ICTP, 21.10.05

Optimization of source performance

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Optimization of source performance for neutron scattering experiments

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Subjects

- **Ways to produce neutrons: the efficiency factor**
- **Global system requirements: contradictory needs of neutron scattering instruments**
- **Optimal performance: Peak flux theorem**
- **Global system requirements: neutron scattering needs vs. accelerator-target realities**
- **Long pulse concept: maximize peak and time average flux at the same time**
- **Conclusion**

Ways to produce neutrons

Energy balance: fast neutrons produced / joule energy (heat produced / energy consumed)

Fission reactors:	~ 10^9	(in ~ 50 liter volume)
Spallation:	~ 10^{10}	(in ~ 1 liter volume)
Photo neutrons:	~ 10^9	(in ~ 0.01 liter volume)
Nuclear reaction (p, Be):	~ 10^8	(in ~ 0.001 liter volume)
Laser induced fusion:	~ 10^4	(in ~ 10^{-9} liter volume)

Also: Nature (Apr 2005): table top fusion by accelerating pyroelectric fields

Spallation (0.5 – 5 GeV protons): best energetics

One amazing example: table top neutron source

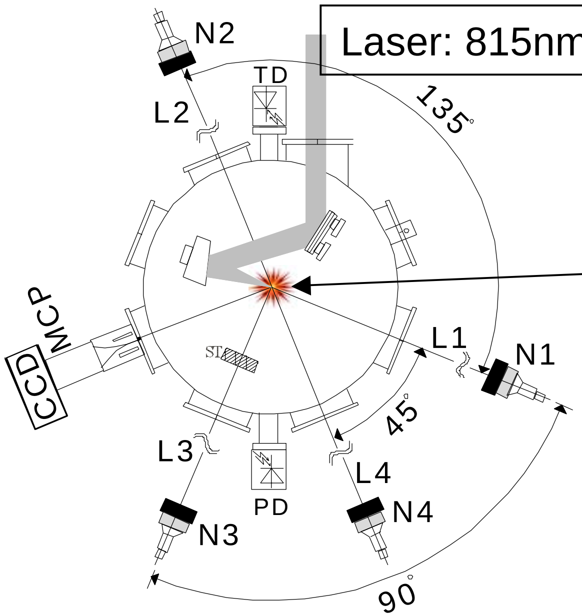
- **Nanoaccelerator by ultrashort, focussed laser pulse on 20 μ D_2O droplet: relativistic light intensities.** Field-strength: 1 MV/μm

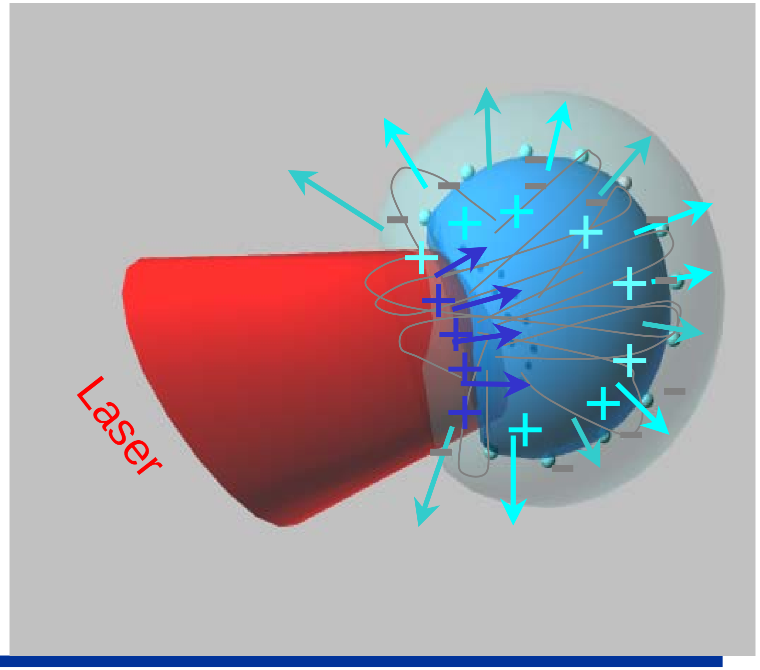
  10^{19} W/cm^2 power → plasma → deuterons accelerated to MeV → **fusion !**

  Distribution of neutrons reveals plasma formation mechanism

  Laser driven μ-size source of (fast) neutrons (~10^4 neutron/ ~ 0.5 j pulse)

  d + D => 3He (0.82 MeV) + n (2.45 MeV): Neutron – spectroscopy





Development of neutron sources

- **Parasitic use of energy research reactors**
- **Dedicated beam reactors (1958,….)**
- **Pulsed spallation sources (1970's,… new facilities under construction):**

  fewer neutrons more efficiently produced and used

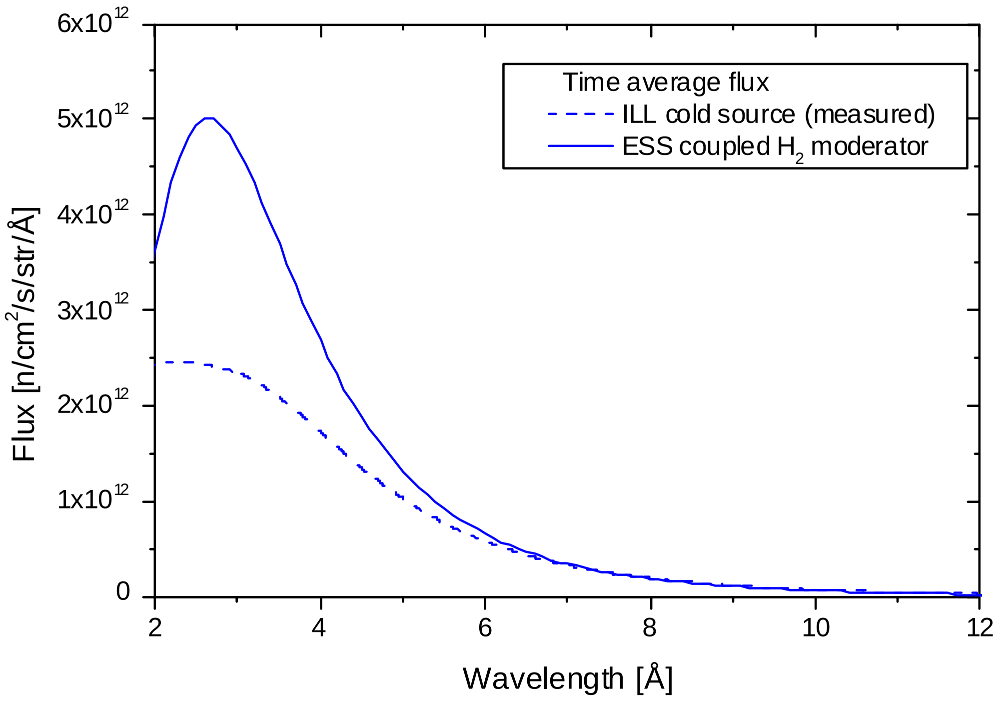
- **Next challenge in optimization:**

  produce more neutrons and use them more efficiently

Efficiency gain by pulsed nature

5 MW spallation source:

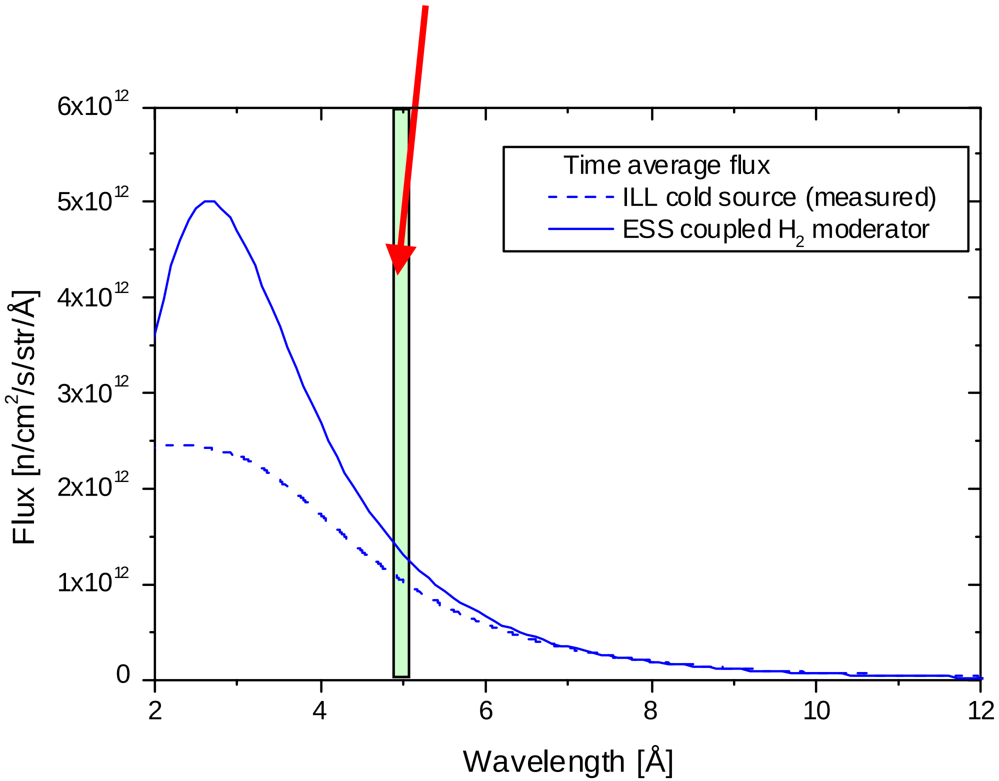
coupled cold moderator flux ~ ILL cold source



