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N.J. Fisch

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CURRENT GENERATION BY PHASED INJECTION OF PELLETS

Nathaniel J. Fisch

Plasma Physics Laboratory, Princeton University
P.O. Box 451, 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-fueled 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 modeling of the one-pellet problem.

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I. 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 favored 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 traveling waves. These have been extensively studied, and to some degree, as mentioned, have been found wanting. The first ideas involved neutral beams¹ or low-frequency waves² that would deposit their momentum primarily to low-energy electrons. The efficiency of these schemes is limited by the slowest electrons that can be pushed, since the slower the electron the larger its ratio of momentum to energy. Since, in both schemes deposition of the external power into the ions must be avoided, it turns out that momentum must be absorbed by electrons traveling at least several times the ion thermal speed. A similar efficiency limit arises in the case of current-drive by minority-species heating.³

In all the above methods, currents are induced in the bulk of the electron velocity distribution, that is, currents are carried by thermal electrons. An alternative is to induce current in the fast, superthermal electrons, which can carry current more effortlessly because they collide so infrequently.⁴ Momentum could be deposited directly into these electrons through the damping of high-phase-velocity waves, such as lower-hybrid waves. Alternatively, an asymmetry in the collisionality of superthermal

electrons could be induced by electron-cyclotron waves.⁵ The efficiency of these s-waves increases with increasing velocity, meaning reduced collisionality of the resonant electrons, until a relativistic effect eventually limits attainable efficiencies.⁶

Apart from what might be called active current generation techniques, there are also the passive techniques. Something originally discounted by some authors,¹ but given new life by others,⁷ is the possibility of asymmetrically reflecting radiation back into the plasma. There is also, of course, the bootstrap current, arising from neoclassical effects, which some authors have suggested might naturally provide toroidal current at least off the magnetic axis.⁸ It has also been suggested that this neoclassical effect could be augmented by asymmetrically injecting rf waves into the tokamak.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 worthwhile to ponder whether other possibilities exist by means of the injection of solid pellets, such as frozen hydrogen, into the tokamak. This type of fueling is something that in any case may be necessary, and, perhaps, a useful asymmetry might be achieved with less power.

II. PELLET EFFECTS

Pellet fueling 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.

One obvious asymmetry is achieved through the tangential injection of

pellets, although this does not appear to be a useful means of current generation. 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 to 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, that is it can favor 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 traveling to the left lose their current immediately upon colliding with the pellet; while hot electrons emitted to the right carry current 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

$$W = m_e v_{Te}^2 / 2 \quad (1)$$

and they absorb an additional energy

$$\Delta W = m_e v_{Te} \Delta v_{Te} \quad , \quad (2)$$

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 into the pellet, then the incremental current density carried due to the energy absorption is

$$J = ne\Delta v_{Te}/2 \quad . \quad (3)$$

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 $\tau = 1/\nu^{e/i}$, where $\nu^{e/i}$ is the slowing down rate of thermal electrons on ions, we can calculate the power density

$$P_d \equiv n\Delta W/\tau \quad (4)$$

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

$$\frac{J}{P_d} = \frac{e}{2m_e} \frac{1}{\nu^{e/i} v_{Te}} \quad , \quad (5)$$

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

$$\frac{J}{P_d} = \frac{e}{m_e} \frac{1}{\nu(v)v} \quad , \quad (6)$$

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 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, and perhaps it is worthwhile describing how this might operate.

III. 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 purposes 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 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 $\Delta z/\Delta t = v_{Te}$. In such an arrangement, each pellet shields from thermal electrons its neighbor to the right that arrives later than it to 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 favor, for example, cars traveling at a reasonable speed northward, while impeding cars traveling at reasonable speeds southward, or, for that matter, northward at any but the favored speed. If the favored northward speed is indeed reasonable, that is, many cars can travel at it - in a plasma it would be the thermal velocity - then a net northward car-current tends to develop.

