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# A SURVEY OF LINEAR MAGNETIC FUSION REACTORS*

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The promise and problems of Linear Magnetic Fusion (LMF) for the generation of electrical power are surveyed. A number of axial confinement schemes are described and compared on an n· basis. Likewise, the range of heating methods is described. The results of seven conceptual LMF reactor design studies are summarized with an emphasis on the interfaces between reactor operation, confinement scheme, and heating methods.

## I. INTRODUCTION

Since the inception of controlled thermonuclear fusion research, the attractiveness of plasma confinement in linear geometries has been apparent. The excessive plasma length required to sustain the D-T plasma density at thermonuclear temperatures against free-streaming endloss for times sufficient to achieve a net energy breakeven led to early abandonment of Linear Magnetic Fusion (LMF) in favor of closed geometries. The attractions of LMF, however, remain: proven heating methods, neutrally-stable plasma equilibrium, high plasma density and beta, accessible and convenient geometry. Two LMF workshops[1,2] have recently addressed the primary obstacles to LMF: axial particle/energy confinement and total system length. Although free-streaming endloss has been the subject of experimental and theoretical study, methods of particle/energy endloss reduction relative to the free-streaming case until very recently have received little in-depth consideration.

Conceptual LMF reactor designs reflect a rich array of potential heating and axial confinement options. Heating to ignition by a combination of beams (neutral atoms,[3] relativistic electrons,[4] lasers[5,6], fast implosions coupled with adiabatic compression[7,8] and high-frequency heating[9] have been proposed and investigated. Endloss reduction by the following techniques has been proposed: material endplugs, re-entrant endplugs, electrostatic trapping, simple mirrors, multiple mirrors, cusped fields, reversed fields, high-frequency stoppering, plasma-gun injection. Only the first five of these end stoppering methods have received consideration in a reactor embodiment,[4-8,10] and experimental studies under reactor-like plasma conditions are nonexistent.

This survey of the LMF approach to fusion power first reviews and stresses the physics scaling and its reactor implication, after which a summary of LMF reactor concepts which have considered one or more of the abovementioned heating and confinement schemes are described and compared. Specifically, the Laser-Heated Solenoid (LHS),[5,6] the Electron-Beam-Heated Solenoid (EBHS),[4] the Linear Theta Pinch (LTP),[8] and the Steady-State Fusion Burner (SSFB)[11] are discussed. Included also are the very dense systems, such as the slowly

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imploding liner (LINUS),[12] the Fast-Liner Reactor (FLR),[13] the Dense-Z-Pinch Reactor (DZPR),[14] and approaches that have proposed multiple-mirror confinement.[3,15] Although the Dense Plasma Focus (DPF), the Field-Reversed Mirror (FRM), and the Tandem Mirror Reactor (TMR) logically belong to the LMF class of confinement schemes, in the cause of brevity these concepts will not be treated.

## II. LMF REACTOR PHYSICS AND SCALING

The broad and diverse nature of LMF allows within the constraints imposed by this survey only a brief and simplified presentation of those physics points (confinement, heating, stability/equilibrium) that are crucial to reactor performance. The trends presented here should be used for comparative purposes and must be tempered by inherent assumptions and the corroboration between theory and experiment.

### A. Confinement

For most LMF concepts radial confinement is provided by axial magnetic field, which, except for the field-reversed configurations,[12,16,17] result in open field lines and a potentially efficient channel for plasma particle/energy loss. Axial confinement, therefore, is a major issue for LMF that is being addressed by a variety of methods to reduce the axial loss rate, to stopper or plug the ends, or to achieve a significant net fusion gain in times that are short compared to axial loss times. It is not surprising that a majority of LMF concepts envisage pulsed operation. Except for LMF concepts which require very small plasma radii (e.g. LHS, EBHS, FLR), radial confinement appears as a secondary issue. With one exception,[18] experiments have not confined plasma for sufficient periods to measure radial effects.

The confinement issue, therefore, becomes one of axial loss; with few exceptions, LMF concepts simply do not exhibit axial equilibrium. The following axial containment schemes have been proposed: free-streaming, simple mirrors, material endplugs, re-entrant endplugs, cusped endplugs, and multiple mirrors. The reactor implications of each are summarized below.

#### 1. Free-Streaming Endloss (FS)

A cylindrical plasma column of length $\ell$(m) that has been instantaneously heated to a temperature T(keV) will flow axially from the confinement region in a time $\tau_{FS} \simeq \ell/v_{iTH}$, where $v_{iTH}$ (m/s) is the ion thermal speed. The transient behavior of the associated area waves, self-mirroring and magnet throat conditions, and diffusion profiles have been quantified theoretically[19,20] and experimentally.[21] A comparison of theory and experiment is shown on Fig. 1 in terms of a parameter $\tau_{EL}$, where

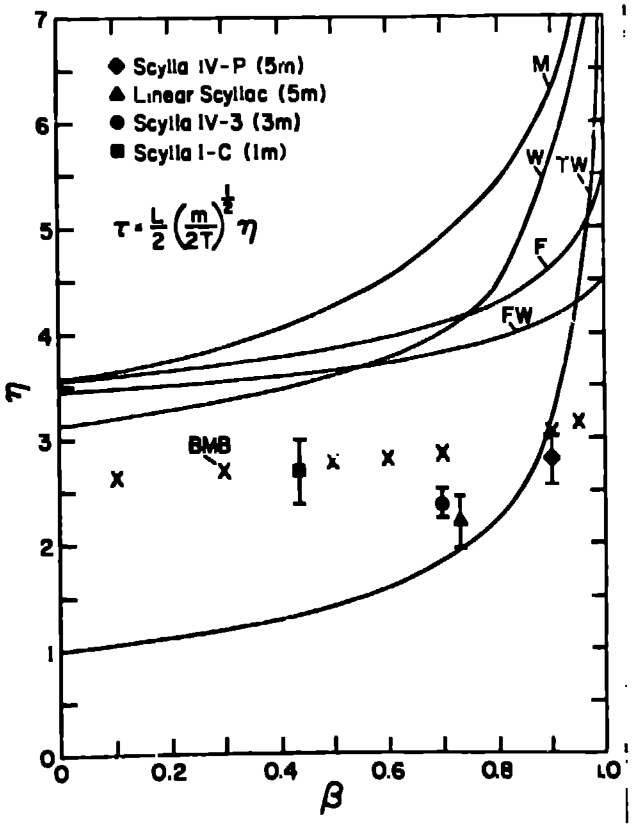


FIGURE 1. A comparison of theory and experiment for free streaming endloss from a LMF device[21]: M(Ref. 22), W(Ref. 23), TW(Ref. 24), F(Ref. 25), FW(Ref. 19), 3MB(Ref. 20).

