1048

RECEIVED BY TIC JUL 23 1974

MAY 1974

MATT-1048

TWO-ENERGY-COMPONENT FUSION REACTORS
WITH SUSTAINED SUPRATHERMAL-ION ENERGY

BY

D. L. JASSBY AND H. P. FURTH

PLASMA PHYSICS LABORATORY

MASTER

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

This work was supported by U. S. Atomic Energy Commission Contract AT(11-1)-3073. Reproduction, translation, publication, use, and disposal, in whole or in part, by or for the United States Government is permitted.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TWO-ENERGY-COMPONENT FUSION REACTORS WITH SUSTAINED SUPRATHERMAL-ION ENERGY*

D. L. JASSBY and H. P. FURTH

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540, USA

ABSTRACT

The energy multiplication factor of the D-T two-energy-component reactor scheme can be enhanced by a factor of about two if the suprathermal ion energy is "clamped" at the value W_0 that gives maximal ratio of fusion reaction rate to plasma drag. The optimal energy W_0 is in the range 105 to 145 keV (depending on T_e), significantly lower than the optimal energy in the conventional scheme. To realize the maximum gain, the clamping period must be many times the "slowing-down time," or else the suprathermal energy must be recovered (e.g., by magnetic decompression at the end of the clamping period). In a tokamak device there are several possible techniques for accomplishing energy clamping; the most promising is slow major-radius compression. Application of this method, whose principle has been demonstrated, could lead, for example, to a "break-even" device with $\langle T_e \rangle \approx 3.3$ keV, compression ratio 2.2, and $nt \sim 5 \times 10^{12} \text{ cm}^{-3} \text{ sec}$.

*This work was supported by U. S. Atomic Energy Commission Contract AT(11-1)-3073.

MASTER

1. INTRODUCTION

One straightforward way to operate a controlled fusion reactor is to bombard a fairly cold tritium plasma with fast deuterons, whose energy is to be fixed at the value $W_m \approx 125$ keV, corresponding to the maximum fusion reaction rate, until these ions disappear by fusion reactions. An attractive approach to this scheme was recently published by Dawson, Furth and Tenney [1], who proposed injecting into a low-temperature tritium plasma fast deuterium neutrals at an energy somewhat above W_m . As the resulting D ions lose energy by Coulomb collisions with the bulk plasma, they pass through the region of maximum fusion reactivity, and produce F times their injected energy in fusion reactions. For $T_e \gtrsim 4$ keV, $F > 1$, and F can be as large as 3.9 for $T_e \rightarrow \infty$. In Ref. [1], this scheme was specifically proposed for a tokamak plasma, but Post, et al. [2] later suggested its application to an open-ended device. In both cases, the bulk-plasma energy content is maintained only by power input from the fast ions.

In this paper we investigate the advantages to be gained if one applies external power in order to maintain the deuteron energy near W_m . Although input energy additional to the injection energy is thus required, it turns out that ideally the F -factors can be almost doubled. We shall also consider practical means for realizing this improvement.

2. DERIVATION OF MAXIMUM ENERGY GAIN

Figure 1 shows schematically the power flow in the modified two-energy-component reactor scheme, wherein the D energy is "clamped" at the value W_0 by means of an external power input that just balances the drag $|dW/dt|$ of the bulk-plasma electrons and ions. The energy gain for a single ion is thus

$$G = \frac{n_T \sigma v E_F \tau_h}{W_0 + |dW/dt|_0 \tau_h} \quad (1)$$

where $E_F = 22.4$ MeV, σv is the fusion reactivity, n_T is the triton density, τ_h is the fast-ion lifetime, and $|dW/dt|$ is the Coulomb power flow to the bulk plasma, which is balanced by the external source. Since $W_0 = \tau_s |dW/dt|_0$, where τ_s is the slowing-down time, the maximum value of G is attained when $\tau_h \gg \tau_s$:

$$G_{\max} = \frac{n_T \sigma v E_F}{|dW/dt|_0} \quad (2)$$

(Even if $\tau_h \geq \tau_s$, $G_{\max}$ can be realized if the injection energy W_0 is recovered, as shown below.)

