

## Accelerator-based neutron source using a cold deuterium target with degenerate electrons

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(Received 20 December 2012; accepted 9 July 2013; published online 17 July 2013)

A neutron generator is considered in which a beam of tritons is incident on a hypothetical cold deuterium target with degenerate electrons. The energy efficiency of neutron generation is found to increase substantially with electron density. Recent reports of potential targets are discussed. © 2013 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License. [<http://dx.doi.org/10.1063/1.4816407>]

Neutron generators are in use in a number of scientific and commercial endeavors. They function by triggering fusion reactions between accelerated ions (usually deuterons) and the nuclei within a stationary cold target (e.g., containing tritium). The energy efficiency of neutron generation can be increased, provided that the energy transferred from injected ions to target electrons can be reduced. A target that consists of nuclei and degenerate electrons is considered here. Degenerate electrons become partially transparent to energetic ions, because each electron can have a minimum excitation energy. The average minimum excitation energy may be expected to increase with electron density.<sup>1</sup>

An instantaneous efficiency factor is evaluated, followed by evaluation of a total efficiency factor. A total efficiency factor is defined as the average number of neutrons produced per ion divided by an ion's incident energy. An instantaneous efficiency factor is defined to have two parts: the energy lost to electrons in the target and the neutrons produced by fusion reactions between ions and nuclei. (Only the incident beam ions will be referred to as "ions.") References 2–4 provide theoretical descriptions of the average energy loss per unit path length of slow charged particles within a non-relativistic degenerate electron gas. Associated analytical expressions are summarized in Ref. 5 and are repeated here with some simplification:

$$\frac{dE}{dl} = \zeta \ln\left(\frac{\eta}{\pi}\right), \quad (1)$$

$$\frac{dE}{dl} = \zeta \left[ \ln(1 + \eta) - \frac{1}{1 + (1/\eta)} \right], \quad (2)$$

$$\frac{dE}{dl} = \zeta \left[ \ln\left(\frac{2}{3} + \eta\right) + \frac{1 - 3\eta}{2 + 3\eta} \right] \left[ \frac{1}{1 - (1/[3\eta])} \right]^2. \quad (3)$$

Here,  $\zeta = 2v(k_c e^2 Z m_e)^2 / (3\pi \hbar^3)$ ,  $\eta = (3\pi^5 n_e)^{1/3} \hbar^2 / (k_c e^2 m_e)$ ,  $v$  is the ion speed,  $k_c$  is the Coulomb force constant,  $e$  is the proton charge,  $Z$  is the ion charge state,  $m_e$  is the mass of an electron,  $\hbar$  is Planck's constant divided by  $2\pi$ , and  $n_e$  is the electron density. In SI units,  $k_c = 1/(4\pi\epsilon_0)$ , where  $\epsilon_0$  is the permittivity of free space. Reference 6 provides (for  $Z = 1$ ):

$$\frac{dE}{dl} = \zeta \left[ \frac{(1/2) + \eta}{\eta - 2 + (1/\eta)} \right] \left[ \ln(\eta) - 1 + \frac{1}{\eta} \right]. \quad (4)$$

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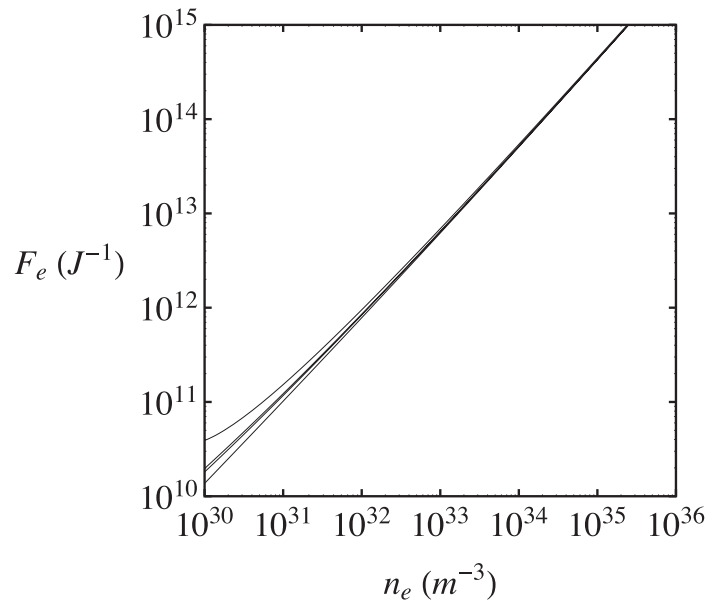


