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Optimization of Neutron Source

E. B. Hooper

SUMMARY

I consider here the optimization of the two component neutron source [1-3], allowing beam species and energy to vary. A simple model is developed, based on the earlier publications, that permits the optimum to be obtained simply.

The two component plasma, with one species of hot ion (D^+ or T^+) and the complementary species of cold ion, is easy to analyze in the case of a spatially uniform cold plasma, as to good approximation the total number of hot ions is important but not their spatial distribution. Consequently, the optimization can ignore spatial effects. The problem of a plasma with both types of hot ions and cold ions is rather more difficult, as the neutron production by hot-hot interactions is sensitive to their spatial distributions. Consequently, consideration of this problem will be delayed to a future memorandum.

The basic model is that used in the published articles on the two-component, beam-plasma mirror source. I integrate the Fokker-Planck equation analytically, obtaining good agreement with previous numerical results. This simplifies the optimization, by providing a functional form for the neutron production.

The primary result is expressed in terms of the power efficiency: watts of neutrons/watts of primary power. The latter includes the positive ion neutralization efficiency. At 150 keV, the present model obtains an efficiency of 0.66%, compared with 0.53% (including neutralization efficiency) of the earlier calculation.

The advantage of this approach is in determining optimum conditions. I find that to good approximation the efficiency is a function of E_{inj}/A_h , the injection energy per nucleon. Thus, 120 keV deuterons have the same efficiency as 180 keV tritons. For the same beam power, operation is at the same plasma beta, so the maximum number of neutrons produced (e.g. at $\beta_h = 1$) is unchanged. Furthermore, the optimum efficiency, say for deuterons, is at 110-120 keV, rather lower than the 150 keV used in the earlier studies. The efficiency at 115 keV, 0.87%, is an improvement of 32% over that at 150 keV.

Note that the use either of negative ions to produce the neutrals or of energy recovery would negate the conclusion that the efficiency is a function of E_{inj}/A_h . The operation of the source would obviously be improved significantly.

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HOT IONS AND NEUTRON PRODUCTION

Even though the electrons in the plasma are relatively cold, their thermal velocity is greater than that of the injected ions. The electron thermal velocity is

$$v_e = 1.9 \times 10^7 T_e^{1/2} \quad \text{m/s} \quad (1)$$

with the electron temperature, T_e , in keV. At 0.1 keV, $v_e = 6 \times 10^6$ m/s. The ion velocity is

$$v_h = 2.2 \times 10^5 E_h^{1/2} / A_h^{1/2} \quad \text{m/s} \quad (2)$$

with the hot ion energy, E_h in keV. For D^+ ($A_h = 2$) at 150 keV, $v_h = 1.9 \times 10^6$ m/s, small compared to the electron velocity. We are thus free to apply the collision frequencies in the limit $v_e \ll v_h$. Furthermore, as the diffusive effects of the collisions are much less, by T_e/E_h , than the slowing-down effects, the Fokker-Planck equation has the simple form:

$$-\nabla_v \cdot (v_s v f) \approx \dot{n}_h \delta^3(v - v_{inj}) \quad (3)$$

where $\dot{n}_h$ is the hot ion density injection rate and v_s is the slowing-down rate.

We are only interested in the speed (energy) dependence of the distribution function f , and thus integrate Eq. (3) over the angles in velocity space to obtain

$$-\frac{v_s}{v^2} \frac{\partial}{\partial v} [v^3 f(v)] = \dot{n}_h \frac{\delta(v - v_{inj})}{v^2} \quad (4)$$

so that

$$\begin{aligned} f(v) &= \frac{\dot{n}_h}{v_s v^3} & v \leq v_{inj} \\ &= 0 & v > v_{inj} \end{aligned} \quad (5)$$

Converting to energy from speed, the distribution is

$$\begin{aligned} f(E) &= \frac{\dot{n}_h \tau_E}{E} & E \leq E_{inj} \\ &= 0 & E > E_{inj} \end{aligned} \quad (6)$$

where the energy loss time is [4]

$$\tau_E = \frac{1}{2v_s} = 1.0 \times 10^{19} \frac{A_h T_e^{3/2}}{n \ln(\Lambda)} \quad (7)$$

The density is not well defined because of the singularity at $E = 0$. However, the useful variable is the hot-ion beta, found from the stored energy as:

$$\beta_h = 4.03 \times 10^{-22} \frac{\dot{n}_h \tau_E E_{inj}}{B^2} \quad (8)$$

with the magnetic field, B , in tesla.