Efficiency gain by pulsed nature

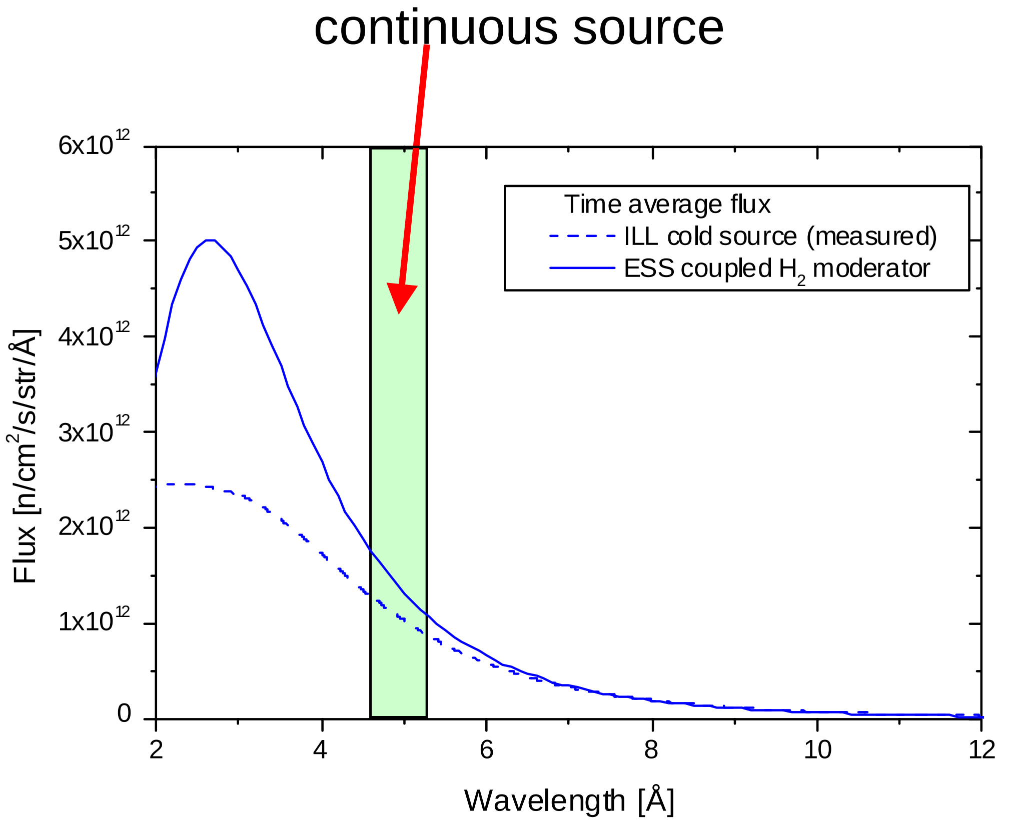
Part of spectrum used by a diffractometer for large structures (e.g. biological membranes)

continuous source



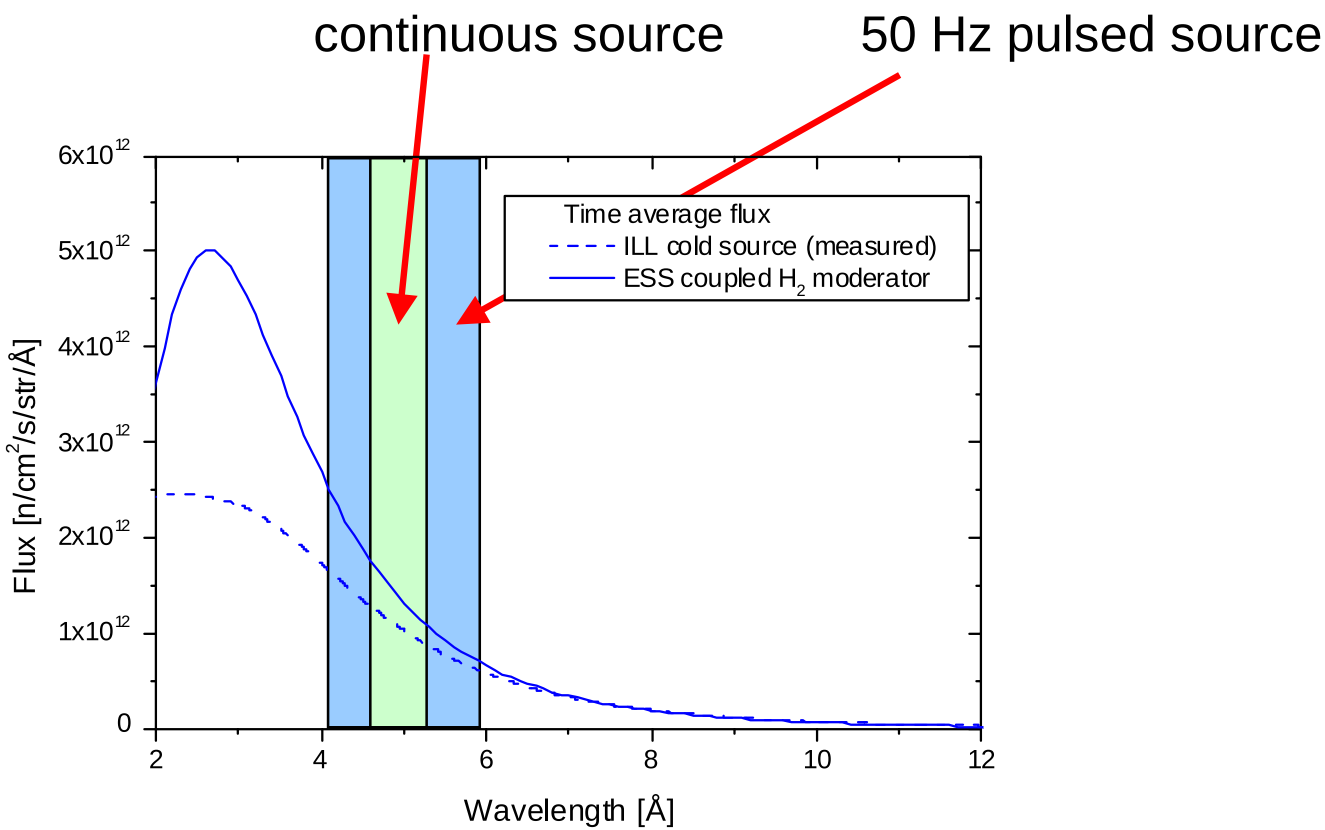
Efficiency gain by pulsed nature

Part of spectrum used by a D22 (ILL) class instrument (Small Angle Neutron Scattering)



