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TRAIL: A TOKAMAK RAIL GUN LIMITER FOR FUSION REACTORS*

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Abstract - An attractive new limiter concept is investigated. The Tokamak Rail Gun Limiter (TRAIL) 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

Currently, control of the plasma boundary in Tokamak discharge involves high temperature, non-cooled material limiters, which will not be acceptable for the next generation of reactors, but will be larger in size and operate for much longer pulses. For such systems, magnetic divertors or water-cooled tubes have been proposed. Divertors greatly complicate reactor design and increase cost, however, it is doubtful whether water-cooled tubes can handle the very high heat fluxes expected, particularly at local hot spots.

A new limiter concept, termed TRAIL, is proposed. An E-M mass accelerator continuously launches high velocity, small pellets through the plasma edge region to cool it and define its boundary--much as conventional material limiters do. Practical heat fluxes with the TRAIL concept are two orders of magnitude higher than the maximum heat fluxes possible with water-cooled limiters; and since pellets are collected, cooled, and recycled to the accelerator, damage can be circumvented by appropriate reconstitution techniques.

In a second version of the TRAIL concept, E-M mass accelerators can be used to locally control the plasma temperature and current profiles, so as to forestall potential plasma disruptions. If a disruption should occur, a TRAIL system could inject a large number of pellets within a few milliseconds to rapidly remove plasma energy, therefore preventing damage to the first wall.

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E-M guns being developed for military applications have velocities of interest on the order of a few km/sec. The highest velocity achieved to date for intact projectiles is ~ 6 km/sec, but velocities several times this appear feasible. A variety of accelerator devices are being developed; the simplest is the classic rail gun consisting of a pair of metallic rails with a projectile between. Current is applied for a few milliseconds to the breech of the rail gun. The intense magnetic pressure of one current discharge between the rails accelerates the projectiles along the rails at $\sim 10^6$ g to velocities of a few km/sec in ~ 1 meter. The projectile can be conducting or non-conducting. [In the latter case, a plasma arc discharge drives the projectiles.]

For TRAIL, the rail gun would function as a augmented rail gun, using a transverse magnetic field (in this case, the toroidal field) to assist the acceleration. This considerably reduces the required current. Accelerators would be located above the plasma chamber with the rails aimed vertically downward. The pellets would be accelerated at constant toroidal field strength (i.e., constant major radius) by a relatively small applied current.

Mass-driver type accelerators are also promising for TRAIL. In this case, the driving bucket would accelerate a large number of small pellets which are launched into the plasma. The bucket would then be refilled with a new batch of pellets.

The accelerated pellets would pass down a small diameter entry tube, skin the edge of the plasma (on either the inboard or outboard edge, depending on accelerator location), leave through a small diameter exit tube, and be collected in a chamber beneath the reactor. This trajectory permits the use of conducting pellets, since β along this path is zero until the pellet leaves the toroidal field. Conducting pellets could be smoothly decelerated--if desired--by suitably modulating the field in the exit channel. Non-conducting pellets could also be decelerated by an E-M force. The most attractive option is probably to use a pellet that is initially solid and melts as it goes through the plasma edge. In this case, deceleration is probably not necessary since liquid can be readily collected and refrozen into new pellets.

Transient heat transfer analyses of melting (Li and Al) and nonmelting pellet (C, Cu, and Mo) materials have been carried out to determine the response to both uniform and triangular-shaped heat pulses, for a range of heat fluxes (50 to 1000 MW/m²) and pellet diameters (0.5 to 1.5 cm). The Heating-5 Code has been used with time-dependent changes of state incorporated where necessary. The principal factors affecting choices of pellet size and velocity are: a) the limit to the amount vaporized during transient, which is a function of surface temperature (determined by heat flux and transient time) and pellet material; b) the dimensionless heat absorption efficiency parameter, $E_H = \frac{1}{2} \frac{CPAT}{Vp^2}$. (E_H is the ratio of the thermal energy

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absorbed (including melting) in the pellet to its kinetic energy.]

Aluminum appears to be the leading pellet candidate for the limiter application because of its high thermal conductivity, low vapor pressure, and moderate density. For typical reactor conditions, E_H will be on the order of 100, with ~50% of the pellet melted during flight. Approximately 10^5 pellets per second (1 cm diameter) would be required for a 4000 MW(th) commercial reactor in which 4% of the fusion power (20% of the fusion alpha power) is absorbed by the TRAIL limiter. The neutron power (80% of total reactor power) would not be absorbed by the small mass of moving pellets, while the balance of the alpha power would be radiated as Bremsstrahlung x-rays to the walls.

