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COLLAPSE OF Z-PINCH NECKS FOR INERTIAL FUSION

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The ignition is possible under the condition of collarring z-pinch neck up to the diameter 10^{-4} cm. The current pulse with duration 10^{-7} s and 10^{7} A must be applied to a cylinder of condensed D-T mixture in order to obtain the parameter $\rho r \geq 0{,}4$ g/cm^2

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Introduction

The basic assertion of this paper - the Z-pinch features an anomalous low energy threshold in comparison with other schemes of inertial fusion, including a laser fusion. 10 MA current is thought to be sufficient with an energy contribution to plasma of about 70 kJ [1] . So low parameters are possible for two reasons: 1) a use of the collapse physical phenomenon makes it possible to raise an energy flux density in plasma focuses and micropinches by 10^6-10^9 times against a mean density of Poynting's vector on the pinch surface; 2) to reach high, specific parameters one should employ a pinch with minimum possible initial diameter $D \approx 1$ cm, made of a condensed D-T mixture.

A brief scenario of processes in Z-pinch is following. A current pulse with duration $\tau \leq 10^{-7}$ s is applied to a cylinder of D-T mixture with density $\rho = 0.2$ g/cm^3 with an already due neck. After heating-up by a shock wave a plasma flow-out begins from the neck along the pinch, resulting in a collapse along radius. An ohmic resistance can be neglected at the stage of collapse, and the process can be described with a simple modele [2,3] based on two assumptions:

1) a current in the pinch is conserved and the Bennet evaluation is valid (a magnetic pressure is of the order of thermal):

$$I^2 = 3{,}3 \cdot 10^{-22} \pi r^2 (n_e + n_i) T[eB] \quad (1)$$

where h is a concentration, r is a radius in cm, I is a current in mA; 2) secondary shock waves are absent and a temperature grows adiabatically:

$$T \sim \rho^{2/3} \quad (2)$$

a characteristic time of the process development is determined by an acoustic velocity

$$\tau \approx r/10^6 \sqrt{T} \quad (3)$$

From (1) it follows that the Lawson criterion for α-particles $\rho r \gtrsim 0.4$ g/cm^2, where ρ - a density, T = 10 keV, I = 10 MA, can be fulfilled at $2r = 10^{-4}$ cm. At so small sizes an energy in the neck is merely about 10 J and a characteristic time of existence (3) is 10^{-12} sec.

A thermonuclear energy distribution in the neck is low as well but a burning wave propagation to the rest pinch is capable of giving a amplification factor of 10^4 [1] relative to an initial energy contribution. An evaluation of parameter ρr from (1,2) gives

$$\rho r \sim r^{-1/5} \quad (4)$$

The possibility of burning is related to a weak dependence of parameter ρr on a radius, which arose as a casual small difference between the degree of magnetic pressure increase with the decrease in radius $P_m \sim r^{-2}$ and the adiabatic exponent $\frac{\gamma - 1}{\gamma} = 1/5$.

Apart from evaluations (1), (2) the cited scheme is based on the assumption on a possible neck contraction by 10^4 times over a radius. The discussion of neck evolution models is given in Section 1, limitations on contraction - in Section 2, the interpretation of some experimental results - in Section 3. Weak points of the scheme are presented in Section 4.

1. Models for Z-pinch neck collapse

Historically Z-pinches were first thermonuclear machines with magnetic confinement [4] . It is these installations where first neutrons were obtained; the first MHD-instability was found by theorists in 1952 for Z-pinches and published in [6] . Z-pinch was destructed by a sausage instability and, apparently, could not pretend to a role of thermonuclear device. But an experimental observation of a nonlinear stage of the neck instability, leading to a plasma focus formation, has made again the Z-pinch attractive but already for an inertial rather than magnetic confinement. Usefulness of necks was realized finally in papers [2,4,5,7] . The present-day point of view at a neck as an automodel discontinuity was expressed also in [2] , important evaluations were suggested ibid (1-3). Z-pinch neutrons of the fifties were interpreted completely justly as accelerating [8] ; but with an increase in current up to 1 MA it was noticed that no barriers were seen to an increase of neck temperature up to thermonuclear values at the neck collapse, which strenghtens significantly the model (1-3), [9,3].

Let us consider the possibility of violation of evaluation (1). It is rather evident that the state with strong excess of a thermal pressure over magnetic one cannot be realized. A contrary case will result in a shock wave formation and an immediate increase of thermal pressure up to magnetic one. An exception is a formation of a forceless configuration with current being parallel to a magnetic field; but in the Z-pinch geometry with one component of a magnetic field H_φ it is impossible. The neck length is assumed to be of the order of diameter, this means that the neck energy tends to zero as the size decreases, $H^2r^3 \sim r$. From this it follows that the current in (1) can be regarded as constant; independently of a generator power the pinch inductance is sufficient for preservation of current. Thus, the evaluation (1) is very reliable.