$\tau_{EL} = r_{EL}(m/2kT)^{1/2}\ell/2$. Expressed in terms of an $n\tau$ criterion, and using pressure balance ($\beta B^2/2\mu_0 = 2nkT$), the following expression results.*

$$(n\tau)_{FS} = 2.24(10)^{15}\beta r_{EL}(B^2\ell)/T^{3/2} \quad . \qquad (1)$$

In comparing this criterion with those generated for other axial flow conditions, $r_{EL}$ is taken to be 2.5 (Fig. 1). For T = 10 keV, $\beta$ = 0.8, and $n\tau = 10^{21}$ s/m$^3$, Fig. 2 depicts the relationship between B(T) and $\ell$(m); for B $\leq$ 20 T lengths in excess of 15 km would be required to achieve "inertially" the specified $n\tau$ value in the presence of free-streaming endloss.

## 2. Material Endplugs (MEP)

Since the first proposal[26] to insert ablative materials into the end regions of an LMF device, experiments have been performed,[27] and Fig. 3 illustrates preliminary

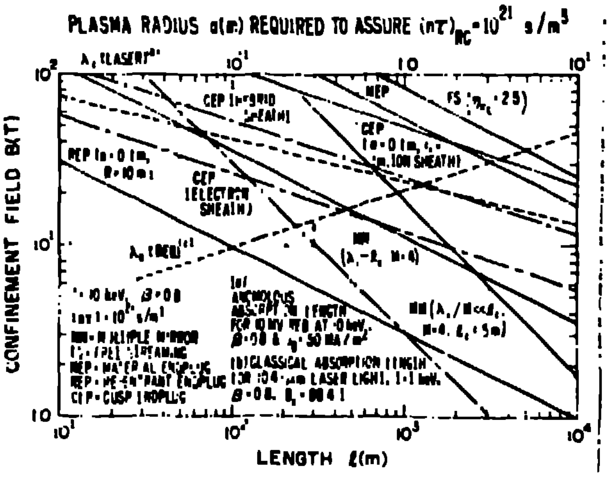


FIGURE 2. Dependence of field B(T) on plasma column length $\ell$(m) for various end stoppering schemes to assure $n\tau = 10^{21}$ s/m$^3$ when $\beta$ = 0.8 and T = 10 keV: FS(free streaming), MEP(material endplugs), REP(re-entrant endplugs), MM(multiple mirrors), and CEP(cusp endplugs). Also shown as a function of B(T) are laser absorption length, REB absorption length, and plasma radius a(m) for radial conduction.

*Except for plasma temperature T(keV), mks units are consistently used.

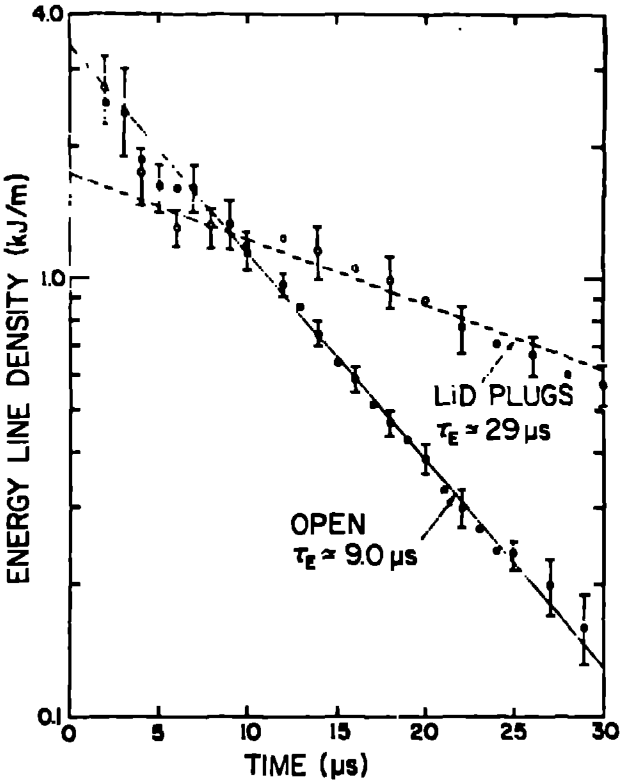


FIGURE 3. Experimentally observed increase in energy confinement time resulting from the use of material endplugs.[21,27]

experimental evidence that a low-atomic number MEP can significantly reduce the axial particle flow. Under the assumption that an ablative MEP can effectively support the axial plasma pressure, the free-streaming endloss problem is transformed into one of axial (parallel-field) thermal conduction by electrons. It is easily shown[28] that the energy flux conducted to a cold MEP is $P_\parallel(W/m^2) = (16/7)k_e T/\ell$, where $k_e = 9.8(10)^{14}T^{5/2}/\ln\Lambda$ is the classical (electron) thermal conductivity,[29] and all quantities are evaluated at the axial center. Defining a conduction time as $(3/2)nkT\ell/P_\parallel$, setting the Coulomb logarithm $\ln\Lambda$ = 17, and using pressure balance the following $n\tau$ criterion results for the MEP case

$$(n\tau)_{MEP} = 2.81(10)^{12}\beta^2(B^2\ell)^2/T^{9/2} \quad . \qquad (2)$$

Eqn. (2) is compared to the FS case on Fig. 2; little improvement relative to the FS case is indicated. Since any deviation from classical conductivity enters under a square root, reductions in $k_c$ of at least two orders of magnitude will be required before significant improvements in the MEP situation depicted in Fig. 2 results. Including the constraint of alpha-particle confinement makes this prediction even worse.[28]

3. Reentrant Endplugs (REP)

A second approach to the LMF axial endloss problem would return to the plasma column a significant part of the conduction and non-thermalized alpha-particle energy that normally would be lost to a cold MEP. The reentrant endplug (REP) concept[1,30] proposes two parallel LMF devices supplying each other with a portion of the thermal conduction losses by means of marginally-stable and short "U-bend" end sections. Preliminary LMF reactor studies[8] show that this approach can yield interesting reactor designs that are a few hundred meters in length and require modest fields ($B \sim 10$ T) for a linear-to-REP volume ratio of $\sim 10$ and cross-field conduction times in the end region less than ten times classical predictions. Furthermore, the REP approach provides a loss mechanism which may make possible nearly quasi-steady-state (long-pulsed) operation. The loss mechanism(s) in the REP region remain unquantified at this time, although MHD activity, micro-turbulence, and cross-field (ion) diffusion will certainly occur; both relatively poor equilibrium and stability in the "U-bend" sections, however, may be tolerable. For the purposes of the present analysis, the confinement time is taken as that associated with cross-field thermal conduction in a REP plasma of radius a(m) and a linear-to-REP plasma volume ratio of $\ell/\pi R$, where R(m) is the radius of the REP section. Only the trapped field within the plasma is assumed to contribute to conduction resistance. Using pressure balance, the effective $n\tau$ for the REP case becomes

$$(n\tau)_{REP} = 1.60(10)^{20}(1-\beta)(a^2/R)(B^2\beta)T^{1/2} \quad . \quad (3)$$

The predictions of Eqn. (3) are compared to the FS and MEP cases on Fig. 2 for a = 0.1 m and R = 10 m. The promising results given in Fig. 2 and Ref. 8 must be tempered with the many physics uncertainties. The use of internal rings, axial currents, and high-beta stellarator configurations have been suggested as means to achieve the required poor-to-marginal toroidal-like equilibrium and stability in the REP sections.

