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TRAIL--A TOKAMAK RAIL GUN LIMITER^{††}

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Summary

An attractive new limiter concept is investigated. The TRAIL (Tokamak Rail Gun Limiter) system impacts a stream of moderate velocity pellets (100 to 200 m/sec through the plasma edge region to absorb energy and define the plasma boundary. The pellets are recycled, after cooling, to the injector in an E-M mass accelerator. Heat fluxes of $\sim 30,000$ W/cm² can be readily accommodated by the pellets, with very low recirculating power requirements ($\sim 0.1\%$) for the accelerator. The mass accelerator velocity requirements are well within the present state-of-the-art (several km/sec). Accelerators injecting pellets at ~ 1 km/sec can be used to control local plasma temperature and current profiles and to act as energy absorbers to shut down the plasma without damage to the first wall if a plasma disruption occurs.

Introduction

Present Tokamak experiments generally control the plasma boundary through the use of uncooled solid limiters. These are not acceptable for future fusion devices since operation for more than a few seconds will destroy them. Numerous theoretical and experimental studies have been made of magnetic divertors (poloidal and toroidal) which, in principle, could both control the plasma boundary and reduce impurity injections from the first wall. However, it is not certain that divertors will work; even if they are feasible, they greatly complicate reactor design and increase cost.

Recognizing the problems with divertors, the STARFIRE design has proposed an actively cooled limiter using thin wall (~ 1 mm) tantalum structures cooled by high-velocity water at relatively low temperatures. This concept, while it can probably accommodate the calculated heat loading of ~ 4 W/cm², has very little margin to accommodate higher local heating rates and is vulnerable to erosion from charge exchange neutrals and plasma dumps.

In this paper, we propose a new limiter concept, termed TRAIL (Tokamak Rail Gun Limiter). An

E-M mass accelerator continuously launches a stream of small pellets at moderate velocities (e.g., in the range of 100 to 300 m/sec) through the plasma edge region. The moving pellets cool the edge plasma and define its boundary much as conventional material limiters do. TRAIL has several important advantages over an actively cooled limiter, however: (1) It can handle much higher heat fluxes (approximately two orders of magnitude higher), (2) there is no possibility of a coolant leak to the plasma chamber, and (3) since pellets are reformed before recycling to the E-M mass accelerator, materials damage (due to radiation, thermal cycling, etc.) is not of concern.

The TRAIL concept can have important benefits beyond providing a more attractive limiter, however. When necessary, pellets could be injected at appropriate locations, locally cooling the plasma to control its temperature and density profile. This would help to prevent plasma disruptions. Finally, high-velocity pellets (~ 1 km/sec or greater) could be injected when a disruption began; this would rapidly remove plasma energy and prevent it from damaging or destroying portions of the first wall. In this application, TRAIL would function in a similar manner to the SCRAM system in a fission reactor.

E-M mass accelerators are under development for a variety of defense applications. Generally, these involve acceleration of relatively massive projectiles (e.g., in the range of 100 to 1000 g) to velocities of several km/sec. Experiments with rail guns have demonstrated acceleration of projectiles of several grams to velocities approaching 10 km/sec. In general, the mass accelerators required for TRAIL applications are much less demanding than those being developed for defense applications and could be developed relatively quickly for future fusion experiments.

Description of the TRAIL Concept

Figure 1 shows an idealized version of the TRAIL system applied to Tokamak reactors. For boundary layer control, the pellets are fired

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vertically downward past the outer edge of the plasma along a constant toroidal field trajectory (i.e., a constant radius trajectory). Constant field trajectories are probably necessary for electrical conducting pellets (e.g., Al or other metals), but nonconducting pellets (e.g., graphite, which has much lower conductivity) could be fired on nonconstant magnetic field trajectories. Firing conducting pellets on nonconstant field trajectories would cause the trajectory to curve, due to field gradient forces. In principle, this could be compensated for, but it appears difficult and pellet conductivity and size would have to be closely controlled.

As it will be shown in a later section, pellet heat fluxes of up to $\sim 30,000$ W/cm² averaged over the trajectory through the plasma edge can be accommodated so that pellet position need not be critically controlled in its flight through the plasma edge. In contrast, actively cooled material limiters would have to be carefully positioned and controlled so that local hot spots did not occur which could cause burnout at a few hundred watts/cm.

