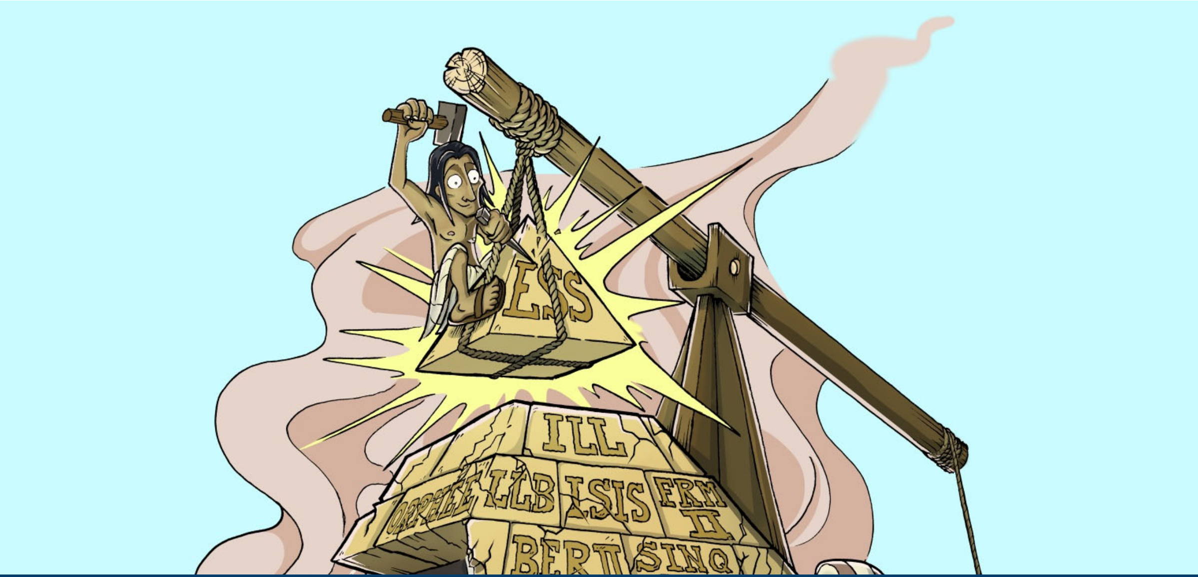


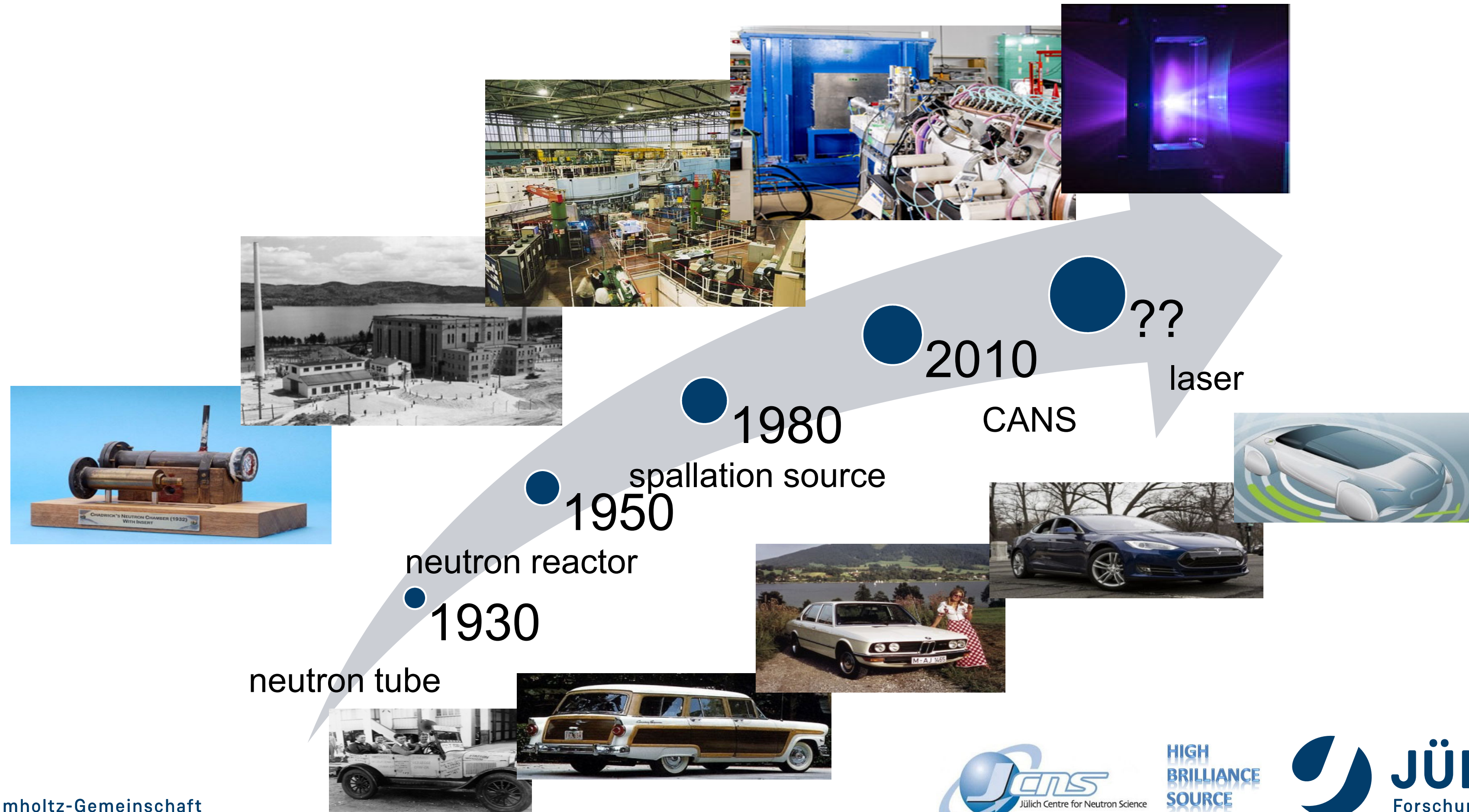
Making ESS a success -

A landscape of European accelerator based neutron sources

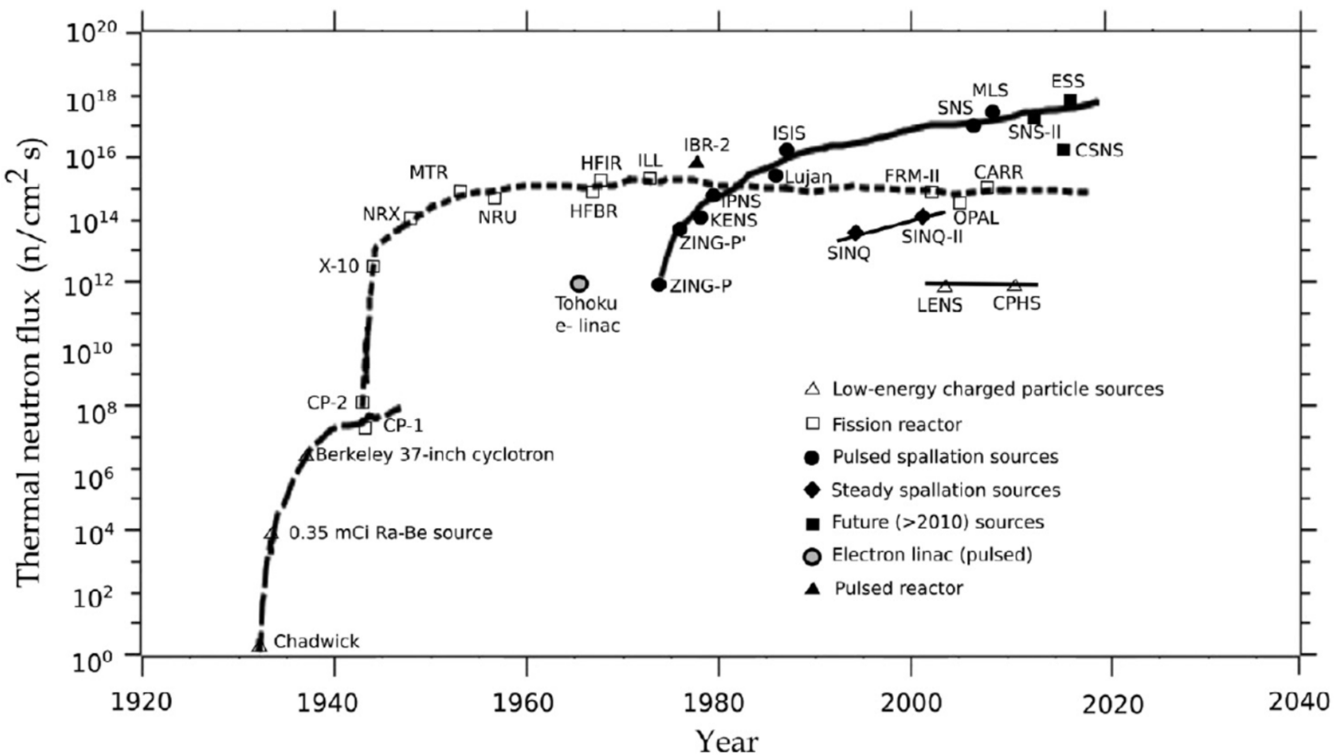
Thomas Gutberlet, JCNS

JÜLICH
Forschungszentrum

Short History of Neutron Sources I



Short History of Neutron Sources II



J.M. Carpenter, W.B. Yelon, Neutron sources, Methods Exp. Phys. 23 (1987) Part A.

Short History of Neutron Sources III

A Network of Sources

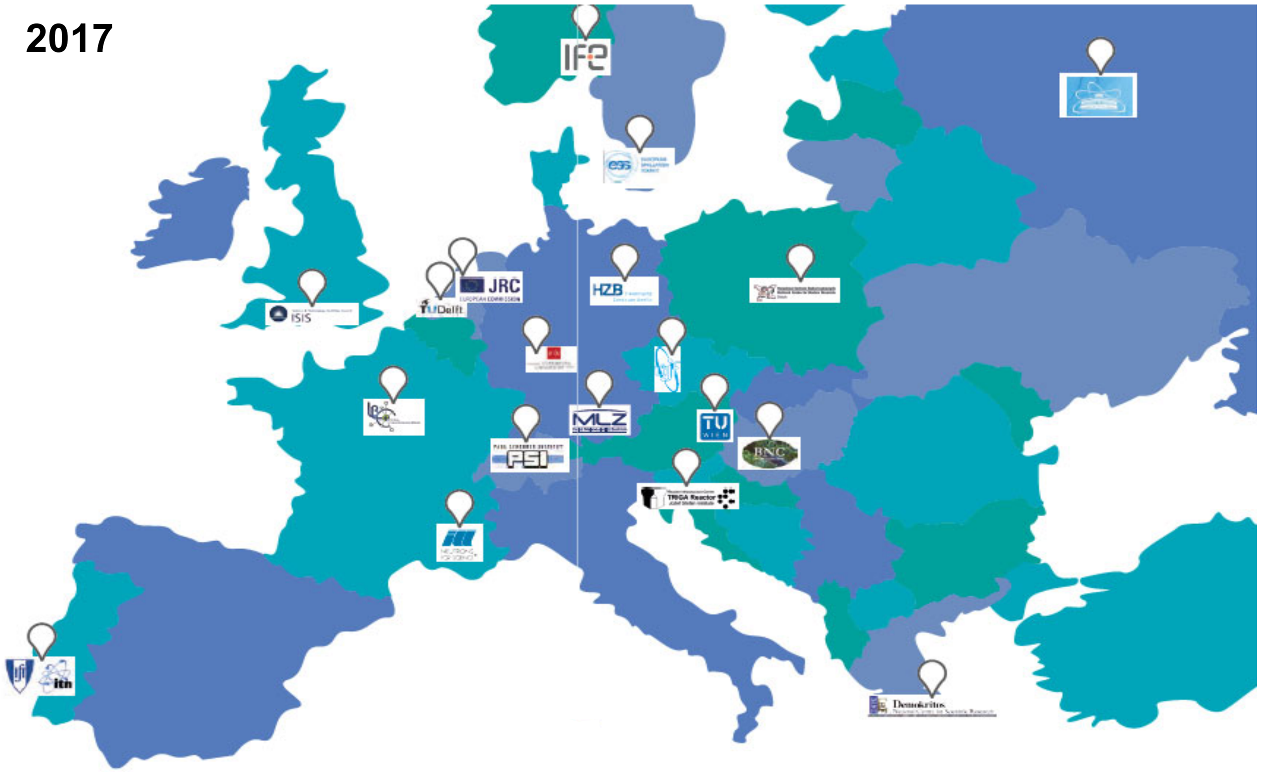
- **ESS, ILL** for flux hungry experiments

- **Medium flux** sources for
  - method development
  - capability
  - user training

- **Low flux** sources
  - at universities
  - (maybe not for
    inelastic instruments)

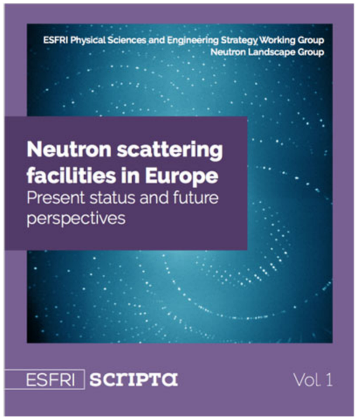
European Neutron Landscape

2017



- 8000 users
- 19 neutron sources in Europe
- 32.000 instrument beam days per year
- 1900 publications each year
- Collaboration and Flow
- New users welcome
- Supporting industry

