Compact Accelerator driven Neutron Source in European Landscape: Efficiency and sustainability aspects

F. Sordo et all,
ESS-Bilbao
28.Nov.2019

Outline

1) **Introduction to ESS-Bilbao**
2) **Neutron Sources in Europe**
3) **Neutron production**
4) **CANS optimization**
5) **Construction and operational cost**
6) **Conclusions**

1. Introduction to ESS-Bilbao

ESS-Bilbao

Who we are?

Public consortium of Central and Basque Governments; bringing knowledge and added value in particle accelerator and neutron scattering science and technologies; by leveraging its in-kind contribution to the European Spallation Neutron Source, in Lund (Sweden)

48 employees
age average: 40

29% women 71% men

Qualification

- 27% PhD
- 13% Post Graduate Degree
- 44% Master's Degree
- 8% Bachellor
- 8% Technician

Headquarters

Poligono Ugaldeguren III
Zamudio (Bilbao)

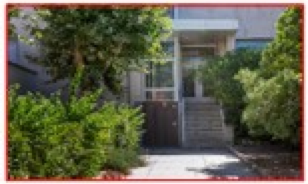
R&D Center

Parque Tecnológico
Zamudio (Bilbao)

AWF

Poligono Industrial Júndiz
Vitoria-Gasteiz

Madrid Satellite

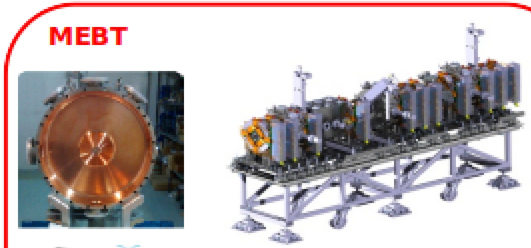


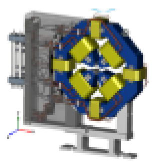
Instituto de Fusión Nuclear
Madrid

ESS-Bilbao

In-Kind Contributions to ESS

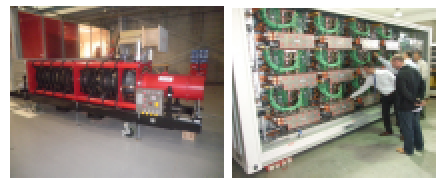
MEBT





Accelerating element: complete subsystem that goes after the RFQ and integrates: design, manufacturing, diagnostics, control, assembly and testing.

RF Systems

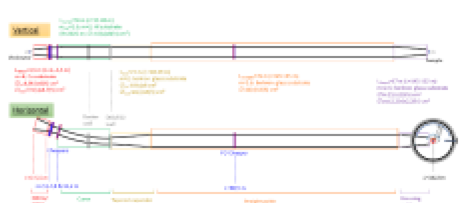


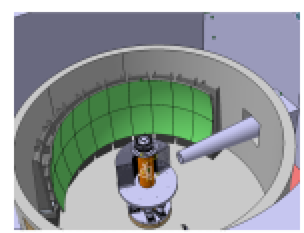
RF chains: 1 for RFQ and 5 for DTL.
Composed by klystrons, modulators, loads, waveguides, interlocks and LLRF

TARGET

The spallation process takes place when the accelerated proton beam hits the Tungsten bricks of the 11-tonne target wheel. This will produce neutron brightness for scientific experiments across multiple disciplines.

MIRACLES INSTRUMENT





Time-of-Flight backscattering instrument for polymer science, energy materials, and magnetism studies.
Prime contractors: design, manufacturing, assembly &cold commissioning

EUROPEAN SPALLATION SOURCE

EUSKO JAURLARITZA
GOBIERNO VASCO

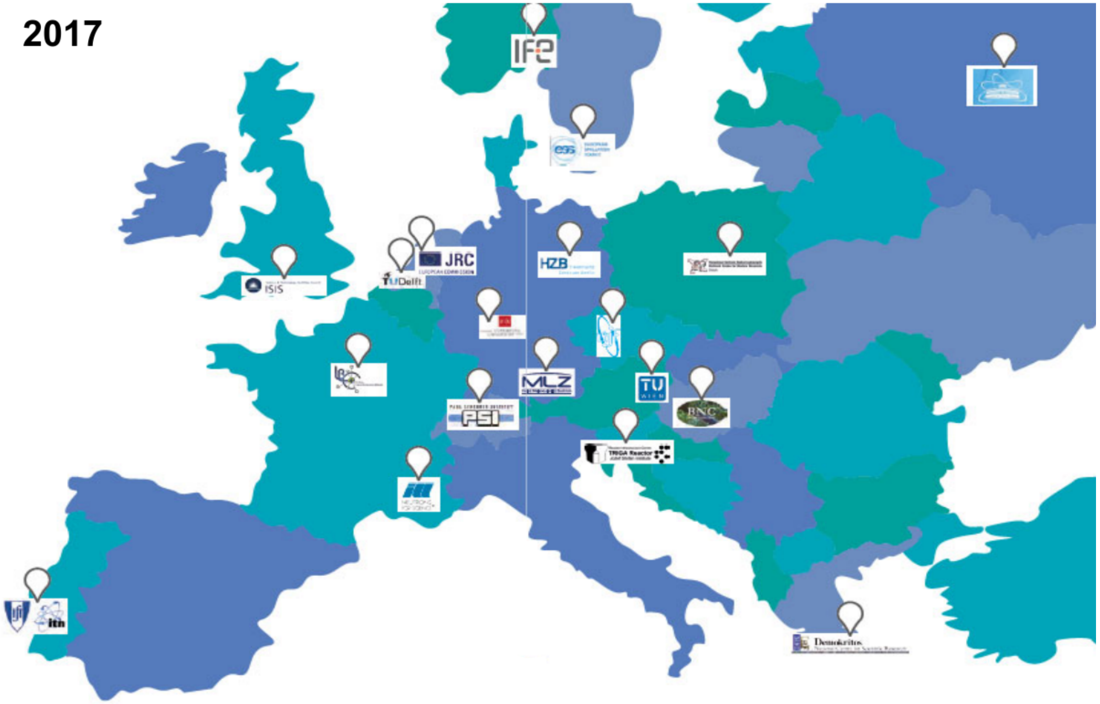
2. Neutron Sources in Europe

Introduction: Neutron Sources

Neutron are highly demand in European research:

- 8000 users
- 19 neutron sources in Europe
- 32 000 instrument beam days per year
- 1900 publications each year

2017



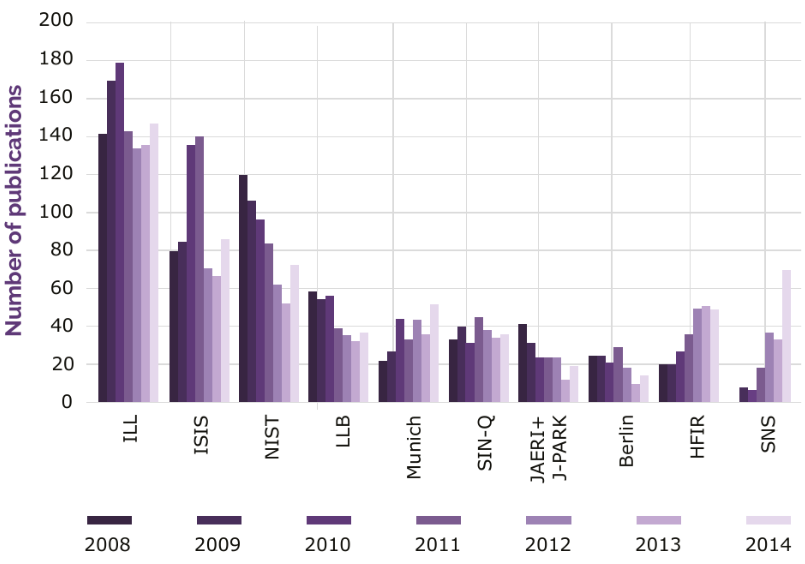
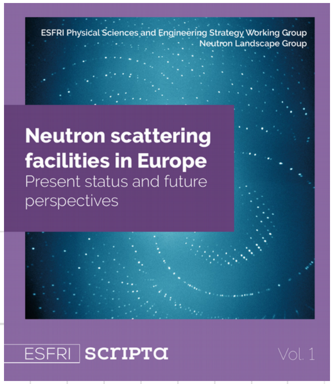


