Neutron sources

CETS Neutron School
May. 23, 2023

F. Mezei
BNC

Neutrons in nature: extracted from nuclei, needs energy
(e.g. cosmic radiation, ...)

Fast neutrons produced / joule heat deposited:

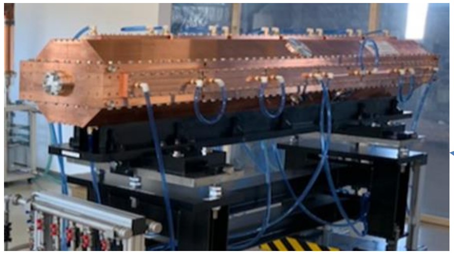
	Fission reactors:	**3**x**10^{10}**	(in ~ 50 liter volume)
→	Spallation (> 400 MeV):	**2**x**10^{11}**	(in ~ 2 liter volume)
	Fusion:	**4x10^{11}**	(in ~ 2 liter volume)
	(but neutron slowing down efficiency reduced by ~20 times)		
	Electron accel.: (50 MeV)	**2x10^{9}**	(in ~ 0.01 liter volume)
→	Low energy p.: (5 MeV):	**2x10^{8}**	(in ~ 0.001 liter volume)
	(100 MeV):	**2x10^{9}**	(in ~ 0.01 liter volume)
	Neutron generators:		
	tabletop fusion	~ **10^{6}**	(in ~ 10^{-5} liter volume)

Spallation: lowest costs per neutron

Compact source: lowest costs per facility

Neutron production: energy deposited in atomic nuclei → fast neutrons

Economy of fast neutron production by accelerated protons



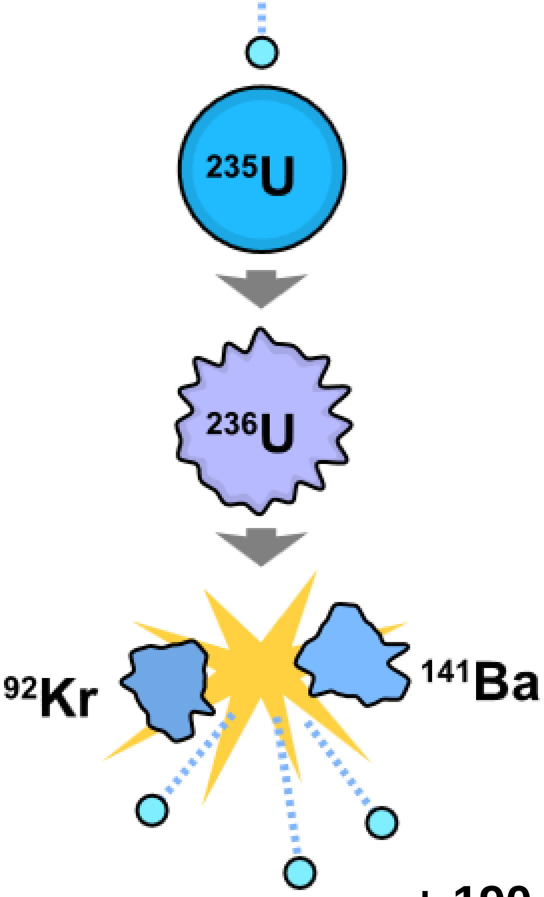
Compact neutron source

Advanced neutron source

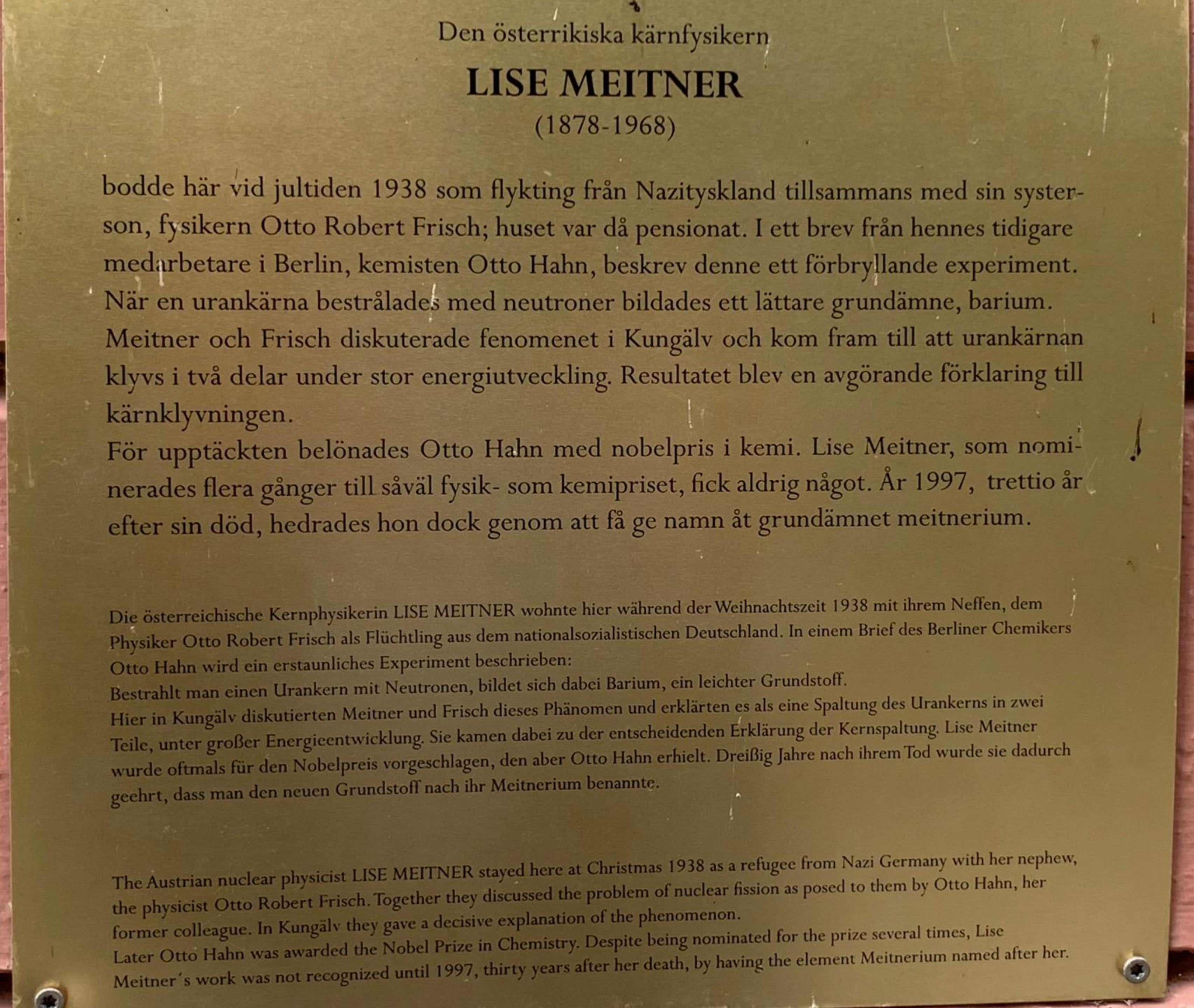
Proton energy (MeV) (MeV)	Target	p beam energy/fast neutron created
2	Li	100 000
5	Li	10 000
10	Li	6 200
25	Be	3 900
50	Be	1 900
100	Be	1 000
200	Ta	700
400	W	60
1300	W	25

Cf. ^{235}U fission in reactors 190

Nuclear fission (1938)
(O. Hahn, L. Meitner, O. Frisch)



+ 190 MeV



Den österrikiska kärnfysikern

LISE MEITNER

(1878-1968)

bodde här vid jultiden 1938 som flykting från Nazityskland tillsammans med sin systerson, fysikern Otto Robert Frisch; huset var då pensionat. I ett brev från hennes tidigare medarbetare i Berlin, kemisten Otto Hahn, beskrev denne ett förbryllande experiment. När en urankärna bestrålades med neutroner bildades ett lättare grundämne, barium. Meitner och Frisch diskuterade fenomenet i Kungälv och kom fram till att urankärnan klyvs i två delar under stor energiutveckling. Resultatet blev en avgörande förklaring till kärnklyvningen.

För upptäckten belönades Otto Hahn med nobelpris i kemi. Lise Meitner, som nominerades flera gånger till såväl fysik- som kemipriset, fick aldrig något. År 1997, trettio år efter sin död, hedrades hon dock genom att få ge namn åt grundämnet meitnerium.

Die österreichische Kernphysikerin LISE MEITNER wohnte hier während der Weihnachtszeit 1938 mit ihrem Neffen, dem Physiker Otto Robert Frisch als Flüchtling aus dem nationalsozialistischen Deutschland. In einem Brief des Berliner Chemikers Otto Hahn wird ein erstaunliches Experiment beschrieben:

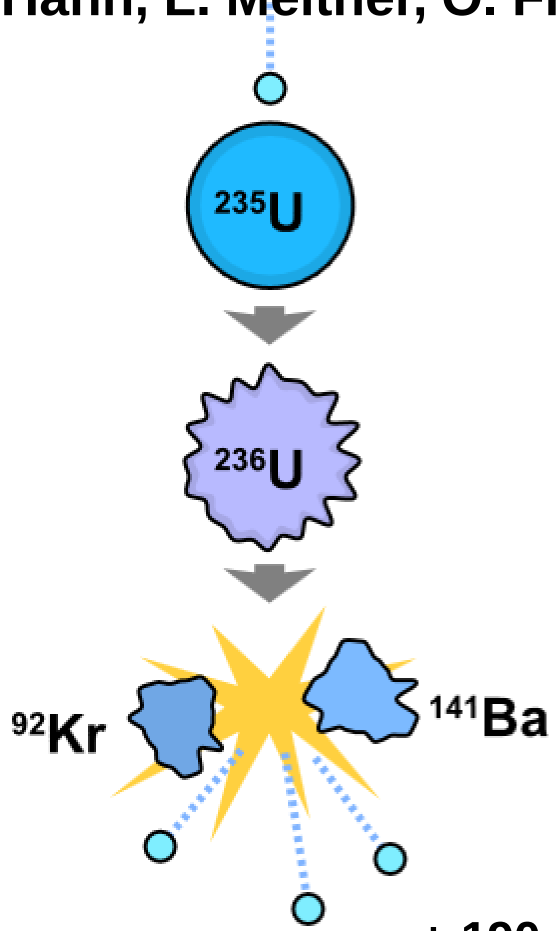
Bestrahlt man einen Urankern mit Neutronen, bildet sich dabei Barium, ein leichter Grundstoff.

Hier in Kungälv diskutierten Meitner und Frisch dieses Phänomen und erklärten es als eine Spaltung des Urankerns in zwei Teile, unter großer Energieentwicklung. Sie kamen dabei zu der entscheidenden Erklärung der Kernspaltung. Lise Meitner wurde oftmals für den Nobelpreis vorgeschlagen, den aber Otto Hahn erhielt. Dreißig Jahre nach ihrem Tod wurde sie dadurch geehrt, dass man den neuen Grundstoff nach ihr Meitnerium benannte.

The Austrian nuclear physicist LISE MEITNER stayed here at Christmas 1938 as a refugee from Nazi Germany with her nephew, the physicist Otto Robert Frisch. Together they discussed the problem of nuclear fission as posed to them by Otto Hahn, her former colleague. In Kungälv they gave a decisive explanation of the phenomenon.

Later Otto Hahn was awarded the Nobel Prize in Chemistry. Despite being nominated for the prize several times, Lise Meitner´s work was not recognized until 1997, thirty years after her death, by having the element Meitnerium named after her.

Nuclear fission (1938)
(O. Hahn, L. Meitner, O. Frisch)



+ 190 MeV

Chain reaction (L. Szilárd 1934)

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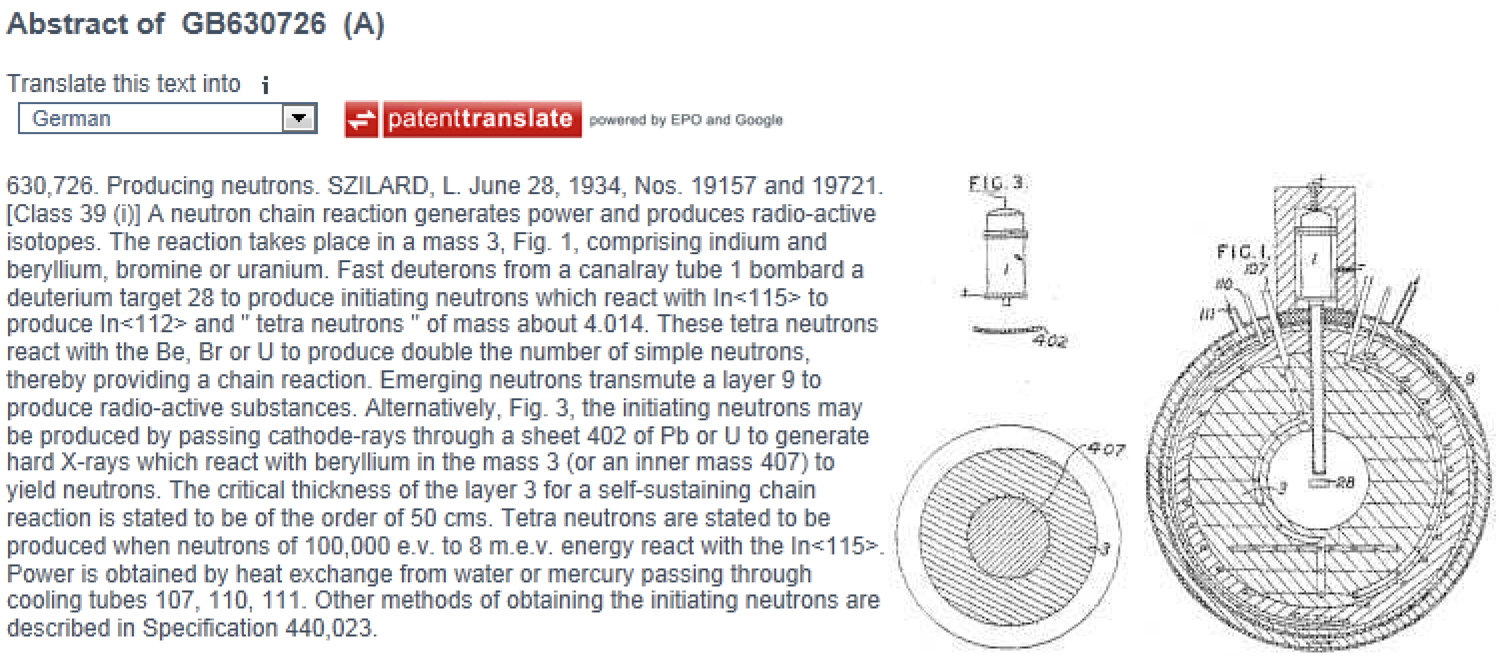