European Neutron Landscape



www.esfri.eu

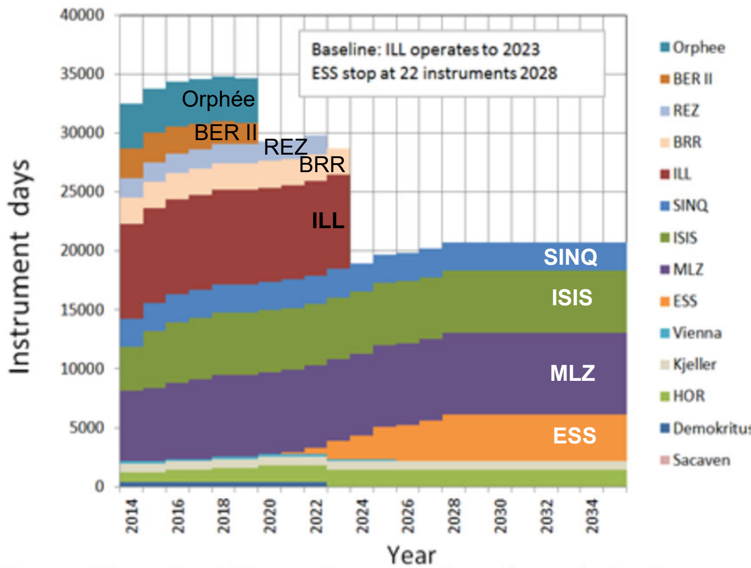


Figure 8. *The predicted delivery of instrument beam days in the Baseline Scenario*

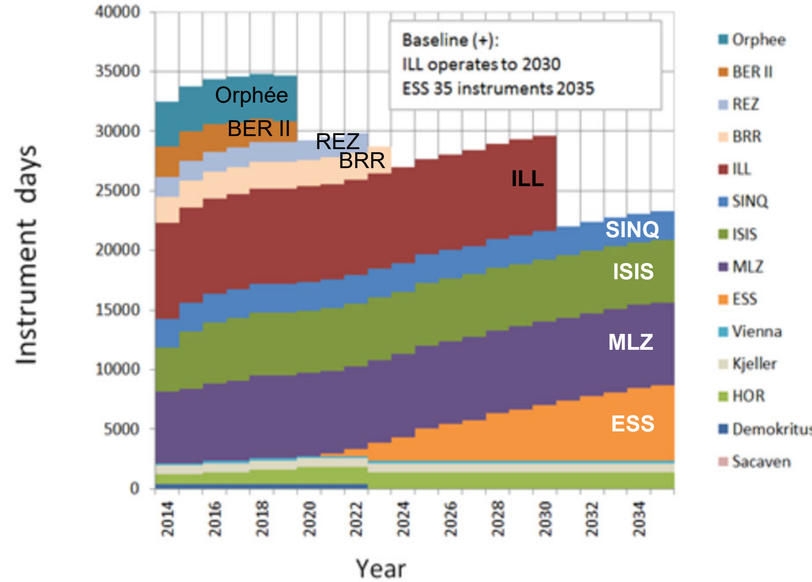
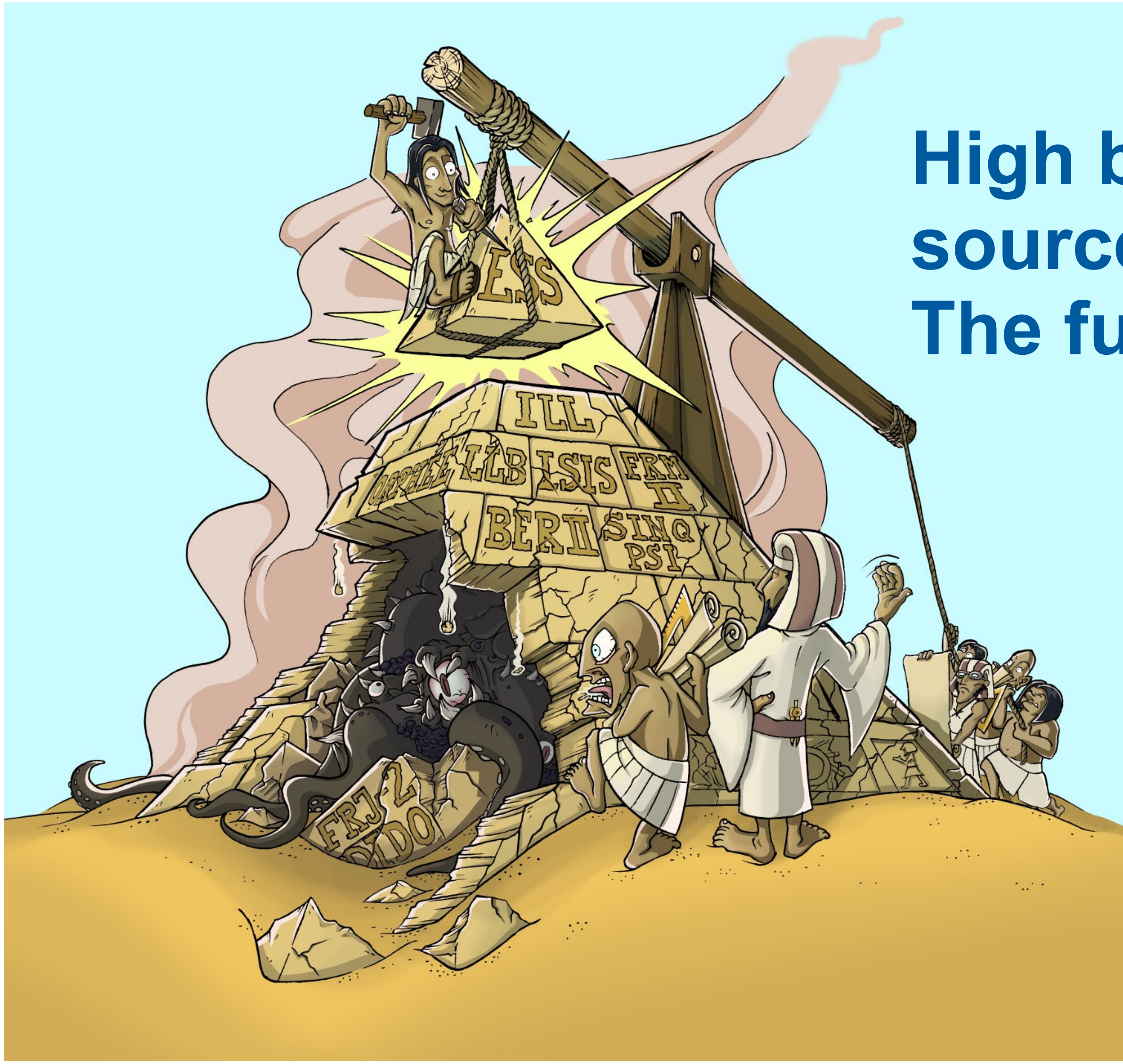


Figure 12. *The predicted delivery of instrument beam days in the Enhanced Baseline Scenario*

Loosing 1/3 of capacity within the next decade !

High brightness sources: The future ???

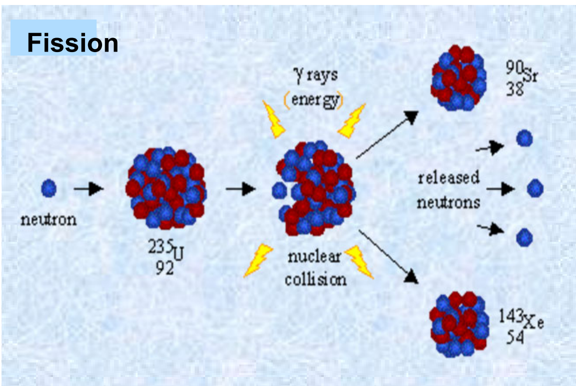


Neutron Landscape – the global view

Mitglied der Helmholtz-Gemeinschaft

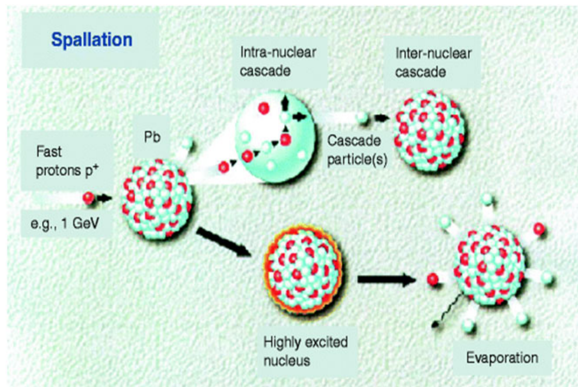
Neutron Production

Nuclear fission



Reactor based neutron source
(ILL, FRM II, NIST, JINR, ANSTO a.m.m.)

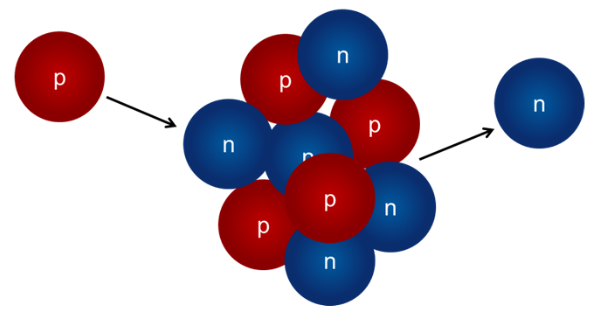
Spallation



Spallation based neutron source
(ESS, ISIS, SINQ, SNS, CSNS, J-PARC, KEK)

Nuclear processes

$$proton \quad + \quad {}^{9}_{4}Be \quad \rightarrow \quad neutron \ (+ {}^{9}_{5}B)$$



Accelerator based neutron source
(LENS, RANS, HUNS, NUANS, IREN a.o.)

Neutron Production

Nuclear Process	Example	Neutron Yield	Heat Release [MeV/n]	Source
D-T in solid target	400 keV d on T in Ti	4×10^{-5} n/d	10000	
Deuteron stripping	40 MeV d on liq. Li	7×10^{-2} n/d	3500	
Nuclear photo effect from e-Brems-strahlung	100 MeV e^- on ^{238}U	5×10^{-2} n/e^-	2000	HUNS, n-ELBE
$^{9}Be(d,n)^{10}Be$	15 MeV d on Be	1.5×10^{-2} n/d	1000	
$^{9}Be(p,n:p,pn)$	11 MeV p on Be	4×10^{-5} n/d	2000	RANS, LENS
Nuclear fission	Fission of ^{235}U by thermal neutrons	1n/fission	180	MLZ, ILL
Spallation	800 MeV p on ^{238}U or Pb	27 n/p or 17 n/p	55 or 30	ISIS, SINQ, ESS

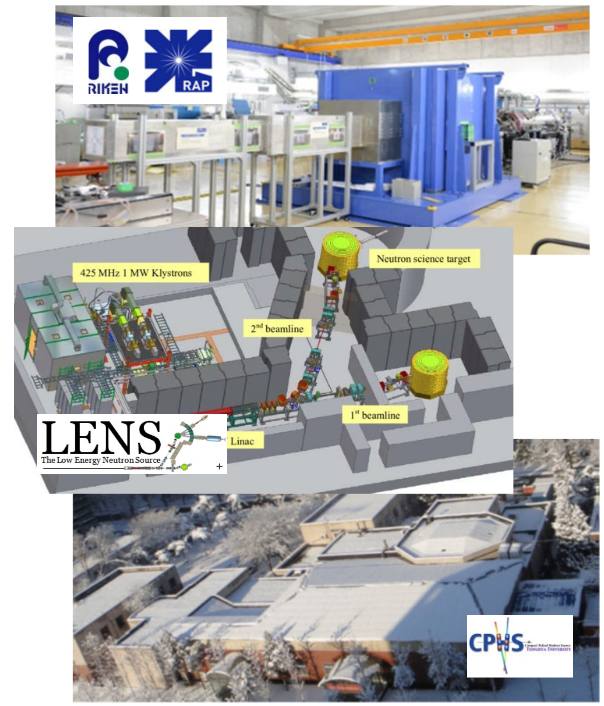
Ref.: G. Mank, G. Bauer, F. Mulhauser, Accelerators for Neutron Generation and Their Applications, Rev. Accl. Sci. Tech 04, 219 (2011)

Neutron Production

Nuclear fission

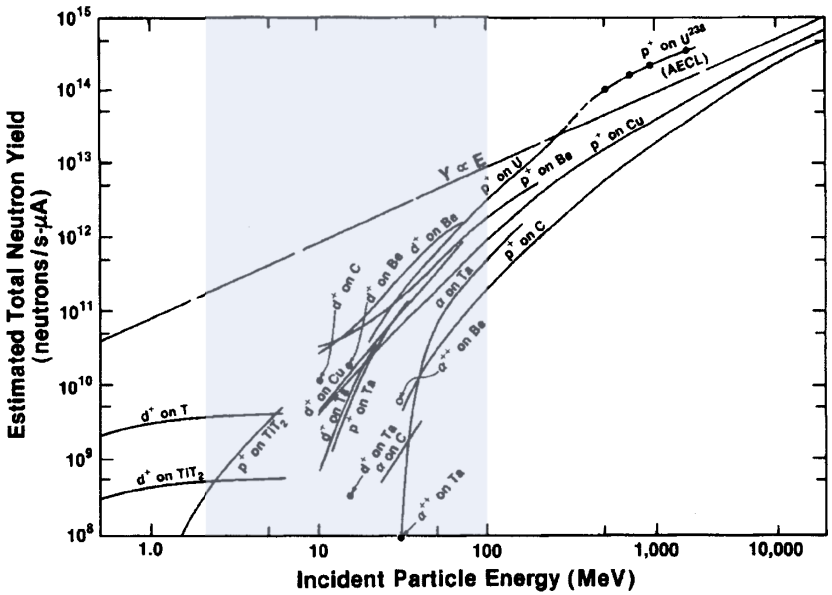
Spallation

Nuclear processes



Neutron Production

Low energy nuclear processes



J. Carpenter, C.-K. Loong, Elements of Slow-Neutron Scattering, Cambridge University Press, 2015

Nuclear process	E [MeV]	n/ion	n/(s mA)	n/(s kW)
p ⇒ Be	50	2.70%	1.68E+14	3.37E+12
d ⇒ Be	50	5.90%	3.69E+14	7.38E+12
p ⇒ Li	20	0.33%	2.08E+13	1.04E+12
p ⇒ V	50	5.08%	3.18E+14	6.35E+12
p ⇒ Ta	50	6.40%	4.00E+14	8.01E+12
p ⇒ W	50	6.95%	4.35E+14	8.70E+12

