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FUELING OF TANDEM MIRROR REACTORS*

George E. Gorker
Fusion Engineering Design Center
Oak Ridge National Laboratory
P.O. Box Y, Oak Ridge, TN 37831

B. Grant Logan
Lawrence Livermore National Laboratory
University of California
P.O. Box 5511, Livermore, CA 94550

Abstract: This paper summarizes the fueling requirements for experimental and demonstration tandem mirror reactors (TMRs), reviews the status of conventional pellet injectors, and identifies some candidate accelerators that may be needed for fueling tandem mirror reactors. Characteristics and limitations of three types of accelerators are described; neutral beam injectors, electromagnetic rail guns, and laser beam drivers. Based on these characteristics and limitations, a computer module was developed for the Tandem Mirror Reactor Systems Code (TMRSC) to select the pellet injector/ accelerator combination which most nearly satisfies the fueling requirements for a given machine design.

Introduction

During the past several years, TMR conceptual design studies were performed for experimental machines such as the Tandem Mirror Technology Demonstration Facility (TDF) and for a MFTF-B follow-up experiment known as MFTF-α+T. Some TMR studies were also focused on Fusion Power Demonstration (FPD)-type machines, namely FPD-I, -II, and -III, and more recently, Minimars. These studies have identified fueling requirements for experimental and demonstration types of machines that are more stringent than those for tokamak machines. To meet these requirements, both conventional centrifugal or pneumatic fuel pellet injectors and high energy accelerators are needed to achieve deep plasma fueling.

The subject of this paper is limited to deep plasma fueling of the thermonuclear reactors. Fueling of fusion power reactors requires higher fuel pellet velocities than the short pulse experimental reactors that operate today at low plasma temperatures and densities. Pellet velocity requirements of TMRs are generally higher than for tokamak reactors, because of their higher plasma temperature and because there is no recycle pumping. There are no ignited steady-state fusion machines in operation today; therefore, the fueling requirements for these machines have a high degree of uncertainty. Unlike most physics models, the fueling model described in this paper takes into account both alpha particle and fast ion heating.

Data from Tandem Mirror Reactor Studies

During the past three years, mirror reactor studies were performed that range from technology experimental reactors to power producing reactors.[1-4] Table 1 contains some comparison data for these reactors and their fueling systems. The very low power experimental reactors are fueled with neutral beam injectors (NBIs) that are needed for plasma heating. These reactors also require a deuterium pellet injector for plasma flow stabilization through the choke coil region. Centrifugal injectors are required because of the small pellets and high repetition rate. The FPD-I and FPD-II intermediate power fusion reactors are assumed to be fueled with DT pellet injectors consisting of a pneumatic gun launcher, followed by a second-stage electromagnetic (EM) rail gun accelerator. The octopole end cell FPD-III and Minimars TMRs are assumed to be fueled with a pneumatic gun launcher and a laser beam driver.

Table 1. Fuel system data base for several TMRs.

Parameter	TDF-α+T	FPD-I,-II	Minimars
Fusion power, MW	< 25	500-800	1250
CC[a] length, m	4-20	90	90
CC plasma radius, cm	10-25	46-60	36
CC ion temperature, keV	25-37	37-40	26.7
CC electron temperature, keV	2-12	26-28	20.9
CC plasma density, 10^{14} cm^{-3}	1.9-6.0	1.67	3.8
Pellet species	D	DT	DT
Pellet diameter, mm	0.6	2.75	2.8
Pellet mass, mg	0.34	4.0	3.8
Max. pellet rate, s^{-1}	500	10	10

[a] Central cell.

Fueling Systems

Some fueling systems that have been proposed for thermonuclear reactors include pneumatic pellet guns, centrifugal pellet injectors, NBIs, EM rail guns and laser-ablated pellet drivers.[5-9] Only the first two types of injectors have been developed and proven for experimental tokamak reactors. The maximum pellet injection velocity for pneumatic gun and centrifugal injectors is ≤ 2 km/s.

