Compact Accelerator-based Neutron Sources: recent developments

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Outline

- How to get neutrons ?
- The various types of Compact Accelerator-based Neutron Source (CANS) and HiCANS
- What does « compact » really mean ?
- Recent developments towards HiCANS
    - Accelerators
    - Targets
    - Moderators
    - Simulation codes

Disclaimer: I will not talk about

- **The importance of neutrons for various applications in medicine, industry, academic research…**
- **All the types of accelerator-based neutron sources**

See for example IAEA-TECDOC-1981: https://www-pub.iaea.org/MTCD/publications/PDF/TE-1981web.pdf

How to get neutrons ?

Neutron flux
(n/s total flux)

10^{18}

10^{15}

10^{12}

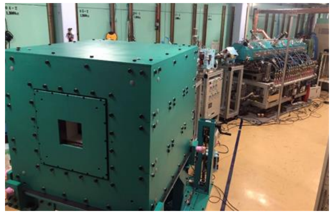
10^{10}

10^{7}

Research Reactors
$5\ 10^{16}$ n/s/MW
224 RR in 53 countries

(mostly) continuous

Spallation sources
ISIS, SINQ, J-PARC, SNS, CSNS, ESS…
100s MeV to GeV protons
Hg, W, Pb targets



Compact ABNS = CANS
2.5 – 70 MeV p (D), 10s MeV e
Li, Be, … Pb targets
$10^{11} – 10^{15}$ n/s

ABNS

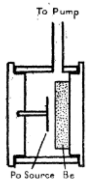
Continuous
or
Pulsed

Adelphi Technology Inc.

D-D, D-T, T-T generators
$10^{6} – 10^{11}$ n/s

Spontaneous fission sources
1 µg of ^{252}Cf emits 2.3 10^{6} n/s
10^{10} n/s

Continuous



Alpha particles – Be / Li
AmBe few 10^{7} n/s
AmLi, PuBe

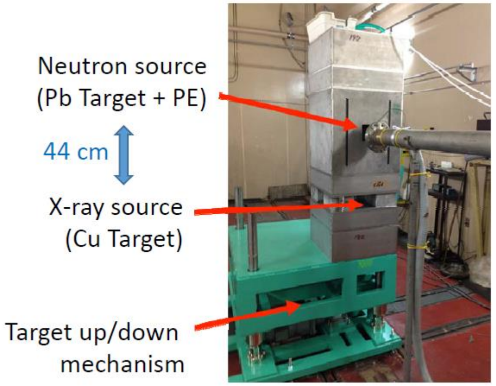
Continuous

cm | m | 10 m | 100 m | km | Size / price of facility

Various types of CANS

Electron Linacs
Example: HUNS 2 (Hokkaido University)

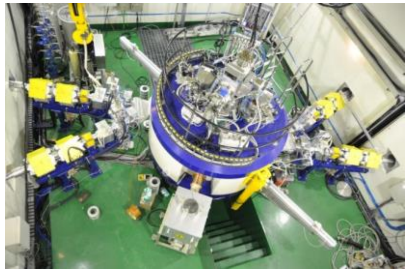
32 MeV, 100 µA



5 10^{12} n/s with Pb target

(Courtesy T. Kamiyama)

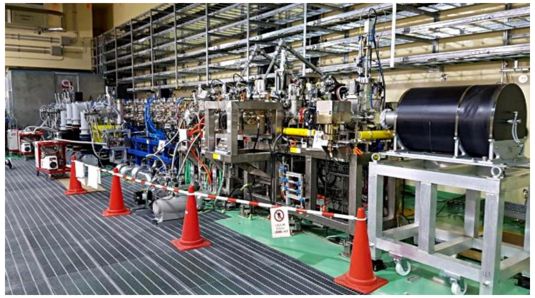
(Commercial) electrostatic p accelerators
Example: 30 mA, 2.6 MeV → ~ 10^{13} n/s with Li target
https://www.d-pace.com/?p=accelerators



(Courtesy D.W. Lee)

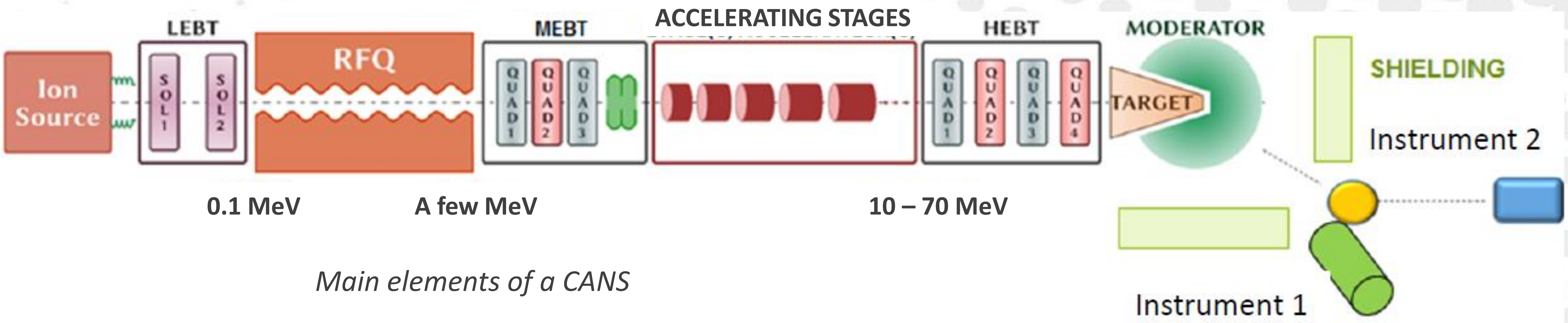
(Commercial) cyclotrons
Examples: 30 MeV cyclotrons at INER, Taiwan and KAERI, Korea
Operation in the ~100 µA range ~ 10^{13} n/s Be target
Limit ~70 MeV, 1 mA → 5 10^{14} n/s

Light ion linacs
Few MeV (Li or Be target)– 40 - 70 MeV (other)
100 µA – 100 mA (HiCANS)
Beam power 100s of W to 100s of kW
Pulsed or continuous



