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FRANZ AND SMALL-SCALE ACCELERATOR-DRIVEN NEUTRON SOURCES

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Abstract

This paper gives an overview of the opportunities and challenges of high-intensity, low-energy light-ion accelerators for neutron production. Applications of this technology range from the study of stellar nucleosynthesis and astrophysical phenomena to medical applications such as Boron neutron capture therapy (BNCT). The paper includes details of the FRANZ facility, under development at Frankfurt University.

INTRODUCTION

Applications of Neutron Beams

Neutrons are an important tool for probing the structure of matter. They are electrically neutral, but sensitive to the magnetic properties of the material, as well as for different isotopes, providing excellent opportunities for material sciences [1]. Their high penetration depth in material and their strong sensitivity for light elements facilitate neutron imaging techniques [2, 3].

Nuclear Astrophysics The investigation of neutron capture processes is especially relevant to provide a deeper understanding of stellar nucleosynthesis and astrophysical phenomena. About 50% of the element abundances beyond iron are produced via the slow neutron capture process or s-process. This process takes place mostly inside of asymptotic-giant-branch (AGB) stars. Here, the neutron temperature ranges from 8 keV to 90 keV. Therefore, a proper modeling of the stellar nucleosynthesis requires the knowledge of neutron capture cross-sections between 1 keV and 400 keV [4, p. 14].

BNCT There are increasing efforts to use neutron beams for cancer therapy. Presently, there are eight initiatives in the world to develop accelerator-based Boron Neutron Capture Therapy (BNCT) [5]. If boron-10 that has been selectively incorporated into the tumor tissue captures a neutron, it decays into short-ranging alpha particles and lithium-7 nuclei, which can efficiently destroy the cancer cells [6]. Epithermal neutrons of up to 10 keV are required to assure sufficiently high penetration depth into the tissue while still having a sufficiently high capture cross section.

Neutron Production

Since free neutrons are unstable, dedicated production setups are required. Traditionally, nuclear fission reactors have been used for neutron production. They provide a high average neutron (n) flux of typically up to 1×10^{15} n s^{-1}cm^{-2}. Recently, spallation neutron sources combine a comparable or even higher flux than reactors with a flexible time structure.

Complementary to these large-scale facilities, small-scale accelerator-driven neutron sources based on light ion beams at low energy can provide intense neutron beams with flexible time structure in the energy range from keV to MeV.

SMALL-SCALE ACCELERATOR-DRIVEN FACILITIES

Opportunities

Typical small-scale accelerator-driven neutron sources employ light ions at several MeV energy to generate neutrons via nuclear reactions as the ^{7}Li(p,n)^{7}Be, the ^{9}Be(p,n)^{9}B or the ^{9}Be(d,n)^{10}B reaction. For low proton energies, the ^{9}Be(p,n) reaction produces less (and higher-energetic) neutrons than the ^{7}Li(p,n) reaction [7]. However, the target material might be easier to handle.

The ^{7}Li(p,n)^{7}Be reaction as the most prolific reaction has a relatively low production threshold of 1.88 MeV. The resulting neutron energy lies in the keV to hundreds of keV range, depending on the primary proton energy. This includes the relevant energy spectrum for stellar nucleosynthesis as well as for BNCT application.

In contrast, reactors or spallation neutron sources provide neutrons in a wide energy spectrum, including much lower and much higher energetic neutrons. In a reactor, the fission neutrons, starting with several MeV energy, are typically moderated down to thermal energies. In spallation processes, some neutrons can reach energies up to the incident proton energy of hundreds of MeV, with the larger part having energies around 1 MeV to 10 MeV.

At small-scale facilities, the neutron energy spectrum can be further refined by adjusting the primary beam energy and the thickness of the production target [4, p. 23]. This allows to limit the neutron spectrum to the region of interest for the given application, reducing the background that is induced by higher energy neutrons and creating a neutron flux for the energy region of interest that is comparable to the flux in large-scale facilities.

This effect is increased for the ^{7}Li(p,n)^{7}Be reaction when proton energies just above the production threshold are employed. In this case, due to kinematic collimation, neutrons are only emitted in a forward cone with an opening angle of 120°, significantly increasing the neutron flux at the sample position [4].

