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Magnetized Target Fusion: Prospects for Low-cost Fusion Energy

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Abstract

Magnetized Target Fusion (MTF) has attracted renewed interest in recent years because of its potential to resolve one of the major problems with conventional fusion energy research – the high cost of facilities to do experiments and in general develop practical fusion energy. The requirement for costly facilities can be traced to fundamental constraints. The Lawson condition implies large system size in the case of conventional magnetic confinement, or large heating power in the case of conventional inertial confinement. The MTF approach is to use much higher fuel density than with conventional magnetic confinement (corresponding to mega bar pressures), which results in a much-reduced system size to achieve Lawson conditions. Intrinsically the system must be pulsed because the pressures exceed the strength of any known material. To facilitate heating the fuel (or "target") to thermonuclear conditions with a high-power source of energy, magnetic fields are used to insulate the high-pressure fuel from material surroundings (thus "magnetized target"). Because of magnetic insulation, the required heating power is reduced by many orders of magnitude compared to conventional inertial fusion, even with relatively poor energy confinement in the magnetic field, such as that characterized by Bohm diffusion. This paper shows semi-quantitatively why MTF should allow fusion energy production without costly facilities within the same generally accepted physical constraints used for conventional magnetic and inertial fusion. We also report on the exploratory research underway, and the interesting physics issues that arise in the MTF regime of parameters.

Keywords:

fusion energy, inertial fusion, magnetized target fusion, pulsed power

1. Introduction

During the years that John Clarke headed DOE's Office of Fusion Energy, he sometimes quipped: "Beta is beautiful, but B is better." He was referring to the fact that magnetic fusion power density is proportional to $\beta^2 B^4$. In this paper we intend to generalize that point by thinking of B^2 as pressure. By considering pressure as a wide-ranging variable rather than a given quantity based on conventional magnet technology, we argue that fusion has important unexplored possibilities. Eventually the technology requirements for working with the high

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pressures considered here will determine the practicality of this pathway. From a physics perspective, once pressure is specified, it is somewhat surprising how much can be calculated given a small number of other relatively well-established and fixed parameters. In fact, for thermonuclear fusion, *ie.*, fuel ions with a thermal velocity distribution, pressure seems to be the only variable available for significant variation of fusion systems and cost.

Arguments for magnetic fusion systems operated at high pressure have been made and generally rejected for many years, probably in part because the technology for pulsed mega-gauss magnetic fields is unfamiliar and less developed than for conventional magnets. This appears to be a good time to reexamine this type of system because 1) pulsed high-field technology has advanced, 2) plasmas such as compact toroids appropriate to this approach have been developed, and 3) fusion research has been called into question by skeptics. The skeptics ask whether practical fusion is possible given the expense and complexity of facilities needed for progress in the parameter regime of burning plasmas. Such costs are sometimes claimed to be generic to fusion. According to the arguments in this paper, one should state more carefully that high-cost facilities are intrinsic to *conventional* fusion. Indeed, a large and expensive tokamak is needed for progress on burning plasma issues. However, expensive facilities might not be needed for the unexplored regime of pressure intermediate between conventional magnetic and inertial fusion. With this issue in mind we will estimate the cost of an MTF facility capable of energy gain (Q = fusion energy output/ liner kinetic energy ~ 1), which corresponds to the Lawson condition of $n\tau \approx 3\times10^{20}$ sec/m^3. For the purpose of doing a broad survey covering ten orders of magnitude in pressure, we will adopt a rough approximation that cost is proportional to two quantities: a constant times total system energy plus a different constant times system power (system energy/τ). The constants of proportionality and the general trend for costs will be derived from costs of existing facilities and projected costs for new facilities such as ITER-FEAT.

2. Cost Estimates for Nominal Tokamaks

The range of parameters available for conventional magnetic fusion is strongly constrained by the field strength available from steady-state magnets. The ITER design has a toroidal field of 5.5 T, corresponding to a magnetic pressure of 120 atmospheres. An alternative approach to burning-plasma tokamak experiments would be the use of pulsed copper magnets as selected in the IGNITOR and FIRE designs. The FIRE design [4] operates with 10 T (400 atmospheres) and achieves the same Q~10 with a smaller less-expensive facility.

