ISNIE
Engineering Summer School

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Part II
Neutron Choppers
Theory

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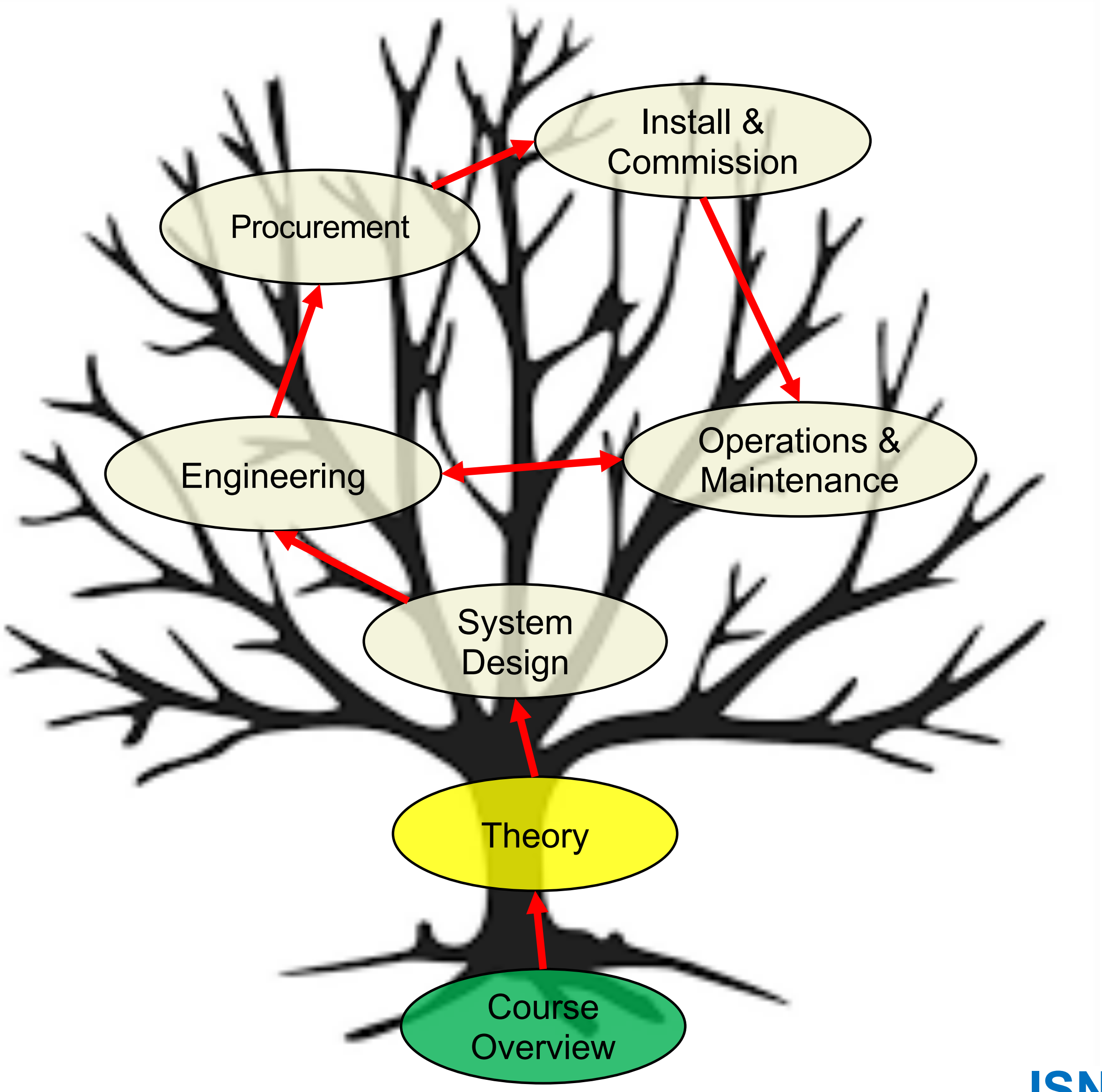
Branches

Iain just gave the course overview now off to the basics of neutron chopper theory!

Here I plan to discuss a number of topics related to the theory of neutron chopper systems.



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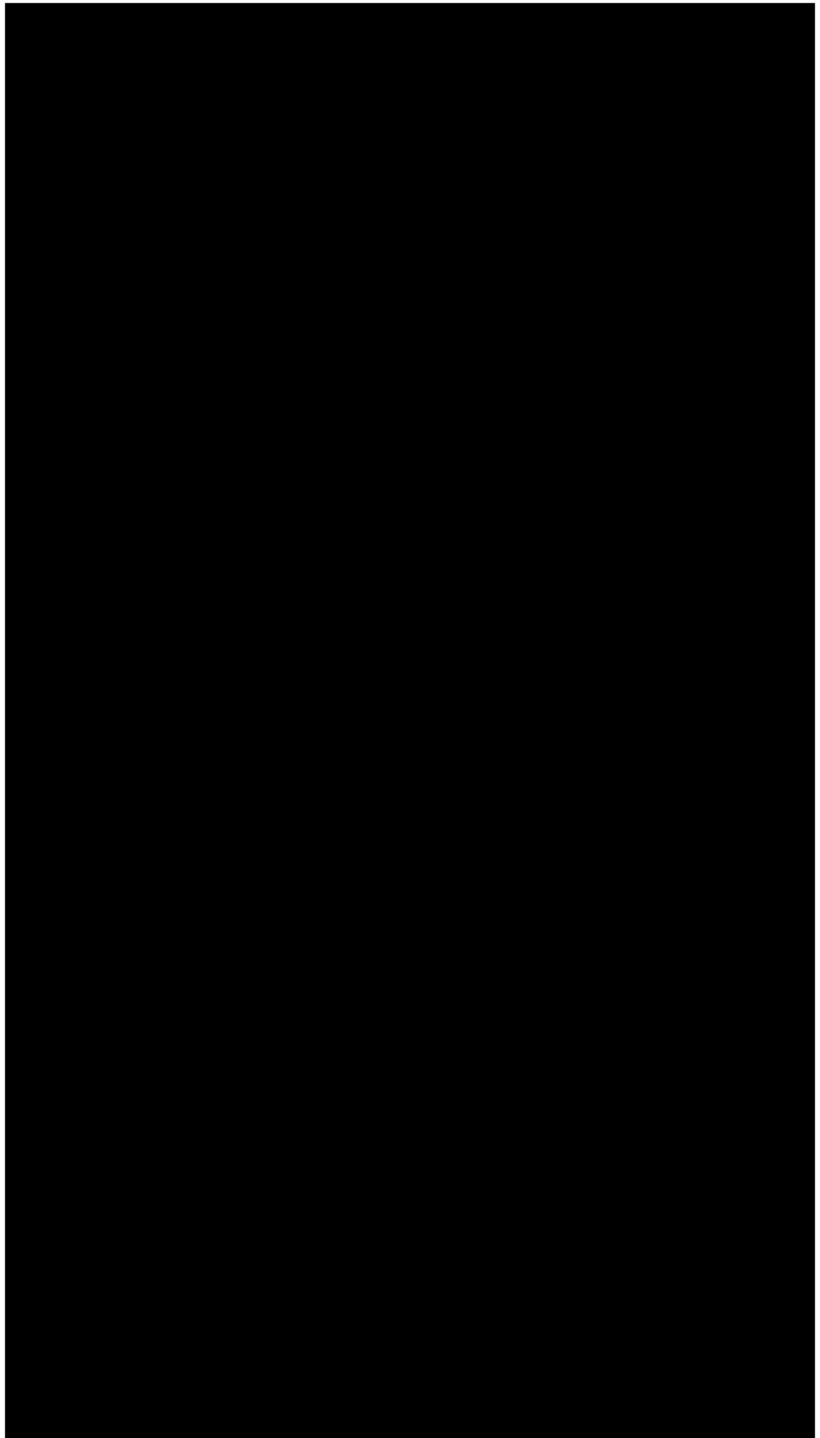
Theory

1. What is a neutron chopper what does it do?
2. Why do neutron scattering instruments need choppers?
3. TOF diagrams
4. What are the different types of neutron choppers? Family,naming
5. Basic parameters of choppers related to performance
6. How do the choppers function in combination?



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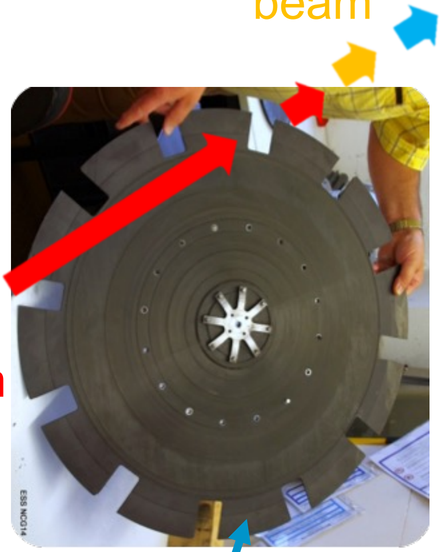
Theory

A chopper is a device or machine that cuts something with a fast movement, or cutting out unnecceray parts and keeping what's necessary

What is a neutron chopper?

A rotating device that can shape the neutron beam in time and space by means of a rotating disk with cutouts

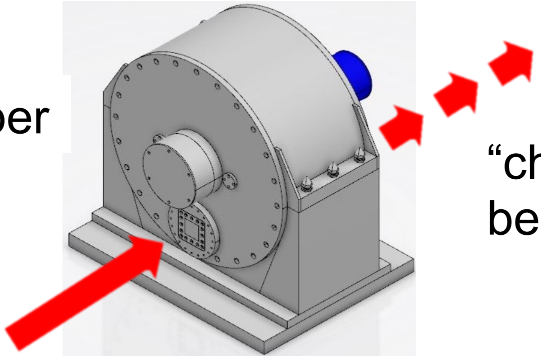
Outgoing beam



Incoming neutron beam

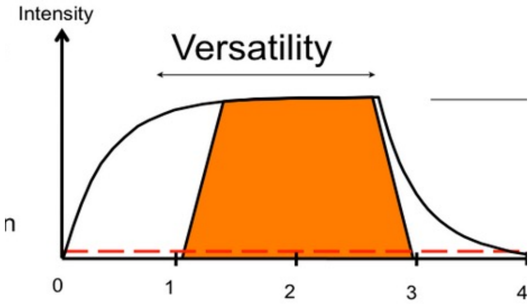
Chopper disk coated with neutron absorber

T0 chopper

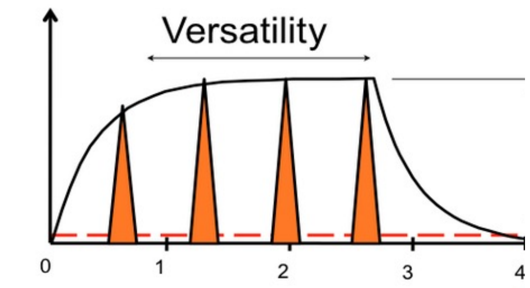


Incoming beam

"chopped" beam



Use as much as possible of the whole pulse:
Good for low wavelength resolution instruments.
SANS, Reflectometry, single crystal diffraction.
Estimated gains 10-100 times tha
currently available.



