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Free Lunch Theorem in Pulsed Source Instrument Optimization

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Flux on sample

Continuous sources:

$$\varphi = \eta \, \Phi \, \delta\Omega \, \delta\lambda$$

Performance: Flux / (Wavelength) Resolution Ratio (FRR)

$\varphi / \delta\lambda = \eta \, \Phi \, \delta\Omega$ = const. for given λ

⇒ ***Flux and resolution directly (inversely) related***

No free lunch!

Pulsed sources: elastic scattering & inverted geometry spectroscopy

$$\varphi = \int_{\lambda_{min}}^{\lambda_{max}} \eta \, \Phi \, \delta\Omega \, d\lambda$$

➡ ***No direct relation between flux and resolution !!!***

$\Delta\lambda = \lambda_{max} - \lambda_{min} = c\, T/L$

$\delta\lambda = c\, dt/L$

c = 3.96 Å.m/ms

T = source pulse repetition time

dt = source pulse length, f = dt / T = duty factor

L = source-detector (sample) distance

L is a crucial design parameter, FRR is L dependent

but in direct view $\varphi \propto \delta\Omega \propto 1/L^2$. **Constrain for L!**

Old instrument design paradigm:

shortest possible distance to mitigate $1/L^2$ (or guide losses)

➔ shortest pulse to keep resolution

➔ lowest source brightness

Advances in neutron beam delivery

Supermirror neutron optics:

$\delta\Omega$ of direct view (or more) can be delivered with small beam losses for both thermal and cold neutrons to any distance 10 m < L < 1 km

New instrument design paradigm:

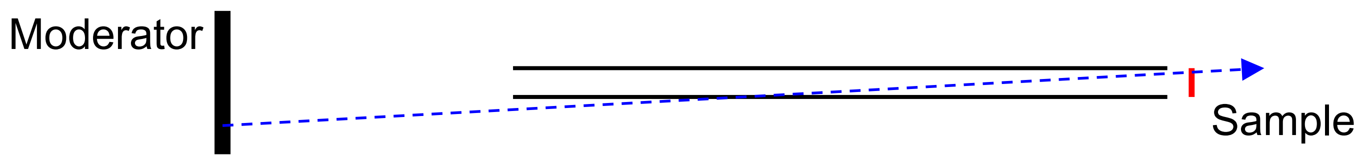
$\eta\delta\Omega$ is independent of L, thus

*L becomes a **free** instrument design parameter*

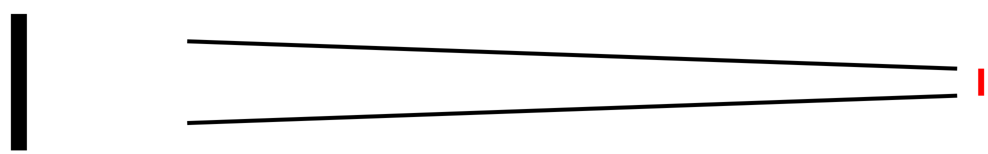
Neutron beam delivery for short wavelength neutrons
over shortest feasible distances to sample (~12 m):
direct view of moderators implies very small solid angle
(0.5°x 0.5° vs. up to 2°x 5° at reactor sources)

