Feedback Stabilization Experiment on a Screw Pinch

R. Keller, A. Pochelon, and W. Bachmann
Centre de Recherches en Physique des Plasmas, Ecole Polytechnique Fédérale de Lausanne, CH-1007 Lausanne, Switzerland

(Received 8 December 1975)

Suppression of the $m=1$ growing mode of a screw pinch is obtained by feedback stabilization. The transverse field produced by $l=1$ windings is automatically controlled by the magnetically detected plasma motion, in order to create a restoring force for both displacement coordinates.

Automatic control systems of the magnetic field have been used for stabilizing slow plasma motions in tokamaks.[1-4] The important task of suppressing fast-growing modes by feedback stabilization of a high-β plasma is being undertaken in the Scyllac experiment.[5,6] We report the results of a feedback stabilization experiment conducted on a screw pinch driven unstable in the fast $m=1$ mode. Preliminary results were presented in a previous paper.[7]

The pinch configuration and plasma characteristics are the following: The theta coil measures 142 cm and has an inner diameter of 9 cm. Two slits are machined in the midplane for observing the plasma motion in orthogonal directions, 45° above and below the horizontal. The main field reaches 16 kG in 3.8 μsec at which time the crowbar is switched on. The quartz discharge tube has an inner diameter of 5 cm. The time evolution of the axial current J_z is similar to that of the main field B_z. Two electrodes, 1.2 cm in diameter, are 142 cm apart, and are protected by limiters in order to concentrate the axial current on the front of the electrodes. In this way, definite boundary conditions exist for the pinch. In fact, dipole probe measurements show a screw-shaped pinch with a sinusoidal displacement vanishing at the electrodes.[8] At 45-mTorr-deuterium filling pressure, diamagnetic probe measurements show an axial β of 0.2 and a mass collection of 85% at 3 μsec after the start of the pinch. From growth-rate measurements we find the Kruskal-Shafranov limit for the fixed-end screw pinch at $J_z = 2100$ A which corresponds to a mean plasma radius of 0.8 cm. The same radius is obtained from the luminosity profile. A mean plasma temperature of 11 eV follows from pressure balance.

For each degree of freedom of the transverse motion a feedback loop is installed. It consists of a magnetic dipole probe sensing the plasma motion near the midplane, a power amplifier, and a feedback coil. The detected and amplified signal is fed to the coil wound in such a way as to exert a force in the opposite direction to the displacement.

The feedback coils have an $l=1$ configuration and are similar to the saddle coils used by Kiyama, Newton, and Wootton.[9,10] In their extensive work, concerned with the response of a plasma column to an external force, good agreement was found between optical and magnetic measurements of the plasma motion. Moreover, the displacement was consistent with the computed value. In our preliminary measurements on plasma response we obtained the same result. Proportionality between the integrated probe signal and the optical displacement was observed for amplitudes not exceeding the plasma radius.

The feedback coils are built in two straight sections 30 cm long and are located symmetrically on each side of the dipole probes. Sufficient spacing must be provided in order to avoid an adverse coupling between coils and probes; the gap was set at about 2×10 cm. Each coil has twelve turns, equally spaced and covering 90° opposite sectors. The Fourier component of the force acting on the $m=1$, $n=1$ mode is 45% of the force that results from a coil which covers the full length of the discharge tube, but this loss of efficiency is partly recovered by the fact that a shorter coil needs less energy for the same current. Higher harmonics of the force, $n \geqslant 2$, are also present, but these modes remain stable below twice the Kruskal-Shafranov limit.

