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School on Pulsed Neutrons: Characterization of Materials

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Neutron Sources & Scattering Techniques (5)

Guenter Bauer

Forschungzentrum Julich GmbH
Julich
Germany

The Abdus Salam
International Centre for Theoretical Physics

School on **Pulsed Neutron Sources: Characterization of Materials**
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Introductory Lecture:

Basics Concepts in Neutron Scattering Techniques and Neutron Sources (5)

Günter S. Bauer
Forschungszentrum Jülich
in der Helmholtz Gemeinschaft

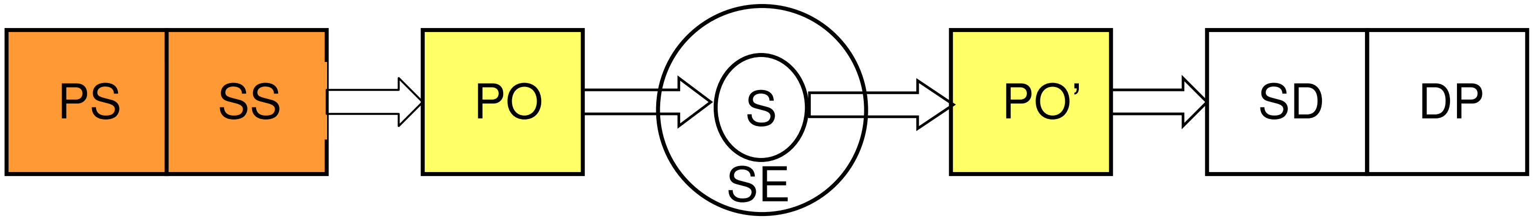
guenter@bauer-wt.de

Part 5

Design Considerations for Neutron Sources

Neutron Sources for Neutron Scattering

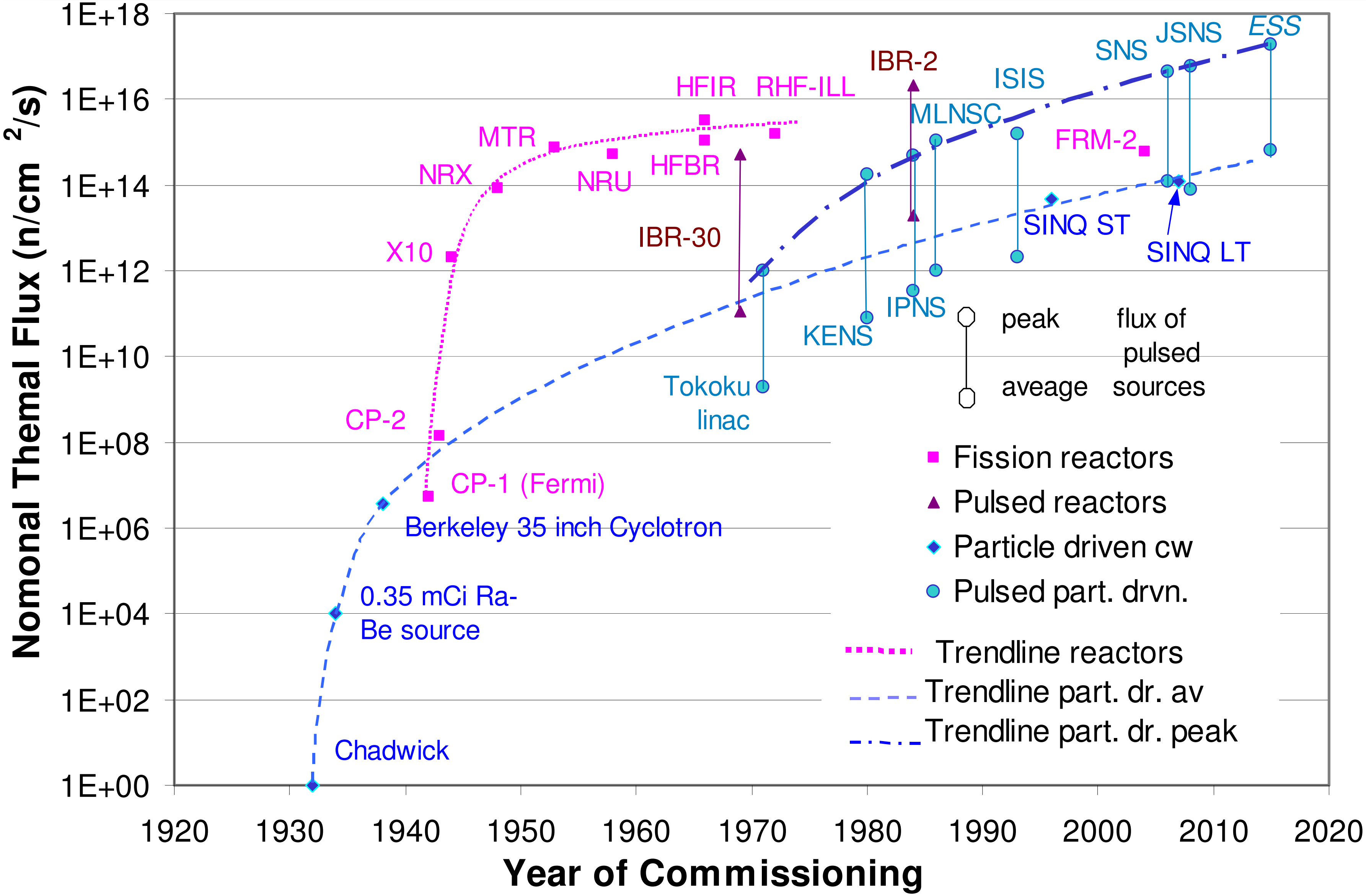
- Neutron scattering instruments can be designed to work in continuous mode or in time of flight mode.
- There is no one instrument that can cover most of the Q-ω space with sufficient resolution and flexibility.
- Instruments have varying requirements with respect to spectral properties and time structure.
- This is why instrument and source designers have come to interact ever more closely in conceiving new systems (not so in the early days of reactor development).



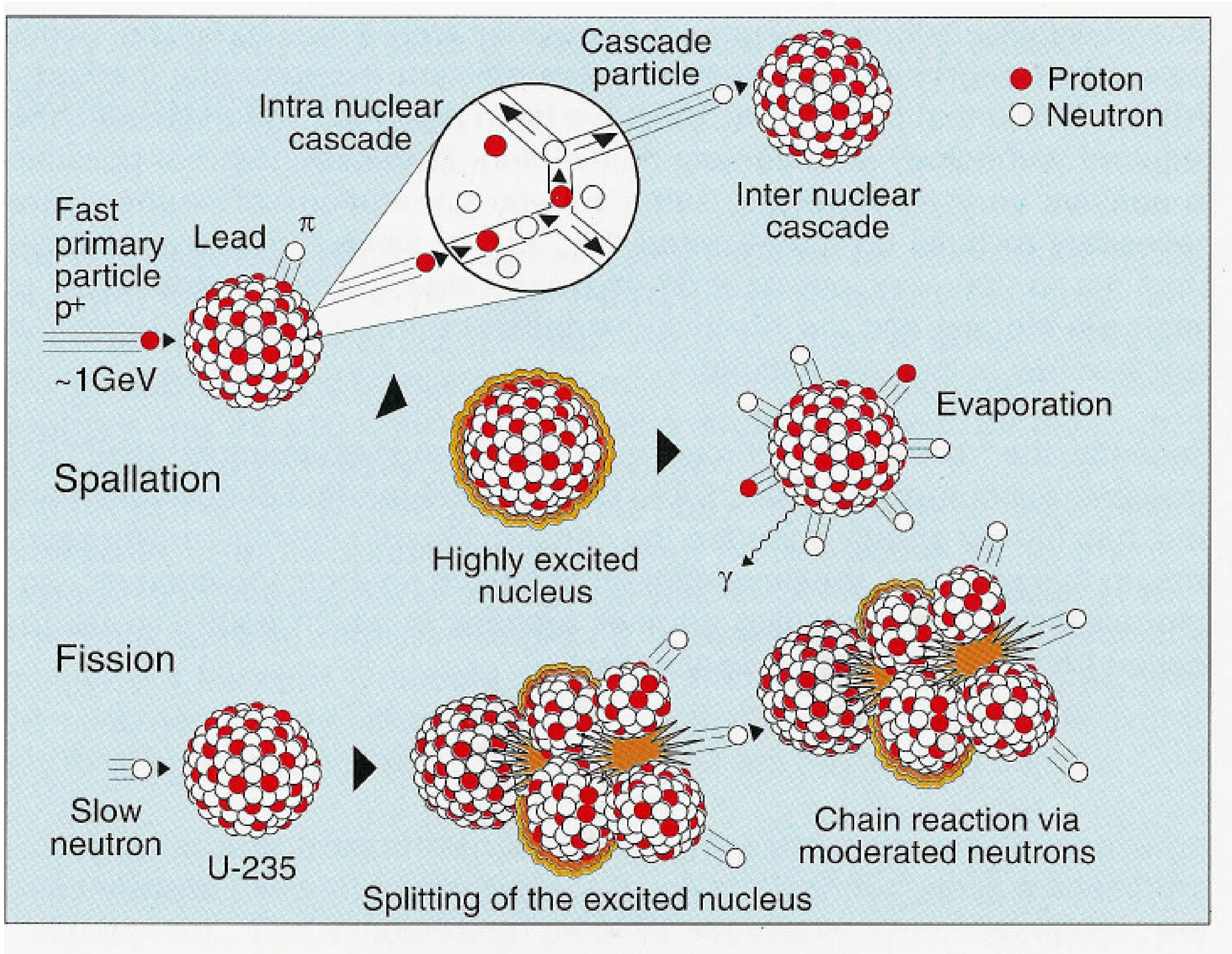
Neutron Yield of Different Nuclear Reactions

Nuclear process	Example	Neutron yield	Heat release (MeV/n)
D-T in solid target	400 keV deuterons on T in Ti	$4*10^{-5}$ n/d	10 000
Deuteron stripping	40 MeV deuterons on liquid Li	$7*10^{-2}$ n/d	3 500
Nuclear photo effect from e^--bremsstrahlung	100 MeV e^- on ^{238}U	$5*10^{-2}$ n/e^-	2 000
^9Be (d,n) ^{10}Be	15 MeV d on Be	1 n/d	1 000
^9Be (p,n;p,pn)	11 MeV p on Be	$5*10^{-3}$ n/p	2 000
Nuclear fission	fission of ^{235}U by thermal neutrons	1n/fission	180
Nuclear evaporation (spallation)	800 MeV p+ on ^{238}U on Pb	27 n/p 17 n/p	55 30

Development of Neutron Sources ("Top of the Line")



Visualisation of the Spallation and Fission Processes

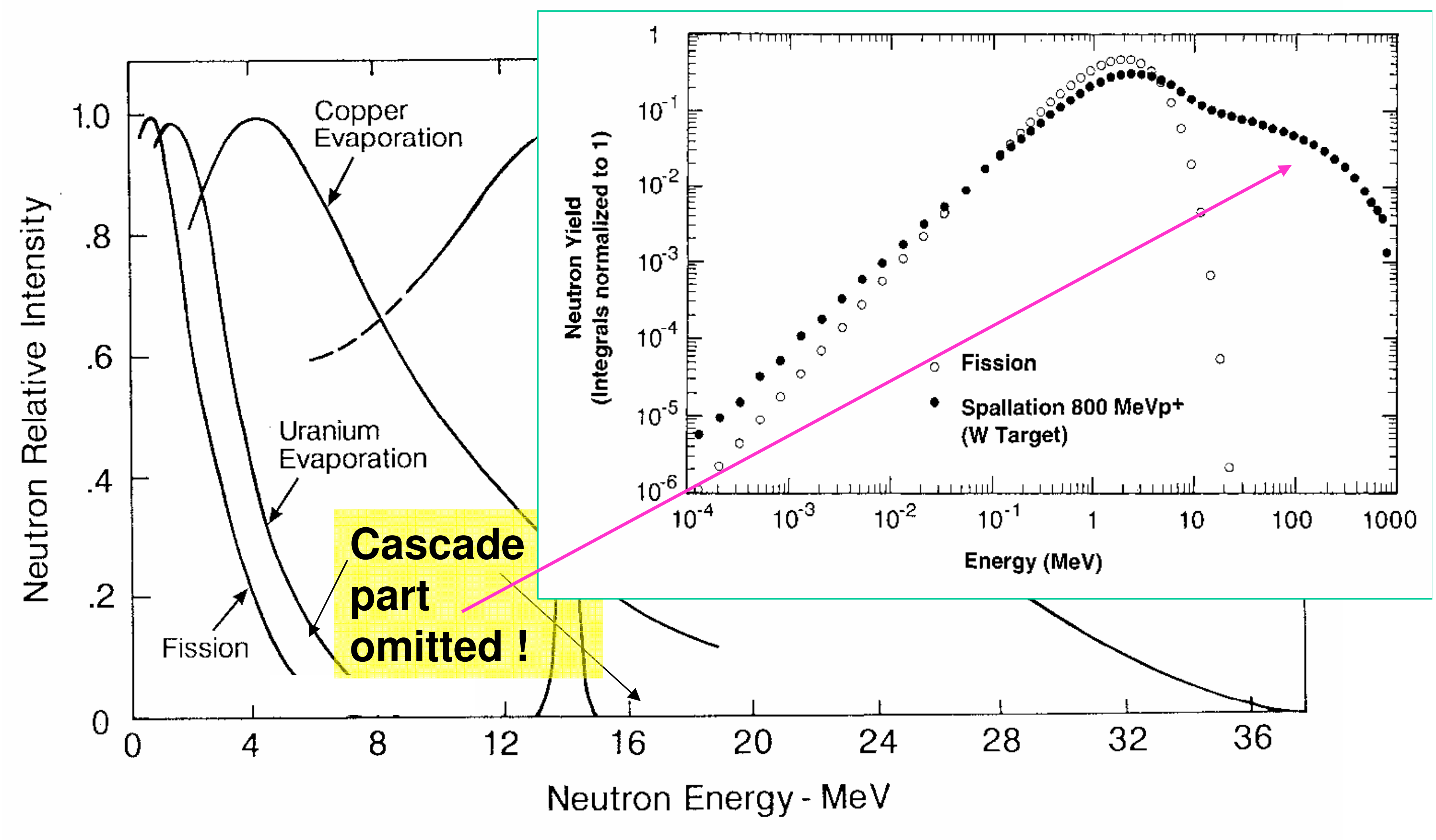


Cascade particles have energies up to the incident proton energy and can cause evaporation reactions in other nuclei

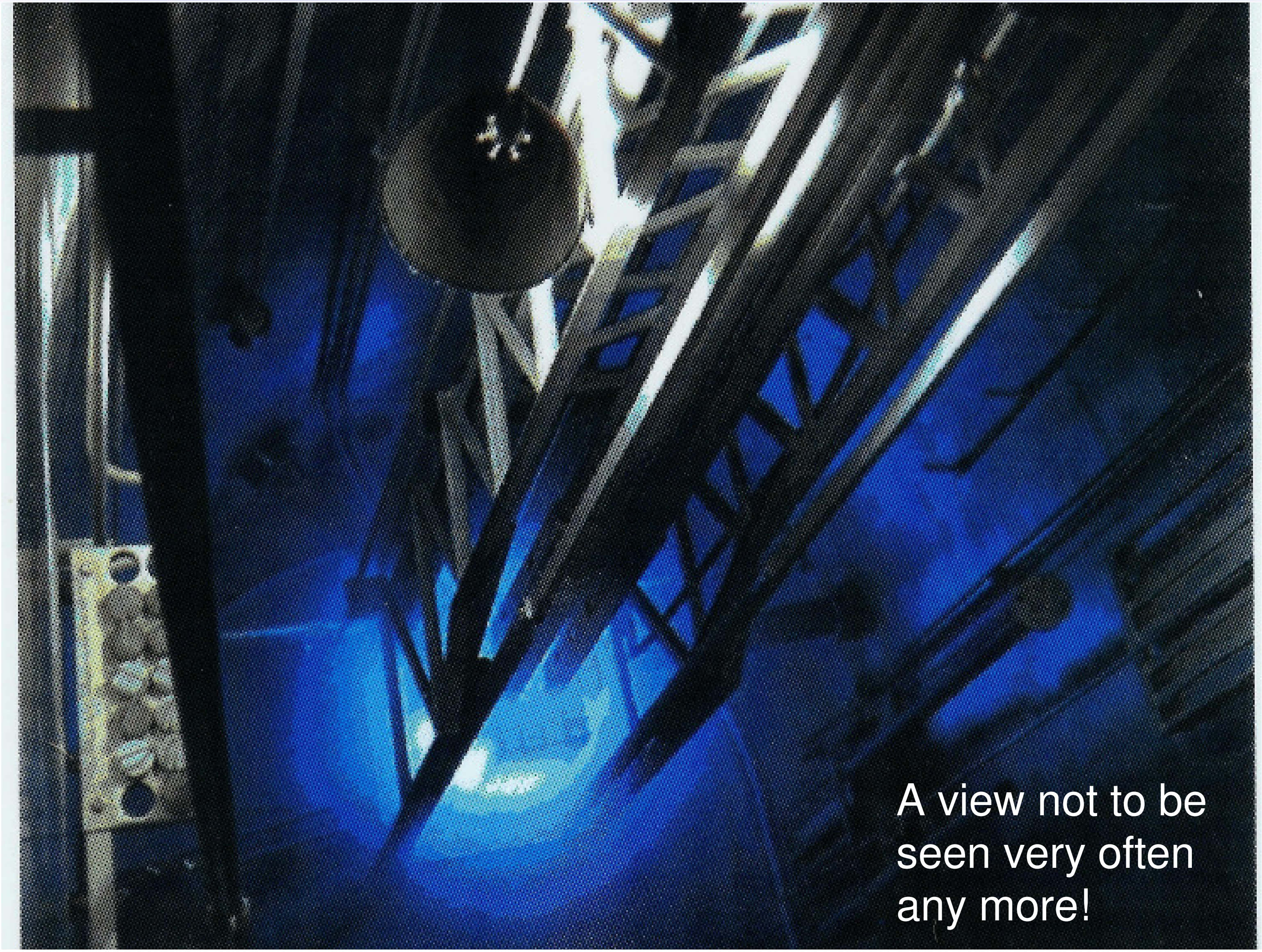
In contrast to fission, spallation cannot be self sustaining!

