Synchrotron and Neutron Sources

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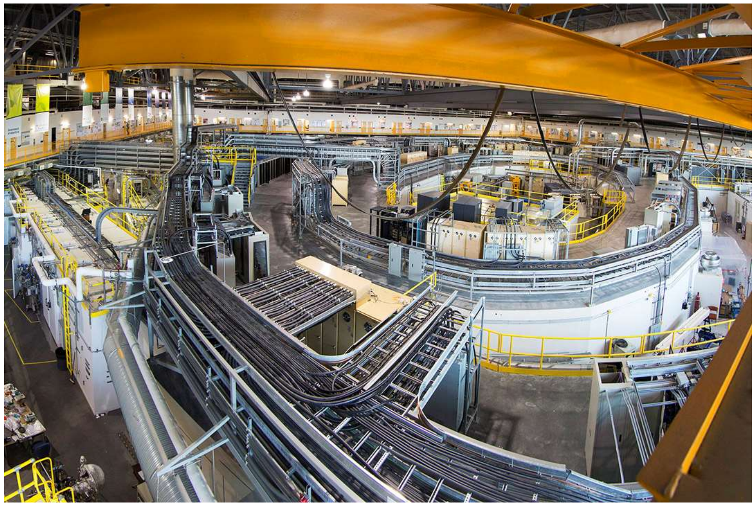
DISCOVERY AT THE SPEED OF LIGHT

What Does a Synchrotron Do?

It accelerates electrons to highly relativistic speeds to produce very intense beams of photons.



How a Synchrotron Works

Step 1: Get electrons going very fast.

An electron gun is used to strip electrons from tungsten metal using very high voltage.

A linear accelerator speeds up the electrons to 99.9998% of the speed of light using radio frequency cavities. Extremely fast but not fast enough!

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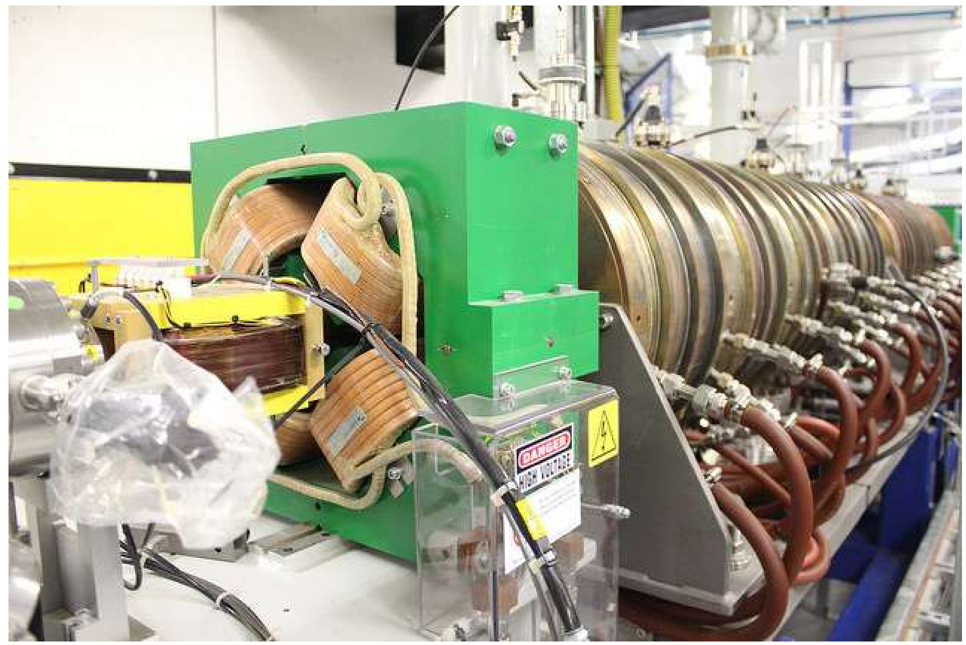
How a Synchrotron Works

Step 2: Get electrons going even faster.

