Instrumentation for Small Angle Neutron Scattering

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SwedNess SANS Course 2021

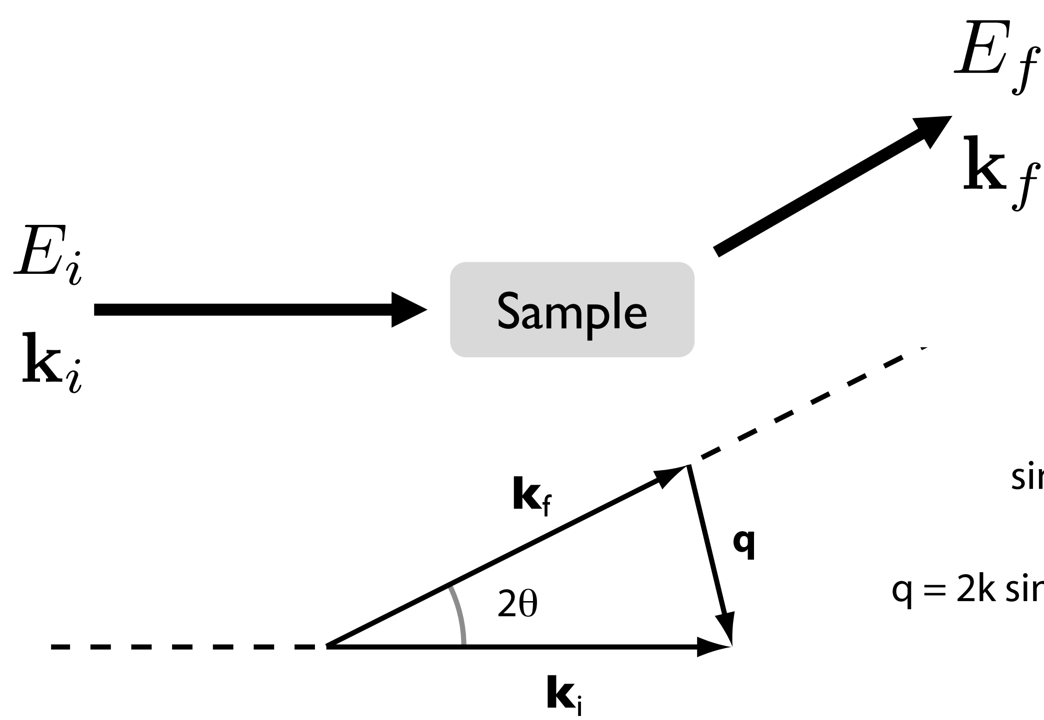
Lecture 4

What do we measure in SANS?

$$k = |\mathbf{k}| = \frac{2\pi}{\lambda}$$

$$momentum = \hbar\mathbf{k}$$

$$energy = \frac{(\hbar k)^2}{2m}$$



$$\mathbf{q} = \mathbf{k}_i - \mathbf{k}_f$$

$$\hbar\omega = E_i - E_f$$

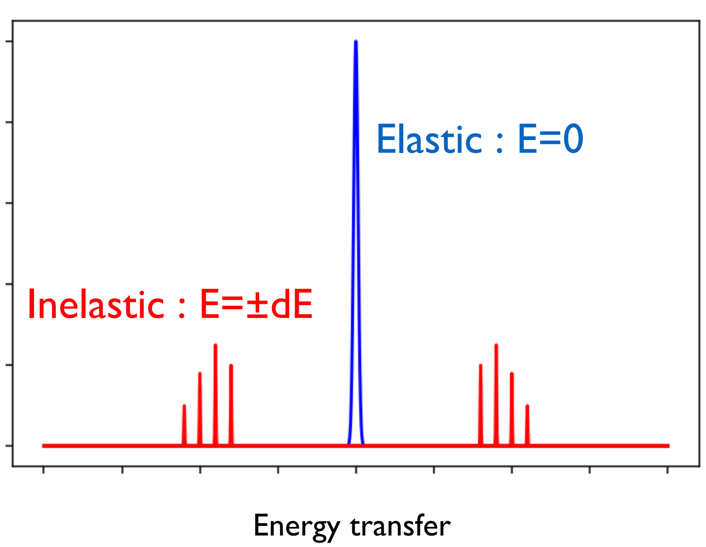
$$\sin\theta = \frac{|\mathbf{q}|}{2}\frac{1}{|\mathbf{k}|}$$

$$q = 2k\sin\theta = \frac{4\pi}{\lambda}\sin\theta$$

Measure number of neutrons scattered as function of Q

Intensity of scattering as function of Q is related to the Fourier transform of the spatial arrangement of matter in the sample => Correlations in **Space**

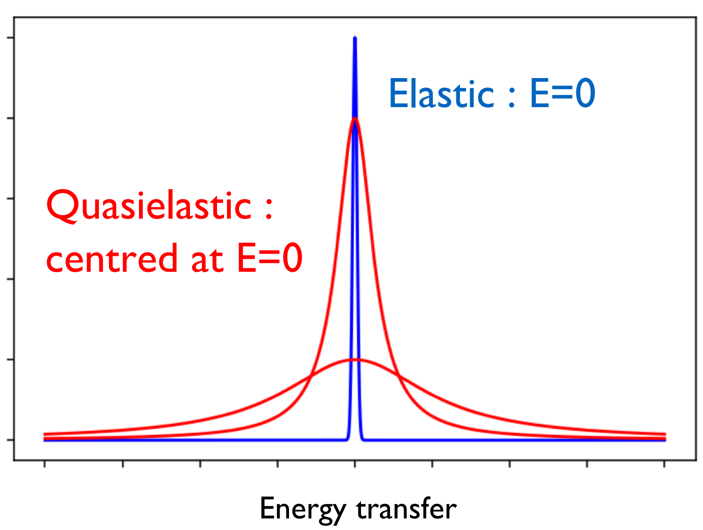
Q is "inverse space" – smaller Q means larger structures in real space



What happens to energy transfer ω?

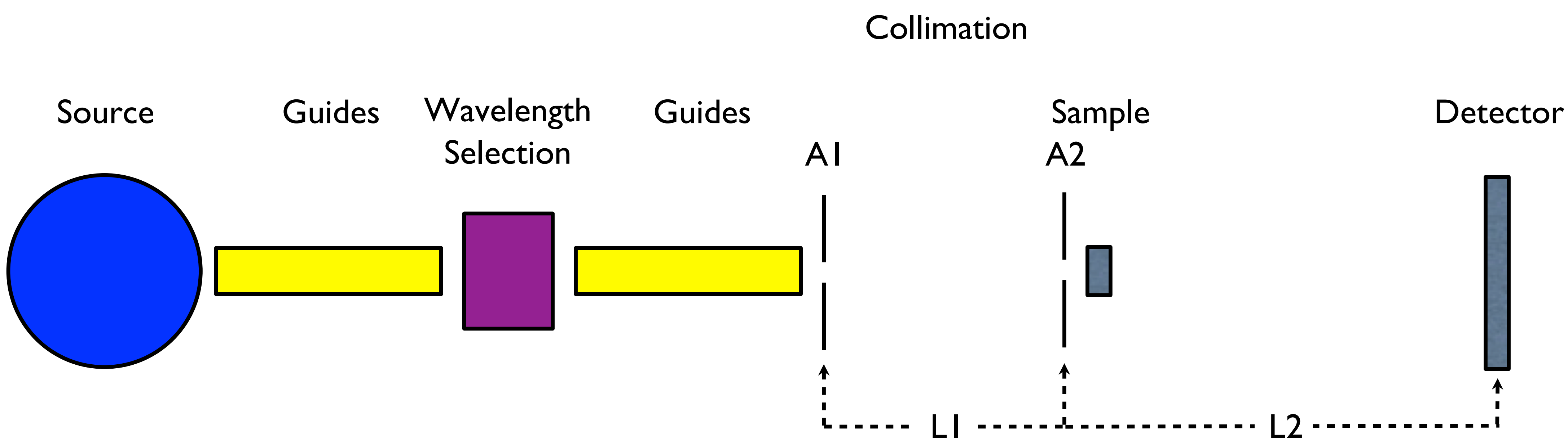
It is still there! – is is an intrinsic function of the interaction of neutrons with our sample.