Fission neutrons must be moderated (slowed down to thermal energies) to cause fission in other nuclei

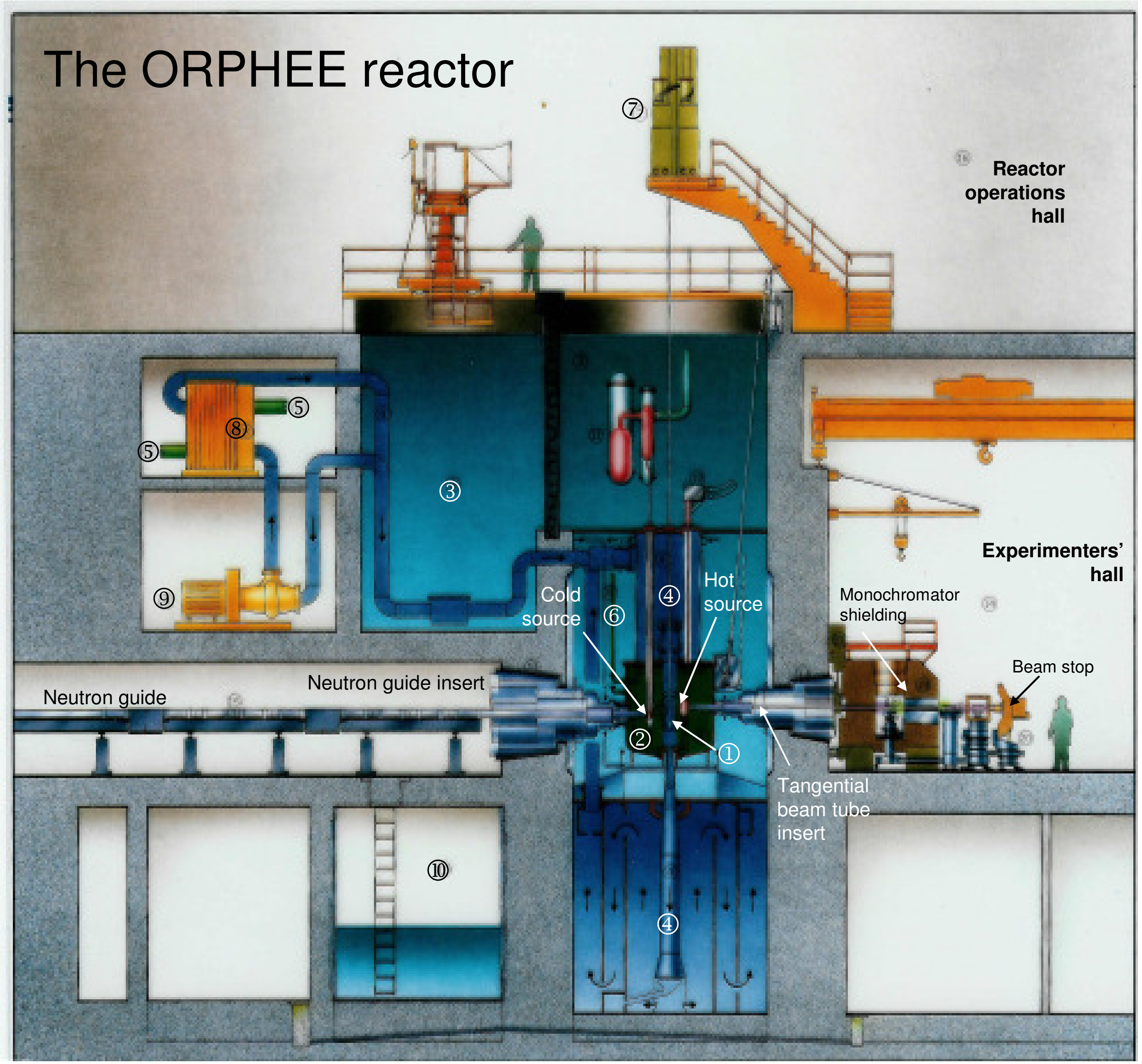
Neutron Spectra from Different Nuclear Reactions



Fission Neutron Sources (Reactors)



Fission Neutron Sources (Reactors)



1 Reactor core
2 Heavy water reflector
3 Reactor pool
4 Primary cooling system
5 secondary cooling system
6 heavy water system
7 Control rod drive
8 Heat exchanger
9 Primary coolant pump
10 Pool drain tank

Fission Neutron Sources (Reactors)

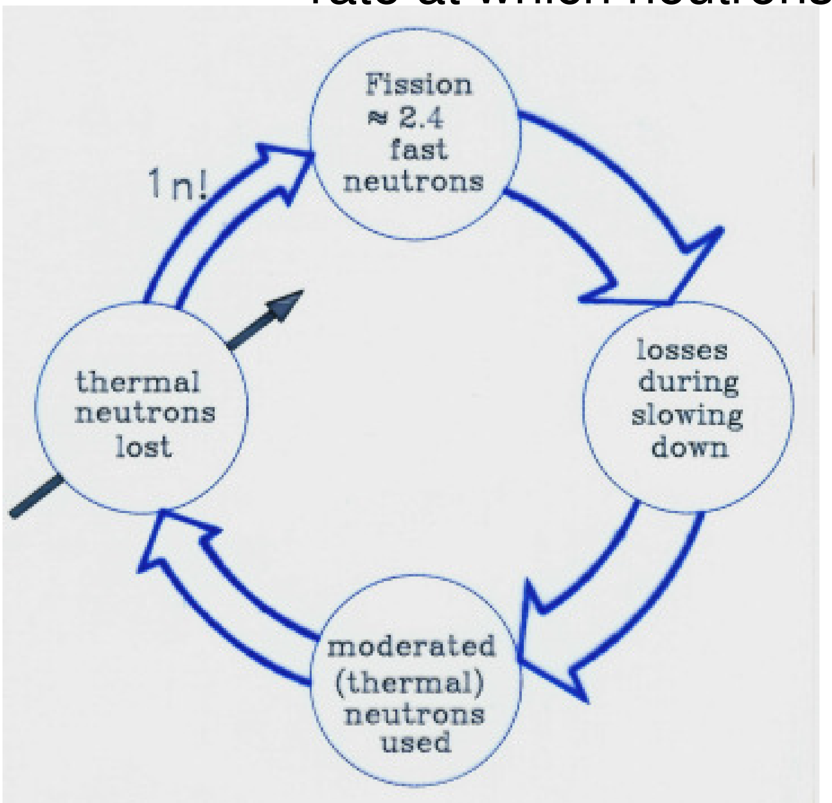
Functional Principles of a Nuclear Reactor

Steady state research reactors work by consumption of thermal neutrons (moderation needed)

Multiplication factor: $k_{eff} = \frac{\text{rate at which neutrons are released}}{\text{rate at which neutrons are removed}}$

k_{eff} =1 must be maintained at all times!

Thermal neutron loss is controlled by absorbers



During the slowing-down process neutrons are lost by leakage from the system and by non-productive captures

Fission Neutron Sources (Reactors)

Reactor kinetics

Rate of change of the neutron population, if mean generation time is τ (τ is of the order of μs!)

$$\frac{dn}{dt} = n(k-1) \cdot \frac{1}{\tau},$$

Accounting for delayed neutron precursors produced at a fraction $\beta = \Sigma_i \beta_i$ with a mean decay constant $\bar{\lambda}$ at concentration $C = \Sigma_i C_i$

$$\frac{dn}{dt} = n \cdot \frac{k(1-\beta)-1}{\tau} + \bar{\lambda} \cdot C$$

$$\frac{dC}{dt} = -\bar{\lambda} \cdot C + k \cdot \beta \cdot \frac{n}{\tau}$$

Can be affected through k(t) by insertion or removal of absorbing material *because 1/$\bar{\lambda}$ is if the order of seconds*.

β is of the order of 0.6% in U^{235} and 0.2% in Pu^{239}. This shows why a continuous reactor based U^{235} is easier to control than one based on Pu^{239}, although Pu^{239} has a higher neutron yield per fission (2.9 vs. 2.4)

Fission Neutron Sources (Reactors)

Reactor kinetics (cntd.)

The quantity $\rho(t) = \frac{k(t)-1}{k(t)} = 1 - \frac{1}{k(t)}$ is called "reactivity"

Introducing
- the number of neutrons per fission ν,
- the normalised generation time $\ell = \frac{\tau}{k}$
- the neutron production rate $P = \frac{1}{\nu} \cdot \frac{n}{\ell}$ (proportional to the reactor power)

one obtains from *ρ (t) :*

$$\frac{dP}{dt} = \frac{dn}{dt} \cdot \frac{dP}{dn} = P \cdot \frac{\rho(t)-\beta}{\ell} - \frac{\overline{\lambda} \cdot C}{\ell \cdot \nu}$$

$$\frac{dC}{dt} = -\overline{\lambda} \cdot C + \beta \cdot P \cdot \nu$$

A system is called *delayed critical* if *ρ (t) =0* ; and *prompt critical* if *ρ (t) =β*

A system which exceeds prompt criticality can only be controlled in the time average ⇒ pulsed reactor

Fission Neutron Sources (Reactors)

Pulsed operation of a fission reactor by periodic variation of ρ

Time between pulses:

$$\frac{dP_b}{dt} \stackrel{!}{=} 0$$

with $\epsilon(t) = \rho(t) - \beta$ (deviation from prompt criticality)

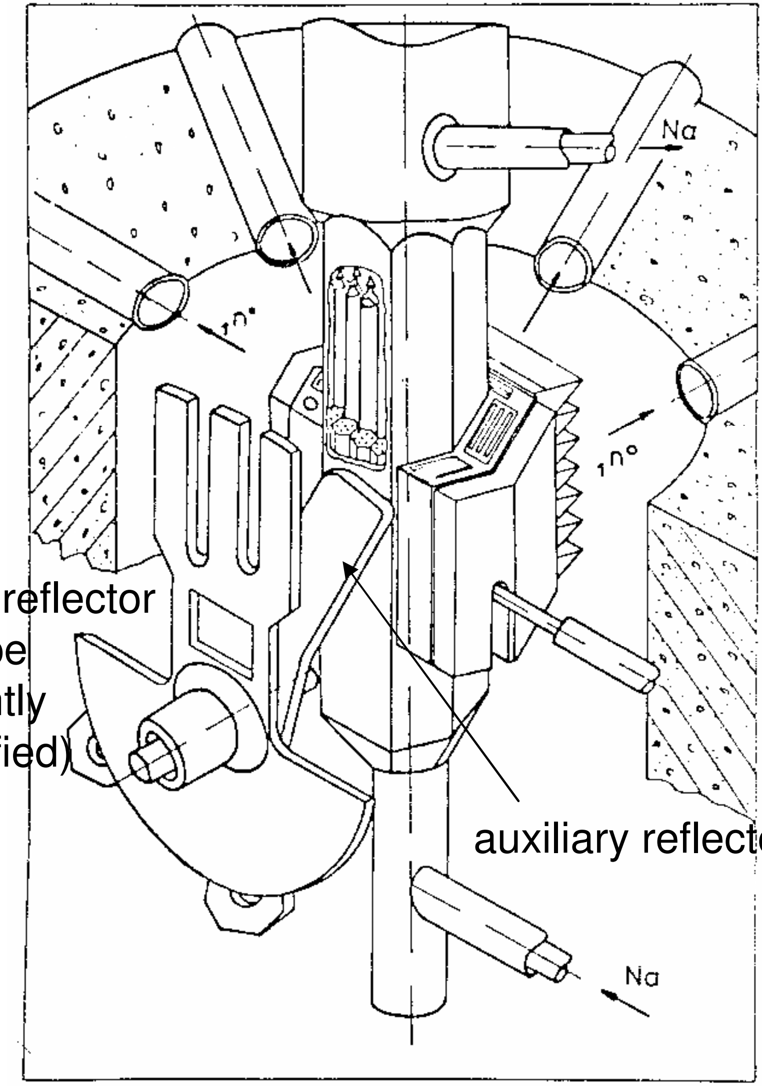
$$P_b = \frac{\overline{\lambda} \cdot C}{|\, \epsilon_0 \,| \cdot \nu}$$

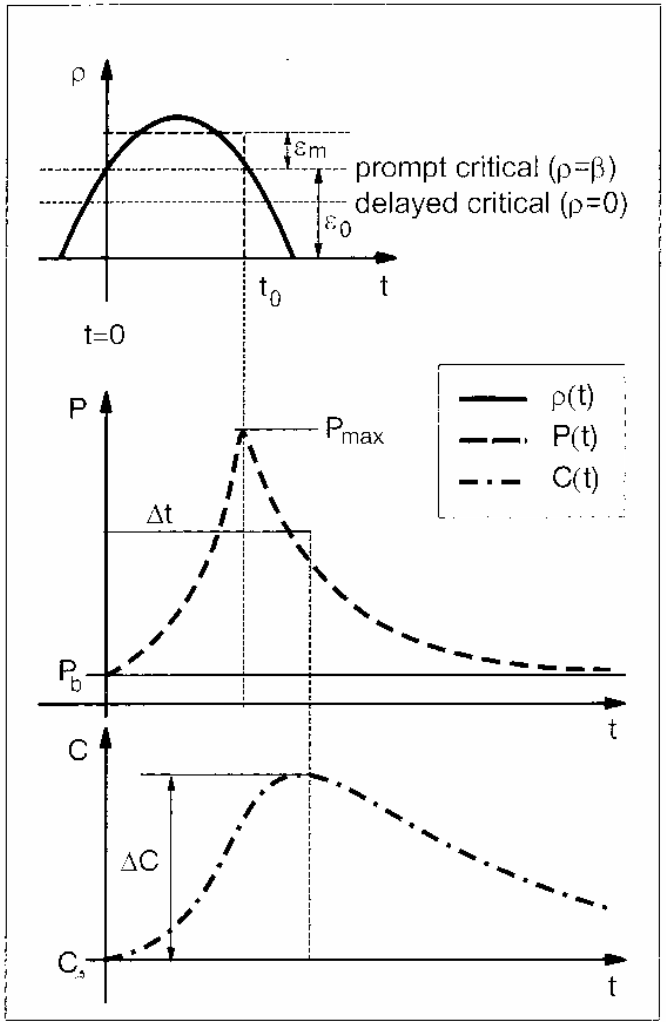
⇒ Power between pulses determines neutron background
→ should be low
→ Small concentration of delayed neutron precursors and high fission yield are desirable for pulsed reactor ⇒ <u>^{239} Pu is the preferred fuel</u>

Pulsing is accomplished by sudden insertion of reactivity
→ by moving part of the fuel (IBR-30, 30kW$_{av}$ cooling problem)
→ by moving parts of the reflector (IBR-2, 2MW$_{av)}$

Fission Neutron Sources (Reactors)

