Nuclear Instruments and Methods in Physics Research A 797 (2015) 37–43

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Thermal neutron flux monitors based on vibrating wire ☆

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ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form
2 June 2015
Accepted 5 June 2015
Available online 22 June 2015

Keywords:
Neutron
Detector
Vibrating wire
Gadolinium

ABSTRACT

Two types of neutron monitors with fine spatial resolutions are proposed based on vibrating wires. In the first type, neutrons interact with a vibrating wire, heat it, and lead to the change of its natural frequency, which can be precisely measured. To increase the heat deposition during the neutron scattering, the use of gadolinium layer that has the highest thermal neutron capture cross-section among all elements is proposed. The second type uses the vibrating wire as a "resonant target." Besides the measurement of beam profile according to the average signal, the differential signal synchronized with the wire oscillations defines the beam profile gradient. The monitor's spatial resolution is defined by the wire's diameter.

1. Introduction and overview

Many research centers in the world use neutrons as probes for investigating diverse properties of matter in different states (disordered, amorphous, glass, crystalline, non-equilibrium, and nanocomposite materials). Because neutrons are scattered by atomic nuclei, they provide information on the structure and dynamics of atoms and molecules over a wide range of length and time scales. Because neutrons possess magnetic moment, they can also be used for studying magnetic structures [1].

Neutrons have found interesting applications in medicine, both in the treatment of cancer and in the development of ultra-sensitive analytical techniques for studying the internal and external chemical environments of humans [2–6]. There are a few centers specializing in neutron therapy [7]. For these applications, controlling the spatial distribution and intensity of neutron beams is vital. In addition, devices capable of real-time acquisition/tracking of the neutron beam intensity are much needed.

Most of the existing neutron sources are based on nuclear reactors with strong time-averaged neutron flux and mature technologies (both source- and instrument-wise). Neutrons can also be generated at the so-called spallation facility, where neutrons are produced by bombarding a heavy nucleus target by a beam of energetic protons. Spallation sources can be either pulsed or continuous. Several new neutron sources are planned to become operational in the future.

Of great importance is forming the neutrons into a beam with strong flux, and obtaining well-identified and precisely controlled parameters of intensity, divergence, geometrical coordinates, and sizes. So far, neutron beams with fluxes of 10^{13}–10^{15} n/cm^2/s have been obtained. The new and important task is to achieve neutron beams with higher intensity.

Neutron beams require a variety of detectors and monitors for measuring and controlling. Today, all known detectors for slow neutrons are based on the conversion of neutrons into charged particles/photons (see e.g. [8]). After this conversion, the following technologies are normally used: gas proportional counters, ionization chambers, scintillation detectors, and semiconductor detectors. As conversion materials, He, Li, B, and Gd are often used owing to their high nuclear reaction cross-sections. In most cases, information on the spatial distribution of a neutron beam is also necessary.

For neutron beam measurements, we suggest a novel method based on the heat release by neutrons in a wire. The proposed novel detectors have fine spatial resolution defined by the wire diameter, ranging from 10 to 200 μm. We intend to combine two unique properties – the unprecedented sensitivity of the natural frequency of a clamped vibrating wire to the wire temperature, and remarkable neutron-capturing ability of several gadolinium isotopes. The dependence of frequency on the wire temperature was used as the operational principle of the vibrating wire monitors for beam diagnostics in accelerators [9–11]. The characteristic mode of natural oscillation in the wire is generated by the interaction of an AC drive current through the wire with a permanent magnetic field [12]. A special feedback scheme selects the resonant frequency at which AC current frequency is equal to the wire's natural frequency. A microcontroller measures the

☆The authors are grateful to Prof. T. Reetz for his friendly help.
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http://dx.doi.org/10.1016/j.nima.2015.06.008
0168-9002/

frequency with 0.01 Hz resolution at 1 s sampling. A frequency shift arises when the beam particles penetrate the wire and change the wire temperature. For charged particles, ionization loss is the main contributor to the energy transfer.

The vibrating wire technology was first applied for measuring low-current electron beams in the injector of Yerevan synchrotron [9]. The principle of the operation was to measure the frequency shift of natural frequency of a stretched wire exposed to the beam. Even a small number of electrons penetrating the wire were sufficient for producing a detectable change of frequency. Since then, many other applications using vibrating wires have been proposed. For example, it was demonstrated that very high sensitivity (minimum detectable temperature change as low as mK) could be achieved in the measurement of temperature shift. This feature was used for beam halo measurements (see e.g. [10,11]).

We propose to measure temperature increase of the wire containing gadolinium isotopes, which occurs when neutrons penetrate the wire and deposit some energy into the wire. To ensure efficient neutron capture, we plan to use composite wires with few layers. At the same time, the wire should have proper mechanical properties for obtaining high quality factor that defines the frequency measurement's accuracy. We primarily intend to utilize tungsten wires covered by a layer of gadolinium with different thicknesses. The proposed vibrating wire neutron monitor (VWNM) with composite wires and wide dynamic range can be used for precise profiling of high flux neutron beams from specialized neutron sources (research reactors and spallation sources) on the ends of the tubes that transport neutron beams to the numerous instruments. Different from the existing neutron measurement principles, the proposed method has high spatial resolution, depending on the wire diameter.