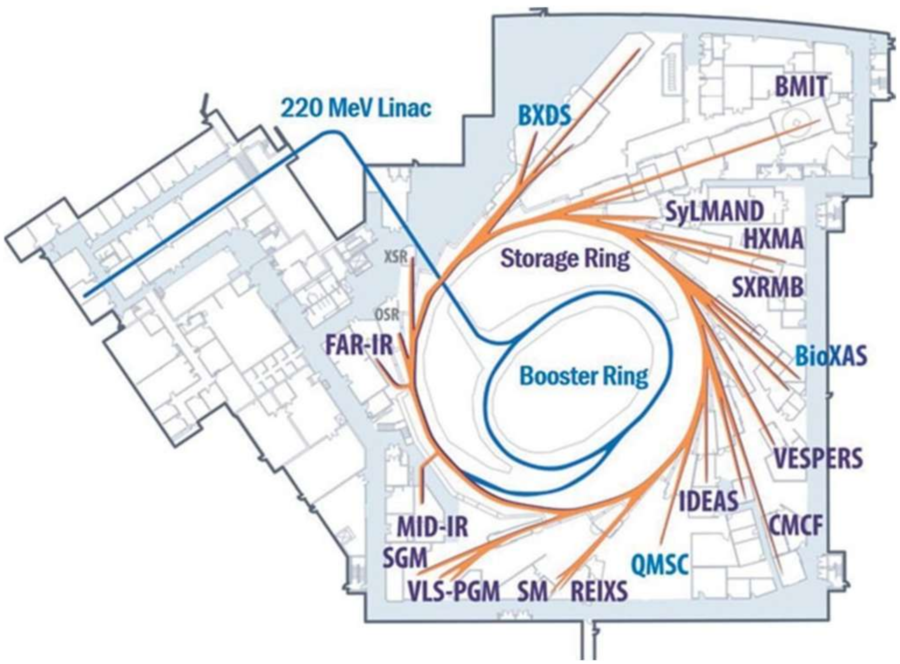
The electrons go into a booster ring where they are accelerated to 99.999998% of the speed of light!

Finally fast enough.



How a Synchrotron Works

Step 3: Keep the electrons going very very fast.



The electrons enter a storage ring, where they keep circulating at the same speed.

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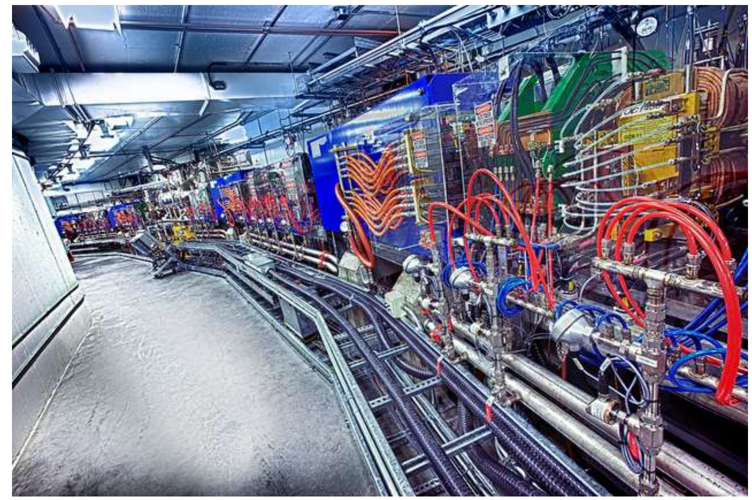
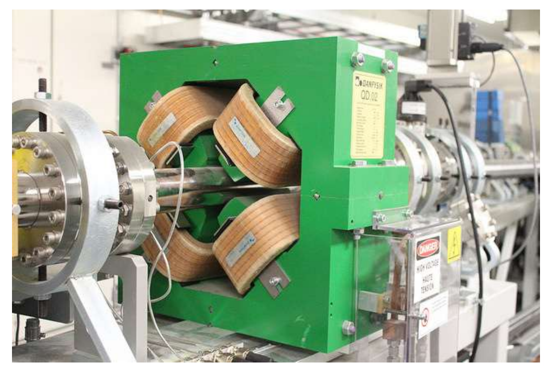
How the Storage Ring Works

- Called a ring, but really a many-sided polygon. CLS has 12 straight sections. Larger synchrotrons have many more.
- At each corner a powerful magnets bends the electron beam.
- An RF cavity gives them a boost to replace the energy lost by irradiating photons.
- Quadrapole and hexapole magnets refocus and shape the beam.
- Must have extremely high vacuum. Ion pumps are used.
- The electrons travel in bunches, so the beam is pulsed. The pulses are very short (10^{-11}-10^{-10} seconds) so the beam seems continuous, but the pulses can be utilized for certain experiments.





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How Photons are Produced

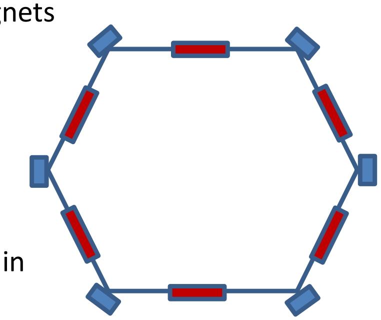
Whenever electrons accelerate, they emit photons. Changing directions, even while maintaining the same speed, is still acceleration.

When the bending magnets cause the electrons to turn, photons are given off. These can used for experiments.