The main reason for this trend is that smaller size becomes possible as pressure is increased. Although thermal diffusivity χ and normalized plasma pressure β tend to stay constant as pressure changes, density and therefore fusion reaction rate increases for given beta and temperature:

$$n = \beta P/2T. \quad (1)$$

Temperature is necessarily ~ 10 keV for DT fusion, and we use T to represent kT. Pressure in eq. 1 is $P = B_T^2/2\mu_0$ in a tokamak. We consider a nominal tokamak with a circular plasma cross section of radius a. We can then write the pressure dependence of the radius as:

$$a = (\tau\chi)^{1/2} = (2Tn\tau\chi/\beta)^{1/2}/P^{1/2} \quad (2)$$

For given values of nt and χ/β, the required minor radius decreases as the square root of pressure. For a burning tokamak we take $n\tau = 5\times10^{20}$ s/m^3 corresponding to Q ~ 10.

The toroidal magnets are the largest-cost component for a tokamak. For the present purpose we assume that costs for the balance of the facility also increase in proportion to the amount of magnetic energy. According to four contemporary tokamak designs (ITER-FEAT, FIRE, PCAST, and ARIES-RS), the ratio of total facility cost to magnetic energy is reasonably constant (0.16 ± .07) for magnetic energy ranging from 5 to 85 GJ, so we will use $0.16 per joule to estimate tokamak facility cost based on energy.

For our nominal tokamak, the plasma radius estimated from eq. 2, and the aspect ratio allow us to calculate the plasma volume $V = 2\pi^2 A a^3$. We define a parameter x, equal to the ratio of plasma radius to magnet inner radius, and calculate the magnet volume as V/x^2. The system energy is then calculated as follows:

$$\begin{aligned} E &= (1/x^2 + \beta/2)PV \\ &= (1/x^2 + \beta/2)2\pi^2 A(2T\chi n\tau/\beta)^{3/2}/P^{1/2} \\ &\approx 200\ \text{GJ} / P(\text{atm})^{1/2} \end{aligned} \quad (3)$$

This numerical example for the dependence of E upon P is based on the numbers in Table 1 below. We see here, as noted by Sheffield [5], that the ratio β/χ is a figure of merit for physics performance of a magnetized plasma. The larger that ratio, the smaller the magnet energy and facility cost. However, alternate concept research so far has not demonstrated a very large improvement in β/χ. So we next consider what might be possible with significantly increased pressure.

The point of developing eq. 3, is to show how magnet energy in a tokamak with fixed nt depends strongly upon the magnetic pressure. Then the approximation of cost proportional to magnetic energy allows an estimate of the tokamak cost. Such a crude approximation ignores significant differences, like those between superconducing and copper magnet technology, nuclear shielding requirements, and so forth. The approximation is not unreasonable as seen in Fig. 2 below. But for the purpose of this paper, cost variations of less than a factor of two are considered as a nonessential detail, even though such differences are obviously important when choosing between competing tokamak technologies and proposing an experiment.

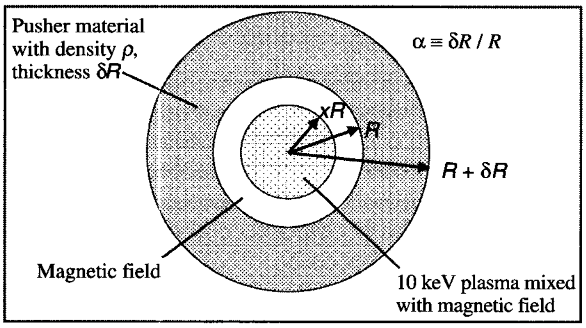

Fig. 1 Parameters ρ, x, α, R, δR for a generic liner-imploded MTF system.

