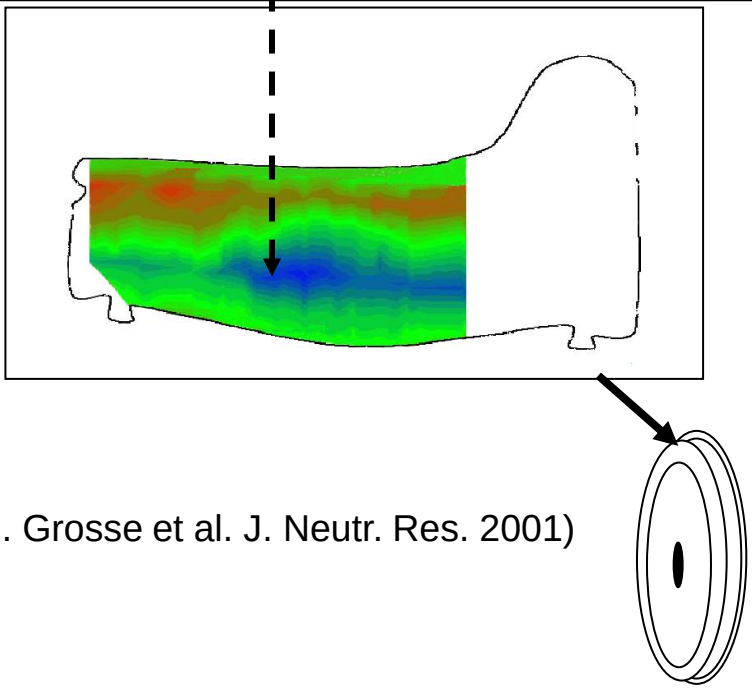
Neutron production, neutron scattering facilities

F. Mezei
ESS & Wigner RCP

Neutron can see deep inside matter…

ICE accident, Eschede

Neutrons see **(tensile) stress** inside bulky metal parts that caused wheel failure: **standard engineering theory of plastic deformation stresses in error in the 1990s!!**



(M. Grosse et al. J. Neutr. Res. 2001)

Knowledge based society??
Safety philosophy??

Neutrons are non-destructive probes … etc, etc

Tiziano Vecellio (Tizian)

Neutron activation radiography

Fast neutrons produced / joule heat deposited:

Fission reactors:	**3×10^{10}**	(in ~ 50 liter volume)
→ Spallation (> 400 MeV):	**2×10^{11}**	(in ~ 2 liter volume)
Fusion:	**4×10^{11}**	(in ~ 2 liter volume)

(but neutron slowing down efficiency reduced by ~20 times)

Electron accel.: (50 MeV)	**2×10^{9}**	(in ~ 0.01 liter volume)
→ Low energy p.: (5 MeV):	**2×10^{8}**	(in ~ 0.001 liter volume)
(35 MeV):	**2×10^{9}**	(in ~ 0.01 liter volume)
Laser induced fusion:	~ **10^{4}**	(in ~ 10^{-9} liter volume)

Spallation: lowest cost per neutron
Compact source: lowest cost per facility

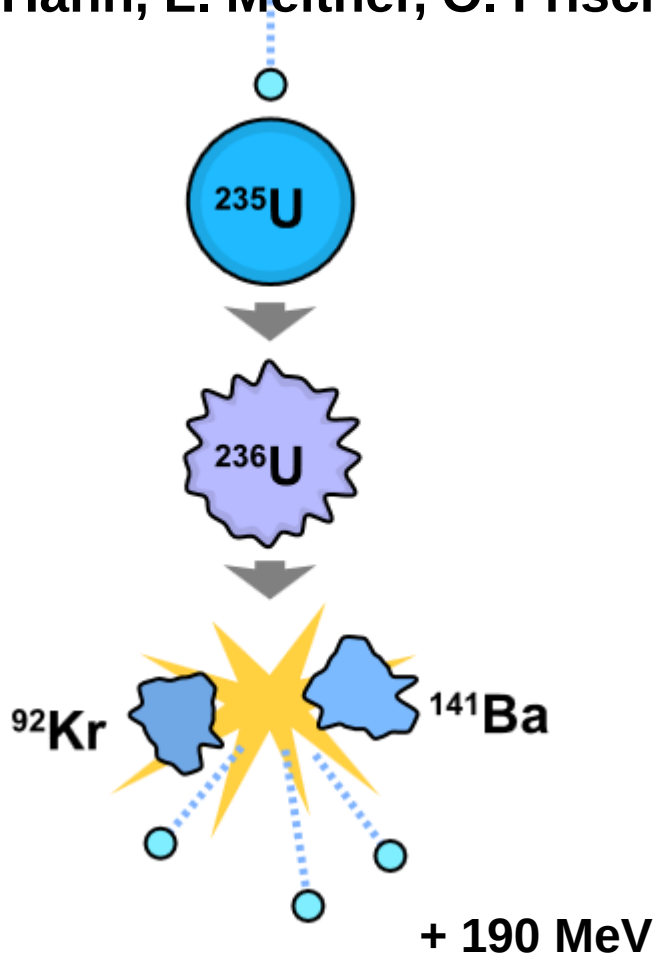
Energy costs are important: 20 % of staff costs at ESS in operation

Fast neutrons produced / joule heat deposited in target station

Fission reactors:	**~ 10^9**	**(in ~ 50 liter volume)**
Spallation:	~ 10^{10}	(in ~ 2 liter volume)
Fusion:	~1.5×10^{10}	(in ~ 2 liter volume)
	(but neutron slowing down efficiency reduced by ~20 times)	
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)

Spallation: most favorable for the foreseeable future

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



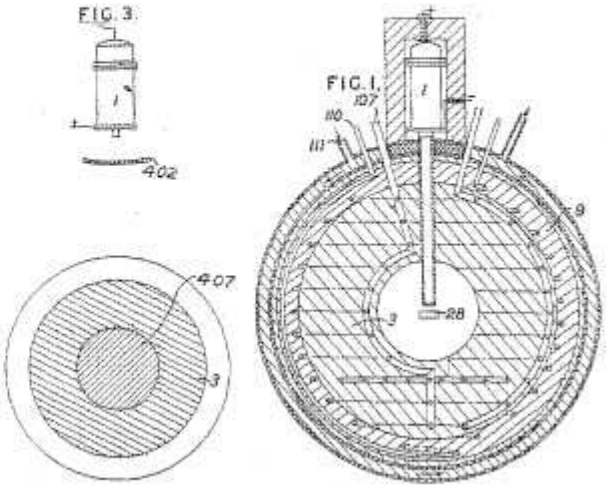
Chain reaction (L. Szilárd 1934)

Chain reaction (L. Szilárd 1934)

Abstract of GB630726 (A)

Translate this text into German patenttranslate powered by EPO and Google

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.

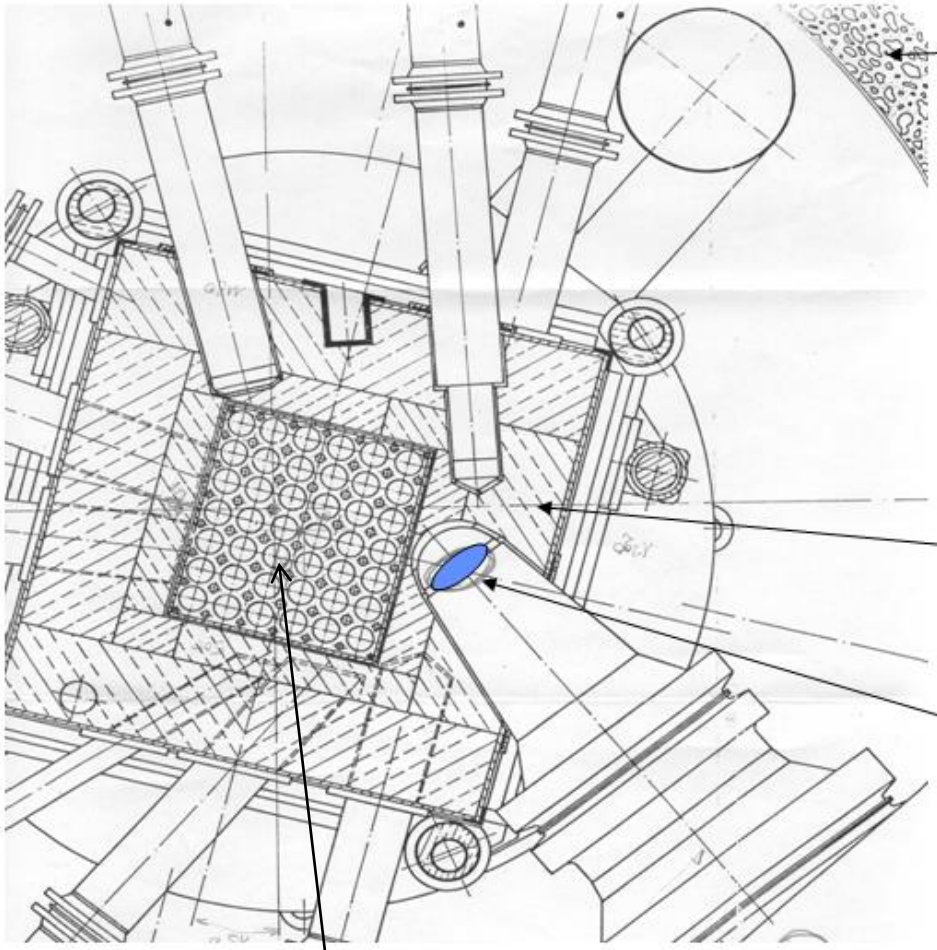


→ **nuclear weapons**

Secret patent: Szilárd delays nuclear arms race

→ **research reactors**

→ **nuclear energy**



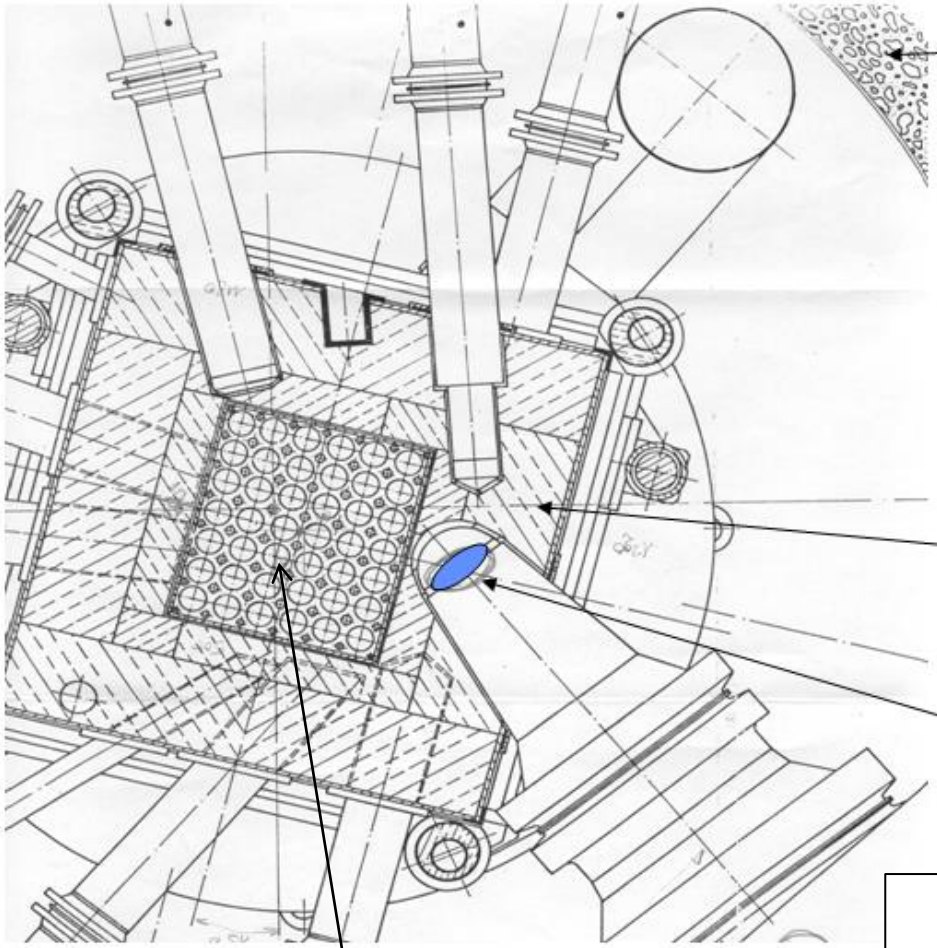
Shielding: ø 10 - 12 m

Example of a fission reactor (HMI)

Thermal neutron source (Be reflector)

Cold neutron source (liquid H_2 bottle)

Fission fuel: enriched ^{235}U



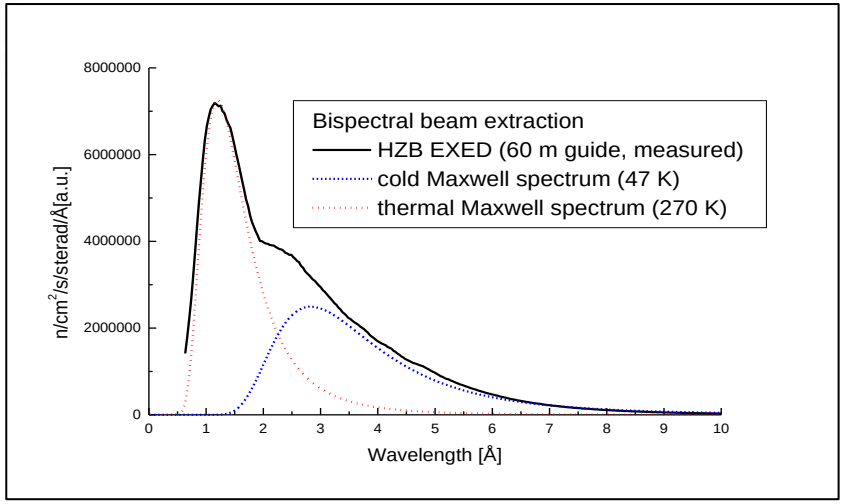
Shielding: ø 10 - 12 m

Example of a fission reactor (HMI)

Thermal neutron source (Be reflector)

Cold neutron source (liquid H_2 bottle)

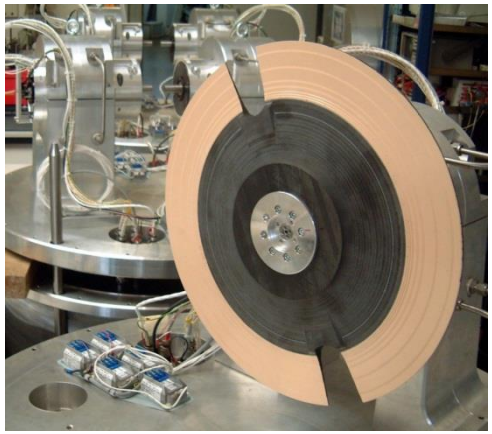
Fission fuel: enriched ^{235}U
Low (<20 %) vs. High enrichment
Plutonium in waste
Neutrons for waste transmutation

