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Progress of the first accelerator-based compact neutron source in Hungary

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Abstract. The first compact accelerator-based neutron source (CANS) for industrial and healthcare use in Hungary, the 'LvB' project, is being installed at the premises of Mirrotron Ltd. at Martonvásár. In the first phase of the operation, a fast neutron spectrum with energies up to 1 MeV is generated by the impact of a 2.5 MeV and 1 mA time-average intensity pulsed proton beam on a Li target. This target is surrounded by a lead reflector and the beam extraction opening faces of a bi-spectral para-H_2 and H_2O quasi-one-dimensional moderator, to provide cold and thermal neutron beams primarily for applied material investigations by neutron scattering. Recent results of MCNP6.2 simulations of the initial configuration of the 'LvB' compact neutron source confirm the expected neutron beam brightnesses to be approx. 10^7 n/cm^2/s/sr/Å time-average at 4 Å neutron wavelength.

1 Introduction

In the upcoming decades, most of the hundreds of research reactors in the world will reach their operational lifetime. With the foreseen decrease in the number of research reactors, spallation neutron sources are being built to provide available high flux neutron beamtime. However, the high cost of spallation sources makes them unaffordable for most countries, for instance, the expected cost of the European Spallation Source (ESS) exceeds 3 billion euros. Therefore, low-cost alternative neutron sources are needed for some applications. The compact accelerator-based neutron sources (CANS) developed in the past decades, primarily in Japan [2], have proved to be a practical and very cost-effective (5 - 300M euros) alternative for uses that do not require particularly high neutron beam intensities. Broad availability of CANS facilities for the community is an important condition for the efficient use of the highest beam intensities at large spallation sources, by reducing user demand at large spallation sources on neutron beam studies that do not require high neutron beam intensities. CANS facilities can consequently improve the availability of neutron beam instruments for broad common uses (e.g. education) and commercial uses (e.g. quality testing for industrial production).

Compared to spallation neutron sources, the neutron yield of nuclear reactions used in a CANS facility is in orders of magnitude lower than that of the spallation reaction (20 – 30 neutrons per accelerated proton), but the lower neutron yield of CANS can be somewhat compensated by arranging instruments closer to the neutron source due to lower moderation and shielding requirements [1]. With a broad range of fast neutron yield (10^{10}- 10^{15} n/s) in the target, CANSs have already been applied in various fields, such as reflectometry, neutron imaging, instrument development, and cross-section measurements [1]. In addition, CANS irradiation facilities are increasingly and advantageously applied in boron neutron capture therapy (BNCT) [3,4].

The Budapest Research Reactor (BRR), serving as the primary research neutron source in Hungary, has been in operation for over 60 years [5] and recently received an extension of its operating permission until the end of 2033. However, its future beyond this date remains uncertain. The first CANS project 'LvB' in Hungary has been jointly developed by Mirrotron Ltd. and the HUN-REN Centre for Energy Research. The 'LvB' is an abbreviation representing 'Lithium vagy Beryllium,' which translates to 'Lithium or Beryllium', emphasizing the project's development potential.

2 LvB CANS design

Currently, the 'LvB' project is in the initial stage of development, i.e. with a Li target and a 2.5 MeV pulsed proton beam with 1 mA time-average current. The design parameters of the Linac accelerator system are shown in Table 1. The electron cyclotron resonance (ECR) ion source and the low energy ion beam transport system are being developed by HUN-REN Centre for Energy Research, Hungary. The ECR ion source provides a 35 keV/20 mA proton beam for injection into the radio-frequency quadrupole (RFQ) linac accelerator, in pulses of 1.25 ms duration and 40 Hz repetition rate. The RFQ was manufactured, installed, and successfully tested for electric performance by Time Inc, Hiroshima, Japan. The RFQ linac accelerates the injected protons to 2.5 MeV energy. The Li target manufactured by Sanki Industry Co., Ltd is now positioned 1.5 m from the RFQ beam exit. The V-shaped Li layer covers a 3.5×3.5 cm^2 cross section facing the proton beam. The 50 μm thick Li layer is plated on a water-cooled copper plate and is placed at an angle of 15° with respect to the proton beam direction. The resulting approx. 190 μm long path for the incident protons in the Li layer stops the protons within the Li layer. The expected target lifetime is approximately 720 hours, assuming a 1 mA time-average, 2.5 MeV proton beam loads on the target.