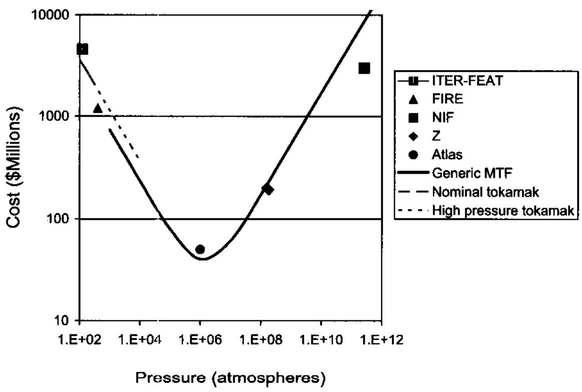

Fig. 2 Facility cost vs. pressure for nominal tokamak and generic MTF systems

3. Cost Estimates for Generic Magnetized Target Fusion (MTF)

We consider now pressures that exceed the strength of any material, and involve pulsed technologies of some type. Liner technology [6] has demonstrated pressures in the megabar range and corresponding magnetic fields of up to about 200 T. The liner approach involves rapid compression of a metal cylinder, often by the use of the pinch effect from an axial current applied to the outer surface of the liner. Inward motion proceeds until pressure inside the cylinder stops the implosion. Another MTF approach called LINUS involved compression of a cylindrical chamber by the use of thick rotating liquid metals [7]. In laser fusion, the final hot spot that initiates fusion is compressed by the rapid implosion of a "pusher" material from the outside. In Fig. 1 we show parameters for a generic MTF system.

All such approaches have in common the feature that a pressure pulse is sustained for a limited time given by:

$$\tau \approx \delta R \,/\, (P/\rho)^{1/2} \qquad (4)$$

We take eq. 4 to be the defining feature of generic MTF. This is a quite general relationship that can be derived by thinking of the shock and rarefaction waves that must propagate through the pusher material at peak compression, or by considering the impulse ($P\tau$) that must balance the momentum change of incoming pusher (liner) mass [2,8]. Fusion reactions stop when the pressure drops, so this characteristic time must satisfy the same Lawson criterion, as does the energy confinement time. The energy confinement time, estimated as x^2R^2/χ, will be larger than the dwell time of eq. 4 so long as χ is smaller than the following:

$$\chi\,(\text{maximum}) = 2x^2(n\tau)T/\rho\beta\alpha^2 \qquad (5)$$

The value is about 10 m^2/s independent of pressure. Fortunately this is a rather high diffusivity, which gives hope we can find acceptable magnetic configurations. Specific ways this might be achieved will be discussed in the next section.

The parameters we have defined for the nominal tokamak and the generic MTF system are listed in Table 1 along with typical values used in calculations.

Assuming a pusher efficiency ε, the required pusher kinetic energy, KE, is the magnetic plus plasma thermal energy inside the chamber divided by ε:

$$\begin{aligned} KE &= (1 + \beta x^2/2)PV/\varepsilon \\ &= (1 + \beta x^2/2)16\pi e(n\tau)^3T^3/[\varepsilon\alpha^3\beta^3\rho^{3/2}P^{1/2}] \\ &\approx 23\text{ GJ} \,/\, P(\text{atm})^{1/2} \end{aligned} \qquad (5)$$

Power requirements are also an important consideration for MTF. We calculate facility cost divided by output power for the following state-of-the-art pulsed power devices: NIF \$6/megawatt; Z machine \$3/megawatt; and Atlas \$12/megawatt. We expect that Atlas or Z technology are the most likely to be useful for MTF, so we adopt \$1/joule for energy and \$10/megawatt as the characteristic energy and power costs for the generic model and estimate facility cost as follows:

$$\text{Generic MTF facility Cost (\$)} = \$1 * KE(\text{J}) + \$10 * \text{Power(MW)} \qquad (6)$$

The justification for this crude approximation is the same as for the nominal tokamak. We investigate how cost depends upon major parameters, and ignore important issues such as cost for nuclear shielding as a detail. We chose liner kinetic energy and pulsed power level because existing large pulsed power facilities show those to be major characteristics, just as magnet energy is the most important parameter for a tokamak. Neither the nominal tokamak cost, nor the generic MTF facility cost, represent the full cost of a fusion reactor. We focus here on the cost of the nuclear island, not the costs for power conversion, fuel processing (tritium breeding), and so forth. Such a focus is reasonable because the main technical uncertainties and remaining development cost concern the nuclear island.