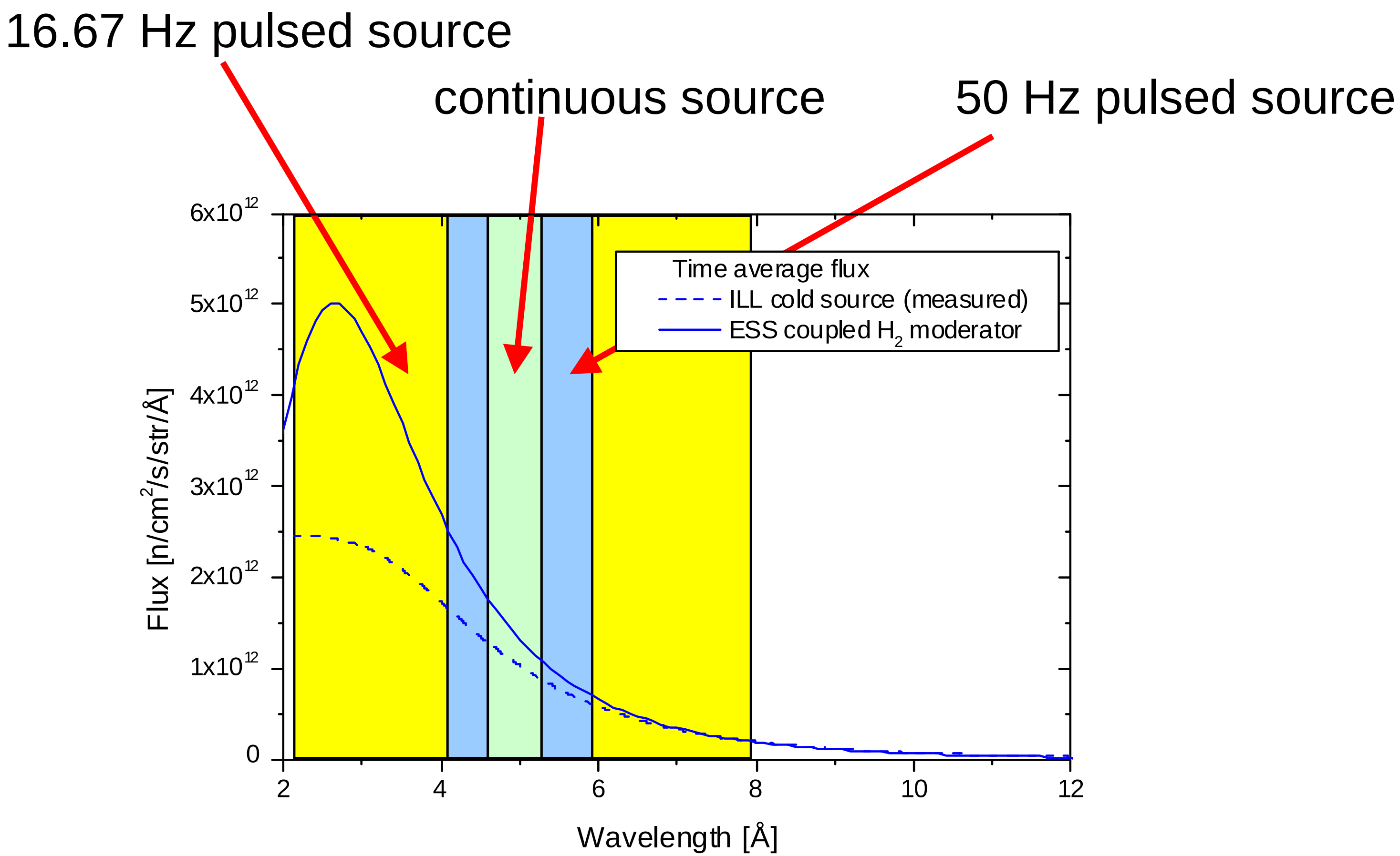
Efficiency gain by pulsed nature

Part of spectrum used by a SANS instrument



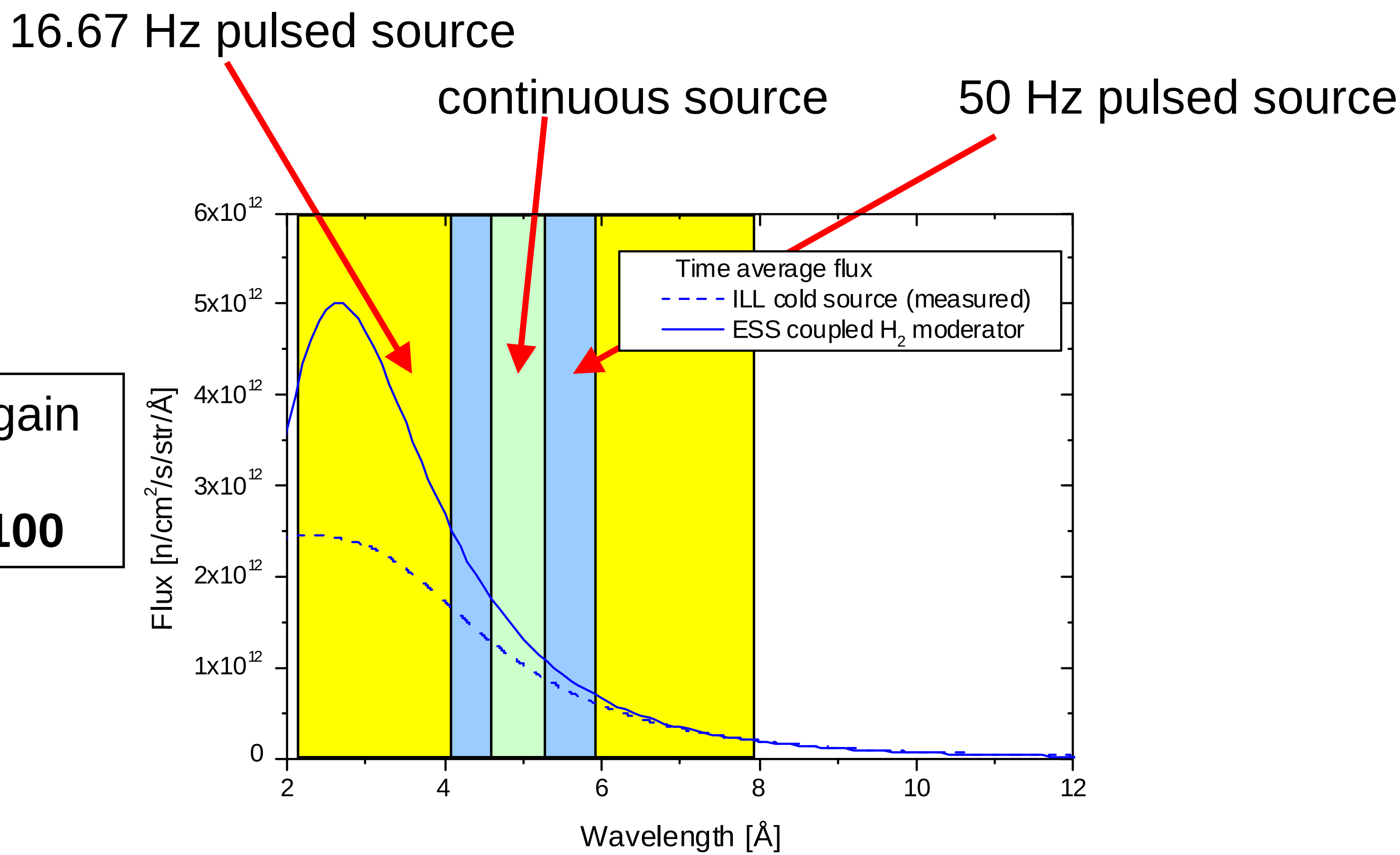
Efficiency gain by pulsed nature

Part of spectrum used by a D22 (ILL) class instrument



Efficiency gain by pulsed nature

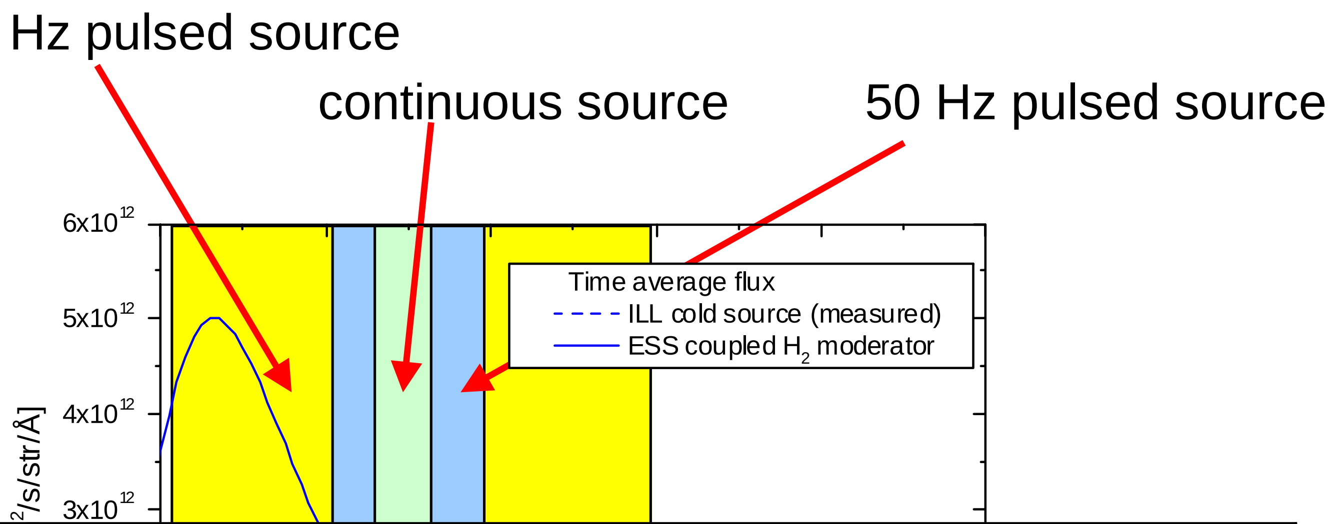
Part of spectrum used by a D22 (ILL) class instrument



Efficiency gain by pulsing:
≈ $\delta\lambda/\lambda$ **~8-100**

Efficiency gain by pulsed nature

Part of spectrum used by a D22 (ILL) class instrument



Efficiency gain by pulsing: ≈ $\delta\lambda/\lambda$ **~8-1000**

Substantial overall progress beyond continuous sources in cold neutron research (soft matter, nanoscience): need to surpass their time average flux in low repetition rate

Efficiency gain by pulsed nature

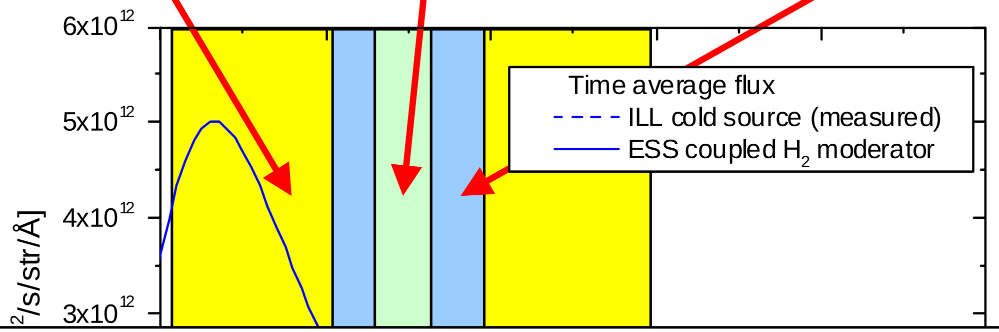
Part of spectrum used by a D22 (ILL) class instrument

16.67 Hz pulsed source

continuous source

50 Hz pulsed source

Efficiency gain by pulsing:
≈ δλ/λ **~8-1000**



Substantial overall progress beyond continuous sources in cold neutron research (soft matter, nanoscience): need to surpass their time average flux in low repetition rate
→ Large energy per pulse > 300 kj