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The ^{7}Li(p,n)^{7}Be reaction offers an additional feature that makes it especially attractive for nuclear astrophysics experiments. For a proton energy of 1.912 MeV, 30 keV above the reaction threshold, the energy spectrum resembles a Maxwellian distribution at 25 keV temperature, which is a typical s-process temperature. Therefore, it can be used for activation measurements of the integrated neutron capture cross section in an energy range that is relevant for stellar nucleosynthesis. In this setup, the sample can be placed directly behind the production target thus gaining dramatically in neutron flux. A neutron spectrum measured at Forschungszentrum Karlsruhe (FZK) is depicted in Fig. 1. This approach, developed at FZK [8], is still being pursued and refined [4, 9].

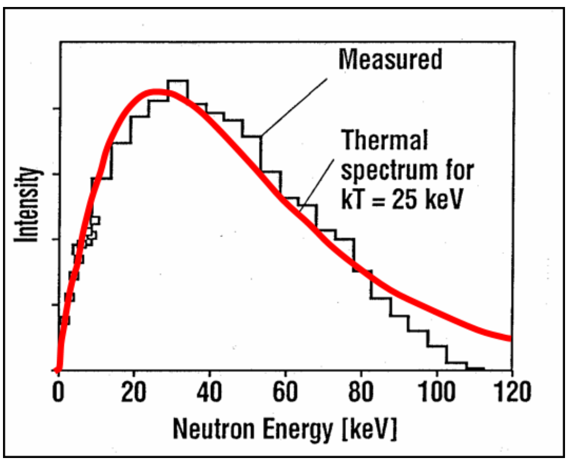

Figure 1: Neutron spectrum measured at Forschungszentrum Karlsruhe for a primary proton energy of 1.912 MeV at a flight path of 0.8 m (black) and Maxwellian distribution at 25 keV neutron temperature (from [10]).

The primary beam energy for most facilities range between 2 MeV and 5 MeV, though higher energies of up to 13 MeV are not uncommon. These relatively low energies make different accelerator setups possible. The primary ion beam can either be provided by an electrostatic accelerator [11–13], by a Radio-Frequency Quadrupole (RFQ) [2, 9] or by an RFQ-drift tube linac (DTL) combination [14–17].

Presently, small-scale accelerator-driven neutron sources operate or are under construction in more than 10 countries, with noticeable activity in Japan [11, 18]. A consequence of their compact size and modest cost is that they can be constructed outside of large accelerator laboratories. This is reflected in the remarkable number of small-scale facilities that have been or are currently being developed within a university framework. Examples are Peking [2] and Tsinghua University [17] in China, Nagoya [11] and Kyoto University [19] in Japan, Indiana University, USA [16] and University of Frankfurt, Germany [14]. In addition to providing an important research infrastructure within the academic environment, they offer a valuable resource for the in-situ education of students in the field of accelerator physics.

Challenges

High Intensity Since the number of produced neutrons is directly proportional to the number of incident ions, a high primary beam intensity is required for most applications. For nuclear astrophysics, this is crucial to ensure high-precision measurements of capture cross sections for short-living isotopes, for isotopes available only in small samples, or for those with very small capture cross sections. The FRANZ facility aims to produce more than 1×10^{11} n s^{-1} for activation measurements and 1×10^7 n s^{-1}cm^{-2} for Time-of-Flight (TOF) measurements. For accelerator-based BNCT, a neutron flux of 1×10^9 n s^{-1}cm^{-2} is required in the desired energy range [7], excluding thermal or fast neutrons.

In general, these requirements lead to primary beam currents of several milliamperes to several tens of milliamperes. At present, several facilities operate with or aim at reaching peak proton (p) or deuteron (d) currents above 10 mA. This includes: NUANS (p, 15 mA) [11, 18], LENS (p, 25 mA) [16], TESQ (p, 30 mA) [12], CPHS (p, 50 mA) [17], FRANZ (p, 50 mA) [14], LENOS (p, 50 mA) [9], and PKUNIFTY (d, 50 mA) [2].

Two of these facilities are based on electrostatic accelerators: NUANS, where a dynamitron will be used [11, 18], and TESQ, a folded Tandem-Electrostatic-Quadrupole (TESQ) accelerator facility under development for BNCT treatment [12]. The latter represents an attempt to overcome the lack of focusing typical for electrostatic accelerators by adding electrostatic quadrupoles inside the high voltage tube.