4. Cusp Endplugs (CEP)

Reduction of the cross-sectional area for particle and energy flow, while simultaneously maintaining a large cross section in the bulk plasma, represents another approach to reduce the free-streaming endloss process. Although the application of simple mirrors to each end of the plasma column effectively achieves this goal, it is well-known[7,31,32] that this configuration induces unstable MHD activity (particularly, ballooning and interchange modes). Line tying considerably reduces this MHD activity, but the increased conduction losses may be intolerable. The use of a simple cusp geometry represents another method to reduce the flow area at the ends of the device. For a spindle cusp of radius $R_c$(m) and sheath thickness $\Delta_s$(m), the flow area is $2\pi R_c\Delta_s$ (neglecting the point cusp), and the potential reduction in flow area relative to the column area $\pi a^2$ is $2R_c\Delta_c/a^2$. If $\Delta_s$ equals an ion gyro-radius $r_i(m) = 8.85(10)^{-3}T^{1/2}/B$, then the expression for an effective $n\tau$ parameter becomes

$$(n\tau)_{CEP} = 3.17(10)^{17}\,(a^2/R_c)B^3/T^{5/2} \quad . \quad (4)$$

If $\Delta_s$ could be as small as an electron gyro-radius, $r_e$, $(n\tau)_{CEP}$ would be increased by

$(m_i/m_e)^{1/2}$ = 67.6, whereas if a hybrid gyroradius[33] $(r_e r_i)^{1/2}$ better characterizes $\delta_s$, then $(n\tau)_{CEP}$ would be enhanced by a factor $(m_i/m_e)^{1/4}$ = 8.2. The relationship between the field B(T) and length $\ell$(m) needed to achieve $n\tau = 10^{21}$ s/m$^3$ at T = 10 keV and $\beta$ = 0.8 is illustrated on Fig. 2 for CEP sheath thicknesses equal to $r_i$, $(r_i r_e)^{1/2}$, and $r_e$, respectively, with a = 0.1 m and $R_c$ = 1 m. Although the case where $\delta_s \simeq r_e$ is attractive (e.g. $\ell$ = 500 m for B = 15 T), achieving and maintaining a sheath thickness on the order of an electron gyroradius seems unlikely.[33] For the case where $\delta_s \simeq r_i$, the simple CEP offers little advantage relative to the MEP or FS cases.

## 5. Multiple Mirrors (MM)

The use of axial corrugations or modulations in the magnetic field to reduce particle loss has been proposed and experimentally investigated. The multiple mirror configuration has been examined[34,35] as a means to inhibit the axial flow of a dense, wall-confined plasma by viscous drag, whereas other efforts[3,15,36] have focused on linked, average-minimum-B confinement. Radial energy confinement may present a problem for the wall-confined system, whereas MHD stability at high beta in an average-minimum-B configuration may require dynamic (rf) stabilization, feedback stabilization, complex field geometries (e.g. multipoles) or combinations thereof.

Application of a simple kinetic theory to MM systems[34,36] has indicated conditions where the sequential trapping-untrapping of ions in linked mirrors will lead to diffusion-like scaling (loss time $\propto \ell^2$); this behavior has been demonstrated experimentally for very low-density, cold plasma.[3] For a given mirror ratio M, the magnitude of characteristic system lengths (mirror-to-mirror cell length $\ell_c$, field gradient lengths $\ell_m$, low angle scattering mean-free-path length $\lambda$, and loss-cone scattering mean-free-path length $\lambda$/M) determine the confinement regime and hence scaling relationships. For the case where M>>1, $\lambda$/M $\simeq \ell_c$, $\ell_m \simeq \ell_c$, and $T_e = T_i = T$, the MM confinement time[3] is approximated by $M\ell^2/4\ell_c v_{iTH}$; when cast into an $n\tau$ criterion,

$$(n\tau)_{MM}^{\lambda/M\simeq\ell_c} = 9.93(10)^{14}\ell^2 M(B_o)^2/\ell_c T^{3/2} \quad . \quad (5)$$

On the other hand, when $\lambda \simeq \ell_c$, the MM confinement time is given by $M^2\ell^2/8\ell v_{iTH}$, which in terms of an $n\tau$ criterion becomes

$$(n\tau)_{MM}^{\lambda\simeq\ell_c} = 3.77(10)^{14}\ell^2 M^2 (B^2_o)^2/T^{9/2} \quad . \quad (6)$$

Although valid only for M>>1, weak mirrors can be described by these equations if M is replaced by the mirror modulation,[1] $\Delta$B/B = M-1. Equation (6) represents a near optimum case; an ion scattered into a loss cone of the $i^{th}$ mirror has a high probability of scattering out of the loss cone of the $(i+1)^{th}$ mirror, thereby undergoing a random-walk or diffusion-like process. Equations (5) and (6) are incorporated into Fig. 2 for the case $\ell_c$ = 5 m and M = 4. For a design with $\lambda \simeq \ell_c$ (Eqn. (6)), the B versus $\ell$ reactor requirements ($n\tau = 10^{21}$ s/m$^3$, $\beta$ = 0.8, T = 10 keV) are comparable to the optimistic CEP($\delta_s = r_e$) scaling predictions. As for all mirror systems the strong temperature scaling makes the mirrors less effective as T increases. Enhancement of non-adiabatic scattering at high beta may overcome this problem,[3,37] but the question of MHD stability remains.

## 6. Radial Confinement

The following expression based on classical thermal conduction gives the effective $n\tau$ parameter for radial heat conduction

$$(n\tau)_{RC} = 5.04(10)^{20}(1-\beta)T^{1/2}B^2a^2 \quad . \quad (7)$$

Setting $(n\tau)_{RC}$ equal to $10^{21}$ s/m$^3$, T = 10 keV and $\beta$ = 0.8 gives Ba = 1.78 Tm, which is also shown on Fig. 2. Since particle diffusion transverse to field lines involves electron-ion collisions, the relevant diffusivity is decreased, and the associated $n\tau$ is correspondingly increased by approximately $(m_i/m_e)^{1/2} = 67.6$.

On the basis of this analysis LMF devices operating with moderate fields ($B < 20$ T) and lengths ($\ell < 500$ m) appear feasible only for the REP and MM approaches. Approaches which invoke the MEP or CEP and still maintain $\ell < 1000$ m must operate at $\beta \simeq 0.8$ plasma densities that are equivalent to fields of 40-50 T. This high-field approach to LMF is characterized by the Laser Heated Solenoid (LHS),[5,6] which has chosen to address magnet-design[38] and first-wall[39] technology problems rather than evoke the unresolved physics of high-$\beta$ MM or REP approaches, although LHS reactor designs have assumed some degree of unspecified end stoppering. On the other hand, the Linear Theta-Pinch Reactor (LTPR)[8] and the Electron-Beam Heated Solenoid (EBHS)[4] approaches to LMF have selected, respectively, the REP and MM axial confinement schemes in order to ease these technological problems. An important ingredient in making the respective choices for axial confinement is the plasma heating scheme proposed by each.