Neutron Production

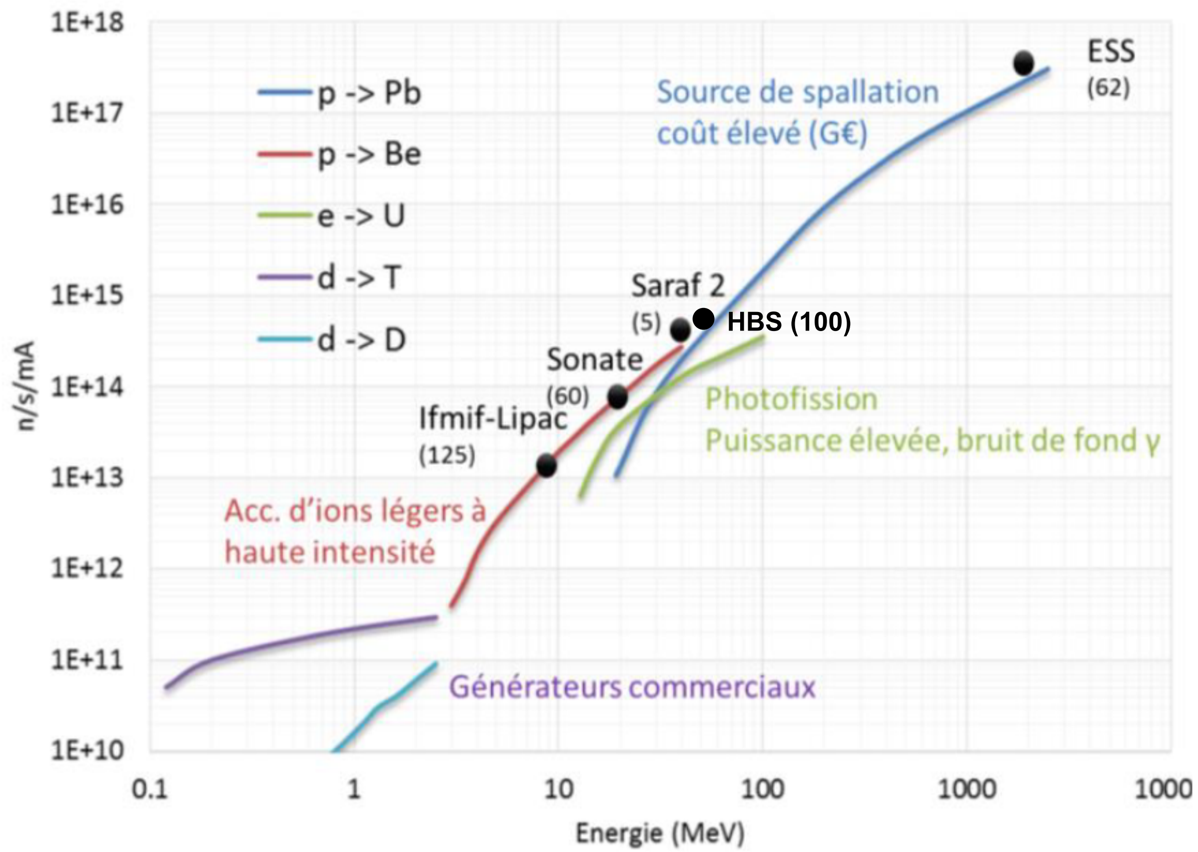


Figure 1: Neutron production using particle accelerators

Ref.: LLB – Compact Neutron Sources for Neutron Scattering

Accelerator Based Neutron Sources

Advantages / drawbacks of CANS

- Low energy protons (10-100 MeV vs 1 GeV)
- "Light" shielding (20-100 tons vs 6000 tons)
- Instrument line starts from the inside of the moderator
- Less high energy neutrons (less secondary background)
- Reduced costs
- Accelerator of 20-100 m versus 600 m at ESS
- CANS is not a nuclear facility
- CANS are scalable on demand

- Flux is intrinsically limited by peak current (I_{peak} ~ 100 mA)

Accelerator Based Neutron Sources

Scalable Neutron Sources

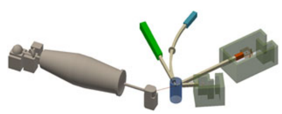
0.01 kW	0.1 kW	1 kW	10 kW	100 kW
0.001-0.01 mA	0.01-1 mA	0.5-5 mA	1-20 mA	50-100 mA
~10^{11} n/s	~10^{12} n/s	~10^{13} n/s	~10^{14} n/s	~10^{15} n/s

10 Mio EUR → 400 Mio EUR

HOKKAIDO UNIVERSITY

MIRROTRON THE WORLD OF NEUTRON

RIKEN RAP

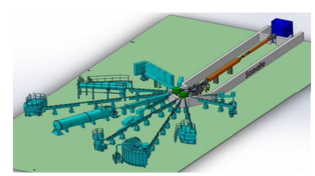


NOVA ERA

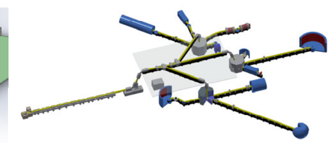
LENS The Low Energy Neutron Source + JCNS Jülich Centre for Neutron Science HIGH BRILLIANCE SOURCE

Prototype

Sonate NEUTRONS FOR MATERIALS SCIENCE



JCNS Jülich Centre for Neutron Science HIGH BRILLIANCE SOURCE



- **Closing the gap and shaping the future**

Accelerator Based Neutron Sources


Physics Reports 654 (2016) 1–58

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ELSEVIER

Research opportunities with compact accelerator-driven neutron sources

CrossMark

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[a] Oak Ridge National Laboratory, Oak Ridge, TN, USA
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[c] CNR-IPCF Sezione di Messina, Messina, Italy
[d] Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, Roma, Italy
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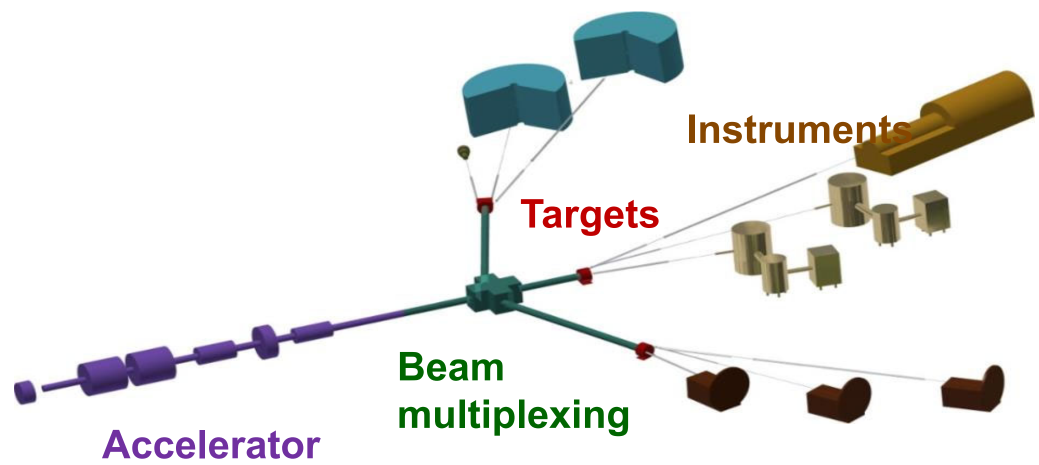
Accelerator Based Neutron Sources

- Accelerator driven pulsed neutron source
- Optimized for neutron scattering on small samples
- Low- or medium flux neutron laboratories
- Reasonable costs (~10 to ~300 MEUR)

Holistic optimization of

- Accelerator
- Target
- Moderator
- Instrumentation

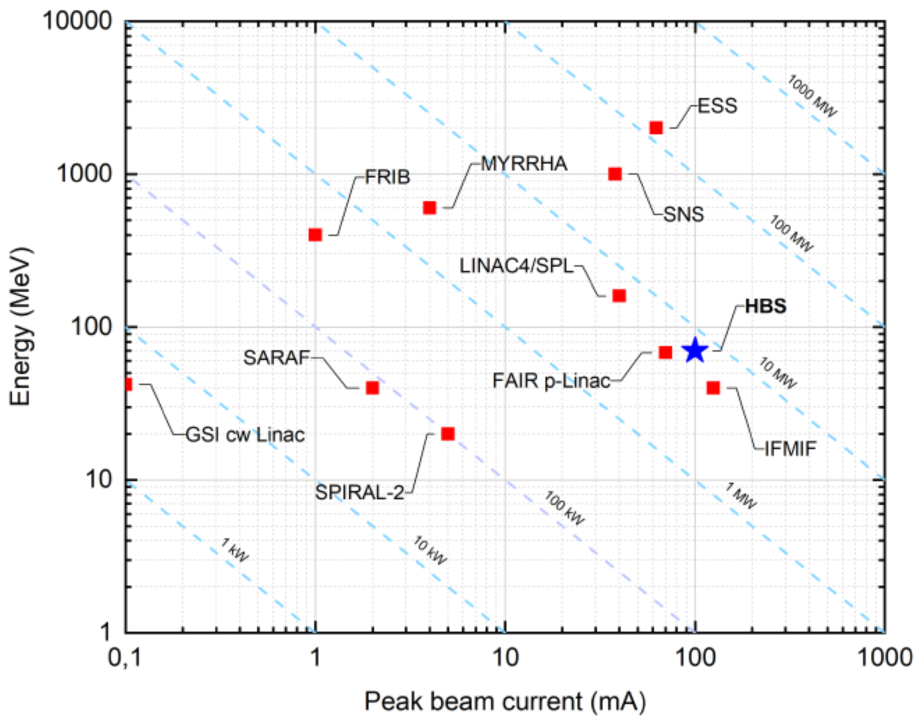


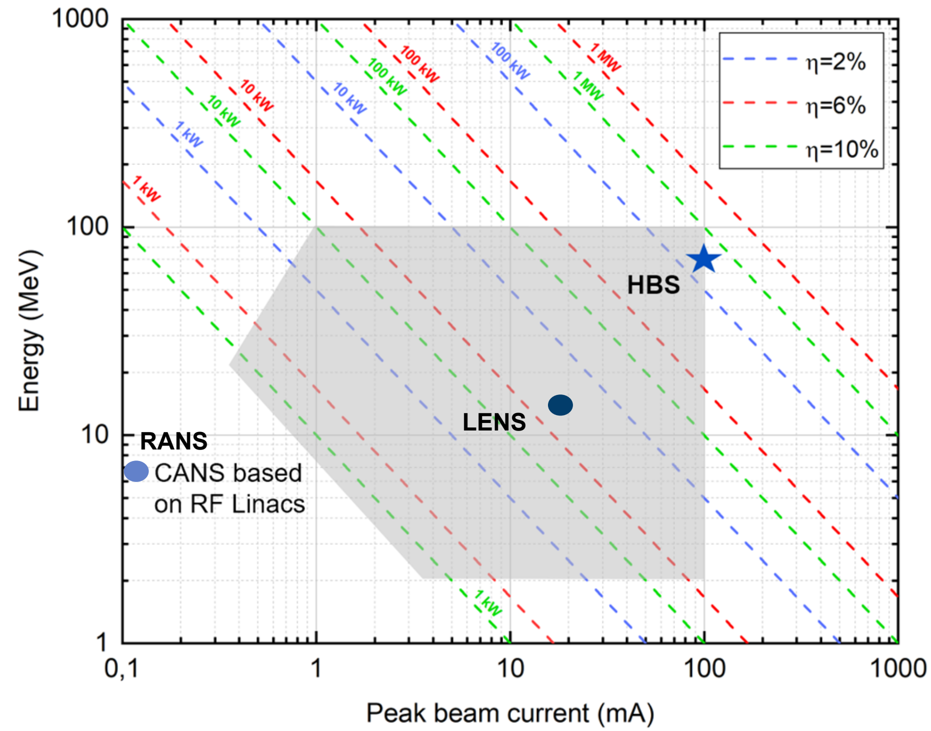
Accelerators

Accelerator type	Advantage	Disadvantage
Cyclotron	• Proven technology • Commercially available • Lower floor space requirement	• Usually offered for CW beams Beam intensity is limited to roughly a few mA
Electrostatic accelerator	• Variation of beam energy and particle species over a wide range • High currents up to about 50 mA • Low power and low cost	• Limited in beam energy. A few tens of MeV are commercially available • Not a compact design
RFQ / LINAC	• Low power and stable operation Variable pulse structure and CW operation • Repetition rate of several 100 Hz • Peak current up to about 100 mA	• High price level, a lot of experience in accelerator science and not simple to operate and maintain if not turn-key systems
FFAG (Fixed-Field Alternating-Gradient accelerator)	• Low cost, compact design • High pulse repetition (kHz range) and flexible pulse length • Large momentum acceptance	• Presently not commercially available • High-power operation not demonstrated