The volumetric neutron production rate is given by

$$\frac{d\Phi}{dV} = n_h \langle \sigma v \rangle n \tau_E \quad (9)$$

where the reaction rate, $\langle \sigma v \rangle$, normalized essentially to the trapped current, is

$$\langle \sigma v \rangle = \left(\frac{2}{A_h m_p} \right)^{1/2} \int_0^{E_{inj}} \sigma(E) E^{-1/2} dE. \quad (10)$$

Here m_p is the proton mass and $\sigma(E)$ the fusion cross section which is a function of the center of mass energy. Thus, the general reaction rate can be written as

$$\langle \sigma v \rangle = Sv(E_{inc}/A_h) \quad (11)$$

The normalized reaction rate obtained from the DT reaction rate for stationary tritons,

$$Sv(E_{inj}/A_h) = \left(\frac{2}{m_p} \right)^{1/2} \int_0^{E_{inj}/A_h} \sigma_{DT}(2E) E^{-1/2} dE \quad (12)$$

is calculated in the Appendix and plotted in Fig. 1. Comparison with numerical calculations using the Fokker-Planck equation are included from the Appendix, demonstrating good agreement.

The volumetric neutron production rate thus becomes

$$\frac{d\Phi}{dV} = n_h Sv(E_{inj}/A_h) n \tau_E. \quad (13)$$

Figure 1. Normalized neutron production rate as a function of injection energy. The points are from the numerical calculation.

Note that $n\tau_E \sim A_h T_e^{3/2}$. As the electron temperature is a weak function of the parameters, we will postpone discussing its effects until later in the memorandum but include the dependence on the hot species here.

The efficiency of neutron production can be defined in several ways. We consider two approaches.

(a) Neutron production rate per trapped ion:

$$\begin{aligned}\eta_n &= \frac{1}{n_h} \frac{d\Phi}{dV} \\ &= A_h S v(E_{inc}/A_h) \left(\frac{n\tau_E}{A} \right).\end{aligned}\tag{14}$$

The efficiency defined this way would apply if negative ions or energy recovery were used in the neutral beam efficiency, so that the efficiency of producing a neutral were approximately independent of energy. In that case, the use of a triton beam rather than deuterons would increase the efficiency at a fixed E_{inj}/A_h . (We will see later that this conclusion is not changed by the electron temperature considerations.)

(b) Neutron power efficiency, watts of neutrons/watts of input power. To obtain this, we need the neutralization efficiency of the original ion beam. For present purposes, assume that positive ions are used and define the equilibrium fraction in terms of that for protons, f_p :

$$f(E_{inj}) = f_p(E_{inj}/A_h).\tag{15}$$

The function $f_p(E_{inj}/A_h)$ is plotted in Fig. 2.

Figure 2. Equilibrium fraction for protons in hydrogen gas.

The energy efficiency is

$$\eta_P = \frac{E_N f_p(E_{inj}/A_h)}{n_h E_{inj}} \frac{d\Phi}{dV} \quad (16)$$

with $E_N = 14.1$ MeV. Equation (9) yields

$$\eta_P = \frac{E_N}{E_{inj}/A_h} S v(E_{inj}/A_h) f_p(E_{inj}/A_h) \left(\frac{n \tau_E}{A_h} \right). \quad (17)$$

The function

$$G(E_{inj}/A_h) = \frac{E_N}{E_{inj}/A_h} S v(E_{inj}/A_h) f_p(E_{inj}/A_h) \quad (18)$$

is plotted in Fig. 3. The energy at the maximum is surprisingly low, about 110 keV for deuterons. Thus, in the absence of electron temperature effects, the most efficient production of neutrons, assuming the use of positive ion beams to generate the neutral atom beams, is at an energy about equal to that used in the TFTR neutral beam sources.

Figure 3. Efficiency function, neglecting electron temperature effects.

ELECTRON TEMPERATURE EFFECTS

The injected energy is removed from the injection volume primarily by electron thermal conduction along the magnetic field lines to the end tanks of the system. We follow the analysis of references [1-3] by equating the injected power to the Spitzer heat flow,

$$\frac{dP_{inj}}{dV} \ell_h = 1.06 \times 10^{14} \frac{T_e^{7/2}}{\ell_c R} \quad (19)$$

where ℓ_h is the length of the hot ions in the central cell, ℓ_c is the length of the solenoids connecting the central cell to the ends, and R is the mirror ratio of the solenoid region to the midplane of the central cell. The temperature is thus

$$T_e = \left(0.94 \times 10^{-14} \frac{dP_{inj}}{dV} \ell_h \ell_c R \right)^{2/7}. \quad (20)$$

To estimate the electron temperature, we use parameters from the earlier studies [1-3]. Thus, $P_{inj} = 60 \times 10^6$ watts, $V/\ell_h = \pi a^2 = 5.0 \times 10^{-3} \text{ m}^2$, $\ell_c = 10 \text{ m}$, and $R = 3$ yield $T_e = 0.38 \text{ keV}$, in good agreement with the earlier 0.4 keV .

