LA-UR- 99-3628

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Title: MAGNETIZED PLASMA CONFIGURATIONS FOR FAST LINER IMPLOSIONS: A VARIETY OF POSSIBILITIES

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Submitted to: Comments on Plasma Physics and Controlled Fusion (to be published)

Magnetized plasma configurations for fast liner implosions: a variety of possibilities

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Abstract

A variety of plasma configurations suitable for adiabatic compression by fast liners has been identified. Among them there are field-reversed configurations, spheromaks, diffuse Z pinches, spherical tokamaks, and others. The initial plasma is assumed to have density in the range of 10^{17}-10^{18} cm^{-3} and the temperature of the order of 100 eV. Relative advantages and disadvantages of various plasma configurations are discussed. The very fact of the existing broad spectrum of plasma configurations compatible with the liner compression increases the probability of a success in this branch of fusion research.

1. Introduction

In this paper, we discuss various plasma configurations that can be adiabatically compressed by an imploding liner to produce fusion-grade plasma near the liner turn-around point. In the past, two configurations were most popular among the researchers in this area: a field-reversed configuration (FRC), and a configuration of the type of a diffuse pinch. The adiabatic compression of the first was discussed, e.g., in [1,2], while the adiabatic compression of the second, e.g., in [3]. A common name used at present to describe this type of controlled fusion is “Magnetized Target Fusion” (MTF) [4].

More recently, in addition to the FRC and diffuse pinch, other configurations were proposed as candidate “targets.” In Refs. [5,6], three types of targets were discussed: FRC, diffuse pinch, and spheromak. In Ref. [7], a spherical tokamak and a solenoidal (linear) target were added to the list of candidate targets.

Particular realizations of MTF can involve systems with the fusion yield ranging from many gigajoules (e.g., [2,8]) to tens of megajoules [5,6]. High-yield systems are implied by relatively slow compression of plasma targets with initial size of a few meters. A range of yields including values as low as 100 MJ become possible with centimeter-size targets, where the initial plasma density is relatively high (in the range of 10^{18} cm^{-3}) and the implosion time is less than a couple of microseconds. In this note, we will discuss this second class of the systems, i.e., compact systems with relatively fast liners. We will consider the ways of creating initial plasma configurations, and discuss relative advantages and disadvantages of these configurations as MTF targets.

We will assume that implosions are 3-dimensional, with the shape of the imploding objects remaining geometrically self-similar. For example, when discussing FRCs, we assume that the ratio of their length to their radius remains constant. The advantage of 3D implosions (compared to 2D implosions, where the plasma object is compressed only in the radial direction) was emphasized in Ref. [5]: 3D implosions allow one to reduce requirements to the linear convergence and/or to initial plasma parameters. In some cases, like in implosions of spheromaks and spherical tokamaks, only 3D implosions allow sustainment of the approximate sphericity of the configuration. In these cases 3D implosions are mandatory.

As was shown in Ref. [5], the scaling laws for 3D implosions are:

$$T=T_0C^2,\ n=n_0C^3\ B=B_0C^2,\ b=b_0C, \tag{1}$$

where C is a linear convergence, T, n, and B are the temperature, a number density, and the magnetic field strength, respectively, and b is the ratio of a plasma pressure to a magnetic pressure. The subscript "0" refers to the initial state. A very important feature of 3D compression is attainability of high plasma b: if one starts with the state where b_0~1, the plasma pressure becomes higher than the magnetic pressure early in the implosion process. In other words, the compression work is performed over the plasma, not over the magnetic field, thereby allowing one to reach fusion parameters at modest convergences. This observation also means that the plasma pressure will have to be confined by the liner, not by the magnetic field (a so-called wall-confinement regime [9]). An interesting aspect of high-beta wall confinement when compressing with a metal (electrically conducting) liner is that a very thin magnetic sheath containing low-beta plasma is often predicted to arise between the high-beta plasma and the liner during the implosion. The details of such sheaths are currently an active area of research.

It is, of course, possible to start also with initial configurations with $b_0<1$. Then b would remain less than one until convergence $C\sim 1/b_0$ is reached. In what follows, we assume $b_0\sim 1$ (unless stated otherwise). Scaling laws for other modes of compression, including the ones which can be called 2.5D modes (axial compression results from field-line tension rather than liner compression) can be found in Refs. [2,10].

