PROCEEDINGS OF SCIENCE

FAST-NEUTRON DIAGNOSTICS FOR TRANSMUTATION IN ACCELERATOR-DRIVEN SYSTEMS

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In critical reactors, the neutron energies extend up to a few MeV. The neutron diagnostics is commonly based on activation techniques and fission ionization chambers. In accelerator-driven systems, the neutron spectrum will extend all the way up to the incident beam energy, i.e., several hundred MeV or even up to GeV energies. The high energy allows diagnostics with measurement techniques hitherto not used in reactor environments.
Such measurements are primarily connected to system safety and validation. It is shown that in-core fast-neutron diagnostics can be employed to monitor drifts in the position of incidence of the primary proton beam onto the neutron production target. Moreover, fast-neutron detection can be used to reveal temperature-dependent density changes in a liquid lead-bismuth target.

International Workshop on Fast Neutron Detectors and Applications
April, 3 - 6, 2006
University of Cape Town, South Africa

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PoS(FNDA2006)068

1. Introduction

The basic idea of an accelerator-driven system (ADS) is to operate a sub-critical reactor driven by an accelerator that generates high-energy (around 1 GeV) charged particles (e.g. protons), which strike a heavy material target in the centre of the core. This bombardment leads to the production of a very intense neutron flux. Because the fission multiplication chain reactions in a sub-critical core are not self-sustained, this external neutron source must be continuously supplied to the core.

An ADS is a highly integrated system, where neutrons are the driving agent of the processes involved. The present work is focused on whether detection of neutrons in various places could be used to reveal technical system properties. An extensive account of the present investigation is found in ref. [1]. To make the scope limited, some restrictions have been made. Neutron diagnostics at traditional critical reactor energies, i.e., up to 10 MeV, are not the primary aim of the present work. The primary focus of the present investigation is the potential to use very fast neutrons, above 10 MeV, to reveal technical properties of an ADS.

The more general issue of system validation is not explicitly discussed in the present work, but could potentially become an important by-product. In any ADS research experiment, measurements of neutron properties, like energy spectra, in various places can be used to validate the design as well as the input used in the simulations. Integral experiments can be used to verify the quality of, e.g., the nuclear data libraries used. Although the present work is focused on neutron diagnostics for system performance, the measurement techniques investigated could potentially, or even likely, be used for design validation.

When outlining the present project, a few boundary conditions were identified. The only source of the neutrons above 10 MeV is the spallation target, while neutrons below that energy can be created also in the blanket, primarily by fission reactions. Thus, fast neutron diagnostics is primarily a means for target investigations. This in turn leads to important boundary conditions on the detection methods. In a realistic ADS, the target and blanket must be closely coupled, leaving little room for detectors. As a consequence, all diagnostics embedded in the system has to be performed with small-size equipment.

An alternative approach, not considered in the present work, is to use neutron guides out from the core to port holes where external detectors could be used. Such guides are in general interfering with the system, and are very difficult to install after the system has been commissioned. Thus, they have to be very well motivated, and have to be part of the design already from the initial phase. There is, however, one particular neutron guide that will inevitably be installed in all ADS systems: the proton beam line. In it, neutrons produced in the target can escape the system. This so called neutron backstreaming can provide possibilities for high-quality diagnostics outside the core, thereby enabling use of much more sophisticated techniques than for in-core monitoring.

As has been discussed above, the only source of very fast neutrons is the target. Thus, fast-neutron diagnostics is a potential tool for investigation of target properties. It makes therefore sense to study the target parameters that can change during operation. This essentially limits the investigation to two properties. The position of incidence of the primary proton beam could move and the target density could change as a result of a higher temperature, in both cases resulting in a changed spatial or energy distribution of the neutron production. The former is possible in all ADS systems, while the latter is a real possibility only for liquid targets. In the present work, we have used the SAD system [2] as reference. SAD uses solid targets only, but since the aim of the investigation is to study general features, we have taken the liberty to model a lower target density simply by artificially forcing a reduced density in the simulation input.

2. Simulations

Simulations have been performed for the SAD system [2], which is a research project on ADS at low power. A 600 MeV proton accelerator is coupled to a core of fast-reactor MOX fuel (30/70 % Pu/U), with the beam entering from below. In principle, any system could have been simulated. One reason for using SAD is that it is a real project, underway to be installed, where possible results of the present work could be used. Also, an MC code based on MCNP [3] had already been developed, and thereby only minor changes of an existing code were needed for the present investigations.