IV. 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

$$\Delta z < L_s, \quad (7)$$

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 a distance 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 $D_{\perp} = v_0 a_e^2$, where a_e is the electron gyroradius and v_0 is the 90° scattering rate of thermal electrons, then we can write

$$L_D = \frac{d^2 v_{Te}}{D_{\perp}} = \left(\frac{d}{a_e} \right)^2 \frac{v_{Te}}{v_0} \quad , \quad (8)$$

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 in distance L_D through spatial diffusion, there is also the possibility of collisional backscattering of oppositely traveling electrons, tending to isotropize the electron velocity distribution. This effect occurs in a distance

$$L_{\parallel} = v_{Te} / v_0 \quad , \quad (9)$$

which is a result, essentially, of our definition of v_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 $\Delta z / \Delta t = v_{Te}$. 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

$$\delta t \equiv d/v_p \quad . \quad (10)$$

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

$$\Delta v \equiv v_{\max} - v_{\min} \approx v_{Te} \quad , \quad (11)$$

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 neighbor, i.e.,

$$v_{\max} \equiv \frac{\Delta z}{\Delta t - \delta t} \quad (12a)$$

$$v_{\min} \equiv \frac{\Delta z}{\Delta t + \delta t} \quad , \quad (12b)$$

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

Note that $\Delta v \sim v_{Te}$, per Eq. (11), means that any effect which scatters or slows down an electron an amount less than $\Delta v \sim v_{Te}$ has little effect. 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 worthwhile 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

$$\rho_p d^3 \frac{d^2}{dt^2} z_p = \rho_e v_{Te}^2 d^2, \quad (13)$$

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 where 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

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

where $T_e = T_i$ was assumed to write the ratio in this form. The inequality obtains for typical parameters, $n_e = 10^{14}/\text{cc}$, $T = 10$ keV, $v_p = 10^4$ m/s, $d = 1$ 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.

V. MATERIAL LIMITS

The power necessary to bring the pellets into the reactor is small compared to the power necessary to heat the injected matter. This is because even the highest contemplated injection velocities (perhaps $v_p \sim 10^4$ m/s) are still small compared to an ion thermal velocity, e.g., for deuterium $v_{Ti} \approx 5 \times 10^5 T_{10}^{1/2}$ m/s. Thus, for injection into a 10 keV tokamak, the energy required to heat the pellets to the ambient temperature is about 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 power 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 α -particle power density, which is roughly 20% of the fusion power density, as

$$P_d \approx 1.5 \times 10^5 n_{14}^2 (3T_{10} - 2) \text{ W/m}^3, \quad (15)$$

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

$$P_h \equiv 3T\dot{N}_p. \quad (16)$$

Using now an expression for the volume

$$V \approx 2 \times 10^3 R_{10} a_3^2 \text{ m}^3, \quad (17)$$

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

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

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 a lower bound too that might be put on $\dot{N}_p$ in order to assure 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

$$I(t) = e v e^{-vt} \quad , \quad (19)$$

in its being stopped by the pellet at time $t = 0$. Here $v(v)$ 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

$$J = \frac{e v \, dn/dt}{v} = \frac{e v}{v M v} \dot{N}_D \quad (20)$$

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

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

giving rise to total current

$$I = a_3^2 \, n_{14} \, T_{10} (3T_{10} - 2)/M \, \text{MA} \quad . \quad (21b)$$

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 proportional to v_1 and the collision time proportional to v_1^3 , it follows that the most current will be generated around the maximum of the function k , where

$$k(v_1) = v_1^4 e^{-v_1^2/2} \quad , \quad (22)$$

which occurs at $v_1 = 2$. Note that electrons going at $2v_{Te}$ that are selectively stopped produce about six times the current as those traveling 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 worthwhile to be painstaking here in maximizing k .

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

$$J_{req} = 4 \left(\frac{nT}{u_o a R} \right)^{1/2} \approx 3 \times 10^5 \left(\frac{n_{14} T_{10}}{a_3 R_{10}} \right)^{1/2} \text{ Amps/m}^2 \quad (23a)$$

or a total required current

$$I_{req} = \pi a^2 J_{req} \approx 10^7 \left(\frac{n_{14} T_{10} a_3^2}{R_{10}} \right) \text{ Amps} \quad . \quad (23b)$$

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

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

which can be substantial only for hotter ($T_{10} > 2$) 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.

VI. POSSIBILITIES FOR EFFICIENT STOPPING OF ELECTRONS

A number of models¹¹⁻²¹ 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 fueling - 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,^{11,13,19} 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 $M \approx M_1$, where

$$M_1 \approx \frac{10^4 T_{10}}{(36 + 3T_a)} \sim 300, \quad (25)$$

where T_a is the ablatant temperature in eV. In Gralnick's analysis¹² T_a was

found to be around 30 eV, but Parks^{14, 16-18} and Lengyel²⁰ 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, and we look now to see what other effects could possibly ameliorate this situation. We will look for effects that may be present in the later stages of the ablation problem - and hopefully relevant for larger pellets. Although we do not explore them in detail, we point now to effects connected with electrostatic shielding and collisionless instabilities as possible candidates for decreasing M .