Figure 4. High impact publications

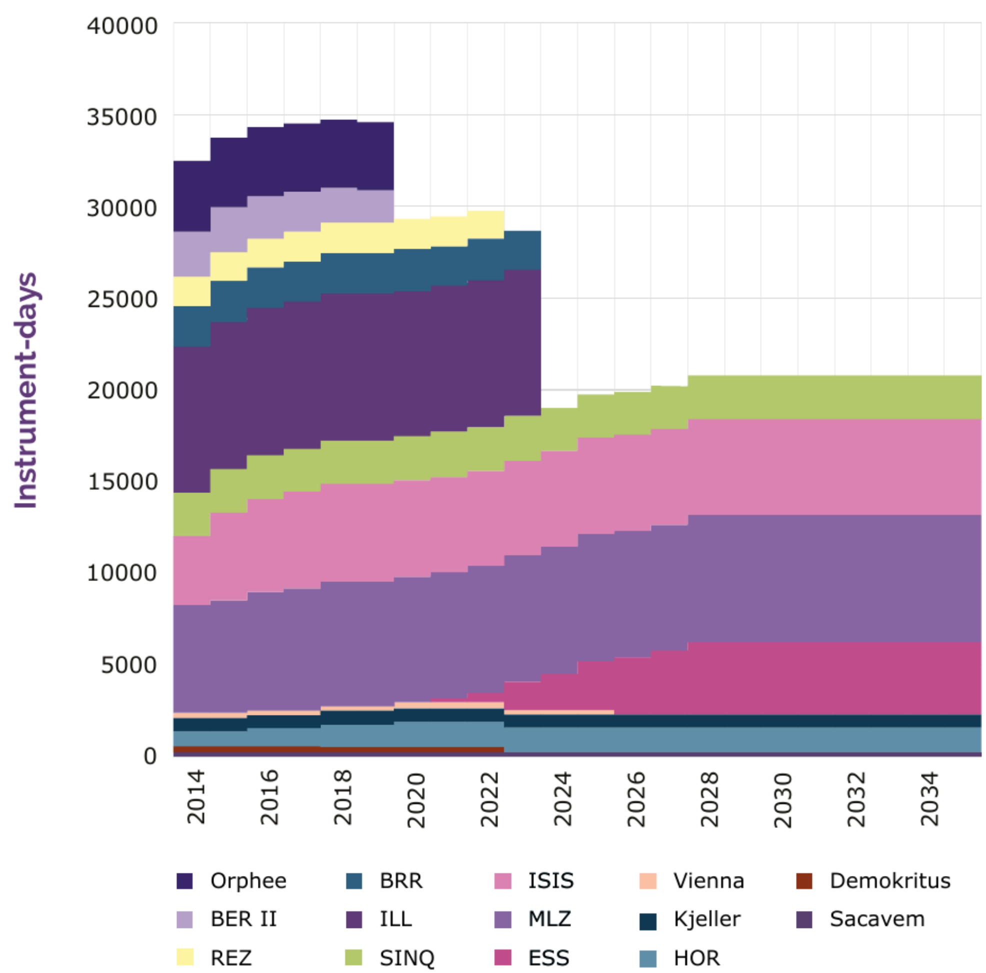
Number of papers published in high impact journals using data from leading neutron sources around the world, up to 2014. Adapted from image courtesy of ILL: Christian Vettier, Helmut Schober & Bill Stirling.

Introduction: Neutron Sources

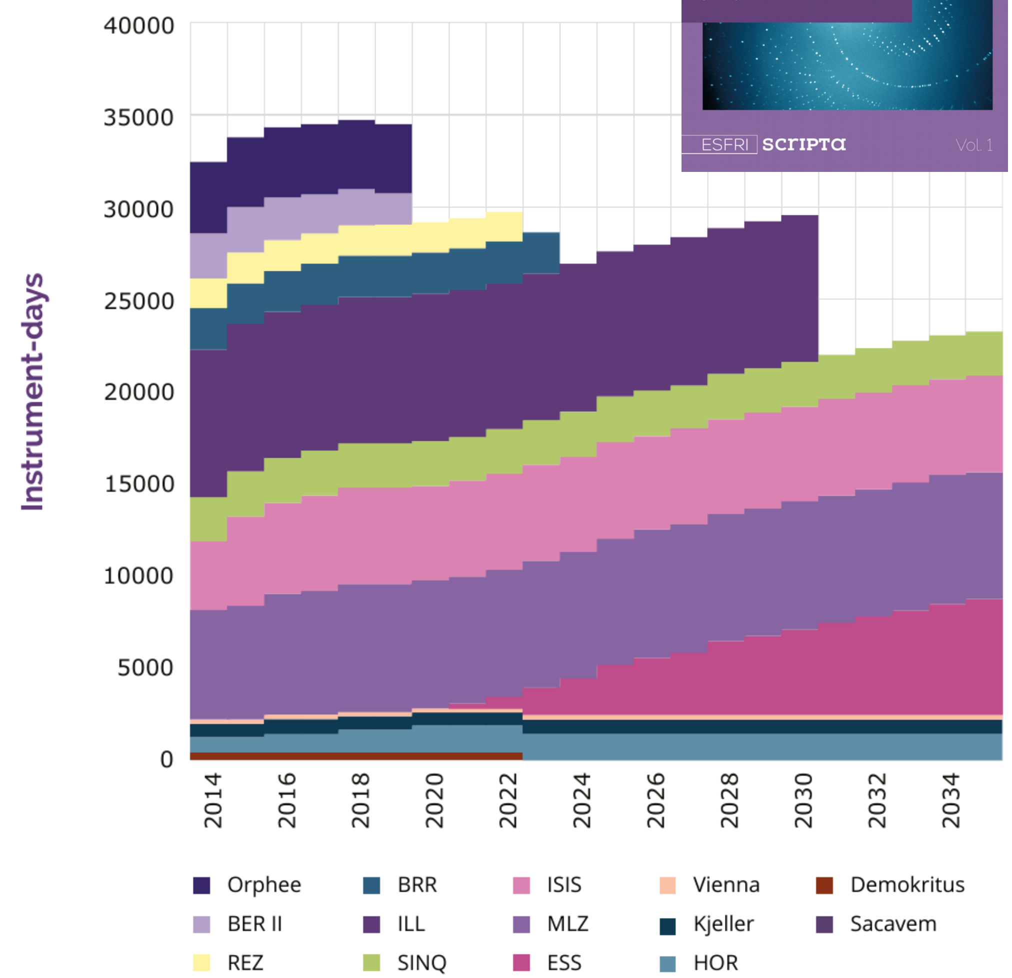
Neutron scattering facilities in Europe



Along the next decade it will be a significant reduction of the available instrument days produced by the reactor based facilities shutdown.