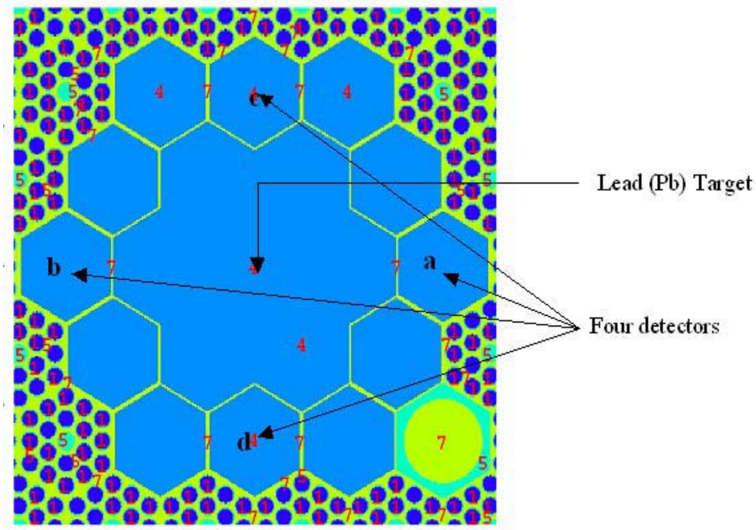

Figure 1: Horizontal cross sectional view of the SAD target. The distance between two opposite sides of each hexagonal target cell is 3.6 cm. Detector positions used in the simulations are indicated.

The SAD target consists of lead rods, 60 cm high with hexagonal cross sections (see fig. 2). In the simulations, we have installed four detector chains (a-d). Note that the detector pair c-d is closer to the target centre than the a-b pair. Each chain has been divided into four vertical segments, numbered 1 to 4 from bottom to top.

3. Results

The effect of a displacement of the incident beam has been investigated by simulating the neutron emission from the target for two cases, one in which the beam hits the target centrally, and one with the beam moved 1 cm sideways towards detector a. In fig. 2, the integrated neutron flux in the range from 20 to 600 MeV is presented. There is a significant increase at detector a and decrease at detector b and no changes at detector c and d. The flux ratio between detectors a and b changes from 0.98± 0.01 to 1.57± 0.02. The errors quoted are statistical only. The magnitude of this change is in agreement with simple estimates in which the attenuation of neutrons is presumed to depend on the total cross section.

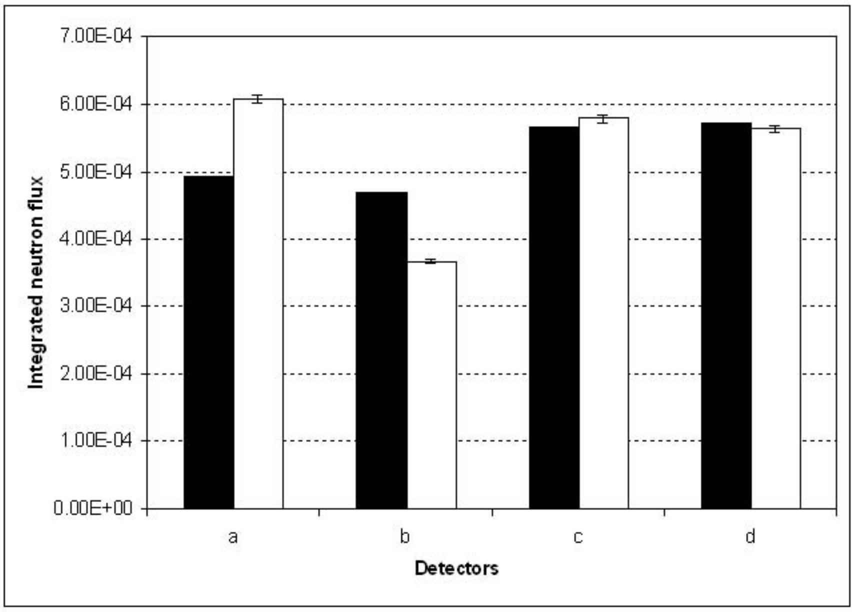

Figure 2: Neutron flux in the detectors a-d for central beam (filled bars) and for incident beam moved 1 cm towards detector a (unfilled bars). The neutron flux refers to integration of the 20 to 600 MeV energy range. The flux scale is in arbitrary units. The errors presented are statistical only.

Thus, a beam position change of 1 cm results in a clear effect, but such a change is far larger than what is realistic. We have therefore computed the change due to a realistic move, 1 mm, which results in a ratio change of about 7%. Such a change can most likely be detectable. About 5% absolute uncertainty is achievable for a well-calibrated fission detector. However, in our case only detection of relative changes are needed, and in that case 1-2% changes are relatively easy to detect. Thus, this could provide a beam position monitoring system.

The effect of a target density change is displayed in fig. 3. It shows neutron emission spectra integrated from 20 to 600 MeV at four detector positions along a vertical detector chain, with detector 1 at the bottom and 4 at the top. The beam enters the target from below. The resulting total fluxes show a notable change when the density is reduced by 10 %. The centroid of the production is moved upwards in the target, i.e., further into the material as consequence of the lower stopping power of the incident proton beam, as well as the reduced attentuation of the produced neutrons.