Nevertheless, most high-current designs are based on an rf linac, consisting of either an RFQ-DTL combination or a long RFQ. The strong focusing capabilities of the RFQ allow efficient transport of high beam currents. In front of the RFQ, in the Low-Energy Beam Transport (LEBT) section, the use of magnetic lenses (typically solenoids) allows space-charge compensated transport. For a more compact design, a low transition energy from the RFQ to the DTL, which has a higher accelerating efficiency, can be chosen [14].

Target technology At the same time, target technologies have to be developed that can withstand high primary beam currents that deposit kilowatts of power at small penetration depths. Assuming an average beam current of 2 mA at 2 MeV energy and a 10 mm beam spot size, the surface power density at the target reaches 5 kW/cm^2. Since the penetration depth of MeV protons into matter is only fractions of a millimeter, a high volume power density of hundreds of kW/cm^3 is reached. Therefore, a key challenge for future facilities is to develop target and cooling techniques that can keep pace with increasing beam intensities. Presently, several approaches are taken.

For lithium targets, an established method is to evaporate a thin lithium layer onto a copper backing that is then being cooled. For the FRANZ project, water cooling will be used. The backing will be directly cooled through a small water duct of only 0.2 mm and indirectly through a secondary cooling circuit with larger dimensions. Simulations showed

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that the setup is capable of removing the heat that is generated by 4 kW beam power at a 14 mm beam size while maintaining a surface temperature below the lithium melting point of 180 °C [20]. The duct dimensions were chosen as small as possible in order to minimize moderation effects. An alternative to water cooling is the use of liquid metals, which have a much higher thermal conductivity [9].

Another approach is to use liquid lithium that simultaneously acts as neutron production target and as cooling agent. Significant progress was recently made at the SARAF facility [21], where a liquid lithium target was successfully commissioned with 2.3 kW of proton beam power at 1.91 MeV energy. It uses a liquid lithium film at 200 °C in a free-surface, windowless setup [22].

Time structures For different applications or experimental needs, competing requirements for the time structure can exist. First, continuous-wave (cw) operation (or high duty cycles) can be needed to provide a high average neutron flux. This is valid for BNCT and for activation measurements of neutron capture cross sections. Continuous operation can also provide a constant power deposition on the neutron production target, reducing thermal stress and thus alleviate the target requirements. However, cw operation with high average power can lead to thermal issues not only at the target but also inside the accelerator. Therefore, improved cooling scenarios are crucial for reliable cw operation at high intensities. The results of a new cooling approach developed for the FRANZ RFQ are presented below.

In contrast to cw operation, short beam pulses can be required to reduce the duty cycle and limit the average power deposition for vulnerable machine components, or to allow the TOF method, which can be used for the energy-dependent measurements of neutron capture cross-sections [26] or for pulsed neutron imaging [3]. To form the pulses, beam choppers consisting of high-voltage deflection plates and a collimator system are commonly employed. To reduce the duty cycle for electrostatic deflection and thus the risk of high-voltage breakdowns for high-intensity beams, an $E{\times}B$ chopper can be used [23]. To reduce the pulse length and create a very high peak intensity, an additional bunch compressor can be employed [24].

THE FRANKFURT NEUTRON SOURCE FRANZ

A small-scale accelerator-driven neutron source named FRANZ ("Frankfurt Neutron Source at the Stern-Gerlach-Zentrum") is under construction at the science campus of Frankfurt University, Germany [14, 25]. A high-intensity 2 MeV proton driver linac will be used to produce neutrons via the ^{7}Li(p,n) reaction channel, offering excellent opportunities for nuclear astrophysics experiments [26]. An overview of the facility is given in Fig. 2.

The facility can be operated in two modes. In the Activation Mode, a cw proton beam of several milliamperes facilitates the measurement of integrated neutron capture cross sections with a high average neutron flux. In the Compressor Mode, 1 ns short, intense beam pulses will be produced at 250 kHz repetition rate for the energy-dependent measurement of neutron capture cross-sections using the TOF method.

