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FUSION BASED NEUTRON SOURCES FOR SECURITY APPLICATIONS: ENERGY OPTIMISATION

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Abstract

There is a growing interest in the use of neutrons for national security. The majority of work on security focuses on the use of either sealed tube DT fusors or fission sources, e.g. Cf-252. Fusion reactions enable the energy of the neutron beam to be chosen to suit the application, rather than the application being chosen based on the available neutron beam energy. In this paper we discuss simulations of fusion reactions demonstrating the broad range of energies available and methods for adapting the neutron beam energy produced by target/projectile combinations.

INTRODUCTION

Large scale neutron facilities using either spallation or reactors are the mainstay of neutron research. There are numerous applications of neutron beams in science, medicine and industry many of which are not suited to large scale facilities.

In national security there is increasing interest in the use of neutrons for container inspection. Approximately 90% of freight passes through seaports [1] and the majority of inspection is performed using X-Ray interrogation.

X-Rays operate by taking a line integral of the density between source and detector. Due to the simple nature of an X-Ray it is impossible to distinguish between a thick layer of low density material or a thin layer of high density. Traditional X-Ray scanners can therefore be fooled relatively easily by either shielding or disguising contraband [2]. Improvements can be made by comparing the attenuation of two different energies of X-Ray but the problem of shielding still exists.

Two types of compact neutron source are typically considered for security applications. Sealed tube devices direct deuterons onto a deuterated or tritiated target producing a high flux of quasi-monochromatic neutrons. The sealed tube devices are not suited to mass deployment due to the radiotoxicology concerns of tritium. Alternatively fission sources which use a small sample of fissionable material (e.g. ^{252}Cf) to produce a white spectrum but these are also not ideal as they are uncontrollable and have very long lived by-products.

An alternative to the sealed tube and fission sources is to use a low energy accelerator to initiate fusion reactions with between Protons, Deuterons or Alphas and low-Z targets. In this paper we show how the energy and spectral distribution for Proton induced reactions (p,n) can be varied. Due to the potential for varying the neutron energy a target and projectile combination can be chosen to suit the application and within that combination the spectrum can be varied in real time.

NEUTRON SOURCE

Low energy fusion reactions are a reliable source of neutrons, sealed tube fusors provide reliable off the shelf neutron sources by fusing deuterons with either deuterium or tritium. Sealed tube devices use the $T(d,n)^4He$ (DT) and $D(d,n)^3He$ (DD) reactions which produce neutrons of $E_n \approx$ 14MeV and 2.5MeV respectively.

The presence of tritium in the DT fusors and the production of tritium in DD fusors through the $D(d,p)^3H$ reaction means they are unsuited to mass deployment. Using alternative targets and projectiles offers the potential to avoid the production of tritium and other intermediate life isotopes.

An important consideration when considering a combination is the Q of the reaction, given by:

$$Q = (M_p + M_{TN}) - (M_n + M_{DN})$$

In which M_p is the projectile mass, M_{TN} is the target nucleus mass, M_n is the neutron mass and M_{DN} is the decay nucleus mass.

The Q can be used to approximate the energy of neutrons produced in a fusion reaction. In the center of mass frame the neutron kinetic energy E_n is given by:

$$E_n \approx \frac{E_k + Q}{1 + \frac{M_n}{M_{DN}}}$$

In which E_k is the projectile kinetic energy in the CoM frame. As the neutron emission is approximately isotropic in the CoM frame a distribution of energies is inevitable when returning to the lab frame which, when coupled with the potential for additional decay channels and meta-stable decay nuclei, prevents a perfectly mono-chromatic source being possible.

PROJECTILE ENERGY VARIATION

In this section we show how varying the projectile energy can be used to tune the energies of the neutrons emitted in a fusion reaction. The Monte-Carlo code MCNPX has been used to simulate various (p,n) reactions with a range of proton beam energies to study the effect on emitted neutron energy.

Figure 1 shows the effect of beam energy variation on the neutron spectrum produced by Magnesium under proton irradiation. The increasing proton energy can be seen to increase the neutron energy and the total neutron yield. Increasing the proton energy leads to an increase in the velocity of the CoM frame and therefore the Lorentz boost of the neutron into the lab frame is increased. Additionally to the Lorentz boost the excitation energy of the compound nucleus formed by the fusing of the proton and target is increased leading

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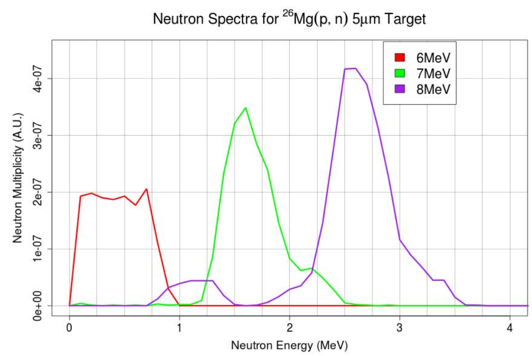

Figure 1: The simulated neutron spectrum produced by a Magnesium target under various energies of proton irradiation.