The required pellet areal flow rate through the plasma edge is given by:

$$\frac{dA_p}{dt} = \frac{3.5}{Q} \frac{P_o(1-f_R)}{q_p} \quad (1)$$

where

P_o = total reactor power, watts,
 f_R = fraction of alpha particle energy radiated to wall by Bremsstrahlung,
 Q = total energy released per fusion event, MeV,
 q_p = integrated energy absorbed by pellet during its passage, J/cm², and

$\frac{dA_p}{dt}$ = total areal flow rate of pellets, cm²/sec with suitable impurity seeding, $f_R \sim 0.85$; for the other parameters typically, $Q \sim 21$, $q_p \sim 400$ J/cm², and $P_o \sim 4 \times 10^3$ W (commercial reactor size). The required areal flow rate is then 2.5×10^5 cm²/sec.

The corresponding number and mass flow rates of pellets are:

$$\frac{dN_p}{dt} = \left(\frac{1}{4\pi r_p^2} \right) \left(\frac{dA_p}{dt} \right) \text{ pellets/sec}, \quad (2)$$

$$\frac{dM_p}{dt} = \frac{r_p}{3} \rho_p \left(\frac{dA_p}{dt} \right) 10^{-3} \text{ kg/sec}, \quad (3)$$

where

r_p = pellet radius, cm, and
 ρ_p = pellet density, g/cm³.

For representative 1-cm-diameter aluminum pellets ($\rho = 2.8$ g/cm³), 80,000 pellets/sec are required,

with a mass flow rate of 110 kg/sec. These can be accommodated with practical pellet accelerators as discussed in a later section.

An important parameter is the dimensionless heat absorption efficiency, E_H , which is the ratio of the heat absorbed during its passage through the edge region of the plasma to its kinetic energy. E_H is given by:

$$E_H = \frac{6q\Delta x}{\rho_p r_p v_p^3} \quad (4)$$

where

q = average heat flux to pellet during passage through the plasma, W/cm²,
 Δx = path length through plasma, cm, and
 v_p = pellet velocity, cm/sec.

Practical TRAIL systems result in E_H values on the order of 100. Further, the E-M accelerators will have efficiencies in excess of 90% (electrical to kinetic energy), and the TRAIL heat system only absorbs $\sim 2\%$ of the reactor thermal power. The recirculating power necessary to operate the TRAIL system is thus very small, on the order of 0.1% of the generated electrical power.

The heat absorption performance of some candidate pellet materials are examined in the next section. A desirable pellet material will have: (1) good thermal conductivity (to keep surface temperature low for a given amount of heat absorption), (2) low-vapor pressure (to minimize the amount vaporized into the plasma), and (3) low density (to minimize accelerator requirements).

Depending on the pellet material and the heat flux/travel time, the pellet can either melt (completely or partially) or remain solid. In the first case, pellets would be caught in a pool of liquid pellet material and pumped away. They then would be refabricated by freezing. This could be done in an appropriate heat exchanger bath, or by a shot tower technique. [For partially melted pellets, it probably would be necessary to provide auxiliary heating in the catcher pool, perhaps by circulating some of the molten pellet through an external heat exchanger to ensure full melting for satisfactory fluid transport.]

Solid pellets could be fabricated and collected by a variety of mechanisms. 1. Periodic modulation of the background magnetic field in the exit channel (for electrically conducting pellets), 2. an applied E-M braking force (E-M decelerator), and 3. collection in a liquid pool.

The latter approach appears simple but would be restricted to relatively low pellet velocities, i.e., on the order of 100 m/sec. The cooled solid pellets would have to be collected, dried, and recycled to the E-M accelerator. A low-temperature liquid salt bath probably would be suitable.

An E-M decelerator would essentially be the inverse of the accelerator, and would reduce pellet velocity to the point (~ 1 cm/sec), where it could be cooled by rolling on a flat heat exchange surface. Pellets would then be collected and recycled to the accelerator. This is probably the most feasible option.

A potentially attractive mechanism is local periodic modulation of the background toroidal magnetic field. This would generate JxB deceleration forces due to the fluctuating field gradient, and would permit a smooth stopping. This option would have to be investigated in detail to see if it is practical to modulate the field to the degree required.