Cut the long pulse into smaller pulses:
Good for higher wavelength resolution instruments
Diffraction, cold/thermal spectrometers.
Long Instruments (80-100 m)
Estimated gains 10-30 times than currently available.
Thermal gains lower.

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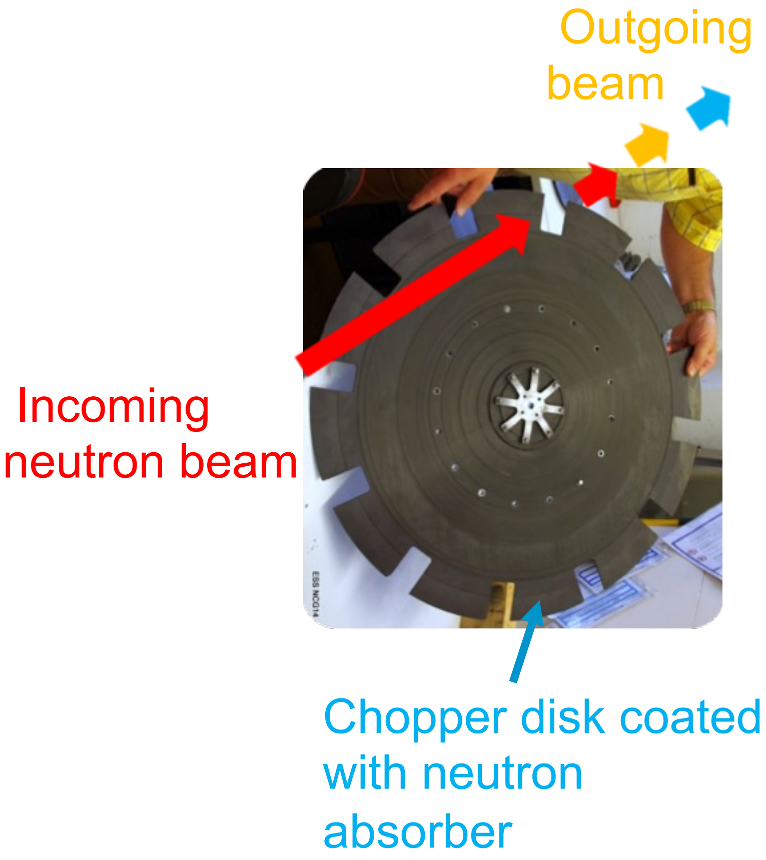
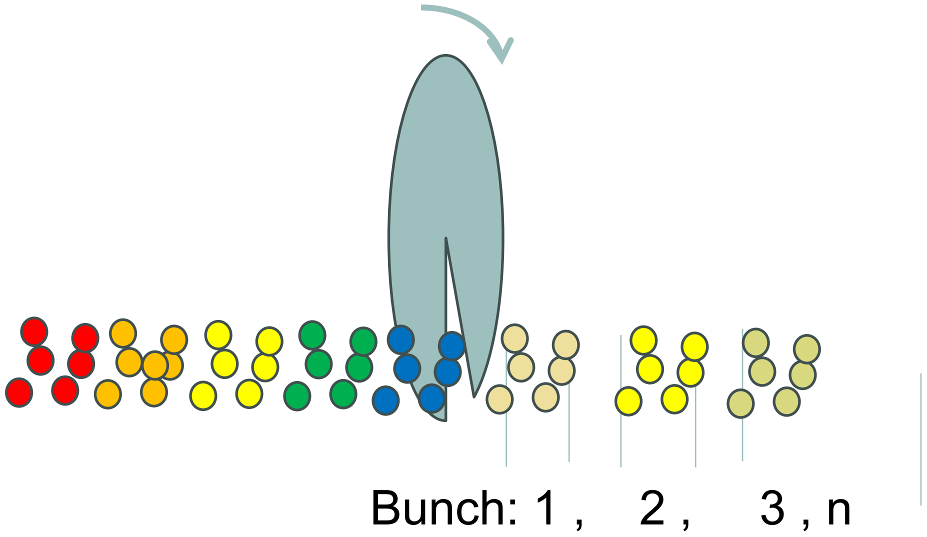
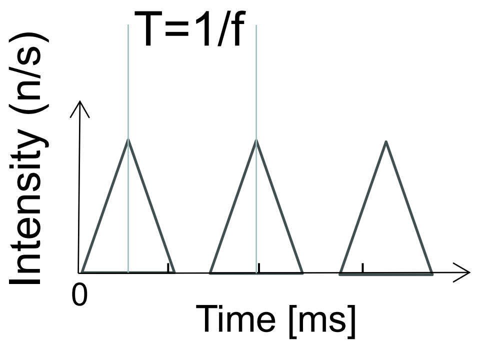
What is a neutron chopper?

A rotating device that can shape the neutron beam in time and space by means of a rotating disk with cutouts





Bunch(pulses)/sec = chopper frequency



t_{on}=angle*T/360

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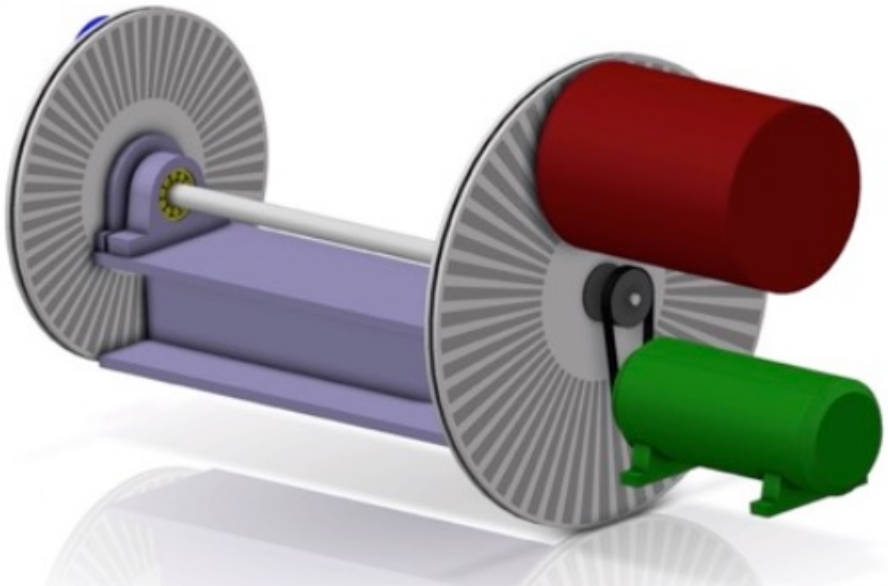
The first ?

1935 – USA, Columbia university

Historic neutron chopper # 1
The 'original' disc chopper

Dunning, Pegram, Fink,
Mitchell and Segre

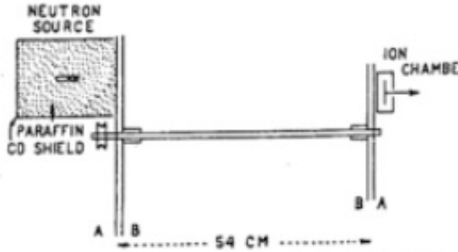


Key features

- (Double) Disc chopper
- Absorber cadmium
- Operating speed 30-60Hz

Function

- Velocity selection



Schematic drawing of mechanical velocity selector slow neutrons. A, rotating disk with Cd sectors; B, fixed disk wit sectors.

J.R. Dunning, G.B. Pegram, G.A. Fink
D.P. Mitchell and E. Segre
Phys. Rev. 48, 704 (1935)

Ref: 80 years of neutron choppers: Iain Sutton

Why do neutron scattering instruments need choppers?

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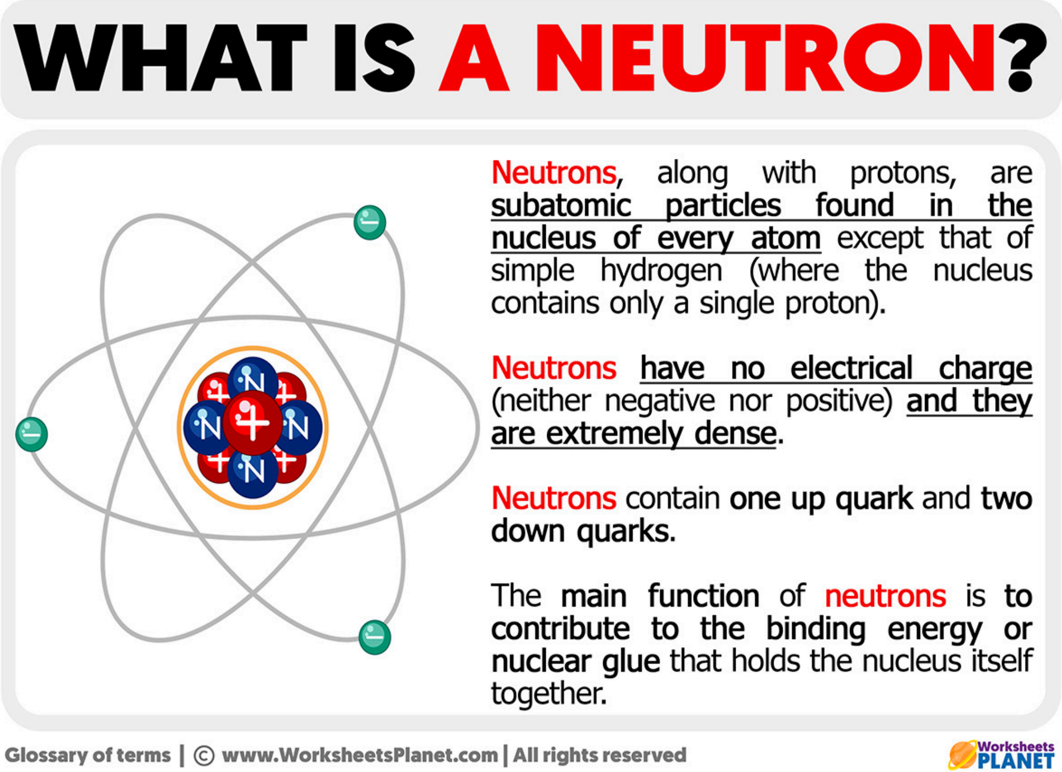
Mass: 1.675x10^{-27} kg.
Charge: 0
Magnetic moment
Lifetime: ~ 15 minutes - $n \rightarrow p^{+} + e^{-}$ + antineutrino

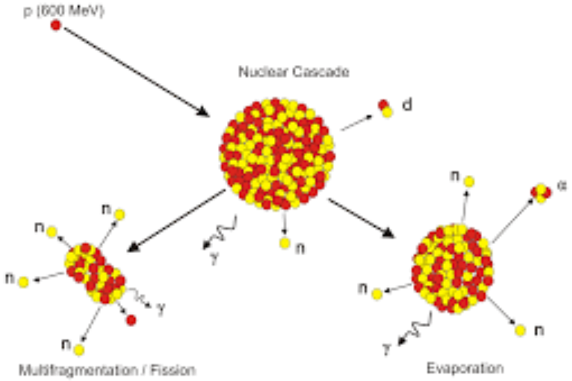
Neutrons interact

1. Atomic nuclei (strong nuclear force - short range)
2. Magnetic fields from unpaired electrons

Advantages of Neutrons

1. Bohr model approximation holds
   → easy to model material's interactions
   → system responds linearly
2. Neutrons probe the bulk (up to 30 cm depth)
   →nuclear and magnetic information
3. Neutrons do not damage the sample
4. Theory is quantitative





Neutron sources (reactor and spallation based) release free neutrons!