Although we are using the term "fast" to describe implosions, this is a relative term: the sound speed in a fusion plasma is ~$1.5\cdot 10^8$ cm/s, i.e., significantly higher than the expected liner velocity. In other words, the plasma evolves over a sequence of quasi-equilibrium states, which have stability and transport properties that determine the success of an implosion experiment.

In the numerical estimates (except for the cases of a spheromak and RFP) we assume that initial plasma parameters are:

$$B_0\sim 100\ \text{kG},\ T_0\sim 100\ \text{eV},\ n_0\sim 10^{18}\ \text{cm}^{-3},\ b_0\sim 1. \tag{2}$$

Initial parameters for spheromak and RFP will be specified in the corresponding sections of this note. Our prime interest will be discussion of the ways of forming initial plasma configurations and imploding them in a 3D fashion. We will not discuss plasma parameters during the implosion phase; this part of the problem has been analyzed in Ref. [5].

2. FRC

An initial FRC suitable for achieving Lawson conditions by adiabatic compression inside a centimeter-size liner would have the following parameters: density n_0 ~10^{18} cm^{-3}, temperature T_0 ~100 eV, magnetic field B_0 ~100 kG, length L_0~6 cm, radius a_0~1cm. Such a configuration could be created by well established methods (see, e.g., [11]), by quickly applying a magnetic field of the polarity opposite to the bias magnetic field. Fig. 1 borrowed from paper [11] shows a sequence of operations used to produce FRC with the parameters: n_0 ~10^{14}-10^{15} cm^{-3}, L_0~100 cm, a_0~15 cm. Scaling analysis presented in Ref. [7] has shown that, in a system with smaller dimensions, one can use the same operations to produce much smaller and denser FRCs, with the needed parameters.

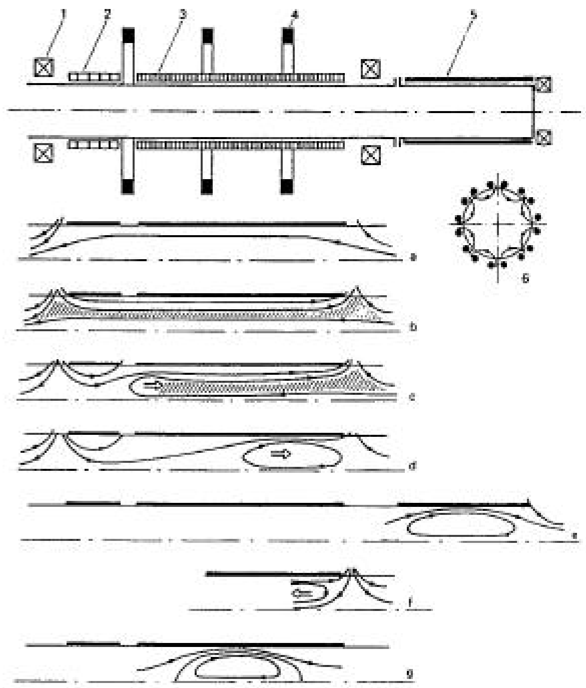

Fig.1. FRC creation and injection: 1) mirror coils; 2) control coils; 3) shock coil; 4) solenoid; 5) liner coil; 6) barrier field bars.

The loop voltage ~ 3 kV that will develop when the reversed field is applied (see Ref. [7]), should be more than sufficient for a fast breakdown of the gas and trapping of the initial flux. Various means have been studied that can provide the energy needed for preheating to 100 eV. Possibilities include conventional theta-pinch high-voltage implosion heating [12], axial compression by field-line tension [11], or turbulent dissipation of the initial bias field [13]. Other ideas such as a pulsed CO_2 laser are possible because the energy needed to create a plasma with n_0 ~10^{18} cm^{-3} and T_0 ~100 eV is only 50 J/cm^3. Radiative losses at the early stage of the FRC formation are negligible if only free-free and free-bound transitions in hydrogen are involved [7]. If, on the other hand, the radiation of heavier impurities is present, the situation may become less favorable. One may expect that, because of a very large line density (~10^{18} cm^{-2}) in the proposed experiments compared to canonical ones, the plasma will be impermeable to the impurities.

