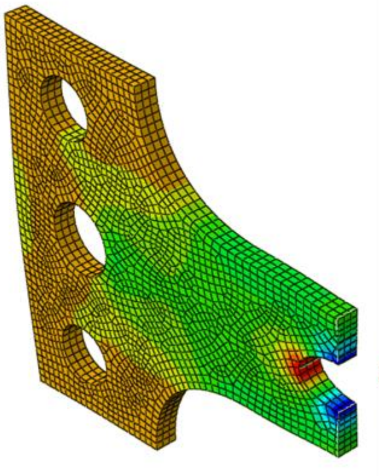
# Wavelength selective imaging 2 - ToF

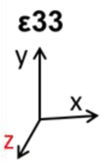
## Bragg Edge Imaging: Strain Radiography

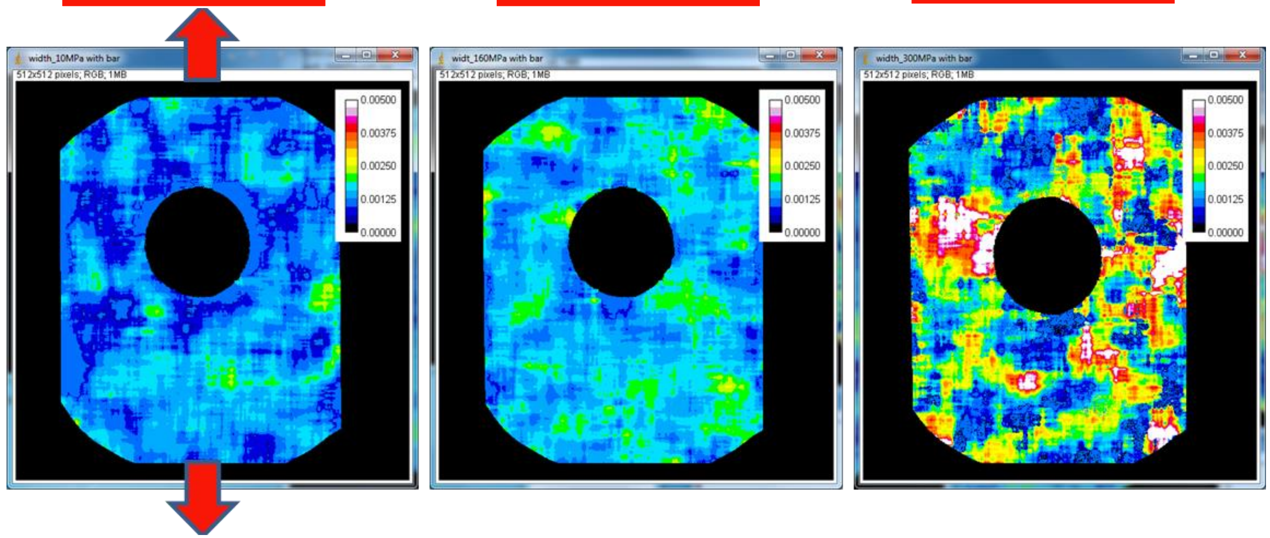
EUROPEAN SPALLATION SOURCE

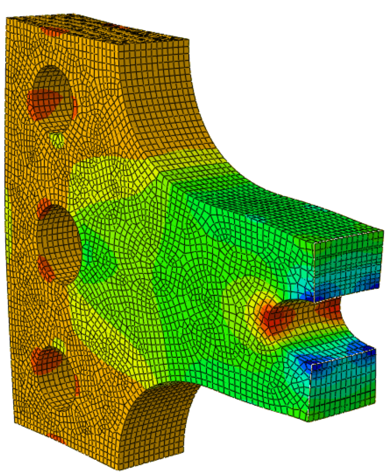
**Edge width parameter for the (110) lattice**

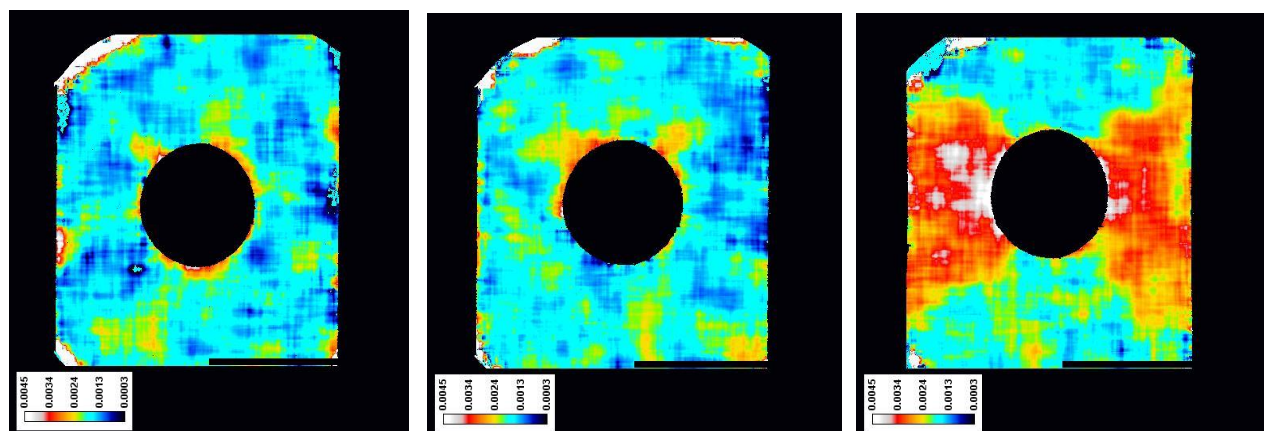
10 MPa | 160 MPa | 300 MPa





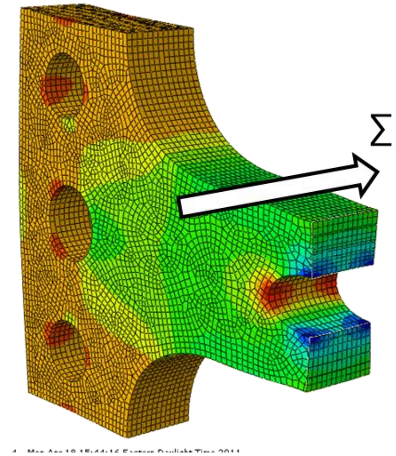





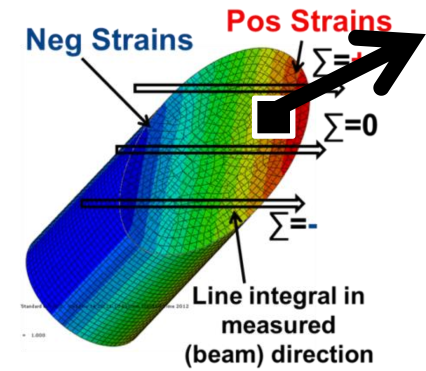
# Wavelength selective imaging 2 - ToF

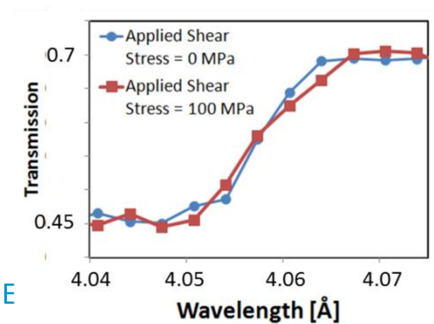
## Bragg Edge Imaging: Strain Radiography




### Conclusions

- Gauge Volume contains complete beam path
- Strain variations though beam paths lead to Bragg edge widening… making quantification difficult
- … but allowing to detect local differences
- Limited choice of scattering vector
- **Neutron and X-Ray diffraction remain method of choice for bulk strain measurements in most cases**
- Useful in specific cases (e.g. plane stress) where precise mapping in one plane is required
- but check if EDXRD a better alternative

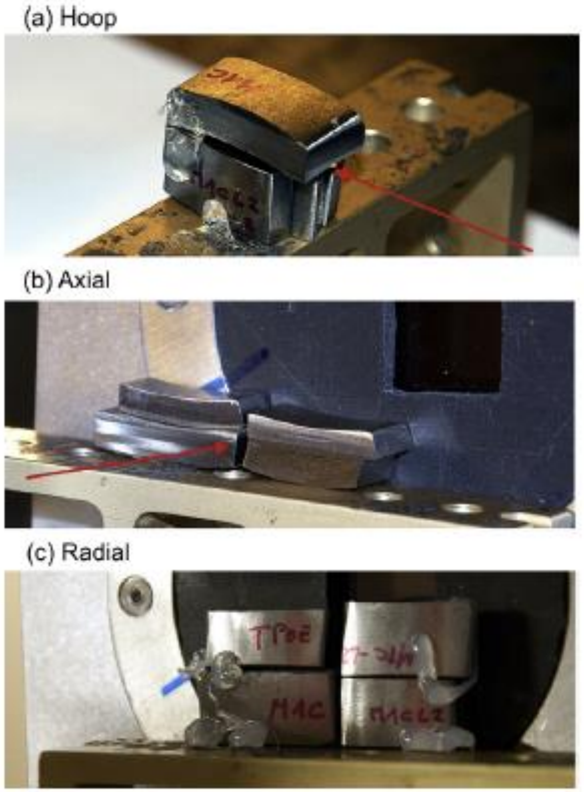


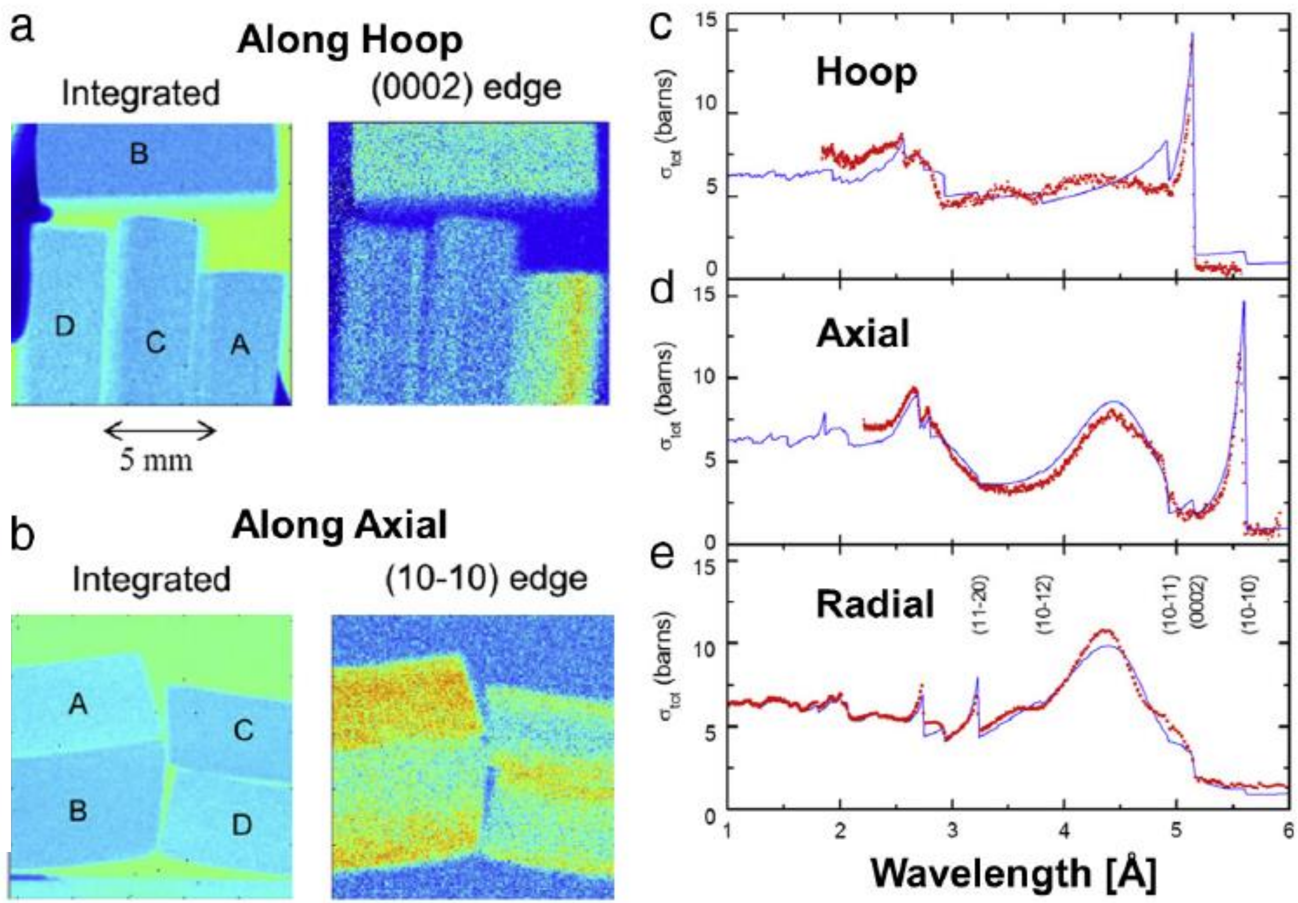




Woracek, SWEDNE

## Part 3: ToF Imaging methods **Diffraction Contrast**

### Texture imaging



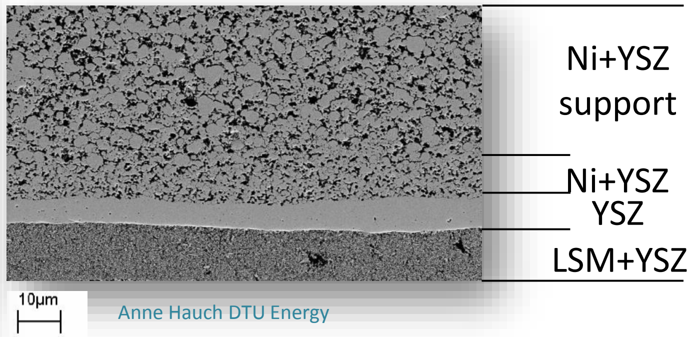

J.R. Santisteban et al. / Journal of Nuclear Materials 425 (2012) 218–227

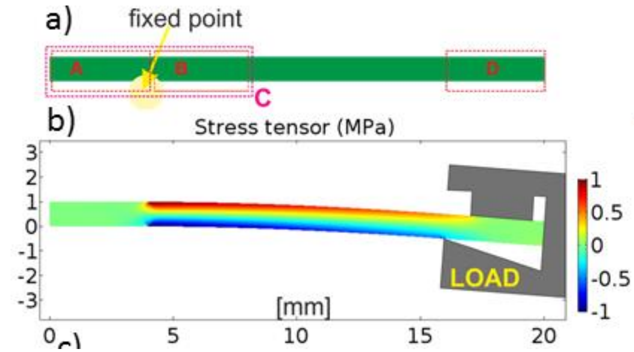
# Wavelength selective imaging 2 - ToF

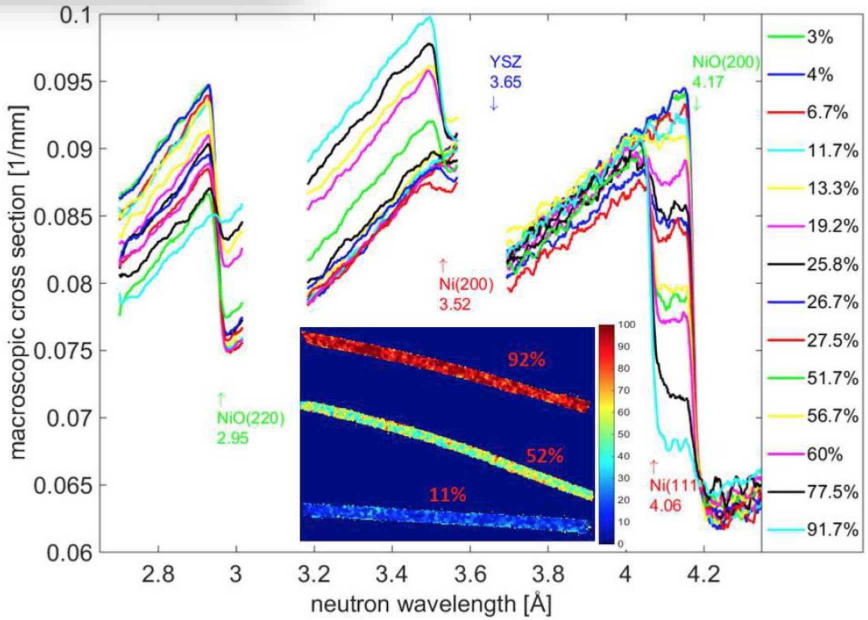
## Part 3: ToF Imaging methods **Diffraction**

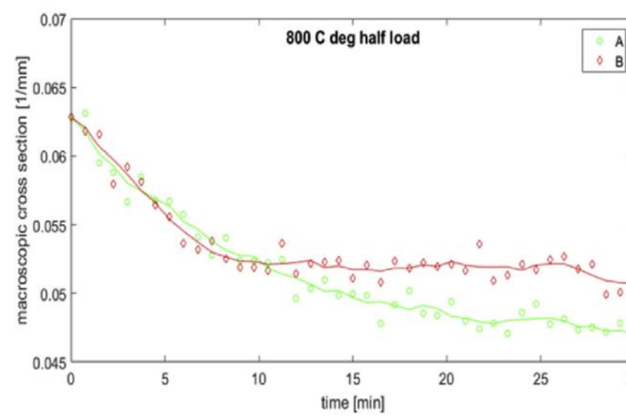
In-situ is a key strength with ToF

In situ Bragg-edge imaging linking strain and reduction in Solid Oxide Cell electrode supports




Makowska, M. G., Strobl, M., Lauridsen, E. M., Kabra, S., Kockelmann, W., Tremsin, A., ... & Theil Kuhn, L. (2016). In situ time-of-flight neutron imaging of NiO–YSZ anode support reduction under influence of stress. Journal of Applied Crystallography, 49(5), 1674-1681.