The Coulomb drag can be written

$$\left(\frac{dW}{dt}\right)_0 = a n_e \frac{W_0 \ln \Lambda_e}{T_e^{3/2}} + b n_T \frac{\ln \Lambda_i}{W_0^{1/2}} \quad (3)$$

where a and b are constants, $\ln \Lambda_e$ and $\ln \Lambda_i$ are the Coulomb logarithms [3], and $n_e \approx n_T$. From Eq. (2), the supra-thermal ion energy should be "clamped" at the value that gives

maximal ratio of fusion reaction rate to plasma drag. When electron-drag is dominant (low T_e), the optimal W_0 is somewhat less than W_m , while if ion-drag is dominant (high T_e), W_0 is somewhat greater than W_m . Figure 2(a) shows the values of W_0 for obtaining $G_{\max}$; these energies are only 53 to 65% of the optimal energies W_F in the conventional scheme [1]; in the latter, the D ions are injected at considerably higher energy than the peak of the σv curve in order to take advantage of the total possible reactivity while falling in velocity space.

Figure 2(b) compares the values of $G_{\max}$ and $F_{\max}$ at $n_e = 10^{14} \text{ cm}^{-3}$. Evidently, $G_{\max}$ is a factor 1.8-2.0 times larger than $F_{\max}$ over the entire range $T_e = 1 - 100 \text{ keV}$, and can be greater than 7 as $T_e \rightarrow \infty$.

A graphical means for estimating the relative values of $G_{\max}$ and $F_{\max}$ can be established as follows. The exact expressions for $F_{\max}$ and $G_{\max}$ are

$$F_{\max} = \frac{1}{W_F} \int_0^{W_F} S(W) dW$$

and

$$G_{\max} = S(W_G) \quad (4)$$

where

$$S(W) = \frac{n_T \sigma v E_F}{|dW/dt|} \propto \frac{\sigma(W) W^{1/2}}{|dW/dt|} \quad (5)$$

Thus

$$\frac{G_{\max}}{F_{\max}} = \frac{W_F S(W_G)}{\int_0^{W_F} S(W) dW} \quad (6)$$

$S(W)$ has a W -dependence fairly similar to that of σv itself, and is plotted in Fig. 3 for D on T and $T_e = 5$ keV. From Eq. (6), $G_{\max}/F_{\max}$ is the ratio of the area of the rectangle to the shaded area. It's evident that for a flat $\sigma(W)$, energy clamping affords little improvement, while for a highly peaked $\sigma(W)$, the improvement is marked. (We have found that $G_{\max}/F_{\max} \leq 2.0$ for D-T, ≤ 2.3 for D-He³, ≤ 1.5 for D-D, and ≤ 2.3 for p-B¹¹.)

Figure 4 shows $G/G_{\max}$ as a function of clamped deuteron energy. In practice, a double-humped ion velocity distribution, with the beam distribution of the form $f(v_b) \propto \delta(v - v_G)$, may be unattainable, because of the susceptibility of such a distribution to microinstabilities. Consequently, it's of interest to compare energy multiplication factors for less peaked $f(v_b)$. Figure 5 shows $G/F_{\max}$ for square $f(v_b)$. The improvement factor $(G/F_{\max} - 1)$ is 90% of its maximum value for a clamped energy distribution that extends from 88 keV to 144 keV. We also find that $G/F_{\max} = 1.38$ for a weakly double-humped ion velocity distribution, with $f(v_b)$ of the form $\exp [-(v - v_G)^2/v_G^2]$, $W_G = 115$ keV (for $T_e = 5.0$ keV), and $W_{\max} = 150$ keV.

The above considerations are applicable to any type of fusion reactor that is capable of confining high-energy deuterons. In the following we shall consider how energy clamping might be accomplished in tokamak devices.

3. ENERGY-CLAMPING METHODS IN TOKAMAKS

3.1 SLOW MAJOR-RADIUS COMPRESSION [4]

The plasma is compressed at such a rate that the power input to the fast ions just balances the bulk-plasma drag. At the end of the slow compression, fast decompression delivers most of the suprathreshold-ion energy to the vertical-field circuit. Thus the gain given by Eq. (2) is approached if the compression ratio is sufficiently large. This method appears to be practical [5,6], and will be discussed in Section 4.

3.2 ELECTRIC-FIELD CLAMPING

A plasma with $Z > 1$ can support a dc toroidal electric field that maintains suprathreshold ions in a certain velocity range against bulk-plasma drag [7]. This effect has been demonstrated in recent neutral-beam experiments on ATC [6]. In principle, one can adjust the plasma resistivity to optimize this effect for D ions of energy W_G , although all these ions must be injected parallel to the electric field. However, a recent investigation [8] indicates that substantial energy multiplication factors may be unobtainable, essentially because of the large ohmic dissipation that accompanies this clamping method, and in fact any method that makes use of a large toroidal electric field.

