SWEDNESS/LINXS Doctoral-level course on neutron imaging

Tuesday, 18 May 2021

Neutron imaging beamlines and systems

- past, present, future

ROBIN.WORACEK@ESS.EU

Neutron imaging beamlines

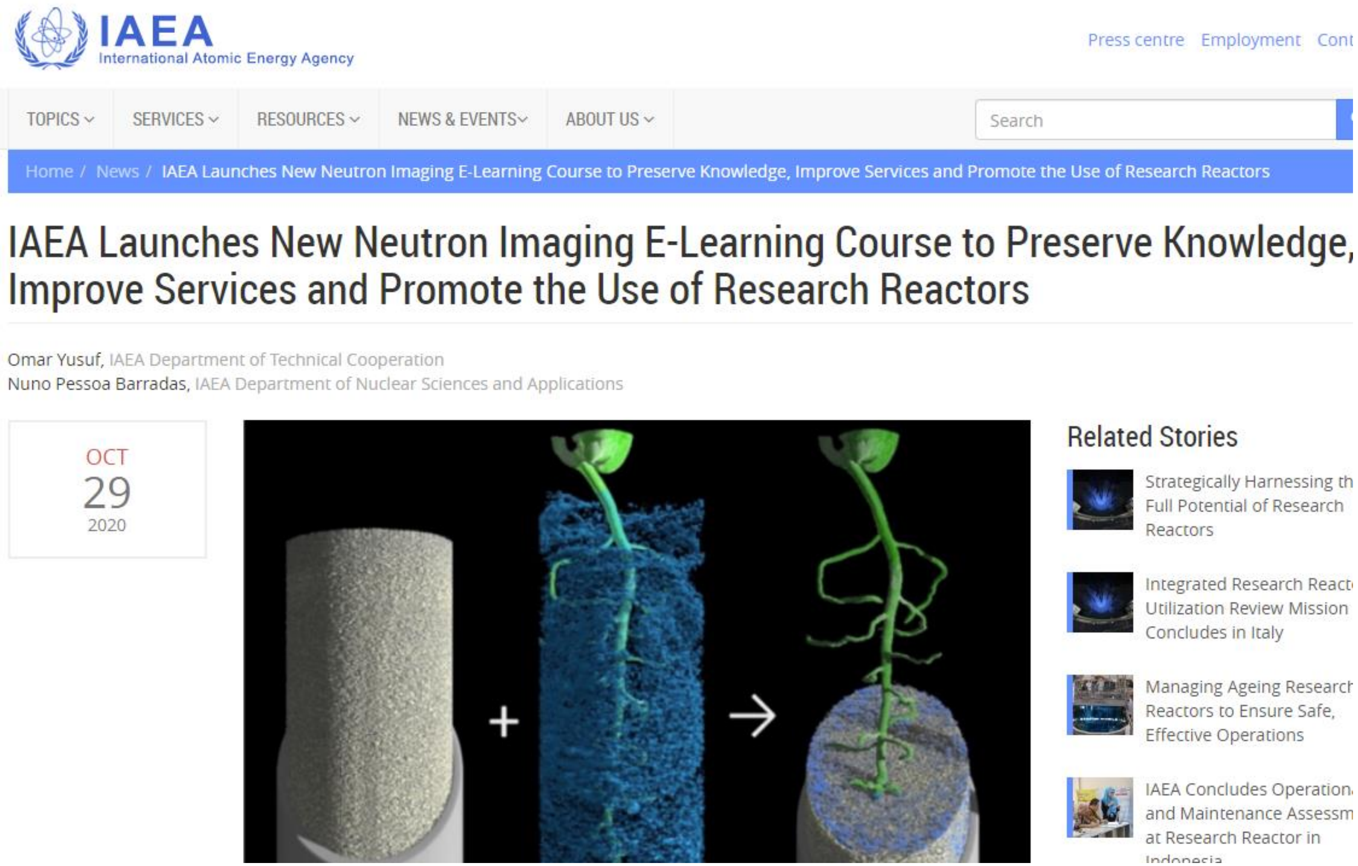
- ❑ Historic developments and a generic imaging instrument
- ❑ Neutron Sources
- ❑ ToF vs steady state instruments
- ❑ Neutron Spectrum
- ❑ Instrumentation: Neutron Transport
- ❑ Instrumentation: Beam conditioning
- ❑ Instrumentation: Neutron Detectors
- ❑ Some example Instruments

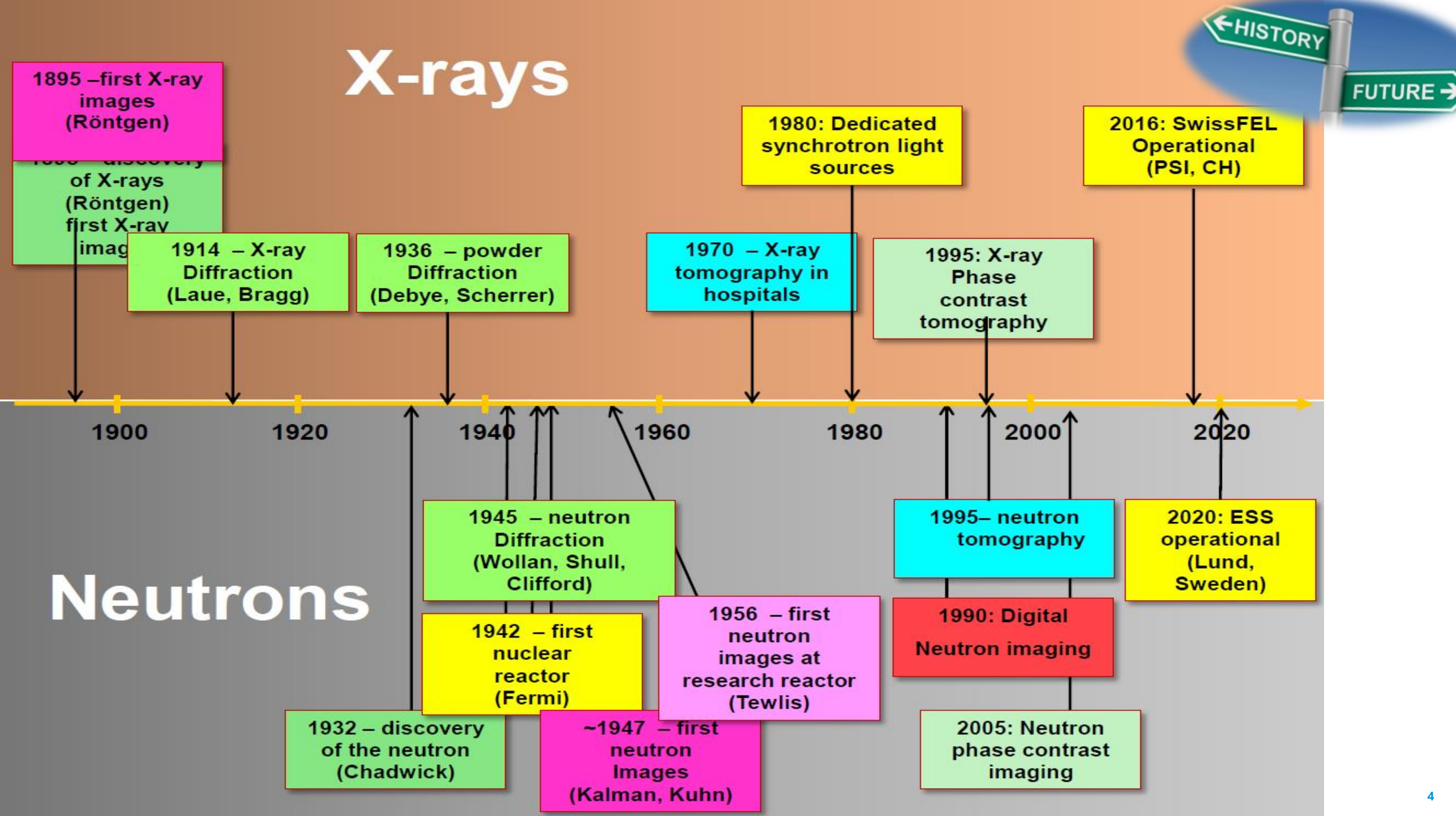
Source Material for this lecture

International Society for Neutron Radiography Established 1996

https://www.isnr.de/

International Society for Neutron Radiography (ISNR)

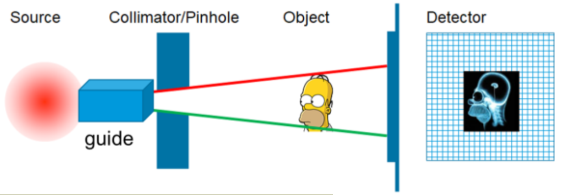


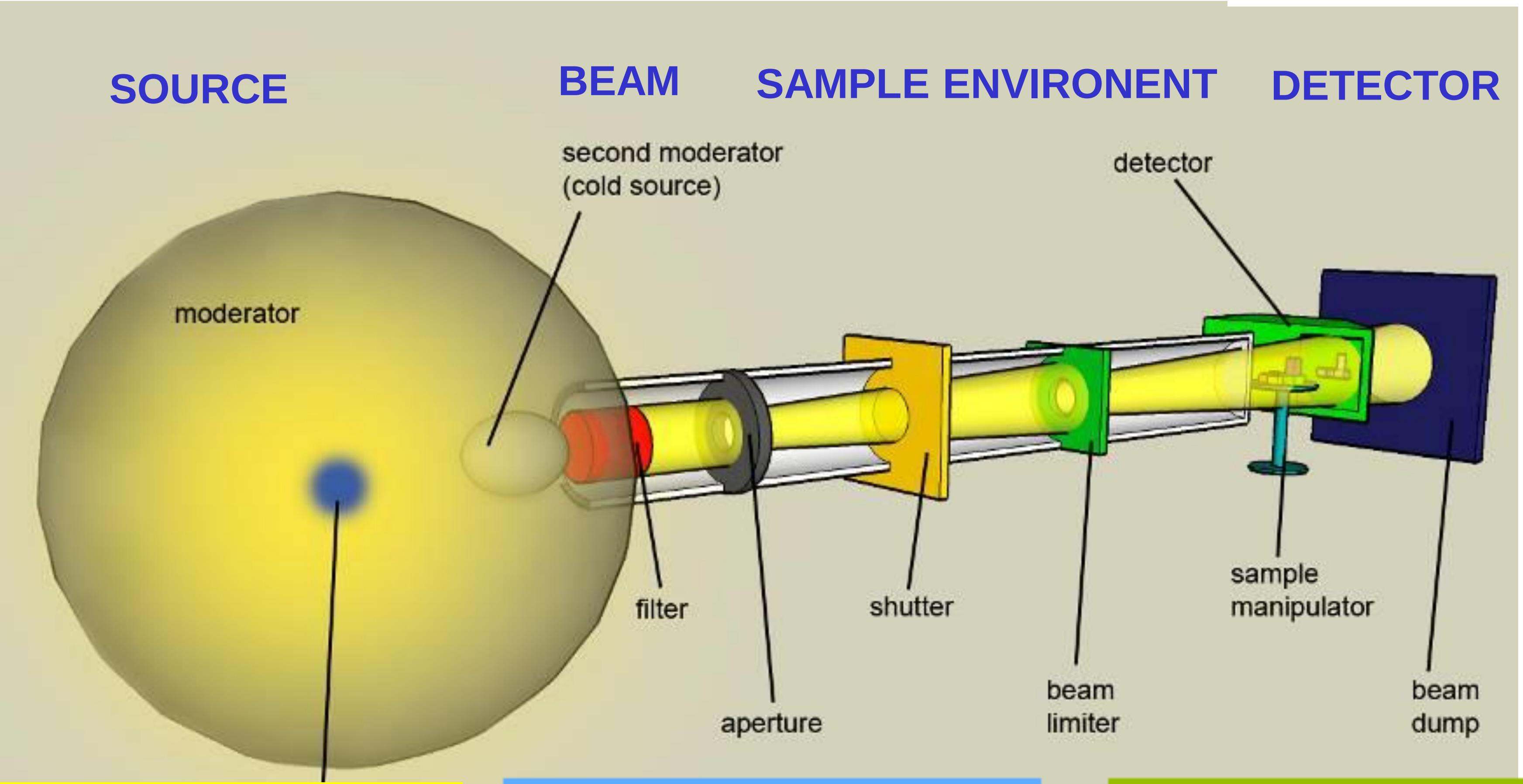

X-rays
HISTORY
FUTURE
1895 –first X-ray images (Röntgen)
of X-rays
(Röntgen)
first X-ray
1914 – X-ray Diffraction (Laue, Bragg)
1936 – powder Diffraction (Debye, Scherrer)
1970 – X-ray tomography in hospitals
1980: Dedicated synchrotron light sources
1995: X-ray Phase contrast tomography
2016: SwissFEL Operational (PSI, CH)
1900
1920
1940
1960
1980
2000
2020
Neutrons
1932 – discovery of the neutron (Chadwick)
1942 – first nuclear reactor (Fermi)
1945 – neutron Diffraction (Wollan, Shull, Clifford)
~1947 – first neutron Images (Kalman, Kuhn)
1956 – first neutron images at research reactor (Tewlis)
1990: Digital Neutron imaging
1995– neutron tomography
2005: Neutron phase contrast imaging
2020: ESS operational (Lund, Sweden)

Neutron imaging beamlines

- free neutrons were discovered 37 years after the X-rays were found
- neutron imaging started 50 years after first X-ray images were made
- neutron diffraction comes 30 years later than X-ray diffraction
- neutron tomography comes 25 years later than X-ray tomography in hospitals
- phase contrast imaging with neutrons comes 10 years later than with X-rays
- neutron imaging is now a competitive and complementary method to state of the art X-ray techniques

A generic neutron imaging instrument





safety requirements:
access control
shielding
dosimetry

advanced components:
E-selector
polarizer
grating interferometer

data treatment:
computers
software, analysis tools
process control

Neutron imaging beamlines

- ❑ Historic developments and a generic imaging instrument
- ❑ Neutron Sources
- ❑ ToF vs steady state instruments
- ❑ Neutron Spectrum
- ❑ Instrumentation: Neutron Transport
- ❑ Instrumentation: Beam conditioning
- ❑ Instrumentation: Neutron Detectors
- ❑ Some example Instruments

Neutron Sources

- Research reactors (ILL, FRM II, HFIR, BNC, ...)
- Spallation sources (ISIS, SINQ, SNS, ESS...)
- Radioactive nuclides (Cf, Ra-Be, Sb-Be)
- Accelerator sources (D-D, D-T reactions)

Neutron Sources

- 15 orders of magnitude in energy variation:

- high energy neutrons (E > 100 MeV)
- fast neutrons (from fission process): E ~ 1 MeV
- epithermal neutrons: E > 0.4 eV
- thermal neutrons: E ~ 25 meV
- cold neutrons: E ~ 4 meV
- ultra-cold neutrons: E ~ 100 neV

- Definitions for some of these energy regions vary in literature.

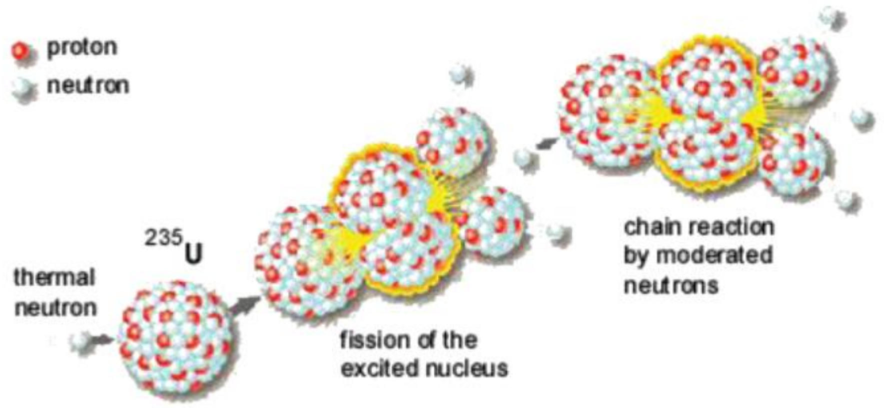
Neutron Sources

Properties of neutron sources for imaging purpose

Source type	*nuclear reactor*	*neutron generator*	*spallation source*	*radio isotope*
Reaction	fission	D-T fusion	spallation by protons	gamma-n-reaction
used material	U-235	deuterium, tritium	high mass nuclides	Sb, Be
neutron generation rate, [neutrons/s]	1,00E+16	4,00E+11	1,00E+15	1,00E+08
beam flux [n/cm2 s]	10^6 to 10^9	10^5	10^6 to 10^8	10^3
neutron energy	fast, thermal and cold	fast, thermal	fast, thermal and cold	24 keV, thermal
limitation of use	burn up	life time tube	target life time	half life Sb-124
typical operation cycle	1 month	1000 h	1 year	0,5 year
costs of the facility	high	medium	very high	low

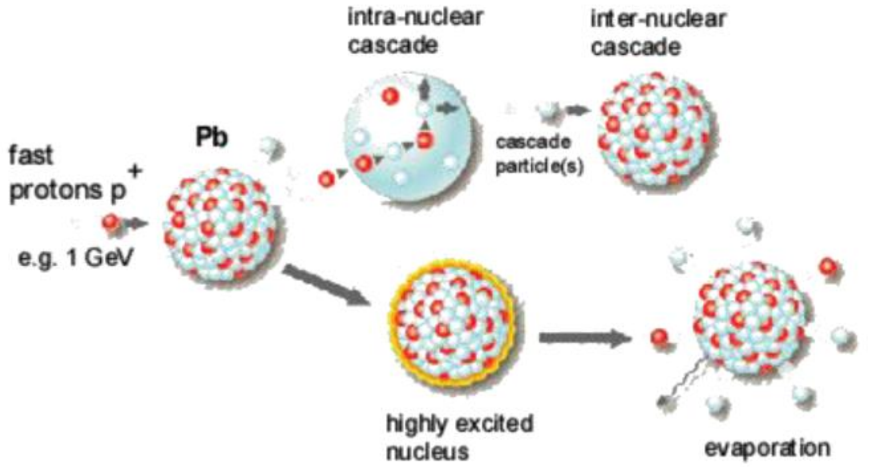
Neutron Sources

How do we produce neutrons?



Fission

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



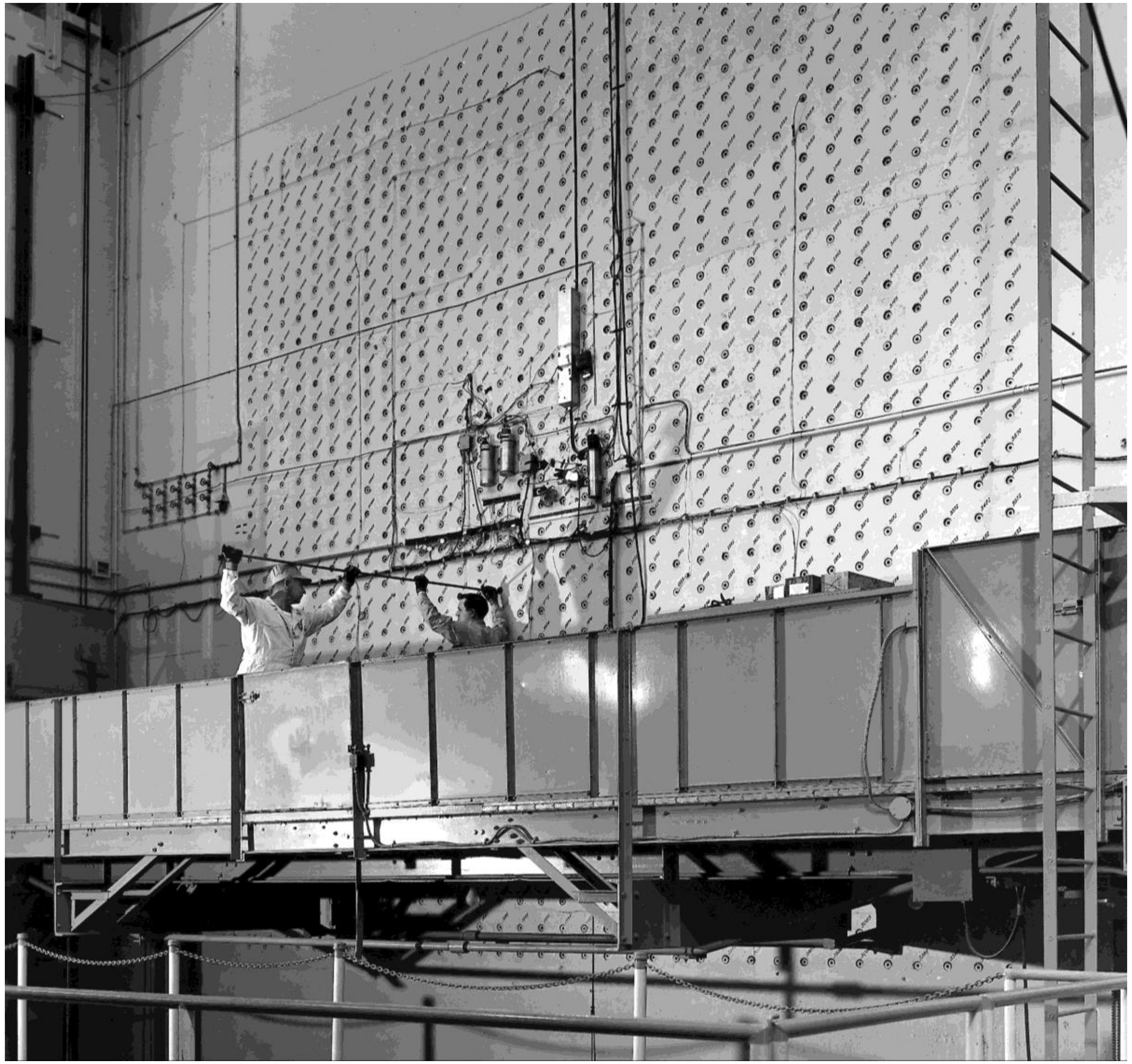
Spallation

- 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)*

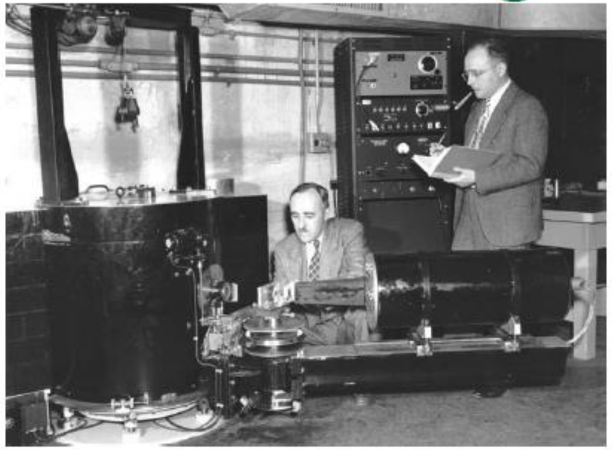
Neutron sources

The **first artificial nuclear reactor**, **Chicago Pile-1**, a graphite-moderated device that produced between 0.5 watts and 200 watts , was constructed by a team led by **Enrico Fermi in 1942**. The construction and testing of this reactor (an "atomic pile") was part of the Manhattan Project.
This work led to the construction of the **X-10 Graphite Reactor at Oak Ridge National Laboratory**, which was the first nuclear reactor designed and built for continuous operation, and began operation in 1943.



Neutron sources

Oak Ridge – has been developing neutron scattering from the beginning ....



In the 1940's Wollan and Shull
applied the ideas of x-ray diffraction
to neutrons (Oak Ridge Graphite Reactor)

The Diffraction of Neutrons by Crystalline Powders
E. O. Wollan and C. G. Shull

The Physical Review, Vol. 75 No 8, 830-841, April 15, 1948

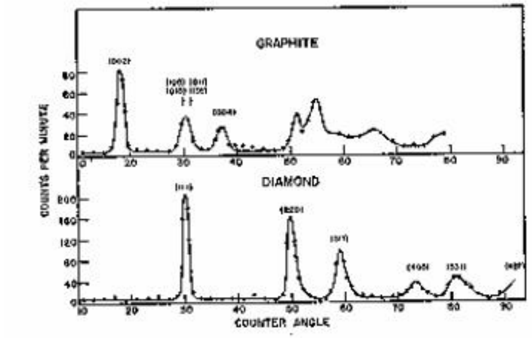
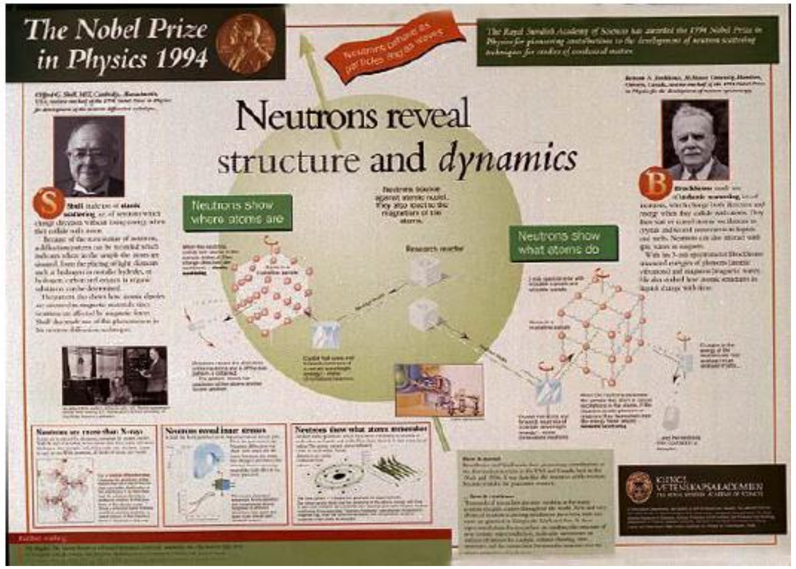


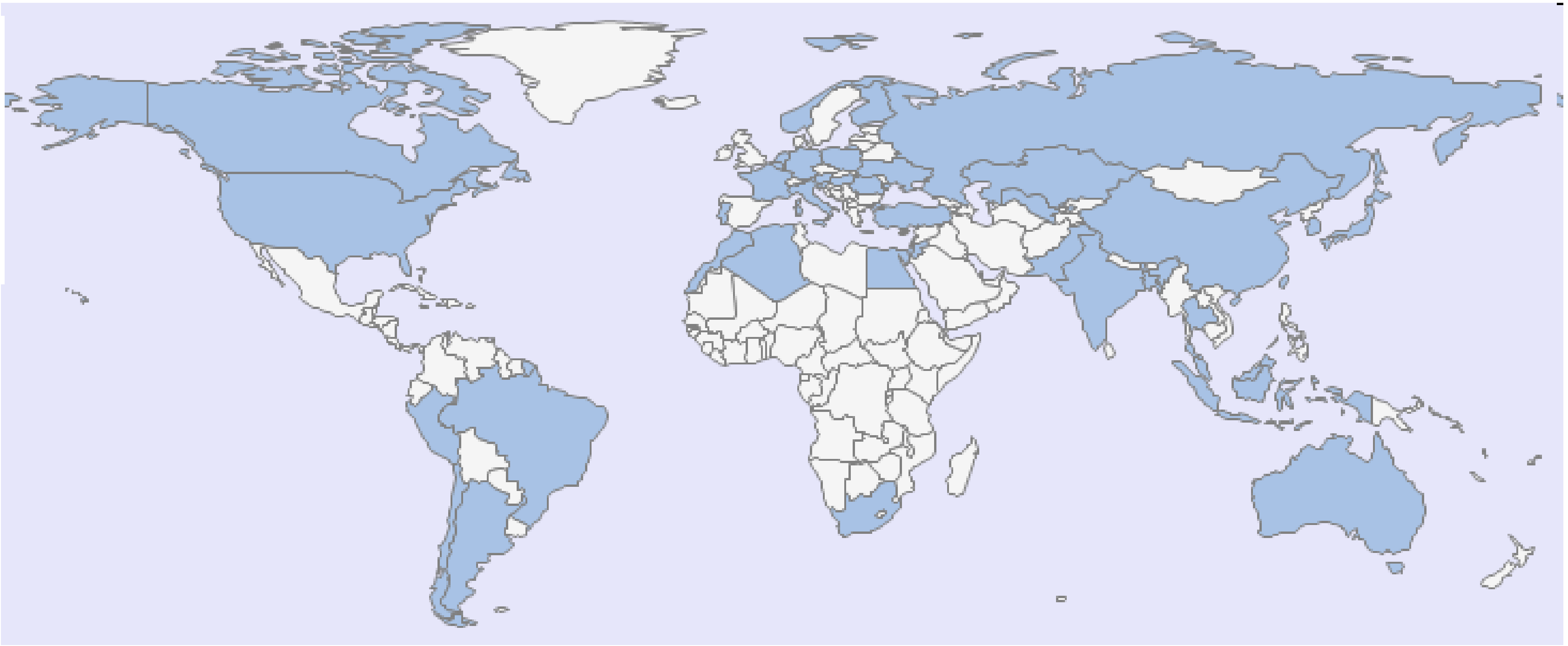
FIG. 3. Powder diffraction patterns for diamond and graphite. The major part of the diffuse scattering in these patterns arises from multiple scattering in the samples.

1994 Nobel Prize in Physics for the development of the neutron scattering technique



Neutron sources: Imaging beamlines

IAEA Research Reactor Data Base



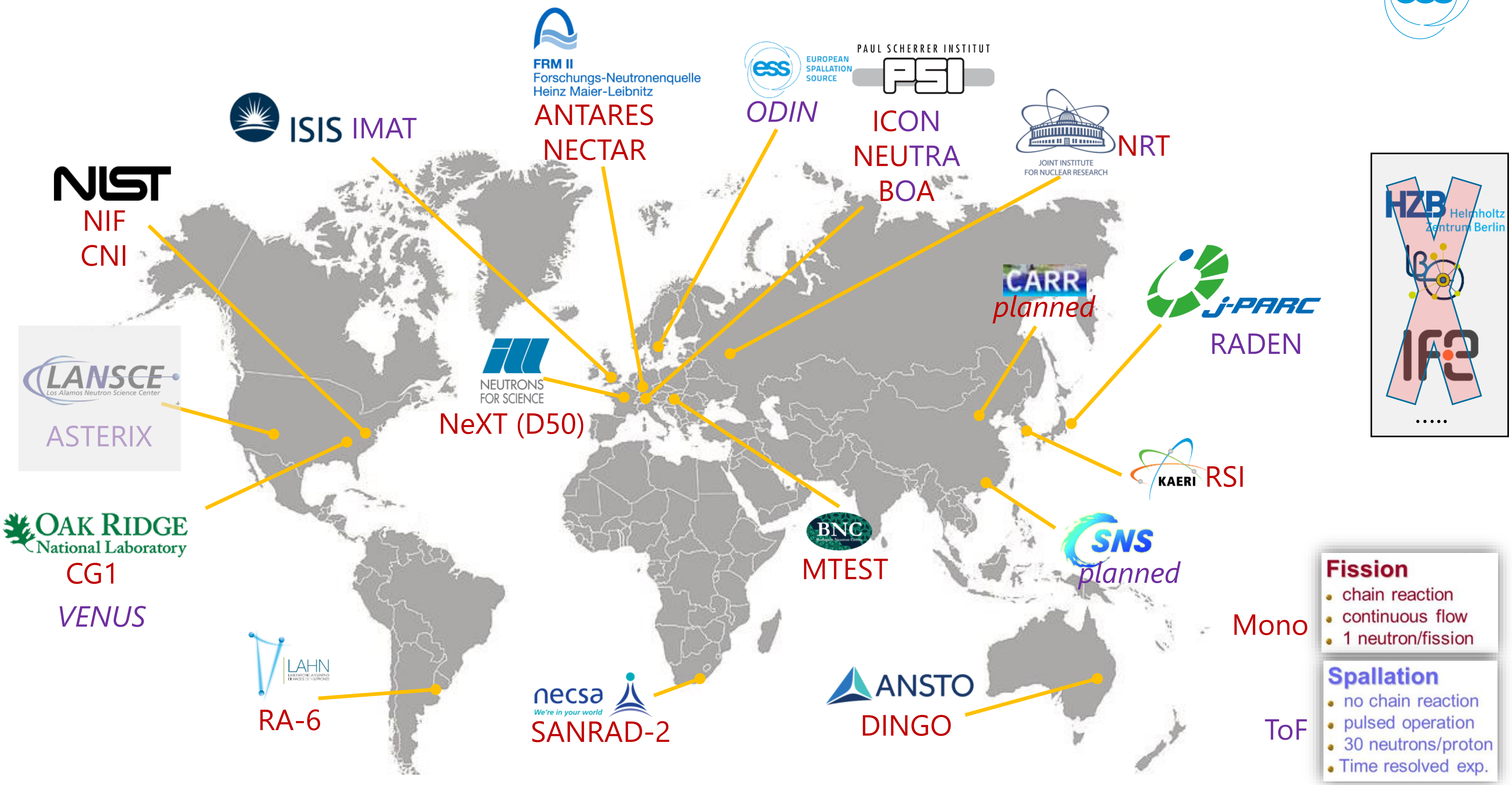
226 research reactors operational in **56** countries

188 with power > 1 kW; **110** with power > 1 MW

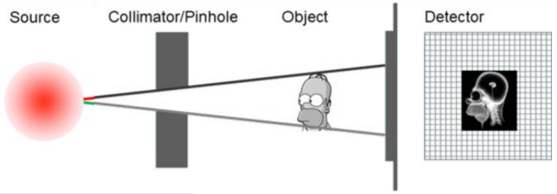
51 facilities claim to perform **neutron scattering**