B. Heating

The flexibility of employing a variety of heating schemes and combinations thereof is claimed as a major advantage for LMF. The open ends which present a crucial containment problem can generally be viewed as an advantage insofar as rendering flexibility and access for purposes of heating. From the view point of an overall system a given (axial) confinement scheme interacts with and strongly influences the heating method.

1. Adiabatic Compression

Adiabatic compression is an effective and proven means to heat a fluid and is particularly applicable to high-beta plasmas wherein the magnetic "piston" can be directly and effectively coupled to both ions and electrons. The efficiency of adiabatic compression $\eta_{AC}$, as measured by the increase in plasma thermal energy $3n_okT_o(T/T_o-1)$ relative to the magnetic energy needed to fill the volume $V_o-V$ created by the displaced plasma, rapidly decreases as the volumetric compression $1/x = V_o/V$ is increased. It is easily shown that

$$\eta_{AC} = \frac{1}{\gamma-1}\left(\frac{x}{1-x}\right)\frac{1-x^{\gamma-1}}{x^{\gamma-2}(1-\beta_o)/\beta_o+1} \quad , \tag{8}$$

where $\beta_o$ is the initial pre-compression plasma beta $(2n_okT_o/(B_o^2/2\mu_o))$. The dependence of $\eta_{AC}$ on $x$ and $\beta_o$ is depicted in Fig. 4, which also shows the dependence of $T/T_o$ for a lossless compression. This behavior clearly illustrates the desire to keep $T/T_o$ as small as possible, which in turn points to the need for significant preheating (i.e. $T_o \gtrsim 1$-2 keV). For this reason the FLR[13,40] requires preheating by gun injection, the LHS invokes preheating by $CO_2$-laser beams,[6,41] and implosion pre-heating is proposed for the LTPR.[8]

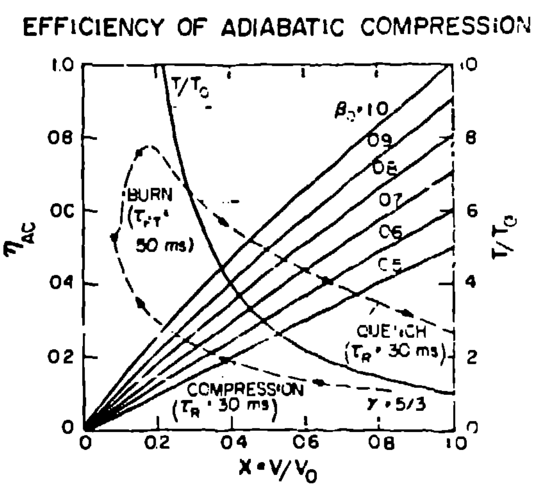


FIGURE 4. Dependence of adiabatic-compression heating efficiency $\eta_{AC}$ on volumetric compression x for a range of initial beta values $\beta_o$. Shown also is the adiabatic relationship for $T/T_o$ as well as the results of a time-dependent "adiabatic" compression, burn, and decompression.

In actual systems the compression to ignition will not be adiabatic, in that over the finite compression (and expansion) time $\tau_R$ radiation losses and alpha-particle heating will occur. Shown on Fig. 4 is a time-dependent plasma compression, illustrating that for a 30-ms compression time bremsstrahlung radiation makes the compression much more sluggish (and less efficient); after ignition has occurred, plasma cooling is delayed becsuse of residual alpha-particle heating. Generally, the use of a significant amount of adiabatic compression to achieve ignition and the lowered efficiency associated with the large compressions will require some degree of reversible recovery of the magnetic energy stored in the reactor chamber.[7,8,41,42] Although the attractiveness of adiabatic compression must ultimately be weighed against the method of preheating, like ohmic heating,[43,44] the natural and close association of adiabatic compression heating with the primary confinement scheme represents its primary attraction.

2. Implosion Heating

Implosion heating is one of the more notable successes of the theta-pinch LMF program, having yielded thermonuclear conditions (2-4 keV at $\geq 10^{22}\ m^{-3}$ densities) when used in conjunction with adiabatic compression. The implosion phase is well understood[7,45] both theoretically and experimentally. The high electric field $E_\theta$ (kV/mm) required to achieve a pre-compression temperature $T_o$(keV) for a given initial filling pressure $P_A$(mTorr) is given for the simple "bounce" model by[42]

$$E_\theta = 0.065\ P_A^{1/2}\ T_o \qquad (9)$$

and is independent of plasma (volume) compression ($x^* = 2/5$); for $\beta \simeq 1$, the heating efficiency, defined similarly to that leading to Eqn. (8), corresponds to $(3/2)x/(1-x) = 1$. Although these relatively uncompressed plasmas are desirable from the view point of wall stabilization of m = 1 MHD modes,[46] the high voltages required make implosion heating impractical for achieving ignition. Consequently, implosion heating is viewed[8,42,46] as a preparatory stage to adiabatic compression. Although the high voltages (optimally $E_\theta$ = 0.1-0.2 kV/mm for $T_o \sim 1$ keV) *per se* do not present particularly difficult problems, these voltages will appear within the reactor blanket and at the first wall, the critical formation of the implosion sheath dictates a minimum first-wall radius ~ 0.1 m, the fast-rising (1-2 μs) implosion fields must be pushed through electrically insulated blanket segments, and the required capacitive energy store is expensive; these factors combine to limit implosion heating in a reactor embodiment to a preheating function despite the unparalleled success of this method in routinely and predictably producing high-quality thermonuclear plasma.

3. Laser Beam Heating

If a high-powered laser beam directed along the axis of a LMF device could be refractively focused and efficiently absorbed by the solenoidally confined plasma column,[26] a heating method presents itself that can physically be decoupled from the reactor core. Similar to implosion heating, this approach has been proposed[5,6,41] as a method to preheat or "stage" into a subsequent adiabatic compression. Experiments have shown the tendency for 10.6-μm laser light to be trapped within a plasma column,[47] and 50-100 eV electron temperatures in plasmas of $10^{23}$-$10^{24}\ m^{-3}$ densities have been reported.[47-49] An $n\tau = 10^{19}\ s/m^3$ experiment has been designed to generate ~ 1 keV plasmas.[50]

For electron densities below the cut-off absorption value $\sim 10^{27}/\lambda\ (m^{-3})$, where $\lambda$ (μm) is the laser-light wavelength, the classical inverse-bremsstrahlung absorption length $\lambda_a$ is given by[51]

$$\lambda_a(m) = 2.36(10)^{11}\ T^{7/2}/(\lambda ZB^2)^2/(\ldots), \qquad (10)$$

which is depicted on Fig. 2 for $T = 1.0$ keV, $Z = 1$, $\lambda = 10.6$ μm and $\ell n\Lambda = 10$; for these conditions fields at $\lambda = 0.8$ in excess of 42 T are needed for $\ell_a \simeq 100$ m; the required length increases to 1200 m if T is increased to 2 keV. The presence of Brillouin backscattering,[48,49] however, can reduce the desired beam-plasma coupling. Multiple passing of the laser light or the use of longer wave-length lasers may be required if anamolous absorption does not occur; LHS reactor studies[6,41] assume a factor of 10 better absorption than predicted by Eqn. (10) or, equivalently, 10 multiple beam passes or the existence of a 34-μm high-powered laser. In dealing with this potential problem, the LHS reactor embodiment involves relatively dense ($\sim 10^{24}$ $m^{-3}$) plasmas, which must be confined in high-field (25-35 T) small-bore (0.05-0.10 m) hybrid magnets; a laser-preheated, staged compression burn cycle is proposed[6,41] in which the laser is used with greater efficiency to produce a ~1-2 keV subignition plasma prior to adiabatic compression to ignition. Because of constraints not unlike those cited for implosion heating, the technological and economic necessity to limit the total laser energy has naturally lead to the staged LHS reactor. In this way the physics of LHS heating couples to the endloss process, in that, if technological solutions to the high-field magnet and high-heat-flux wall problems can be found, the $B^2\ell$ scaling quantified for the MEP (Eqn. (2)) may be used to address the axial confinement/equilibrium problem.