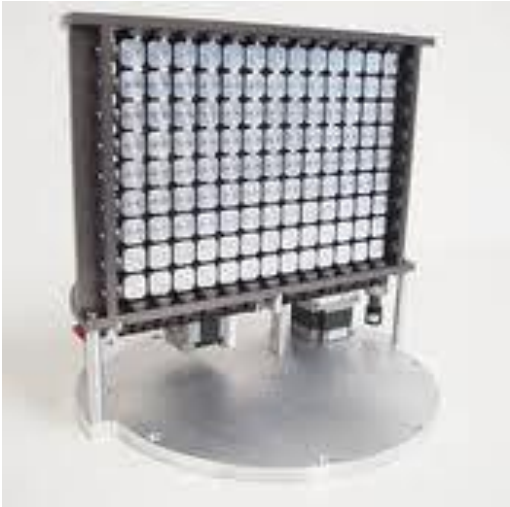


Neutron monochromatization - analysis

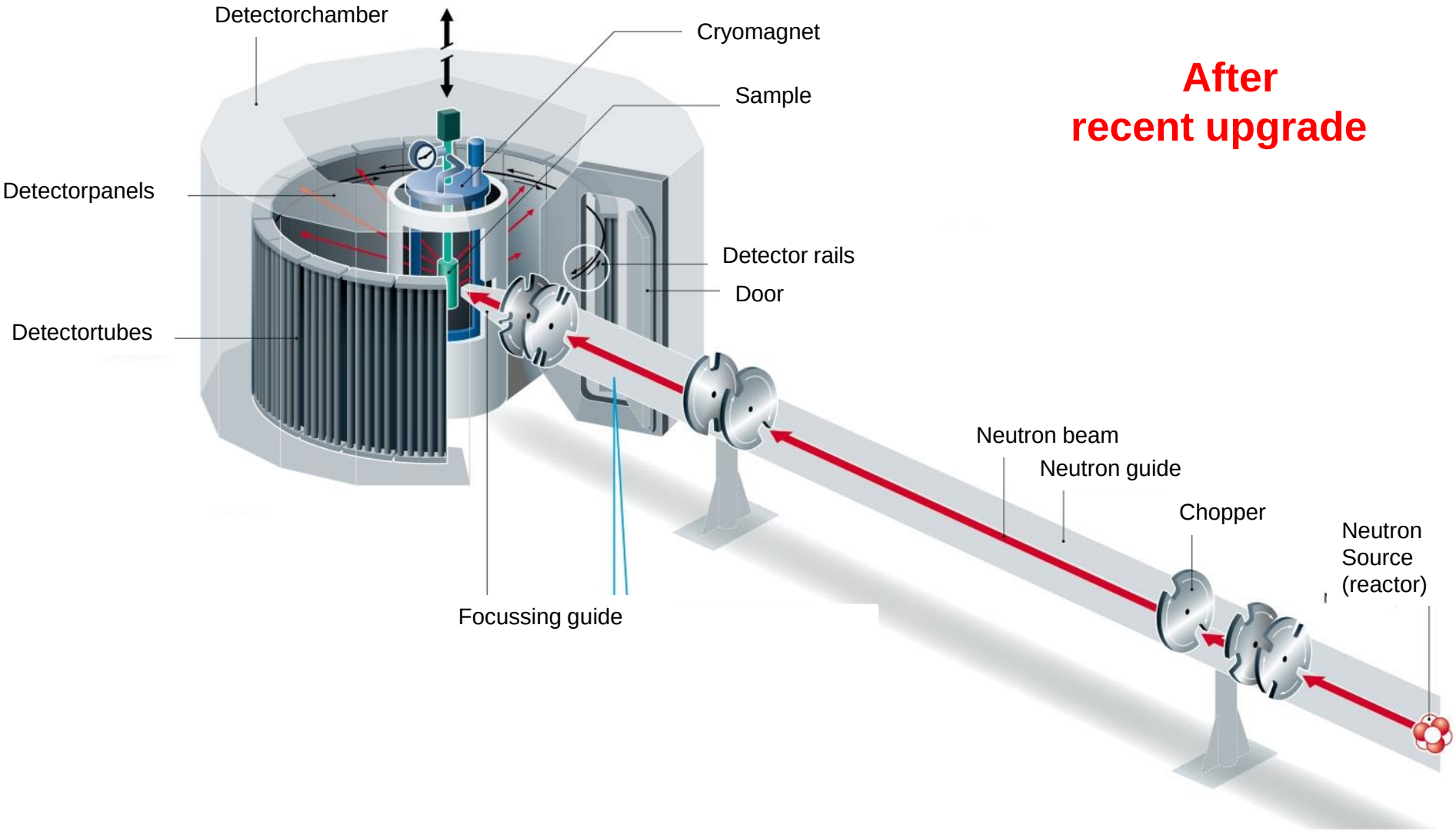
- Mechanical chopper devices

- Crystals – select desirable wavelength





Neutron monochromatization - analysis

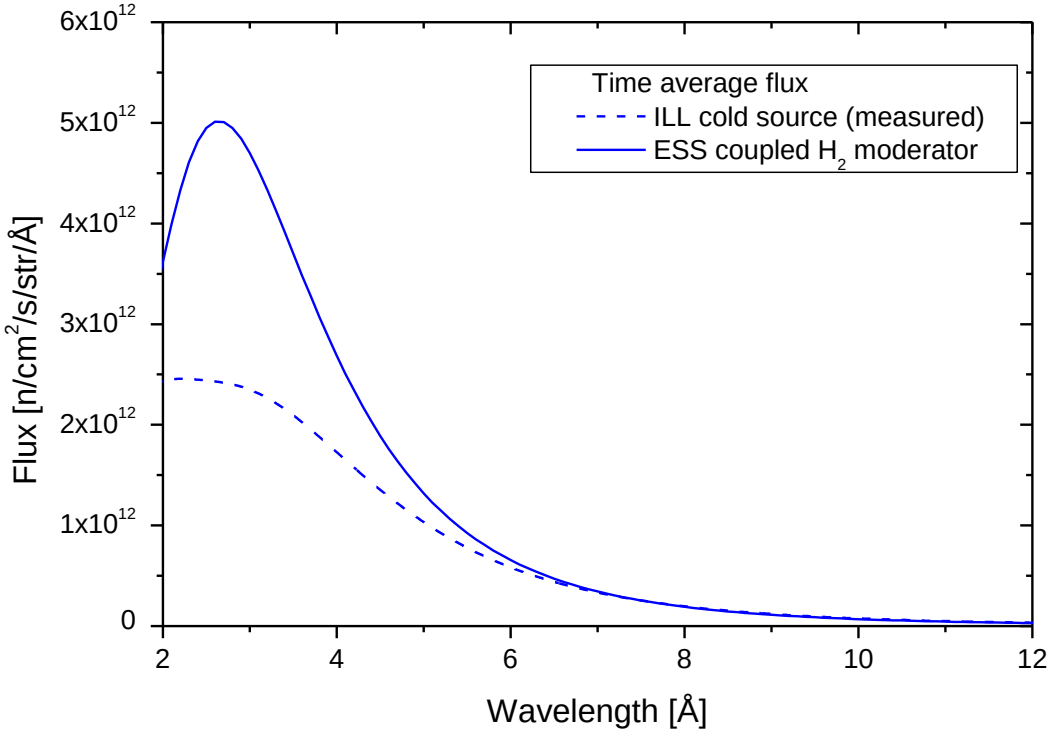


After recent upgrade

Efficiency gain by pulsed neutron sources

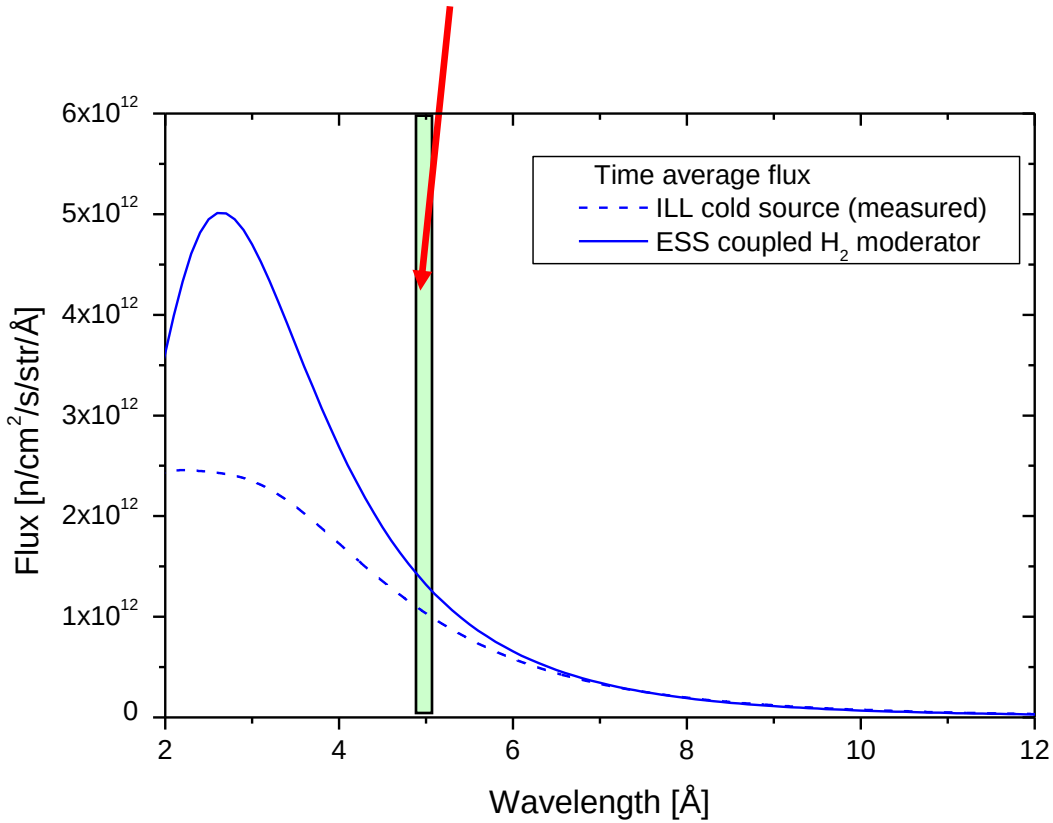
5 MW spallation source:

coupled cold moderator flux ~ ILL cold source

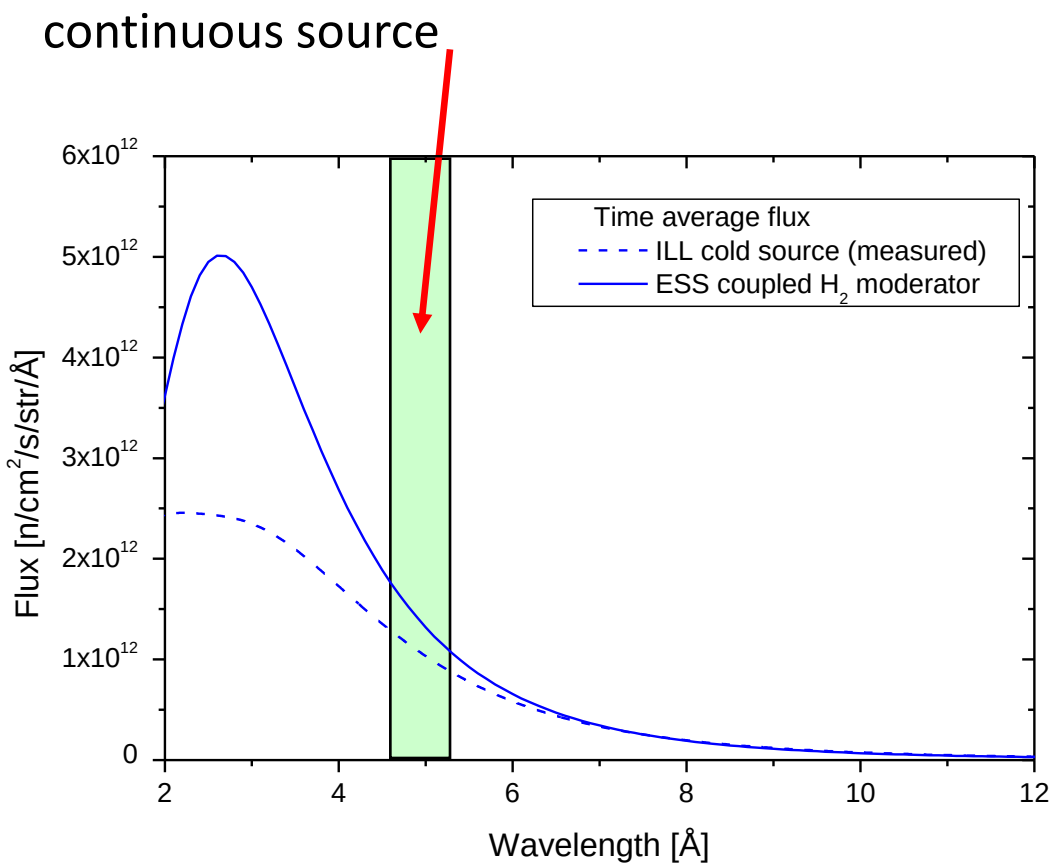


Part of spectrum used by a diffractometer for large structures (e.g. biological membranes)

