Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 10-11, 2007

Conceptual Design of a 14-MeV D-T Neutron Source for Material Inspection

Jinchoon Kim,[a] Byung-Hoon Oh,[b]
a ProScience 11212 Almazon St., San Diego, CA 92129, kimj2@sbcglobal.net
b Korea Atomic Energy Research Institute 150 Deokjin-dong, Yuseong-ku, Daejeon 305-353

1. Introduction

There is a worldwide need for the efficient inspection of cargo containers at airports, seaports and border crossings. And there is also a growing need for non-destructive inspection of metal objects such as airplane parts. The limitations of X-ray systems for the detection of explosives, drugs, and thick metal structures have stimulated interest in neutron radiograph or tomography. [1,2]

The weak link in such applications is the *neutron source*. The ideal neutron source should provide a high-intensity, high-energy for sufficient penetration and activation, a reliable long-term operation, and a monoenergetic neutron beam.

In this paper, we describe a conceptual design of a DT fusion neutron source (monoenergetic 14 MeV neutron generator) which satisfies the fore-mentioned requirements. The current design is based upon the actually proven system [3] using the drive-in target principle [4]. The design is versatile enough to accommodate various applications, ranging from material inspection and explosive interrogation to medical probing and cancer treatment.

2. Neutron Radiography

Neutrons are an effective probe for the elemental characterization of bulk samples since they can penetrate deeply into matter, interacting only with nuclei. For example, the main constituents of narcotic and explosive substances (H, C, N and O) differ strongly from one-another in their interactions with neutrons and thus one can infer the nature of the material from such characterization.

Various techniques are being considered depending upon the applications [5]. Just to mention a few of the techniques, there are: i) fast neutron inelastic gama analysis, ii) DT neutron gama and associated alpha particle analysis, iii) source neutron and source gama analysis, iv) pulsed fast neutron analysis, and v) thermal neutron analysis.

3. Design Philosophy of Fast Neutron Source

There exist a multitude of neutron sources, including particle accelerator-produced (broad energy spectrum), isotopic sources (monoenergetic but low intensity), D-D and D-T fusion neutron sources (monoenergetic), and nuclear fission reactors (broad spectrum). The fusion neutron sources exhibit a superior advantage in that high-intensity monoenergetic neutrons can be generated with a relatively low accelerator voltage (<300 KeV). Sealed tube sources using DD or DT ions have been commercialized and readily available although the price is rather high and the intensity is typically below 10^8 n/s.

Considering the various requirements of different inspection applications, we have arrived at the following design criteria, which will cover a wide range of applications:

- The system assembly does not have to be a "sealed-tube" but to be miniaturized such that it is portable, making the vacuum vessel and utility connections flexible.
- The 14-MeV DT neutron intensity can be as high as 10^{11} n/s and readily lowered to 10^8 n/s if needed.
- Gas handling is via regenerable getter pump for 50%-50% D-T gas mixture without the need of frequent recharging.
- Ion source options include PIG (Penning ion gauge ion source), ECR (electron cyclotron resonance ion source), and duoplasmatron.
- The drive-in target idea can give an unlimited lifetime. We make a best use of the experimentally proven system developed by one of the authors (JK).
- The drive-in target is actively cooled and maintained at a relatively low temperature for a maximum concentration buildup.

4. Calculation of Expected Neutron Yields

Hydrogen ions driven into a target fill up the target to the stopping range (R) and diffuse back toward the surface, establishing more or less a constant equilibrium concentration (C) across the range. As the incident hydrogen particles (D and T) lose energy while penetrating into the target, the fusion reaction cross-section, σ[E(x)], becomes a function of the depth (x) via E(x) which is to be determined by the stopping power formula, dE(x)/dx. In general, C is also a function of the depth. The neutron source intensity (S) is then given by

$$S = \frac{j}{e}\int_0^R \sigma[E(x)]C(x)dx$$

where R is the stopping range and e is the electronic charge

If C is constant across the range, then the integration can easily be performed to yield W_{DD} for D-D case, for example. The sum in W_{DD} is to account for the three species of ions typically existing in hydrogen ion sources (D_1^+, D_2^+, D_3^+). It is then dependent only on the initial acceleration energy per atom (E_b/k), where E_b is the beam energy, k stands for the number of atoms in each species, and f_k represents the fraction of k-species

$$S_{DD} = \frac{jC}{e} W_{DD}$$

$$W_{DD} = \sum_{k=1}^{3} k f_k V_{dD}(E_b / k)$$

$$V_{dD}(E_b / k) = \int_{0}^{R} \sigma_{DD}(E_b / k)$$

For the case of D-T mixed ions, both the incoming deuterons onto the embedded tritons and the incoming tritons onto the embedded deuterons can produce DT fusion, d(T, α)n. Therefore W_{DT} is more involved than W_{DD} and has three more terms. In Figure 1, W_{DT} and W_{DD} are calculated for chromium (a candidate plating material) and for different ion species of the mixed DT beam.