3.3 TRANSIT-TIME RESONANCES

It may be possible to transmit energy to suprathermal ions at a frequency resonant with their transit frequency around the torus [9]. One such method could be a rigid displacement of the plasma column at the transit frequency, with all the fast ions suitably phase-bunched. The rigid displacement is accomplished by applying a uniform horizontal magnetic field. An axisymmetric scheme that avoids phase bunching could make use of an unstable compression cycle [10], but this method might also impart energy (irreversibly) to the bulk plasma. These and other "wobble" techniques have not been thoroughly explored.

3.4 HARMONIC ION-CYCLOTRON RESONANT HEATING

Harmonic ion-cyclotron heating experiments have customarily demonstrated the formation of long "tails" on the ion-energy distribution [11]. Such suprathermal-ion production suggests an alternative to neutral-beam injection. Furthermore, a type of "energy-clamping" of fast ions is inherent to the rf method. An evaluation of the rf-activated two-component reactor indicates serious problems, however: (1) The bulk plasma receives some energy directly from the rf, whereas it is desirable to have all energy supplied via (rf-produced) suprathermal ions. (2) If the energetic ions are D, the bulk plasma cannot be 100% T. (3) Since $W_{\perp} \gg W_{\parallel}$ for the harmonic-resonant ions, harmful instabilities may develop. (4) RF coils may have to be placed inside the vacuum vessel.

3.5 ALFVÉN-WAVE GENERATION

A toroidal electron current can, in principle, be maintained by transit-time damping of Alfvén waves generated by coil structures outside the plasma [12]. By suitable choice of the wave frequency, a fast-ion beam could also be maintained. However, the use of rf coil structures adjacent to the plasma column may be impractical in a reactor.

3.6 DRIFT-WAVE BOOTSTRAP CLAMPING

There are certain mechanisms by which the bulk plasma may transfer some of its energy to the beam ions. Such energy transfer processes may be called "bootstrap clamping," since the bulk plasma obtains all its energy from the beam ions in the first place. An example of such a process is the damping of finite-beta drift waves, or possibly the trapped-electron mode, by the suprathermal ions. Bootstrap clamping by means of unstable plasma waves may also be expected to improve the plasma confinement.

4. ENERGY CLAMPING BY MAJOR-RADIUS COMPRESSION

If the vertical magnetic field in a tokamak is increased, the plasma column will shift to smaller major radius. If $C = R_0/R$ is the compression ratio, then for an adiabatic compression [4], $n_e = n_{eo} C^2$ and $T_e = T_{eo} C^{4/3}$, where n_{eo} and T_{eo} are the uncompressed values. Fast ions injected tangentially to the toroidal field attain an energy $W_0 = W_I C^2$ during fast compression, where W_I is the injected energy. These relations have been recently verified by experiments on the ATC device [5,6].

4.1 ADIABATIC ELECTRONS

We assume, as in the conventional two-component scheme, that the transport and radiation losses of the plasma are just balanced by power input from the beam ions. Then T_e increases adiabatically during the compression, and the energy furnished to the bulk plasma by compression is completely retrieved upon decompression. The compression cycle outlined in Fig. 6 is optimum for obtaining maximum fusion energy gain with minimum injection energy. Since $T_e \propto C^{4/3}$, the fusion gain is much larger during the latter part of the compression, so the first part ($C \leq C_1$) is best utilized as a fast compression to increase the energy of the injected ions. [In a practical reactor, an incidental advantage of this technique is that the efficiency of the compression circuit (~90%) is likely to be greater than that of the beam injection system.]

The overall energy gain is:

$$G = \frac{\int_0^{\tau_c} n_T \sigma v E_F dt}{\int_0^{\tau_c} |dw/dt| dt + W_0 (C_1 C_2)^{-2}} \quad (7)$$

where τ_c is the period of slow compression, during which $W = W_0 = \text{constant}$, and $W_0 (C_1 C_2)^{-2}$ is that part of the beam energy that is not retrieved by the compression circuit. Using Eq. (3) and $n_e \approx n_T$, we have

$$G = \frac{\sigma v E_F n_{e0} \int_0^{\tau_c} C^2(t) dt}{W_0 \tau_c / \tau_{se} + W_0 / \tau_{si} \int_0^{\tau_c} C^2(t) dt + W_0 (C_1 C_2)^{-2}} \quad (8)$$

where τ_{se} and τ_{si} are the slowing-down times on the bulk-plasma electrons and ions at $T_{e1} = T_{e0} C_1^{4/3}$, and we ignore the (negligible) changes in $\ln \Lambda$ during the slow compression.