The results are shown in Fig. 2. The potential for considerable cost savings in the intermediate pressure regime is immediately obvious. We emphasize that this conclusion is based on costs of representative pulsed-power facilities and the implications of eq. 4, not upon plasma physics. We next consider particular possibilities for plasma targets.

4. Potential Plasma Targets and the Influence of Thermal Diffusivity

We examine here three possible MTF targets: conventional inertial fusion, Field-Reversed Configurations, and a less explored idea of wall-confinement with Bohm diffusion. In these cases we change some generic MTF parameters as listed in Table 2.

Pressure is still the major variable as before, but there is now an important transition pressure, P_T, for which the maximum allowed thermal diffusivity (eq. 5) becomes equal to the thermal diffusivity applicable to the particular plasma target. Above the transition pressure the dominant time constant is given by the inertial dwell time, with the opposite below the transition pressure. For a rough estimate of ICF parameters inside the central hot spot where burning begins, thermal diffusivity can be taken as $\chi \sim \lambda V_e$, where λ is the mean free path and V_e is the electron thermal speed. For the Field Reversed Configuration, heat loss by particle diffusion is observed to have an effective thermal diffusivity of $\chi \sim v_o \rho_{io}$, where v_o is an empirical constant equal to 4×10^4 m/s, and ρ_{io} is the ion gyroradius calculated with the central temperature and the external magnetic field. In the expressions for transition pressure, r_o is the classical electron radius used for dimensional simplicity. There are interesting new theoretical results suggesting that experimentally observed FRC stability can indeed be explained by elongation [9], as considered in earlier analysis [10]. In the FRC model of this paper, elongation was adjusted at

Table 1 The parameters used to characterize a nominal tokamak and a generic Magnetized Target Fusion system.

Quantity	Symbol	Nominal tokamak	Generic MTF
Pressure	P	$B_T^2/2\mu_o$ 100–400 atm.	$10^3 - 10^{12}$ atm.
Temperature	$T = T_e = T_i$	10 keV	10 keV
Lawson parameter	$n\tau$	5×10^{20} sec/m^3	3×10^{20} sec/m^3
Beta	β	.04	0.7
Ratio of plasma radius to magnet inner radius	x	0.5	0.8
Thermal diffusivity	χ	1 m^2/s	10 m^2/s
Aspect ratio	A	3.5	Not,applicable
Pusher density	ρ	Not applicable	10
Thickness ratio δR /R	α	Not applicable	3
Pusher elongation L/2R	e	Not applicable	5
Pusher efficiency = E / KE	ε	Not applicable	0.5

Table 2 Parameters and relationships to be substituted in the generic MTF model for three potential MTF plasma targets

Quantity	ICF	FRC	Wall confined Bohm
P_T	$\alpha^2\rho\lambda V_e/\tau$	$v_o^2\beta^2\rho^2\alpha^4(m_i/m_e)/[2^4\pi r_o(n\tau)^2Tx^4]$	$\alpha^4\beta^2\rho^2/[2^{12}\pi m_e r_o(1-\beta)(n\tau)^2]$
T	10 keV	10 keV	10 keV
$n\tau$	3×10^{20} sec/m^3	3×10^{20} sec/m^3	3×10^{20} sec/m^3
β	1.0	0.8	0.95
x	1.0	0.8	1.0
χ	λV_e	$v_o \rho_{io}$	$v_i \rho_i / 16$
ρ	3	20	20
α	3	4	3
e	1	Determined from S*	1
ε	0.5	0.5	0.5

each pressure to meet the stability requirement:

$$S^*/e = [xR/(c/\omega_{pi})]/e = 3.5. \qquad (7)$$

The idea of high-beta wall confinement has been examined theoretically and computationally [1,11]. The β used in this paper is the plasma pressure relative to total pressure, which does not exceed unity. Imagine that inside the confinement chamber, that a uniform B and nT are compressed, then the local internal beta would be $\beta/(1-\beta)$, or 19 for β=0.95. While this regime has not been studied experimentally so far, the results from the model of this paper support earlier work [2] suggesting that such a system would indeed allow larger Q in a reasonably small system, compared for example with the FRC when the required elongation is considered. The estimated cost for these various systems are shown in Fig. 3 and compared with the generic MTF model. The

