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Magnetized Targets for Fast Z-Pinch Implosions: A Spectrum of Possibilities

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1. Introduction

In this brief communication, we discuss various plasma configurations that can be adiabatically compressed by an imploding liner and 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 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 FRC and diffuse pinch, other configurations were proposed as candidate "targets." In Ref. [5], four types of targets were discussed: FRC, diffuse pinch, spheromak, and reversed-field-pinch. In Ref. [6], a spherical tokamak and a solenoidal (linear) targets were proposed.

Particular realizations of the MTF can involve systems with the fusion yield ranging from many gigajoules (e.g., [2,7]) to tens of megajoules [5]. The high-yield systems are based on the use of plasma targets with initial size of a few meters compressed by slow liners. The low-yield systems are based on the use of centimeter-size targets, where the initial plasma density is relatively high (in the range of 10^{18} cm^{-3}), the implosion time is less than a couple of microseconds, and the energy yield is below 100 MJ. 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 advanages 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 FRC's, we assume 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:

$$T=T_0C^2,\ \ n=n_0C^3\ B=B_0C^2,\ \beta=\beta_0C \qquad (1)$$

where C is a linear convergence, and the subscript "0" refers to the initial state. A very important feature of 3D compression is attainability of high plasma β: if one starts with the state where $\beta_0\sim1$, 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 [8]). It is, of course possible, to start with initial configurations with $\beta_0<1$. Then, plasma β would remain less than one until convergence $C\sim1/\beta$ is reached. In what follows, we assume $\beta_0\sim1$ (unless stated otherwise).

Although we are using the term "fast" to describe implosions, this is a relative term: the sound speed in a fusion plasma is $\sim 1.5 \cdot 10^8$ cm/s and is significantly higher than the expected liner velocity. In other words, the plasma evolves over a sequence of quasi-equilibrium states, and the existence of suitable equilibria is a pre-requisite of successful implosion experiment.

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

$$B_0 \sim 100 \text{ kG},\ T_0 \sim 100 \text{ eV},\ n_0 \sim 10^{18} \text{cm}^{-3}\ \beta_0 \sim 1. \qquad (2)$$

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 discussion of the ways of 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

The FRC suitable for the adiabatic compression by a centimeter-size liner could have the following parameters: density $n_0 \sim 10^{18}$ cm^{-3}, temperature $T_0 \sim 100$ eV, magnetic field $B_0 \sim 100$ kG, length $L_0 \sim 6$ cm, radius $a_0 \sim 1$cm. Such a configuration could be created in a canonical way (see, e.g., [9]), by quickly applying a magnetic field of the polarity opposite to the bias magnetic field. Fig. 1 borrowed from paper [9] shows a sequence of operations used to produce FRC with the parameters: $n_0 \sim 10^{14}$-10^{15} cm^{-3}, $L_0 \sim 100$ cm, $a_0 \sim 15$ cm. Scaling analysis presented in Ref. [6] has shown that one can use the same operations to produce much smaller and denser FRC's, with parameters as in Eq.(2).

The loop voltage ~ 3 kV that will develop when the reversed field is applied, should be more than sufficient for a fast breakdown of the gas. In principle, an independent source of preionization and preheating, e.g., a pulsed CO_2 laser, could be used. The energy needed to create a plasma with $n_0 \sim 10^{18}$ cm^{-3} and $T_0 \sim 100$ eV is 50 J/cm^3. This sets the energy requirements for the preheat source (if one is used: as we have already pointed out, there may be no need in using it).

Radiative losses at the early stage of the FRC formation are negligible if only free-free and free-bound transitions in hydrogen are involved [6]. 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 in the proposed experiments compared to canonical ones ($\sim 10^{18}$ cm^{-2} vs $\sim 10^{16}$ cm^{-2}), the plasma now will be much less permeable to the impurities. The role of radiative losses at the later stages of the implosion was discussed in Ref. [5], with a conclusion that the radiative losses from the bulk plasma are relatively unimportant. 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. We will not return to this issue again.

After FRC is formed, it could be translated into the liner through a hole in one of the ends. In order to prevent FRC from being ejected back into the formation section, one has to provide conditions where the injection hole would be closed early in the implosion. As was pointed out in [10] (and later mentioned in Refs. [1] and [5]), this can be reached by using the liner with a properly varying mass per unit length, with a lighter part of the liner situated near the injection hole.