Neutral beam injectors have been developed for plasma heating and conditioning, but they have insufficient current for fueling power reactors. They can be used to fuel low power experimental reactors where the fueling current is low and the NBI is needed for plasma heating. Disadvantages of NBI systems include: (1) large power consumption, (2) large line-of-sight penetrations through the radiation shield, (3) high cost, and (4) low availability.

There are two types of electromagnetic rail guns. One of them is constructed like a linear induction motor that accelerates metal-encased pellets (sabots). The saboted pellets are accelerated by interaction of induced eddy currents with the traveling magnetic field. This type of accelerator has two major disadvantages: (1) very high electrical power requirements and (2) sabot separation from the fuel and its recovery. The other type of EM rail gun is constructed like a linear dc motor. Rails[3] are connected to an

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DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED energy storage source. An arc discharge is initiated across the rails, and the I X B force drives the pellet ahead of the arc to the end of the rail gun. Experiments with dielectric pellets have demonstrated muzzle velocities up to 12 km/s. Analytical techniques given in Ref. 7 were used to compute the data in Fig. 1 for two limiting acceleration pressures σ_m for a 3-mm DT pellet. Length of the rail gun varies as the square of the velocity. For practical rail gun limits < 20 m, the theoretical muzzle velocity is limited to 13 km/s for $\sigma_m = 3$ MPa and 18 km/s for $\sigma_m = 6$ MPa.

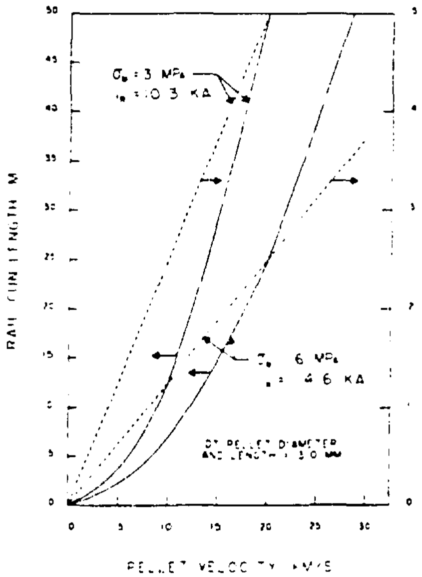

Fig. 1. Rail gun data for a 3-mm DT pellet.

Several key issues need to be resolved before the feasibility of rail gun accelerators can be established. Rail gun experiments with dielectric pellets show that performance degrades rapidly when the pellet does not fit the barrel to close tolerance. Fuel pellets may erode in a long barrel until the leakage becomes intolerable. A fuel pellet will also ablate when pushed by a hot arc, producing gas products that must be removed between successive pellet shots. The vacuum cleanup system may not be able to remove the residual gases before the next pellet is fired. Arcing between rails may also produce contaminants that enter the plasma and shut down the reactor. Even though the gun rails are liquid cooled, erosion will eventually make it necessary to replace a rail gun that is radioactive because of neutron-induced radiation.

Only the laser-driven pellet fueling system illustrated in Fig. 2 has the capability of achieving the high pellet velocities needed for TMR power reactors. Several laser beams are combined about 25 m from the reactor, and the converging beam is focused near the plasma boundary. For better reliability and more flexibility, two pneumatic gun pellet launchers inject pellets in the same plane as the laser beam. The pellet crosses the beam at an angle of less than 5° near the plasma boundary. When a pellet enters the crossover zone, the lasers are triggered to provide a high energy pulse for about 100 ns. The burst of energy ablates away the rear part of the pellet at high velocity. The reaction thrust increases the forward velocity of the remaining pellet until the desired velocity (~50km/s) is attained.

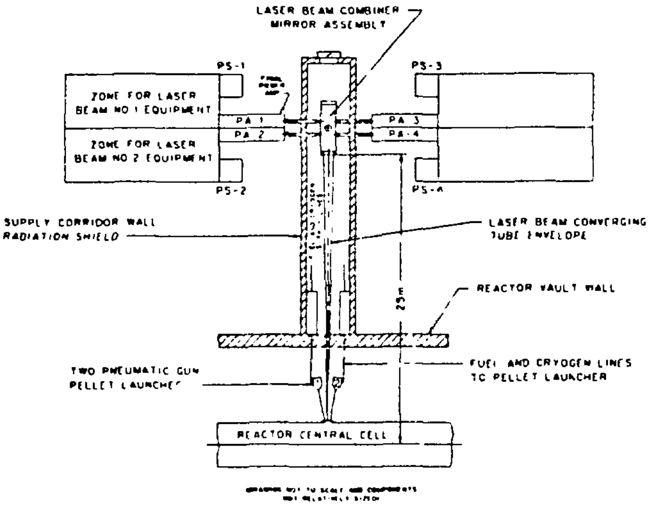

Fig. 2. Overall plan view of laser-driven pellet fueling system.