The magnetic dipole probes are located near the viewing ports. They are wound on an annular core of 0.9-cm^2 cross section surrounding the discharge tube, and are oriented to minimize the pickup of the main field. The 62 windings are equally spaced and cover 120° sectors. The remaining coupling between probe and coils is not negligible and its value is negative. Theory shows that stability is only possible if the coupling is positive and relatively small. We compensate for this inconvenience by means of a loop

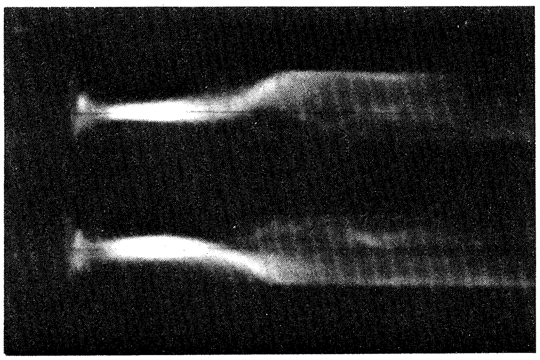

FIG. 1. Streak photograph of the kink.

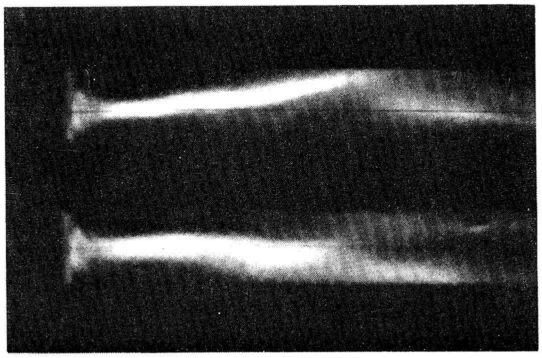

FIG. 2. Streak photograph of the plasma motion with stabilization.

connected in series with the probe, and coupled to the feedback current in a correct way.

The probe signal is integrated and amplified with a driver stage consisting of a transistorized preamplifier and a three-stage vacuum-tube section. It reaches a 400-V level at very low impedance, necessary to drive the two power triodes (Siemens RS 1041) connected in push-pull configuration. The available peak current and voltage between anodes is 70 A and 40 kV. A 2.31:1 step-down output transformer feeds the power to the twelve-turn feedback coils, thus providing a current sweep of nearly ± 2000 At. The resulting transverse force can cope with a 3-mm plasma amplitude. In order to compensate the 0.6-μsec overall delay of the amplifier, a lead circuit is incorporated at low level in the feedback loop. When the power amplifier is switched on, a reset prevents the preamplifier input from receiving spurious signals until the pinch is formed and opens when the kink is about to grow.

The measurements were performed at 1.8 times the Kruskal-Shafranov limit, for filling pressures in the range of 35 to 60 mTorr D_2. One difficulty in conducting the experiment was the fact that for a well-aligned discharge tube, the kink motion was only observable at too late a time. Not enough time was left for feedback action before end effects began to perturb the pinch strongly. It was possible to change this situation by inclining the tube at a small angle (0.1%) with respect to the main magnetic field. By doing this, not only did the kink start growing sooner, but a general upward drift appeared from the beginning.

Consequently a supplementary force had to be provided by the amplifier to hold the plasma in a new equilibrium position, and less power was available for stabilization. In order to have sufficient power for feedback action we did not attempt to maintain the plasma near a steady equilibrium. Instead we let the amplifier work around a slowly drifting position. This was accomplished by subtracting a slope function from the integrated probe signal in such a way as to cancel the detected drift.

The stereoscopic streak pictures of Figs. 1 and 2 show the plasma motion at 45-mTorr filling pressure, without and with stabilization. The total length of the visible trace is 25 μsec, and the vertical scale may be read from the spacing between the two zero lines of the traces which corresponds to 7.5 cm. The measured growth rate $\gamma = 0.55\times 10^6$ sec^{-1} multiplied by the amplifier rise time $\tau = 0.6$ μsec equals 0.33. To obtain stability the gain of the feedback loop must be set above unity. The stable range is relatively narrow and a gain exceeding 1.4 drives the system overstable. At lower pressure the stable range narrows. At the lowest filling pressure (35 mTorr) where stability was still obtained, we found a product $\gamma\tau = 0.42$. Thus we confirm the fact that $\gamma\tau$ must lie below about 0.5, in accordance with results computed for the Scyllac experiment.[6,11] As mentioned above, the upper trace of Fig. 2 shows a plasma drifting upward at a constant speed. The small superimposed fluctuations indicate the feedback action. The exponential growth is eventually suppressed and stability is achieved.