## 4. Relativisric Electron Beam Heating

Relativistic electron beam (REB) current densities on the order of $10^9$ $A/m^2$ are state-of-the-art and represent a potent heating source for solenoidal LMF devices. The axial electric field induced in an REB-injected plasma drives an axial return current in the plasma. In order that the REB couple with the plasma in a reasonable distance, two kinds of anomalous processes are cited:[4,52,53] a) turbulent interactions between REB and plasma electrons (electron-electron modes or two-stream instabilities), and b) turbulent interaction between plasma electrons and ions (electron-ion modes). The electron-ion modes give rise to an effective dc resistivity associated with the scattering of slow electron waves off ion density fluctuations, whereas the fast electron-electron mode results in plasma heating by Landau damping mechanisms; both resistive return-current and non-resistive heating mechanisms occur. On the basis of these REB energy deposition mechanisms, a maximum deposition length can be derived[54,55]

$$\ell_a(m) = 1.90(10)^5(V_B \theta/J_B)^2 \lambda^{3/2} B^3/T^{3/2} \quad , (11)$$

where the REB voltages, rms angular divergence, and current densities are, respectively, $V_B(V)$, $\theta$, and $J_B(A/m^2)$. The dependence of $\ell_a$ on B is depicted on Fig. 2 for $V_B = 10^7$ V, $\theta = 0.25$, $J_B = 5.0(10)^8$ $A/m^2$, $T = 10$ keV, and $\beta = 0.8$. It is generally believed that the ions share little in the anomalous energy deposition; the REB is primarily a heater of electrons. As for laser heating, therefore, the confinement scheme that is coupled to the REB-heated solenoid must allow efficient ion-electron equilibration. For reactor applications[52] REB sources of 100 MW average power are required that can deliver 30-100 MJ/pulse at $J_B = 5(10)^8$ $A/m^2$ and $V_B = 10^7$ V; the AURORA REB system[55] generates several megajoule REB from a 5 MJ, 12 MV and 90% efficient Marx circuit.

As a means to create a plasma in a closed reversed-field configuration prior to adiabatic compression by a liquid liner, the LINUS concept[12] proposes the use of a rotating, annular REB. Rotation is produced by passing an annular REB through a magnetic cusp. When the REB exits the relatively short (~12 m) LINUS device, an ionized and pre-heated plasma results that supports the image currents necessary to sustain a closed-field configuration; the REB parameters for this application are $V_B$ = 3 MV, $I_B$ = 3 MA, and 40 MJ delivered in ~ . . .

5. Magnetoacoustic Heating

Magnetoacoustic heating (MAH) is applied to a cylindrical plasma by an oscillatory pumping of the confining magnetic field.[9,57] Unlike joule or beam (REB or laser) heating but like implosion heating, MAH can act preferentially on the ions if an appropriate dissipative mechanism is available. When the ratio of resonance frequency to ion-ion collision frequency is small, classical resistivity and ion viscosity provide the dissipation, and the experimentally observed plasma behavior[58] can be described theoretically by viscous magnetohydrodynamics. At higher ion temperatures, when the resonance frequency is much larger than the ion-ion collision frequency, classical dissipation is no longer sufficient to account for the experimentally observed heating effects. Recent theoretical results[59] in both regimes indicate ion heating times in the milliseconds range for reactor conditions.

From the reactor view point the use of gradual MAH has the potential advantage that the induced in-core electric fields, compared to implosion heating, may be considerably smaller. MAH also presents an attractive continuous source of energy for operating a LMF device as a "wet wood burner."[7,59] A comprehensive study of the potential advantages and problems for reactor-like applications of MAH, however, is not available.

6. Alpha-Particle Heating

The 3.5-MeV alpha particles produced in D-T reactions represent a significant source of energy in a thermonuclear plasma. If this energy can be transferred to the ions, the efficiency of the reactor can be enhanced. On the other hand, anomalous transport and long-wavelength plasma instabilities driven by alpha particles can be detrimental to plasma confinement. Classical scattering at LMF plasma densities causes fast alpha particles to transfer about half their energy to the plasma in a range of several kilometers; some degree of alpha-particle confinement, therefore, is necessary. Among the proposed end stoppering schemes, multiple mirrors that would confine some fraction of the alpha particles, and re-entrant endplugs that would retain almost all the alpha particles seem most promising. Classical alpha-particle scattering, however, primarily heats the electrons thereby increasing radiative losses; this effect should not be strong, since most LMF devices would operate with nearly equal electron and ion temperatures. Anomalous scattering associated with microturbulence may permit direct transfer of the alpha-particle energy to the ions, as well as provide much shorter mean-free-paths for thermalization. The influence of classical alpha-particle thermalization on the ignition of an MEP-stoppered LMF device has been examined,[28] and Fig. 5 gives the dependence of $B^2\ell$(ignition) on the axial center temperature and the degree of anomalous decrease in parallel-field thermal conductivity; even with total elimination of the thermal conduction loss ($k/k_c$ = 0 on Fig. 5) for the MEP case,

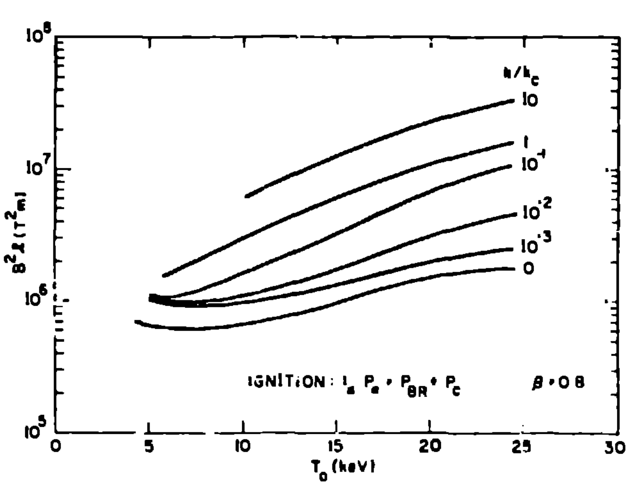


FIGURE 5. Dependence of $B^2\ell$(ignition) on axial center temperature for a LMF device with material endplugs, including the constraint of classical alpha-particle thermalization.[28]

the alpha-particle thermalization constraint still requires substantial $B^2 \ell$(ignition) values.