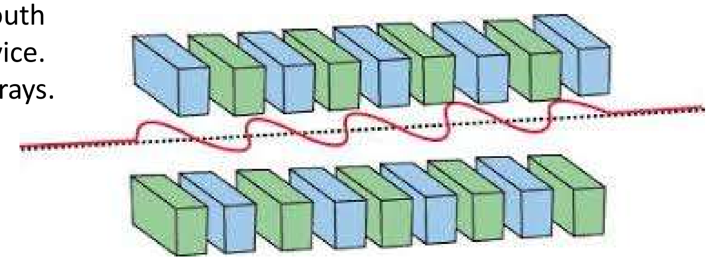
Usually insertion devices (IDs) are put in the straight sections which cause the electrons to wobble many times. Each wobble gives off radiation, producing many more photons than the bending magnetic does. There are two types of IDs, wigglers and undulators.

Bending magnets at corners.

Insertion devices in straight sections.

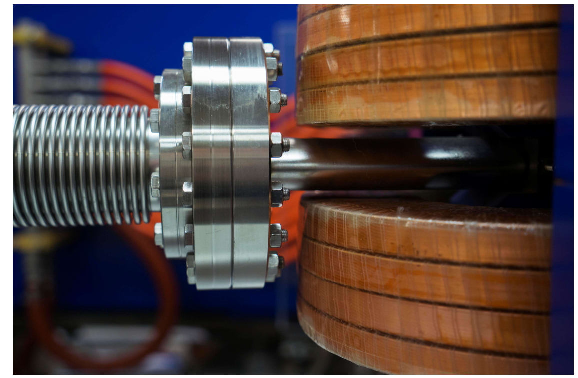


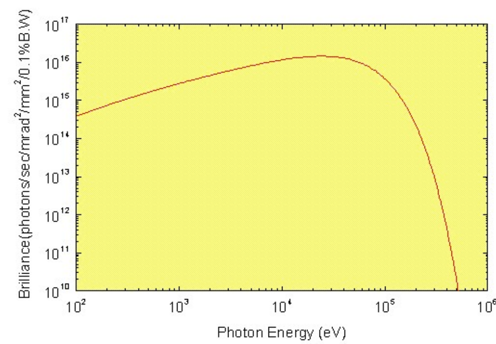
Alternating north and south poles in an insertion device. Each wiggle produces X-rays.



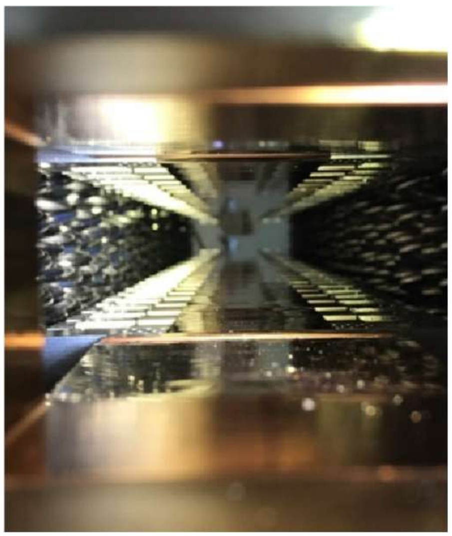
Bending Magnets (BMs)

- Essential to any synchrotron.
- Their main purpose is to keep the electrons circulating.
- They also produce X-ray beams that can be used for science.
- The beams are weaker than ID beams.
- Most BM beams are not used, but usually a few are since they are there anyway.
- Each bend usually consists of multiple magnets. The more gradual the bend the lower the emittance.
- CLS has double-bend achromats. Newer generation synchrotrons have multi-bend achromats with many small bends.
- They produce a broad spectrum of X-ray energies, which depend on the energy of the electrons and the magnetic field. The radiation is polarized.
- Half the total power is radiated at energies below the critical photon energy E_C (peak flux is not at E_C).

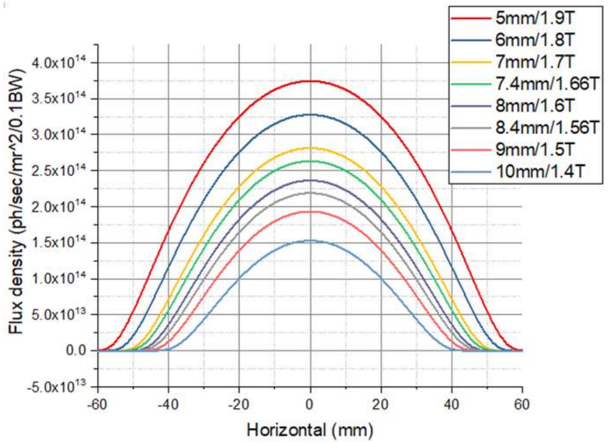




Wigglers



- Multi-pole IDs with strong magnetic fields.
- The radiation does not constructively interfere.
- Flux is just 2N, where N is the number of poles.
- Produces a broad spectrum, including higher energy photons.
- Spectrum similar to a BM but tens of times brighter.