If the electrostatic potential were not shorted out by cold, ablated electrons, then the heat flux to the pellet would be much smaller, in fact by a factor $(m_e/m_i)^{1/2}$, since the ions would have to carry the heat. In effect, M would be reduced to

$$M_s = M_1 (m_e/m_i)^{1/2} = 5 \quad , \quad (26)$$

which would be very fortunate both for pellet penetration and current generation. However, in contrast to the case of cold probe theory, where the probe does not emit electrons, potential shielding is not expected to happen here, where many electrons are emitted. Nonetheless, it is worthwhile to inquire whether perhaps at an advanced state of the ablation, such effects can become relevant.

The effect of electron emission on electrostatic shielding has been considered in contexts other than the pellet problem, including, for example, heat containment in material plugged cusps.²² In that problem, it was shown that while electrostatic shielding occurs in the absence of electron emission,

even a small number of secondary electrons emitted (less than one per incident electron) destroys the shielding. The model employed for that problem does not however, directly apply to the pellet problem, in particular, in that the cold electrons in the ablation cloud were assumed to be collisionless (long-mean-free-path limit), and in that electrons, but not ions, are produced.

The production of secondary, or ablated, electrons is also thought to be important in preventing electrostatic shielding in the pellet problem. Here both ions and electrons are prodigiously produced by the incident heat flux. The ablation region here, in contrast to the material plug region, is found to be highly collisional, but conducting, so that while cold electrons cannot freely expand to short out the electrostatic potential, the finite conductivity in this region allows only a small potential to develop. This small potential is properly ignored in numerical studies of the ablation problem; however, if the ablation region becomes large enough, even a smaller field acting over it implies a large potential. Eventually, if enough material is ablated from a slowly enough moving pellet, the return or cancelling current will have to pass through a large, cool ablation region requiring large potentials. 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 , that is

$$J = en v_{Te} = \sigma \phi / L \quad , \quad (27)$$

from which we can find the relevant ratio

$$\frac{e\phi}{kT} = \left(\frac{n_0}{n}\right) \frac{L}{\tau_e v_{Te}} = 10^2 \frac{L_1 n_{14}}{T_{10}^{1/2} T_L^{3/2}} \quad , \quad (28)$$

where τ_e is the collision time in the ablation layer, L_1 is the length of the layer in meters, 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 $T_L \gtrsim 30$, however, it appears that $e\phi/kT$ can become appreciable with $L_1 \sim 1$. If the pellets are large and move slowly through the plasma, and if the ablation cloud can be treated as one-dimensional, then it appears too that there easily would be enough matter in a single pellet and the pellet will remain in place long enough to populate a cloud extending on the order of a meter, at which point shielding effects can be important.

A large electrostatic potential does more than shield the pellet; it can change the operation of the current generation mechanism. Suppose, for example, that pellets were perfect reflectors of electrons, something that would be approached in the event of such large potentials. We may then no longer phase the pellets quite as we would traffic lights. If the pellets were infinitely thin and perfect specular reflectors, then they do nothing, i.e., if the electrons are homogeneously distributed in the toroidal direction, they remain so, no shadows are formed, and no current-drive effects are possible. However, if the pellets have finite size or if reflection is not perfect or immediate (there may be a time-delay), then inhomogeneities in the toroidal direction are formed - in particular, there may be both bright spots and shadow regions. At the bright spots there is an excess of electrons traveling in one direction due to the additive effects of electrons reflected and electrons unaffected. There is now some choice in the phasing. Pellets could be placed, as before, in each other's shadows, as traffic lights are phased. Additionally, however, pellets could be phased so as to intersect each other's bright spots, which is probably an arrangement without a usual

counterpart in traffic flow. In either case, the spatial inhomogeneities are exploited to produce current. Which case to be preferred would depend on such issues as timing and ablation (pellets placed in bright spots may ablate more than those placed in shadows), but it is hardly worthwhile now to expand further on these possibilities in view of the conjectural nature of the present discussion.

In addition to electrostatic shielding, there are collisionless processes that provide hope for a decreased M . The hope is that these processes could degrade the energy of incident electrons, at least in the later stages of the ablation. At present, studies on pellet ablation assume that incident electrons pass through the ablation cloud relatively unimpeded, losing energy to the cloud only quite near the pellet. This is because the Coulomb cross section of the energetic incident electrons is quite small. In a strong magnetic field, however, a collisionless instability of the type explored by Kadomtsev and Pogutse²³ might be possible.