Melting pellets appear as the most attractive choice, provided pellet integrity is maintained during passage, and provided vaporization does not result in excessive impurities in the plasma. The heat transfer studies described later indicate that the surface temperature can be readily controlled to the level where vaporization effects are not serious. For Al pellets, this requires that the peak surface temperature during transit not exceed $\sim 1500^\circ\text{C}$, for example. With regard to pellet integrity, MHD effects might cause the molten layer on a pellet to be partially stripped if the pellet trajectory involves a substantial variation in field. [At constant field, there will simply be an induced electrical charge on the pellet, and no JxB force.] The toroidal magnetic field will be constant on the planned trajectory at constant major radius, but there will be some small change in field due to the spatially varying poloidal field. These effects would have to be investigated in detail, including experimentally, but initial examination indicates that the induced E-M forces on the liquid layers are too small to cause stripping.

Pellet injection to control local plasma current and temperature profiles will involve similar considerations to those discussed above for edge control. However, it is likely that average rate of pellet injection will be much less than for edge control, since only relatively fine control capability would be needed. It is likely that pellet injection rate for control would be at least an order of magnitude smaller, and possibly even much less. It is also likely that since some relatively deep penetration capability would be required, with peak heat fluxes on the order of 10^5 W/cm², pellet velocities on the order of 500 to 1000 m/sec would be necessary.

Finally, for shutdown during plasma disruptions, there are several possible options: 1. Absorb plasma energy in a "curtain" or injected pellets on the inboard plasma region, with the pellets in effect acting as the instantaneous first wall against which the plasma dumps. The velocity would be sufficiently high that pellet vaporization and/or fragmentation would be negligible. 2. absorb energy as in (1), except that the pellet

would lose a substantial part of its mass. The injected impurity would further remove plasma energy by increased Bremsstrahlung to the first wall, and 3. inject very high-velocity pellets carrying a high Z gas (e.g., Kr or Xe) into the plasma to radiation of energy.

Detailed calculations of plasma behavior during a disruption would have to be carried out to see which option was more desirable. The TRAIL approach could carry out any of the three options. For Option 1, pellets would be injected at constant major radius (Fig. 2). For Options 2 and 3, other trajectories could be used if desired.

For Options 2 and 3, one would probably prefer a pellet material that would not leave any objectionable residue. It should, therefore, be made of material with very low vapor pressure at the normal operating temperature of the first wall/blanket, and preferably should be of low Z. Carbon, SiC, and Al are promising possibilities. Carbon, in particular, could always be removed in a gaseous form as C_n or CH_m , if necessary.

Heat Transfer Performance of TRAIL System

Transient heat analyses were carried out for a number of pellet materials (Al, Cu, Li, C, and Mo) over a range of heat fluxes (5000 to 1000 W/cm²), heat pulse length (2.5 to 40 msec), and pellet diameters (0.5 to 1.5 cm).

The analyses assumed that only conduction occurred in the pellet, no radiation from the pellet surface (negligible compared with the applied heat flux), spherical pellets with uniform heat flux (in the time scale of plasma ion and electron thermal velocities, the pellet is essentially stationary).

Heating-5, a finite difference conduction code, is used with temperature dependent changes of state incorporated where necessary. For any given case, surface and internal temperature distributions are determined as a function of time after the heat flux is applied, along with the fraction of the pellet that melts. The corresponding amount of material evaporated is determined by the time-dependent surface temperature and the associated vapor pressure. Free molecular flow of the evaporated material is assumed. The evaporation rate is taken as $nv/4$, where n and v correspond to values for the equilibrium vapor. This approximation fixes an upper bound on evaporation rate, since kinetic or flow impedance effects may act to lower the time evaporation rate.

Heat transfer response is evaluated for both uniform applied heat flux and a triangular-shaped heat flux with the same average value to approximate the nonconstant conditions as the pellet moves through the edge region. In general, the two approximations yield similar maximum surface temperatures and melting fractions, indicating that pellet performance primarily depends on total

energy applied during the pulse, rather than on its shape.

Results for different pellet materials are shown in Figs. 2 through 13 for average heat fluxes of $50,000 \text{ W/cm}^2$. An Al pellet barely melts on the surface (Fig. 2) even for relatively long transit times (i.e., 40 msec). The surface melts at ~ 20 msec with a triangular-shaped pulse (peak of $10,000 \text{ W/cm}^2$) but quickly refreezes as heat flux drops. With a uniform heat flux of 5000 W/cm^2 , melting only starts to occur after ~ 40 msec.

Under the same heat flux conditions, Li pellets show much higher surface temperatures (Fig. 3), reaching levels at which evaporation becomes a concern. This is a result of the considerably lower thermal conductivity for lithium. Accordingly, Li pellets are probably only suitable for relatively low heat fluxes and/or short transit times.

