Development of a neutron time-of-flight source at the ELBE accelerator

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Abstract. The ELBE electron beam at Forschungszentrum Rossendorf, Dresden, with energies up to 40 MeV, can be used to produce a beam of intense neutron pulses in a liquid-lead radiator, where bremsstrahlung photons created by the electrons produce neutrons in ($\gamma$,xn) reactions. The 5 ps electron beam pulses create very short neutron pulses, giving an energy resolution of less than 1 % with a flight path of 3.9 m. A beam repetition rate of 1.6 MHz enables measurements with neutron energies from 200 keV to 10 MeV – an interval where neutron cross section measurements are needed for fission, fusion, and transmutation. The neutron beam will be shaped by a 2.4 m long collimator made from borated polyethylene and lead, reducing the background of scattered neutrons and of photons at the sample position. Monte Carlo simulations with MCNP4C3 were performed to optimise the collimator composition. About 92 % of the neutrons at the experiment site retain their correct energy-to-ToF correlation. The neutron energy resolution is 0.4 % (FWHM) at the maximum intensity. For neutron-capture $\gamma$ rays, a BaF$_2$ scintillation detector array of up to 60 crystals is being built, whereas for neutron detection, Li-glass scintillators and a 1 m$^2$ plastic scintillator wall will be used.

1. Introduction
Fast neutron facilities have traditionally been of two types; white sources and quasi-monoenergetic ones. While the latter deliver high-intensity neutron beams at a single energy, the white sources produce neutrons in a continuous range of energies when a beam of charged particles hits a heavy target like tungsten or lead. In this case, the energy for a neutron is determined by measuring its velocity by flight time.

At the superconducting electron linear accelerator ELBE (Electron Linear accelerator with high Brilliance and low Emittance), at Forschungszentrum Rossendorf (FZR), Dresden, a very compact neutron time-of-flight (nToF) system is being developed. The electrons can be used to produce neutrons in a liquid-lead neutron radiator, and the neutron energies that can be measured range from

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200 keV up to 10 MeV with an electron beam repetition rate of 1.6 MHz. In this energy interval, there is a need for neutron cross section measurements relevant for the transmutation of minor actinides in nuclear waste, as well as for applications to fission and fusion reactors. In addition, energies in the 30-100 keV range, accessible with a reduced electron beam intensity due to a lower repetition rate, can be utilised for nuclear astrophysics experiments. The long-term needs for nuclear data have been formulated, e.g., by the International Atomic Energy Agency [1].

Section 2 gives an overview of the ELBE facility, while section 3 focuses on the properties of the liquid-lead neutron radiator. In section 4 the collimator shaping the neutron beam is discussed, and in section 5 the development of detectors for neutron-induced reactions is described. The excellent neutron energy resolution and neutron intensity at ELBE is compared with other facilities in section 6.

2. The radiation source ELBE

The nToF system utilizes the electron beam of the ELBE accelerator at Forschungszentrum Rossendorf, shown in figure 1. The electrons are accelerated in two 20 MeV superconducting linear accelerator modules cooled with liquid helium, giving an electron beam energy range from 6 to 40 MeV. The micropulse duration is about 5 ps, the maximum average beam current 1 mA, and the repetition rate is variable up to 13 MHz. A superconducting RF photo electron injector (SRF gun) is being developed, allowing for a beam current of 1 mA at a repetition rate of 1 MHz [2]. Thereby, the factor 10 intensity loss when lowering the frequency to 1.6 MHz will be compensated for.

Figure 1. The radiation source ELBE with the neutron hall in the upper right part, containing experiments of TU Dresden and the liquid-lead target discussed here.

The electron beam can be distributed to different setups, such as a bremsstrahlung facility, X-ray experiments, and a free electron laser setup. The site for neutron experiments is found in the right part of the figure, and shown in some detail in figure 2.