Several sources in operation, under construction or foreseen

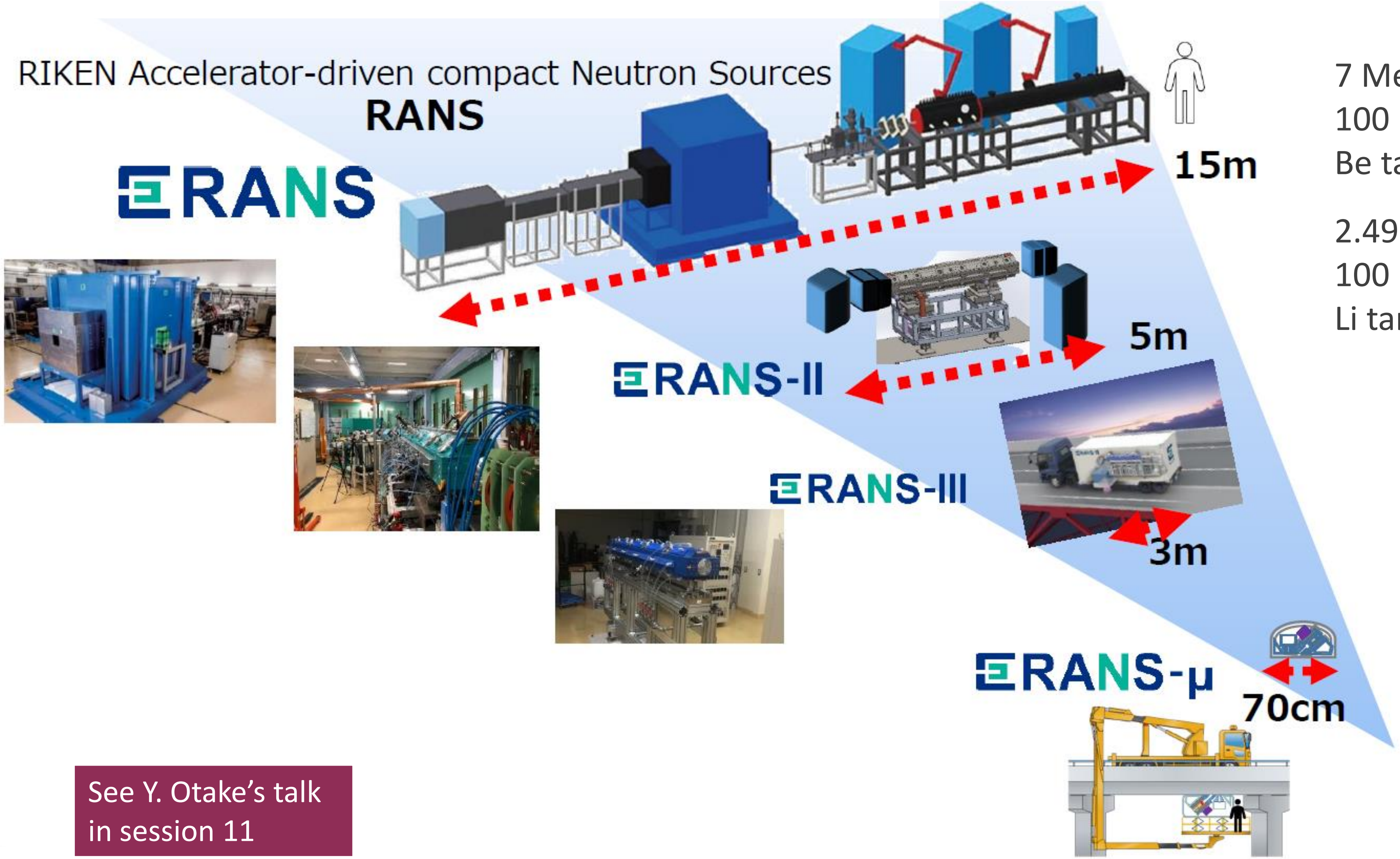
See the IAEA database:
https://nucleus.iaea.org/sites/accelerators/Pages/default.aspx



Main elements of a CANS

L(M,H)EBT = Low (Medium, High) Energy Beam Transport lines

- Light ion (p, D) source (few mA – 100 mA)
- Radio-Frequency Quadrupole (RFQ): first accelerating stage
- Additional accelerating stage(s) (warm or superconducting)
- Target
- Moderator to adapt the neutron energy spectrum (thermal = 25 meV or colder)
- Neutron Instruments