Figures 4 and 5 compare the surface temperatures of Cu, Al, Mo, and C pellets for an average heat flux of $30,000 \text{ W/cm}^2$ [uniform and triangular-shaped pulse of 5 msec length are compared].

Copper does not melt, aluminum does, but its surface temperature is still well below the limit ($\sim 1500^\circ\text{C}$) at which vaporization becomes excessive. Both Mo and C pellets would also be suitable with Mo well below its melting point of 2610°C . Although Mo and C have much higher surface temperatures, vaporization is still very small.

To further minimize impurity affects accompanying vaporization, one could coat pellets with layers of low Z, high-melting point materials, e.g., Be, B_4C , B, etc. Copper pellets with a few mils of Be, for example, should make a very attractive pellet. Triangular heat pulses show somewhat higher peak surface temperatures than uniform heat pulses, but only by a relatively small amount.

Figure 6 compares surface temperatures for aluminum pellets as a function of heat pulse length (2.5, 5, and 10 msec) and pellet diameter (0.5 and 1.0 cm) for a triangular heat pulse maximum heat flux of $60,000 \text{ W/cm}^2$. The limiting heat pulse length under these conditions appears to be about 10 msec. Assuming a 2-m path length past the edge of the plasma, this corresponds to a velocity of 200 m/sec, which would be relatively easy to achieve. For lower heat fluxes velocities of 50 to 100 m/sec appear ample, as illustrated in Fig. 7. Here, it is clear that average heat fluxes of $10,000 \text{ W/cm}^2$ could be accommodated for periods much longer than the 20 msec limit chosen for the analyses.

Average heat fluxes substantially greater than $30,000 \text{ W/cm}^2$ appear difficult to accommodate. Figure 8 compares the performance of C, Mo, Al, and Cu pellets to a triangular-shaped heat flux of $200,000 \text{ W/cm}^2$ and 2.5 msec duration. All exhibit an excessive temperature rise; copper and carbon pellets probably could accommodate this heat flux

if the pulse length were somewhat shorter, however. Figure 9 shows the performance of C pellets as a function of heat flux magnitude and pulse length. Only extremely high heat fluxes of $\sim 100,000 \text{ W/cm}^2$ average pose problems and these can probably be avoided by using somewhat shorter heat pulse lengths.

Figure 10 summarizes the heat transfer performance of aluminum pellets in terms of peak surface temperature during the pulse. Aluminum is a very attractive candidate for average heat fluxes up to $\sim 30,000 \text{ W/cm}^2$, but is not suitable for very high average heat fluxes ($\sim 100,000 \text{ W/cm}^2$). Depending on heat flux, integrated energy absorption values of $>300 \text{ J/cm}^2$ can be accommodated.

Figure 11 shows the fraction of the Al pellet that would be melted as a function of heat flux and pulse length. For the higher heat flux range of 10,000 to $30,000 \text{ W/cm}^2$, approximately half of a 0.1-cm-diameter pellet could be melted. A larger fraction, e.g., up to $\sim 80\%$, could be melted if somewhat smaller pellets were used. At low-heat fluxes, a large (1.5 cm) pellet was used so that only a small fraction melted ($\sim 5\%$ at 40 msec). With longer heat pulse lengths and smaller pellets, it should be possible to melt virtually all of the pellet at an average heat flux of $\sim 5000 \text{ W/cm}^2$.

Figures 12 and 13 show heat absorption efficiency for 1.0 diameter as a function of heat pulse length for an average heat flux of $10,000 \text{ W/cm}^2$, for varying path lengths through the plasma (2, 3, and 4 m). For all heat pulse lengths up to 40 msec, peak surface temperature remains below limiting values. The corresponding heat absorption efficiencies are relatively low for short heat pulse lengths (because of high pellet velocity) but reach the range of 100 to 1000 at the longer (lower velocity) heat pulse conditions.

Figure 13 shows the heat absorption efficiency as a function of heat pulse length and pellet diameter. Smaller pellets have higher efficiency since their surface-to-volume ratio is greater. As before, Al pellets can readily handle $\sim 10,000 \text{ W/cm}^2$ with excellent heat absorption efficiency (100 or better). Heat absorption efficiency could probably drop below 10 before recirculating power to the E-M accelerators exceeded 1% of the plant output power.