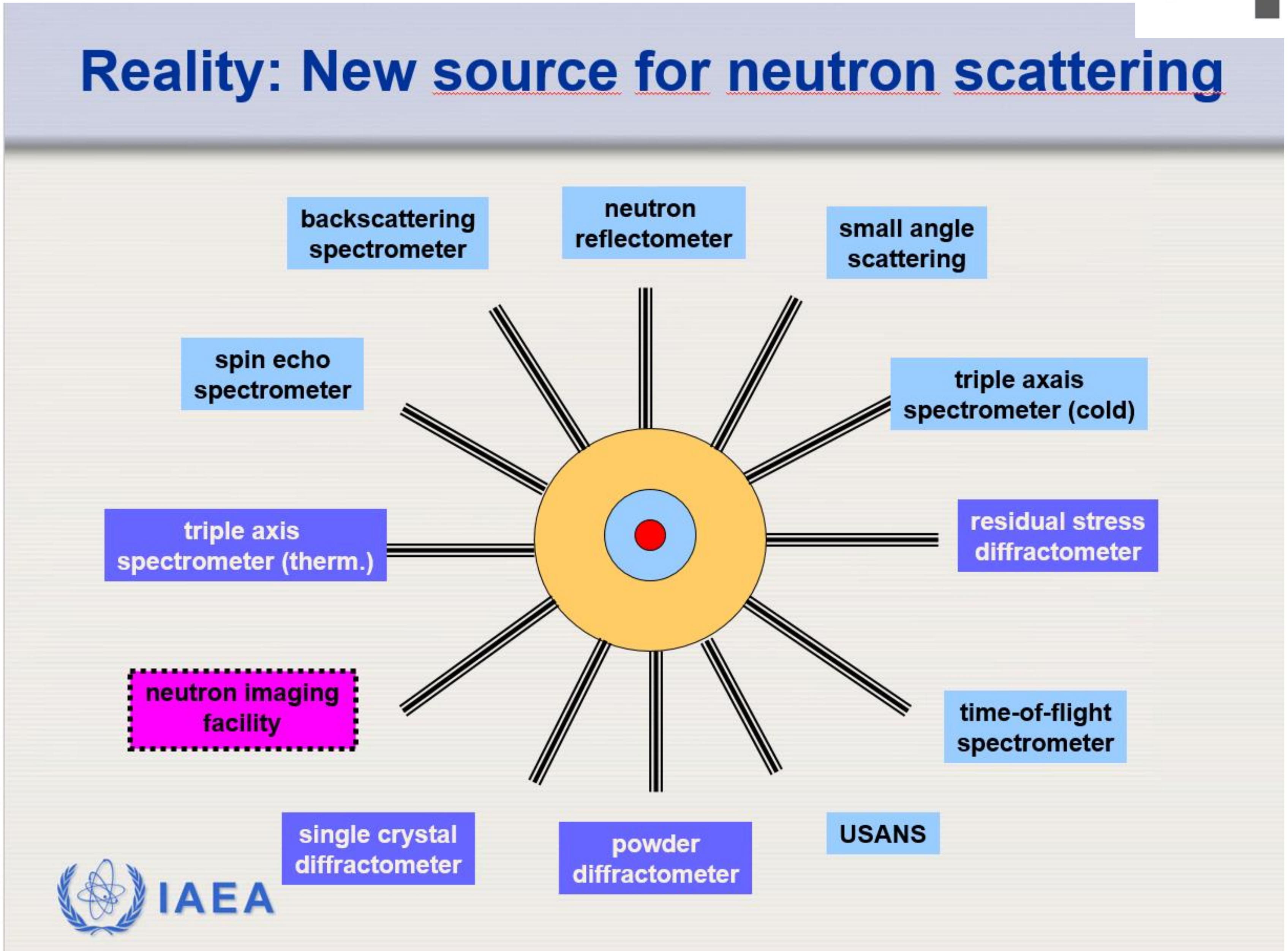
76 facilities claim to perform **neutron radiography!**

Neutron sources: Imaging beamlines

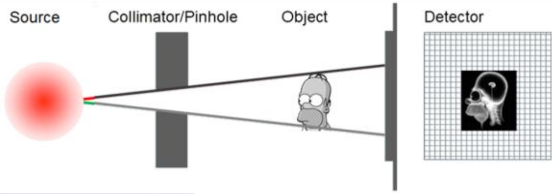


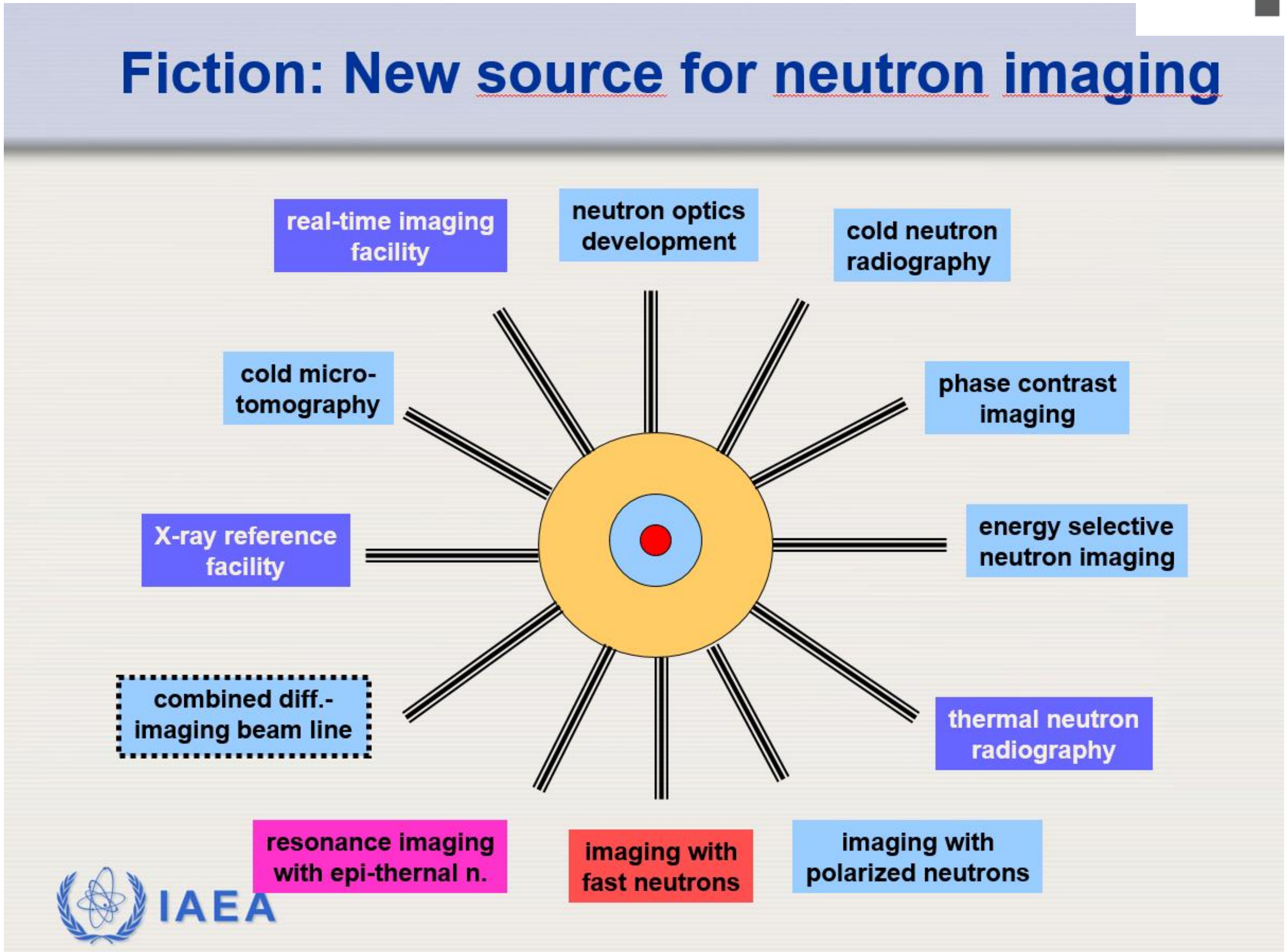
Neutron Sources



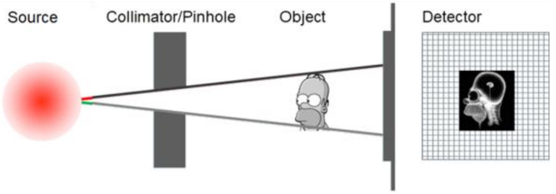


Neutron Sources

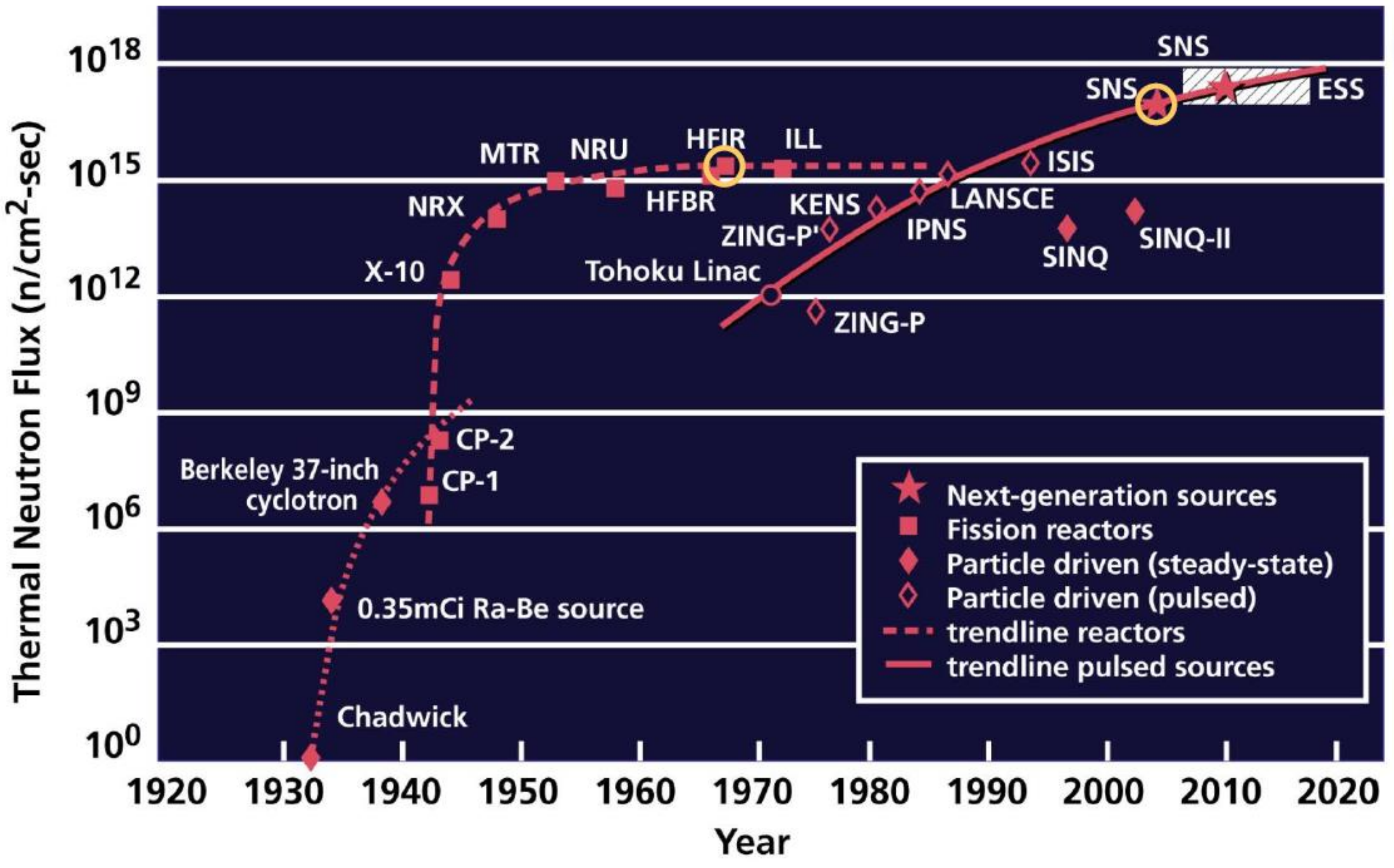




Neutron Sources



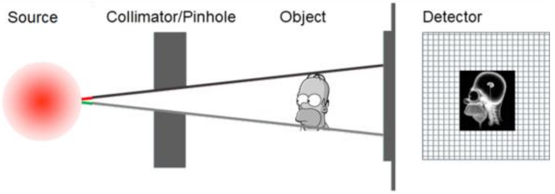
Neutron Source Trends



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

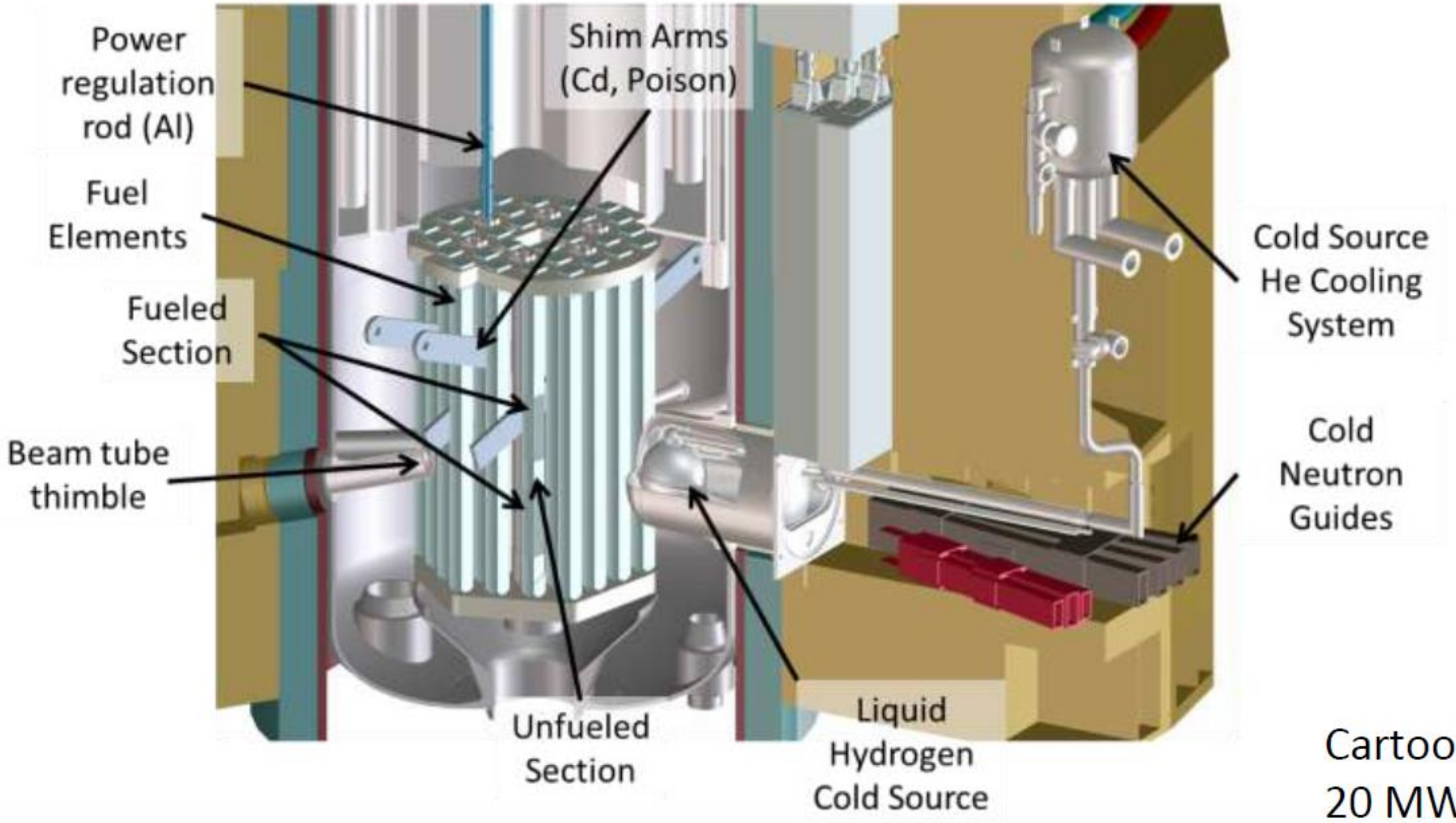
Neutron Sources

Reactor Sources



Neutron Sources: Uranium Fission Reactors

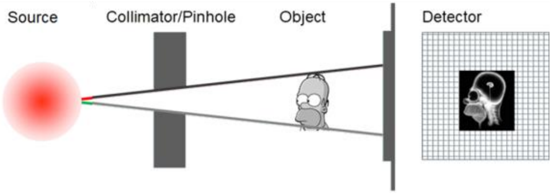
- “Large” (~10^{14} cm^{-2} s^{-1}) flux of neutrons at the core
- Continuous spectrum or one wavelength for a long time
- Generally more stable operation than an accelerator-based source



Cartoon of the NIST 20 MW reactor

Neutron Sources

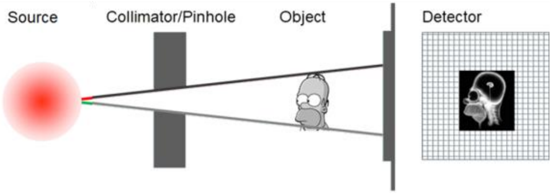
Spallation Sources



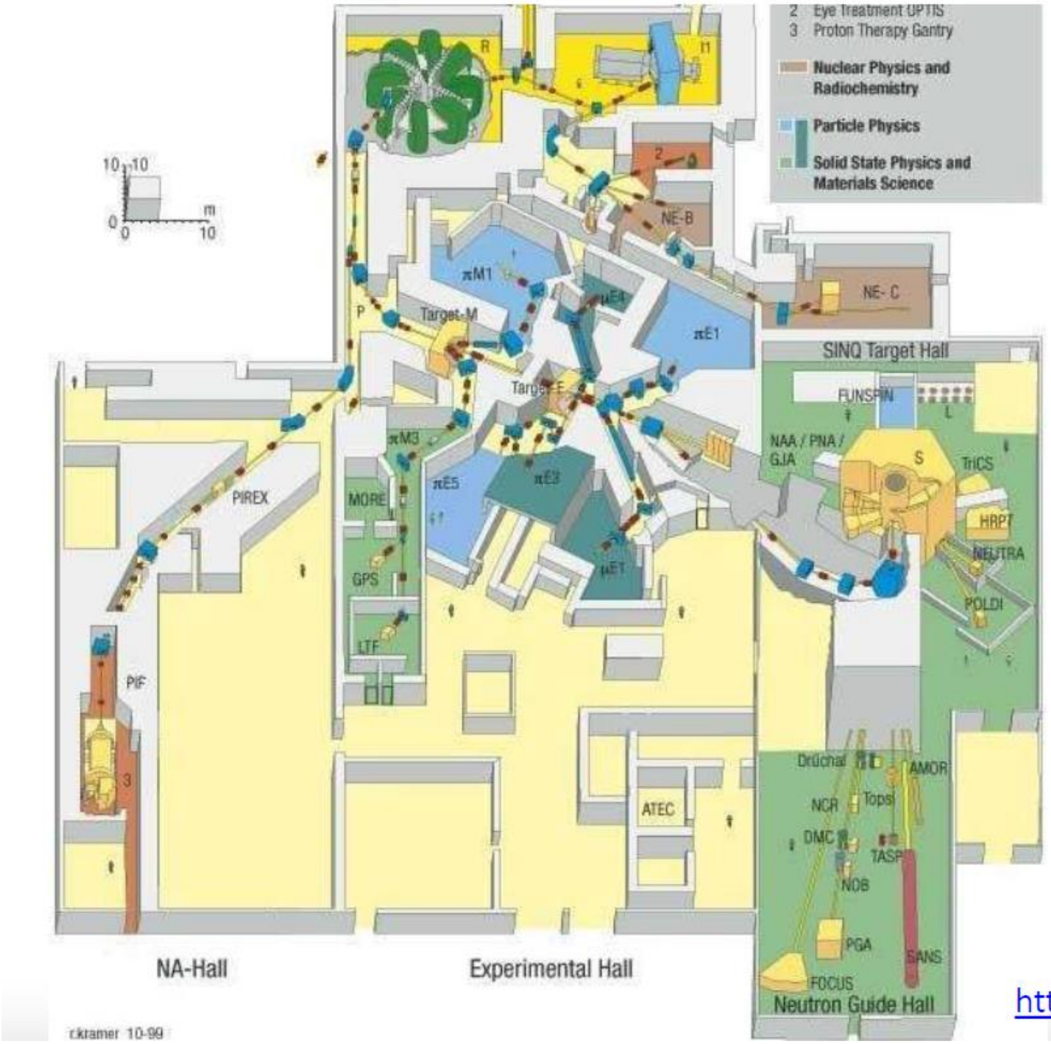
Neutron Sources: Pulsed Spallation

- 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



Special case: Continuous Spallation Source

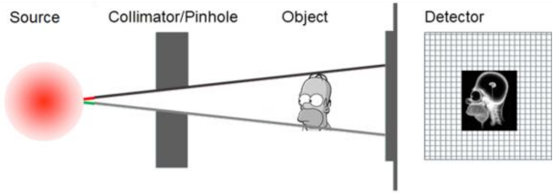


- SINQ at the Paul Scherrer Institute is the only major facility
- 3 accelerators feed a multi-use facility and direct a 570 MeV continuous proton beam with thermal power of ~0.75 MW onto SINQ's lead spallation target
- Neutrons are produced "continuously", no intrinsic time of flight information
- Comparable 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

Neutron Sources

Special case: pulsed reactor



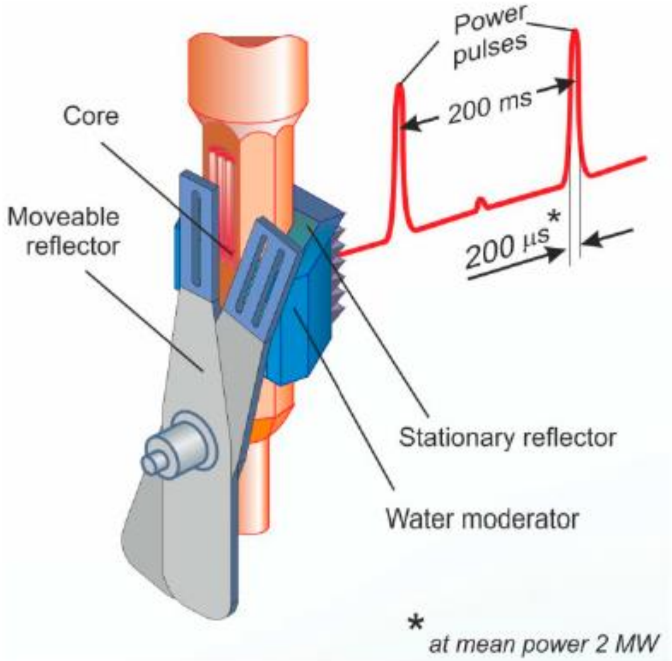


Figure 2. Core of the IBR-2 reactor with a movable reflector.

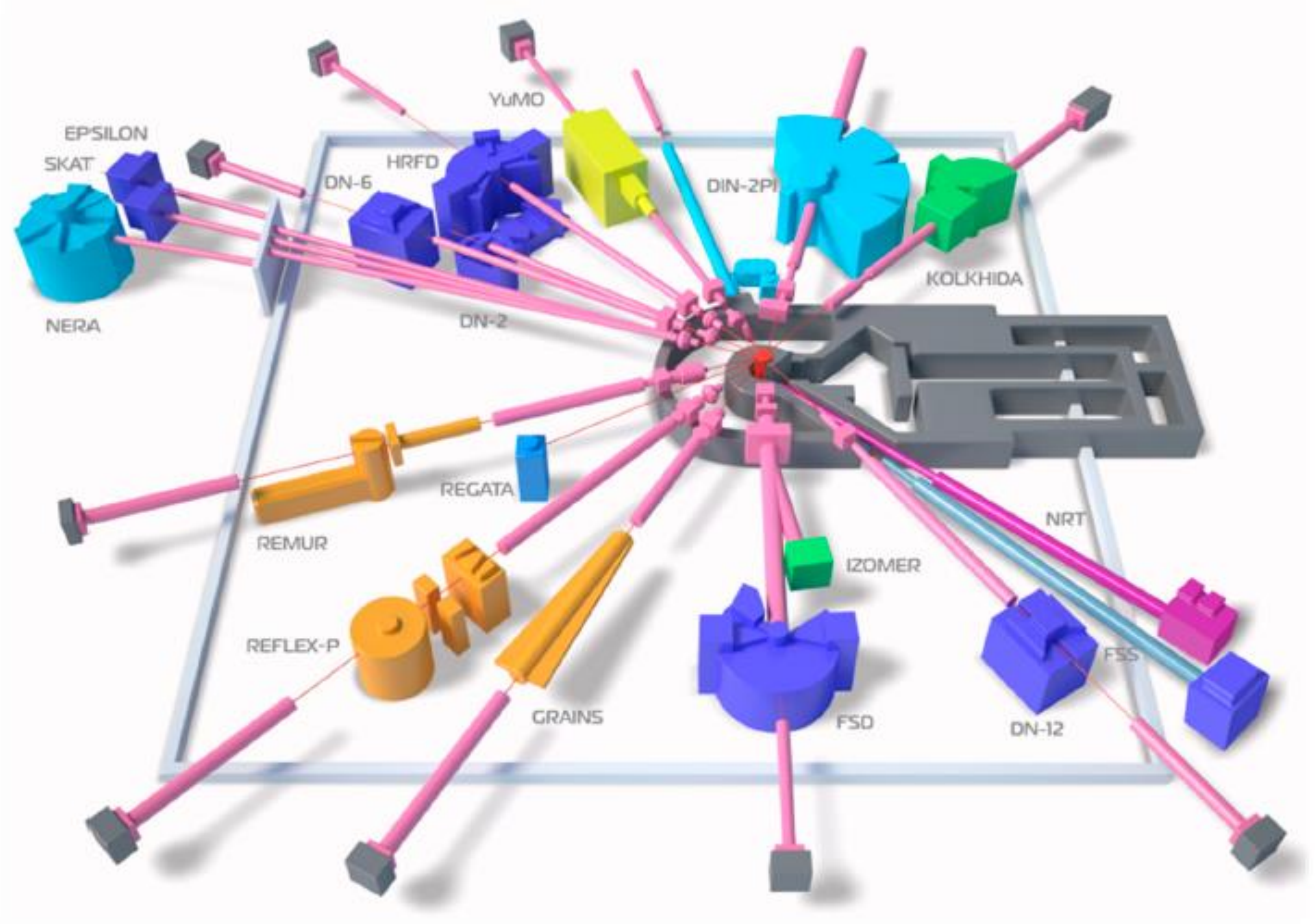
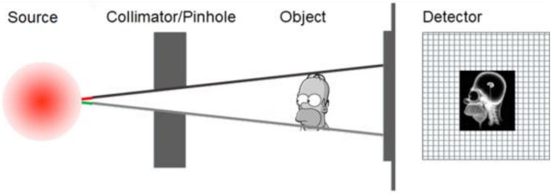


Figure 3. Layout of the IBR-2 spectrometer complex.

