Current generation in tokamaks by phased injection of pellets

1984 Nucl. Fusion 24 378

(http://iopscience.iop.org/0029-5515/24/3/012)

4. CONCLUSIONS

The initially excited fast wave and the mode-converted ion Bernstein wave are measured near the ion-ion hybrid resonance layer ($\omega/\omega_{CH} = 0.8 \sim 1.0$) in a deuterium-hydrogen plasma. A magnetic probe inserted into the plasma measures the fast wave dispersion through the phase shift at several radial locations. The amplitude of the electric field of the incident fast wave is calculated from the magnetic field according to the cold-slab model with boundary conditions at antenna and walls. The amplitude is $1000\ \mathrm{V\cdot m^{-1}}$ at the location of the probes when the current flowing in the antenna is 130 A. The ion Bernstein wave dispersion is first measured by 2-mm microwave scattering at several wave-numbers ($k_\perp < 3.0\ \mathrm{cm^{-1}}$), the toroidal field being varied. The amplitude of the electric field of the mode-converted ion Bernstein wave is roughly estimated from the density fluctuation level [12]. The amplitude is $20\ \mathrm{V\cdot m^{-1}}$ at the location of the scattering volume. The amplitude of the electric field of the ion Bernstein wave at a toroidal angle of 90° away from the antenna is 2% of that of the incident fast wave at a toroidal angle of 4° away from the antenna. Both modes as measured experimentally agree with the theoretical wave dispersion obtained by a numerical solution of the hot-plasma dispersion equation.

REFERENCES

[1] Equipe TFR, in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 8th Int. Conf. Brussels, 1980), Vol.2, IAEA, Vienna (1981) 75.
[2] HWANG, D., BITTER, M., BUDNY, R., CAVALLO, A., CHRIEN, R., et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 9th Int. Conf. Baltimore, 1982), Vol.2, IAEA, Vienna (1983) 3.
[3] KIMURA, H., MATSUMOTO, H., ODAJIMA, K., KONOSHIMA, S., YAMAMOTO, T., et al., ibid., 113.
[4] AMANO, T., FUJITA, J., HAMADA, Y., ICHIMURA, M., KANEKO, O., et al., ibid., Vol.1, 219.
[5] JACQUINOT, J., McVEY, B.D., SCHARER, J.E., Phys. Rev. Lett. **39** (1977) 88.
[6] LEE, P., TAYLOR, R.J., PEEBLES, W.A., PARK, H., YU, C.X., et al., Phys. Rev. Lett. **49** (1982) 205.
[7] TFR Group, TRUC, A., GRESILLON, D., Nucl. Fusion **22** (1982) 1577.
[8] TOYAMA, H., IWAHASHI, A., KANEKO, H., KAWADA, Y., MAKISHIMA, K., et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 7th Int. Conf. Innsbruck, 1978), Vol.1, IAEA, Vienna (1979) 365.
[9] IDA, K., NAITO, M., SHINOHARA, S., MIYAMOTO, K., Nucl. Fusion **23** (1983) 1259.
[10] SCHARER, J.E., McVEY, B.D., MAU, T.K., Nucl. Fusion **17** (1977) 297.
[11] LAPIERRE, Y., Excitation et propagation de l'onde rapide dans un plasma non uniforme, Association Euratom CEA Report, EUR-CEA-FC-1043 (1980).
[12] ONO, M., Phys. Fluids **25** (1982) 990.

(Manuscript received 12 October 1983
Final manuscript received 18 January 1984)

CURRENT GENERATION IN TOKAMAKS BY PHASED INJECTION OF PELLETS

N.J. FISCH (Plasma Physics Laboratory, Princeton University, Princeton, New Jersey, United States of America)

ABSTRACT. By phasing the injection of frozen pellets into a tokamak plasma, it is possible to generate current. The current occurs when the electron flux to individual members of an array of pellets is asymmetric with respect to the magnetic field. The utility of this method for tokamak reactors, however, is unclear; the current, even though free in a pellet-fuelled reactor, may not be large enough to be worth the trouble. Uncertainty as to the utility of this method is, in part, due to uncertainty as to proper modelling of the one-pellet problem.

1. INTRODUCTION

There is a continuing search for the most efficient means of generating continuous toroidal current in a tokamak. The object of such means is to replace the conventional inductive means, the Ohmic coils, which can operate only in a pulsed mode. The drawbacks to the steady-state methods that have so far been suggested lie primarily in their large power requirements.