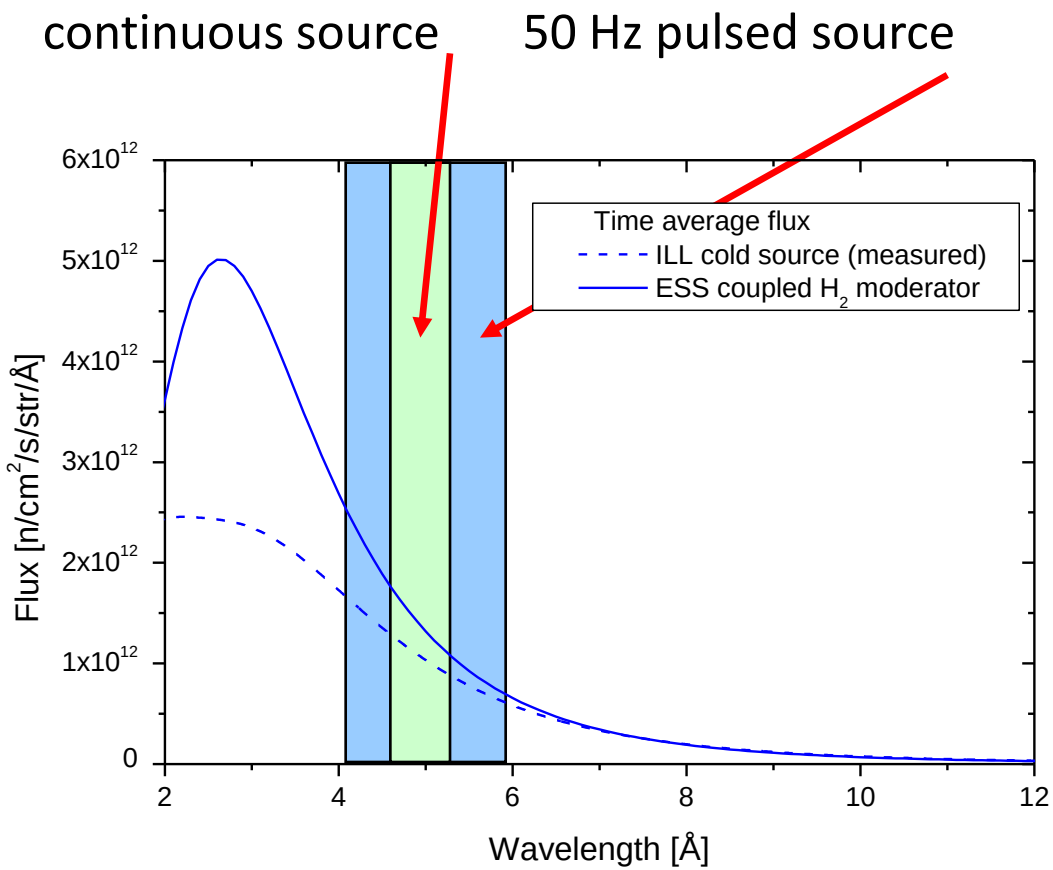
continuous source



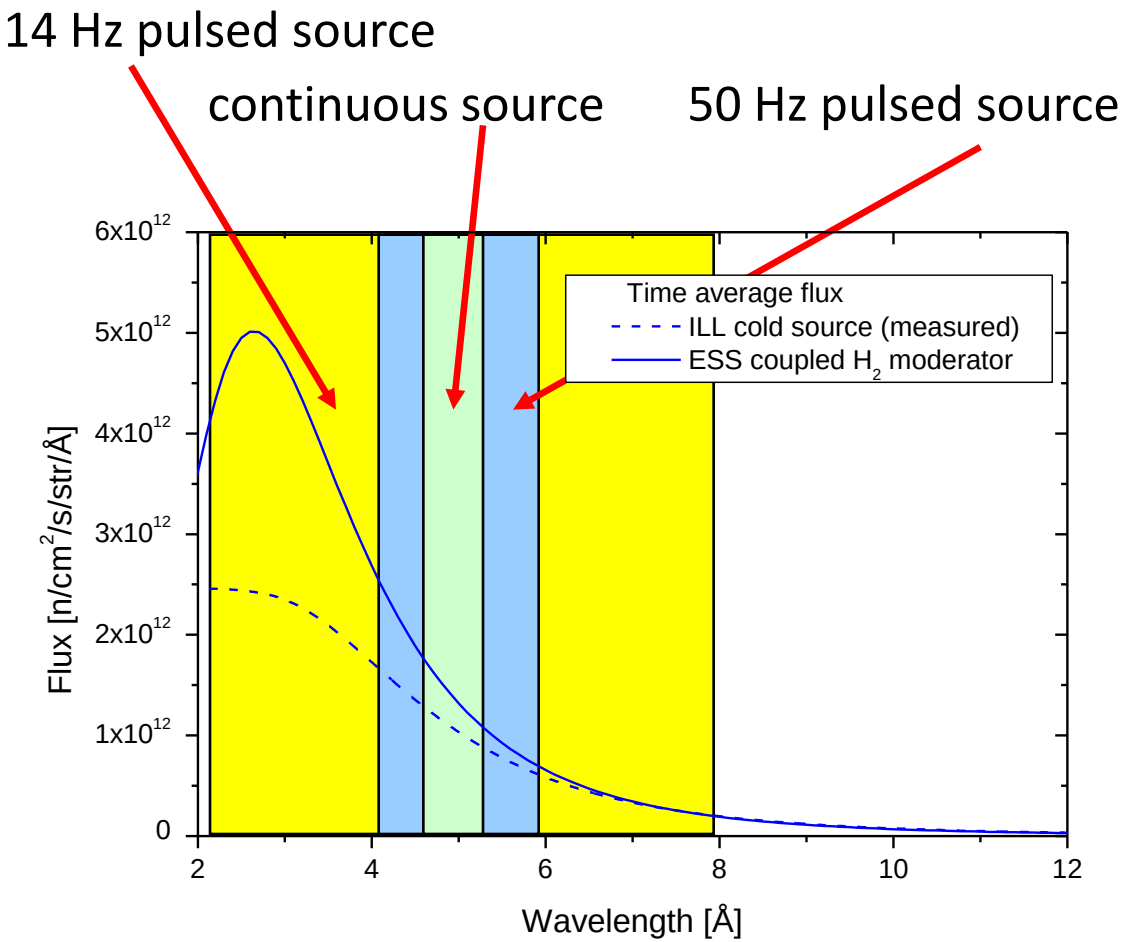
Part of spectrum used by a D22 (ILL) class instrument (Small Angle Neutron Scattering)



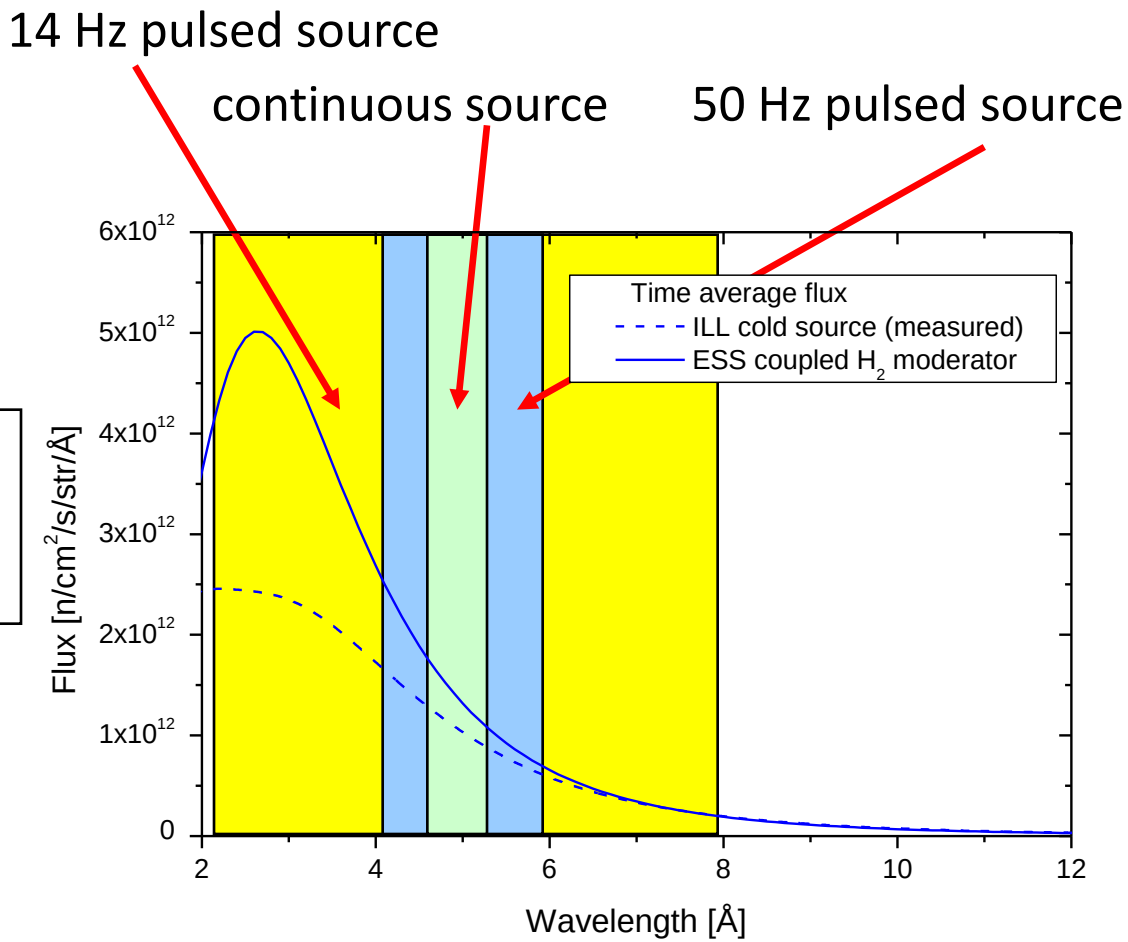
Part of spectrum used by a SANS instrument



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

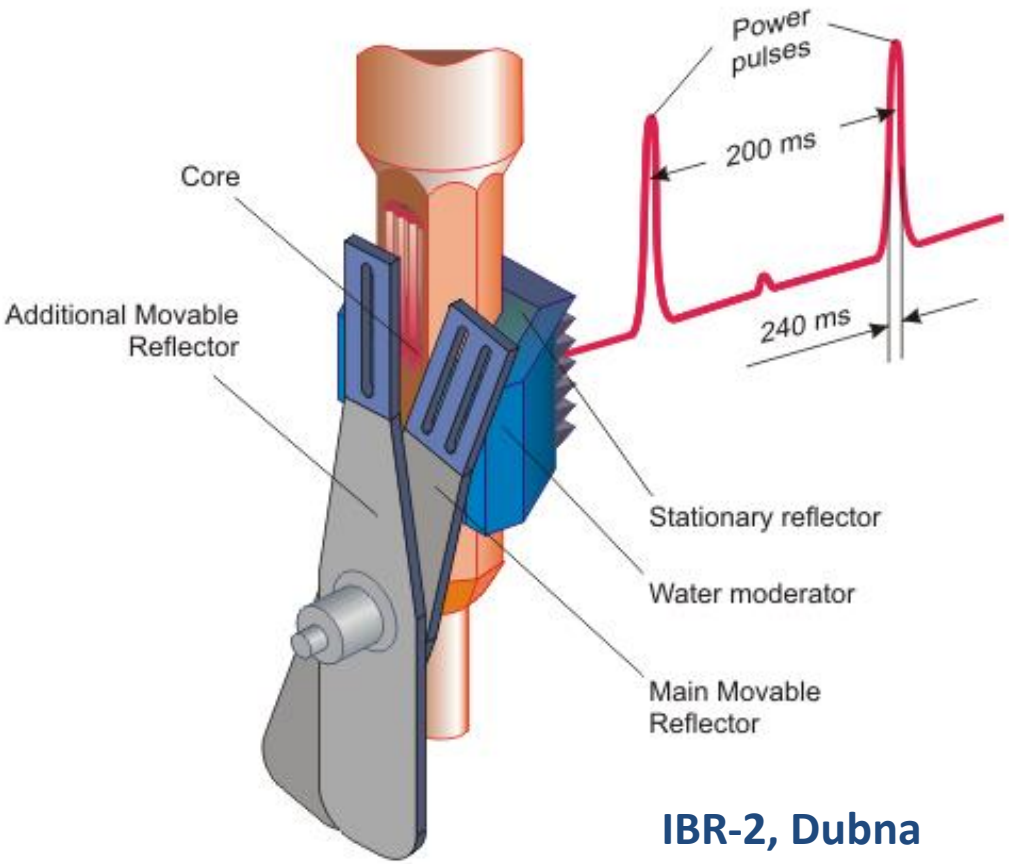


Part of spectrum used by a D22 (ILL) class instrument



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

Neutron production economy: pulsed reactor



IBR-2, Dubna

Pulsed reactor source

Time average power:
2 MW

Peak power in pulse:
850 MW

Great fuel economy!

Fast neutrons produced / joule heat deposited in target station

Fission reactors:	~ 10^9	(in ~ 50 liter volume)
Spallation:	**~ 10^{10}**	**(in ~ 2 liter volume)**
Fusion:	~1.5×10^{10}	(in ~ 2 liter volume)
	(but neutron slowing down efficiency reduced by ~20 times)	
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)

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**

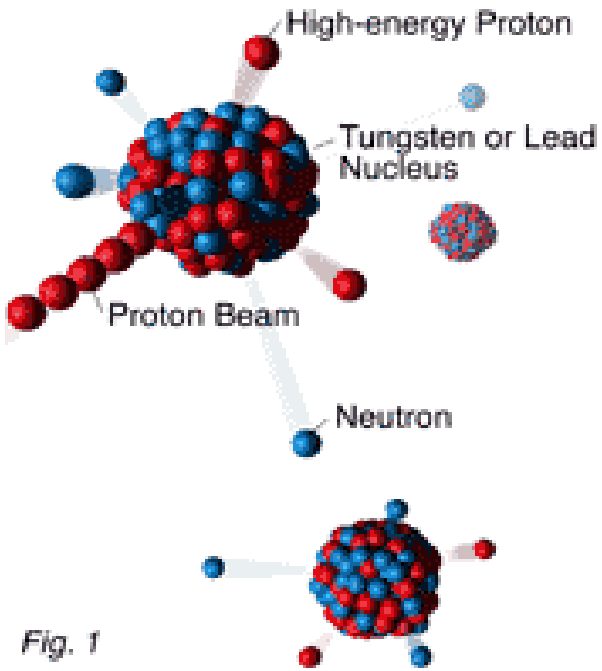
→ **Pressure wave: 300 bar**

Reaches limits of technology

Production of slow neutrons: the "source"