Neutron Sources

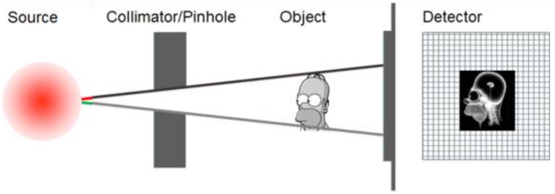


Spallation Sources

- Example of a Spallation Source: SNS

Mercury Target

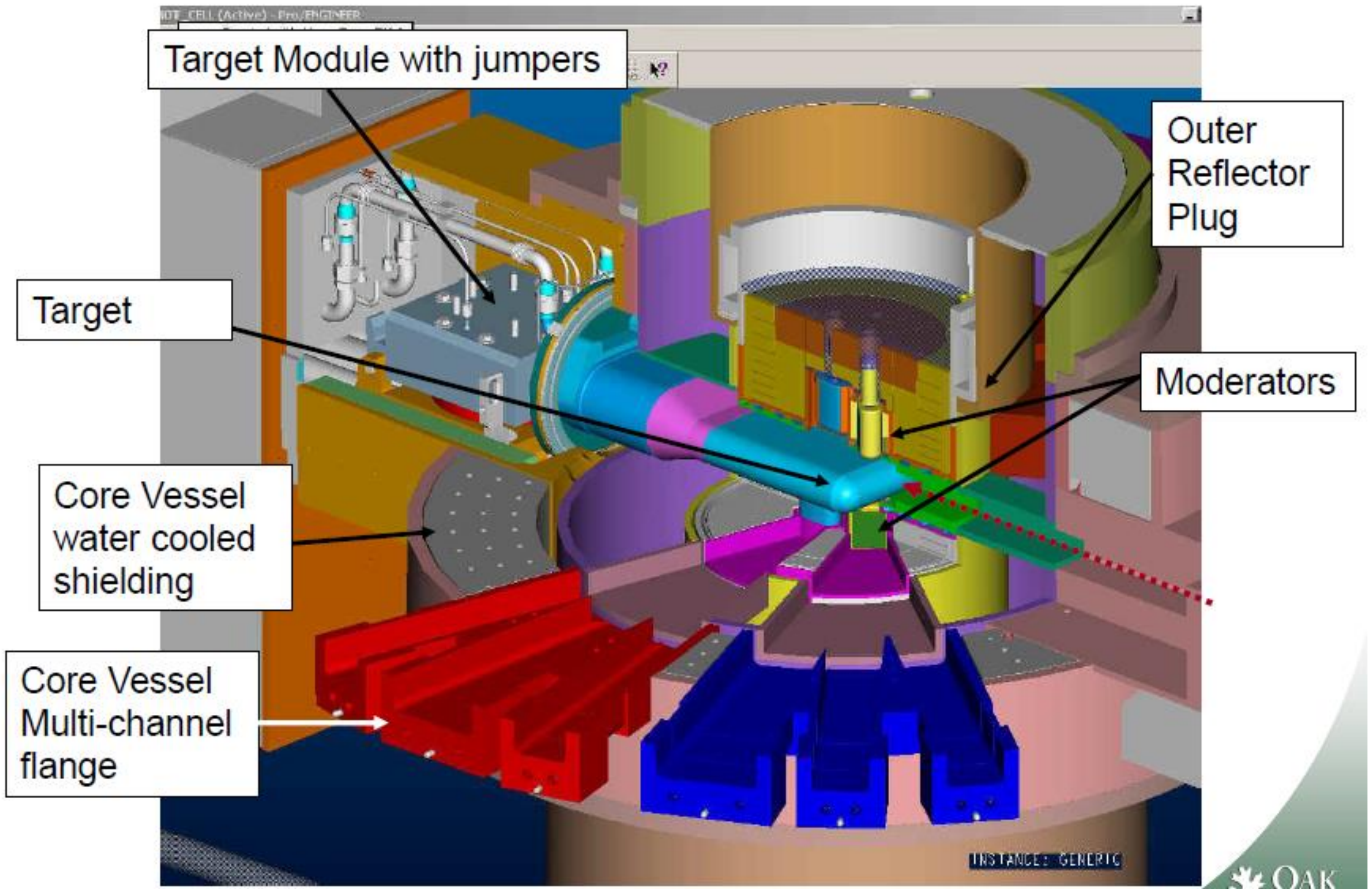
Neutron Sources



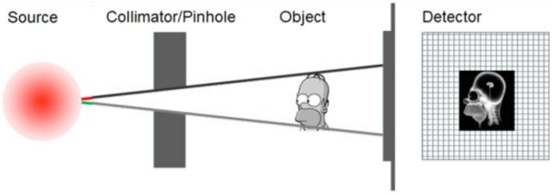
Spallation Sources

- Example of a Spallation Source: SNS

Target Region Within Core Vessel

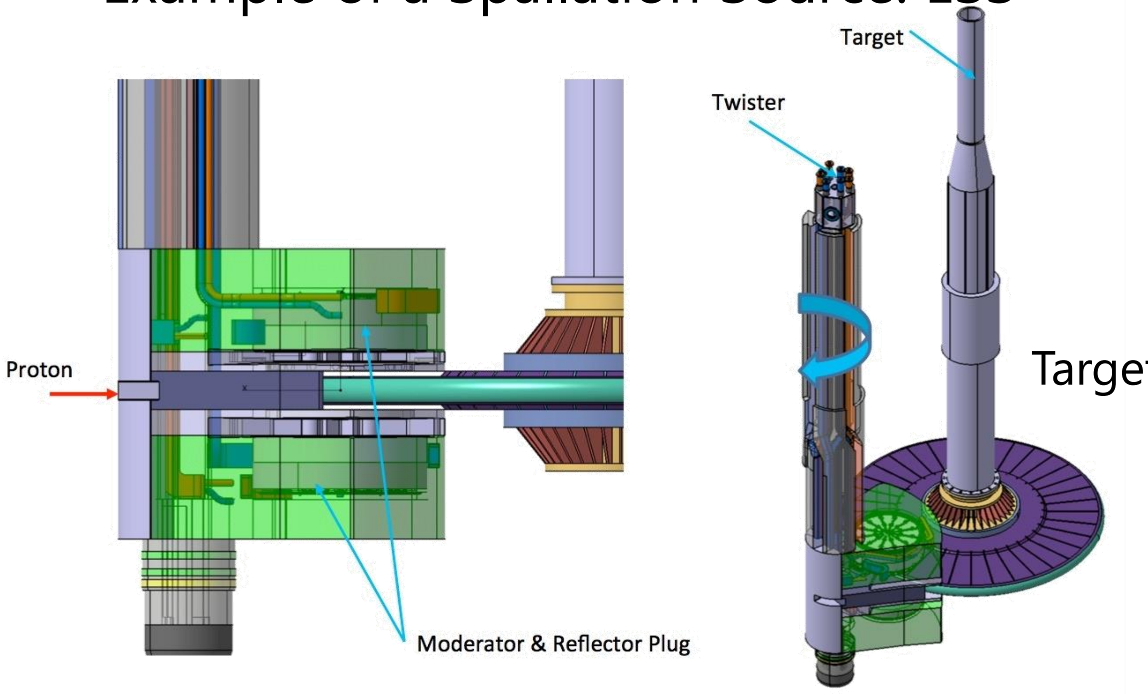


Neutron Sources

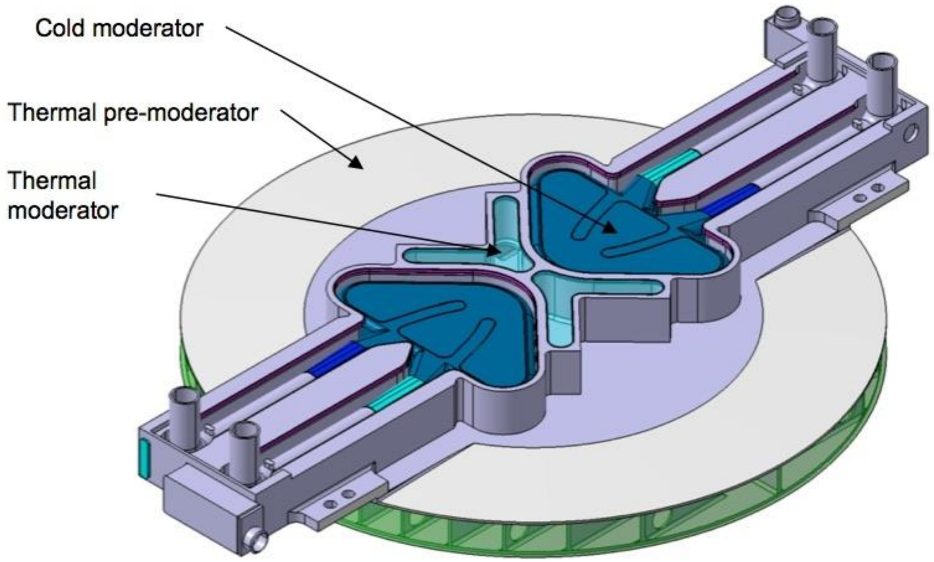


Spallation Sources

- Example of a Spallation Source: ESS



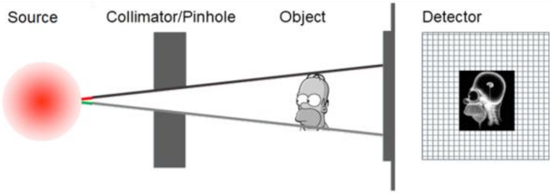
Target Wheel

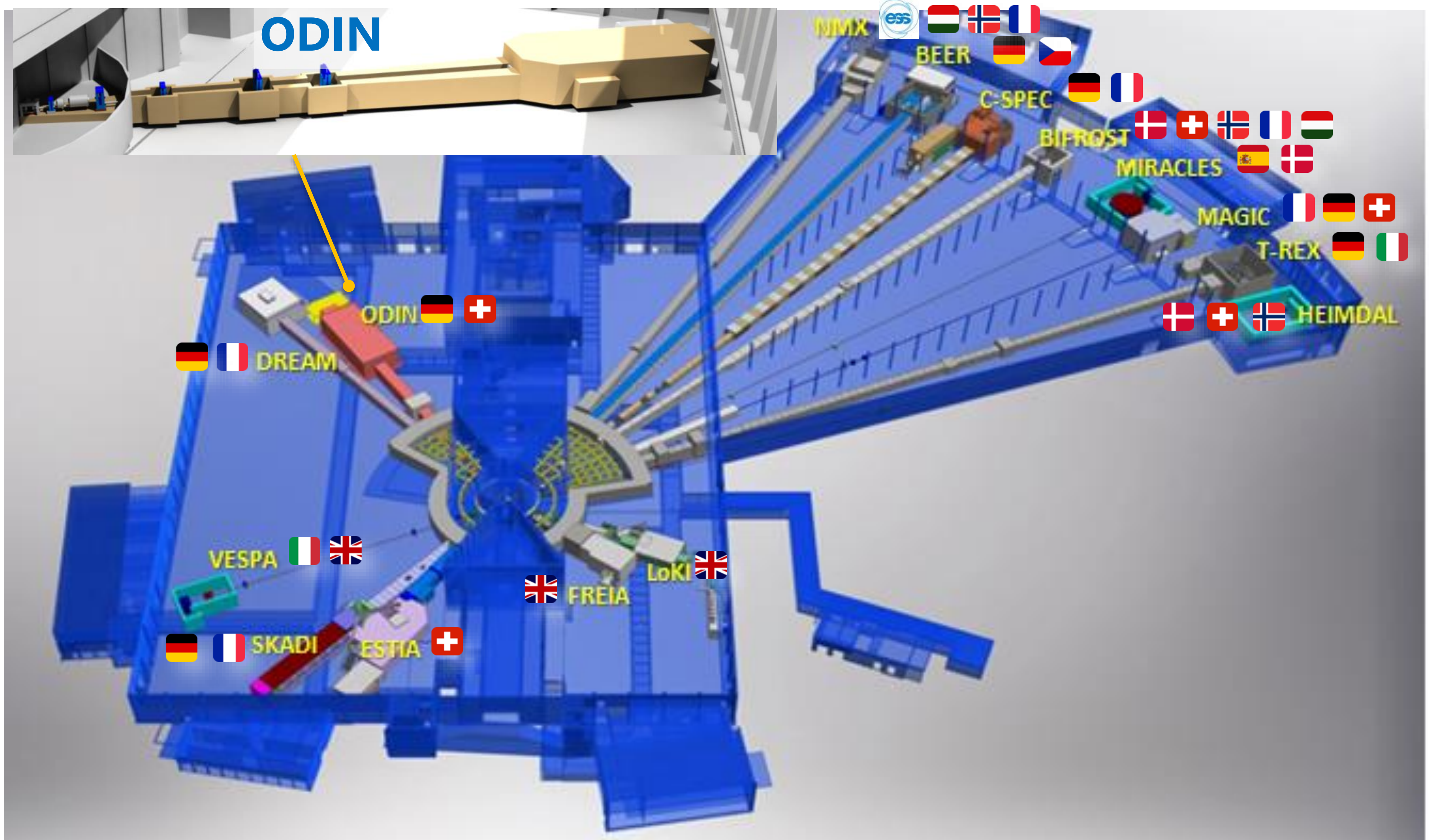


Neutron Sources

Spallation Sources

- Example of a Spallation Source: ESS





Neutron imaging beamlines

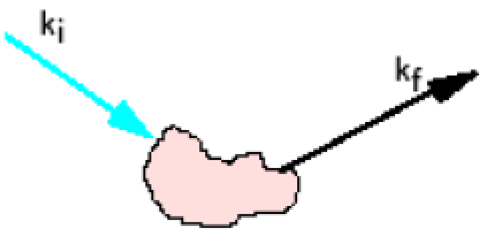
- ❑ Historic developments and a generic imaging instrument
- ❑ Neutron Sources
- ❑ ToF vs steady state instruments
- ❑ Neutron Spectrum
- ❑ Instrumentation: Neutron Transport
- ❑ Instrumentation: Beam conditioning
- ❑ Instrumentation: Neutron Detectors
- ❑ Some example Instruments

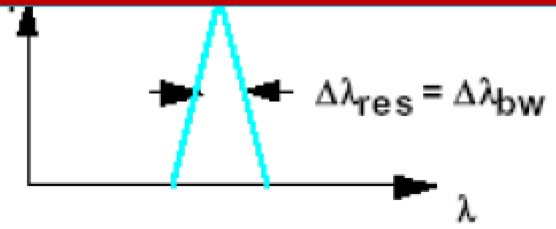
ToF vs steady state

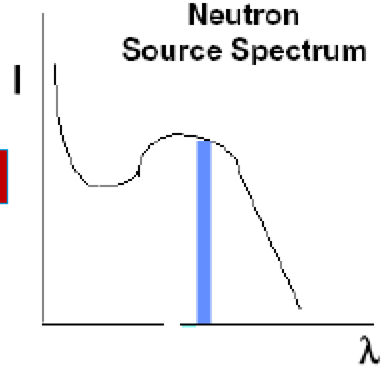
Differences between TOF and steady-state

Steady-state
- uses single wavelength
- bandwidth (bw) = resolution width (res)
- range of data requires multiple angles

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





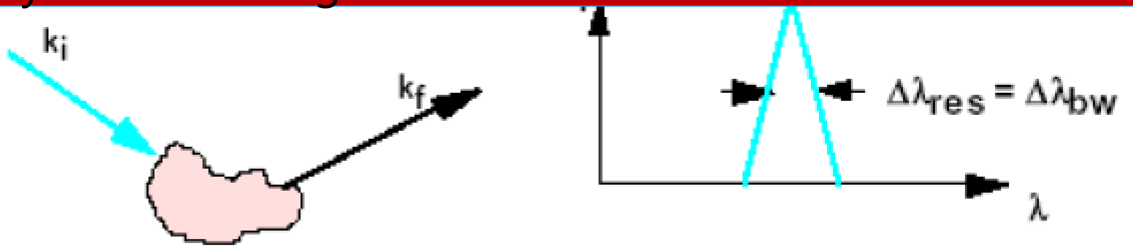


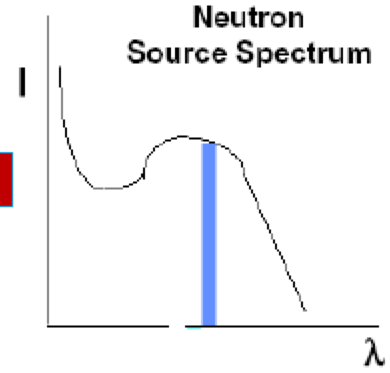
ToF vs steady state

Differences between TOF and steady-state

Steady-state
- uses single wavelength
- bandwidth (bw) = resolution width (res)
- range of data requires multiple angles

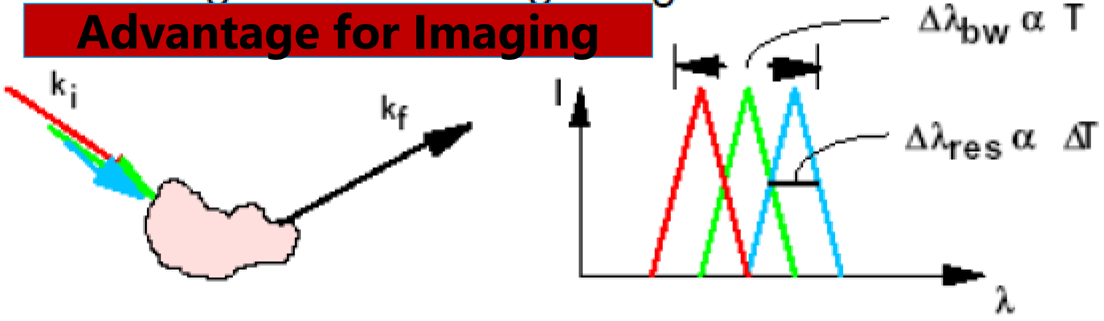
Imaging: We only have one angle! -> need to tune the monochromator!

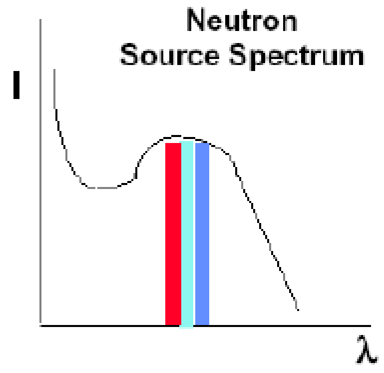




TOF
- uses range of wavelengths
- bandwidth (bw) >> resolution width (res)
- range of data at single angle

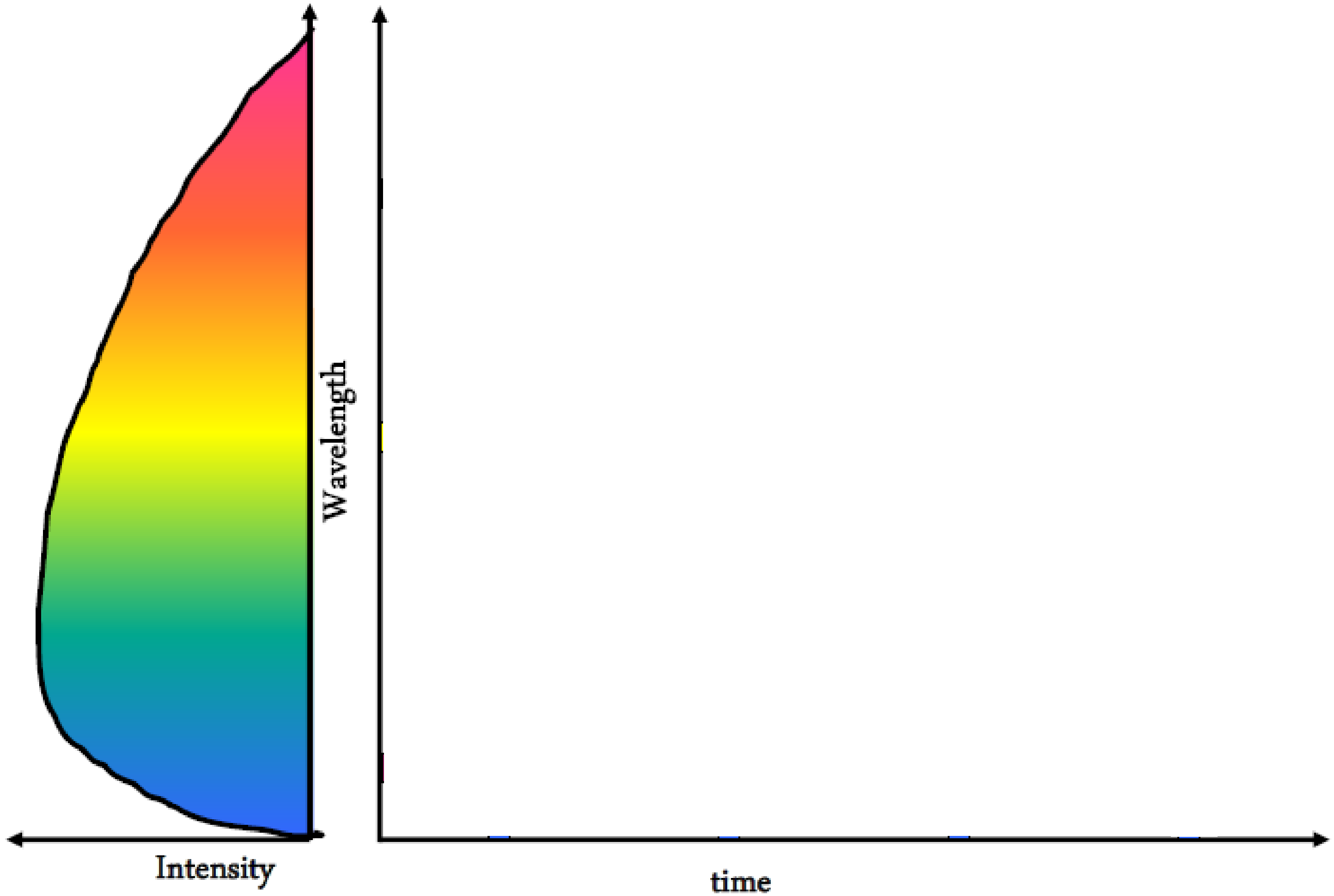
Advantage for Imaging



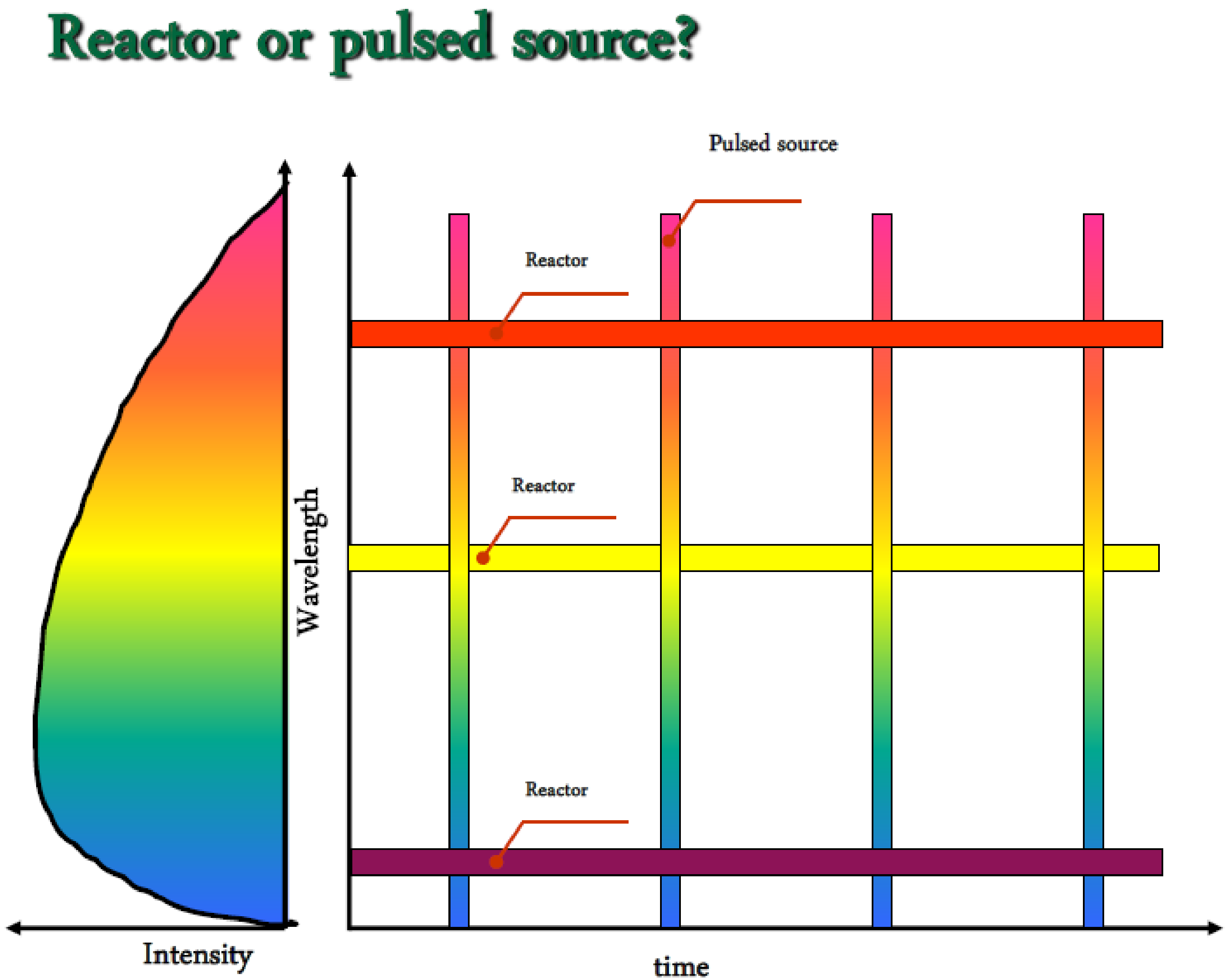


ToF vs steady state

Reactor or pulsed source?



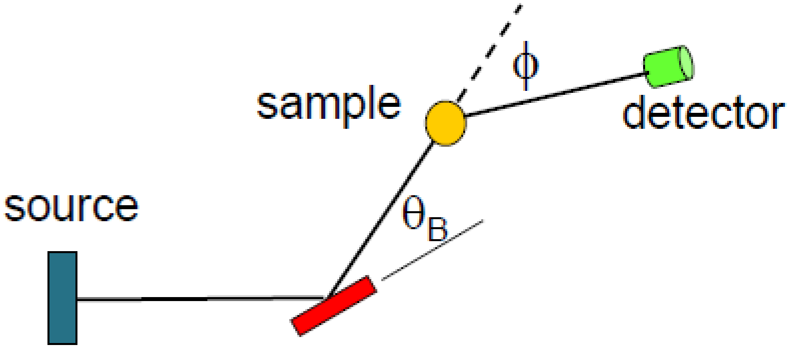
ToF vs steady state

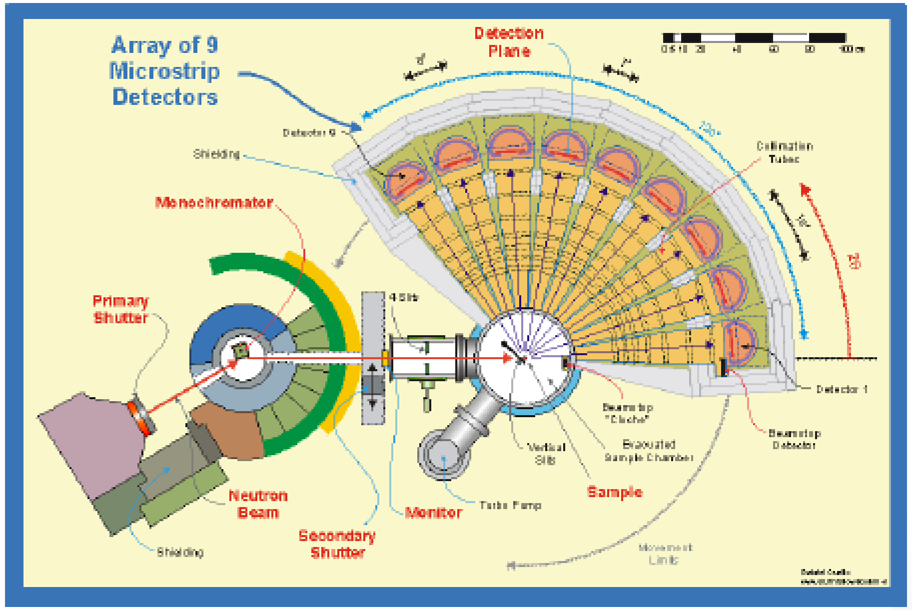


ToF vs steady state

Determining the Wavelength – reactor (continuous) source

crystal monochromator
(Bragg diffraction)





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

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

ToF vs steady state

The wavelength resolution

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

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	Given by extraction time from moderator = pulse width/flight time	10–15%	About 3%	About 2%
Beam geometry	Unchanged	Limited by the window	Limited by the crystal size	Limited by setup
Detector system	Triggered CCD, time dependent	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

ToF vs steady state

The wavelength resolution

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

	• ToF	• Steady state source	see next chapter	
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) ~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	Triggered CCD, time dependent	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.

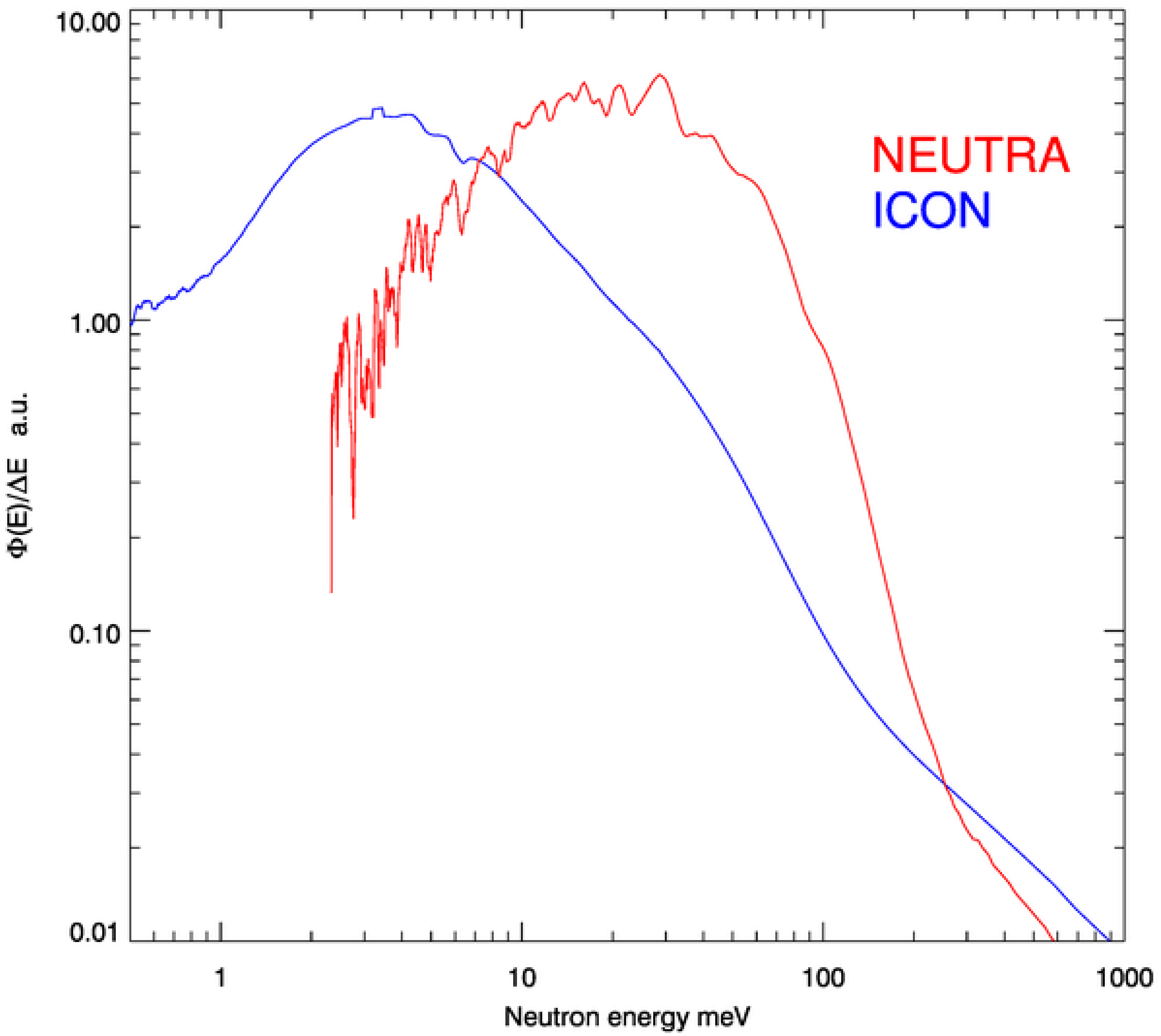
E.H. Lehmann et al. / Nuclear Instruments and Methods in Physics Research A 603 (2009) 429–438

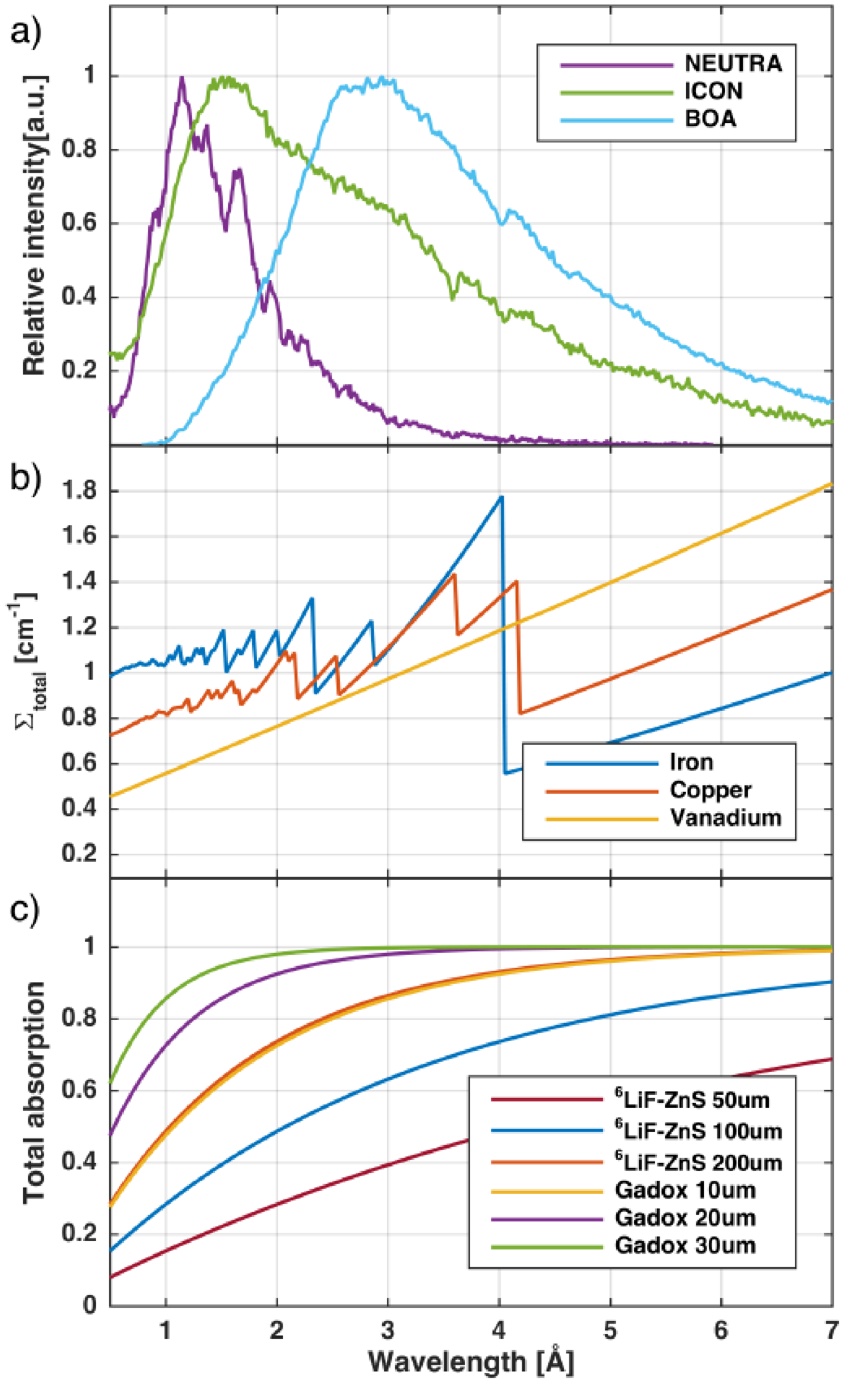
Neutron imaging beamlines

- ❑ Historic developments and a generic imaging instrument
- ❑ Neutron Sources
- ❑ ToF vs steady state instruments
- ❑ Neutron Spectrum
- ❑ Instrumentation: Neutron Transport
- ❑ Instrumentation: Beam conditioning
- ❑ Instrumentation: Neutron Detectors
- ❑ Some example Instruments

Neutron Sources

Moderators





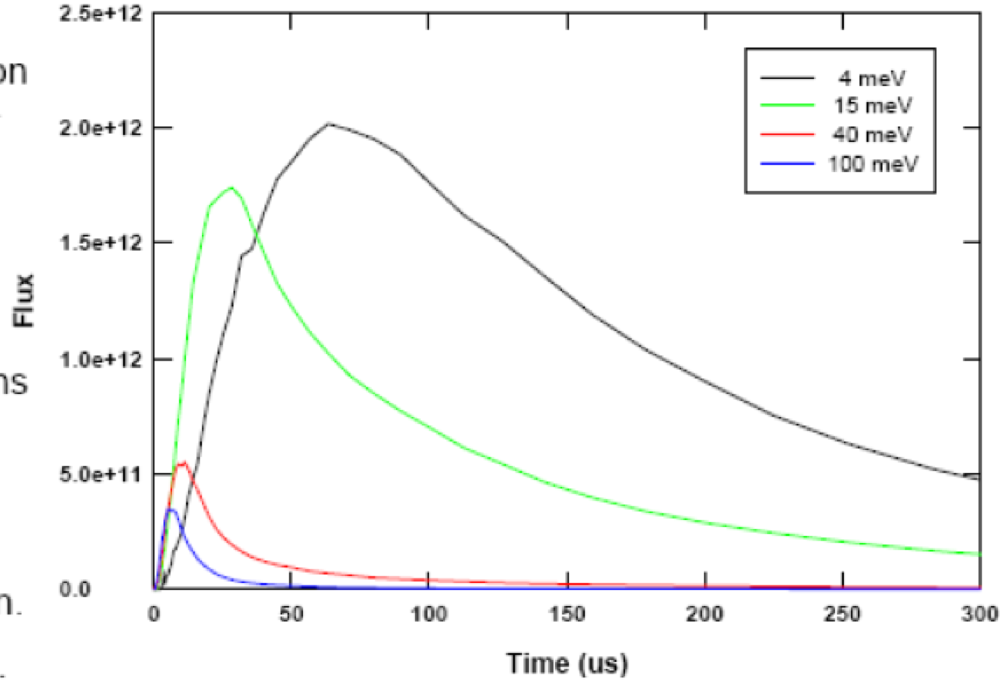
Neutron Sources

Spallation Sources: Moderators

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

Slowing down time or T0(λ) or T0(E)

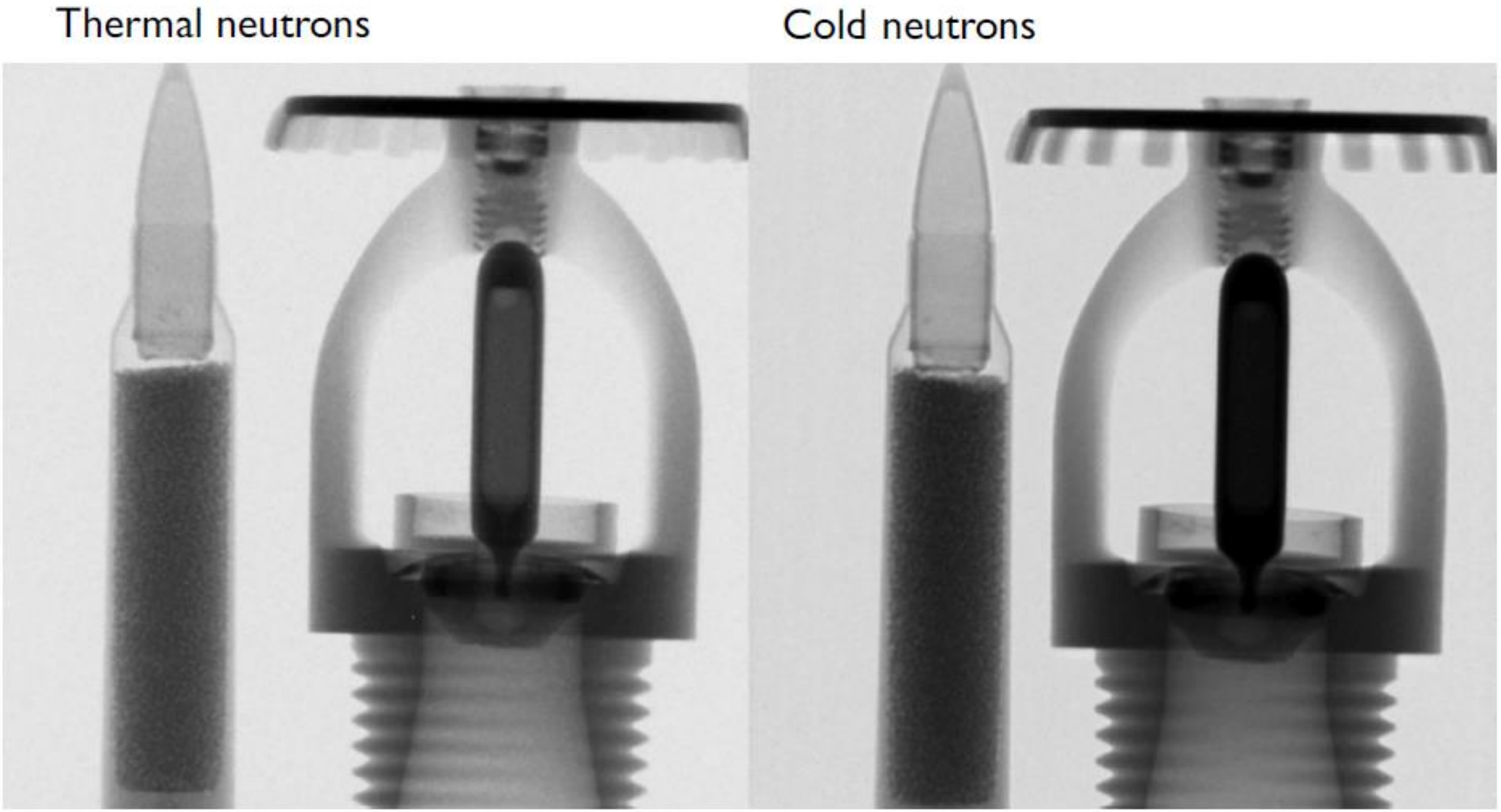
- Neutrons emerging from moderators have a distribution of energies = a Maxwellian + a 1/E (epithermal) tail.
- But different neutron energies (wavelengths) emerge from the moderator with different time distributions (see example on right).
- Need to calibrate a T0(E) function for each moderator and 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