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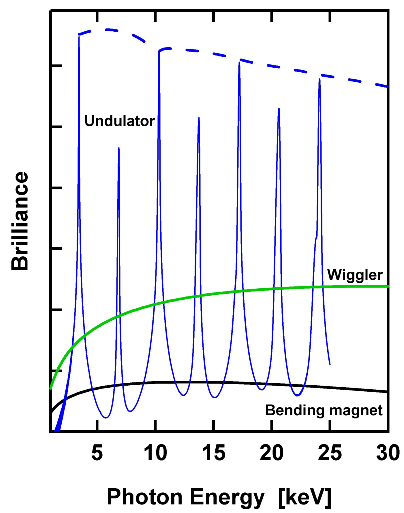
Undulators

- IDs with lower field magnets.
- The radiation interferes to produce peaks at certain wavelengths.
- Total flux is lower than a wiggler, but peak flux at harmonics can be much greater. Peak brightness proportional to N^2 instead of 2N.
- Energy of harmonics can be tuned by changing the magnet gap.
- Cannot produce very high energy X-rays.
- Useful due to high brightness, low divergence, and tunability.



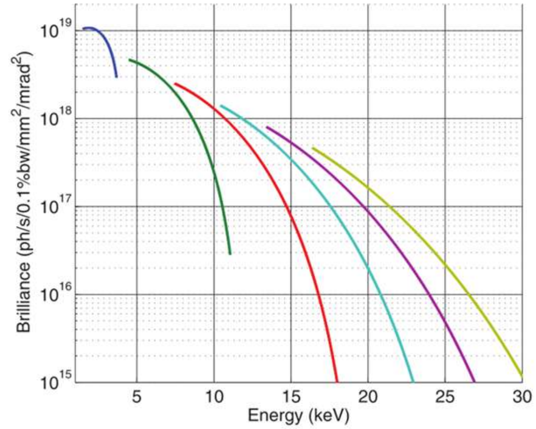
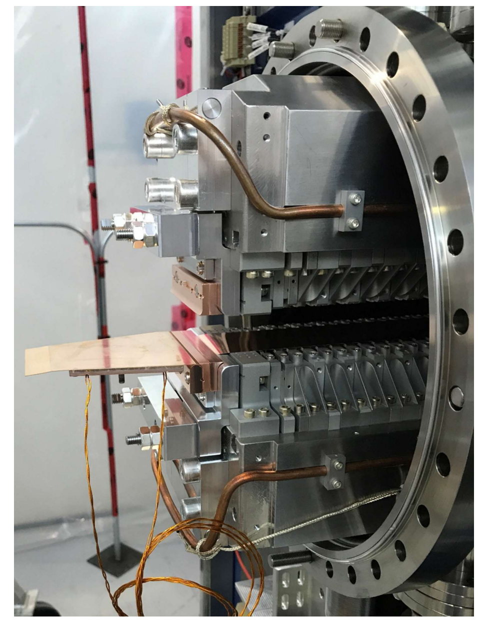


FIG. 1. Undulator brilliance considering odd harmonics up to the 11th, for a maximum ring current of 500 mA (routine operation current is 250 mA).



Relativity and Synchrotron Radiation

$$\gamma = \frac{E}{E_0} \qquad \beta = \sqrt{1 - \frac{1}{\gamma^2}} = v/c$$

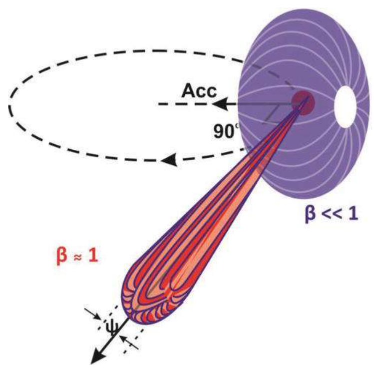
E is the e^- energy
E_0 is the e^- rest mass

From the electrons perspective it is emitting radiation radially.

As γ is grows, from the beamline frame of reference the radiation concentrates in the forward direction.

For very large γ, such that β is very close to 1, the radiation becomes highly collimated, with an opening angle $\theta \approx 1/\gamma$.

From the electron frame of reference, the radiation is much longer wavelength. Doppler effects shorten the wavelength to the X-ray range.



One reason synchrotrons are so bright is the concentration of the radiation into a narrow, nearly parallel beam.

Key Parameters for Storage Rings and Beamlines

Electron Beam Energy (E): The energy of the e^- circulating in the storage ring. Usually in GeV. CLS is 2.9 GeV. Brillance scales with E^2 as flux and opening angle each scale with E. Higher E also shifts X-ray energies higher.