SANS experiments integrate over all ω

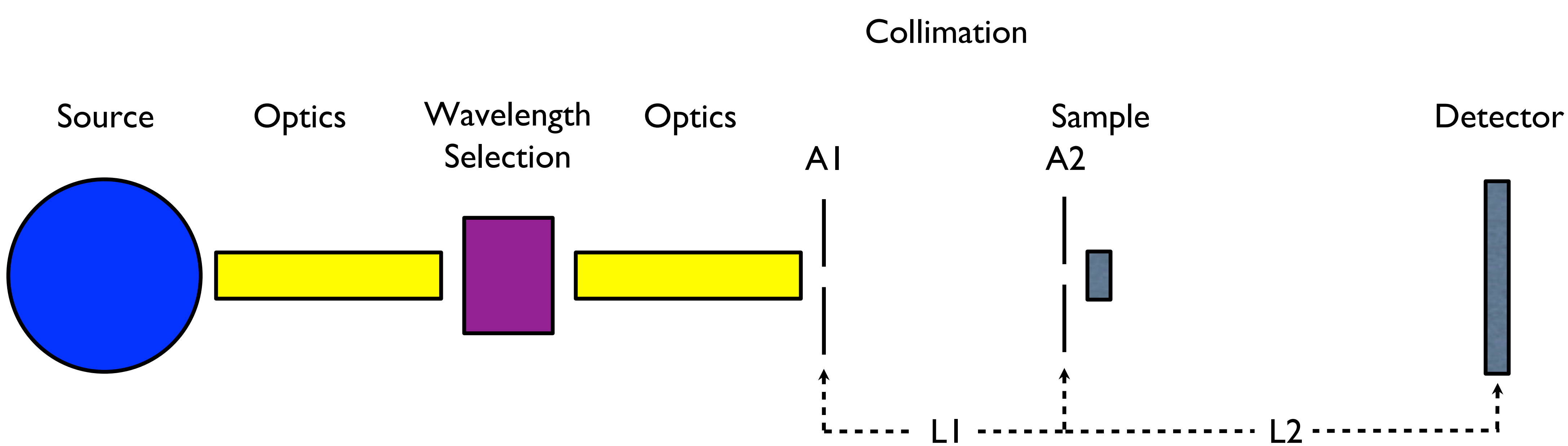


Anatomy of a SAS Instrument

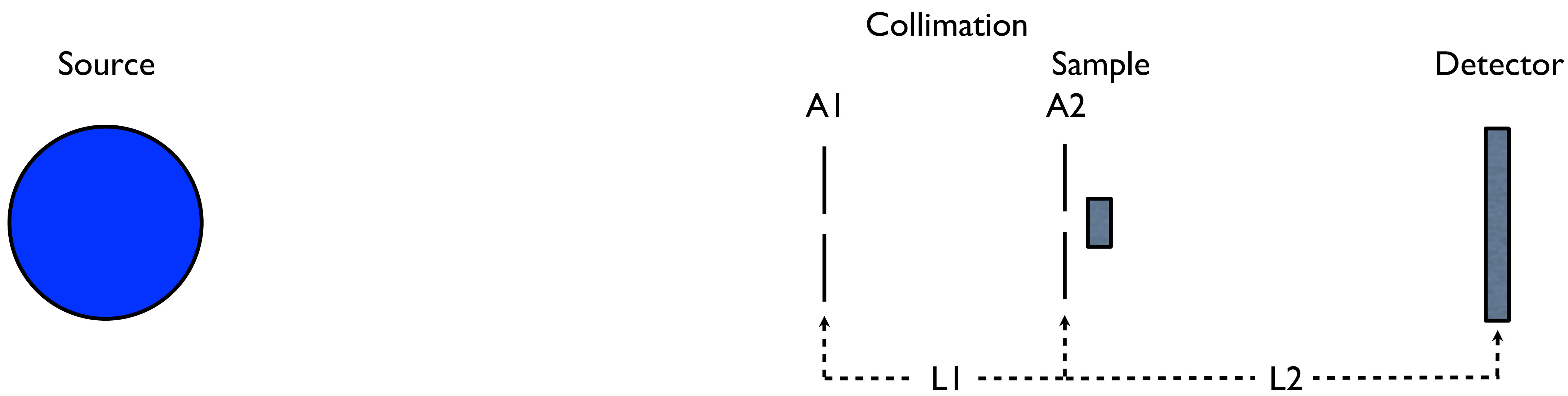
Neutrons



X-Rays



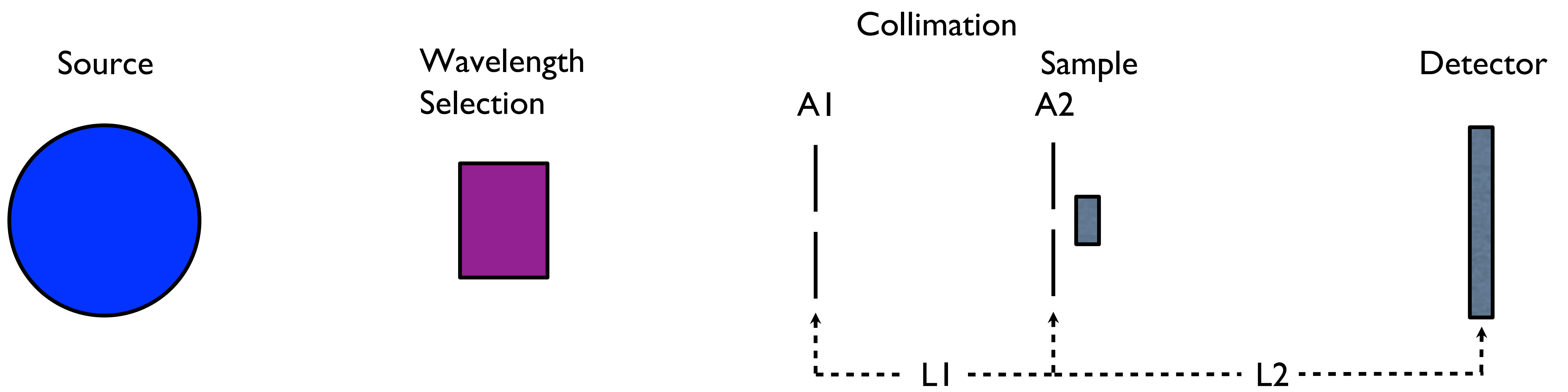
Anatomy of a SANS Instrument



$$Q = \frac{4\pi}{\lambda} sin\theta$$

- Longer L2 = smaller angle = lower Q = larger structures
- Longer wavelength = lower Q = larger structures

Anatomy of a SANS Instrument



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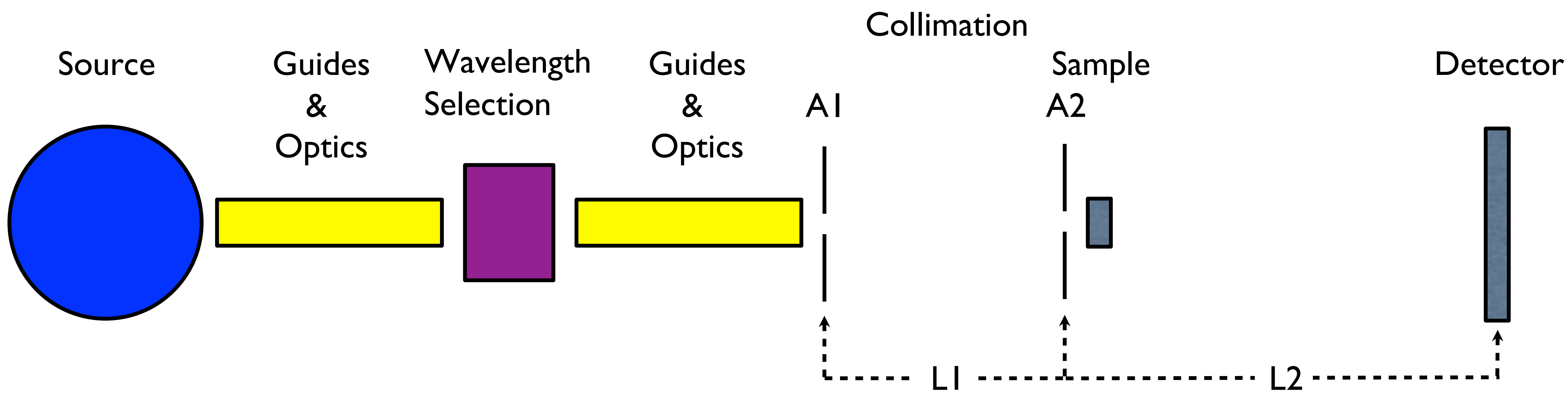