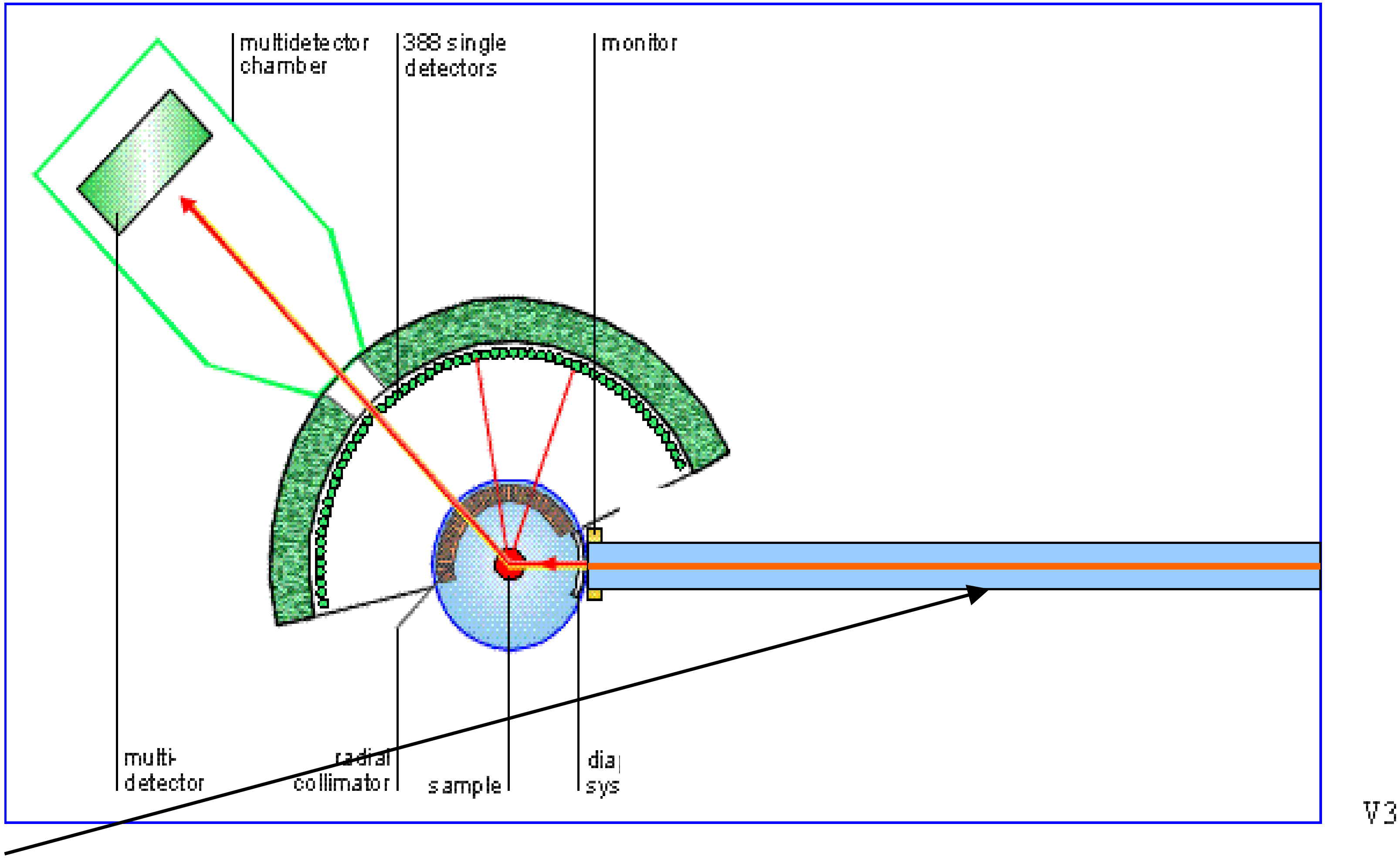
Contradictory requirements by instruments

Pulse parameters:

- **Duty factor c ~ resolution $\delta\lambda/\lambda$**
  → low resolution vs. high resolution (0.1 % - 10 %)

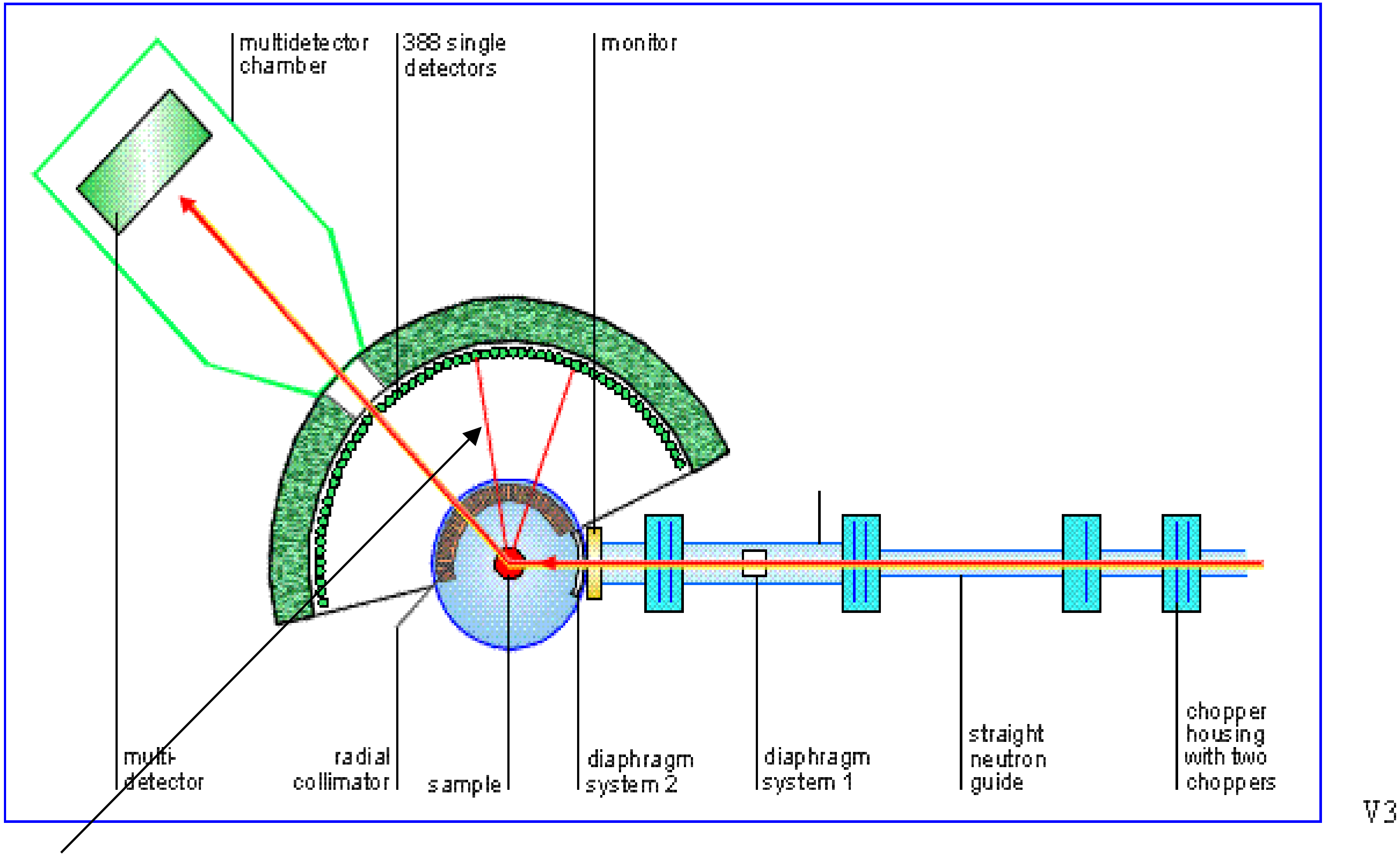
- **Pulse repetition rates ~ match neutron flight times**
  → (very) cold neutrons vs thermal/hot neutrons
  elastic scattering: 5 vs. 100 Hz
  inelastic scattering: 30 vs. 1000 Hz

Contradictory requirements by instruments



Flight path to determine repetition rate: 30-100 m for time-of-flight diffractometer

Contradictory requirements by instruments



Flight path to determine repetition rate: ~ 3 m for time-of-flight spectrometer

Continuous vs. pulsed beams

Ways to make neutrons monochromatic

- **Time-of-flight: velocity v**

  $$mv = h / \lambda$$

- **Crystals: wavelength λ**

  $$\lambda = 2d_{hkl} \sin\theta$$

$$v[m/s] = 3956 / \lambda[Å]$$

Continuous vs. pulsed beams

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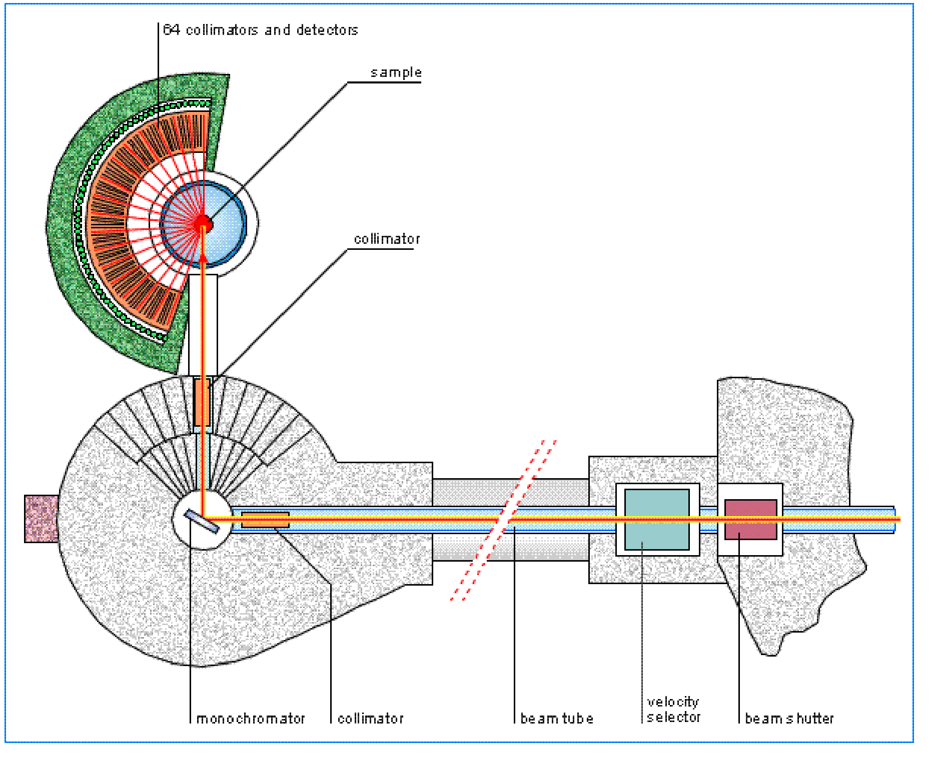
Powder Diffractometer