# AGENDA

- **Part 1: Introduction to ToF imaging**
  - Basics (neutron energy, wavelength, velocity)
  - The ToF concept
  - ToF vs steady state instruments
- **Part 2: What do we need for a ToF neutron imaging instrument?**
  - ToF Neutron Source
  - Examples of of ToF imaging beamlines
  - ToF Detectors
- **Part 3: ToF Imaging methods**
  - The bigger picture: overview and comparison to other neutron techniques
  - ‘Attenuation’: Monochromatic, ‘white-beam’ and ‘pink-beam’ (narrow wavelength) applications
  - Diffraction Contrast / Bragg edge imaging (including diffraction basics)
  - Other methods to profit from ToF: Polarized, phase and dark field, 3DND, resonance absorption
- **Part 4:** Hands on example (please install https://imagej.net/Fiji/Downloads or https://imagej.nih.gov/ij/download.html)

# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods **Resonance Absorption**

EUROPEAN SPALLATION SOURCE

- Can be performed if the “epithermal” range of energies is accessible.
- The underlying principle is that **individual isotopes of each element absorb neutrons of defined energies**. This a**bsorption in return causes an excitation of the nucleus, resulting in the emission of several gamma-ray photons** in order to return to its ground state.
- The **conventional neutron resonance capture analysis (NRCA)** detects the gamma-rays as a function of incident neutron energies, and requires a pulsed neutron beam for time of flight analysis (there is no need to measure the energy of the gammas) (Postma et al. 2003,133; Postma et al. 2009,134)
- **Neutron resonance absorption imaging (NRAI)** is performed at spallation sources by directly measuring transmitted neutron beam through the sample, and “dips” become visible in the time of flight spectrum whenever a neutron is absorbed.
- depths of neutron absorption resonances can be used to quantify amounts of specific elements in the sample
- temperatures could be measured analyzing the Doppler broadening effect.
- Example measurements are presented in (Sato et al. 2009,135; Cippo et al. 2011,136; Tremsin et al. 2012,97; Tremsin et al. 2013,137).
- For most elements the energies of neutron resonant absorption are in the range of 1 eV (~0.28 Å) to 1000 eV (~0.009 Å).(Tremsin et al. 2013,137)
- Existing analysis software for NRCA (for example SAMMY (Larson 2001,138) can be used for the analysis of NRAI data.(Vogel et al. 2014,139)

# Part 3: ToF Imaging methods **Resonance Absorption**

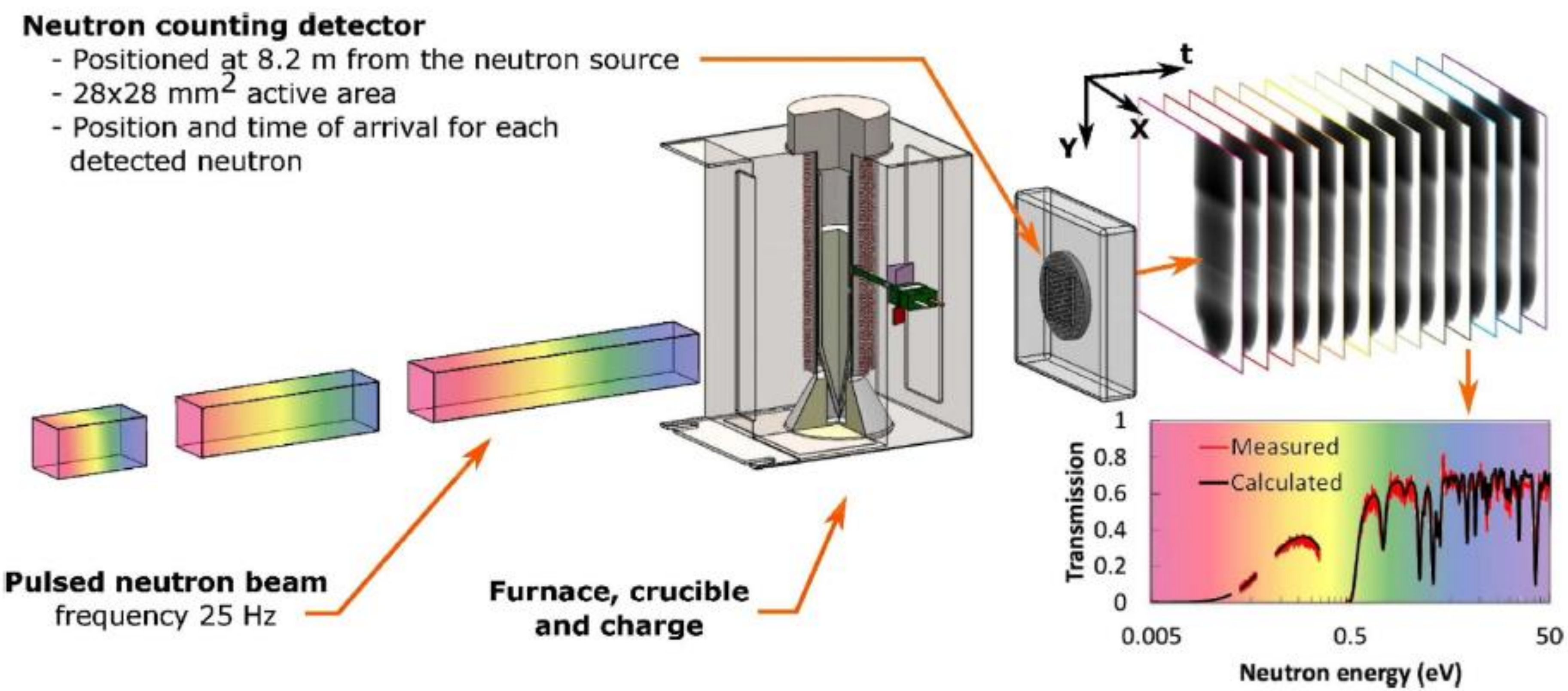
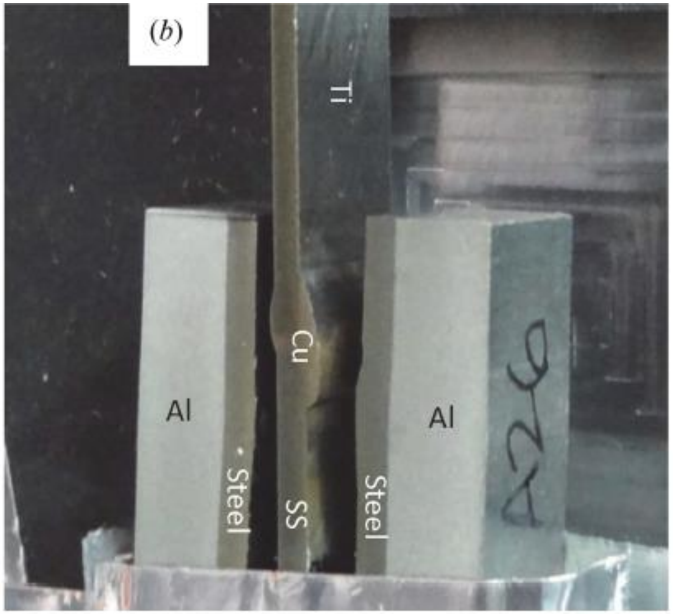


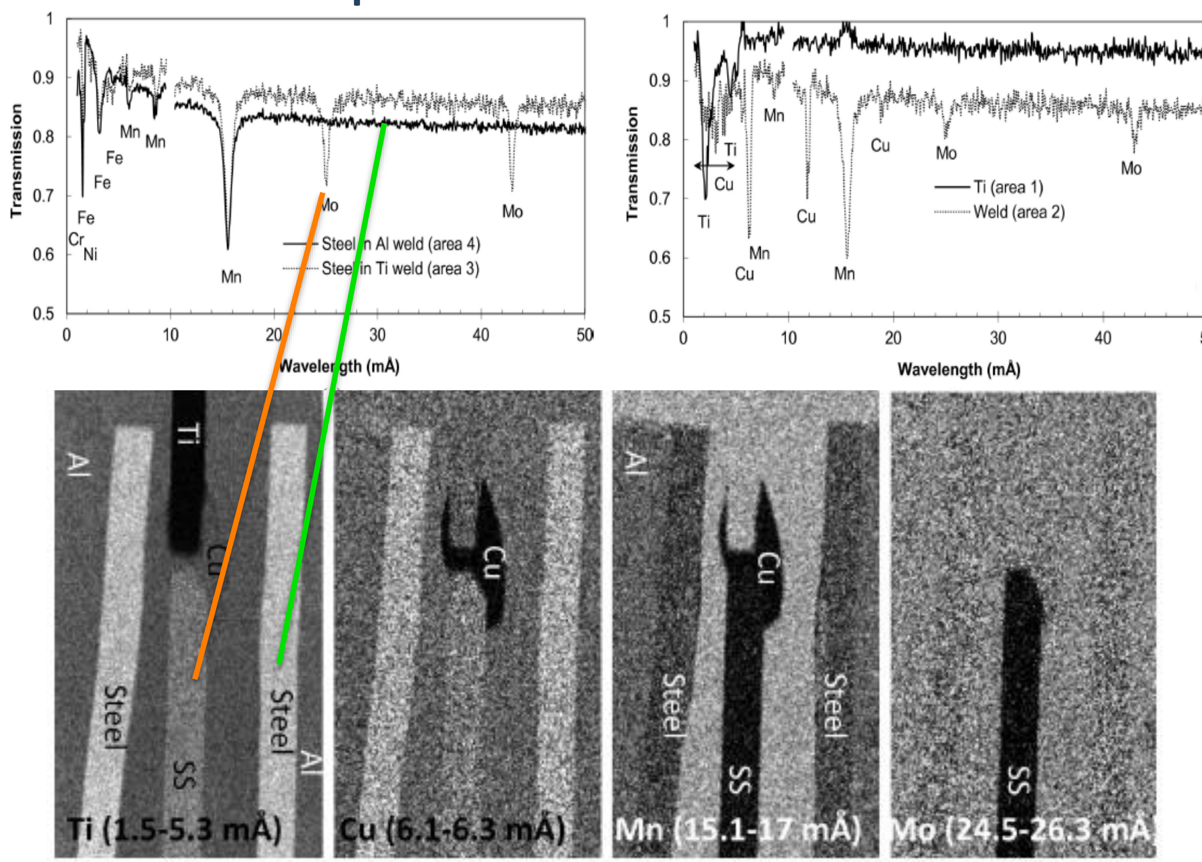

**Figure 1. Schematic diagram of the experimental setup.** A pulsed neutron beam travels towards the neutron counting detector installed at ~8.2 m from the source. Both position (~55 µm) and time (0.1–1 µs) are measured by the detector for each registered neutron. A furnace with a BaBrCl:Eu charge is installed a few centimeters from the detector. A set of images, each corresponding to a particular neutron energy, is acquired in each experiment, spanning neutron energies from epithermal range (1–100 eV) to cold neutrons of meV energies. 262,144 spectra are acquired simultaneously (within each of the 512 × 512 pixels of 55 × 55 µm$^2$ area).

## Part 3: ToF Imaging methods **Resonance Absorption**



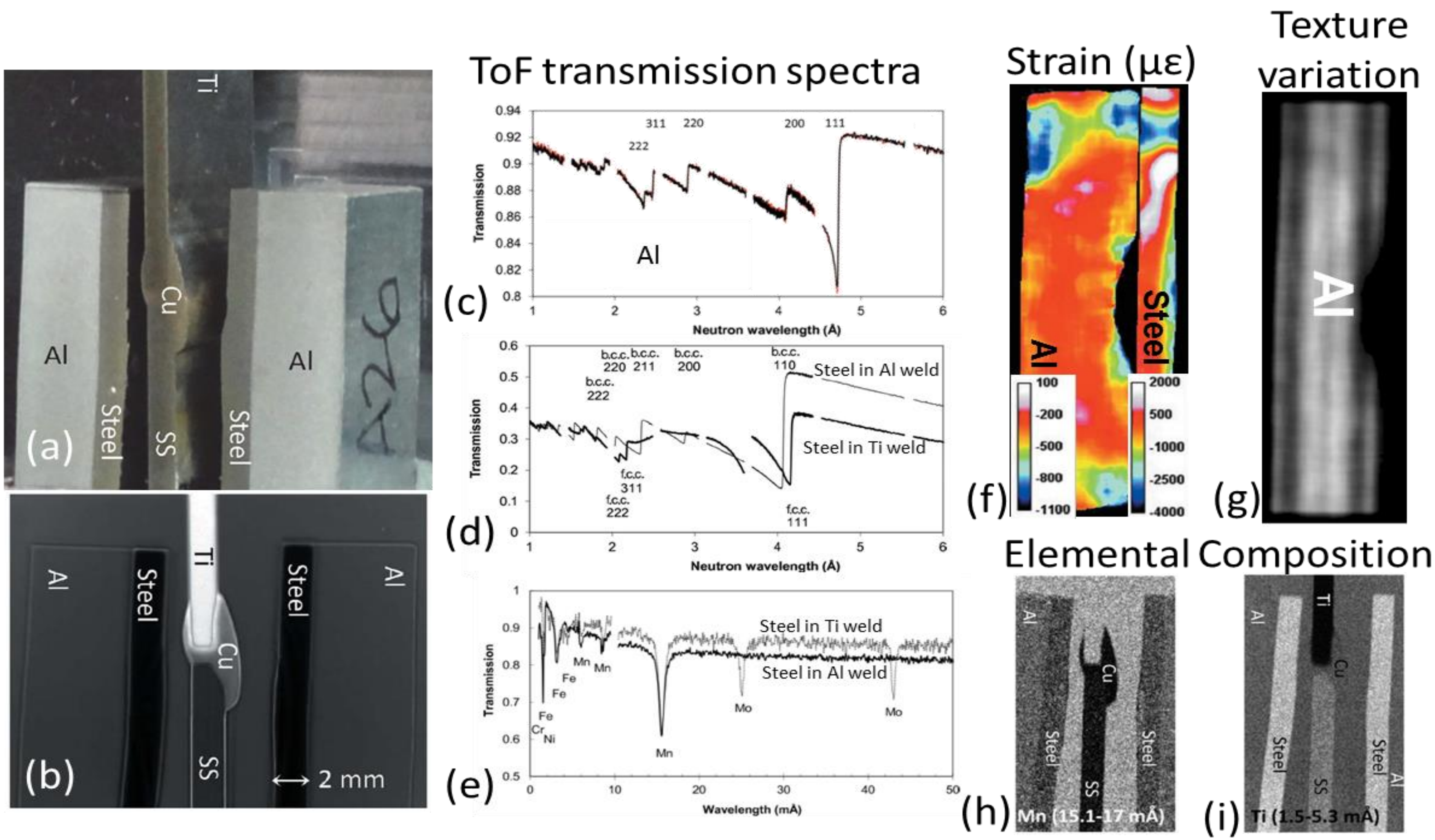

**Resonance absorption contrast:**

Elemental contrast: E.g. check diffusion processes




(a) (b) (c) (d)

A lot of information from one ToF imaging experiment!



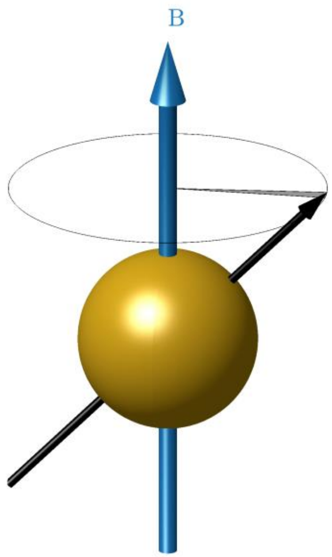

Tremsin, A. S., et al., Journal of Applied Crystallography (2016) 49 (4)

# Wavelength selective imaging 2 - ToF

Part 3: ToF Imaging methods **Polarized**

## Polarized Neutron Imaging in ToF mode

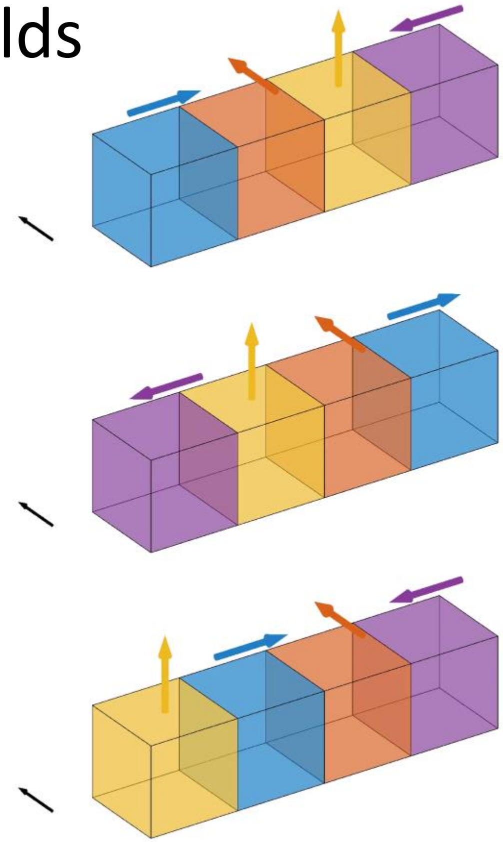
### Polarized Neutrons in Static Magnetic Fields




The **spin of a neutron** passing through a magnetic field will undergo an amount of **precession proportional** to the **strength of the magnetic field and the time spent** by the neutron in the magnetic field.
The **time is proportional to the neutron wavelength, λ, and the path length** through the magnetic field, L.
The precession angle is given:

$$\phi = cB\lambda L$$

c: Larmor constant (c = 4.632 × 1014 T−1 m−2)
B: is the magnetic field strength.