Abstract of GB630726 (A)

Translate this text into

630,726. Producing neutrons. SZILARD, L. June 28, 1934, Nos. 19157 and 19721. [Class 39 (i)] A neutron chain reaction generates power and produces radio-active isotopes. The reaction takes place in a mass 3, Fig. 1, comprising indium and beryllium, bromine or uranium. Fast deuterons from a canalray tube 1 bombard a deuterium target 28 to produce initiating neutrons which react with In<115> to produce In<112> and " tetra neutrons " of mass about 4.014. These tetra neutrons react with the Be, Br or U to produce double the number of simple neutrons, thereby providing a chain reaction. Emerging neutrons transmute a layer 9 to produce radio-active substances. Alternatively, Fig. 3, the initiating neutrons may be produced by passing cathode-rays through a sheet 402 of Pb or U to generate hard X-rays which react with beryllium in the mass 3 (or an inner mass 407) to yield neutrons. The critical thickness of the layer 3 for a self-sustaining chain reaction is stated to be of the order of 50 cms. Tetra neutrons are stated to be produced when neutrons of 100,000 e.v. to 8 m.e.v. energy react with the In<115>. Power is obtained by heat exchange from water or mercury passing through cooling tubes 107, 110, 111. Other methods of obtaining the initiating neutrons are described in Specification 440,023.

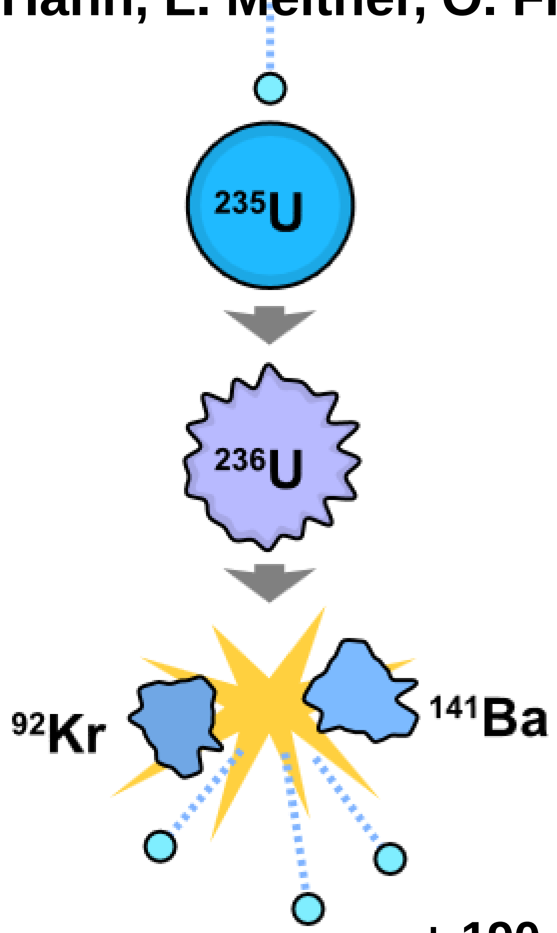
→ **nuclear weapons**

Secret patent: Szilárd delays nuclear arms race

→ **research reactors**

→ **nuclear energy**

Nuclear fission (1938)
(O. Hahn, L. Meitner, O. Frisch)



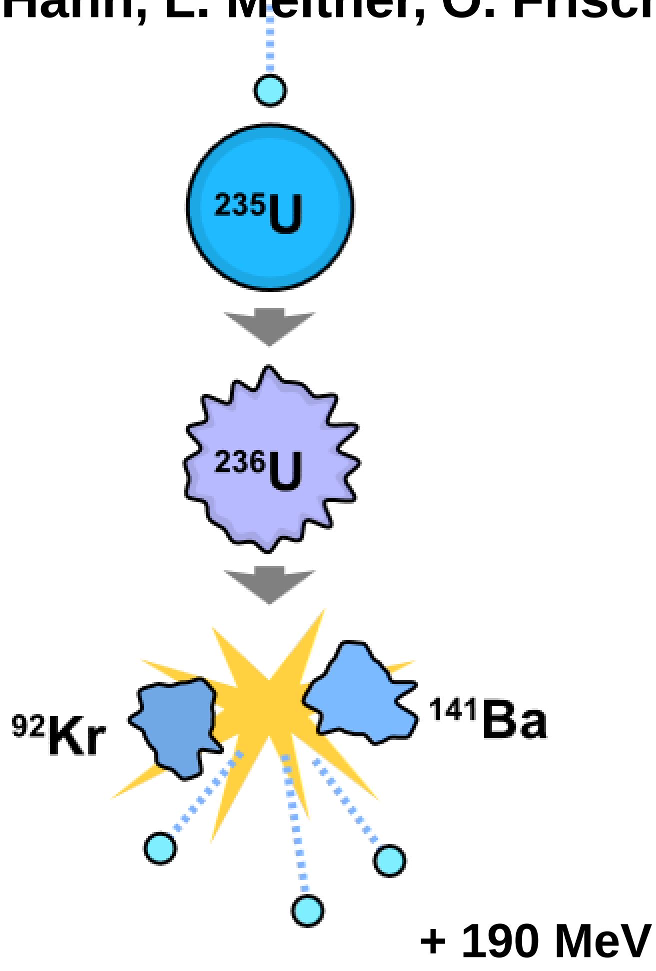
+ 190 MeV

Chain reaction (L. Szilárd 1934)

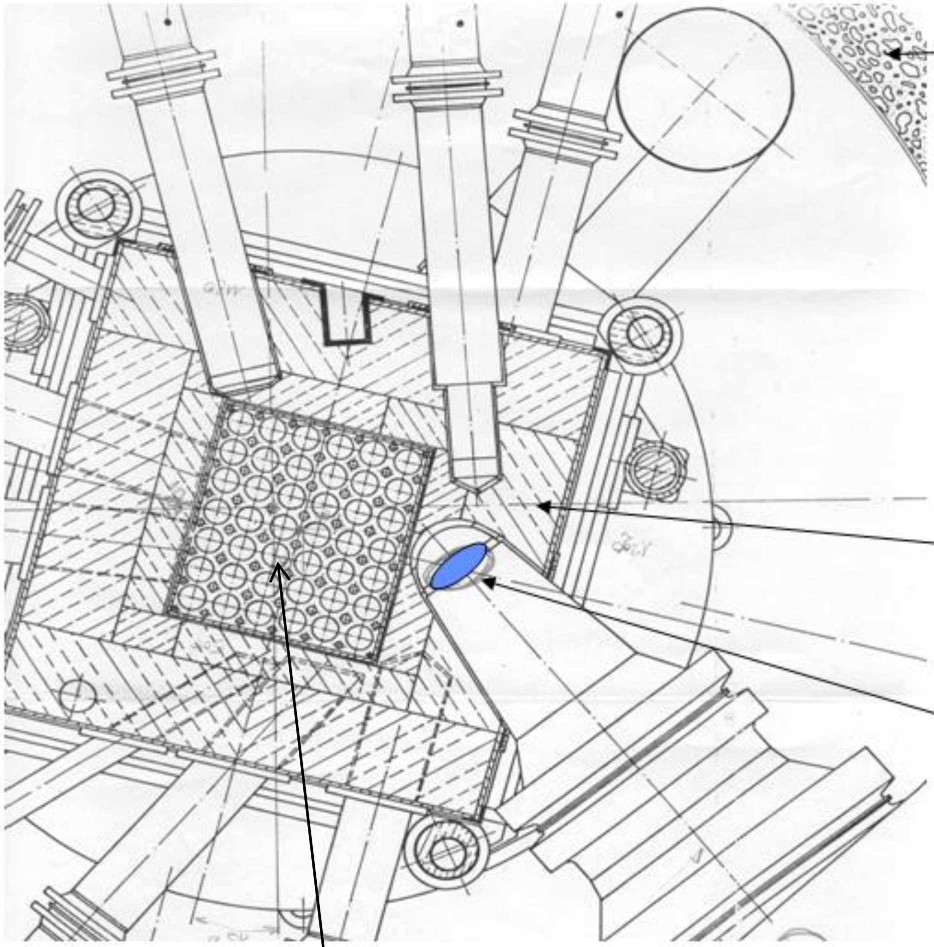
E. P. Wigner: nuclear reactors

A. Weinberg: beam tubes in reactors

Nuclear fission
(O. Hahn, L. Meitner, O. Frisch)



Chain reaction (L. Szilárd 1934)



Shielding: ø 10 - 12 m

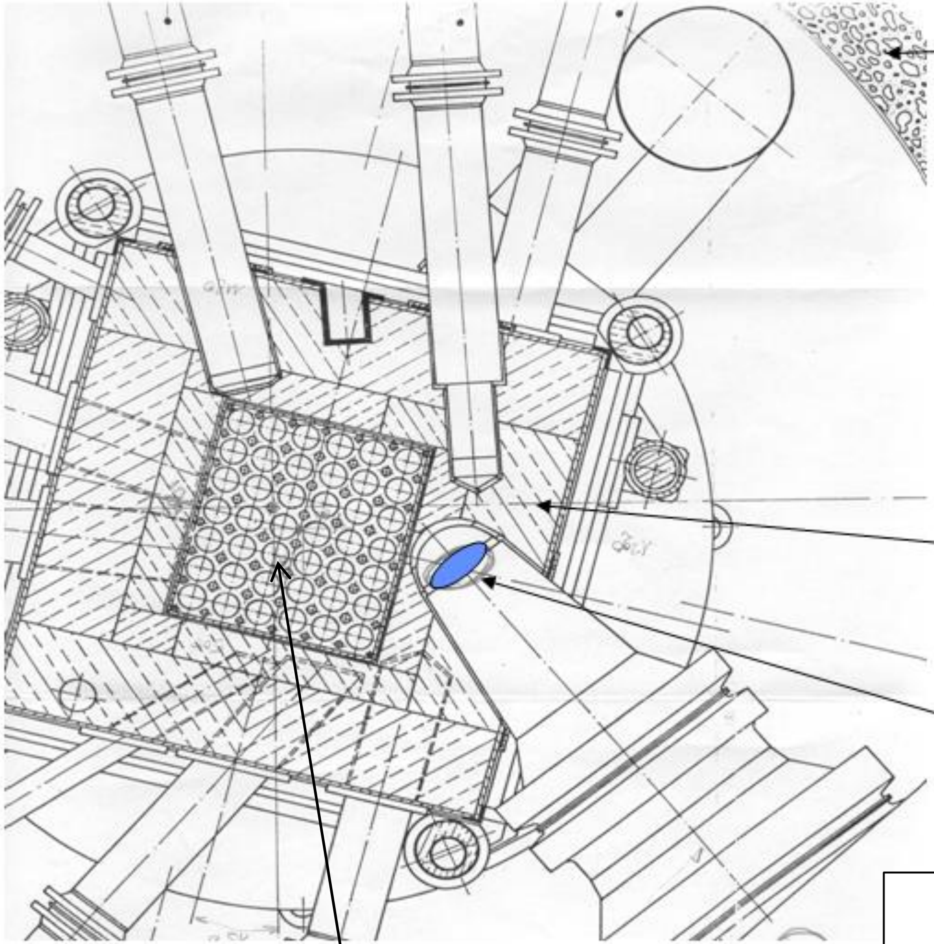
Example of a fission reactor (HMI)

Thermal neutron source (Be reflector)

Cold neutron source (liquid H_2 bottle)

Fission fuel: enriched ^{235}U

Example of a fission reactor (HMI)

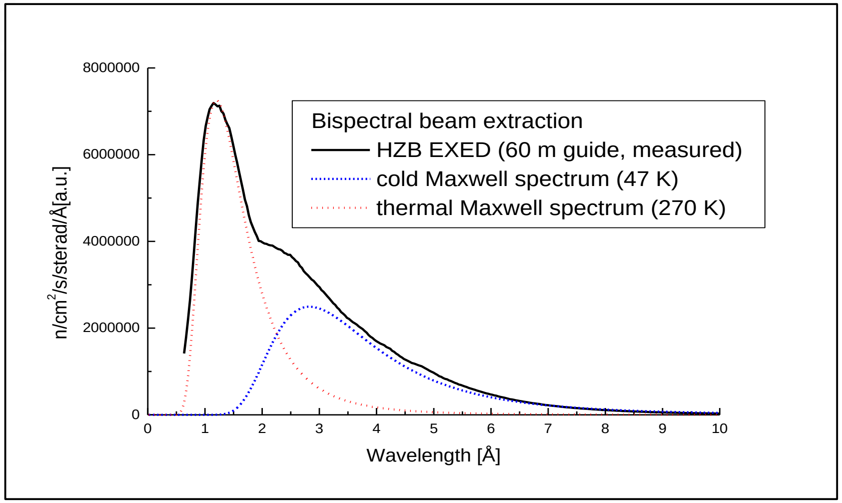


Shielding: ø 10 - 12 m

Thermal neutron source (Be reflector)

Cold neutron source (liquid H_2 bottle)