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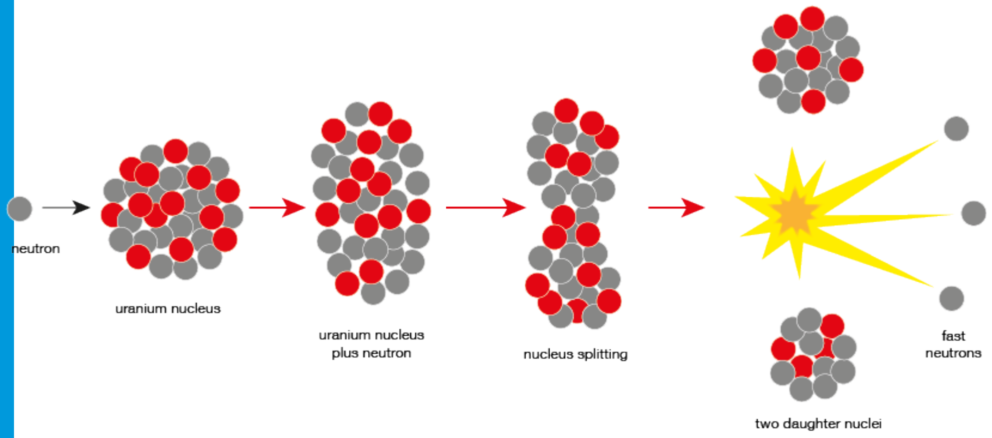
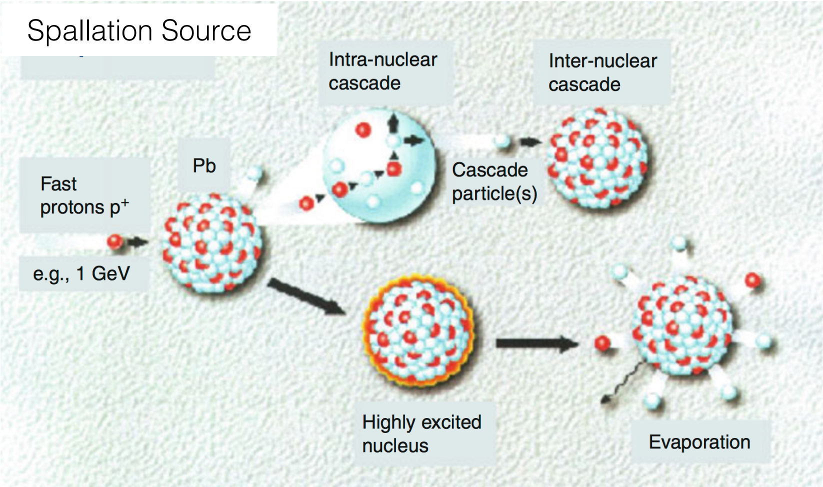
Neutron Production: Continuous-Pulsed

Produced neutrons have different energies



Chain reaction
Continuous flow
approx 1 neutron/fission



- **Spallation**:

p + heavy nucleus = 20 ~ 30 n + fragments

1GeV *e.g. W, Pb, U*

~ 30 MeV/n (as heat)

Spallate = Accelerator driven: 2 GeV - MeV
Pulsed operation
Approx 30 neutrons/proton

Further reading: Neutron production and moderation

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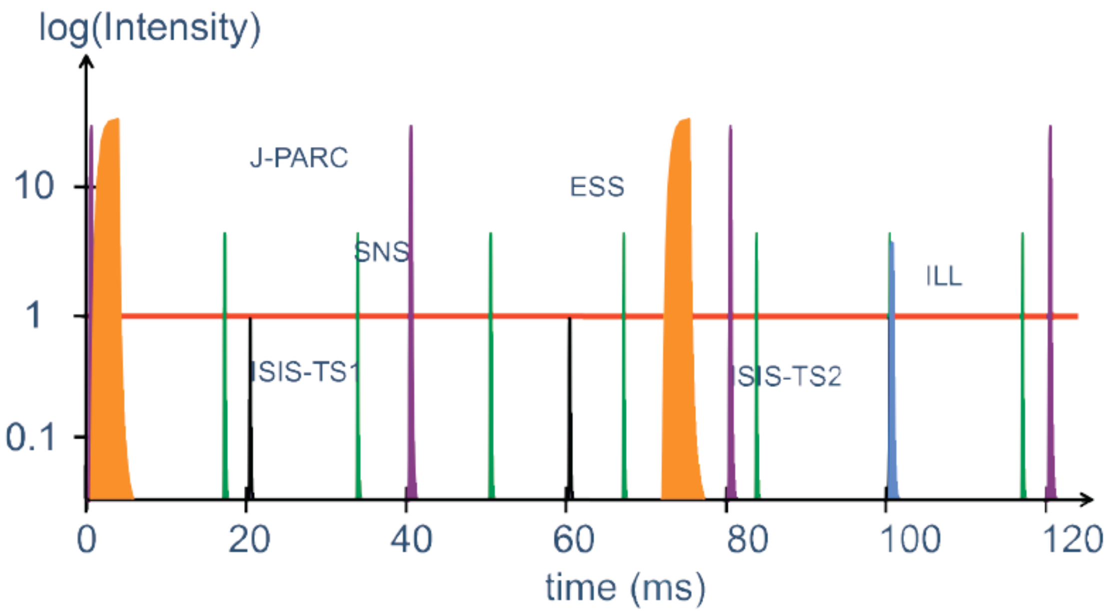
Types of neutron sources

- ISIS/SNS very short pulse (60us), repetition rate 10/50/60Hz, high time precision, excellent for spectroscopy, high-res diffraction
- JPARC : short pulse (120us), 25 Hz
- ESS: long pulse 2860 us,14Hz , ;low time precision but lower frequency and long pulse allows techniques such RRM,WFM
- ILL : continuous, excellent for crystal based instruments and all round performance



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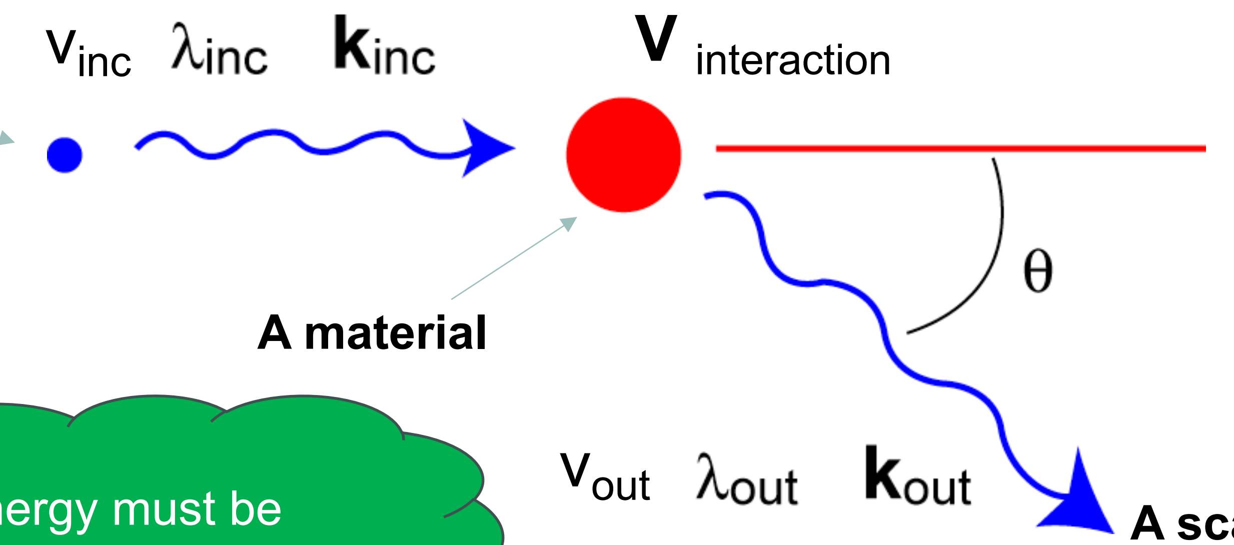
Neutron scattering

- Neutron scattering delivers the answer to the question:

"where are the atoms? what are they doing?"

- Energy and momentum exchange between the neutrons & the materials



Each neutron has mass + energy (or velocity)

Neutron energy must be known to be useful

Particle

$E = \frac{mv^2}{2} = 81.8/\lambda^2$

$\mathbf{p} = m\boldsymbol{v}$

Wave

$E = \hbar\omega$

$\mathbf{p} = \mathbf{k}\,\hbar$

Scattering process

$\hbar\omega = E_{out} - E_{inc}$ ⟵ Information about atomic motion / magnetic states

$\mathbf{Q} = \mathbf{k}_{out} - \mathbf{k}_{inc}$ ⟵ Information about atomic / magnetic structure

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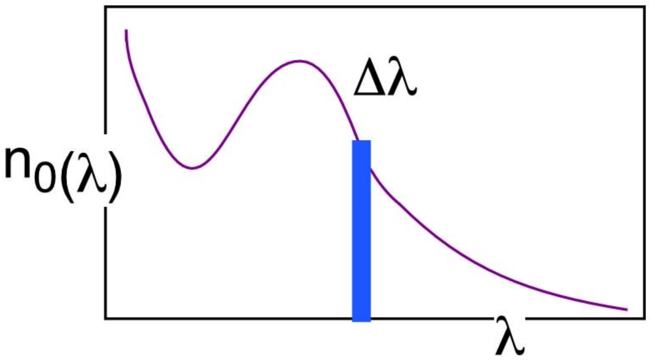
Why choppers: Define the energy

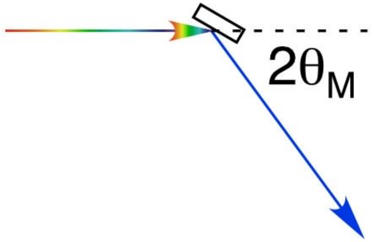
How to Define the Energy of a Neutron Beam?