In general, alpha-particle heating for LMF devices is a crucial issue from both the view point of heating and confinement. Unfortunately, because of the theoretical difficulty in analyzing thermalization processes in finite geometries, this aspect of reactor-related plasma and energy balance modeling has received only cursory treatment to date.

## C. Stability and Equilibrium

Hot and dense plasmas produced in straight solenoidal geometries have been shown both experimentally[60,61] and theoretically[31,32] to exhibit radial equilibrium and neutral stability. The m = 1 "wobble" MHD instability, which is believed to be induced by partial shorting of radial electric fields in the plasma at the end region,[62] saturates at a low amplitude, is not observed for large radius plasmas (radius approximately equal to half of the wall radius), and is completely damped by the use of a MEP.[27] Recent theoretical work[63] indicates that finite-Larmor-radius effects are responsible for the stabilization of higher mode rotational instabilities. Although LMF devices generally should be stable to non-ideal MHD rotational instabilities, the question of curvature-driven instabilities (ballooning and interchange modes), such as those expected at high beta in multiple mirror configurations, is unclear; finite-Larmor-radius and wall-stabilization effects may play an important stabilizing role, but some form of feedback or dynamic stabilization may be required. Although the simple theta-pinch configuration permits operation outside the plasma parameter range where resistive and collisionless tearing modes are active, LMF approaches that operate with trapped or reversed field may have to deal with this problem.

In summary, although the charactistic of neutral stability for LMF is generally valid, this claim must be examined more carefully in the context of the specific heating and axial confinement schemes being proposed. For instance, beam-driven instabilities which enhance radial field or particle transport may become crucial for LMF concepts that require very small radii plasmas. Other anomalous phenomena related to the particular heating scheme may also reduce the final plasma beta, thereby diminishing the overall efficiencies projected for specific LMF reactor embodiments.

# III. SUMMARY DESCRIPTION OF LMF FUSION REACTOR CONCEPTS

The essential elements of most LMF approaches to fusion power are determined in large part by the benefits and limits of particular confinement and heating schemes invoked. The intent here is to present only a qualitative summary of each design as they presently exist; the variability in study level, physics assumptions, and projection of certain technologies all combine to make a quantitative comparison inadvisable at this time. An emphasis is placed, however, on both the general merits and problems anticipated for each approach. The results of an ongoing comparative assessment by Electric Power Research Institute and Bechtel Corporation[64] on the basis of economic and technology guidelines, however, should be of significant value in making a more quantitative assessment. It is also noted that of the seven LMF concepts reviewed here only the Laser Heated Solenoid (LHS)[5,6,41] and the Electron-Beam Heated Solenoid (EBHS)[4,52] reactors have received indepth study, although a significant part of the toroidal Reference Theta-Pinch Reator (RTPR) study[42,46] is applicable to the Linear Theta-Pinch Reactor (LTPR)[8] concept. Since the few reactor design parameters cited are based on either interim or older values, they should be viewed only as indictative, and no comparative assessment is implied or intended.

A. Laser-Heated Solenoid (LHS)[5,6,38,41]

Because of previously noted limitations on coupling 10.6-μm laser light to the plasma and the desire to minimize both total laser energy (50-75 MJ) and reactor length (≲500 m), the LHS envisages at least four small bore (.05-m radius first wall) plasma chambers embedded into a ~1.5-m radius blanket. The $2.0(10)^{23}$ $m^{-3}$ dense plasma is heated to 1.7 keV by laser absorption that is enhanced over the predictions of inverse-bremsstrahlung absorption by a factor of 10; multiple-pass heating is proposed. The 28-T compression field that brings the plasma to a ~18-mm ignition radius is generated by nulling an 18-T superconducting field with a normal, room-temperature coil located immediately behind the first wall. The firing sequence for a nominal 20-ms burn pulse is shown in Fig. 6, and a 4-s dwell time between sequential burn pulses in each of the four plasma chambers is envisaged. In order to achieve a 20-ms burn in a 500-m long device, an unspecified axial confinement was assumed to an extent

BURN SEQUENCE FOR STAGED LHS

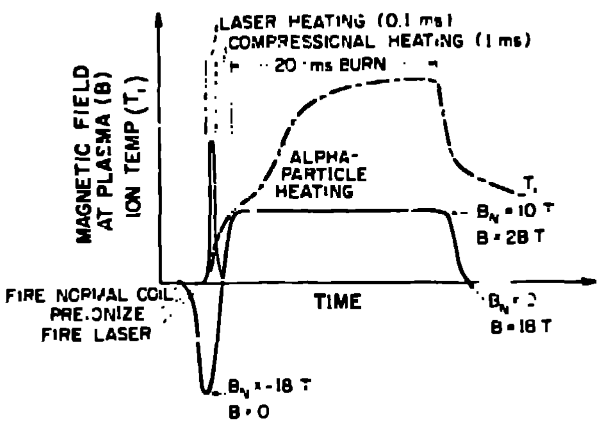


FIGURE 6. Typical burn cycle for a staged Laser Heated Solenoid (LHS) using axial confinement that is 10 times better than free streaming.

that allows the burn to occur for ~ 8 free-streaming endloss times or ~ 4 thermal conduction times (if a MEP was employed). The pulsed normal magnet requires 1.3 GJ of homopolar motor/generator storage,[45] and 770 MWe(net) of electricity at 3.4 MW/$m^2$ fusion neutron wall loading is produced with a recirculating power fraction of 0.25 and a total system power density* of 0.25 MWt/$m^3$. The advantages of a decoupled pre-heating source (i.e. the laser), the possibility of high-field LMF in the small-bore coils, and the relatively high plasma filling fraction (reduced magnetic energy storage and transfer requirements) must be weighed against the problems and/or uncertainties associated with severe thermal pulses and neutron doses at the first wall magnets, the unresolved end-stoppering and laser-absorptivity factors, the large laser energy and power densities (50-75 MJ, $10^{14}$-$10^{16}$ W/$m^2$), and the lower margin allowed for the effects of anomalous radial transport.

B. Electron-Beam Heated Solenoid (EBHS)[4,52]

The EBHS concept proposes the injection of a ~30-MJ, 10-MV REB into a plasma of 17-mm radius and 275-m length to provide the total heating required for ignition. The 80% efficient REB source would deliver a total current of 0.45 MA (500 MA/$m^2$) along a 5.9-T guide field; the 15.3-T confining field would be produced by superconducting coils. The 334 MWe(net) power is achieved with a recirculating power fraction of 0.35 and a 260-ms pulse period to give a first-wall fusion neutron wall loading of 4 MW/$m^2$ from the single plasma chamber. The total system power density is 0.73 MWt/$m^3$.

The burn cycle proposed for the EBHS, as illustrated in Fig. 7, would inject along a guide field cold plasma (few eV) from annular plasma guns located co-axially with and in front

*Defined always as the total thermal power divided by the volume enclosed by the confinement system.