7 MeV protons
100 μA
Be target

2.49 MeV protons
100 μA
Li target

In operation

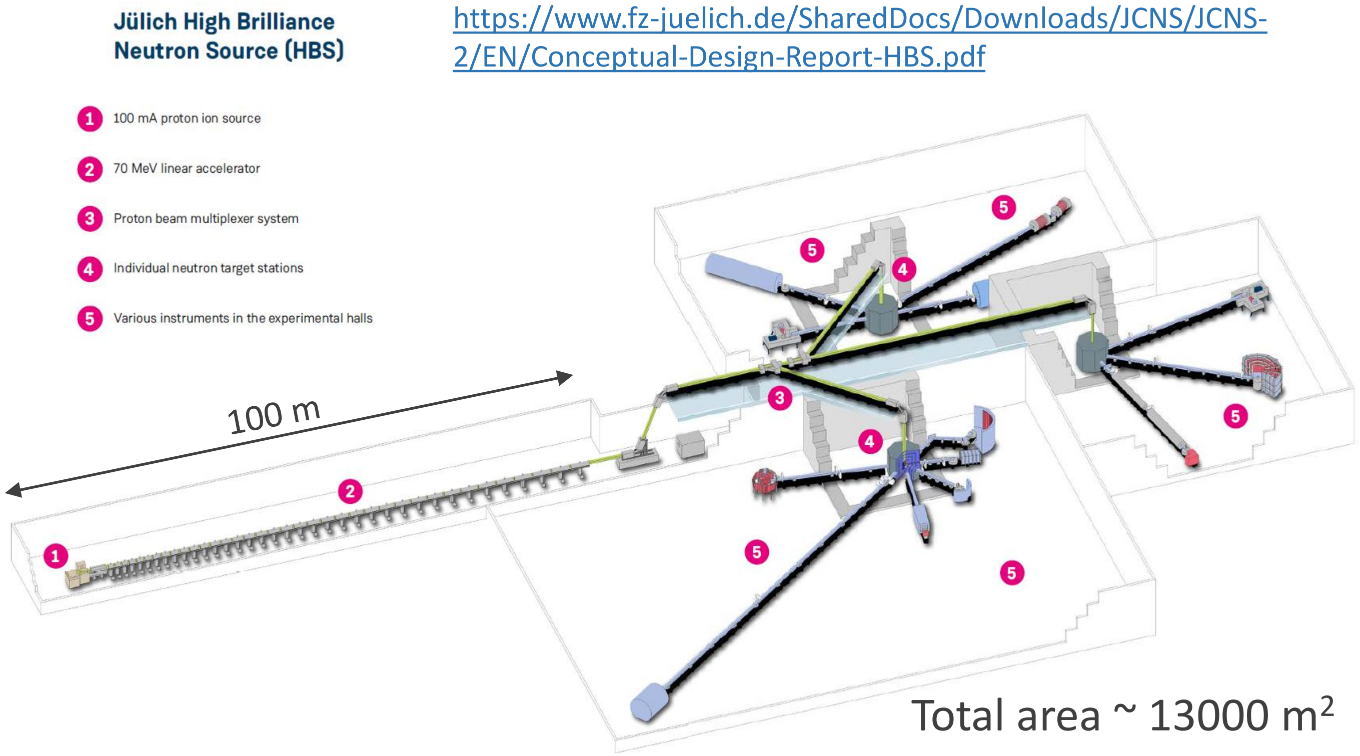
Under development

See Y. Otake's talk in session 11

Example of Jülich High Brilliance Source (HBS) project

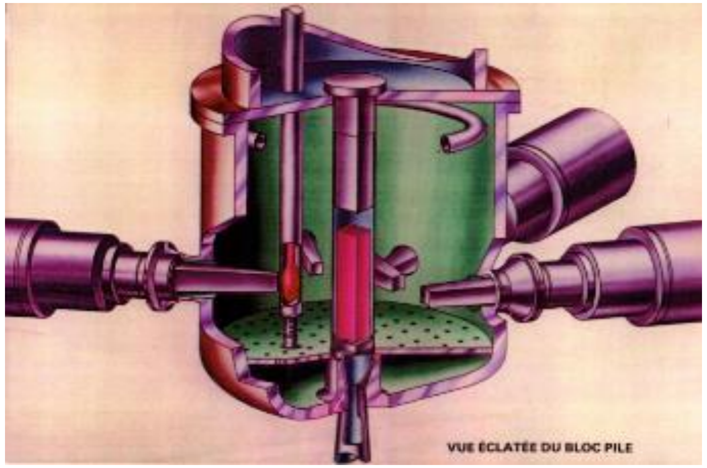
- Accelerator 70 MeV, 10 – 100 mA, duty factor up to 10% (beam power up to 1 MW)
- The accelerated beam can be split to feed several target stations
- Each target station can be optimized:
  - Optimize pulse structure (length, rep. rate)
  - Optimize thermal spectrum
  - Several neutron beam ports per target station
- Every beam port serves only 1 instrument
  - Optimize cold source spectrum
  - Optimize geometry
  - Integrate neutron optics with beam port

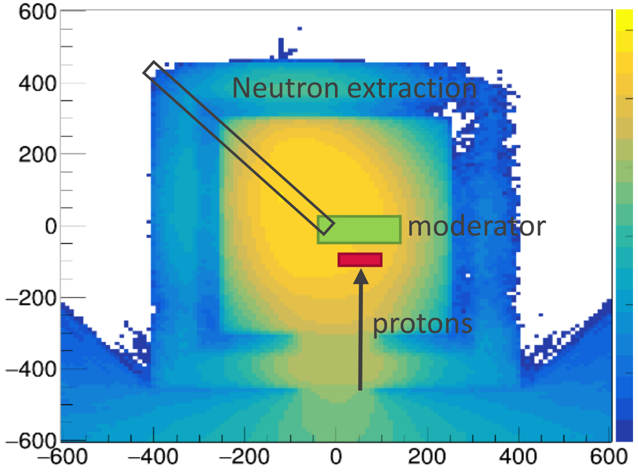
https://www.fz-juelich.de/SharedDocs/Downloads/JCNS/JCNS-2/EN/Conceptual-Design-Report-HBS.pdf



Total area ~ 13000 m^2

What is really compact ?





Orphée in Saclay ***(continuous)***

Source volume (core)	~ 5 10^4 cm^3
Moderation volume	~ 8 10^5 cm^3
# neutrons	~ 1 10^{18} $n.s^{-1}$
Neutrons average density	~ 1 10^{12} $n.cm^{-3}.s^{-1}$

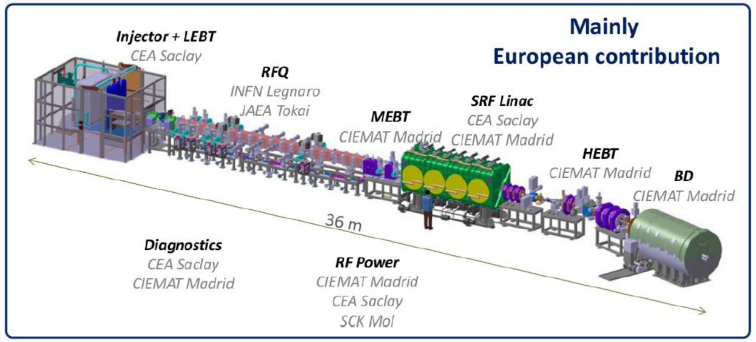
CANS ***(pulsed)***

Source volume	~ 2 cm^3	
Moderation volume	~ 5 10^3 cm^3	
# neutrons	~ 5 10^{15} $n.s^{-1}$	(Peak)
Neutrons average density	~ 1 10^{12} $n.cm^{-3}.s^{-1}$	