(Continuous source)

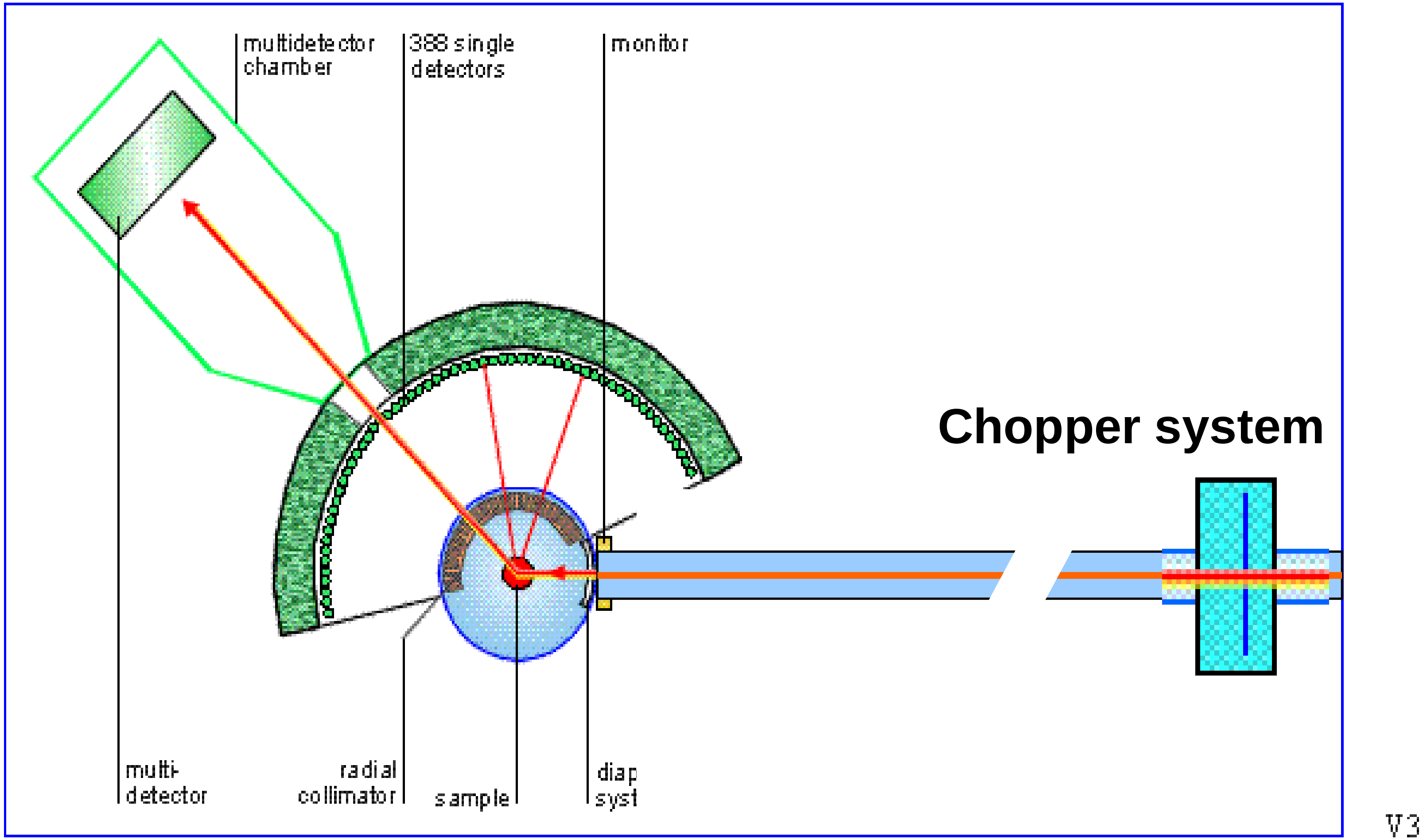


Continuous vs. pulsed beams: Mean flux theorem

On a continuous neutron source:

The time average (mean) neutron flux at the sample at equal wavelength and angular resolution is the same for both time-of-flight (TOF) and wavelength selection (crystal) monochromatization for reasonable TOF pulse repetition rate

TOF monochromatization at continuous source



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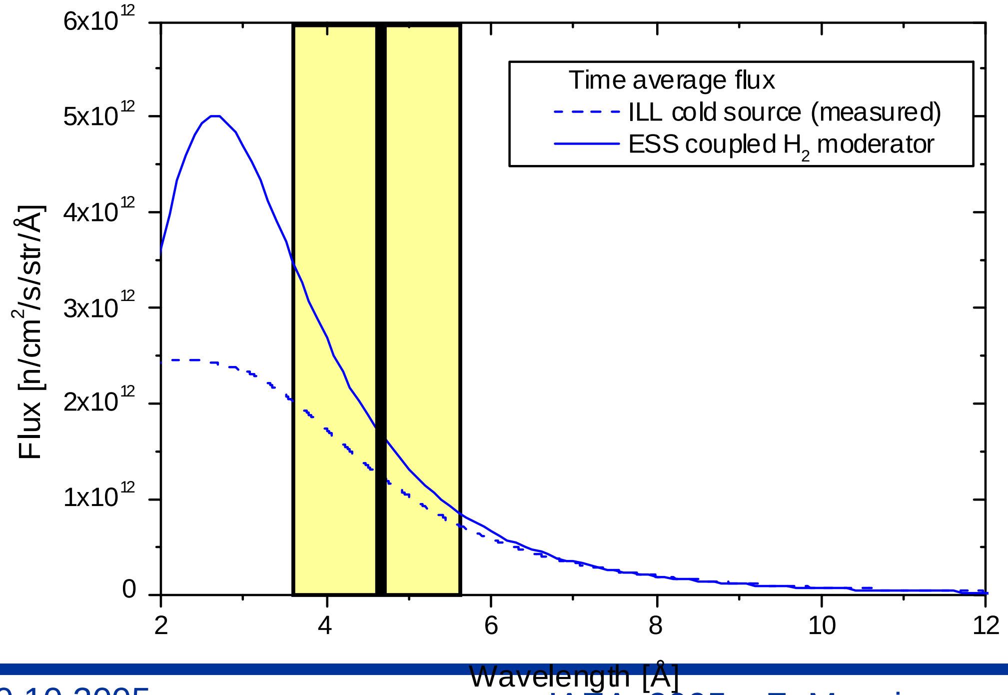


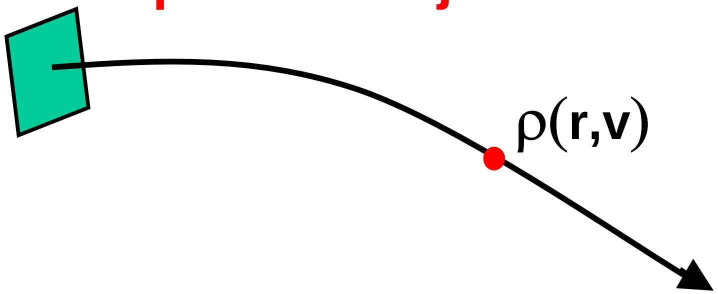
"narrow band"

Exercise!

Continuous vs. pulsed beams: Mean flux theorem

Flux is governed by Liouville theorem:

Phase space density ρ is constant along particle trajectories in conservative force fields



No. of particles hitting in unit time a surface perpendicular to trajectory (local z axis):

$N = dx\, dy\, dz\, dv_x dv_y dv_z =$

$= \rho\, dx\, dy\, v\, v\alpha_x\, v\alpha_y\, v^2 d\lambda\, m/h \propto$

$\propto$ **$\phi(\lambda)$ df dΩ dλ**

where the brightness

$\phi(\lambda) = \rho\, mv^5/h$ **is a constant** if the neutron velocity is preserved (i.e. little acceleration)

Note: for Maxwellian tail ρ is independent of v.

Absolute flux determination:

at any point along the beam

$$\phi(\lambda) = \eta\, \phi(\lambda)_{source}$$

(absorption) loss factor ≤ 1

Continuous vs. pulsed beams: Mean flux theorem

On a continuous neutron source:

The time average (mean) neutron flux at the sample at equal wavelength and angular resolution is the same for both time-of-flight (TOF) and wavelength selection (crystal) monochromatization for reasonable TOF pulse repetition rate

The brightness of the continuous source only matters, the pulsed (TOF) and continuous methods of beam monochromatization are equivalent!