Accelerators

Peak beam power and average beam power levels of proton linacs

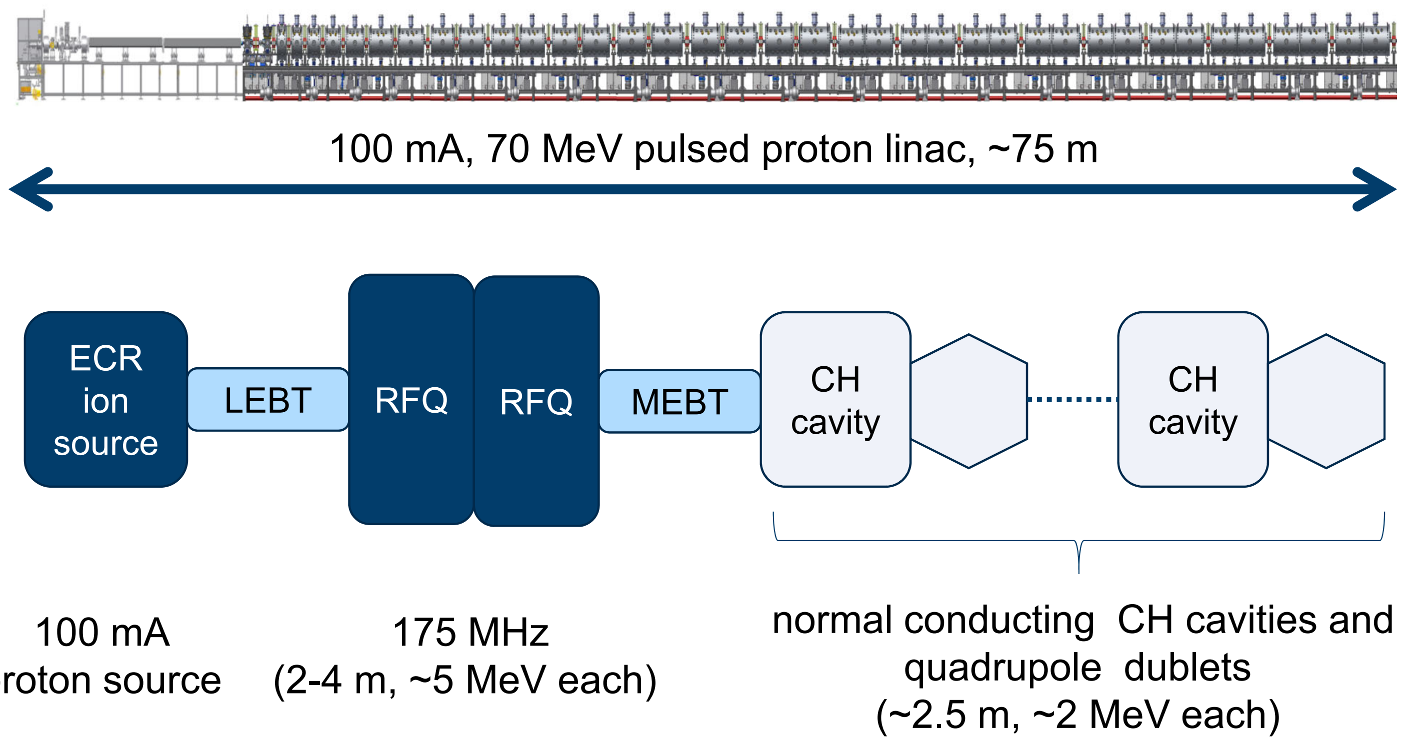




Accelerators

Concept of the HBS-Accelerator

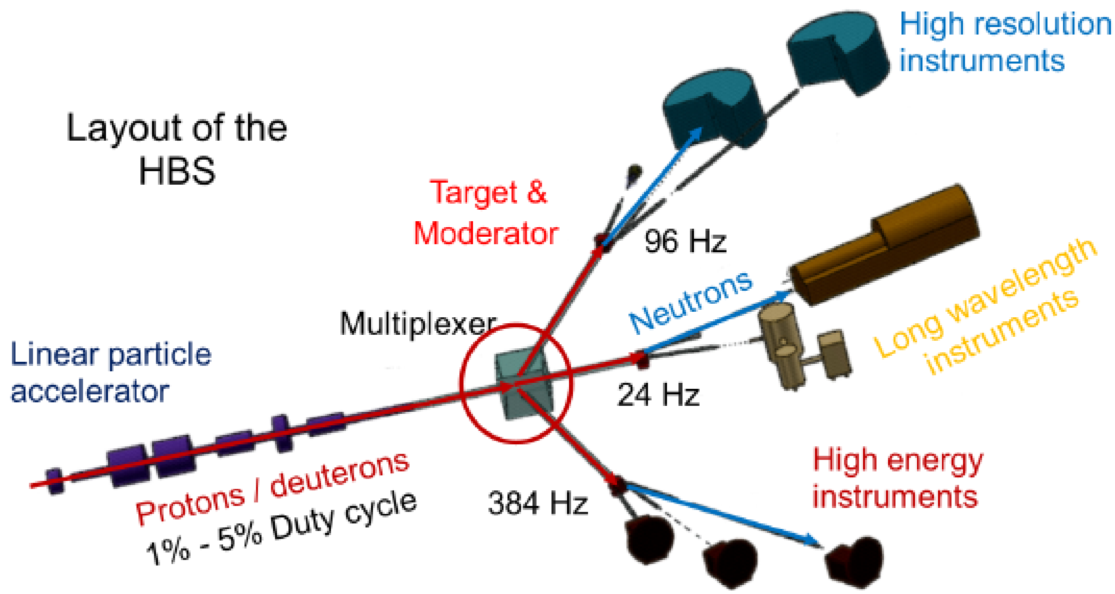
Parameter	Value	Unit
Particles	Protons	
Energy	70	MeV
Current	100	mA
Pulse length	52/208/833	µs
Rep rate	384/96/24	Hz
Duty cycle	6	%
Frequency	176.1	MHz
Beam power	420	kW

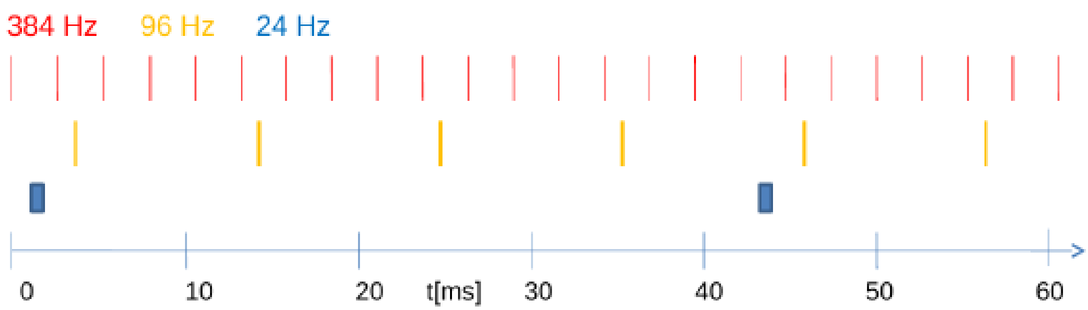


Distributing the protons

Multiplexer

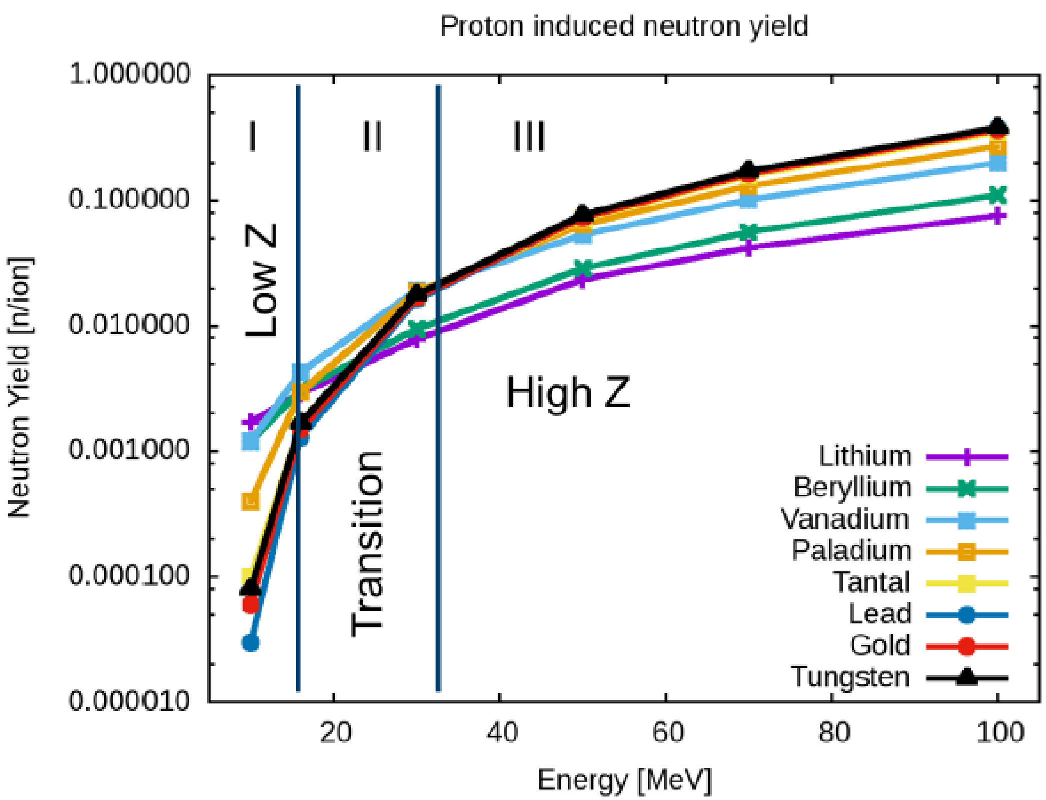
- Separate proton beam to 3 different target stations
- Duty cycle of 2%
  T_{384} = 2.6 ms t_{384} = 52 µs
  T_{96} = 10.4 ms t_{96} = 208 µs
  T_{24} = 41.7 ms t_{24} = 833 µs





Neutron Production

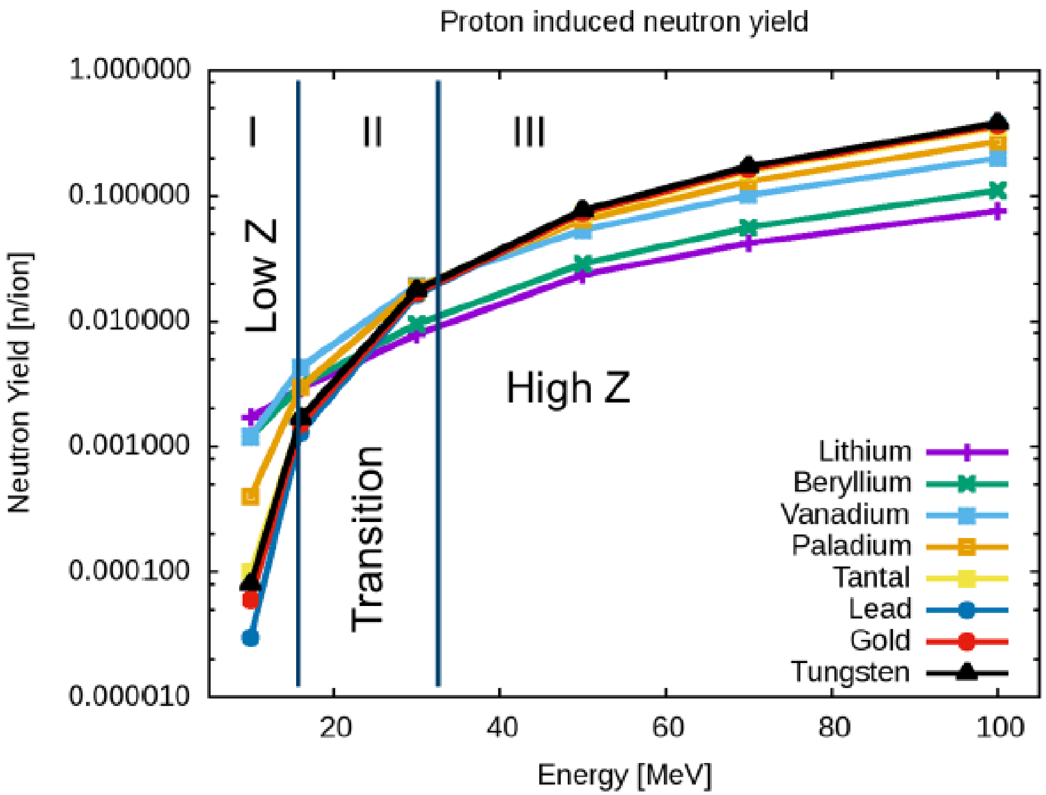
Target material



- Above 35 MeV, high Z-material preferable
- Power up to 100 kW possible
- Complex target design