Base line scenario

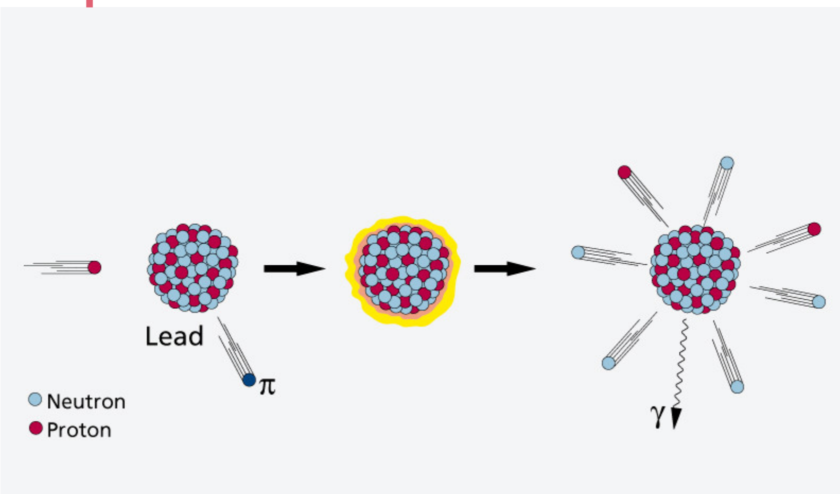


Optimistic scenario

3. Neutron production

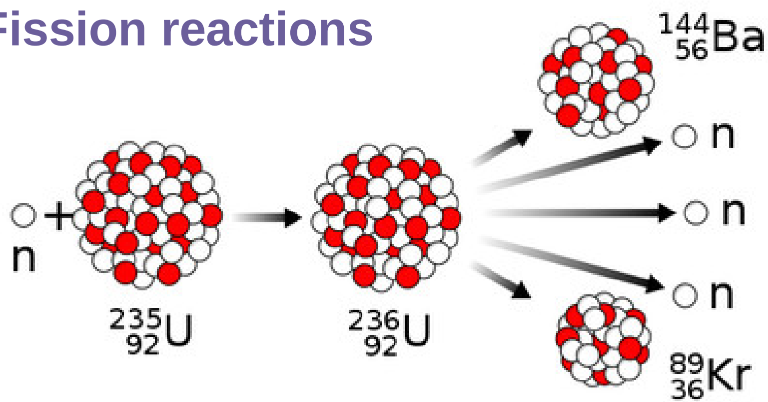
3.Neutron Production

Spallation Reactions



https://www.psi.ch/en/media/the-sinq-neutron-source

Fission reactions



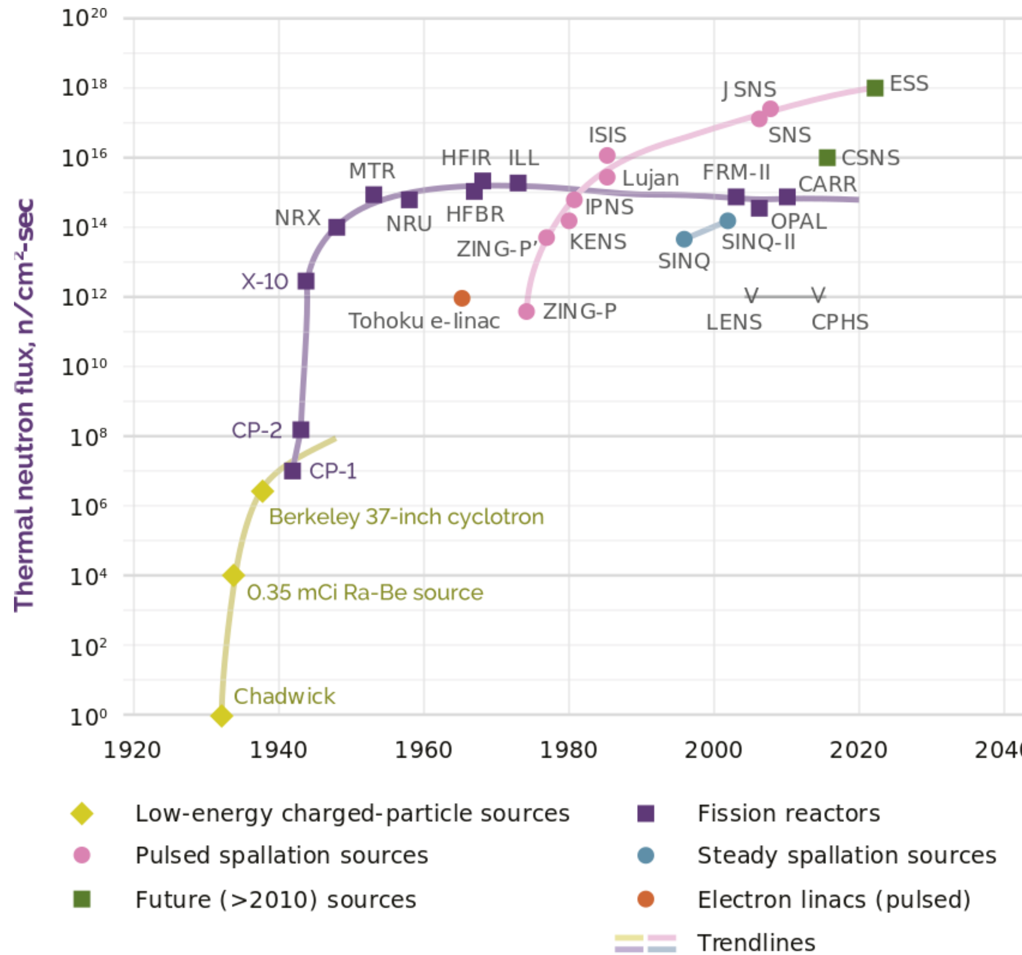


Figure 3. Thermal neutron sources f uxes

The evolution of ef ective neutron source f uxes as a function of calendar year, from the discovery of the neutron in 1932 to the time horizon of this report. HFIR, ILL, ISIS, SINQ, SNS, J SNS and FRM-II (MLZ) are still operational and CSNS and ESS are under construction. Adapted from image courtesy of Gerry H. Lander.

Source: Neutron scattering facilities in Europe

3.Neutron Production

Spallation Reactions

Fission reactions

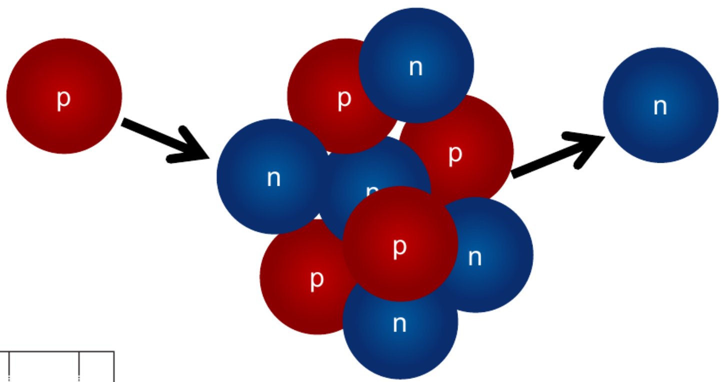
Mitglied der Helmholtz-Gemeinschaft

3.Neutron Production

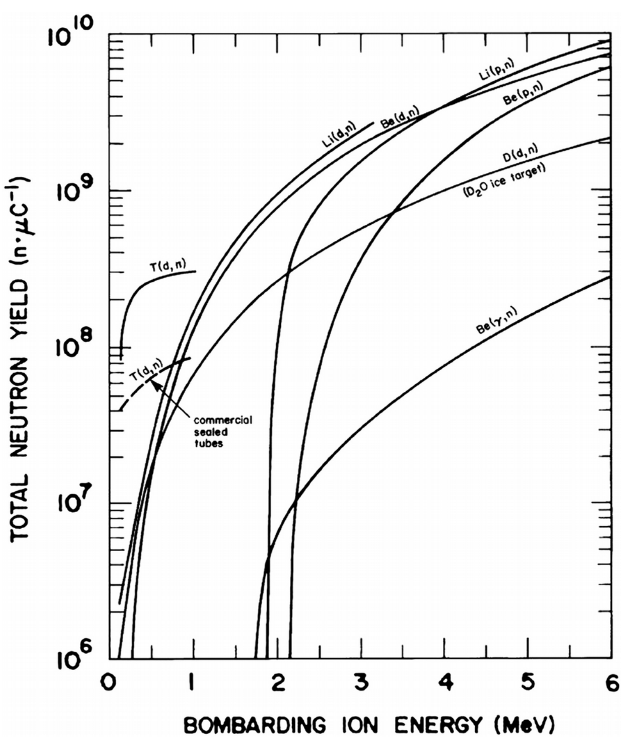
$${}^{9}_{4}Be(p,n;p,pn)$$

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

Nuclear process: low energy ion induced reactions



Reactions produced by low energy ions (<60-70 MeV) on light isotopes like lithium or beryllium. It neutron production rate is far below fission or spallation reactions.



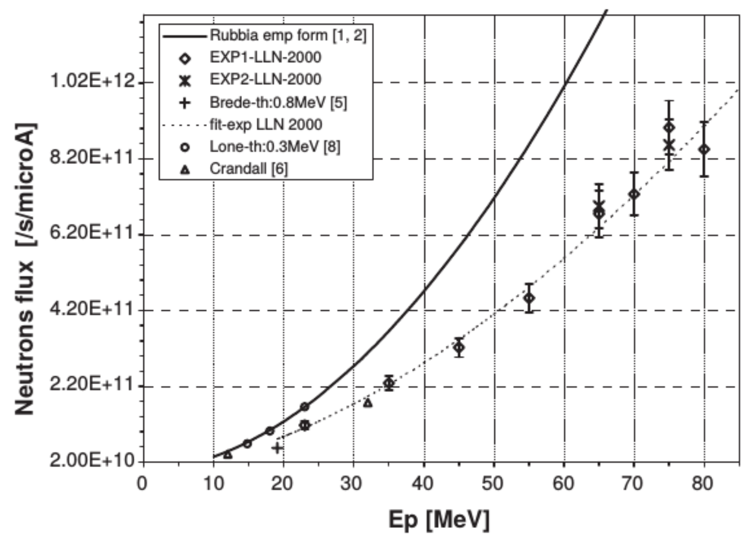


Fig. 2. Measured total number of neutrons emitted when protons bombard a Be target. The results obtained at the LLN cyclotron (23, 35, 45, 55, 65, 70, 75 and 80 MeV) are shown and compared with previous experimental data and with the theoretical curve proposed by Rubbia [1,2].