Advantages of the FRC as a target stem from the fact that the FRC is a well studied configuration, with $\beta \sim 1$ reached in many experiments [11]. Main concerns about this configuration are related to the issue of possible strong MHD instabilities. To some extent, these instabilities can be possibly stabilized if the plasma is wall-confined.

In the FRC configuration, there exist field lines intersecting the liner surface (in the case of the liner encapsulating the FRC). 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 stems from the fact that it is relatively easy to create such a configuration inside the liner [3]. Two end electrodes electrically insulated from the liner could be used for this purpose. The voltage ~ 2-3 kV required to reach a fast breakdown of the gas is not a problem. The gap will be closed early in the implosion. One can note in passing that the MAGO configuration [7] is topologically identical to the diffuse Z-pinch, as it has only toroidal magnetic field. 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 plasma equilibria are such that the p=const surfaces are nested coaxial cylinders [12]. In other words, the plasma pressure must be constant all way from one electrode to another. There are some doubts in that such equilibria are compatible with good plasma confinement, unless the pinch is very long. Of a similar nature is the problem of alpha-particle confinement: the drift trajectories of alpha-particles are open and hit the end-surfaces. Still, because of its simplicity, the diffuse Z pinch configuration is interesting for the studies of the physics of 3D implosions.

4. Spheromak

Spheromak configuration is suitable for 3D implosions [5]. Its advantages stem from the fact that it can be created inside the liner, by using a gun injection technique [13, 14]. The slot in the liner through which the spheromak is injected is closed early in the pulse. If quasi-sphericity of the liner implosion is provided by the axial variation of the liner thickness, the prolate configuration of the type shown in Fig. 2a is preferred. If spherical configuration proves to be more stable, spherical liner of the type used in [15] may become more appropriate as a driver (Fig. 2b).

Typical experimentally reached values of plasma beta are in the range of 0.1. Therefore, one will probably have to start from a low-beta plasma. For the convergence ~10, one can expect to reach $\beta \sim 1$. Assuming that the initial magnetic field is still determined by Eq. (2), $B_0 \sim 100$ 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 making the system less attractive as a target for fast implosions. On the other hand, it looks quite attractive as a target for slow 3D implosions [16].

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 $\beta \sim 1$, at a low level of investments.

5. Spherical tokamak

The spherical tokamak is suitable for 3D implosions because its central post can be made thin enough (it goes without saying that it is evaporated in each shot) not to limit the attainable linear convergence. The schematic of the implosion of a spherical tokamak is shown in Fig. 3.

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 skin time in the liner, which is limited by the L/R time of the circuit, in other words, ~10^{-4} s. The total energy stored in the initial toroidal magnetic field will be ~ 3 kJ. All these numbers are not too demanding.

A more complex task would be to generate the toroidal 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 [17], 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 [13, 14]. One can expect that the initial β in the spherical tokamak will be 0.5 and even higher [17]. For the purpose of the first rough assessment, we will assume that is ~1. The subsequent scalings will then be the same as

Initial configuration will be compressed by the imploding liner as shown in Fig. 3a. 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: the parameter that enters the equilibrium problem is not the pressure but the pressure gradient; the pressure variation between the magnetic axis and the plasma edge will remain of the order of $B^2/8\pi$. the rest of the plasma pressure will be confined by the walls. The MHD stability of such a system may be better than stability of a canonical β<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 thermal 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 restrictive 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 pinches (see [18] and references therein) are toroidal configurations with approximately equal poloidal and toroidal magnetic field and a relatively large ratio of the major and the minor radii of the torus (this makes it different from a spherical tokamak). The RFP provides a reasonably good confinement of a plasma with β~0.1. Imploding such a configuration could allow one to see if the RFP can reach the regimes of wall confinement with β>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 slot are needed to let the loop voltage to couple with the plasma. Both toroidal and poloidal slots would be closed early in the implosion.

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. it 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 a diagnostic access along the axis. This circumstance may justify using open-ended systems at the exploratory stage of MTF research. At plasma temperatures below 1 keV and plasma densities ~10^{20} 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 [19]. 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.

8. Summary

MTF promises a relatively inexpensive path to development of commercial fusion power plants [20]. One of its advantages is it can use a number of very different plasma configurations as targets (TABLE 1). This 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 serves a direct goal of developing commercial MTF reactor, but also allows to shed new light on the physics of their quasi-steady-state counterparts.