- **A compact target / moderator increases the brightness of the neutron source**
- **Working in (accelerator) pulsed mode leads to a high peak neutron flux while limiting the total power → adapt the time structure (pulse length and repetition rate) to specific applications.**

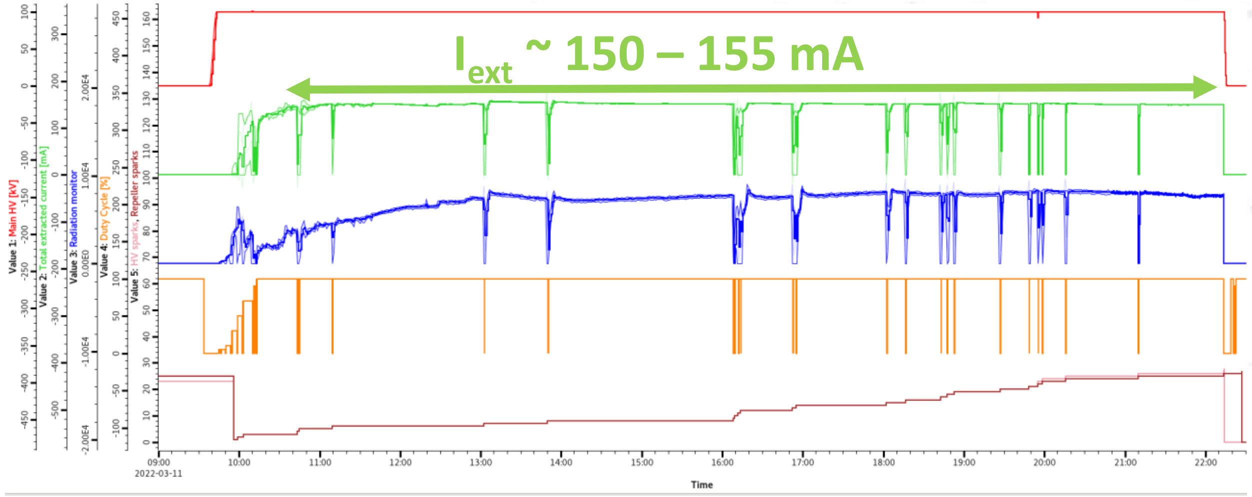
Commissioning of IFMIF – Lipac at Rokkasho (Japan)

Deuterons
9 MeV, 125 mA cont.



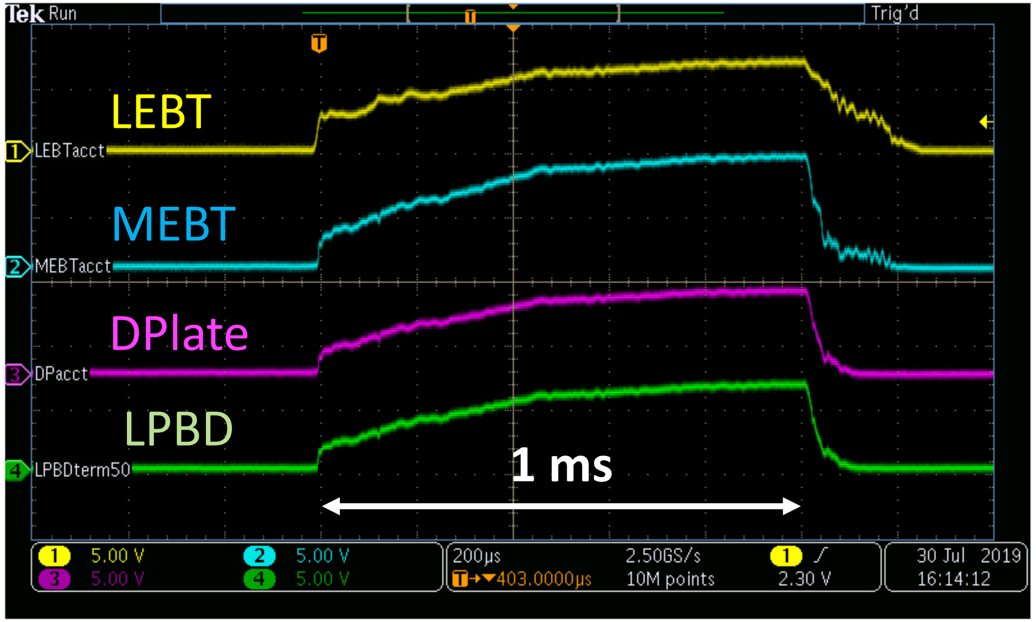
▶ Deuteron source + LEBT commissioning:

- 155 mA continuous extracted from source
- D^+ fraction ~ 90%
- “Long runs” of 11 hours



▶ Ion source + LEBT + RFQ + MEBT commissioning:

- 160 mA extracted from source, D^+ fraction ~ 85%
- End of LEBT : 139 mA
- MEBT : 125 mA
- Beam pulse: 1 ms/1Hz



Recent developments: Radio-Frequency Quadrupoles (RFQ)

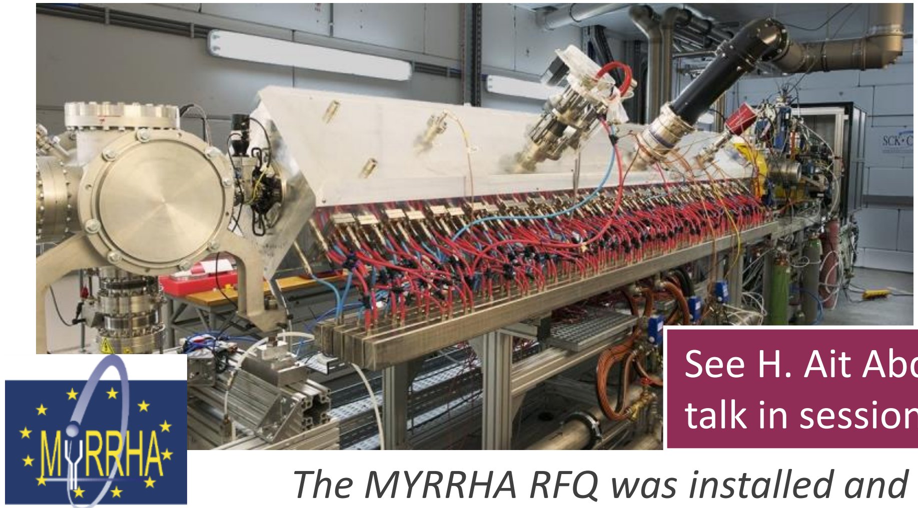
The RFQ is the first accelerating stage of high intensity proton beams. Challenge = high beam transmission (95%)