Peak flux theorem

In neutron scattering work for a neutron source **with sufficiently long source pulses the peak flux alone matters**, independently of any reasonable source time structure (continuous or pulsed)

Peak flux theorem

For an arbitrary source repetition rate f one will choose the instrument length L so that to assure the desired band $\Delta\lambda$:

$$L = A\,\Delta\lambda^{-1} f^{-1}$$

(A=3956 Åm/s). With this L the pulse length t for the required resolution $\delta\lambda$ has to be

$$t = A^{-1} L\,\delta\lambda = f^{-1} (\delta\lambda / \Delta\lambda)$$ **Can be as much as 10 % of f^{-1}=T**

The neutron flux on the sample will be given in terms of the peak source brightness function $\Phi_P(\lambda)$, beam divergence $\delta\Omega$ and the efficiency factor of the beam delivery system η

$$\varphi = \eta\,\delta\Omega\, t\, f \int \Phi_P(\lambda)\, d\lambda = \eta\,\delta\Omega\, (\delta\lambda/\Delta\lambda) \int \Phi_P(\lambda)\, d\lambda\ ,$$ **Independent of f**

The integral is over the wavelength band $\Delta\lambda = \lambda_{max} - \lambda_{min}$.

Peak flux theorem

What is "sufficiently long pulse t_{min}"?

- **Irradiation work: ∞**
- **Single (Q,ω) experiments (D3, TAS?): ∞**
- **SANS, NSE: 2 – 4 ms**
- **Reflectometry: 0.5 – 2 ms**
- **Single Xtal diffraction: 100 – 500 μs**
- **Powder diffraction: 5 – 500 μs**
- **Cold neutron spectroscopy: 50 – 2000 μs**
- **Thermal neutron spectroscopy: 20 – 600 μs**
- **Hot neutron spectroscopy: 10 – 300 μs**
- **Electronvolt spectroscopy: 1 – 10 μs**
- **Backscattering spectroscopy: 10 – 100 μs, …**

Rough estimate: $t_{min}/T \sim \delta\lambda/\lambda$

Peak flux theorem

Technical preconditions, enabling technologies:

Advanced neutron guides (low loss at any L for λ>1 Å),

Peak flux theorem

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Repetition Rate Multiplication for TOF Spectroscopy: to allow "reasonable" repetition rates both in diffraction (elastic scattering) and TOF spectroscopy (inelastic scattering) at the same time

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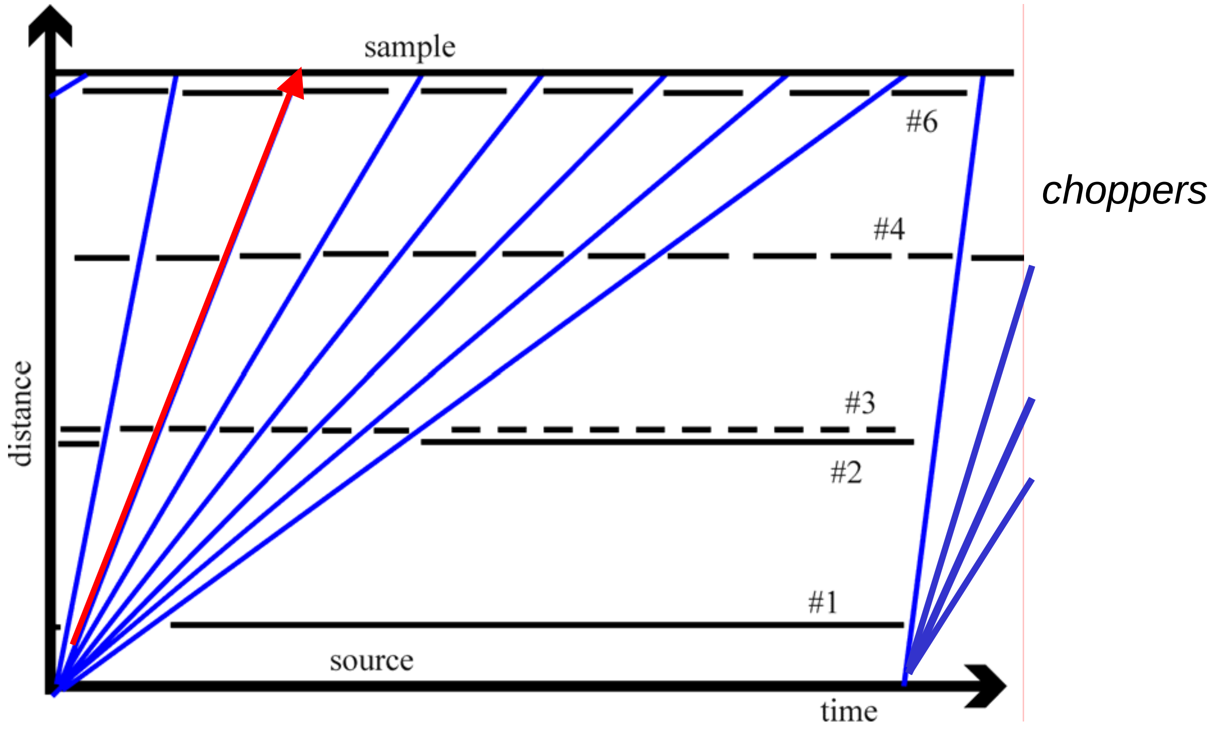

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Pulse shaping: to allow to choose the best pulse length for each application

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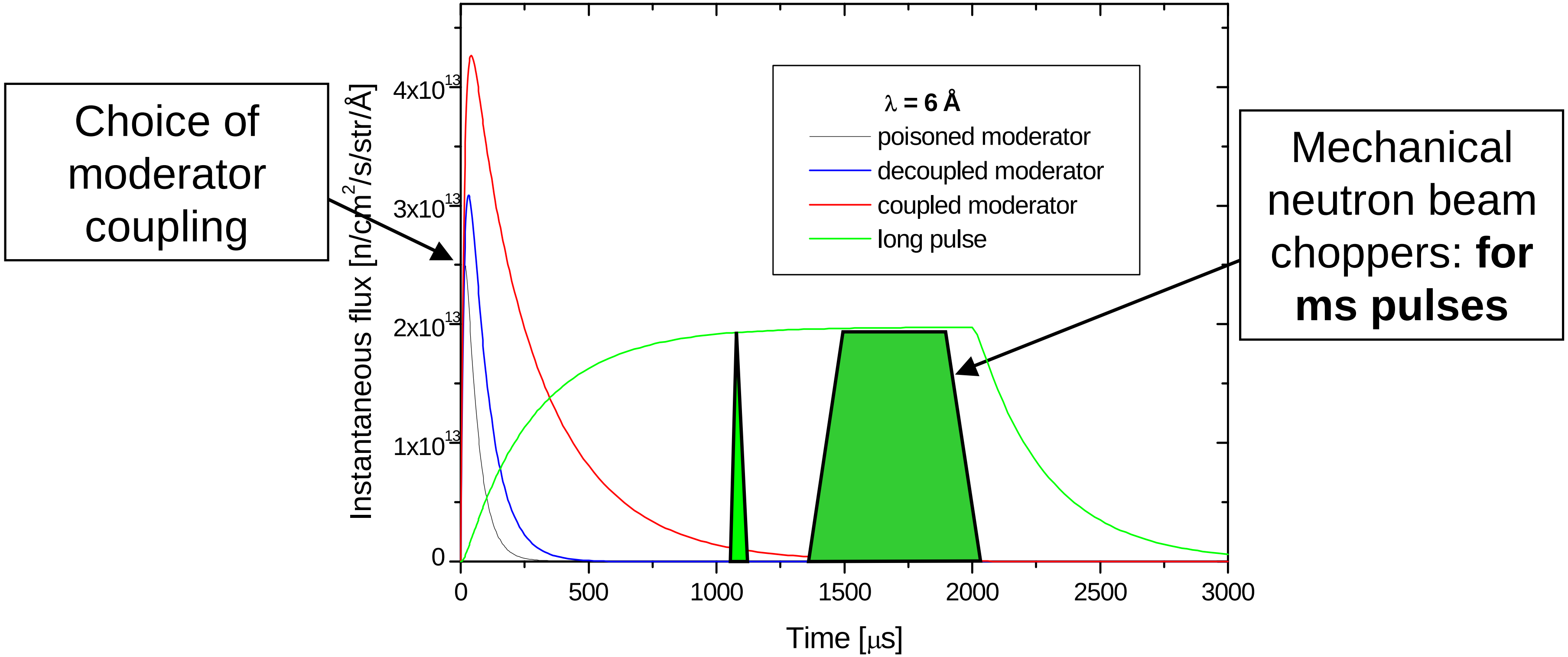