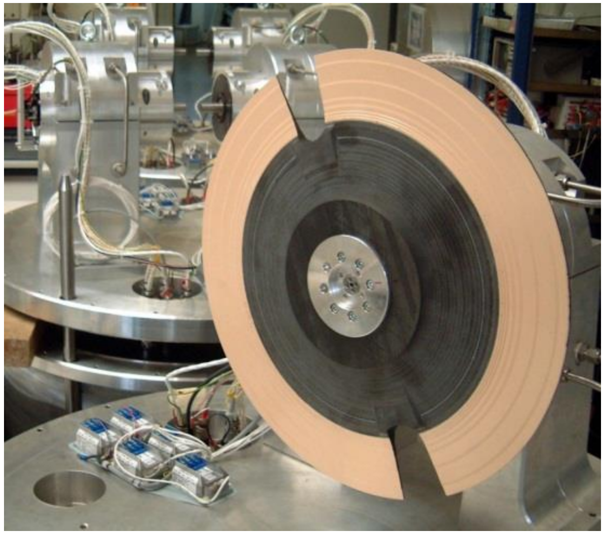
Fission fuel: enriched ^{235}U
Low (<20 %) vs. high enrichment
Plutonium in waste
Neutrons for waste transmutation

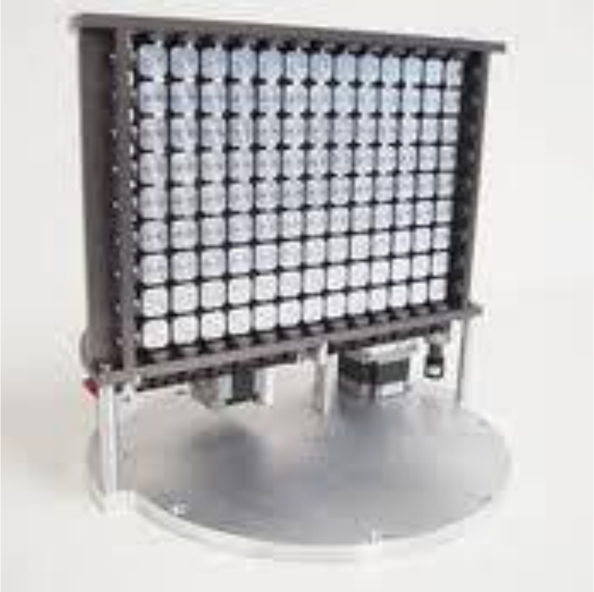


Neutron monochromatization – analysis

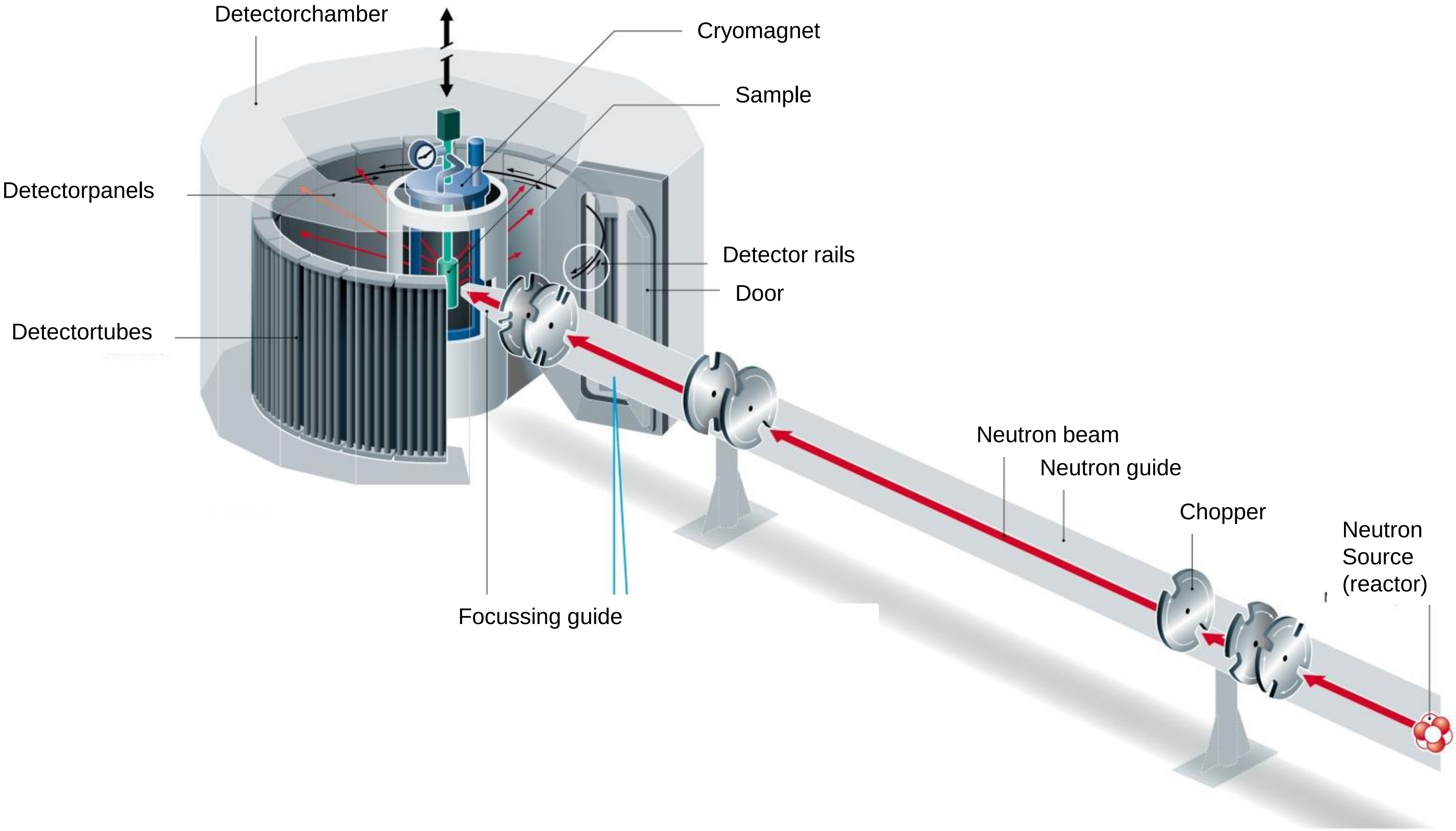
- **Mechanical chopper devices**

- **Crystals – select desirable wavelength**





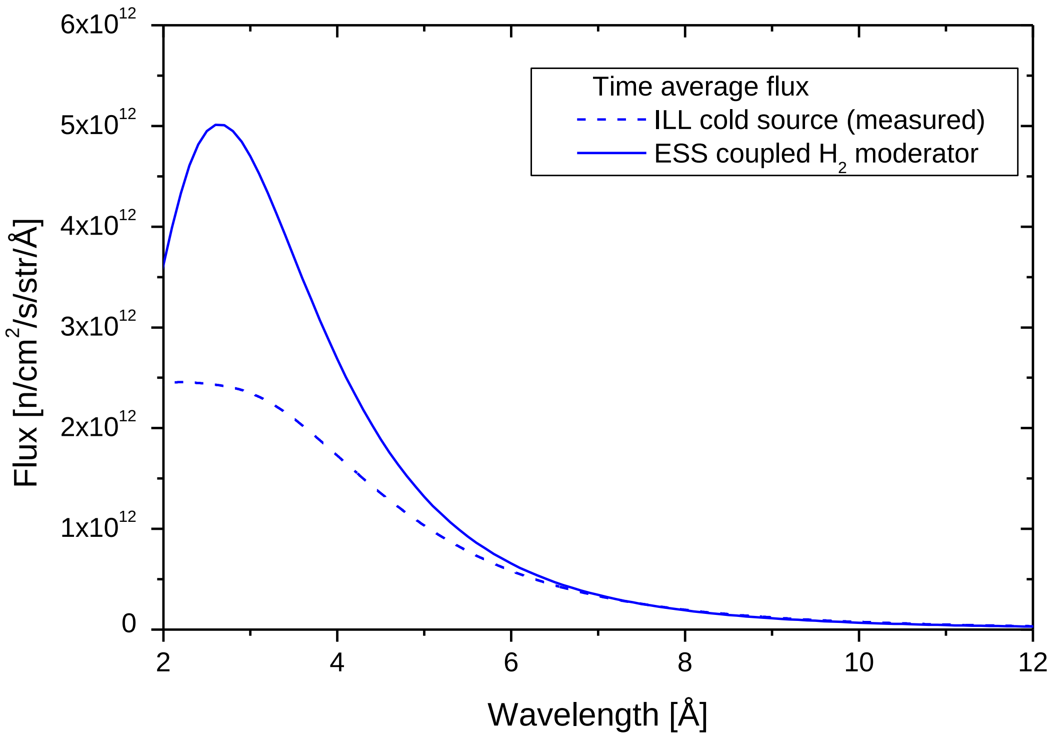
Neutron monochromatization - analysis



Efficiency gain by pulsed neutron sources

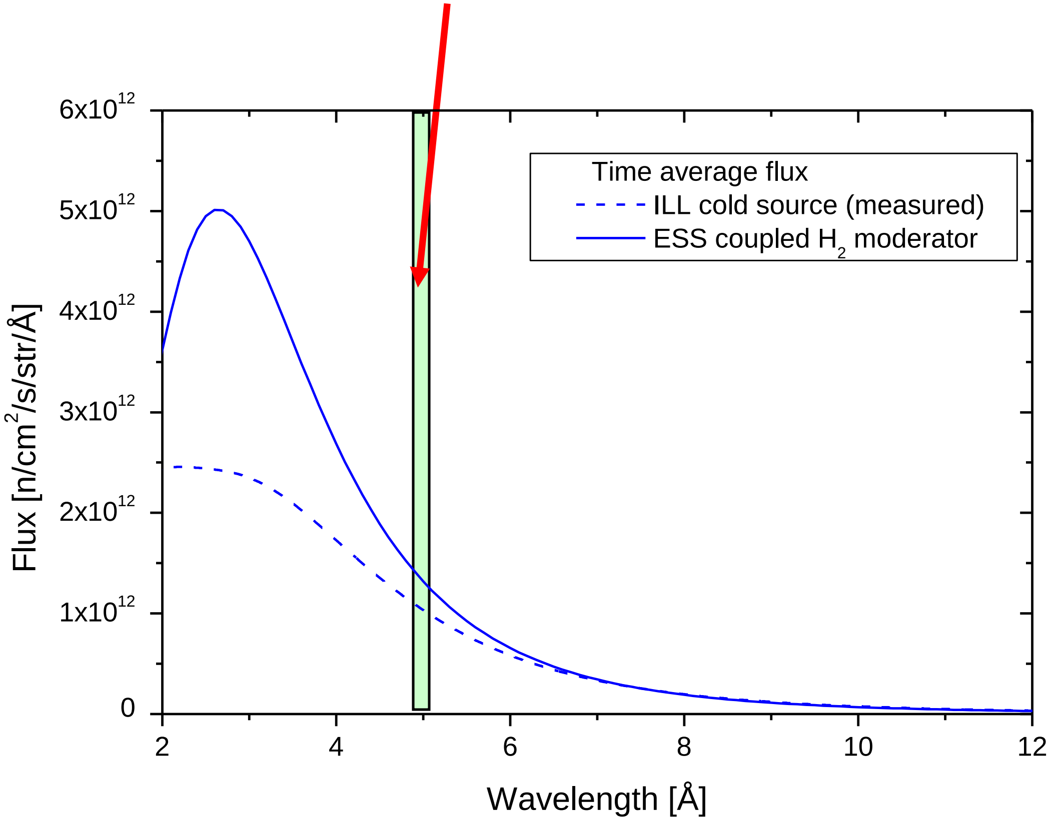
5 MW spallation source:

coupled cold moderator flux ~ ILL cold source



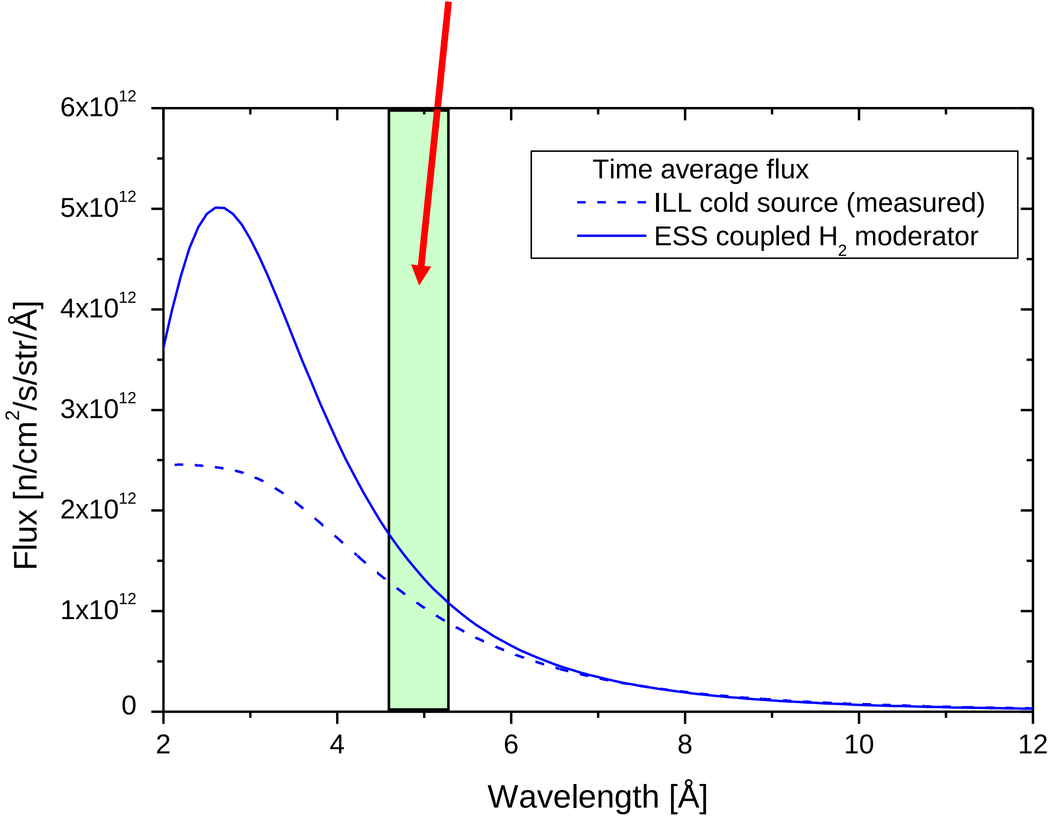
Part of spectrum used by a diffractometer for large structures (e.g. biological membranes)