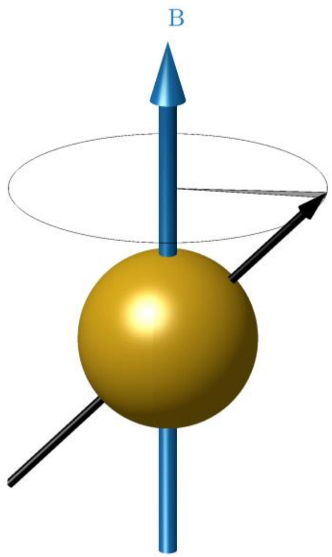


*Credit: Morten Sales*

Sales, M., Strobl, M., Shinohara, T., Tremsin, A., Kuhn, L. T., Lionheart, W. R., ... & Schmidt, S. (2018). Three dimensional polarimetric neutron tomography of magnetic fields. Scientific reports, 8(1), 2214.

## Polarized Neutron Imaging in ToF mode

# Polarized Neutrons in Static Magnetic Fields

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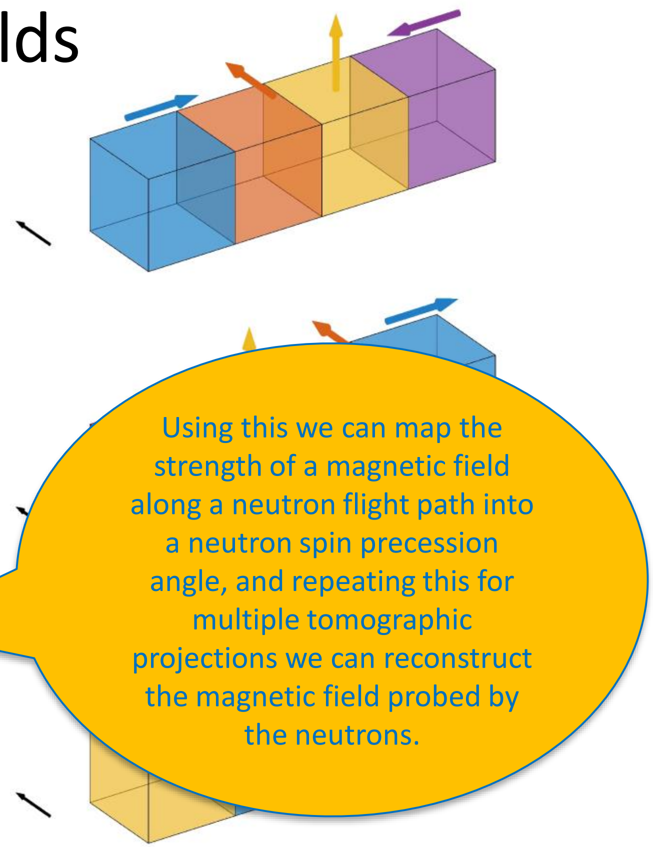


Using this we can map the strength of a magnetic field along a neutron flight path into a neutron spin precession angle, and repeating this for multiple tomographic projections we can reconstruct the magnetic field probed by the neutrons.

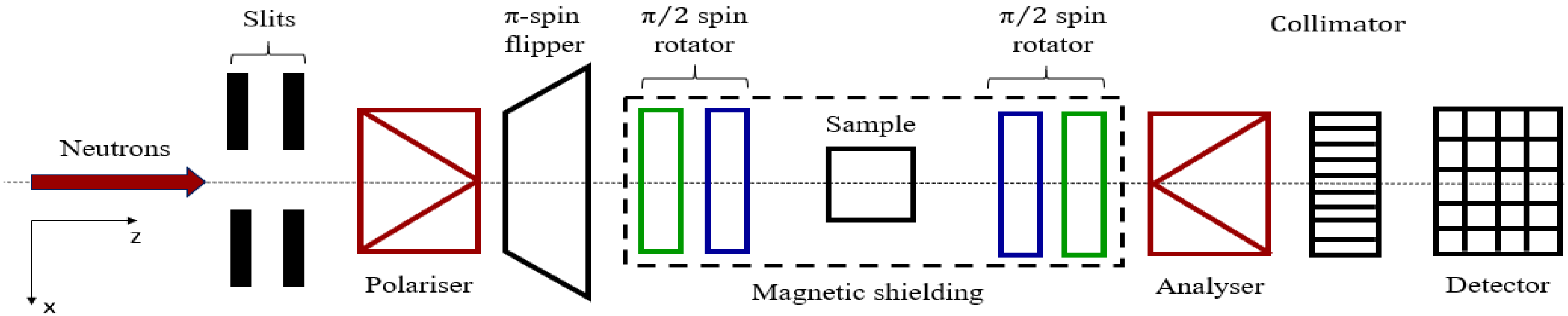
*Credit: Morten Sales*

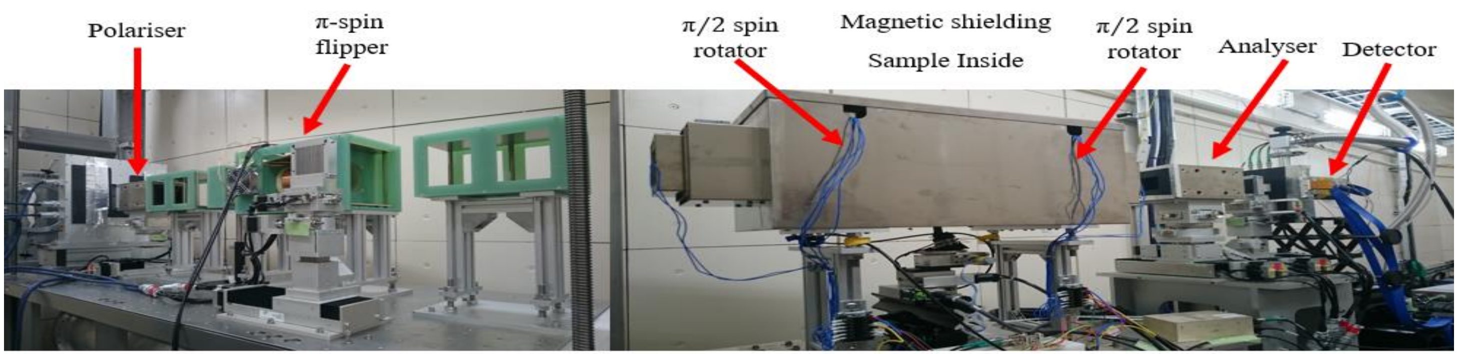
Sales, M., Strobl, M., Shinohara, T., Tremsin, A., Kuhn, L. T., Lionheart, W. R., ... & Schmidt, S. (2018). Three dimensional polarimetric neutron tomography of magnetic fields. Scientific reports, 8(1), 2214.

## Polarized Neutron Imaging in ToF mode

$$P_{i,j} = \frac{I_{(i,j)} - I_{(-i,j)}}{I_{(i,j)} + I_{(-i,j)}} \quad i \in \{x, y, z\}, \ j \in \{x, y, z\}$$

# Experimental Setup - RADEN




Neutron intensity data, $I_{\varepsilon i,j}$, for 60 projection angles between 0° and 360° was recorded with 18 different combinations of directions of spin polarisation, ±i, and analysis, j, for each projection, with $i \in \{z, y, z\}$, $j \in \{x, y, z\}$, $\varepsilon \in \{-1, 1\}$. The acquisition time for each of the 60 × 18 measurements was ≈370 s *(=4.6 days total)*.

Sales, M., Strobl, M., Shinohara, T., Tremsin, A., Kuhn, L. T., Lionheart, W. R., ... & Schmidt, S. (2018). Three dimensional polarimetric neutron tomography of magnetic fields. Scientific reports, 8(1), 2214.

## Polarized Neutron Imaging in ToF mode

$$\mathbf{P}(\lambda,\theta) = \begin{pmatrix} P_{x,x} & P_{x,y} & P_{x,z} \\ P_{y,x} & P_{y,y} & P_{y,z} \\ P_{z,x} & P_{z,y} & P_{z,z} \end{pmatrix}$$

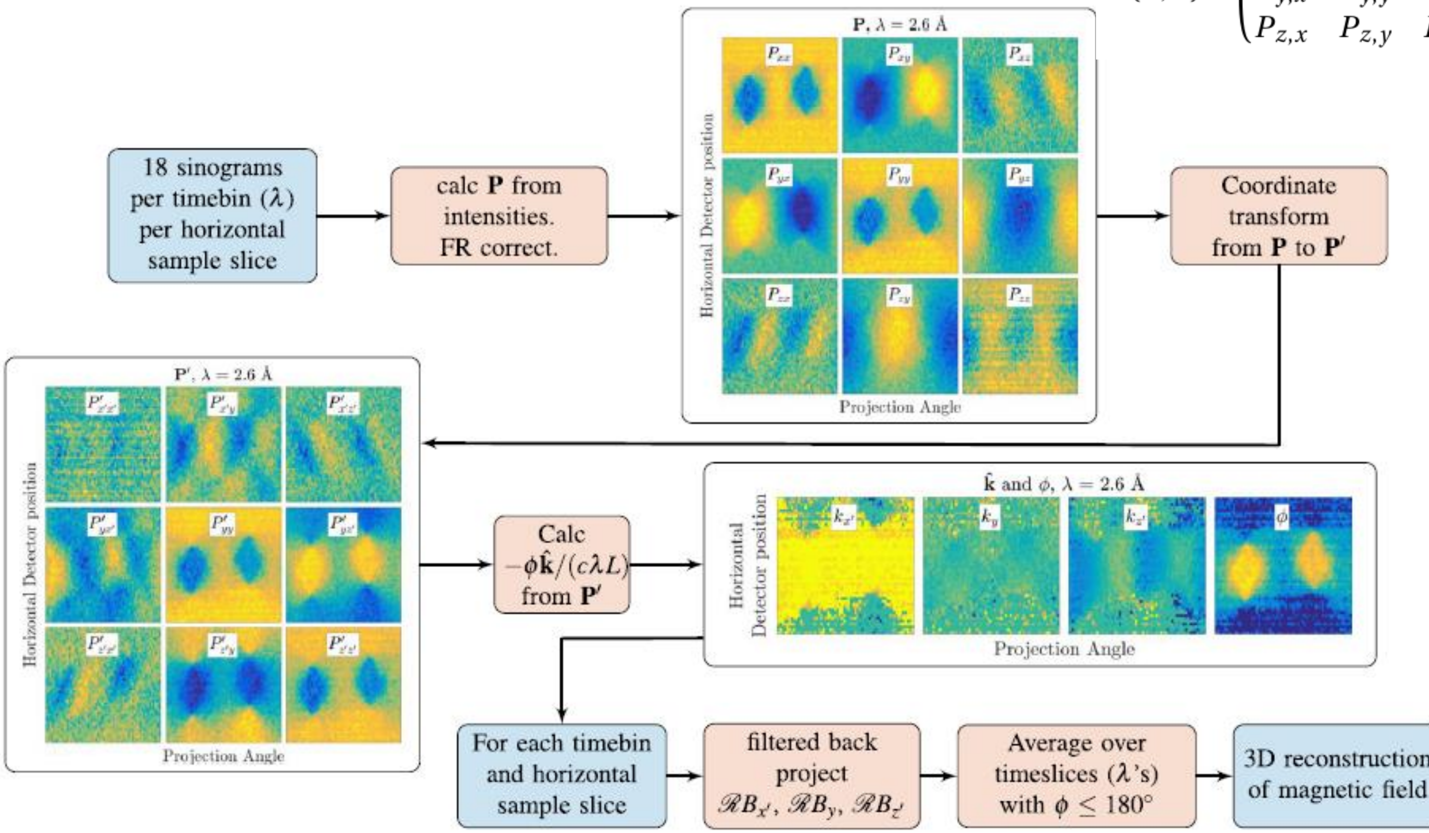
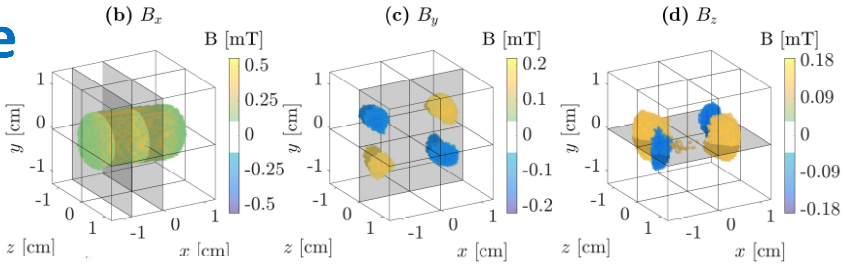



**Figure 2.** Procedure for reconstructing a 3D magnetic field measured with polarimetric neutron tomography. The measured intensities are reduced to 3 scalars that can be filtered back projected in order to obtain the reconstructed three dimensional magnetic field.

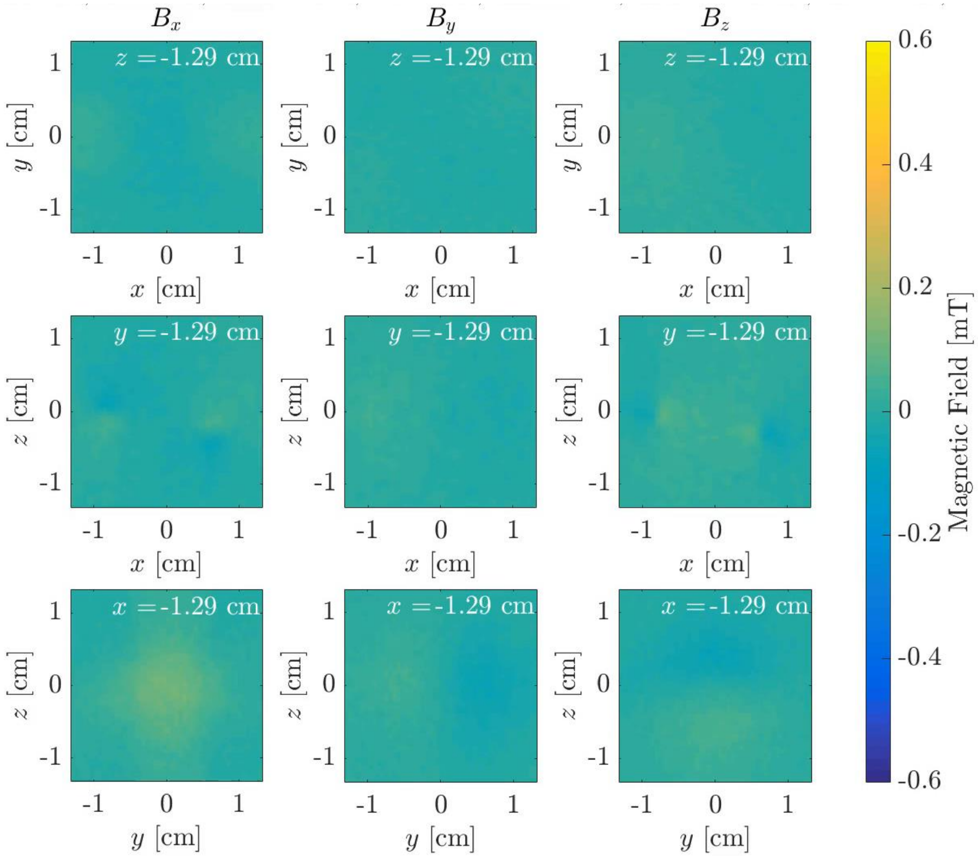

Sales, M., Strobl, M., Shinohara, T., Tremsin, A., Kuhn, L. T., Lionheart, W. R., ... & Schmidt, S. (2018). Three dimensional polarimetric neutron tomography of magnetic fields. Scientific reports, 8(1), 2214.