Neutron Production

Target material

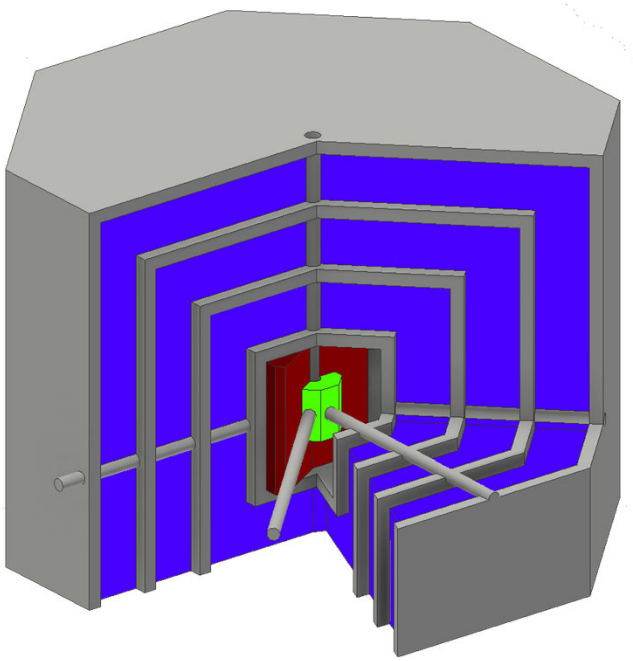


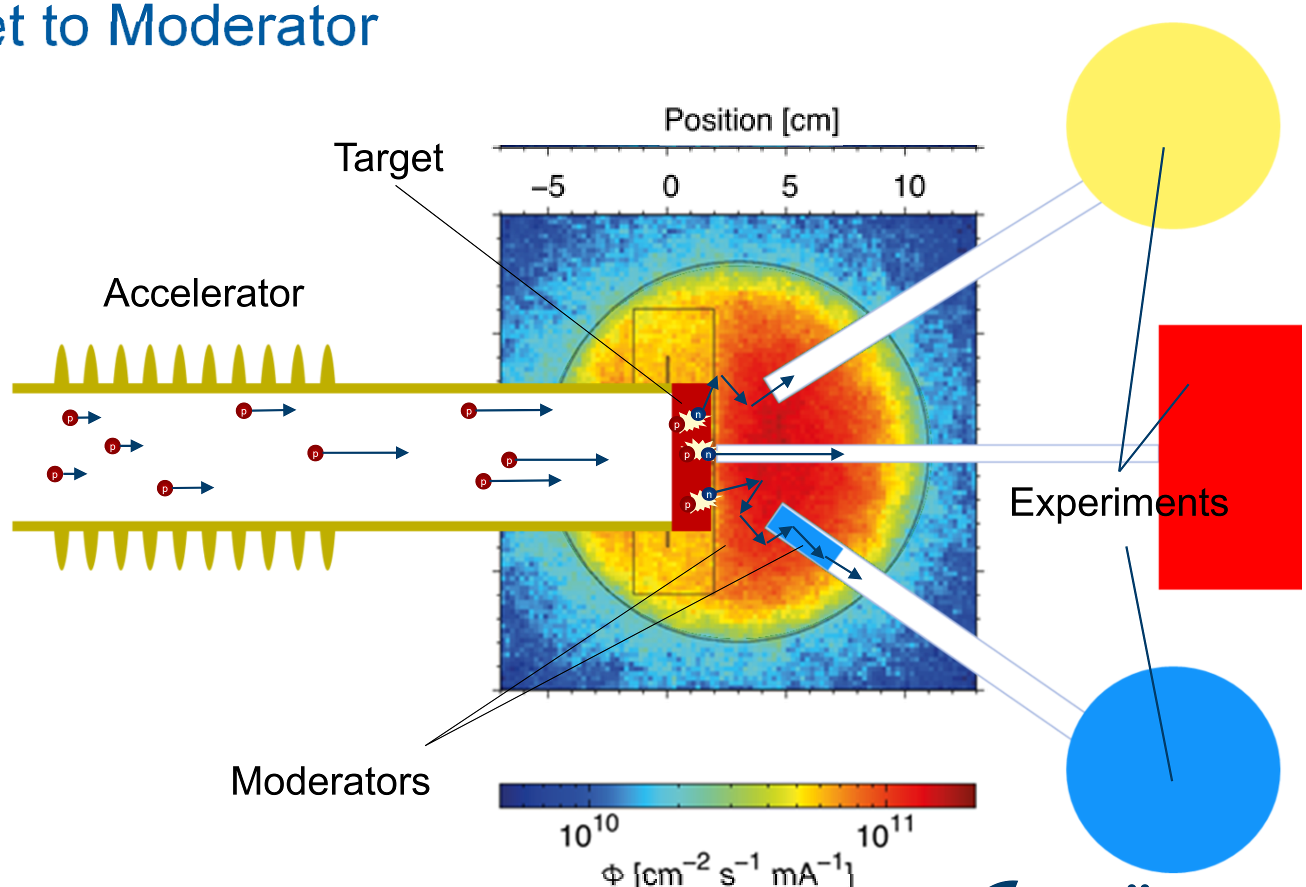
- high neutron yield
- mechanical stable
- thermally stable
- workable
- corrosion resistance
- high blistering treshold
- activation & decay
- price

Tantalum (Ta)

From Proton to Neutron

Efficient Coupling of Target to Moderator

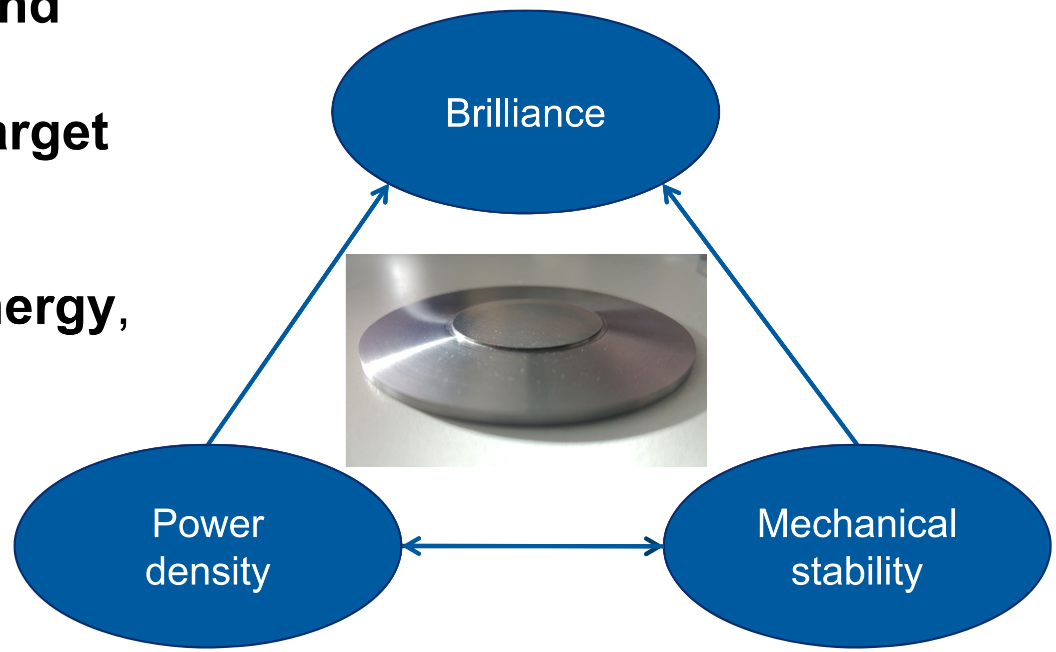




Target

Engineering challenges

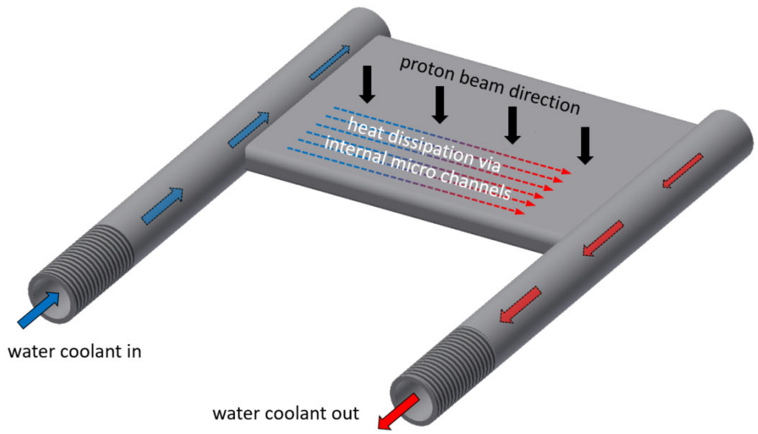
- **Target optimization for brilliance and mechanical stability**
- **Large heat deposition density in target**
  - Temperature rise inside target
  - Temperature induced stress
- **Parametric study** (**Particle type**, **energy**, target material and geometry, **heat deposition density**)
  - Thin target preferable



P. Zakalek et al., Physica B, 551, 484, 2018

Pushing Targets to the Limit

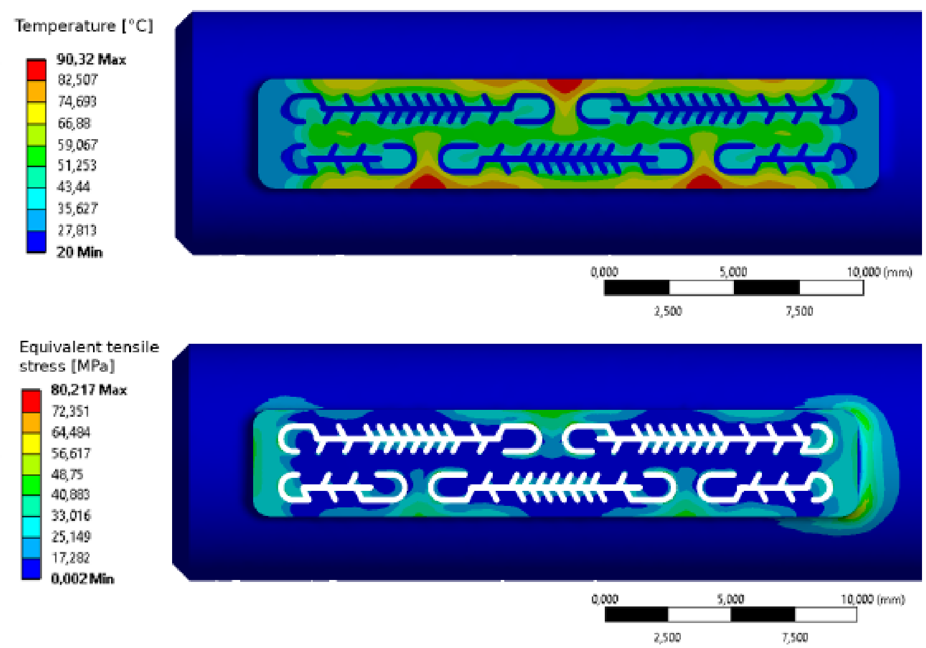
Cooling efficiency and mechanical stability



cooling power on 100 *cm²* :

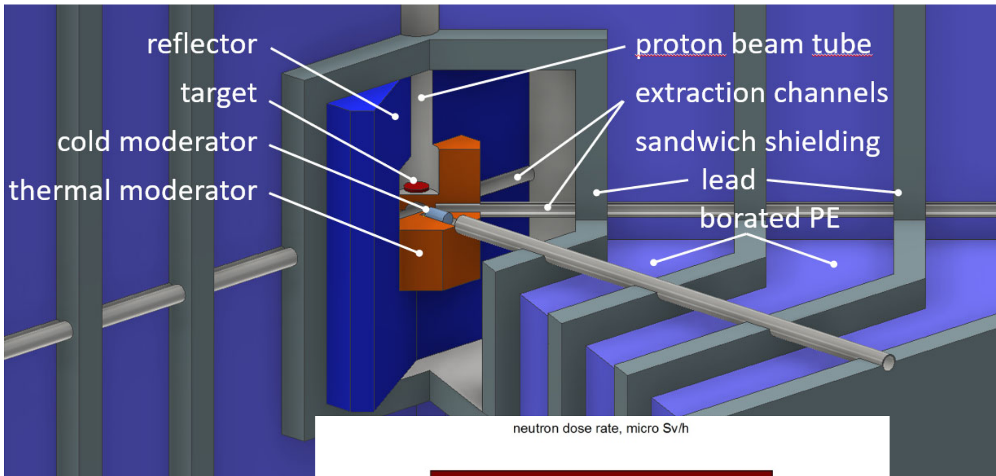
$$\dot{p}_{max} \sim 1000 \; {}^{W}/_{cm^2}$$

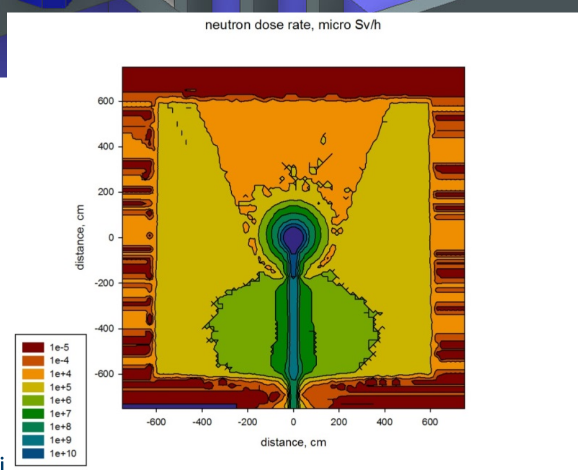
Engineering challenges manageable:
Neutron yield: ~10^{15} n/s