I. Tilquin et al. / Nuclear Instruments and Methods in Physics Research A 545 (2005) 339–343

3.Neutron Production

Nuclear process: low energy ion induced reactions

Advantages: low accelerator cost, lower shielding requirements, large reduction of radioactive inventory and remote handling requirements …

Disadvantages: low neutron production, heat load on target

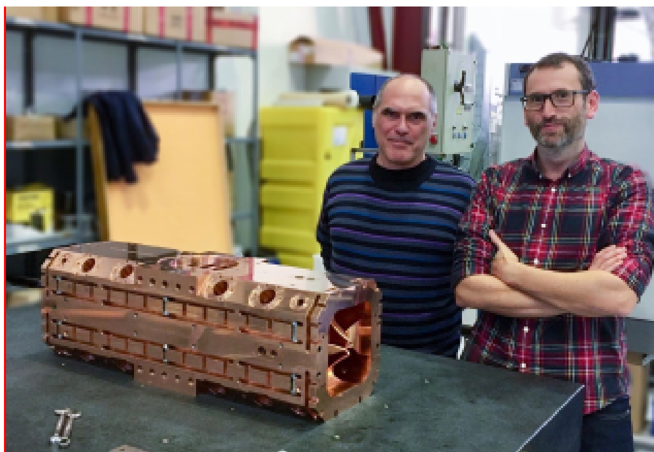
Nuclear Process	Example	Neutron Yield	Heat Release [MeV/n]	Source
Deuteron stripping	40 MeV Li(d,n)	7 x 10-2 n/d	3500	
Nuclear photo effect from e-Bremsstrahlung	100 MeV e- on 238U	5 x 10-2 n/e-	2000	HUNS, n-ELBE
9Be(d,n)10Be	25 MeV d on Be	1.7 x 10-2 n/d	1000	
9Be(p,n:p,pn)	11 MeV p on Be	2.3 x 10-3 n/d	5000	RANS,LENS
9Be(p,n)	50 MeV p on Be	2.6 x 10-2 n/d	2000	
Nuclear fission	Fission of 235U by thermal neutrons	1n/fission	180	MLZ,ILL
Spallation	800 MeV p on 238U or Pb	27 n/p or 17 n/p	55 or 30	ISIS, SINQ, ESS

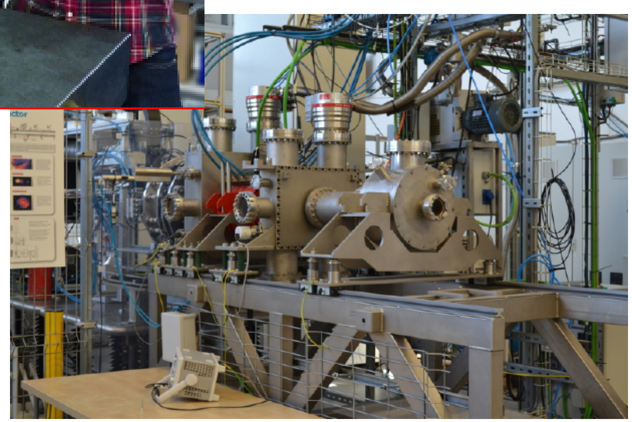
3.Neutron Production

Nuclear process: low energy ion induced reactions

In order to produce a compact source, accelerators based on well known technology are proposed

ESS-B 2013 neutron source accelerator



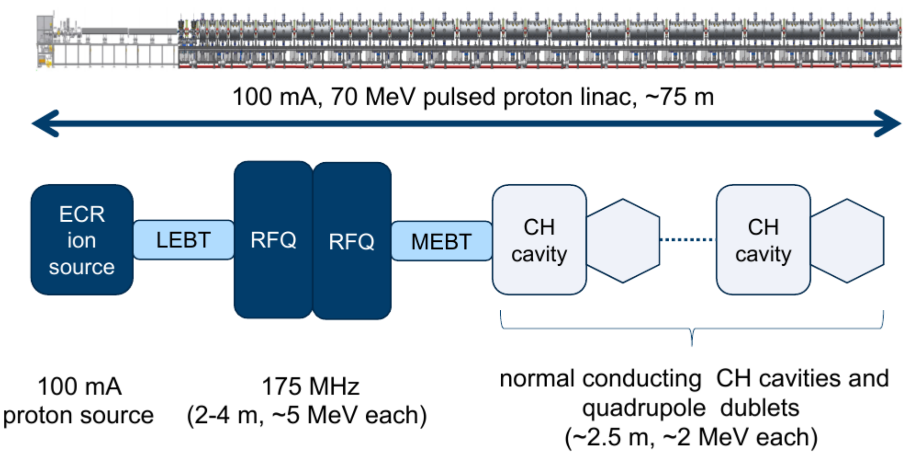


75 mA, 50 MeV
1.5 ms, 20 Hz

Table 1. An example of a table.

Element	Length (m)	Energy (MeV)	No. cavs.	No. gaps	FR pow. (MW)	No. klystrons
Ion Source	1.5	0.045				
LEBT	3					
RFQ	3.2	0.045-3	1	306 cells	1.2	1
MEBT	1.3	3	2	2 buncher	0.15	
DTL	14.6	3-50	3	108 DTs	3.8	3

Hight Brilliance neutron Source (HBS)



3.Neutron Production

Nuclear process: low energy ion induced reactions

Considering and standard pulsed high current accelerator (ESS injector) a compact source could produce ~10^{15} n/s, far below neutron production in large facilities like ESS (~1.5 10^{18} n/s). **If we only considered the neutron source, compact sources are not a very efficient solution.**

			ESS-B 2013	HBS*	ISIS-TS2	ESS
Accelerator Parameters	Energy	[MeV]	50	70	800	2000
	Peak Intensity	[mA]	75	100		62,5
	Pulse length	[ms]	1,8	0,833		2,857
	Repetition Rate	[Hz]	20	24		14
	Average Current	[mA]	2,70	2,00	0,10	2,50
Target-Moderator	Power	[kW]	135	139,944	80	4999,75
	Y_n(Ep)	[n/mu-C]	4,15E+11	9,23E+11		
	Neutron yield	[n/s]	1,12E+15	1,85E+15	2,15E+16	1,49E+18
	Proton Current	[p/s]	4,32E+16	3,20E+16	1,60E+15	4,00E+16
	Neutron yield	[n/p]	2,59E-02	5,77E-02	1,35E+01	3,72E+01
	Head load Target	[MeV/n]	1,93E+03	1,21E+03	5,94E+01	5,37E+01
Construction Cost		[M€]	100,0	400,0	800,0	1847,0
		[M€/10^{14} n]	**8,9**	**21,7**	**3,7**	**0,1**

4. CANS optimization

4. CANS optimization

CANS advantages for Target-Moderator-Reflector-Optics optimization

CANS neutron source in lower than in large facilities, but to complete history have to include moderator, reflector and neutron optics to transport neutrons form source to the sample.

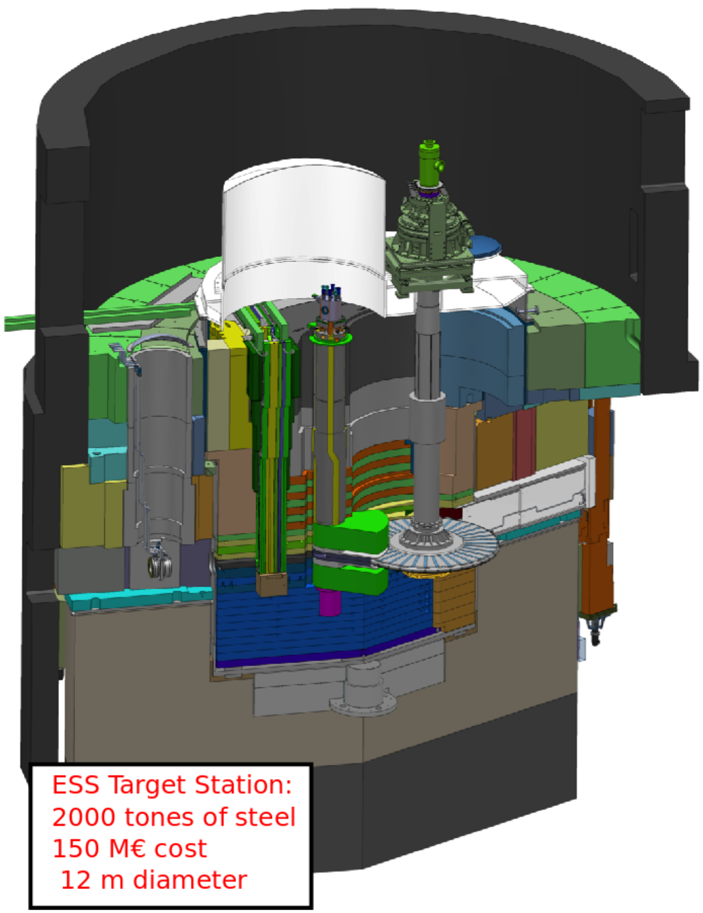
In the second step of the process, the compact sources have significant advantages:

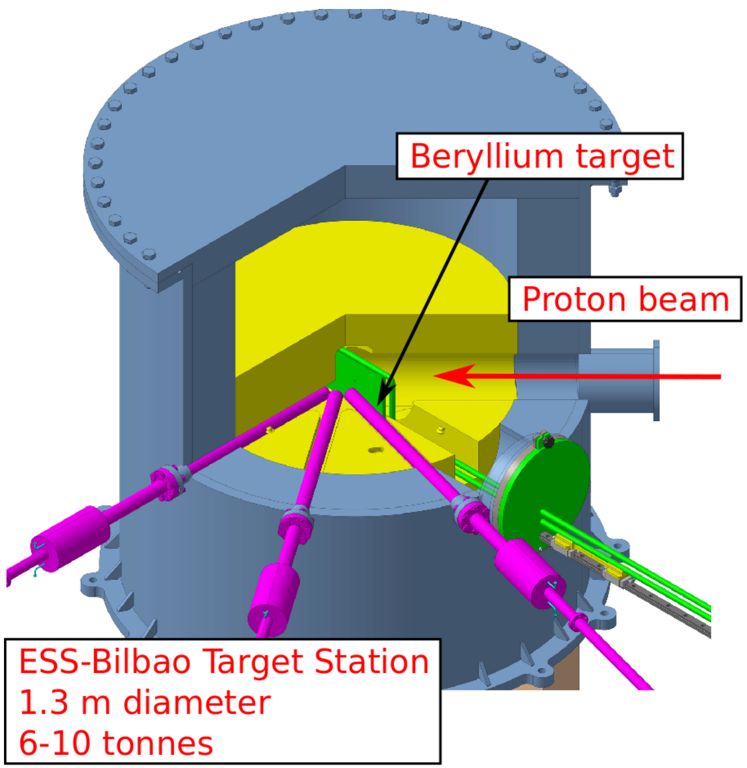
- Target stations are affordable (2-3 M€)
- Better coupling between moderator and target
- Low radiation damage

4. The CANS concept

4.1 Low amount of shielding is needed, several target stations are affordable

The energy of the neutrons produced is limited by the energy of the incident particle thus, in compact sources there is no neutrons above 50-70 MeV an thus, shielding thickness is significantly lower than spallation sources.

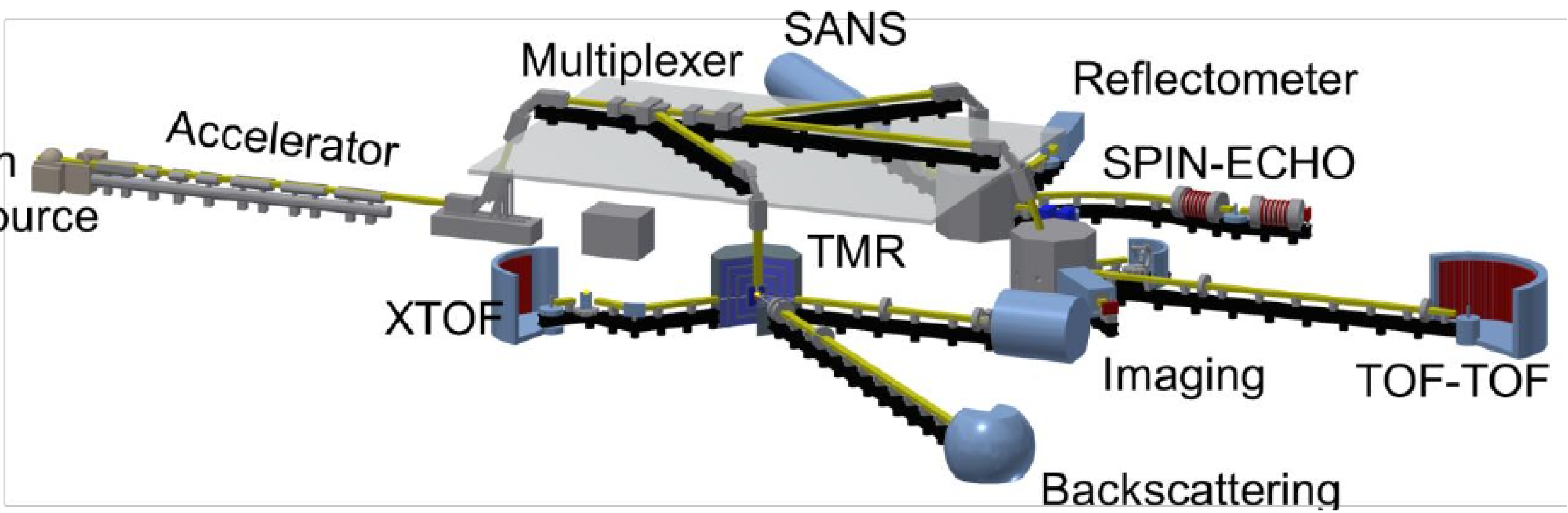




4. The CANS concept

4.1 Low amount of shielding is needed, several target stations are affordable

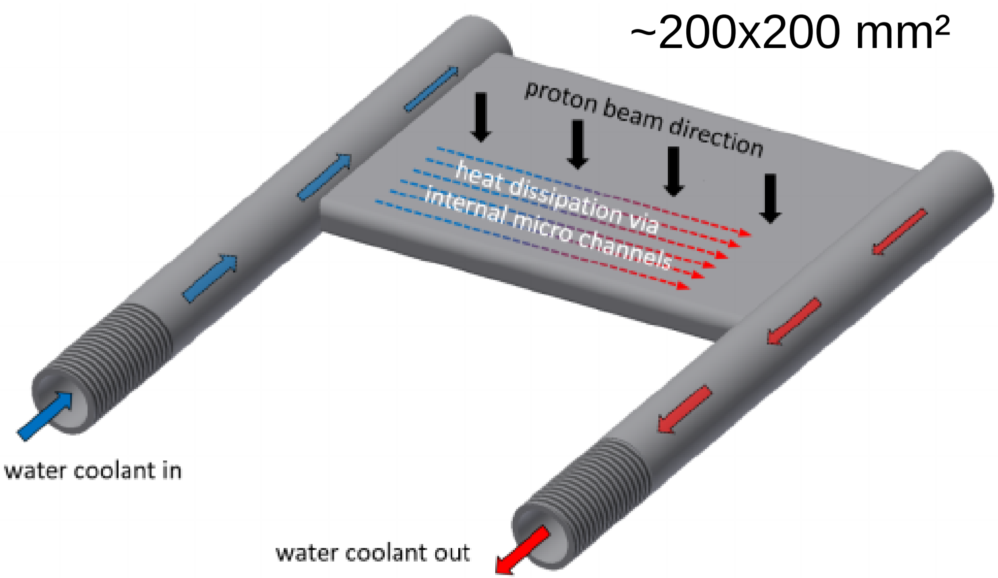
ESS Target station is in the range of 180 M€ however, CANS target stations will be between 2-3 M€. Each instrument suit will have his own target station optimized for his needs.

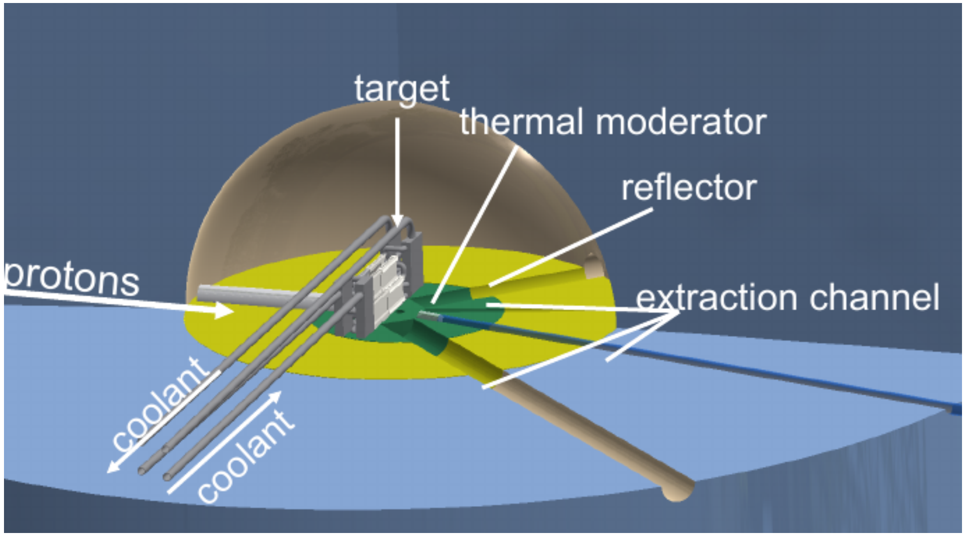


4. The CANS concept

4.2 Better coupling between moderator and target

Low energy protons penetration in beryllium is juts 10-15 mm compared with 500-600 mm for high energy protons in tungsten. Total mass of CANS target will be 40-50 kg compared with the 5000 kg of ESS Target.