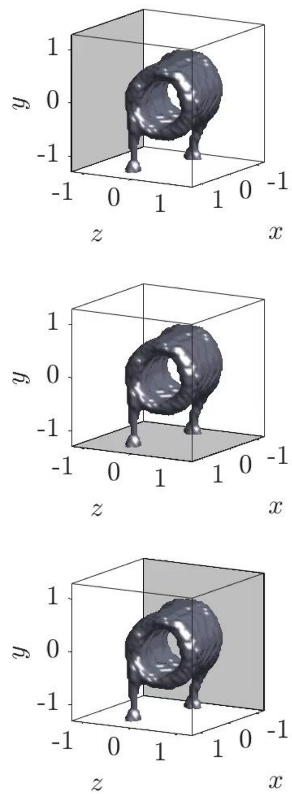
EUROPEAN SPALLATION SOURCE

# Polarized Neutron Imaging in ToF mode




Reconstruction results



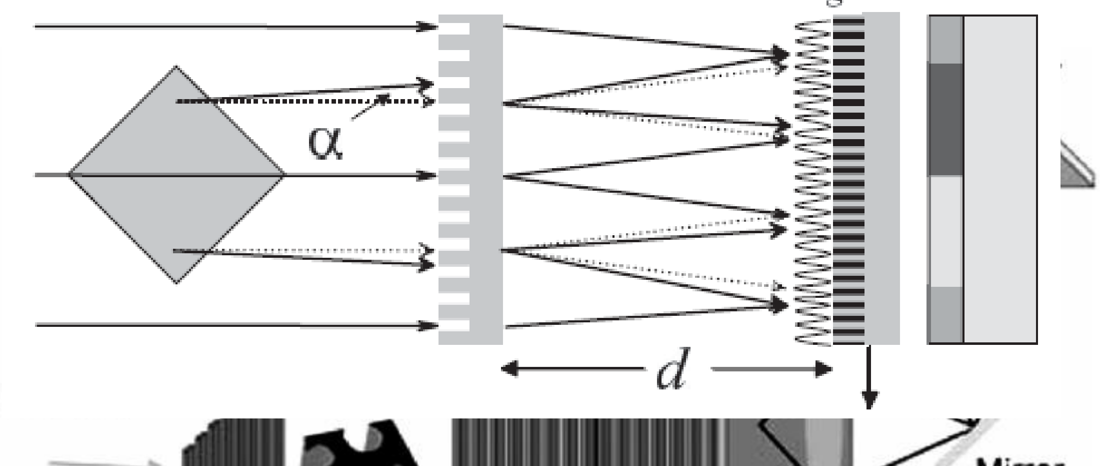



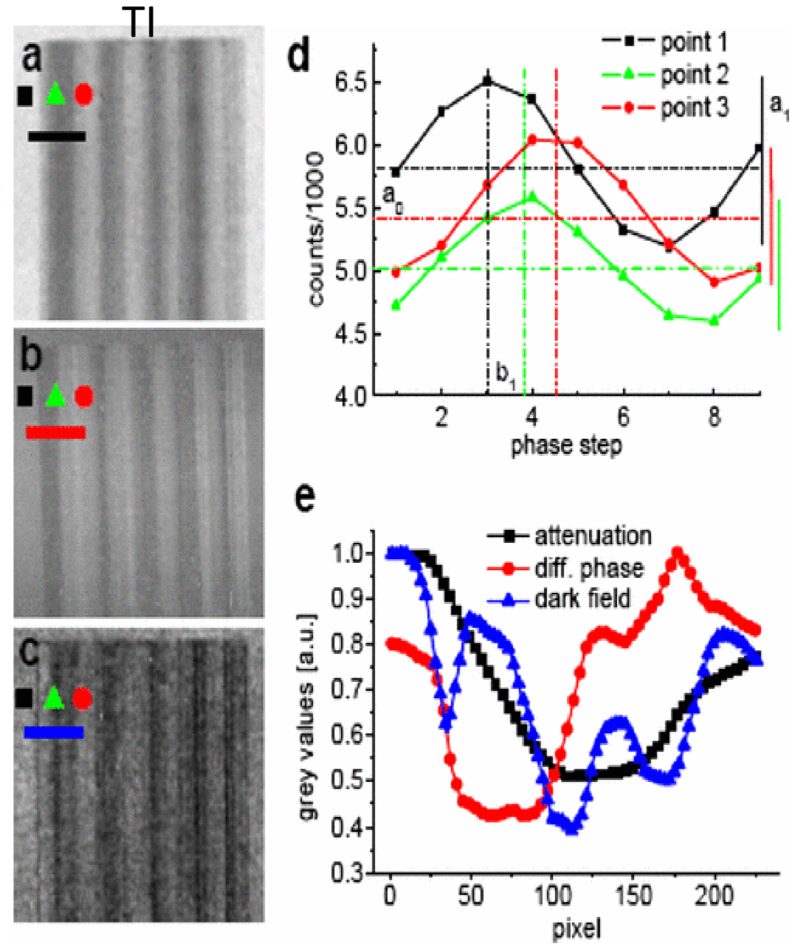
Sales, M., Strobl, M., Shinohara, T., Tremsin, A., Kuhn, L. T., Lionheart, W. R., ... & Schmidt, S. (2018). Three dimensional polarimetric neutron tomography of magnetic fields. Scientific reports, 8(1), 2214.

# Part 3: ToF Imaging methods **Modulation**

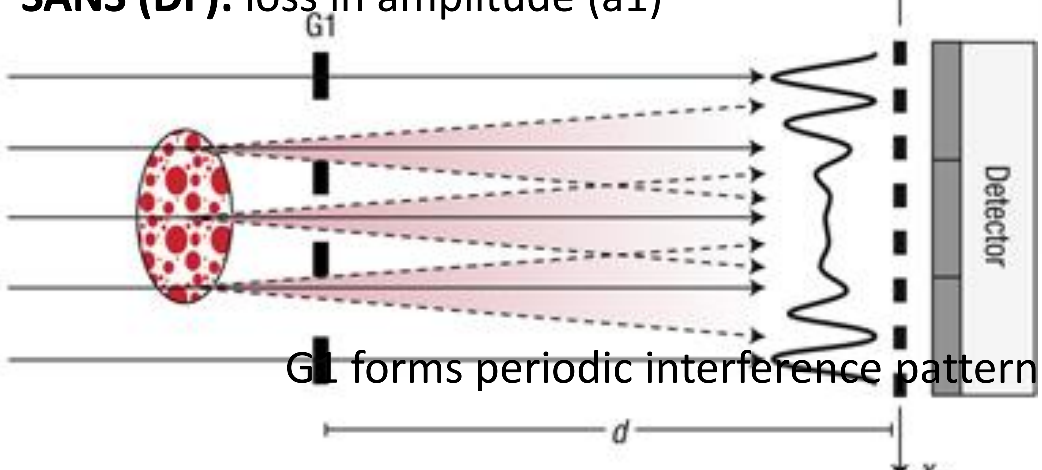
## Neutron Grating Interferometry (NGI) in ToF mode

**Phase shift:** Object causes refraction, resulting in changes of locally transmitted intensity through G2 (b1)




**SANS (DF):** loss in amplitude (a1)




G1 forms periodic interference pattern

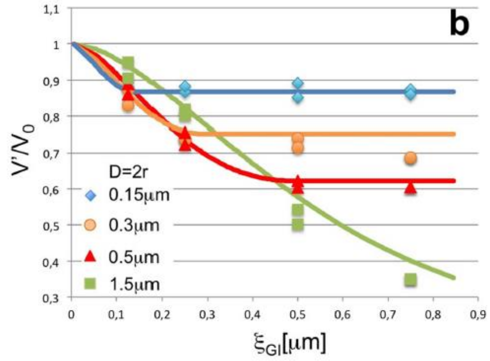
Pfeiffer, F., Grünzweig, C., Bunk, O., Frei, G., Lehmann, E., & David, C. (2006). Neutron phase imaging and tomography. Physical review letters, 96(21), 215505.

## Neutron Grating Interferometry (NGI) in ToF mode

**Goals:**

- Demonstrate NGI in ToF for first time (gratings are designed for certain λ, but work around ±1Å)
- Dark Field Contrast probes (U)SANS: λ dependent signal (Autocorrelation length ) allows quantification

$$\xi_{GI} = \frac{\lambda L_s}{p}$$




$$V_s(\xi_{GI}) / V_0(\xi_{GI}) = e^{\Sigma_s t (G(\xi_{GI})-1)}$$

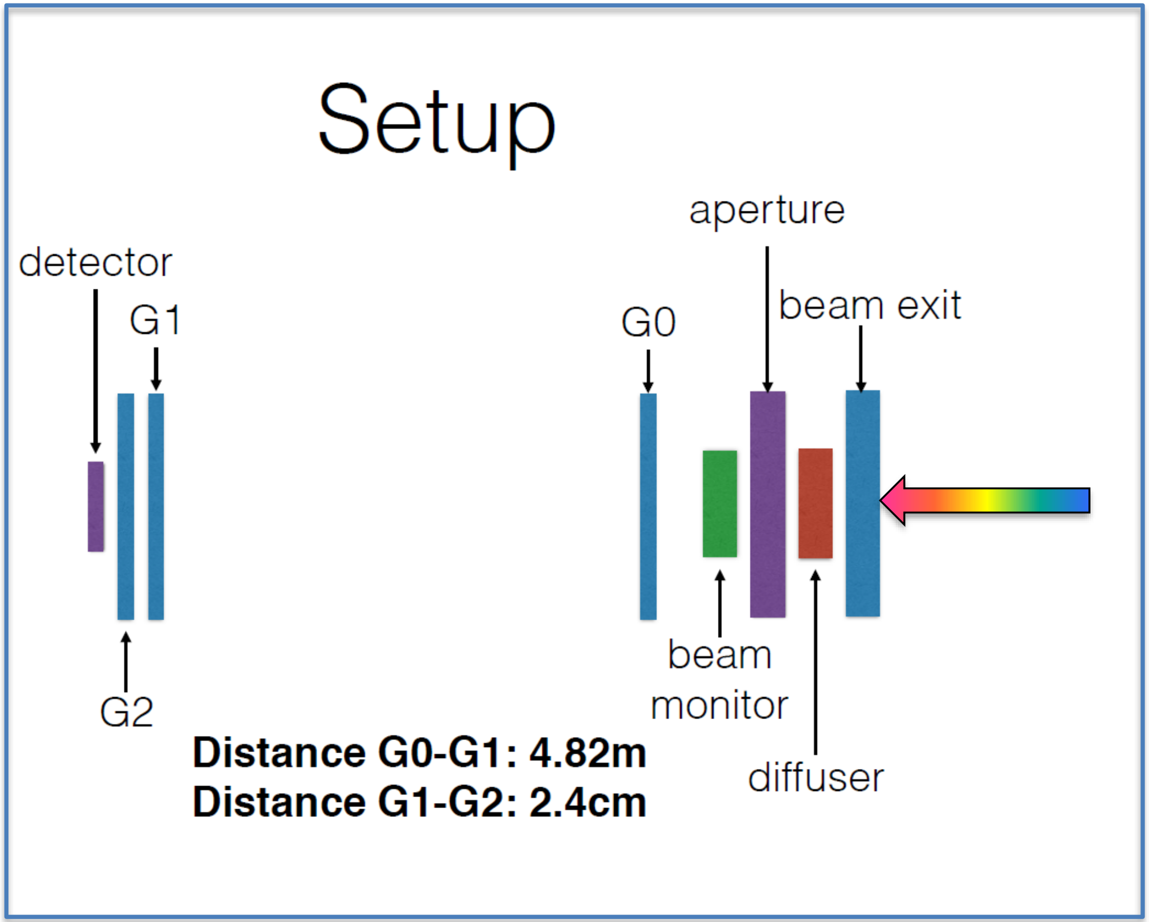
λ: wavelength
p: Modulation period
Ls: effective sample to detector distance

- Enables USANS with spatial image resolution

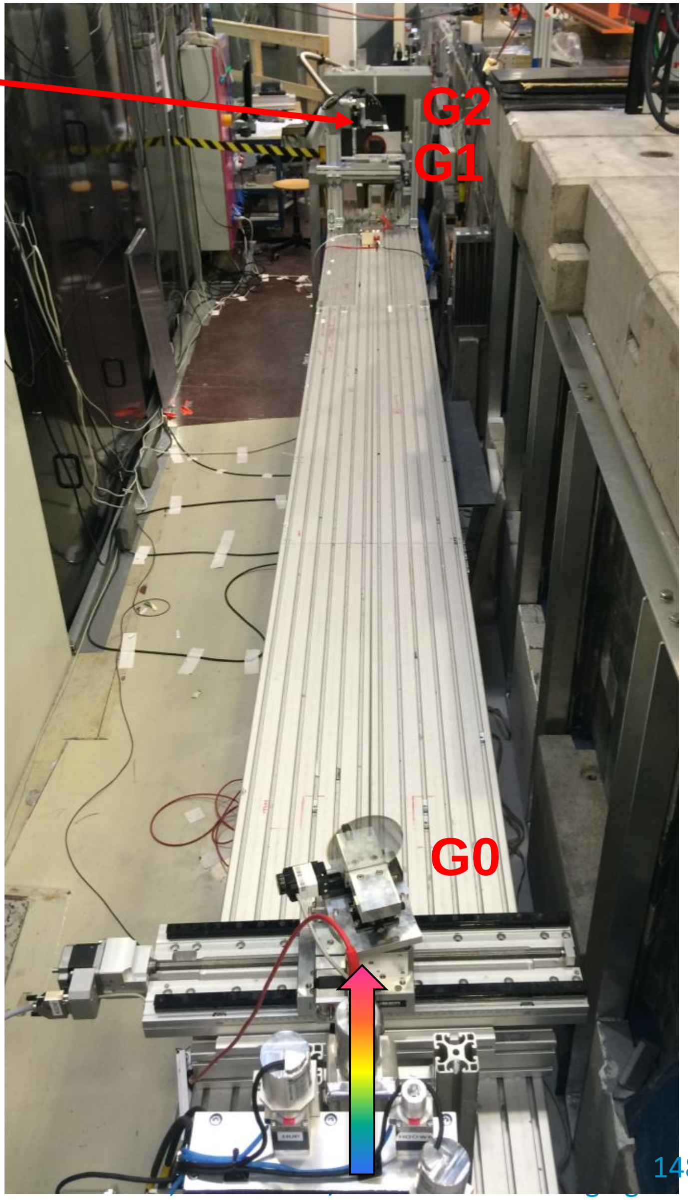
Ref: M. Strobl, Scientific Reports 4 (2014) 7243

# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods **Modulation**



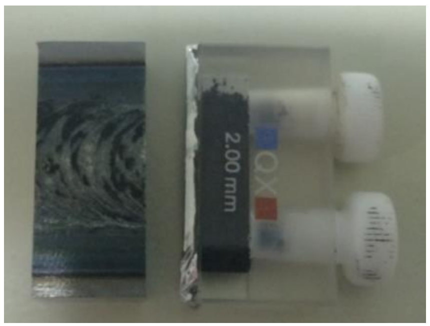

**Distance G0-G1: 4.82m**
**Distance G1-G2: 2.4cm**



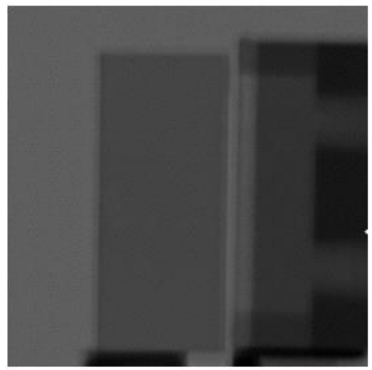
# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods **Modulation**

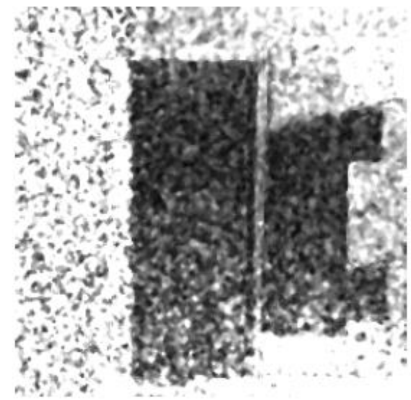
- First reconstruction using white beam (adding all images in stack: 1000 time channels) and no additional normalizations yet




TI



DFI



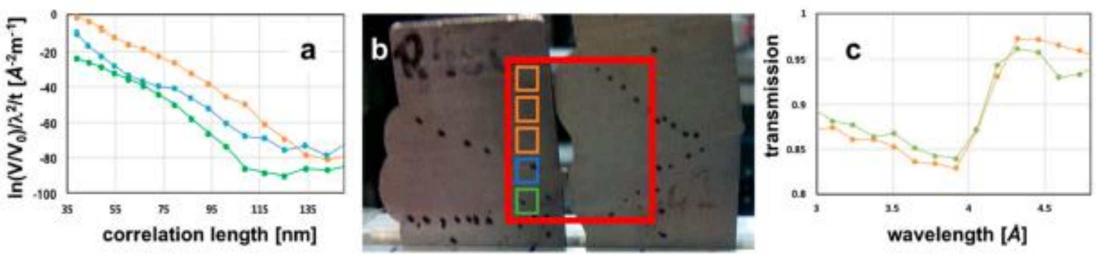



**Figure 6.** Time-of-flight dark-field imaging of steel welds: (**a**) real space correlation functions of three distinct areas of a 1.5 mm thick steel weld; (**b**) photograph of the sample(s) with the color coded regions of interest analysed in (**a**) and (**c**); (**c**) simultaneously recorded wavelength dependent transmission data of two color coded regions of interest (**b**) in the weld, displaying the Bragg edge pattern around the Fe(110) Bragg edge.