Sketch of the IBR-2 core and reflector zone

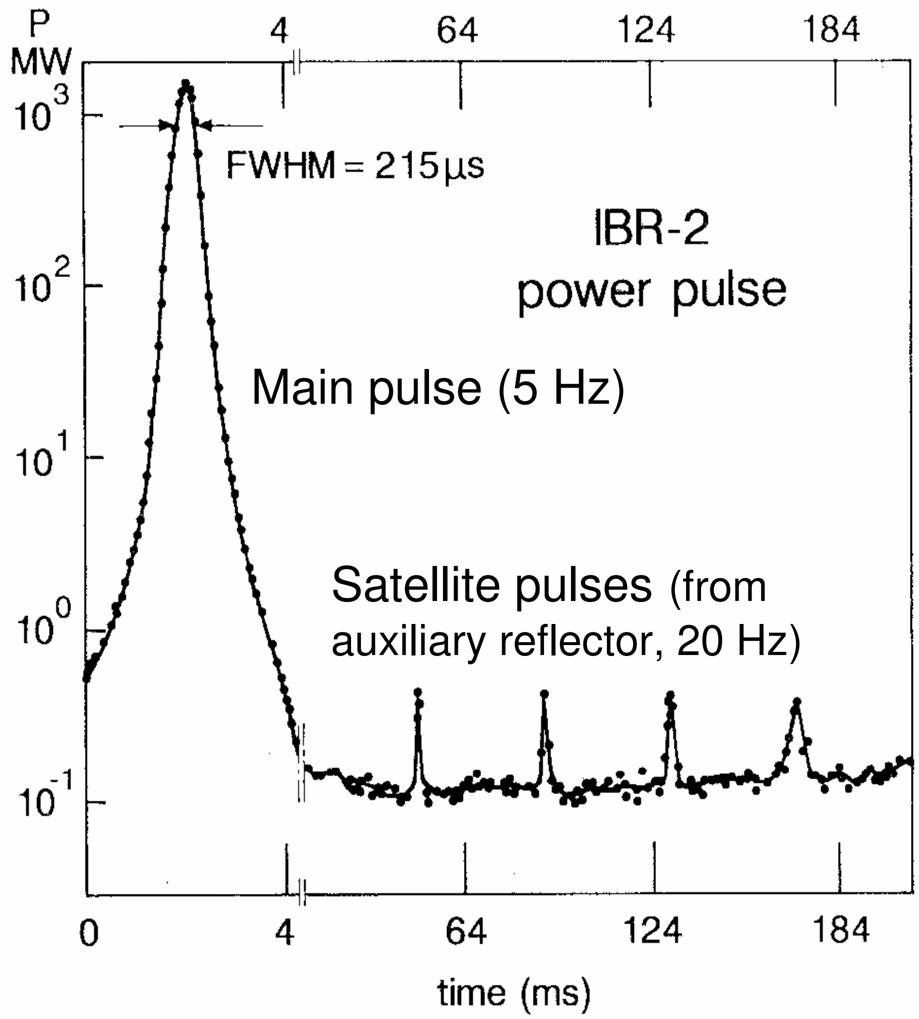




Time dependence of the reactivity, power and delayed neutron precursor concentration

Fission Neutron Sources (Reactors)

Pulse characteristics of IBR-2
(old reflector)



Average thermal power	2MW
Power during pulse	1500 MW
Power between pulses:	100 kW
Pulse repetition rate:	5Hz
Power pulse duration(FWHM):	215 μs
Fast neutron generation time:	60 ns
Fuel:	PuO
Coolant:	Na
Reactivity modulation:	2 rotating reflectors
Peak thermal neutron flux:	$7*10^{15}$ n/cm^{2}s
Average thermal neutron flux:	10^{13} n/cm^{2}s

Main characteristics of the IBR-2 pulsed reactor

Fission Neutron Sources (Reactors)

TRIGA-Reactors

- TRIGA reactors use a mixture of about 12 wt% of low enriched (20%) uranium in a fuel matrix of $ZrH_{1.6}$.
- Moderation to sustain the chain reaction thus occurs primarily in the fuel.
- Moderation becomes insufficient if the fuel temperature increases (prompt negative temperature coefficient of reactivity, aided by the Doppler effect in the ^{238}U).
- In the case of a sudden insertion of reactivity (withdrawal of the control rod) the fuel heats up and the reactor shuts down within milliseconds.
- Although up to 10 MW average power are possible in TRIGA reactors, most of them operate in the 250 kW – 1MW regime.
- Pulsing up to 250 MW (40 ms pulses) is possible but is limited to 12 p/h.
- TRIGA reactors are useful tools for training and speciality research.

Summary on Fission Reactors

- Fission reactors are the strongest sources of thermal, cold and hot neutrons in the time average and will remain so for the foreseeable future (RHF at ILL: Φ_{th} = 1.5 10^{15} at 56 MW_{th}).
- Their development has reached its limits due to heat removal problems from the fuel.
- Use of highly enriched uranium is getting increasingly difficult due to proliferation problems.
- Fission reactors are basically cw; apart from several TRIGA reactors (usually not run in a pulsed mode) only one pulsed reactor (IBR-2, 2 MW,5 Hz) is in operation for neutron scattering.
- Deployment of new fission reactors has slowed down considerably since the advent of pulsed spallation neutron sources.

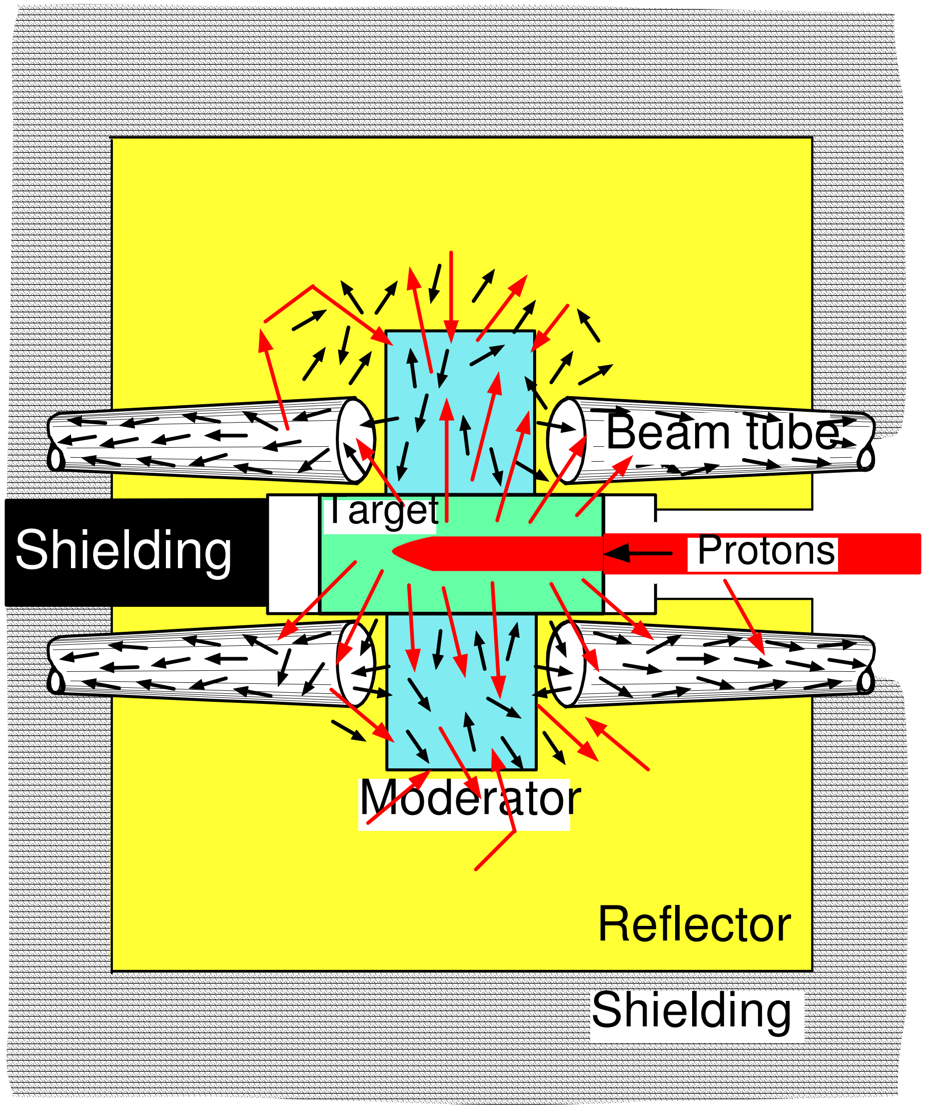
Spallation Neutron Sources

Arguments used in their favour

- No criticality issues
- No actinide waste
- Proliferation safe
- Advantage by exploiting time structure
- Less heat per neutron than other nuclear processes
- High degree of design flexibility (accelerator and target system)

- **But**
- Demanding shielding issues
- Extra complexity by need for accelerator
- More distributed radioactivity (e.g. in cooling loops and shielding)

Principal Target-Moderator-Reflector Arrangement



The **target** should be optimised for neutron generation and coupling into the moderators

The **moderators** are designed according to users' needs for best output intensity at the desired neutron energy and time structure

The **reflector** serves to enhance the neutron output from the moderator at minimum adverse effect on time structure

The **beam tubes** are arranged such as to avoid direct view on the target to minimize high energy neutron and γ contamination

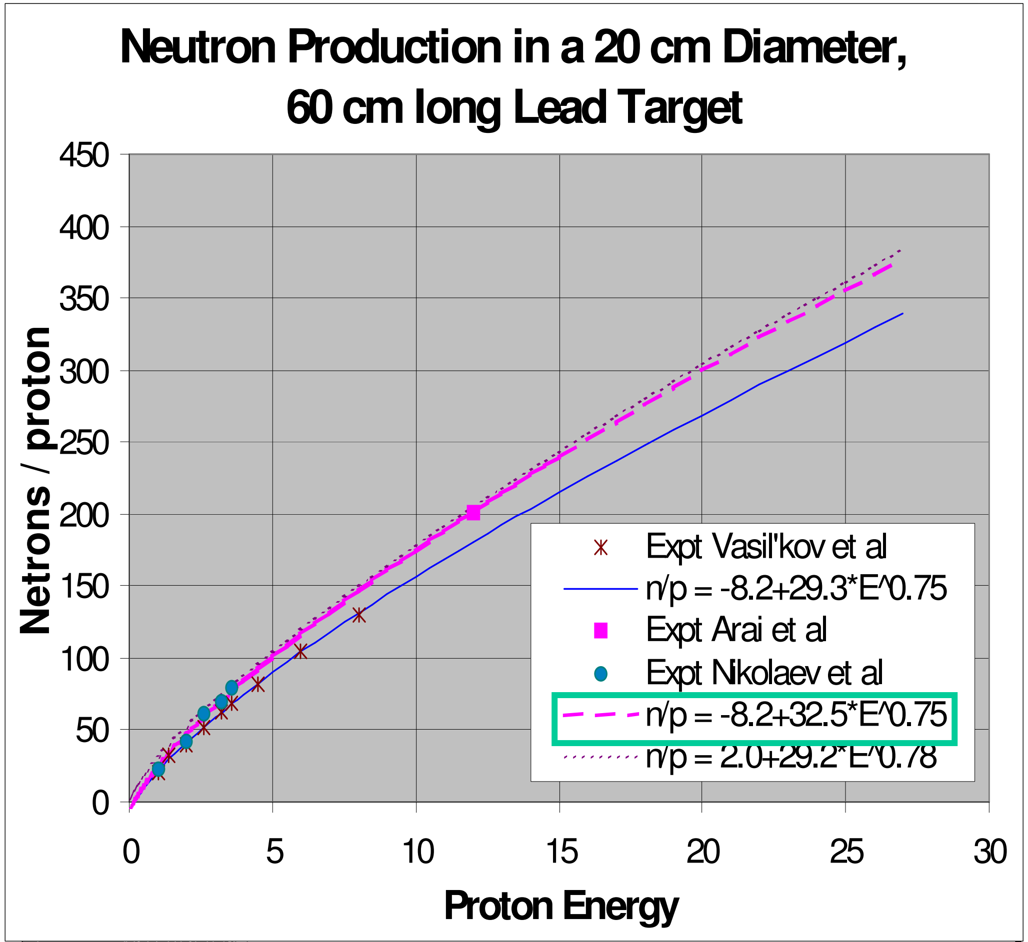
Spallation Neutron Sources with P_b>100kW

Source and location	Type of accelerator	Proton energy (Gev)	Pulse frequency (Hz)	Aver. beam power (MW)	Type of target	Peak thermal flux* ($cm^{-2}s^{-1}$)	Time av. thermal flux* ($cm^{-2}s^{-1}$)	Status
SINQ, CH	cyclotron	0.57	contin.	0.6	solid, Pb rods liquid, PbBi	$6x10^{13}$ $1x10^{14}$	$6x10^{13}$ $1\ 10^{14}$	operating demonstrated
ISIS, UK	synchrotron	0.8	50	0.16	solid, vol. cooled, Ta	$2.3x10^{15}$	$2x10^{12}$	operating
MLNSC, USA	linac plus PSR	0.8	20	0.08	solid, vol. cooled, W	$2.3x10^{15}$	$1x10^{12}$	operating
ESS, EU	linac ~~plus 2 compressors~~	1.33	~~50~~ 16 2/3	5	liquid metal (Hg)	~~$2x10^{17}$~~ $1x10^{16}$	~~$2.5x10^{14}$~~ $3x10^{14}$	deferred
SNS, USA	linac plus compressor	1	60	1,4	liquid metal (Hg)	$2x10^{16}$	$8x10^{13}$	under commissioning
AUSRTON Austria	synchrotron	1.6	10	0.5	solid, edge cooled W,	$4x10^{16}$	$6x10^{12}$	proposed
JSNS-1 Japan	synchrotron	3	25	1	liquid metal (Hg)	$1x10^{16}$	$8x10^{12}$	under commissioning
JSNS-2 Japan	2-ring synchrotron	3	50	5	liquid metal (Hg)	$2x10^{17}$	$2.5x10^{14}$	proposed
MMF RUS	linac (plus comp)	0.6		0.6	solid, vol. cooled W			commissioning (low power)

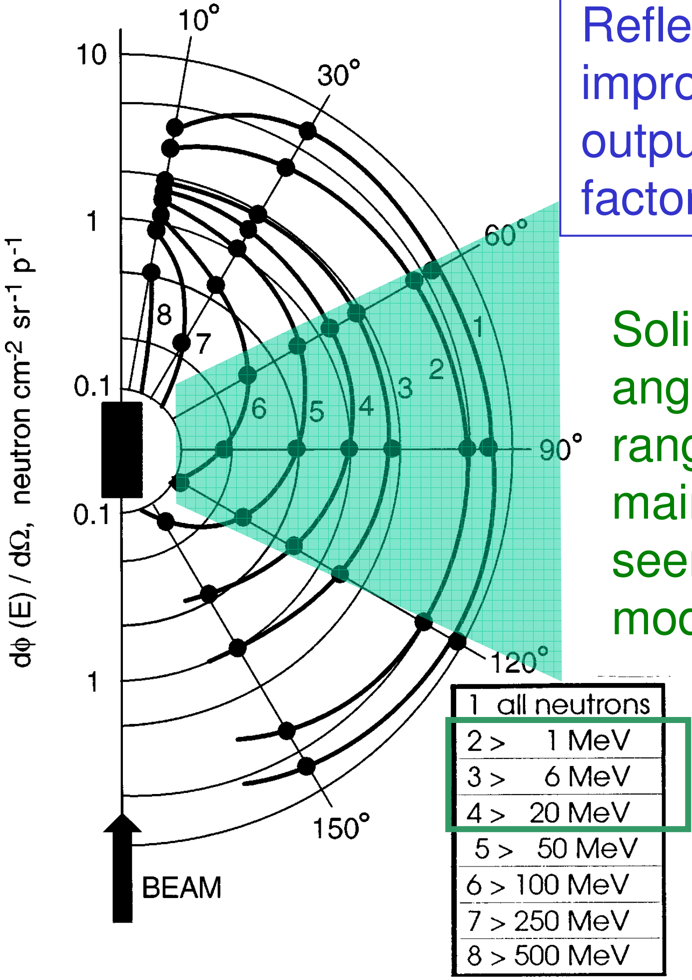
** typical maximum values; precise figures vary, depending on type of moderator*

Spallation Neutron Sources – General Aspects (1)