Crystal monochromators and analysers (semi-static) & Choppers(rotating)



Wavelength resolution $\Delta\lambda/\lambda$

crystal (monochromator or analyzer)



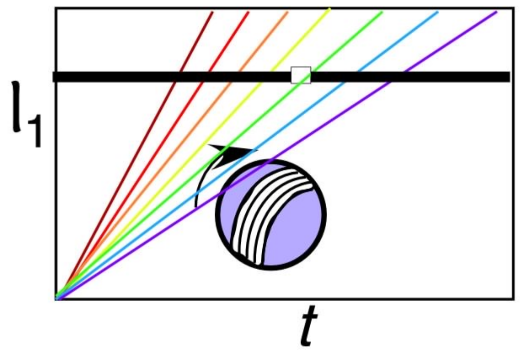
$\lambda = 2d_M \sin\theta_M$

$\delta\lambda \sim \cos\theta_M$

$\delta\lambda/\lambda \sim \cot\theta_M$

highest resolution
=> Backscattering

time-of-flight $\Delta l_1 \; \Delta t$



chopper (velocity selector)

highest resolution
=> limit the $\Delta l \; \Delta t$ spread
=> time focusing techniques

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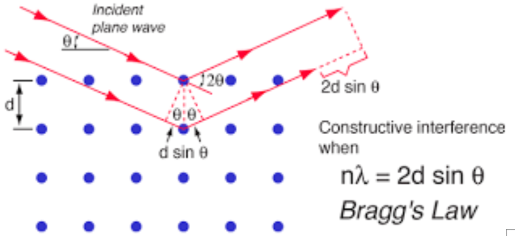
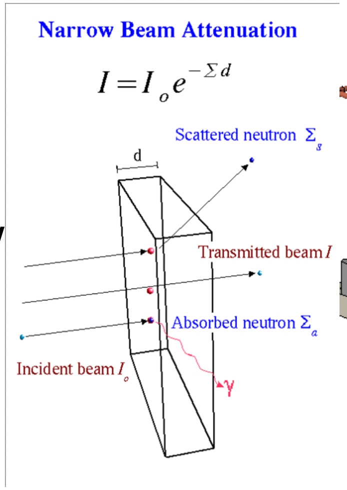
Non-choppers

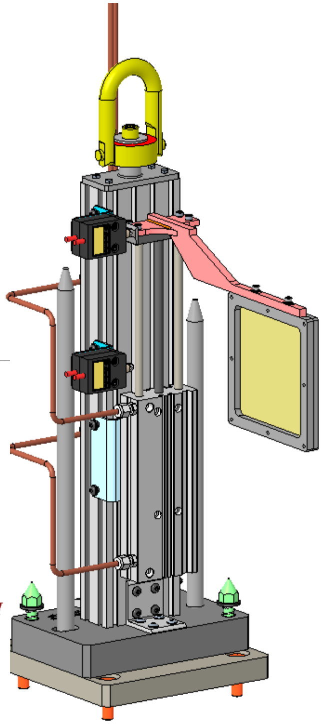
- Monochromators and Analyzers
- Mirrors
- Braggs Law
  - nλ=2dsin2θ



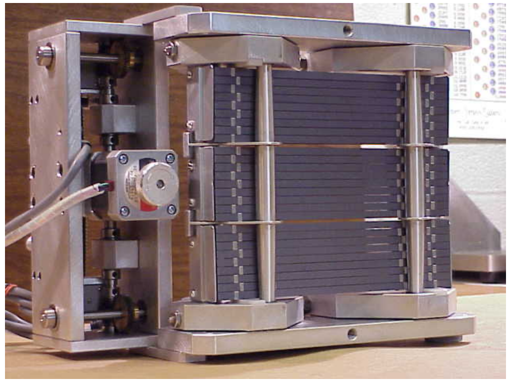
- Neutron Filters
  - Beer-Lambert Law



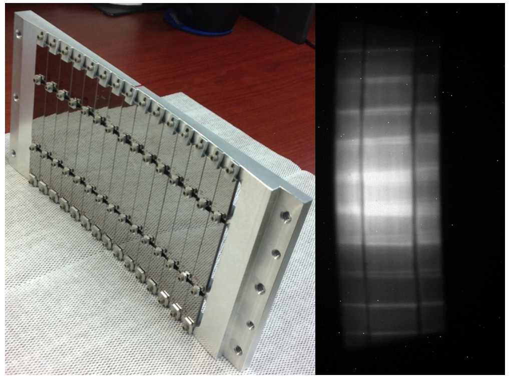
Cadmium Filter



Popovici-style elastically bent Silicon monochromator

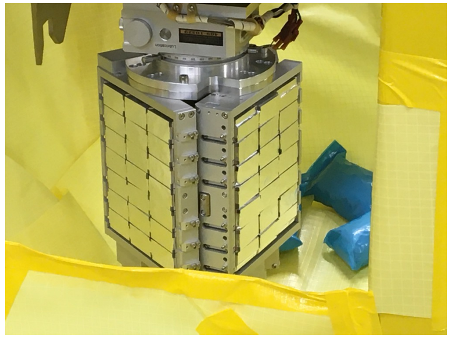


Fixed Focusing Highly Oriented Pyrolytic Graphite Array



Double Focusing Pre-monochromator Copper Crystals

Selectable (Graphite, Silicon, or Beryllium) focusing monochromator assembly



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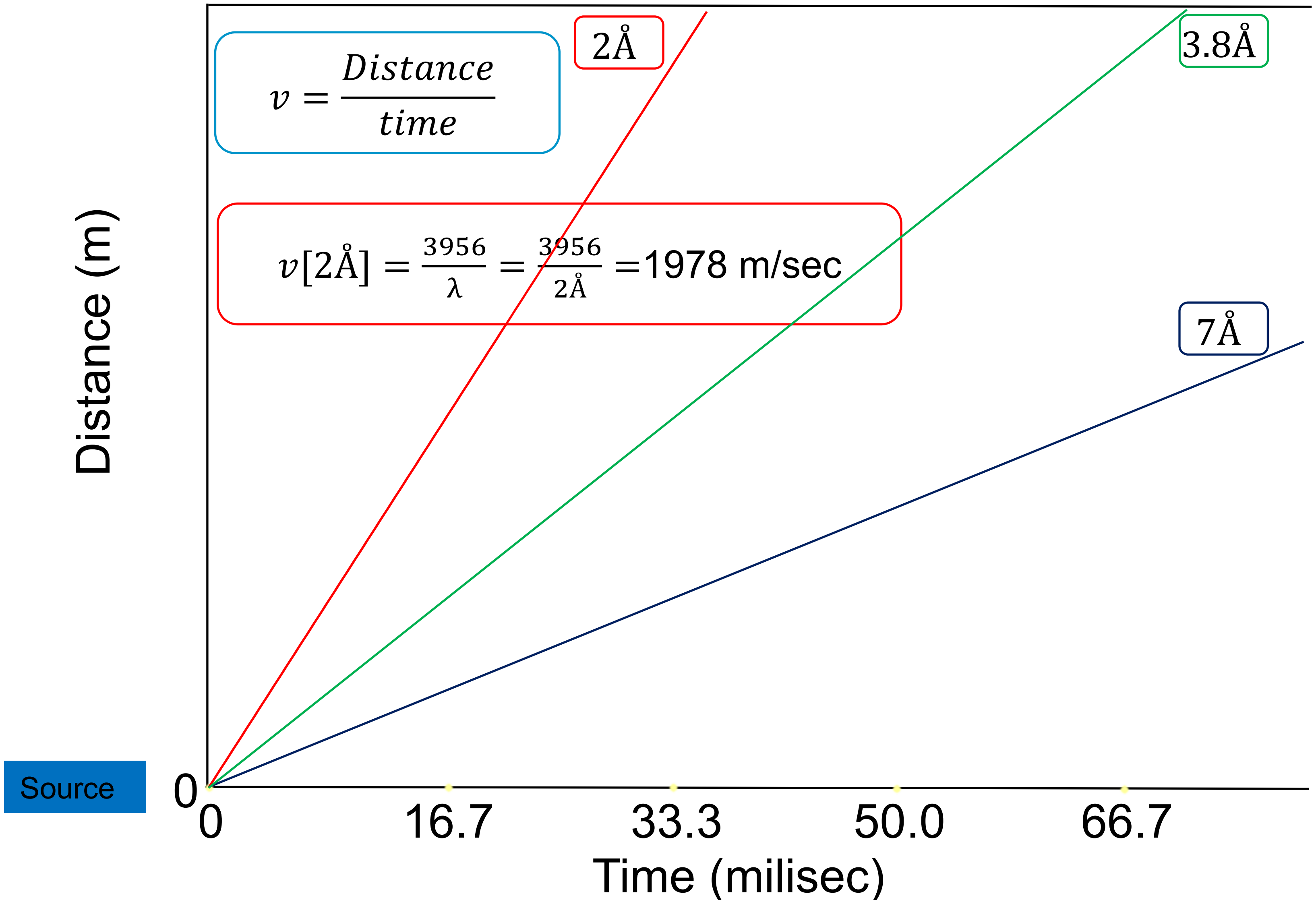
Why choppers

Time of flight diagram



Position of choppers(disc) with respect to source is known or can be calculated

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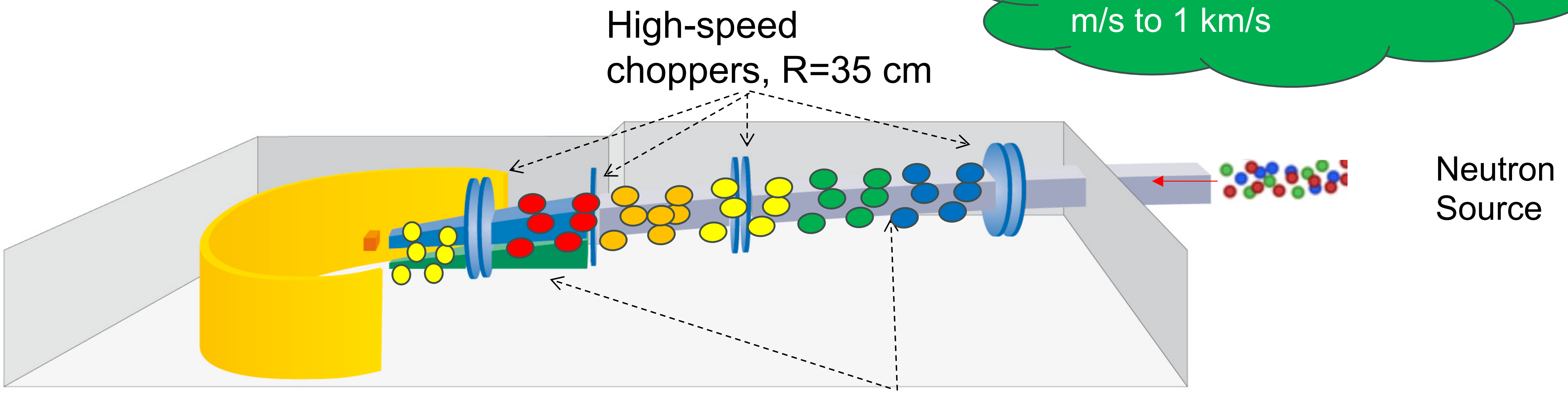
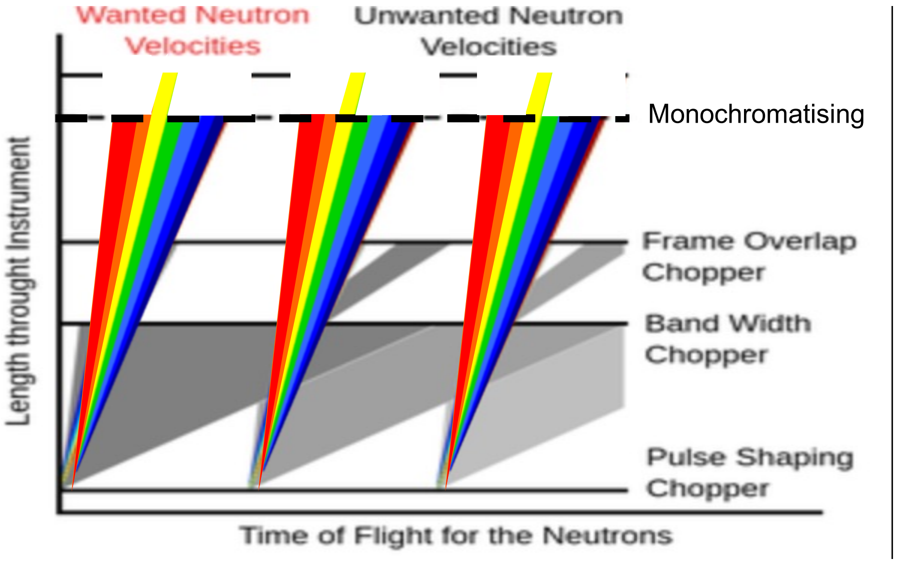
Why choppers