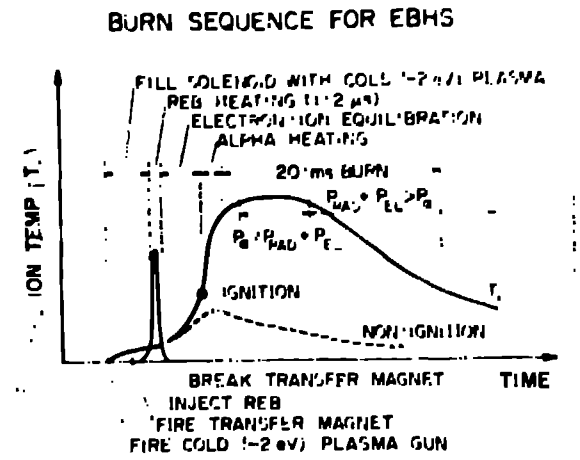


FIGURE 7. Typical burn cycle for an Electron Beam Heated Solenoid (EBHS) using multiple mirror confinement.

of the REB diode structure at each end of the device. After radially expanding the guide field to the vicinity of the annular REB diode by means of a transfer magnet, the REB is guided along the magnetic field lines into the plasma chamber after being compressed by a factor of 10. The transfer magnet then forces in ~1 ms the solenoidal fields radially inward and through the annular REB cathode to protect that part of the REB apparatus from the eventual plasma loss. The REB energy is assumed to be uniformly deposited along the interaction length given by Eqn. (11) to an extent sufficient to cause a stationary burn (alpha-particle deposition equals radiation losses). The 20-ms high-beta burn period at $2.1(10)^{22}$ $m^{-3}$ density is assumed to occur uninhibited by endloss through the use of feedback-stabilized multiple mirrors; a scaling similar to that given by Eqn. (6) is used, with the assumption of non-adiabatic scattering in the presumed very sharp mirrors. The vacuum mirror ratio was taken to be 2, although the effective, high-beta mirror ratio could be as high as 4-6. Streaming plasma from the EBHS ends passes through the central hole in the annular REB cathode and must be expanded in radius by a factor of 500 to suppress secondary electron emission from and thermal conduction to the cooled endplates.

The unique feature and major attraction of the EBHS approach is the decoupling of the efficient primary (REB, 30 MJ) and secondary (plasma gun, 2-3 MJ) heating sources from the confinement system. This advantage is reflected by the fact that the EBHS achieves recirculating power fractions that are comparable to other pulsed LMF approaches, but with a tenth the [illegible] value. The required REB compression and transport, the general stability and efficiency of the REB-plasma interaction (radial beam diffusion, and dispersion, [illegible]), unresolved issues associated with the target plasma formation, the overall effectiveness and stability of high-beta multiple mirrors, the feasibility of thermally stable [illegible], and the question of radial plasma transport. [illegible], present uncertainties for this approach.

c. Linear Theta-Pinch Reactor (LTPR)[?]

The heating and (radial) confinement principles for the LTPR would be identical to those envisaged for the toroidal Reference Theta-Pinch Reactor[42,46], were it not for the rapid loss of plasma energy from the open ends. Hence, a pre-ionized D-T gas is heated by a fast (~1 μs) implosion (~0.1-kV/cm azimuthal [illegible] electric field) to temperatures of ~1 keV; this preheated plasma is subsequently compressed adiabatically to ignition temperatures (~5 keV), and a burn cycle occurs along a plasma radius/temperature trajectory determined primarily by the dynamics of an energetic, high-beta plasma. The LTPR study invokes the REP, wherein the endloss particles and energy emanating from a LTP are directed by a small radius-of-curvature conduit to a second, parallel plasma column. The plasma within the REP region may not necessarily be in "toroidal" equilibrium and will be subject to cross-field transport losses. An intermittent toroidal equilibrium may be established in the REP region which is similar to that envisaged for the

RFPR,[36] and the [illegible] would [illegible] to a [illegible] plasma [illegible] the [illegible] first wall. This [illegible] has not yet been fully resolved. The REP is assumed to contain 80% of the 3.5-MeV alpha particles. A typical LTPR burn cycle [illegible] determined by a time dependent, [illegible], 1-D (axial) burn and energy balance code, 1DBURN, is depicted on Fig. 8, which also lists key operating parameters. With a [illegible] power fraction of 0.21, a 2-MW/m² fusion neutron wall loading would result in a net electrical power of 83[illegible] MWe(net), a system power density of [illegible] MWe/m³, and a pulse frequency of 0.08 Hz [illegible]. The [illegible]-m long device uses a [illegible] m radius REP with a cross-field thermal conductivity [illegible]. Both the implosion and adiabatic compression coils are located [illegible] the [illegible]-m radius first wall and [illegible] blanket, operate [illegible], and require [illegible] GJ and [illegible] GJ of pulsed energy delivered in [illegible] s and 30 ms, respectively; reversible recovery of the adiabatic compression energy at 95% efficiency is specified.[35] The longer LTPR burns ([illegible] ms) relieve [illegible] the problems associated with pulsed thermal [illegible] of the first wall, energy

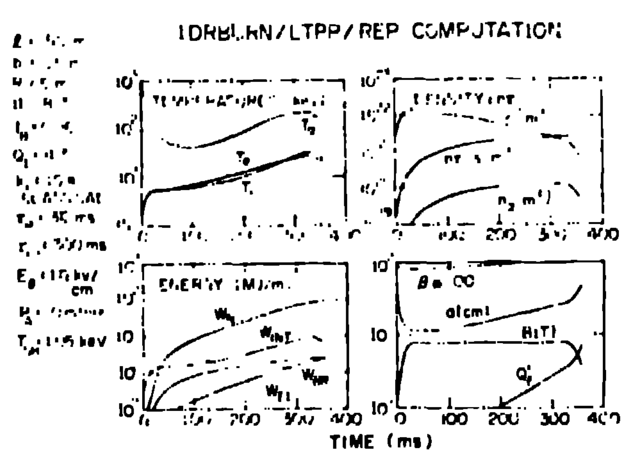


FIGURE 8. Typical burn cycle for a Linear Theta Pinch Reactor (LTPR) using re-entrant endplugs.[8]

transfer and storage and magnet stresses (8-T peak fields). The present uncertainties of the REP approach, the close coupling of the implosion preheating to the [illegible] core (high voltage [illegible] blanket and first wall are required), and the need for a highly efficient (95%) energy transfer/storage system represent crucial issues for the LTPR.