Spallation Neutron Yield and Angular Distribution



Measured neuron yield from thick lead targets



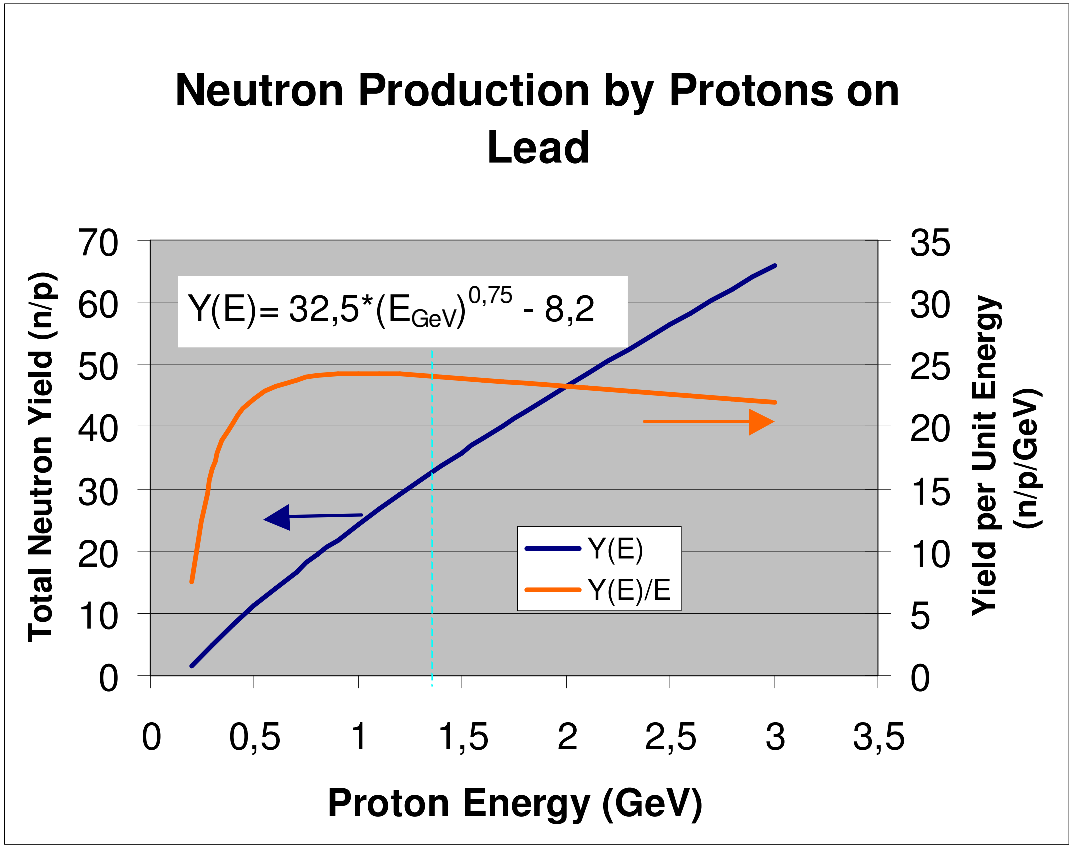
Reflector improves output by factor 2

Solid angular range mainly seen by moderator

Measured angular distribution of neutrons in different energy groups for a 20 cm diameter lead target bombarded by protons of 2 GeV

Spallation Neutron Sources – General Aspects (2)

Choice of proton energy



Arguments for higher proton energy:

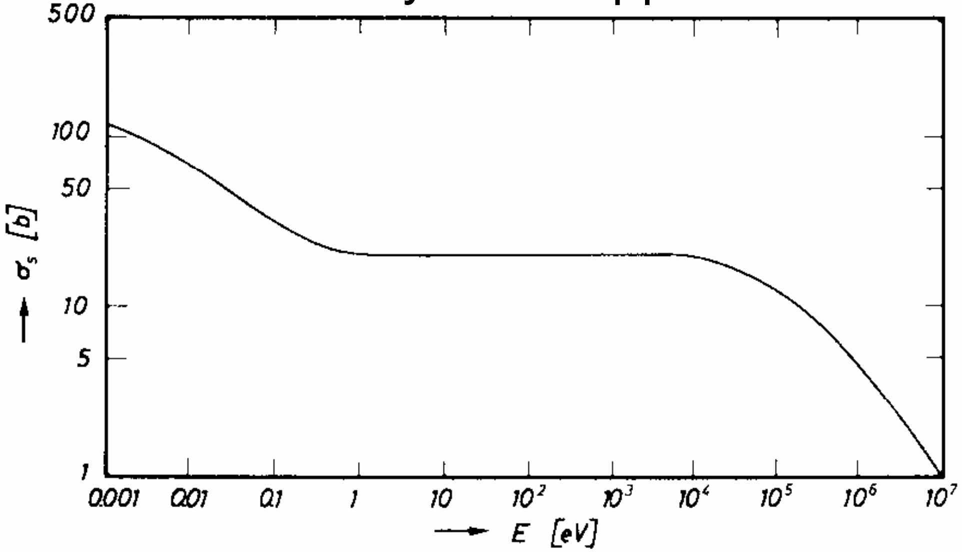
Easier to accelerate to higher energy than to increase current (in particular with circular accelerators)

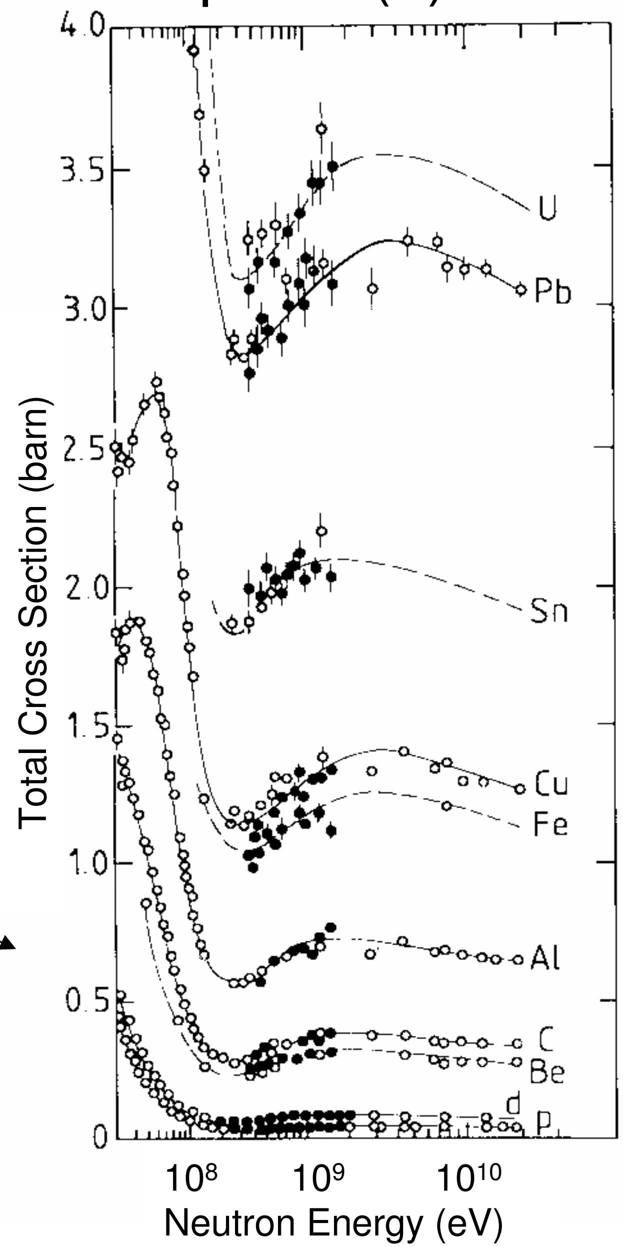
Radiation damage in target and window materials scales roughly with number of protons, not with beam power

Spallation Neutron Sources – General Aspects (3)

Moderation and Shielding

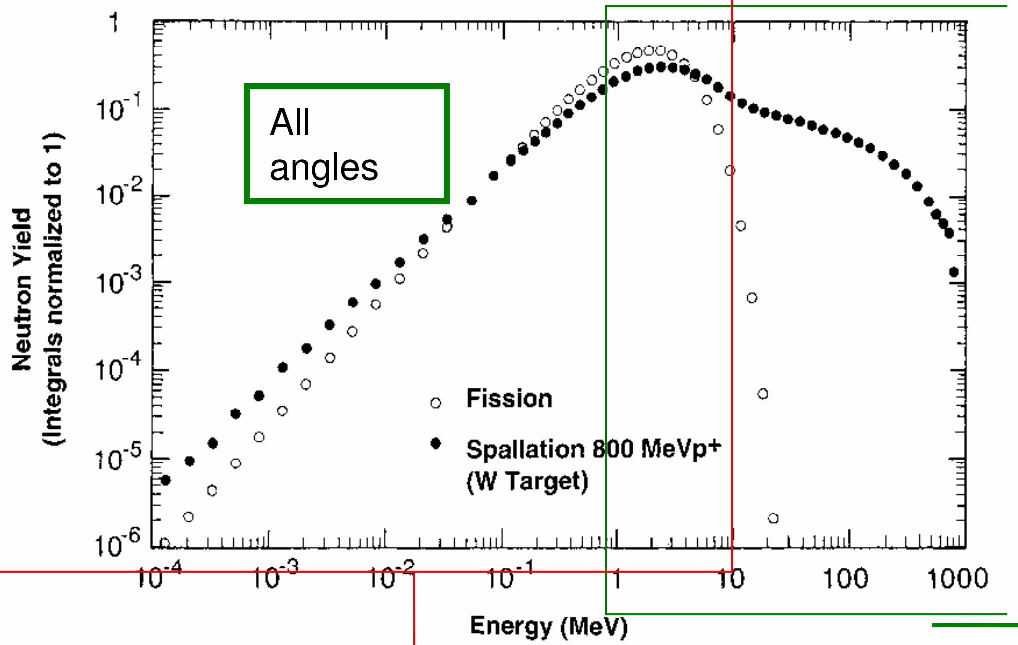
- The important processes for n-shielding are moderation and absorption ($\propto 1/v$)
- Moderation by H "disappears" above 10 MeV

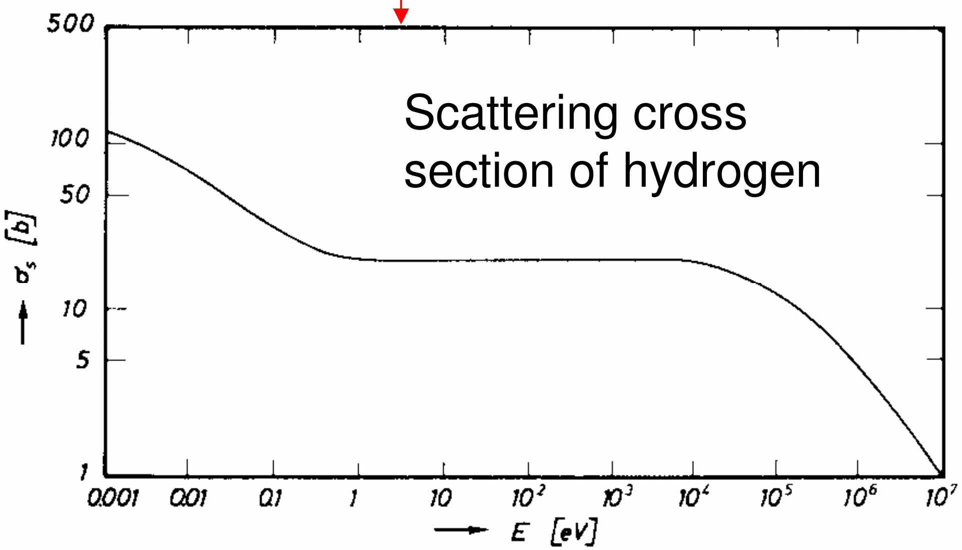


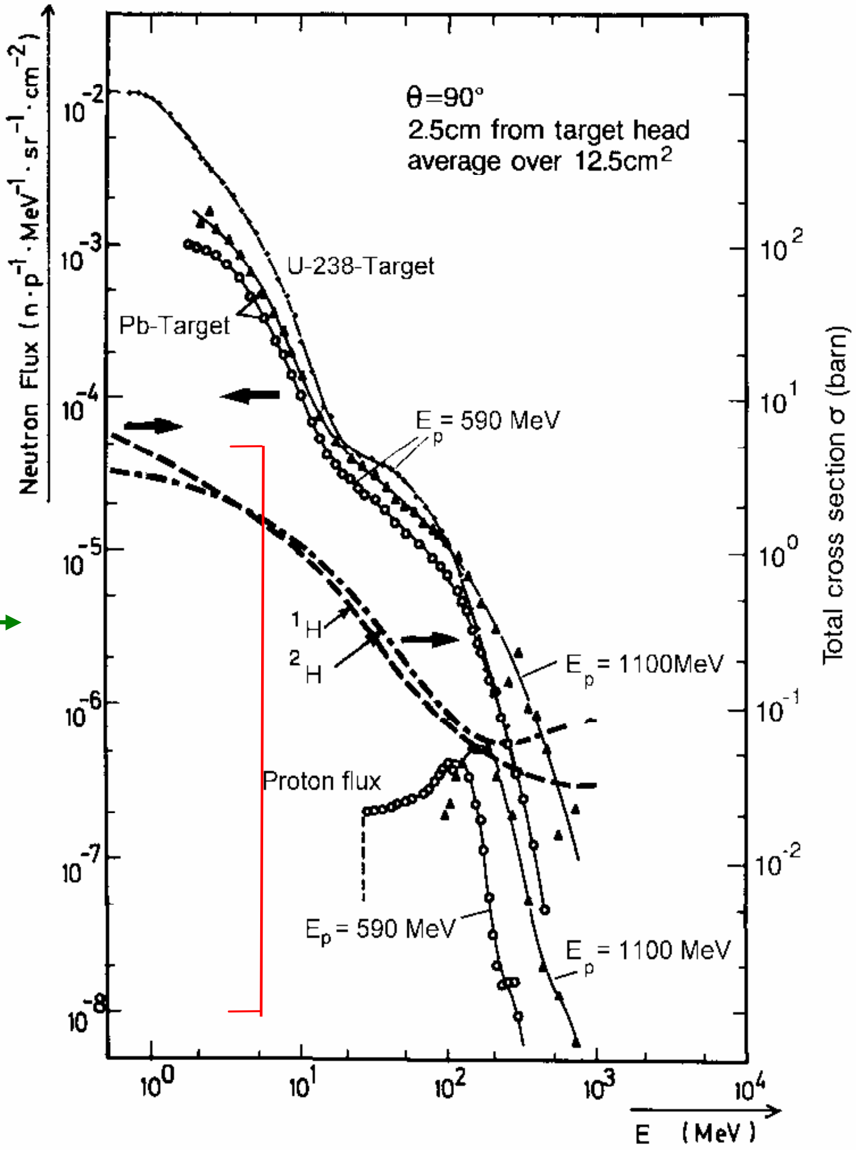


- Require n-transport to slow down
- Cross section of all materials has minimum above 100 MeV

Primary Neutron Spectra and Moderation by H







Spallation Neutron Sources – General Aspects (4)

High Energy Neutron Shielding

Dose at angular position θ relative to the beam subtending a solid angle Ω to the source with different shielding materials of attenuation lengths λ_i

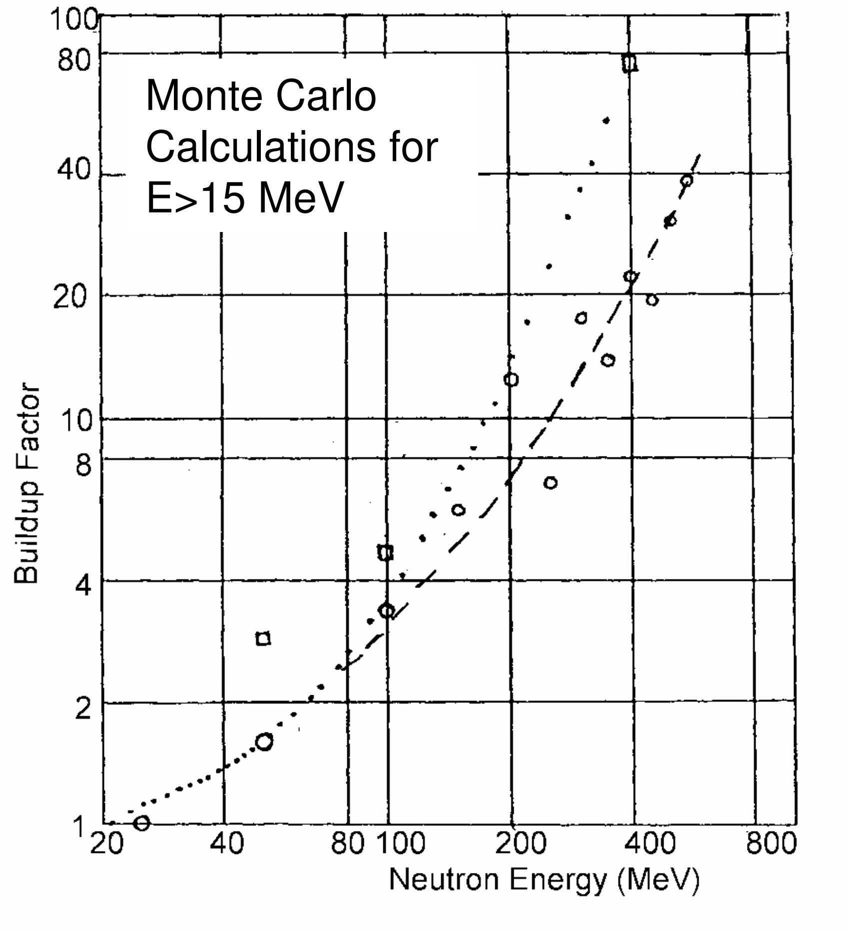
$$D(\theta) = \Omega \int dE \, \{\Phi(E,\theta) * F(E) * B(E) \, \Pi_i \, [\exp(-s_i/\lambda_i)],$$

$\Phi(E,\theta)$ source particle spectrum in direction Ω

F(E) flux-to-dose conversion factor

B(E) buildup factor

$\Pi_i \, [\exp(-s_i/\lambda_i)]$ dose reduction by stretches s_i of different materials with attenuation lengths λ_i .