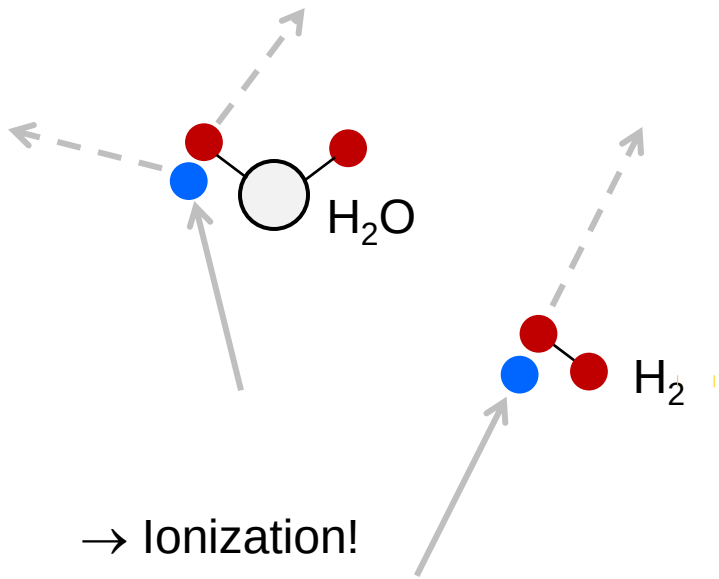
Two step process in the target station

A) Series of nuclear reactions:
spallation → fast neutrons
~100 billion °C



Time: << 1 μs

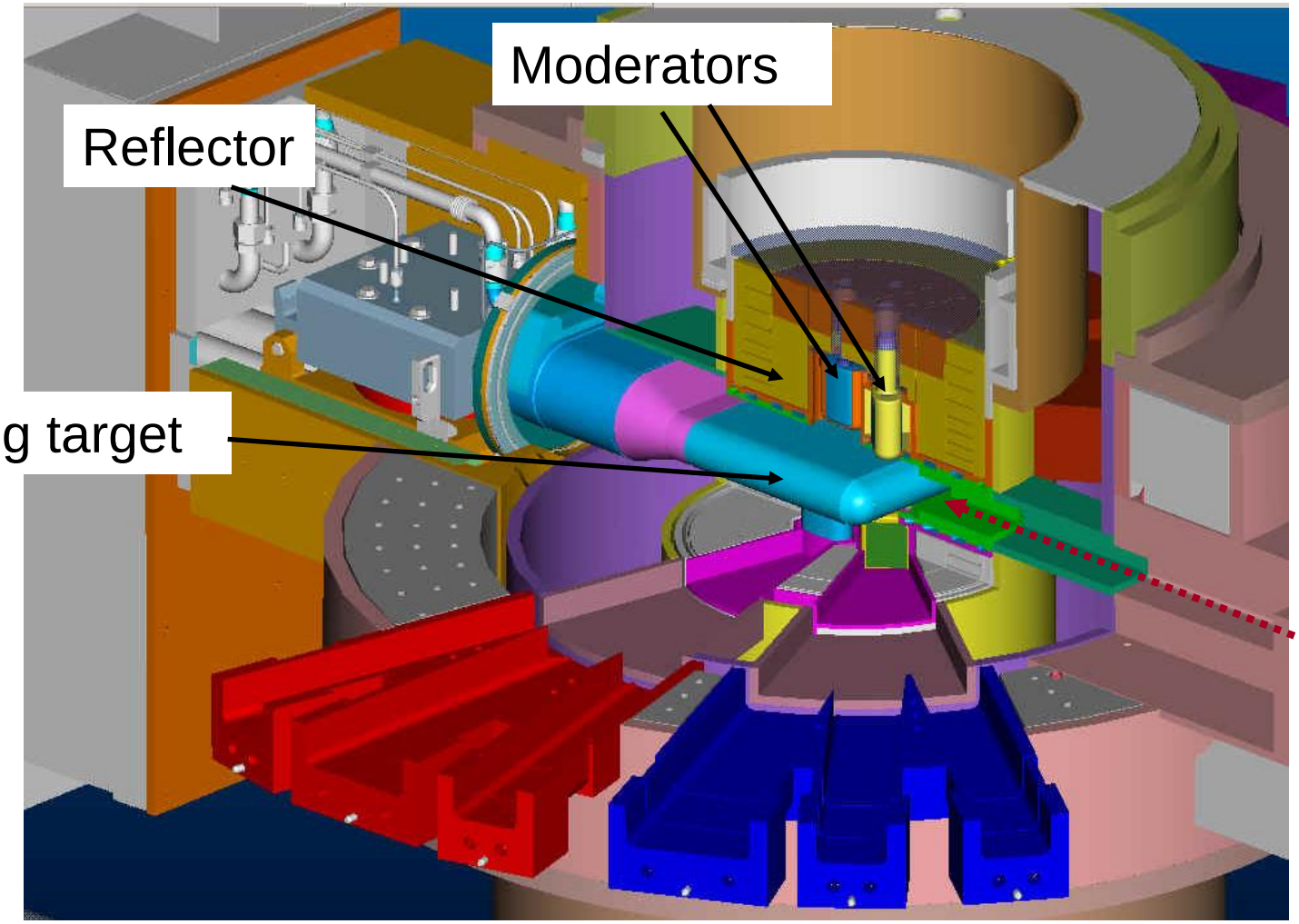
B) Collisions with H atoms:
moderation → slow neutrons
"Hot": ~ 2000 °C
"Thermal": ~ 20 °C
"Cold": ~ -220 °C ≈ 50 K ≈ 1000 m/s



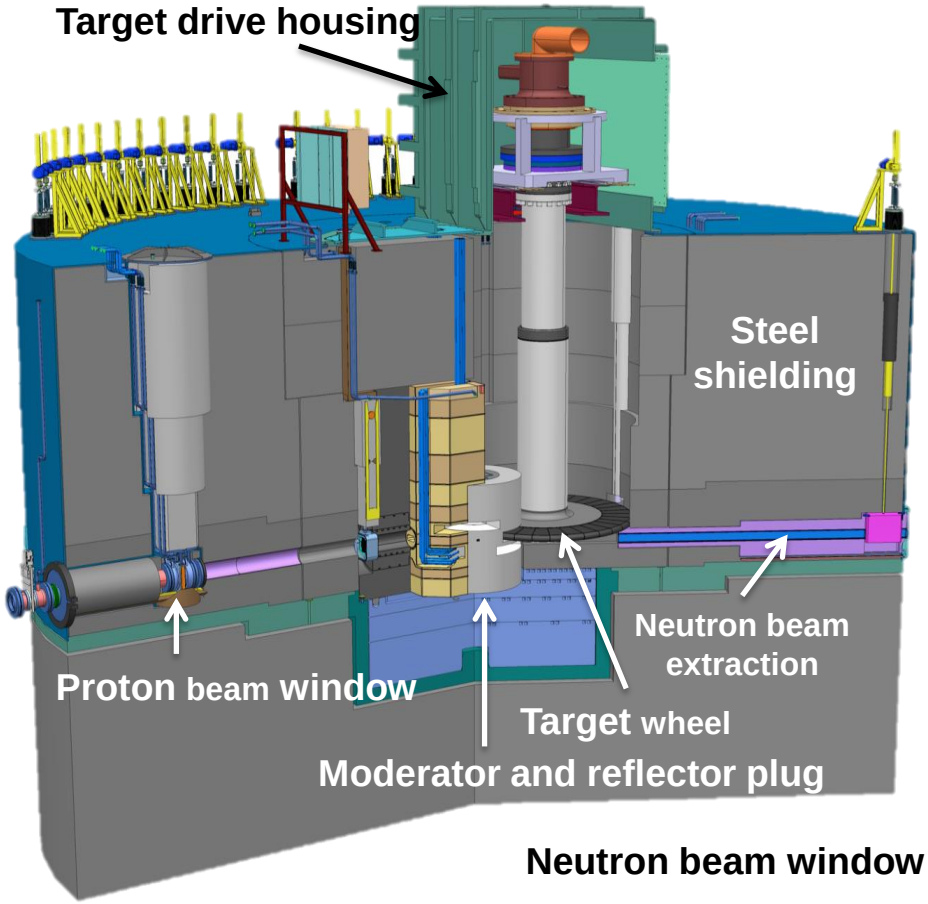
→ Ionization!

10 – 500 μs

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



He gas:
~ 1 bar



EUROPEAN SPALLATION SOURCE

Functions:

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

Unique features:

- Rotating target
- He-cooled W target

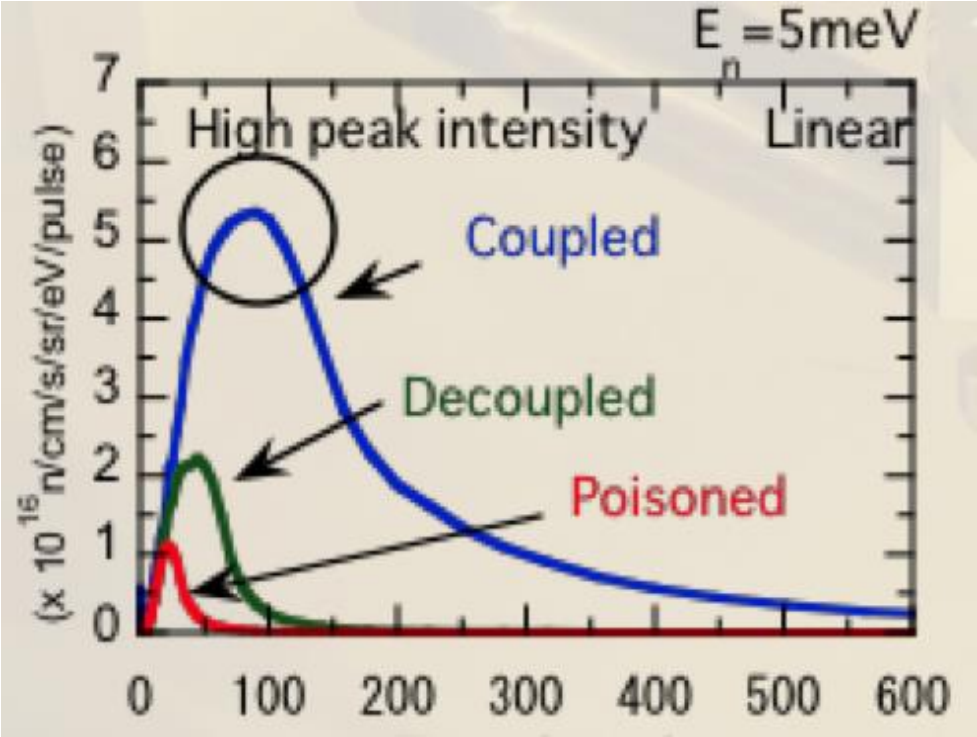
Safety of public, staff, environment ↔ cost & schedule

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.

Loss of Life Expectancy (LLE) by professions (40 years activity):

Building demolition	1500 day
Coal mining	1100
Fire fighter	800
Railway	500
Agriculture, farmers	300
Construction (buildings)	200
Traffic, utilities	160
Average of all professions	60
Civil service	55
Airline crew (radiation only)	< 50
Services / nuclear power plant operators	45
Commerce	30
One time 10 mSv radiation	< 1.5
Natural radiation in Europe (upper limit)	< 8 – 25
Inhabitant of Chernobyl (radiation, upper limit)	< 66

Accidents: banks are more dangerous than nuclear power plants.



Short pulse spallation sources

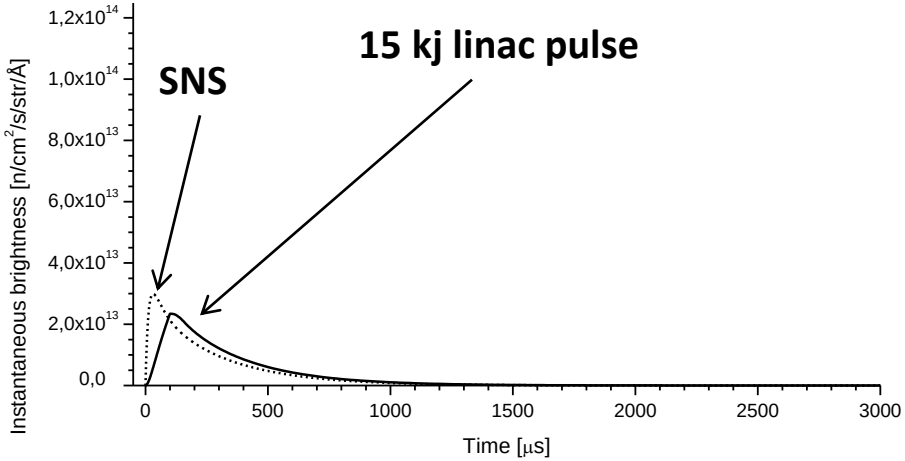
pulse parameters imposed by the source design and/ or fixed at each beam-line

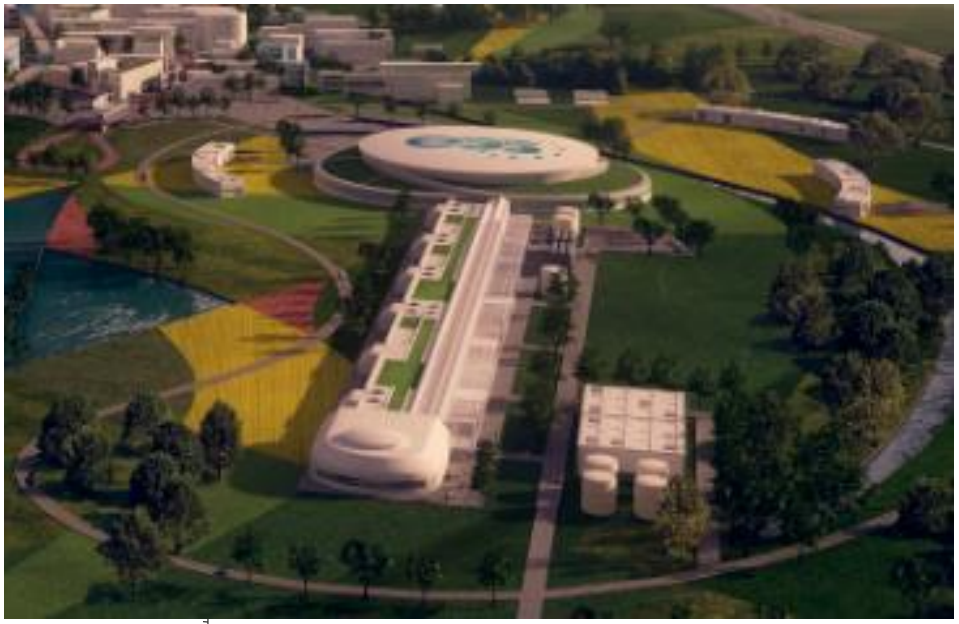
Next generation: long pulse spallation sources

EUROPEAN SPALLATION SOURCE

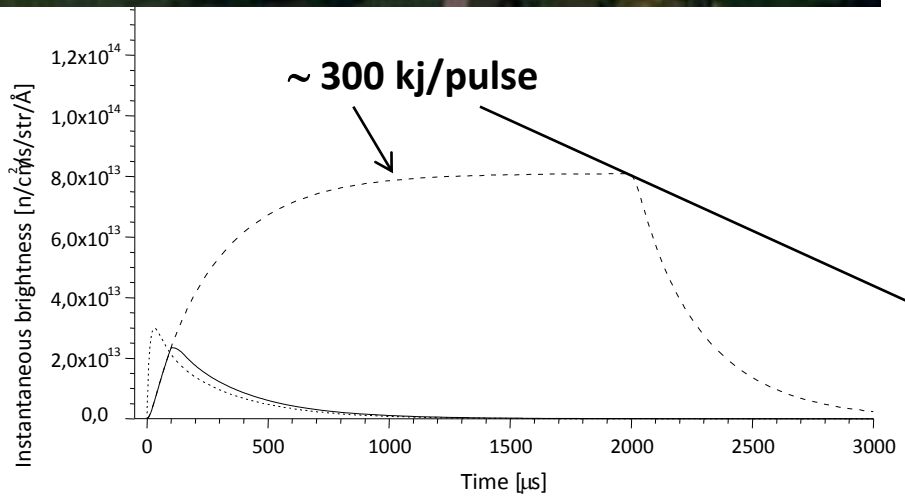
But:

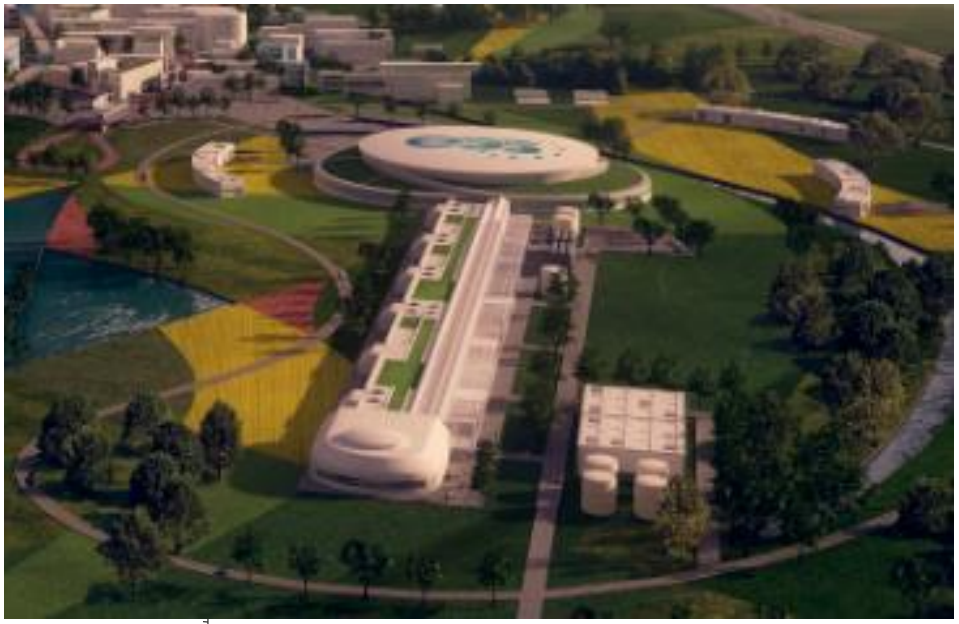
Cost equivalent linear accelerator alone can produce the same **cold neutron pulses by ~100 μs proton pulses at ~ 0.15 GW instantaneous power: 2 x ILL**

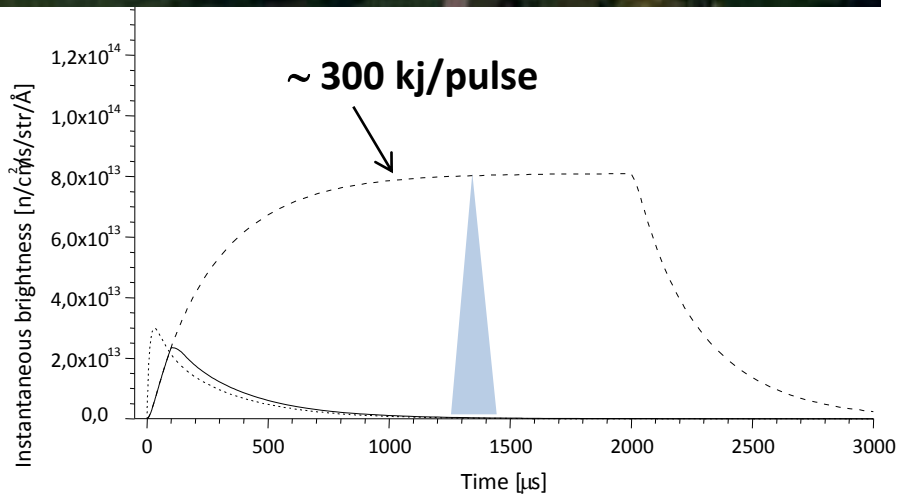




Cost equivalent linear accelerator alone can produce the same cold neutron pulses **by ~100 μs proton pulses at ~ 0.15 GW instantaneous power** → Leave the linac on for **more neutrons per pulse and higher peak brightness…**







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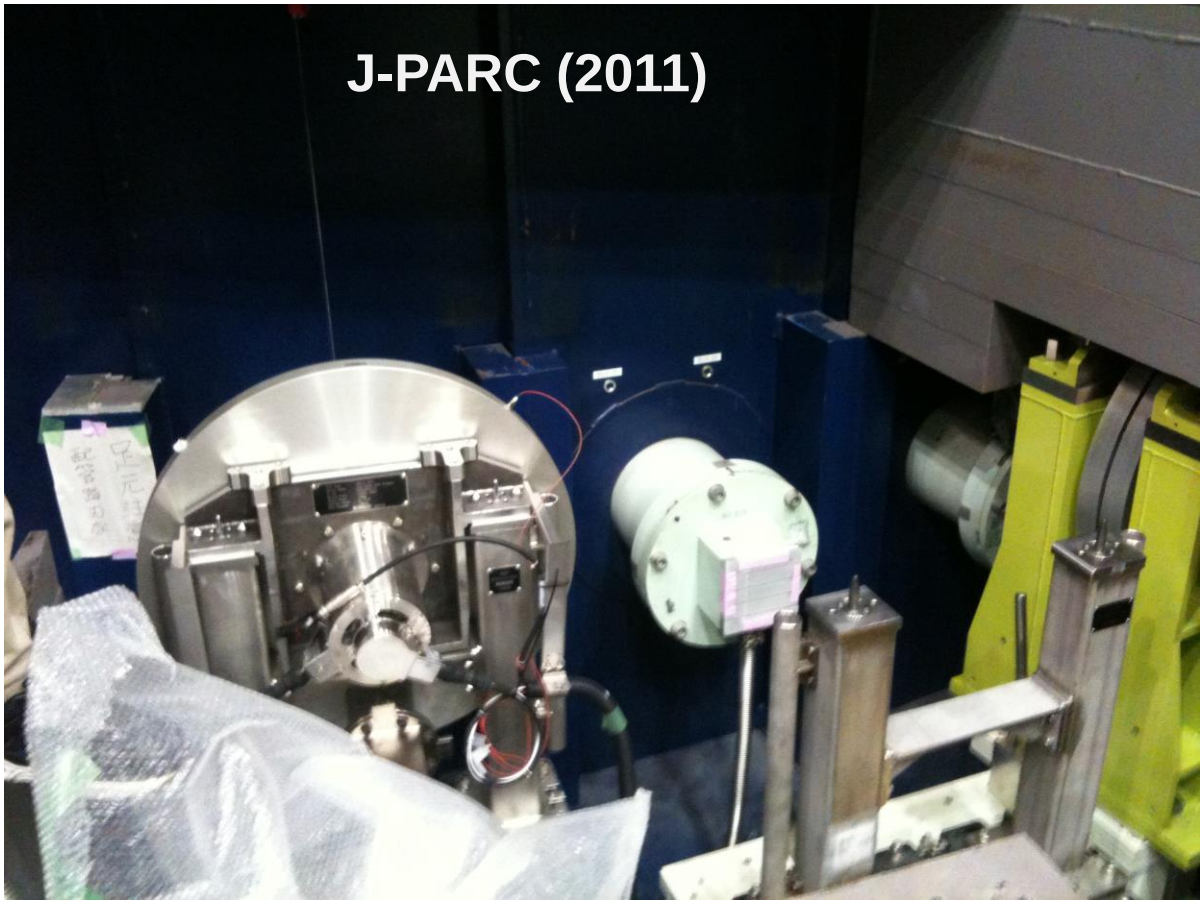
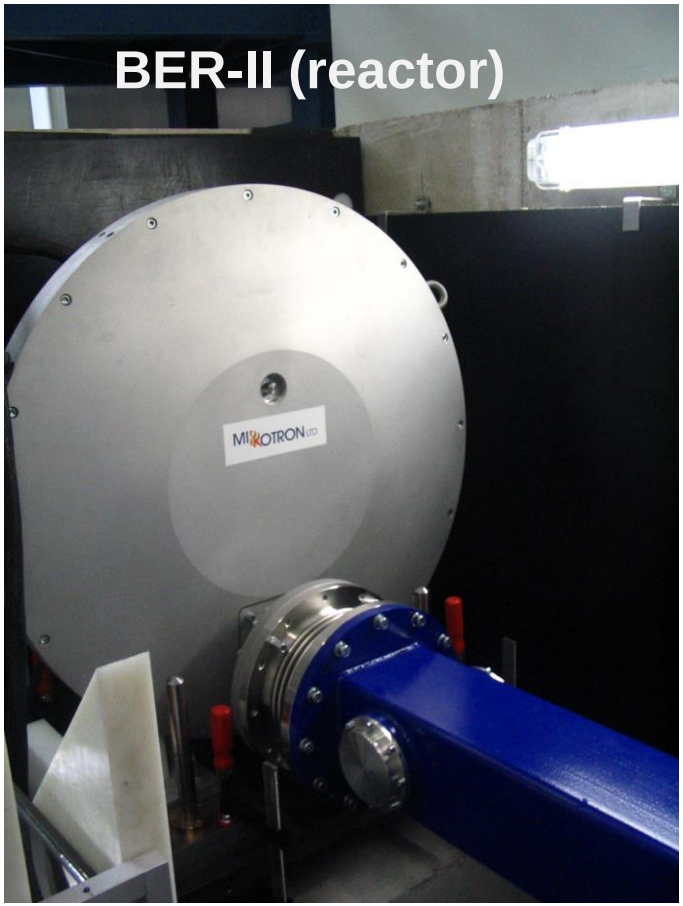
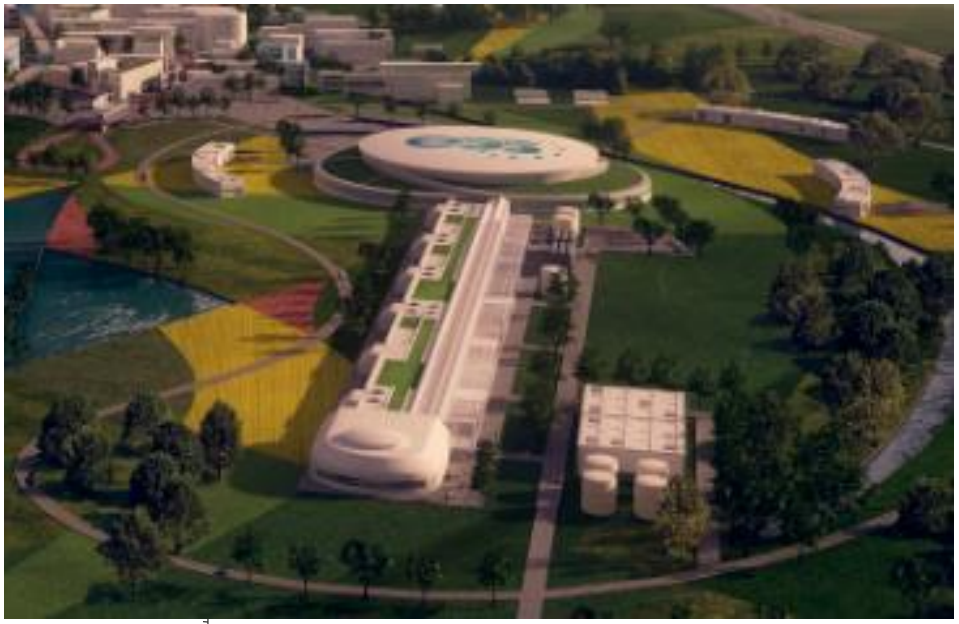
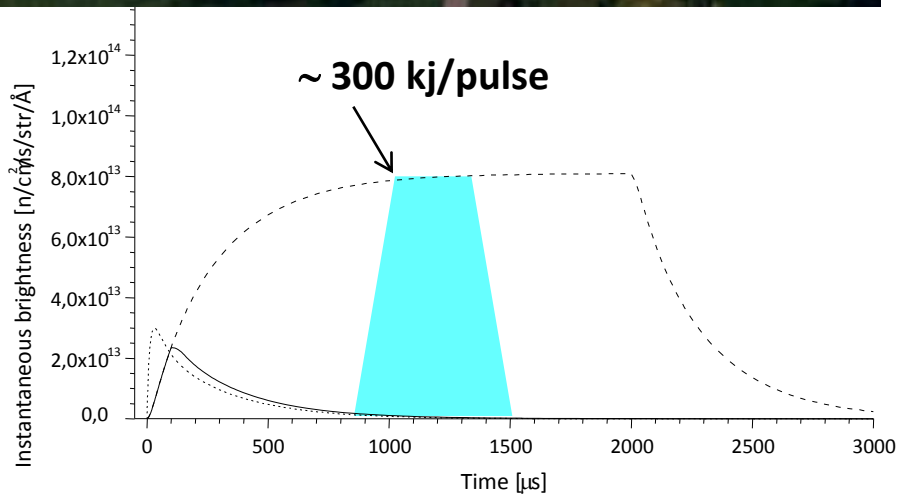
and use mechanical pulse shaping → **Long Pulse source**