The IPHI RFQ (Saclay) has been accelerating a proton beam to 30 kW for more than 100 hours

See J.G. Weisend II's talk in session 3.A

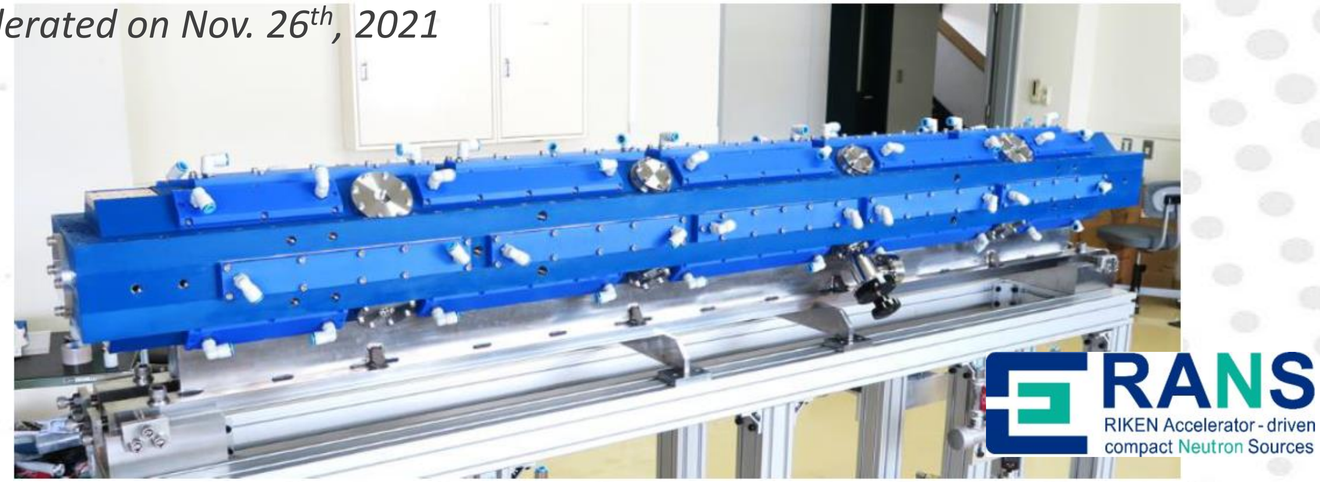
The ESS RFQ was conditioned to nominal RF power in July 2021, first beam accelerated on Nov. 26th, 2021

The RFQ for the ARGITU project (Bilbao) is under construction



See H. Ait Abderrahim's talk in session 2

The MYRRHA RFQ was installed and commissioned with beam in Belgium in 2020



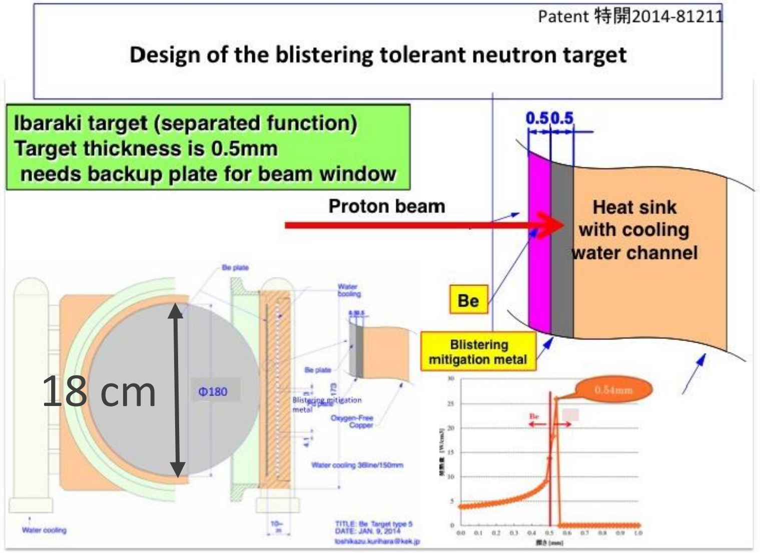
Compact 500 MHz RFQ for the RANS III project (Riken)
Output energy 2.49 MeV, peak current 10 mA, max duty cycle 3%

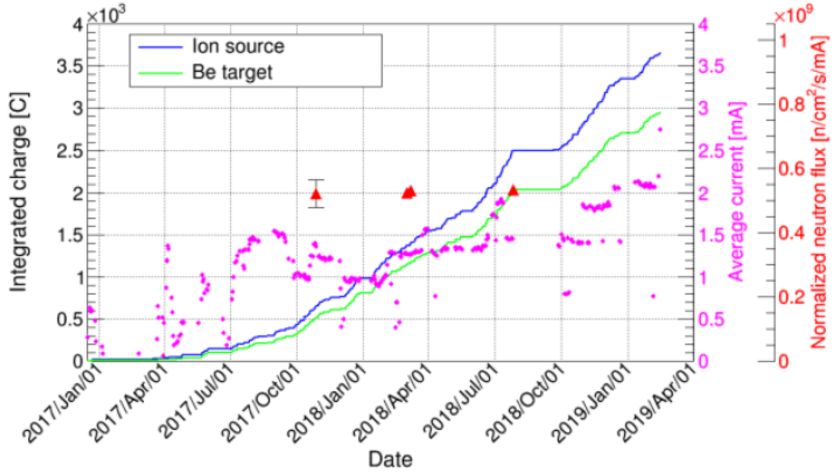
Solid Be targets are an apparently easy solution (compact, no activation) for 3 – 30 MeV accelerators

However bulk Be targets are prone to blistering due to proton implantation

Multilayer targets have been developped in Japan

- RANS at 7 MeV, 350 W
- iBNCT (Tsukuba) at 8 MeV, 22 kW





Multi-layer Be tested between 2017 and 2019 at 22 kW. 3000 C integrated charge.