Bottom line:

Higher proton energy gives increased neutron yield per proton, but adds to shielding problems (accelerator issue)

Accelerator Drivers for Neutron Sources

- **Synchrotron plus linac**: good solution to obtain high energy at relatively low cost; yields short pulses naturally; intensity limited by injection energy; rep-rate limited (60 Hz), but not a problem.
- **Compressor ring plus linac**: allows high intensity due to full energy injection; cost relatively high; might run at higher rep-rate (multiple target stations).
- **Linac alone**: *long pulse* or cw; high power possible; high cost
- **Cyclotron**: essentially cw; good performance record; cascade may be required for high energy; av. current up to 2 mA demonstrated; 5-10 mA deemed possible; comparatively low cost.
- **FFAG** (Fixed Field Alternating Gradient Synchrotron): often proposed, now under development at KEK; short pulses; high rep-rate (400 Hz) possible; rep-rate reduction by pulse stacking (?); cost comparable to cyclotron (?)

  ⇒ Hope for the future

Neutron Moderation (1)

- Moderation of neutrons occurs by collisions with moderator atoms
- In each collision a constant fraction of the energy is lost
- "Logarithmic energy decrement":

$$\xi = \ln E_1 - \ln E_2 \quad \begin{cases} = 1 \text{ for } A=1 \\ \approx 2/(A+2/3) \text{ for } A>1 \end{cases}$$

A is the atomic number of the moderator atom

- Number of collisions x required to slow down from energy E_0 to E_f

$x = 1/\xi * \ln(E_0/E_f)$ for = E_0 2MeV and E_f = 1 eV: $x = 14.5/\xi$

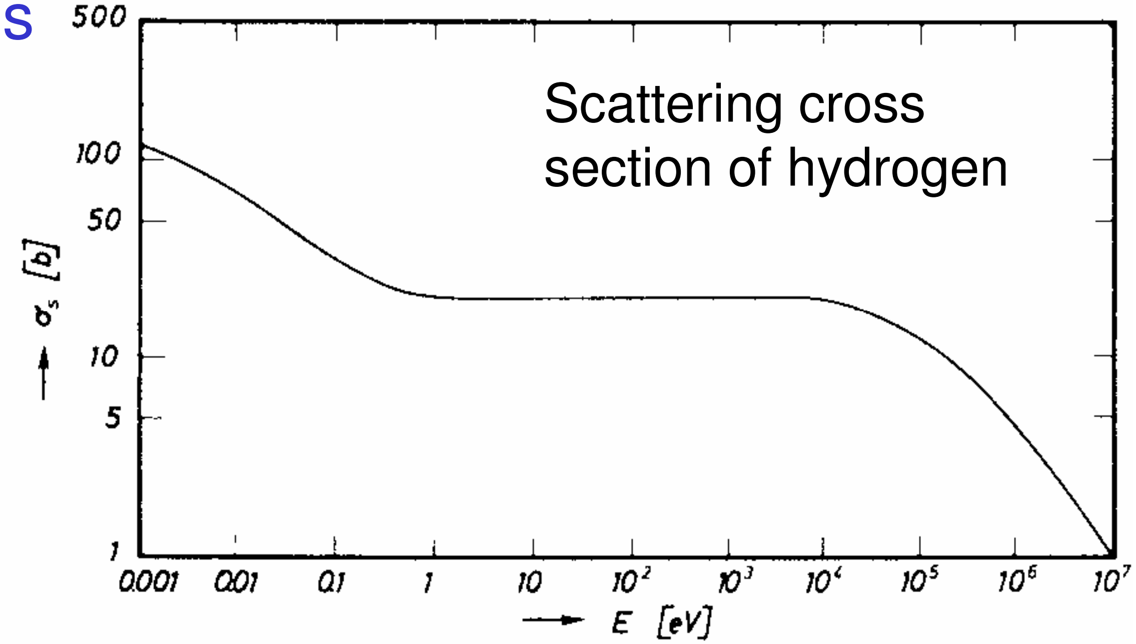
Parameter	Element						
	H	D	Be	C	O	Hg	Pb
A	1	2	9,01	12,01	16	200,6	207,19
σ_{fr} (10^{-24} cm^2)	20,51	3,40	6,18	4,73	3,75	26,53	11,01
ρ (g/cm^3) (*)	0,07	0,163	1,85	2,3	1,13	13,55	11,3
$\Sigma_{fr} = N*\sigma_{fr}$ (cm^{-1})	0,86	0,17	0,76	0,55	0,16	1,08	0,36
ξ	1,000	0,725	0,206	0,158	0,120	0,010	0,010
x (2MeV→1eV)	14,5	20,0	70,3	92,0	121,0	1460,1	1507,9

Neutron Moderation (2)

The slowing down process

$$\Sigma = \sigma/N = 1/\Lambda$$

σ microscopic cross section
N number of atoms per unit volume
Λ is the mean free path between collisions



The time t_i between collisions and therefore the number of neutrons present in a certain velocity interval is inversely proportional to the neutron velocity, v_i.

$t_i = \Lambda/v_i = 1/(\Sigma_{fr} * v_i)$ or $t_i * v_i = \Lambda \approx$ const in the slowing down regime (>1eV)

This means that, in the slowing down regime the spectral neutron flux I(E), which is the *product of the neutron density and their velocity*, is proportional to v^2 or :

I(E)*E=const.

Neutron Moderation (3)

The slowing down process (cntd.)

In small moderators, where losses during slowing down are significant, or if absorption plays a role, one obtains

$$<I(E)_{sd}> = I(E_0)*(E_0/E)^{(1-\alpha)} = [E*I(E)]_{Eo}*(1/E)*(E/E_0)^{\alpha}$$

E_0 is a reference energy (usually 1eV) and α depends on absorption in and leakage from the moderator during the slowing-down process. For non-reflected moderators α is of the order of 0.2, but can be significantly affected, by a ***reflector.***

In a large moderator, a “Maxwellian” flux distribution develops when thermal energies are reached, which depends on the moderator temperature:

$$\Phi(E)_M = \Phi_{th}\ E/(k_B T_{eff})^2 \exp(-E/(k_B T_{eff}))$$

Φ_{th} is the thermal neutron flux integral
k_B = 0,08866165 meV/K is Boltzman's constant
T_{eff} is the effective moderator temperature, which is somewhat higher than the physical temperature

Neutron Moderation (4)

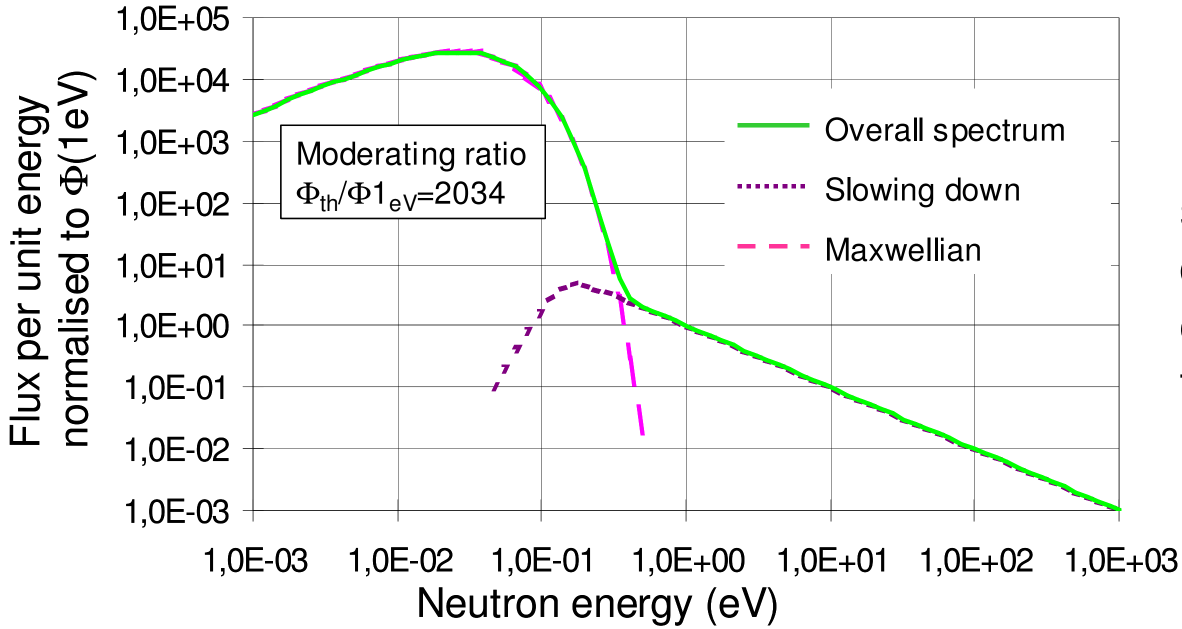
Thermalisation

The transition between the slowing-down regime and the thermal equilibrium spectrum at about $5kT_{eff}$ is usually taken into account by a switch function $\Delta_1(E)$, by which the slowing down spectrum is multiplied. A frequently used formula is

$$\Delta_1 = 1/(1+5\ k_BT_{eff})^5$$

The full representation of the spectrum, then reads:

$$\Phi(E) = \Phi_{epi}.*(1/E)*(E/E_0)^{\alpha}\ \Delta_1(E)+\ \Phi_{th}\ E/(k_BT_{eff})^2 \exp\ (-E/k_BT_{eff})$$



Neutron spectral distribution characteristic for a large heavy water moderator

Neutron Moderation (5)

Characterisation of moderators

The slowing down power $\zeta^*\Sigma_s$

determines the rate (distance) at which neutrons are slowed down in a moderator.

The moderating ratio $\zeta^*\Sigma_s/\Sigma_a$ is a measure for the thermal neutron flux integral relative to the flux at one eV

Σ_a is the mean macroscopic absorption cross section

Moderator	**Density** (g/cm^3)	$\zeta^*\Sigma_s$ (cm^{-1})	$\zeta^*\Sigma_s/\Sigma_a$
H_2O	1.00	1.35	71
D_2O (pure)	1.10	0.176	5670
D_2O (99.8%)	1.10	0.178	2540
Graphite	1.6	0.060	192
Beryllium	1.83	0.158	143

For a mixture of N nuclei:

$$\overline{\zeta} = (1/\Sigma_s) \sum_{i=1}^{i=N} \Sigma_{s,i}\,\zeta_i$$

Neutron Moderation (6)

Slowing down of a neutron pulse

Since, in the slowing down regime (>0.5 eV for room temperature moderators)
$t_i = \Lambda/v_i = 1/(\Sigma_{fr} v_i)$ or $t_i\, v_i = \Lambda \approx$ const
The time it takes to slow a neutron down to the velocity v is essentially determined by the processes near that velocity

Time to slow down to v: $v^* t_s = (1+2/\gamma)^* \gamma/(\xi^* \Sigma_{fr})$

Standard deviation: $v^* \Delta t_s = (1+2/\gamma)^{1/2} \gamma/(\xi^* \Sigma_{fr})$ with γ $= 1$ for A=1; $\approx 4/(3A)$ for A>1.

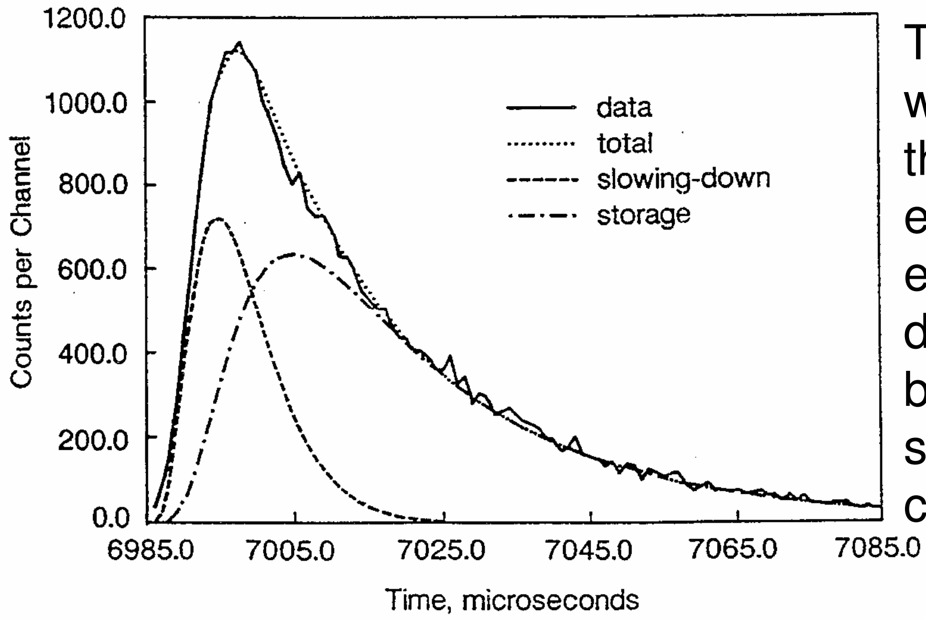
FWHM: $v^* \Delta t_{1/2} = 3/(\xi^* \Sigma_{fr})$

Material	Density	Σ_s (cm^{-1})	ξ	γ	$v \cdot t_s$ (cm)	$v \cdot \Delta t_s$ (cm)	$v \cdot t_{1/2}$ (cm)
H_2O	1	1.5	0.92	0.99	2.17	1.25	2.4
CH_4	0.94	1.8	0.9	0.98	1.84	1.05	2.0
D_2O	1.1	0.35	0.51	0.56	14.3	6.71	14.2
Be	1.7	0.75	0.21	0.15	13.6	3.61	7.9
C	1.8	0.43	0.16	0.11	30.7	7.0	16.0
Fe	7.9	0.75	0.035	0.024	77.1	8.4	19.2
H_2 (liqu)	**0.07**	**0.86**	**1.0**	**1.0**	**3.47**	**1.05**	**2.16**

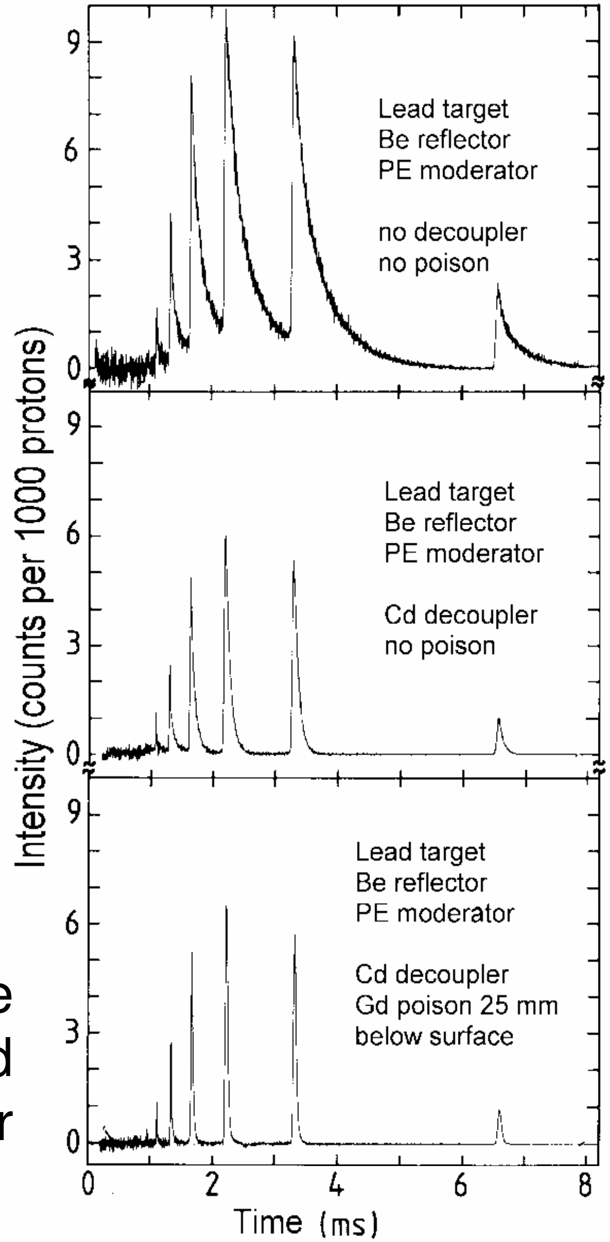
Neutron Moderation (6)

Slowing down of a neutron pulse (cntd.)