Ring Current: The number of e^- circulating in the ring. Usually 100's of mA. CLS runs at 220 mA. X-ray flux is linearly proportional to ring current.

Emittance: The width of the e^- bunch. Generally wider horizontally than vertically, although in 4^{th} generation sources the two are becoming close. Effects X-ray flux, divergence, and coherence.

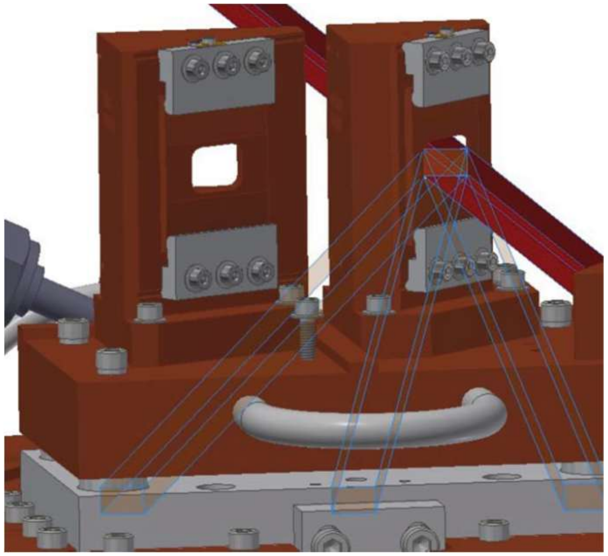
Lifetime: How quickly the ring current decays (most due to imperfect vacuum). Measured as $1/e$ in hours.

Flux = $\frac{\boldsymbol{Photons}}{\boldsymbol{S} \times \boldsymbol{0.1\%BW}}$ **Brillance** = $\frac{\boldsymbol{Photons}}{\boldsymbol{S} \times \boldsymbol{0.1\%BW} \times \boldsymbol{mm^2} \times \boldsymbol{mrad^2}}$

Brillance is the main parameters of interest as it takes into account the area and divergence of the beam (BW is band width).

Synchrotron Optics: Monochromators

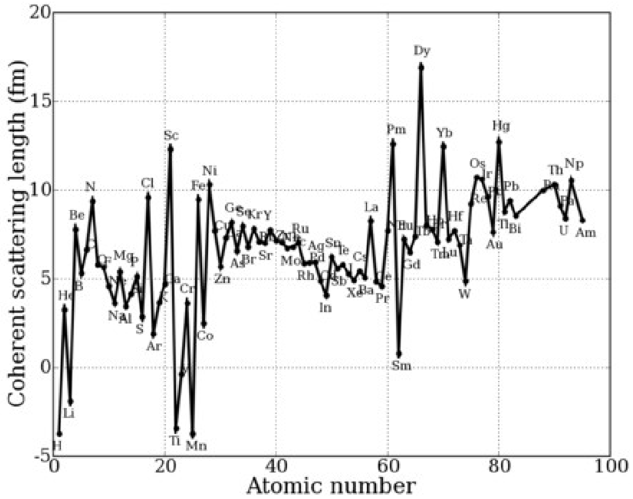
- Usually made from Si wafers, as it is relatively easy to grow large perfect Si crystals and they give a bandpass around 1 x 10^{-4}.
- Crystal is rotated to select different energies.
- Often different Bragg planes are used to access different energy ranges.
- Multilayer or zone plates are used for long wavelengths.



Neutron Sources, Instrumentation, and Uses

Advantages of Neutron Scattering

- **Sensitivity to light elements.** Neutrons scatter off the atomic nuclei. The scattering cross section varies randomly with Z, Many light elements scatter similarly to heavy elements.
- **Differentiating neighboring elements.**
- **High Penetration**
- **Magnetic Scattering.** Neutrons have a magnetic moment which allows them to scatter off unpaired electrons, allowing magnetic structures to be determined.
- **No Form Factor.** Peak intensity falls off at small d-spacing more slowly.
- **Low Flux** is the main disadvantage of neutrons.



Overview of Neutron Sources

Two Main Types

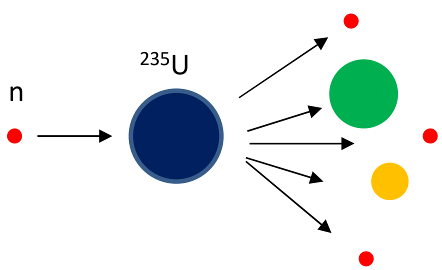
Reactor:

- Based on fission of radioactive elements (U), similar to a nuclear power plant.
- Usually used for monochromatic beams.

Spallation:

- Uses proton beams to blast apart heavy elements.
- Usually used for pulsed beams (time-of-flight).