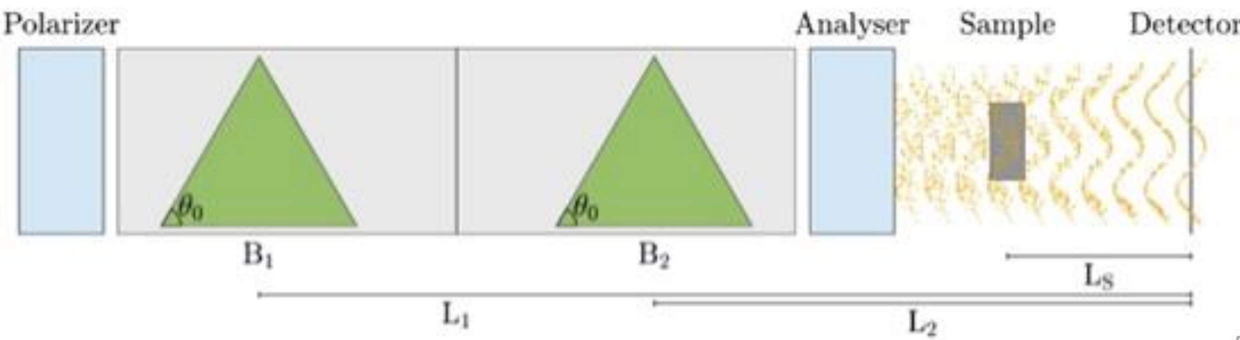
- Detailed corrections and analysis ongoing ☺

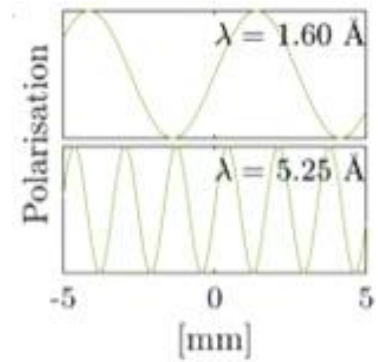
R. Harti, M. Strobl, R. Woracek et al, unpublished results

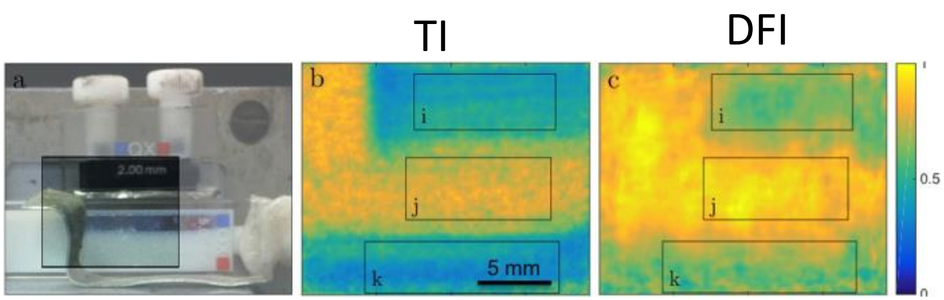
# Part 3: ToF Imaging methods **Modulation**

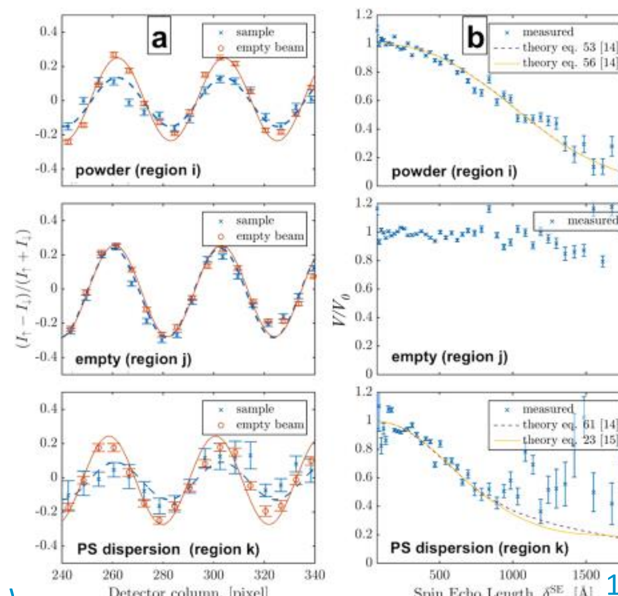
## Spin Echo Modulated Small Angle Neutron Scattering (SEMSANS)

- SEMSANS is a new technique to measure SANS with beam modulated through spin-echo approach



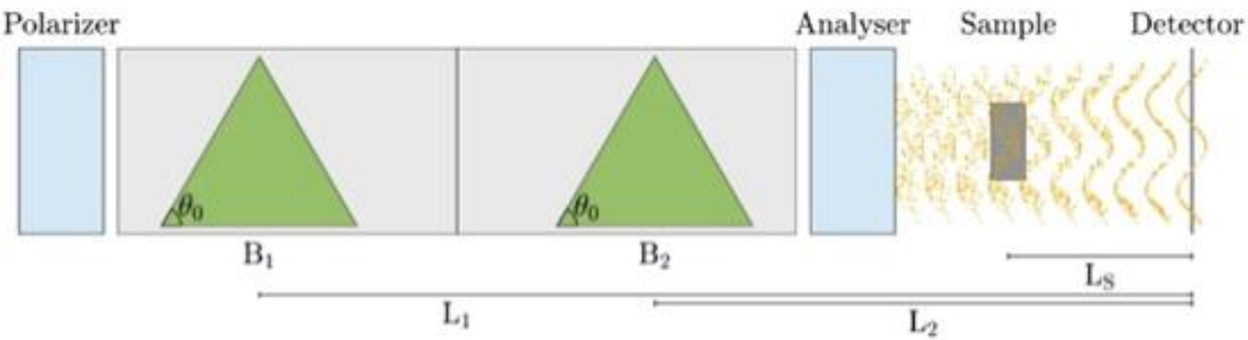

Strobl, M., Sales, M., Plomp, J., Bouwman, W.G., Tremsin, A.S., Kaestner, A., Pappas, C. and Habicht, K., 2015. Quantitative Neutron Dark-field Imaging through Spin-Echo Interferometry. Scientific reports, 5.

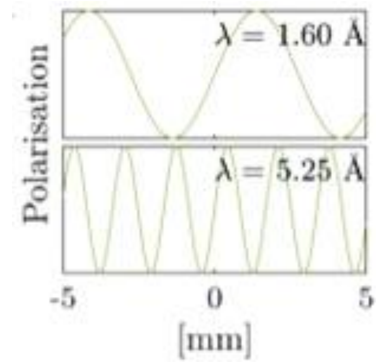
# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods **Modulation**

### Spin Echo Modulated Small Angle Neutron Scattering (SEMSANS)

- SEMSANS is a new technique to measure SANS with beam modulated through spin-echo approach



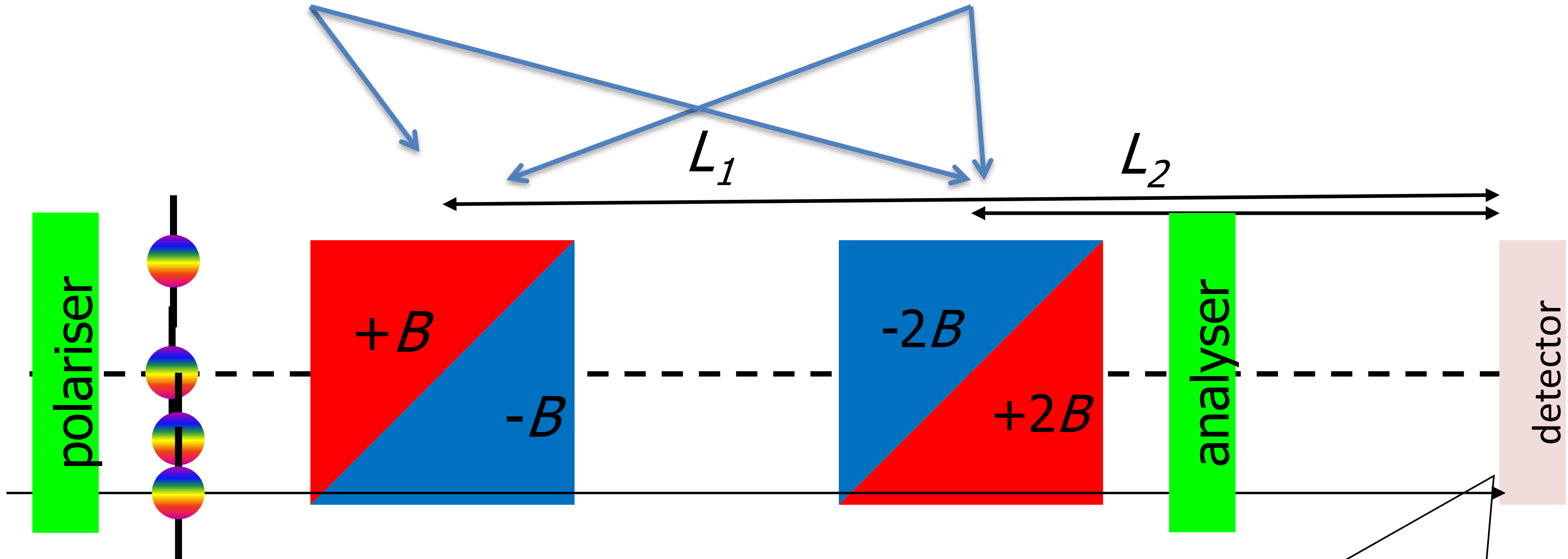

**Goals:**

- Combine with imaging like in the grating case
- Demonstrate that that it can be implemented effectively in ToF mode using ESS long pulse structure
- Test a new field set-up as compared to first proof of principle

# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods **Modulation**

**1st setup: Triangular** **2nd setup: RF magnets**




neutrons arriving same point
same polarisation

W.G. Bouwman, C.P. Duif, R. Gähler, Physica B **404** 2585-2589 (2009)

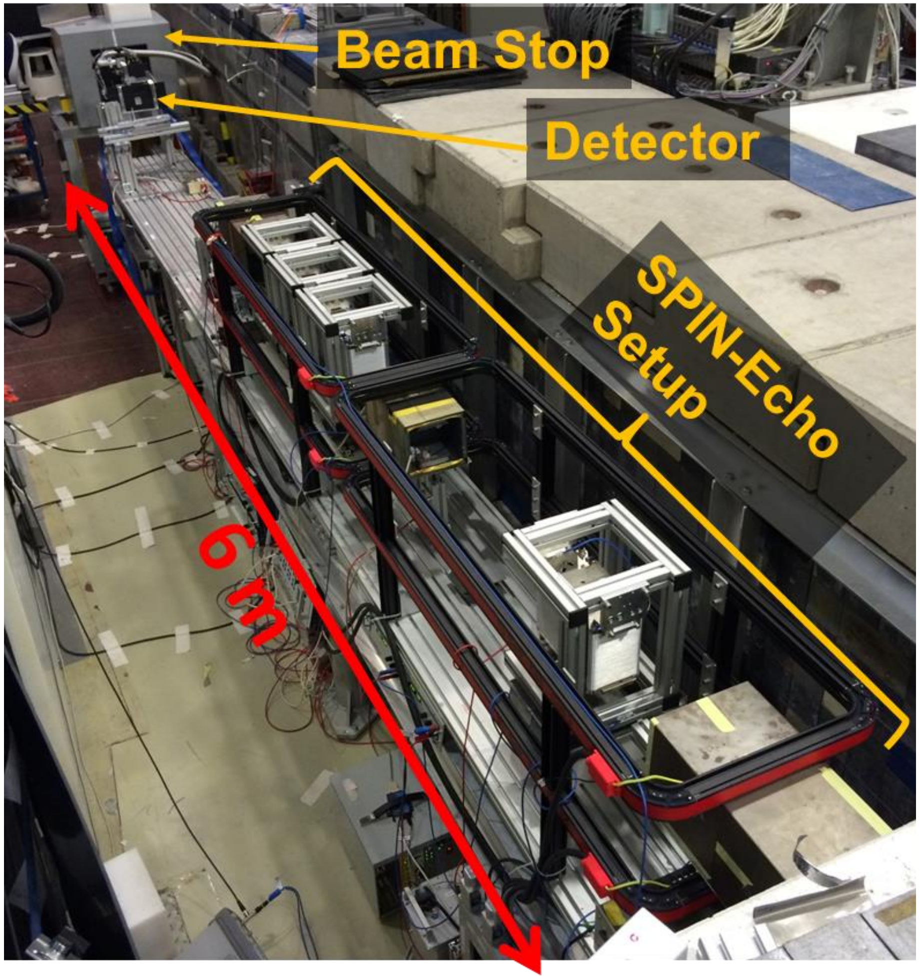
TU Delft: Jeroen Plomp, Michel Thijs, Andre Kusmin
PSI: Markus Strobl, Ralph P. Harti

Animation: Courtesy of J. Plomp

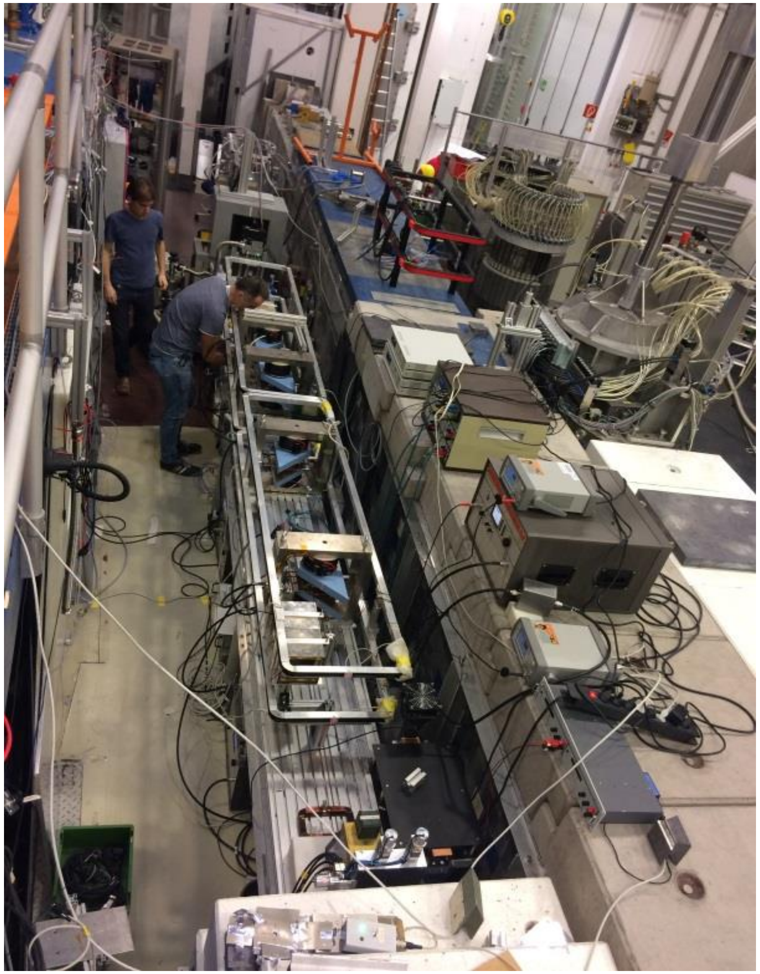
# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods **Modulation**