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









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…**

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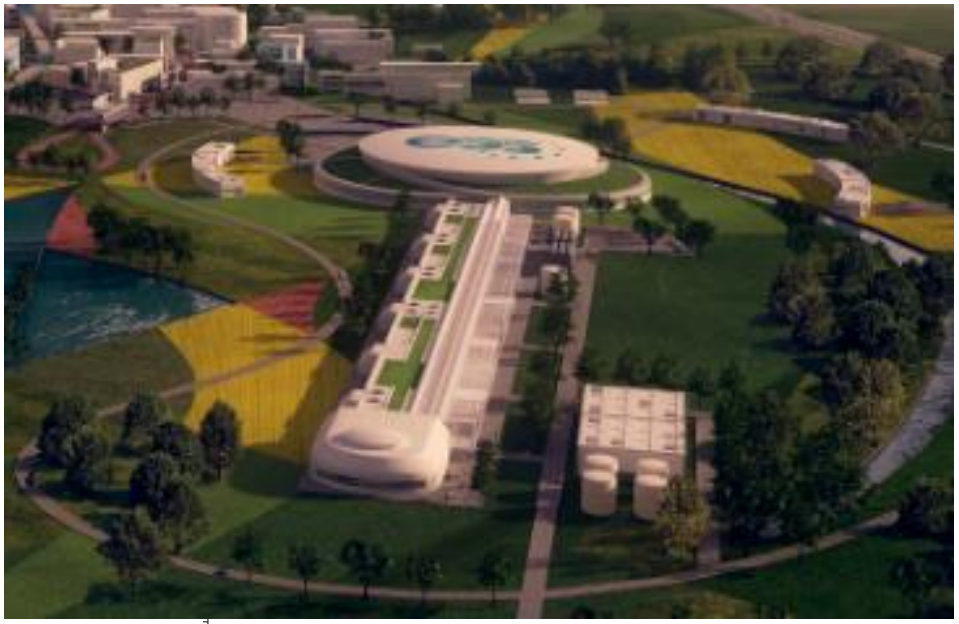
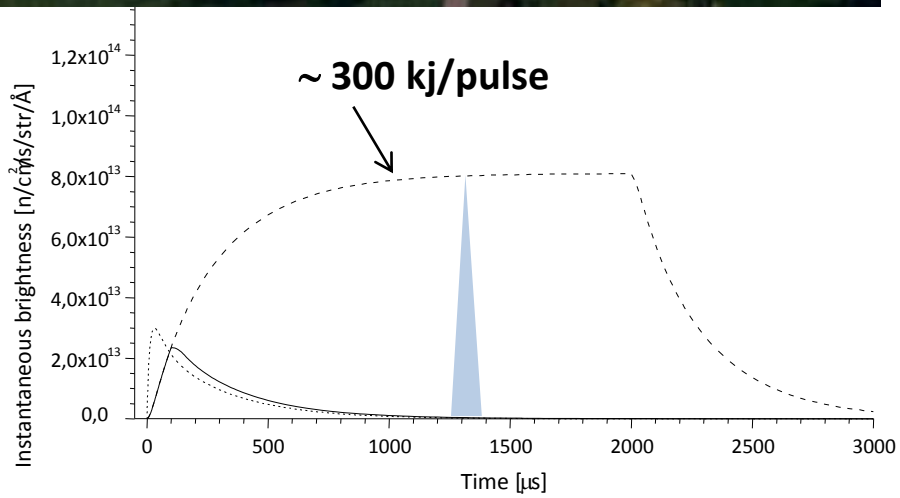
ESS: 5 MW accelerator power → **more neutrons for the same costs and reduced complexity**





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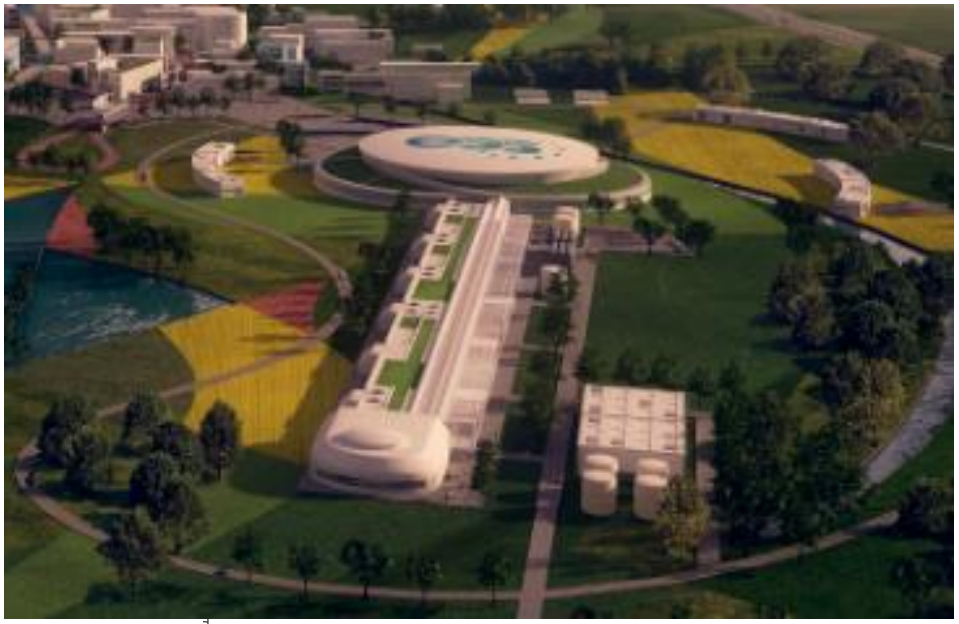

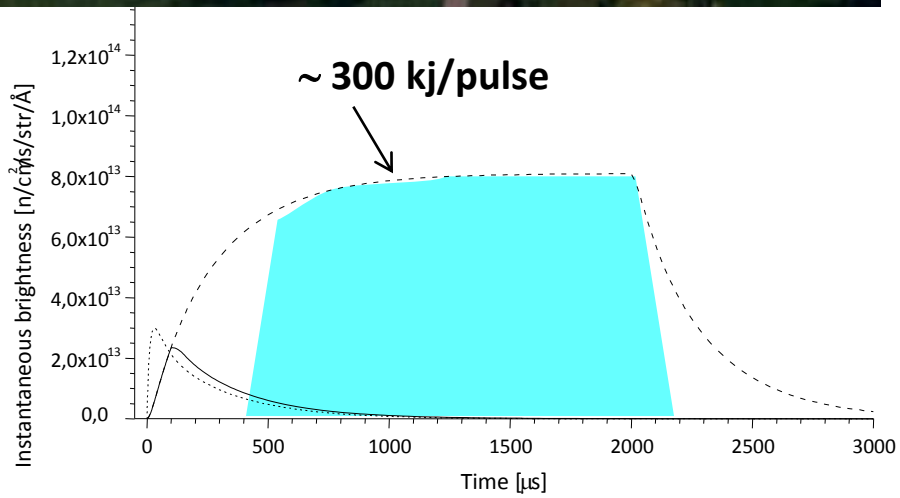

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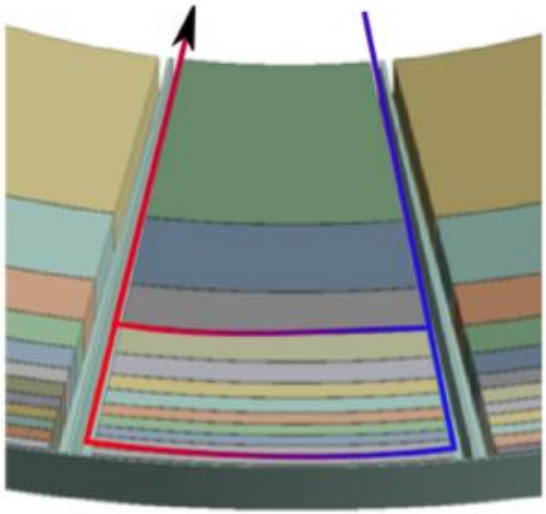
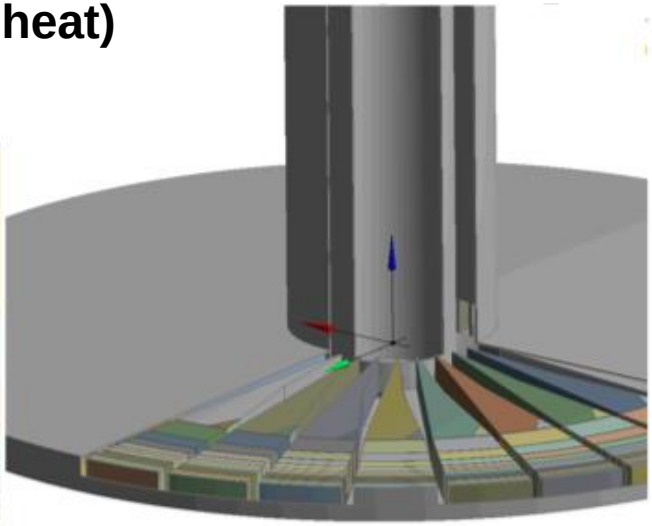
Safe target for high power spallation

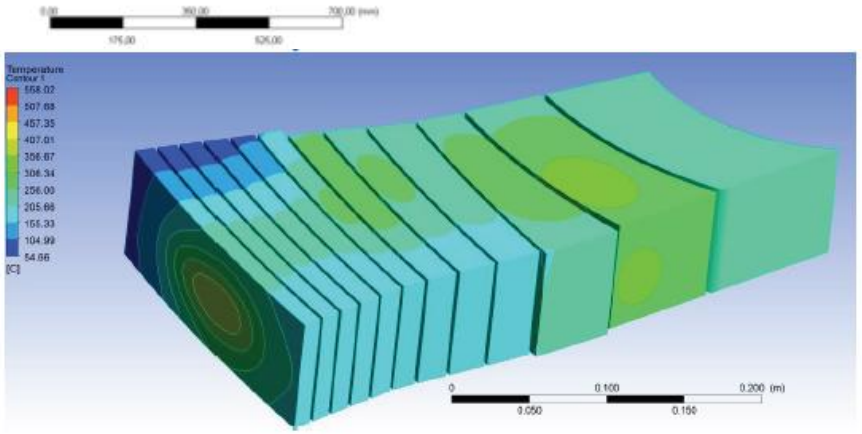
No fissionable material….

but **significant afterheat (decay heat)**

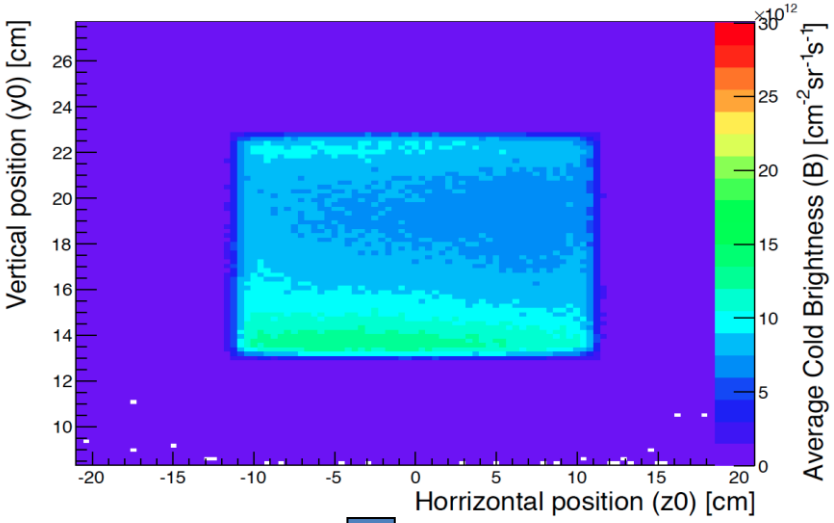
Safe solution: rotating target

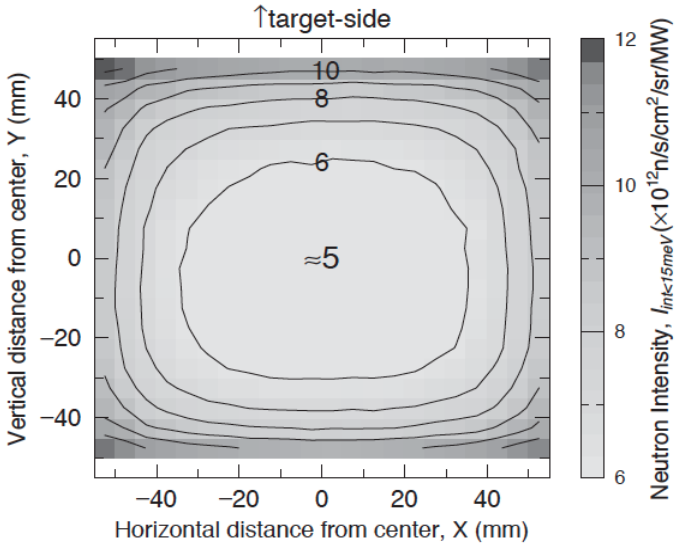




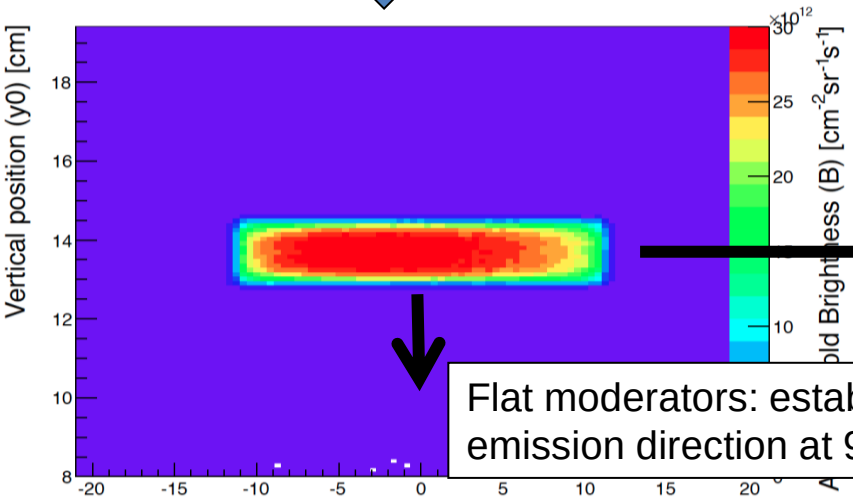


New moderator concept: follow the walls





(Kai et al, 2004)