For shutdown applications where pellets need not survive their trip through the plasma, graphite appears desirable. The vaporized graphite will deposit out as a very thin coating over the large surface area (~1000 m²) of the first wall. This is desirable since the graphite will act as a low Z coating during normal reactor operation to prevent contamination of the plasma by high Z impurities (e.g., from a stainless or refractory metal first wall) introduced by sputtering reactions. If desired, the graphite layer could be periodically removed by oxidation and pumping.

In the rest of this paper, the TRAIL concept is described in more detail, together with results from heat transfer analyses. Accelerator designs for representative operating conditions are also presented.

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 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 non-conducting pellets (e.g., graphite, which has much lower conductivity) could be fired on non-constant magnetic field trajectories. Firing conducting pellets on non-constant field trajectories would cause the trajectory to curve due to field gradient forces. In principle, this could be compensated for but it adds complexity, 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 ~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:

$$\frac{dA_p}{dt} = \frac{3.5}{Q} \frac{P_0(1-f_R)}{q_p} \quad (1)$$

where

- P_0 = 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

Fig. 1. TRAIL system for plasma control.

$\frac{dA_p}{dt}$ = total areal flow rate of pellets, cm²/sec. With suitable impurity seeding, $f_R \sim 0.85$, for the other parameters typically $Q \sim 21$, $q_p \sim 300$ J/cm², and $P_0 \sim 4 \times 10^3$ W (commercial reactor size), the required areal flow rate is 3.3×10^5 cm²/sec.

The corresponding number and mass flow rates of pellets are:

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

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

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) 100,000 pellets/sec are required, with a mass flow rate of 140 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:

$$E_H = \frac{6q\Delta x}{\rho_p r_p v_p^2} \quad (4)$$

where

q = average heat flux to pellet during passage through the plasma, W/cm^2 ,
 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 ~2.5% 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 such as: 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 pellet velocities 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 m/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 $J \times B$ 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.

For the limiter application, 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 transient not exceed ~1500°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 $J \times B$ 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 $10^5 W/cm^2$, pellet velocities on the order of 500-1000 m/sec would be necessary.

Finally, for shutdown during plasma disruptions, there are several possible options: 1) absorb plasma energy in a "curtain" of injected pellets on the in-board 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 all or most 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. 1). For options 2) and 3), other trajectories could be used if necessary.

For Options 2) and 3), one would 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 CO_x or CH_x --if necessary. The easiest and simplest disruption shutdown system would be to inject low Z pellets (graphite) which are completely vaporized and absorb the plasma energy. This is the option selected for analysis in a following section.

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 average heat fluxes (5000 to 10^5 pellet diameters (0.5 to 1.5 cm).

The analyses assumed: conduction (no convection) in the pellet, no radiation from the pellet surface (negligible compared with the applied heat flux), and spherical pellets with uniform heat flux (in

Journal

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 non-constant 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 transient 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 re-freezes 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).

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.

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.

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

Fig. 7. Surface temperature of Al pellet.

Fig. 6. Surface temperature of Al pellet.

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

Fig. 9. Surface temperature of C pellet.

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.

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 1 m path length past the edge of the plasma, this corresponds to a velocity of 100 m/sec, which would be relatively easy to achieve. For lower heat fluxes, velocities of 50 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 $\geq 300 \text{ J/cm}^2$ 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 1.0 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 pellets 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.

The disruption shutdown application appears to have the simplest system requirements and easiest accelerator design. The pellets are allowed to vaporize since the plasma is to be shut down. This permits much greater energy to be absorbed per unit mass if

injected pellets is small. The injection velocity is moderate and need only be large enough to ensure that pellets reach and quench the plasma before it can damage the reactor first wall.

For disruption shutdown by pellet vaporization, graphite appears to be the leading candidate. It has a high specific heat of vaporization ($60,000 \text{ J/g}$), high temperature capability ($>3000^\circ\text{K}$), good mechanical strength and thermal shock resistance, relatively small effect on plasma performance (low Z), and the reaction products can be either deposited as a thin coating on the reactor first wall or pumped away as CO_x (by oxidation) or CH_x (by reaction with hydrogen).