Two scenarios have been considered for laser-driven accelerators, one which uses a long pulse laser (~5 μs)[8] and one which uses a short pulse laser (~0.1 μs). The first scenario has a lower ablation rate, but requires laser tracking of the pellet for about 13 cm of the trajectory. The second scenario requires a much higher ablation rate, but laser tracking of the pellet is avoided because the pellet moves only a few millimeters (mostly in the direction of the laser beam). Average unconstrained pellet acceleration is about 10^{10} m/s^2 for scenario 1 and 5×10^{11} m/s^2 for scenario 2. The pellet may disintegrate after the laser shot of scenario 2, but the forward velocity of the center of mass will carry the "fuel bubble" deep into the plasma as described below.

Physics Fueling Model

During the Minimars study, Grant Logan developed a physics model that includes alpha particle and hot ion heating of the pellets. The model reveals an expanding fuel bubble scenario, illustrated in Fig. 3 for several different times after triggering the laser pulse. When T = 0, the pellet is in the crossover zone just inside the plasma. After the 100-ns ablation, the pellet bubble center of mass is moving into the plasma with a velocity of 40 to 50 km/s. Alpha particles and hot ions heat the fuel to create a fuel plasma bubble that expands until its beta = 1 at 3 μs . Expansion then continues predominantly in the axial direction. The motion of the bubble is not well defined after beta = 1, but there is some evidence that it will gravitate to the center of the plasma after a few radial oscillations. The fueling impact on the reactor stability needs to be investigated further.

The following conditions define the fueling requirements and key features of Fig. 3. The nomenclature is defined in Table 2, together with typical values.

1. Time, τ_1 , for the bubble expanding initially at the speed of sound to reach beta = 1 equilibrium:

$$\tau_1 = 8.9 \times 10^{-6} R_C^{5/6} \; F^{5/12} / [\beta_\alpha^{1/6} \; B_{co}^{1/3}] .$$

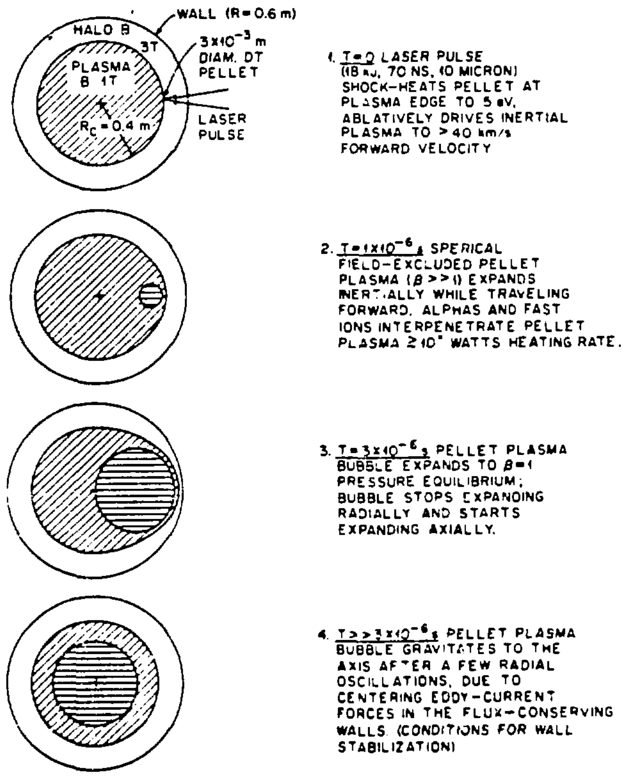

Fig. 3. Sequence of laser-ablated pellet plasma injection.