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References

1.Alikhanov, S.G., V.P. Bakhtin, V.M. Brusnikin, I.S. Glushkov, R.Kh. Kurtmullaev, A.L. Lunin, A.D. Muzychenko, V.P. Novikov, V.V. Pichugin, V.N. Semenov, G.E. Smolkin, E.G. Utyugov, I. Ya. Shipuk. "Investigation of model thermonuclear systems with liners." *Plasma Physics and Controlled Nuclear Fusion Research, Proc. of the 6th Intern. Conf.,* Vienna, IAEA, 1977, v. 3, p. 517.

2.Turchi, P. "A compact-toroid fusion reactor design at 0.5 Megagauss, based on stabilized liner implosion techniques," In: *Proc. 3rd Intern. Conf. on Megagauss Magnetic Field Generation and Related Topics*, Moscow, Nauka Publ. House, 1984, p. 184.

3.Sherwood, A.R., E.L. Cantrell, I. Henins, H.W. hoida, T.R. Jarboe, R.C. Malone, J. Marshall. "The LASL fast liner experiment." *Plasma Physics and Controlled Nuclear Fusion Research, Proc. of the 8th Intern. Conf.,* Vienna, IAEA, 1981, v. 2, p. 691.

4.Kirkpatrick, R.C., I.R. Lindemuth, M.S. Ward. "Magnetized Target Fusion, an Overview," Fusion Technology, **27,** 201 (1995).

5.Drake, R.P., J.H. Hammer, C.W. Hartman, L.J. Perkins, D.D. Ryutov. "Adiabatic compression of a closed-field-line configuration by a centimeter-size liner". Proc. 16th Symposium on Fusion Engineering, Sept. 30-Oct. 5, 1995, v. 1, p. 97; "Submegajoule liner implosion of a closed field line configuration." Fusion Technology, **30**, 310.

6.Ryutov, D.D. "A user facility for research on fusion systems with dense plasmas" *Proc. of the 2nd Symp. "Current Trends in International Fusion Research,"* Wash. DC, March 1997, To be published by NRC Research Press, Ottawa, Canada.

7.Lindemuth, I.R. , C.A. Eckdahl et al. *Proc. 16 Intern. Conf. on Plasma Phys. and Controlled Nucl. Fus. Res.,* (Montreal, Canada, October 1996), International Atomic Energy Agency, Vienna, 1997, v.2, p.723.

8.Budker, G.I., "Thermonuclear fusion in installations with a dense plasma." In: *Proc. 6th European Conf. on Controlled Fusion and Plasma Physics*, Moscow, 1973, v. 2, p. 136.

9.Eskov, A.G., R.Kh. Kurtmullaev, et al. "Principles of plasma heating and confinement in a compact toroidal configuration" In: *Plasma Physics and Controlled Nuclear Fusion Research, Proc. of the 7th Intern. Conf.,* Vienna, IAEA, 1979, v. 3, p. 187.

10.Velikhov, E.P. Private communication to D. Ryutov (1971).

11.Tuszhewski, M. "Field Reversed Configurations." Nucl. Fusion, **28**, 2033 (1988).

12.Ryutov, D.D., R.E. Siemon. "On the possible equilibria in a configuration of the type of a diffuse pinch." To be published.

13.Jarboe, T.R. "Review of spheromak research." Plasma Phys. and Contr. Fus., **36**, 945 (1994).

14.Hooper, E.B., R.H. Bulmer, B.I. Cohen, D.N. Hill, L.D. Pearlstein, K.I. thomassen, A. Turnbull, R. Gatto, T.R. jarboe, C.W. Domier." Sustained spheromak physics experiment." Paper CN-69/ICP/04 presented at 17th IAEA. Conf. on Plasma Physics and Contr. Fus. Res., Yokohama, October 1998.

15.Degnan, J.H. et al (25 co-authors). "Electromagnetic Implosion of Spherical Liner". Phys. Rev. Lett., **74**, 98 (1995).

16.Fowler, T.K. "Pulsed spheromak reactor with adiabatic compression." To be published.

17.Robinson, D.C. "The physics of spherical confinement systems." Plasma Phys. Contr. Fus., **41**, A143 (1999).

18. Prager, S.C. "Dynamo and anomalous transport in the reversed field pinch". Plasma Phys. Contr. Fus., **41**, A129 (1999).