In the second method, we propose to use a vibrating wire oscillating at its fundamental mode as a moving target, by measuring neutron scattering at the wire's maximal deviation positions. To detect the beam of neutrons we intend to use gadolinium-covered wires. After the neutron capturing reaction, the neutron's binding energy is released as a cascade of gamma radiation, during the time interval of approximately 10^{-16} s [13,14]. If the neutron beam's flux varies along the distance approximately equal to the oscillation amplitude, the difference between the measurements of prompt gamma rays at subsequent extreme positions during the wire's oscillation can provide the information on the neutron beam gradient. To measure prompt gamma rays we intend to use nonselective scintillator detectors. Measurements of the differences in the prompt gamma-ray signals, synchronously with measuring the wire's oscillation frequency, will allow us to extract only neutron capture events from any homogeneous background of gamma rays with wide spectrum of energies.

The proposed method is aimed at profiling centimeter scale neutron beams with vibrating wires of a few centimeters long. For such wire sizes, the response times of the wire heating are too long (several seconds). The main advantage of the proposed resonant target approach is to reduce the measurement time down to $\sim$1 ms or less, which corresponds to the oscillation period of a few centimeter long wires.

Transverse beam profile measurement by using this method was tested with lightening the oscillating wire by using a laser beam [15]. Monitors of this type will be called resonant target vibrating wire neutron monitors (RT-VWNMs).

The developed monitors can be widely used in all applications of neutron beams. For example, the VWNM can be used as a precise monitor with excellent spatial resolution for high flux neutron beams in the specialized neutron sources with multi-branch infrastructure of numerous instruments for materials research. The RT-VWNM can be used as a robust and reliable instrument with excellent spatial resolution for diagnostics of low flux neutron beams (e.g. at the neutron therapy centers). Specialized multi-wire VWNM capable of rotating along the beam axis can be used for the recovery of complicated 2D profiles of large cross-section neutron beams in neutron tomography, imaging, and radiography.

For example, the VWNMs can be used in the 18 MeV cyclotron (Cyclone-18) of Yerevan's oncological center for direct beam profile measurements in medical treatment. Another area of use can be neutron beam diagnostics that is being planned to be generated at Cyclone-18 for use in a broad class of studies and experiments (engineering of materials, investigations of biological, chemical, and physical systems, astrophysics, nuclear physics, and materials science). Preliminary experiments and tests are planned to be performed on the ^{252}Cf spontaneous fission neutron source accessible in Yerevan Physics Institute.

2. Neutron sources and detectors

Most of the existing neutron sources are based on nuclear reactors. Nuclear reactors use the fission process to produce neutrons. Most of the current reactor sources for scattering applications were primarily designed for materials testing for the nuclear industry [16].

Neutrons can also be generated at the so-called spallation facility, where neutrons are produced by bombarding a heavy nucleus target by a beam of energetic protons. Spallation sources can be either pulsed or continuous. Several new neutron sources are planned to become operational in the future [16].

To illustrate more clearly the complicated and manifold structure of the specialized neutron sources, we present detailed information on a reactor-based neutron source, hi-flux advanced neutron application reactor (HANARO) [17].

The main parameters of HANARO are as follows [18]:

Reactor power 30 MW

Max thermal flux 5×10^{14}n/cm^2/s

Typical flux at port nose 2×10^{14}n/cm^2/s

7 horizontal ports and 36 vertical holes

The tubes and holes, as well as the positions of the instruments available at HANARO reactor, are shown in Fig. 1.

The design characteristics of the neutron fluxes at HANARO reactor are presented in Table 1 [19].

In Table 2, we list some other existing neutron sources in the world, with brief description of the source type and parameters, main characteristics of the generated neutron beam, and listing of some instruments with the values of fluxes [20–26].

Neutrons can also be produced by spontaneous fission [16]. Higher intensities can be achieved by using small accelerator-based neutron sources. Sealed tube sources with a typical length of 1 m and diameter of 10 cm, operating at a power of 0.5 kW, can produce up to 3×10^{10} n/s.

Because neutrons are neutral particles and do not ionize the matter directly, straightforward detection of these particles is impossible. Thus, most detection approaches rely on detecting various reaction products [27]. Any neutron–nucleus interaction leaves the nucleus in an excited state from which it decays by emitting gamma rays. Prompt gammas are emitted within 10^{-13} s and are always associated with the neutrons moving in the matter. The energy of prompt gamma rays depends on the neutrons energy. In gas detectors, a typical reaction involves a chamber filled with Helium 3. In the ionization mode of a gas detector, electrons drift to the anode, producing a charge pulse and the