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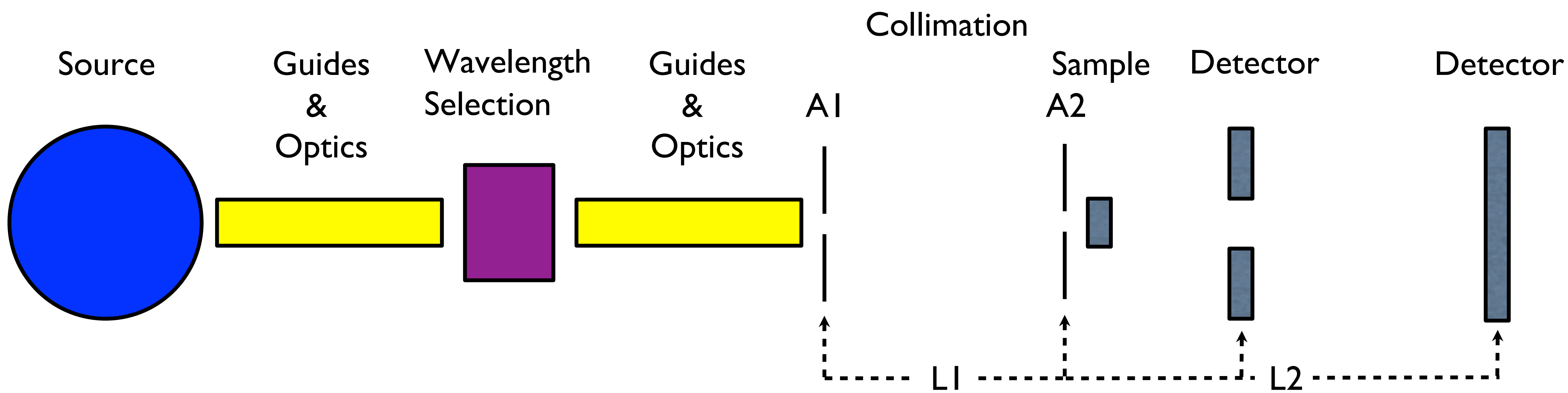

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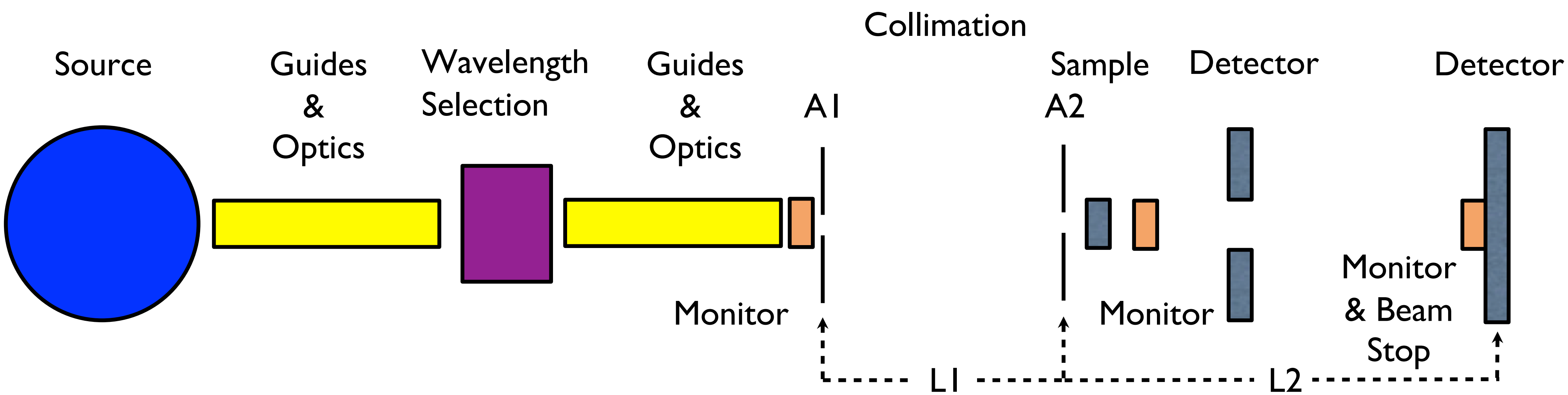

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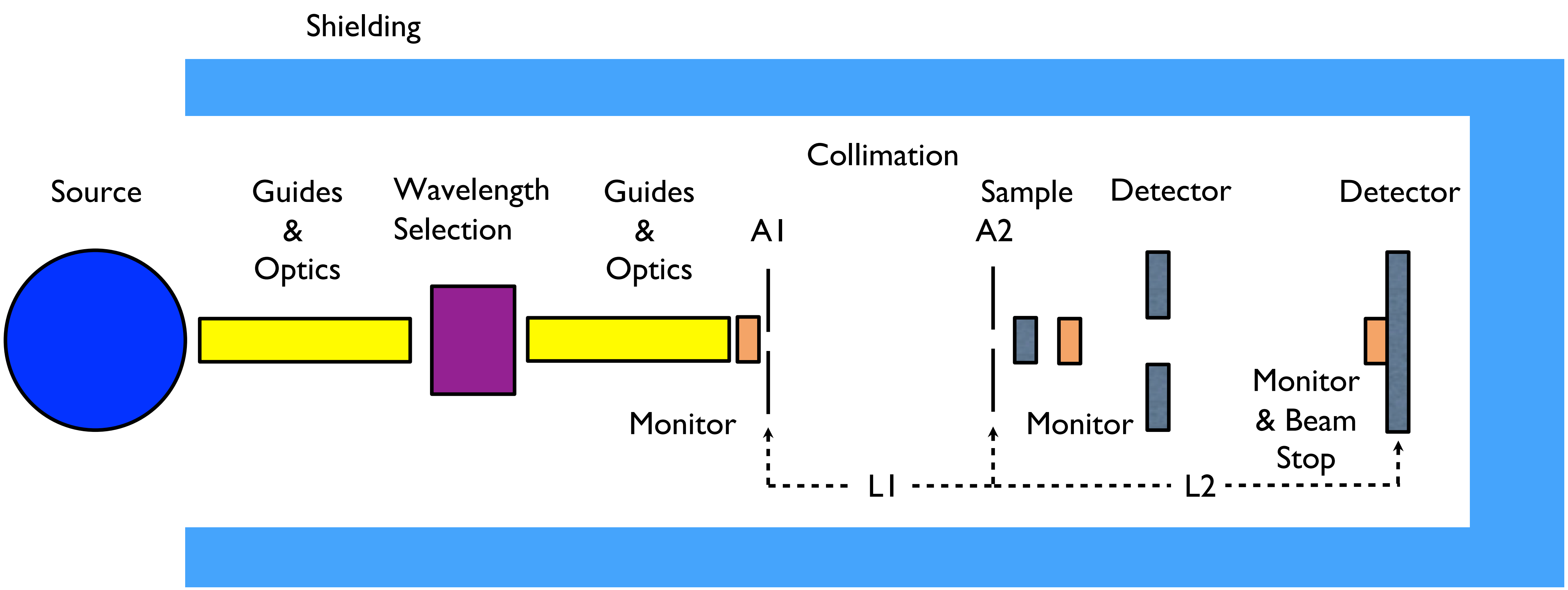

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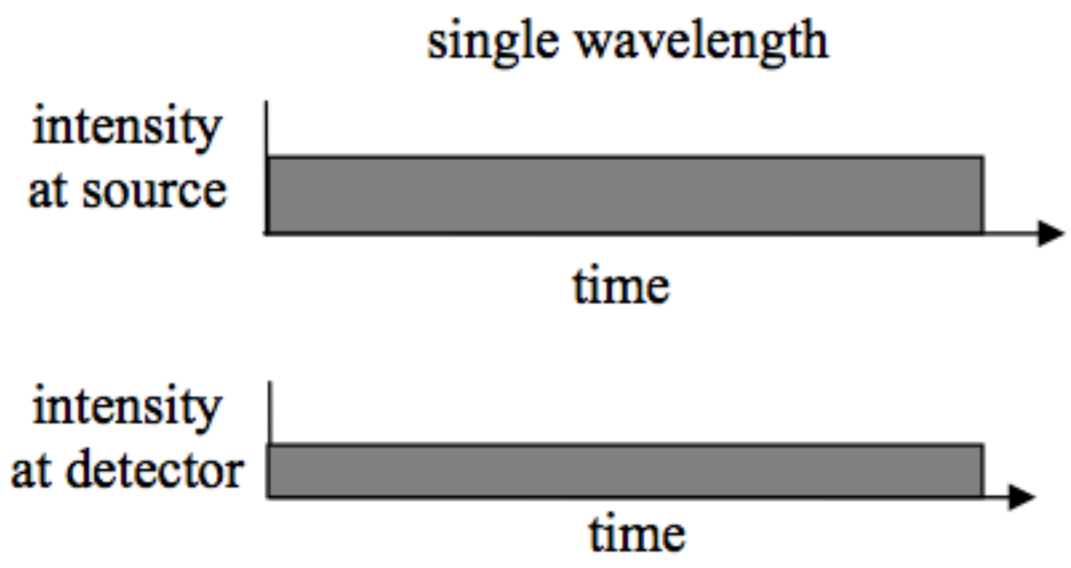
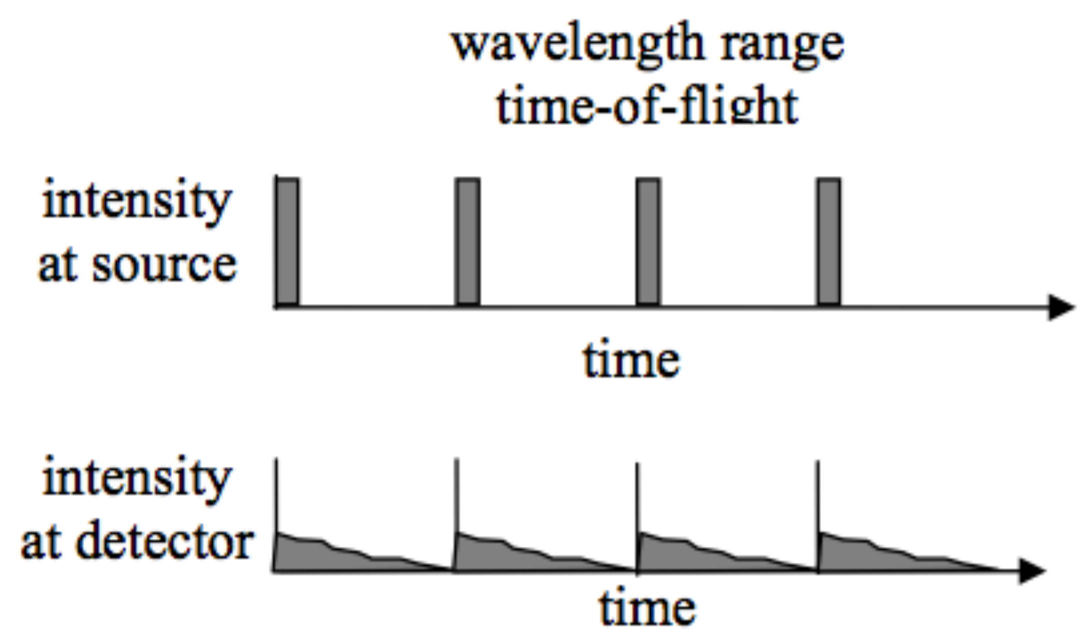
“Monochromatic” vs TOF SANS