A time of flight chopper spectrometer



Neutron source produces neutrons velocities 50 m/s to 1 km/s



A neutron of 300 m/s takes 0.5 s to traverse instrument length of 150 m, λ= ?

$$\lambda = \frac{h(\mathrm{tof}_2 - \mathrm{tof}_1)}{mL}$$

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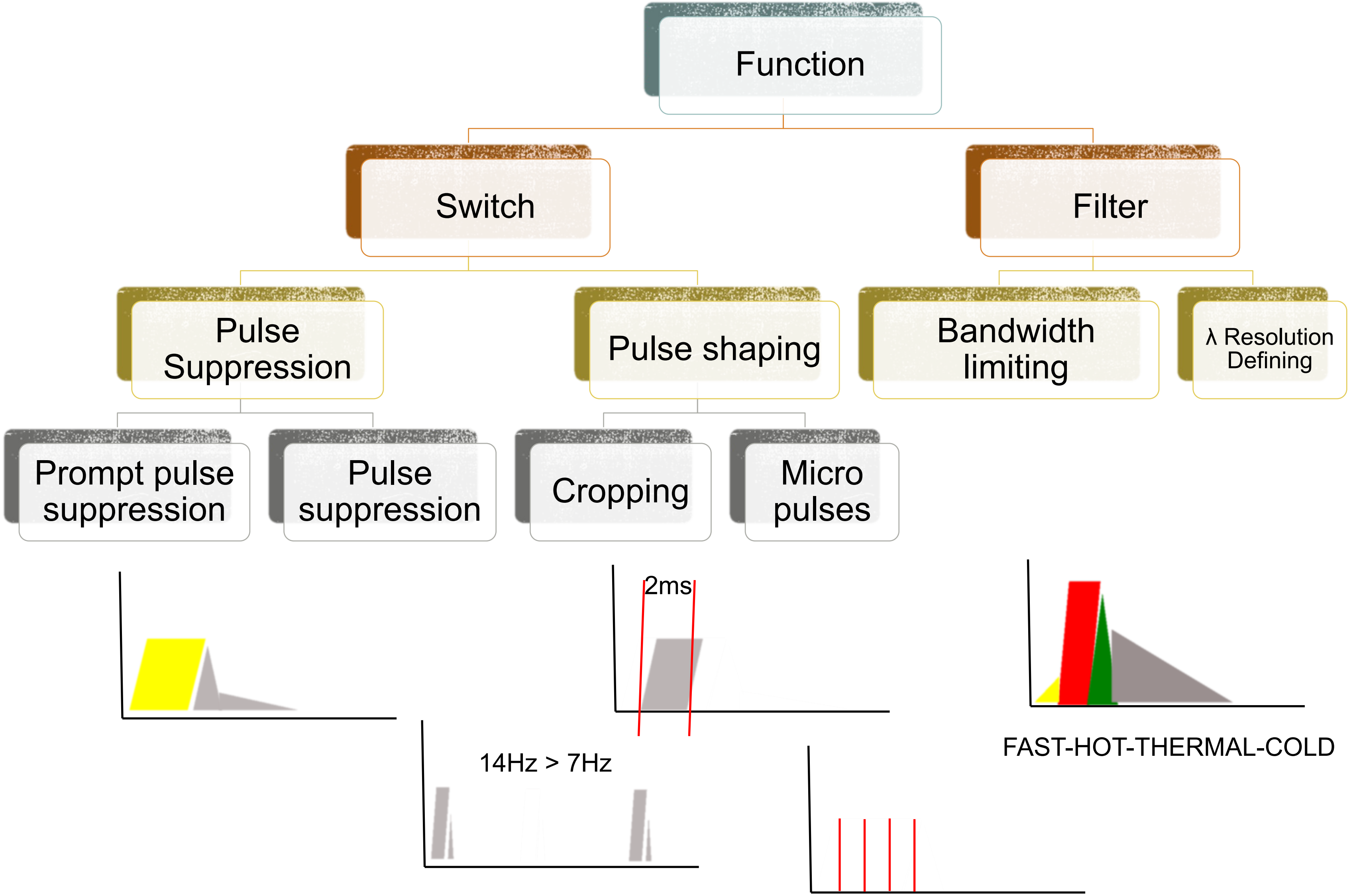
What are the different types of neutron choppers? Family tree



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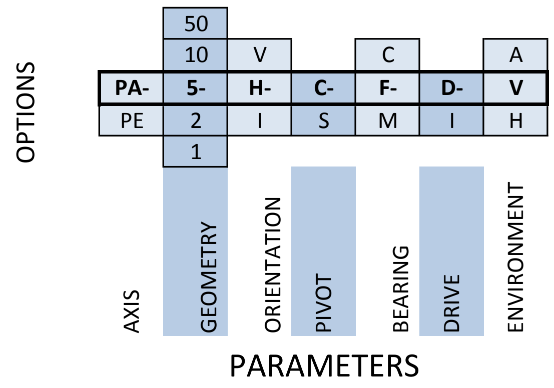
Chopper naming

- **PSC/PWD/Monochromatisation**

λ/E resolution defining: Fast disc chopper >100Hz, small opening, short pulses can be also Fermi type 600Hz

- **WB/WBD** : Wavelength band: Slow disc chopper <100Hz, large opening, long pulses
- **FO**: Frame overlap/order: Slow disc chopper <100Hz, large opening, long pulses
- **WFM**: Slow disc chopper <100Hz, large opening, large disc diameters
- **RRM**: Medium high speed disc chopper <200Hz, small opening, small disc diameters
- **T0, Nimonic, PPS**: Very heavy payloads/Hammer type, typically >100kg, below 100Hz
- **Wavelength selector(frame order selector):** Velocity selectors ~100Hz, complex rotating element, typical in reactor sources

CHOPPER UNIT DESIGNATION MATRIX



Rotor Axis	PA	Parallel to beam
	PE	Perpendicular to beam

Rotor Geometry	50	Needle	length to thickness ratio
	10	Drum	length to thickness ratio
	5	Barrel	length to thickness ratio
	2	Wheel	length to thickness ratio
	1	Disc	length to thickness ratio

Orientation	V	Vertical
	H	Horizontal
	I	Inclined

Pivot type	C	Cantilever
	S	Simply supported

Bearings	C	Contact
	F	Fluid
	M	Magnetic

Drive type	D	Direct
	I	Indirect

Environment	A	Atmospheric
	V	Vacuum
	H	High vacuum

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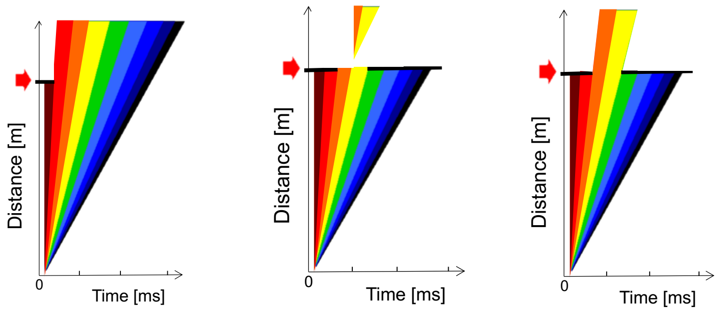
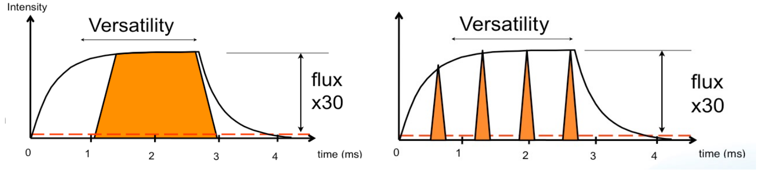
What are the different types of neutron choppers?