Besides the liquid-lead radiator, the neutron cave accommodates two setups of Technische Universität Dresden: a tungsten radiator which stops the electron beam bremsstrahlung and converts it into a white neutron spectrum, and a 14 MeV DT neutron generator, that in conjunction with the white spectrum provides a neutron field closely resembling that in a future fusion reactor. This cocktail beam will be used for fusion neutronics.
3. The liquid-lead neutron radiator

Figure 2 schematically shows the floor plan of the neutron cave. Different beam lines guide the electron beam to the tungsten target, or the liquid-lead radiator, respectively. In the latter case, the electron beam passes a beryllium window mounted on a stainless steel vacuum chamber and hits the radiator, consisting of a molybdenum channel confining the liquid lead. Behind this, a lead-shielded, water-cooled aluminum beam dump absorbs the unused radiation (electrons, photons, neutrons). Apart from the molybdenum channel in the vacuum chamber, the liquid lead is transported in an isolated and electrically heatable stainless-steel tube circuit, and cooled through a heat exchanger using an InGaSn eutecticum as an intermediate heat transfer fluid.

The neutrons are emitted almost isotropically from the radiator, while a large part of the electrons and the bremsstrahlung photons mainly emerge in the forward direction. Thereby, using the neutrons emitted about 90 degrees from the direction of the electron beam, a high suppression of the photon-to-neutron rate is obtained. The neutrons are shaped by a collimator into a well-defined beam, entering the experimental site in the adjacent room.

Figure 2. Floorplan of the nToF setup in the neutron cave. Inserts show a side view of the neutron radiator and the planned experimental site. The different neutron sources sit on a common axis together with the collimator.

To take advantage of the picosecond electron beam pulse length, the radiator volume needs to be small enough to keep the time interval of beam passage and photoneutron production in the sub-nanosecond range. This also minimizes scattering inside the radiator, and the background of thermal neutrons. At the same time, the radiator volume has to be large enough to obtain a reasonable conversion efficiency. Simulations have shown that a good trade-off between source strength and energy resolution is obtained with a volume of approximately 1 cm$^3$.

The electron beam will deposit up to 25 kW thermal load in the radiator – too high to be dissipated by gas cooling and heat radiation for a solid target of such small size. Since cooling with water is unfavorable due to its neutron-moderating properties, liquid lead was chosen as radiator material. This also has the advantages of a low-lying giant dipole resonance giving a high ($\gamma$,xn) neutron yield, a large temperature interval (1420 K) between melting and boiling points, and less activation compared to other possible radiator materials (e.g., mercury). A lead channel with a cross section of (11.2 mm)$^2$ was chosen, corresponding to two radiation lengths for electrons in lead. Molybdenum was selected for the channel walls (0.5 mm thick) due to its good strain tolerance and heat conductivity.

A spindle lifter was constructed to raise the whole radiator and beam dump assembly 3 m up from its rest position inside a lead shield, to the level of the electron beam line, as shown in figure 3. The park position allows for the accessibility of the cave and the operation of the other neutron sources.
Figure 3. 3D rendering of the pulsed neutron radiator in the neutron production cave of the ELBE building. The liquid-lead loop with the radiator and the beam dump can be lowered into a lead house when not operated.

Monte Carlo simulations were performed using MCNP4C3 [3] to characterize neutron and photon intensities, time and energy distributions, and resolutions. The main parameters determining the neutron intensity at the sample position are the radiator dimensions, the energy of the beam electrons, the beam current, and the length of the neutron flight path. For electrons with energy $E_e = 40$ MeV and a beam current of $I_e = 1$ mA (with a repetition rate of 13 MHz, or with 1.6 MHz in conjunction with the SRF gun), the simulations predict a neutron source strength of $2.7 \cdot 10^{13}$ s$^{-1}$ from the radiator and a neutron flux density of $1.5 \cdot 10^7$ cm$^{-2}$ s$^{-1}$ at the measuring position 3.9 m from the radiator (after the collimator). Table 1 shows a compilation of fluxes for different electron energies.