The role of radiative losses at the later stages of the implosion was discussed in Ref. [5], with a conclusion that radiative losses from the bulk plasma are relatively unimportant. In a $b>1$ wall-confined plasma, the radiation losses per unit plasma volume increase in a dense plasma region near the wall [14]. However, if beta is not too high, $b<20$, the total (integrated over the volume) losses remain relatively small, because the volume of enhanced radiation is limited to a thin plasma layer near the wall. Only at very high betas the increase of the radiation power density begins to overbalance the decrease in the thickness of a dense plasma layer. The issue of radiative losses is present in the case of other configurations, too, but there is no much difference there compared to the FRC case, and one can expect a reasonable overall performance at betas below 10-20. Discussion of the radiation losses at very high betas (reaching the ion-to electron mass ratio *M/m*) can be found in a survey paper [15].

After an FRC is formed, it could be translated into the liner through a hole in one of the ends. The possibility of translating FRC by a distance exceeding several its lengths has been experimentally demonstrated in Ref. [16,17]. The FRC was even reflected from the magnetic mirror without a significant loss of energy [17] - a sign of the robustness of this configuration. In most cases the kinetic energy of translation is converted back to thermal energy when an FRC is trapped between magnetic mirrors, which means an FRC does not bounce back from the liner after injection.

In order to ensure the FRC remains trapped in the liner, and to provide axial compression by the liner as well as radial compression, the liner shape during implosion can be programmed by varying the initial mass per unit length, and situating the lighter part of the liner near the ends. This was pointed out in [18] (and later mentioned in Refs. [1,5]).

Advantages of the FRC as a target stem from the fact that the FRC is a well studied configuration, with b~1 reached in many experiments [19]. Main concerns about this configuration are related to the issue of possible strong MHD instabilities. To some extent, these instabilities can be stabilized if the plasma is wall-confined. There exist also non-MHD mechanisms, which may suppress gross instabilities, among them the shear-flow stabilization of the FRC configuration [20]. This mechanism may considerably increase the parameter domain where FRCs are sufficiently stable. A region of s-parameters approaching many tens may become attainable (s is, roughly speaking, the ratio of the plasma radius to the ion gyroradius). Another non-MHD effect that may provide much better (than previously expected) stabilization of the curvature-driven modes is related to a presence of mirror-trapped particles in the zones of a weak magnetic field near the X-point, where the curvature is large, and the drift frequency exceeds greatly the growth-rate of MHD perturbations [21].

Another advantage of the FRC is that wall-plasma interactions can be controlled to some extent by how the initial bias magnetic field is embedded in the liner. Minimum wall interaction (but good diagnostic access) can be achieved with a relatively strong magnetic field completely parallel to the liner, which provides maximum separation between the FRC separatrix and the metal liner. In that case however, the increase of beta is limited to 2.5D (field line tension, see Sec.1), and significant work during compression is done on the field rather than the plasma. Another possibility is to taper the end sections in the course of the implosion, without a complete closure of the axial holes. If remaining holes are small enough, they will not lead to a “bursting” of a high-beta FRC through them. A relevant discussion can be found in Ref. [22]. In an FRC configuration where the liner fully surrounds the FRC and provides 3D compression, there exist field lines outside the separatrix that intersect the liner surface. Interaction of the plasma on these field lines with the liner may complicate the picture of 3D implosions. This issue has not yet been studied in any detail.

3. Diffuse Z pinch

The attractiveness of the diffuse Z pinch is related to a relative simplicity of creating such a configuration inside the liner [3]. Two end electrodes electrically insulated from the liner could be used for this purpose. For the molecular hydrogen density ~$5\cdot 10^{17}$ cm^{-3} and the distance between the electrodes ~ 2 cm, the breakdown voltage, according to the Paschen law [23], is

~ 1 kV. The voltage ~ 2-3 kV required to reach a fast breakdown of the gas is not a problem. The insulating gap would be closed by the inward motion of the liner early in the implosion. One can note in passing that the MAGO configuration [8] is topologically identical to the diffuse Z-pinch, as it has only toroidal magnetic field. The magnetic field is everywhere tangential to the surface of the liner.