In general, to generate current, an asymmetry must be introduced into the toroidal geometry so that one toroidal direction is favoured over the other. To accomplish this, there are a limited number of external things that can be brought to bear on the tokamak, namely various particle beams or travelling waves.

Suggestions have included neutral beams [1], low-frequency waves that interact with thermal electrons [2] or with minority ions [3], high-frequency waves [4–6], reflection of plasma emission [7], bootstrap current [8] and a wave-enhanced bootstrap current [9].

In view of the considerable attention given to these many means of tampering with toroidal symmetry in order to provide current, and the fact that no means appears to be undeniably desirable, it is worth while to ponder whether other possibilities exist by means of the injection of solid pellets, such as frozen hydrogen, into the tokamak. This type of fuelling is something that in any case may be necessary, and, perhaps, a useful asymmetry might be achieved with less power.

The paper is organized as follows: Section 2 examines what current-drive effects might be possible with individual pellets and concludes that there probably are no useful effects to be had. Section 3 puts forth the new idea of the paper, that a properly phased array of pellets produces a promising current-drive effect. This current-drive effect is subject to concerns that are different from those in other current-drive methods. Section 4 examines how the pellets must be timed to maximize the current-drive effect. Also, deflection of the pellets is shown not to pose a serious problem. Section 5 treats the question of efficiency. Here, not input power, but input material, poses the important limit on the current. This limit threatens the utility of the technique. Section 6 speculates on the kinds of helpful, if unlikely, effects that must obtain if there is to be hope for generating substantial current. Section 7 summarizes our findings.

2. PELLET EFFECTS

Pellet fuelling may be useful for current generation merely because it may provide a particle source on axis that can drive the neoclassical bootstrap effect. Apart from this effect, it may be possible to inject pellets asymmetrically so as to generate current even in the absence of neoclassical effects. In this section, we summarize how current might be generated with a single pellet.

One obvious asymmetry is achieved through the tangential injection of pellets. The pellets have toroidal momentum which will be deposited in the plasma, but, unfortunately, the momentum is likely to be deposited on ions rather than electrons, resulting merely in plasma rotation rather than current generation. In this respect, the mechanism at play is similar to that used in current generation by neutral beams – except that neutral beams are much more energetic (faster than the majority ion thermal speed) and deposit their momentum on electrons. Tangential pellet injection would act like a very slow beam: energetically efficient to inject, but incapable of much current production.

An individual pellet can be asymmetric, i.e. it can favour one toroidal direction over the other, not only in its trajectory but in its material composition. For example, one side may be deuterium, the other side tritium, with the orientation maintained by a spin imparted to the pellet upon injection [10]. It is possible that some current may be produced by such methods because the ablation rate or the fusion rate is now asymmetric. Unfortunately, however, these currents are likely to be small. A more likely effect is parallel motion of the pellet itself, which we have noted is not particularly useful for current generation.

A third possibility with single pellets relies on a thermoelectric effect. Suppose that pellets are injected into the tokamak while means are provided to heat the plasma adjacent to the pellet, say to the right of each pellet, as sketched in Fig. 1. The means of heating could be any of the conventional methods of heating with particle beams or waves, so long as the heating is highly localized. From the heated region, hot electrons will be emitted which will travel away from the heated region along the magnetic field lines. These electrons travel symmetrically, until one group loses its momentum upon colliding with the pellet. Current is generated since the hot electrons travelling to the left lose their current immediately upon colliding with the pellet, while hot electrons emitted to the right carry current

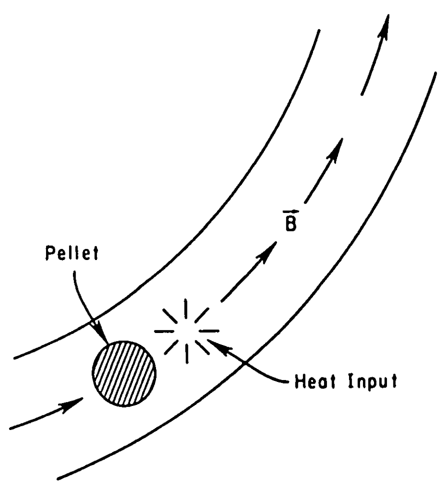

FIG. 1. Thermoelectric effect by plasma heating adjacent to pellets.

much longer, i.e. until they collide with the pellet after going the long way around at least once, or possibly with plasma ions, but in either case carrying current for far longer than those electrons that had collided with the pellet immediately. In the steady state, the circuit of current is completed by the diffusion (the short way around) of electrons from the pellet to the heated region, since the sharpest density gradients exist along this path.