As shown in Fig.1, the target-moderator-reflector (TMR) system is built into a casted, high purity Pb reflector of 60×60×60 cm^3 external dimensions. The bi-spectral moderator consists of a quasi-one-dimensional water premoderator and a quasi-one-dimensional liquid para-H_2 cold moderator. Low dimensional moderators were first introduced in ESS [6]. L. Zanini et al. found that quasi-one-dimensional moderators at a CANS [7] can provide an order of magnitude gain in the ratio of moderator brightness and initial fast neutron yield in the target, as compared to ESS. The TMR system is shielded by 10 cm of borated polyethylene (PE) containing 10% boron.

Table 1. Design parameters of the 'LvB' project linac system.

Ion Source	Mode	Pulsed beam
	Pulse width	1.25 ms
	Output energy	35 keV
	Pulse frequency	40 Hz
	Peak current	20 mA
RFQ	Output energy	2.5 MeV
	RF frequency	200 MHz
	Duty factor	5%

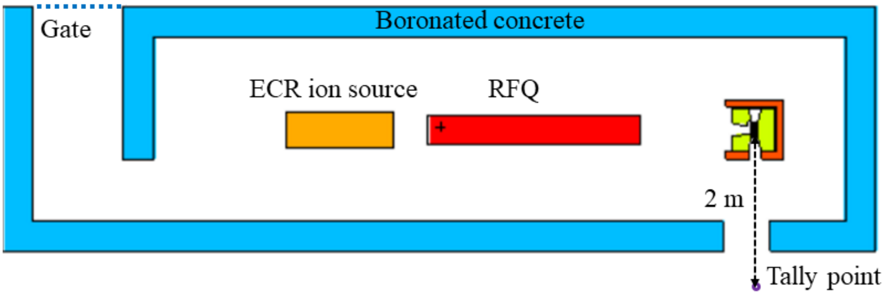

Fig. 1. Layout of the CANS source 'LvB' at Martonvásár. The primarily boronated concrete cave (blue) provides radiation shielding to allow unlimited accessibility of the area around the cave, while the inside of the cave is not accessible during CANS neutron production operation.

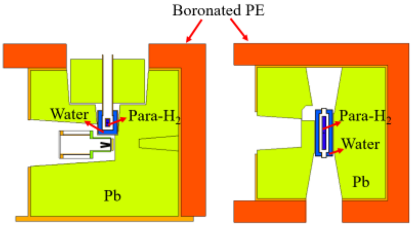

Fig. 2. Two cuts of the TMR system. In the vertical plane around the proton beam propagation axis (left) and in the horizontal plane around the moderated neutron beam extraction axis (right).

The quasi-one-dimensional liquid para-H_2 cold moderator is located at the centre of the bi-spectral moderator and is held at a pressure of 1.5 bar and a temperature of 20 K. It is surrounded by a quasi-one-dimensional water premoderator at room temperature. The para-H_2 cold moderator is of rectangular shape with a beam extraction cross-section of 1.5×3 cm^2 and a length of 15 cm. The thickness of the water premoderator is 1.5 cm. The cold moderator and the premoderator are separated by vacuum serving as a thermal insulator and by a sheet of Al serving as a thermal radiation insulator. The thermal beam extraction surface of the premoderator, viewed from the beam extraction direction in Fig 1, is a rectangle of 7.8 cm × 8.5 cm, with its middle part of 1.5 cm × 3 cm left open for the cold neutron beam to emerge from the cold moderator inside the premoderator.

3 CANS performance

The "LvB" project is modelled in MCNP6.2 [9-11]. Our present study starts with the impact of 2.5 MeV protons on the target area and follows the evolution of the neutrons generated by the protons hitting the Li target. The library used in this simulation is ENDF/B-VIII. Thermal neutron scattering libraries lwtr.20t and hpara.20t are employed.