Consider tangential injection of the fast ions into a $Z = 1$ plasma of sufficiently low T_e that angular scattering can be neglected. The expression for $C(t)$ is found from the condition that the power input to the fast ions from the compression just balances the Coulomb drag of the bulk plasma:

$$\frac{dw}{dt} = \frac{2W_0}{C} \frac{dC}{dt} + \left(\frac{dw}{dt} \right)_0 = 0 \quad (9)$$

Using Eq. (3), we find that

$$C^2(t) = \frac{\exp(t/\tau_{se})}{1 + \mu[1 - \exp(t/\tau_{se})]} \quad (10)$$

where $\mu = \tau_{se}/\tau_{si}$. Hence, Eq. (8) becomes

$$G = \frac{G_{\max}(1 + \mu^{-1})}{2 \log(C_2) + (C_1 C_2)^{-2}} \log \left[\frac{1 + \mu(C_2)^2}{1 + \mu} \right] \quad (11)$$

where $G_{\max}$ is evaluated at $T_{e1} = T_{e0} C_1^{4/3}$. As an example, consider a set of parameters for obtaining energy "break-even"; that is, $Q_E = \eta(1 + G) = 1.0$, where η is the energy recycling efficiency. If $\eta = 0.40$, then $G = 1.5$ for break-even. $G = 1.53$ can be attained with 50-keV D beams injected into a 100% T plasma at $T_{e0} = 1.5$ keV, utilizing $C_1 = 1.5$ and $C_1 C_2 = 2.2$. The period of slow compression is given by $n_{e1} \tau_c = 2.9 \times 10^{12} \text{ cm}^{-3} \text{ sec}$. Thus if $n_{e0} = 2 \times 10^{13} \text{ cm}^{-3}$, then $\tau_c = 65$ msec, and the total fast-ion lifetime, including injection, compression, and fast decompression, should be about 115 msec. The time-averaged temperature during the slow compression is $\langle T_e \rangle = 3.3$ keV. The required $n_e \tau_E$ for the bulk plasma depends on the ratio $\Gamma = \text{beam energy density/plasma energy density}$. For $\Gamma \sim 1$, $n_e \tau_E \sim 6 \times 10^{12} \text{ cm}^{-3} \text{ sec}$.

It is interesting to compare these results with the conventional scheme whereby one injects D beams into the final compressed plasma at $T_e = 4.3$ keV. Then for $W_F = 177$ keV (see Fig. 2), $F_{\max} = 1.24$. Although $G/F_{\max}$ is only 1.23, the

conventional scheme requires an injected beam energy of 177 keV rather than 50 keV, and utilizes an average T_e of 4.3 keV rather than 3.3 keV, so that the plasma is more susceptible to trapped-particle instabilities. The conventional method also requires a somewhat larger plasma current to confine the 177 keV ions (cf. 113 keV during the slow compression), as well as to accommodate the poloidal-beta limitation at the higher T_e .

4.2 ISOTHERMAL ELECTRONS

Here we assume that the plasma energy loss rate is sufficiently large that T_e remains constant during the compression. That portion of the energy input supplied by the beam is recovered at the wall in the usual fashion. But in order to avoid including in the expression for G the energy furnished to the bulk plasma by compression, we must assume that this energy (which is not retained by the plasma) is recovered at 100% efficiency by a direct conversion process. This assumption is obviously not realistic for a tokamak, but the illustrative examples to follow are in fact applicable to other confinement devices, such as magnetic mirrors, where compression can be carried out with 80 - 100% direct conversion of the escaping energy. In this section we do not use a fast compression; i.e., $C_1 = 1$ in Fig. 6.

For tangential injection into a $Z = 1$ plasma of low T_e , Eq. (9) is applicable, and Eq. (7) becomes

$$G = \frac{G_{\max}(T_e)}{1 + (2C^2 \ln C)^{-1}} . \quad (12)$$

The compression period is $\tau_c = \tau_{so}(1 - C^{-2})$. In the case of a completely isotropic ion beam, which is applicable to a high- T_e or $Z \gg 1$ plasma, or with both perpendicular and tangential injection, the gain is given by

$$G = \frac{G_{\max}(T_e)}{1 + [(4/3)C^{4/3} \ln C]^{-1}}. \quad (13)$$

Here $\tau_c = 2/3\tau_{so}(1 - C^{-2})$.

Figure 7 shows $G/F_{\max}$ as a function of C ; there is negligible dependence on temperature in the range $T_e = 2 - 7$ keV. Evidently, the maximum values of G are obtainable at $C \approx 3$. As an example, $Q_E = 1.0$ can be obtained at $T_e = 3.0$ keV, using $W_o = 110$ keV, $C = 2.3$, and $n_{eo}\tau_c = 4 \times 10^{12} \text{ cm}^{-3} \text{ sec}$. If $\Gamma \sim 1$, $n_e\tau_E \sim 3 \times 10^{12} \text{ cm}^{-3} \text{ sec}$.