continuous source



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

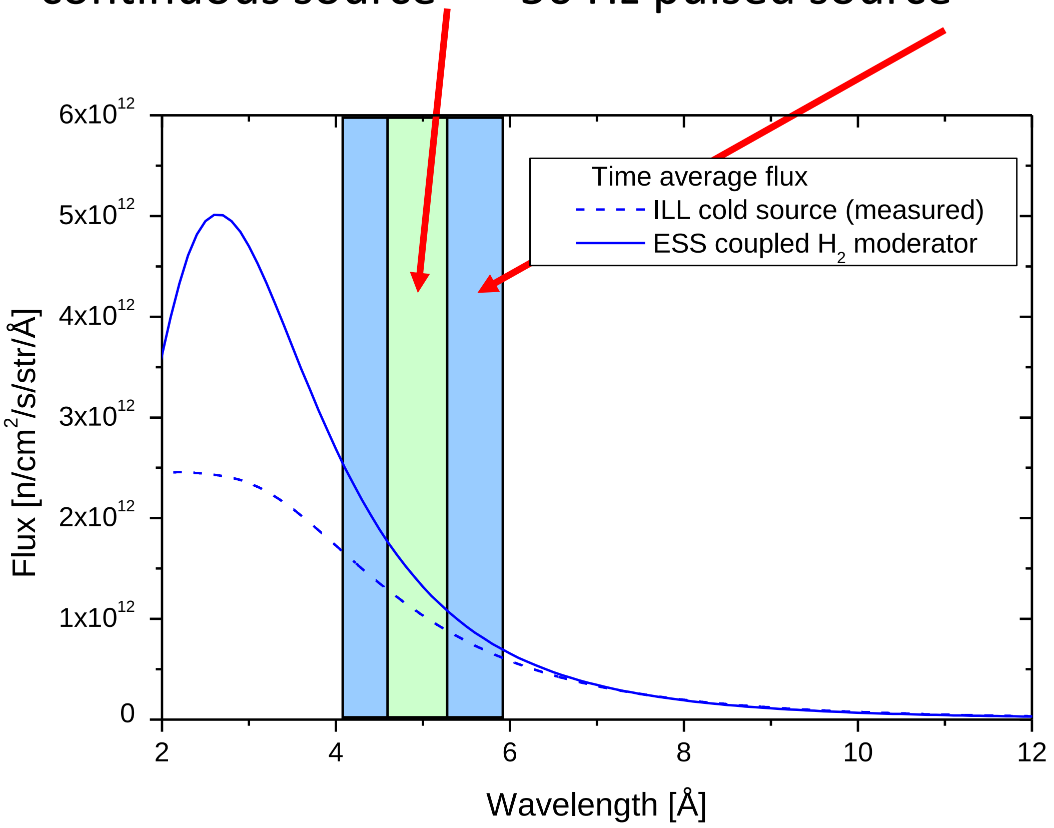
continuous source



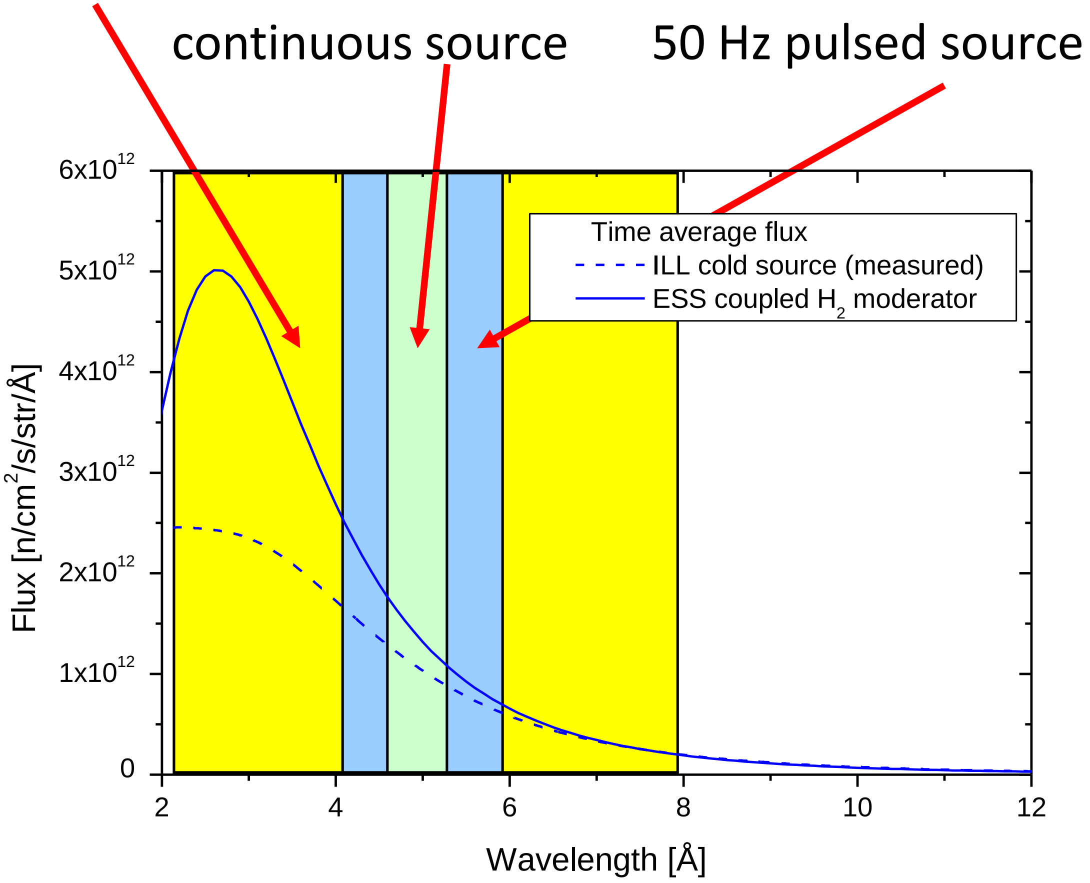
Part of spectrum used by a SANS instrument

continuous source

50 Hz pulsed source



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



14 Hz pulsed source

continuous source

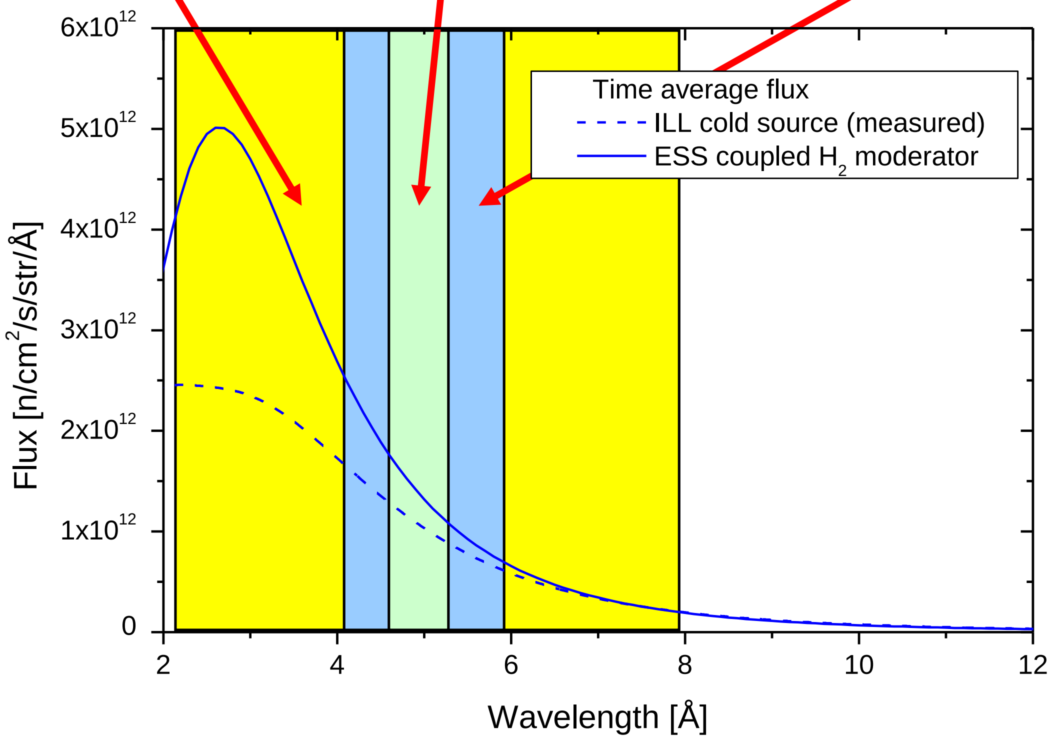
50 Hz pulsed source

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

14 Hz pulsed source

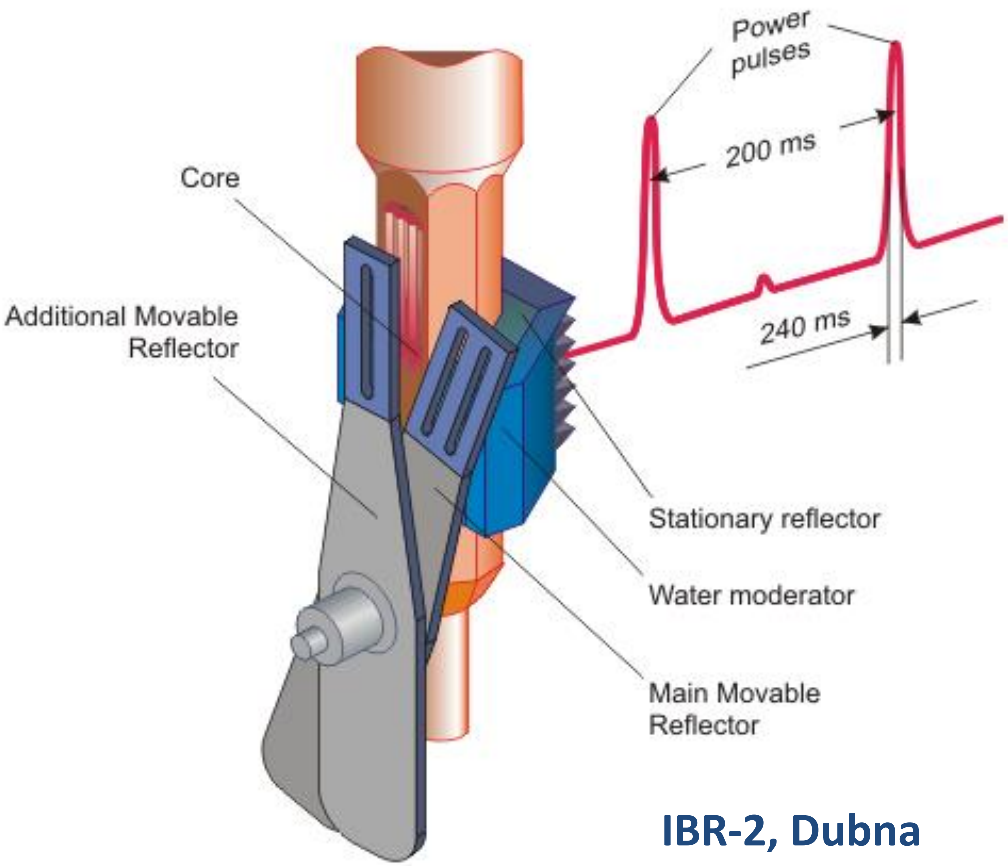
continuous source

50 Hz pulsed source



Efficiency gain by pulsing: **≈ δλ/λ ~8-100**

Neutron production economy: pulsed reactor



IBR-2, Dubna

Time average power:
2 MW

Peak power in pulse:
850 MW

Great fuel economy!