D. Slowly Imploding Liner (LINUS)[12]

The LINUS approach to IMF attempts to achieve high-beta plasmas of 2-3·10²³ m⁻³ (B ≃ 64 T) density. The high densities and fields are produced reversibly by driving with gas pistons a rotating (3 Hz) liquid-metal cylinder (1.6-m inner radius, 1-m thick, 12-m long) radially inward onto a low temperature plasma (2.5·10²¹ m⁻³, ~1 keV) and guide field. The plasma and guide field are compressed by a factor of 100 within ~26 ms, and the burn period is sustained by the inertia of the LIPS liner before it reversibly "bounces" radially outward towards its starting position. Hence, adiabatic compression represents the major heating mechanism, and a major portion of the ~6 GJ initial radial kinetic energy (which must also supply the final rotational energy as angular momentum is conserved) must be reversibly recovered. The alpha-particle pressure generated during the burn is more than enough to compensate for liner losses and to assure a reversible cycle. Approximately 3.5 GJ of thermonuclear energy would be released, and the pulse frequency would be ~1 Hz. The liner is driven by a 24 MPa (3500 psi) gas reservoir, which under reversible operation serves as the primary energy store.

For the peak compression field (64 T) and LINUS length (12 m), a nearly closed axial confinement will be required (re: Fig. 2). A rotating, hollow REB (40 MJ, 3 MA, 3 MW, 4 s) is injected into one end of the device, which breaks down the gas, preheats the plasma, generates the precompression fields, and upon exiting the device leaves residual plasma currents that through field diffusion create a closed, reversed field configuration [illegible]. In this way both efficient preheating and axial [illegible] field confinement are achieved by a FRR energy source that is only loosely coupled to the reactor core. The compactness (system power density equal 13.5 MWt/m³) and the regenerated first wall represent other attractions of the LINUS concept. Major questions for this IMF approach are associated with the plasma and closed-field preparation, the efficiency with which the liner energy can be reversibly recovered, and the general technology required to reversibly implode such a second, a massive (115 tonnes), rotating liner system.

E. Fast Liner Reactor (FLR)(11,60)

Unlike the LINUS approach,(12) the FLR attempts to eliminate the need for reversible and controlled recovery of the liner energy, which may equal or exceed the thermonuclear output. The FLR approach envisages a small liner system (initially ~0.2 m/1 m radius and length) that is rapidly ([illegible] s) driven into a preheated and dense (~500 eV, ~$10^{24}$ $m^{-3}$) plasma with sufficient speed (~$10^4$ m/s) and energy (400-500 MJ) a) to operate with increased thermonuclear yield per unit of initial liner energy (high-Q), b) to eliminate the need for liner rotation (for stabilization of Rayleigh-Taylor hydrodynamic modes), and c) to open the possibility of wall (inertial) confinement in the presence of a thermally insulating magnetic field. Hence, adiabatic compression supplies the major heating for the FLR, preheating can be provided by plama-gun injection, and the axial (and radial) confinement falls into the MEF (with magnetic insulation) category. The advantages cited for the LINUS also apply to the FLR which has a system power density of 9.3 MWt/m³, a pulse rate of 10 Hz, a net power of 270 MWe(net), and a recirculating power fraction of 0.25. To circumvent the potential LINUS problems of reversible energy recovery, heating and confinement, the faster operating mode for the FLR [illegible] liner [illegible] time [illegible] [illegible] of blast containment, material destruction and [illegible] cost, and fast pulsed energy transfer (leads) and storage.

F. Dense Z-Pinch Reactor (DZPR)([illegible],66)

The DZPR is proposed([illegible]) as another means to achieve in a very compact configuration a [illegible] burning (2-3 [illegible]) and dense ([illegible] $10^{26}$ $m^{-3}$) plasma. A straight ([illegible] m long x 1.0 mm radius), self-constricting current channel ([illegible] MA or [illegible] GA/m²) is proposed to be driven by a 70 MJ, 40 MV low-impedance power supply into a dense gas ([illegible] $m^{-3}$) that previously was subjected to a laser-initiated channel breakdown. For conditions where the ion Larmor radius is large the required voltages and currents may be considerably reduced.([illegible]) Plasma heating would be provided respectively by ohmic losses, compression and [illegible] thermalization. The self-constricting or Z-pinch, because of its inherent simplicity in efficiently providing from a single source both heating and confinement, has received early experimental consideration, and thermonuclear plasmas of ~10 [illegible] and n ~ [illegible] have been reported([illegible]) with [illegible] currents. Stabilization against the notorious kink and sausage instabilities by gas embedding, plasma flow or finite-Larmor-radius effects may prove feasible.(14,65) Although the problems of blast containment and energy transfer/storage are not unlike those noted for the FLR and certain beam-pellet fusion schemes, the more elegant configuration offered by a stabilized, self-constricting pinch represents a major attraction.

G. Steady-State (Solenoidal) Fusion Burner (SSFB)(11,68,[illegible])

It seems appropriate to conclude this survey with an IMF scheme that in principle promises to fulfill the two most cherished goals of fusion research: a) simple physical and magnetic geometry, and b) steady-state operation. The [illegible] would be [illegible] at the [illegible] ignited. At some stage [illegible] perhaps [illegible] the plasma at the other end would be ignited, and approximately one half of the charged-particles generated by fusion reactions at the flow exit end would migrate "upstream" and heat the incoming, cooler plasma and gas; a steady-state operation, much like a gas burner, would ensue. Detailed computations[(5)] based on classical thermal conduction, the REP [illegible] the incoming cold [illegible] gas over a wide range of flow conditions indicates that the product of mass flow M [illegible] and system length [illegible] must exceed [illegible] kg/s m, and the minimum total fusion power required for a self-sustained system was found to be [illegible] $a^2$ W, where a(m) is the plasma radius. As expected on the basis of [illegible] for REP and classical thermal conduction, very large systems will be required to achieve a self-sustained steady state.

The use of multiple mirrors to effectively [illegible] drag[(5,15)] may reduce the length and total power required for self-sustained operation. The possibility of such steady state multiple mirror operation has been noted,[(1)] in which a 1000 MWe reactor operating point with a recirculating power fraction of [illegible] and [illegible] m length are indicated. Computations for the LLPR with a REP, similar to those given on Fig. 8, also show the potential for quasi steady-state operation, wherein axial density and temperature profiles are maintained relatively constant for times when radial field diffusion[(7)] becomes important.

## IV. SUMMARY AND CONCLUSIONS

The major constraints imposed on LMF by the physics of heating and confinement have been discussed, and the impact of these constraints on a wide range of conceptual LMF reactors designs was reviewed. Two generic approaches to LMF emerge from this review which are intimately related to the axial confinement issue. First, the long times required for the order 1000 m and technologically achievable densities [illegible] will require a level of confinement equal to that predicted for either multiple mirrors or re-entrant end-plugs (and possibly reversed field configurations). A number of approaches to high beta MM or REP confinement remain to be explored, and each generally projects the issue of plasma stability as a trade for axial confinement. Secondly, the high-field LMF approach retains the advantages of neutral stability and attempts to "outrun" the axial confinement problem by means of the $B^2$ scaling (Eqs. (1) or (2)). In setting this course high-field LMF opts to address the technological problems of high-field magnets and high heat-flux first walls in exchange for well understood and predictable physics; the imploding-liner and fiber Z-pinch approaches promise a unique solution to the high heat flux wall problem. At this stage in the development of fusion power, both approaches seem justified. Ultimately the advantages of LMF cited may be realized by a symbiosis of results that emerge from experimental and theoretical studies of both approaches.

## V. ACKNOWLEDGMENTS

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