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HIGH DENSITY FUSION AND THE Z-PINCH*

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ABSTRACT

The formation of a Z-pinch in dense gas is investigated using numerical modeling in 1- and 2-dimensions. Hot, dense Z-pinchs are calculated with $n \approx 2 \times 10^{21} \text{ cm}^{-3}$ and $T = 10 \text{ keV}$. Relaxation by Sausage instability of an unstable pinch profile to a marginally stable one is calculated along with end losses in 2-dimensions to show that if plasma is confined for $N = 50$ to 200 sound transits across the radius a , pinches with length $L = Na$ are of interest for fusion power. A conceptual, "no-wall" fusion reactor is discussed.

INTRODUCTION

We reexamine the gas-embedded Z-pinch [1,2] as a means of achieving controlled thermonuclear fusion. We consider the high density regime $n > 10^{19} \text{ cm}^{-3}$, where the Z-pinch provides sufficient field for magnetic confinement and where, because of the short time for fusion energy release, losses from hydromagnetic instability [3] may be overcome. A central question here, as discussed earlier by Morozov [4], is to achieve net energy release at feasible levels of power and total system energy.

Since the diffuse Z-pinch is hydromagnetically unstable to the kink ($m=1$) mode, it is expected that the plasma confinement time scales "acoustically," i.e., $\tau = Na/v_{\text{sound}}$, where a is the pinch radius and N is the number of sound transits across a during τ (kinking of the whole column can couple to external mass increasing τ [5]). For a pinch that

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satisfies the Lawson criterion with length $L = Na$, the total pinch energy scales as $U \approx n^{-2} N^{-2}$ and the power scales as $P \approx n^{-1} N^{-2}$. Large values of n , N are therefore required to maintain reasonable values of U and P . Experimental evidence [6,7,8] suggests that in some cases pinched plasma columns may persist for $N = 50$ to 200 in contrast with the linear growth time, $N \approx 1$. In this paper we consider pinches with $N \approx 100$, and conclude that for $n \approx 10^{20}$ to 10^{21} cm^{-3} and $U \approx 1$ to 50 MJ, it is possible to achieve a net energy release from fusion under practical conditions.

We examine the formation and stability of Z-pinches using 1- and 2-dimensional numerical modeling. Specifically, we model in 1-dimension the formation of a hot Z-pinch in dense, room temperature gas in the range 1 to 100 atm starting from a conducting channel formed by an intense, pulsed electron beam. Feasible ways are found to form pinches of interest for fusion. We study the effects of plasma flow and end losses in two dimensions. We find end loss takes place at an axial flow rate not greater than v_{sound} consistent with the assumption $L = \tau v_{\text{sound}}$.

A successful, energy-producing Z-pinch would be isolated from an influx of impurities from nearby solid or liquid material by the surrounding column of dense gas. It appears possible, therefore, to eliminate the "first wall" of conventional reactor approaches. Elimination of the first wall along with the inherent simplicity of the Z-pinch as a plasma heating and confinement system allows simple, conceptual reactor configurations.

Z-PINCH SCALING

Table I gives approximate values of voltage, current, pinch radius, and energy for several values of plasma density and N . The pinch with length $L = \tau v_{\text{sound}}$ is assumed to satisfy the Lawson criterion $n\tau = 10^{14}$ at $T = 10 \text{ keV}$, and the Bennet relation [2]. The ratio of pinch radius to the return current radius is taken to be 0.01, giving a ratio of magnetic energy to plasma energy $U_m/U_p = 9.7$. The quantities U , I , and V are in megajoules, mega-amperes, and megavolts respectively, and a is in centimeters.

For $N = 200$, Table I shows that feasible pinches lie in the range $n = 10^{20}$ to 10^{21} cm^{-3} , while for $N = 50$, $N = 10^{21}$ to 10^{22} cm^{-3} must be considered to maintain a sufficiently low U .