Reactor Sources



- Neutrons are produced by controlled fission of enriched uranium fuel.
- When a U atoms decays several neutrons are released. Some of these trigger new nuclear decays while other escape down flight tubes to be used for experiments.
- Similar to a nuclear power plant but the goal is neutron production instead of heat production.
- Beryllium reflectors used inside.
- Reactors produce a **steady supply of neutrons**.

Reactor Powder Diffractometers

- Generally similar to synchrotron beamlines.
- A large single crystal monochromator is used to select a single wavelength.
- The diffraction pattern is then collected as a function of angle.
- Often many detectors are used in an array to speed data collection as the flux is much smaller than for X-rays.

The BT-1 diffractometer at the NIST NCNR. It has 32 detectors that only need to rotate 5 degrees.

Spallation Sources

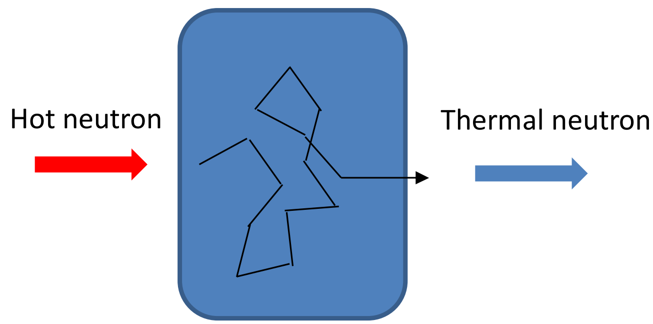
- Spallation is a process by which a heavy nucleus is blasted into pieces after being hit by another particle.
- Spallation neutron sources use pulsed proton beams.
- The protons are created by stripping the electrons off hydrogen, accelerating them to near the speed of light in a liner accelerator, then smashing them into a target.
- The target is often W but could be other heavy metals. Hg is used in some newer facilities for easier cooling.
- The heavy nucleus breaks into two smaller nuclei and also releases many free neutrons.
- This creates pulses of neutrons, usually at rates of 10's of hertz.*
- Most new facilities being built are spallation.

The linear accelerator at LANSCE, Los Alamos National Lab.

* It is possible to produce a steady source of neutrons by spallation by using a constant stream of protons. The SINQ facility at the Paul Scherrer institute works this way.

Moderators

Neutrons produced by fission or spallation are very high energy (MeV). To be useful for diffraction they need to be slowed down (meV).



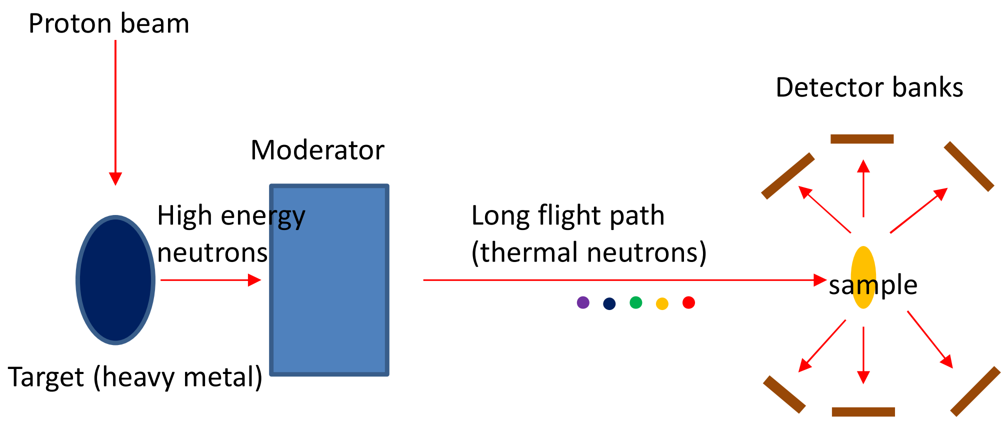
- This is done by having the neutrons collide with nuclei to give up their energy.
- **The temperature of the moderator determines the spectrum of neutron energies exiting.**
- For diffraction room temperature neutrons have the right wavelength range.
- Materials with lots of H are usually used. Often just water, sometime liquid methane or liquid H_2.
- Some neutrons don't fully thermally equilibrate. These epithermal neutrons are important for the high Q-range of spallation source.

Time-of-Flight (TOF) Diffraction

In TOF the angle is fixed and the wavelength is varied. → $\lambda = 2d\sin(\theta)$ ← Normally the wavelength is fixed and the angle is varied to get d.