This thermoelectric method of current generation, utilizing both pellets and a heat source, is not, unfortunately, substantially more efficient than other, more straightforward methods. In fact, it is, at best, probably somewhat less efficient as we shall now show. To calculate the efficiency, consider that power P_d is dissipated at a rate $\Delta W/\tau$, where ΔW is the incremental energy absorbed as heat in the plasma and τ is the time it takes thermal electrons to slow down by collisions with ions. We assume that electrons that are not promptly stopped by the pellet will slow down on ions rather than, at a later time, on pellets; this assumption is probably realistic since, given the helicity of the field lines, electrons would have to cover a large fraction of the magnetic surface before encountering the pellet, if they have not done so promptly.

Thus, we define that thermal electrons have energy

$$W = m_e v_{Te}^2/2 \tag{1}$$

and they absorb an additional energy

$$\Delta W = m_e v_{Te} \Delta v_{Te} \tag{2}$$

where Δv_{Te} is the increment in the electron thermal velocity upon the absorption of the supplementary energy. If density-n electrons absorb this energy, and half of these electrons promptly collide with the pellet, then the incremental current density carried due to the energy absorption is

$$J = ne\Delta v_{Te}/2 \tag{3}$$

This current lasts only as long as the electrons, which do not promptly collide with the pellet, can carry directed momentum – in other words, only as long as τ. Taking $\tau \cong 1/\nu^{e/i}$, where $\nu^{e/i}$ is the slowing-down rate of thermal electrons on ions, we can calculate the power density

$$P_d \equiv n\Delta W/\tau \tag{4}$$

necessary to sustain the current J. Using Eqs (2) and (3), we can write

$$\frac{J}{P_d} \cong \frac{e}{2m_e} \frac{1}{\nu^{e/i} v_{Te}} \tag{5}$$

where J/P_d is the efficiency parameter, unnormalized here, by which different non-Ohmic current generation schemes have been compared [4]. For example, for lower-hybrid-wave current drive, a similar calculation would give

$$\frac{J}{P_d} \cong \frac{e}{m_e} \frac{1}{\nu(v)v} \tag{6}$$

where $\nu(v) \sim 1/v^3$ for superthermal electrons of velocity v. From Eq.(6), it can be seen that the highest efficiencies are obtained when very fast rather than thermal electrons are pushed by the waves, and, by comparison with Eq.(5), it can be seen that the thermoelectric effect described corresponds roughly, in terms of efficiency, to pushing the thermal electrons, which are the least efficient current carriers.

In summary, the trouble with the thermoelectric effect is that the asymmetry in electron velocity distribution is achieved only at the rather large expense of heating the plasma. The expense of accelerating the pellet is, in principle, negligible, since the pellets travel so much slower than any of the plasma constituents. Note that achieving an asymmetry in the electron velocity distribution is essentially equivalent to achieving an imbalance in the electron flux to the pellet. After all, it is clear from momentum conservation that if an electron current is induced in one direction, a recoil must be felt on the pellet which provides this momentum. The pellet recoil motion is, as we have seen above, damped largely by ions and inconsequential in terms of current generation. There is a possibility, it turns out, of achieving an imbalance in the electron flux to the pellet without an external heat source, namely by injecting a phased array of pellets, which we now set out to describe.

3. PHASED PELLET INJECTION

Electrons impinging upon a pellet give up their energy in ablating and ionizing pellet atoms and in heating the resultant cloud of cold ions surrounding the pellet. These electrons also give up their momentum; for the purpose of describing a current generation effect, let us assume that the pellet is a perfect absorber of electron momentum, much as was assumed in the previous section in connection with a thermoelectric effect.

Consider that immediately to the right of a pellet immersed in a magnetic field pointing to the right, there is an influx of left-going thermal electrons impinging on the pellet, but there is a scarcity of right-going thermal electrons, since such electrons are shadowed by the pellet. Similarly, to the left of the pellet, right-going hot electrons can be found, but not left-going electrons. A second pellet situated to the right of the first pellet would experience electrons impinging from the right, but not from the left. This arrangement, of course, is entirely symmetric, as the exact opposite effect is experienced by the first pellet. Now, however, suppose that both pellets are moving forward, perpendicular to the magnetic field, as depicted in Fig.2. If the second pellet lags the first one in the forward direction, then it may be shadowed by, while not shadowing, the first pellet. This is no longer symmetric, since the first, unshadowed pellet absorbs electron momentum from both directions, while the second, partially shadowed pellet absorbs momentum from only one direction.