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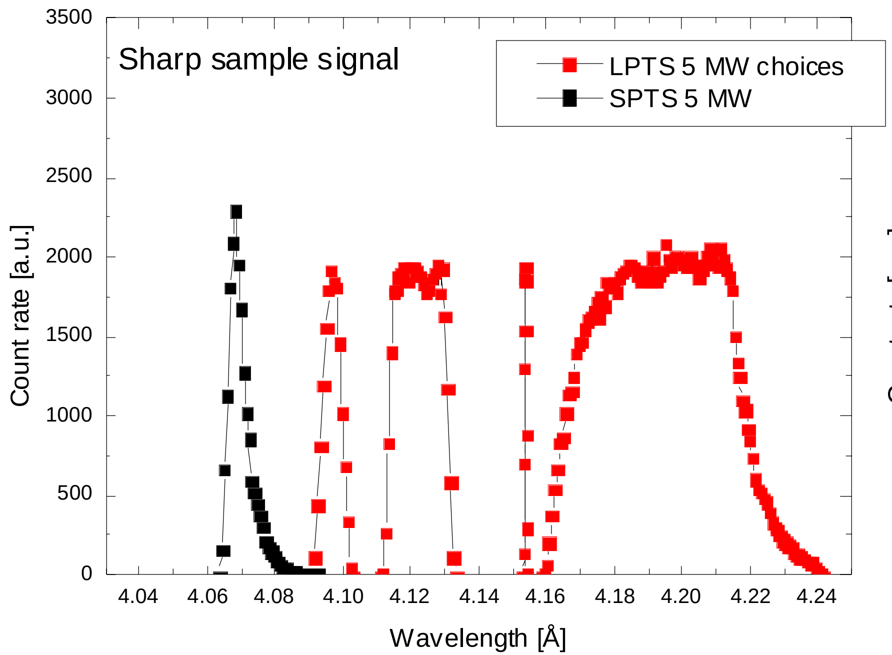
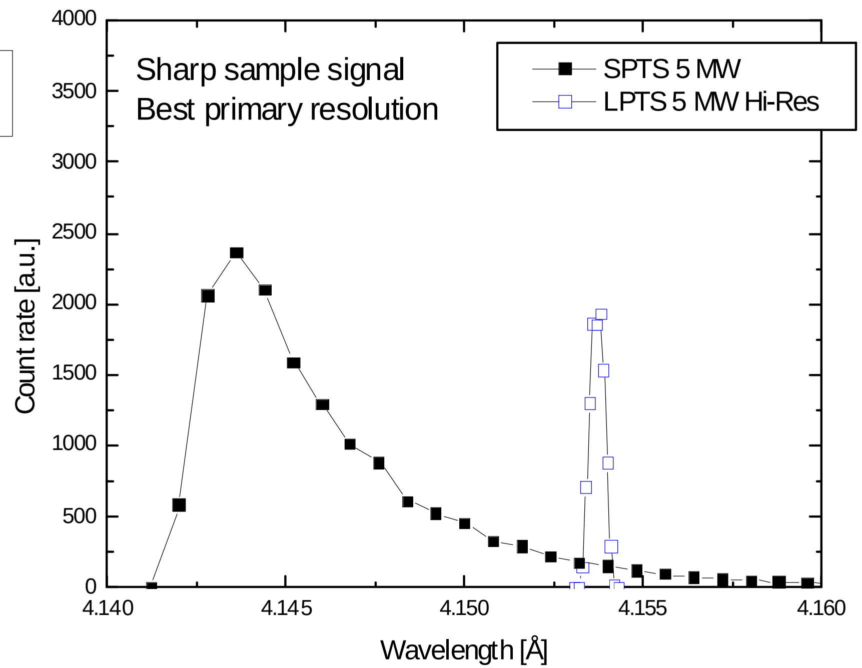
Repetition Rate Multiplication for TOF Spectroscopy

Pulse shaping: to allow to choose the best pulse length in <u>each experiment</u> on the same instrument

E.g. variable resolution powder diffraction: trade intensity ⇔ resolution





Peak flux theorem: resolution of contradictory needs

Technical preconditions, enabling technologies:

Advanced neutron guides (low loss at any L for λ>1 Å): to make the distance L a free parameter

Repetition Rate Multiplication for TOF Spectroscopy: to allow "reasonable" repetition rates both in diffraction (elastic scattering) and TOF spectroscopy (inelastic scattering) at the same time

Pulse shaping: to allow to choose the best pulse length for each application

Engineering reality: guides and choppers work with full efficiency for thermal and cold neutrons only (E < 100 meV)

Peak flux theorem: optimization criteria

Highest peak flux and longest pulses

Ideal solutions are unrealistic:

CW source with infinite brightness

Pulsed source with infinite intensity

Accelerator / target realities vs. instruments

Neutron moderation time

- **lower limit on neutron pulse length** τ
- **peak flux:** $\propto E_p / \tau$
- **decoupled moderators with shorter moderation time are of disproportionately lower efficiency**

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Proton beam energy per pulse E_P technologically limited

- **to < 50 – 100 kj (?) for μs short proton pulses (from rings): $W_{instant} > 50$ GW**
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→ highest time average flux requires long pulses

→ highest peak flux is achieved by long pulses for moderation times > 50 – 100 μs (thermal & cold neutrons)

Long pulse approach

Optimized spallation neutron source:

Maximum peak proton beam power in ms pulses

Possible (optimistic?) parameters for H^+ only linear accelerator:

3 GeV, 150 mA proton beam
2 ms pulses
20 Hz repetition rate → 18 MW beam power

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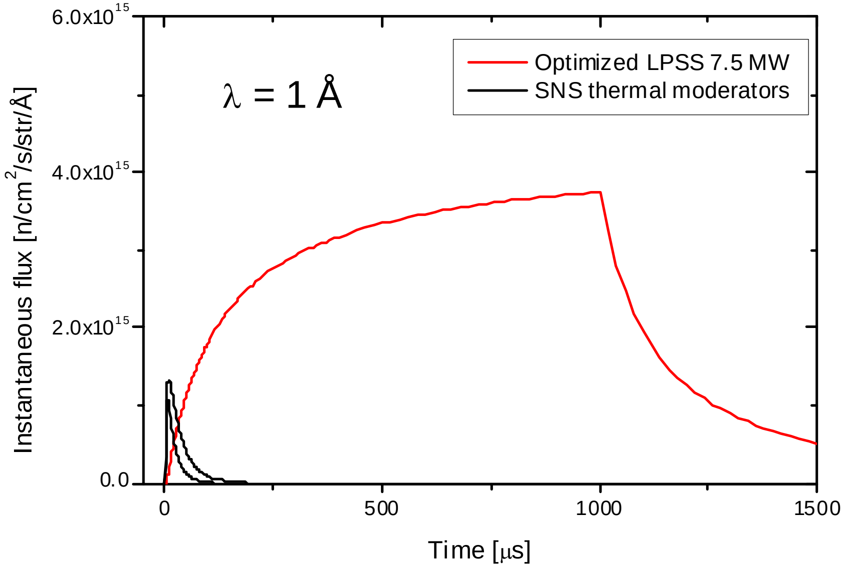
Compromise options to lower power:

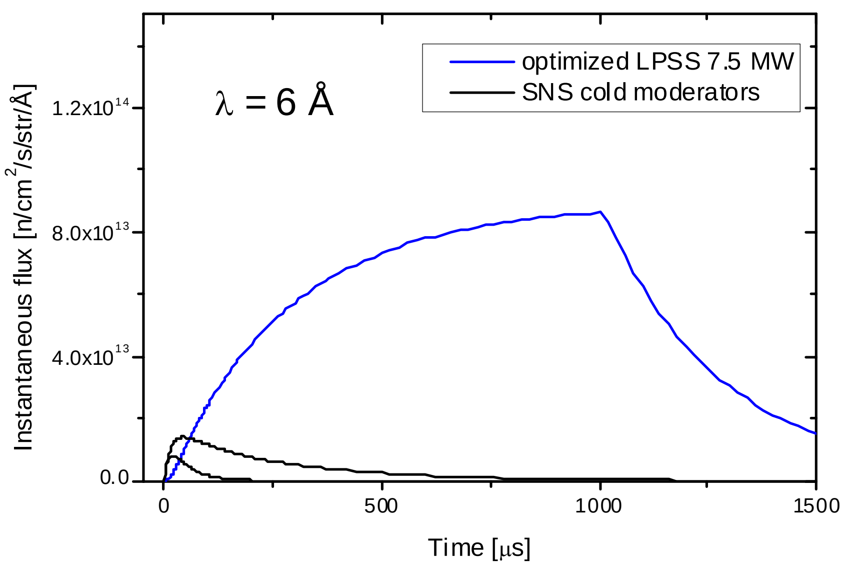
- **shorter pulses: lower performance for low resolution, cold neutron work**
- **lower repetition rate: lower thermal neutron performance**
- **lower peak power: all applications affected**

Long pulse approach

Optimized long pulse sources can produce not only higher time average, but also higher peak flux than short pulses in the cold and thermal neutron range (above 3 and 6 times higher energy/pulse, respectively).

Example: 450 kj/pulse long pulses, vs 23 kj/pulse short pulse (SNS at 1.4 MW):