The assumption on adiabaticity (2) is less reliable for three reasons. The neck compression proceeds with a speed of the order of sound, therefore, the absence of secondary shock waves follows only from numerical calculations [10,11], reliable qualitative arguments are not available. Besides, at the plasma flow-out from the neck, a magnetic flux also flows out from it, resulting in a formation of current layers on the neck surface [11]. For a skinned current an increment of short-wave necks $\gamma \sim \sqrt{k}$ [12] tends to infinity at $K \to \infty$. This means that the pinch surface is heated by an instability and the adiabaticity does not take plase. Fortunately, there are hopes that this process does not touch the pinch core. Indeed, a characteristic rate of the instability penetration $V \approx \delta/K \to 0$ at $K \to \infty$. Such a heating-up is also not seen in calculations [10, 11] . Finally, there exists a danger of radiation cooling of the pinch. At 10 MA current a condition of insignificancy of radiation losses in comparison with a gas-dynamic heating for time r/Cs is of the form (in an approximation of low optical thickness [1]:

$$\rho r \ll 10^{-4} T[eB] \qquad (5)$$

At low temperatures this condition would be burden some, if it were not for imprisoning of radiation. In this case the condition of insignificancy of radiation cool'ing has the form: $\sigma T^4 S \ll n T r^3 C_s r^{-1}$,

$$T \ll 200 \rho^{2/5} \qquad (6)$$

Thus, the radiation cooling can be neglected with an exception, possibly, of a narrow range of temperatures about 5keV. Note, that in contrast to paper [3] the radiation cooling effect is not thought to be so positive for pinches with initially great parameter ρr .

The value $\rho r = 2.10^{-5} r^{-1}$ corresponds to the Bennet condition at a temperature of 10 keV and 10 MA current; necessary for ignition is reached at $r < 10^{-4}$ cm. A pressure of degenerated Fermigas comes up to 4% from thermal one and be not taken into account.

2. Limitations on radial compression

In hydrodynamic numerical calculations [10] the radial compression was limited by nothing but such limitations arise when gone out of the scope of approximations used.

a) The most evident limitation is related to violation in symmetry at the stage of neutral gas ionization. If in this case the magnetic field H_z will be captured inside the pinch then at an ideal freesing-in it will grow as r^{-2}, whereas $H_\varphi \sim r^{-1}$. After compressing by H_{φ_0}/H_{z_0} times the fields will be equal and the compression will stop. A preionization and other experimental tricks are capable of raising the symmetry. The number of strimmers and, consequently, symmetries grows with a rate of current rise.

b) When the neck developments the linear number of particles $N=\pi nr^2$ decreases and as soon as the linear number of ions ceases to exceed unity

$$\Pi_i \equiv Z N e^2 / A M c^2 < 1 \qquad (7)$$

an applicability of usual one-fluid hydrodynamics is violated. The current velocity and thermal drift velocities of particles begins to exceed Alfven one, an anomalous resistance occurs. A normal evolution of the neck is impossible in this case, which can be easily seen in the assumption of ideal freezing-in.

At $\Pi_i \ll 1$ the current rate exceeds the Alfven one and in the first approximation one can consider a stationary flow of electrons at immobile ions distributed with a prescribed concentration $n(r,z)$. The magnetic field has one component $H = H_\varphi(r, z)$ only. Mentally let us single out a thin torus limited by magnetic surfaces. Let S be its small cross-section. Then, in virtue of freezing-in

$$S H = \frac{S I}{r} = const \tag{8}$$

where H is a magnetic field, I - a current in a circle of radius r.

In virtue of quasineutrality:

$$S r n = const \tag{9}$$

from whence it follows:

$$I = I(n r^2) \tag{10}$$

Let us emphasize that this is an exact solution of electron hydrodynamic equations for the case of ideal freezing-in. The neck evolution is associated with the decrease in the linear density nr^2 but from (10) it is seen that the current cannot flow-in into the region with reduced linear density, therefore the magnetic field is carried away from the neck by the electrons current and the neck should not develop. This mechanism is described in great detail in [13].

A violation of the condition $\Pi_1 = \frac{Z N e^2}{4 M c^2} > 1$ results also in an appearance of Larmor finite radius of ions and anomalous resistance. In paper [14] the neck stabilization was studied by a direct numerical simulation.

c) The most serious limitation on compression was indicated in [15] and related to a low pressure rare plasma surrounding the pinch. The fact is that only a plasma inside the skin-layer can flow-out from the neck and an external plasma frozeen-in in the magnetic field should be compressed with a rise of density $n \sim r^{-2}$, which with allowance for heating-up by compression gives $nT \sim r^{-10/3}$, i.e. a thermal pressure increases more rapidly than magnetic one. This means that if we would like to compress plasma by 10^4 times over a radius, the surrounding plasma thermal pressure should be low:

$$\frac{nT\,8\pi}{H^2} < \left(\frac{r}{R}\right)^{4/3} \approx 10^{-5} \tag{11}$$

These limitations in less direct form are contained in [11].