E-M Mass Accelerator Design

The simplest type of E-M mass accelerator is the simple rail gun, consisting of a pair of electrically conducting rails, with a projectile between the rails. When a voltage and current are applied to the breech of the rail gun, a JxB force develops on the projectile causing it to accelerate along between the rails. Either electrically conducting or nonconducting projectiles can be used in a rail gun. In the former case, current flows through the projectile creating a direct JxB body force, while in the latter case, a plasma arc

drives the projectile ahead of it.

In numerous experiments, Marshall¹ accelerated gram-size projectiles, both conducting and nonconducting, to several km/sec using a simple rail gun. The highest velocity achieved was with a Lexan projectile at 5.9 km/sec. Tests are now being carried out at LASL to produce even higher velocities² using explosively driven-flux compression rail guns.

For control of the plasma edge, aluminum pellets injected at ~ 100 m/sec appear satisfactory. A 1-cm pellet accelerated in a 0.2 m long augmented rail gun ($B_T = 3$ T) would require an applied current of only 1100 A during the acceleration period of 0.004 sec and would experience an acceleration of 2.5×10^4 m/sec² (2500 g).

The I^2R loss in the pellet would be trivially small compared with the kinetic energy gain (~ 0.01 vs ~ 10 J). Frictional and electrical losses at the boundary between the sliding pellet and the rails will be considerably larger than the I^2R loss. These will have to be measured in an actual accelerator, but it appears likely that they will still be small compared with the kinetic energy gain.

Achieving the desired velocity and efficiency is relatively easy and straightforward in terms of present knowledge about E-M mass accelerators. The only development needed appears to be in the area of accelerators to handle high-pellet flow rates.

Figure 14 shows a design approach for a multiple aperture rail gun with high pellet flow rate. Pellets are synchronously injected at low velocity (~ 1 m/sec) into a set of channels. A pulsed current (controlled by a SCR, for example) is applied to the accelerator when the falling pellets reach the appropriate point. The multiple channels are electrically connected in series to ensure uniform current (and acceleration) in each pellet.

Conclusions

The feasibility of using an E-M mass accelerator to inject streams of small pellets to act as a renewable material limiter for shaping the plasma boundary has been examined. Velocity requirements are well within current capabilities and the only development needs are for high feed rate devices.

Very high heat fluxes, up to $\sim 30,000$ W/cm², can be handled by the pellet stream at moderate velocities, up to ~ 200 m/sec, without surface vaporization causing objectionable impurity effects in the plasma. The heat absorption capability of pellets is several hundred J/cm² of surface area. The heat absorption's efficiency--the ratio of heat absorbed in the pellet to kinetic energy of the pellet--is high, on the order of 100. The pellets absorb on the order of 2% of total reactor power, and

recirculating power requirements to the E-M accelerator are small, on the order of 0.1% of output electric power.

Aluminum pellets appear to be very promising since they have high-thermal conductivity and can be collected as a liquid after passage through the plasma edge. The liquid would be frozen into pellets and recycled to the accelerator. Copper, Mo, and C pellets were examined and also appear promising.

The TRAIL concept also appears very attractive for controlling local plasma current and temperature profiles to help prevent disruptions. If a disruption occurs, a TRAIL could inject high velocity pellets (~ 1 km/sec) to absorb plasma energy and enhance plasma radiation. Such a safety system would prevent the disruption from causing damage to the first wall.

More detailed investigation of the TRAIL concept is recommended, including analyses of heat flux profiles for various trajectories through the plasma. If more detailed studies show TRAIL to be as attractive as it appears now, high flow E-M mass accelerators should be tested, and experiments on a small Tokamak should be carried out.

References

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Fig. 1. Trail system for plasma control.

Fig. 2. Surface temperature of Al pellet.

Fig. 3. Surface temperature of Li pellet.

Fig. 4. Surface temperature of Al, Cu, Mo, and C pellets.

Fig. 5. Surface temperature of Al, Cu, Mo, and C pellets.

Fig. 6. Surface temperature of Al pellet.

Fig. 7. Surface temperature of Al pellet.

Fig. 9. Surface temperature of C pellet.

Fig. 8. Surface temperature of Al, Cu, Mo, and C pellets.

Fig. 10. Maximum surface temperature of Al pellet.

Fig. 11. Volume fraction (melting) of Al pellet.

Fig. 12. Heat absorption efficiency of Al pellet with surface flux of 10,000 W/cm².

Fig. 13. Heat absorption efficiency of Al pellet at three pellet diameter.

Fig. 14. Multi-aperture E-M pellet accelerator.