It was assumed that the proton beam hitting the Li target area has a time-average intensity of 1 mA. The CrN layer protecting the Li surface causes a reduction in neutron production by 5%. The ENDF/B-VIII gives a neutron yield of 1.7×10^{-4} neutron per proton colliding with the Li layer at 15° impact angle. As shown in Fig.2, there are two symmetrical neutron beam extraction channels. The neutron flux was tallied by an F5 card at one of these channels, at 2 m from the moderator surface. Three different cases have been simulated, in order to reflect the multiple neutron collision actions in the TMR system: 1) empty moderator vessels, 2) the water premoderator vessel filled with room temperature water, 3) in addition to 2), the cold moderator vessel filled with liquid para-H_2 of 20 K temperature. The tallied neutron fluxes observed at the tally point in Fig. 1 are presented both as a function of neutron energy in Fig. 3 a) and as a function of neutron wavelength in Fig. 3 b) respectively, in order to cover in practically relevant details, the whole energy range of emission.

It is seen that there is no notable difference in the fluxes for neutrons with energies larger than 0.1 eV (i.e. wavelengths smaller than 0.9 Å) between the case of a filled water moderator vessel and the case when both the water and para-H_2 moderator vessels are filled. With respect to neutrons with energies lower than 0.1 eV, the case with empty moderator vessels shows the lowest neutron flux, in fact, significantly lower than with filled moderators. The neutron flux of the bi-spectral moderator, in the case when the water moderator vessel is only filled, peaks at around 40 meV (1.43 Å) neutron energy. While the combined flux in the case of both moderator vessels properly filled peaks at approximately 12.5 meV (2.56 Å). In common neutron beam operation, the various beam instruments can focus on one or the other emitting moderator surfaces or can advantageously use the combined flux shown in Fig. 3.

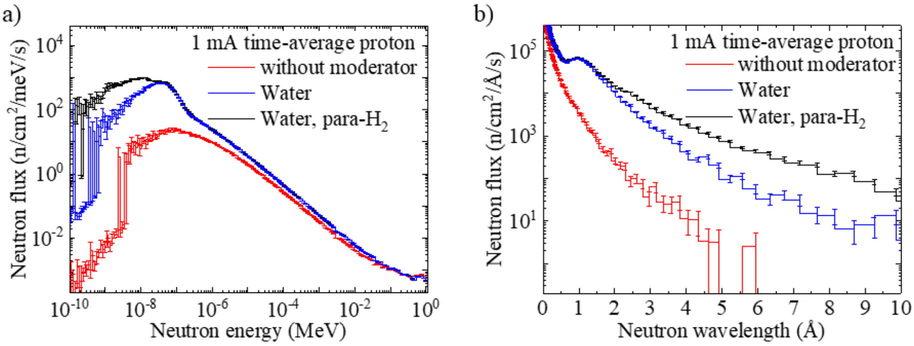

Fig. 3. The time averaged neutron spectrum observed at the tally point in Fig. 1. Plotted either a) as a function of neutron energy or b) as a function of neutron wavelength. The time-average proton current on the Li target is assumed to be 1 mA.

4 Conclusion

The 'LvB' project at Martonvásár, Hungary is progressing and getting ready for hot commissioning. We have employed MCNP6.2 to determine the expected neutron beam intensities emerging at 2 m from the moderator in the direction of the neutron instruments. At 1.0 Å outcoming neutron wavelength, most emerging neutrons come from the approx.60 cm^2 thermal water moderator surface towards the tally point, and the time-average brightness of this moderator surface is found to be 4.3×10^7 n/cm^2/s/sr/Å. At 4 Å neutron wavelength, most of the neutrons emerge from the 4.5 cm^2 front surface of the low dimensional para-H_2 moderator, resulting in 1.2×10^7 n/cm^2/s/sr/Å time-average brightness for 1 mA time-average proton beam current on the target. These numbers are approximately 5 - 6 orders of magnitude lower than those observed at the most powerful research reactor in the world, the Institut Laue-Langevin (ILL) [8].