In order to obtain substantial improvement over F when only small compressions are available, it is best not to decompress, but rather to hold the compressed plasma until the fast ions thermalize. The overall energy gain is

$$G = \frac{\sigma v E_F n_{eo} \int_0^{\tau_c} C^2(t) dt + W_o F(W_o)}{\int_0^{\tau_c} |dW/dt| dt + W_o}. \quad (14)$$

Comparisons of $F_{\max}$ with G from Eq. (14), for both non-scattered and isotropic beams, are shown in Fig. 5. Evidently, substantial improvement is possible for $C \approx 1.5$.

One can easily show that isothermal compression requires that $n_e \tau_E$ be constant. For an adiabatic compression ($T_e \propto C^{4/3}$), the confinement requirement is more complicated, but can often be approximated by $\tau_E \approx \text{constant}$ during the compression.

4.3 USE OF DECOMPRESSION FACILITY

If compression clamping turns out to be inconvenient in a particular device, or if the entire compression facility is needed to elevate the beam energy, the effectiveness of some other clamping method (see Sec. 3) can be enhanced by utilizing fast decompression at the end of the clamping period. Here one injects the beams into the compressed plasma position, where the beam energy W_0 is clamped for a period τ_h . Decompression immediately follows, so that the energy multiplication factor is

$$G = \frac{n_T \sigma v E_F \tau_h}{\frac{dW}{dt} \tau_h + \frac{W_0}{C^n}}$$

$$= \frac{G_{\max}}{1 + \frac{\tau_s}{\tau_h} \frac{1}{C^n}} \quad (15)$$

where $n = 4/3$ to 2 . For $\tau_h = \tau_s$ and $n = 2$, $G \approx 1.5 F$ if $C = 1.8$.

REFERENCES

- [1] DAWSON, J. M., FURTH, H. P., and TENNEY, F. H., Phys. Rev. Letters 26 (1971) 1156.
- [2] POST, R. F., et al., Phys. Rev. Letters 31 (1973) 280.
- [3] SIVUKHIN, D., Reviews of Plasma Physics, Consultants Bureau, New York (1966) Vol. 4, pp. 93-128.
- [4] FURTH, H. P. and YOSHIKAWA, S., Phys. Fluids 13 (1970) 2593.
- [5] BOL, K., et al., Phys. Rev. Letters 29 (1972) 1495.
- [6] BOL, K., et al., Phys. Rev. Letters 32 (1974) 661.
- [7] FURTH, H. P. and RUTHERFORD, P., Phys. Rev. Letters 28 (1972) 545.
- [8] SWEETMAN, D. R., private communication (1974).
- [9] LIDSKY, L. M., Private communication (1974).
- [10] FURTH, H. P. and ELLIS, R. A., JR., Plasma Physics 15 (1973) 719.
- [11] HOOKE, W. M. and HOSEA, J. C., Proceedings Fifth European Conference on Controlled Fusion and Plasma Physics (Grenoble, France, 1972) I, p. 107; SWANSON, D. G., et al., Phys. Rev. Letters 28 (1972) 1015; HOOKE, W. M. and JASSBY, D. L., Princeton University Plasma Physics Laboratory Report TM-270 (1973).
- [12] WORT, D. J. H., Plasma Physics 13 (1971) 258.

743235

Fig. 1. Power flow diagram for clamped two-energy-component reactors.

743134

Fig. 2(a) Optimal beam energies for maximum energy multiplication factors for clamped (W_G) and unclamped (W_F) deuteron beams in a 100% T target plasma.

743258

Fig. 3. $S(W)$ is defined in the text. $G_{\max}/F_{\max}$ is the ratio of the area of the rectangle to the shaded area.

743137

Fig. 4. Energy multiplication factors vs injection energy.

743257

Fig. 5. $G/F_{\max}$ for clamped beam-velocity distributions of the form $f(v_b) = \text{constant}$, $v_{\min} \leq v_b \leq v_{\max}$, $W_G = 115 \text{ keV}$, $W_{\max} \leq 152 \text{ keV}$, and $\Delta W = 1/2 M_D (v_{\max}^2 - v_{\min}^2)$.

743259

Fig. 6. Schematic of injection and compression cycle for major-radius compression in a tokamak.

743148

Fig. 7. $G/F_{\max}$ for compression clamping with $W_{\text{inj}} = W_G$ and isothermal electrons. The curves are nearly identical for all T_e in the range 2-7 keV. The "nonscattered" cases are for tangentially injected beams. In the "hold" cases, there is no decompression. S.C. $\equiv$ slow compression.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

J. Gosh #1