Pulsed reactor source

Long pulse reactor: Dubna >2030, 15 MW, ~0.5 ms pulses
~ 5 Hz → peak flux 100 x ILL

Sate-of-the-art: short pulse spallation sources

SNS (Oak Ridge, USA)

J-PARC (Tokai Japan)

Instantaneous power on target (e.g. 1 MW at 60 Hz, i.e. 17 kj in ~1 μs pulses on target): **17 x**

→ **Pressure wave: 300 bar**

Reaches limits of technology

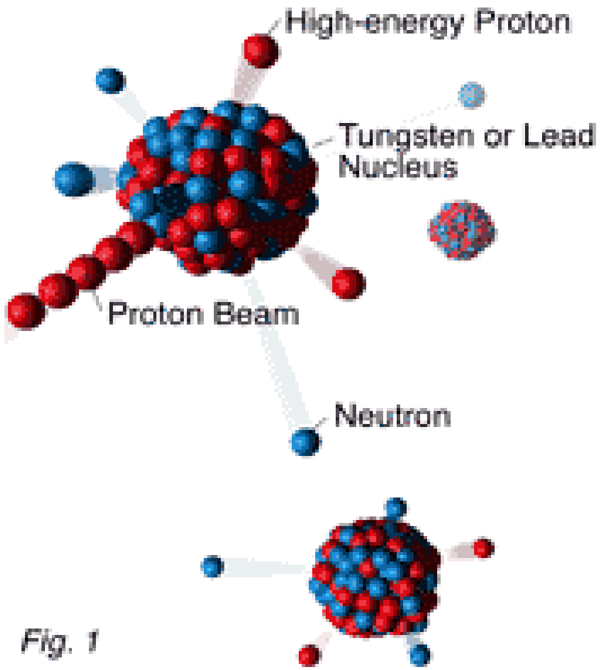
Production of slow neutrons: the "source"

Two step process in the target station

A) Series of nuclear reactions:

spallation → fast neutrons

~100 billion °C



Time: **<< 1 µs**

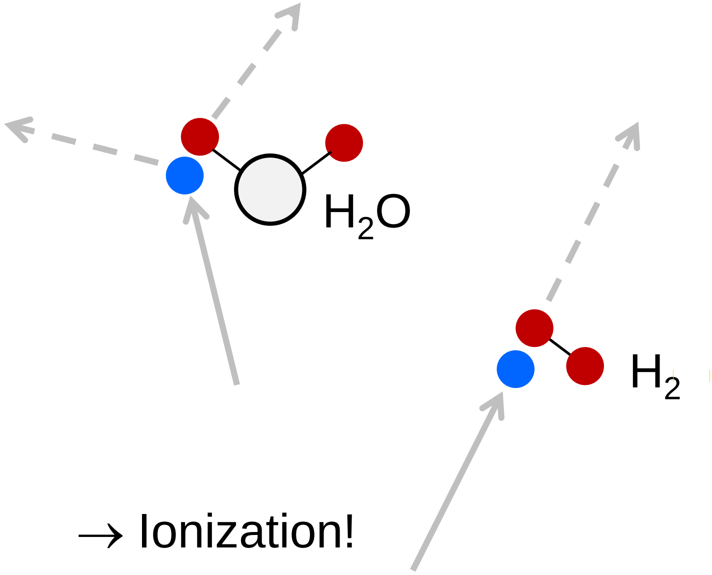
B) Collisions with H atoms:

moderation → slow neutrons

"Hot": ~ 2000 °C

"Thermal": ~ 20 °C

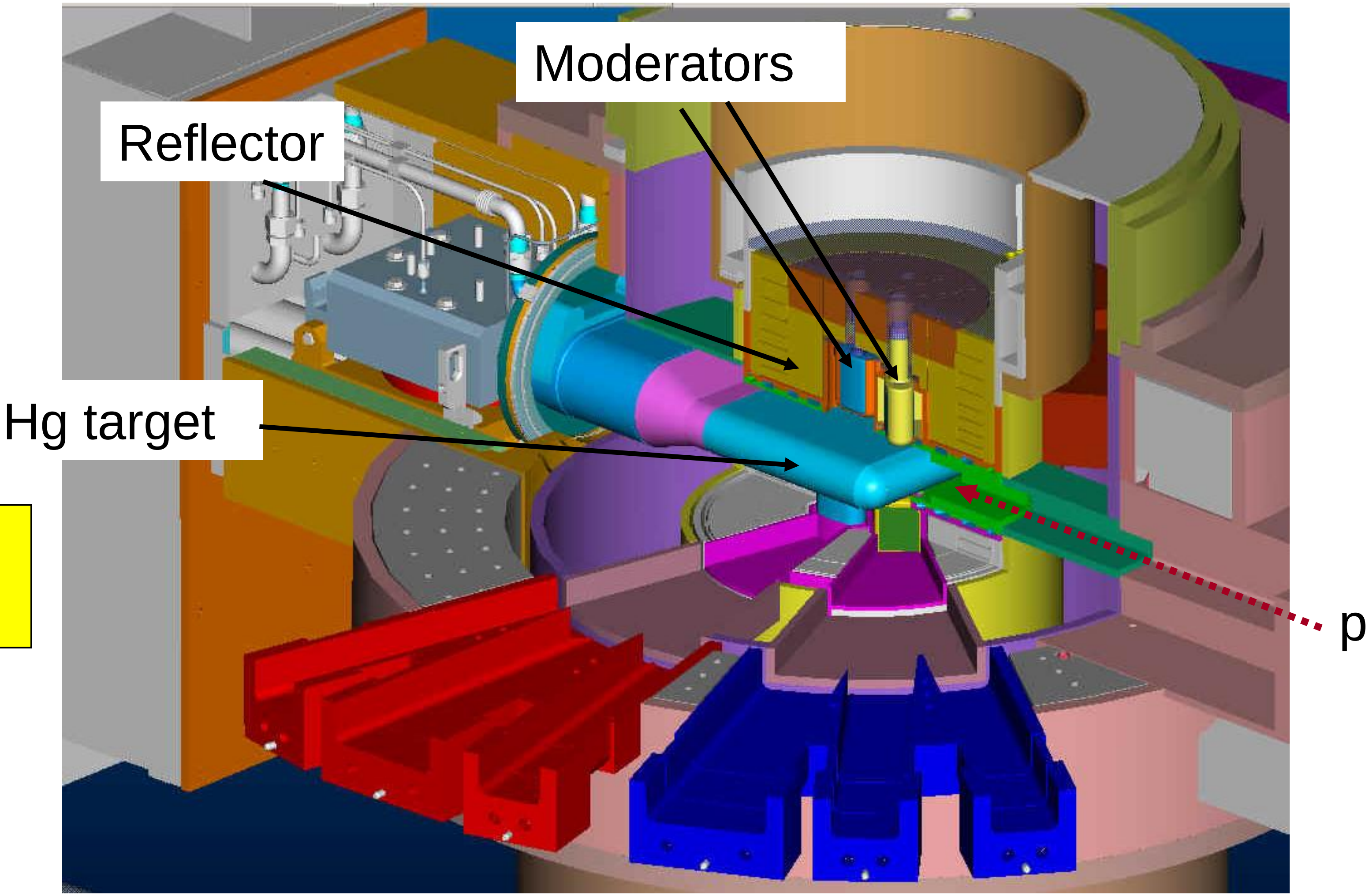
"Cold": ~ -220 °C ≈ 50 K ≈ 1000 m/s



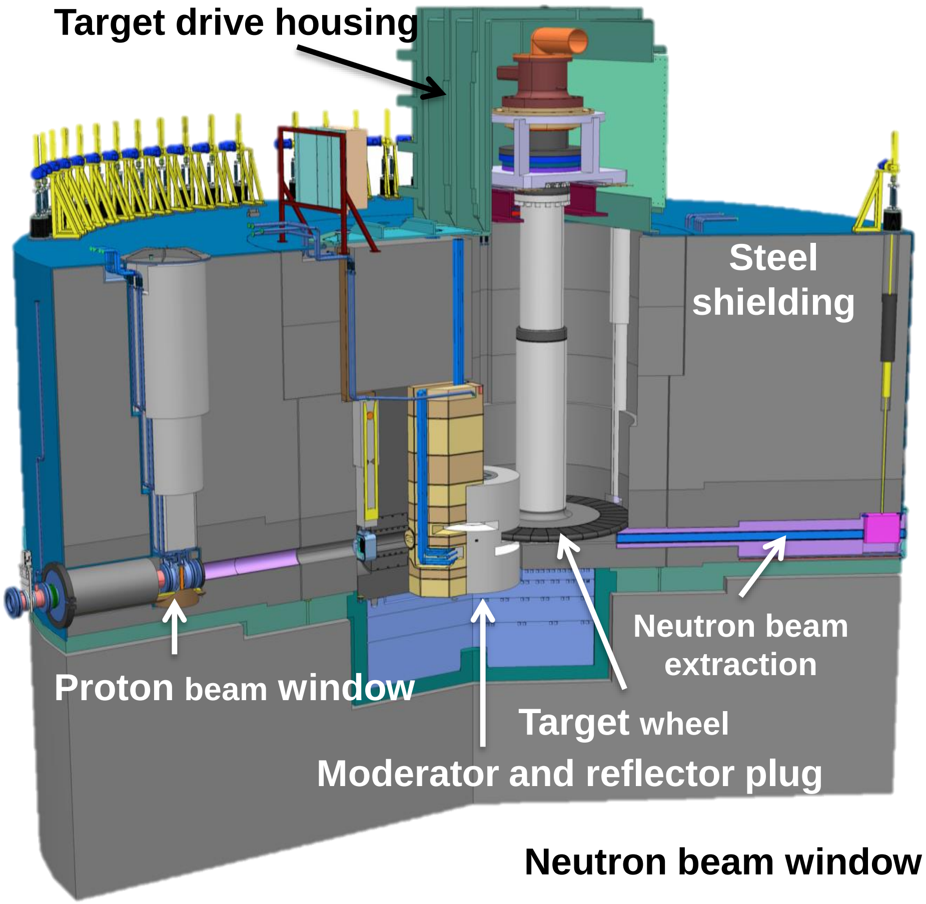
→ Ionization!

10 – 500 µs

State-of-the-art spallation target (SNS)



He gas:
~ 1 bar



Functions:

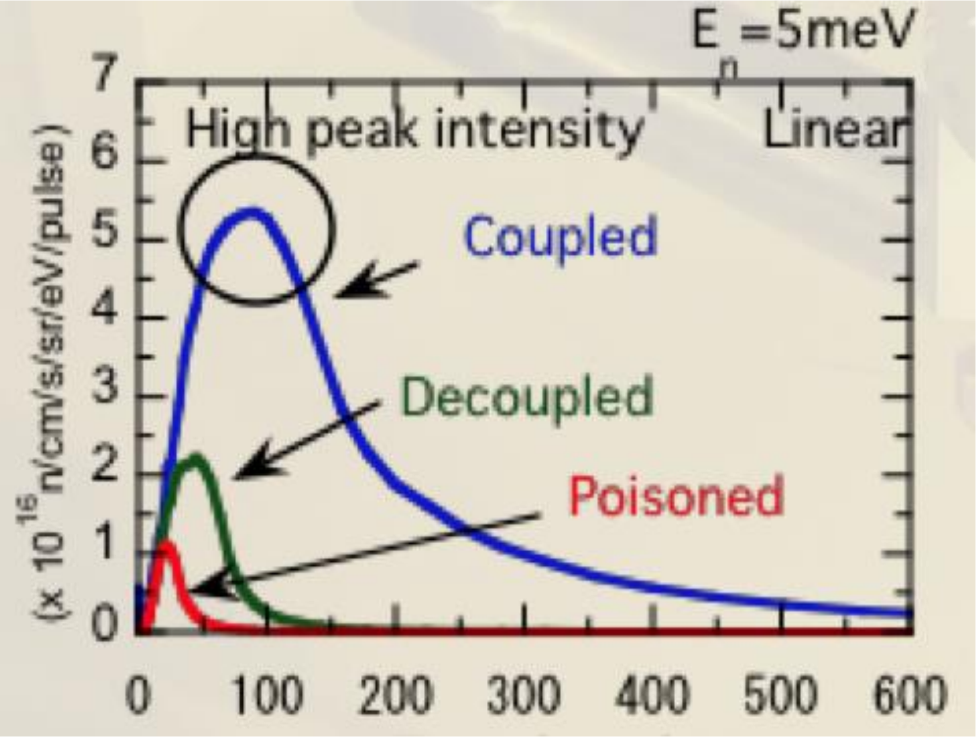
- Convert protons to neutrons
- Heat removal
- Confinement and shielding

Unique features:

- Rotating target
- He-cooled W target

Safety of public, staff, environment ↔ cost & schedule

Example: **accidents with probability > 1 in 1 million years and > 1 in 10 000 years → effect on public must be less than 4 years of natural radiation in Sweden. Includes > 6 scale earthquake.**

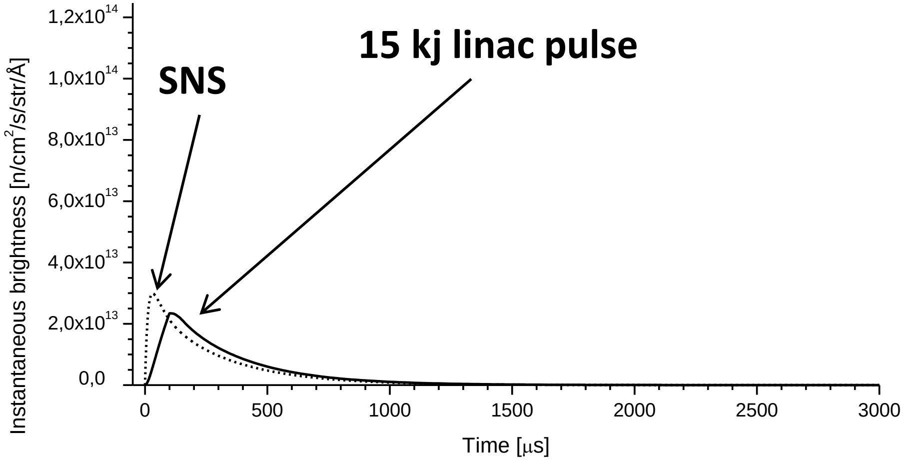


Short pulse spallation sources

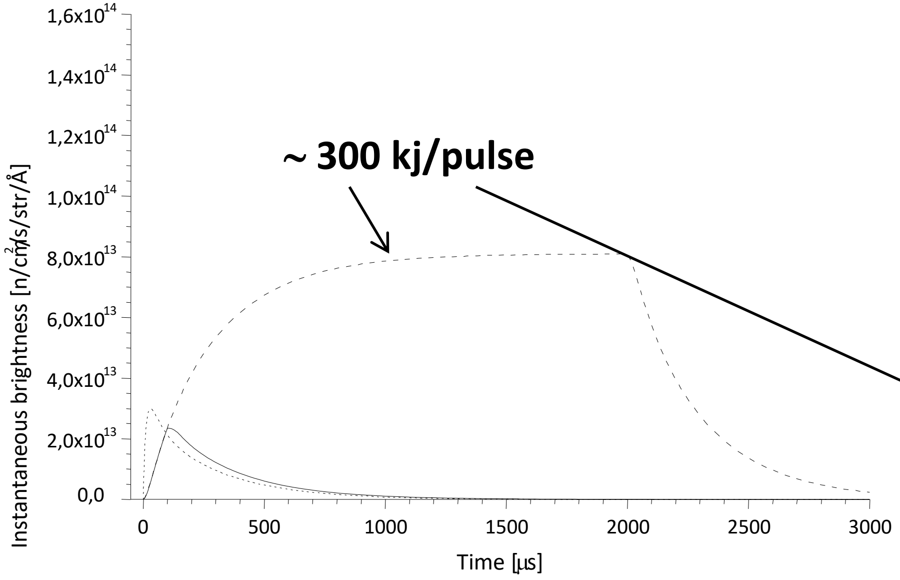
pulse parameters imposed by the source design and/or fixed at each beam-line