2. Alpha particles and fast DT ions penetrate and heat the fuel plasma bubble to temperature, T.

$$T(\tau) \geq 25\ [\hat{\beta}_\alpha\ B_{co}^2\ \tau]^{0.4}\ .$$

3. At beta = 1 equilibrium, the ratio of the bubble cross section to the reactor plasma cross section, F, must be ≥ 0.5 so that the wall eddy currents provide the stability needed to center the bubble. The minimum required pellet mass is

$$M_1 = 2.2 \times 10^{-5}\ R_c^3\ B_{co}^2\ F^{3/2}\ (1 - \hat{\beta}_c)/T_1\ .$$

4. The forward velocity (V_F) of the pellet bubble must be sufficient to prevent the expanding bubble from contacting the wall:

$$V_f\ \tau_1 + \Delta R_{halo} \geq 1.1\ R_{bubble} = 1.1\ R_c\ \ F\ ,$$

ΔR_{halo} = one or two alpha particle gyro radii.

5. The laser pulse width time, τ_L, should be about equal to the time required for the speed of sound to travel the ablated pellet radius:

$$\tau_L = R_o/\left(2T_o/M_{dt}\right)^{1/2}$$

where T_o = 5 eV is the temperature of the ablated pellet and M_{dt} is the weight of a DT molecule.

The pertinent data for a typical Minimars are given in Table 2 for the target reactor plasma and the pellet plasma. Some laser fueling data are also included.

Table 2. Typical parameters for a Minimars laser-ablated pellet injector.

Equilibrium target	
$R_c = 0.417$ m	Central plasma radius
$R_w = 0.60$ m	Central wall radius
$\hat{B}_{co} = 2.96$ T	Central vacuum field
$\hat{\beta}_c = 0.9$	Central peak beta
$\beta_\alpha = 0.15$	Central alpha beta
$F = 0.5$	Bubble cross-section fraction
$I_{fuel} = 811$ A	Average DT fueling current
$\tau_p = 3.0$ s	Central cell particle lifetime
Pellet plasma	
$R_o = 1.4 \times 10^{-3}$ m	Initial pellet bubble radius
$M_1 = 2.83 \times 10^{-6}$ kg	Pellet bubble mass
$R_1 = 0.30$ m	Pellet β = 1 radius
$T_0 = 5 \times 10^{-3}$ keV	Initial pellet temperature
$T_1 = 0.174$ keV	Pellet β = 1 temperature
$N_1 = 6 \times 10^{21}\ m^{-3}$	Pellet β = 1 density
$\tau_1 = 3.07 \times 10^{-6}$ s	Expansion time to β = 1
$V_F = 4.6 \times 1-^{4}$ m/s	Pellet bubble forward velocity
Laser driver	
$\tau_L = 70$ ns	Laser pulse time
$E_L = 26.8$ kJ	Absorbed laser energy per pellet
$F_L = 10\ s^{-1}$	Maximum number of pellets/s
$M_0 = 3.8 \times 10^{-6}$ kg	Initial mass of DT ice pellet
$\lambda_L = 0.249\ \mu$	Laser wave length

Laser Ablation of Fuel Pellets

The required laser pulse time determines the mass ablation rate needed to achieve the desired final velocity of the pellet. These ablation rates may or may not be achievable with lasers having the desired pulse time. Figures 4 and 5 illustrate some laser constraints.[9] The first figure shows that only about 30% of CO_2 laser radiation can be absorbed by the pellet because of the low critical density associated with 10.6 μ radiation. Once the ablation plasma reaches the critical density of 10^{19} particles/cm^{-3}, the infrared radiation can no longer penetrate the ablation cloud. Shorter wavelength radiation has higher critical densities and higher absorption. The visible light spectra has absorption efficiencies between 80 and 90% when the laser beam intensity lies between 10^{12} and 10^{13} W/cm^2. The ultraviolet KrF laser is especially good because of its short wavelength (0.249 μ). The shorter wavelength radiation gives rise to much higher mass ablation rates, as shown in Fig. 5. Therefore, the KrF laser is especially desirable for short laser pulse requirements (<100 ns).