When pushed from the sides and from the ends by the imploding liner, the diffuse Z pinch will evolve according to the same scaling laws as the FRC. So one could expect similar performance from both systems. However, in a configuration where only toroidal magnetic field is present, the only plasma equilibria allowed are such that the p=const surfaces are nested coaxial cylinders [24]. In other words, the plasma pressure must be constant all the way from one electrode to another. On the other hand, heat losses to the electrodes will almost certainly cause a significant axial pressure variation near the electrodes, thereby violating the equilibrium condition. The imbalanced forces, in turn, would create convective plasma flows, which could bring impurities into the bulk plasma. The significance of this phenomenon for plasma confinement has not yet been studied in any detail, and any firm conclusions on that issue would be premature. Fusion under MTF conditions of high density and short pulses allows considerably relaxed requirements for energy confinement, and the quantitative implications of unstable convective motions requires careful theoretical and experimental study.

In a purely toroidal magnetic field, the alpha-particles experience toroidal drift directed along the pinch axis, so that alpha-particles get lost to the electrodes. For a hot fusion-grade plasma the energy-exchange time between the alphas and the plasma is long compared to the axial loss time (unless the plasma density is extremely high). This means that there is little plasma heating by alpha particles in the Z pinch configuration.

The plasma current in a Z pinch begins and ends on the electrodes. Axial flow of the electrons leads to the axial enthalpy flux and, thereby, opens a specific channel of the energy losses [25]. However, for the pulsed systems with a dense-enough plasma this loss channel is not catastrophically strong.

Both plasma convection, axial losses of alpha particles, and axial enthalpy flux become less important for diffuse pinches whose length is much greater than their radius. However, it is difficult (although, perhaps, not impossible) to reach a 3-D compression in a highly elongated Z-pinch system. Still, because of its simplicity, the diffuse Z pinch configuration is certainly interesting for the studies of the physics of 3D implosions. In regimes of very high densities all the aforementioned loss channels may become insignificant even for $L \sim a$.

4. Spheromak

The spheromak configuration is suitable for 3D implosions [5, 6]. Its advantages stem from the fact that it can be created inside the liner by using a gun injection technique [26, 27]. The annular slot in the liner through which the spheromak is injected would be closed early in the pulse. If the 3-dimensional liner implosion is provided by the axial variation of the liner thickness, the prolate configuration of the type shown in Fig. 2a is preferred (see Ref. [5]). If a spherical configuration proves to be more stable, a spherical liner of the type used in [28] may become more appropriate as a driver (Fig. 2b).

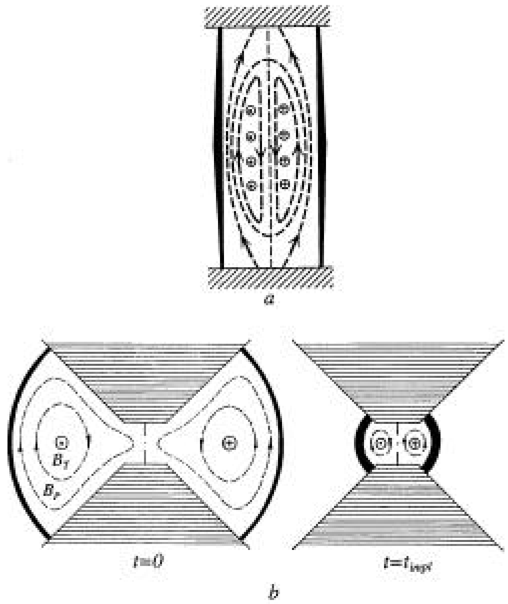

Fig. 2. Liner implosion on a spheromak. The electrodes are shaded, the liner is shown in black, the dashed lines are the magnetic field lines. a) Initial state in a 3D implosion of a prolate spheromak by a liner with a varying thickness. Later in the pulse, the ends move to the axis faster than the central part, thereby creating a 3D implosion. b) Implosion of a "spherical" spheromak by a spherical liner sliding along conical electrodes. In reality, the thickness of the spherical liner varies with the latitude (to maintain sphericity of the implosion, Ref. 28).