Evidently, the optimum arrangement is the successive injection of pellets into a tokamak, spaced a distance (say measured to the right) Δz in the toroidal direction and at time intervals Δt, such that $\Delta z / \Delta t \cong v_{Te}$. In such an arrangement, each pellet shields from thermal electrons its neighbour to the right that arrives later than it at each flux surface in the tokamak. Each pellet is thus bombarded preferentially by electrons arriving from the right, and the selective absorption of momentum from right-going electrons creates the current.

Note that when left-going electrons are stopped by a pellet, there is a shadow region (or left-going-electron deficiency) that, in effect, travels around the tokamak and may affect successive pellets. This effect, however, is weak, since the shadow region may have to travel many times around the torus before encountering succeeding pellets. This is, in part, due to the helicity of the field lines as in the thermoelectric effect above, and, in part, due to the movement of the pellets which can make a 'collision' of pellet and shadow less likely.

It may be recognized that the effect described here is similar to traffic regulation by phased stop lights on city streets. Such lights can be phased to favour, for example, cars travelling at reasonable speed northward, while impeding cars travelling at reasonable speed southward, or, for that matter, northward at any but the favoured speed. If the favoured northward speed is indeed reasonable, i.e. many cars can travel at it (in a plasma it would be the thermal velocity), then a net northward car current tends to develop.

4. TIMING AND SPACING

Having described the effect of current generation by phased pellet injection, we shall now identify some of the issues that are relevant to the usefulness of the scheme in tokamaks. First, we must be sure that the pellets can be injected such that, indeed, they asymmetrically shadow each other. Here we direct ourselves to the problem that the shadow region of one pellet is localized in space and time, and a succeeding pellet must find itself substantially in this shadow at the right moment.

Ignoring for the moment the issue of timing, we consider the necessary (but not sufficient) condition for effective shadowing

$$\Delta z < L_s \tag{7}$$

where Δz is the pellet spacing and L_s is the length over which each pellet casts its shadow with respect to thermal electrons. Several effects come into play to limit L_s. One is the distance L_D over which electrons diffuse in the perpendicular (to magnetic field B) direction, of the order of the pellet radius, rendering any shadow too diffuse to be of use. If we assume that the spatial diffusion coefficient in the perpendicular direction is given approximately by $D_\perp \cong \nu_0 a_e^2$, where a_e is the electron gyroradius and ν_0 is the 90° scattering rate of thermal electrons, then we can write

$$L_D \cong \frac{d^2 v_{Te}}{D_\perp} \cong \left(\frac{d}{a_e}\right)^2 \frac{v_{Te}}{\nu_0} \tag{8}$$

where d is the pellet diameter and v_{Te} is the electron thermal velocity, the velocity with which we assume the electrons travel in the parallel direction while diffusing spatially in the perpendicular direction.

Apart from the filling in of the shadow region at the distance L_D through spatial diffusion, there is also the possibility of collisional backscattering of oppositely

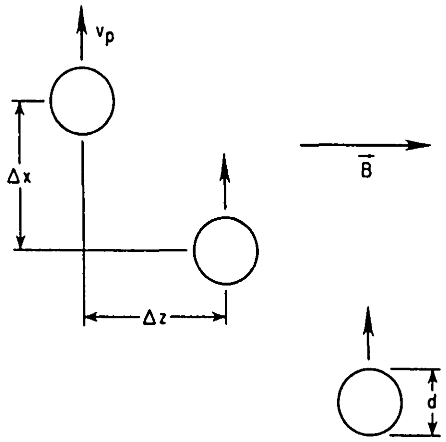

FIG.2. Phased pellet injection with $\Delta x = \Delta z\ v_{Te}/v_p$.

travelling electrons, tending to isotropize the electron velocity distribution. This effect occurs at a distance

$$L_{\parallel} \cong v_{Te}/\nu_0 \tag{9}$$

which is a result, essentially, of our definition of ν_0. For $d/a_e \gg 1$, which we expect for relevant tokamak parameters, it follows that $L_{\parallel}$ is much smaller than L_D and represents the important limitation on L_s.