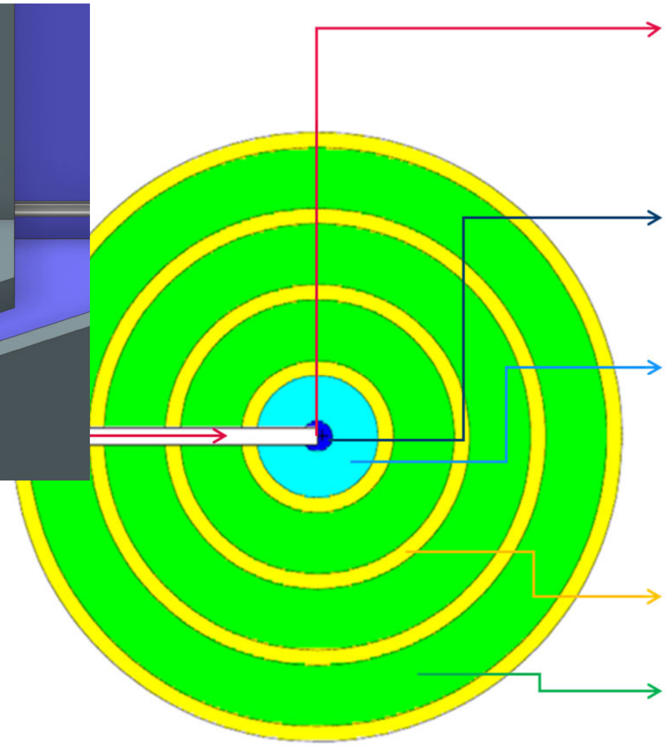


Target

Biological shielding



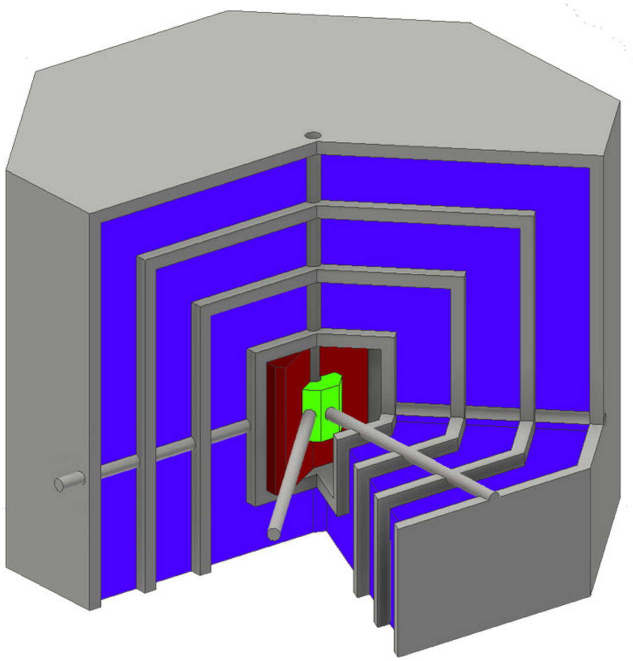


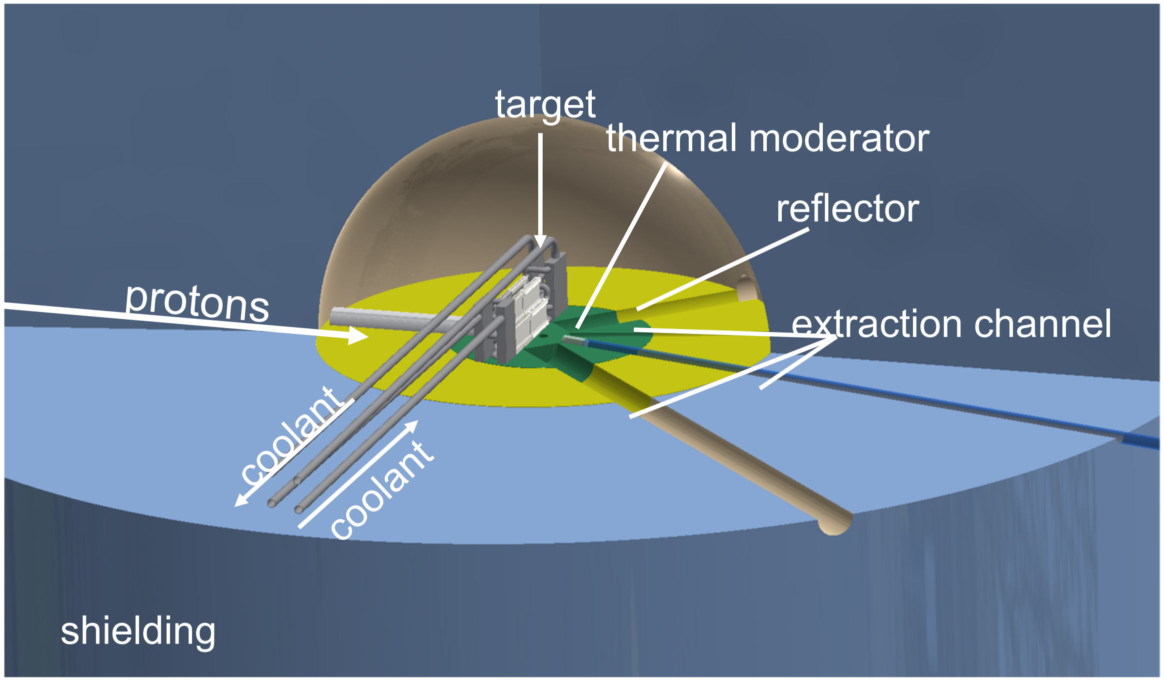


- Tantalum target:
  - Thickness: 0.5 cm
  - Surface: 100 cm^2
- Polyethylene Moderator:
  - Radius:10 cm
- Reflector
  - Be, Pb, Borated-PE
  - Thickness: 10 or 30 cm
- Multilayer shielding
  - Lead
  - Thickness: 10 cm
  - Borated-PE
  - Thickness: 10 to 40 cm

Target

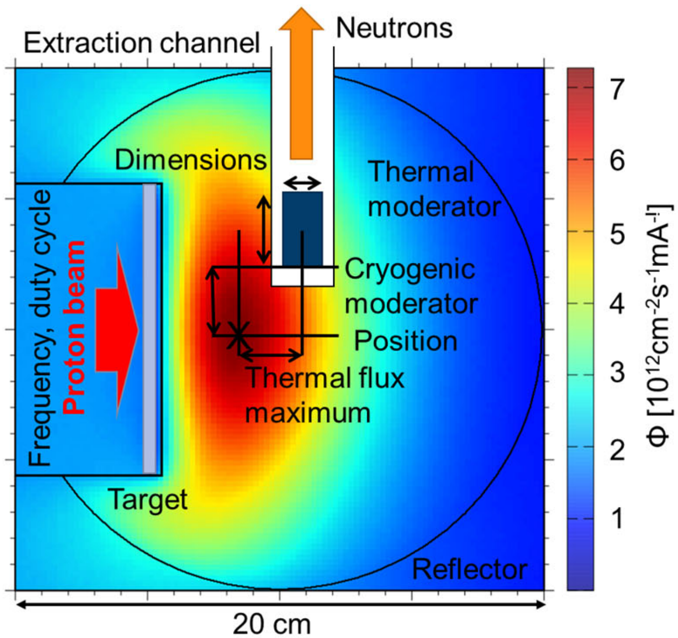
Efficient Coupling of Target to Moderator

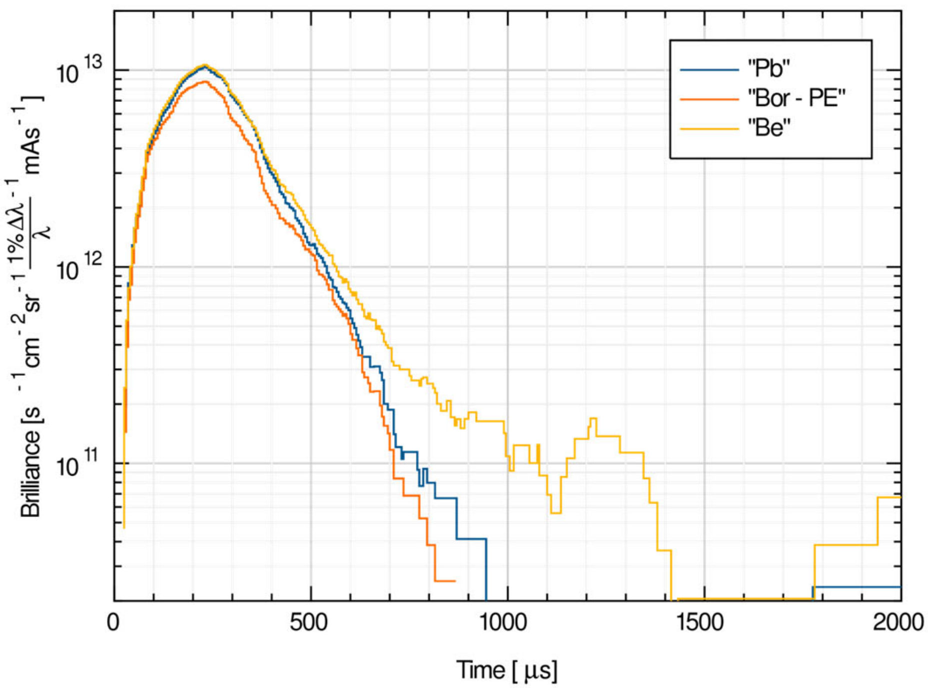




Target

Moderator / Reflector optimisation

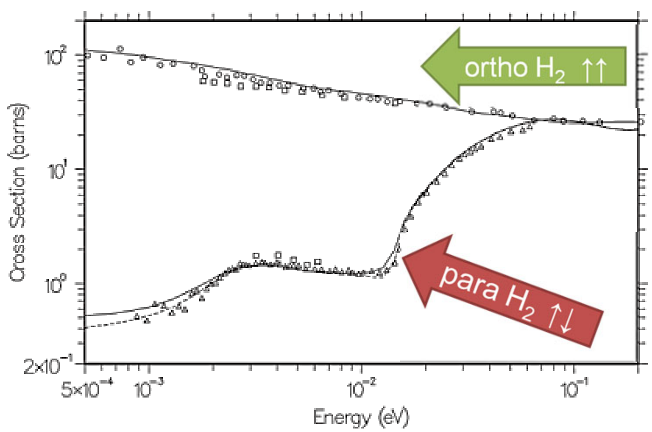


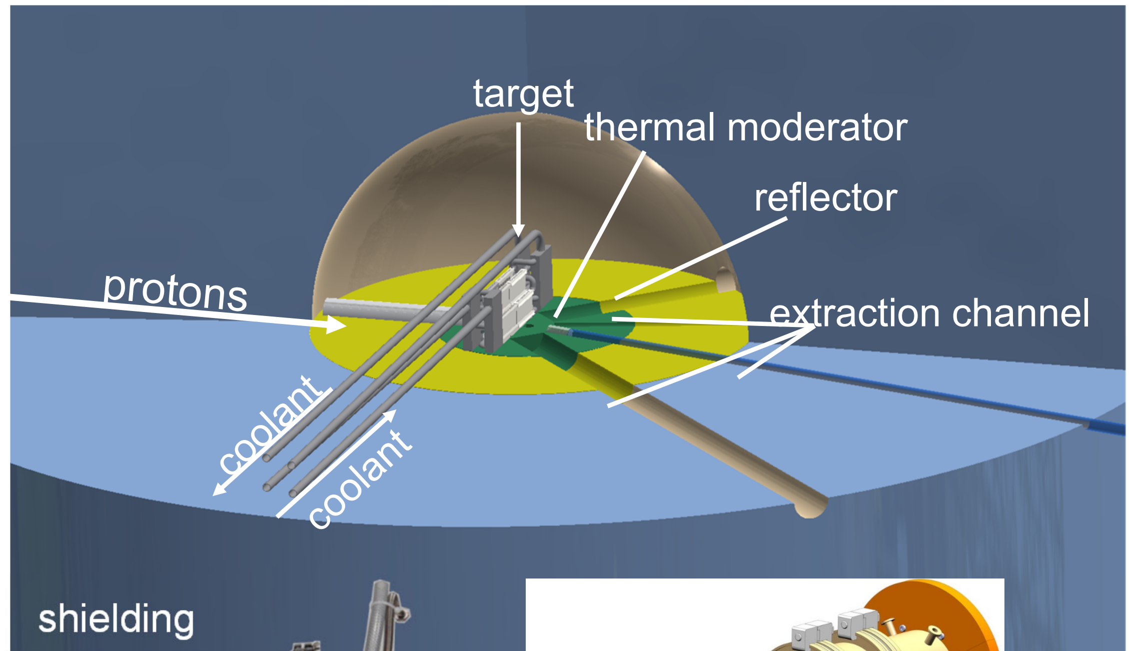


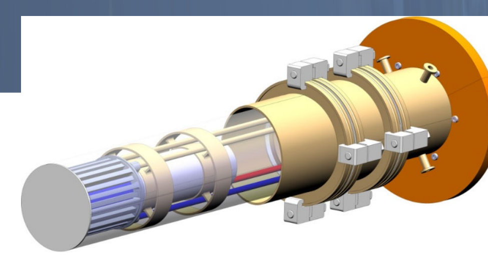
Cold Moderators

Thermal and cold moderators

- **Moderation** of fast neutrons to thermal and cold energies
- “one”-dimensional **“finger-”moderators with high brilliance**!
- **e.g. para-hydrogen**