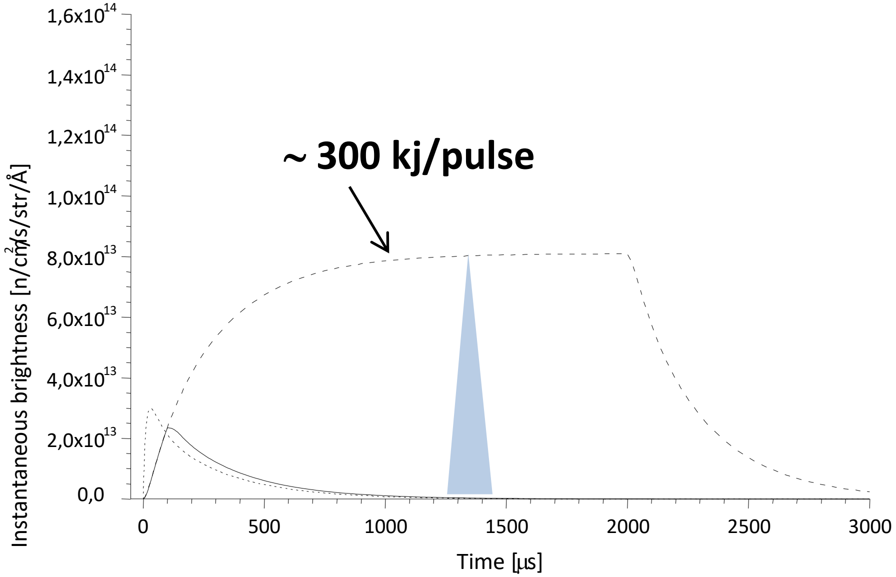
Next generation: long pulse spallation sources

But:
Cost equivalent linear accelerator alone can produce the same **cold neutron pulses by ~100 μs proton pulses at ~ 0.15 GW instantaneous power: 2 x ILL**



Cost equivalent linear accelerator alone can produce the same cold neutron pulses **by ~100 µs proton pulses at ~ 0.15 GW instantaneous power** →
Leave the linac on for **more neutrons per pulse and higher peak brightness…**





~ 300 kj/pulse

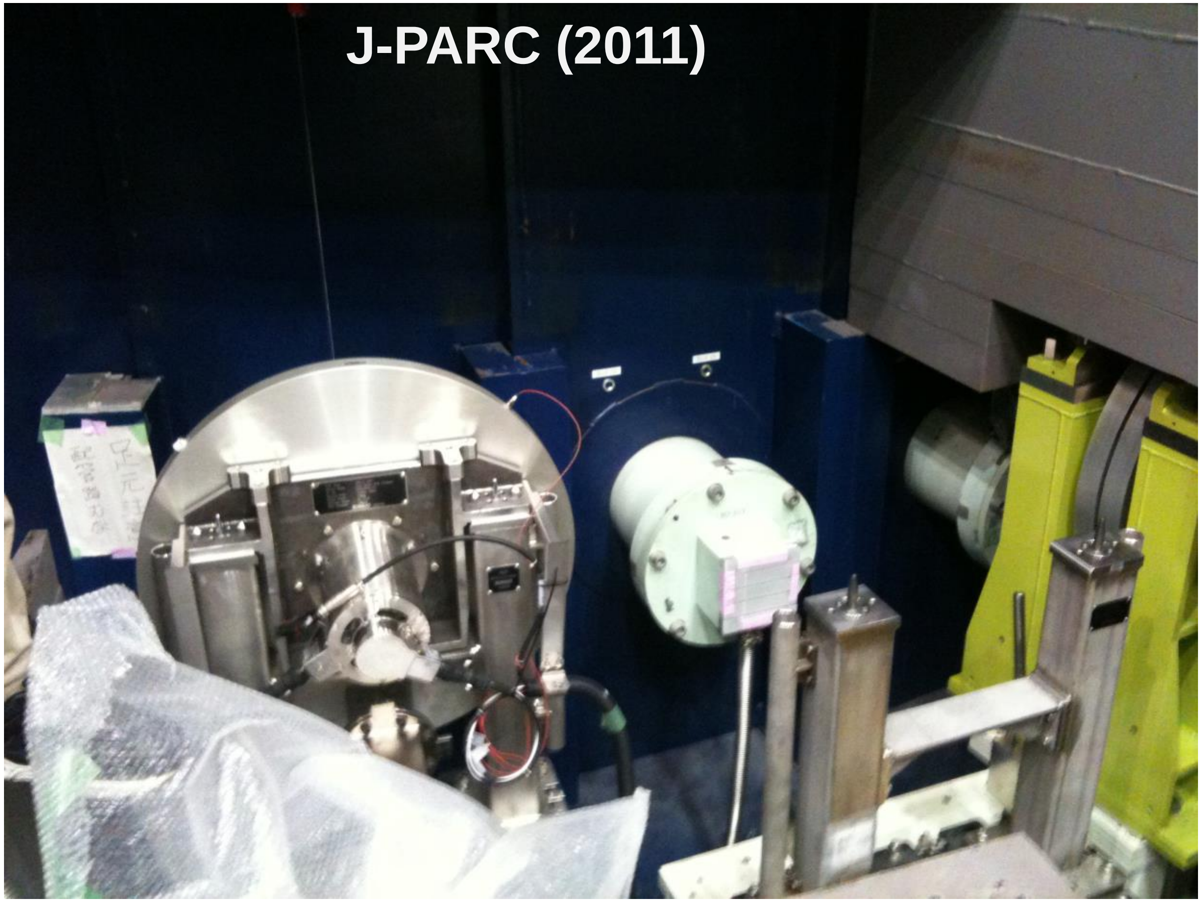
Cost equivalent linear accelerator alone can produce the same cold neutron pulses **by ~100 µs proton pulses at ~ 0.15 GW instantaneous power** →

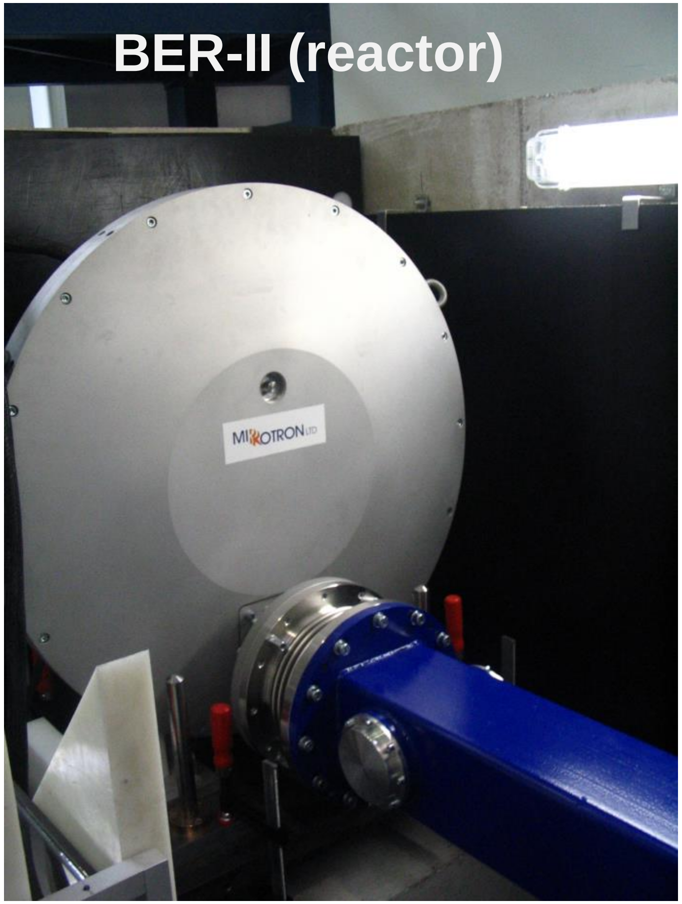
Leave the linac on for **more neutrons per pulse and higher peak brightness…**

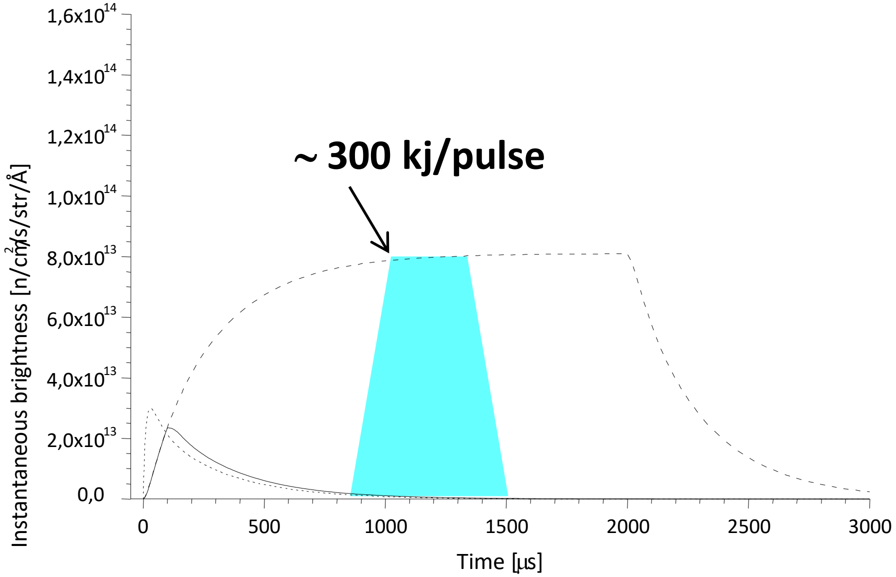
and use mechanical pulse shaping →

Long Pulse source

Neutron beams with mechanical choppers (since Fermi, 1940s)


J-PARC (2011)

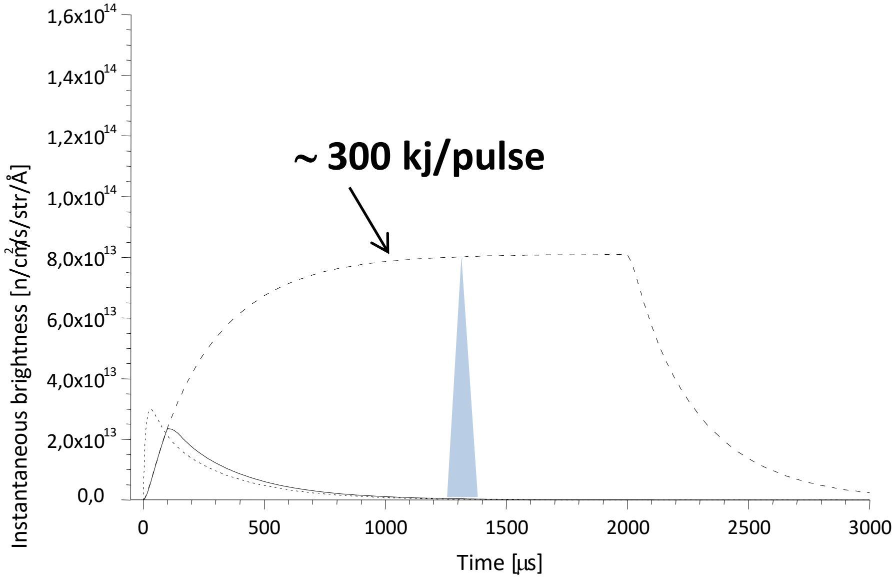

BER-II (reactor)



Cost equivalent linear accelerator alone can produce the same cold neutron pulses **by ~100 µs proton pulses at ~ 0.15 GW instantaneous power** → Leave the linac on for **more neutrons per pulse and higher peak brightness…**

and use mechanical pulse shaping → **Long Pulse source**

ESS: 5 MW accelerator power
→ **more neutrons for the same costs and reduced complexity**



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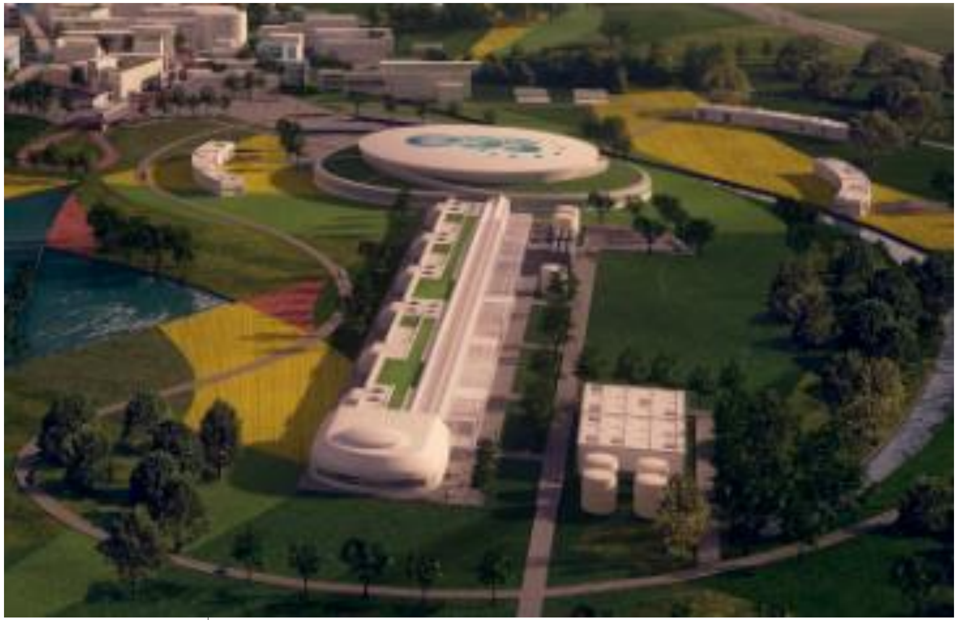