Even if the shadow region is long enough, the pellets must be carefully timed. To involve the maximum number of electrons in the shadow region, we assume that pellets are fired Δt time-delayed and Δz space-delayed such that $\Delta z/\Delta t \cong v_{Te}$. Suppose that the pellets have diameter d and velocity v_p perpendicular to the magnetic field lines, so that on each field line a pellet blocks electrons, or in effect tarries, for a time

$$\delta t \equiv d/v_p \tag{10}$$

This situation is depicted in Fig.3. A substantial number of thermal electrons will be involved in the shadow only if

$$\Delta v \equiv v_{max} - v_{min} \cong v_{Te} \tag{11}$$

where v_{max} and v_{min} are, respectively, the maximum and minimum velocities of electrons whose unimpeded trajectories would intersect the trajectories of both a pellet and its neighbour, i.e.

$$v_{max} \equiv \frac{\Delta z}{\Delta t - \delta t} \tag{12a}$$

$$v_{min} \equiv \frac{\Delta z}{\Delta t + \delta t} \tag{12b}$$

so that $\delta t/\Delta t$ must not be too small if the approximate equality in Eq.(11) is to be satisfied.

Note that $\Delta v \approx v_{Te}$, per Eq.(11), means that any effect which scatters or slows down an electron by an amount less than $\Delta v \approx v_{Te}$ has little consequence. This means also that using the 90° collision time in Eq.(9) is sufficient. If Δv were much smaller than v_{Te}, however, then deflections of order Δv, occurring much sooner than those of order v_{Te}, could upset the timing with which the shadows reach succeeding pellets and could render the shadow too incoherent to be of use.

If the scheme for current generation should work, there will be a considerable imbalance in momentum flux to the pellet. This will deflect the pellet in the parallel direction and it is worth while to inquire whether this deflection is so great that pellet penetration would be affected. Accordingly, consider a pellet, for simplicity cubic with side d, so that we can write the force equation

$$\rho_p d^3 \frac{d^2}{dt^2} z_p = \rho_e v_{Te}^2 d^2 \tag{13}$$

where z_p is the deflection of the pellet along the field line, and where ρ_p is the pellet mass density and ρ_e is the mass density of the impinging electrons, which are assumed to hit the pellet from one side only. The crucial ratio is z_{po}/R, where R is the major radius and z_{po} is the deflection of the pellet in the time it takes to penetrate a minor radius, r. If this ratio is much greater than unity, the pellet is deflected so much that it avoids the tokamak altogether. Assuming injection velocity v_p, the pellet should penetrate a minor radius in a time r/v_p. Thus, assuming d constant in time, we can solve Eq.(13) and get

$$\frac{z_{po}}{R} \cong \left(\frac{n_e}{n_p}\right)\left(\frac{v_{Ti}^2}{v_p^2}\right)\left(\frac{r}{d}\right)\left(\frac{r}{R}\right) \ll 1 \tag{14}$$

where $T_e \cong T_i$ was assumed so as to allow writing the ratio in this form. The inequality obtains for typical parameters, $n_e = 10^{14}\ cm^{-3}$, $T = 10$ keV, $v_p = 10^4\ m\cdot s^{-1}$, $d = 1$ mm, so that $n_e/n_p \sim 10^{-8}$, $v_{Ti}/v_p \sim 50$, $r/d \sim 10^3$, rendering $z_{po}/R \sim 10^{-2}$. A more precise calculation, including the time dependency of the pellet mass, would give a somewhat larger ratio z_{po}/R. It does appear, however, that deflection, should the effect occur, will not pose a problem.

5. MATERIAL LIMITS

The power necessary to bring the pellets into the reactor is small compared with the power necessary to heat the injected matter. This is because even the highest contemplated injection velocities are still small compared with an ion thermal velocity, e.g. for deuterium, $v_{Ti} \cong 5 \times 10^5\ T_{10}^{1/2}\ m \cdot s^{-1}$. Contemplated injection velocities are perhaps $v_p \sim 10^4\ m \cdot s^{-1}$ [11], although Mayer [12] calculates, as necessary for INTOR, $v_p \sim 5 \times 10^4\ m \cdot s^{-1}$. In any event, for injection into a 10 keV tokamak, the energy required to heat the pellets to the ambient temperature is about 100 to 2500 times the injection energy. Although the power to heat the pellets is relatively cheap since it is the plasma heat itself, this source of heat does have limitations; one upper limit is the ignition condition, i.e. for the tokamak to remain ignited in the absence of auxiliary heat sources this power must be less than the alpha-particle heating power from fusion reactions. In effect, this limits how much matter may be injected, which, in turn, limits how much current can be generated.