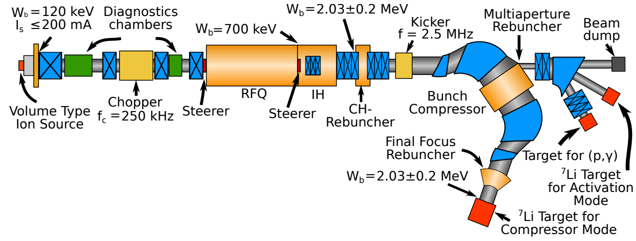

Figure 2: Schematic overview of the Frankfurt neutron source FRANZ.

Ion Source, LEBT and Chopper

The primary high-intensity proton beam for the Compressor Mode is generated by an arc discharge driven volume type ion source. At a dedicated ion source test stand, a dc proton current of 240 mA was successfully extracted at 50 keV beam energy using an emission opening radius of 4 mm [27].

The design current for the first operation phase is 50 mA. Due to the high repetition rate, the ion source will be operated in dc and the beam pulses are shaped by a dedicated chopper system that is located in the center of the LEBT section. Consequently, a four-solenoid LEBT is used with two solenoids injecting the beam into the chopper and two solenoids matching the beam into the RFQ.

Detailed numerical investigations of the LEBT show an efficient transport of the 50 mA proton beam to the RFQ, whereas the undesired hydrogen fractions, H_2^+ and H_3^+ are largely removed before and inside the chopper system [28].

The $E{\times}B$ chopper system combines a static magnetic deflection field with a pulsed electric compensation field in a Wien filter-type $E{\times}B$ configuration [23, 29]. This way, the advantages of magnetic deflection, i.e., stable deflection without risks of voltage breakdown even at high beam intensities, and of electric deflection, i.e., operation with low power consumption even at high repetition rates, can be combined. The chopper shapes pre-pulses of at least a 50 ns flat-top length at a 250 kHz repetition rate.

The LEBT section including the chopper has been successfully commissioned using a low-current He^+ beam at 14 keV energy [23]. Presently, the HV terminal is being conditioned for beam operation at the design energy of 120 keV. The control system, including the personnel and machine protection system, is under development [30].

For the future operation with high currents, a beam-separation system will be employed behind the chopper. It consists of a static C-magnet, which transports the undesired beam into the dump, and a magnetic shielding tube, which shields the on-axis beam from the fringing field of the dipole [31].

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Linac

A four-rod RFQ of 1.7 m length will bunch the beam and accelerate it to 700 keV. The main acceleration to the design energy of 2 MeV will be provided by an Interdigital H-type (IH) DTL. Both structures will operate at an rf frequency of f_{rf} = 175 MHz.

Since a pulsed operation at the required repetition rate of 250 kHz is not feasible, both structures have to be operated in cw. To investigate possible thermal issues, an RFQ prototype module with improved cooling technique was manufactured. Figure 3 shows the 40 cm long prototype module.

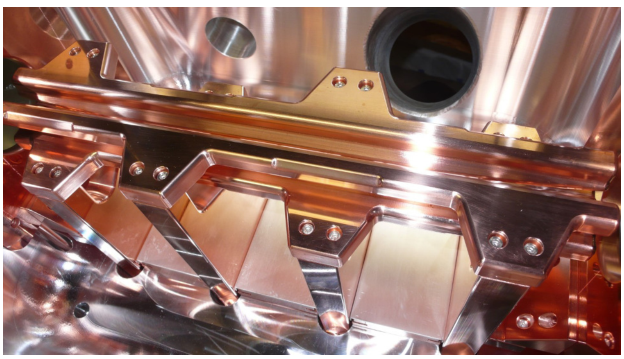

Figure 3: Inside view of the RFQ prototype module.

During a test run of more than 70 hours, the prototype was successfully operated in cw with a power of $P_{th} = \frac{30\,\mathrm{kW}}{0.4\,\mathrm{m}} = 75\,\mathrm{kW/m}$. The power and the pressure during the measurement are depicted in Fig. 4. This performance is well above the design requirements for the FRANZ RFQ of $P_{th} = \frac{100\,\mathrm{kW}}{1.7\,\mathrm{m}} = 59\,\mathrm{kW/m}$ for operation with a 50 mA proton current.