As the neutrons approach thermal equilibrium with the moderator the pulse can be analysed in terms a slowing down and a storage component



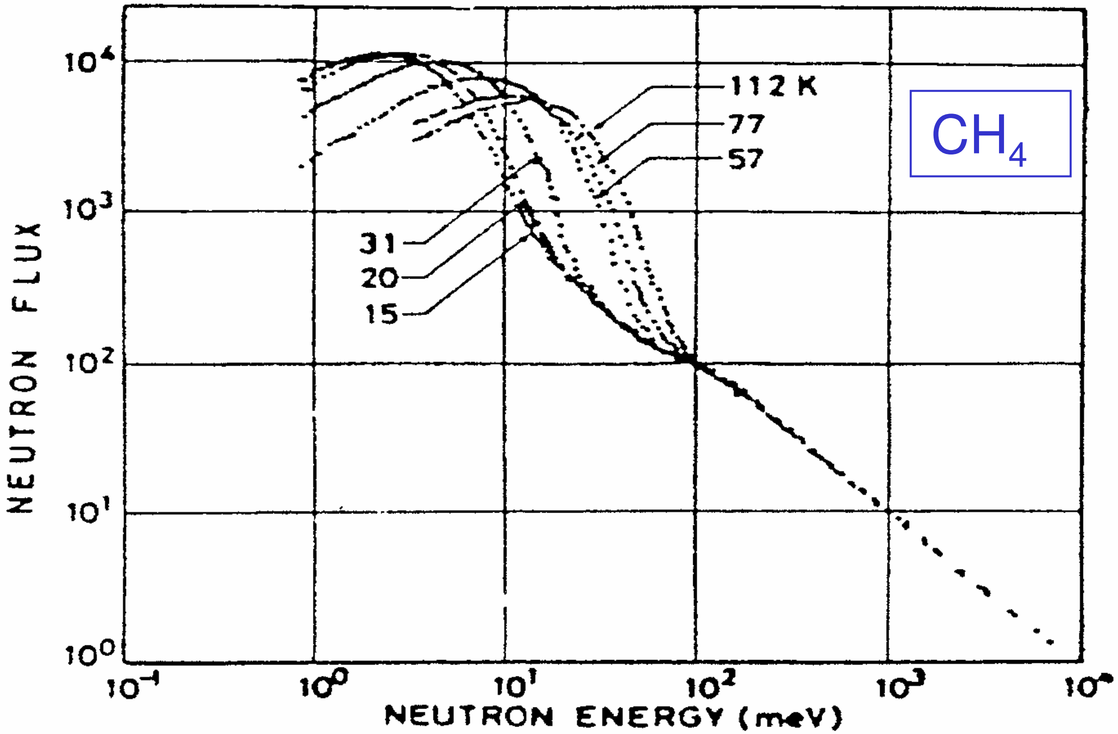
The pulse width at thermal energies is essentially determined by the storage component



The life time of the storage component can be strongly affected by poisoning the moderator and by decoupling it from the reflector

Neutron Moderation (7)

Cold Moderators



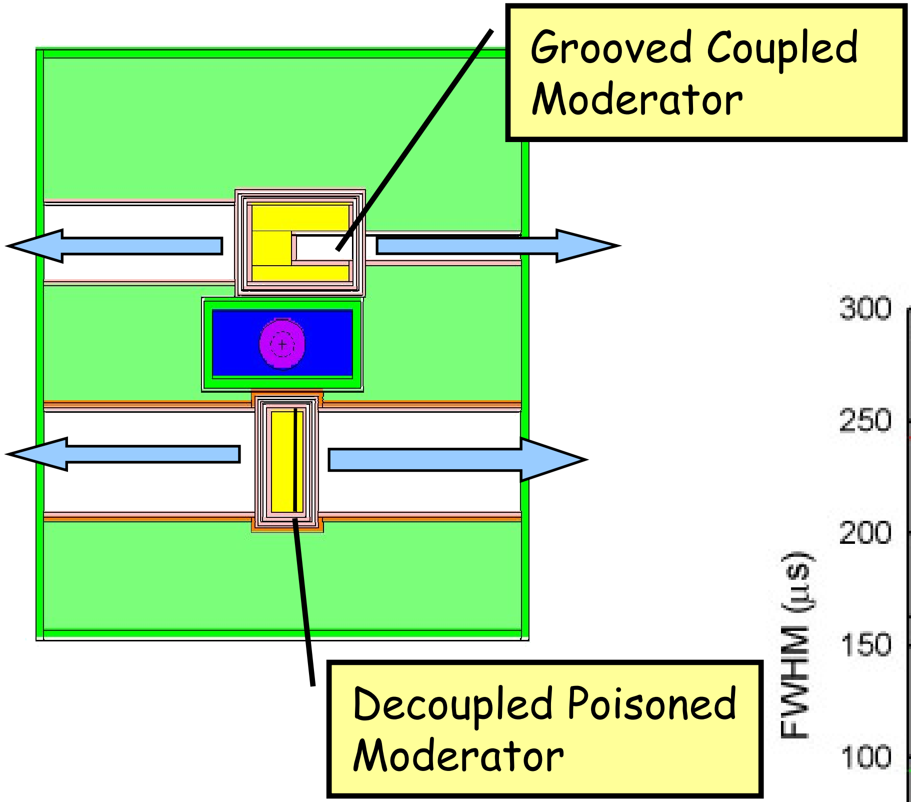
Lowering the temperature of a moderator shifts the Maxwellian to lower energies.

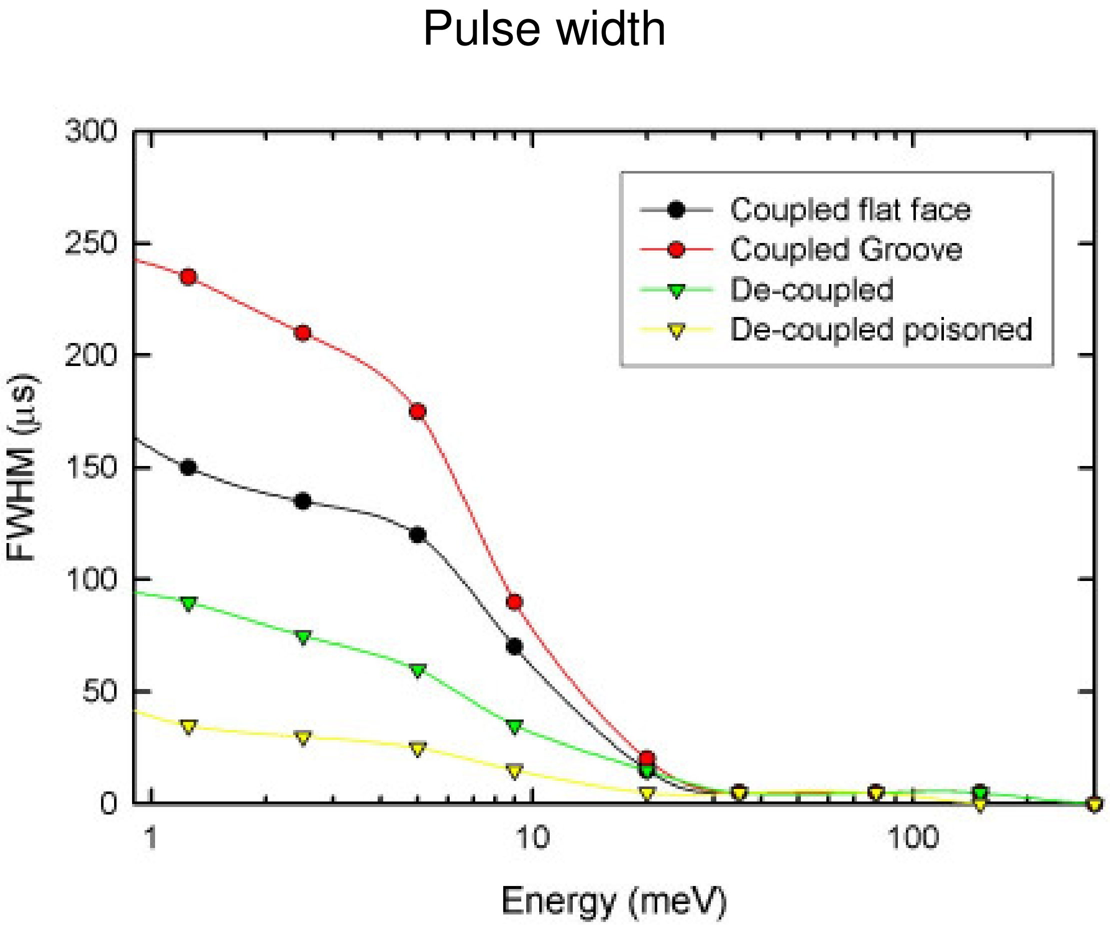
This also extends the regime of naturally narrow lines to lower energies

Problems with solid methane:

- difficult to cool
- decomposition by radiation
- spontaneous release of stored energy

Studies for the ISIS-TS2 Moderator System

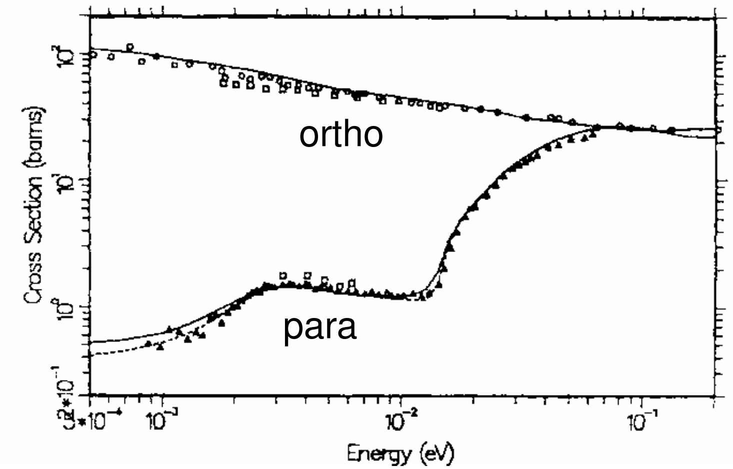




S. Bennington, ISIS, 2002

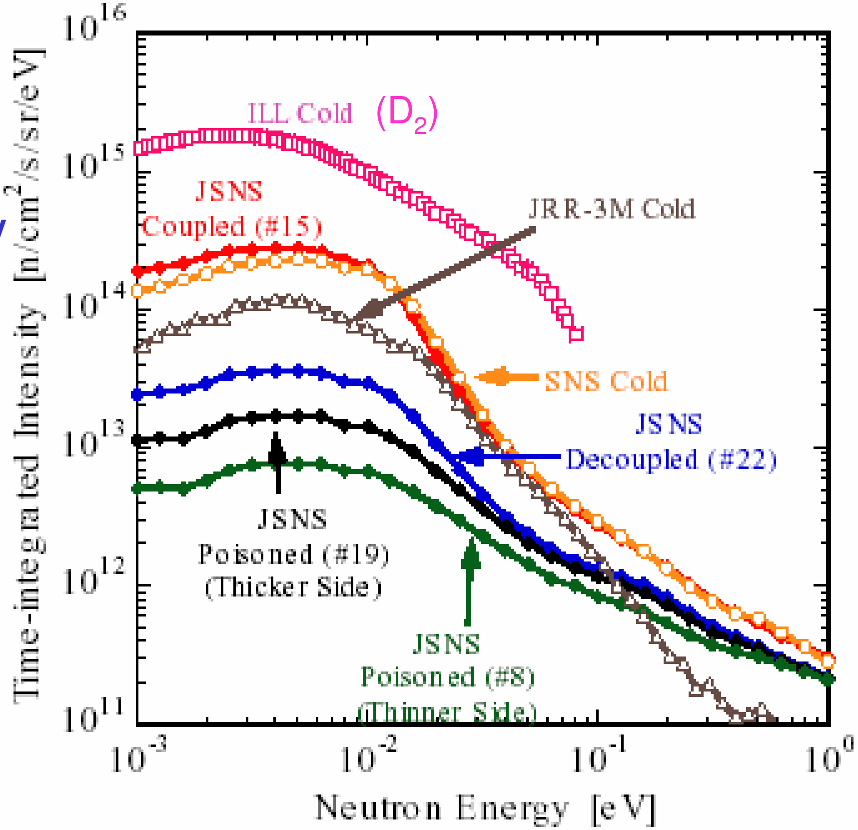
Neutron Moderation (8)

Liquid hydrogen moderators



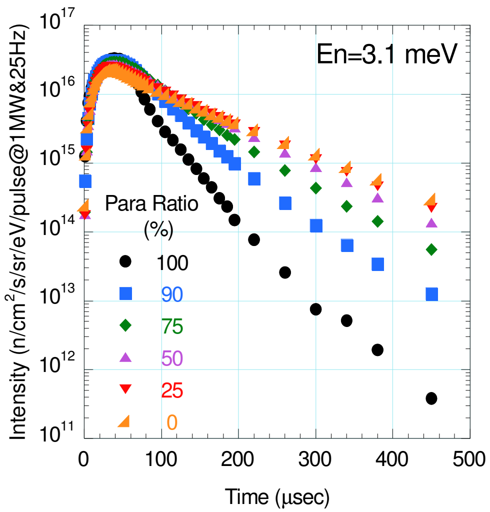
Scattering cross section of H_2 at low temperatures

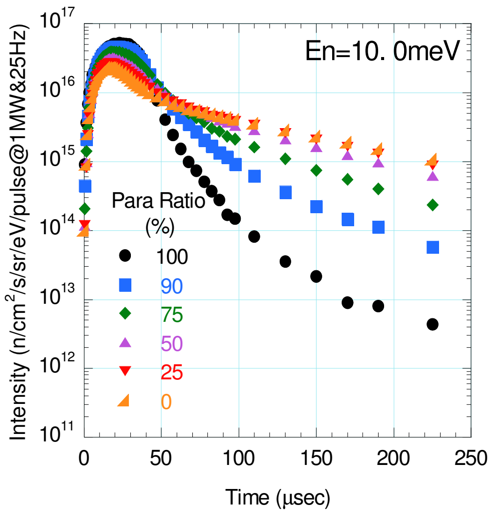
Scattering in p-H_2 drops dramatically below 15 meV → enhanced leakage of neutrons from moderators



Comparison of cold neutron spectra

(Hasegawa, N-TAC3)