To calculate how much matter can be injected, we write the alpha-particle power density, which is roughly 20% of the fusion power density, as

$$P_d \cong 1.5 \times 10^5\ n_{14}^2 (3T_{10} - 2)\ W \cdot m^{-3} \tag{15}$$

which is a fairly good approximation in the relevant range $1 < T_{10} < 3$, and where n_{14} is the density

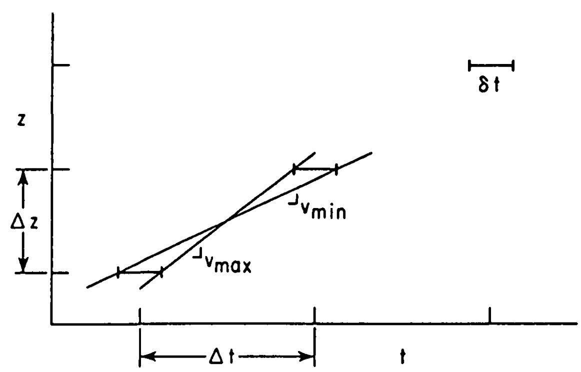

FIG.3. Electron shadowing of adjacent pellets.

normalized to $10^{14}\ cm^{-3}$ and T_{10} is the temperature normalized to 10 keV. If we write the rate at which pellet atoms are injected into the tokamak as $\dot{N}_p$, then the heating power necessary to bring these atoms to temperature T is

$$\dot{P}_h \equiv 3T\dot{N}_p \tag{16}$$

Using now an expression for the volume

$$V \cong 2 \times 10^3\ R_{10} a_3^2 \quad m^3 \tag{17}$$

where R_{10} and a_3 are, respectively, the major radius in units of 10 m and the minor radius in units of 3 m, we can write the inequality $P_h < P_\alpha$ as

$$\dot{N}_p < P_\alpha/3TV \cong 3.2 \times 10^{22}\ n_{14}^2 (3T_{10} - 2) R_{10} a_3^2/T_{10} \tag{18}$$

where the units are atoms per second.

Alternatively, $\dot{N}_p$ could be found from other, related arguments, making use of semi-empirical formulas for the particle confinement time or the energy confinement time. These approaches are equally valid at this level of sophistication and the expressions obtained for $\dot{N}_p$ will not be much different. Of course, there is also a lower bound that might be put on $\dot{N}_p$ in order to ensure that particles lost through transport or fusion reactions are replenished.

Given a limit to the amount of material that may be injected, how much current can be generated? Assume that each plasma electron impinging on the pellet gives up both its energy and momentum to the pellet. Assume that in the process of slowing down either on the pellet itself or the surrounding cold, ablated plasma, an electron ablates, ionizes and heats M pellet atoms. A more precise definition of M will become apparent later, but it is essentially the number of pellet atoms required to stop an electron in a sufficiently localized manner that the momentum loss can be exploited.

An electron with velocity v impinging on a pellet produces a net current imbalance of

$$I(t) \cong ev \cdot \exp(-\nu t) \tag{19}$$

in its being stopped by the pellet at time $t = 0$. Here $\nu(v)$ is the parallel slowing-down rate of the electron.

The time dependence of I arises from the fact that the imbalance in current is large at impact, but disappears on a time-scale in which the electron in any event would have slowed down. This argument follows that given in Ref.[5]. The current density due to density-n electrons being stopped is

$$J = \frac{ev\, dn/dt}{\nu} = \frac{ev}{\nu MV} \dot{N}_p \tag{20}$$

where dn/dt is the rate at which electrons give up their momentum and where we used $n = N_p/MV$. For $v \cong v_{Te}$, we can recast J as

$$J \cong 3 \times 10^4\, n_{14} T_{10} (3T_{10} - 2)/M \quad A \cdot m^{-2} \tag{21a}$$

giving rise to total current

$$I \cong a_3^2 n_{14} T_{10} (3T_{10} - 2)/M \quad MA \tag{21b}$$

Note that Eqs (21) hold for the case where the electrons that are selectively stopped have velocities very nearly equal to the thermal velocity. Actually, it is probably best to phase the pellets such that slightly faster electrons are selectively stopped; the principle is to try to stop as many of the fastest electrons as possible, since it may be difficult to phase the pellets such that all electrons going one way are selectively stopped. Since the distribution of electrons in parallel velocity space is Maxwellian, the current is proportional to $v_\parallel$ and the collision time is proportional to $v_\parallel^3$, it follows that the most current will be generated around the maximum of the function k, where

$$k(v_\parallel) = v_\parallel^4 \exp(-v_\parallel^2/2) \tag{22}$$

which occurs at $v_\parallel = 2$. Note that electrons going at $2v_{Te}$ that are selectively stopped produce about six times the current as those travelling at v_{Te}, the value used for Eqs (21). Given the uncertainties, however, in the calculation here, especially in calculating M, it is probably not worth while to be painstaking here in maximizing k.