Supermirror neutron optics offers improvement

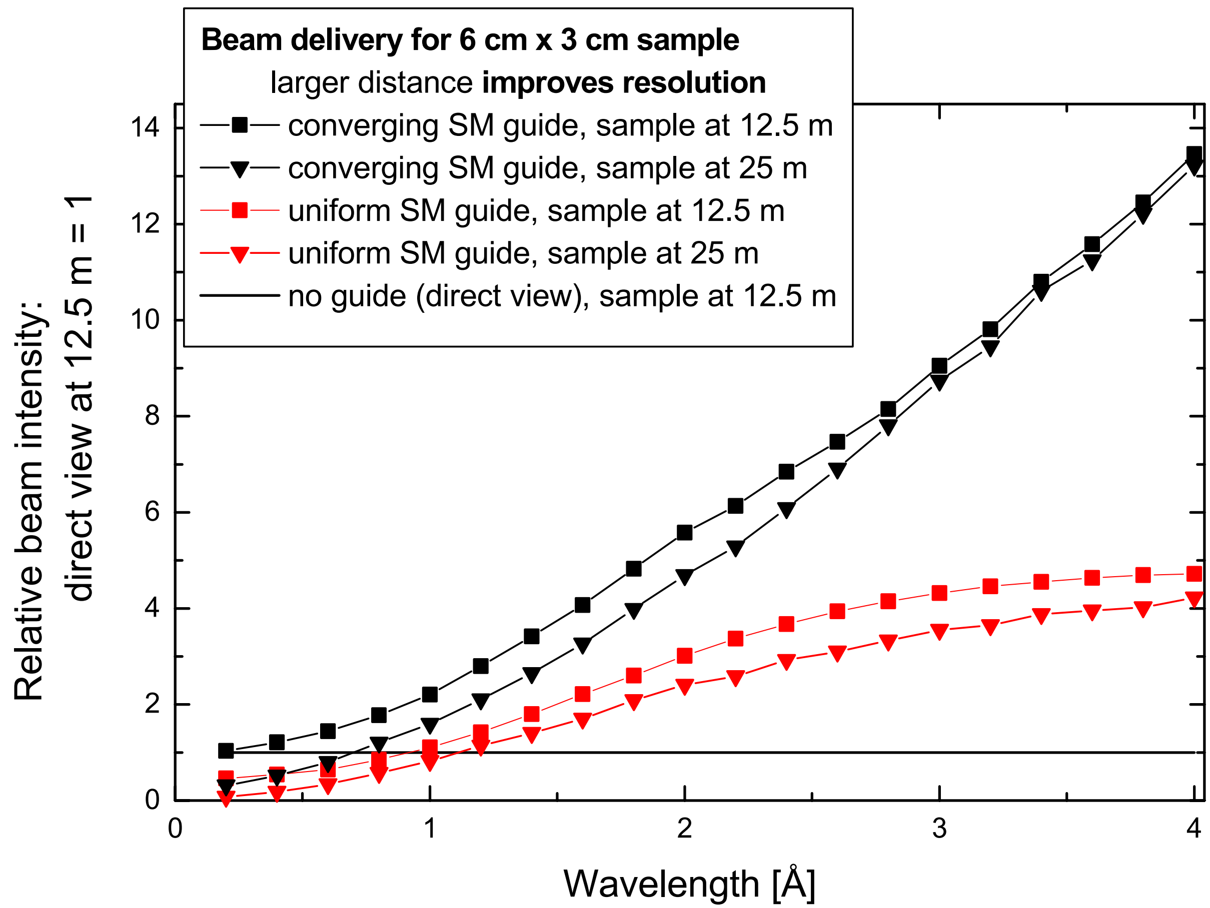
Conventional uniform guide: shadows direct view



Converging neutron guide: combines reflection and direct view

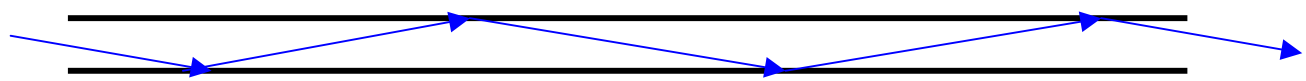


Supermirror optics: enhanced beam delivery for all distances for $\lambda > 0.8$ Å

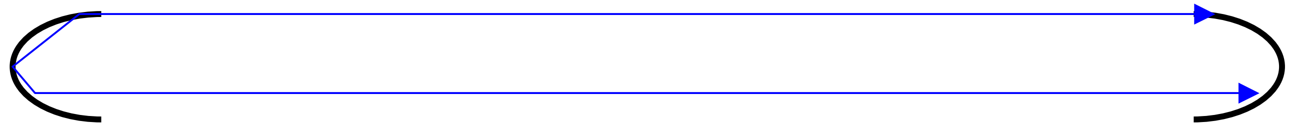


<u>Neutron beam delivery</u> over large distances:
neutron guides

But reflection losses are still substantial:



Principle of **ballistic** guide: reduce the number of reflections:



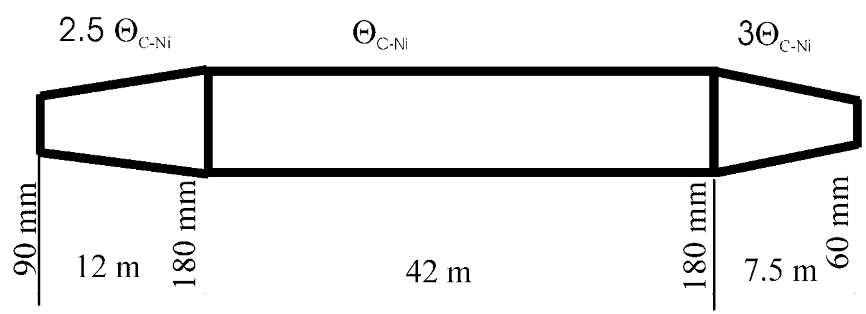
Prototype ballistic guide in the making (LANSCE)

Average number of reflections at 10Å:

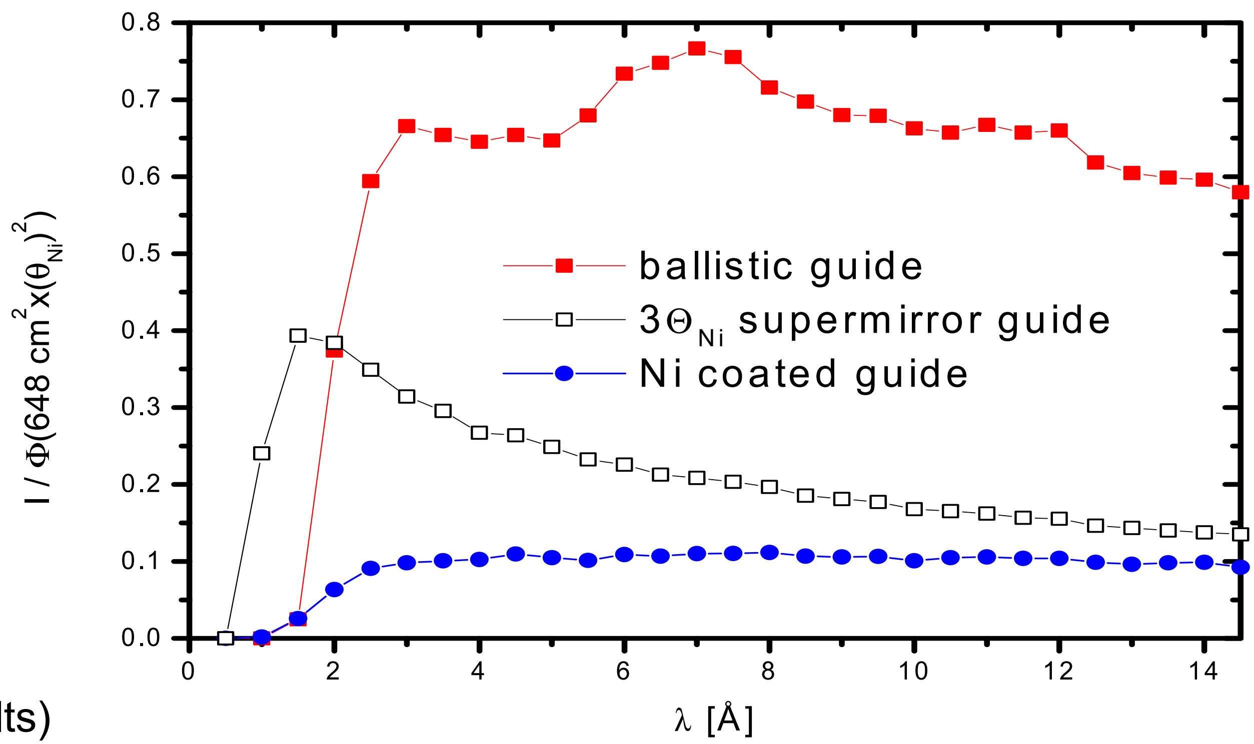
SM guide 70

Ni guide 25

Ballistic guide 10



Largely enhanced beam delivery
over large distance (> 60 m)



(Simulation results)

Flux on sample

Pulsed sources: elastic scattering and inverted geometry spectroscopy

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⇨ ***No direct relation between flux and resolution***

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If L is variable at constant δΩ:

$L \to \infty$: $\varphi = \eta \, \Phi \, \delta\Omega \, \Delta\lambda = \eta \, \Phi \, \delta\Omega \, \delta\lambda \, /f$

narrow band limit, FRR is independent of L (like CW)

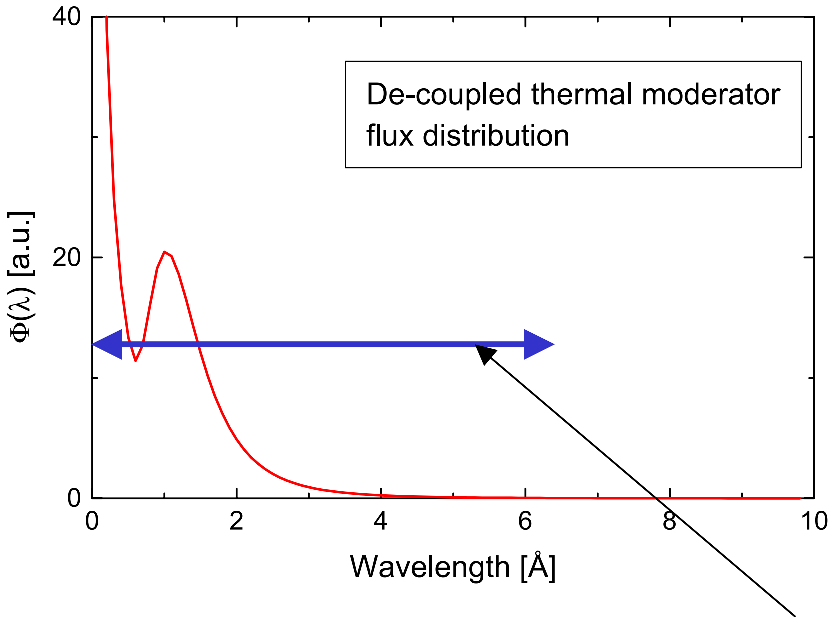
$L \to \mathbf{0}$: $\varphi = \int \eta \, \Phi \, \delta\Omega \, d\lambda = \text{const}$

broad band limit, FRR $\propto$ L = **Free lunch!**

Free lunch theorem for pulsed source instruments:

Non-uniform flux (or information contents) distribution makes FRR steadily increase with increasing L: on a given beam the ***resolution increases without loss of intensity*.**

Small print: $\lambda > 0.8$ Å, long guides and wavelength band definition choppers are needed, residual losses introduce an optimal length,