FIG. 1. Instantaneous efficiency factor for 165 keV tritons and a cold deuterium target with degenerate electrons. (Further details are given in the text.)

The instantaneous efficiency factor is defined simply as the neutron production rate divided by power lost:

$$F_e = \frac{\dot{N}_f}{\dot{E}} = \frac{n_n \sigma_f v N_f}{v \frac{dE}{dl}} = \frac{n_e \sigma_f N_f}{Z \frac{dE}{dl}}. \quad (5)$$

Here,  $\dot{N}_f$  is the average rate at which neutrons are produced per ion,  $\dot{E}$  is the average rate at which an ion losses energy to electrons,  $n_n$  is the density of target nuclei,  $\sigma_f$  is the fusion reaction cross section, and  $N_f$  is the number of neutrons produced by one reaction. A neutral target is assumed,  $n_n = n_e/Z$ .

Evaluations of  $F_e$  are shown in Fig. 1. The four curves represent instantaneous efficiency factors calculated using Eqs. (1)–(4) for  $dE/dl$ . Note that all four theories show similar results for the parameter values considered. The parameter values used for Fig. 1 are as follows: The maximum fusion reaction cross section is used for a deuterium-tritium (DT) reaction,  $\sigma_f = 5 \times 10^{-28} \text{ m}^2$ . The ion energy associated with the maximum fusion reaction cross section for energetic tritons and a cold deuterium target is  $E = 165 \text{ keV}$ . The number of neutrons generated from one DT reaction is  $N_f = 1$ .

An instantaneous efficiency factor that considers ion energy losses to cold target nuclei instead of electrons is<sup>7</sup>

$$F_n = \frac{\dot{N}_f}{\dot{E}_n} = \frac{\sigma_f N_f m_n E}{2\pi k_c^2 Z^2 Z_n^2 e^4 m \lambda}, \quad (6)$$

where  $\dot{E}_n$  is the average rate at which an ion of mass  $m$  losses energy to target nuclei, and  $m_n$  and  $Z_n$  are the mass and charge state of a target nucleus. A Coulomb logarithm that considers cutoff Coulomb interactions is<sup>8</sup>

$$\lambda = \frac{(1 + \Lambda)^2}{2(2 + \Lambda)^2} \ln \left( \frac{\zeta_{\max}}{\zeta_{\min}} \right) - \frac{\Lambda(1 - \beta_{\min}^2)}{2(2 + \Lambda)}, \quad (7)$$

where

$$\Lambda = \frac{2Eb_{\max}}{k_c Z Z_n e^2 (1 + (m/m_n))}, \quad (8)$$

$\zeta_{\max} = 1 + (2 + \Lambda)\Lambda$ ,  $\zeta_{\min} = 1 + (2 + \Lambda)\Lambda\beta_{\min}^2$ , and  $\beta_{\min} = b_{\min}/b_{\max}$ . A benefit to using this complex form for the Coulomb logarithm is that the parameter  $b_{\min}$  can be used to exclude those collisions that result in a fusion reaction with  $b_{\min} = \sqrt{\sigma_f/\pi}$ , provided  $0 \leq \beta_{\min} < 1$  is satisfied. The maximum impact parameter is set equal to the Thomas-Fermi screening length:

$$b_{\max} = \sqrt{\frac{k_B T_F}{6\pi k_c e^2 n_e}}. \quad (9)$$

Here,  $T_F = E_F/k_B$  is the Fermi temperature,  $k_B$  is Boltzmann's constant, and  $E_F = [\hbar^2/(2m_e)](3\pi^2 n_e)^{2/3}$  is the Fermi energy. It is interesting to note that the Thomas-Fermi screening length becomes the Debye-Hückel screening length, which applies for a non-degenerate electron plasma, if the substitution  $T_F \rightarrow \frac{3}{2}T_e$  is made, where  $T_e$  is the electron temperature.