Typical experimental values of plasma beta reached in the existing experiments are in the range of 0.1. Therefore, one will probably have to start from a low-beta plasma. According to the scalings (1), for the convergence ~10, one can expect to reach b~1. Assuming that the initial magnetic field is still determined by Eq. (2), B_0~100 kG, one would have to reduce the initial density by a factor of 10 compared to Eq. (2). Accordingly, the final density will be a factor of 10 lower, and this would require a longer stagnation time to reach the same fusion gain. This in turn leads to a necessity to increase initial plasma size and plasma energy content, which may be undesirable if one is aiming at fast implosions. On the other hand, the spheromak with b_o~0.1 looks quite attractive as a target for slow 3D implosions [29].

Near the axis of the spheromak, there exists a bundle of field lines beginning and ending on the material surfaces. The current flowing through this bundle will lead to heat losses of the same type as in Z pinches. However, in the case of spheromaks, this process will take place only in a small fraction of the total volume.

In the fast-liner scheme, one can use spheromaks with initial dimension of a few centimeters to study the physics of this interesting plasma configuration, in particular, the attainability of regimes b~1, at a low level of investment. Indeed, by dropping a constraint of a significant fusion yield, one can reduce the size of the system to a few centimeters, and still produce b~1 plasma. It is also conceivable that new techniques will be found, allowing creation of initial spheromak configurations with b~1; in the spheromak core the pressure would be almost constant as required by an (almost) force-free nature of a spheromak confinement; a sharp pressure drop occurring in a thin layer near the walls could be stabilized by both the proximity of the walls and viscous dissipation in the near-wall plasma. This possibility has not been explored in any detail.

5. Spherical torus

The spherical torus is suitable for 3D implosions because its central post can be made thin enough (it goes without saying that it is evaporated after each shot) not to limit the attainable linear convergence. Schematic of the implosion of a spherical torus is shown in Fig. 3. Initial height, as well as initial diameter, are of the order of 6-7 cm.

The initial toroidal magnetic field can be generated by driving the current through the central post and external shell as shown in Fig. 3a. We need a magnetic field ~ 100 kG at a distance ~ 0.5 cm from the axis. This means that the required current is ~ 250 kA. The time for activating this current is limited by the *L/R* time of the circuit, in other words, $\sim 10^{-4}$ s (for the shell made of a LiPb eutectic). The total energy stored in the initial toroidal magnetic field will be ~ 3 kJ. The voltage needed to generate this magnetic field within a fraction of the *L/R* time (say, $3 \cdot 10^5$ s) is ~ 500 V. All these numbers are not too demanding.

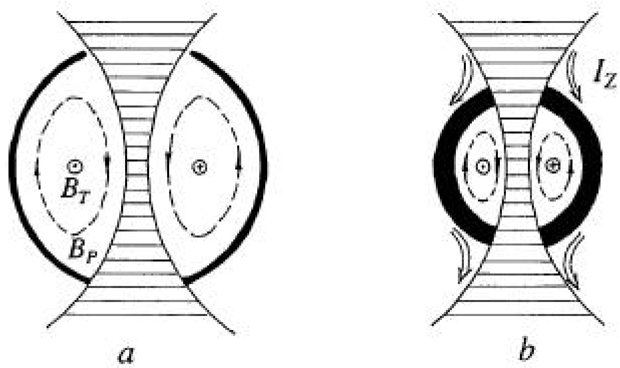

Fig. 3. Implosion of a spherical torus. The central post is shaded, the liner is shown in black. a) A pre-implosion stage, with a gap needed to activate the current in the central post. Tokamak configuration is produced by the gas breakdown and excitation of the toroidal current by inductive or non-inductive techniques. b) The late stage of the implosion. The Z-pinch current I_Z flows along the surface of the central post and the outer surface of the liner.