Some of the neutrons all of the time

All of the neutrons some of the time

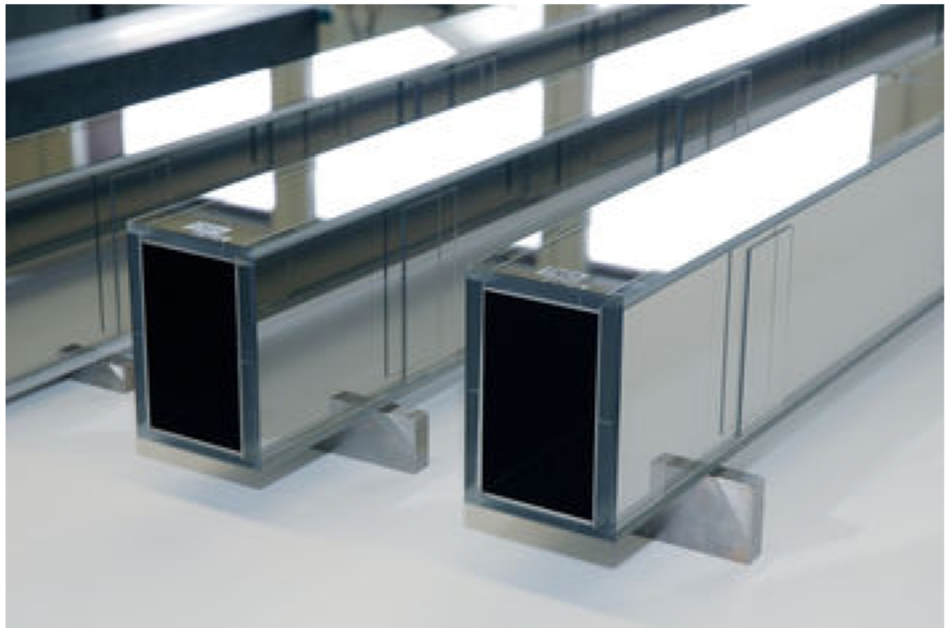
$$Q = \frac{4\pi}{\lambda} sin\theta$$

Varying **angle** to access different Q values

Varying **angle and wavelength** to access different Q values

Neutron Guides

Make use of **total reflection** of neutrons from thin layers of nickel and other materials on a glass or metal substrate.



Act as “optic fibres” for neutrons, transporting the neutrons from the source to the instrument.

All neutrons that impinge on the guide surface below the critical angle for their wavelength will be reflected.

$$n = 1 - \frac{\lambda^2 \rho}{2\pi}$$

$$\theta_c = \lambda \sqrt{\frac{\rho}{\pi}}$$

Choosing the neutron wavelength

Monochromator

Filter

Velocity Selector

Chopper

Makes use of **Bragg diffraction** to select the desired wavelengths.

$$n\lambda = 2d \sin\theta$$

Materials with different **d-spacings** aligned with different crystallographic planes at the appropriate angles to the neutron beam will select different wavelengths.

Exercise :

Using Si (111) with d-spacing = 3.136 Å and a take-off angle of 90° ($2\theta = 90°$) what wavelength of neutrons will be selected by the monochromator?

Choosing the neutron wavelength

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Taking the first order peak :

$\lambda = 2 \times 3.136 \times \sin(45)$

$\lambda = 4.435$ Å

Choosing the neutron wavelength

Monochromator

Filter

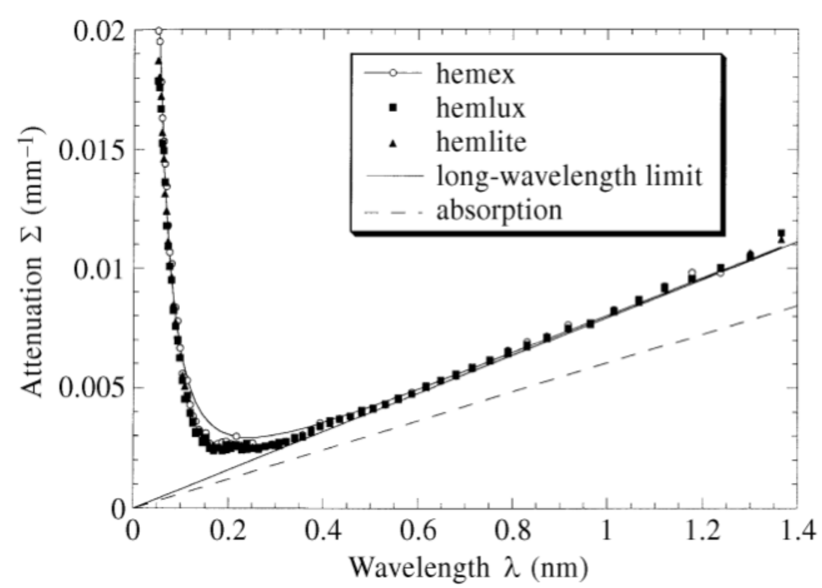
Velocity Selector

Chopper

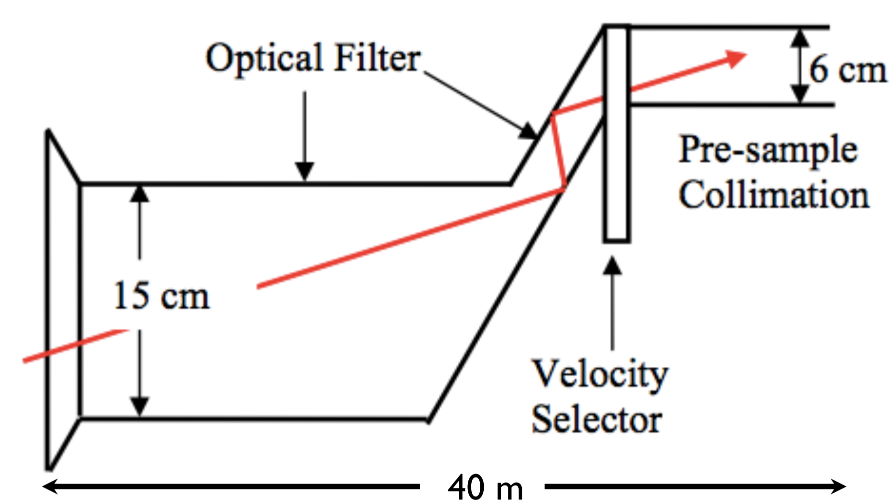
Filters are used to **exclude** unwanted wavelengths of neutrons.

In the case of SANS this is usually cutting out unwanted **thermal** neutrons while allowing the **cold** neutrons to pass.

The filter may be a crystal such as **Beryllium** which cuts off wavelengths below **4 Å** or a neutron guide with a particular shape that only allows certain wavelengths to be transmitted. **Curved guides**, **multi-channel benders** and **optical filters** ("kinked guides") are such devices.