19. Mirnov, V.V., D.D. Ryutov. ."Linear gasdynamic system for plasma confinement". Sov.Tech. Phys Lett., **5**, 279 (1979)

20.Siemon, R.E., I.R. Lindemuth, K.F. Schoenberg. "Why Magnetized Target Fusion offers a low-cost development path for fusion energy." To be published in Comments on Plasma Phys. and Contr. Fus.

Figure captions

Fig. 1 Sequence of FRC creation and injection: 1) mirror coils; 2) control coils; 3) shock coil; 4) solenoid; 5) liner coil; 7) barrier field bars.

Fig. 2 Spheromak: a) prolate spheromak; b) "spherical" spheromak imploded by a spherical liner.

Fig. 3 Spherical tokamak: a) initial state, with a gap needed to activate the toroidal magnetic field; b) final state.

Fig. 4 RFP: 1 - outer liner; 2) inner liner driven by the RFP magnetic field; 3) central rod.

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

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

Configuration	Plasma beta demonstrated experimentally	Can the initial configuration be created inside a conducting liner?	Is the confining magnetic field everywhere tangential to the liner surface	Main problem	Main advantage	Amount of information collected from the studies of related magnetically-confined systems
FRC	1	NO (?)	NO	MHD stability	Demonstrated high initial beta in a relatively simple configuration	Moderate
Diffuse Z pinch	1	YES	YES	No equilibria with closed p=const surfaces; no alpha confinement	Simplicity of the configuration	Small
Spheromak	0.1	YES	NO	MHD stability	Presence of magnetic surfaces	Moderate
Spherical tokamak	0.5	YES	YES	Difficult to create initial configuration	Good MHD stability and presence of magn. surfaces	Large
RFP	0.1	YES	YES	Small beta; complex geometry of the implosion	Interesting fusion-related physics	Large
Mirror	0.5	YES	NO	End losses	Diagnostic access from the ends	Large