1-DIMENSIONAL MODELING

One-dimensional modeling investigates the conditions under which it is possible to form a hot Z-pinch in a dense gas. Since the voltage that drives the pinch also appears across the surrounding gas, it is necessary to provide transient conditions such that the gas remains nonconducting during the formation of the pinch. Otherwise, the current drives an expanding conduction front or, if pinching occurs, the pinch accretes mass at the expense of temperature. To achieve the desired conditions it is necessary to form an ionized channel in the gas, or to depress the gas density by shocks so that breakdown occurs in the desired region [9]. We investigated the first possibility assuming the channel was formed by the propagation of an intense, self-pinched, high-energy electron beam.

An E-beam pulse deposits energy in the high pressure gas (1 to 100 atm) primarily by ionization and excitation for the parameters considered ($E = 1$ to 10 MeV, $\tau = 50$ ns, $J = 10^5$ to 10^6 A/cm²). During the pulse, free electrons are created in competition with recombination. Afterwards, the electron density rapidly decreases by further recombination if a large "breakdown" electric field is not applied. The deposited energy causes the channel to expand launching a shockwave radially outward. The pinch formation sequence we have investigated begins with a weak pinch current $\sim 10^6$ A that ohmically preheats the expanding channel to $T \approx 50$ to 400 eV in 5 to 20 μ s. Following the preheat the pinch current is increased rapidly to $\sim 10^7$ A in about 0.5 μ s. The resulting compression and heating brings the plasma to the desired temperature of $T = 10$ keV.

The calculations were done using a Lagrange, 1-dimensional magnetohydrodynamic (MHD) code [10]. The code assumes thermal equilibrium (except for radiation) to calculate the appropriate equation-of-state, and thermal and electrical conductivity for molecular, atomic, and ionized deuterium. Bremsstrahlung and the approximate [11] bound-free radiation power are treated as an energy loss, assuming the plasma and gas are optically thin. In this code the electrons and ions have the same temperature.

Figure 1 shows the pinch configuration considered, and the computed density and temperature profiles following the preheat phase and after compression. The initial gas density and temperature were $n = 1.2 \times 10^{19}$ D₂/cm³ and $T_{go} = 0.02$ eV (58.5 atm at 0°C). The channel was started with $n_D = 2.4 \times 10^{21}$ D/cm³, $T_{co} = 0.5$ eV, and initial radius $a_0 = 0.15$ cm. At the end of the preheat phase, the current increased almost linearly in time to $I = 0.575$ MA at $t = 5.97$ μ s, heating the center region of the channel to $T = 75$ eV. During the preheat, the outer region of the channel failed to conduct enough current to heat, but remained considerably hotter ($T = 0.4$ eV) than the surrounding gas because of the initial internal energy of dissociation. (This appears as a temperature step at $T \approx 0.4$ eV in the 5.97 μ s curve of Fig. 1.) After compression in Fig. 1, all of the initial channel and some of the surrounding gas were swept into the pinch. The final pinch had parameters $n = 2 \times 10^{21}$ cm⁻³, $T = 10$ keV, $a = 0.1$ cm, and $I = 24$ MA. The plasma energy per centimeter is $U_p = 0.4 \times 10^6$ J/cm and the magnetic field energy is $U_m = 1.7 \times 10^6$ J/cm. At the final density the Lawson time is $\tau_L = 0.05$ μ s, which corresponds to $N = \tau_L / \tau_D = 10$. The formation time of the pinch takes about $N = 120$ sound transits for the preheat phase and about $N = 100$ sound transits for compression to the final state, which is roughly consistent with the assumed stability criterion $N \approx 100$.

Avoidance of breakdown in the outer gas is of great importance. Many factors (radiation, shock heating and dissociation, impurities, magnetic field, etc.) complicate detailed assessment of the electrical breakdown strength of the gas. However, since the Townsend coefficient for electron multiplication varies exponentially in the quantity E/p [12], the complicating factors are likely to influence the allowable E/p only weakly. We therefore compare the results given in Fig. 1 with the dielectric strength of H₂ gas $E = 20$ KV/cm [12] (at stp) which is assumed to be the same for D₂ gas. The breakdown field is $E = 9.9 \times 10^6$ V/cm at the initial gas density so that during the pinch, the applied electrical field reaches a maximum value of $E = 0.34 \times 10^6$ V/cm or $E_{\text{applied}}/E_{\text{breakdown}} \approx 0.4$.