### 1st setup: Triangular




### 2nd setup: RF



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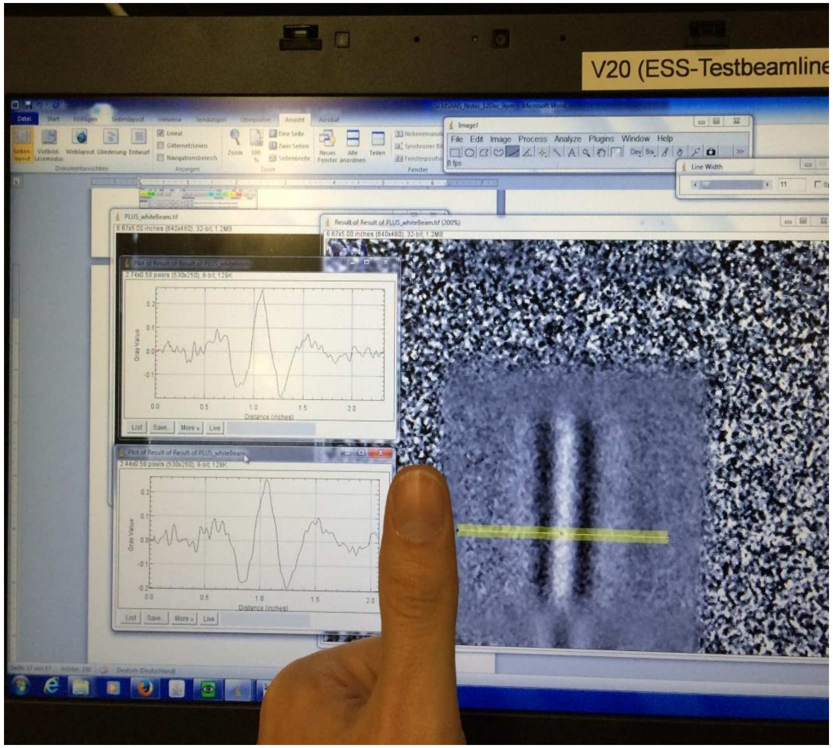
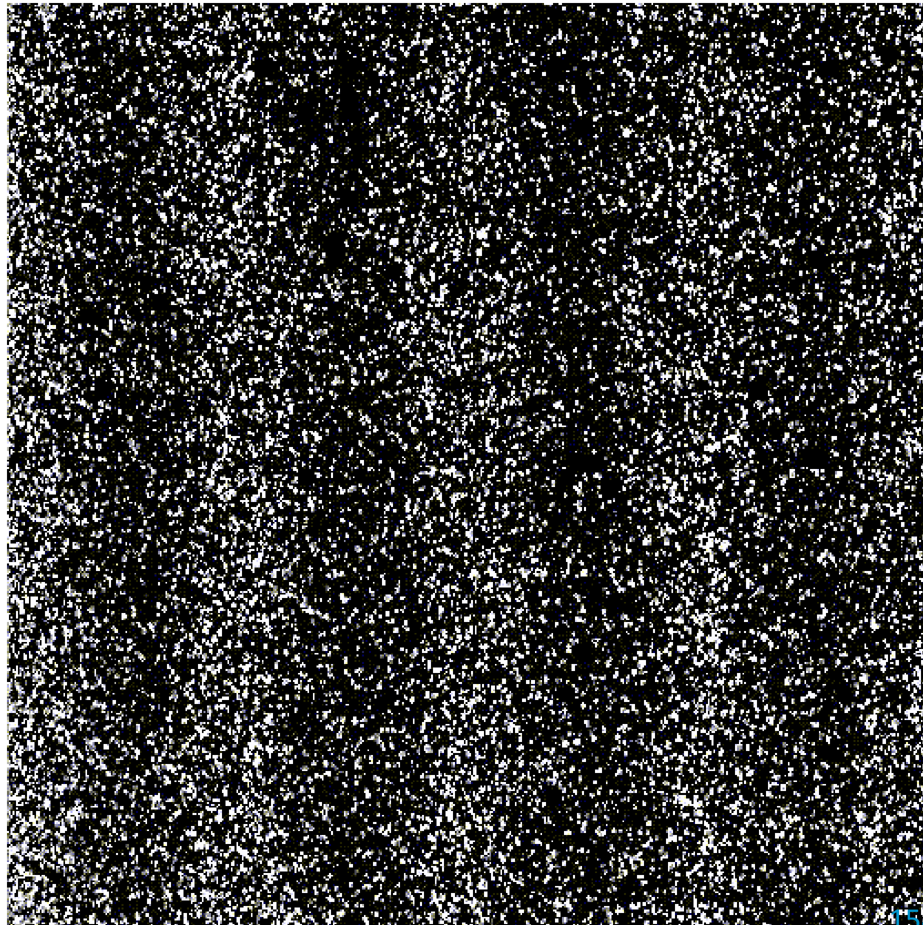
PSI: Markus Strobl, Ralph P. Harti

## SEMSANS

- Modulation successful: White beam

**and ToF mode**



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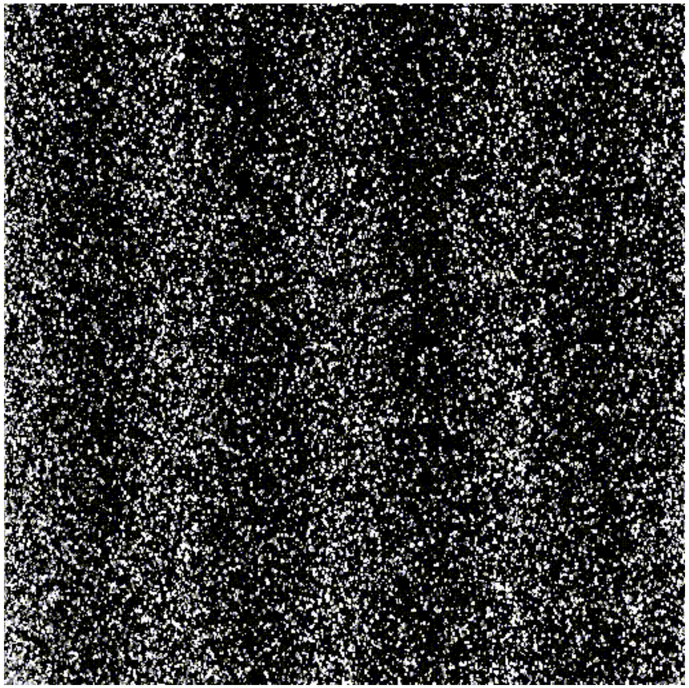
PSI: Markus Strobl, Ralph P. Harti

# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods **Modulation**

### 1st setup: Triangular

### 2nd setup: RF



**Modulation periods:** $\zeta = \pi \tan\theta_0 / (c\lambda(B_2 - B_1))$

**SE lengths:** $\delta^{SE} = c\lambda^2 L_s (B_2 - B_1)/(\pi \tan\theta_0) = \lambda L_s/\zeta$

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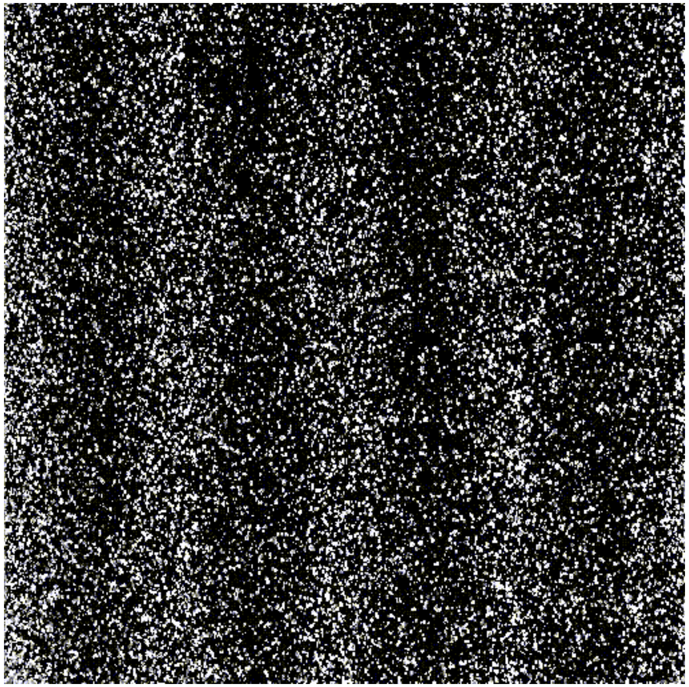
# Part 3: ToF Imaging methods **Modulation**

## 1st setup: Triangular

## 2nd setup: RF



**Modulation periods:** $\zeta = \pi \tan \theta_0 / (c\lambda (B_2 - B_1))$

- limited by the maximum field we could reach.

**SE lengths:** $\delta^{SE} = c\lambda^2 L_s (B_2 - B_1)/(\pi \tan \theta_0) = \lambda L_s / \zeta$

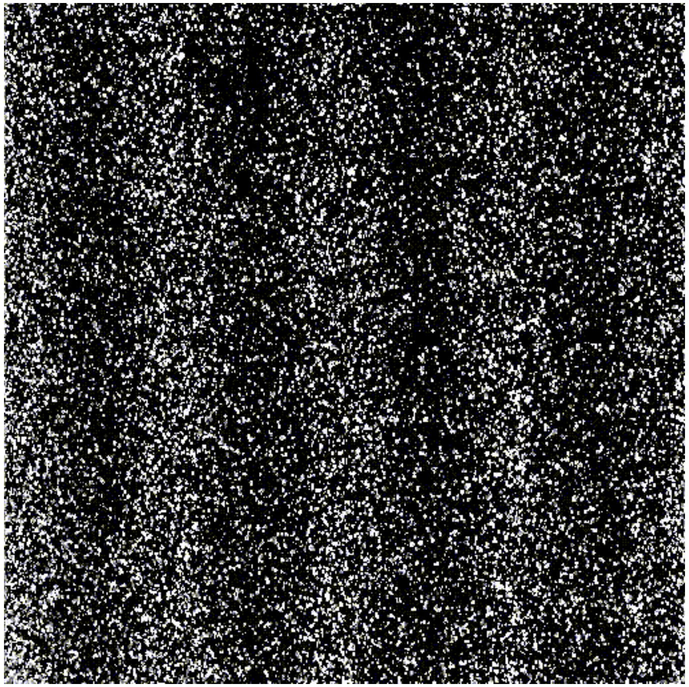
- S-D distance large (50-100cm) to get ~10-**150nm**

# Wavelength selective imaging 2 - ToF

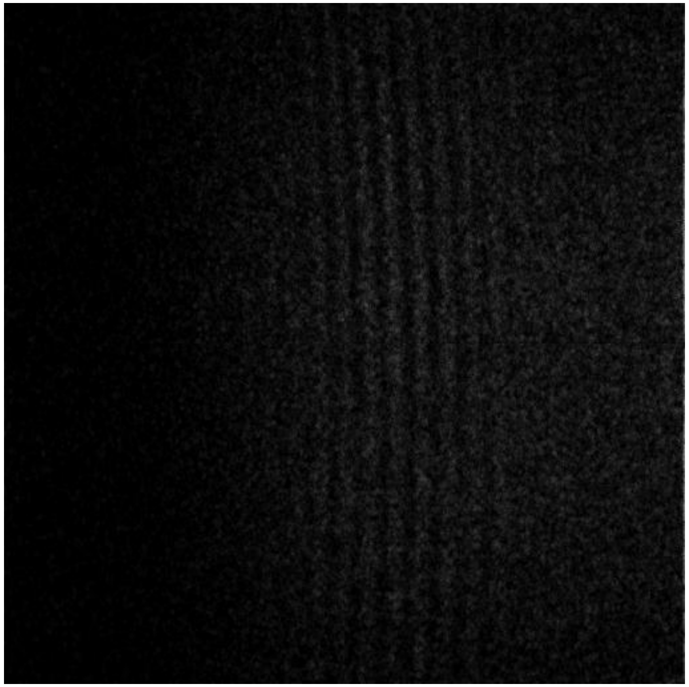
## Part 3: ToF Imaging methods **Modulation**

EUROPEAN SPALLATION SOURCE

### 1st setup: Triangular



### 2nd setup: RF



**Modulation periods:** $\zeta = \pi \tan\theta_0 / (c\lambda(B_2 - B_1))$

- limited by the maximum field we could reach
- limited by the detector resolution

**SE lengths:** $\delta^{SE} = c\lambda^2 L_s (B_2 - B_1)/(\pi \tan\theta_0) = \lambda L_s/\zeta$

- S-D distance large (50-100cm) to get ~10-**150nm**
- S-D of 20cm is reasonable to get **~400nm** (at 6Å)