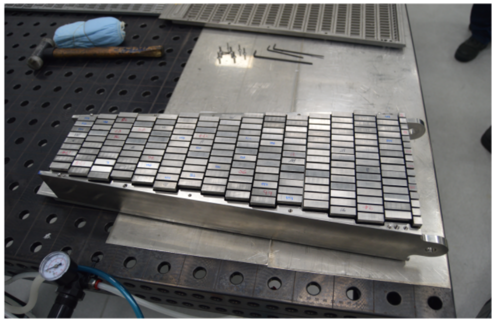


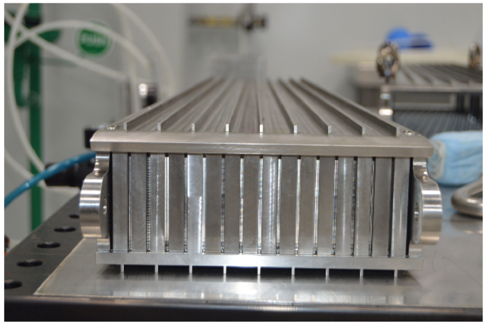
4. The CANS concept

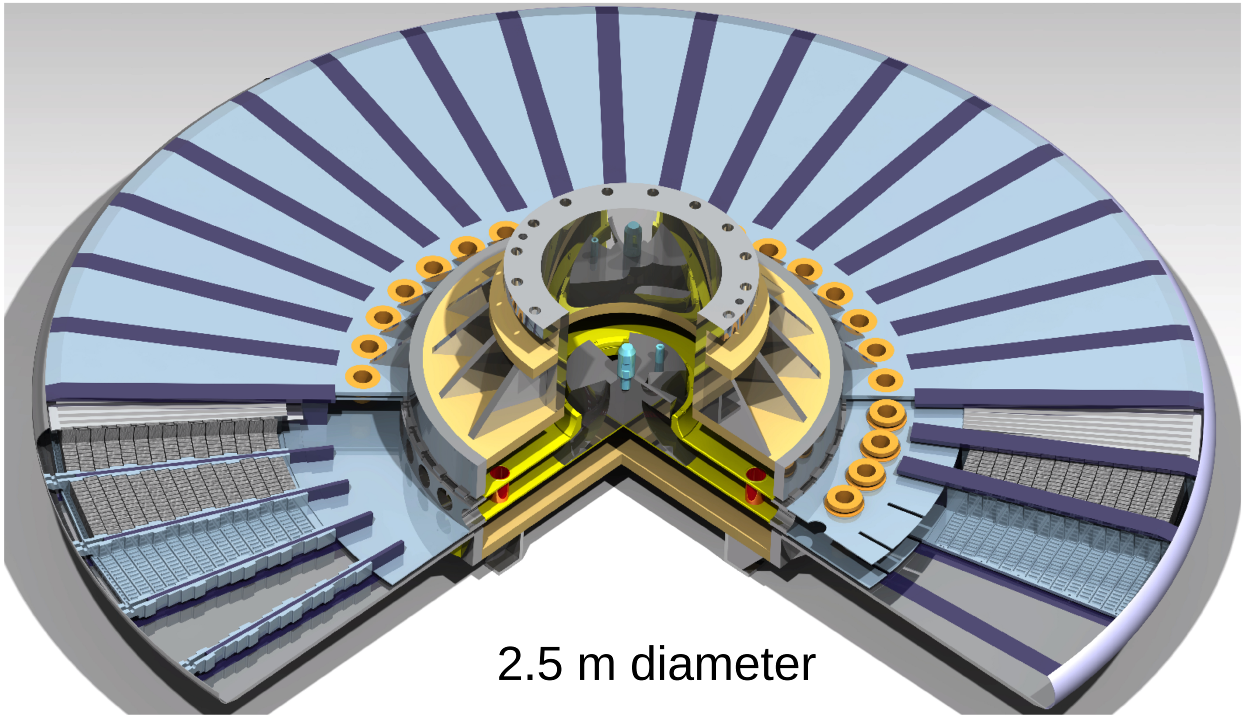
4.2 Better coupling between moderator and target

Low energy protons penetration in beryllium is juts 10-15 mm compared with 500-600 mm for high energy protons in tungsten. Thus, the source is much more concentrated and the coupling with moderators is clearly better.

37 Cassettes will be assembled in the Target Wheel Vessel







4.2 Better coupling between moderator and target

The ESS moderator developments (pancake and butterfly moderators) will be even better coupled in a compact source. This development improves by a factor ~3 neutron brightness on ESS moderatos compared with 2013 proposal.

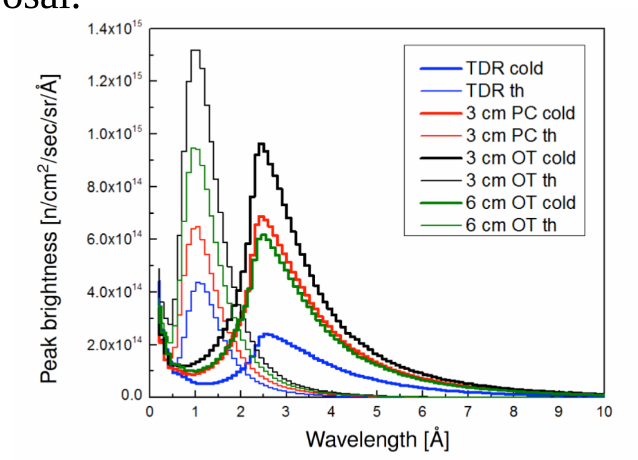
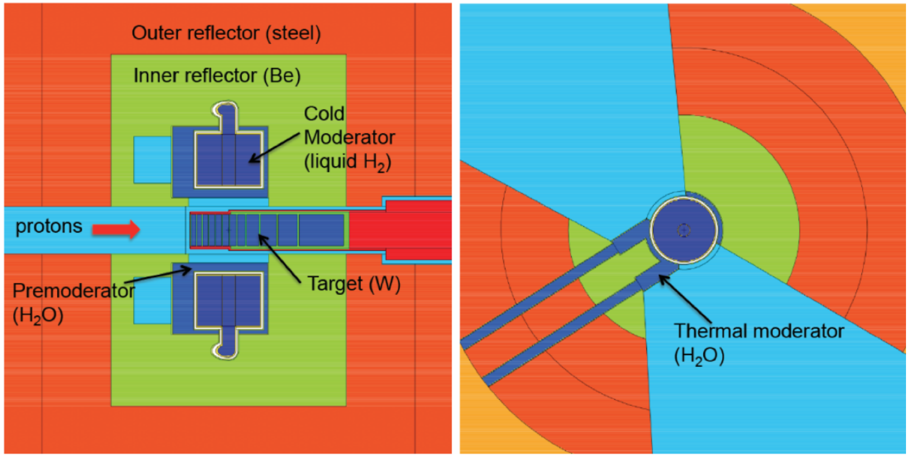
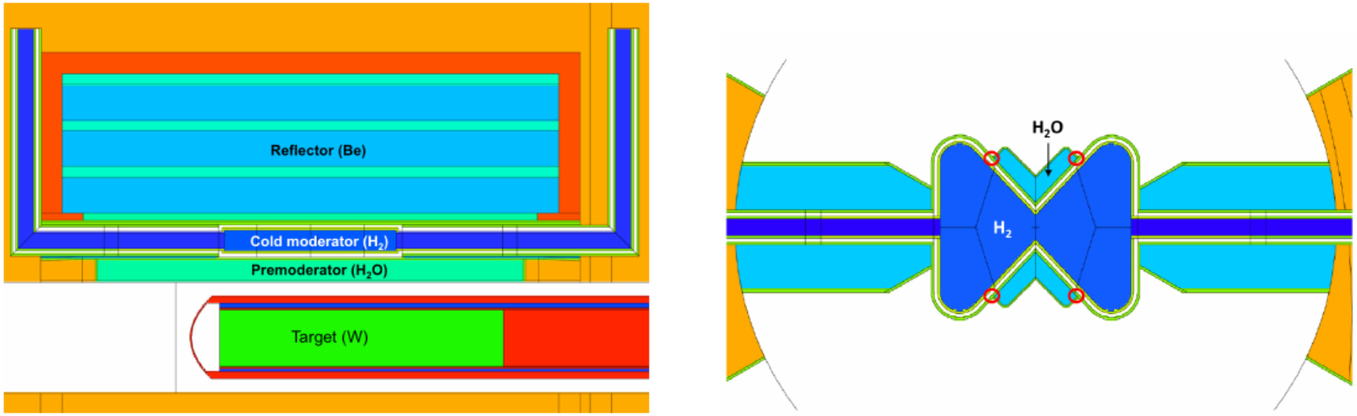


Figure 7. Calculated wavelength spectra from TDR, pancake (PC) and Optimized Thermal (OT) configurations. See explanation in the text.