Table 1 summarizes representative design parameters for a TRAIL shutdown accelerator using graphite pellets. A deep penetration trajectory is selected with average heat flux along the trajectory of $\sim 3 \times 10^5$ watts (cm^2) over a distance of ~ 5 meters. A small pellet diameter is chosen ($\sim 0.2 \text{ cm}$) so that essentially all of the pellet will be vaporized during its flight. The injection velocity of 500 meters/sec allows rapid response to an impending disruption while remaining low enough to be readily achieved by the E-M mass accelerator.

TABLE I

DESIGN PARAMETERS FOR A TRAIL DISRUPTION SHUTDOWN DEVICE

Pellet material	graphite
Pellet velocity	500 m/sec
Average heat flux along integrated trajectory	$3 \times 10^5 \text{ W/cm}^2$
Heat absorption capability (complete vaporization)	60,000 J/g
Pellet lifetime	10 msec
Pellet diameter	0.2 cm
Pellet weight	0.006 g
Total number of pellets injected to absorb $5 \times 10^8 \text{ J}$	1.6×10^6
Period of injection	20 msec
Number of injection points	12
Number of injection sequences at each point	2
Total mass injected	10 kg
Mass per injection	0.4 kg
Energy per injection	0.05 MJ (500 m/sec)

Pellets would be injected from a number of locations around the torus. Twelve injection points are chosen (Tokamak reactors are typically designed with 12 toroidal field coils), and two separate injection sequences with different accelerators are assumed for each location to achieve overlapping sequential energy absorption during the 20 millisecond plasma shutdown. [Both could be injected at the same time instead of in sequence.] This would result in a faster shutdown, e.g., 10 milliseconds of injected pellets is quite small (10 kg) to absorb the 5×10^8 Joules plasma energy. With 24 separate injections, only 0.4 kg is injected per shot, with a kinetic energy of 0.05 MJ.

The only unusual requirement for the E-M accelerator is the very large number of pellets injected,

$\sim 1.6 \times 10^6$ or $\sim 70,000$ per shot. This is far too many (and the pellets are too small) to conveniently inject in an individual manner, even in a repetitively firing accelerator. Some batch-type accelerator is clearly called for, with each batch of pellets being on the order of 0.4 kg.

Figure 14 shows a promising accelerator approach where the batch of pellets is held in place by an E-M actuated shutter. When a disruption begins, the shutter would be rapidly withdrawn and an E-M driven piston behind the pellets would accelerate them to injection velocity, 500 meters per second, in 2 milliseconds. The pellets would then traverse a shot channel through the reactor blanket and enter the plasma.

Fig. 14. E-M accelerator for disruption control.

The drive piston would be a sliding metallic armature carrying the applied current. It would travel between two rails which would function as an augmented rail gun.

DISRUPTION SHUTDOWN APPLICATION

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 voltage and current are applied to the breech

of the rail gun, a $J \times B$ force develops on the projectiles causing it to accelerate along between the rails. Either electrically conducting or non-conducting projectiles can be used in a rail gun. In the former case, current flows through the projectile creating a direct $J \times B$ body force, while in the latter case, a plasma arc drives the projectile ahead of it.

The accelerator shown in Fig. 14 is an augmented rail gun with the background toroidal field serving to considerably increase the applied force for a given current. Table II summarizes the operating parameters for the disruption shutdown accelerator. The acceleration (25,000 g) and applied force (375 atm) are modest compared to most other applications. The total applied current (665,000 amps) is comparable to that required for other E-M accelerator applications (for example, it is approximately one half of that required for anti-tank armor guns), but the current per unit electrode area (10,000 amp/cm²) is much smaller than that for other systems.

TABLE II

OPERATING PARAMETERS FOR DISRUPTION SHUTDOWN ACCELERATOR

Acceleration distance, S_a	50 cm
Acceleration, a	2.5×10^7 cm/sec (25,000 g)
Injection velocity, V	500 m/sec
Acceleration time, τ_a	0.002 sec
Applied force, F_a	3.75×10^8 dynes/cm ² (375 atm)
Current per unit length is piston, I_l	50,000 A/cm of depth (into paper)
Total current, I_t	665,000 amp (13 cm deep channel)
Acceleration mass, M_a	15 g/cm ² (graphite and piston)
Total accelerated volume, V_{tot}	400 cm ³ (0.4 kg)

The flow current density and the expected infrequent use of the disruption shutdown accelerator makes it probable that it will function satisfactorily over the life of the reactor (the piston must be reset and new batches of graphite pellets poured in so the accelerator is ready for the next shutdown, however).