A more complex task would be to generate a toroidal plasma current ~100-200 kA which is necessary to create the tokamak configuration. Related issue is reaching a significant degree of ionization, and heating the start-up plasma to T_0~100 eV. The energy required for that is ~ 1-2 kJ. A possible solution is the use of a vertical initial magnetic field, which would then be imploded by the liner and generate a loop voltage necessary to break the gas down and excite the toroidal current. This technique was used in early shots in the START tokamak [30], with a difference that there was no implosion, and the vertical field was varied by varying the current in the poloidal field coils. If this approach does not work, one could try the helicity injection approach suggested for the NSTX device (the voltage would be applied within the gap between the central post and the liner; this gap will be closed early in the implosion). This technique is similar to that used to create spheromaks by the gun injection [26, 27]. More futuristic approaches to a pulsed current drive can also be conceived of.

One can expect that the initial ***b*** in the spherical torus will be 0.5 and even higher (see Ref. [30] and references therein). For the purpose of the first rough assessment, we will assume that b_0 is ~1. The subsequent scalings will then be the same as given by Eq. (1).

Initial configuration will be compressed by the imploding liner as shown in Fig. 3. The magnetic field remains frozen into compressed plasma, so that relative magnitude of the toroidal and poloidal magnetic fields remains unchanged. The plasma beta increases and becomes significantly greater than unity. This does not contradict in any way to the possibility of sustainment of the stable tokamak-like configuration of the magnetic field: stability of the system is determined not by the pressure but by the pressure variation over the plasma cross-section, which (pressure variation) will remain of the order of $B^2/8p$. The rest of the plasma pressure will be confined by the walls (or by a thin magnetic sheath formed near the walls). The MHD stability of such a system may be better than stability of a canonical $b<1$ tokamak because of a narrower class of allowable perturbations (the plasma displacements should be almost divergence-free not to create a prohibitively large positive perturbations of the plasma compressional energy).

The central post will experience very high magnetic pressure and will certainly melt. Its inertia must be large enough, so that the kink and sausage instabilities of the central post would not develop. This is not a very severe constraint if the central post is made of a dense enough material, e.g., PbLi alloy. During the final stage of implosion, the compressibility of the central post may become important. One could exploit this circumstance for a better control of a plasma configuration near the point of a maximum compression.

6. RFP

Reversed-field pinch (see [31] and references therein) is a toroidal configuration with approximately equal poloidal and toroidal magnetic fields and a relatively large ratio of the major and the minor radii of the torus (this makes RFP different from a spherical tokamak). The RFP provides a reasonably good confinement of a plasma with b~0.1. Imploding such a configuration could allow one to see if the RFP can reach regimes of wall confinement with $b>1$. The shape of the liner suitable for this purpose is shown in Fig. 4. The toroidal magnetic field could be produced by a voltage applied to a toroidal cut. The current could be initiated by a pulsed transformer, as in conventional tokamaks and RFP's (this possibility does not exist for a spherical tokamak, because of too small a radius of the central post). One or more poloidal slots are needed to let the loop voltage to couple with the plasma. Both toroidal and poloidal slots would be closed early in the implosion.

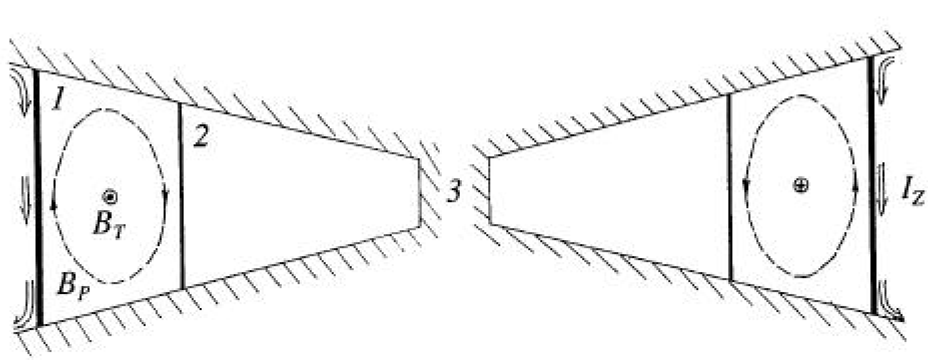

Fig. 4. Implosion of the RFP: 1) outer liner; 2) inner liner driven by the magnetic pressure of the RFP magnetic field; 3) central plug. The inner liner is lighter than the outer one. The current pattern of the external current driving implosion is shown in double arrows.

