LA-UR -83- 2311

CONF-8309147--1

LA-UR--83-2311

DE83 017311

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SUBMITTED TO: 3rd International Workshop on Plasma Focus Research
12-13 September 1983
Stuttgart, W. Germany

HIGH-DENSITY Z-PINCH RESEARCH*

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The linear Z pinch is a plasma configuration which in its simplest form requires no auxiliary magnetic field; an axial current carried by the plasma produces an azimuthal confining field and provides ohmic (resistive) or implosion heating. The Lawson criterion ($n\tau > 10^{20}$ m^{-3} s) and high temperatures (T > 10 keV) must be simultaneously satisfied in any reactor scheme. Early Z-pinch experiments concentrated on the sub-atmospheric fill pressure regime, with 10^{19} m^{-3} < n < 10^{23} m^{-3} and a corresponding confinement time constraint of 10^{1} s > τ > 10^{-4} s. In addition, these studies involved plasmas formed at the surface of an insulating wall; the plasmas were subsequently pinched inward by the radial j×B force. Following the implosion phase, gross MHD instabilities were invariably observed on a time scale short compared to the required confinement time.

The high-density, gas-embedded Z-pinch program (HDZP) at Los Alamos National Laboratory is a modification of the conventional Z-pinch approach in several respects. First, the density regime presently investigated is n ~ 10^{26} m^{-3} with a commensurately short confinement time requirement of only 10^{-6} s. In addition, the plasma is initiated in the center of a large chamber filled with neutral gas by a Q-switched laser. This removes the problem of wall-related impurities and may generate a pressure profile which is m=0 stable. Laser initiation helps to set the spatial (radial) scale of the plasma, which in our experiments begins at approximately 100 µm. Furthermore, there is a possibility that the presence of a coronal region surrounding the plasma column can provide some stabilization against m=1 kink mode development.

A fusion reactor using a high density Z-pinch plasma would be an inherently pulsed device with burn times of approximately one microsecond. By making the assumption that the plasma will remain stable on this time scale, simple calculations[1] indicate that a plasma with n ~ 10^{27} m^{-3}, ℓ ~ 0.10 m, and r ~ 10^{-4} m would have an energy output of 4.4 MJ with an input energy of only 140 kJ. This drastic departure from conventional magnetic confinement reactor schemes provides the chief motivation for the continued effort in the HDZP program.

The design of an HDZP experiment is based on a simple model of the plasma equilibrium. This model uses Bennett equilibrium, i.e., a balance between plasma internal pressure and magnetic field pressure, in conjunction with an equation for energy balance. The source term is the ohmic heating of the plasma through its Spitzer resistivity while the

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*Work performed under the auspices of the U.S. Department of Energy.

loss is the bulk radiation via bremsstrahlung. In steady state, one observes a balance at a unique value of plasma current, which for hydrogenic plasma is $I_p \sim 1.4$ MA. This asymptotic limit (called the Pease current[2]) is approached according to a specific waveform when the time-dependent equations are solved.[3] The current must rise rapidly at early times, with $dI/dt \gtrsim 5\times10^{12}$ A s^{-1}, then the rise rate must decrease as I approaches the Pease current. We have used the equilibrium model results to determine the proper configuration of the current generator for the HDZP experiments.

The present HDZP apparatus consists of a current generator which can produce a peak current of 400 kA in 250 ns. A six-stage Marx bank generator, erected to 600 kV, is directly coupled to a 1.6-Ω water-dielectric coaxial transmission line with a one-way transit time of 100 ns. The water line drives a self-breaking water switch which is in turn connected to the plasma load chamber through an additional transmission line section. The low inductance switch is used to generate a rapidly rising current at the load in an attempt to approximate the time-dependent equilibrium waveform. The plasma chamber is typically filled with hydrogen at pressures ranging from 5-45 psia, and diagnostic access is achieved through transverse-viewing ports.

Application of the high voltage pulse across the 10 cm discharge path in the hydrogenic atmosphere would result in a multi-channel breakdown if some form of single column designation were not used. In the HDZP experiments, a Q-switched (30 ns FWHM) Nd-glass or ruby laser illuminates a path between the two electrodes and is fired 100 ns <u>before</u> the voltage wave reaches the load chamber. The initiation laser is operated below the threshold for laser-induced breakdown to avoid the problems associated with axial inhomogeneities.

Our present complement of diagnostics includes standard current and voltage probes, soft x-ray emission detection through thin metallic foils, and a quantitative optical density diagnostic based on the schlieren effect using a 1-ns N_2 laser pulse.

The most striking observation of the plasmas produced in the HDZP experiments is their lack of gross MHD instabilities; the plasma has an initial radius of ~ 50 μm and grows at a rate of $1\text{-}2\times10^4$ ms^{-1} during the first 60 ns, remaining well-bounded and extremely straight throughout its history. A simple estimate for the instability growth time based on ion-thermal transit across the plasma column would suggest that grossly unstable behavior should be observed during the first few nanoseconds. Our detailed determination of the plasma density profile using the schlieren diagnostic indicates that the peak density occurs on axis, and it is probable that a monotonically decreasing radial pressure profile is achieved which permits the observed stability against the m=0 sausage mode.[4]

The temporally-resolved x-ray diagnostic gives a plasma temperature from the bremsstrahlung emission. Temperatures of several hundred electron volts are reached within the first 10 ns in agreement with the equilibrium model predictions. The observed temperatures then drop rapidly below the threshold of the diagnostic (~ 100 ev), contrary to our initial expectations. This result has been explained[5] using the data obtained by the schlieren diagnostic and indicates the chief obstacle in the HDZP program, i.e., the accretion of new plasma at the channel-neutral gas interface.

The growth of the initial, 100-μm plasma channel was originally believed to be a simple expansion of the plasma. Quantitative density measurements reveal, however, that the line density itself is growing, i.e., the total number of plasma particles is monotonically increasing. Thermal equilibration results in a rapid cooling of the column because the ohmic heating input cannot keep pace with the plasma accretion, and the temperature drop agrees with the soft x-ray emission data. This accretion must be controlled before higher and more sustained temperatures can be achieved.

The mechanism which drives the creation of new plasma remains unknown, although several hypotheses have been examined. First, radiation from the central plasma may ionize the surrounding neutral gas. This complicated radiation transport problem has only been studied to date by simple computational estimates, and further work must be done to appreciate the effects of this process. A second mechanism involves thermal conduction into the cold, neutral region, and present computer models suggest that this effect is not sufficient to explain the observed accretion rate. Third, the plasma column dynamics at early times may launch an ionizing shock wave into the surrounding gas. Again, this mechanism is under computational investigation.[6] It is also possible that the accretion is driven by excitation of a large volume of hydrogen by the initiation laser. The majority of the HDZP experiments have been performed using a high-divergence initiation laser which illuminates a broad region in the load chamber. Indeed, the observation of a 100-μm initial channel remains a mystery, as this spatial dimension is much smaller than the initiation-laser spot size. Recently, a low-divergence Nd-glass laser was implemented to help eliminate this possible accretion mechanism. Finally, the electric field applied to the discharge electrodes may be exceeding the breakdown threshold for the neutral gas during the entire first 50 ns of current flow and result in Townshend ionization outside the central plasma channel. A pulse-sharpening transmission line has been installed in the current generator between the water switch and the plasma load chamber to decrease the effects of electron avalanching after the initial plasma is formed. Our experimental program is proceeding with the goal of controlling the creation of new plasma in the high density Z pinch and allowing the plasma to reach the Pease current at high temperatures.

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