Table 1. Simulated neutron fluxes from the radiator and flux densities after a flight path of 3.9 m (electron beam current $I_e = 1$ mA).

| Electron energy (MeV) | Radiator source strength (s$^{-1}$) | Flux density at measuring position (cm$^{-2}$ s$^{-1}$) |
|-----------------------|-----------------------------------|---------------------------------|
| 20                    | $7.9 \cdot 10^2$                  | $4.3 \cdot 10^7$               |
| 30                    | $1.9 \cdot 10^3$                  | $1.0 \cdot 10^7$               |
| 40                    | $2.7 \cdot 10^3$                  | $1.5 \cdot 10^7$               |

Figure 4 shows the energy distribution of the significant contributions to the neutron flux density at the measuring position, with $E_e = 30$ MeV and $I_e = 1$ mA. The total distribution is represented by black diamonds. Almost 92 % stem directly from the lead in the radiator (light squares), while about 8 % of the neutrons were scattered or created in the molybdenum channel (circles an order of magnitude below the total). A very small fraction (< 0.1 %) was scattered in the steel housing accommodating the radiator (triangles).
4. The collimator

A further objective was to optimize the collimator between the neutron radiator and the experimental hall. This aimed at eliminating neutrons and photons scattered or produced in the collimator, thereby creating a well-defined beam of unscattered neutrons with a sharp edge, having a minimal background of both neutrons and photons outside the beam. In addition to this, the component of slow neutrons coming directly from the radiator, overlapping into the next beam pulse and creating measurement ambiguities, had to be minimized. It was also desirable to reduce the direct photon intensity at the experimental site.

Due to these requirements, the simulations grouped into two categories: (i) finding a geometry and a combination of materials that effectively eliminates particles scattered or produced in the collimator, and (ii) designing an absorber – to be inserted into the beam – that stops photons and slow neutrons without significantly reducing the intensity or destroying the energy-ToF correlation of the higher-energy neutrons.

Figure 5 shows six examples of investigated collimator compositions placed in the wall consisting of 1.2 m concrete and 1.2 m of heavy concrete (seen from left to right). Dark-colored collimator insertions are made from lead and light ones from borated polyethylene (CHB), while uncolored regions do not contain any material. The neutrons travel from left to right, and the lead insertions are placed after the CHB sections in order to absorb photons created in $(n,\gamma)$ reactions. An additional 10 cm thick lead shield is placed after the wall.

Collimator types C, Q, S and R have the same thickness of CHB and lead in the axial direction, but distributed mainly in 4, 3 and 2 groups, respectively. Types T and U are completely filled; the former
with the same ratio between materials as the types mentioned first, and the latter with 50% each of CHB and lead. All collimators have an opening (beam diameter) of 3 cm. Type C has an outer diameter of 12.5 cm near the openings and 5 cm in a narrower mid-section, while each of the other collimators have increasingly larger outer diameters of 5, 6 and 7 cm. These ones are also surrounded by a stainless steel tube with 1 cm thick walls.

The neutron beam profile for the different collimators is shown in figure 6, given by detectors placed at an axial distance of 3.9 m from the radiator, and at radial distances \( r = 0.2, 1.5, 1.7, 2, 3, 4, 5.5, 7, 9.5, 12, \) and 25 cm from the beam centre, respectively. All collimators shape a neutron beam with a sharp edge, indicated by the intensity drop between \( r = 1.5 \) cm and \( r = 2.0 \) cm. At larger distances, the intensity is four orders of magnitude less than in the beam. A similar trend is shown for photons in figure 7.

![Figure 6. Neutron flux densities after the collimator (3.9 m from the neutron radiator), at different distances from the beam center (\( E_e = 30 \) MeV, \( I_e = 1 \) mA).](image)

![Figure 7. Photon flux densities after the collimator.](image)

The uncertainties at large radial distances complicate the conclusion on which collimator type to choose. However, a close inspection of the flux densities at points with small errors (at \( r = 1.7, 2, \) and
3 cm) show that collimators that are not fully filled (i.e., types C, Q, S, R) produce less neutron background outside the beam than those without air gaps. At these points, the neutron flux densities from types C, Q, and R are about 10% larger than from type S, while for types T and U they are about 50% larger. Thus, an S-type collimator with three groups of CHB and lead would be preferred for reduction of the neutron background. The photon plot, on the other hand, advocates using a C-type collimator with more material in the radial direction.