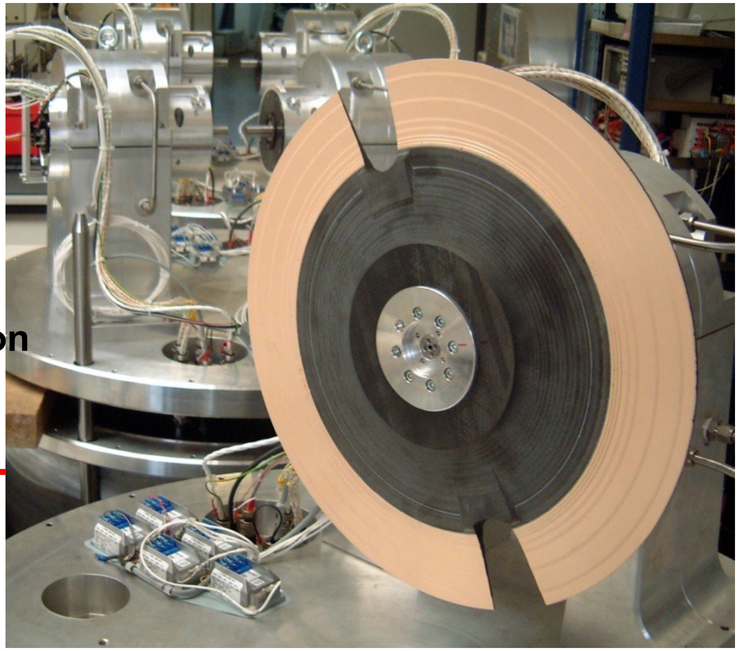
Disc Chopper: The versatile



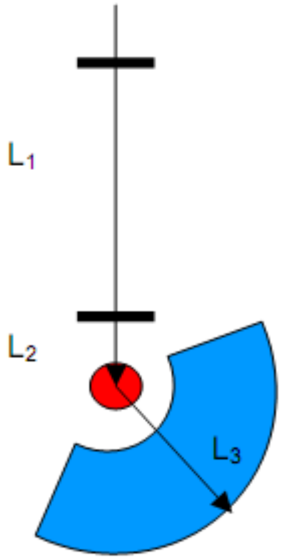


Disc Chopper

Disc choppers OK for λ > 0.7 Å
Rotation speed for 3.5 - 350 Hz



- Can act as a filter, a pulse creator, a pseudo source, bandwidth, bandpass, Frame overlap , resolution defining for thermal and cold neutrons
- Can rotate at any frequency ☺
- Phasing (syncronisation) of sets of chopper transmits required neutron wavelength



Ch1 – Ch2 Resolution defining Choppers

$$\delta\omega = m_n\left[\left(\frac{v_i^3}{L_1}+\frac{v_f^3 L_2}{L_1 L_3}\right)^2 \delta t_m^2 + \left(\frac{v_i^3}{L_1}+\frac{v_f^3(L_2+L_1)}{L_1 L_3}\right)^2 \delta t_c^2 + \left(\frac{v_f^3}{L_3}\right)^2 \delta t_d^2\right]^{\frac{1}{2}}$$

In a chopper spectrometer: 2 choppers define the energy(wavelength) resolution

$$\mathrm{I}(\lambda) \simeq \phi_o(\lambda)\cdot\frac{\tau_1\cdot\tau_2}{L_{12}}\cdot\frac{\omega}{N}, \tau_i = \alpha_i/2\omega$$

Lechner 1990b Optimisation of a chopper spectrometer

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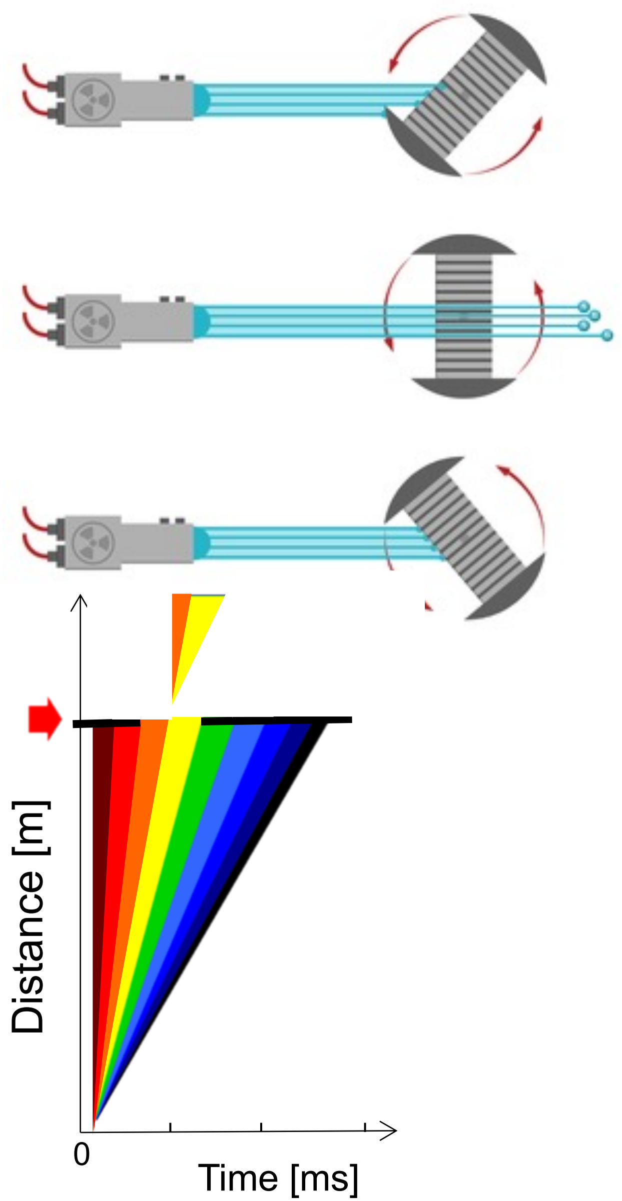
Fermi Chopper: The speedy

Fermi choppers OK for λ > 0.1 Å
Rotation speed for 3.5 - 600 Hz

- Can act as a filter, resolution defining for epi-, thermal and cold neutrons
- Heavy and light versions.
- Fermi's are used predominantly in spectrometers (highest speed, provides shortest pulses and highest energy/wavelength resolution)
- If used in eV spectroscopy then absorbers out of high density metals



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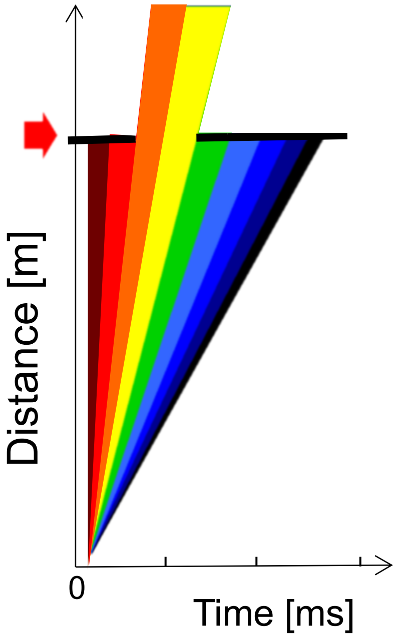
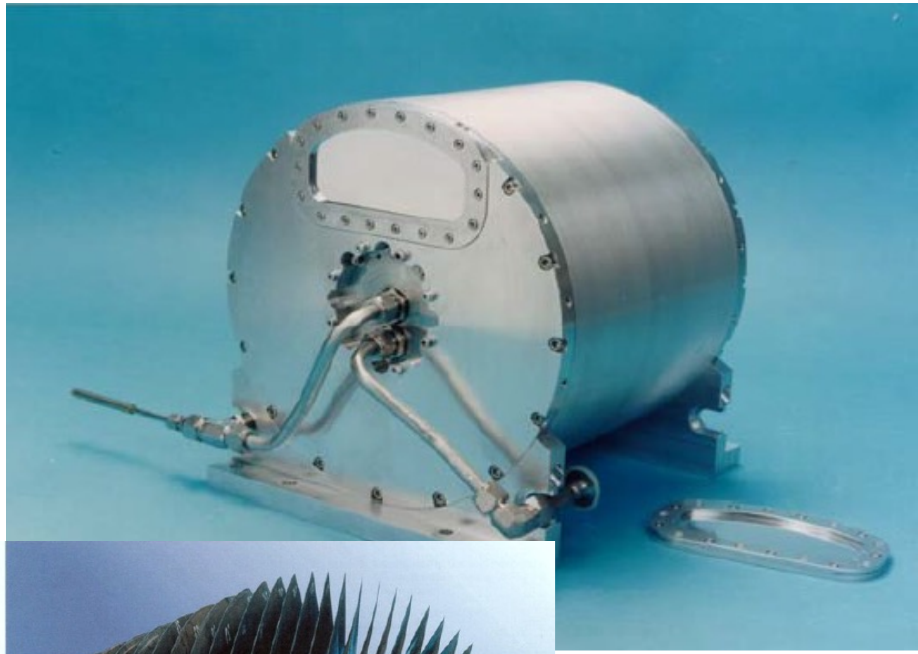
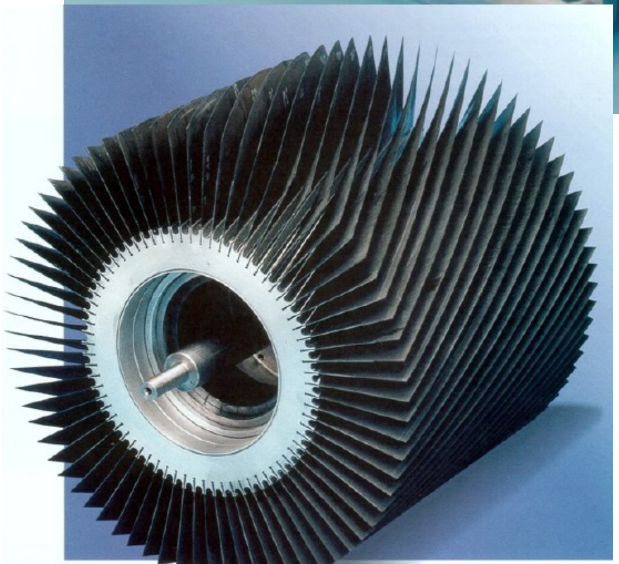
Velocity selector: Selective ?

Velocity choppers OK for λ > 0.1 Å
Rotation speed for 3.5 - 600 Hz

- Can act as a neutron bandpass filter (fine or coarse) for thermal and cold neutrons
- Performs 3 functions in one system
- Also known: frame-order selector
- Used nearly always at reactor source based instruments and in conjunction with crystal analyzer instruments
- The curved path is calculated so that only neutrons with a:
  - Mean Velocity range
  - Divergence range (range of incoming neutrons trajectory angle compared to the parallel)







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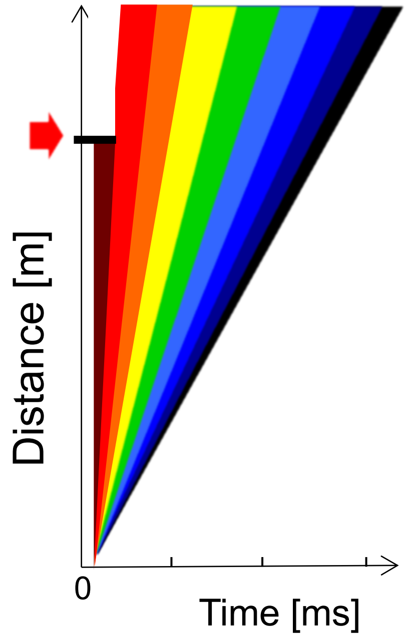
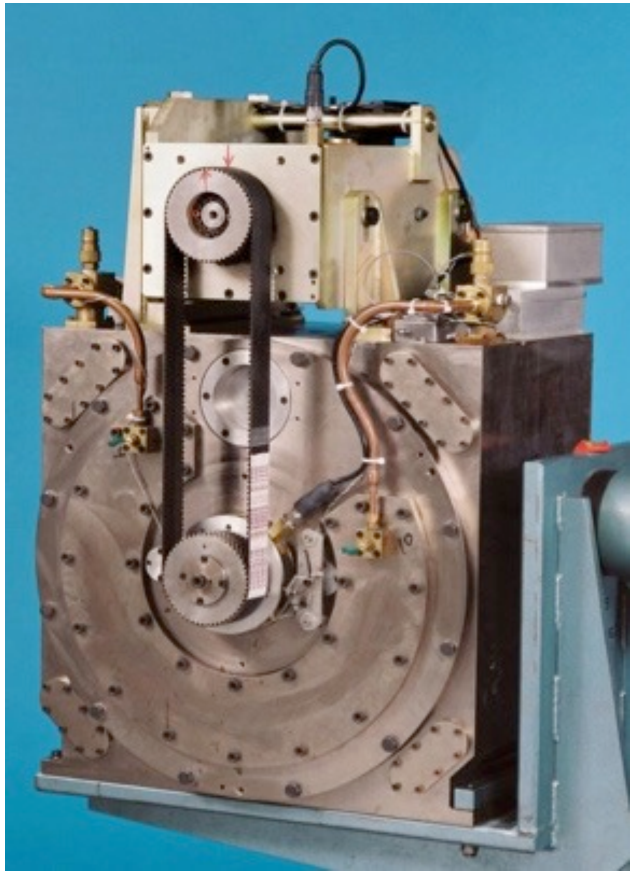
T0 Chopper: The heavy weight