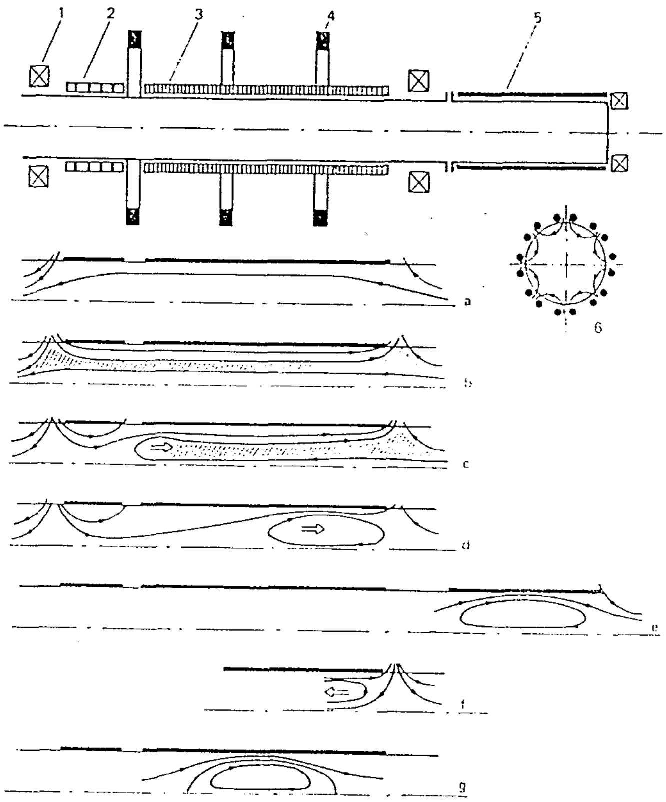

Fig. 1

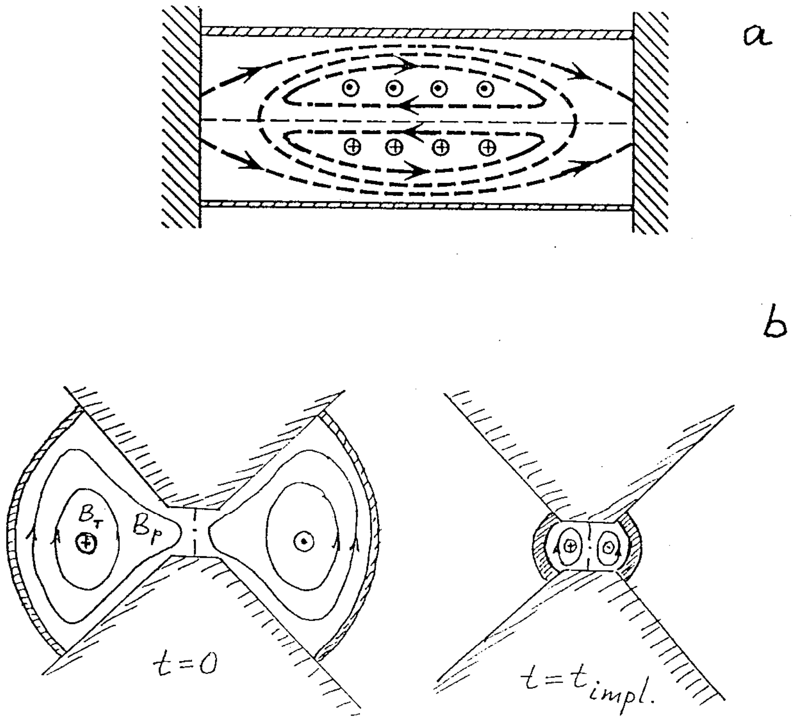

Fig. 2

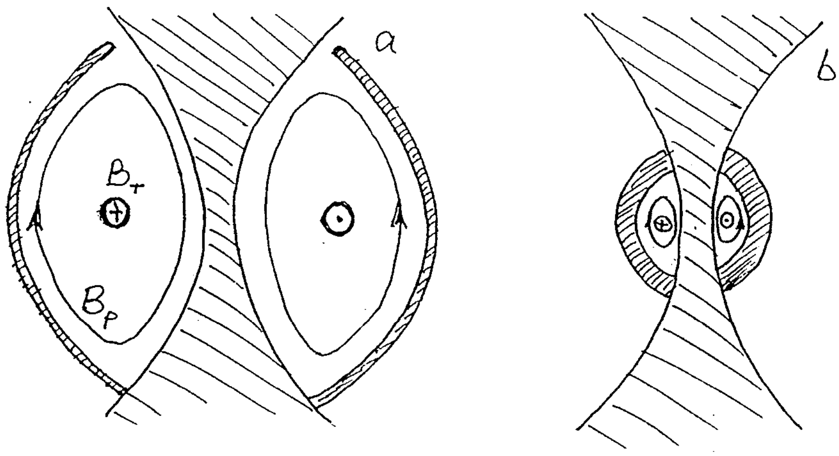

Fig. 3

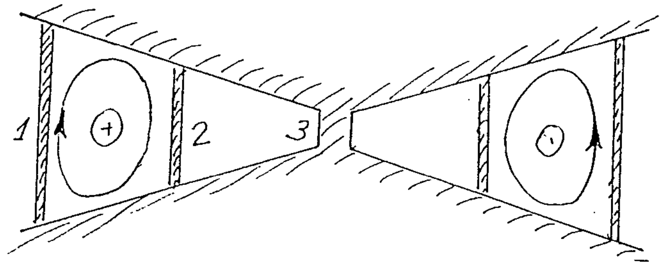

Fig. 4

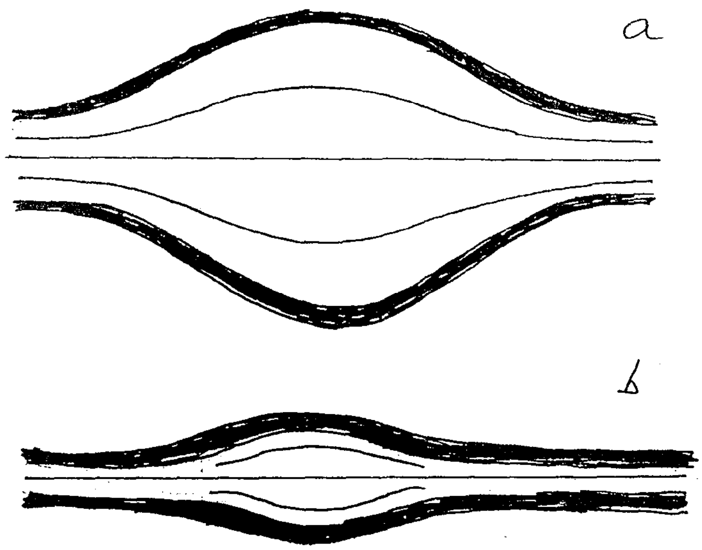

Fig. 5