Neutron Sources

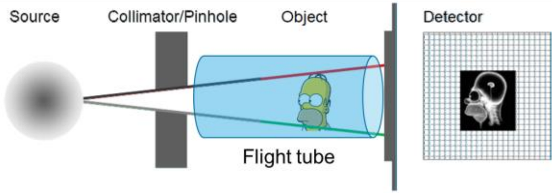
Cold vs Thermal



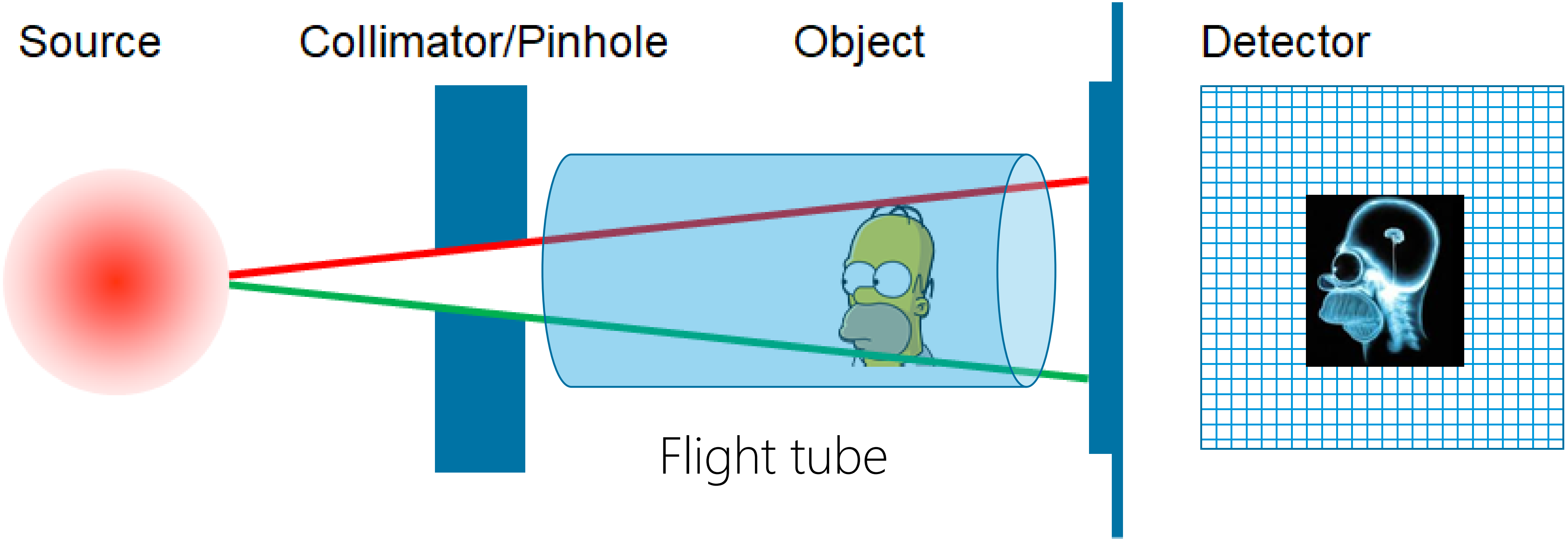
Neutron imaging beamlines

- ❑ Historic developments and a generic imaging instrument
- ❑ Neutron Sources
- ❑ ToF vs steady state instruments
- ❑ Neutron Spectrum
- ❑ Instrumentation: Neutron Transport
- ❑ Instrumentation: Beam conditioning
- ❑ Instrumentation: Neutron Detectors
- ❑ Some example Instruments

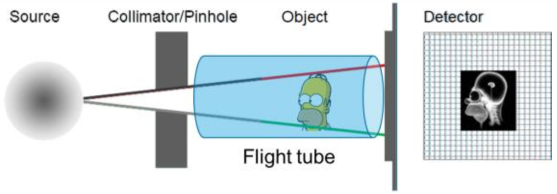
Instrumentation Neutron Transport



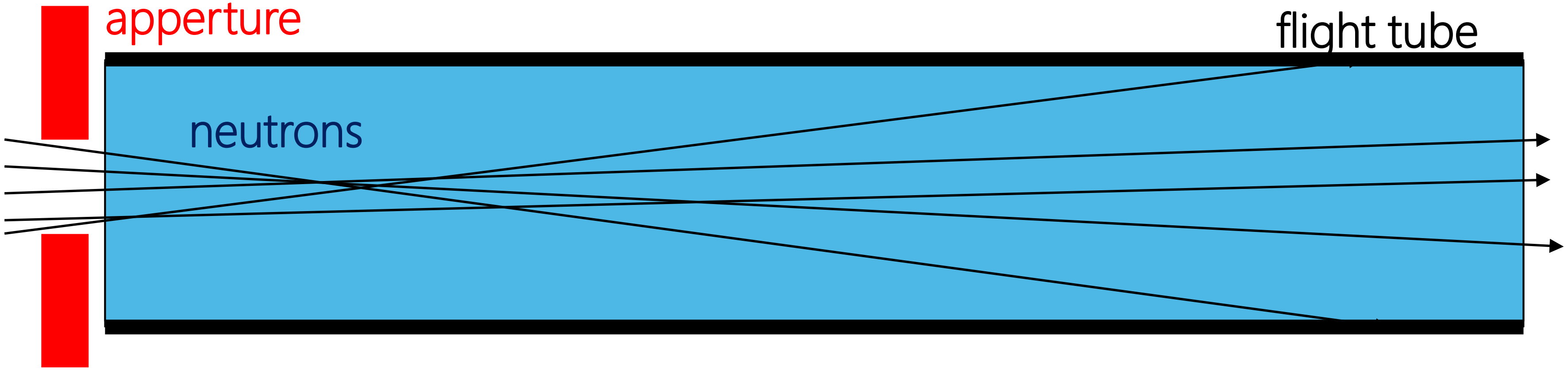
Flight tube



Instrumentation Neutron Transport



Flight tube

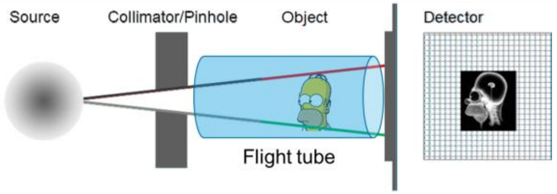


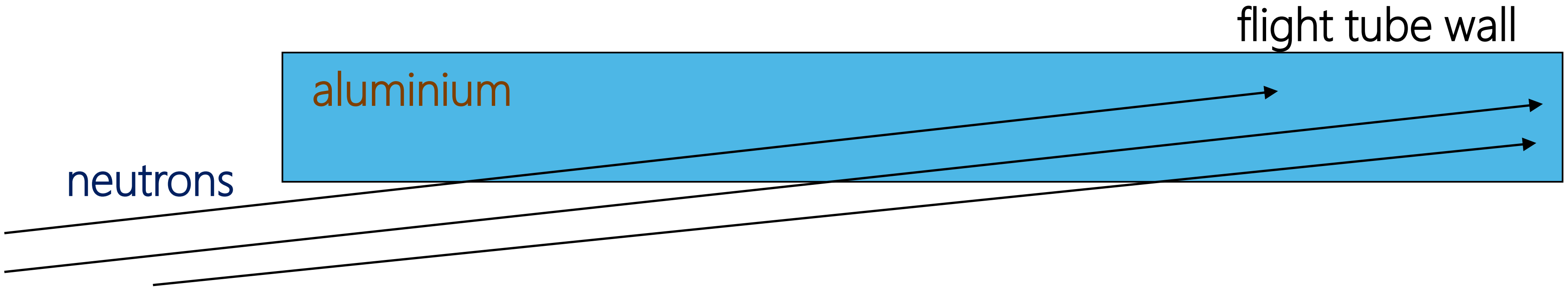
- **A neutron beam suffers several % loss in air – and activates N, O and Ar in the air.**
- **The beam must thus be encased in a flight tube which is either evacuated or filled with He.**
- **Aluminium is the material of choice for tube and windows – high transparency and short activation time (2.5 mins half-life).**

Slide courtesy: Dr. Burkhard Schillinger (FRM-II, Munich, Germany)

Instrumentation Neutron Transport

Flight tube



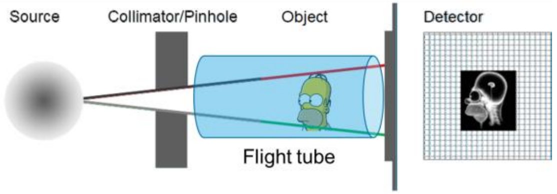


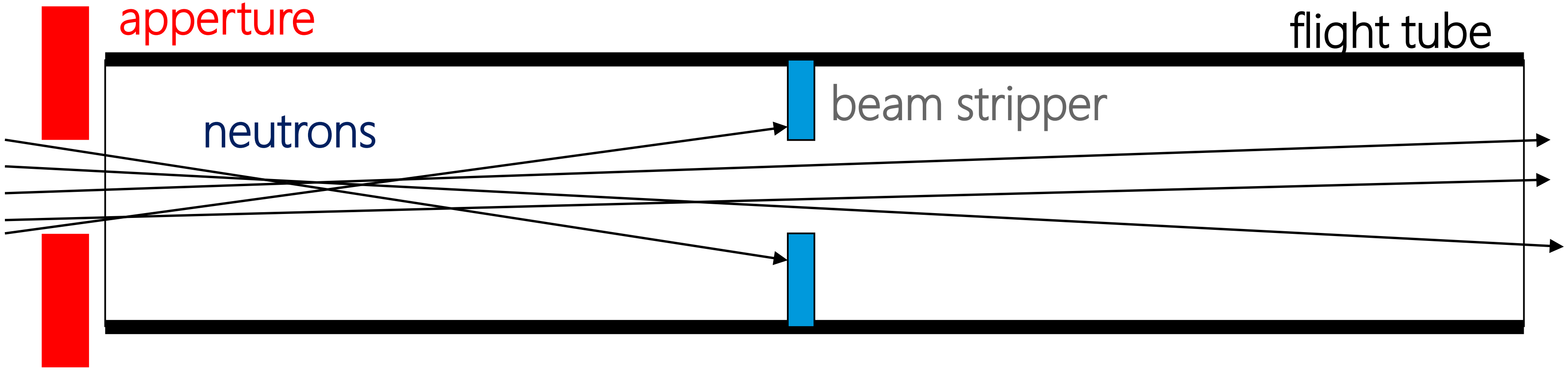
- **BUT even though the absorption probability in aluminium is low, absorption creates a hard 8 MeV gamma.**
- **IF the beam runs into the tube wall tangentially, it sees a meter of aluminium, is fully absorbed – and generates so much hard gamma radiation that a meter of heavy concrete will not be sufficient!**

Slide courtesy: Dr. Burkhard Schillinger (FRM-II, Munich, Germany)

Instrumentation Neutron Transport

Flight tube

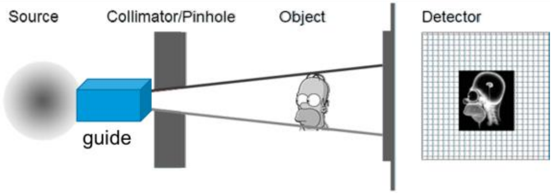




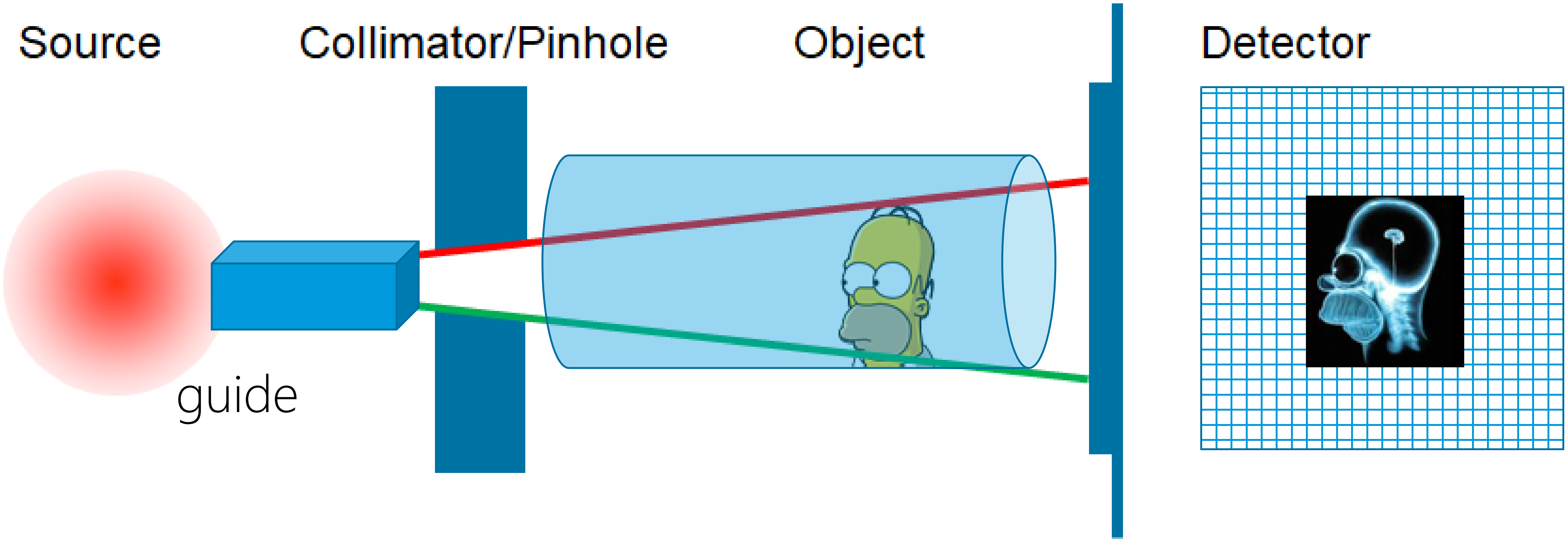
- **This can be remedied by introducing beam strippers of borated PE inside the flight tube – which produces comparatively low gamma energies of only 487 keV.**

Slide courtesy: Dr. Burkhard Schillinger (FRM-II, Munich, Germany)

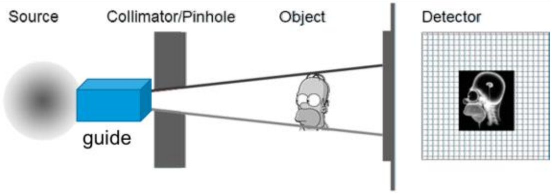
Instrumentation Neutron Transport



Neutron guide



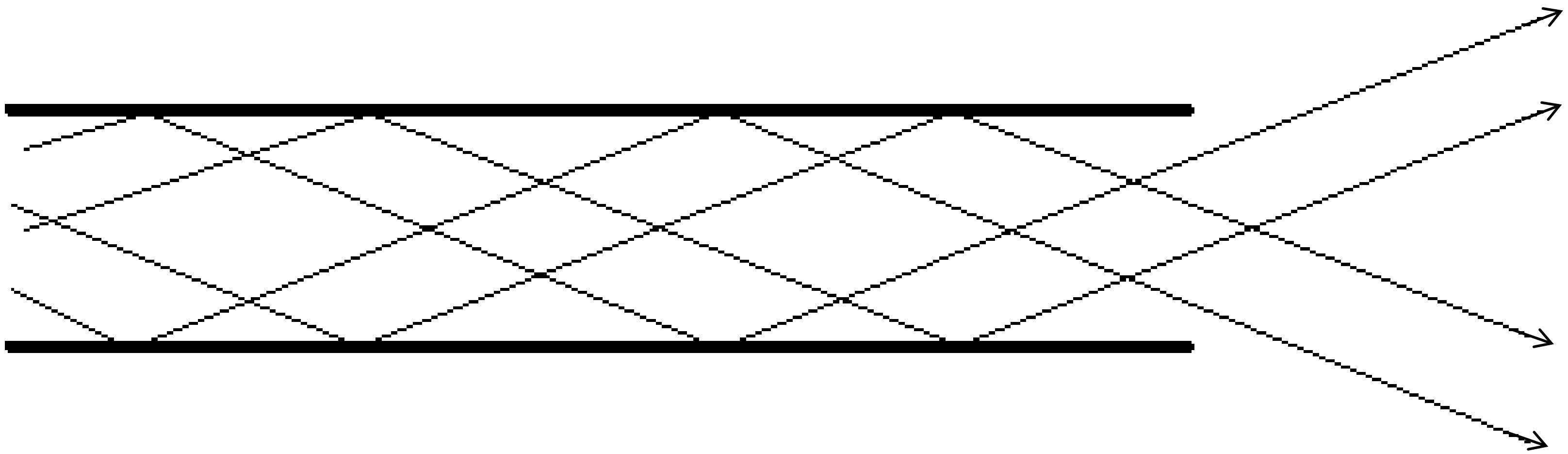
Instrumentation Neutron Transport



Neutron guide

- **If radiography is performed at the end of a neutron guide, the divergence of the beam is given by the critical angle of reflection γ_c of the neutron guide.**

- **The divergence is constant within the cross section of a straight neutron guide, it acts like a divergent area source.**

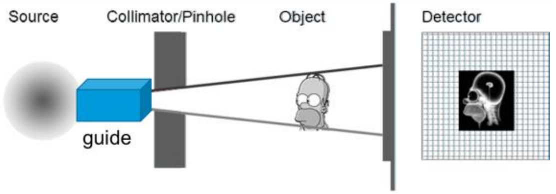


Beam geometry at a neutron guide

Slide courtesy: Dr. Burkhard Schillinger (FRM-II, Munich, Germany)

Instrumentation Neutron Transport

Neutron guide



Slow neutrons can be totally reflected from surfaces up to a critical angle of:

$$\gamma_c = \sqrt{2(1-n)} = \lambda \sqrt{\frac{Na}{\pi}} \qquad \approx 10^{-3} \ldots 10^{-2}$$

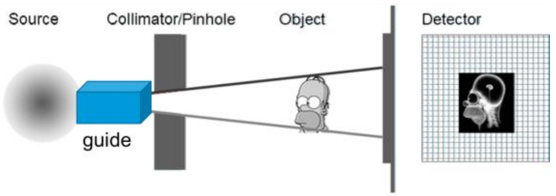
N is the atomic density of the wall material, *a* the coherent scattering length, and λ the neutron wavelength .

For a guide coated with natural nickel, we get
γ_c = 1.73·10^{-3} rad /Å, or 0.1°/ Å .

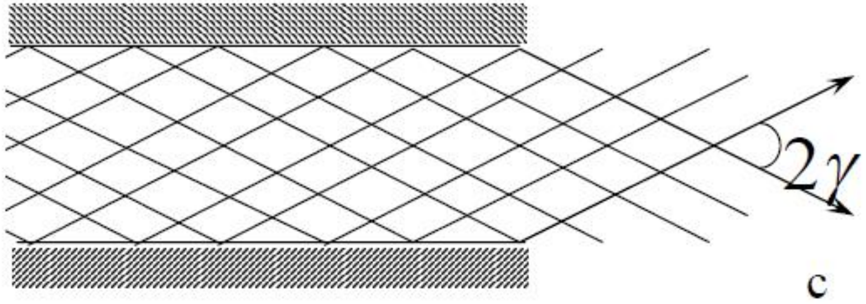
For a supermirror guide, the angle is multiplied by the parameter m of the supermirror.

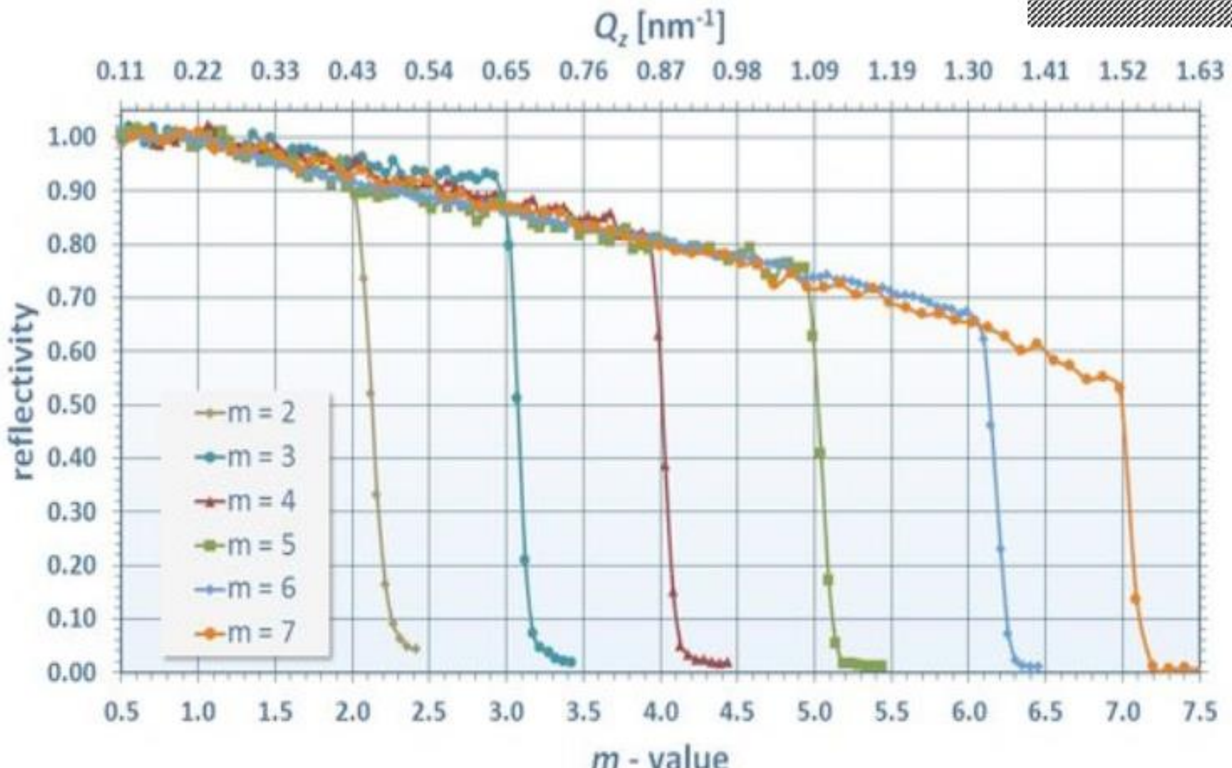
Slide courtesy: Dr. Burkhard Schillinger (FRM-II, Munich, Germany)

Instrumentation Neutron Transport



Neutron guide



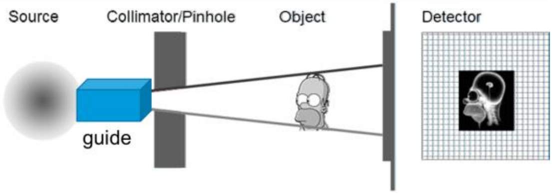


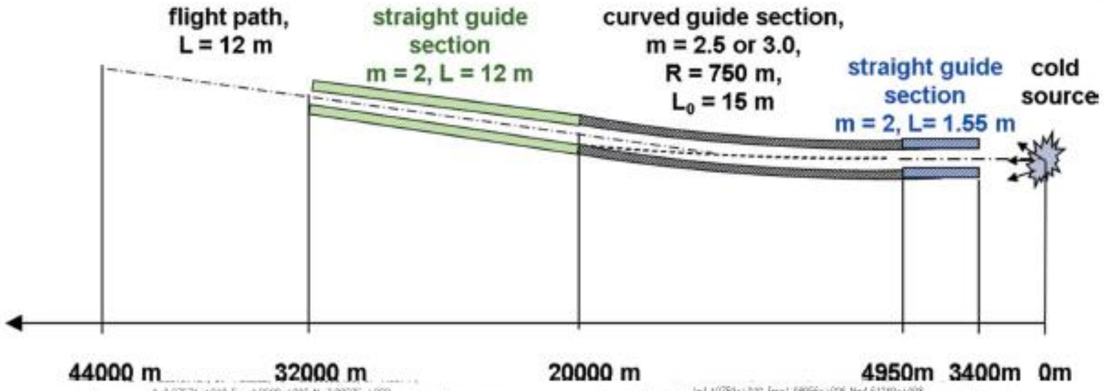
beam divergence depends on wavelength, and we need to calculate an ”effective” *L/D*-ratio which determines the quality of a projection.

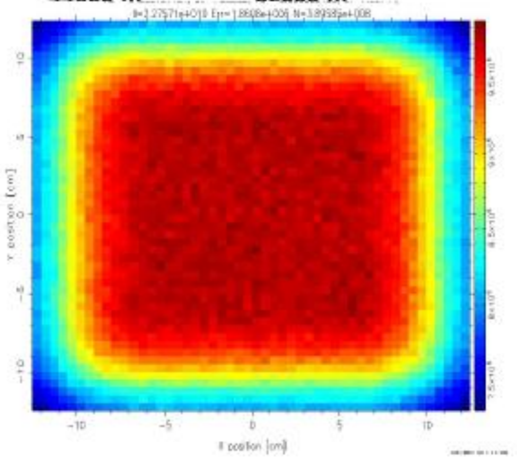
$$L/D = 1/\tan(2\gamma_c(\lambda)).$$

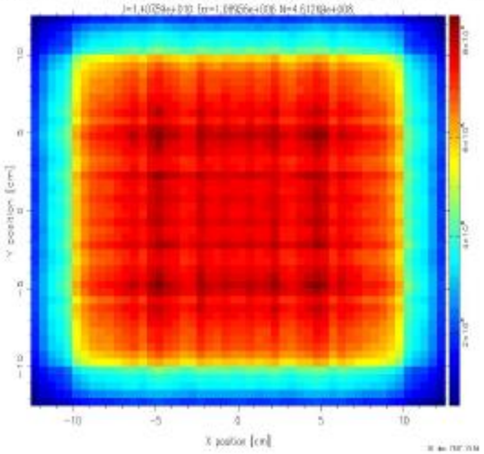
Instrumentation Neutron Transport

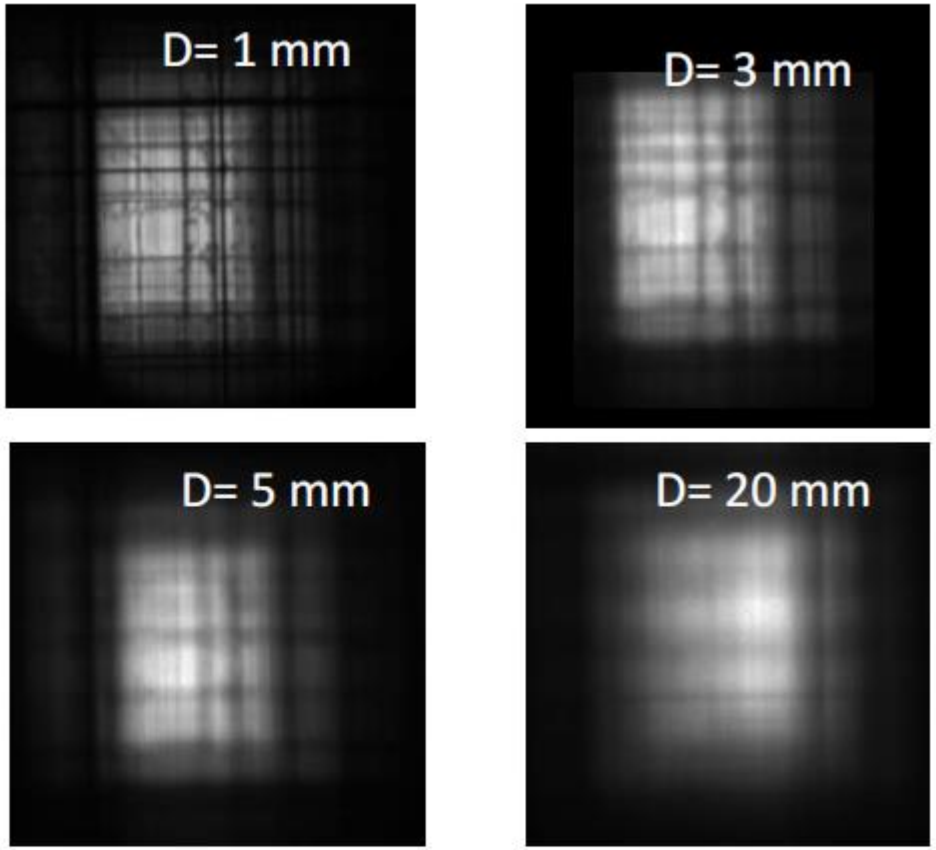
Neutron guide











Neutron imaging beamlines

- ❑ Historic developments and a generic imaging instrument
- ❑ Neutron Sources
- ❑ ToF vs steady state instruments
- ❑ Neutron Spectrum
- ❑ Instrumentation: Neutron Transport
- ❑ Instrumentation: Beam conditioning
- ❑ Instrumentation: Neutron Detectors
- ❑ Some example Instruments

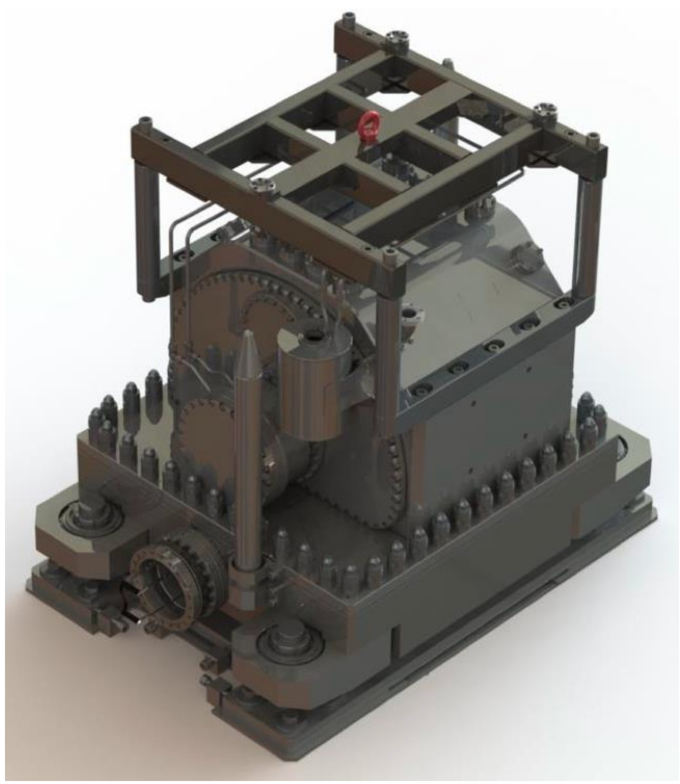
Beam conditioning

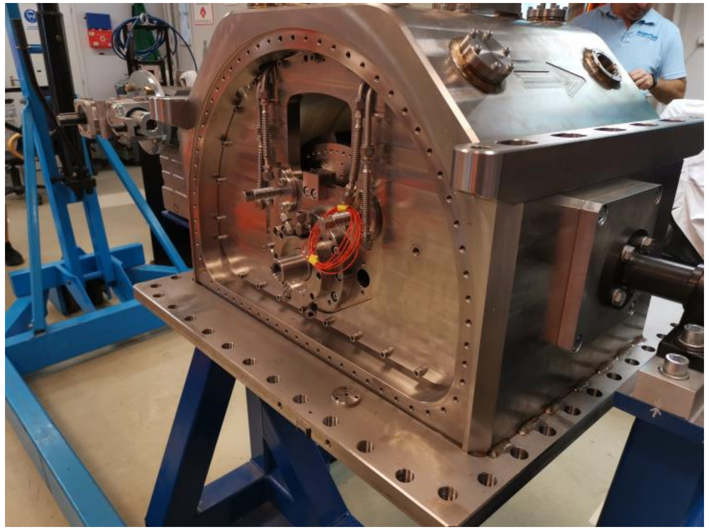
T0 chopper and curved guides

- When the proton beam strikes the target (time T0) a burst of ~1GeV neutrons and a flash of gamma rays are produced. Some neutrons are moderated but some emerge into the beamline at time T0. Have to get rid of the fast neutrons and gamma rays!

- Two methods -**T0 chopper** or **curved guide**

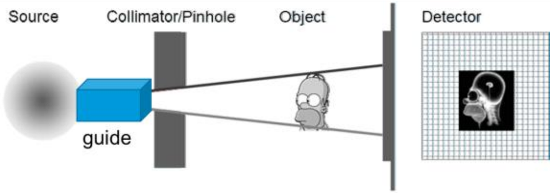
- T0 chopper –rotating plug of e.g. Inconel (200→300mm) that blocks the beam at time T0.