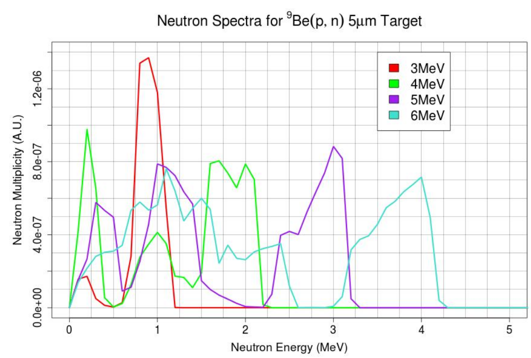

Figure 2: The simulated neutron spectrum produced by a Beryllium target under various energies of proton irradiation.

to more energy being available for the emitted neutron. The increased neutron yield is due to the cross-section for the $^{26}Mg(p,n)^{26}Al$ reaction increasing over the energy range simulated, in (p,n) reactions on other elements the yield can decrease with increased beam energy due to a reduction in the cross-section.

The $^{26}Mg(p,n)^{26}Al$ reaction shows a fairly narrow spectral distribution which makes it ideal for applications based on Time-Of-Flight however most of these applications require higher beam energies. The Q of $^{26}Mg(p,n)^{26}Al$ is ≈ -5.3MeV resulting in the neutron energy being significantly below the irradiating proton energy.

Unlike the $^{26}Mg(p,n)^{26}Al$ reaction the neutrons produced by the $^{9}Be(p,n)^{9}B$ reaction have a complex spectrum as shown in Fig. 2. The large number of spectral peaks in the $^{9}Be(p,n)^{9}B$ reaction make it unsuitable for any Time-Of-Flight dependant method but for those requiring a white or moderated flux it would be suitable.

TARGET THICKNESS VARIATION

In this section we show the relationship between target thickness and neutron spectrum. Simulations were performed with a range of target thicknesses and a single proton energy to understand the impact of target thickness.

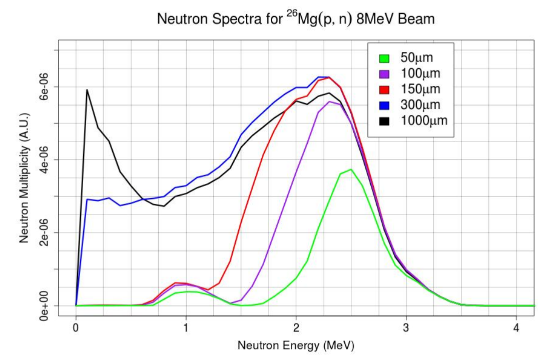

Figure 3: The simulated neutron spectrum produced by a Beryllium target under various energies of proton irradiation.

The results in Fig. 3 show a gradual increase in neutron flux and spectral width with increasing target thickness. The increased target thickness is shown to have two effects, the total neutron yield increases with thickness, at the same time the spectral width also increases.

After the target has become thick enough that the protons drop below the reaction threshold energy the neutron production will not increase however the neutron moderation will continue increasing, this produces the difference which can be seen in Fig. 3 between the 300μm and 1000μm thickness, the total number of neutrons is approximately constant between both thicknesses but there is a significant shift in the spectrum towards lower energies.

The increased spectral width is due to two effects. Predominantly the gradual energy loss of the protons as they propagate through the target results in a range of energies being available at interaction. The protons which interact earlier in the target have greater kinetic energy and therefore are able to produce higher energy neutrons. Additionally a small contribution to the spectral width comes from neutron moderation through the target

The increased neutron yield is caused by an increase in the number of target nuclei available for the beam to interact with. As the thickness increases the number of atoms per unit area also increases giving a higher probability of interaction.

As the protons propagate through the target losing energy they will at some point lose too much energy to be able to interact. If the target is thicker than this the neutron yield will not increase however as there will be more moderating material the spectral width will still increase. Figure 3 shows the point at which yield has maximised to be between 300μm and 500μm for $^{26}Mg(p,n)$ with an 8MeV proton beam.