The total number of disruption shutdowns to be expected during the life of the reactor cannot be predicted with certainty. However, from an operational power plant standpoint, it is doubtful that a practical plant system could stand a shutdown frequency higher than once every few days, since grid load would probably have to be dropped. The total number of accelerator firings would then be at most a few thousand over a thirty-year period.

Other accelerator design approaches are possible. The coaxial mass driver approach is quite attractive for a disruption accelerator using an accelerated bucket with a normal conductor coil traveling along a sequence of inductive driver coils. The bucket would carry the graphite pellet batch. It could have spring loaded bottom sections that would open when the bucket started to decelerate. The accelerated pellets would then stream out from the bucket bottom and continue down the transport tube to the plasma. A spring loaded cap could hold the top closed during acceleration, re-opening when the bucket returned to its starting

position. A pellet supply tube would then refill the bucket and the system would be reset for the next shutdown when required.

Both accelerator approaches appear practical and neither should be very difficult. Determination of the most desirable approach will require further analysis and tests of prototype systems. R&D requirements for disruption accelerators appear relatively straightforward with a minimum of material and technological problems.

PLASMA LIMITER APPLICATION

The limiter application requires a different accelerator approach than that for a disruption shutdown. Pellets must be continuously accelerated through the boundary region of the plasma during the time that the reactor operates. The surface temperature rise of the pellet must be kept low enough that only a very small fraction, e.g., less than 10^{-7} , of the pellet mass evaporates during its flight. Excessive evaporation will introduce impurities into the plasma and cause it to cool below the temperature needed to sustain fusion.

From the heat transfer analyses presented previously, it appears that aluminum is an attractive candidate for the limiter application. Aluminum pellets have high thermal conductivity, relatively high allowable surface temperatures ($\sim 1500^\circ\text{C}$), and can absorb large amounts of thermal energy per unit area. Aluminum's low density is attractive from the standpoint of accelerator current and power requirements. Finally, its melting temperature is low (660°C) compared to its maximum allowable surface temperature, so that a large fraction ($>50\%$) of the pellet can melt during its passage through the edge plasma. Additional melting can be carried out in the collecting pool, and pellets can be readily refabricated.

Representative operating conditions for an aluminum pellet limiter are:

- o Average heat flux over trajectory in plasma = $30,000 \text{ W/cm}^2$
- o Transit time through plasma edge region = 10^{-2} sec
- o Flight velocity = 100 meters/sec
- o Transit distance through edge region = 1.0 meters
- o Energy absorbed per cm^2 = 300 Joules/ cm^2
- o Maximum surface temperature = 1500°C
- o Total energy absorbed by pellet limiter = 100 MW(th)
- o Total number of pellets per second (1.0 cm diameter pellet) = 100,000
- o Total mass flow rate (1.0 cm diameter pellet) = 140 kg/sec

The pellet limiter would absorb 2.5% of the total reactor power (4000 MW(th) reactor) and 15% of the total alpha power ($Q = 21 \text{ MeV}$ per fusion and alpha energy = 3.5 MeV per fusion). As in recent Tokamak reactor designs, the remaining alpha power would be radiated to the first wall as Bremsstrahlung x-rays.

The pellet velocity is quite low in terms of most E-M accelerator applications. Further optimization

of the limiter application may even reduce the velocity by choosing a pellet trajectory that has a lower average heat flux. Lower velocity would simplify accelerator design and would lose pellet collection.

Taking 100 meters per second as the design velocity for the present, however, there are a number of accelerator design approaches that could be used. These include:

- o Multi-aperture rail guns
- o Bunched pellets
- o Bunched pellet flow in multiple channels

Figure 15 shows a multiple-aperture rail gun design. The multiple channels are electrically connected in series by current flow through the pellets, with insulators between channels. When a current pulse is applied to the accelerator electrode, pellets at the entrance to the channel will accelerate in step since all experience the same current and accelerating force.

Fig. 15. Multi-aperture E-M pellet accelerator.

The pellets leave the accelerator and travel as a group down the transport tube into the plasma edge region. Small velocity differences due to differing rail drag, pellet current distribution, mass, etc. will produce some smearing of their spatial positions as they enter the plasma. This will not affect limiter performance, however, since--in general--the pellets are sufficiently far enough apart that they will not shadow each other, and heat deposition by the very hot plasma particles will be essentially uniform over the pellet surface.