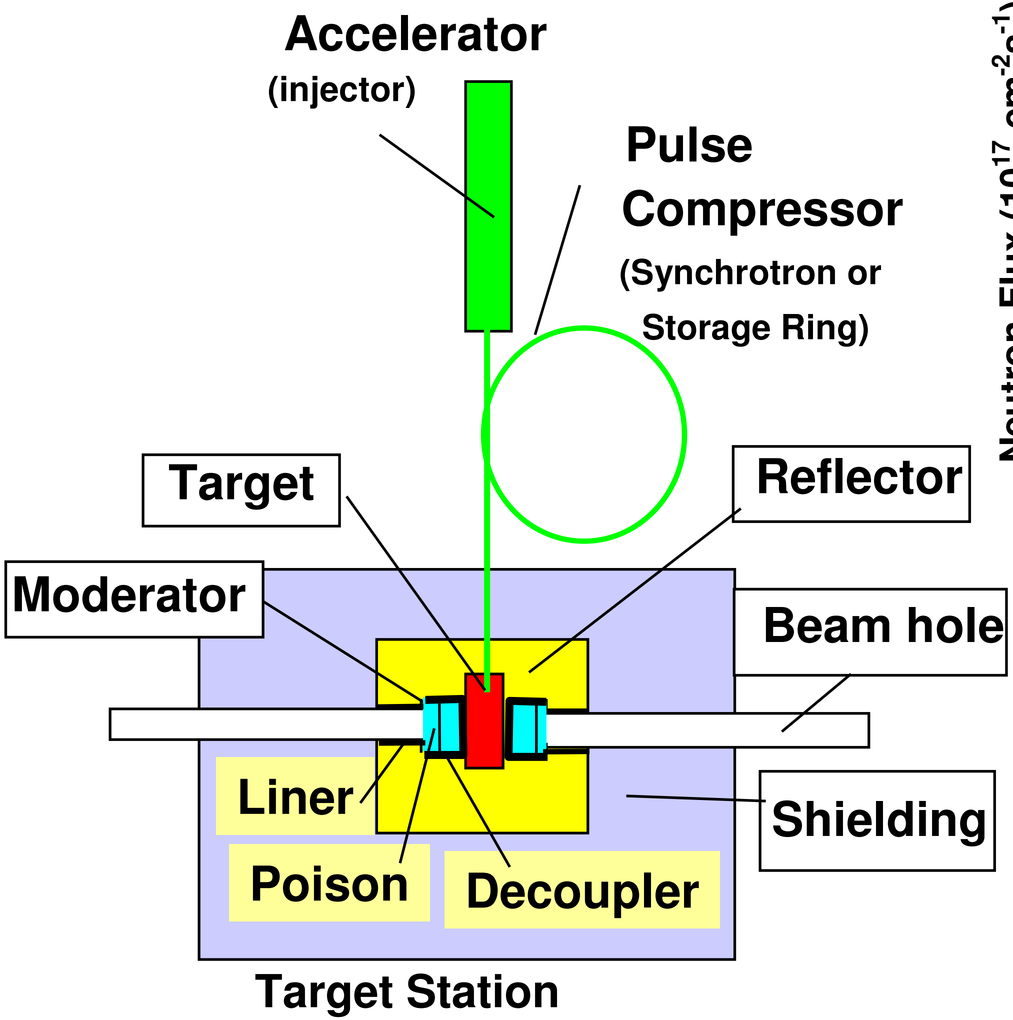


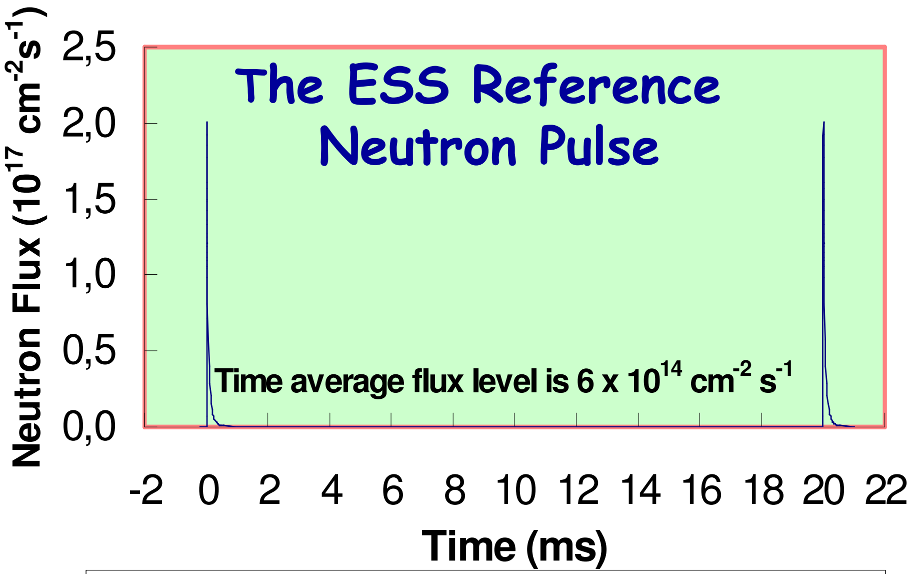


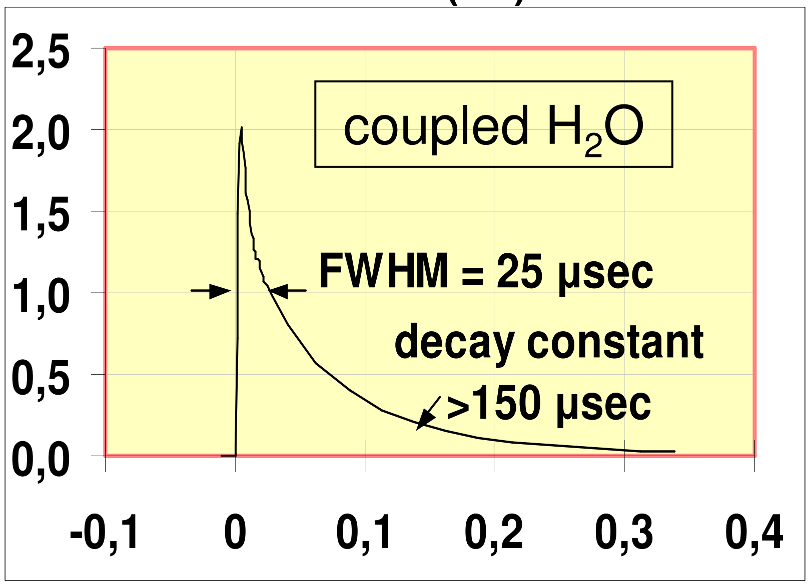
Calculated pulse shapes for different o-p ratios in H_{2liqu}

M. Harada, M. Teshigawara, N. Watanabe,T. Kai and Y. Ikeda , ICANS XVI

Short Pulse Neutron Source

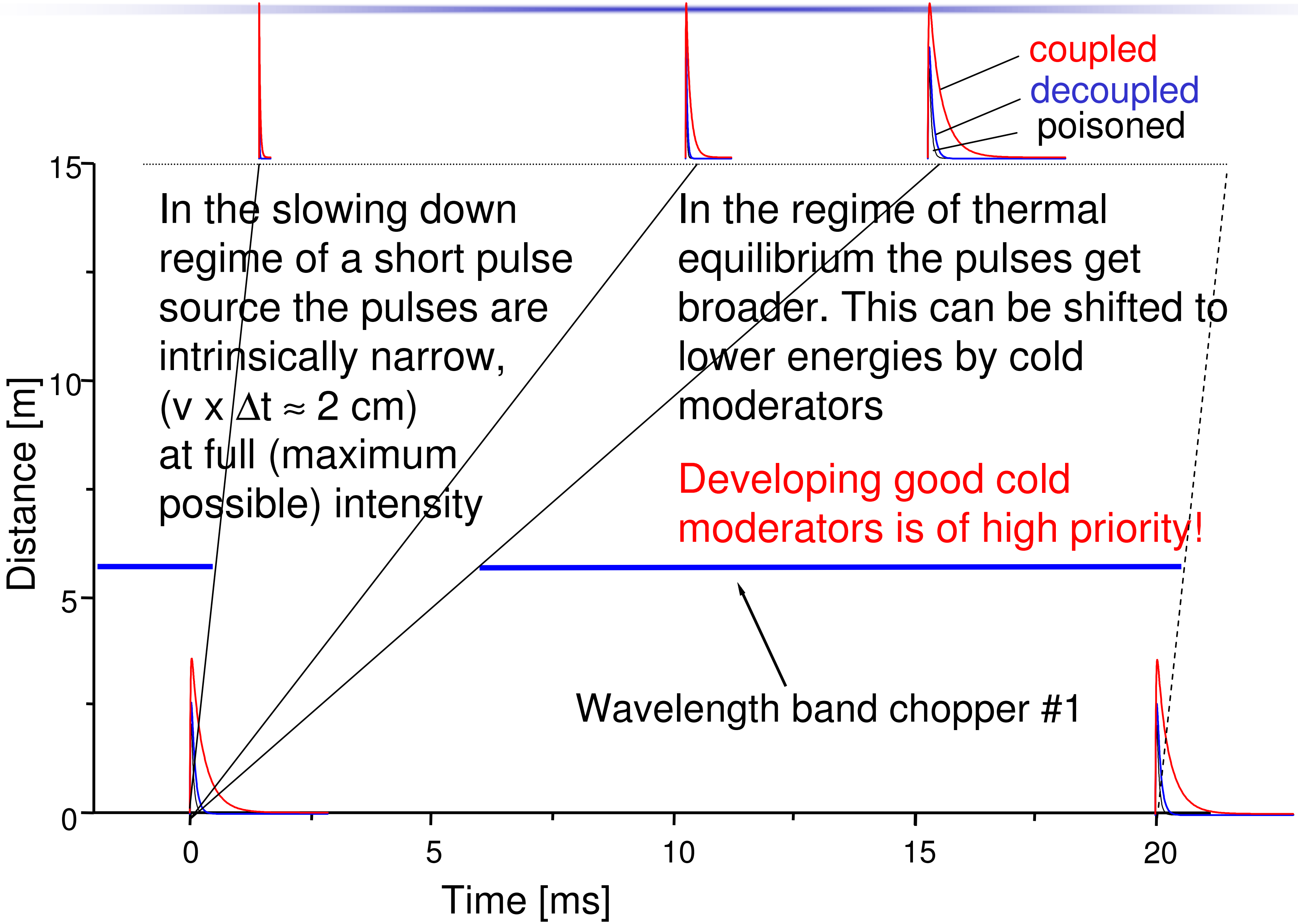






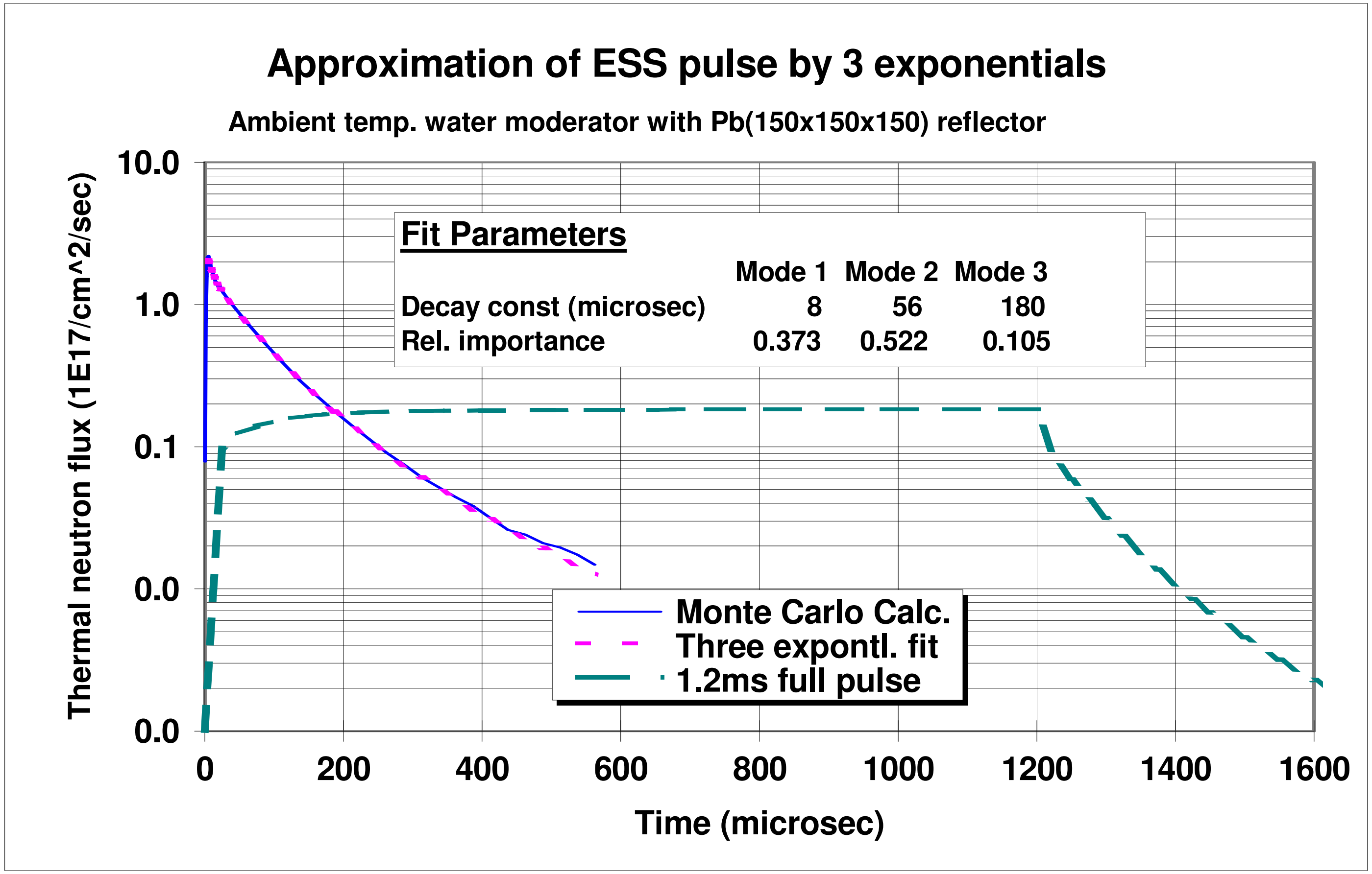
Moderators are usually arranged above and below the target in order to reduce fast neutrons