3. Interpretation of certain experiments with Z-pinches

a) The Fusion scheme proposed in [1] assumes a strong compression of the neck. From this point of view the most impressing are results on micropinches compression up to a radius of the order of 10^{-4} cm [16], interpreted as a radiation collapse [17].

I have another view-point on these experiments. The most known is the neck collapse model described in Introduction where the Joule heating is neglected. This model is central to reach thermonuclear parameters but has a limited scope of application for heavy elements plasma. The cause is an ionization adiabat small power value, as a result the heavy elements plasma temperature increases too slowly with a density

$$T \sim n^{\gamma-1}, \qquad \gamma-1 \approx 0{,}2 \div 0{,}3 \tag{12}$$

and the growth of temperature does not compensate the increase in resistance due to the radius decrease. Once the Joule heating will be equal to a gas-dynamic work, a new collapse regime will come which, naturally, can be called Joule. In this model $\tau_J \approx \tau_{gas}$,

$$R/C_J = \frac{R^2 4\pi\sigma}{c^2} \qquad (13)$$

for elements with $Z_n \gtrsim 50$ simple approximations are possible: $C_s = 10^5 T^{3/4}$ [eV], $\sigma = 10^3 T$ [eV]. The evaluation (13) gives

$$T = (100/R)^{4/7} \qquad (14)$$

which at $R = 10^{-4}$ cm leads to T = 3 keV, in accordance with experimental results [16] ($r = 10^{-4}$ cm, $T \approx 3$-5 keV).

If (14) is supplemented with the Bennet condition, one can obtain the Joule polytrope power

$$T \sim n^{0,4} \qquad (15)$$

in experiments this power is close to 0.5, which is in agreement with the Joule regime and points directly to the increase in specific entropy in contrast to the purely radiation collapse regime [3,17].

This model does not work deliberately for hydrogen. The value of experiments with micropinches lies in demonstrations of collapse possibilities up to $r \approx 10^{-4}$ cm which neither the pressure of a surrounding plasma [15] nor the violation of symmetry prevent to.

b) The review of experiments with hydrogen plasma focus is presented in [18]. In these experiments it was not possible to compress the neck to sizes less than 10^{-1} cm. The plasma density measurements show that in this case the linear number of ions (7) is of the order of unity and a further compression is difficult by virtue of arguments presented in Section 2. So early violation of the condition (7) is associated with a small initial linear number, which in its turn, is caused by a relatively low current ($I \lesssim 1$ MA) and a low initial density. Under the thermonuclear conditions (7) will deliberately not be violated.

The important experimental achievement is a direct proof (according to the Faraday rotation of light polarization plane) of flowing of the whole of current inside the radius $r = 10^{-1}$ cm [19]. The hypothesis of heating adiabaticity, being the most important for thermonuclear fusion, and the assessment (4) $\rho r \sim r^{-1/5}$ following from it, have not been verified.

c) The experiment on explosion of frozen deuterium filaments [20] has gained a wide fame. After corrections the number of neutrons is described satisfactorily by the Sasorov formula [15]; as for the dependence of stability on $\dot{I}$, this dependence is inverse.

From the character of dependence I(t) it is seen that the instability has caused a drastic increase in resistance and current drop.

When interpreted absolutely all experiments on Z-pinches one should bear in mind that the neck does not tear ever up to violation of quasineutrality and its resistance (even at an ideal conductivity) is estimated by the formula [13,21], a - radius

$$R_{[\mathrm{Ohm}]} = 30\,\frac{u}{c}, \quad u = \frac{I}{2\pi n e a^2} \qquad (16)$$

In this state the neck exists for 10-100 MHD-times, whereupon the number of particles increases and the resistance (16) decreases.

4. Weak spots of the scheme [1]

It is quite natural that the weakest and strongest spots coinside. An anomalous low energy threshold of ignition in the neck is the consequence of strong radial compression (10^4 times). This is a very strong compression, its impossibility deprives at once the neck of attractiveness. Thus, the increase in finite dimension by 10 times results in the necessity to raise the current by $\sqrt{10}$ times.

It should be emphasized that in contrast to shells compression the neck is a nonlinear stage of the fastest instability and, therefore, is relatively free from secondary instabilities. This is an automodel collapse, similar to wave one [22], in fulfilling the Sasorov condition (11) and deliberately met $\Pi_i \gg 1$ (7) the collapse is being continued without limit.

Unfortunately, the violation of axial symmetry terminates the compression quickly.

Possible difficulties beginning from the most dangerous ones

a. The axial symmetry violation at an initial ionization and in the process of compression.

b. The neck stabilization at $r > 10^{-4}$ cm according to the Sasorov mechanism [15] .

c. The pinch overheating can lead to attaining thermonuclear temperatures at an insufficient ρr . Also, an over-cooling is possible due to radiation losses [3] .

d. Slipping the discharge between an electrode and D-T mixture.

e. The high anomalous resistance of the pinch skin (it is impossible to speed-up the current).

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