Repetitive firing of the multi-aperture rail gun is accomplished by timed injection of a new batch of pellets into the breech portions of the channels. Injection timing could be performed by a set of small register pins as shown in Fig. 15, which could be either electromagnetically, hydraulically, or

A. Cowell

mechanically actuated. Feed tubes above the register pins would be filled by gravity flow of the pellets from a large feed pipe.

Table III lists operating parameters for a multi-aperture limiter rail gun. Twelve guns are used for a Tokamak reactor with twelve TF coils. Each gun fires a total of 8000 pellets per second or 50 pellets per second through each of the 200 apertures. The total cross sectional area of the gun would be on the order of 600 cm², counting the area of the apertures, rails, structural materials, coolant channels, and insulators. The pellets would travel to the plasma in a transport channel of dimensions 30 x 30 cm.

TABLE III

PARAMETERS FOR MULTI-APERTURE RAIL GUN LIMITER

Total pellet injection rate per gun	8000/sec
Number of apertures per gun	200
Pellets per sec per aperture	40
Pellet velocity	100 m/sec
Pellet acceleration distance	20 cm
Pellet acceleration time	4 milliseconds
Pellet acceleration	2.5×10^4 m/sec
Current @ $B_T = 30$ kG	1200 amp
Maximum J x B back voltage (apertures in series)	600 volts
Pellet KE per batch (200 per batch)	1400 J

The pellet acceleration is relatively small (2500 g) and the applied current very small (1200 amp). The background toroidal field is very helpful in keeping current low; this should result in very low rail erosion. The low current also permits high repetitive fire rates, since cooling the rail is simple and energy requirements minimal. For example, kinetic energy is only 1400 Joules per batch of 200 pellets accelerated, which is trivial to supply from capacitive or inductive energy storage.

Pellet acceleration time is 4 milliseconds over the 20 cm accelerator channel. This corresponds to a duty cycle of 16% from the 40 pellets per second firing rate. Placing all 200 apertures in series results in a J x B back voltage of only 600 volts. Resistive and contact losses will probably increase the necessary voltage to ~1000 volts. Higher voltage would still be acceptable in terms of accelerator design, however.

A potentially simpler accelerator approach for limiters is shown in Fig. 16. Here, pellets fall freely in a pipe from some feed arrangement. A periodic bunching of pellets is accomplished with a variable flow resistance, e.g., some type of pulsating shutter (either mechanical or electromagnetically activated). The pellets are bunched along some distance (e.g., ~20 cm) in the accelerator channel. The flow resistance is then removed and the pellet bunch accelerated from the rear towards the plasma. This acceleration could be done inductively on the bunched mass of pellets or directly by an applied current, as shown in Fig. 16. Bunching is maintained by having the E-M force application at the rear of the bunch. Pellets at the front of the bunch continue to be caught up and accelerated by those at the rear.

After acceleration, pellets are debunched as they travel down the transport tube, so that plasma particles

will impact on all pellets, not just those on the outside of the bunch. The easiest way to debunch is probably to use a set of alternating multiple coils (quadrupole or sextapole) along the transport tube. Pellets on the outside of the bunch will be slightly slowed down by the alternating field gradient, while those on the inside (which experience less of an E-M retarding force) will continue along the tube at a somewhat higher velocity. In effect the bunch will be drawn out into a long sausage of pellets which then enter the plasma edge region. These coils would be simple, passive current loops requiring no control. Active control for debunching could also be used with pulsed inductive coils, but this is more complicated and should not be necessary.

Fig. 16. Bunched pellet flow TRAIL system.

Operating parameters for the bunched pellet flow accelerator are shown in Table IV. As in the multi-aperture rail gun accelerator, pellet accelerations are low and energy storage requirements very small. The applied current is relatively high (210,000 amps) because many (450) pellets are accelerated in parallel. The electrode current density is very low, however, (~5000 amp/cm²) compared to most E-M accelerator applications, and electrode life and heating problems should be minimal.