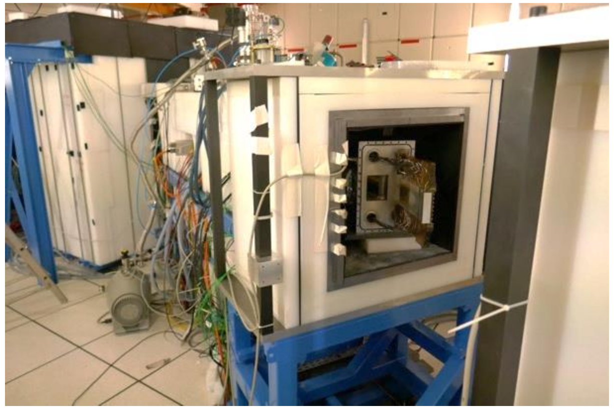
Kurihara, Toshikazu & Kobayashi, Hitoshi. (2020). *Diffusion bonded Be neutron target using 8 MeV proton beam*. EPJ Web of Conferences. 231. 03001. 10.1051/epjconf/202023103001.
https://www.researchgate.net/publication/339857840_Diffusion_bonded_Be_neutron_target_using_8MeV_proton_beam

Recent developments: targets (2)

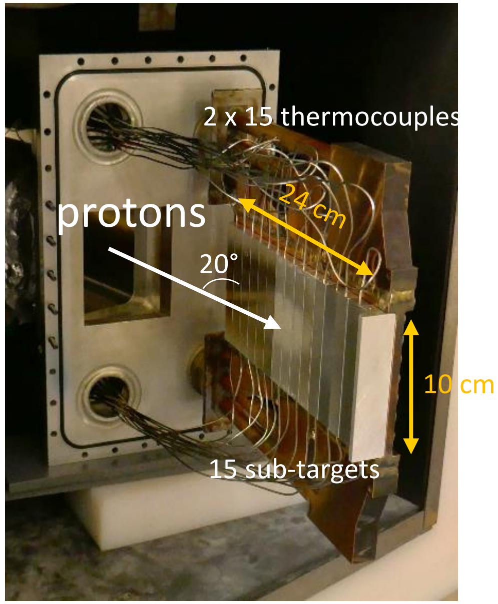
Another approach : bulk Be target operated at high temperature (T_{surf} > 400°C) to ease hydrogen diffusion

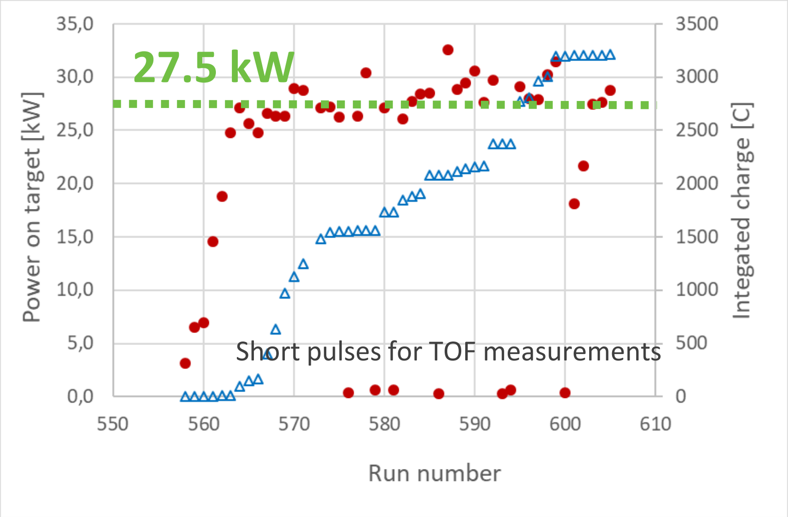
A prototype was tested at the IPHI accelerator in January – February 2022 (3 MeV, 25 – 30 kW)

Target was operated at ~ 27.5 kW for more than 100 hours (integrated charge = 3200 C). Blisters do occur but show only a very slow evolution

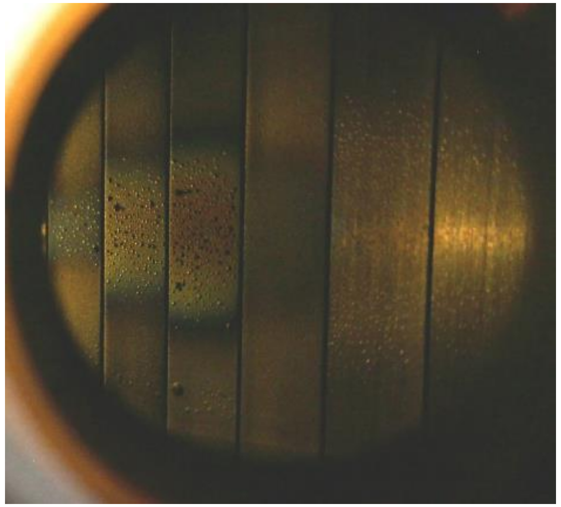


Target at the end of the IPHI accelerator. The target is inclined with respect to the proton beam direction to decrease the surface heat load.





See F. Ott's talk in session 12.A

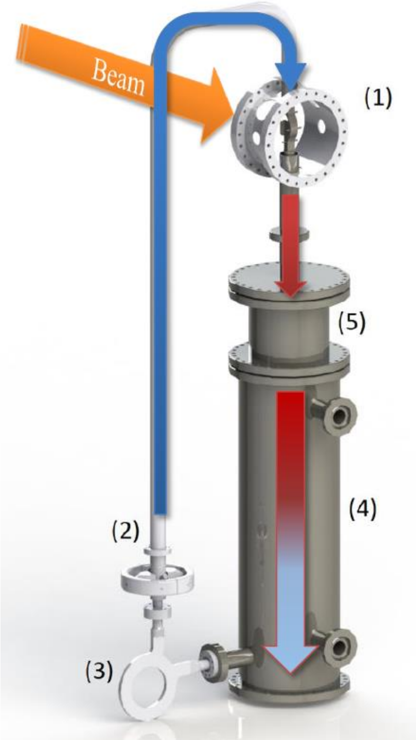


The degradation of Be sub-targets by the proton beam stabilized itself after a few hours of operations.