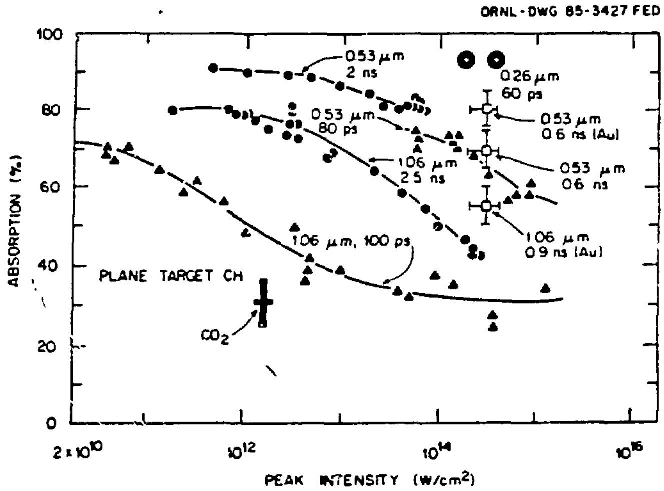

Fig. 4. Short wavelengths, long pulse lengths, and low intensities yield high absorption efficiency.

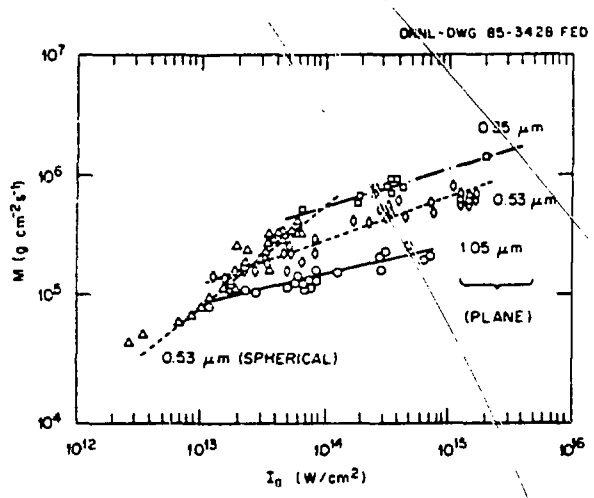

Fig. 5. Mass ablation rate vs laser intensity for spherical and planar targets and various laser wavelengths. (From Ref. 9.)

The fueling requirements determine the size of the ablated pellet entering the plasma, but not the unablated pellet size. It is possible to trade off mass ablation for energy, provided the laser pulse mass ablation rate is not exceeded. Figure 6 shows the relationship between energy per pellet and the ratio of the ablated pellet mass (M_p = 2.3 mg) and the pellet mass before ablation. The minimum energy per pellet occurs when the mass ratio is about 0.4, but even with a KrF laser, the pulse time is 240 ns. The two design points shown in Fig. 6 correspond to the data given in Table 3 for a KrF laser-driven fueling system. Note that lower energy design point requires a laser pulse time of 145 ns, compared to 70 ns for the higher energy design point. If the pulse time must be ≤ 100 ns, the low energy design will not meet the requirements.

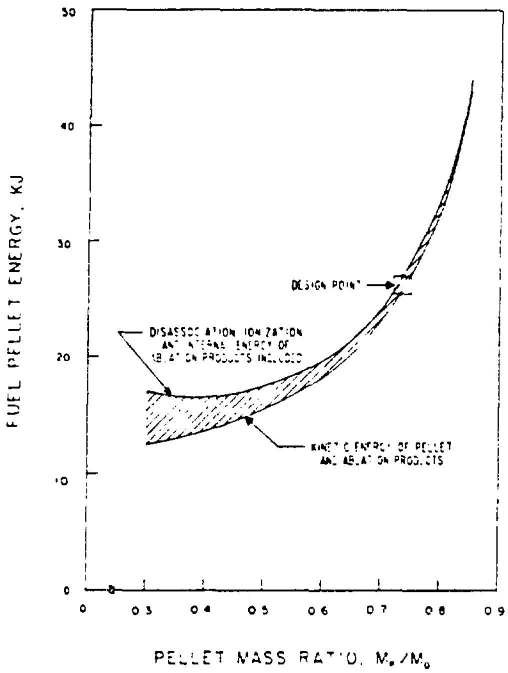

Fig. 6. Energy in pellet and pellet ablation products for a pellet bubble mass of 2.8 mg with a forward velocity of 45 km/s.