Imploding a large-aspect-ratio toroidal configuration is a challenging problem. We assume that the upper and lower electrodes in Fig.4 are heavy and are not involved into the motion. The outer cylindrical liner is driven towards the axis by an axial current. The inner cylindrical liner is driven by the magnetic pressure of the RFP magnetic field. This inner liner is lighter than the outer liner. Its mass is adjusted in such a way as to provide the desired time-dependence of the plasma volume. One may use a heavy cylindrical plug inside this inner liner to stop the motion of the latter in the desired point and reach the final plasma compression by the external liner. The tilt of the upper and lower electrodes should me small (to avoid jetting).

7. Linear systems

Linear systems with open field lines (Fig. 5) have an obvious problem with the electron thermal conductivity along the field lines. On the other hand, they possess an attractive feature of providing good diagnostic access along the axis. This circumstance may justify using open-ended systems at an exploratory stage of MTF research. At plasma temperatures below 1 keV and plasma densities ~10^{20} cm^{-3} the mean free path of plasma particles is less than 0.3 mm, and the axial heat loss via the electron channel are small. The plasma outflow through the end holes could be slowed down by using a high-enough mirror ratio of the order of 5-10, as in the gas-dynamic trap concept [32]. By tailoring the axial distribution of the liner mass, one could provide conditions where the mirrors would move towards each other, thereby driving a 3D implosion.

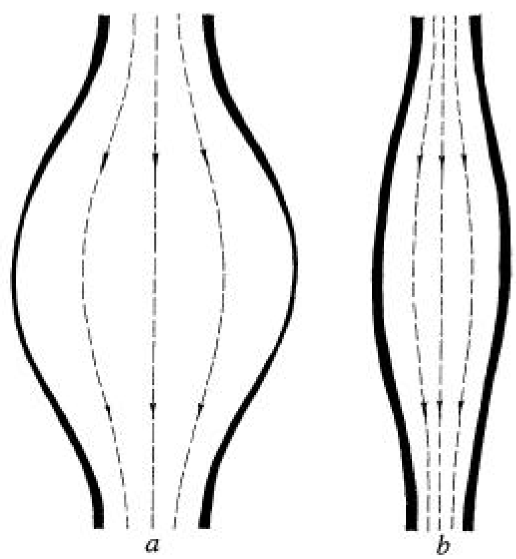

Fig. 5. Linear system: a) initial state; b) final state.

8. Summary

MTF promises a relatively inexpensive path to development of commercial fusion power plants [6]. One of its attractive features is that it can use a number of very different plasma configurations as targets. Table 1 summarizes the results of our discussion. Various targets have specific advantages and disadvantages, but the very fact that there are so many potentially interesting targets that can be studied with quite modest investments certainly increases the probability of eventual success. All these configurations have approximately the same dimensions (a few centimeters), require essentially the same set of power supply systems, and can be studied with the same set of diagnostics. Their studies in the pulsed mode not only serve a direct goal of developing commercial MTF reactor, but may also shed new light on the physics of their quasi-steady-state counterparts. In addition, a new light may be shed on some interesting astrophysical problems, specifically, on the reconnection processes in a $b>1$ plasma (as is the case for the sub-photospheric plasma in the Sun) and radiation-condensation instabilities in the isobaric medium (again, the condition $b>1$ is required for that).

TABLE 1. General comparison of various candidate configurations for 3D implosions

Configuration	Plasma beta demonstrated experimentally	Is the confining magnetic field everywhere tangential to the liner surface	Main problem	Main advantage
FRC	1	PROBABLY NOT	MHD stability	Demonstrated high initial beta; diagnostic access from the ends.
Diffuse Z pinch	1	YES	No equilibria with closed p=constant surfaces; no alpha confinement	Simplicity of the configuration
Spheromak	0.1	NO	MHD stability	Presence of magnetic surfaces
Spherical torus	0.5	YES	Difficult to create initial configuration	Good MHD stability and presence of magnetic surfaces
RFP	0.1	YES	Small beta; complex geometry of the implosion	Interesting fusion-related physics
Mirror	1	NO	End losses	Diagnostic access from the ends

Acknowledgment

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48 and by Los Alamos National Laboratory under contract W-7405-ENG-36.

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