Wavelength dependent attenuation by sapphire (from Mildner & Lamaze, J. Appl. Cryst, 31, 1998)



Optical filter on the NG3 beamline at the NCNR

Choosing the neutron wavelength

Monochromator

Filter

Velocity Selector

Chopper

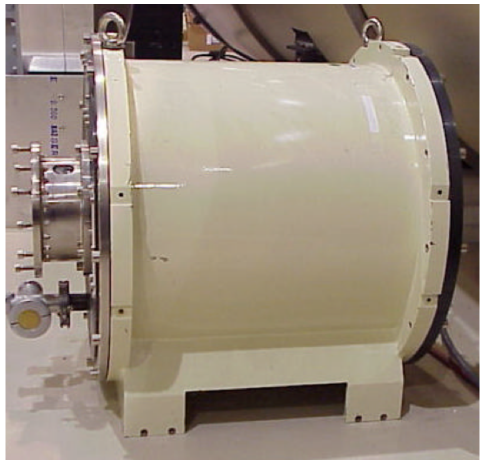
A velocity selector is a rotating device made up of alternating absorbing and transmitting material with a **helical path** for the neutrons.

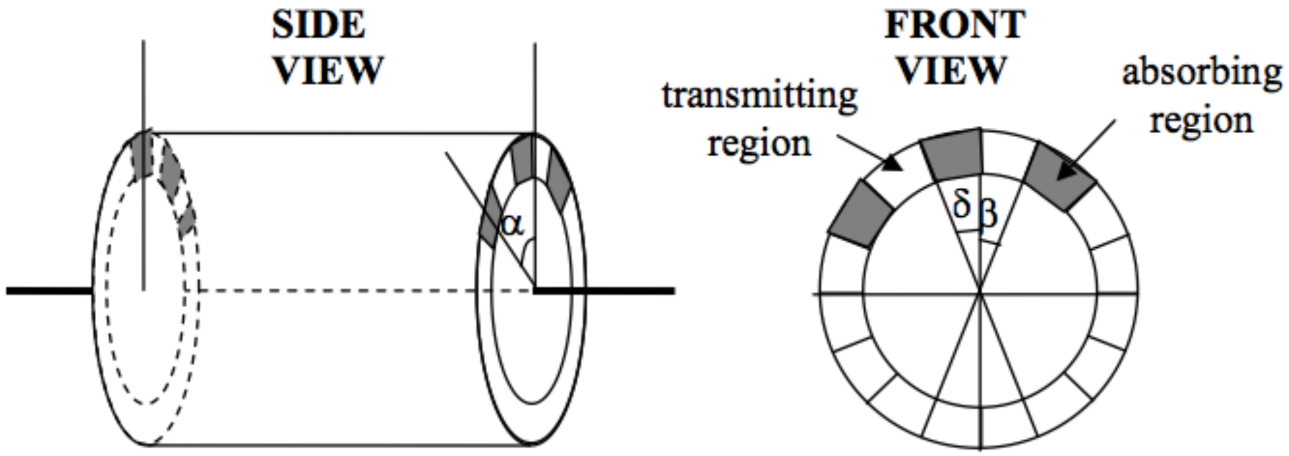
The speed of rotation determines the velocity of the neutrons that will pass through the device without being absorbed.

The transmitted neutron wavelength is given by

$$\lambda = \frac{\alpha h}{L m \omega}$$

where α is the helical pitch angle, L is the length of the selector and ω is the rotational frequency.





Choosing the neutron wavelength

Monochromator

Filter

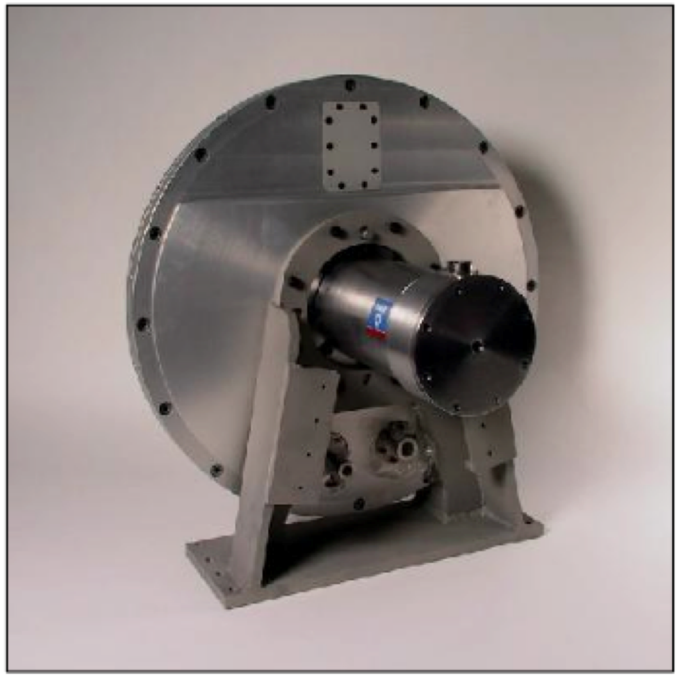
Velocity Selector

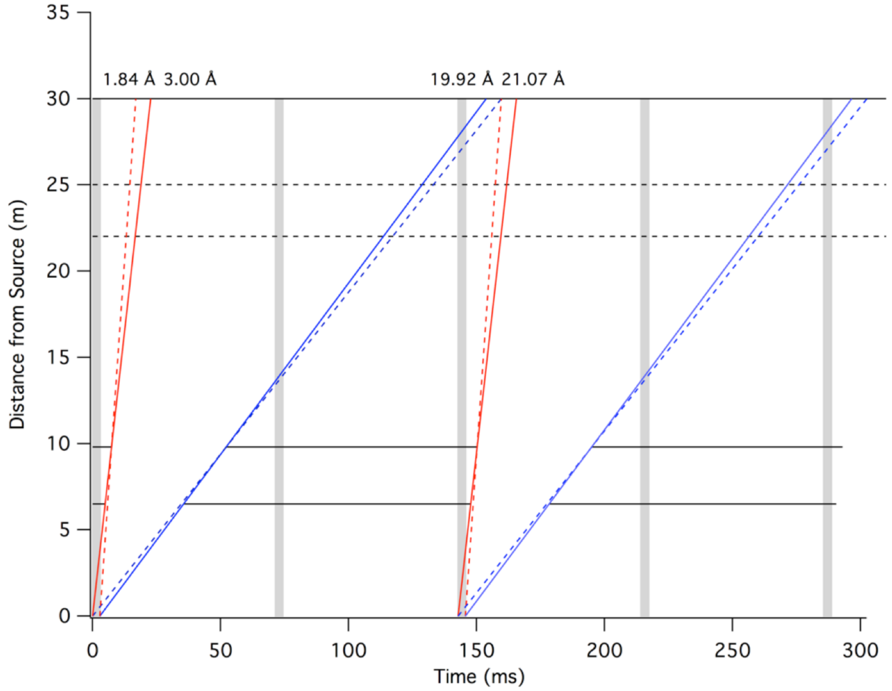
Chopper

A chopper is a rotating device that is absorbing except for one or more openings that allow neutrons to pass.

The speed of rotation and the size of the opening determine the range of wavelengths that are allowed to pass.

Choppers are used either at pulsed sources to select a specific wavelength range or at continuous sources to generate a pulsed neutron beam.





Time-distance diagram for a SANS instrument at ESS

Choppers

We use time-distance diagrams to visualise chopper operation.