Recent developments: targets (3)

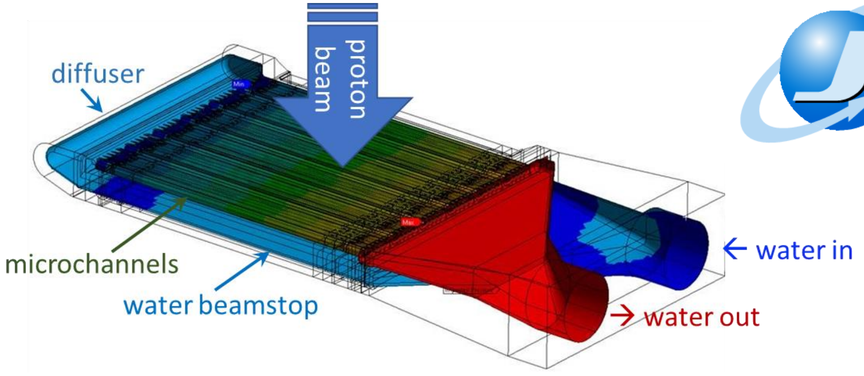
At higher energies, different target materials can be used

Gallium Indium Liquid jet Target (GaLiT) for SARAF2
2.4 10^{14} n/s/mA @ 40 MeV, hazardless



Measurements of neutron production to be published

High Power Tantalum Target for HBS
10^{15} n/s/mA @ 70 MeV, high blistering threshold

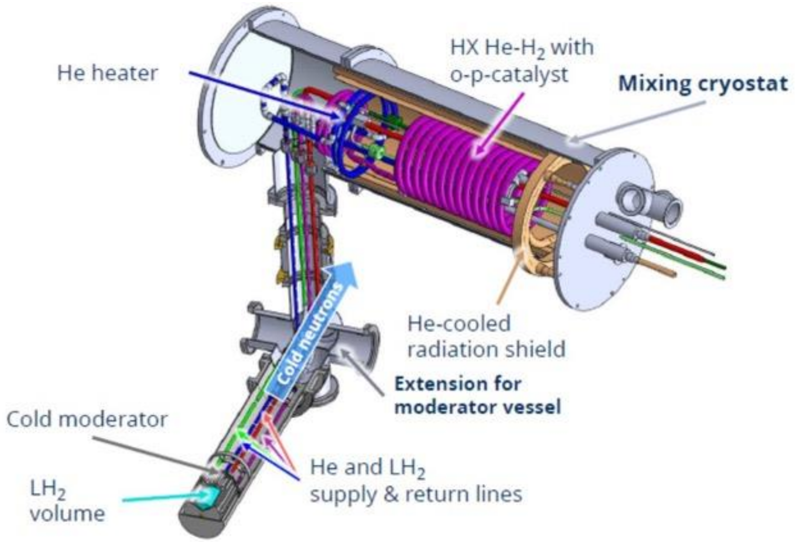



"herringbone patterned" - micro channel target

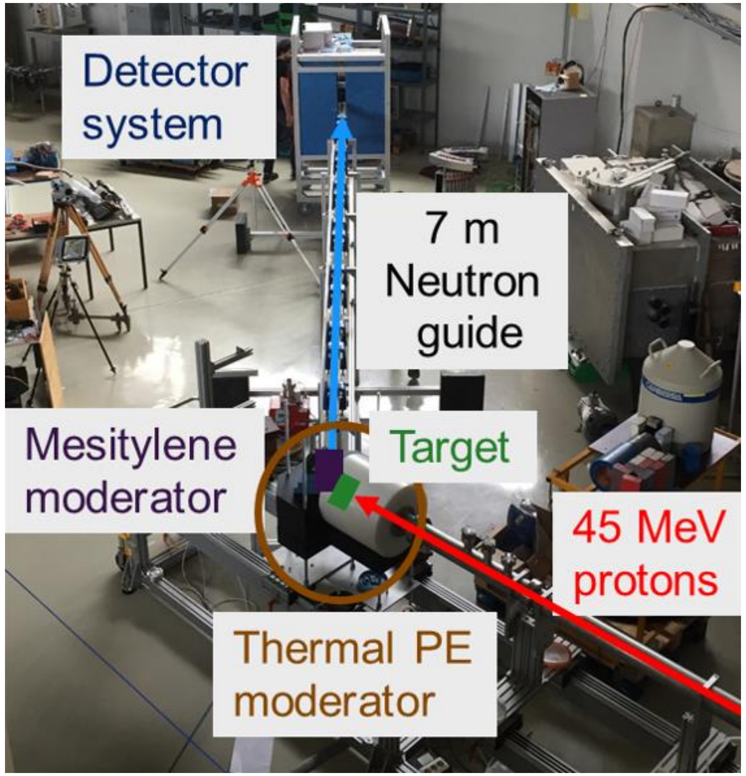
Tested with electron beam up to 1 kW / cm^2

At CANS, (cold) moderators and the neutron extraction channels can be optimized for each intrument