ESS 2013 volumetric moderators (ESS Technical Design Report, S. Peggs editor, ISBN 978-91-980173-2-8, 2013)

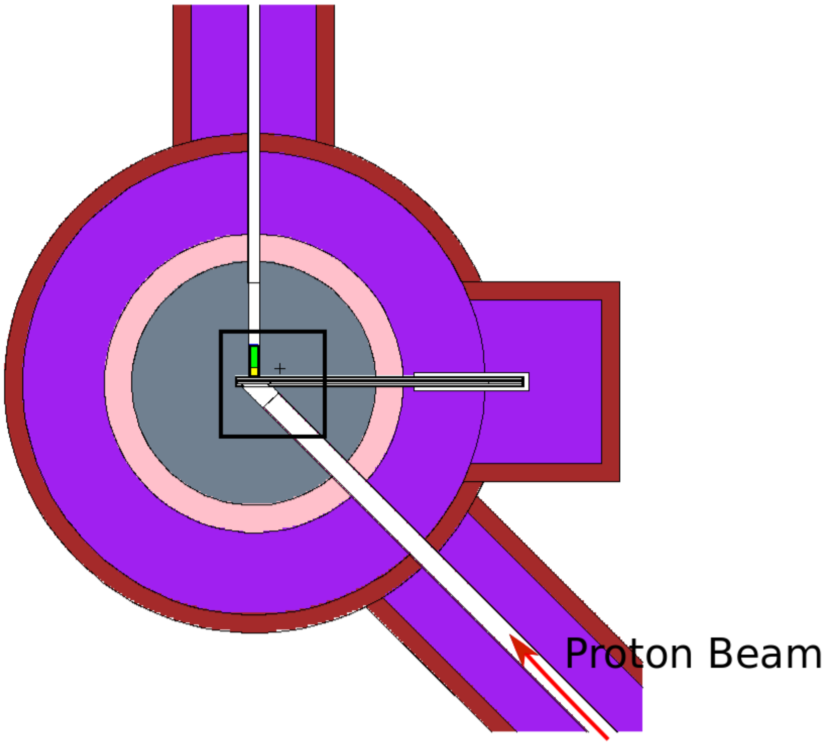


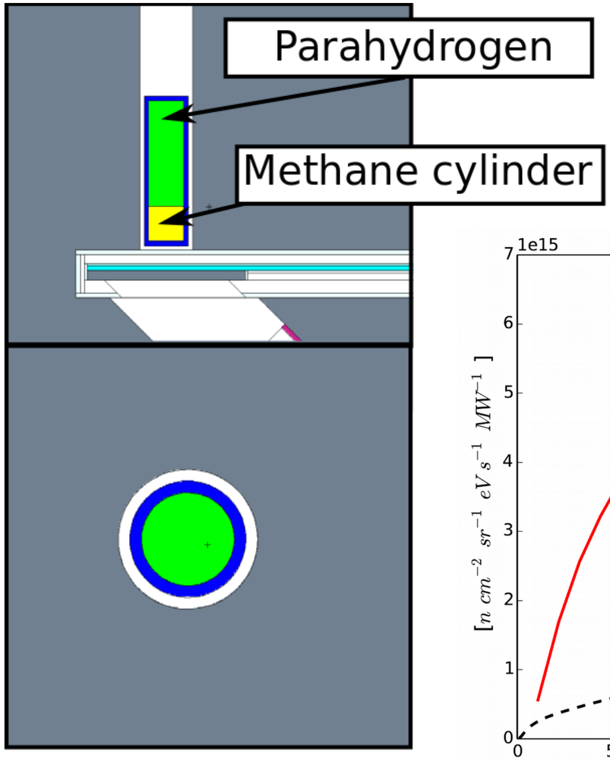
ESS 2019 volumetric moderators (Zanini, L., et al. "The neutron moderators for the European Spallation Source." Journal of Physics: Conference Series. Vol. 1021. No. 1. IOP Publishing, 2018.)

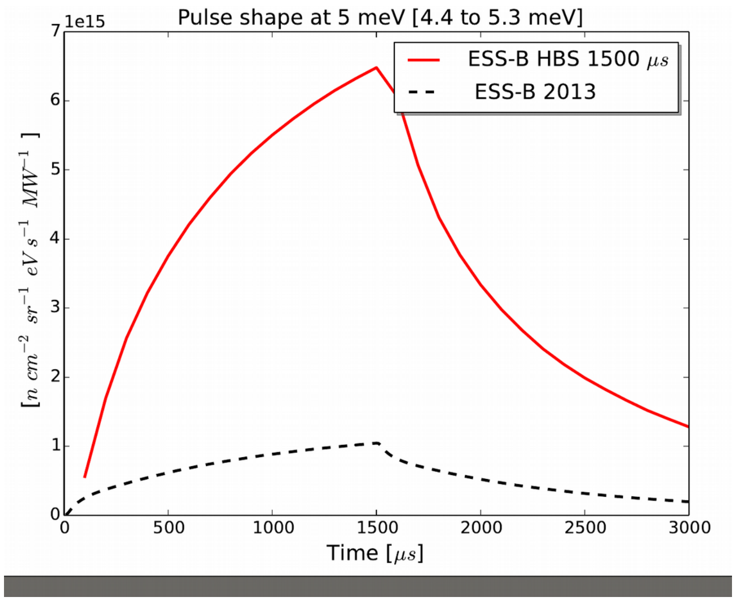
4. The CANS concept

4.2 Better coupling between moderator and target

HBS Team (Cronert, et al. Journal of Physics: Conference Series. Vol. 746. No. 1. IOP Publishing, 2016) proposed to extent the pancake concept to one dimensional moderator dedicated for a single instrument. This will increase by a factor of 7 the efficiency of the coupling, even better than



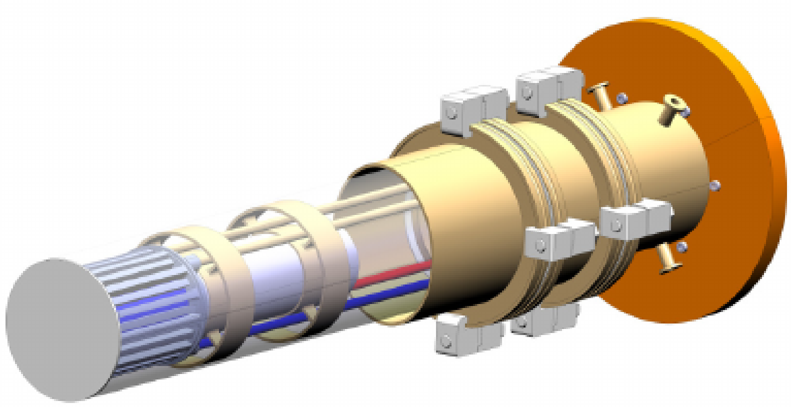


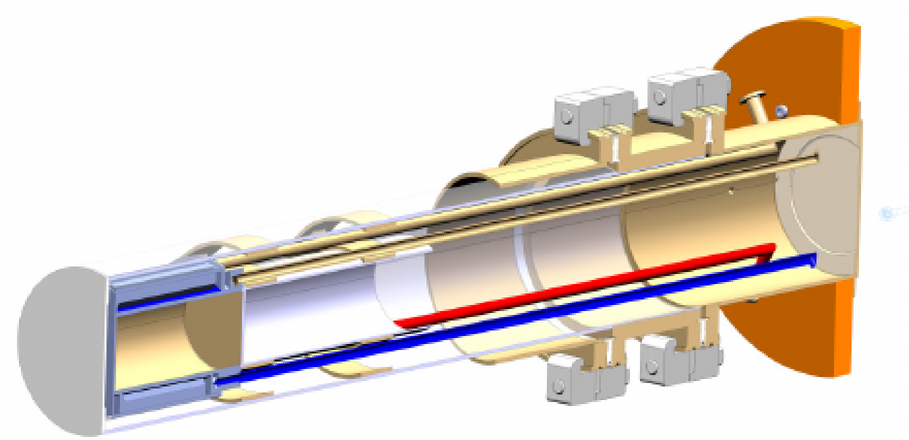


4. The CANS concept

Better coupling between moderator and target

The ESS moderator developments (pancake and butterfly moderators) will be even better coupled in a compact source. They can be converted in a one dimensional moderator considering that it will be one moderator per instrument and only 2-3 instruments per target station.





