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DEVELOPMENT OF COMPACT ACCELERATOR BASED NEUTRON SOURCES FOR CANADA, THE PC-CANS PROJECT

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Abstract

Neutron scattering has proven to be one of the most powerful methods for the investigation of structure and dynamics of condensed matter on atomic length and time scales. The neutron science community faces a decline of sources for neutrons with research reactors shutting down and even with new spallation neutron sources coming online. In an effort to address this challenge, the global neutron community is responding by taking advantage of recent advances in accelerator technology to develop compact accelerator-based neutron sources (CANS). The Canadian community embarks on a prototype Canadian CANS (PC-CANS) development to perform the first step towards a national Canadian facility of a next generation CANS. The technical development towards this new concept in context on activities in North America will be presented.

INTRODUCTION

Innovation in material developments underpins technology solutions that address many aspects of challenges Canada like other countries is facing. This is the driver for thousands of research teams across Canada to study materials, using probes like neutrons, synchrotron radiation, etc. Neutron beams are versatile probes of materials, complementing X-rays amongst other techniques, because many research problems in materials can only be solved using neutron beams, including in situ observation of small atoms such as lithium in battery cathodes or hydrogen in soft and biomaterials, and determination of magnetic structures and excitations in quantum materials.

Because neutron beams are versatile and irreplaceable tools for materials research, they have been in high demand globally since the 1960s. Their scientific value is why Canadian physicist Bertram Brockhouse won 1994 a Nobel Prize in Physics for pioneering neutron spectroscopy techniques, and why many billion dollars have been invested in neutron infrastructure projects globally since the year 2000. However, neutron beams are increasingly scarce due to closures of old facilities with high replacement costs (typically over $1B) creating a need for lower-cost neutron sources. Compact Accelerator-driven Neutron Sources (CANS) [1] are being explored in Canada to fill this need

A CANS takes advantage of recent advances in accelerator technology to generate neutrons via the bombardment of light metal targets, for example lithium (Li) or beryllium (Be) with intense pulsed proton beams with energies on the order of 5-20 MeV [2]. A Be target is best used to lower costs and reduce size and is efficient beyond ~3MeV beam energy. Be is preferable up to 20 MeV, then metal targets made from Nb (up to 35 MeV) and Ta become more efficient. CANS can provide a local neutron source at a fraction of the cost of a spallation source (or a reactor) given the 100-fold reduction in the required energy, the related cost of a linac as well as the target moderator system and reduced radiation safety requirements. The lower energy also reduces the required shielding and allows neutron instruments to be placed closer to the source (hence, 'compact'). The source can also be highly optimized to meet the end requirements of each instrument, resulting in the production of brilliant beams to rival that of medium sized reactor and spallation sources. Further, the low cost of the linac and target, but high proton beam intensities allow to run several targets moderator assemblies in parallel for independent targets producing cold, thermal, or hot neutrons, each optimized for different end uses, but served by the same driver accelerator via a multiplexer [3].

CANADIAN INTEREST IN A CANS

Following the age-related closure of the NRU Reactor and the Canadian Neutron Beam Centre in Chalk River in 2018, Canadian universities established the national neutron strategy to rebuild capacity for materials research with neutron beams. This strategy envisions an infrastructure laid out in a Neutron Long Range Plan (LRP) [4] program for infrastructure and for research and development with neutron beams. Thus, a Canadian R&D program in CANS technology, and as recommended by the Canadian Neutron Long Range Plan, the focus of the neutron community's activities toward new sources must be established.

The ultimate goal of the community would be a neutron users facility delivering neutron flux comparable to ISIS in the UK [5], based on a High-current compact accelerator-driven neutron sources (HiCANS) [6]. The European neutron strategy published by the League of Advanced European Neutron Sources (LENS) concludes the only route for entirely new facilities with significant capacity that could occupy the role played by national reactor-based sources in the past are HiCANS. A staged approach towards this national facility is planned with a first step of a Prototype Canadian Compact Accelerator-driven Neutron Source (PC-CANS), that can produce neutron beams that are (a) bright enough for neutron diffraction and imaging for some high-throughput experiments and thus meet some of the demand from neutron beam users from across Canada, and (b) low-cost enough (e.g. under $30M) to warrant development of

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technology and national consideration of investment in constructing a HiCANS for Canada (on the order of $300M).

PC-CANS

The concept for PC-CANS is patterned after the Jülich NOVA ERA concept [7] that serves as a reference design for the Jülich High Brightness Neutron Source (HBS) project [3]. PC-CANS is going 5 times above the NOVA ERA neutron brightness design by

- using an accelerator with higher beam power
- optimizing the target moderator assembly to maximize neutron flux for the SANS.