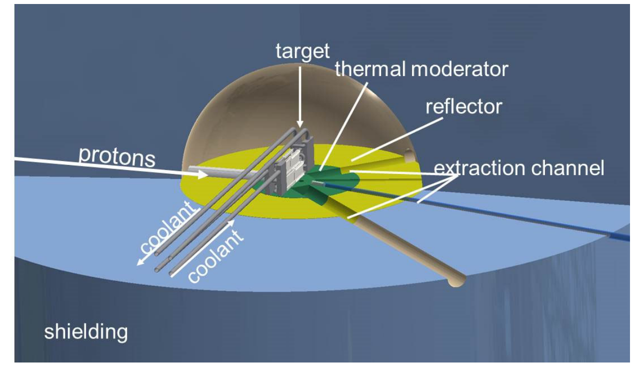


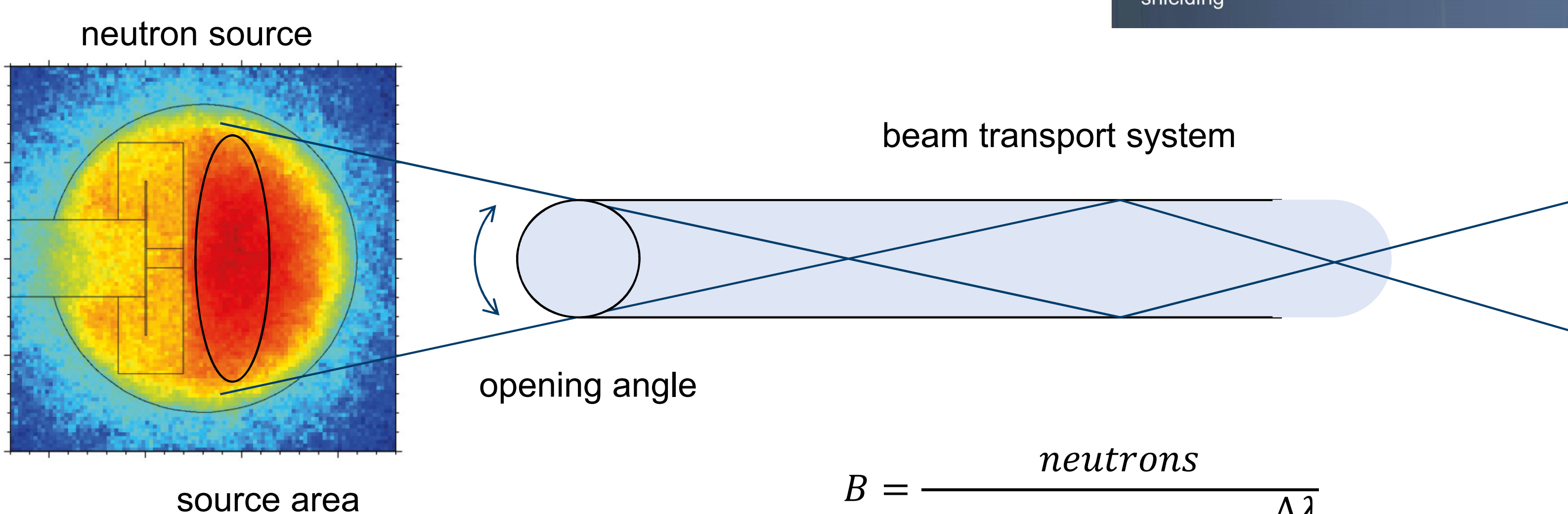




Beam Brilliance

Efficient beam extraction in combination with modern beam transport system



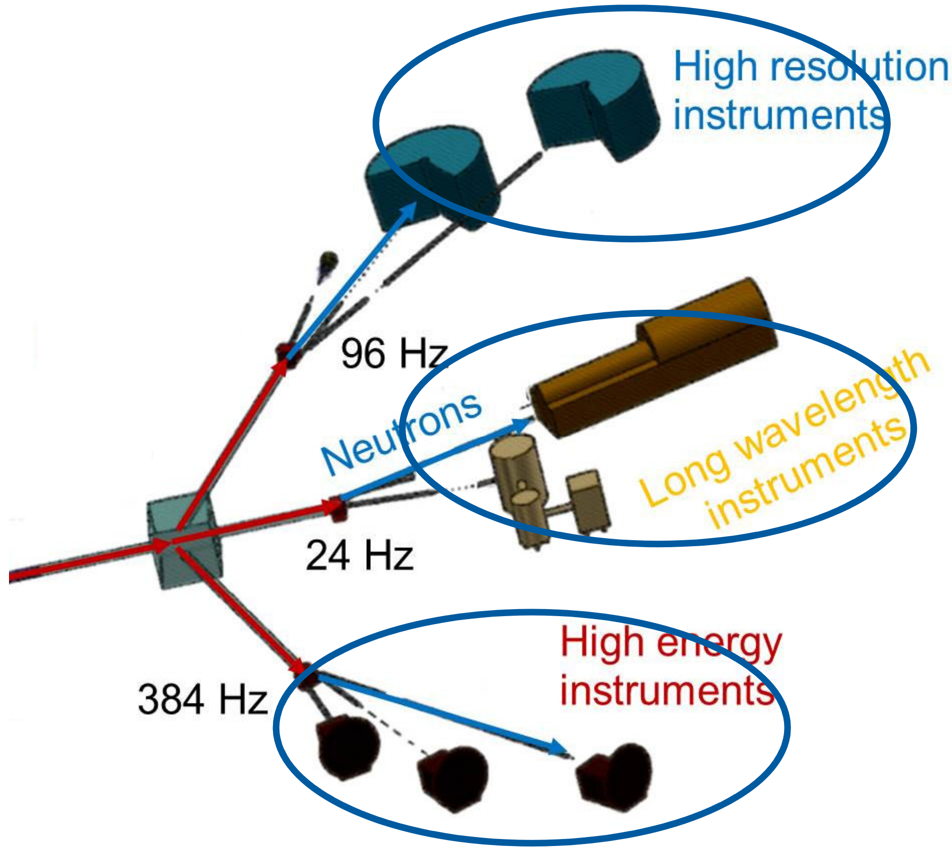


$$B = \frac{neutrons}{s \cdot cm^2 \cdot mrad^2 \cdot 1\% \frac{\Delta\lambda}{\lambda}}$$

Instrumentation

Calculated instrument neutron flux

	Resolution [$Å^{-1}$]	Bandwidth [Å]	Flux [$s^{-1}cm^{-2}$]
Large scale structures operating at 24 - 48 Hz			
Reflectometer	0.2	1.2 - 5.7	$1.3 \cdot 10^8$
SANS	0.31	3 - 8.4	$2.4 \cdot 10^7$
	0.27	3 - 7.7	$5.3 \cdot 10^6$
	0.23	3 - 7	$1.5 \cdot 10^6$
	0.2	3 - 6.4	$6 \cdot 10^5$
Diffractometers operating at 96 Hz			
Powder	0.003	1.3 - 2.6	$6 \cdot 10^6$
Spectrometers operating at 100 - 400 Hz [7]			
Backscattering	1	1.84	$2.5 \cdot 10^7$
Cold ToF	2	5	$1.3 \cdot 10^5$
Thermal ToF	5	45	$1 \cdot 10^5$
Analytics operating at 24 - 96 Hz			
Imaging	0.5 mm, 0.2 Å	1 - 7	$4.4 \cdot 10^6$
PDGNAA, NDP	-	-	$2.5 \cdot 10^{10}$

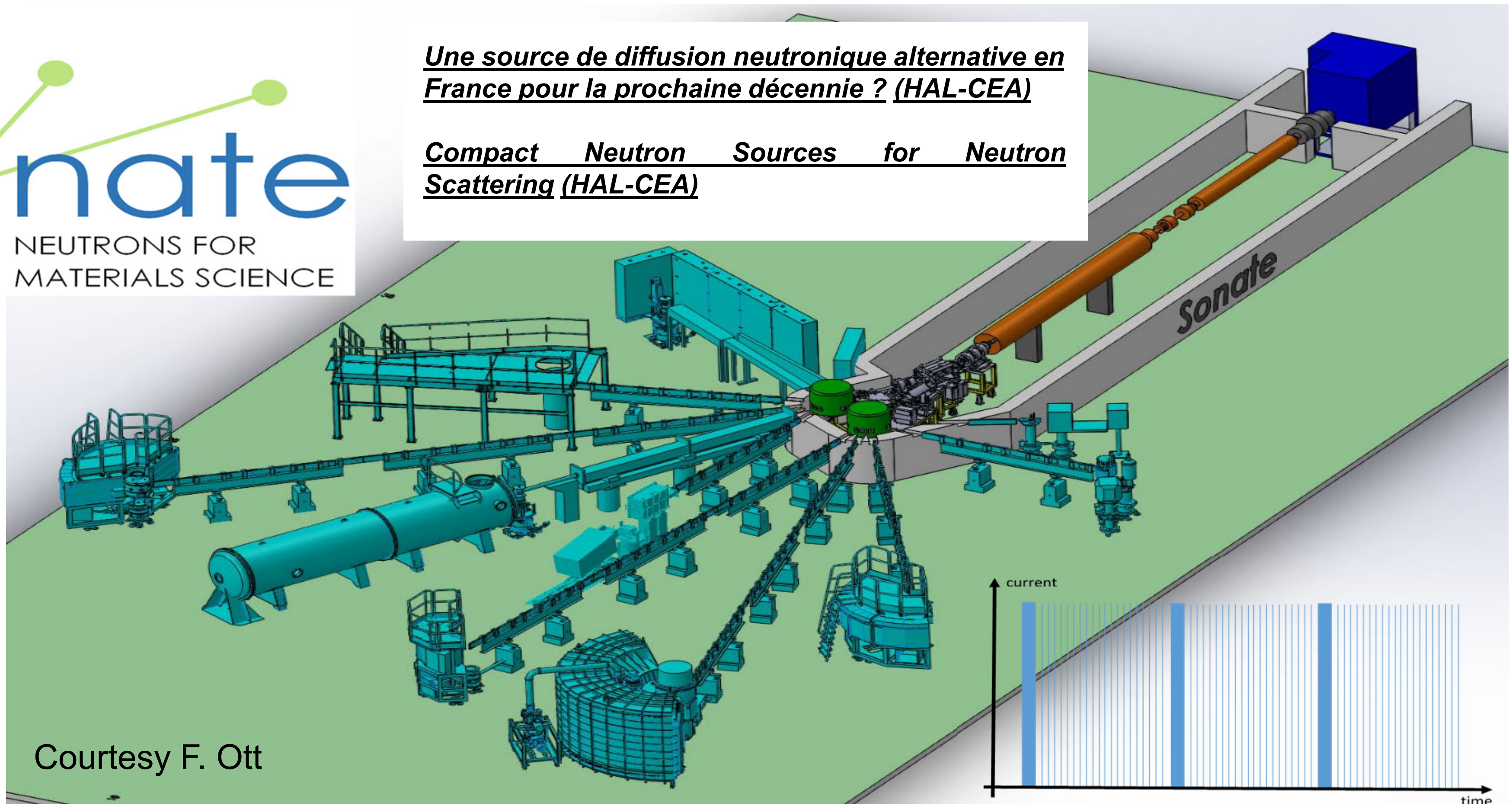


P. Zakalek et al., in press

2030: 10 INSTRUMENTS AROUND 2 TARGETS

Une source de diffusion neutronique alternative en France pour la prochaine décennie ? (HAL-CEA)

Compact Neutron Sources for Neutron Scattering (HAL-CEA)

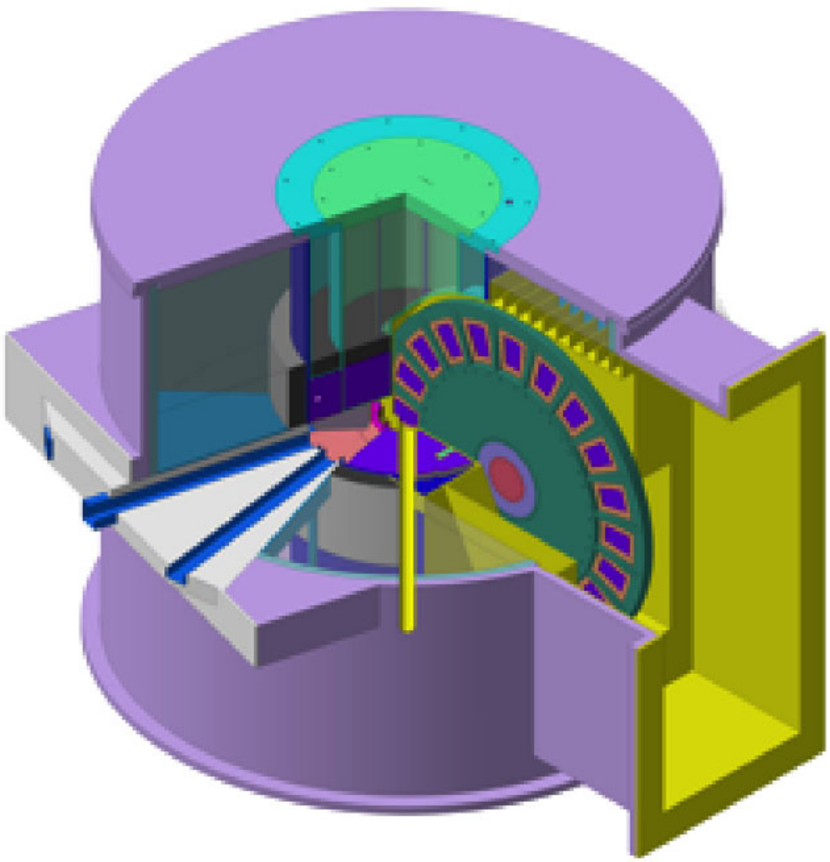


Courtesy F. Ott

Table 4.2.1
Parameters of the ESS-Bilbao project.