The amount of current density required in a tokamak to ensure $\beta_p = R/a$ is

$$J_{req} = 4\left(\frac{nT}{\mu_0 aR}\right)^{1/2} \cong 3 \times 10^5 \left(\frac{n_{14}T_{10}}{a_3 R_{10}}\right)^{1/2} \quad A \cdot m^{-2} \tag{23a}$$

or a total required current

$$I_{req} = \pi a^2 J_{req} \cong 10^7 \left(\frac{n_{14} T_{10} a_3^2}{R_{10}}\right) \quad A \tag{23b}$$

The fraction of the required current that can be provided by phased pellet injection is

$$\frac{I}{I_{req}} \cong \frac{1}{10M} (n_{14} T_{10} a_3 R_{10})^{1/2} (3T_{10} - 2) \tag{24}$$

which can be substantial only for hotter ($T_{10} \gtrsim 2$) tokamaks and if M is not very much larger than one. Unfortunately, it is very likely that M is much larger than one, which would render this method of academic interest only in terms of first-generation reactor designs, although there are some caveats to this statement, as discussed in the next section.

6. POSSIBILITIES FOR EFFICIENT STOPPING OF ELECTRONS

A number of models [11–23] have been advanced to describe the ablation of pellets in contact with hot plasmas. The primary concern of these authors has been the problem of pellet fuelling, i.e. how far the pellets can penetrate into the plasma. Although our concern here is intimately related to the problem of pellet lifetime, it is not quite the same concern dealt with in the literature. What we wish to know here is what we call M, the number of atoms that are ablated per each incident electron that coherently loses its momentum. Thus, the longer the pellet lifetime, the larger, in general, will be M – but not always. For example, ablation may be retarded by magnetic screening [13, 15, 21], which reduces the number of incident electrons; however, this affects only the rate at which electrons are slowed down and not necessarily the number of electrons slowed down per ablated atom. For the purposes here, it does not matter so much if the pellet is quickly vaporized, so long as in the process many electrons are stopped.

Numerical and analytical studies of the ablation problem indicate that ablated atoms absorb only about 36 eV, primarily in the process of ionization, and then form a cold, at least partially ionized, cloud of material that shorts out any electrostatic shielding potential. In this description, we would find $M \cong M_1$, where

$$M_1 \cong \frac{10^4 T_{10}}{(36 + 3T_a)} \sim 300 \tag{25}$$

where T_a is the ablatant temperature in eV. In Gralnick's analysis [14], T_a was found to be around 30 eV, but Parks [16, 18–20] and Lengyel [22] showed it to be closer to 1 eV. In any event, an incident electron deposits its energy in the cloud near the pellet, in the process of which its momentum is lost to the pellet and M_1 electrons share its energy. Such a large number for M would render negligible the current-drive effects we seek, as per Eq.(24).

For current drive by phased pellets to be practical, a much smaller value of M must be achieved. Our present theoretical understanding, which is consistent with present experimental data, is that smaller M is not likely. If smaller M were possible, it would be because of unexpected, helpful effects in a reactor regime. Two speculative possibilities in this category are collisionless processes and electrostatic shielding.

Collisionless processes could degrade the energy of incident electrons. What would be relied on here would be a collisionless instability fed by the asymmetry in the electron distribution. The asymmetry arises because, in the shadow of the pellet, electrons are primarily moving towards it. In a strong magnetic field, one might hope for an instability akin to that explored by Kadomtsev and Pogutse [24].

Electrostatic shielding of the pellet can be significant only if a very large ablation cloud develops around the pellet. To be precise, say that the electron current J to a pellet at potential ϕ is balanced by conduction through an ablation layer of length L, density n, and conductivity σ, i.e.

$$J = en_0 v_{Te} = \sigma\phi/L \tag{26}$$

from which we can find the relevant ratio

$$\frac{e\phi}{kT} = \left(\frac{n_0}{n}\right)\frac{L}{\tau_e v_{Te}} \cong 10^2 \frac{L_1 n_{14}}{T_{10}^{1/2} T_L^{3/2}} \tag{27}$$

where τ_e is the collision time in the ablation layer, L_1 is the length of the layer in metres, and T_L is the temperature of this layer in eV. For $L \sim d$, or $L_1 \sim 10^{-3}$, it is clear that shielding effects are negligible since $e\phi/kT \ll 1$. This is roughly the regime dealt with in the literature. For $T_L \lesssim 30$, however, it appears that $e\phi/kT$ can become appreciable with $L_1 \sim 1$. This would require large, slowly moving pellets. Deep penetration of the pellets, however, may then be difficult to achieve simultaneously.