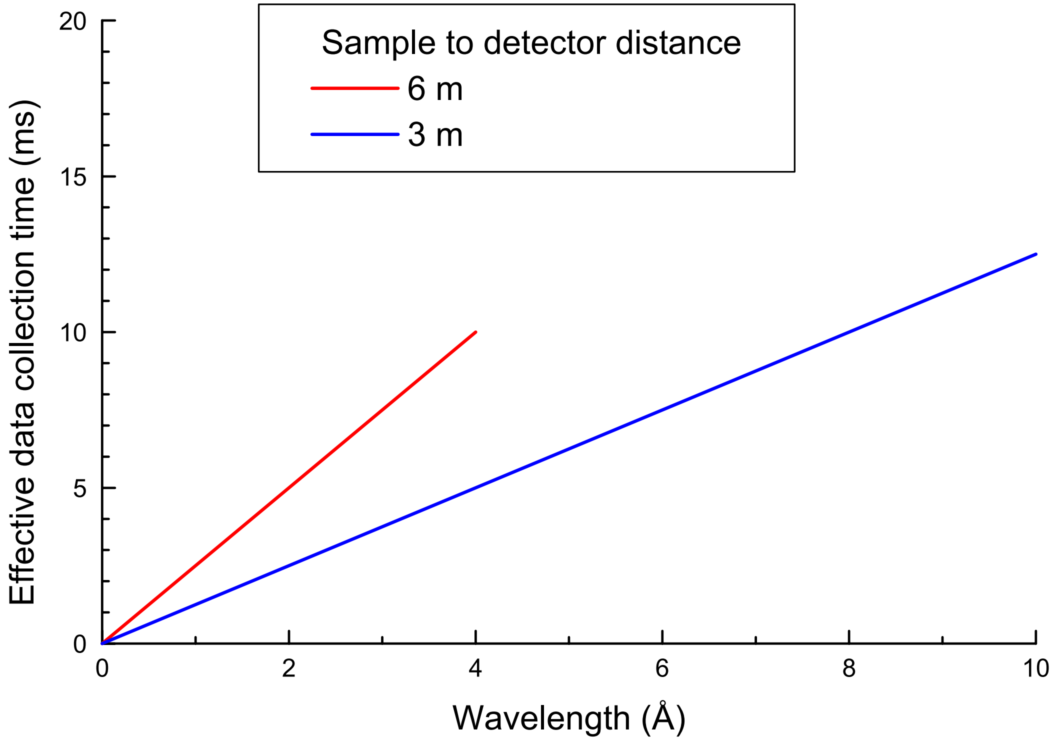


Optimal length varies case by case: e.g. 50 Hz source frequency, ~ 40 - 50 m for thermal neutron machines, 600 m for sub-μeV back-scattering

Wavelength band at L=12 m and 50 Hz

Direct geometry TOF spectroscopy:

Flux relations different, but plenty of room for improvements: low source frequency leads to overwhelming data collection dead times in TOF spectroscopy

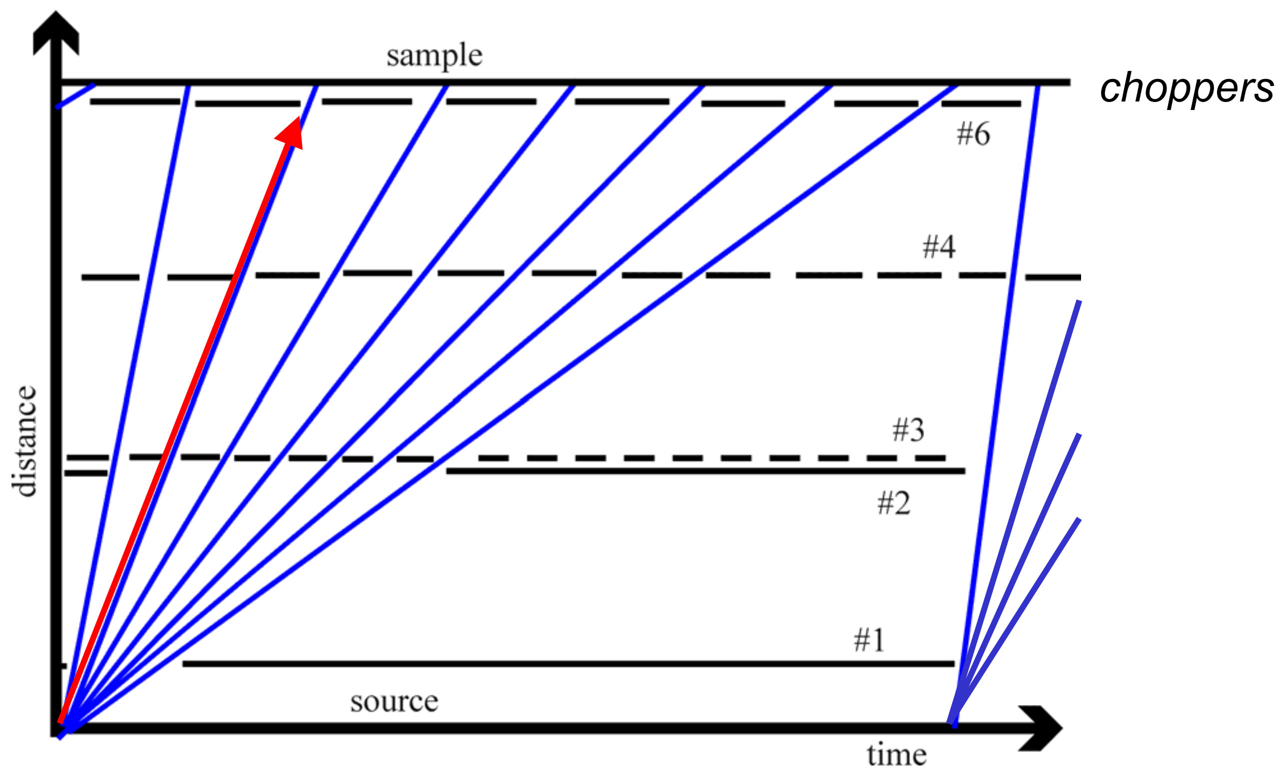


Inelastic scattering:

analysis of velocity after scattering on sample only
requires 2 - 10 ms: ideal pulse repetition 100 - 500 Hz