An expression for a combined instantaneous efficiency factor is

$$F = \frac{\dot{N}_f}{\dot{E} + \dot{E}_n} = \frac{1}{F_e^{-1} + F_n^{-1}}. \quad (10)$$

Define  $G$  as the average number of neutrons produced per ion divided by an ion's incident energy. With ions that slow down within the target,

$$G = \frac{1}{E_b} \int_0^{E_b} F dE, \quad (11)$$

where  $E_b$  is the energy of each incident beam ion. To maximize  $G$ , the ions must be injected with energies higher than the energy associated with the maximum fusion reaction cross section. The fusion reaction cross section is evaluated in SI units using<sup>9</sup>

$$\sigma_f = \frac{4.09 \times 10^{-23} + 5.02 \times 10^{-21}/(1 + [(1.368 \times 10^{-5} E_D/e) - 1.076]^2)}{(E_D/e)[\exp(1453/\sqrt{E_D/e}) - 1]}. \quad (12)$$

This is the cross section for energetic deuterons incident on cold tritons. In the current study, the reverse situation is considered, and the substitution  $E_D \rightarrow (m_n/m)E$  is used in Eq. (12).  $G$  is evaluated by substituting Eq. (12) for  $\sigma_f$  into the expressions for  $F_e$  and  $F_n$ . By way of example, 260 keV tritons incident on a neutral deuterium target with an electron density of  $1 \times 10^{32} \text{ m}^{-3}$  is considered. Then, the use of Eqs. (1)–(4) yields  $3.8 \times 10^{11} \leq G \leq 4.4 \times 10^{11}$ , where  $G$  has units of neutrons per joule.

To arrive at the finding  $3.8 \times 10^{11} \text{ J}^{-1} \leq G \leq 4.4 \times 10^{11} \text{ J}^{-1}$ , the electrons were treated as a degenerate gas, and the following assumptions were made:  $T_e \ll T_F$ ,  $v \ll v_F = \sqrt{2E_F/m_e}$ , and  $v_F \ll c$ , where  $c$  is the speed of light. These three assumptions are reasonably satisfied. For 260 keV tritons incident on a room-temperature target with an electron density of  $10^{32} \text{ m}^{-3}$ :  $T_e/T_F = 3 \times 10^{-5}$ ,  $v/v_F \leq v_b/v_F = 0.25$ , and  $v_F/c = 0.06$ , where  $v_b = \sqrt{2E_b/m}$  is the speed of each incident beam ion.

In summary, an approach to generating neutrons was investigated in which a beam of tritons is incident on a cold deuterium target with degenerate electrons. The energy efficiency was found to increase substantially with electron density.

It is interesting to note that experimental evidence has recently been reported for the existence of an “ultra-dense” form of hydrogen.<sup>10–29</sup> The findings suggest that deuterium clusters in a condensed-matter state exhibit both superfluid and superconducting characteristics at room temperature and below atmospheric pressure. Ultra-dense deuterium (UDD) was reported in Refs. 10–29 to have an electron density  $n_e = 10^{35} \text{ m}^{-3}$ , and UDD has been proposed for use in inertial confinement fusion. UDD does not appear to have been synthesized in bulk, and no independent confirmation of the existence of UDD has been reported. The method of producing UDD employs a potassium-doped iron oxide catalyst. References 27, 30, and 31 discuss the possibility that dense deuterium clusters could form in other solid materials. Cooper paired electrons in a quantum-mechanical vortex solution have been proposed as forming the electron subsystem in UDD.<sup>32,33</sup> It should also be noted

that advanced theoretical approaches exist for describing the origin of electron vortices in atomic systems.<sup>34–37</sup>

## ACKNOWLEDGMENTS

The authors would like to thank Profs. D. R. Schultz and D. L. Weathers for helpful discussions.

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