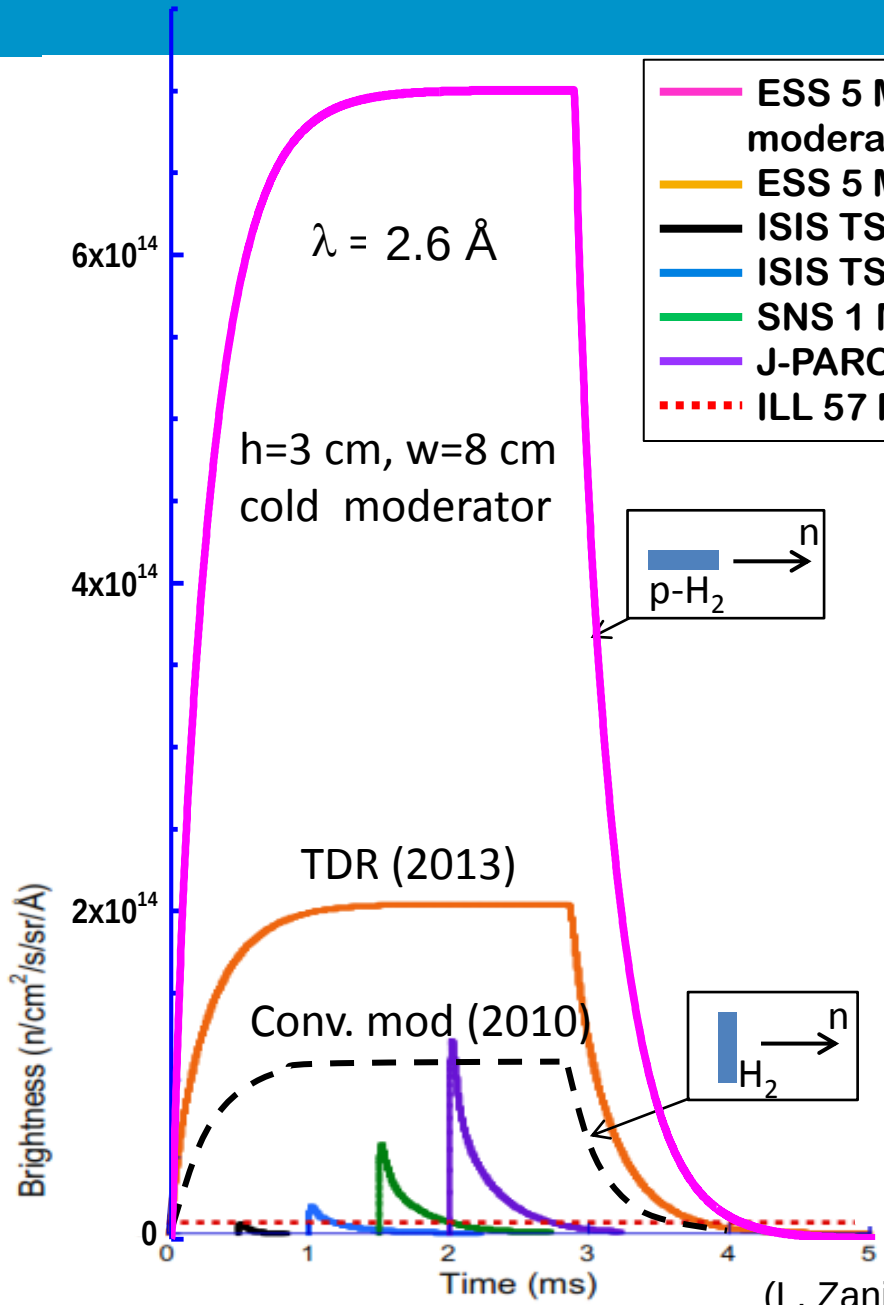


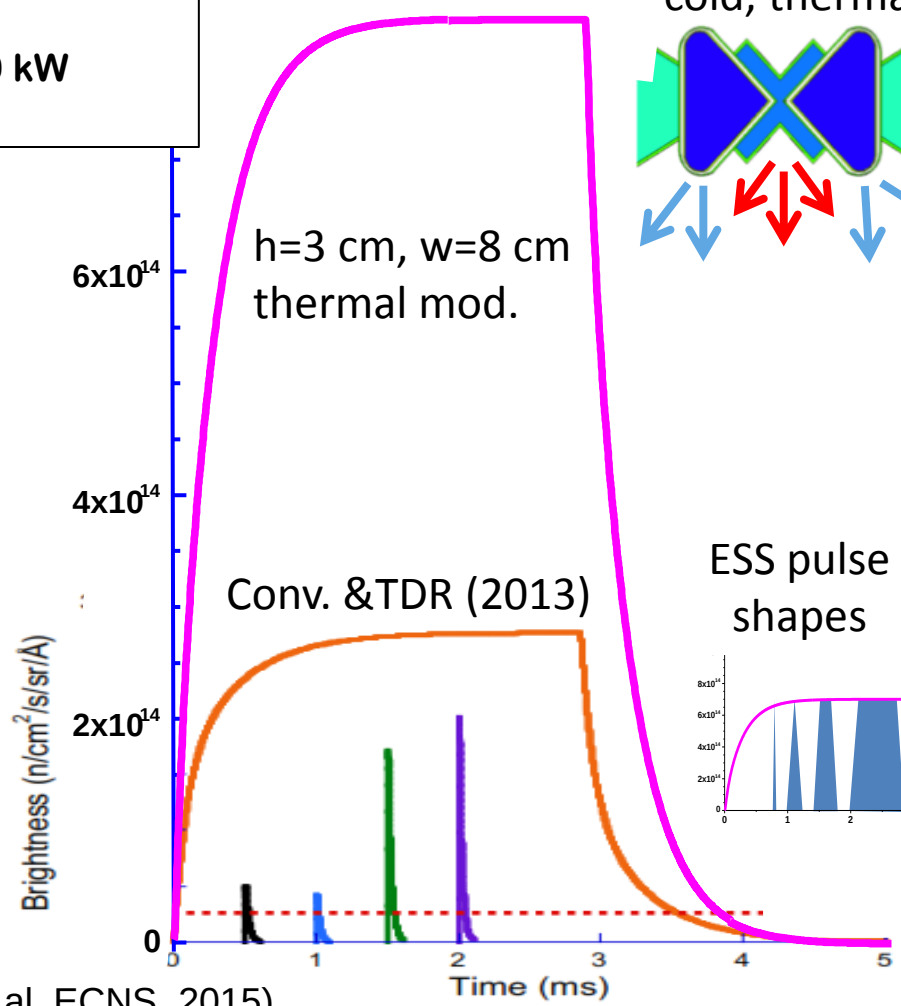
Thermal neutrons arriving from the surroundings are transformed into cold ones within about 1 cm of the walls of the moderator vessel

Direction of high brightness emission

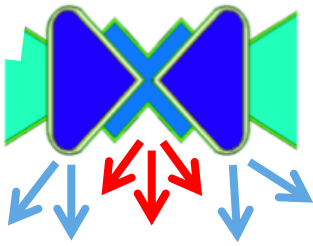
Flat moderators: established practice with emission direction at 90° of preferential directions

Qualitatively new level of beam performance

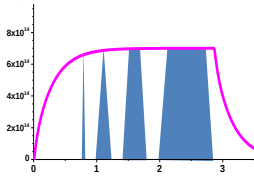




"Butterfly" bi-spectral moderator: cold, thermal

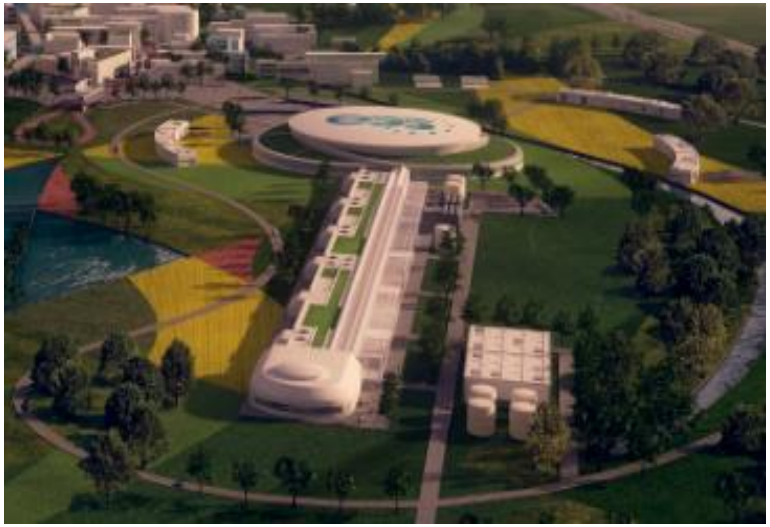


ESS pulse shapes

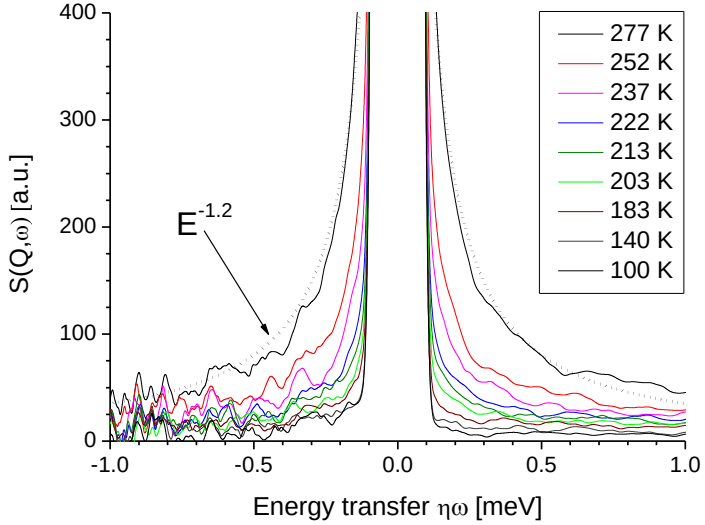


(L. Zanini et al, ECNS, 2015)

New perspectives



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

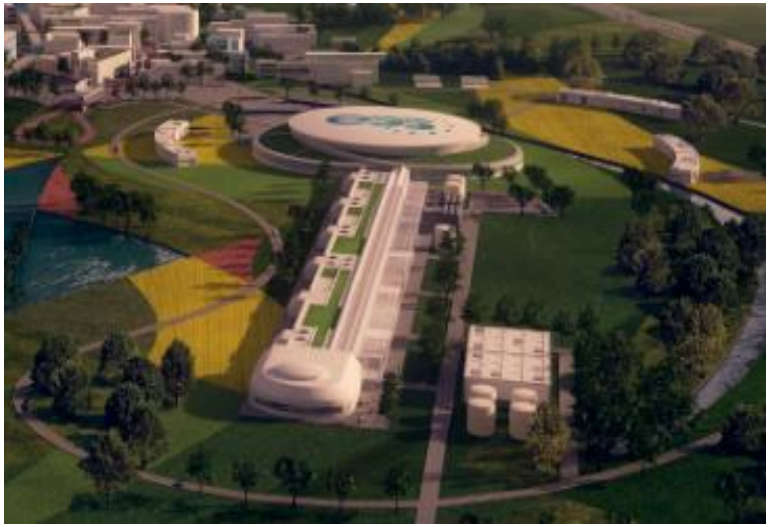


Instrumental progress (x70)
+ new source (x300):

4 h scans → will be made in 1 s

??☹

New perspectives



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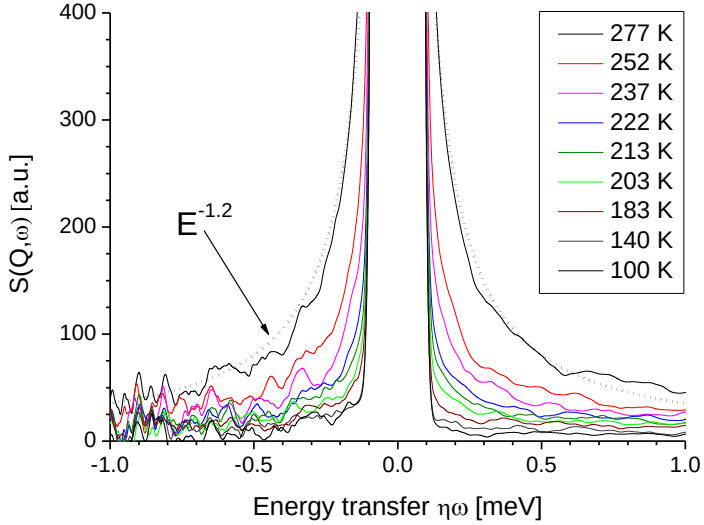


Instrumental progress (x70)
+ new source (x300):

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**

Next generation: ESS

- **Innovative use of established technologies:**
  - **high environmental safety**
  - **lower complexity, new power level is a challenge**
  - **comparable costs to SNS, J-PARC or ILL operations**
  - **order(s) of magnitude higher intensity = sensitivity**
- **Large in-kind fraction, green field site: large challenges**
- **High energy efficiency (35 MW vs. 70 MW at ILL)**
- **Perspectives of European neutron research facilities for ~6000 users:**
  synergetic use: high performance when needed / efficient

Fast neutrons produced / joule heat deposited in target station

Fission reactors:	~ 10^9	(in ~ 50 liter volume)
Spallation:	~ 10^{10}	(in ~ 2 liter volume)
Fusion:	~1.5×10^{10}	(in ~ 2 liter volume)
	(but neutron slowing down efficiency reduced by ~20 times)	
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)

Compact neutron sources

EUROPEAN SPALLATION SOURCE

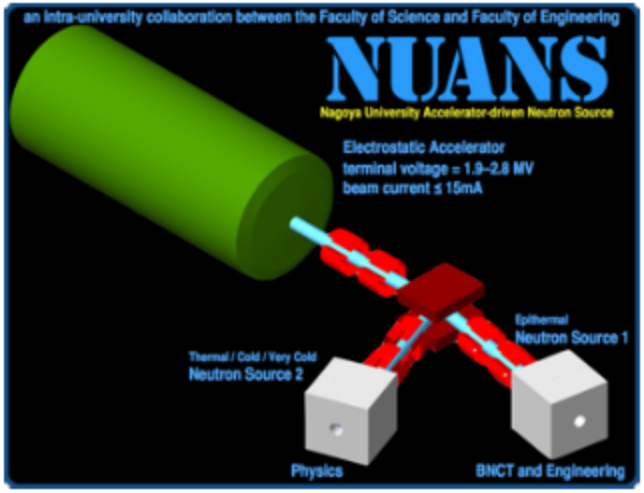
Costs: ~ 10 - 100 M€
Power: 5-50 kW
Flux: ESS / 1000, sufficient for some uses (e.g. radiography)

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

of which multipurpose: 3

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An amazing table top neutron source

Nanoaccelerator by ultrashort, focussed laser pulse on 20 μ D_2O droplet:

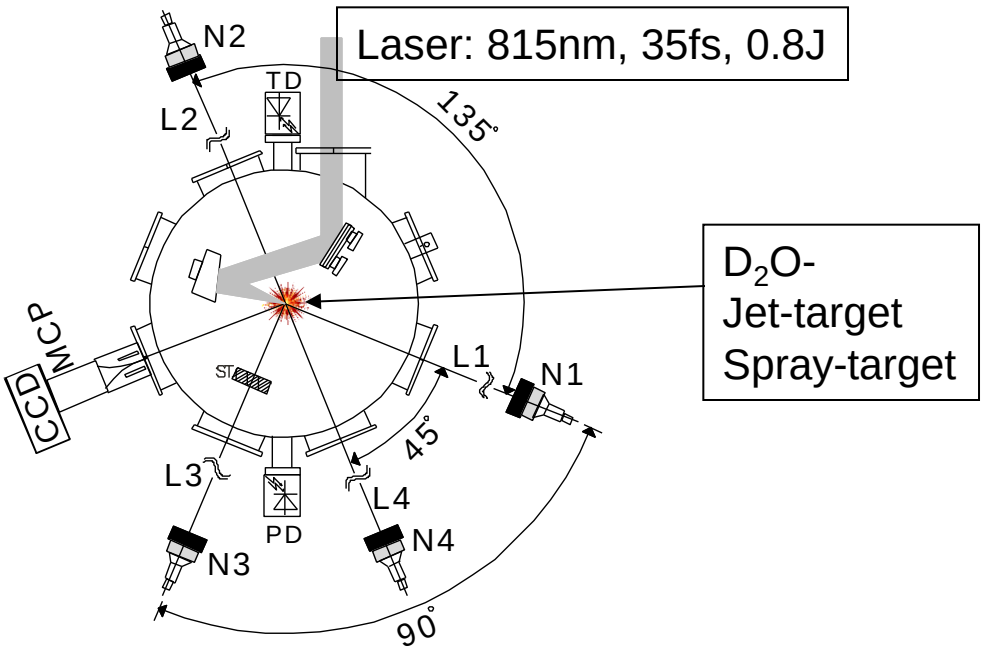
relativistic light intensities, **Field-strength: 1 MV/μm**