For scattering experiments, due to the pulsed nature of the neutron beams at 'LvB', these beams are automatically monochromatized to some degree, owing to their 5-25 ms flight time between moderator and detection, compared to the 1.25 ms proton pulses from which they originate. The typical time neutrons spend in the TMR system is between 0.05 to 0.3 ms, thus useful neutrons arriving to the instruments 5 – 25 ms after the proton pulses, are largely automatically monochromatic, with an uncertain of their flight time (i.e. velocity) of < 6 % for the fastest and < 2 % for the slowest neutrons at their arrival time monitored at the instruments. This offers an order of magnitude gain for 'LvB' in the efficiency of using the total number of the generated neutrons, compared to a continuous source, such as ILL. This also illustrates the increased efficiency of making use of the number of initial fast neutrons to be produced in our CANS facility. These absolute neutron beam brightness values also allow us to estimate the measurement times for various relevant applications.

For example, the duration of testing the reflectivity for neutron supermirrors can be estimated from the counting rate of the 12 cm × 12 cm position-sensitive area detector to be used, assuming a 2 mm x 50 mm slit in front of the tested mirror sample at approximately 10 m from the moderator surface and considering a 3 Å wide useful wavelength band around approximately 4 Å wavelength. The spectrum with the cold moderator in place in Fig.3

suggests an above 10^3/s time average counting rate detected by the area detector for a good quality (i.e. high reflectivity) supermirror sample. In the customary data collection time of about 1 hour per tested mirror, this means approx. 4 million counts in a test run, distributed over the reflectivity curve. Thus, the neutron beam intensities presented here shall allow us to fully monitor the quality of each supermirror produced at realistic production rates at Mirrotron Ltd. (Currently these tests are made on the basis of paying commercial service fees at various neutron sources in Europe, depending on which one is in operation and has free beam time to sell at a given period in the calendar. Sometimes, there is none.)
The neutron scattering instruments, planned at the current stage, incorporate a reflectometer for supermirror testing and a time-of-flight diffractometer with large solid angle coverage and strain analysis capability for industrial material characterization and research. The development of an alternatively usable second target for 2.5 MeV protons is also in progress, to be optimized for the emission of epithermal neutrons for healthcare purposes. On the longer term, there are plans to install an afterburner linear accelerator close to the current position of the target, reflector, and moderator assembly in order to enhance the proton beam energy on the target to above 5 MeV. This will allow us to improve the neutron beam intensities at the same accelerated proton beam current by approximately an order of magnitude in neutron scattering applications and, eventually, to switch to a sturdier Be target. The target development effort for BNCT applications shall remain on an alternatively used 2.5 MeV proton beamline, optionally bent by a certain angle after the RFQ accelerator,.

References

1. IAEA, *Compact accelerator-based neutron sources*, IAEA-TECDOC-1981 (2021)
2. Kiyanagi. Y, et al. Eur. Phys. J. Plus 131:132 (2016)
3. IAEA, Advances in boron neutron capture therapy. IAEAL 23-01601 (2023)
4. INTERNATIONAL ATOMIC ENERGY AGENCY, Interactive Map of Accelerators (2021), https://nucleus.iaea.org/sites/accelerators/Pages/Interactive-Map-of-Accelerators.aspx
5. *Budapest research reactor - 60 years of research and innovation* (2019)
6. Zanini. L, et al., Nucl. Instrum. Methods A 925, 33 (2019)
7. Zanini. L, et al., EPJ Web Conferences, **231**, 04006 (2020)
8. Institut Laue-Langevin, *ILL yellow book* (2008)
9. Werner. C. J, et al, MCNP6.2 Release Notes, Los Alamos National Laboratory, report LA-UR-18-20808 (2018)
10. Werner. C. J (editor). MCNP User's Manual - Code Version 6.2, Los Alamos National Laboratory, report LA-UR-17-29981 (2017)
11. Goorley. J. T, et al., Nuclear Technology, **180**, pp 298-315 (2012)