Cronert, et al. "High brilliant thermal and cold moderator for the HBS neutron source project Jülich." Journal of Physics: Conference Series. Vol. 746. No. 1. IOP Publishing, 2016.

4. The CANS concept

4.2 Better coupling between moderator and target

The ESS moderator developments (pancake and butterfly moderators) will be even better coupled in a compact source. They can be converted in a one dimensional moderator considering that it will be one moderator per instrument and only 2-3 instruments per target station.

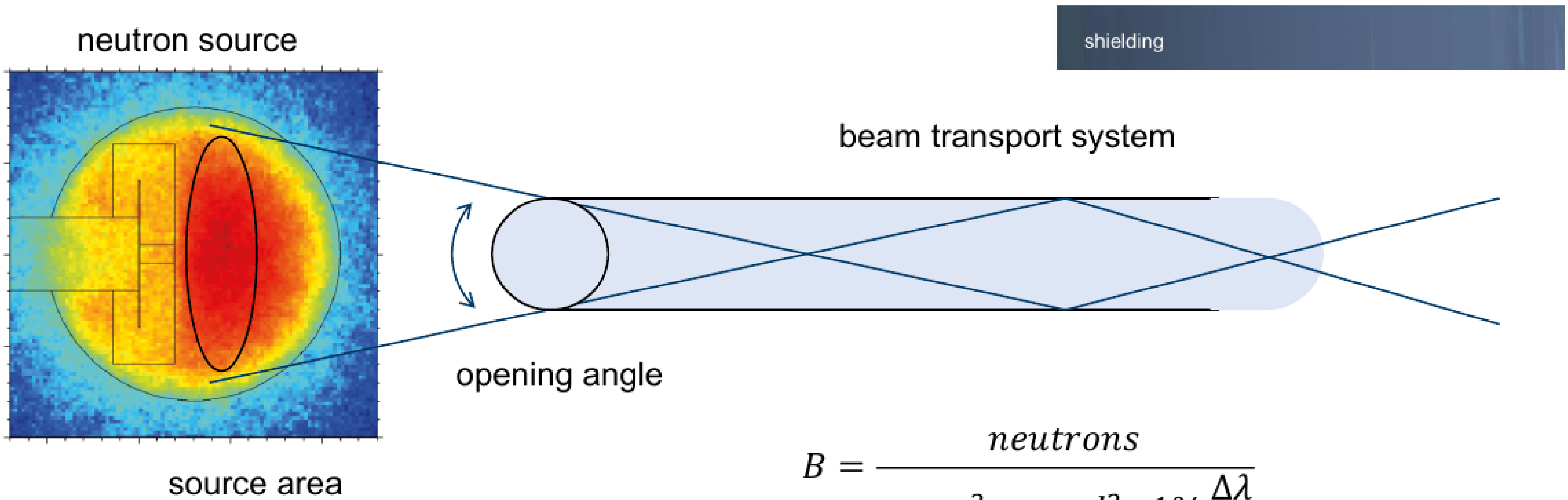
	Power	Rep Rate $[Hz]$	Viewed Surface $[cm^2]$	N. intensity $[n/cm^2 \cdot s \cdot sr]$	N. intensity $[n/cm^2 \cdot pl \cdot sr]$
JSNS C. hydrogen	300	25	100w x 100 h	1,3E+12	5,1E+10
	1000	25	100w x 100 h	4,5E+12	1,8E+11
SNS C. hydrogen	1000	60	120 w x 100 h	2,1E+12	3,5E+10
	1400	60	120 w x 100 h	3,0E+12	4,9E+10
ISIS-TS2 H/CH4, gro.	48	10	83 w x 30 h	5,0E+11	5,4E+10
ISIS-TS2 H/CH4, hyd.	48	10	120 w x 110 h	3,0E+11	3,0E+10
ESS-BILBAO 2013	112	20	120 w x 100 h	1,3E+11	6,6E+09
ESS-BILBAO HBS	112	20	$\phi = 40$	5,6E+11	2.8E+10

Dates from F. Maekawa /NIMA 620 (2010) 159-165

4. The CANS concept

4.3 Low radiation damage

The radiation levels on CANS target area is 3 orders of magnitude lower than hight power neutron sources and thus, neutron optics system can be placed closer to the moderator surface. Considering engineering limitations neutron optics system could be placed at 40 cm from moderator surface.



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

4. The CANS concept

4.4 Effiency considering moderator coupling

If the metric considers the brightness in the moderator surface, the CANS sources are a very effient option to provide neutrons to users.

			SONATE	ESS-B 2013	HBS*	ISIS-TS2
Accelerator Parameters	**Energy**	[MeV]	20	50	70	800
	Average Current	[mA]	4,00	2,25	2,00	0,06
Target-Moderator	**Power**	[kW]	80	112,5	139,9	48
	Neutron yield	[n/s]	5,2E+14	9,3E+14	1,85E+15	1,3E+16
	Proton Current	[p/s]	6,4E+16	3,6E+16	3,20E+16	9,6E+14
	Neutron yield	[n/p]	8,1E-03	2,6E-02	5,77E-02	1,4E+01
Construction Cost		[M€]	60,0	100,0	400,0	800,0
		[M€/10^14 n]	11,5	10,7	21,7	6,2
2019 HBS moderator**	**Brightness peak average**	[n/cm-sr-s]	3,1E+11	5,6E+11	1,1E+12	5,0E+11
Moderator brightness cost		[M€]/[n/cm-sr-s]*1E11	19,2	17,8	36,1	160,0
Ratio Neutron yield			0,04	0,07	0,14	1,00
Ratio Moderator brightness			0,62	1,12	2,22	1,00

5. Construction and operational cost

5. Construction and operational cost

Electricity consumption

The electricity consumption could be a good indicator of the operation budget for accelerator based facilities. Typically corresponds to 40% of the operational budget.

Considering 0.17 €/kWh the electricity cost will be:

- **ESS ~ 47.8 M€/year**
- **ESS-B will be ~ 1.3 M€/year.**

ESS Energy Design Report
Outcomes from the collaboration between ESS, E.ON and Lunds Energi
2011-2012

Component	Electricity	Cooling	Unit
Ion Source	125	125	kW
RFQ	175	140	kW
Bunchers (=MEBT)	19	17	kW
DTL (RF system)	1143	956	kW
Spokes (RF system)	1489	704	kW
Low section (RF system)	3768	2961	kW
High section (RF system)	13894	10066	kW
LEBT & HEBT	500	500	kW
Pumps in cooling circuits	62	62	kW
Fans for ventilation	89	45	kW
Racks for instruments	200	200	kW
RF test stands (RF system)	1300	1300	kW
Cooling of air in klystron gallery	100	100	kW
Linac tunnel	63	380	kW
Cryo-cooling cavities, RF test stands, LHe	4000	4000	kW
Utilities (compressed air, etc.)	500	500	kW
ESS (2000 GeV)			
Total, power	27427	22055	kW
Total, energy use	148,1	119,097	Gwh
Compact Source (~50 MeV)			
Total, power	1518,4	1645	kW
Total, energy use	[illegible]	[illegible]	Gwh

5. Construction and operational cost

Operational cost

The operation cost of Compact sources will be relative low due to low energy consumption

Facility	ILL	ISIS	MLZ	SINQ	ESS	LLB	SONATE TS1 + TS2
First Neutrons	1971	1994	2004	1998	2023	1981	2025-2030
Replacement value (M€)	2000	800	600	750	1847	400	70
Operating costs (M€)	95	62	55	30	140	30	3.65
Instrument-day (k€)	11.9	16.7	9.2	12.5	35.3	7.9	2
Operation cost / replacement value	4.75%	7.75%	9.2%	4%	7.6%	6.7%	5.2%

ESFRI Report, Neutron scattering facilities in Europe, Present status and future perspectives, 2017

Ott, Frédéric, Alain Menelle, and Christiane Alba-Simionesco. "The SONATE project, a French CANS for Materials Sciences Research." arXiv preprint arXiv:1909.01582 (2019).

6. Conclusions

6. Conclusions

Main Remarks:

- Accelerator based compact sources can present a very efficient solution to compensate the research reactors shutdown in the coming years.