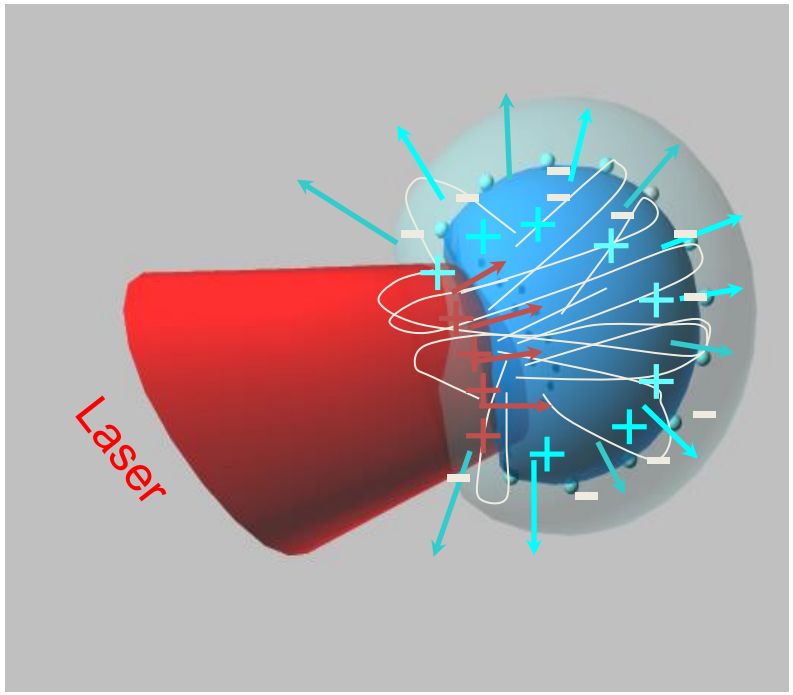
10^{19} W/cm^2 power → plasma → deuterons accelerated to MeV → fusion !

Distribution of neutrons reveals plasma formation mechanism

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

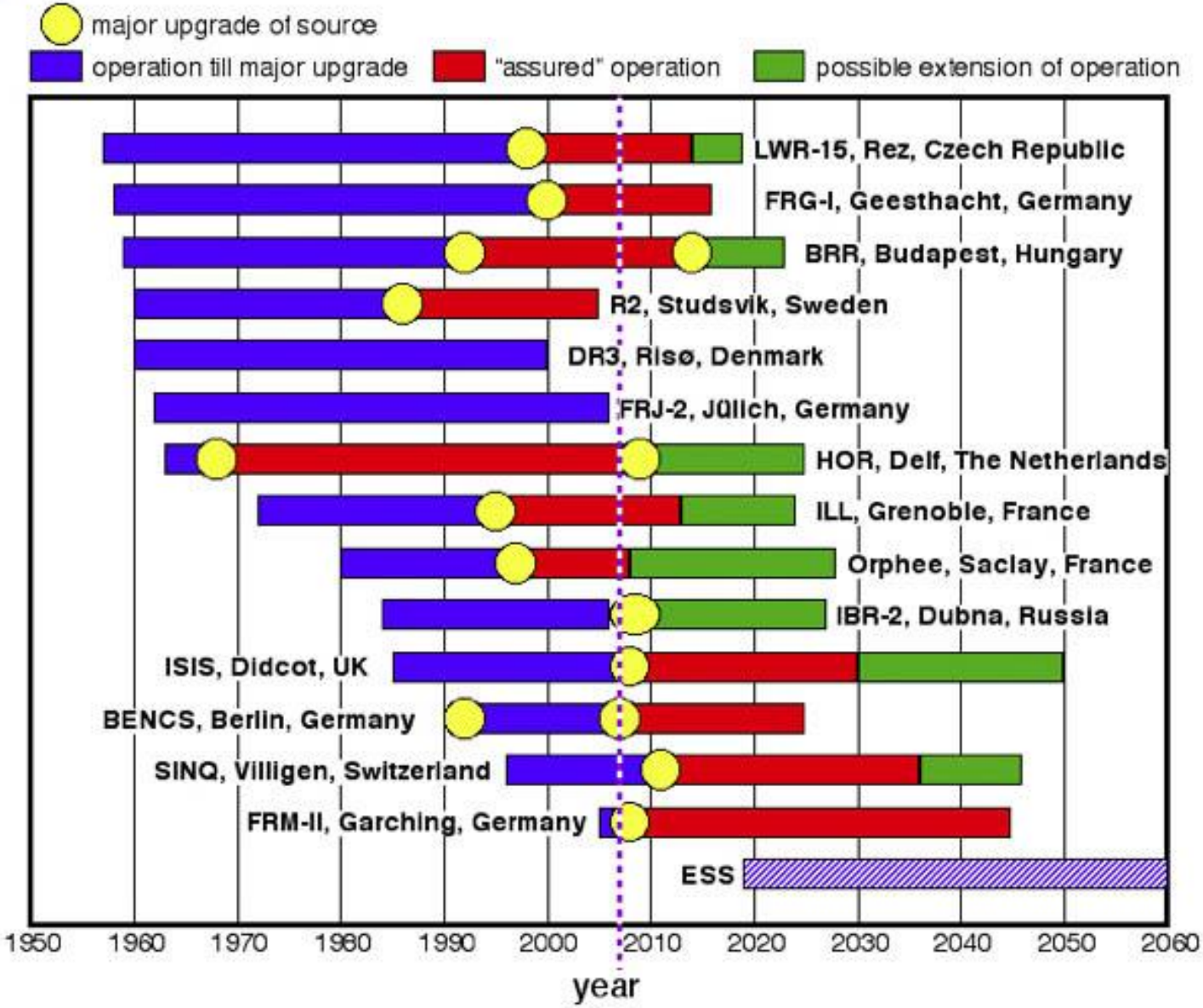
d + D => 3He (0.82 MeV) + n (2.45 MeV): Neutron – spectroscopy





(Max Born Inst, HMI coop)

Neutron research in Europe:
~ 5000 scientists, 11 facilities (and decreasing): ~ 330 M€/a



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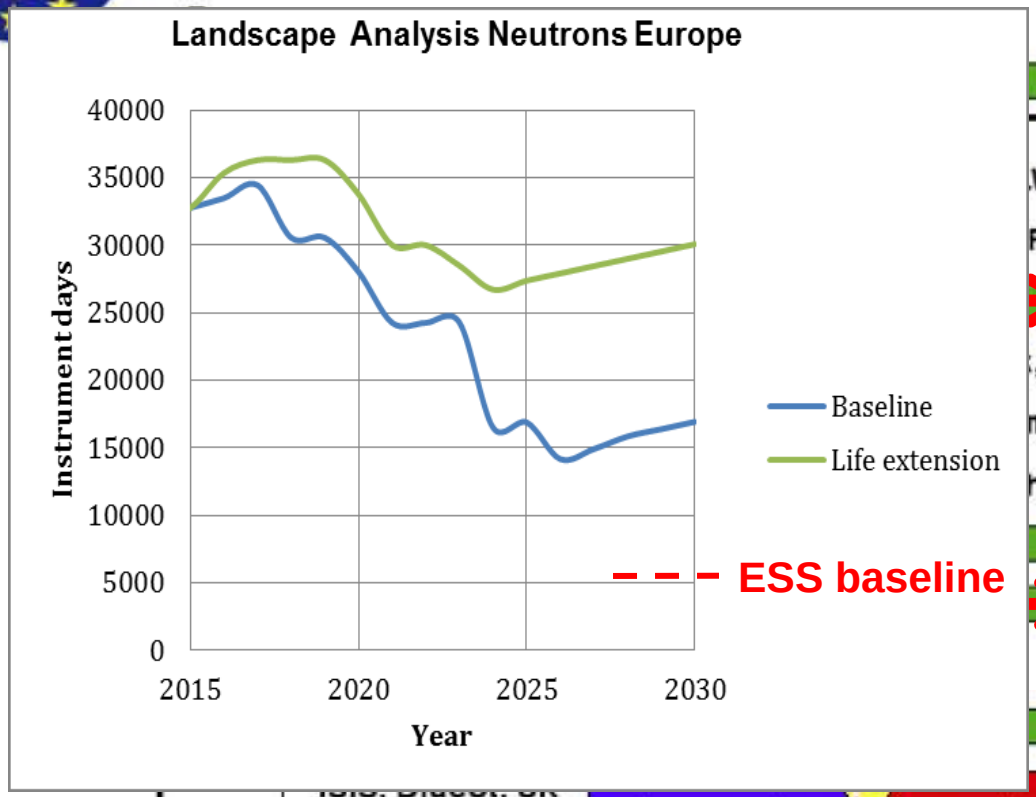

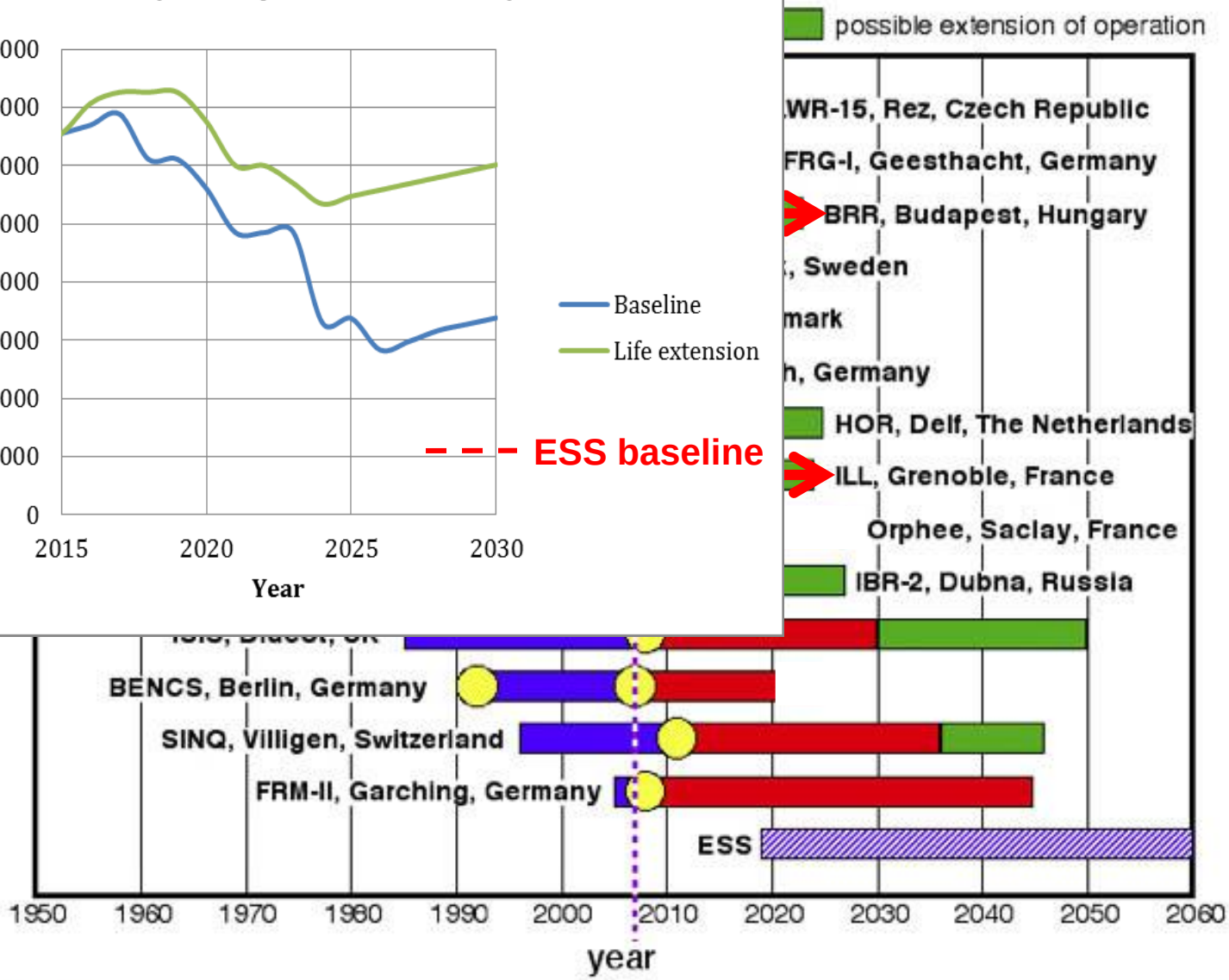

Fast neutrons produced / joule heat deposited:

Fission reactors:	**3×10^{10}**	(in ~ 50 liter volume)
→ Spallation (> 400 MeV):	**2×10^{11}**	(in ~ 2 liter volume)
Fusion:	**4×10^{11}**	(in ~ 2 liter volume)

(but neutron slowing down efficiency reduced by ~20 times)

Electron accel.: (50 MeV)	**2×10^{9}**	(in ~ 0.01 liter volume)
→ Low energy p.: (5 MeV):	**2×10^{8}**	(in ~ 0.001 liter volume)
(35 MeV):	**2×10^{9}**	(in ~ 0.01 liter volume)
Laser induced fusion:	~ **10^{4}**	(in ~ 10^{-9} liter volume)

Spallation: lowest cost per neutron
Compact source: lowest cost per facility

Energy costs are important: 20 % of staff costs at ESS in operation

Conclusions

Trends and opportunities

Multi- MW long pulse spallation sources (e.g. ESS):

- **order of magnitude higher flux / sensitivity for the same costs**
- **order of magnitude better energy efficiency than ILL reactor**
- **2 B€ + 150 M€ operation/year → ~100 k€/publication**
- **energy cost: ~ 15 M€ / year**

Mini (compact) accelerator sources

~ 0.1- 5 % of costs for 0.01 – 0.1 % of neutron production

No use of fissionable materials: access / security simpler

Great potential: neutrons for nuclear waste incineration