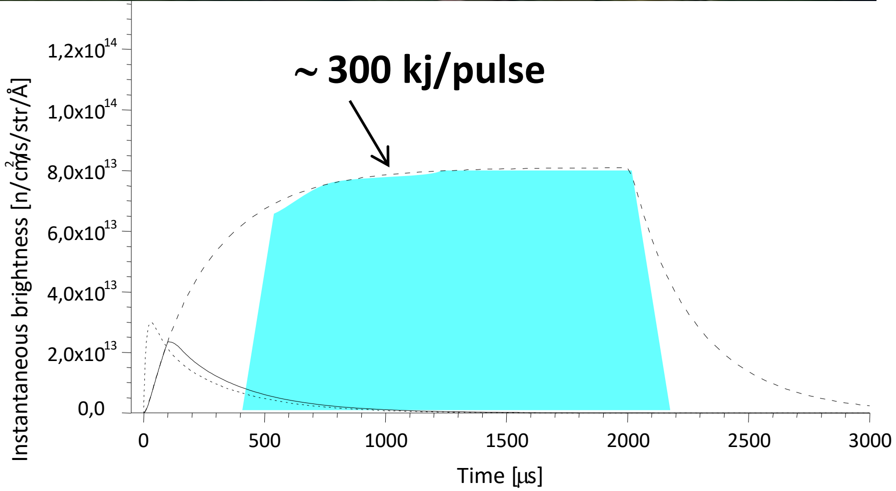

~ 300 kj/pulse

10 MW

Cost equivalent linear accelerator alone can produce the same cold neutron pulses **by ~100 µs proton pulses at ~ 0.15 GW instantaneous power** →

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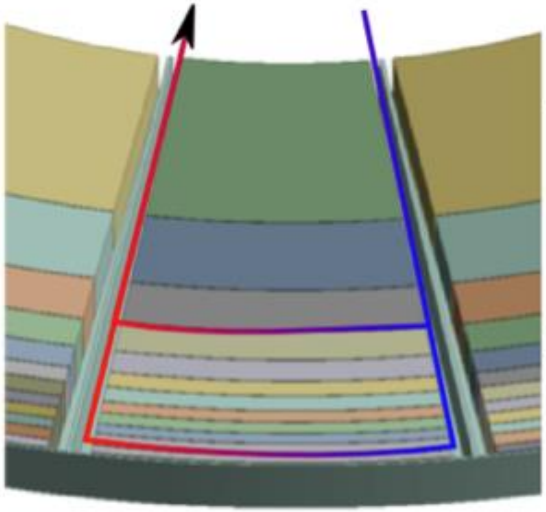
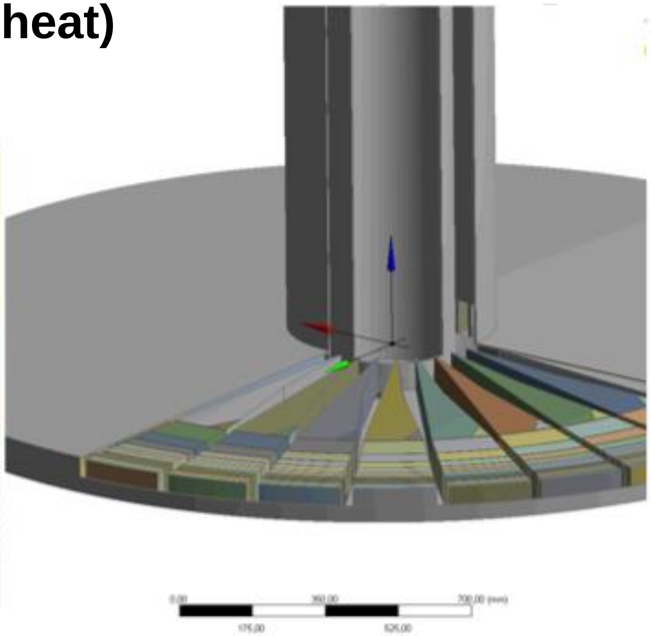
Safe target for high power spallation

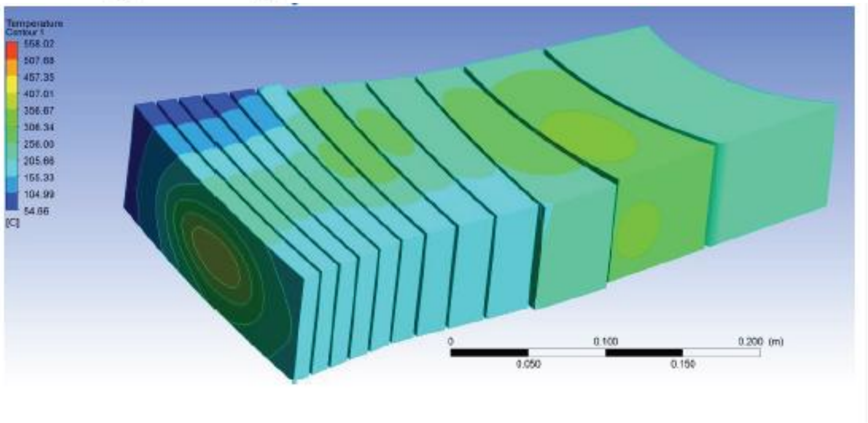
No fissionable material….

but **significant afterheat (decay heat)**

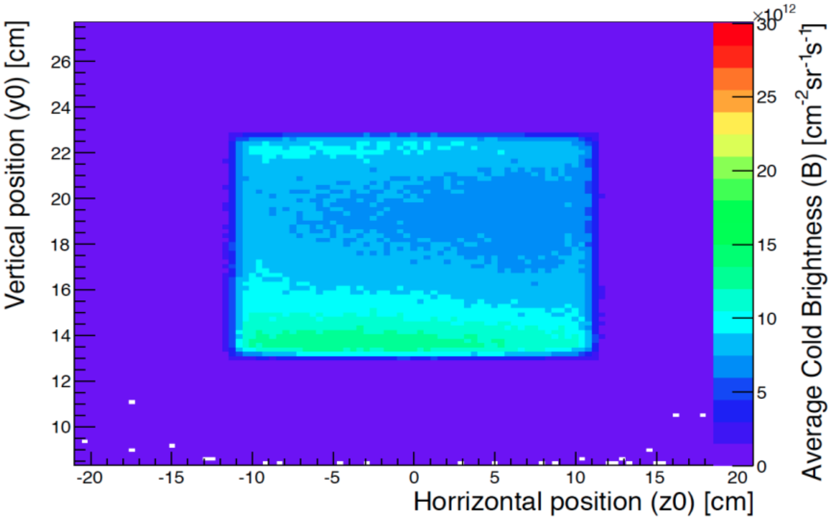
Safe solution: rotating target

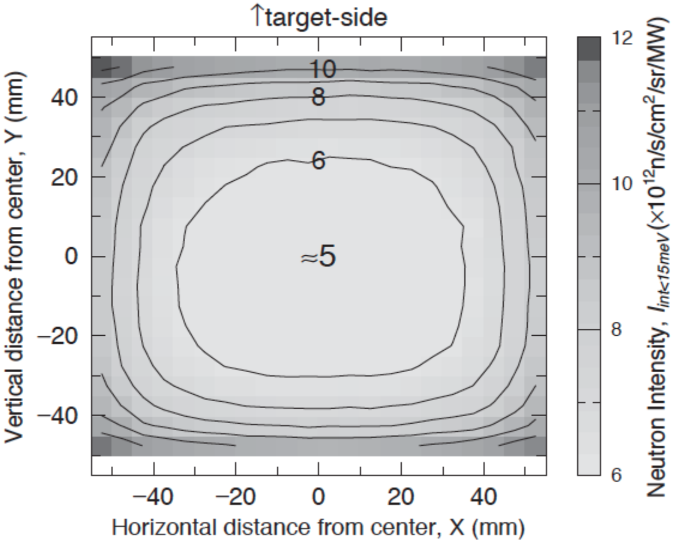




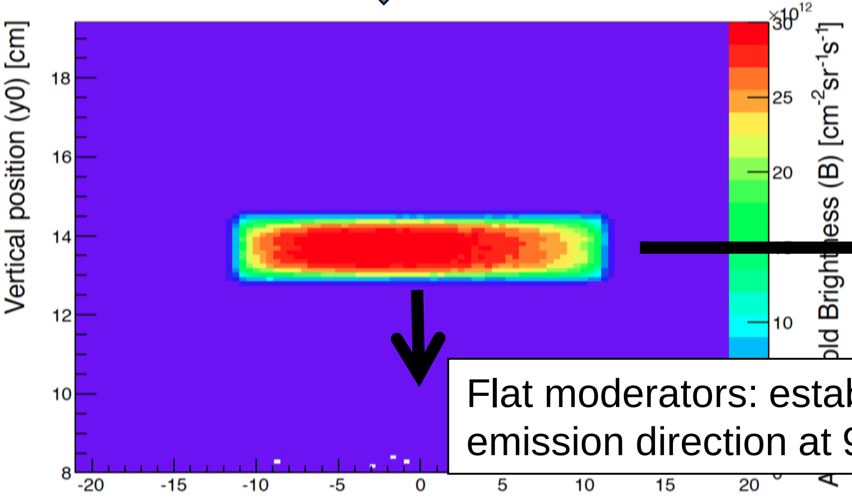


New moderator concept: follow the walls





(Kai et al, 2004)

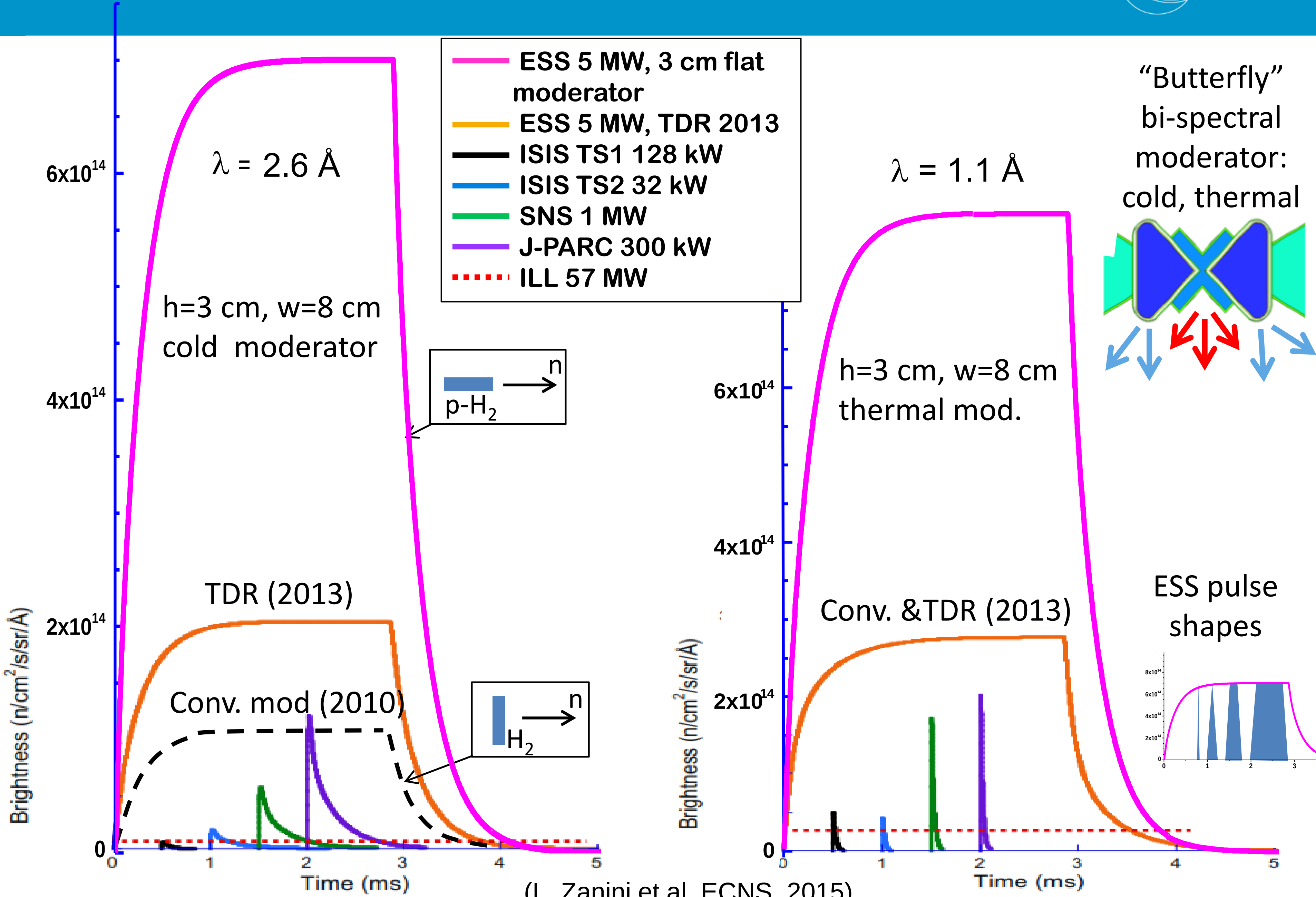


Thermal neutrons arriving from the surroundings are transformed into cold ones within about 1 cm of the walls of the moderator vessel

Direction of high brightness emission

Flat moderators: established practice with emission direction at 90° of preferential directions

Qualitatively new level of beam performance



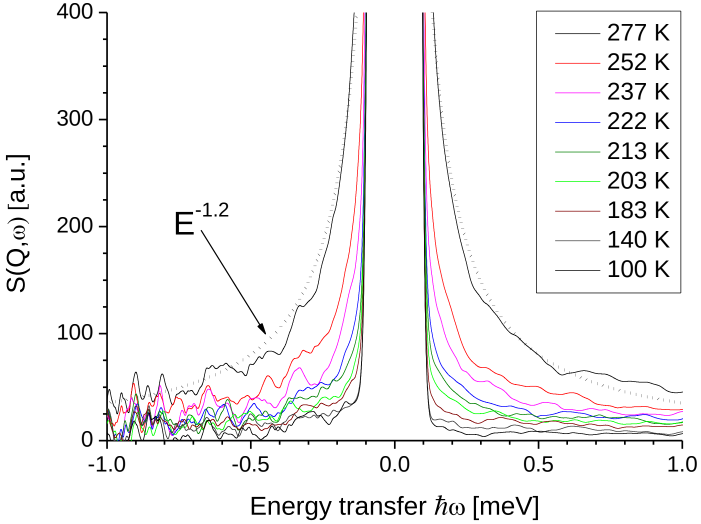
“Butterfly” bi-spectral moderator: cold, thermal

ESS pulse shapes

(L. Zanini et al, ECNS, 2015)

New perspectives

ESS 5 MW long pulse source:
order of magnitude more neutrons for same costs



Instrumental progress (x70)
+ new source (x300):

4 h scans → will be made in 1 s

??