Short Pulse-ToF-Technique



Short vs. Long Pulse Operation

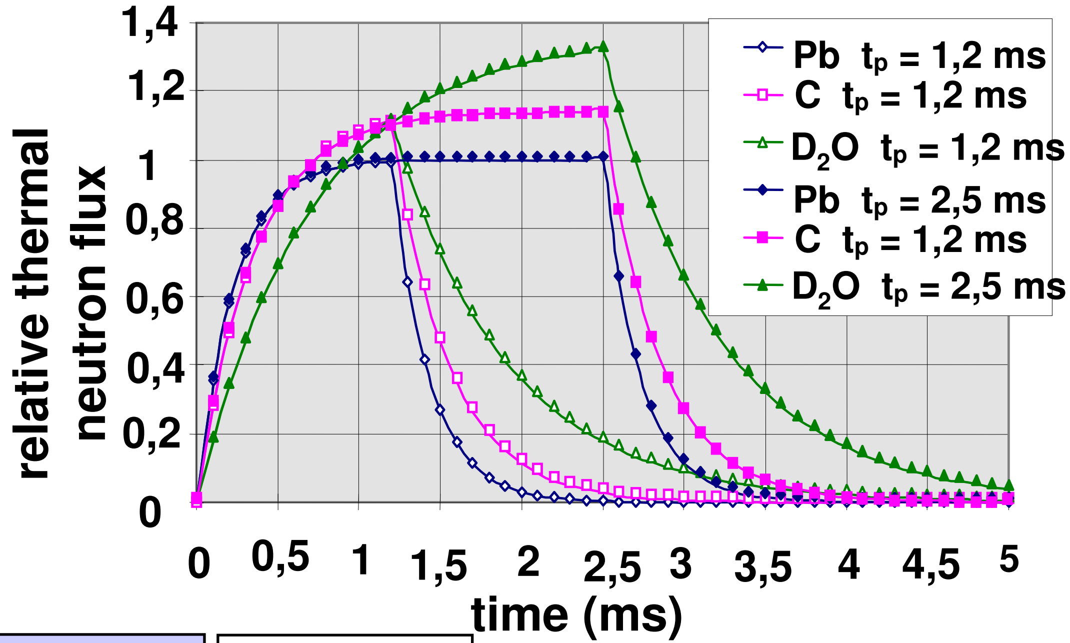
Example: bypass ESS compressors

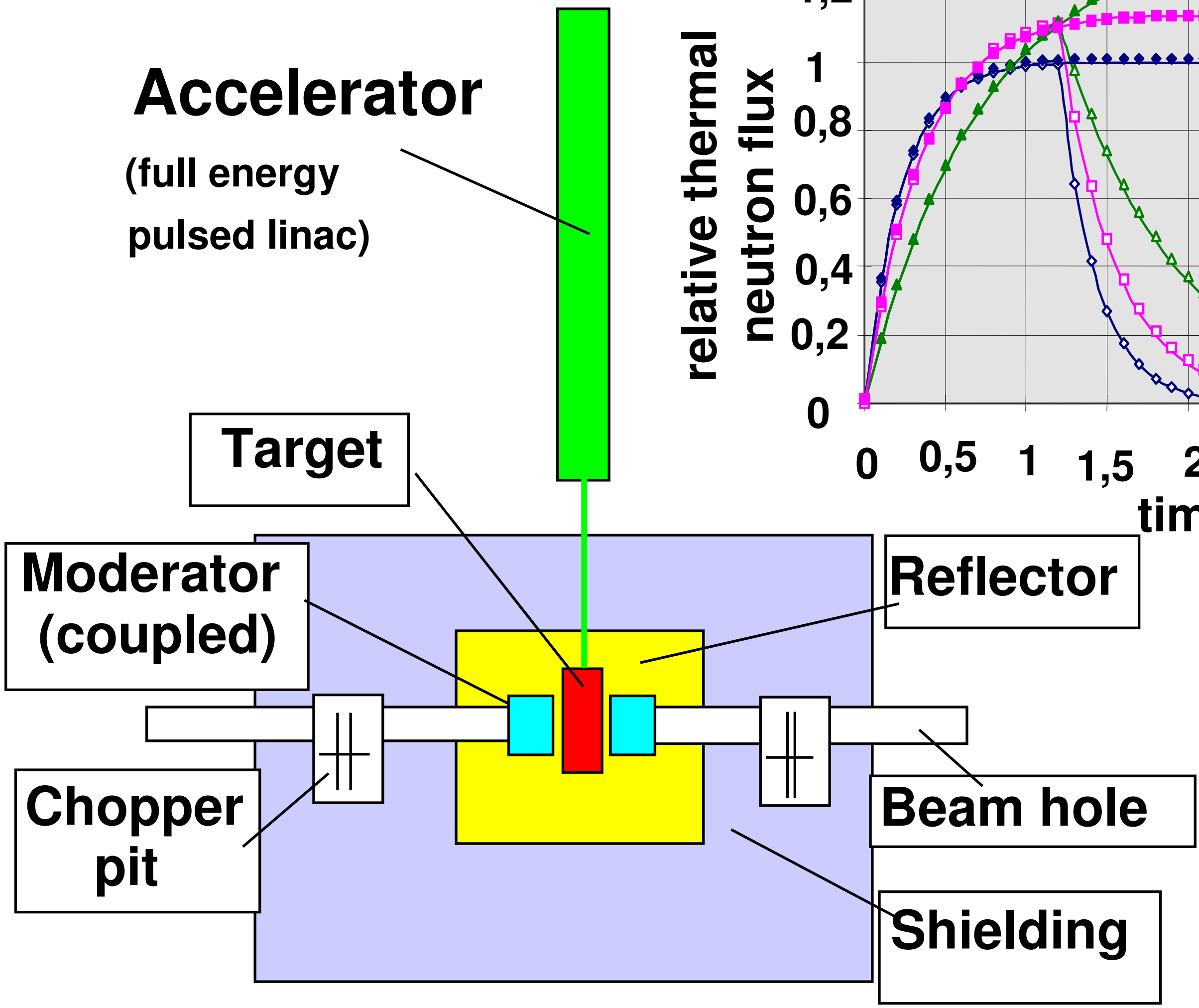


Simply omitting the compressor ring and associated pulse chopping necessary for injection into the ring would result in a 1.2ms long pulse of 10% of the peak intensity of the short pulse source

A higher flux level in the LP moderator (perhaps up to 2x) can be obtained by an optimised design

Long Pulse Neutron Source





Effect of reflector material and t_p on the neutron pulse of an LPTS

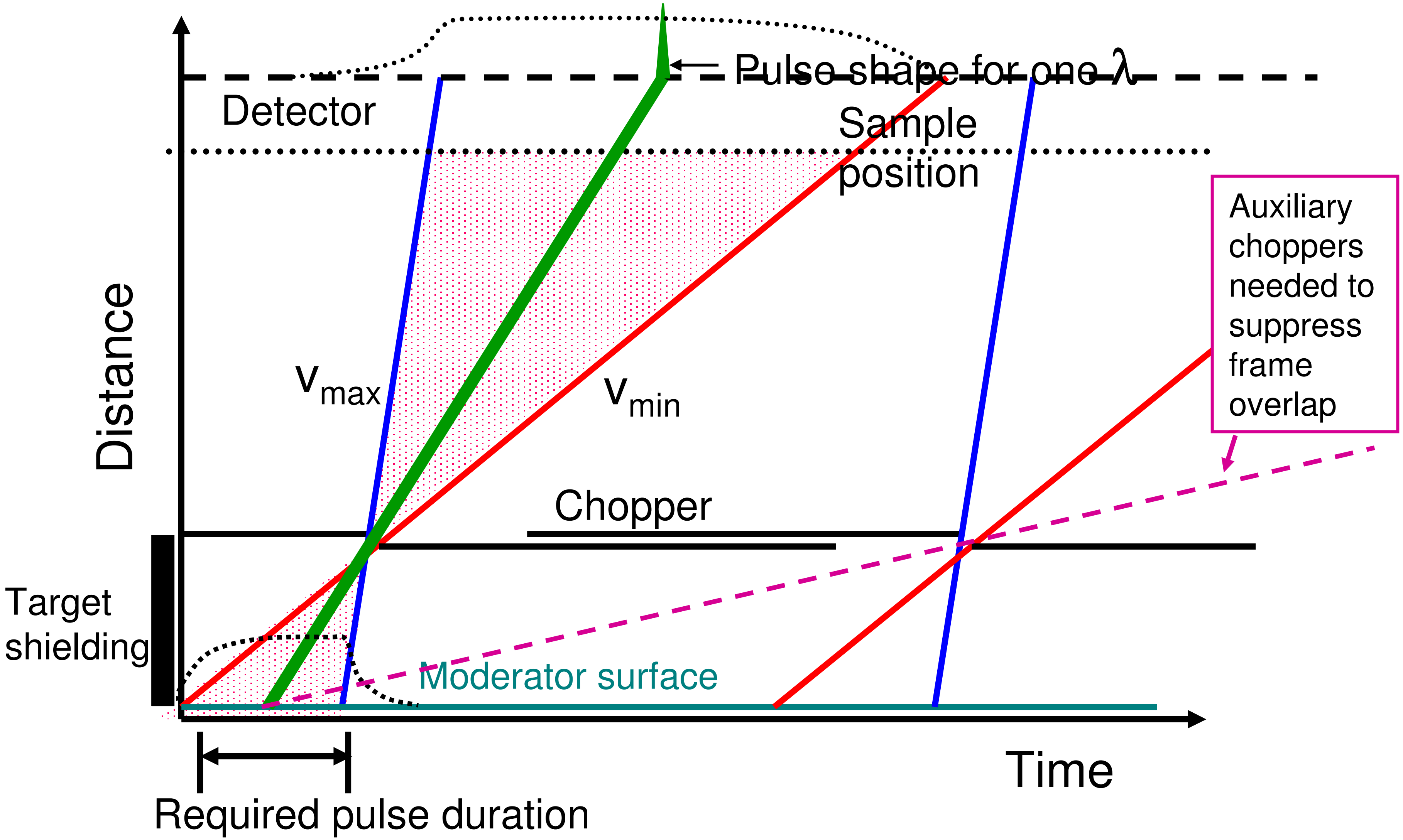
(calculations using experimentally determined decay constants)

Utilisation of Long Pulse Sources

- The most straight forward use of an LPSS is to employ instruments similar to a cw source but gate the detectors to allow data collection only when the “good” neutrons arrive. While using the full time average flux this reduces the background by orders of magnitude.
- More elaborate concepts to use an LPSS exist but in general require advanced and expensive instrument infrastructure
  - multiple chopper systems (ca 1 M$/beam line)
  - complex neutron guide systems
  - in-shield neutron optics
  - etc.
- LPSS-beam lines will generally be longer than on SPSS
- The need for beam line shielding is generally higher on LPSS instruments
- The peak flux used is lower than on SPSS

Utilisation of Long Pulse Sources

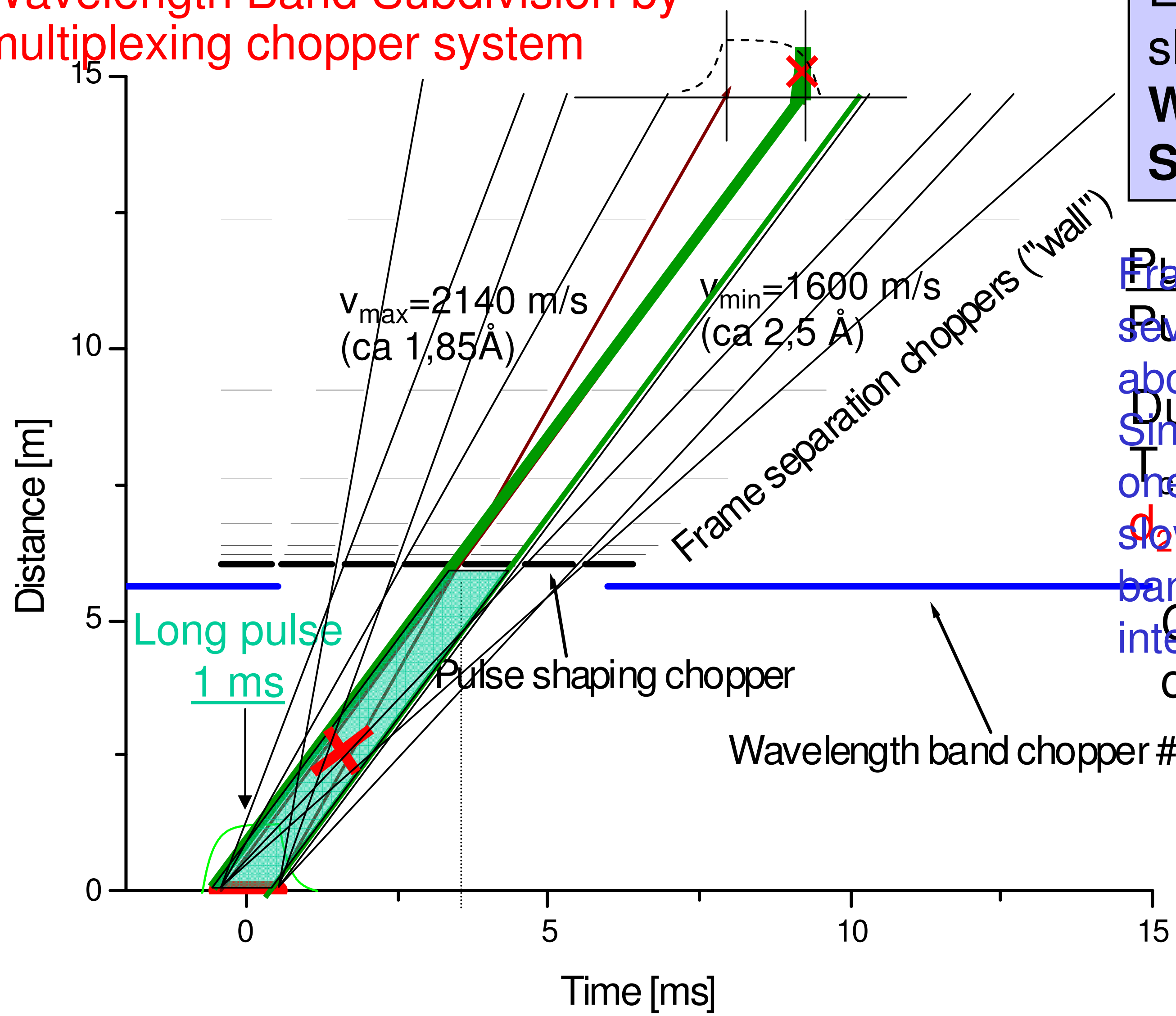
Pulse Shaping by Choppers on a Long Pulse Source



General pulse shaping tool: for long pulses and coupled moderators

F. Mezei

Wavelength Band Subdivision by multiplexing chopper system



Example of pulse shaping with Wavelength Frame Subdivision

Pulse utilisation:

Pulse clipping: d_1 < 0,9

Duty cycle:

T_0 = 1 ms; t_c = 0,03 ms

d_2 = 0,03 / 1 = 0,03

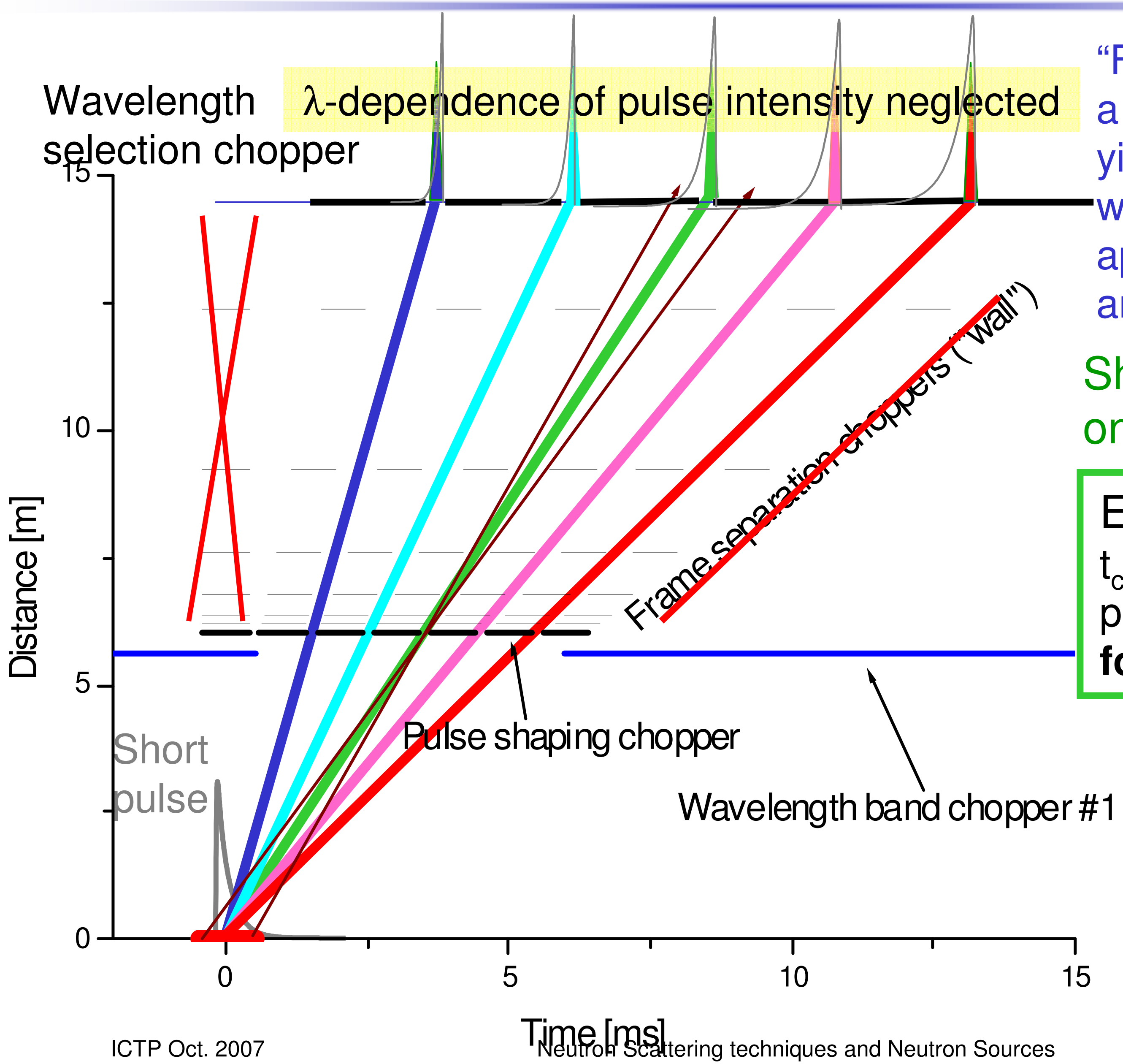
Chopper opening and closing: d_3 = 0.5

Total LP: <1.5%

Frame subdivision yields several wavelength bands about 3 ms apart at 15m. Since fastest neutrons in one band can be faster than slowest neutrons in previous band, the wavelength interval can be fully covered.

Not accounting for the transmission of the open choppers and the gaps in the guide!

Multiple Wavelengths from a coupled moderator of a pulsed source



"Frame multiplication" on a coupled moderator yields five discrete wavelengths about 4 ms apart at 20m (OK for ToF analysis!).

Short Pulse coupled: only WBC + 2 choppers

Efficiency: (depends on λ)
t_c/τ_p= 30/150 ≈ 20%
plus losses in 2 choppers
for selected energies

Total LP: <1.5%, plus losses in 7 choppers and guide gaps
for whole band

Summary on Spallation Neutron Sources

- There exists a very high degree of flexibility in the design and use of spallation neutron sources.
- Choices will often depend on existing boundary conditions; even small facilities have been shown to perform very well.
- Currently the available technology allows to build spallation neutron sources up to a few MW of beam power, which makes it possible to match modern research reactors also in time average flux.
- By properly exploiting the time structure of pulsed sources much better use can be made of the primary neutrons produced than on cw sources.
- Probably there is no clear answer as to which time structure is to be preferred at a given time average power.
- Often, however, the very high efficiency of instruments on pulsed sources is due to the use of very large detector banks.
- The field of source and instrument development is still wide open!

That's it!

Thank you for your patience!