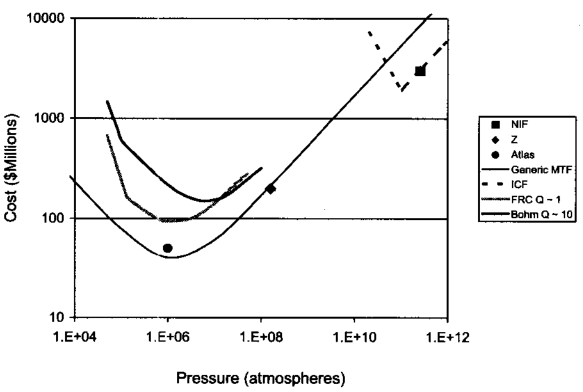

Fig. 3 Cost estimates for specific plasma targets compared with the generic MTF estimate.

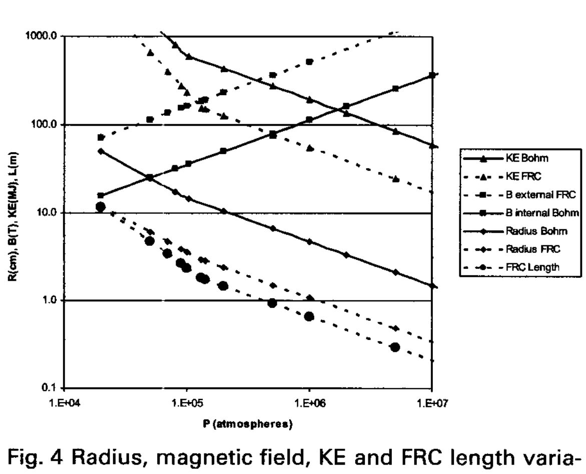

Fig. 4 Radius, magnetic field, KE and FRC length variation with pressure for FRC confinement and wall-confined Bohm confinement.

points where the slope of these curves is discontinuous are at the transition pressure in each case. Above the transition pressure, the generic scaling resembles the curve shape in each case as expected, although the exact values depend upon the parameter variations associated with specific plasma targets.

The typical sizes and energies associated with the FRC and Bohm examples are shown in Fig. 4. The strong variation of FRC length with pressure results from the stability requirement. Magnetic fields range from 10–1000 T, and KE ranges from 10–1000 MJ. While all parameters are not of interest in a practical sense, the variation with pressure is instructive. One of the critical physics issues is how rapidly high Z wall material will mix with low Z fusion fuel. Another issue is the acceptable range of liner thickness (alpha parameter). Large alpha increases the dwell time, but would also reduce efficiency if the equation of state for compressed pusher material were taken into account. As discussed in ref. 2, scaling of gain with energy in a batch-burn MTF system is proportional to $(KE)^{1/3}$. However, as the examples here show, the proportionality constant depends upon details of confinement, which are obviously very important for the ultimate application of this technology.

Present US DOE efforts are focused on producing an FRC target plasma at Los Alamos [3,13], and experiments at the Air Force Research Laboratory [14] show that the Shiva Star facility would allow interesting integrated liner-on-plasma experiments as funding permits. Cost of facilities is also related to the mass of equipment required to produce fusion energy. Specific power (power per unit mass of power supply) is a key parameter for space applications, and MTF has attracted interest in the US NASA space program [12]. The MTF web page http://fusionenergy.lanl.gov is available for additional information.

5. Conclusions

While the status of MTF research is immature at the present time, and many unresolved issues can be identified, the results shown by Figs. 2 and 3 provide a good rationale for investigating the intermediate pressure regime. The cost of facilities needed for development is emphasized here because of its importance to cost of development, a major impediment to achieving practical fusion energy. Other important unresolved issues remain for fusion energy, such as materials to survive the first-wall neutron damage. While it remains to be seen whether alternative concepts such as MTF provide useful solutions, the study of qualitatively different approaches to fusion seems highly prudent at the present time.

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