Slope of lines is neutron velocity = wavelength

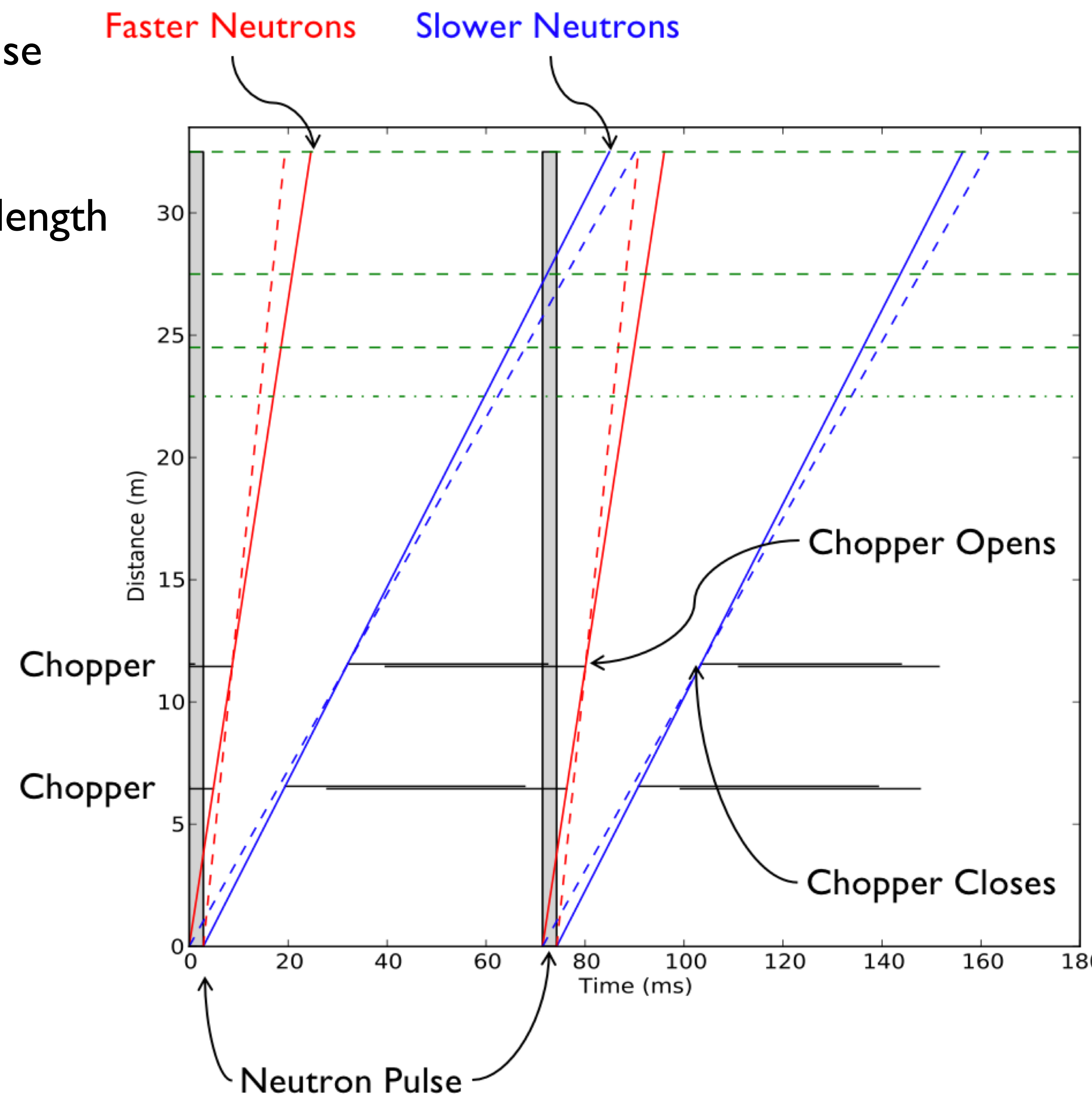
$$\tau = \frac{L}{v}$$

$$\lambda = \frac{h}{mv}$$

$$\tau = \frac{m}{h} L\lambda$$

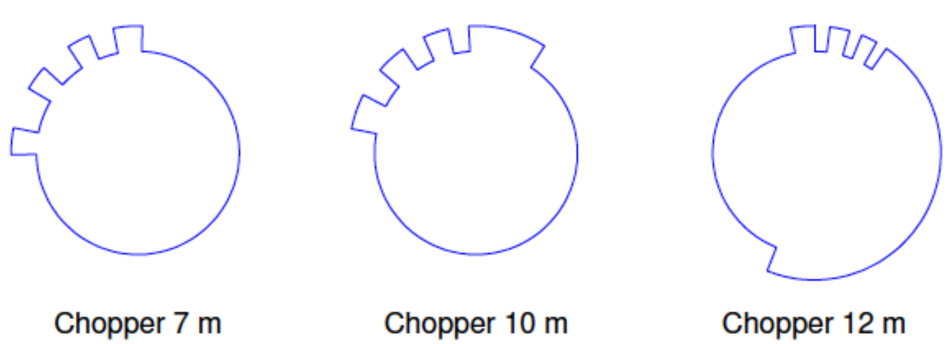
$$\tau[ms] = \frac{L[m]\lambda[\AA]}{3.956}$$

$$\Delta\tau[ms] = \frac{L[m]\Delta\lambda[\AA]}{3.956}$$



Choppers

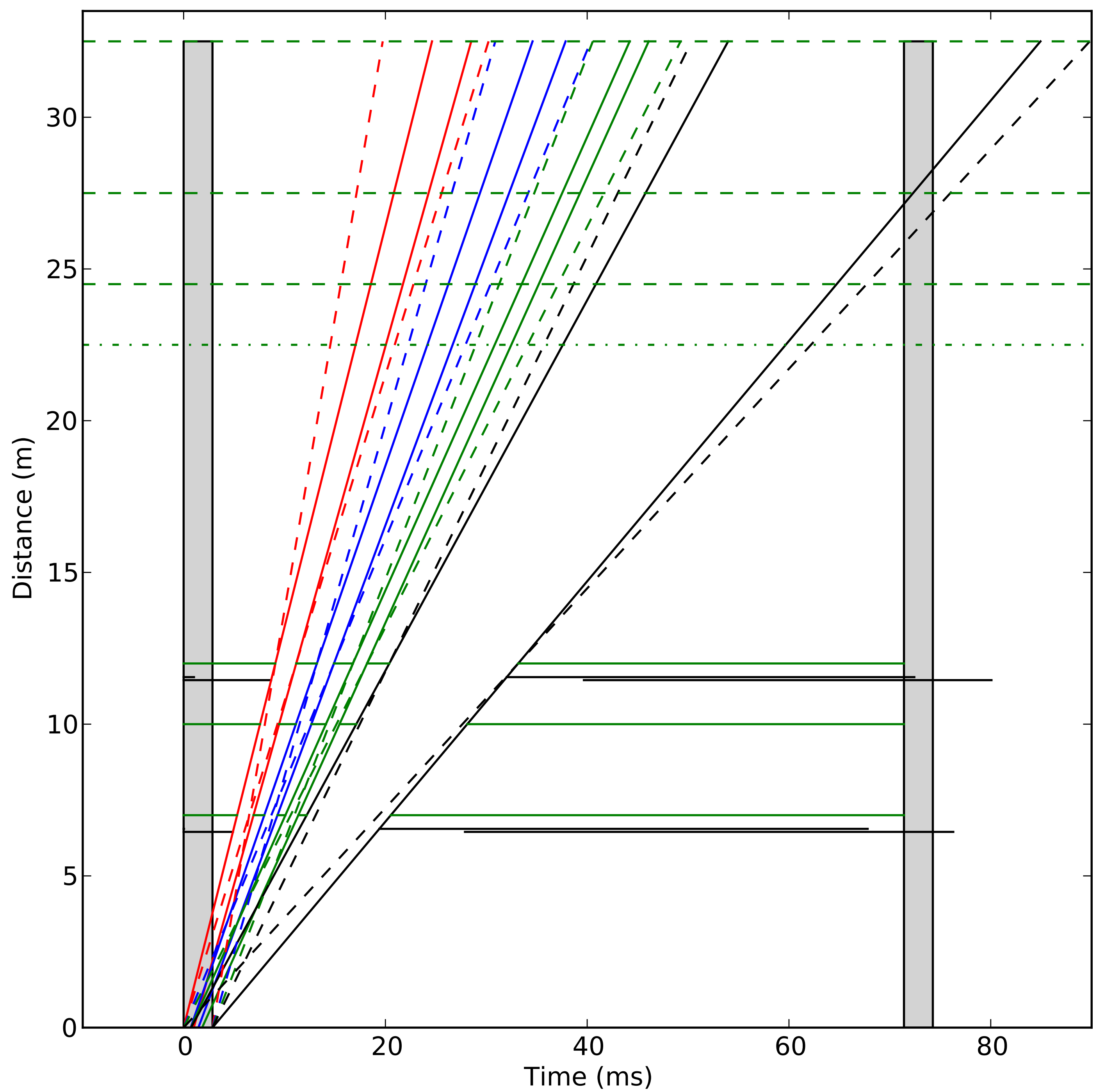
Complex chopper geometries can be used to generate different pulse patterns