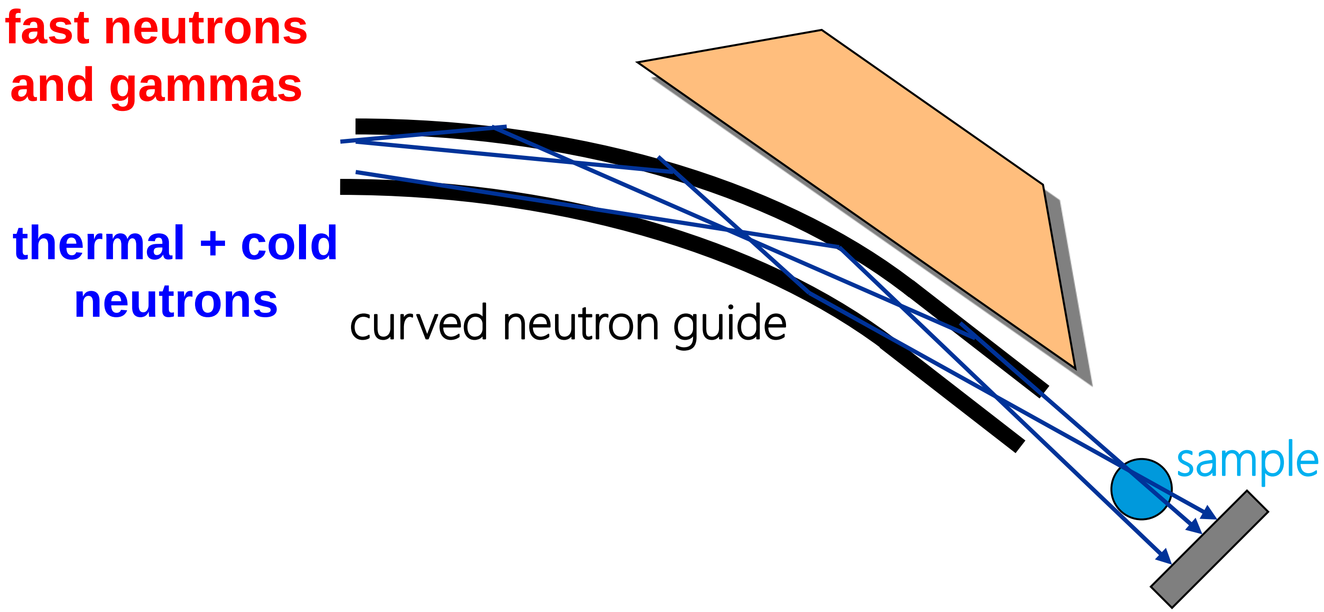


Instrumentation Neutron Transport

T0 chopper and curved guides



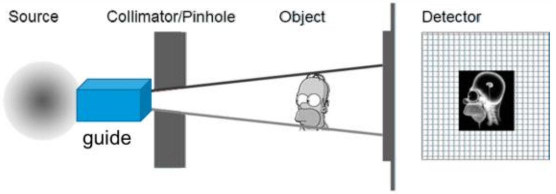
Principle setup with single neutron guide for imaging



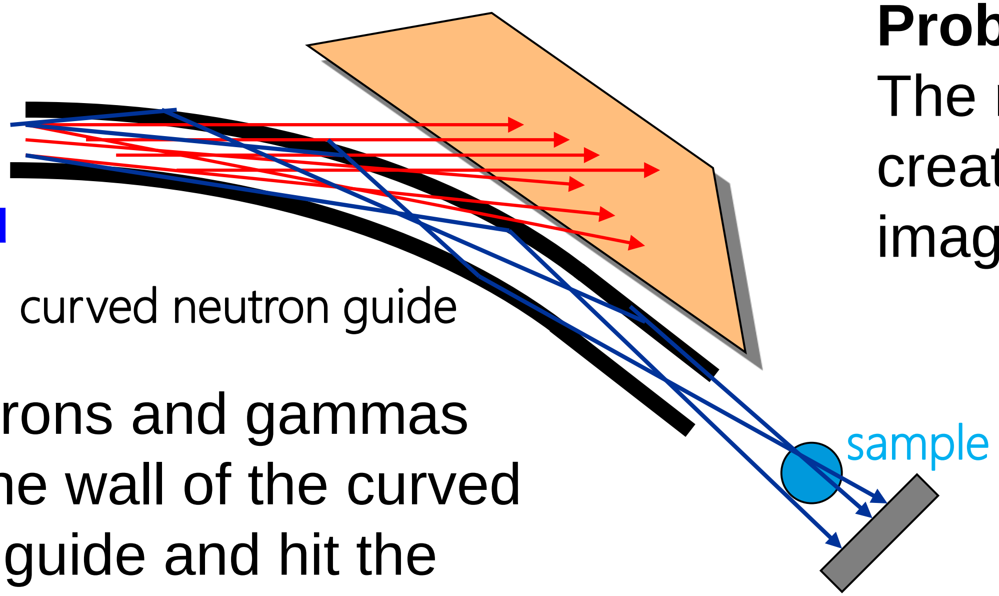
Slide courtesy: Dr. Burkhard Schillinger (FRM-II, Munich, Germany)

Instrumentation Neutron Transport

T0 chopper and curved guides



Principle setup with single neutron guide for imaging



Problem:
The multiple reflections in the guide create a divergent beam and unsharp images.

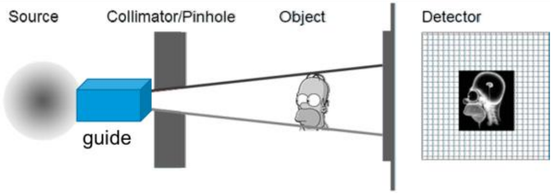
Fast neutrons and gammas penetrate the wall of the curved neutron guide and hit the shielding outside.

Only thermal + cold neutrons are reflected in the neutron guide and guided to sample and detector.

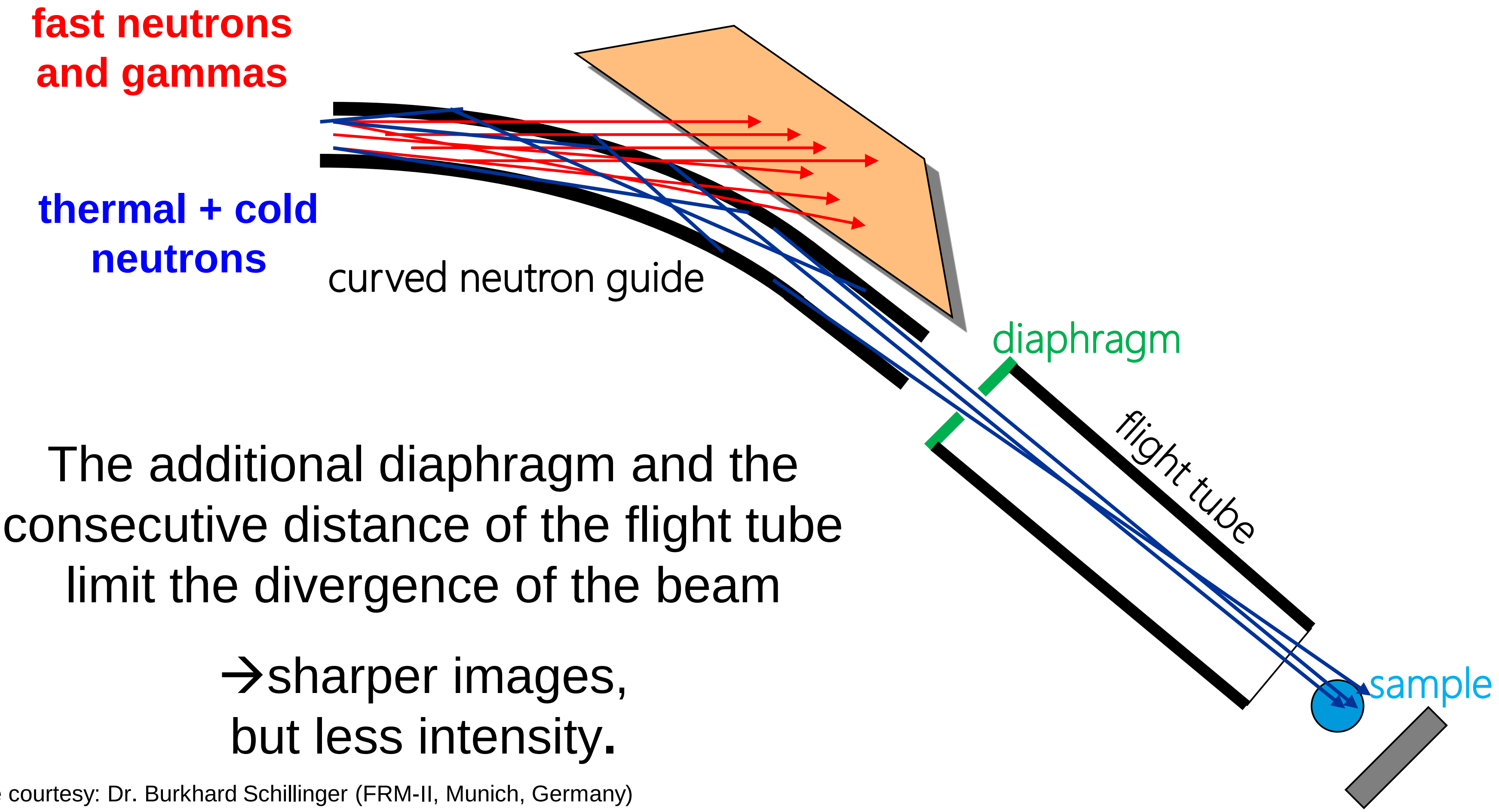
Slide courtesy: Dr. Burkhard Schillinger (FRM-II, Munich, Germany)

Instrumentation Neutron Transport

T0 chopper and curved guides



Principle setup with single neutron guide for imaging



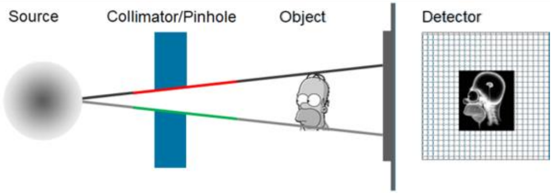
The additional diaphragm and the consecutive distance of the flight tube limit the divergence of the beam

→sharper images,
but less intensity.

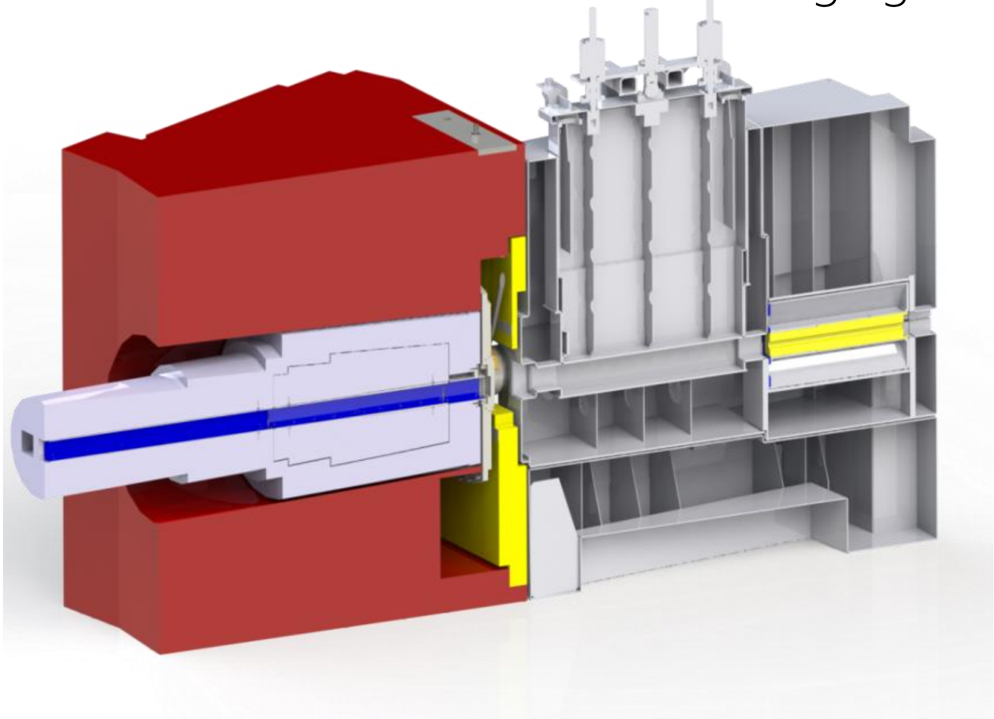
Slide courtesy: Dr. Burkhard Schillinger (FRM-II, Munich, Germany)

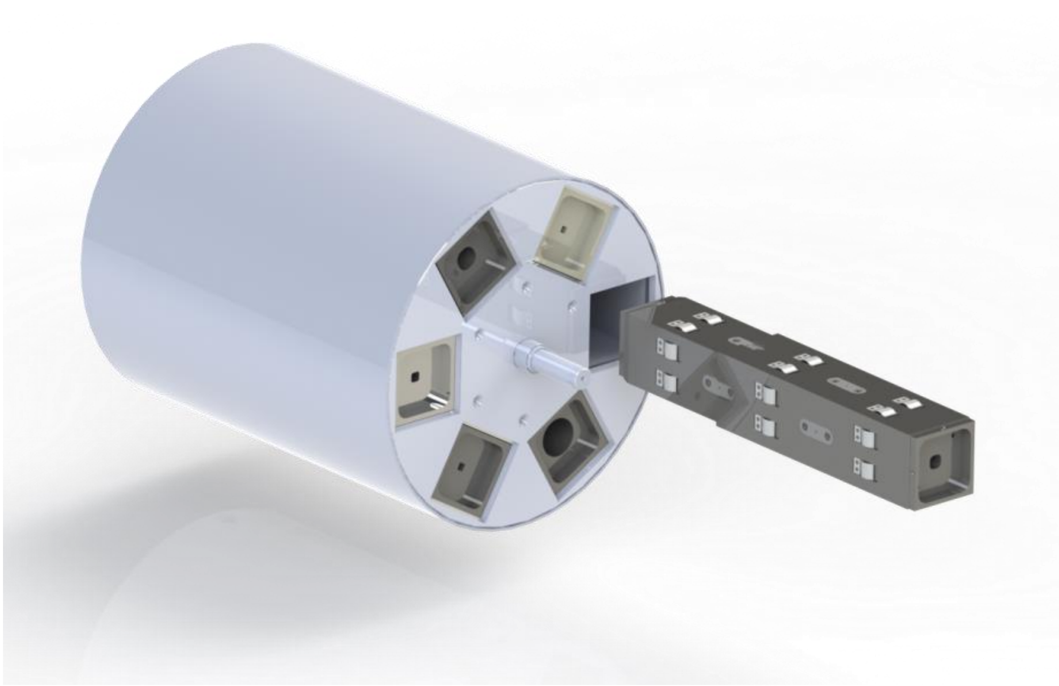
Beam conditioning

Collimators



Neutron imaging facility ANTARES@FRM-II





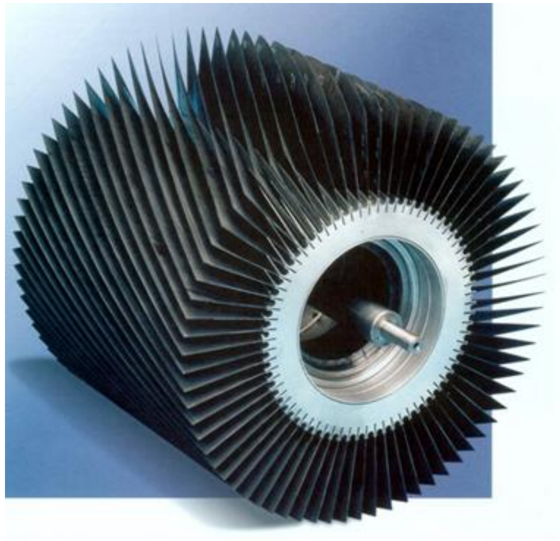
Collimator drum with 6 different collimators

- Pinholes: 2mm … 70mm
- L/D = 200 … 7100
- Flux: 10^8 n/cm^{2}s @ L/D = 400
- Machined from stack of borated steel plates
- Length: 800mm

Beam conditioning

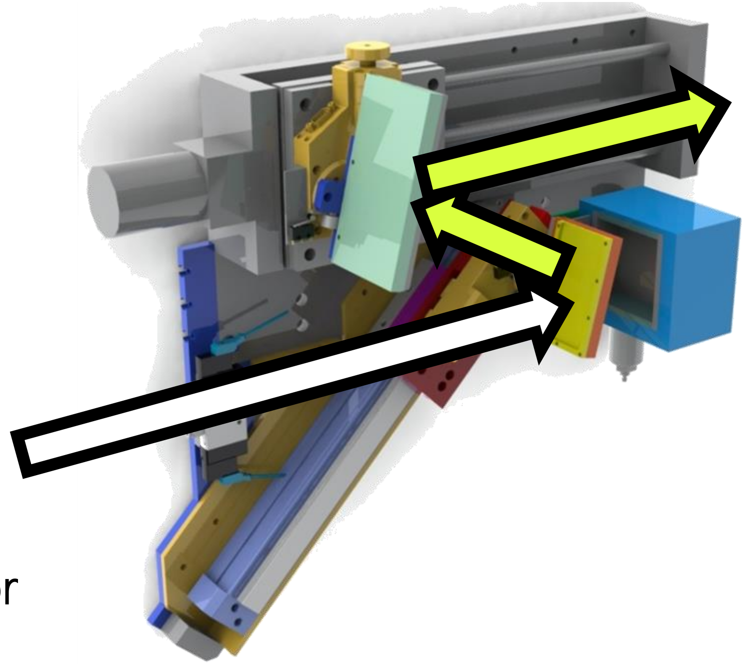
Wavelength selection: Steady state

Monochromatization



Neutron Velocity Selector

- 144 lamellae
- λ_{min} = 2.95Å
- $\Delta\lambda/\lambda$ = 10%
- Peak Transmission > 80%
- FOV ~ 20 x 20 cm



Double Crystal Monochromator

Pyrolytic graphite (002) crystals

- Mosaicity 0.7°
- $\Delta\lambda/\lambda$ = 1% .. 3%
- Wavelength band: 2.7 … 6.5Å

Beam conditioning

Wavelength selection: ToF

- A generic pulsed source instrument

Velocity v

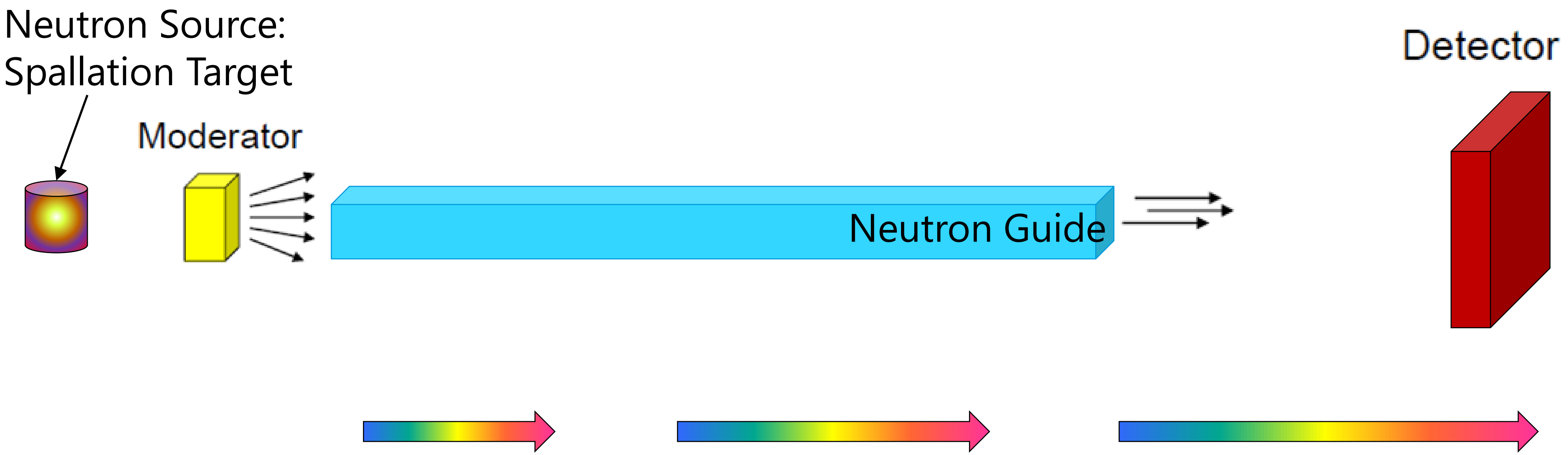
of the neutrons:

1 Å ⇒ ≈ 2000 m/s

5 Å ⇒ ≈ 800 m/s

10 Å ⇒ ≈ 400 m/s

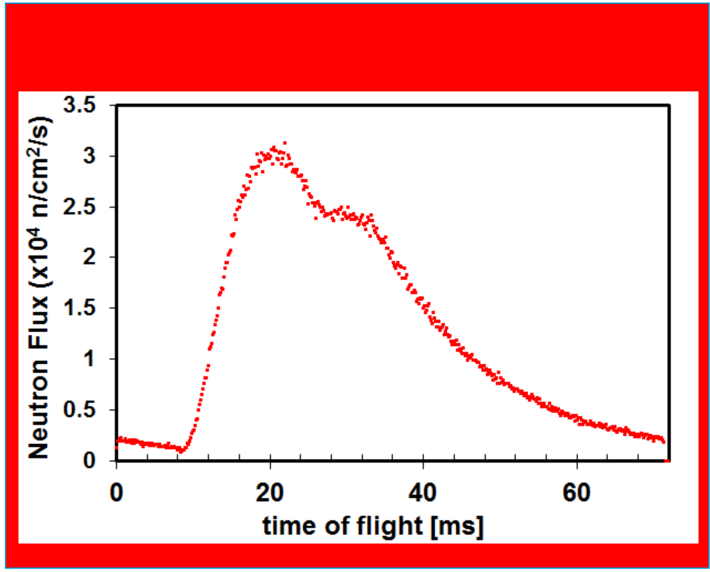
- At 2 m distance:
  1 Å ⇒ ≈ 1 ms
  5 Å ⇒ ≈ 2.5 ms
  10 Å ⇒ ≈ 5 ms

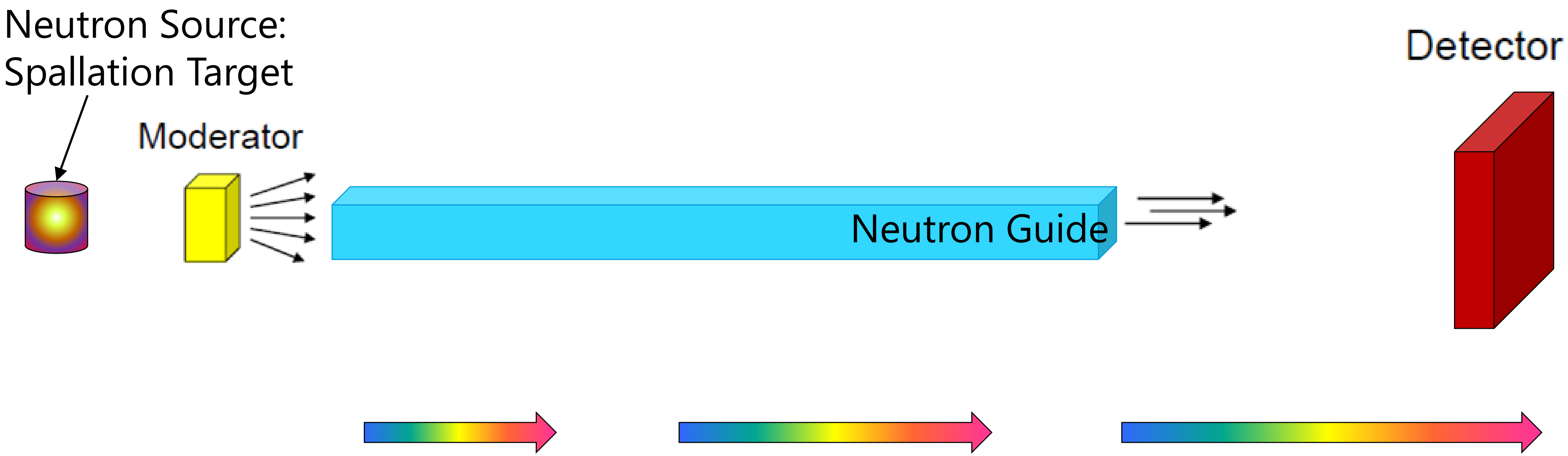


Beam conditioning

Wavelength selection: ToF

- A generic pulsed source instrument

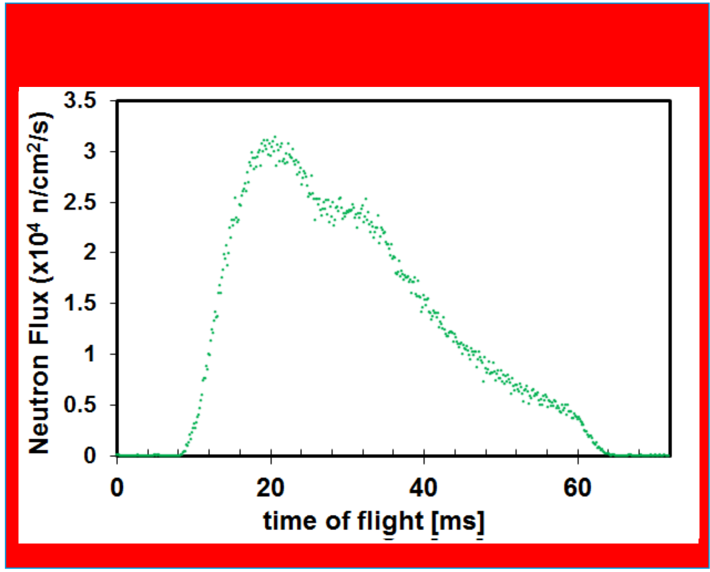


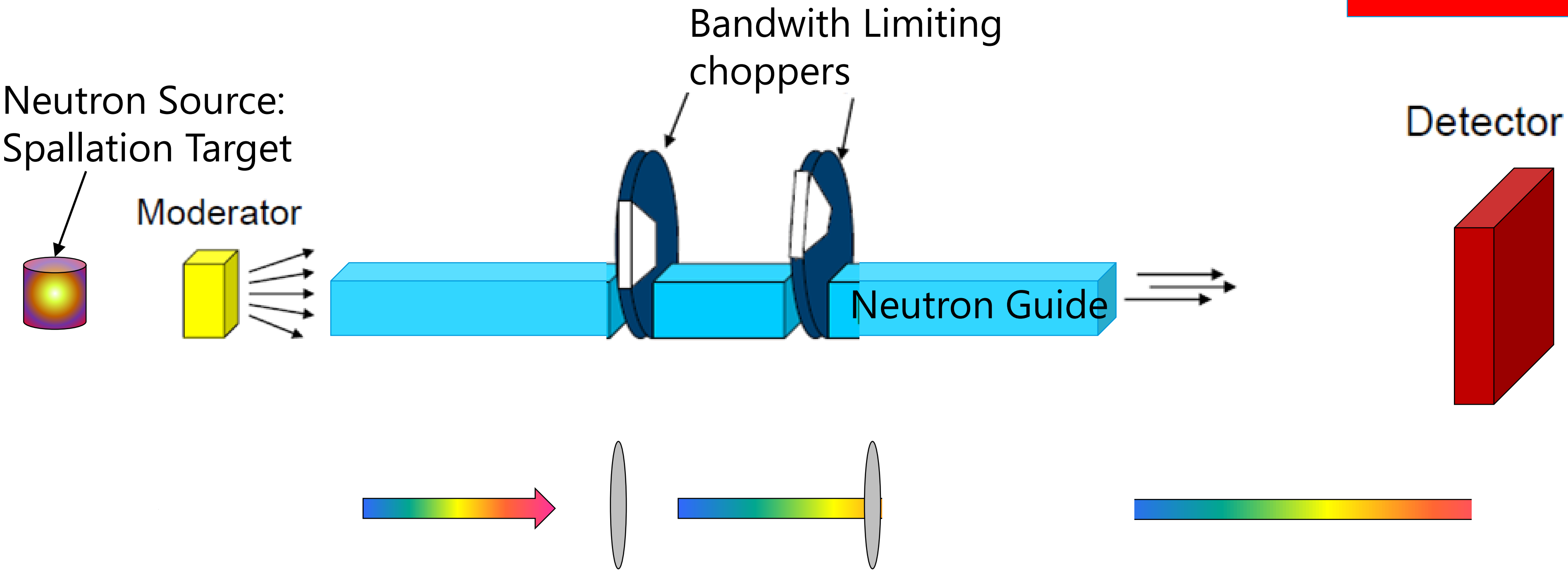


Beam conditioning

Wavelength selection: ToF

- A generic pulsed source instrument
- Introducing choppers

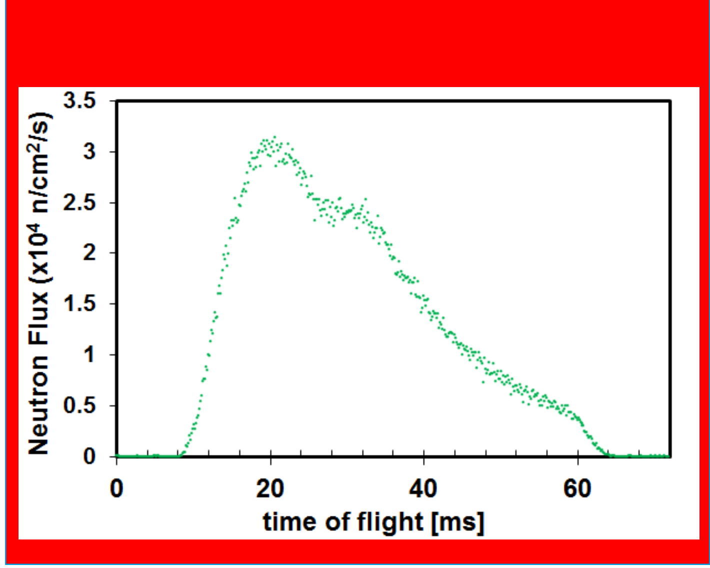


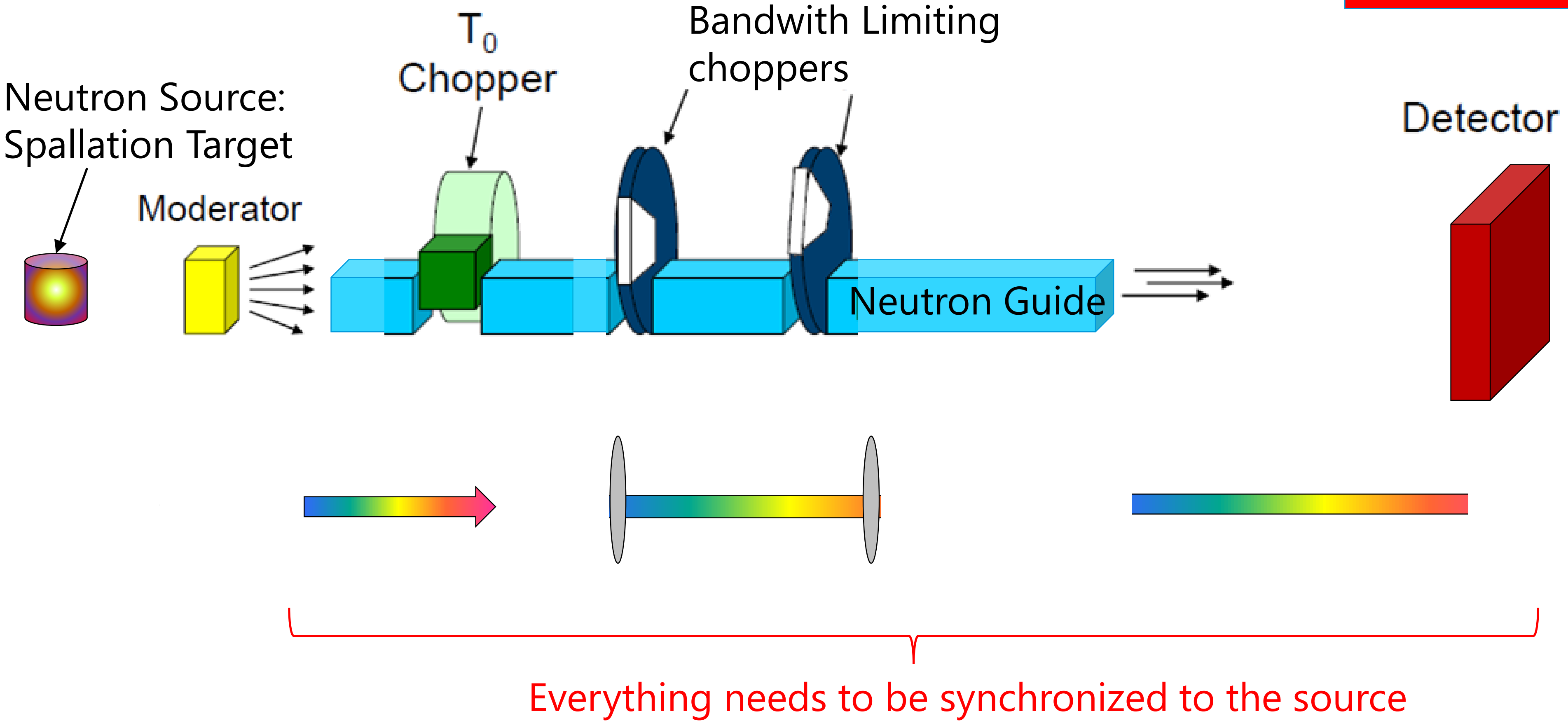


Beam conditioning

Wavelength selection: ToF

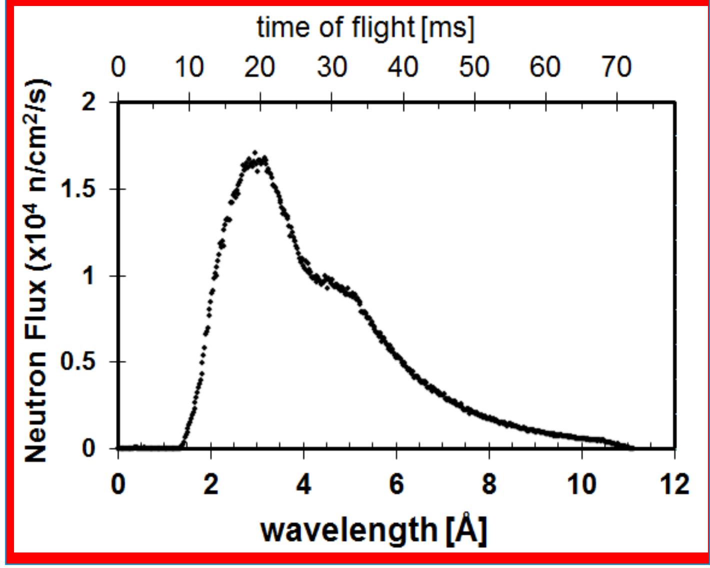
- A generic pulsed source instrument
- Introducing choppers