The injected power is reduced by the conversion efficiency if positive ions are used. (Geometric effects, e.g. plasma radius, may also play a role, but will be neglected here.) Thus, the injected power is reduced from the primary power, P_o , by the equilibrium fraction. Using the expression for $n\tau_E$, Eq. (7), we find:

$$\frac{n\tau_E}{A_h} = \frac{0.98 \times 10^{13}}{\ell n \Lambda} \left(\frac{dP_o}{dV} f_p(E_{inj}/A_h) \ell_h \ell_c R \right)^{3/7} \quad (21)$$

The result is to reduce the energy for maximum efficiency; the factor G becomes

$$G_1(E_{inj}/A_h) = \frac{E_N}{E_{inj}/A_h} S v(E_{inj}/A_h) [f_p(E_{inj}/A_h)]^{10/7}. \quad (22)$$

This result is plotted in Fig. (4). The maximum has been reduced by about 30%, but

Figure 4. Efficiency function, including electron temperature effects.

the optimum energy has shifted by only a small amount. We conclude that for a positive-ion based system, the efficiency is maximized for beams in the range of those used today.

The total power efficiency is thus

$$\eta_P = 8.5 \times 10^{11} \left(\frac{dP_o}{dV} \ell_h \ell_c R \right)^{3/7} G_1(E_{inj}/A_h) \quad (23)$$

At the maximum, we find $\eta_P = 8.7 \times 10^{-3}$ and at 150 keV of D^+ , we find 6.6×10^{-3} . The previous result obtained 1 MW of neutrons for 60 MW trapped, 150 keV deuterons; including a positive ion neutralization efficiency of 0.32, the power efficiency was 5.3×10^{-3} , in fair agreement with the present result. The differences may arise from effects not included here, e.g. the radial variation of T_e due to the Gaussian shape of the hot-ion distribution.

MAXIMUM OPERATING POINT

The production of neutrons is maximum at $\beta_h = 1$, with beta given by Eq. (8). At constant E_{inj}/A_h , the ratio of betas for tritium and deuterium depend only on the cold electron density. Consequently, the maximum operating point will be different only if there is reason to operate at different electron densities. Within the present model, there is no reason to change the densities for the two nuclei.

APPENDIX: DT NEUTRON PRODUCTION RATE

To evaluate the normalized neutron production rate, Eq. (12),

$$Sv(E_{inj}/A_h) = \left(\frac{2}{m_p} \right)^{1/2} \int_0^{E_{inj}/A_h} \sigma_{DT}(2E) E^{-1/2} dE, \quad (12)$$

we use a fit to the cross section: [5]

$$\sigma_{DT}(E) \approx \frac{A_5 + A_2 [(A_4 - A_3 E)^2 + 1]^{-1}}{E [\exp(A_1 E^{-1/2}) - 1]} \quad \text{barns} \quad (A1)$$

with $A_1 = 45.95$, $A_2 = 50200$, $A_3 = 0.01368$, $A_4 = 1.297$, and $A_5 = 647$. The integral is easily done, and plotted in Fig. 1.

Archer Futch [6] has made numerical calculations, integrating the Fokker-Planck equation for deuterium and a given T_e . We compare with sample results, given in Table A1. His results are given in terms of a hot density and average hot ion energy. To compare with our result, we normalize the hot betas from the two methods. The results are plotted on Fig. 1 as

$$Sv(E_{inj}/2) = \frac{E_{inj}}{E_{hot,av}} \langle \sigma v \rangle_{Futch} \quad (A2)$$

The agreement is excellent.

Table A1. Selected data from Futch. The electron temperature varies from 0.12 keV to 0.5 keV in the numerical calculation.

Injection energy (keV)	Av. hot-ion energy (keV)	$\langle \sigma v \rangle_{Futch}$ m^3/s
100	34.4	2.94×10^{-22}
200	58.7	5.17×10^{-22}
100	29.0	2.40×10^{-22}
150	40.3	3.82×10^{-22}
100	19.8	1.58×10^{-22}
150	22.5	2.08×10^{-22}
200	29.8	2.53×10^{-22}
200	62.0	4.71×10^{-22}
250	74.0	5.70×10^{-22}
200	91.5	7.19×10^{-22}
250	72.9	5.52×10^{-22}
120	32.4	2.87×10^{-22}

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