42 Hz

28 Hz

14 Hz



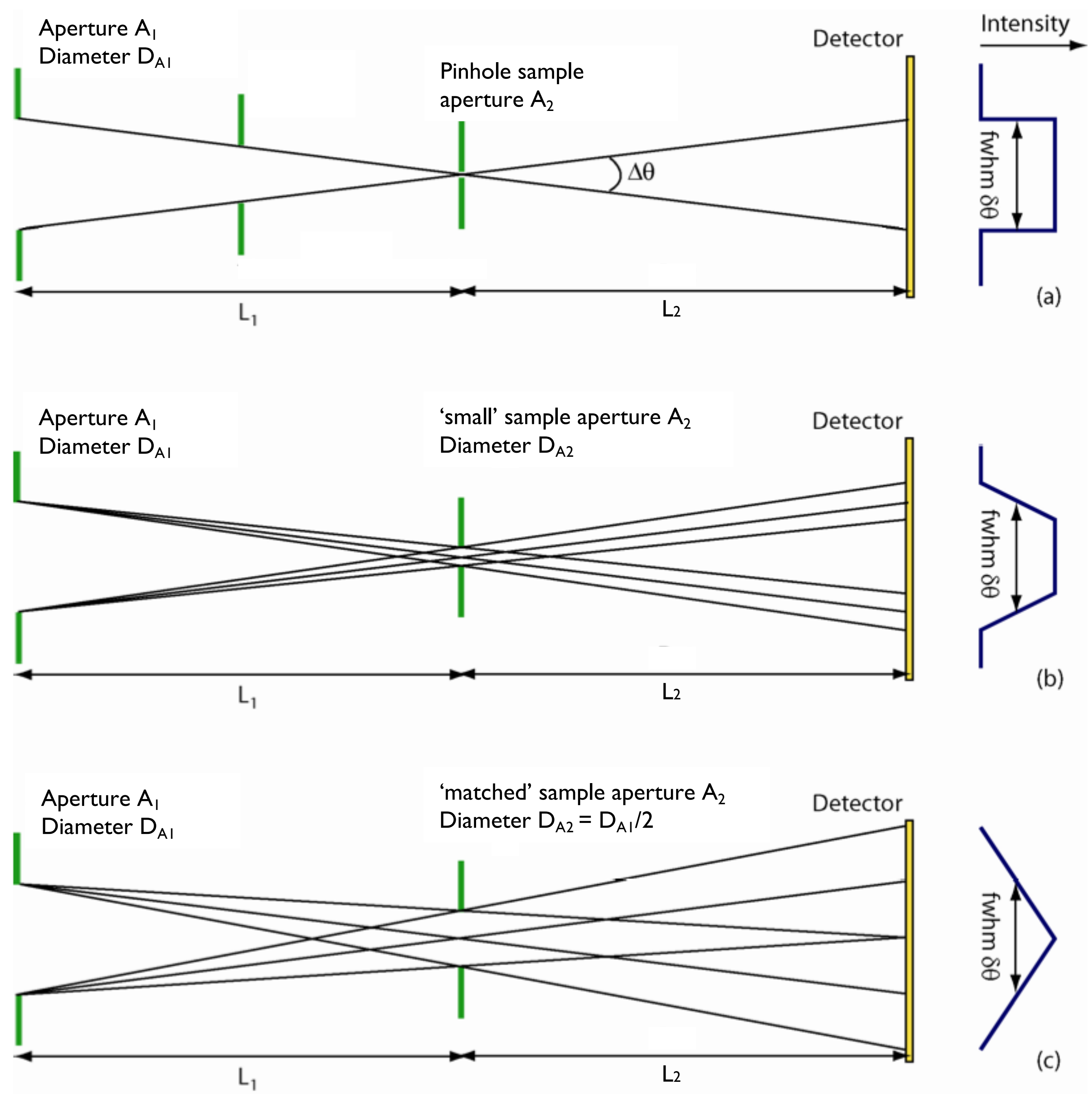
Collimation

The collimation section of the SANS instrument determines the minimum accessible angle and hence the **minimum accessible Q value**.

The collimation is a combination of the source-to-sample distance, the sample-to-detector distance and the sizes of the apertures.

The degree of collimation also affects the **resolution** of the measurement.

$$D_{beam} = D_{A_1}\frac{L_2}{L_1} + D_{A_2}\frac{(L_1 + L_2)}{L_1}$$



from C. Dewhurst, ILL

Detecting neutrons

Neutrons mostly interact **weakly** with matter. This is a problem if we want to **detect** them

In order to detect the neutron we use materials that have **nuclear reactions** with the neutron that produce **detectable products**.

These materials have a **high absorption cross-section** and prompt production of high energy ionized particles.

The absorber can be gaseous or solid within a proportional gas detector, or solid or liquid in a scintillator detector.

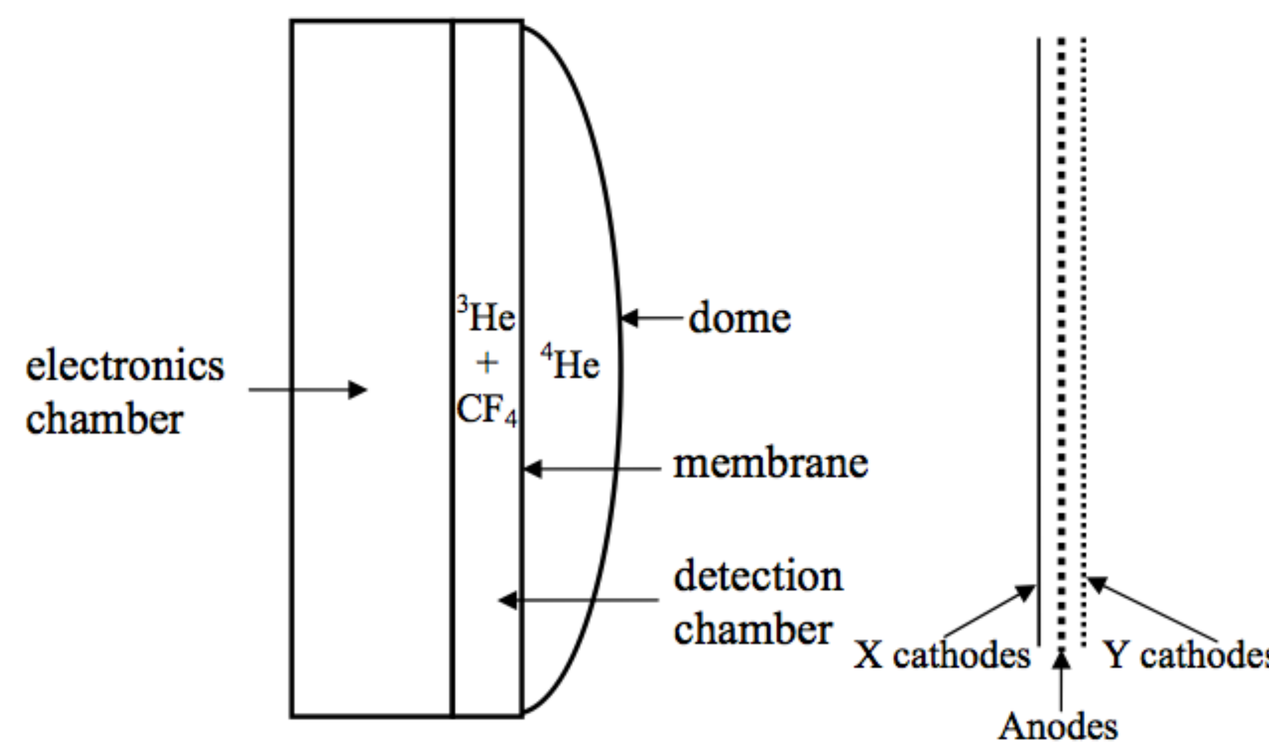
The most common detectors used on SANS instruments are proportional counters containing ^{3}He, either as a multi-wire chamber or as multiple single-wire tubes.

$^{10}B\ (n,\alpha)\ ^7Li + 2.792$ MeV

$^6Li\ (n,\alpha)\ ^3H + 4.78$ MeV

$^3He\ (n,p)\ ^3H + 0.765$ MeV

$^{157}Gd\ (n,\gamma)\ ^{158}Gd + 8$ MeV



Recording Detected Neutrons

Once a neutron is detected, we need to record it.

There are essentially two schemes for doing so:

Histogram recording
The data acquisition electronics fill histograms (in equipment memory) of detection location and time-of-flight (if relevant).

These histograms are then processed to produce the final "reduced" data set.

Event recording
The data acquisition electronics record the location and time of every detection event.

This event stream is then processed into a histogram in Q space which is then finally processed to the "reduced" data set.

Shielding

Why do we need shielding?

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Radiation causes damage to …

Human Body (Sievert or Rem)
Equipment (Gray or Rad)
Experimental data (Noise)

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- Sievert [Sv] and Röntgen Equivalent Man (Rem) are the two most commonly used units that quantifies the dose received by human body.
- 1Sv=100rem
- Sv has the SI unit of J/kg, however Sv is the absorbed dose convoluted with the respective biological damage factors, which are usually published by the International Commission on Radiological Protection (ICRP)

Exposure	Significance
3.5 Sv	50% chance of survival
> 1 Sv	Serious to lethal
> 50 mSv	Requiring medical checks
50 $mSv.y^{-1}$	Occupational dose limit
15 – 50 $mSv.y^{-1}$	Strict dose control necessary
5 – 15 $mSv.y^{-1}$	Professional exposure
< 5 $mSv.y^{-1}$	Minimum control necessary
1 $mSv.y^{-1}$	Natural background
10 $\mu Sv.y^{-1}$	Insignificant

A.H. Sullivan: "A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators." Nuclear Technology Publishing Ashford, Kent, TN23 1JW, England

Shielding

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Experimental data (Noise)

- Gray [Gy] and Radiation Absorbed Dose (Rad) are the two most commonly used units that quantifies the dose received by equipment.
- 1Gy=1J/kg
- 1Gy=100rad

Material	Dose Gy
Electronic components	10^2
Teflon (PTFE)	10^3
Nylon	10^3
Plastic scintillator	10^3
Mylar	5×10^4
Rubbers-butyl	10^4
-silicone	10^5
Organic cables	10^5
Oil-mineral	10^6
-silicone	5×10^4
Polythene	10^6
Polyeurathane	5×10^6
Epoxy resins	5×10^6
Paint-epoxy resin	5×10^6
-celluose ester	10^4
Magnet coil insulation	10^7
Glass filled polyester	10^7
Kapton	2×10^7

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Equipment (Gray or Rad)
Experimental data (Noise)

- Experiment / instrument dependent
- Usually most stringent requirement – detectors are designed to detect!