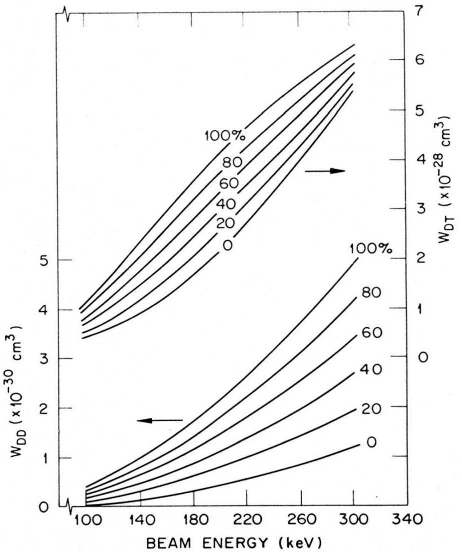

Figure 1. Species-corrected integrated fusion cross-section, W_{DT} and W_{DD} for chromium target for different beam ion compositions.

5. Conceptual Design and Applications

Based on the design principle of Section 3, a conceptual design has been made, which is shown in Figure 2. The size of the system is rather flexible, say 10-cm-diameter by 30-cm-length to 20-cm-diameter by 60-cm-length. The vacuum vessel must be robust and tritium-compatible. Of course, a complete system will contain the neutron shielding/collimator and the power supplies/control.

Neutrons are generated isotropically, but the useful sides are indicated by the arrows. For n-α coincidence technique [6], for instance, the α–particle detector can be placed opposite side, since the neutron and the α–particle are emitted 180° opposite to each other.

The ion source produces a D-T mixed beam of 30 mA at 120 kV. The gas is pumped and regenerated by reversible getter pumps. A copper target (chromium plated if needed) is designed to handle a power density of 0.5 kW/cm^2 over a beam spot of 3-cm diameter. Using Fig.1 for W_{DT} at E_b = 120 KeV and assuming a well establish value of concentration [4] C = 10^{22} cm^{-3} and j = 0.03A, we arrive at a 14 MeV neutron yield of 2x10^{11} n/s. Reducing the intensity, if required, is an easy step.

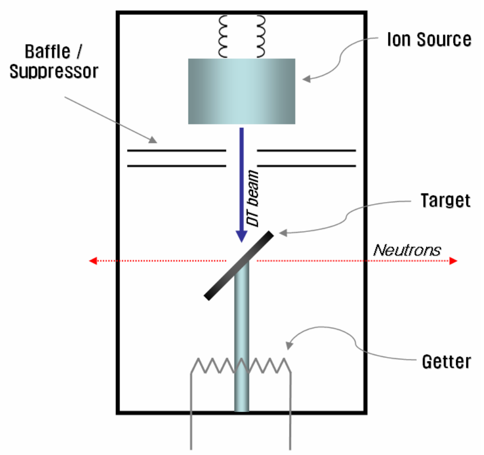

Figure 2. Conceptual design of a DT fusion neutron source

Such a system can be most effectively used for non-destructive structural inspection, seaport/airport screening, and medical diagnostics purpose. The system is easily portable and the neutron beam size/shape can be easily adjusted by the use of modular collimators.

6. Conclusion

A conceptual design of a 14 MeV D-T fusion neutron source has been presented to yield 2x10^{11} n/s steady-state or pulsed. The design was born out from the consideration that the critical elements are the reliable ion source and the well-cooled drive-in target. It is firmly based on the previous successful development of a drive-in target system [3].

REFERENCES

[1] T. Gozani, Neutron based non-intrusive inspection techniques, Proc. Int. Soc. Opt.Eng. **2867** (1997) 174.

[2] J.E. Eberhardt, S. Rainey, R.J. Stevens, B.D. Sowerby_, J.R. Tickner, Appl. Radiation and Isotopes 63 (2005) 179

[3] J. Kim, J.L. Hilton, and G.O. Hendry, Two Duoplasmatrons Used for D-T Fusion Neutron Source, Proc. 2nd Symp. Ion Sources and Formation of Ion Beams, LBL-3399, Berkeley, CA (1974) VII-9 .

[4] J. Kim, Neutron Sources Using D-T Mixed Beams Driven into Solid Target, Nucl. Instrum. Meth. **145** (1977)9.

[5] A. Buffler, Using Fast Neutrons to Detect Explosives and Illicit Materials, IAEA-CN-115/59 (2006).

[6] For example, C-M Sim, Proc. BAERI Workshop on Neutron Sources and Applications, Hoam Center SNU (2007).