- As neutrons are particles with mass, their speed varies with their energy/wavelength.
- At a spallation source, pulses of neutrons with a spectrum of wavelengths are produced. The time it takes them to reach the detector is recorded. Diffraction occurs when they have the right wavelength to satisfy Braggs law.
- A plot of diffraction intensity vs. time is recorded, which can be converted into d-spacing.
- Detectors are placed at fixed angles. Several different angles can be used. These different detector banks each record their own diffraction pattern. Depending on the angle the patterns have different d-spacing coverage and resolution.
- While TOF is normally done at spallation sources, it can be done at a reactor sources by placing a chopper in the beam to create pulses.

Time-of-Flight Instruments



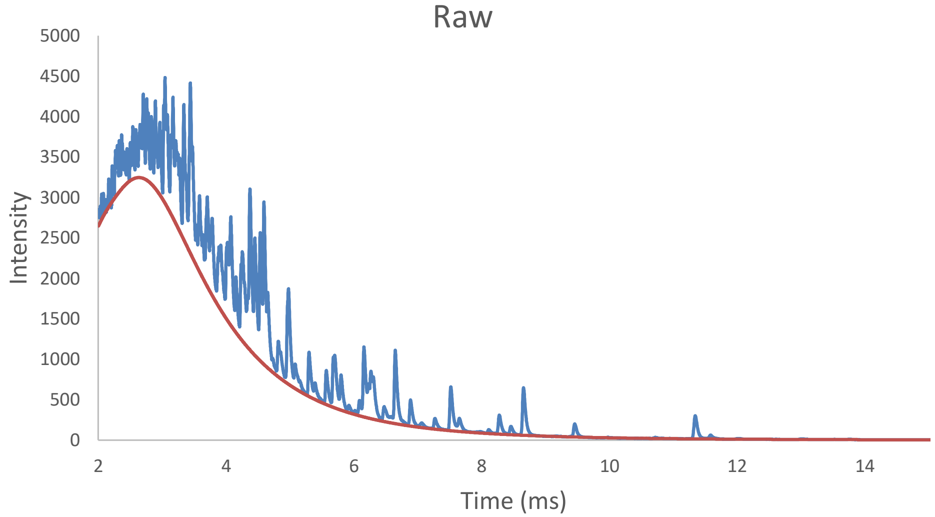
A few other notes:

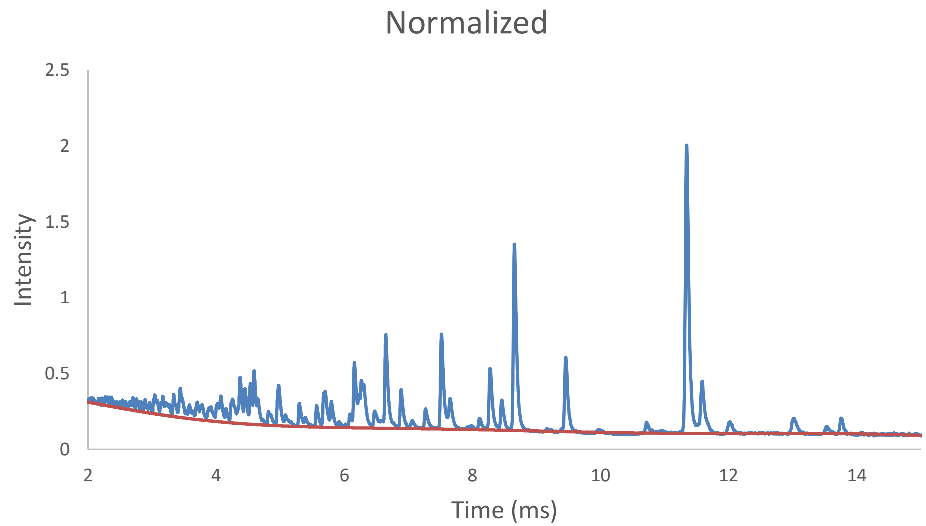
- Beamlines sometimes have a chopper that is closed at t_0 to protect detectors from gamma rays and fast neutrons.
- A trigger measures the t_0 when the proton pulse arrives.
- A "get lost tube" at the end absorbs the un-scattered beam.

Intensity vs. Resolution

- Is determined by the flight path length.
- The longer the path the more time the neutrons have to sort themselves by energy, so the better the resolution.
- The intensity falls off as $1/r^2$, so the closer the better the flux.
- It is important to keep in mind that as neutrons have no charge, they cannot be steered by magnetic fields. They also cannot be easily focused by lenses.
- Neutron guide materials based on refraction do exist to help keep flux on long beamlines, but these are mostly used for longer wavelength neutrons.

Time-of-Flight Data





The distribution of energies in a neutron pulse is not uniform. Patterns usually divided by incident flux. Keep in mind that the high d-spacing region of each bank has lower counting statistics than the small d-spacing region.

Incident flux is determined by measuring vanadium, which has a small coherent *b* of -0.38 fm but a moderate incoherent σ of 5.08 barn.