Shielding

Why do we need shielding?

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	mfp (cm)		
Radiation	Concrete	Iron	Lead
Gamma rays	21	4.7	2.4
Neutrons < 25 MeV	18	16	–
Neutrons 25–100 MeV	28	–	–
Neutrons > 100 MeV	43	18	17

Gamma and neutron dose attenuation lengths

Low Energy Neutron Capture
This process a low energy neutron gets by a nucleus and a different particle will be emitted.

Examples:

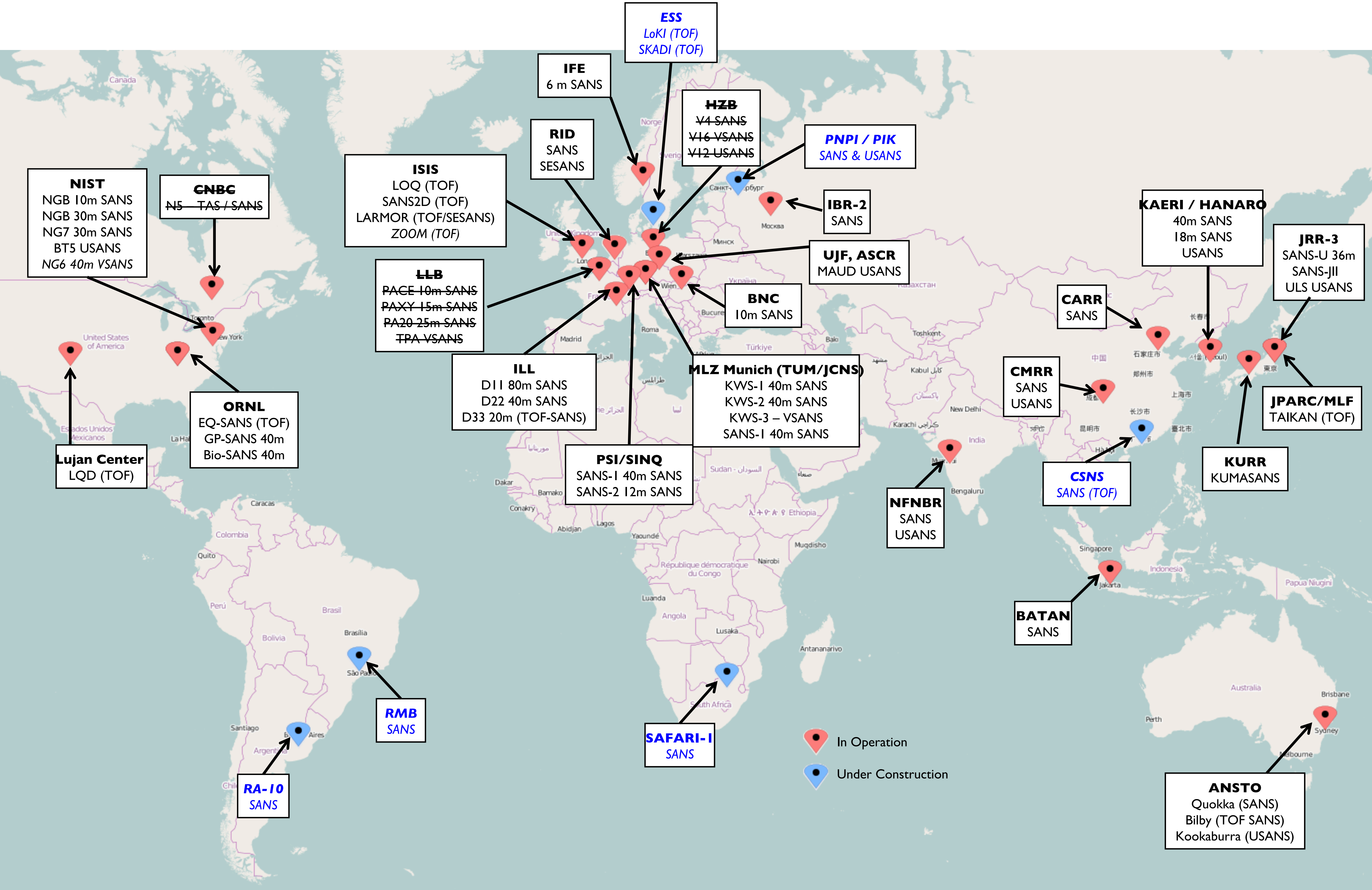
- $^{3}He(n,p)^{3}H$
- $^{6}Li(n,t)^{4}He$
- $^{10}B(n,\alpha)^{7}Li$
- $^{14}N(n,p)^{14}C$
- $^{113}Cd(n,\gamma)^{114}Cd$
- $H(n,\gamma)^{2}H$

Material	Inelastic cross section (barn)	Nominal density ($g.cm^{-3}$)	Attenuation mfp ($g.cm^{-2}$)	Attenuation mfp (cm)	Tenth value (cm)
Beryllium	0.20	1.8	75	42	96
Graphite	0.23	2.0	86	43	100
Water	-	1.0	85	85	195
Concrete	-	2.35	100	43	99
Earth	-	1.8	100	56	128
Aluminium	0.42	2.7	106	39	90
Baryte	-	3.2	112	35	80
Iron	0.70	7.4	132	17.8	41
Copper	0.78	8.9	135	15.2	35
Tungsten	1.61	19.3	185	9.6	22
Platinum	1.78	21.4	190	8.9	20
Lead	1.77	11.3	194	17.0	39
Uranium	1.98	19.0	199	10.5	24

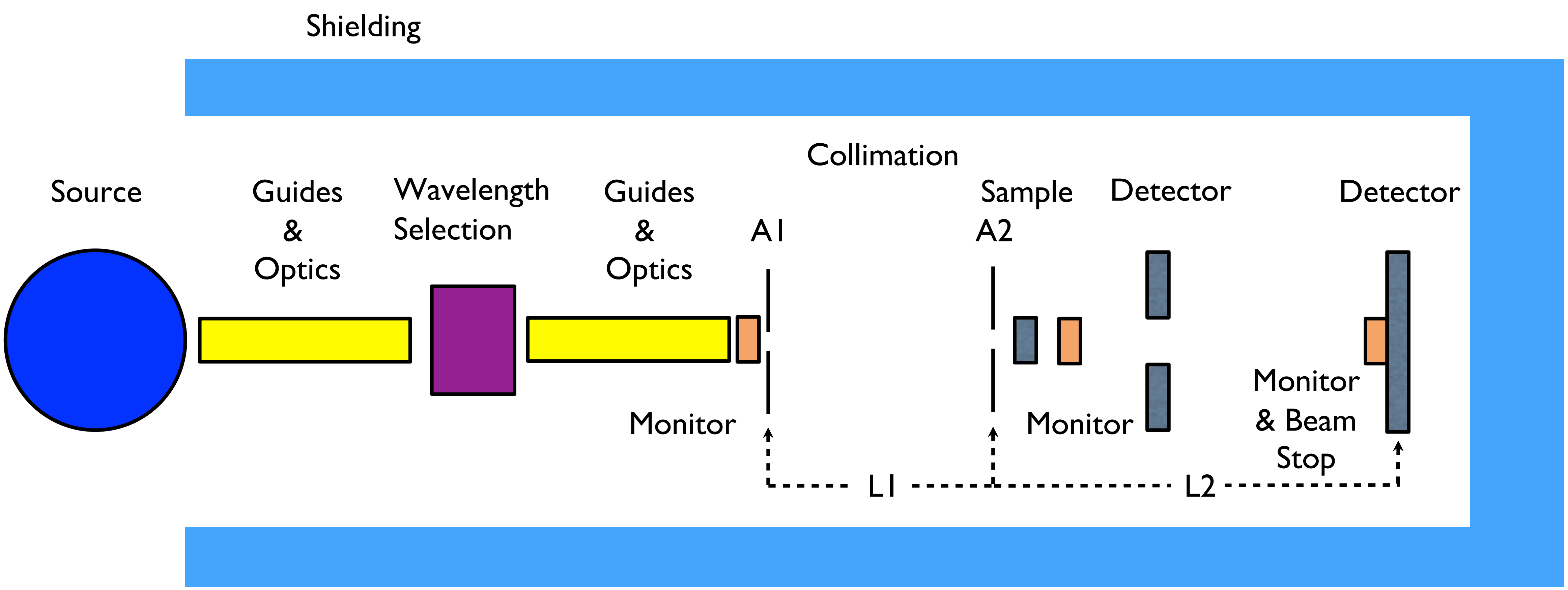
High energy (> 100 MeV) neutron attenuation lengths and tenth values

A.H. Sullivan: "A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators." Nuclear Technology Publishing Ashford, Kent, TN23 1JW, England

SANS Instruments Around the World



Anatomy of a SANS Instrument



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