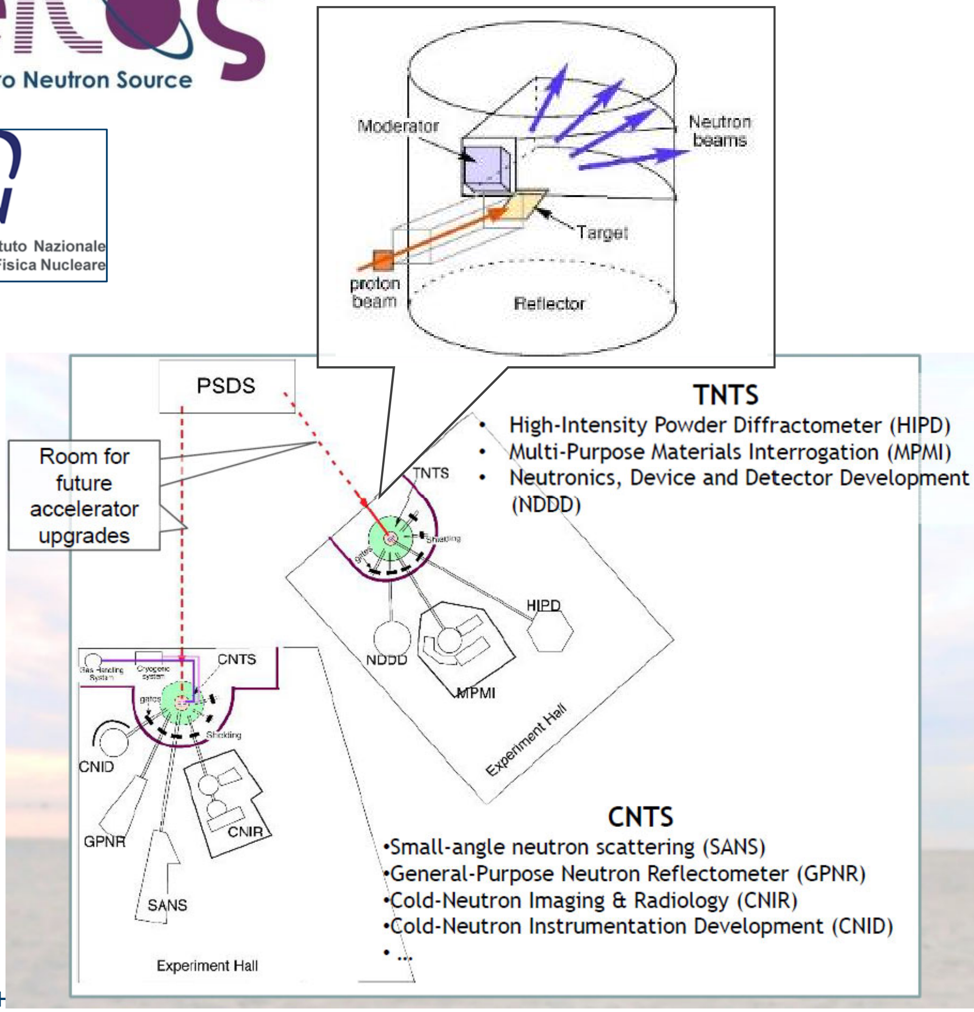
Proton linac
50 MeV, 16 kW 2.25 mA (average), 20 Hz Long pulse, width 1.5 ms

Target station	Major activities
Be(p, n) Solid methane with water premoderator $\sim 1 \times 10^{15}$ n/s (calc.)	SANS, moderator and neutron-scattering component testing



Legnaro Neutron Source

Istituto Nazionale di Fisica Nucleare



Pulse Selection and **Distribution Station** (PSDS)

- ❑ CNTS (**Cold Neutron Target Station**)
  - Be target
  - Cryogenic moderator of solid methane
  - Reflector (graphite or water)
  - Up to 6 ports to expermental halls
- ❑ TNTS (**Thermal Neutron Target Station**)
  - Identical design to CNTS but with water (abient temperature) moderator
  - Initially three ports
- ❑ LENOS (astrophysics)

- **Modular** structure
- **Mild radioactivity** by low-energy protons ($\leq$ 5 MeV)
- Both **Short Pulse** (SP) and **Long Pulse** (LP) options
- Cryogenic and gas handling systems for hydrogenous moderator

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HIGH BRILLIANCE SOURCE

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HIGH BRILLIANCE SOURCE

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Several target stations

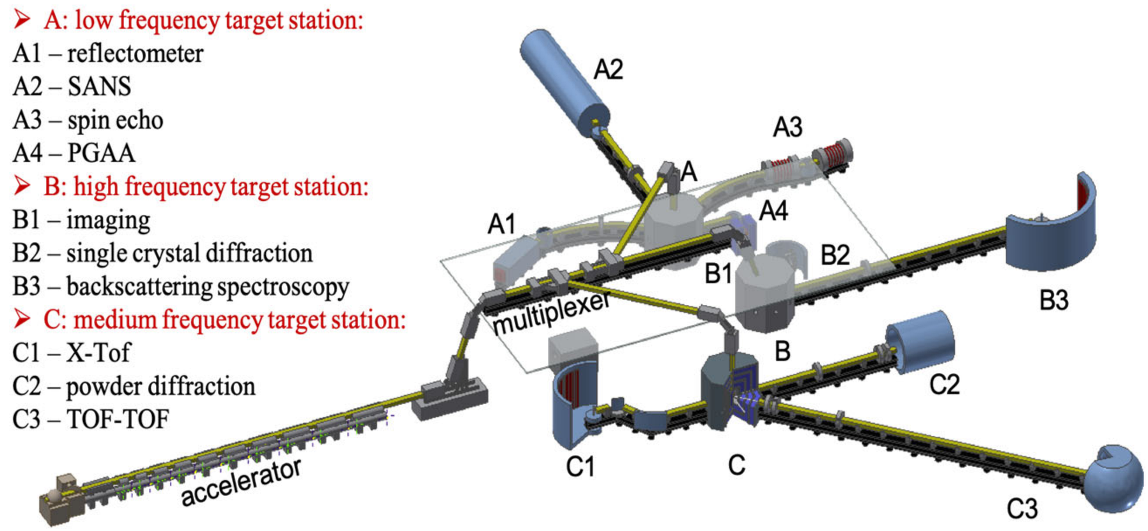
- Optimize pulse structure (length, rep. rate)
- Optimize thermal spectrum

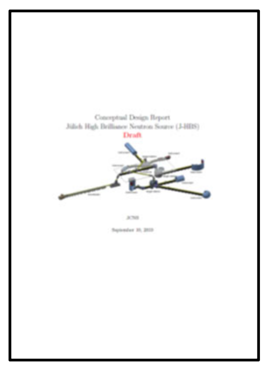
Every beam port serves only 1 Instrument

- Optimize cold source spectrum
- Optimize geometry
- Integrate neutron optics with beam port

Small shielding

- Neutron guide around cold source
- Chopper at <1 m from target





www.fz-juelich.de/jcns/jcns-2/EN/Forschung/High-Brilliance-Neutron-Source/_node.html

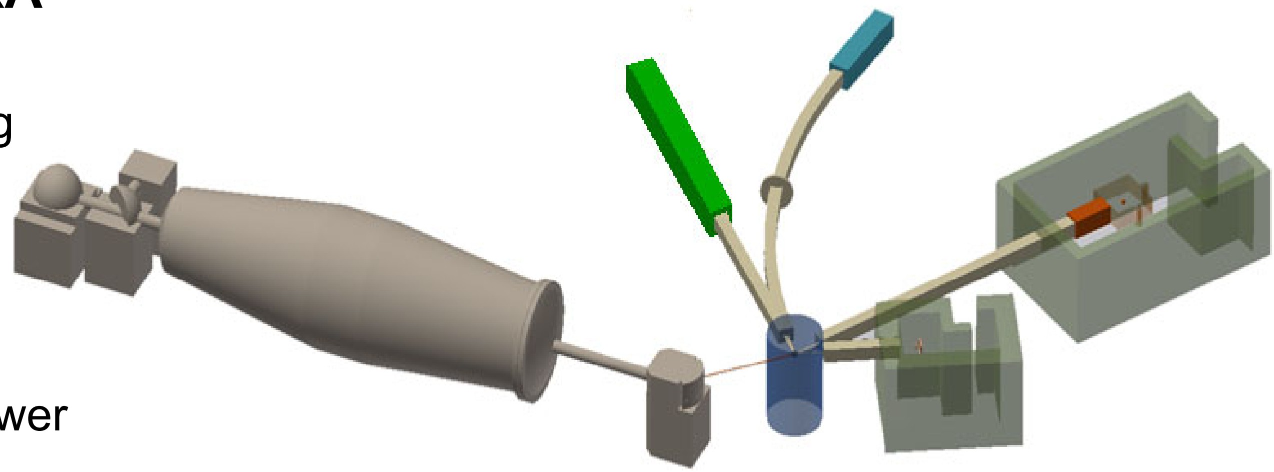
NOVA ERA (Design)

Laboratory facility: NOVA ERA

Workhorse instruments:
scattering / analytics / imaging

University / industry **laboratory**
Easy access, flexible use

Typical flux at sample position:
$10^3 – 10^5$ cm^{-2} s^{-1} at 400 W power



CDR NOVA ERA
FZJ Schriftenreihe, 2017
ISBN 978-3-95806-280-1

http://www.fz-juelich.de/SharedDocs/Downloads/JCNS/JCNS-2/EN/Conceptual-Design.pdf

Martonvásár CANS Project

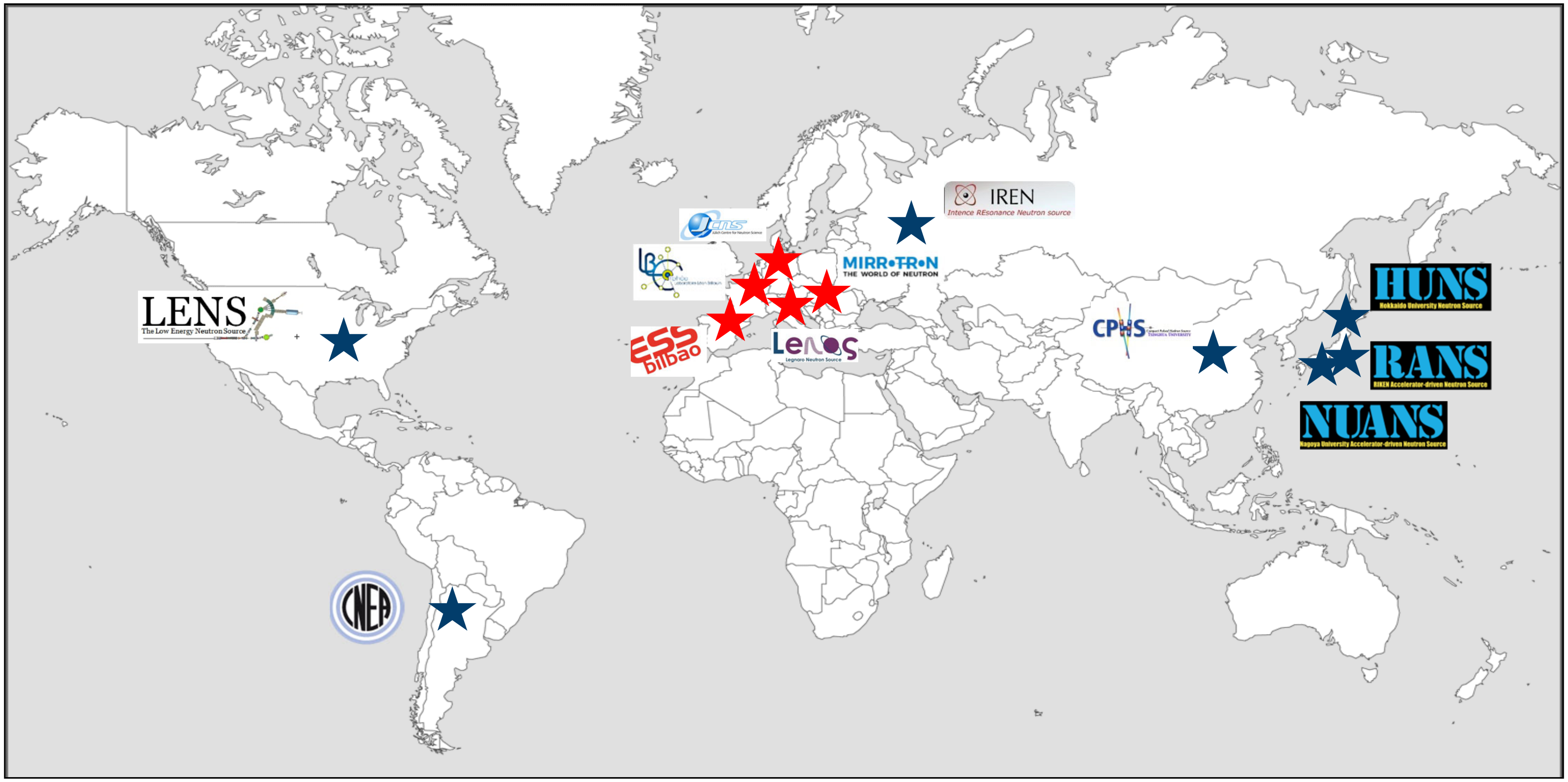
MIRROTRON
THE WORLD OF NEUTRON

- CANS business plan:
  - Neutron instrumentation tests for own needs: saves 100 k€/y
  - Products and services for neutron source development
  - Beams for industrial applications
  - Beam for cancer therapy (BNCT)
  - Development of neutron source for > 2023 in Hungary

Specifications: accelerator

- $\geq$ 2.5 MeV, $\leq$ 20 mA, 50 kW CW capable H^+ beam
- Pulsed operation (5 % duty factor) for material diagnostics
- CW operation for irradiation (50 kW)
- 201.25 MHz (?) RF amplifier, solid state (?)
- Upgradable in energy

Accelerator Based Neutron Sources



European Neutron Landscape – Making ESS as success !

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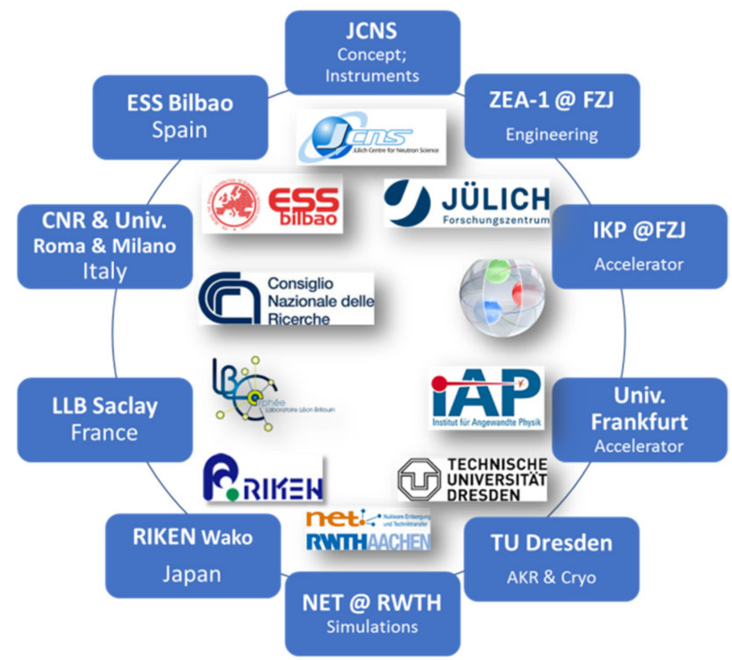

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A landscape of European accelerator based neutron sources