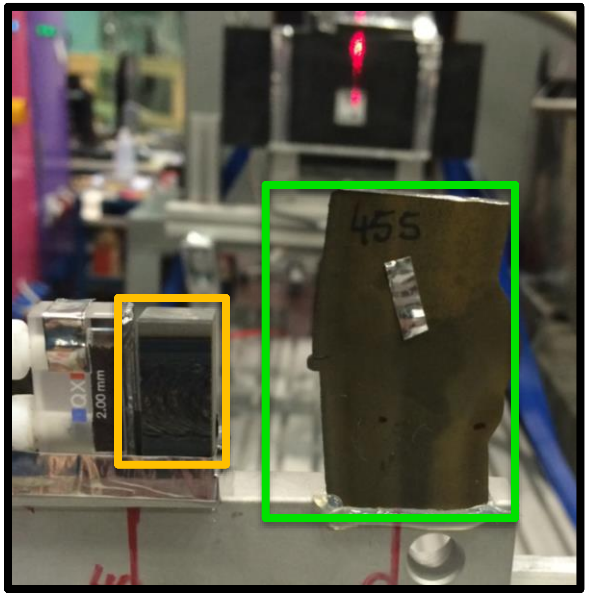
# Wavelength selective imaging 2 - ToF

## Part 3: ToF Imaging methods **Modulation**

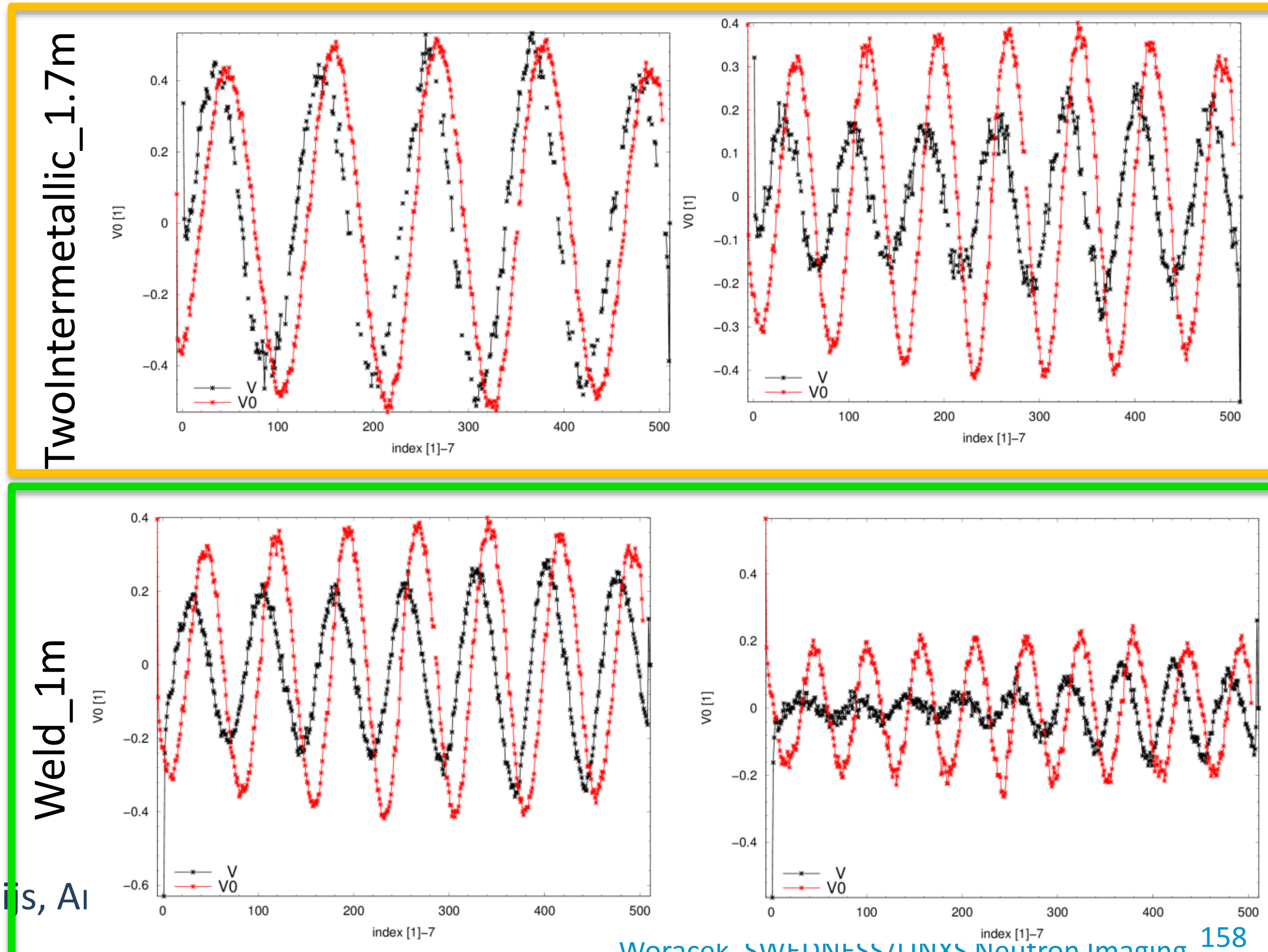
## SEMSANS

- Local differences are visible

Example: raw data




Lambda 1 Lambda 2

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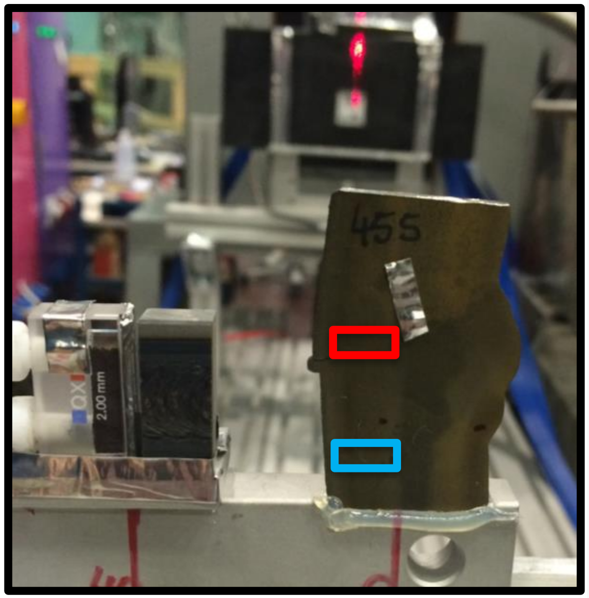
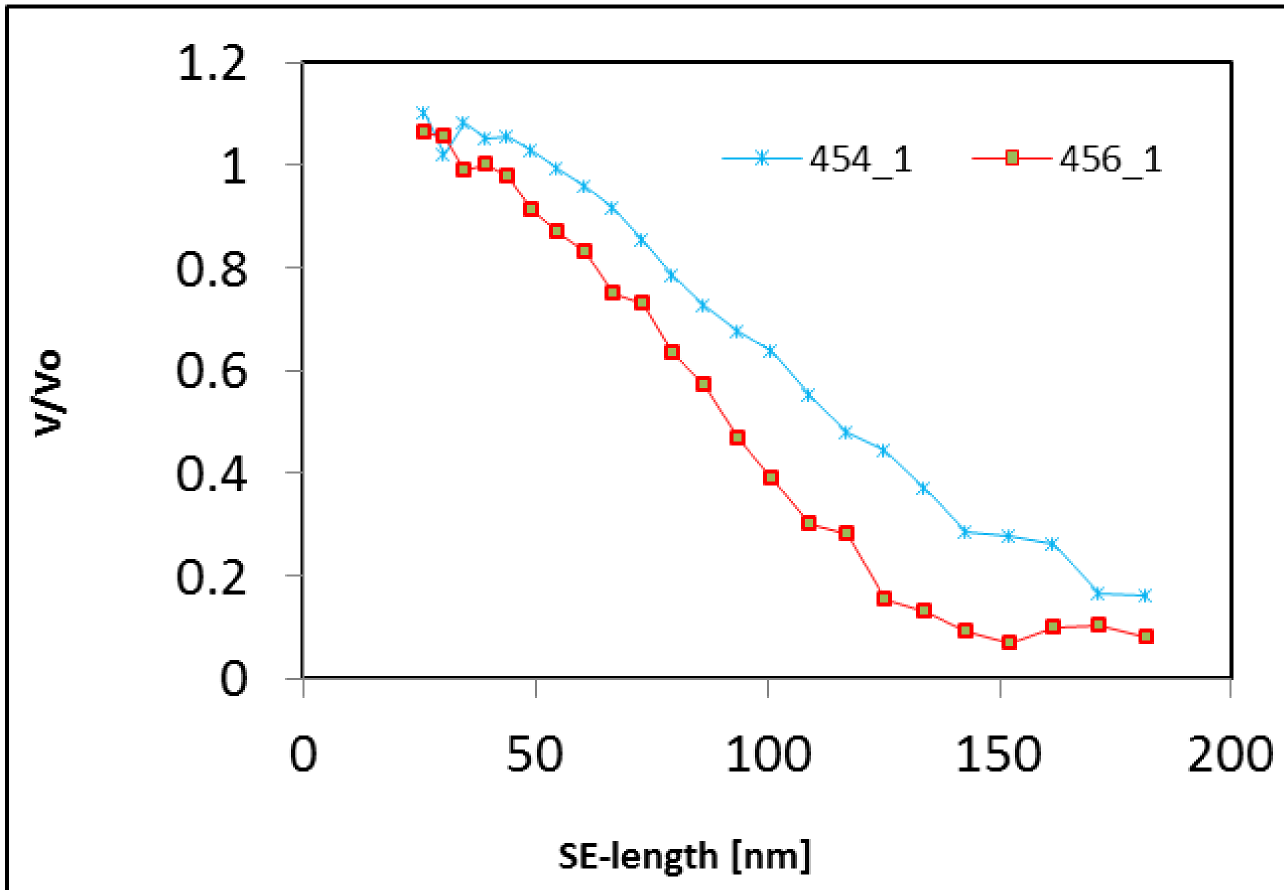
## SEMSANS

- Local differences are visible

Example: first results

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PSI: Markus Strobl, Ralph P. Harti

What we can do now:

| | | |
|---|---|---|
| Phase | Radiography & Tomography | non-textured samples |
| Texture (qual.) | Radiography | textured samples |
| Strain | Radiography | (non-)textured samples |

# Diffractive Imaging

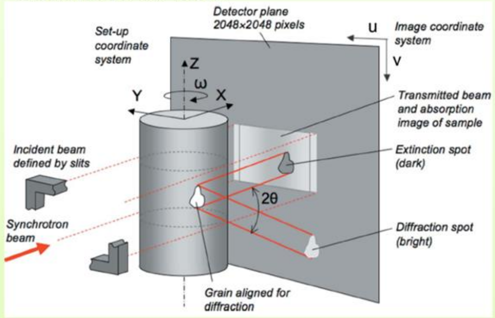
EUROPEAN SPALLATION SOURCE

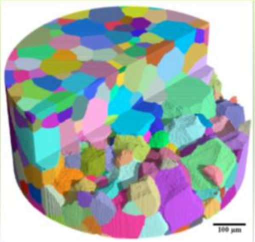
## What we **want to do**:

| | | |
|---|---|---|
| Phase | Radiography & Tomography | textured samples **textured samples** |
| Texture (**quan.**)) | Radiography **& Tomography** | textured samples |
| Strain | Radiography **& Tomography** | (non-)textured samples **textured samples** |

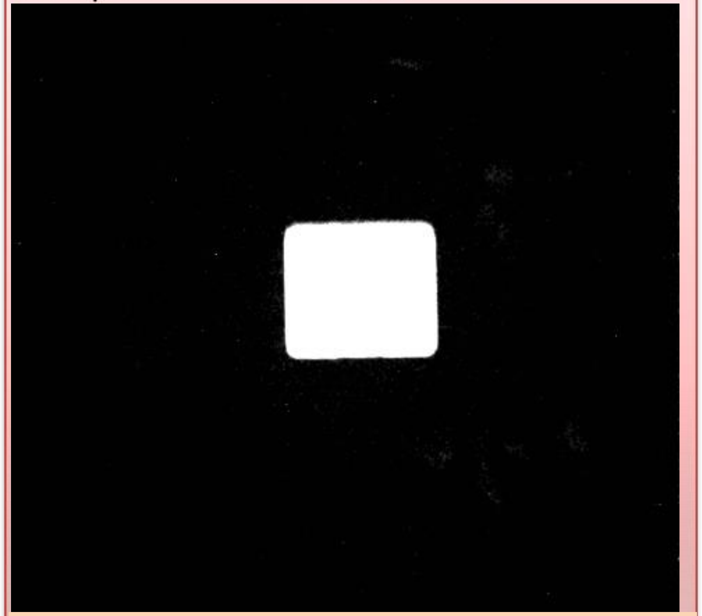
## How to do it? **Combined Imaging & Diffraction**

**From W. Ludwig et al.:** Experimental Setup and 3-D grain orientation map obtained at ESRF

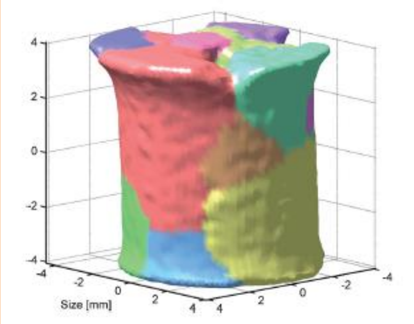


Example Neutron-DCT data obtained at HZB



R. Woracek, N. Kardjilov, W. Ludwig, unpublished

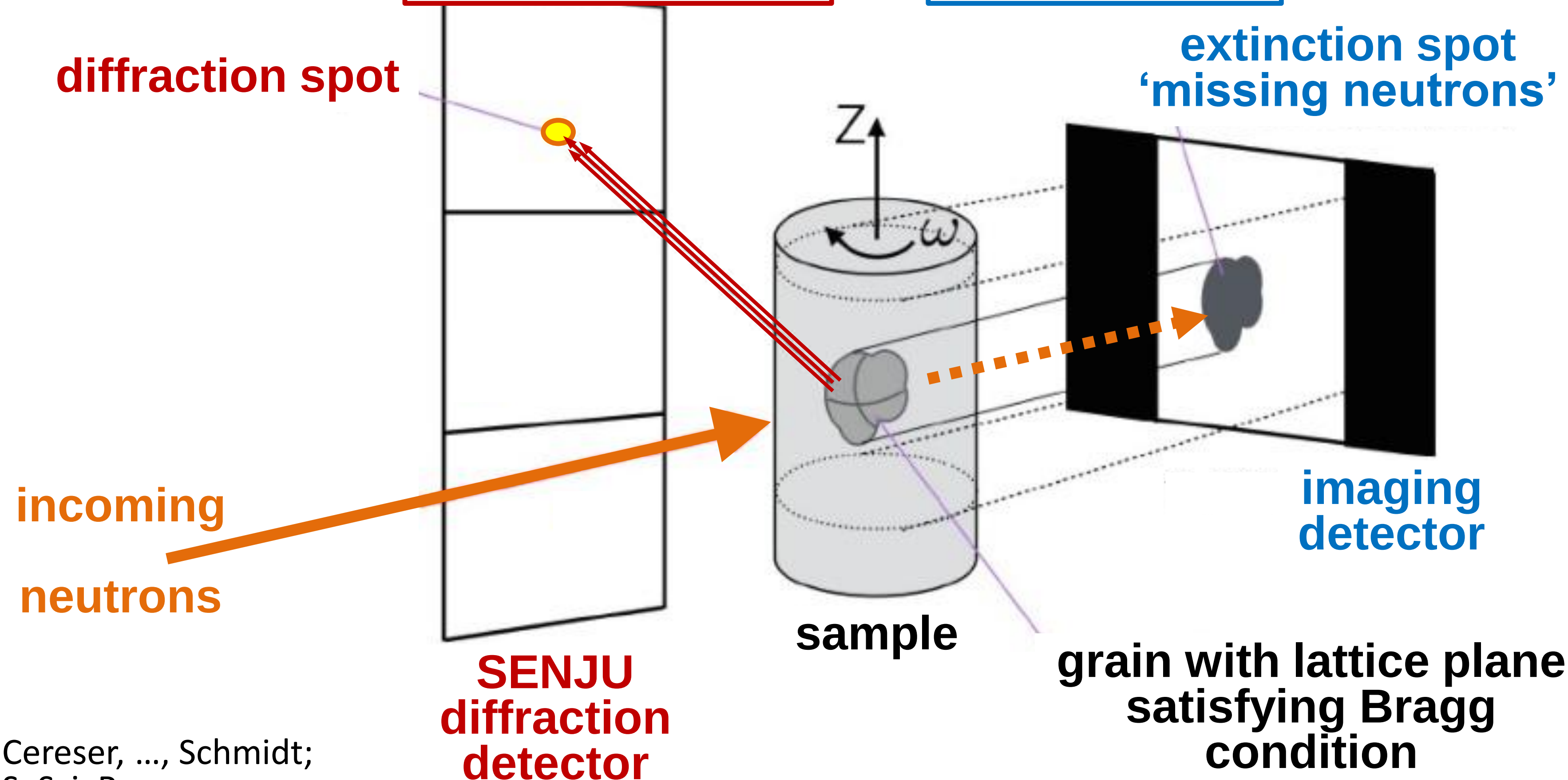



S. Peetermans, A. King, W. Ludwig, P. Reischig, E. Lehmann, **Cold neutron diffraction contrast tomography of polycrystalline material**. *Analyst* 139, (2014).

EUROPEAN SPALLATION SOURCE

## 3 Dimensional Neutron Diffraction (3DND)

**Grain Orientation** & **Grain Shape**




Cereser, …, Schmidt;
S. Sci. Rep.,
2017, 7, 9561.

## 3DND *in situ* Deformation at SENJU @ J-PARC

↓

**Multicrystalline CuAlMnZn Shape Memory Alloy (mm grains)**

↓

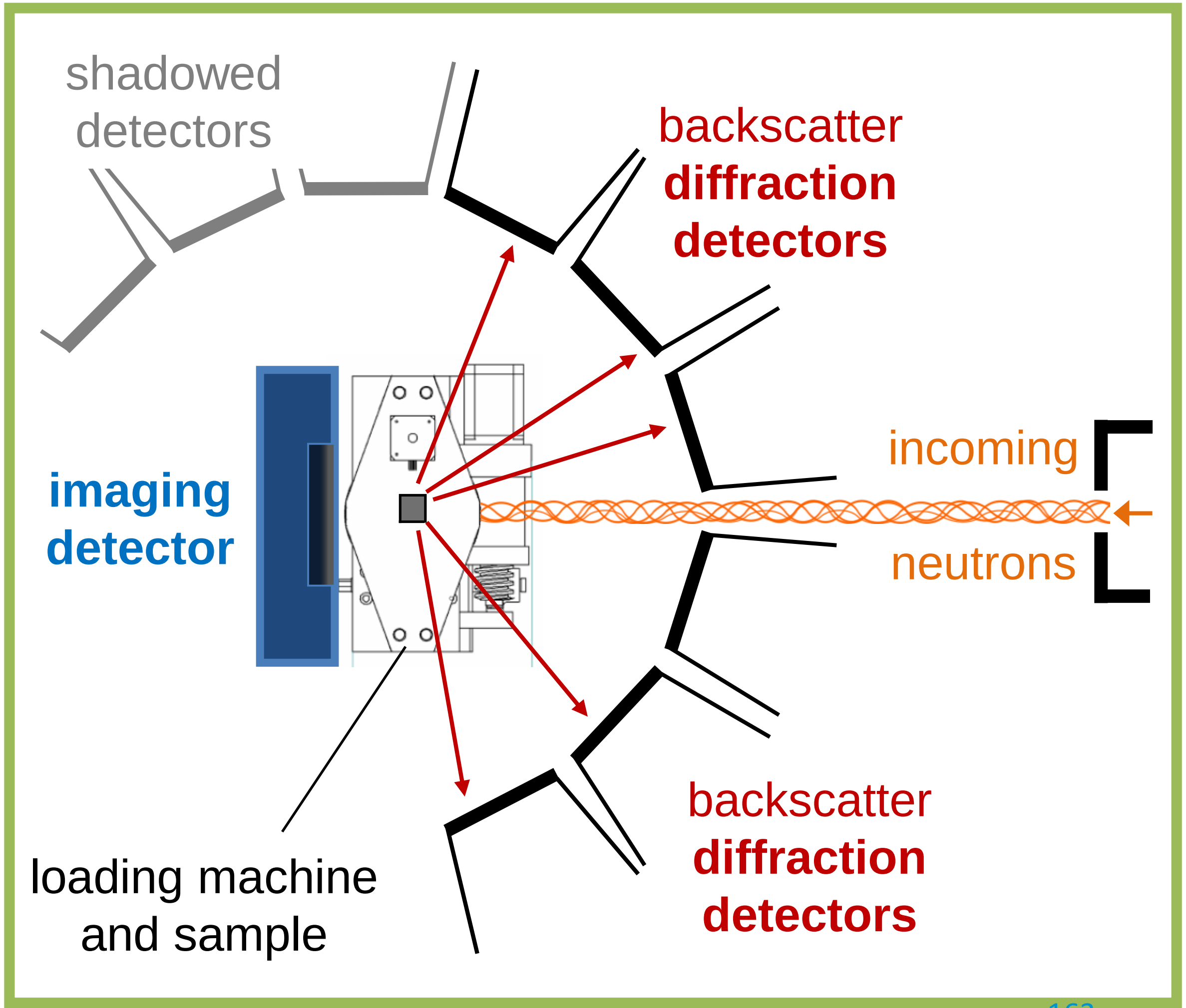
**Tomography**
**+**
**Diffraction**

↓

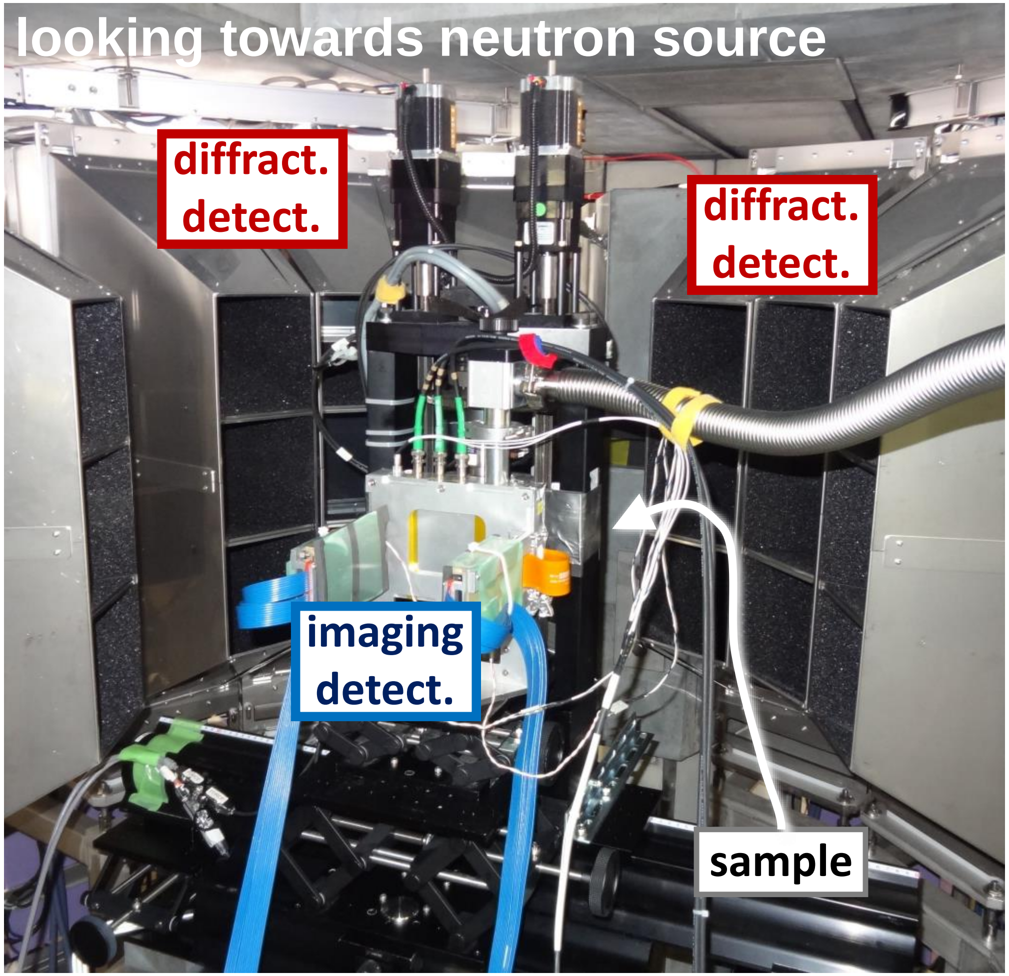
- **Grain Shape**
- **Grain Orientation**
- **Austenite/Martensite**