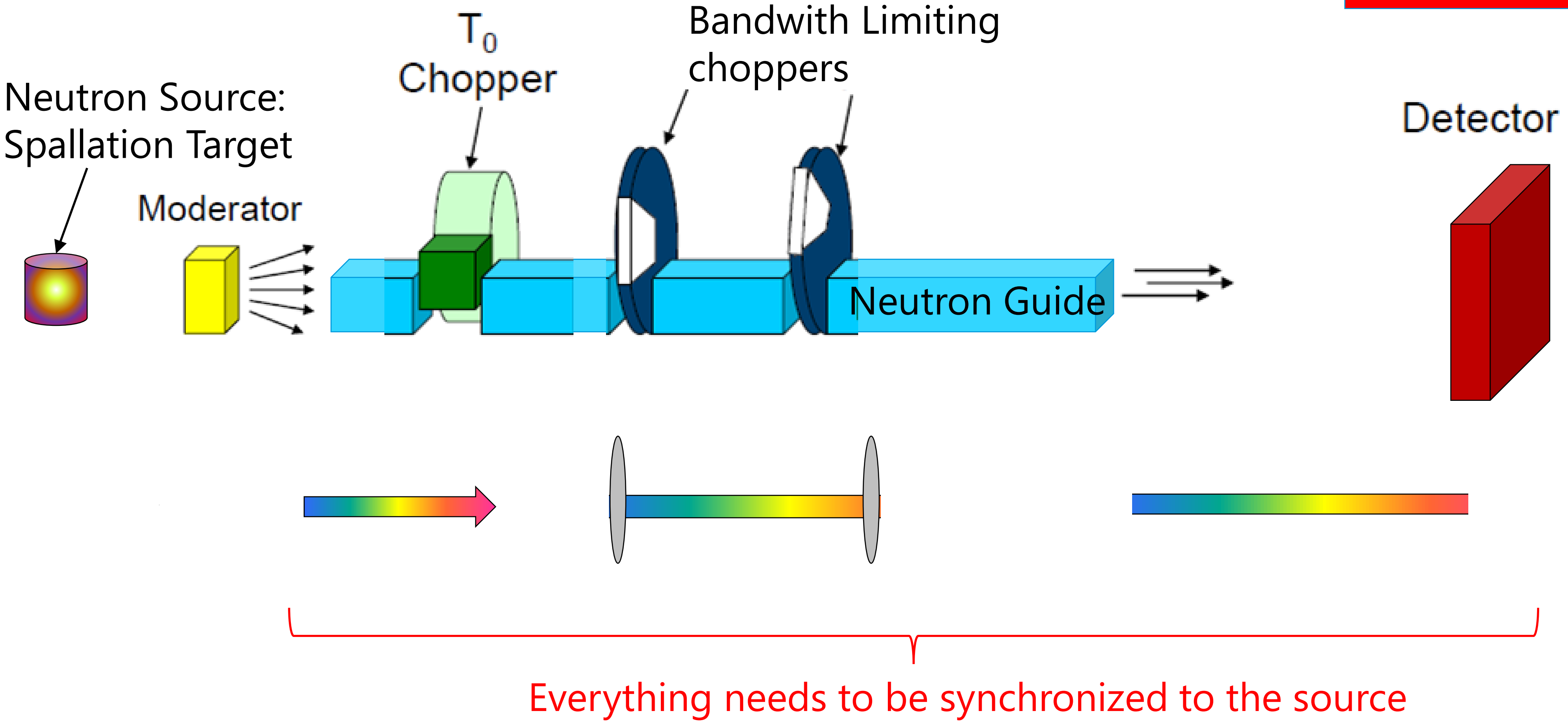


Beam conditioning

Wavelength selection: ToF



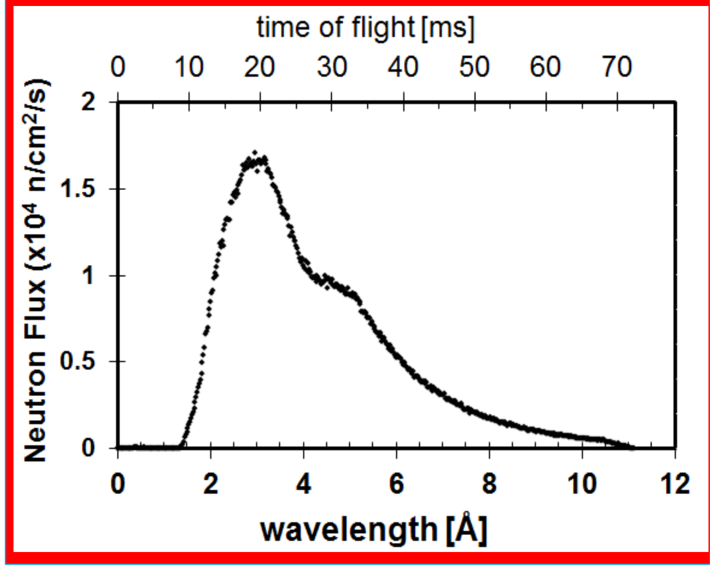
- A generic pulsed source instrument
- Introducing choppers

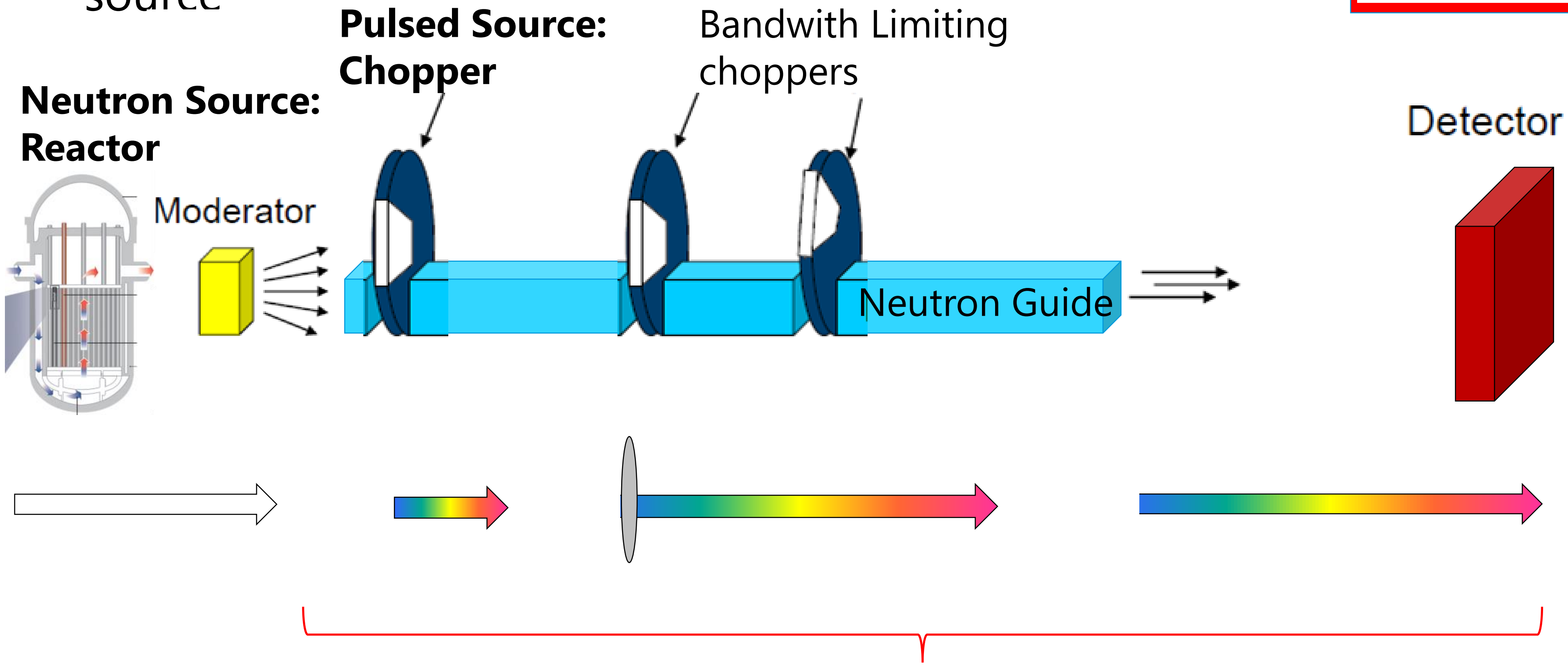


Beam conditioning

Wavelength selection: ToF

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





Everything needs to be synchronized to the source

Beam conditioning

Wavelength selection

Lectures tomorrow!

13:00 → 14:00 **Energy selective imaging 1 (steady state sources)**
Speaker: Nikolay Kardjilov (Helmholtz Berlin)

14:00 → 14:15 Coffee Break

14:15 → 15:45 **Energy selective imaging 2 (ToF)**
Speaker: Robin Woracek (ESS)

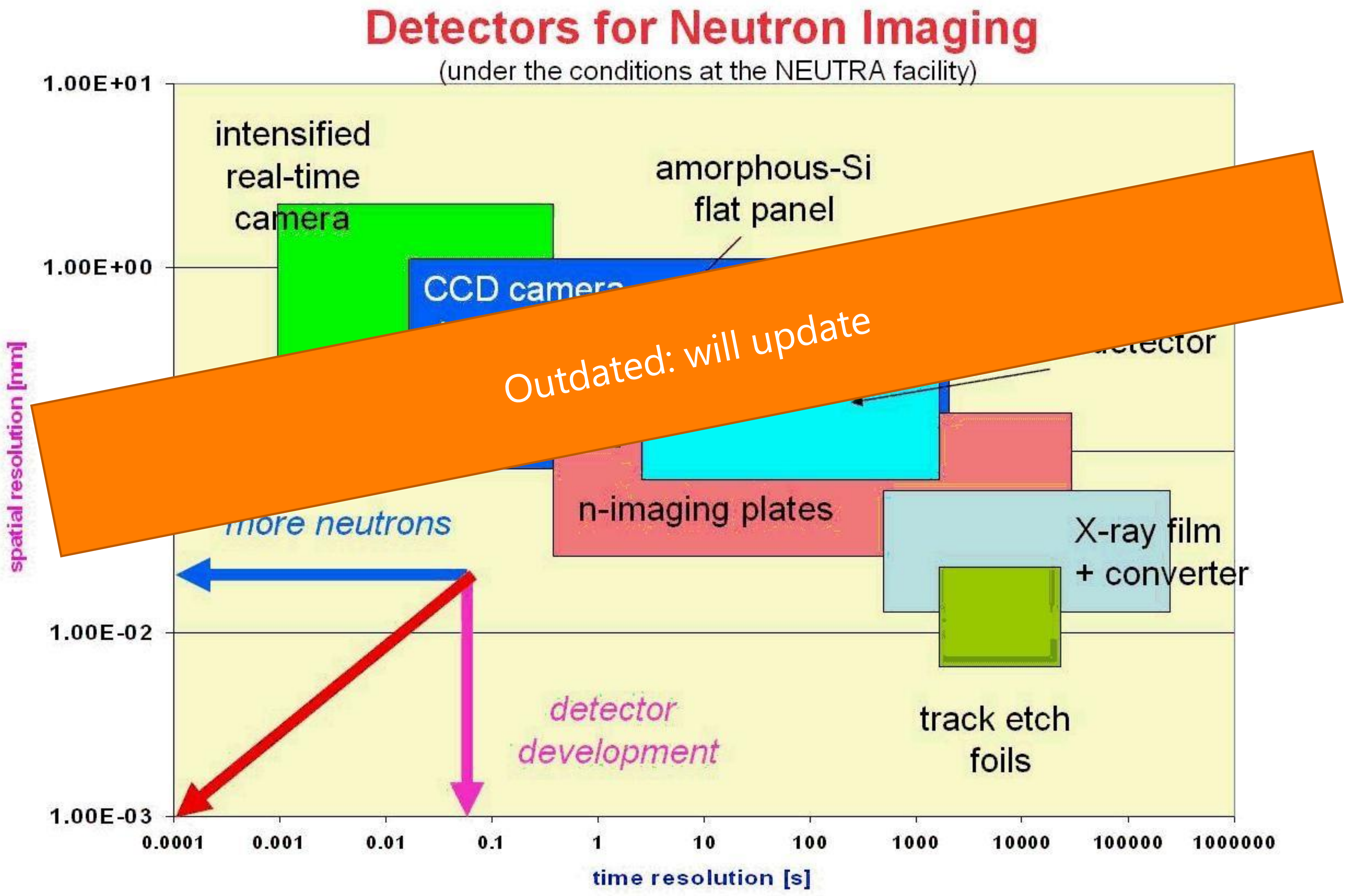
15:45 → 16:00 Coffee Break

Neutron imaging beamlines

- ❑ Historic developments and a generic imaging instrument
- ❑ Neutron Sources
- ❑ ToF vs steady state instruments
- ❑ Neutron Spectrum
- ❑ Instrumentation: Neutron Transport
- ❑ Instrumentation: Beam conditioning
- ❑ Instrumentation: Neutron Detectors
- ❑ Some example Instruments

Detectors

Overview



Detectors

Imaging plate

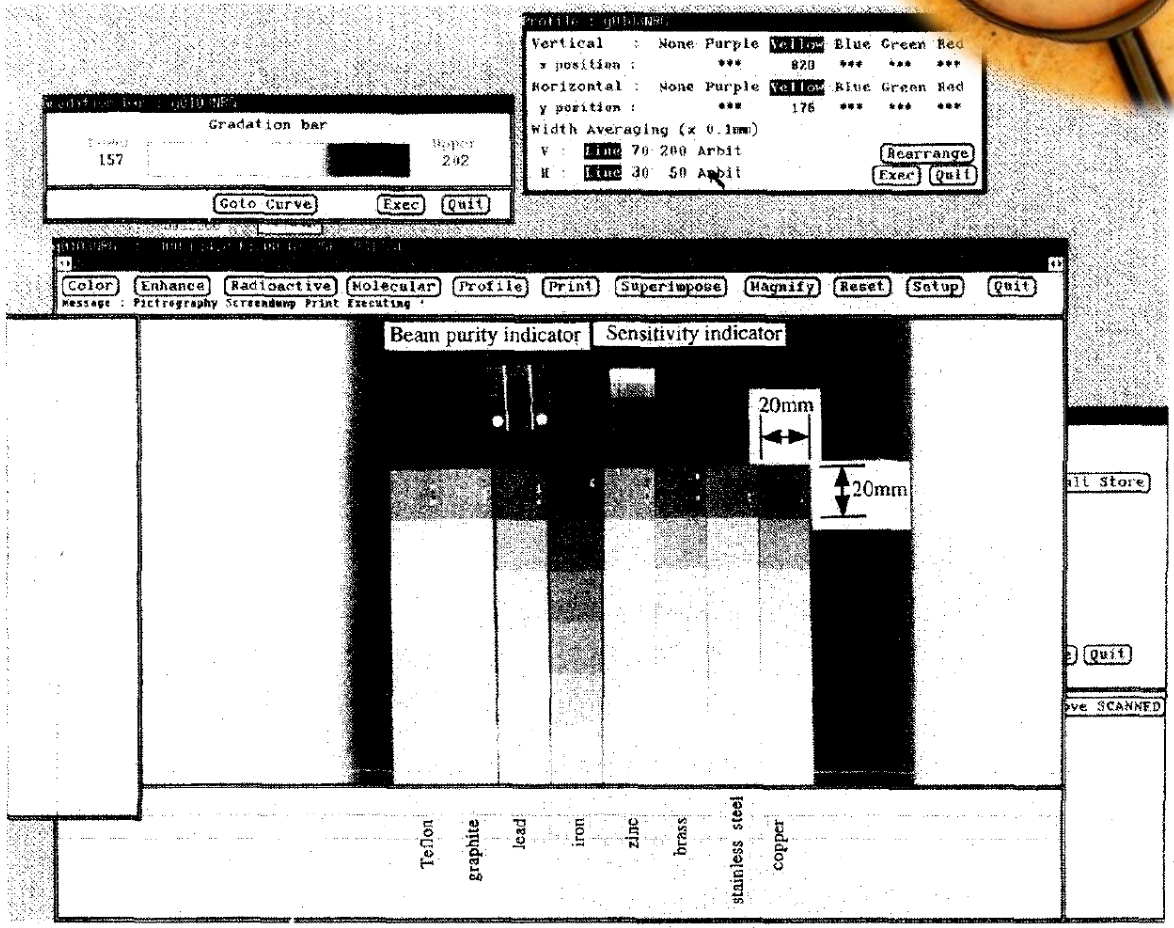
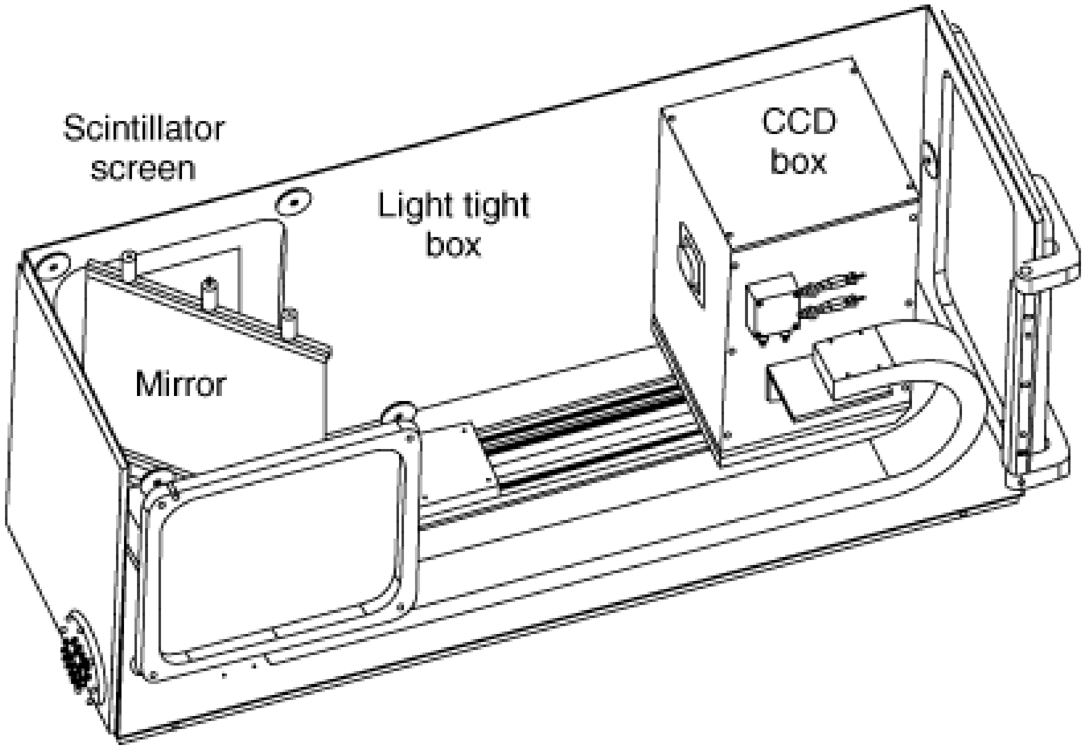


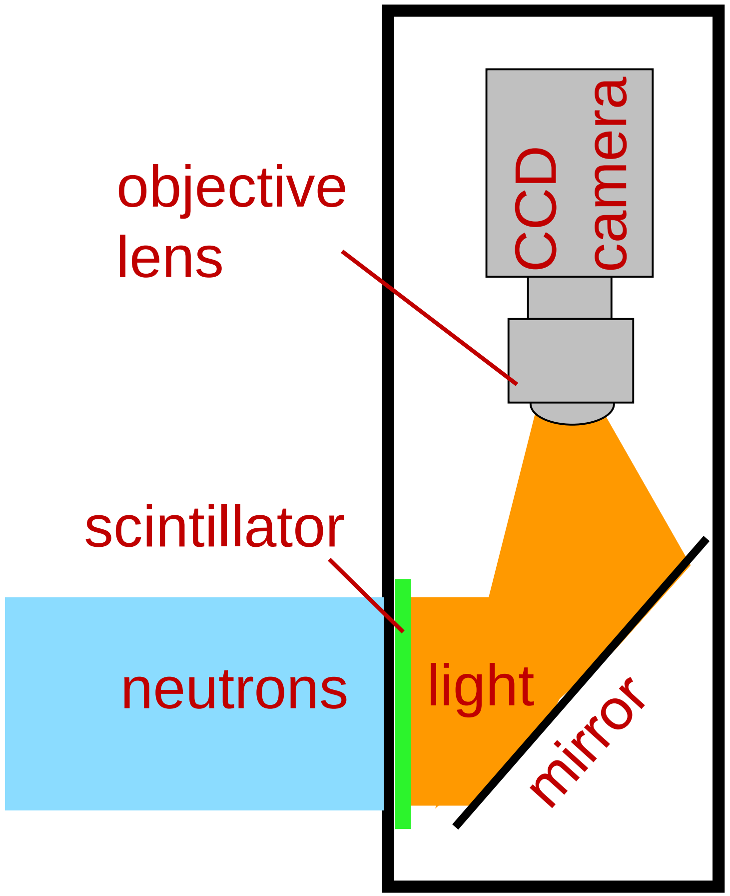
Fig. 4. The neutron radiography images of several standard samples.

Imaging Plates contain Gd as neutron absorber and BaFBr:Eu 2+ as the agent which provides the photoluminescence.
An imaging plate scanner is extracting the latent image information as digitized data file from the plates by de-excitation caused by a laser signal.

Detectors

Camera-Scintillator detectors





Detectors

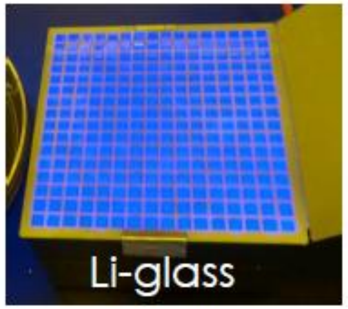
ToF detectors for imaging

A quickly developing field

Detectors at RADEN (JPARC)

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

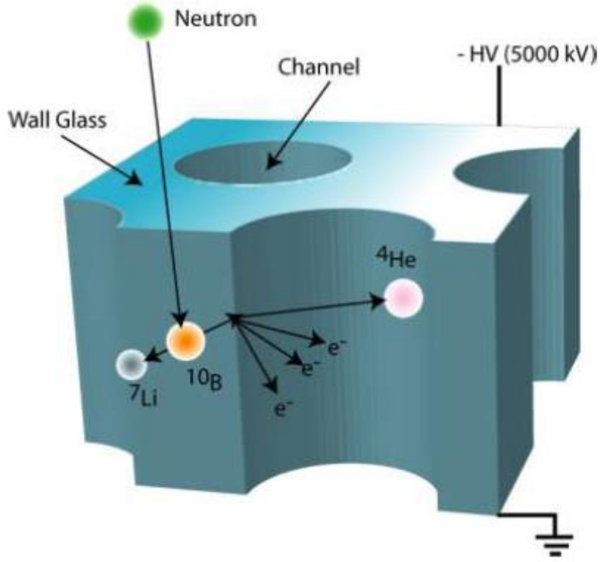
Courtesy: J. Parker

Detectors

ToF detectors for imaging

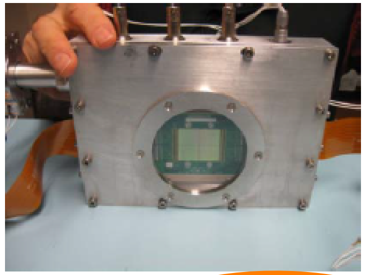
A quickly developing field

MicroChannel Plates (MCP's): Timepix readout



- 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

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

ESS imaging workshop, April 2017

Detectors

Data rates: One example experiment at RADEN

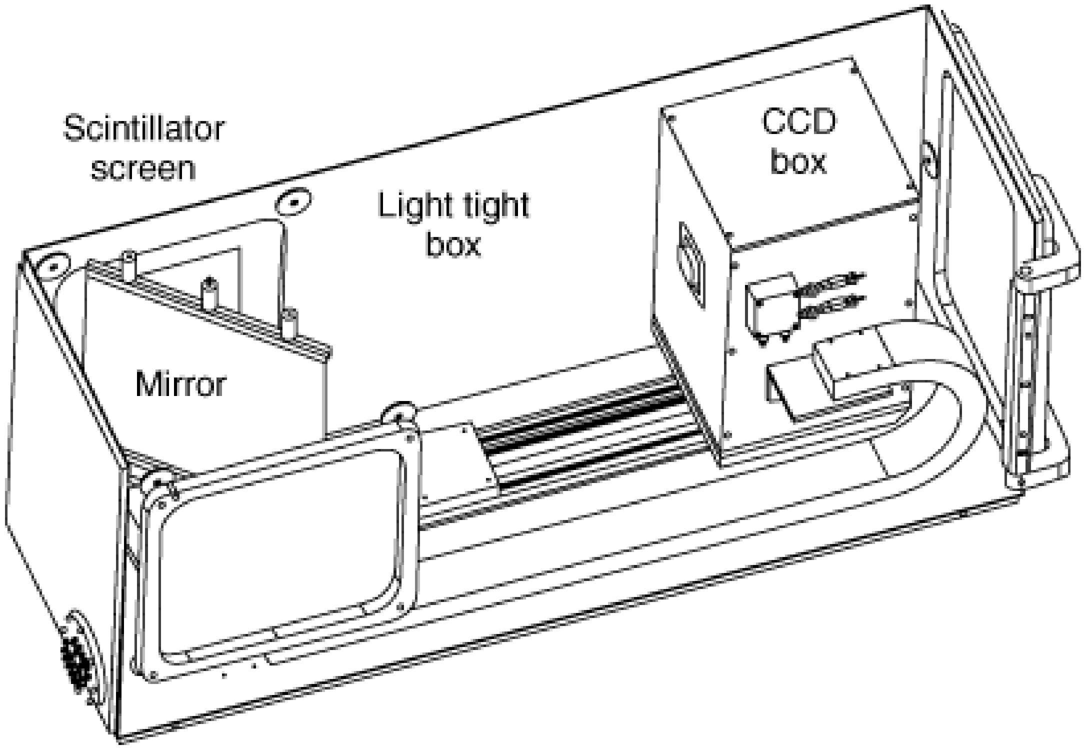
512x512 pixels 16-bit images per time/wavelength bin. The time bin position and width can be freely chosen (to a certain extent) with a small text configuration file that has to be included in the data folder for reference purposes.

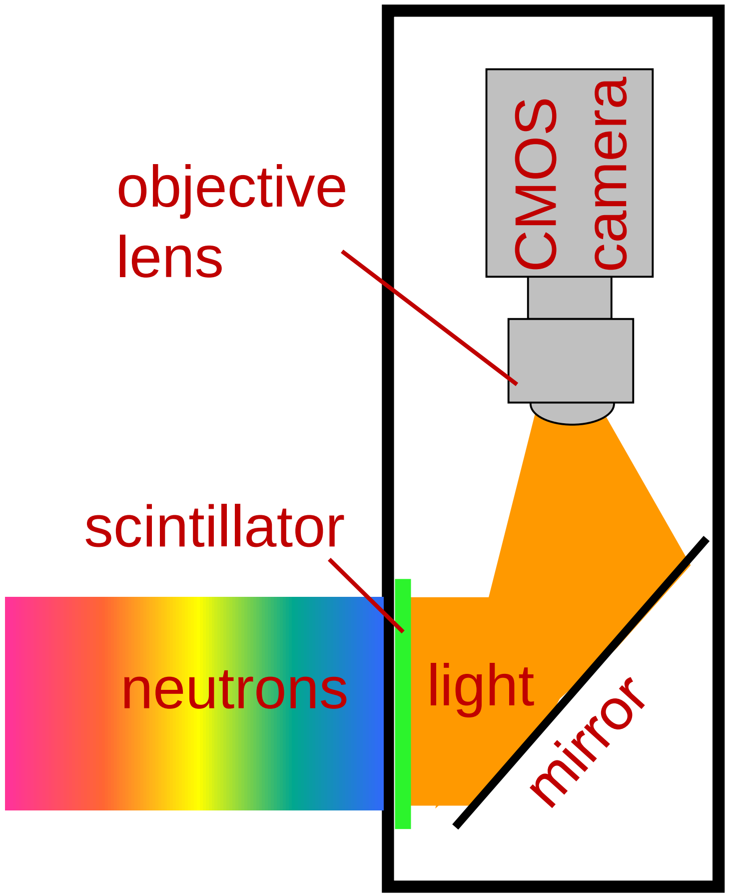
Step	Measurement	Raw data produced (GB)	exposure time (h)	average data rate (GB/h)	Resulting 'raw' data after detector 'correction' (GB)
1	Test Radiographs of a few samples (overnight run after initial setup)	22.0	14.5	1.5	65.9
2	In-situ Furnace test	5.2	1	5.2	15.6
3	Sample alignment	0.5	0.5	1.0	1.5
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

Detectors

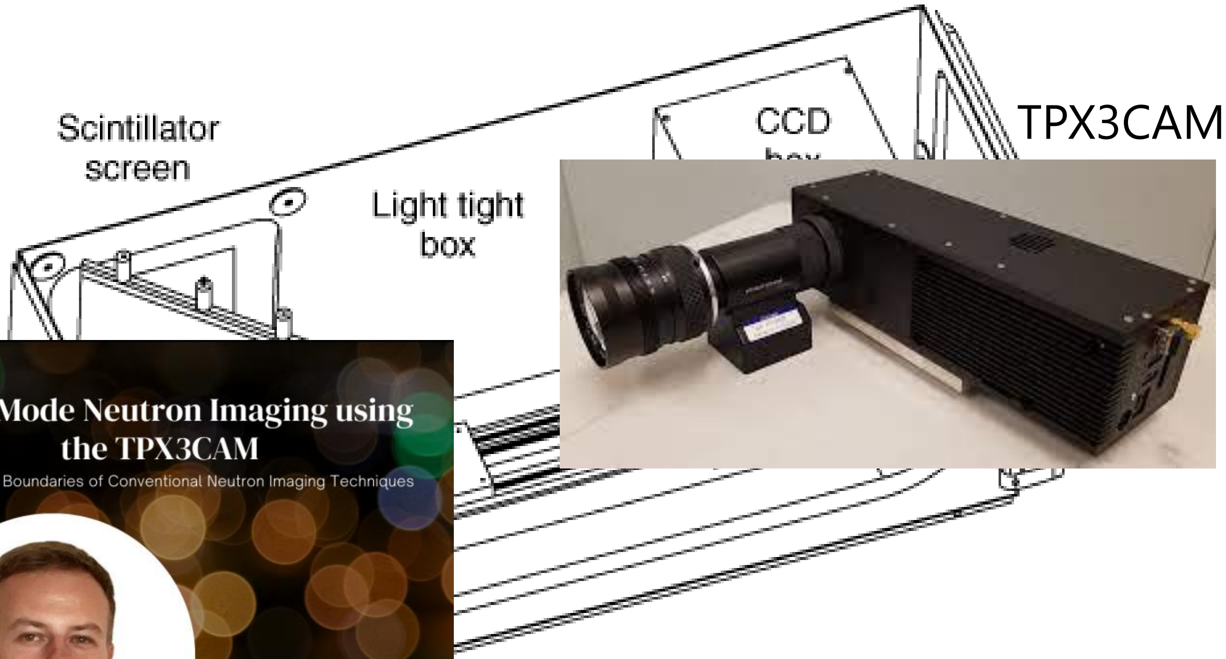
Camera-Scintillator detectors



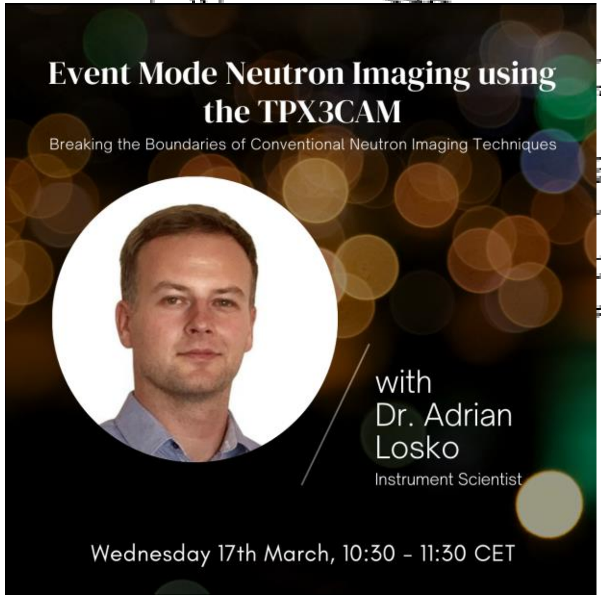


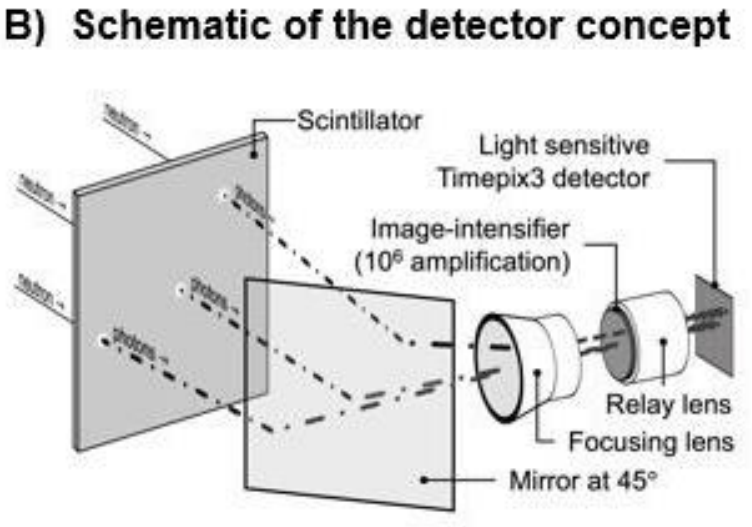
Detectors

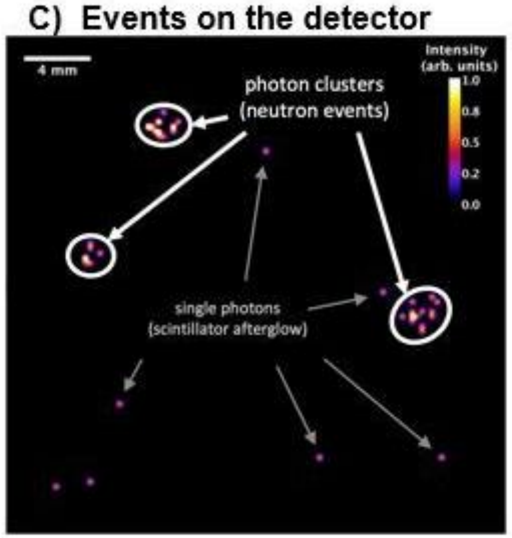
Camera-Scintillator detectors



TPX3CAM







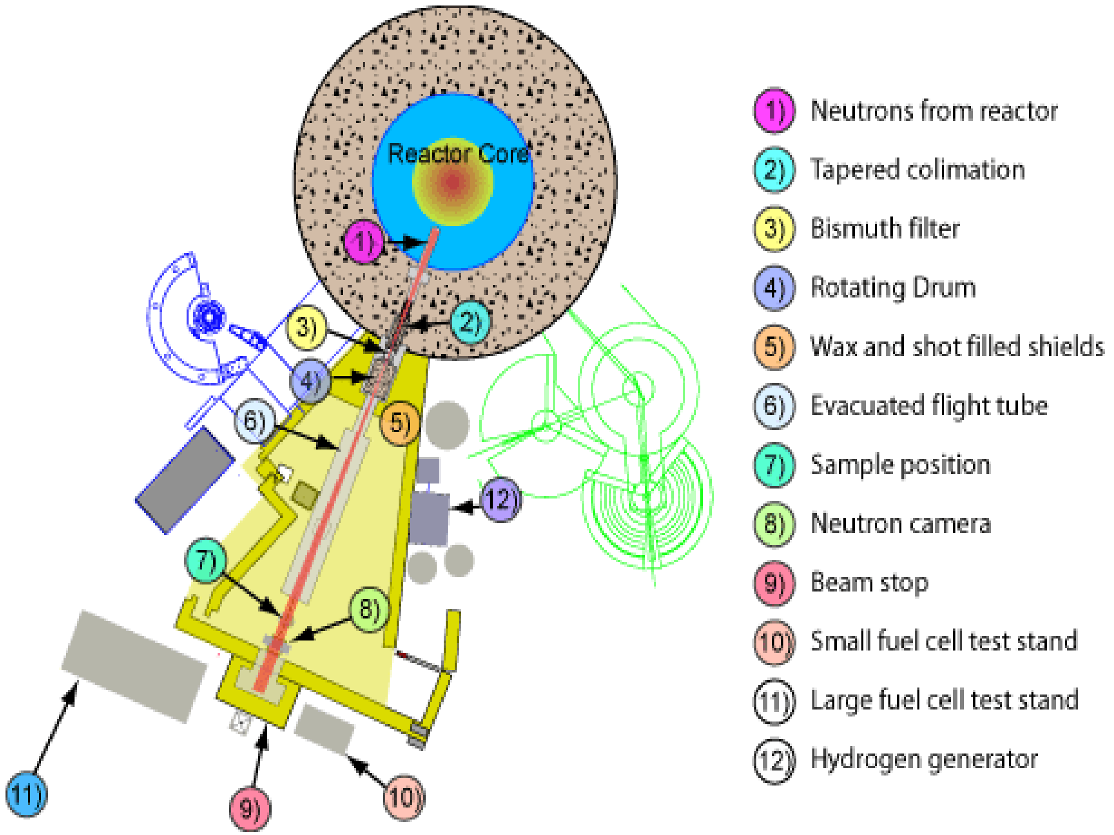
https://www.youtube.com/watch?v=Vl3pRoOf8sA