The PC-CANS concept is shown in Fig. 1. In the baseline design, the linear accelerator will provide protons with a peak intensity of 10 mA at 5% duty factor (0.5 mA average current) to 10 MeV for a peak/average beam power of 100/5 kW. The beam can be distributed to three target stations and shared between three end users. Our plan is staged as the target technology evolves to handle higher power with a time average proton beam of 2 kW in Stage 1, 5 kW in Stage 2 and 10 kW in Stage 3. For this staged approach the linac is designed to be able to accelerate up to a peak/average beam intensity of 20 mA/1mA so that Stage 3 foresees operation with 10kW average power on the neutron Target-Moderator-Reflector (TMR). Depending on the funding and target technology, higher beam intensities could be envisaged.

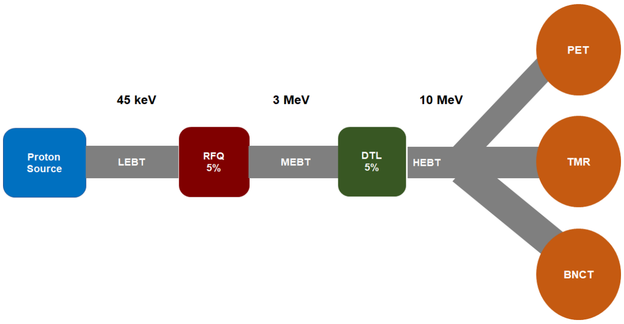


Figure 1: Schematic of the PC-CANS.

The PC-CANS will host three end-uses: neutron sciences (scattering etc.), boron neutron capture therapy (BNCT) research and fluorine-18 (F-18) medical isotope production for positive emission tomography (PET), as shown in Fig. 1. The highest priority beamline for the PC-CANS is the neutron science beamline which will allow for time-of-flight diffraction and small-angle neutron scattering (SANS) experiments. The neutron science instruments will be designed to yield a neutron brilliance a factor of five greater than the proposed NOVA ERA facility with a goal to deliver neutron beams with brightness no less than a factor of five lower than a medium-brightness spallation source like the ISIS neutron facility in the United Kingdom.

The basic building blocks of a CANS, shown in Fig. 2, are the proton driver accelerator, a macro-pulse kicker or multiplexer system (depending on the number of instruments and applications) for parallel operation, the TMR assembly with shielding and the neutron guides and instruments. The typical linac would include an Electron Cyclotron Resonance Ion Source (ECRIS) or an arc discharge volume ion source, an RF quadrupole (RFQ) accelerator to accelerate from source potential to a few MeV followed by a matching section and a drift tube linac (DTL) that accelerates the protons to the final energy.

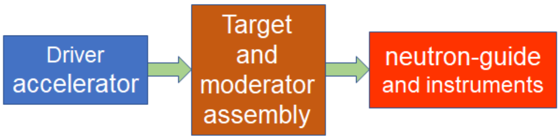


Figure 2: Building blocks of a CANS.

The Proton Driver Accelerator

A schematic representation of the PC-CANS driver linac is shown in Fig. 3. The ion source and low energy transport should be able to inject protons with the required intensities >20 mA into the RFQ with a macro-pulse structure synchronized to the RF pulses, to meet the needs of the downstream target instrument system. Depending on the accelerating structure employed and the RF-frequency choice, the RFQ will take the low energy protons and accelerate them to an energy range of 1.5-3 MeV, suitable for the injection into a DTL. The RF-power in the linac would be pulsed at the same macro-cycle, while the actual macro-pulse structure would depend on the number of target stations and their requirements on the repetition rate.

The high energy beam transport (HEBT) designed to deliver protons to all end stations simultaneously will employ a pulsed deflection kicker which deflect selected bunches periodically. The deflected beam macro pulses are separated by a DC septum magnet. The linac pulse frequency chosen for PC-CANS is 200 Hz. Every fourth macro-pulse would be deflected toward the PET beamline with a first kicker and a second kicker would deflect every second pulse of the remaining beam into the neutron science beamline The undeflected pulsed beam is directed to the BNCT station [8].

HEAVY ION ACCELERATOR TECHNOLOGY OF PC-CANS

The PC-CANS driver linac is using state of the art heavy ion linac technology from the source towards the TMR assembly. One implementation path has been detailed out in the PC-CANS conceptual design report assuming accelerator structures at 352 MHz [9]. An alternative implementation is derived from a design of a proton linac from the University of Frankfurt for industrial and medical applications of a proton driver linac [10] starting with 176 MHz accelerator structures and applying a frequency jump between the DTL tanks. Figure 3 summarizes the different options for the realization of the PC-CANS linac. Several versions employing 352 MHz were investigated through detailed beam dynamics simulations and performance comparisons [11].