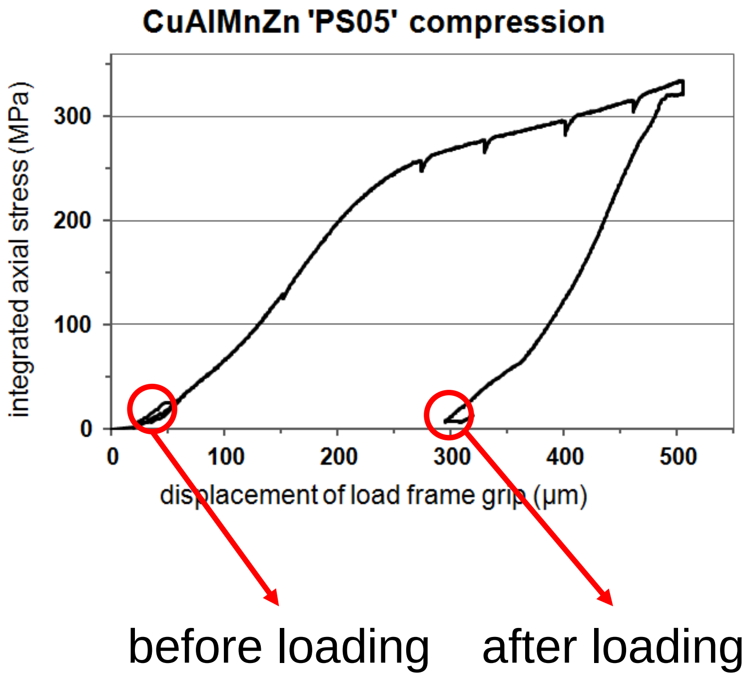
→ **Grain Interactions**

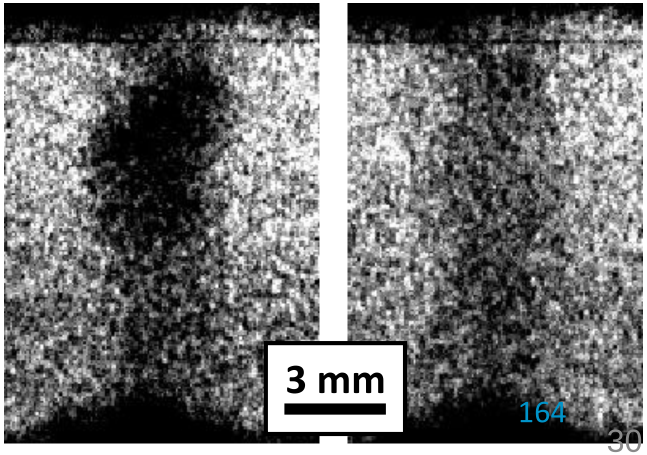
**Top View**



## 3DND *in situ* Deformation

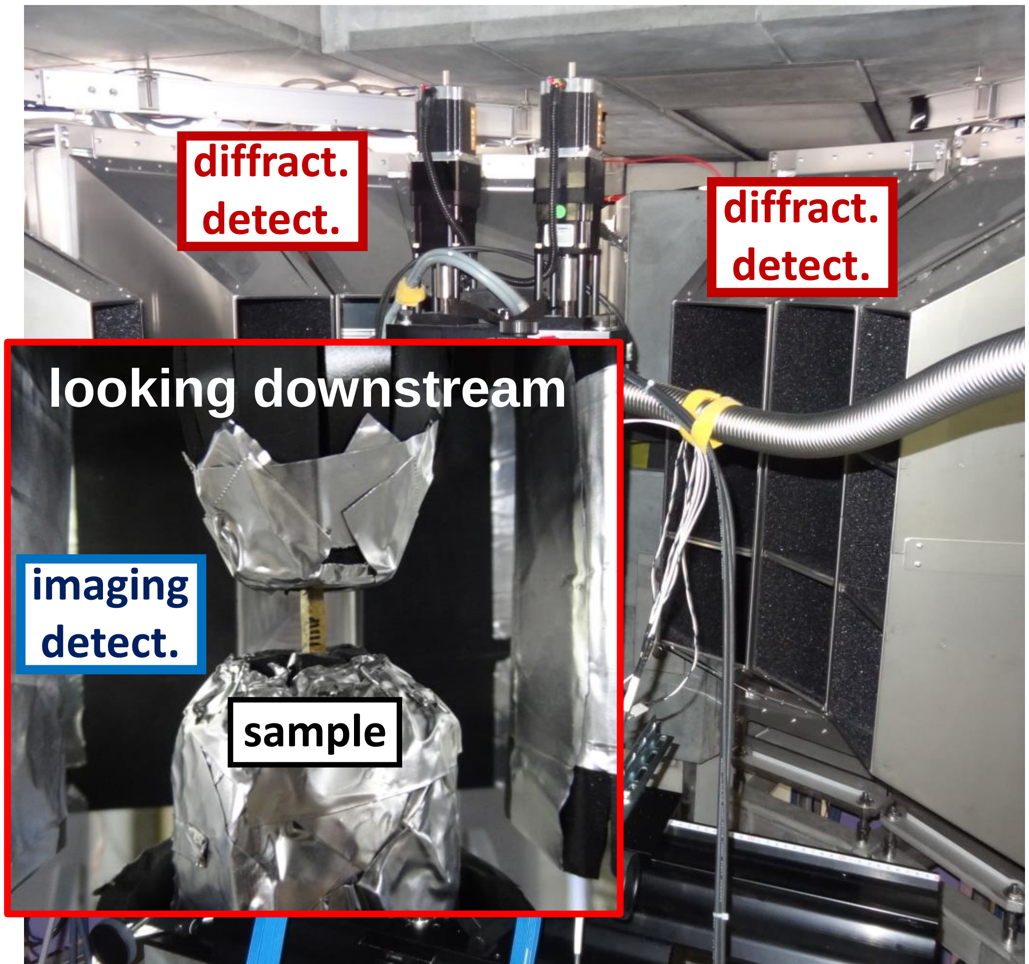


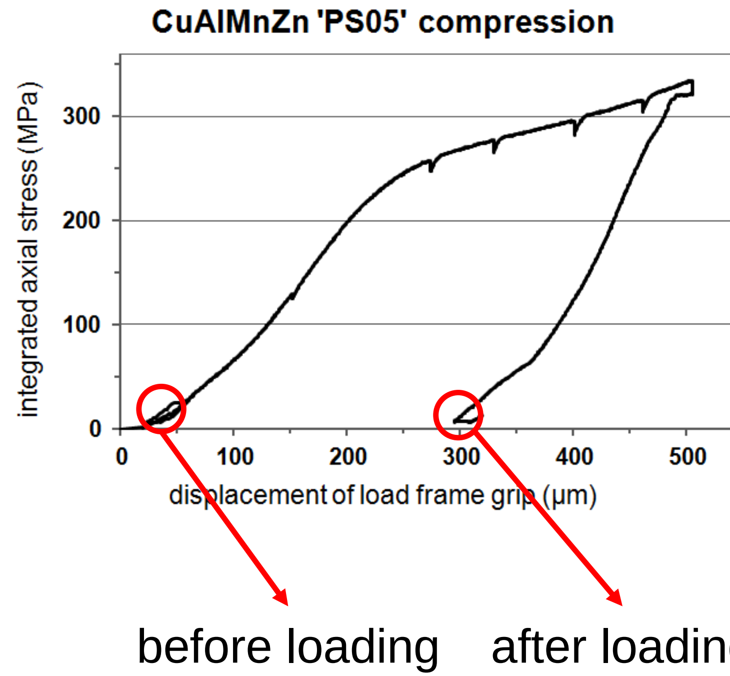



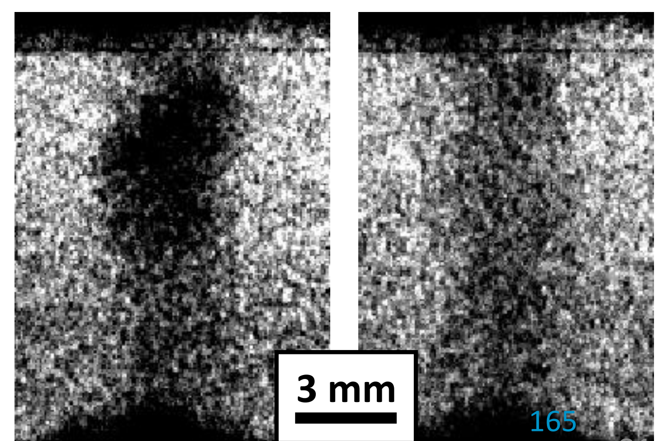



# Diffractive Imaging

## 3DND *in situ* Deformation

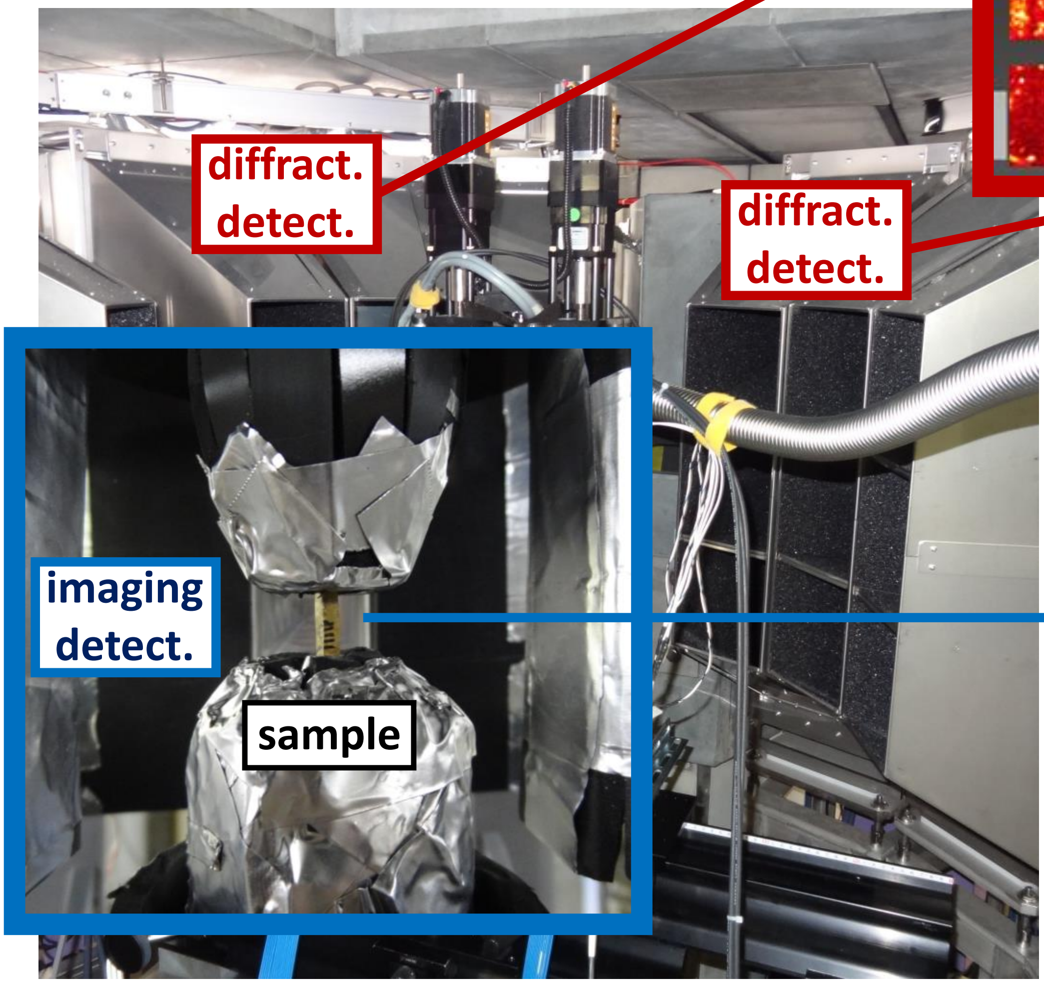


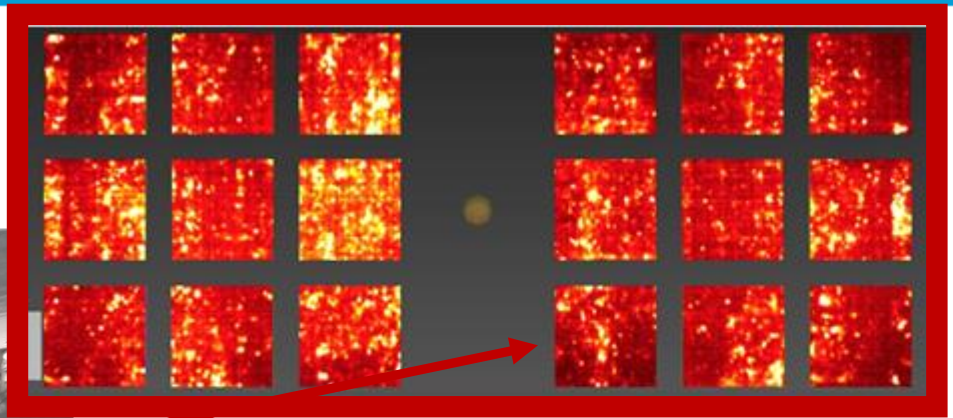



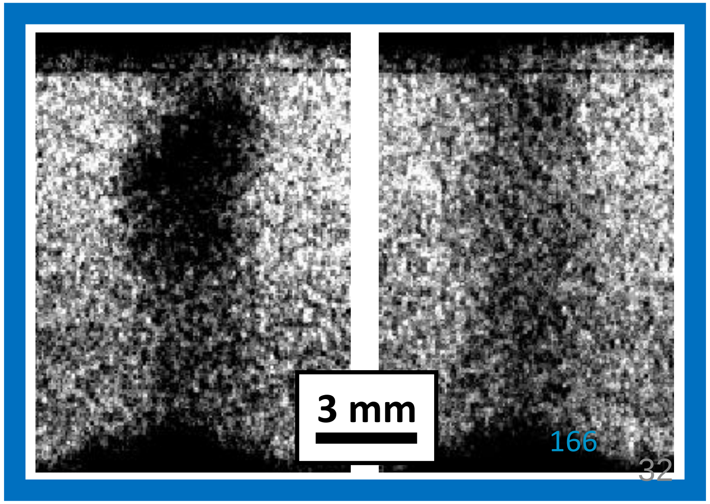
# Diffractive Imaging

## 3DND *in situ* Deformation



**3D representation of crystalline microstructure with austenite and martensite**



# Wavelength selective imaging 2 - ToF

## AGENDA

- **Part 1: Introduction to ToF imaging**
    - Basics (neutron energy, wavelength, velocity)
    - The ToF concept
    - ToF vs steady state instruments
- **Part 2: What do we need for a ToF neutron imaging instrument?**
    - ToF Neutron Source
    - Examples of of ToF imaging beamlines
    - ToF Detectors
- **Part 3: ToF Imaging methods**
    - The bigger picture: overview and comparison to other neutron techniques
    - ‘Attenuation’: Monochromatic, ‘white-beam’ and ‘pink-beam’ (narrow wavelength) applications
    - Diffraction Contrast / Bragg edge imaging (including diffraction basics)
    - Other methods to profit from ToF: Polarized, phase and dark field, 3DND, resonance absorption
- **Part 4:** Hands on example (please install https://imagej.net/Fiji/Downloads or https://imagej.nih.gov/ij/download.html)

# THANK YOU!