Neutron imaging beamlines

- ❑ Historic developments and a generic imaging instrument
- ❑ Neutron Sources
- ❑ ToF vs steady state instruments
- ❑ Neutron Spectrum
- ❑ Instrumentation: Neutron Transport
- ❑ Instrumentation: Beam conditioning
- ❑ Instrumentation: Neutron Detectors
- ❑ Some example Instruments

Instruments

NFI (NIST, USA)

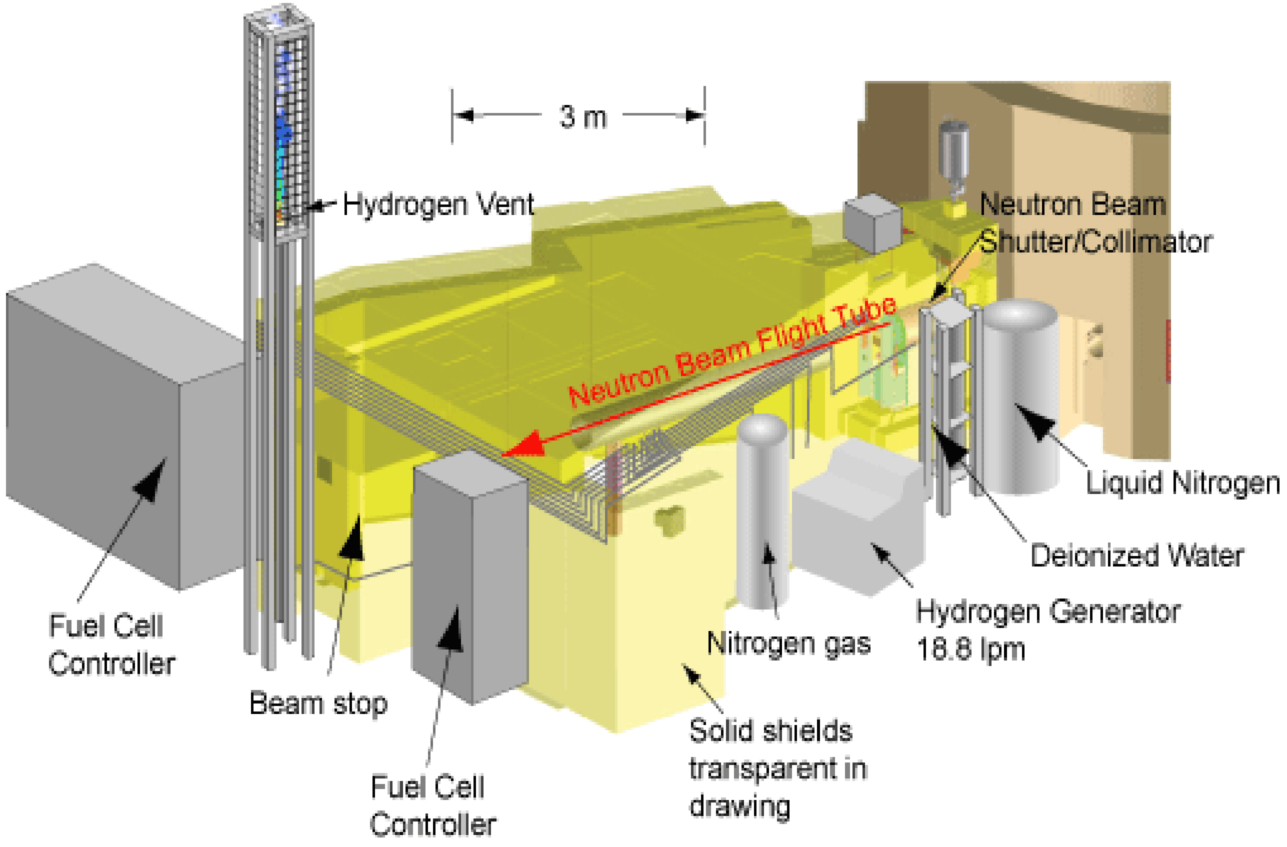


Layout of the neutron imaging instrument at NIST.

Parameter	NIST, USA
Reactor power	20 MW
Beamport	radial
Collimator aperture	2 cm
Distance aperture-sample	6 m
L/D	300
Beam size, diameter	26 cm
Neutron flux	$1x10^8$ n/cm^{2}s
Sample positions	1
Sample manipulator (motorized stages)	N/A

Instruments

NFI (NIST, USA)

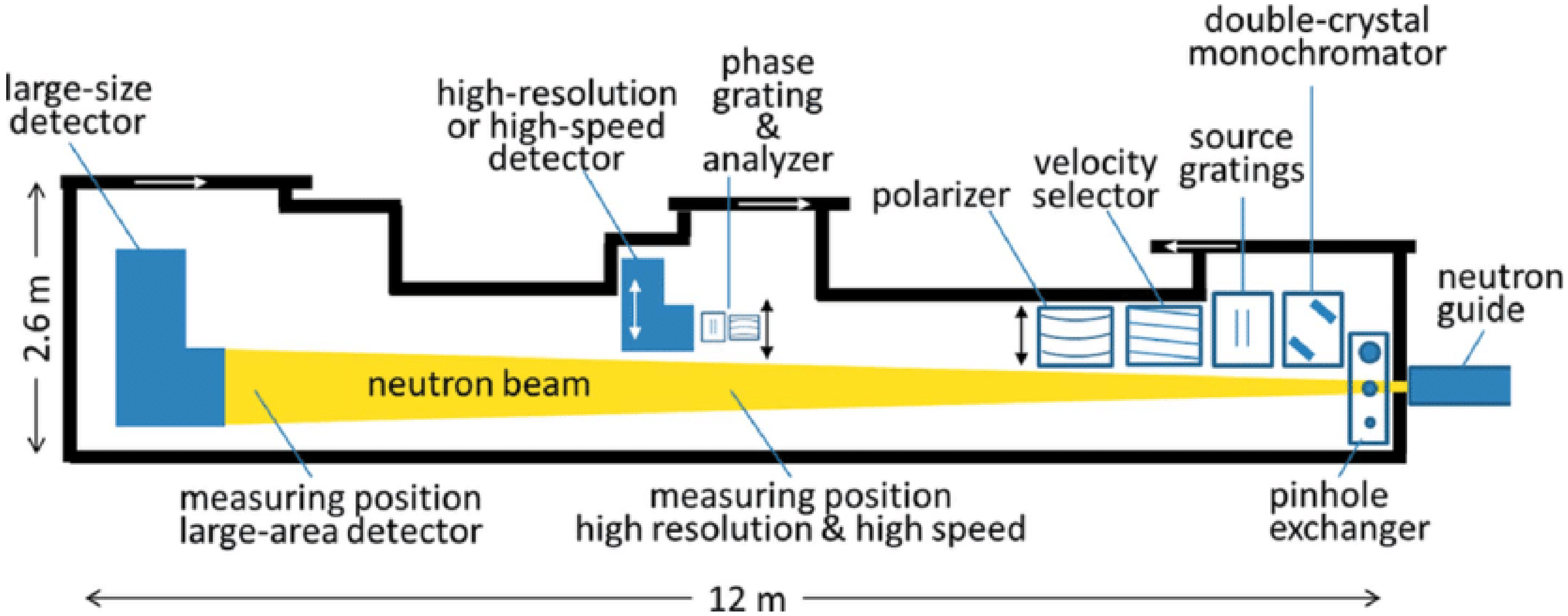


Parameter	NIST, USA
Reactor power	20 MW
Beamport	radial
Collimator aperture	2 cm
Distance aperture-sample	6 m
L/D	300
Beam size, diameter	26 cm
Neutron flux	1×10^8 n/cm^{2}s
Sample positions	1
Sample manipulator (motorized stages)	N/A

Design and infrastructure of the neutron imaging instrument at NIST.

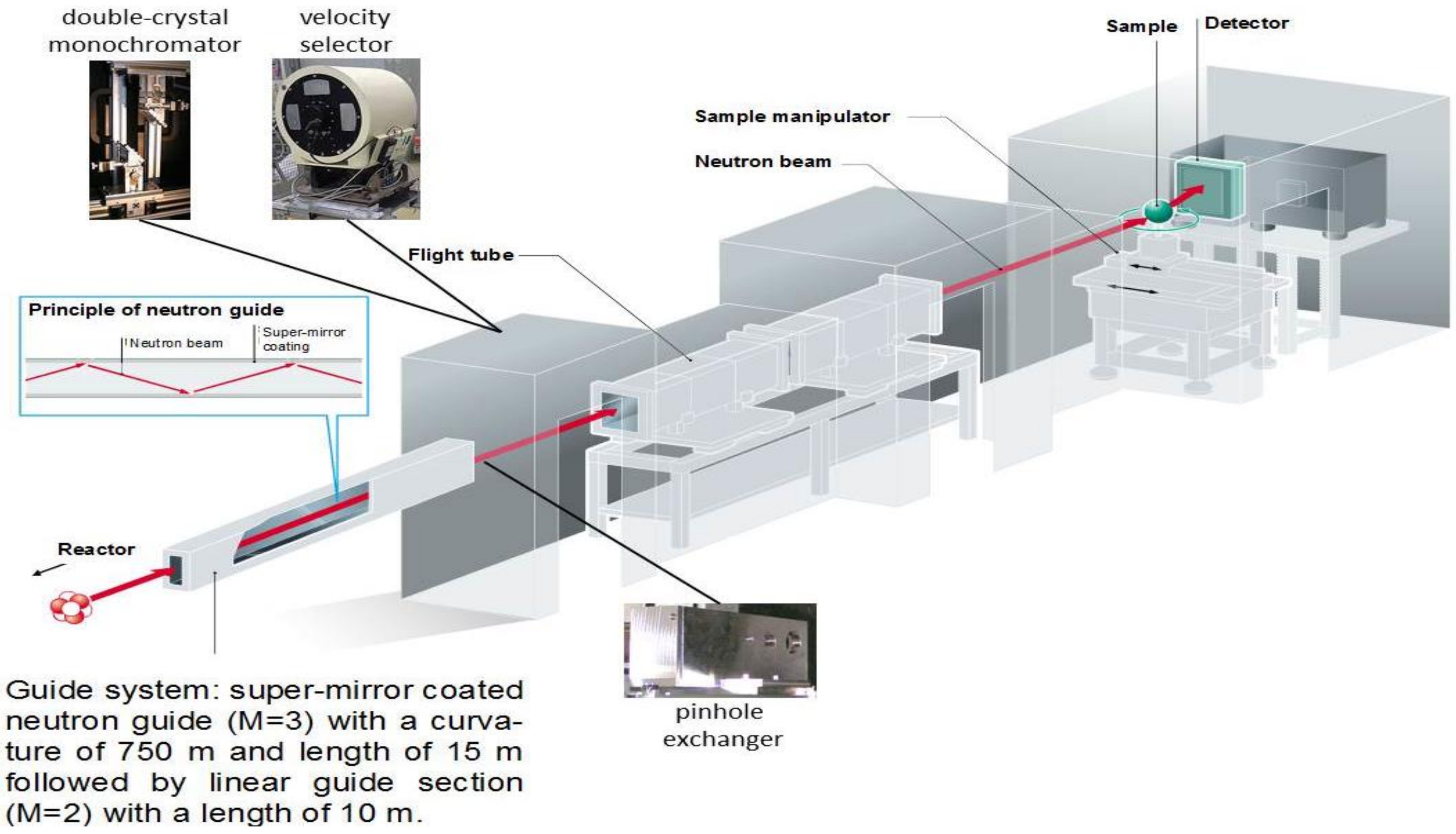
Instruments

CONRAD (HZB) – *closed 2019*



Instruments

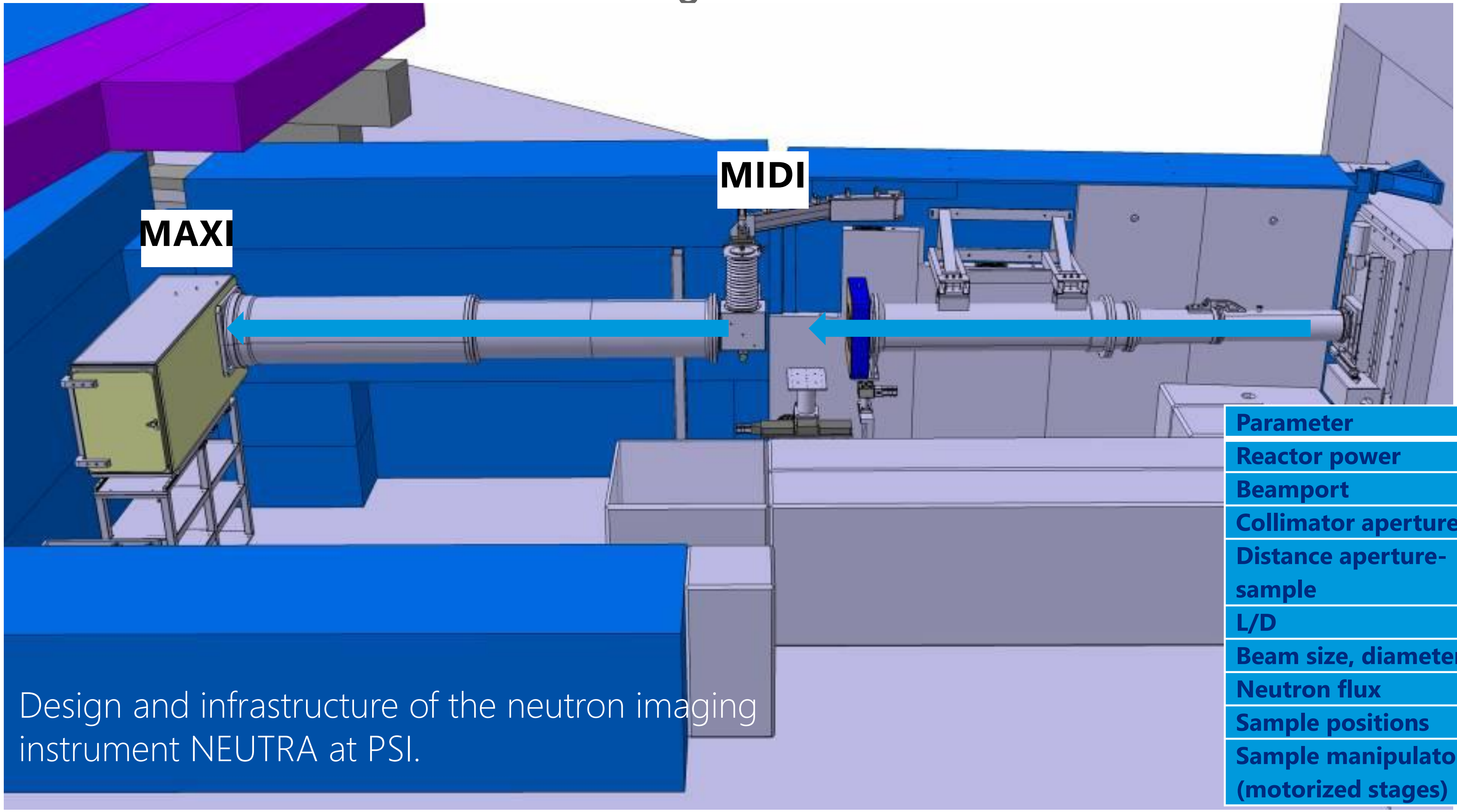
CONRAD (HZB) – *closed 2019*



Instruments

NEUTRA (PSI)

NEUTRA – standard configuration for thermal neutrons

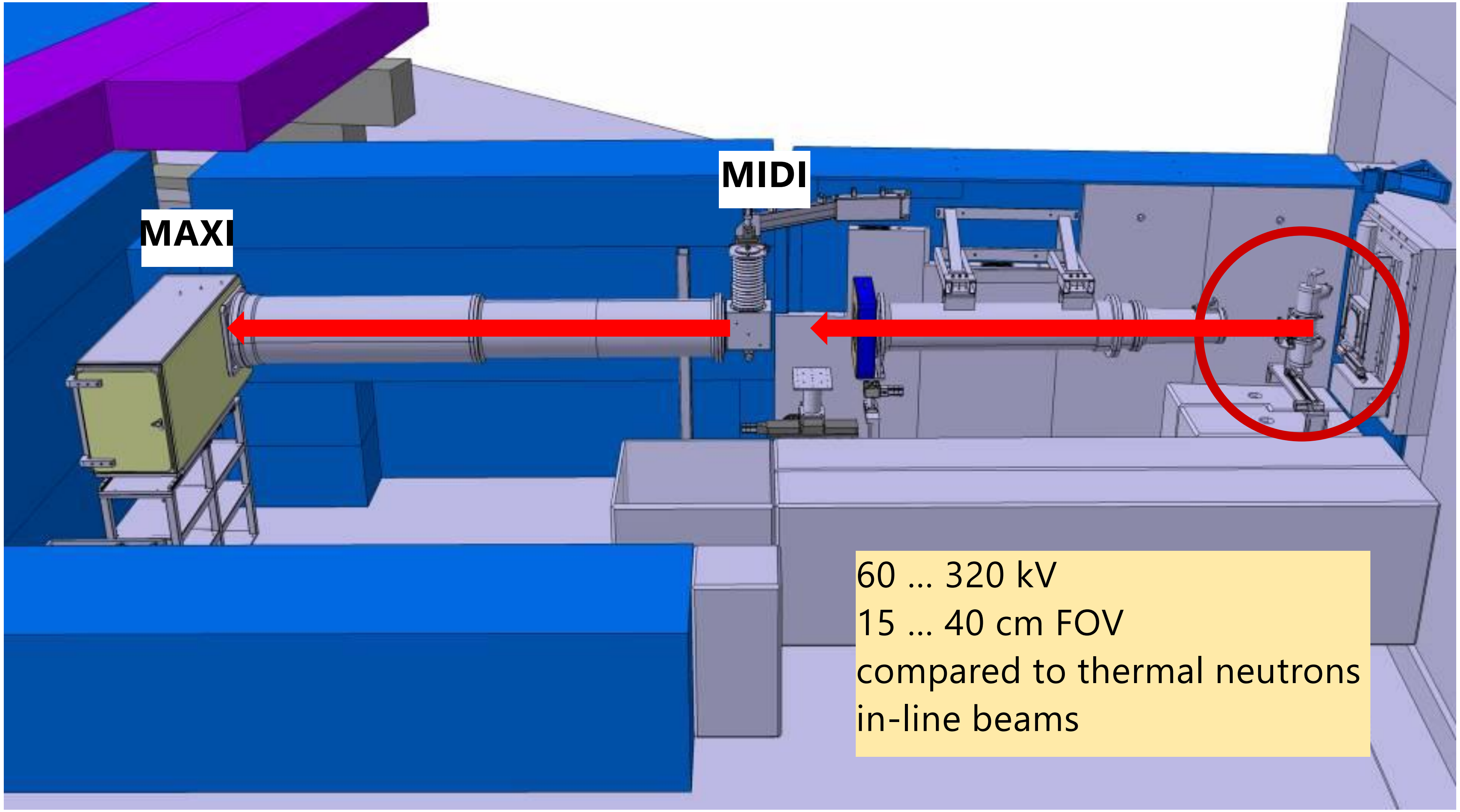


Design and infrastructure of the neutron imaging instrument NEUTRA at PSI.

Parameter	NEUTRA, CH
Reactor power	Spallation source
Beamport	tangetial
Collimator aperture	2 cm
Distance aperture-sample	10 m
L/D	500
Beam size, diameter	40 cm
Neutron flux	$5x10^6$ n/cm^2s
Sample positions	2
Sample manipulator (motorized stages)	-

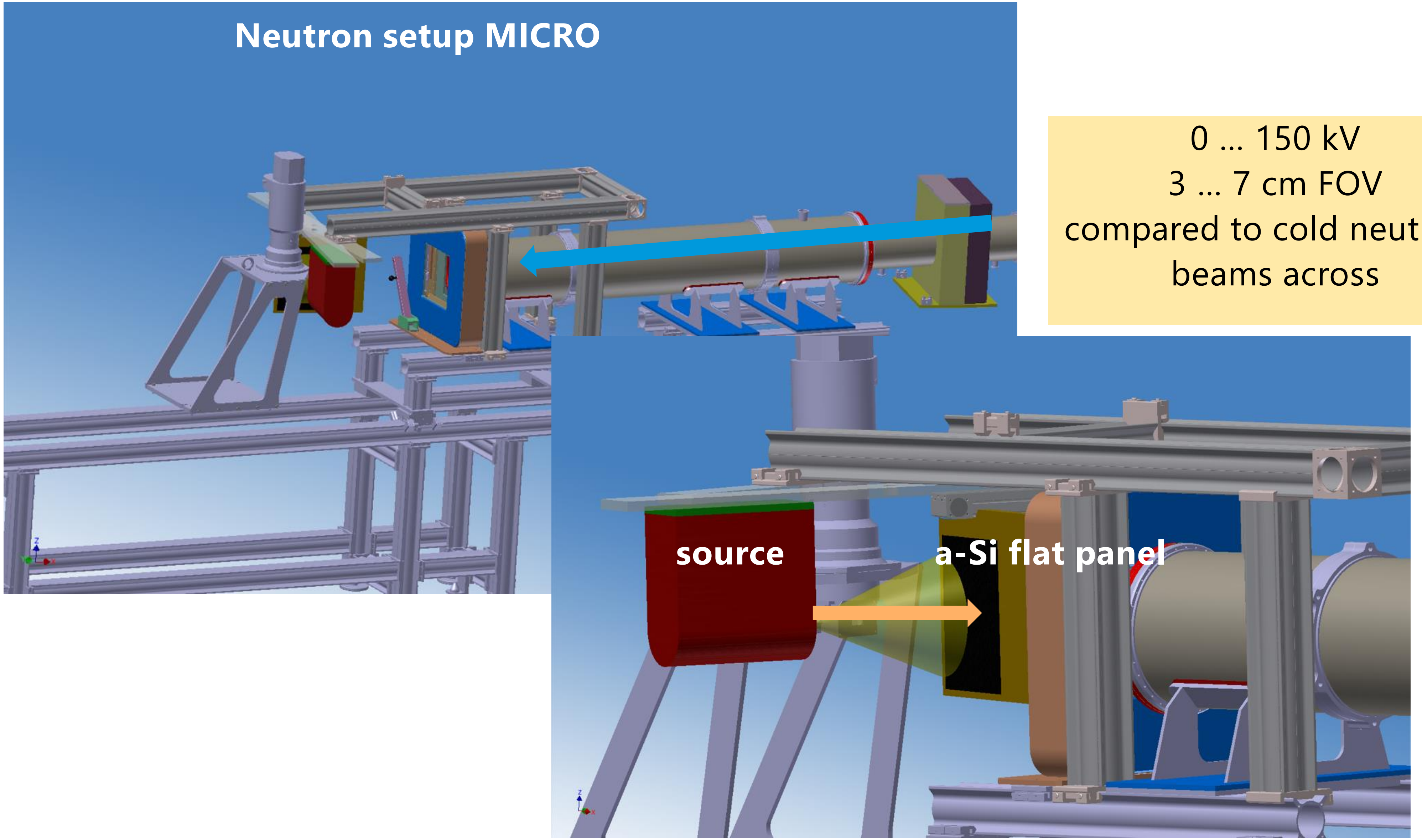
Instruments

NEUTRA (PSI)



Instruments

ICON (PSI)



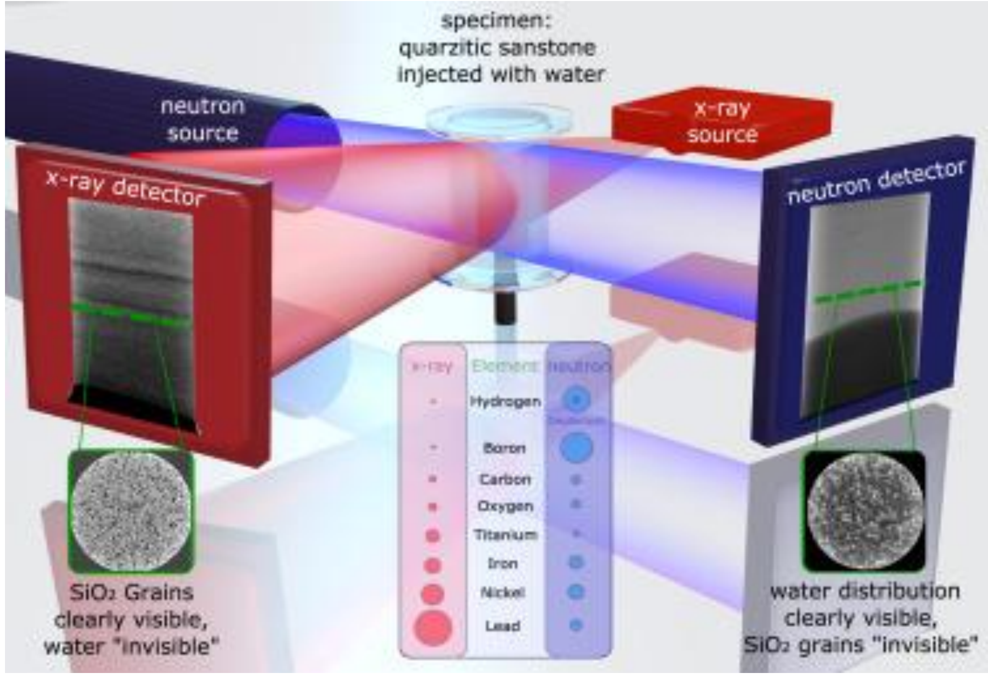
0 … 150 kV
3 … 7 cm FOV
compared to cold neutrons
beams across

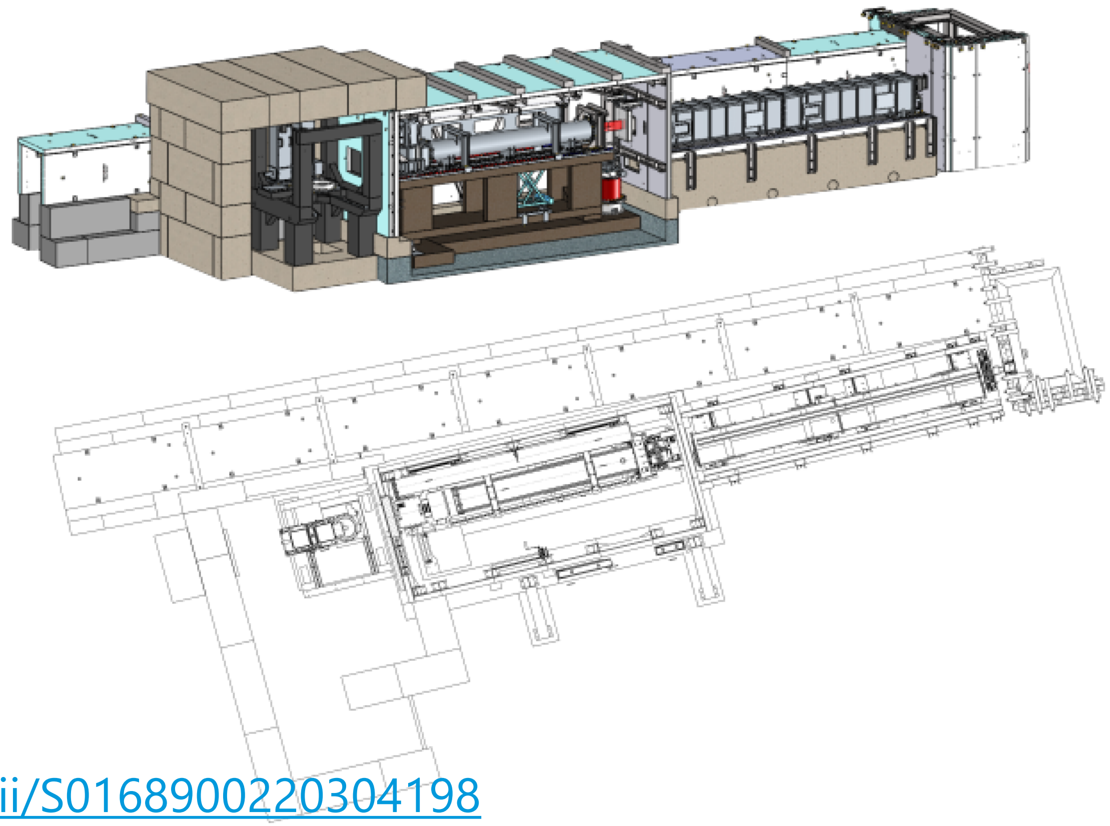
Instruments

NeXT (ILL)

The ILL is the world's most powerful neutron source with its 1.5E15 thermal neutrons neutrons per second per cm2 (n/s/cm2)

Neutron Flux at the instrument: 9*10E7 n/s/cm2 (for a collimation L/D = 500)
Collimation: L = 10m, Range of pinholes from 30 mm to 1.5 mm .





https://www.sciencedirect.com/science/article/pii/S0168900220304198

Instruments

RADEN (J-PARC)

J-PARC -Japan Proton Accelerator Research Complex-

3 proton accelerators

Instruments

RADEN (J-PARC)

RADEN -Energy-Resolved Neutron Imaging System-

J-PARC

The first instrument dedicated to Energy-Resolved Neutron Imaging

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

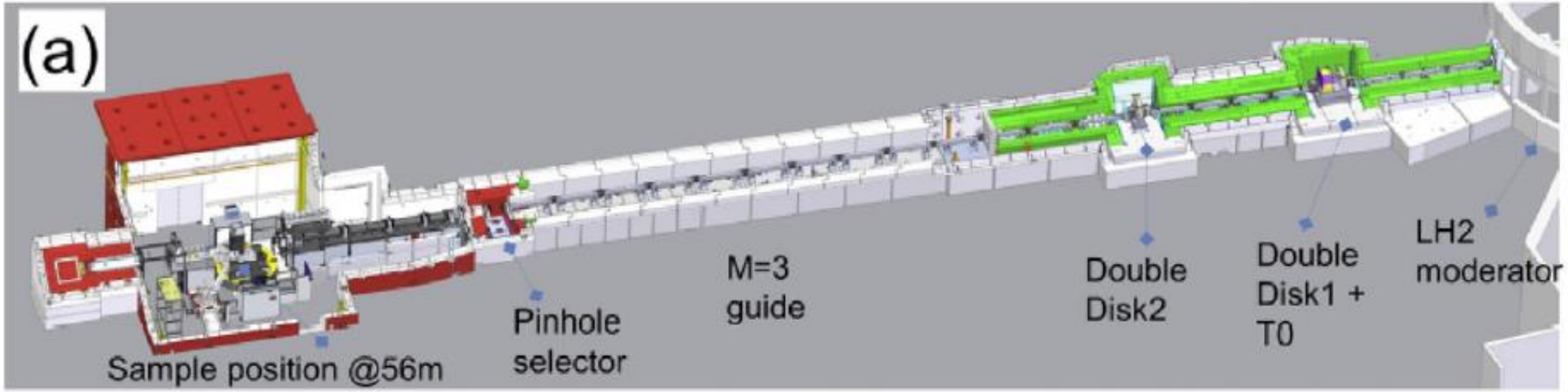
Instruments

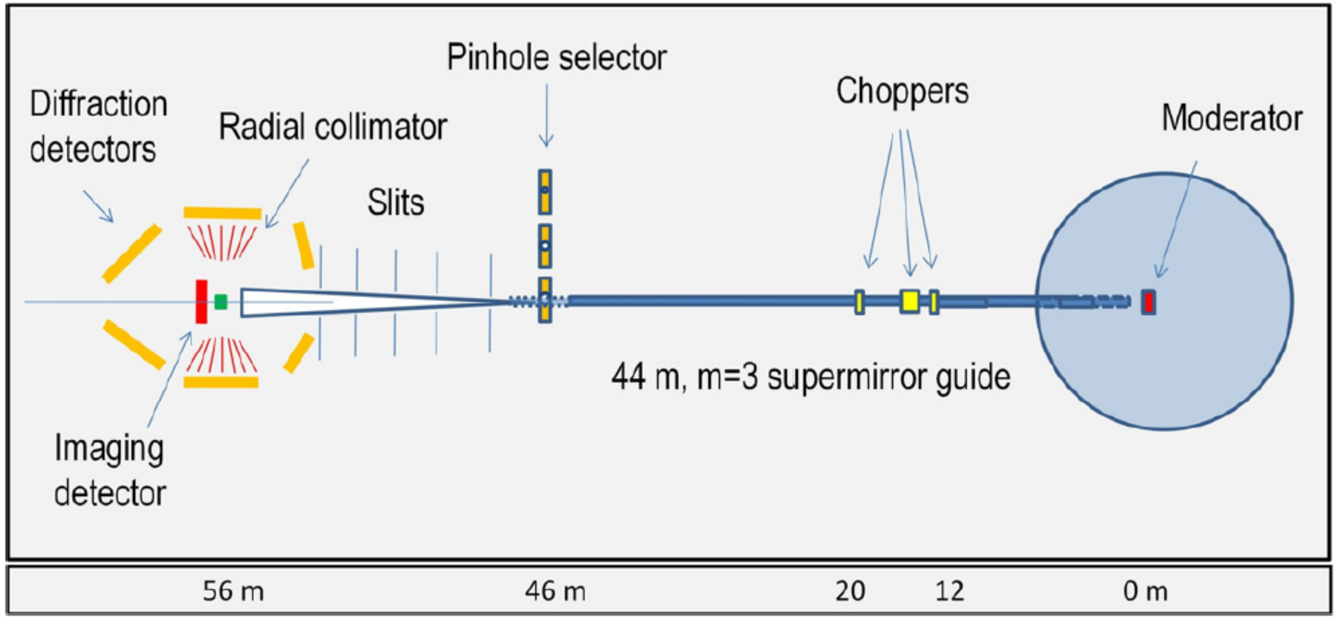
RADEN (J-PARC)

Credit: M. Sales and all....