Tandem Mirror Reactor Systems Code (TMRSC) Fueling

Previously, the Fusion Engineering Design Center (FEDC) Tokamak Systems Code fueling was based using only pneumatic guns and gas injection systems to meet all fueling requirements. Because of the wide variation of TMRs and their fueling requirements, the TMRSC fueling module selects from among several fueling systems or combinations thereof. One programmable pellet rate (PR1) and two programmable pellet velocities (PV1 and PV2) were provided for the logic selection. If the required pellet rate PR ≤ PR1, and pellet velocity PV ≤ PV1, a pneumatic gun is selected. If the PR > PR1 and PV ≤ PV1, a centrifugal pellet injector is selected. If the required pellet velocity is > PV1, but ≤ PV2, a second-stage electromagnetic rail gun is added to a pneumatic gun or centrifugal injector, depending on the required PR. If the required PV is > PV2, the laser ablated pellet accelerator is added to a pneumatic gun pellet launcher. Currently, PR1 = 10 s^{-1}, PV1 = 2 km/s and PV2 = 12 km/s. These limits can be changed to accommodate improvements and projected costs of the several types of injectors.

Research and Development

Research and development are needed on a timely basis to establish a better physics basis for determining the fueling requirements and for computer modeling. Research and development experiments are also needed to establish the engineering feasibility and limitations of pellet acceleration with EM rail guns or laser drivers that transform fuel pellets into high pressure plasmas that can penetrate the confinement magnetic field.

Table 3. Requirements and design data for a KrF laser-driven fueling system.

Description	40% ablation	26% ablation
Final fuel pellet mass, mg	2.8	2.8
Fuel pellet ablation mass, mg	1.9	1.0
Total mass of launched fuel pellet, mg	4.7	3.8
Initial pellet diameter (D=H), mm	2.9	2.7
Maximum pellet rate, s^{-1}	10.0	10.0
Pellet gun launch velocity, km/s	1.0	1.0
Final laser-driven velocity, km/s	46.0	46.0
Absorbed laser energy per pellet, kJ	19.7	26.8
Laser beam energy at the pellet, kJ (75% beam intercept-absorption efficiency)	26.3	35.7
Laser beam intensity at pellet surface, W/cm^2	2.3×10^{12}	6.7×10^{12}
Maximum pellet ablation rate, $g/cm^{-2}s^{-1}$	2.0×10^5	2.5×10^5
Laser pulse duration, ns	145	70
Average ac power for KrF laser, MW (10 pellets/s, 90% transmission efficiency, 5% laser efficiency, 90% power conversion efficiency)	6.5	8.8

References

1. "A Tandem Mirror Technology Demonstration Facility," UCID-19328, Lawrence Livermore National Laboratory, October 1983.
2. "MFTF-Alpha+T Progress Report," ORNL/FEDC-83/9, Oak Ridge National Laboratory, April 1985.
3. "Fusion Power Demonstrations I and II," UCID-19975-1, Lawrence Livermore National Laboratory, January 1985.
4. "Fusion Power Demonstration III", UCID-19975-2, Lawrence Livermore National Laboratory, July 1985.
5. S. L. Milora et al., "Results of Hydrogen Pellet Injection into ISX-B", ORNL/TM-7422, Oak Ridge National Laboratory, September 1980.
6. S. L. Milora, "Review of pellet fueling," *J. Fusion Energy*, vol. 1, no. 1, 1981.
7. R. S. Hawke, "Fusion fuel pellet injection with a railgun," *J. Vac. Sci. Technol.*, April 1983.
8. F. S. Felber, "Laser Acceleration of Reactor Fuel Pellets," GA-A14781, GA Technologies, December 1977.
9. B. Badger et al., "Progress in Fusion Research," 1978-1982, UFWDM-496, University of Wisconsin, Revised September 1983.

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