Mass accretion can occur if the initial channel temperature and dl/dt are not chosen properly. The proper choice depends on matching the radially outward shock propagation and channel expansion and cooling to the inward pinch force and channel ohmic heating. If heating of the gas layers next to the channel is too large they become conducting, and because the increasing current concentrates in the skin, an ohmically heated conduction wave is propagated outward into the gas.

An example of a conduction wave that is triggered by the reflected gas shock is shown in Fig. 2. The shock wave launched by the channel initially reflects off the solid boundary at $r = 2.1$ cm and strikes the pinch at $\tau = 9.9$ μ s. At this time the gas near the pinch is heated and becomes conducting and, because I is increasing, the skin current transfers outward. Ohmic heating in the skin generates pressure that drives the shock in the nearby gas, regenerating the heating. As successive layers of gas become conducting, the pinch force sweeps them inward, leading to mass accretion.

We observe the conduction front phenomenon and a similar tendency toward striation of the ionized plasma at high density ($n = 10^{20}$ to 10^{21} cm^{-3}) in a number of calculations. This general property appears to be a variant of the resistive heating instability [13] with important Bremsstrahlung effects at high density.

2-DIMENSIONAL CALCULATIONS

We performed two types of calculations for deuterium plasma using a 2-temperature, 2-dimensional Eulerian, MHD code [14]. Also included are finite resistivity, collisional coupling of the electron and ion fluids, and magnetic-field-dependent thermal conductivity. The relaxation of a sheet current pinch to the equilibrium marginally stable to Sausage ($m=0$) instability and particle and energy losses caused by end effects are calculated.

Starting from an initial sheet current equilibrium with 1% random noises, the plasma pressure is calculated to relax to the marginal-stability equilibrium [3] in about $N = 60$ sound transits. Figure 3a shows the average pressure profile at three times, and Fig. 3b shows the vortex motion at about the time of maximum flow velocity. The relaxation shown in Fig. 3a takes place with the initial growth of small wavelength vortices that increase in velocity to $v = v_{\text{sound}}/2$, and coalesce gradually as the pressure gradient reduces. The initial growth of the instability is obscured in these calculations by the computational mesh size; however, the overall relaxation process is insensitive to mesh size.

Figure 3b shows the vortex velocity pattern near its maximum value. The vortices are nearly closed so that the gradual broadening of the pressure profile takes place on the slow timescale for dissipation of the vortices, rather than the linear theory growth time corresponding to $N = 1$. Similar results have been obtained with a dense cold plasma ($n_{\text{cold}} = 100 n_{\text{hot}}$) surrounding the pinch.

To estimate the effects of ends on energy and particle losses, we did a 2-dimensional calculation beginning with a uniform current-density pinch placed between electrically conducting, room temperature, particle-reflecting walls at $z = 0$ and 9.2 cm. A similar cylindrical wall was located at $r = 6$ cm. The initial pinch parameters were $a_0 = 2$ cm (current channel radius), $n_0 = 2.4 \times 10^{19}$ D cm³, and $T_0 = 10$ keV. The time-decay of the total plasma and magnetic field energy is shown in Fig. 4. After an initial transient, when the axial temperature distribution develops a normal mode-like shape, the energy decays nearly exponentially. The e-folding time for energy decay corresponds to roughly 9 ion sound transits along the half-length of the pinch. The calculated loss rate is less than that assumed for pinch scaling (2 sound transits), however, further calculations with particle absorbing walls or hollow end conductors are needed to determine more accurately the expected end loss rate.