Instruments

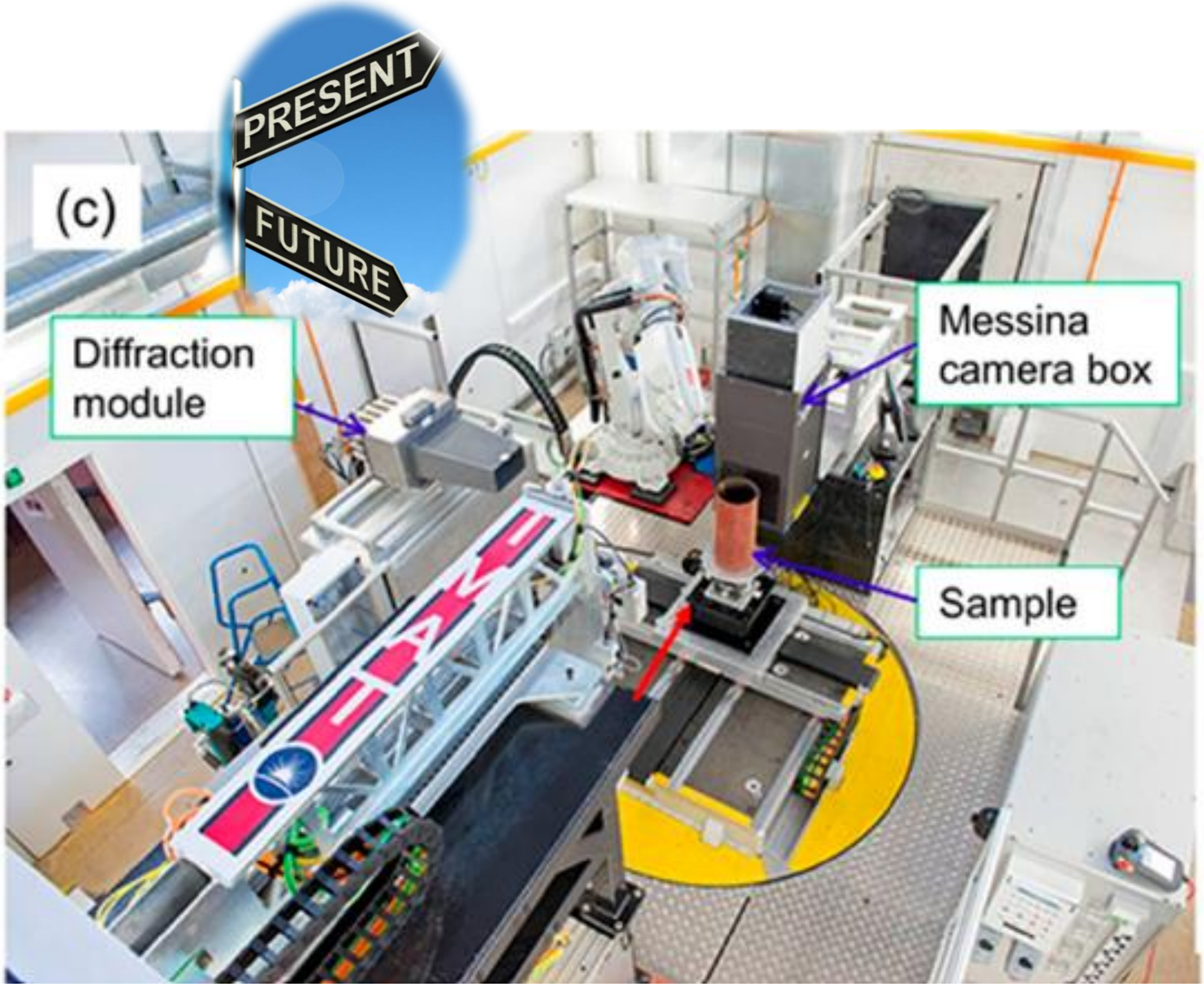
IMAT (ISIS)





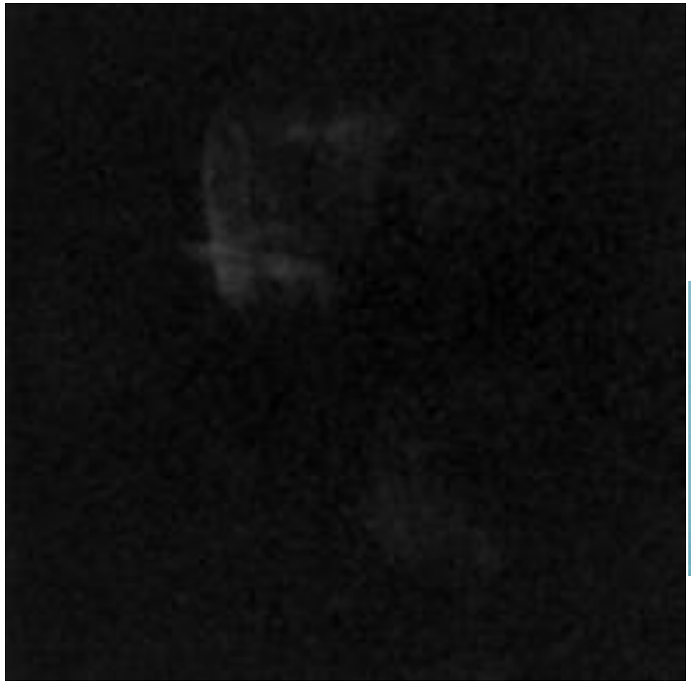
Instruments

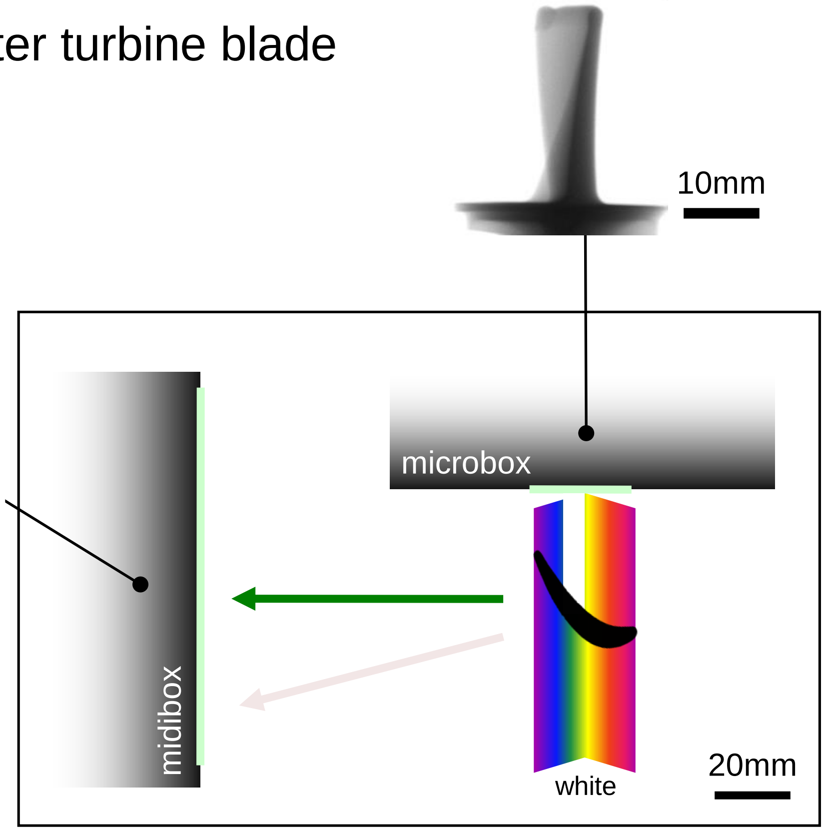
IMAT (ISIS)



Single crystal imaging: practical application

Single crystal nickel-based superalloy helicopter turbine blade





Access to crystalline properties at short exposure times (μ: 10s ; m: 14s)

Instruments

IMAT (ISIS)

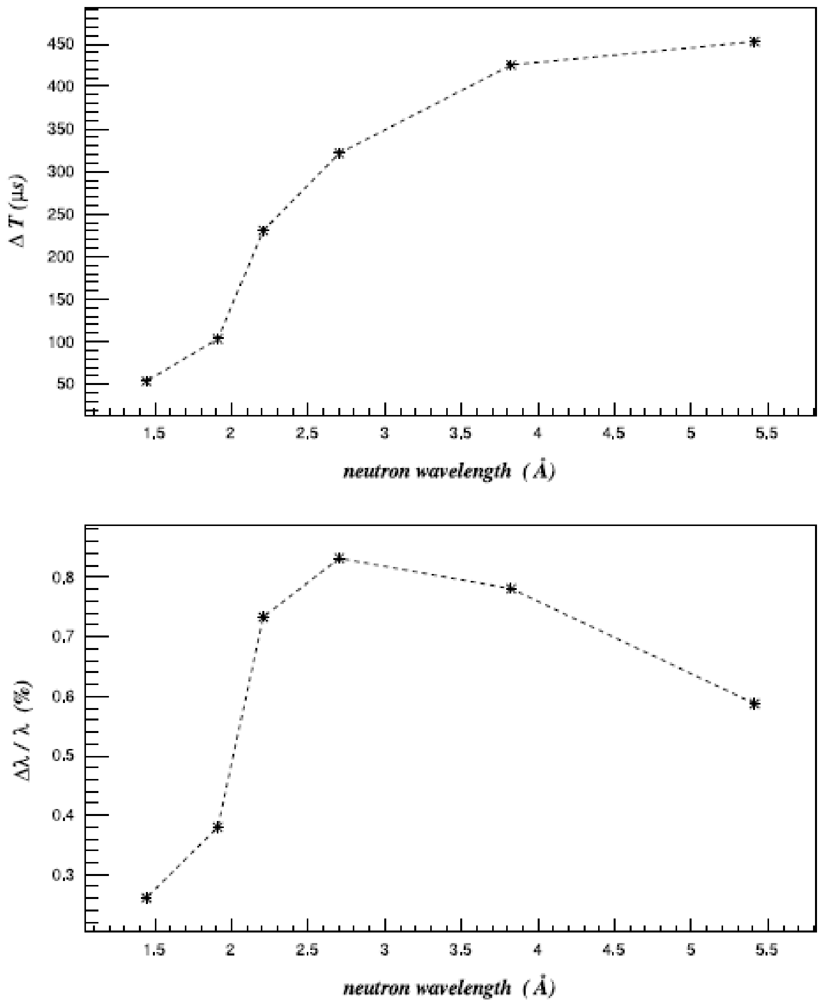
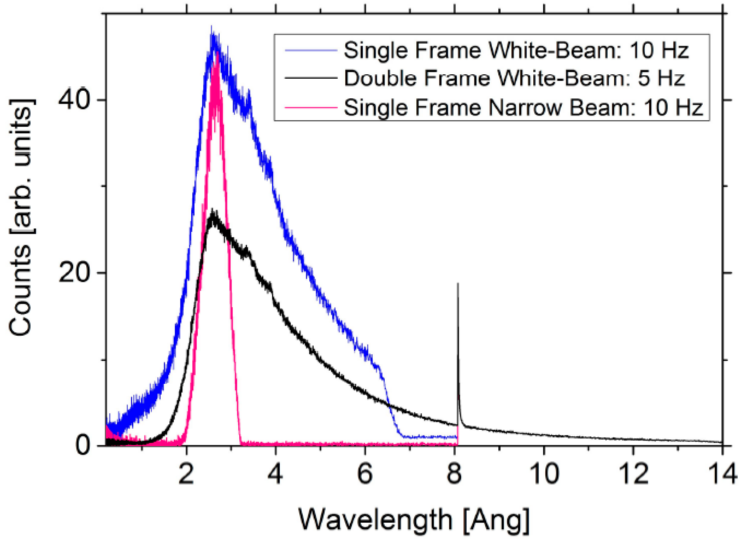


Fig. 16. Neutron pulse width Δt (μs) (top panel), resolution $\Delta\lambda/\lambda$(%) as a function of the neutron wavelength (bottom panel).

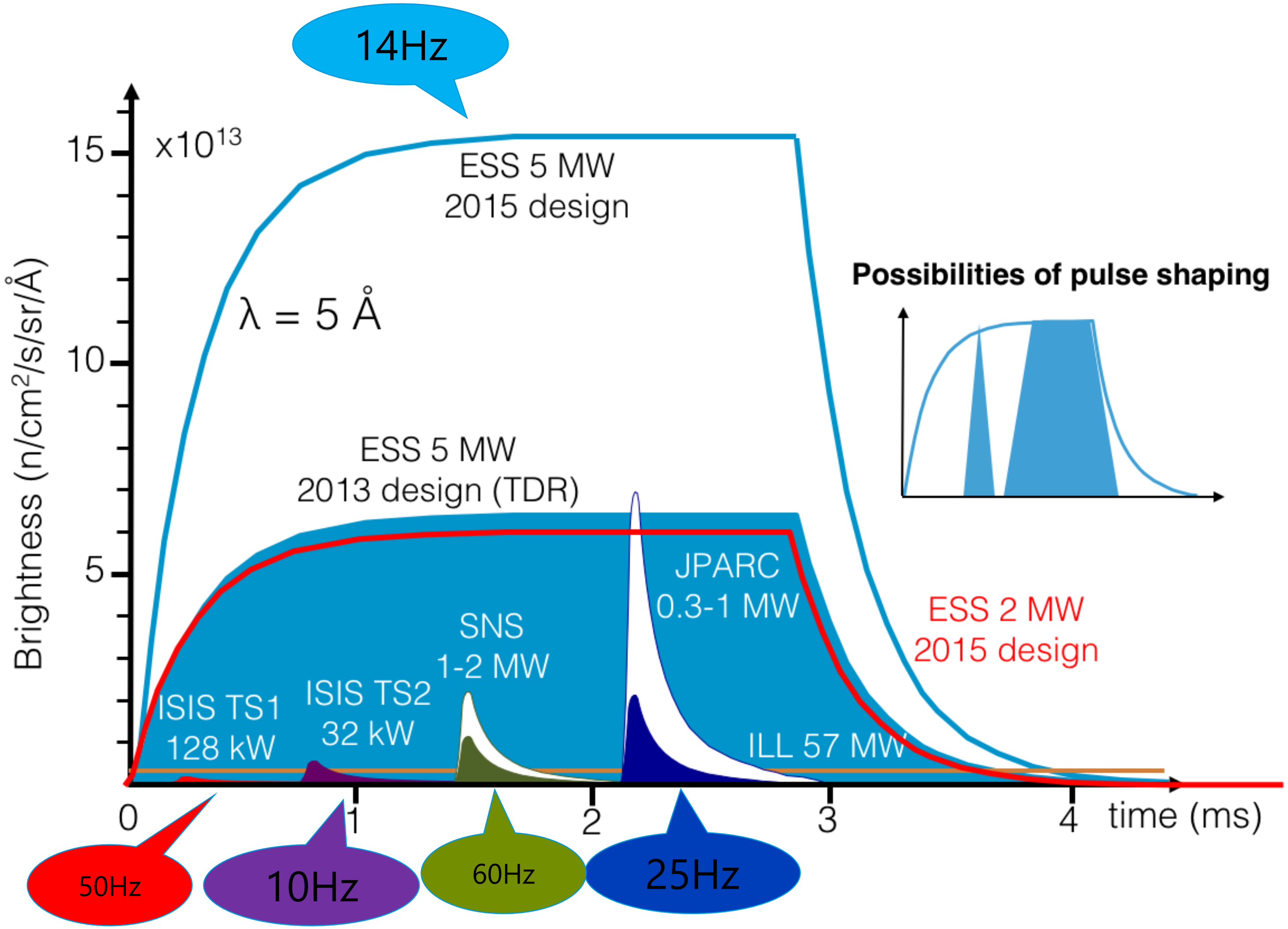


Neutron source	TS-2; 10 Hz pulsed; tungsten target Coupled liquid H-moderator at 18 K
Single frame bandwidth	6 Å (measured)
Flight path to sample	56 m (measured)
L: Distance pinhole – sample D: Aperture diameter	10 m 5, 10, 20, 40, 80 mm L/D: 2000, 1000, 500, 250, 125 (nominal) L/D: 2000, 1150, 510, 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) $\Delta\lambda/\lambda < 0.8$ % (> 2 Å) (measured)

Instruments

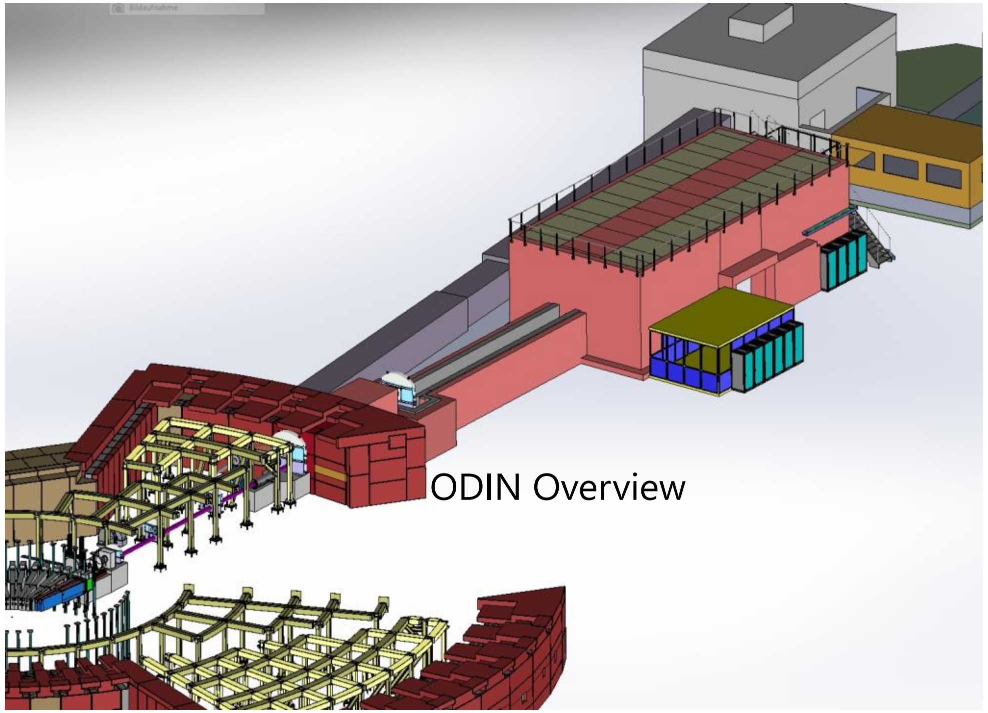
ODIN (ESS)

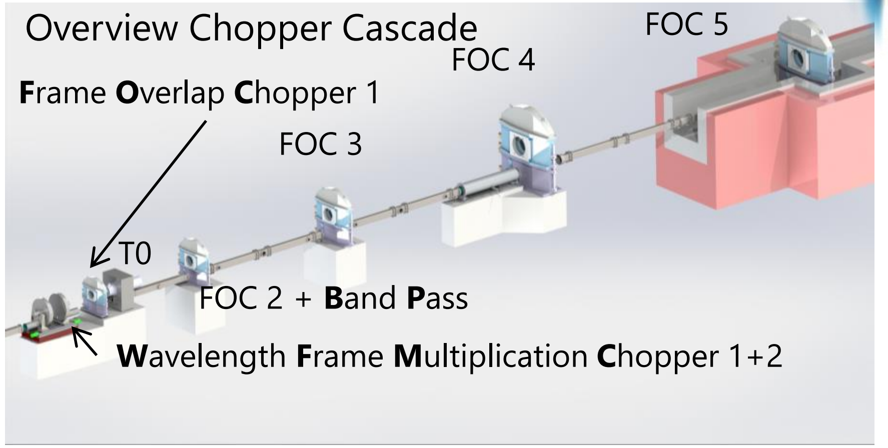
- ESS will be the first Long Pulse Spallation Source

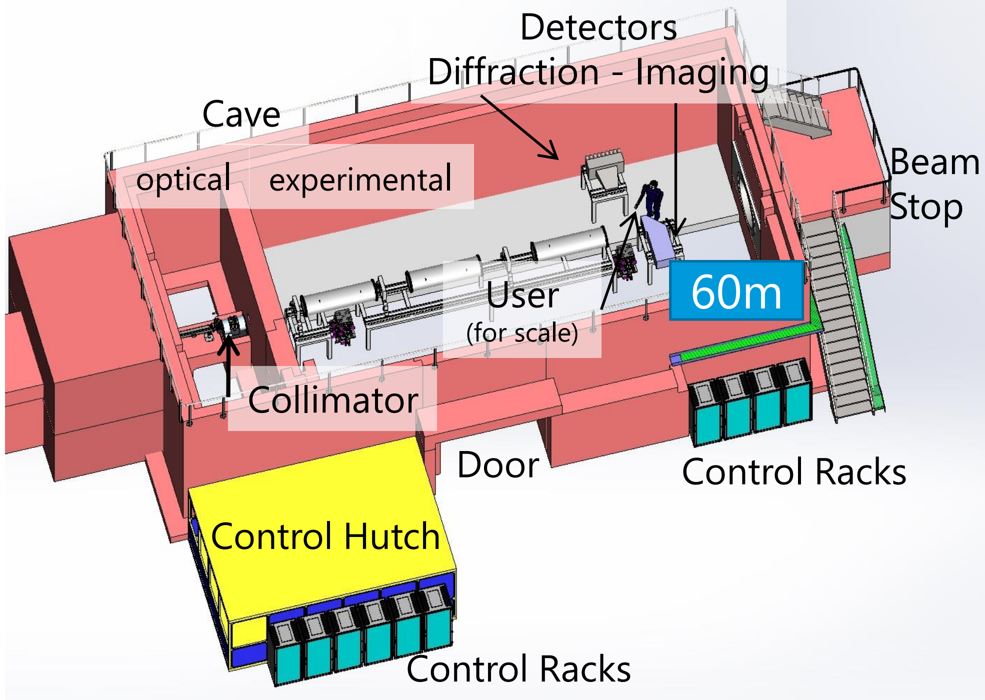


Instruments

ODIN (ESS)





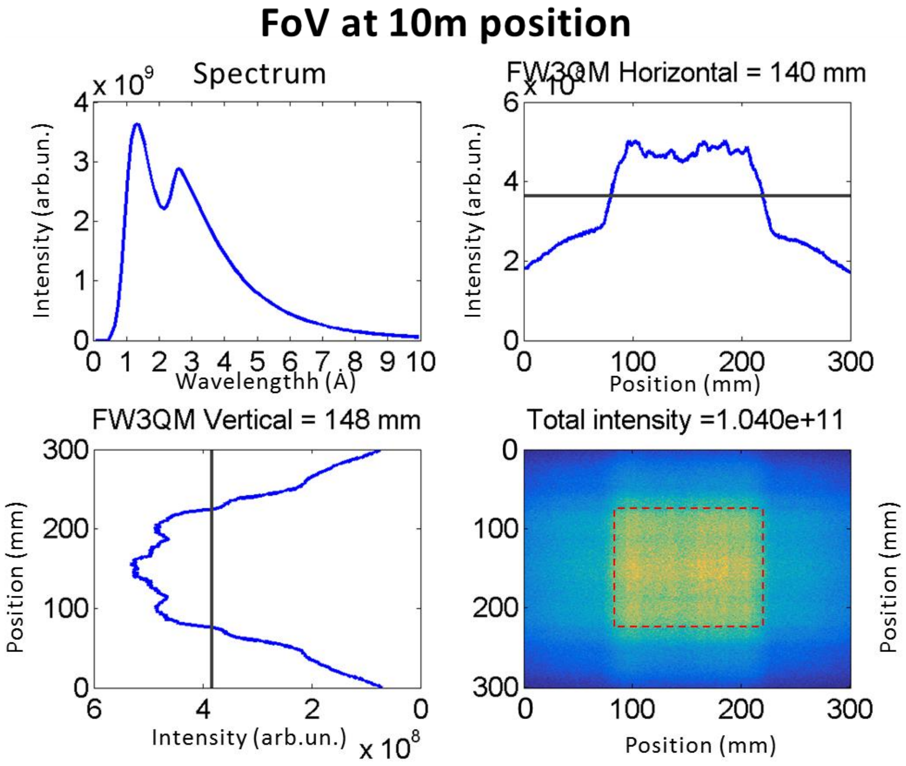


- source-sample distance of 60m will give a natural resolution of 10%
- complex chopper system will provide wavelength resolution of 0.3-1%
- large experimental station this will offer unprecedented versatility

Instruments

ODIN (ESS)

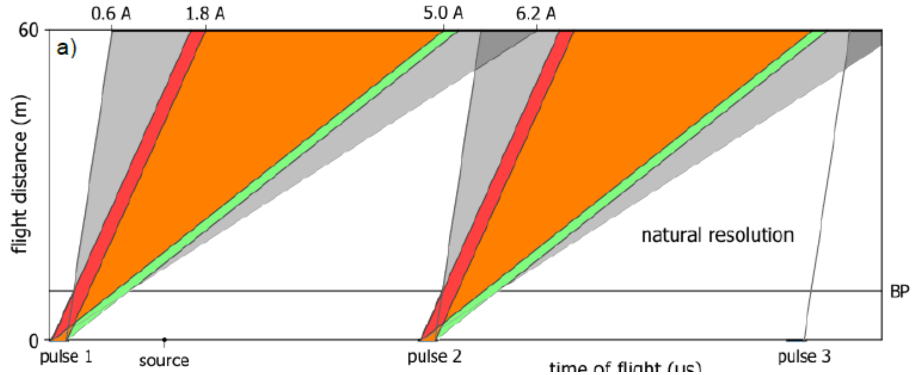
Spectrum and Field of View



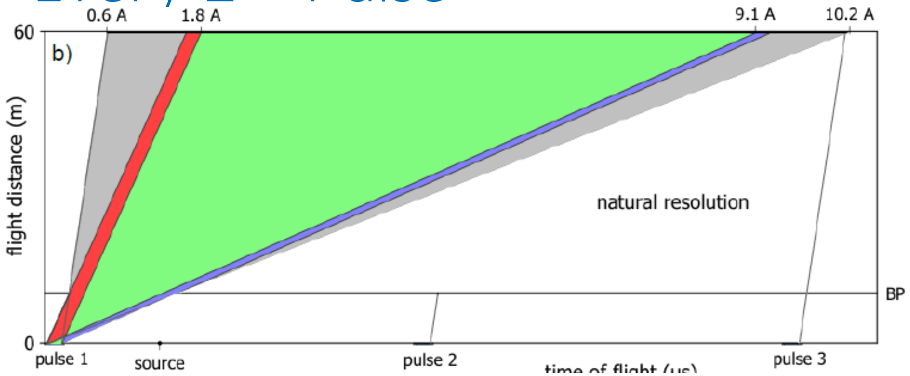
Large, homogenous FoV for large samples in e.g. Geology and Engineering.

Chopper System: flexible resolution

Every Pulse



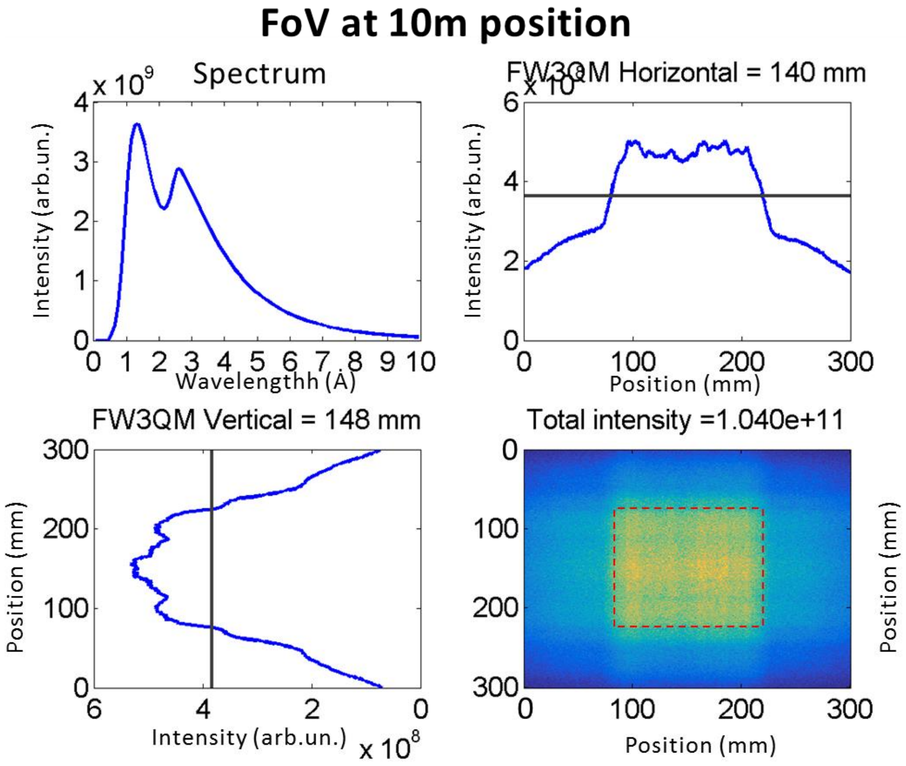
Every 2nd Pulse



Instruments

ODIN (ESS)

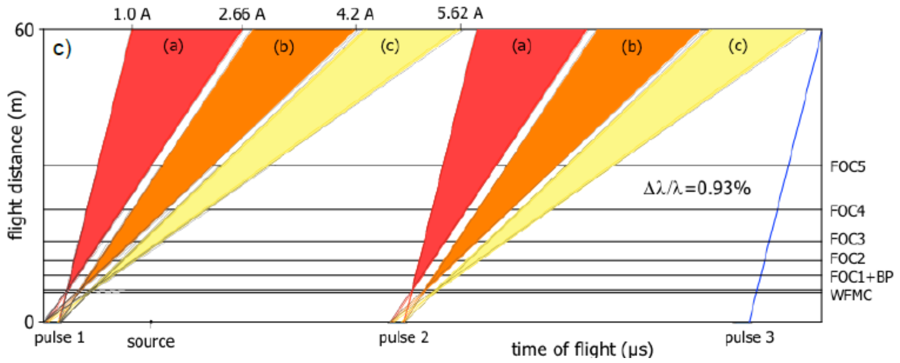
Spectrum and Field of View



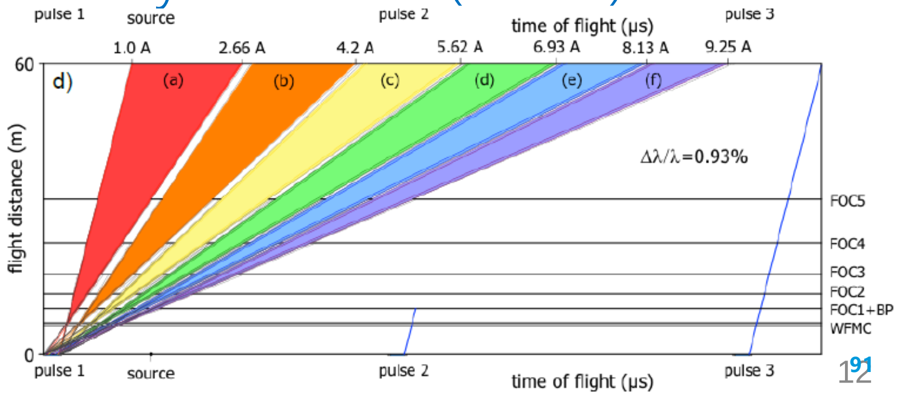
Large, homogenous FoV for large samples in e.g. Geology and Engineering.

Chopper System: flexible resolution

Every Pulse (WFM)



Every 2nd Pulse(WFM)



Thank you! Questions?

Credits and Thanks to colleagues from the neutron imaging community who provided many of these slides!

Website : **http://www.europeanspallationsource.se**   Contact me : **robin.woracek@ess.eu**