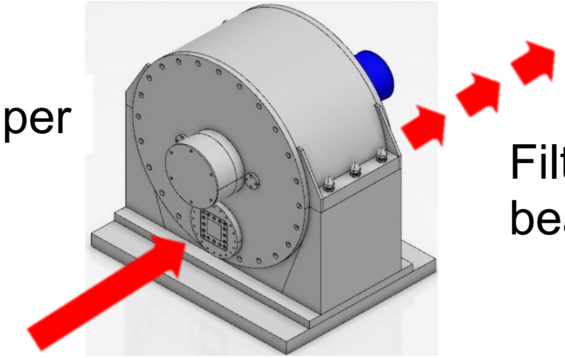
- Block fast neutrons >100MeV and gamma radiation i.e. prompt pulse
- Place an absorber mass of high-cross-section (tungsten steel) material in the neutron beam during the brief time the fast neutrons are present
- Rotate sufficiently rapidly to leave the beam completely unblocked when neutrons of the desired wavelengths travel through the chopper position.
- Typically rotates at the source frequency and is kept in phase with the source.



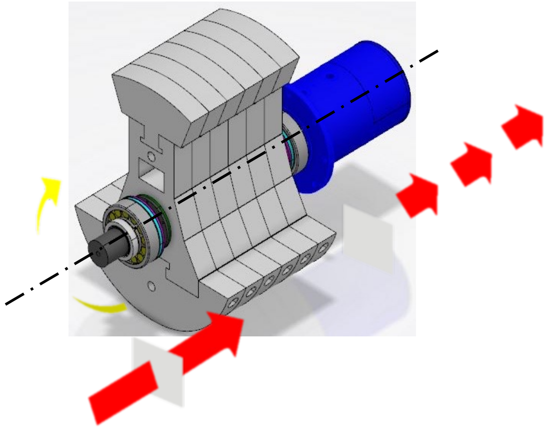


T0 chopper

Incoming beam



Filtered beam



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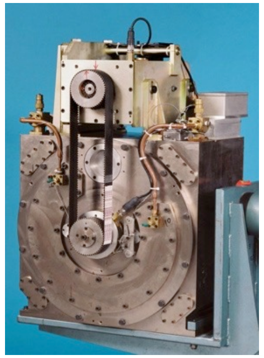
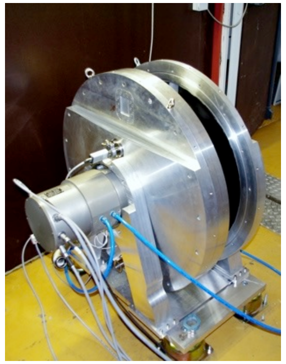
Types of choppers and performance

	X Source	0.5	1	2	4	8	12	16	20	24	28	30	40	50	75
	Hz	7	14	28	56	112	168	224	280	336	392	420	560	700	1050
100	500	PA-10-H-C (Tzero STD)				Tzero HP									
75	600	PA-2-H-C (Std Disc - Contact Bearings)													
100	700														
200	1000														
300	1200														
75	600				PA-1-H-M (Fast Disc - Magnetic Bearings)										
100	700														
25	25							PE-50-V-V							
75	150					PE-10-V-M (Fermi chopper - Magnetic Bearings - 'Light Rotor'									
100	250														
100	350					PA-5-V-M (Fermi chopper - Magnetic Bearings - 'Heavy rotor'									
Beam ht	Rotor dia														



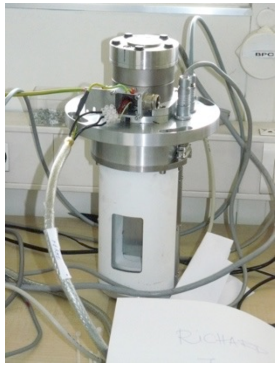
PA-5-H-S

PA-2-H-C



PA-1-H-M

PE-5-V-M



PE-10-V-M

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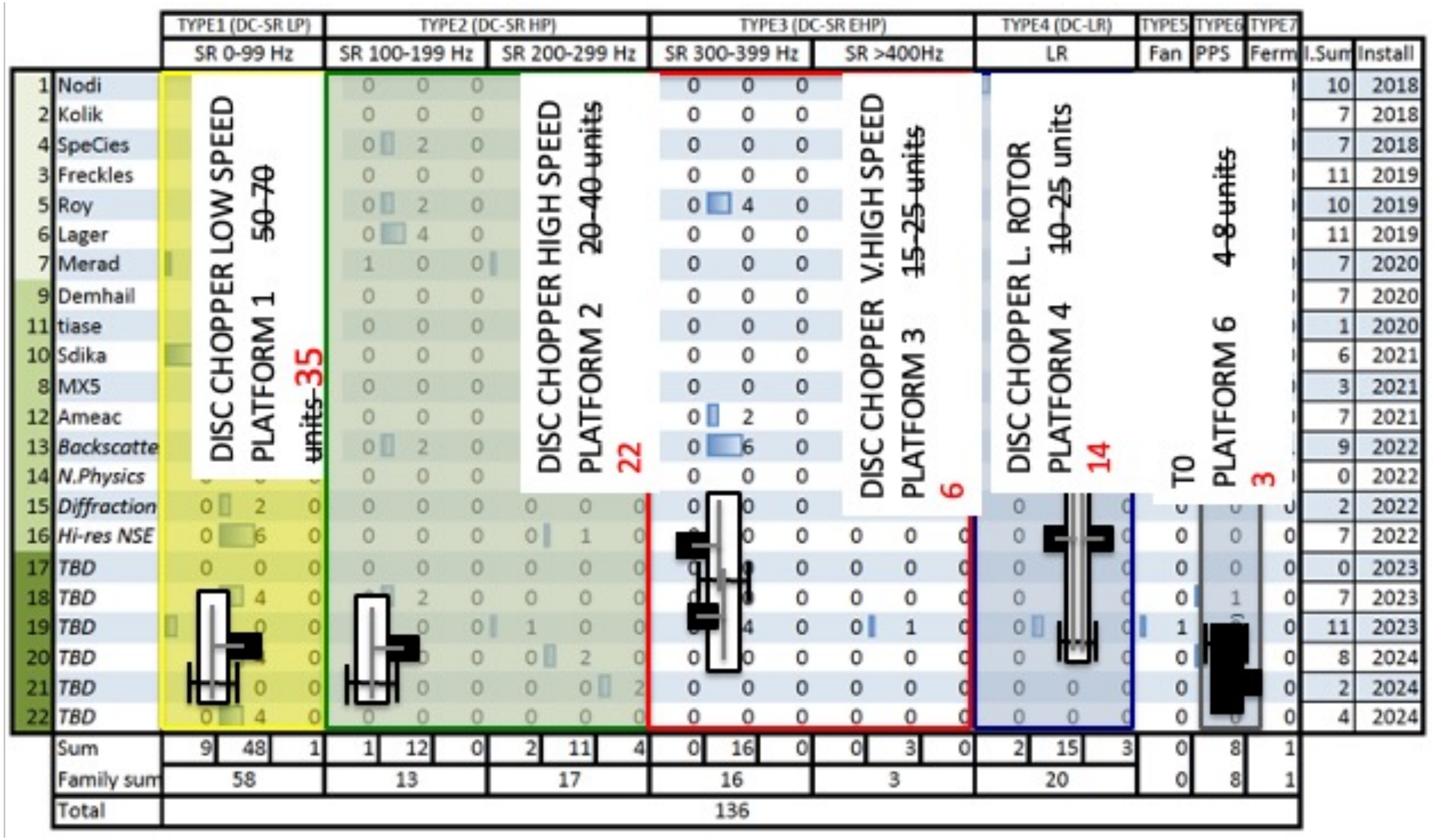
Types of choppers & performance(ESS)



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Chopper performance: calculation of parameters and simulations

- Basic requirements:
  - Pulse width= angular opening of disc opening, frequency of rotation
  - Pulse repetition= number of pulses per rotation (number of openings)
  - Rise time-fall time = Disc diameter/frequency (distance to center of beam)
- Absorption requirement for different neutron energies
  - Attenuation spreadsheet part of the module: type of materials
    - Gadolinium oxide-> very thin coating needed, <0.4mm not good for thermal,epithermal neutrons, emits high energy gammas 4MeV (a lot of shielding is needed) (400Hz)
    - Enriched Boron -> Pure, oxide or carbide forms-> 0.5-1.5mm thickness, very good for thermal even epithemral, only 0.4MeV gammas less shileding, Expensive and heavier than Gadolinum (400Hz)
    - Normal B4C : very inexpesnive coating thickness of 5-10mm very heavey suitable for slower choppers (<100Hz)
    - T0 type: High density alloys (W,Cu,Ni,Cd, Steel,Inconel,Nimonic) thicknesses (100s mm), heavy slow speed… ADD ,minimum wavelength