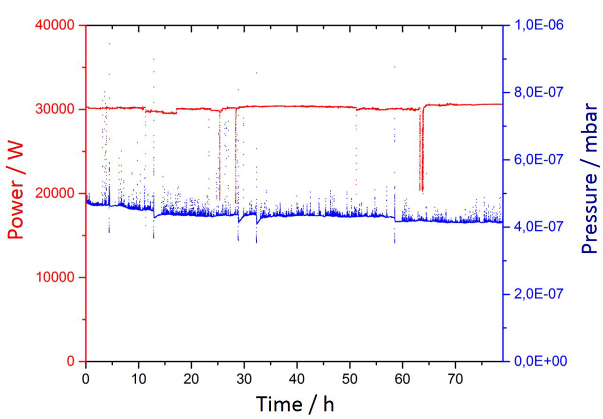

Figure 4: RF power test of the RFQ prototype module.

During an additional power test, the prototype was reliably operated for several hours at $P_{th} = \frac{46\,\mathrm{kW}}{0.4\,\mathrm{m}} = 115\,\mathrm{kW/m}$ without indications of thermal problems. This value corresponds to a rod voltage of $U = 94.5\,\mathrm{kV}$.

The RFQ has been manufactured and the alignment of all components has started. The IH cavity is currently being copper plated. Field measurements have been presented in [32]. In final operation, both structures will be coupled. This allows for operation with a single power amplifier, which significantly reduces the investment costs [32].

MEBT

The Medium-Energy Beam Transport (MEBT) section between the linac and the bunch compressor consists of two magnetic quadrupole triplets for transverse focusing and a crossbar H-mode (CH) rebuncher cavity [33]. In addition, the CH cavity provides an energy variation of ±0.2 MeV around the nominal energy of 2 MeV, which allows to tailor the neutron energy spectrum.

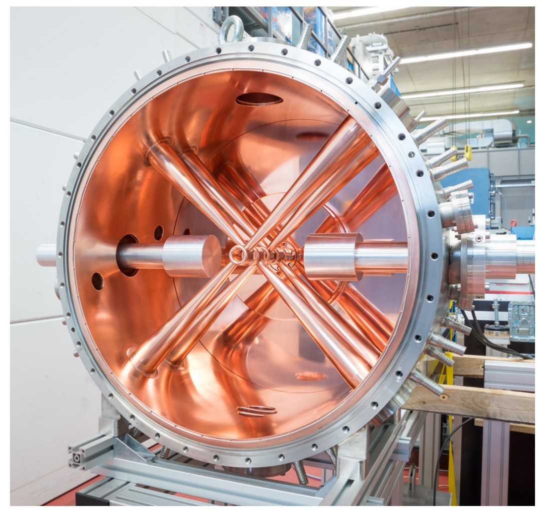

Figure 5: Picture of the CH rebuncher after copper plating.

A picture of the CH cavity is shown in Fig. 5. A promising quality factor of $Q_0 \approx 10\,900$ was measured after copper plating, still using aluminum dummy tuners.

Bunch Compressor and Target

To allow the energy-dependent measurement of neutron capture cross-sections using the TOF setup, a short proton pulse has to be formed in front of the neutron production target. This is achieved by a bunch compressor that merges nine micro bunches into a single, 1 ns long high-intensity pulse [24]. A solid lithium target is under development for beam powers of up to 4 kW [20].

CONCLUSION

Small-scale accelerator-driven neutron sources, based on light-ion beams at low energy, can provide intense neutron beams with flexible time structure in the energy range from keV to MeV. The neutron spectrum can be further tailored to the experimental needs by adjusting the primary beam energy and the target thickness. This reduces the background of high-energy neutrons while generating a neutron flux in the desired energy range that is comparable to that of large-scale facilities.

Applications include nuclear astrophysics, neutron imaging and material science. In addition, modalities for accelerator-based BNCT are being established in various countries to enter the area of in-hospital facilities.

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At Frankfurt University, the FRANZ facility will provide a 50 mA, 2 MeV primary proton beam to produce neutrons via the the ^{7}Li(p,n)^{7}Be reaction. Its flexible design allows cw operation with milliamperes of proton current for activation measurements, as well as operation with 1 ns short, intense beam pulses at 250 kHz repetition rate for the energy-dependent measurements of neutron capture cross section.

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