The neutron flux ratio between detector 1 and 4 is 1.20± 0.03 for normal target density, and 0.92± 0.03 for a density reduced by 10%. The ratio has a close to linear relation to the density, which means that the count rate ratio changes by about 2.3% for a 1% density change. Detection of a count rate ratio change of 1-2% should be possible with fission-based detectors. Thus, density changes of about 1% are feasible to detect with such methods.

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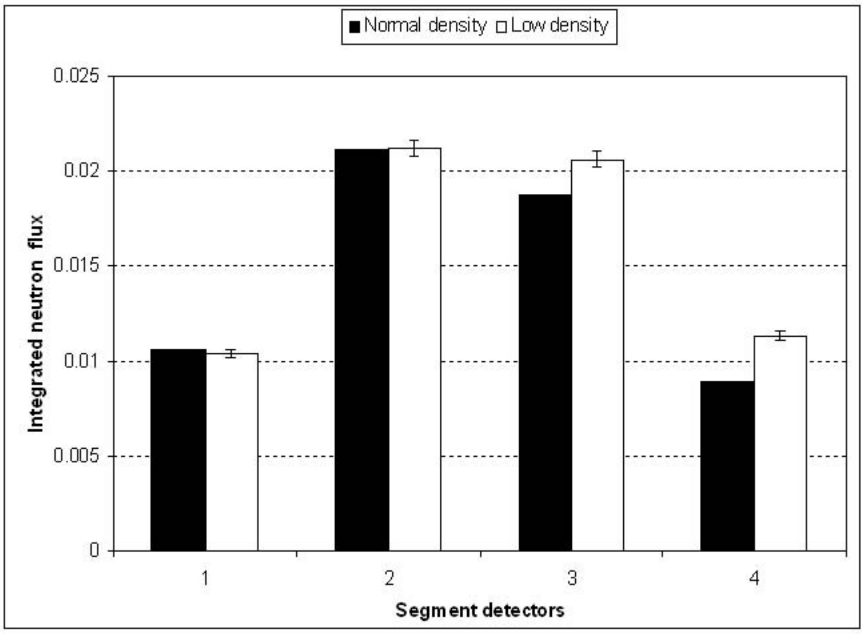

Figure 3: Integrated neutron flux of four segment detectors for normal density (filled bars) and reduced density (unfilled bars). The errors given are statistical only.

4. Discussion and outlook

The choice of techniques for investigations of fast neutrons close to the target is to a large degree dictated by the environment, such as lack of space, very intense neutron flux, and in general hostile conditions. To our judgement, the most likely active detectors to be used are fission ionization chambers. Such detectors are permanently installed in conventional critical power reactors (BWR), however primarily for thermal neutron monitoring. In the present application, fast neutrons are of main interest.

Fission-based detection of fast neutrons requires an element with a neutron energy threshold to be used. This poses some practical limitations. Thorium and uranium are elements that can be readily obtained in sufficiently large quantities. Both these have thresholds of about 1 MeV for neutron-induced fission of the leading isotopes. The next lighter elements that are available for realistic applications are lead and bismuth, the heaviest stable elements, which have effective fission thresholds of about 20-30 MeV. In between bismuth and thorium, all elements have rather short halflives and are therefore difficult to handle and hard to obtain in useful quantities. This limits the practical possibilities to detectors with thresholds either in the 1 or 20 MeV range. For the former, the cross sections are large, resulting in high efficiency, but the relatively low threshold makes them sensitive also to a neutron flux range where the technical changes studied in the present work do not induce very large effects. Thus, the sensitivity might not be very high. On the other hand, for lead- or bismuth-based detection, the high thresholds make the detectors very sensitive for these effects, but the fission cross section is smaller, making the detector itself less efficient. Which solution to use for optimal performance in a practical implementation requires further studies.

If surrounding the target with fission ionization chambers loaded with Pb/Bi and/or ^{238}U/^{232}Th, a 3D-picture of the neutron production could be provided. With such a system, the sideways and vertical movement of the incident beam could be detected. Using both Pb/Bi and ^{238}U/^{232}Th-based systems would also give a rough energy sensitivity. The detailed simulations of such a system and of suitable detector design constitute possible future work.

5. Acknowledgments

The collaboration with Per Seltborg on MCNP simulations is gratefully acknowledged. This work was financially supported by the Swedish Nuclear Fuel and Waste Management Company, the Swedish Nuclear Power Inspectorate, Ringhals AB, Forsmarks Kraftgrupp AB, the Swedish Defense Research Agency, the Swedish Nuclear Safety and Training Centre, and the European Union.

References

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