With an accelerator repetition rate of 13 MHz, the time interval between beam pulses is 77 ns. If the electrons hit the radiator at \( t = 0 \) ns, the photons arrive at the measuring position 13 ns later, and the fastest neutrons at \( t = 65 \) ns. For \( E_e = 30 \text{ MeV} \), the neutron time distribution has a peak at about 180 ns and a tail extending up to 1 \( \mu \)s. This means that most of the neutrons will overlap into the following pulses, making unambiguous measurements impossible. This problem can be overcome by lowering the repetition rate by a factor of 8, to 1.6 MHz, and by placing an absorber in the beam. The loss in beam intensity due to a lower repetition rate will be compensated for with the SRF gun. The effect of different absorbers is shown in figure 8.

With a frequency of 1.6 MHz, the next pulse comes 615 ns later, as indicated in the figure. Thus, neutrons with energies less than \( E_n = 210 \text{ keV} \) create a background in subsequent pulses, and must be suppressed. The plot shows that with a 5 cm thick slab of polyethylene (PE) and a thin disc of Cd (triangles) placed at the collimator entrance, the neutron flux density below 210 keV drops two orders of magnitude, compared to the situation with no absorber (light squares).

![Figure 8. Neutron flux densities with different absorbers, placed in the collimator entrance (seen from the radiator). Neutrons with \( E_n < 210 \text{ keV} \) should be prevented from creating background in subsequent beam pulses.](image)

The cost of using the absorber is a decrease in peak intensity by a factor of 5, but the relative background reduction is considerable. This is illustrated in figure 9. The upper graph with dark squares in figure 9 shows the time distribution of the neutron flux density from one beam pulse, accompanied by the background from the previous pulse (light squares). Below these, the graphs with triangles show the same situation with an absorber of 5 cm PE and 5 mm Cd. If a 2.5 MeV neutron is measured without absorber (arriving 180 ns after leaving the radiator; indicated in the figure), the background flux density from the previous pulse (130 keV neutrons) is 30 times lower. With the absorber in place, the signal-to-background ratio changes to 1200. The situation is also improved at lower energies: when measuring a 240 keV neutron, the signal-to-background ratio changes from 4 to 20, using the absorber.
The correlation between neutron kinetic energy ($E_n$) and time of flight (ToF) is shown in figure 10. The left panel shows the major part of the energy and time ranges, whereas the right panel focuses on the region around the flux density maximum. The main ridge in the spectrum is from neutrons with a correct energy to time-of-flight correlation. Neutrons that have lost their undisturbed correlation between $E_n$ and ToF form a tail to the main ridge. They are suppressed by two to three orders of magnitude, and constitute only 4% of all events. The low intensity ridge approximately 20 ns above the distribution of unscattered neutrons is due to scattering in the stainless steel housing around the radiator. The inset in the right panel shows a horizontal cut through the spectrum at 230 ns. The energy width (FWHM) of the peak for neutrons with this ToF is 5 keV, which corresponds to an energy resolution less than 0.4% at $E_n = 1.5$ MeV.

Figure 9. Time distributions of neutron flux densities from two consecutive beam pulses, with (triangles) and without (squares) an absorber for low-energy neutrons.

Figure 10. Left panel: the correlation between neutron time-of-flight and energy is preserved for 96% of the neutrons, which form a narrow, dark band in a ToF-vs-$E_n$ scatter plot. Right panel: the region around the flux density maximum. The inset shows a horizontal cut of the correlation at 230 ns, giving an energy resolution at FWHM of less than 0.4% at $E_n = 1.5$ MeV.

Figure 11 shows the corresponding spectra when inserting the before mentioned absorber into the collimator. The $E_n$-ToF correlation is maintained, which confirms the feasibility of using such an absorber. The only change is the intensity drop in the peak; by a factor of five.
5. Detector development

For measurements of neutron-induced reactions, different detector types are being developed. For neutron capture $\gamma$-rays, a $\text{BaF}_2$ scintillation detector array of up to 60 crystals is being built, see figure 12. The crystals are 19 cm long and have a hexagonal cross section with an inner diameter of 53 mm. They are read out by fast Hamamatsu R2059 PM tubes, which are UV sensitive to be able to measure both the slow and the fast component of the BaF$_2$ scintillation light. Thereby pulse shape discrimination (PSD) can be utilized to separate photon signals from intrinsic $\alpha$-particle background. The time resolution attained with a $^{60}$Co $\gamma$-source is typically 650 ps (FWHM). The readout will be performed with dedicated ADC/TAC modules [4] that allow simultaneous measurement of timing and energy signals including PSD in VME bus standard. The system will be controlled by a RIO3 real-time Unix computer.