Consider that immediately to the left of the pellet there are thermal electrons moving to the right into the pellet, but thermal electrons moving to the left are absent, having been stopped by the pellet. Thus, there is an asymmetry in the electron distribution function. The electrons moving to the right constitute a broad tail against a background of dense, cold plasma. It is possible that this distribution is monotonically decreasing as a function of speed (it is not quite a beam-plasma problem), which would render it stable in the absence of a magnetic field. In the presence of a strong magnetic field, however, such as occurs in tokamaks, this distribution is unstable to waves which cyclotron resonate with tail electrons, tending to slow them down and to isotropize them. In a similar manner, runaway distributions in tokamaks are also unstable to such waves.

Should such waves become unstable, the ablation cloud may absorb the incident energy at a much quicker rate, tending to decrease M and shield the pellet. Alternatively, if such waves are convectively unstable, it may be desirable to excite them in the plasma in the expectation that the instability will amplify them. We limit ourselves here, however, to what amounts to no more than mere speculation as to the existence of these waves, since it is a separate and rather difficult exercise to analyze the stability of the already complicated hydrodynamic solutions to the ablation problem. What is clear, however, is that at some point in the ablation process such instabilities are likely to arise, although perhaps too slowly to be important here. If, though, the instabilities are or can be made important, then there is the opportunity to reduce M dramatically, although (neglecting ions) probably not to less than about unity. Unless energy is radiated away, at $M = 1$ the ablated products have themselves become thermal particles, at once isotropizing the distribution function, which quenches the instability, and themselves impinging on the pellet.

VII. 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 nonohmic 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 remain 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, such as to challenge the state of the art in pellet injection technology.

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REFERENCES

- ¹T. Ohkawa, Nucl. Fusion 10, 185 (1970).
- ²D. J. H. Wort, Plasma Phys. 13, 258 (1971).
- ³N. J. Fisch, Nucl. Fusion 21, 15 (1981).
- ⁴N. J. Fisch, Phys. Rev. Lett. 41, 873 (1978).
- ⁵N. J. Fisch and A. H. Boozer, Phys. Rev. Lett. 45, (1980).
- ⁶N. J. Fisch, Phys. Rev. A. 24, 3245 (1981).
- ⁷J. M. Dawson and P. K. Kaw, Phys. Rev. Lett. 48, 1730 (1982).
- ⁸R. J. Bickerton, J. W. Connor, and J. B. Taylor, Nature 229, 110-112 (1971).
- ⁹T. Ohkawa, General Atomic Report No. GA-A13847, 1976.
- ¹⁰T. H. Stix (private communication).
- ¹¹D. J. Rose, Culham Laboratory Technology Division Memorandum No. 82, 1968.
- ¹²S. L. Gralnick, Nucl. Fusion 13, 703 (1973).
- ¹³C. T. Chang, Nucl. Fusion 15, 595 (1975).
- ¹⁴P. B. Parks, R. J. Turnbull, and C. A. Foster, Nucl. Fusion 17, 539 (1977).
- ¹⁵S. L. Milora and C. A. Foster, IEEE Trans. Plasma Sci. PS-6, 578 (1978).
- ¹⁶P. B. Parks and R. J. Turnbull, Phys. Fluids 21, 1735 (1978).
- ¹⁷P. B. Parks, Phys. Fluids 22, 1890 (1979).
- ¹⁸P. B. Parks, Model of an Ablating Solid Hydrogen Pellet in a Plasma (Garland Publishing, Inc., New York, 1979).
- ¹⁹P. B. Parks, Nucl. Fusion 20, 311 (1980).
- ²⁰L. L. Lengyel, Phys. Fluids 21, 1945 (1978).
- ²¹S. L. Milora, J. Fusion Energy 1, 15 (1981).
- ²²G. D. Woods and J. A. Wesson, Culham Laboratory Report No. C18/MEA, 1966,
- ²³B. B. Kadomtsev and O. P. Poqutse, Zh. Eksp. Teor. Fiz. 26, 1146 (1968)
J. Sov. Phys. JETP 26, 1146 (1968).

FIGURE CAPTIONS

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

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

FIG. 3. Electron shadowing of adjacent pellets.

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Fig. 1

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Fig. 2

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Fig. 3

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