Repetition Rate Multiplication (RRM): several pulses on sample from each source pulse (prototype in the making at LANSCE)

Example:
at λ = 1 Å
$\lambda_{i+1}-\lambda_i \sim 0.1$ Å
for D_{ms} = 50 m
and D_{sd} = 3 m
at least
4 - 8 pulses
productive



Chopper spectrometers:

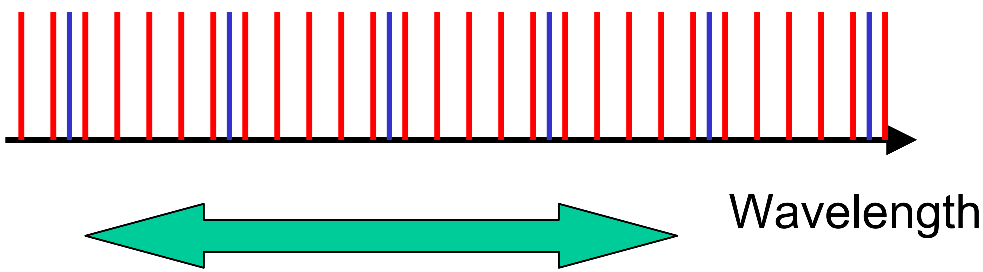
intensity at constant chopper pulse length: $\propto$ **1/L**

number of pulses per unit wavelength with RRM: $\propto$ **L**

→ *flux on sample independent of L (i.e. same as for diffraction and inverted geometry) if RRM is used*

Example:

RRM wavelength sequences for $L_{red} = 4 \times L_{blue}$

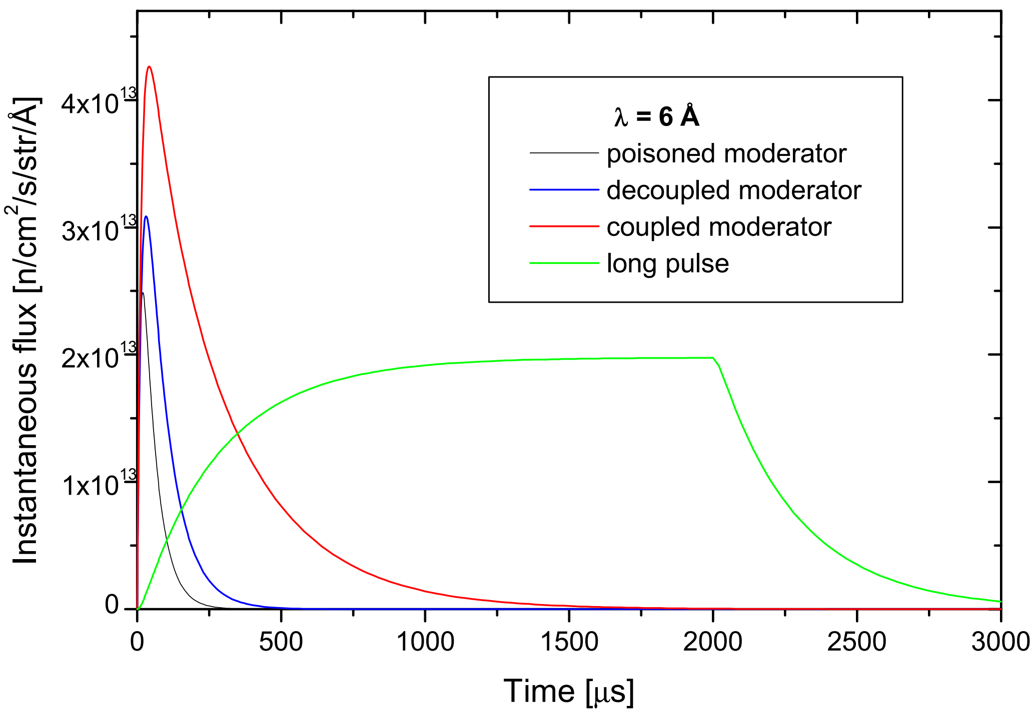


New instrument design paradigm (except eV range):