THERMAL MANAGEMENT

Significant beam power will be required to provide sufficient neutron fluxes for some applications. The thermal characteristics of Lithium make it particularly challenging for this and so a Comsol Multiphysics model of a possible $Li(p,n)$ target system has been studied, a possible geometry is shown in Fig. 4.

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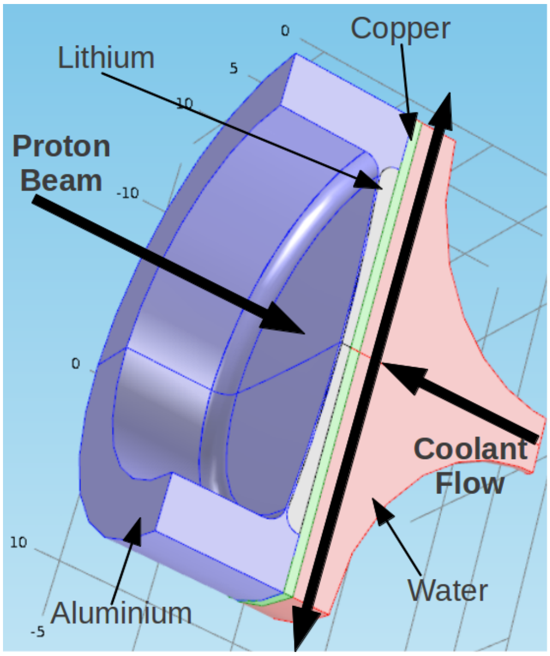

Figure 4: Sample $Li(p,n)$ target geometry.

For the thermal modelling a simplified version was used which considered the water cooling, Copper plate and Lithium target. Water is injected onto the back of the Copper target and carries the heat out at the sides. Figure 5 shows the water velocity and target temperature under sustained irradiation by a 35kW beam on a Lithium target of 20cm radius.

The simulations shown in Fig. 5 demonstrate that the thermal loading of a high flux beam can be managed in an effective way. For systems requiring fast mono-chromatic neutrons a different target system would be required. The presence of water in behind the target will result in a level of moderation, in some scenarios this moderation may broaden the energy spectrum to an unacceptable extent.

CONCLUSION

As the interest in security applications of neutrons grows it is important that the possible source options be well understood. In this paper we have shown how the neutron spectrum produced in fusion reactions can be varied by changing the irradiating beam energy and the target thickness.

Low energy accelerators $E \leq$ 10MeV with variable energy are suitable projectile sources for proving neutron through fusion reactions. Using targets without significant radio-toxicology concerns will enable mass deployment of neutron sources to areas such as security in which they will provide significant benefit. The additional benefits of being able to significantly vary the neutron beam energy will allowing the neutron energy to be optimised for the materials under interrogation.

A high power beam impinging on a thin target will result in significant thermal loading. A target geometry suited to some applications has been presented and shown to be capable of withstanding the necessary beam power.

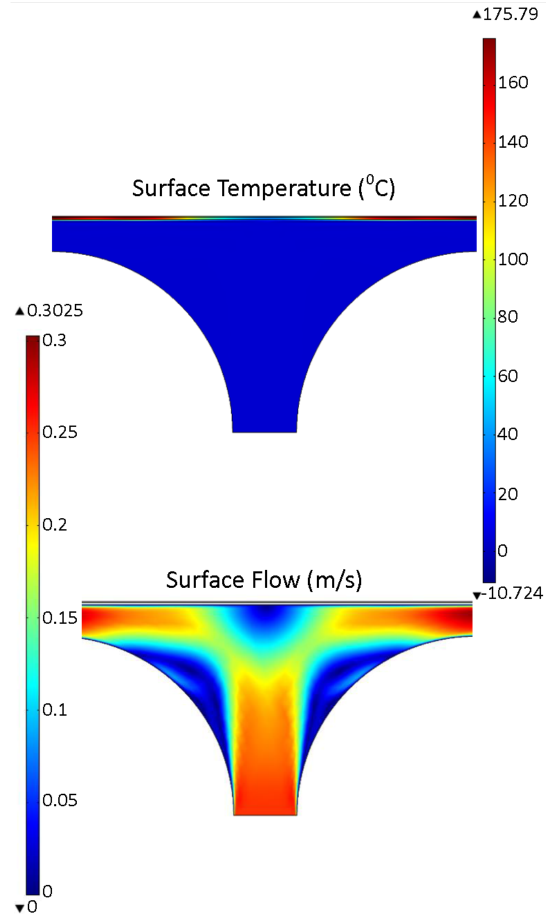

Figure 5: Water coolant velocity (left) and water and target temperature distribution (right) of possible $Li(p,n)$ target design.

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