For neutron detection, Li-glass scintillators and a plastic scintillator wall are being developed. The plastic scintillator wall will allow detection of fast neutrons from approximately 500 keV kinetic energy through proton recoils in the scintillation material. The wall will cover an active area of about 1 m$^2$, consisting of 10 scintillation panels (100 cm x 12 cm x 1 cm) read out on both ends.

For neutron energies below 500 keV, Li-glass scintillators will be used. They are enriched with up to 18 % $^6\text{Li}$ and allow detection of low-energy neutrons mainly through the $^6\text{Li}(n,\alpha)$ reaction.
6. Comparison with other facilities
As can be seen in table 2, the setup is very competitive with all existing high-resolution neutron beams in its luminosity, including n_TOF at CERN-PS. The proton-accelerator based neutron sources at Los Alamos and the planned Oak Ridge Neutron Spallation Source lose a significant part of their intensity advantage over ELBE when they increase their flight path in order to reach an energy resolution of less than 1%, as expected for ELBE.

Table 2. Parameters of operational and planned neutron time-of-flight facilities.

| Facility     | CERN n_TOF | LANL NSC | ORNL SNS | FZK VdG | ORNL ORELA | IRMM GELINA | ELBE with SRF |
|--------------|------------|----------|----------|---------|------------|-------------|---------------|
| Pulse charge / nC | \(10^3\)   |          |          |         |            |             | 0.08          | 0.8           |
| Power / kW   | 45         | 64       | 2000     | 0.2     | 8          | 7           | 5             | 40            |
| Pulse rate / s\(^{-1}\) | 0.4       | 20       | 60       | 25\(\times\)10\(^4\) | 525      | 800         | 1.6\(\times\)10\(^6\) | 10\(^6\) |
| Flight path / m | 183       | \(\approx 20\) | 20       | 50      | 0.8        | 40          | 20            | 3.6           | 3.6          |
| n pulse length / ns | > 7       | 125      | 350      | 2       | 8          | > 1         | \(\approx 0.4\) | \(\approx 0.4\) |
| \(E_{\text{min}}\) / eV | 1         | \(100\) (Phase-2) | 1        | 1       | 3\(\times\)10\(^3\) | 10         | 10            | 2\(\times\)10\(^3\) | 5\(\times\)10\(^3\) |
| \(E_{\text{max}}\) / eV | 5\(\times\)10\(^7\) | 2\(\times\)10\(^7\) | 10\(^7\) | 2\(\times\)10\(^7\) | 5\(\times\)10\(^7\) | 4\(\times\)10\(^7\) | 1\(\times\)10\(^7\) | 1\(\times\)10\(^7\) |
| Resol at 1 MeV / % | 0.5       | \(5\) (Phase-2) | > 10     | > 20    | \(\approx 5\)  | < 1         | < 2            | \(\approx 1\)  | \(\approx 1\)  |
| n flux density / s\(^{-1}\) cm\(^{-2}\) | \(10^4\) | \(5\(\times\)10^4\) | \(10^7\) | 5\(\times\)10\(^7\) | 10\(^4\) | 4\(\times\)10\(^4\) | 4\(\times\)10\(^4\) | 3\(\times\)10\(^6\) |

7. Summary
A new, compact neutron time-of-flight facility based on a liquid-lead radiator is being built at the ELBE electron accelerator at FZR, Dresden. The measurements will address data needs for fission, fusion, and ADS in the 200 keV – 10 MeV neutron energy range, as well as nuclear astrophysics at even lower energies, with a reduced accelerator repetition rate. Monte Carlo simulations predict an energy resolution of less than 1% and a neutron flux density of typically \(10^7\) cm\(^{-2}\) s\(^{-1}\) after a flight path of 3.9 m, which makes the facility very competitive in an international perspective.

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