If significant electrostatic shielding were achieved, then the operation of the current-drive mechanism would proceed somewhat differently, since electrons would be reflected rather than absorbed. Note that if the pellets were infinitely thin, perfectly specular reflectors, no asymmetries can be produced. In general, however, both bright spots and shadow regions appear. Current could then be created by placing pellets either in each other's shadows as before or so as to intersect each other's bright spots, an arrangement which is probably without a usual counterpart in traffic flow.

7. SUMMARY AND CONCLUSIONS

We have put forth the idea that a phased array of injected pellets can drive an electric current in a tokamak. The usually important limitation in non-Ohmic current drive is the power dissipation, which is not important here since the injection power is negligible. However, there is a limit on the amount of mass that may be injected into the tokamak, which limits the amount of current that can be generated.

Although phased pellet injection does appear to represent new possibilities for current drive, it must be said that, based on previous studies of the one-pellet problem, the size of the current-drive effect is probably too small to be of great importance. This is because it takes, in effect, many pellet atoms to stop an electron. On the other hand, if the ablation cloud becomes sufficiently developed, it may be speculated that helpful effects come into play, such as the electrostatic shielding of the pellet or the collisionless slowing down of impinging energetic electrons. If so, an inexpensive, steady-state current driver may not be out of the question. It is hoped that this tantalizing possibility may stimulate new ideas for ways in which the stopping power of the pellets might be enhanced.

It should also be pointed out that even if the scientific problems raised here are overcome, there may still be other problems, for example regarding the depth of pellet penetration. Also, there remain severe technological problems with regard to the timing and spacing of these pellets. Very precise control of both the injection velocity and injection timing will be required so as to challenge the state of the art in pellet injection technology.

ACKNOWLEDGEMENTS

The author appreciates discussions with Dr. A. Boozer, Dr. P. Parks, Dr. G. Schmidt, and Dr. T. Stix. This work was supported by the United States Department of Energy, Contract No. DE-AC02-76-CHO-3073.

REFERENCES

[1] OHKAWA, T., Nucl. Fusion **10** (1970) 185.
[2] WORT, D.J.H., Plasma Phys. **13** (1971) 258.
[3] FISCH, N.J., Nucl. Fusion **21** (1981) 15.
[4] FISCH, N.J., Phys. Rev. Lett. **41** (1978) 873.
[5] FISCH, N.J., BOOZER, A.H., Phys. Rev. Lett. **45** (1980) 720.
[6] FISCH, N.J., Phys. Rev. A. **24** (1981) 3245.
[7] DAWSON, J.M., KAW, P.K., Phys. Rev. Lett. **48** (1982) 1730.
[8] BICKERTON, R.J., CONNOR, J.W., TAYLOR, J.B., Nature (London) **229** (1971) 110.
[9] OHKAWA, T., General Atomic Rep. GA-A13847 (1976).
[10] STIX, T.H. (private communication).
[11] MILORA, S.L., J. Fusion Energy **1** (1981) 15.
[12] MAYER, F.J., Phys. Rev. Lett. **48** (1982) 1400.
[13] ROSE, D.J., Culham Laboratory, Technology Division, Memorandum No.82 (1968).
[14] GRALNICK, S.L., Nucl. Fusion **13** (1973) 703.
[15] CHANG, C.T., Nucl. Fusion **15** (1975) 595.
[16] PARKS, P.B., TURNBULL, R.J., FOSTER, C.A., Nucl. Fusion **17** (1977) 539.
[17] MILORA, S.L., FOSTER, C.A., IEEE Trans. Plasma Sci. **PS-6** (1978) 578.
[18] PARKS, P.B., TURNBULL, R.J., Phys. Fluids **21** (1978) 1735.
[19] PARKS, P.B., Phys. Fluids **22** (1979) 1890.
[20] PARKS, P.B., Model of an Ablating Solid Hydrogen Pellet in a Plasma, Garland Publishing Inc., New York (1979).
[21] PARKS, P.B., Nucl. Fusion **20** (1980) 311.
[22] LENGYEL, L.L., Phys. Fluids **21** (1978) 1945.
[23] FELBER, F.S., MILLER, P.H., PARKS, P.B., PRATER, R., VASLOW, D.F., Nucl. Fusion **19** (1979) 1061.
[24] KADOMTSEV, B.B., POGUTSE, O.P., Zh. Ehksp. Teor. Fiz. **26** (1968) 1146; Sov. Phys. – JETP **26** (1968) 1146.

(Manuscript received 20 June 1983,
Final manuscript received 20 October 1983)