New perspectives

ESS 5 MW long pulse source:
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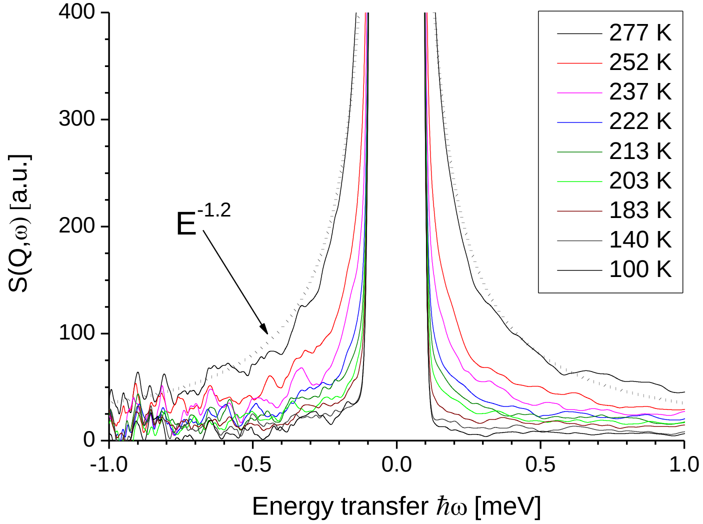


Instrumental progress (x70)
+ new source (x300):

4 h scans → will be made in 1 s

!!

Learn from life sciences how to study huge and one by one poorly understood data sets: **look for systematics in the "raw" pictures**

Compact neutron sources

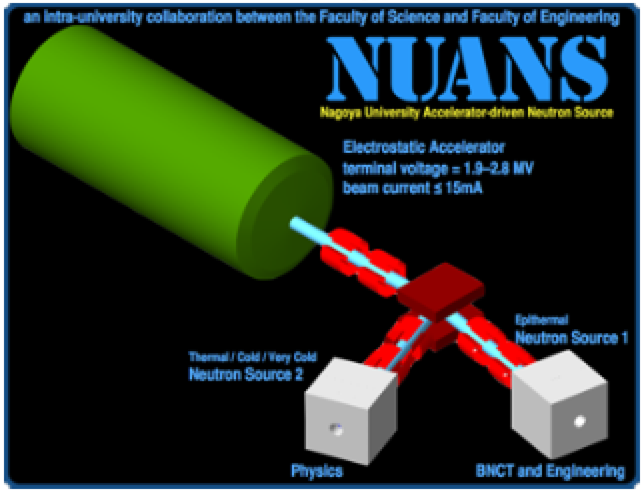
Costs: ~ 10 - 100 M€
Power: 5-50 kW
Flux: ESS / 1000000

LENS
The Low Energy Neutron Source

4. Compact Sources (for Retail Use)

UCANS: Union for Compact Accelerator-driven Neutron Sources
(http://www.ucans.org/)

Long-term occupation and on-demand access enables
pioneering works and practical applications in industry.

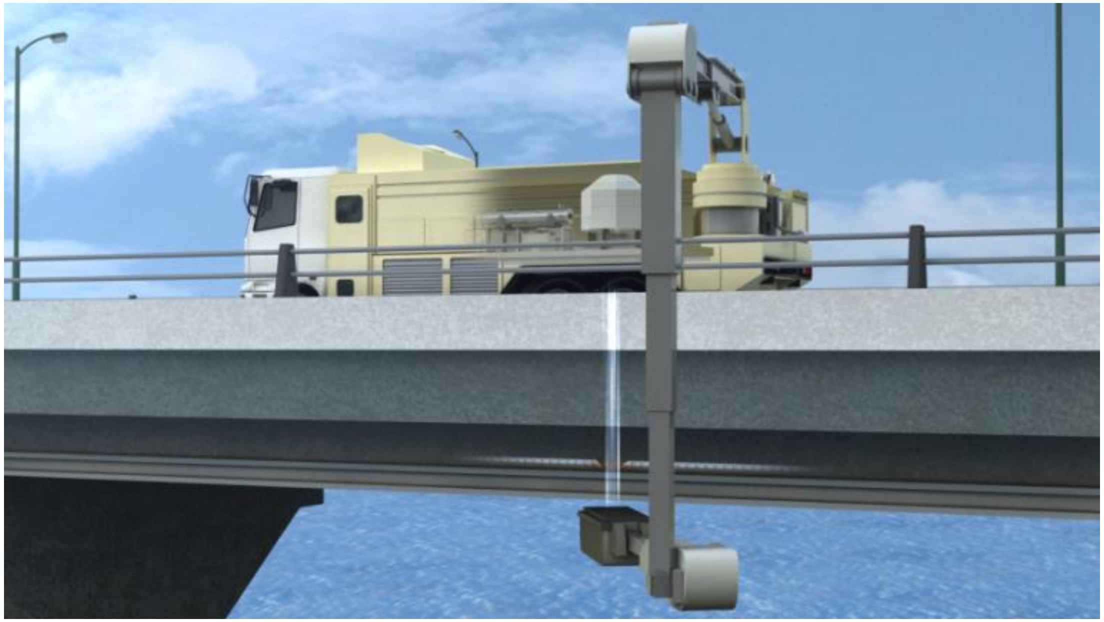


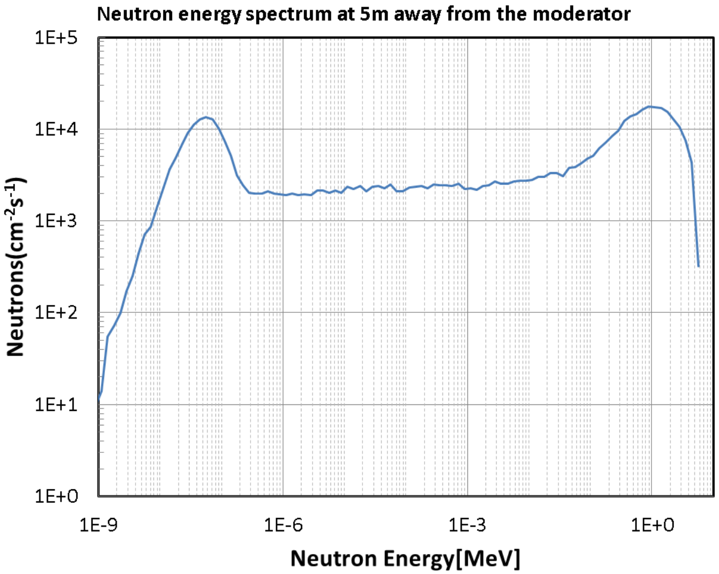
Researches: Optics R&D, principle proof

Applications:
ETN: Boron Neutron Capture Therapy
TN CN: Radiography
TN CN: Bragg-edge Imaging and Microscope
VCN: Focusing SANS, Imaging Reflectometry

Japan 2017: physics & materials: 9, medical: 10

Europe 2022: 4 – 5 plans





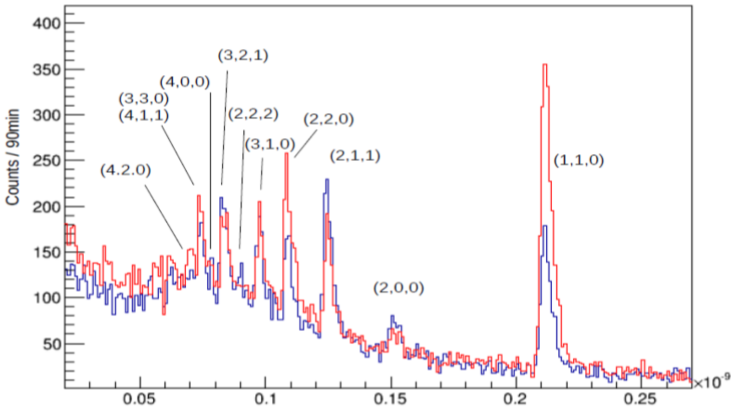
RANS (RIKEN, Tokyo)

Opportunities for (all) neutron sources

Advances in neutron technology in past ~ 25 years: gain in efficiency of using the neutrons produced in a source

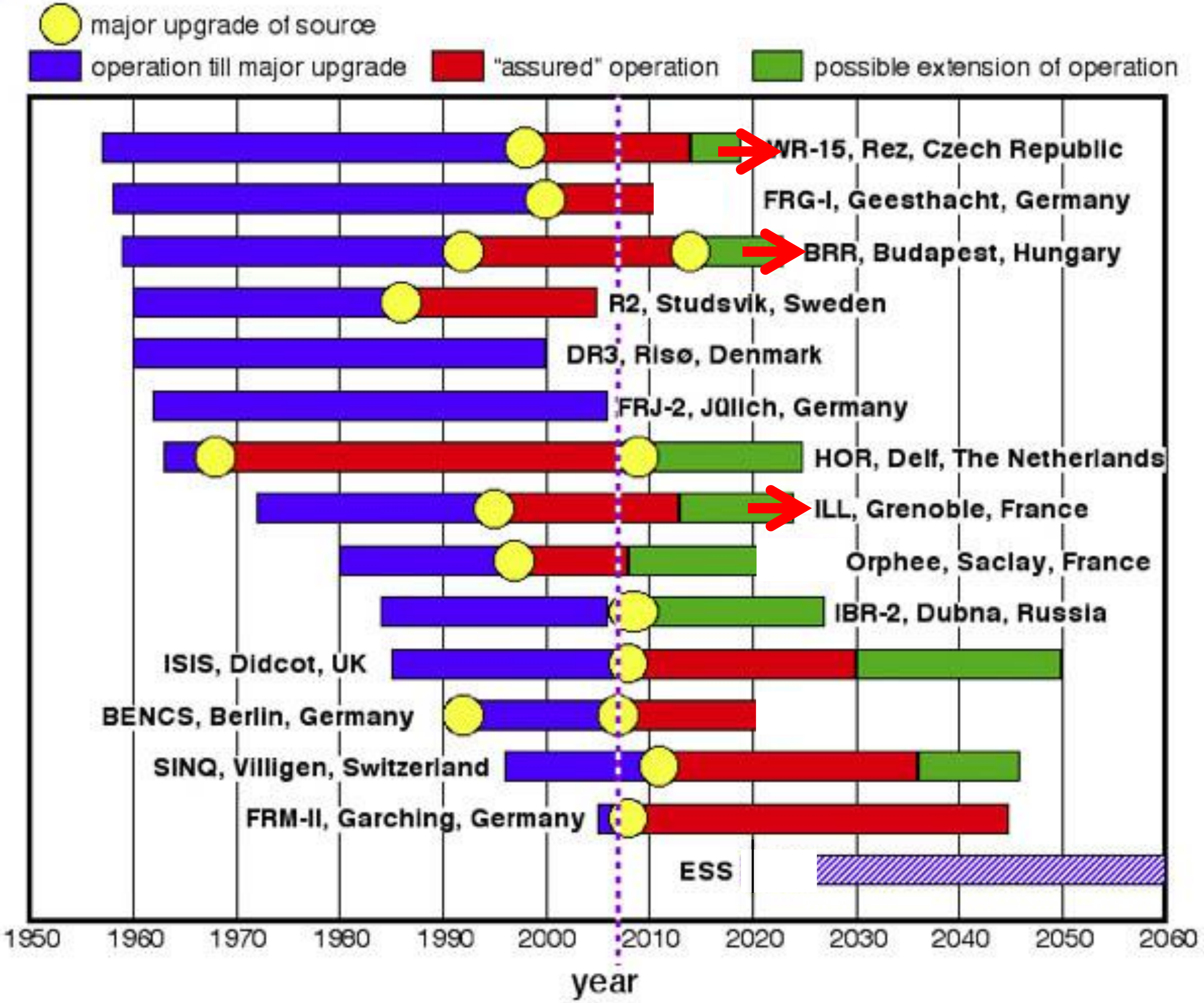
- Pulses with respect to CW (in scattering work)	x 20
- Systematic use of supermirror optics	x 10 – 20
- Bi-spectral beam extension	x 1 – 2
- High brightness low dimensional moderators	x 3
Total moderated flux on sample per fast neutron:	x 600 – 2400

- Upgraded scattering instruments on average	x 10
- Adapted data collection for background / spectral feature	x 5 – 50
Total data collection rate, up to	x 500 000



Neutron research in Europe:

~7000 scientists, decreasing no. of facilities



Trends and opportunities

Multi-MW long pulse spallation sources

- order of magnitude higher flux / sensitivity for the same costs
- order of magnitude better energy efficiency
- costs: 3 B€ construction + 200 M€ operation/year

Compact accelerator driven sources

- ~ 0.1- 5 % of costs for 0.01 – 0.1 % of neutron production
- can be installed at industial facilities, universities, hospitals
- distributed networks for many users

No use of fissionable materials: access / security simpler

Great potential: neutrons for nuclear waste incineration