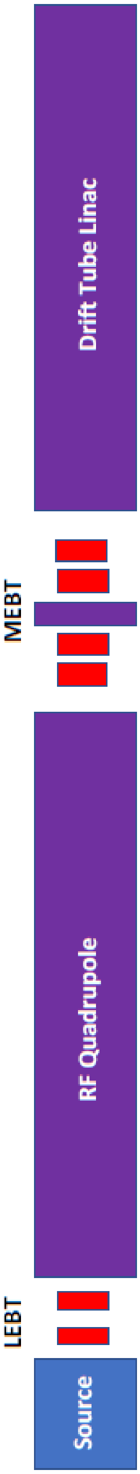
A high intensity proton sources is required for injection of proton beams with intensities above 20 mA and good beam quality. With high production efficiency, proton beam intensities up to 120 mA and no cathode required are 2.45 GHz ECR ion sources that have been demonstrated for instance at CEA Saclay with the SILHI source [12]. As an alternative, new developments of volume sources for these proton beam intensities up to 60 mA have been performed at Frankfurt University and TRIUMF. This type of sources is less expensive than ECRIS but less reliable due to the filament required which can break and needs to be replaced on a regular base.

One linac concept foresees a 352 MHz 3 m long 4-Vane RFQ that accelerates the protons to 3 MeV assuming an inter-vane voltage of about 78 kV. An MEBT with four quadrupoles and a re-buncher will match the beam to the DTL, which could be realized by a 2.5 m Alvarez tank with permanent magnet quadrupoles housed in every second drift tube. The Alvarez is operating with an effective accelerating gradient of ~3 MV/m. As an alternative, two cross bar (CH)-structures [13] using KONUS beam dynamics and providing an effective accelerating gradient of about 6 MV/m could be used. For transverse focusing, quadrupole triplet lenses would be required downstream of each CH-cavity. The linac could also be realized by a 2.5 m long 176 MHz 4-Rod RFQ which accelerates the protons to 1.5 MeV, which requires a moderate inter-rod voltage of about 65 kV, similar to the CERN linac 4 RFQ. A MEBT for beam matching would be used with two quadrupole doublets and a 176 MHz re-buncher structure. The DTL section could be composed of a 176 MHz interdigital H-type (IH) structure that accelerates to 4 MeV, followed by one long CH structure or two short 352 MHz CH cavities that accelerate to the final energy. The combined zero-degree synchronous particle structure (KONUS) or the EQUidistant mUltigap Structure (EQUUS) [14] beam dynamics could be applied in these cases.

Detailed beam optic simulations will be performed to explore these schemes in the future. The different implementations need to go through a realistic cost analysis, based on existing linac structures and support systems (RF, power supplies, vacuum, diagnostics etc.). This will be part of the development of e technical design report for PC-CANS, which is seen as the next step for CANS in the Canadian Neutron LRP.

CONCLUSION

The Canadian neutron scattering community is pursuing the development of a new neutron sources for Canada, based on a CANS. In order to explore the technology suitable for a national user facility, a Prototype Canadian CANS (PC-CANS) based at a Canadian university is proposed and supported by the Canadian community which is documented in the Canadian Neutron LRP. PC-CANS has been conceptualized based on state-of-the-art linac technology utilizing the high proton beam intensity these accelerators can achieve. PC-CANS will allow competitive rates for neutron science, exceeding the NOVA ERA proposal at least a factor of ten for the SANS instrument, while simultaneously producing F-18 for PET and protons to a dedicated BNCT research and development facility. The cutting-edge accelerator techniques developed for this project will advance Canadian science and industry in high power hadron accelerators opening the doors to future applications like clean energy and security.



2.45 GHz ECRIS or bucket sources ~ 30 mA	LEBT at 30-45 keV with quadrupoles and diagnostics	4-Vane RFQ, f = 352 MHz, 3 MeV, 78 kV inter-vane voltage	MEBT at 3 MeV, with two doublets and a 352 MHz re-buncher	Alvarez DTL or two CH tanks with KONUS beam dynamics, 3 CH tanks with constant β (EQUUS)
“	“	4-Rod RFQ, f = 176 MHz, 1.5 MeV, 65 kV inter-rod voltage	MEBT at 1.5 MeV, with two doublets and a 176 MHz re-buncher	IH-structure at 176 MHz, 4 MeV with KONUS beam dynamics and 2 CH-tanks with constant β (EQUUS)

Figure 3: Schematic of the PC-CANS proton driver linac and potential realization schemes.

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