Long pulses: highest cold and thermal neutron peak flux at given costs

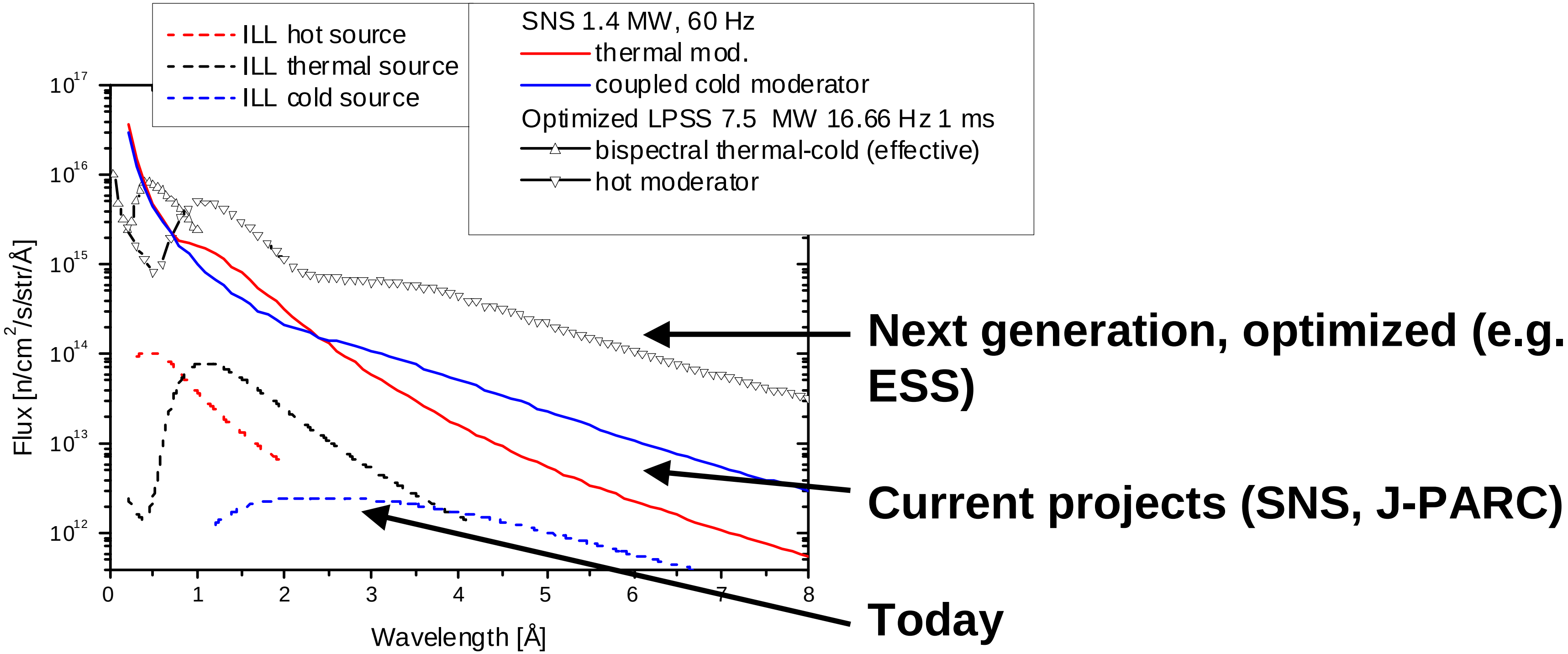
Optimized approach

Long pulses: optimum for thermal and cold neutrons (~90 % of condensed matter research)

Short pulses: superior for $\lambda < 0.4 – 0.9$ Å.

Long (enough) pulses: performance scales with peak flux

Short pulses: performance $\leq$ peak flux



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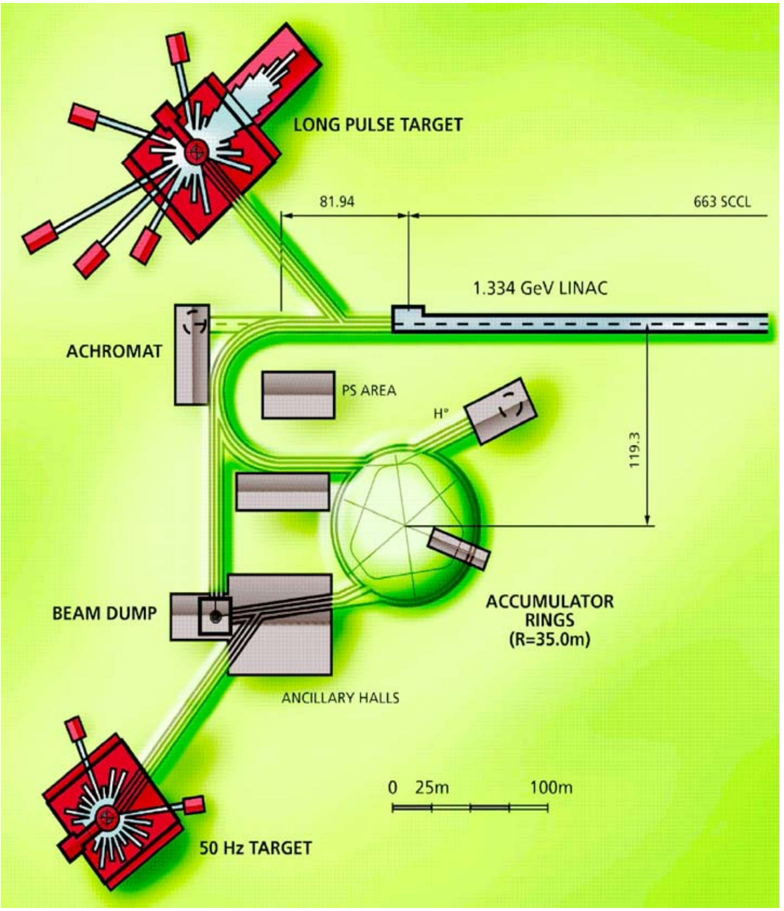

European Spallation Source project: combine both capabilities

Optimized approach

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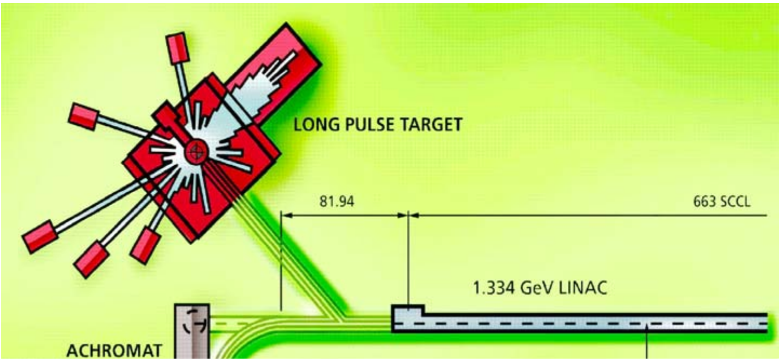


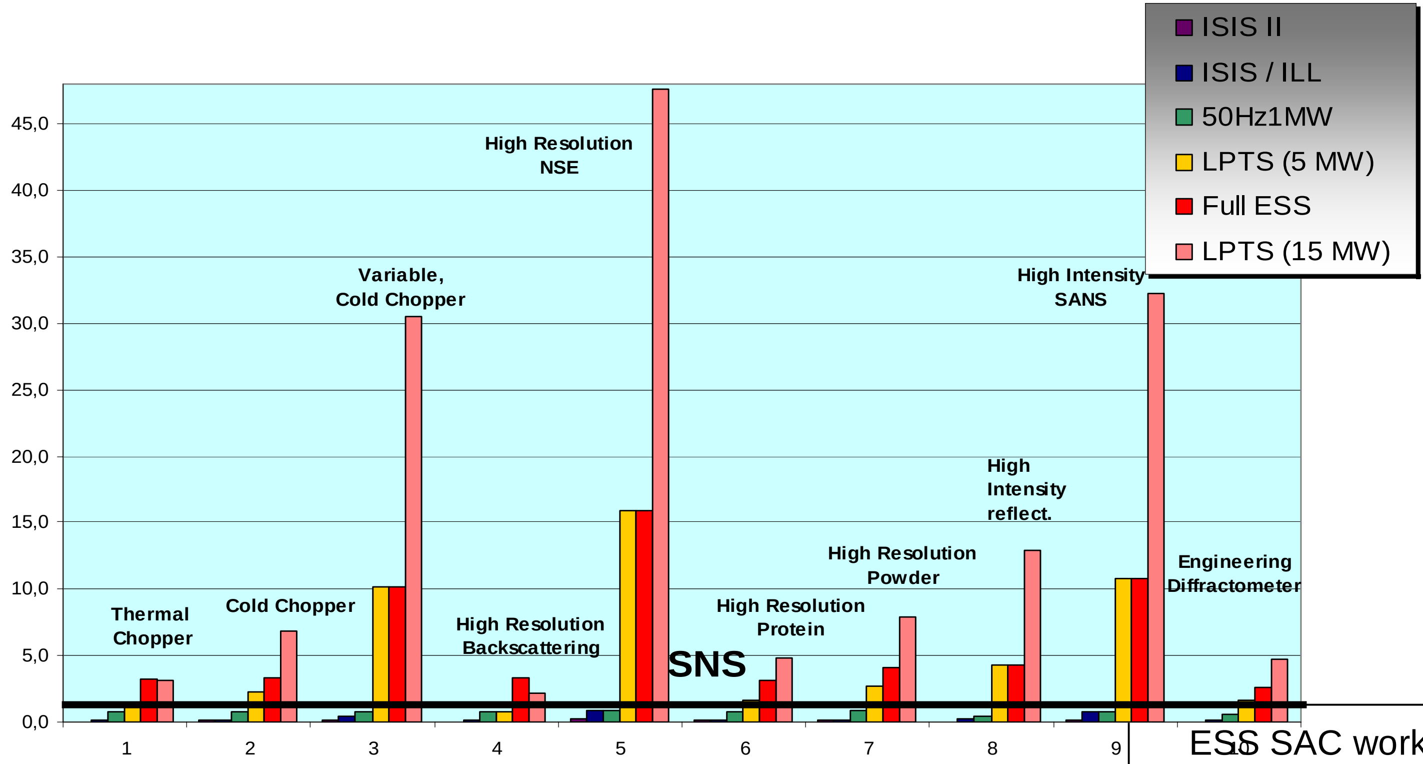
European Spallation Source staged realization plan:
(Sweden, UK, Hungary,..??)

Long pulse only:
- much simpler technically
- easier to operate
- most cost effective

Later upgrade options:
- add short pulse station, *if there still worldwide need (SNS, J-PARC, ILL)*
- enhance long pulse power

Conclusion

Optimized spallation sources: orders of magnitude enhanced research opportunities in condensed matter research by neutron scattering.



ESS SAC workshop, 0ct 2002 for ESFRI report