POSSIBLE REACTOR CONFIGURATION

The surrounding dense gas serves to isolate these particular pinch configurations from impurities released from nearby solid walls. Further, because only high pressures are considered, the need for a vacuum, and particularly the usual design reactor "first wall," is eliminated. However, a different constraint imposed is that the explosively released pinch energy must be contained. A possible "no wall" reactor configuration was suggested earlier in the Blascon concept [15], but it requires electrical isolation and minimized stray inductance of the pinch electrical circuit.

A conceptual Z-pinch reactor configuration modeled after the Blascon concept is shown in Fig. 5. A Lithium vortex forms the neutron-moderating blanket in which Helium bubbles are mixed to dissipate the shock. To form the pinch, an electrode of solid Lithium or a jet of liquid Lithium would be injected. High pressure (100 atm) Helium gas would provide electrical isolation. The DT fuel and E-beam would be injected along the electrode axis. The Blascon system considers an explosive energy release of about 50 MJ which roughly corresponds to the energy content of the pinch calculation given earlier when the length increased to $L = 30$ cm so that $L = 100a$ to $300a$.

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Table I Z-pinch energy, radius, current, and voltage vs n, N.

τ_{sec}	N n cm ⁻³	50				100				200			
		U	a	I	V	U	a	I	V	U	a	I	V
10 ⁻⁸	10 ²²	0.22	0.02	6.3	3.5	0.056	0.01	3.2	1.7	0.014	0.005	1.6	0.87
10 ⁻⁷	10 ²¹	22	0.2	20	11.0	5.6	0.1	10	5.6	1.4	0.05	5	2.8
10 ⁻⁶	10 ²⁰	2240	2	64	34.9	560	1	32	17.5	140	0.5	16	8.75

FIGURE CAPTIONS

- Fig. 1 The pinch is 10-cm long and is formed in D_2 gas with a solid wall return conductor at $r = 2.25$ cm. The electrical circuit starts with $C = 20 \mu$ farad charged to $V_0 = 5 \times 10^6$ V, and S is closed allowing preheat current to flow through $L_1 = 5 \times 10^{-5}$ H. At $t = 6 \mu s$, S_2 is closed and the current rapidly increases through $L_2 = 5 \times 10^{-8}$ H. C was chosen larger than necessary, and the calculation was terminated when $T = 10$ keV. Density and temperature profiles are shown at $t = 0, 5.97$, and $6.57 \mu s$, corresponding to pinch currents of $I = 0, 0.575$, and 24 MA. The maximum electric field applied to pinch is $E = 3 \times 10^5$ V/cm, corresponding to the dielectric strength of H_2 gas at $n = 8 \times 10^{20}$ $ft^{-3} cm^{-3}$.
- Fig. 2 Zone boundary radii vs time, and density vs radius at $t = 0, 9.86$ and $12.25 \mu s$ are shown. The initial channel temperature $T_0 = 0.5$ eV and radius $a_0 = 0.15$ cm extends through zone 11. The shock wave reflects from the solid wall at $r = 2.1$ cm at $t = 5.1 \mu s$ and intersects the pinch at $t = 9.9 \mu s$. At $t = 12.5 \mu s$, the pinch current is $I = 0.24$ MA supplied by an electrical circuit with $C = 20 \mu$ farad, $L = 5 \times 10^{-5}$ H, and initial charging voltage $V = 10^6$ MV.
- Fig. 3 Figure 3a shows average pressure vs radius at $Z = 4.5$ cm for $N = 0, 13$, and 60 sound transits across the initial sheet-pinch radius at the initial pinch temperature $T_0 = 1$ keV. The initial temperature was taken as constant, and the density was reduced by 10 outside the pinch. Fig. 3b shows the flow velocity pattern at $t = 0.76 \mu s$ ($N = 9$ transits). The arrows indicate the direction and magnitude of the flow; the maximum velocity $v_{max} = 0.36 v_{sound}$.
- Fig. 4 Total energy and ion temperature vs time.
- Fig. 5 A conceptual Z-pinch fusion reactor modeled after the Blason concept, and scaled from the calculations of Fig. 1. The pinch is formed between the inserted electrode and the Li blanket which serves as a return conductor.

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