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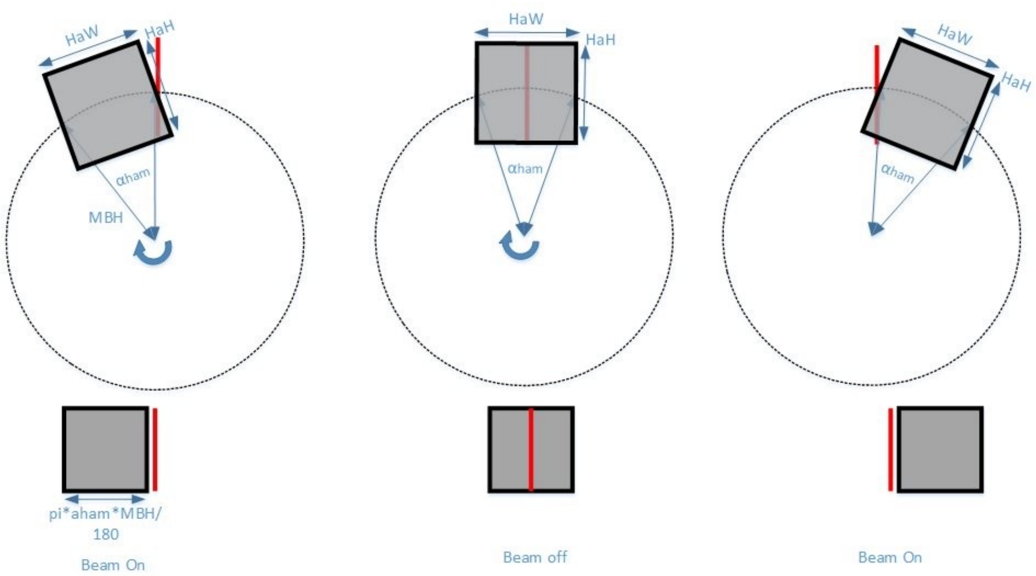
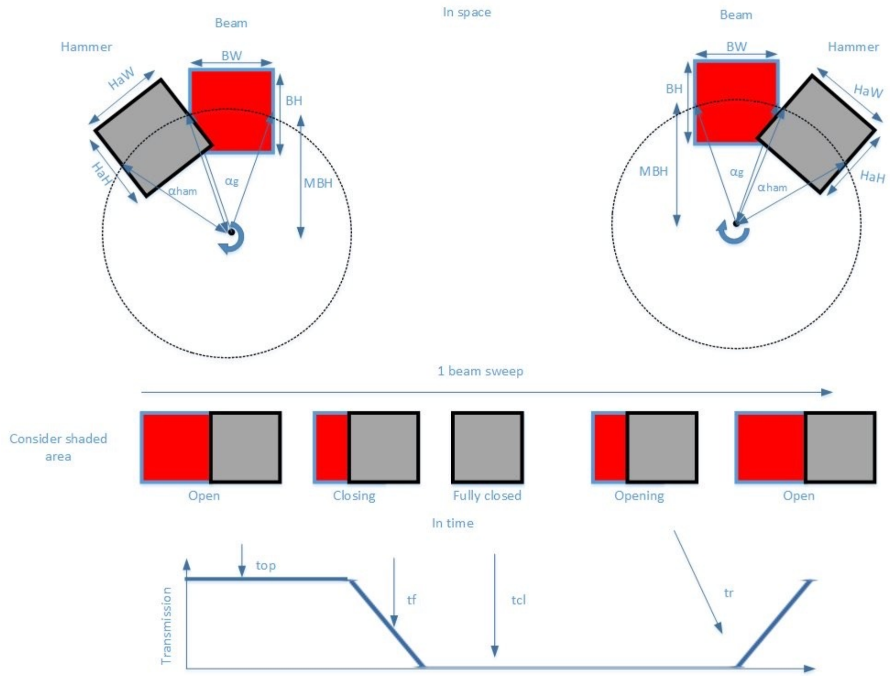
Chopper performance: calculation of parameters and simulations





T= Period of rotation , e.g. f=14 Hz T= 71.4ms

Tcl= Closed time i.e 8.9ms, Beam height H=60mm

SlitWidth=2pi*H*tcl/T = 6.28*60*8.9/71.4= 47 mm

Slit°=45 °

Tcl=T*Slit°/360=71.4*45/360= 8.9ms

For a realistic guide width and height:

HaW= (pi*MBH/180) * (tcl*360/T + 2*atan(0.5*BW/MBH)

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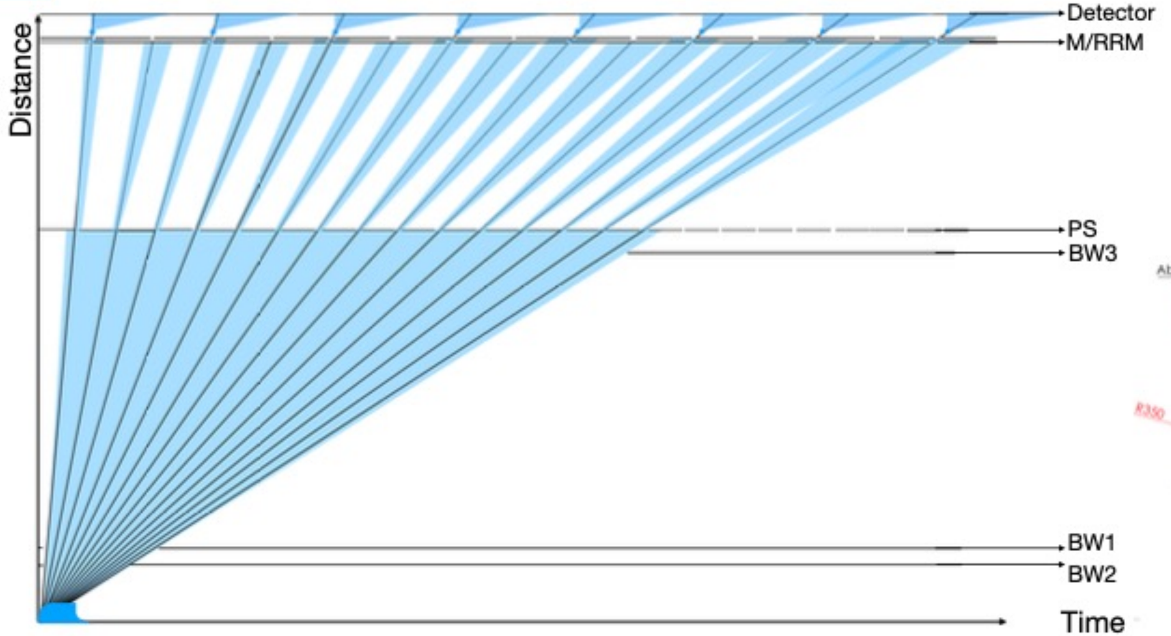
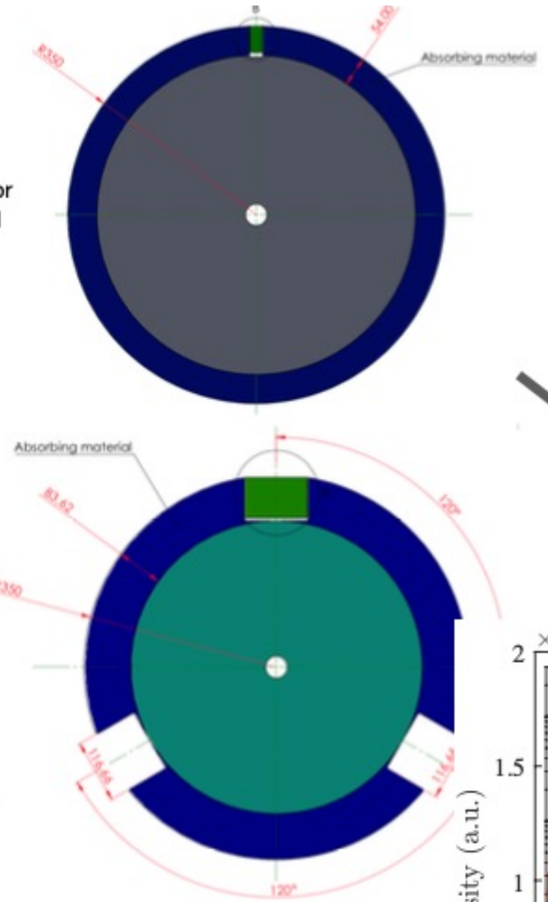
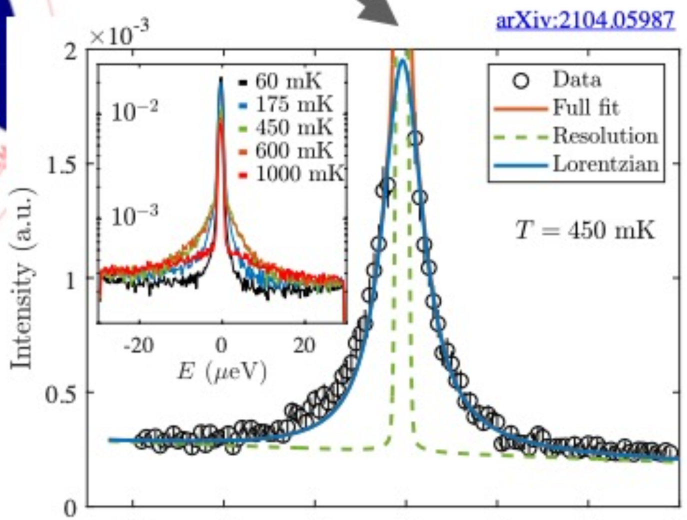
How do choppers function in combination?

Chopper cascade: High speed choppers

8 blades, ⌀ = 700 mm
Fmax: 336 Hz, 20160 RPM.







FWHM = 80 μeV @ 4 Å
FWHM = 6 μeV @ 10 Å
Concomitant with ESS pulse

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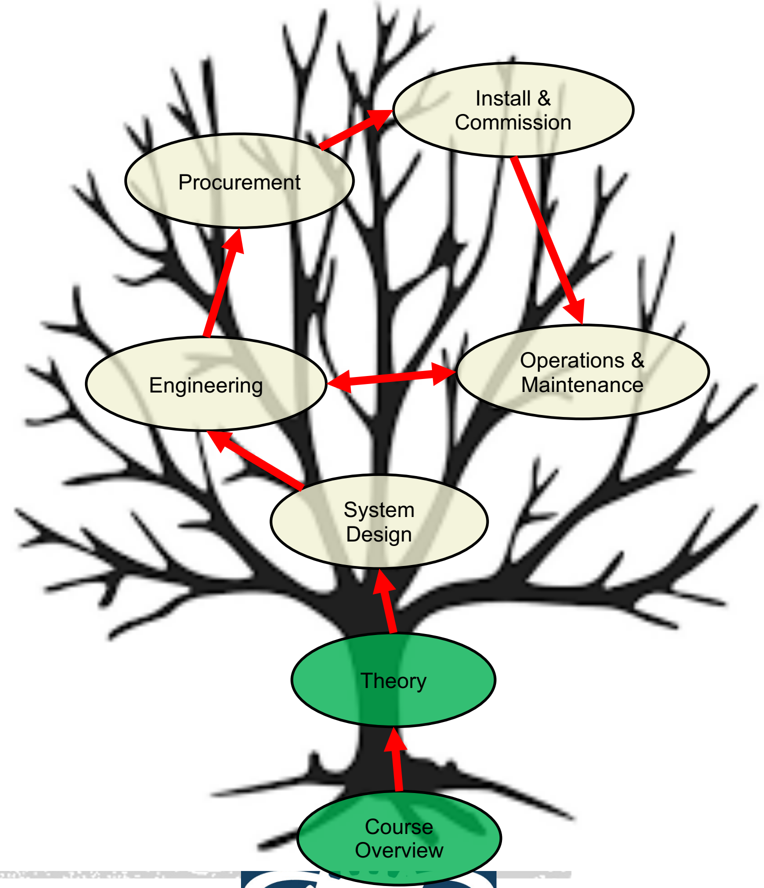
End of the line theory

Thanks for participating



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