TABLE IV

OPERATING PARAMETERS FOR BUNCHED PELLET
FLOW ACCELERATOR

Total accelerator current	210,000 amp (14,000/ cm width)
Cross-section of accelerator tube	15 x 15 cm
Bunch length	20 cm
Number of pellets per bunch	450
KE of pellets in bunch	3000 Joules
Number of bunches accelerated per second	18
Distance between bunches at 100 m/sec	5 meters
Acceleration time	4 milliseconds

The current flow distribution in the accelerating bunch is difficult to analytically determine, and experiments on such accelerators would have to be carried out to fully define the design. Contract losses would also have to be measured in order to determine efficiency with good precision. There appear to be no serious technical problems with such an accelerator approach, however.

CURRENT CONTROL APPLICATION

Current control probably is the most difficult of the three TRAIL applications. In disruption control, relatively high velocity (~ 500 m/sec) is needed to inject pellets sufficiently fast to shut down the plasma in the time-scale of a disruption. The pellets can vaporize, however (and are designed to do so for efficiency), so relatively small accelerated masses are sufficient. In addition, the acceleration is done very infrequently, with days or more between events.

The limiter applications must continuously inject large numbers of pellets which cannot vaporize, but can use relatively low velocities (50 to 100 m/sec) because heat fluxes in the plasma edge region are modest, e.g., up to several tens of kW/cm^2 .

The current control application will probably require part of the injection to be in a heat flux regime considerably higher than that considered for the limiter application. The constraint that vaporized mass should be very small remains, though the amount allowed will probably be somewhat larger than for the limiter—since fewer particles are injected—both with regard to peak and average rates.

More detailed plasma studies are needed to fully define the heat regime requirements for current control, but it appears that heat fluxes in the range of 10^4 to 10^5 watts/ cm^2 are to be expected. The lower end of the range, e.g., up to $\sim 30,000$ W/ cm^2 , can readily be accommodated using accelerators of the type described for the limiter application. For the upper end of the range, i.e., up to $\sim 10^5$ W/ cm^2 , one will need short exposure times to the plasma ($\tau_{\text{max}} \sim 2$ milliseconds), long travel distances (~ 3 meters), and high velocity (1.5 km/sec).

Table V shows the E-M accelerator parameters for a unit controlling current deep in the plasma at an average heat flux of 10^5 W/ cm^2 . Aluminum pellets are used at a velocity of 1.5 km/sec. Maximum pellet flow rate is 8000/sec (660/gun) assuming that 10% of the plasma energy is removed by this set of accelerators in ten seconds. This pellet flow rate is an order of magnitude

less than that for limiter use.

TABLE V

HIGH VELOCITY ACCELERATOR FOR CURRENT
CONTROL APPLICATION

Pellet velocity	1.5 km/sec
Pellet diameter	1.0 cm
Pellet material	aluminum
Absorbed energy (100 kW/cm^2 for 3 meters)	200 J/cm^2
Maximum pellet flow rate (10% of plasma energy—commercial reac- tor—in 10 sec)	8000/sec
Pellet flow rate per gun location (12 locations)	660
Maximum KE flow per gun	1 MW(e)
Number of apertures per gun	60
Pellet flow rate per aperture per sec	11
Accelerator distance	1.0 meter
Acceleration time	1.4 msec
Current for acceleration (50,000 Gauss background field)	30,000 amp

The average pellet flow rate is expected to be much smaller than the peak flow rate, since Tokamak plasmas are very stable for virtually all of their operating period and only go unstable a small fraction of the time. While the maximum flow rate per aperture is 11 pellets per second, the corresponding average rate should be two or three orders of magnitude smaller, which is important in terms of rail life. More apertures per gun could also be used to reduce erosion problems, and rails could be removed during the yearly reactor shutdown when part of the blanket is replaced.

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/ cm^2 , can be handled by the pellet stream at moderate velocities, up to ~ 100 m/sec, without surface vaporization causing objectionable impurity effects in the plasma. The heat absorption capability of pellets is several hundred J/ cm^2 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; 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.

For the disruption shutdown application, rapid injection of batches of small (0.2 diameter) graphite

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pellets, which absorb the plasma energy when they vaporize, appear to be the most promising route. A small mass of pellets (~ 10 kg) is sufficient to absorb the plasma energy ($\sim 5 \times 10^8$ Joules) of a full size commercial Tokamak reactor. Batch accelerators of either the rail gun or inductive mass driver-types appear simple and most suited. Moderate pellet injection velocities are suitable, e.g., ~ 500 meters/sec.

The TRAIL concept also appears attractive for controlling local plasma current and temperature profiles to help prevent disruptions, though the accelerators required are somewhat more complex than the relatively simple types for either the disruption or limiter applications.