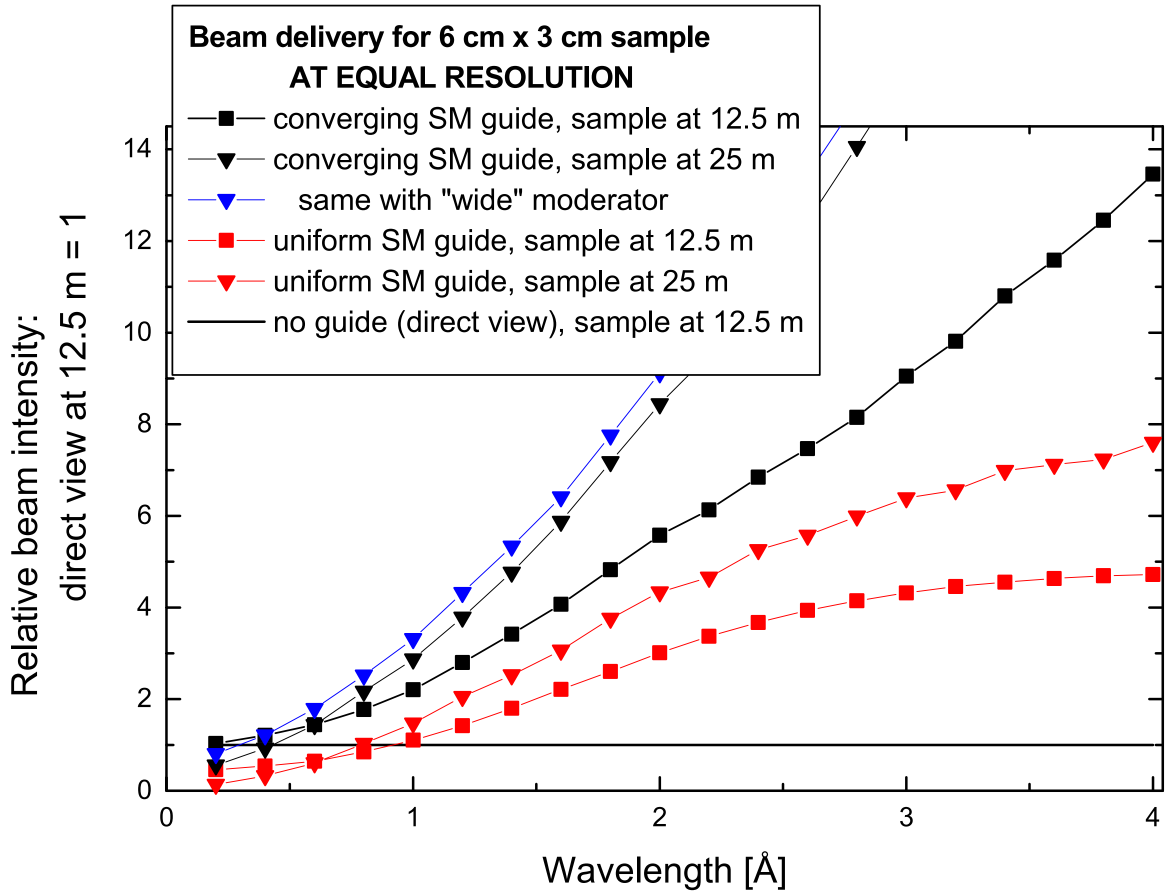
longest possible distance to achieve resolution with the most intense (i.e. longest) pulses

➔ highest source brightness

To maximize intensity at constant resolutions: guides efficient for λ > 0.5 Å



Supermirror guides can make the **enhanced intensity** of less poisoned moderators available **without loss of resolution** for $\lambda \geq 0.5$ Å



Summary:

Advanced neutron guides efficient for wavelengths > 0.5 Å

No $1/L^2$ penalty for large source-detector (sample) distances

Long instruments with sharply defined wavelength band eliminate much of the dead /low efficiency data collection time

Free lunch: turning (some of the) dead time into prime data collection time:

for enhanced resolution without intensity loss: longer instrument

for enhanced intensity without resolution loss: longer source pulses + longer instruments