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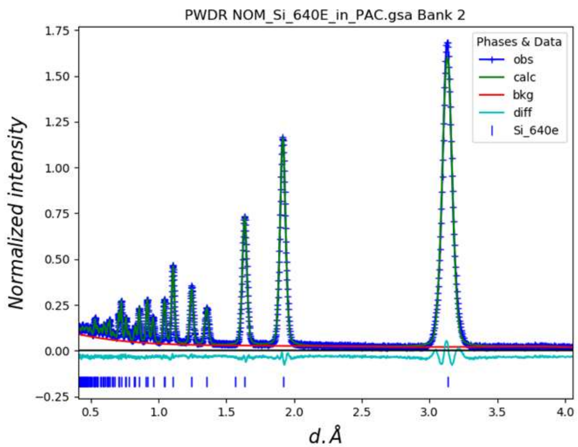
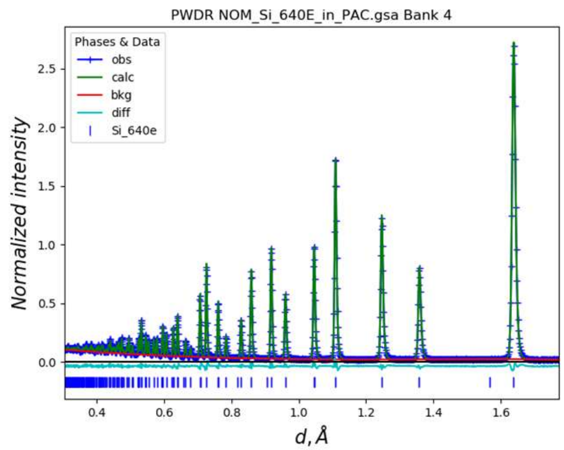
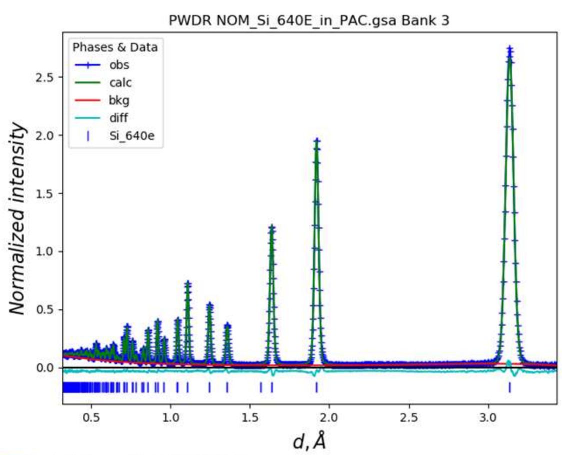
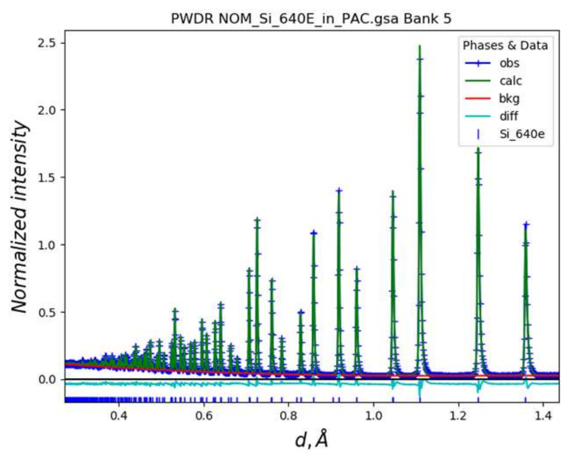
Detector Banks in TOF



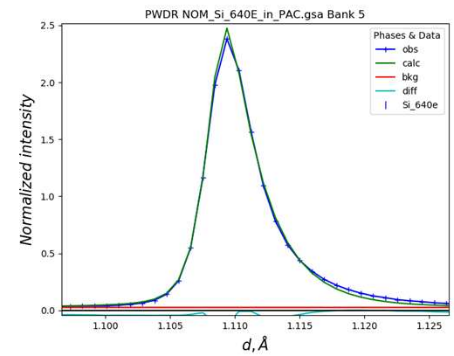






Low angle banks cover a large range of high d-spacing with low resolution.

High angle banks cover small range of low d-spacing with high resolution.



TOF peaks have an odd and complex shape.

How to Access Neutrons in Canada

Neutrons Canada

A new organization formed by Canadas major research universities to be the official administrator of neutron science in Canada.

- Will operate the McMaster reactor (new diffraction beamline being developed)
- Develops collaborative relations with foreign facilities which give Canadian researchers access.

The Canadian Institute for Neutron Scattering represents the user community.

CINS
CANADIAN INSTITUTE FOR NEUTRON SCATTERING