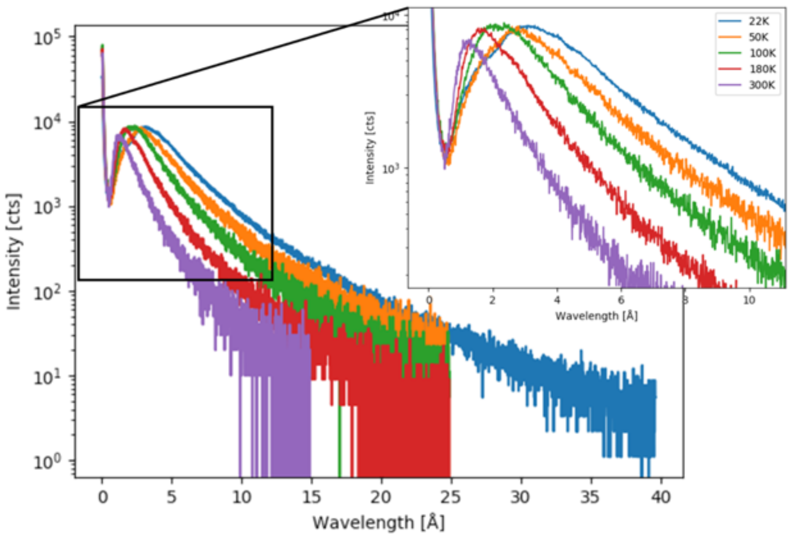
- One dimension (finger like) cold moderator located inside the thermal moderator
- Using liquid H_2, solid methane CH_4, solid mesitylene C_9H_{12}



Design



Experiment

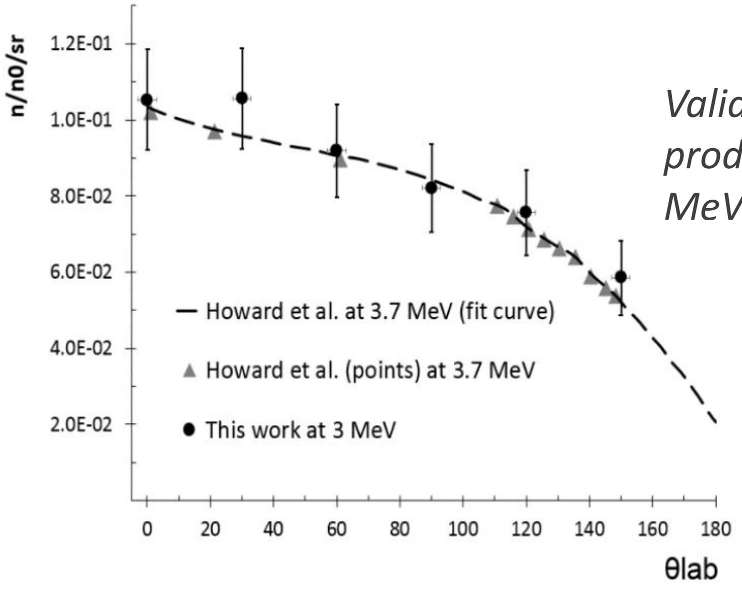


Results

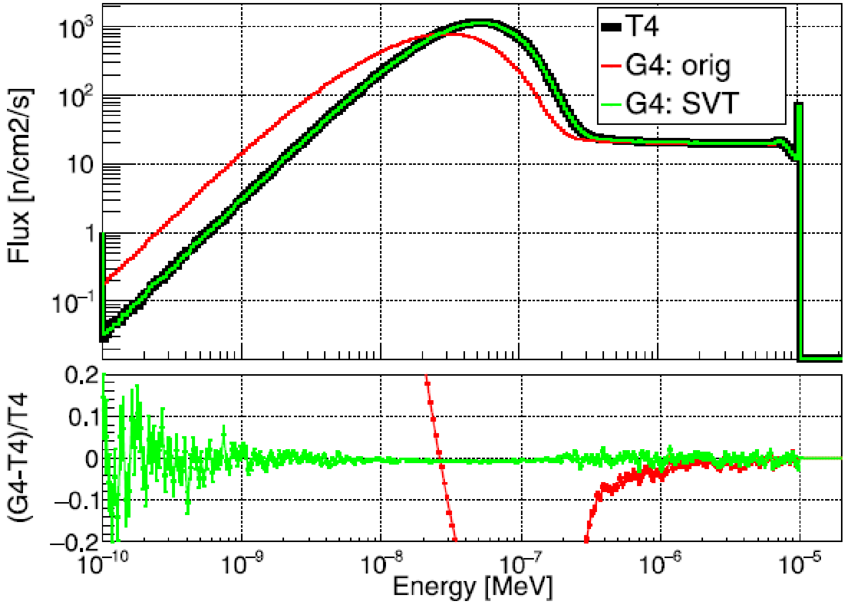
Recent developments: simulations

- **Neutron production distribution from the target was measured at low power and compared with other work**
  - Described in H. Tran et al. *Neutrons production on the IPHI accelerator for the validation of the design of the compact neutron source SONATE*. EPJ Web of Conferences. 231. 01007. 10.1051/epjconf/202023101007.

- **The simulation of the moderation using Geant4 was improved and benchmarked vs Tripoli-4 (Nuc. Reactor Sim. code)**
  - Correction of the thermal scattering laws
  - ENDF/B-VII.1 → ENDF/B-VIII.0 + JEFF-3.3 for cold moderators
  - Will be included in the Geant4 beta version to be released in June
  - Described in L. Thulliez et al. *Improvement of Geant4 Neutron-HP package: From methodology to evaluated nuclear data library*. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 1027, 2022



Validation of the neutron production angle in 3 MeV p → Be reaction



Moderation of 10 eV neutrons inside a sphere: comparisons between Geant4 (red), corrected Geant4 (green) and Tripoli-4

Conclusions

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 — RIKEN RAP — LENS — JCNS HIGH BRILLIANCE SOURCE Prototype — Sonate — JCNS HIGH BRILLIANCE SOURCE

MIRROTRON THE WORLD OF NEUTRON

Taken from LENS report on the potential of Low Energy Accelerator-driven Neutron Sources (2020)
* League of advanced European Neutron Sources

- Compact accelerator-based neutron sources exist in a wide range of size / cost / neutron flux (10^{11} n/s – 10^{15} n/s)
- Low power CANS (~ 1 kW) have been in operation for many years
- Currently no high power (> 10 kW) CANS in operation. Thanks to recent developments on high power accelerators and targets, several projects under construction or foreseen
- High power CANS with optimized moderators and pulse structures could reach performances comparable to research reactors for some applications

Thank you for your attention