We wish to thank Dr. K. Appert, Dr. R. Gruber, and Dr. F. Troyon for their stimulating discussions. This work was performed with the aid of the National Foundation for Scientific Research.

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Density Cavitons and X-Ray Filamentation in CO_2-Laser-Produced Plasmas

T. P. Donaldson* and I. J. Spalding

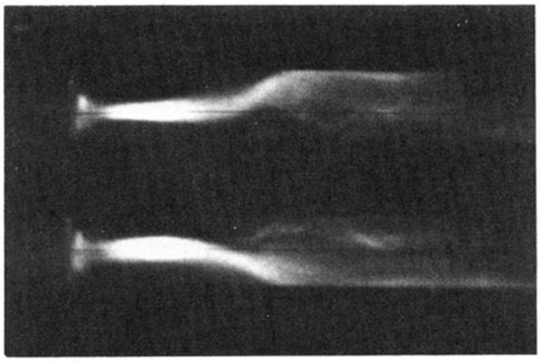
Euratom/United Kingdom Atomic Energy Authority Fusion Association, Culham Laboratory,
Abingdon, Oxon, OX14 3DB, United Kingdom

(Received 26 November 1975)

Measurements of electron density and x-ray emission have been made on a C VII plasma, generated by a 9×10^{12}-W-cm^{-2} CO_2 laser beam. A density cavity and x-ray filamentation are observed. The relevance of these results to theories of resonance absorption, soliton formation, self-modulation, and filamentation of laser light is noted.

The interaction of an intense electromagnetic field with the critical-density layer in a nonuniform plasma is a problem of topical interest in laser-heating and -compression experiments. Microwave experiments in a tenuous plasma[1] have demonstrated resonant enhancement of electric fields at this layer, and a density cavity, or caviton, was observed for times of order $10^5(\omega_{pe})^{-1}$. Relativistic computer simulations of such interactions have been undertaken[2,3] and the importance of resonance absorption,[4] its relation to self-generated magnetic fields[5] and second-harmonic generation,[6] its enhancement at sharp gradients near the critical surface, self-consistent modifications to the density profile,[2] and the influence of density scale length on parametric instability thresholds[7] have been widely discussed. The relationship between these instabilities, self-modulation and filamentation instabilities,[8] and soliton formation[9-12] have been active areas of related research. This paper describes the first observation of a density caviton in a *laser-produced plasma*; a preliminary description of the technique has been presented elsewhere.[13]

Measurements were made on plasma generated by an unpolarized 1.5-GW CO_2 laser pulse focused onto plane carbon targets at an intensity of 9×10^{12} W cm^{-2}, with a 50-nsec (full width at half-maximum) pulse duration and an energy of 75 J.[13] A holographic interferometer[14] was used to measure $\int n_e dl$, using a ruby oscillator which generated 100-MW, 10-nsec pulses to probe the plasma at 90° to the CO_2-laser axis. The interferograms were recorded on Agfa 10E 75 plates 25 nsec after initiation of the CO_2-laser pulse; the object resolution was 40 μm. Line densities deduced from fringe shifts were converted to radial density profiles by Abel inversion (Fig. 1). Mea-



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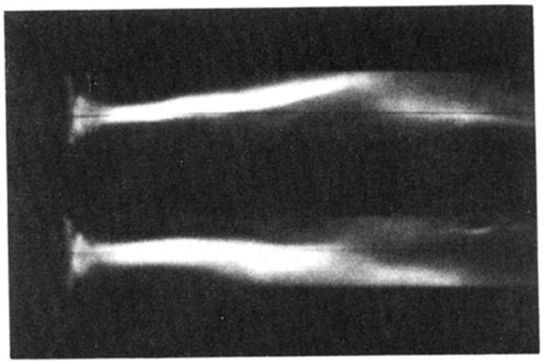

FIG. 2. Streak photograph of the plasma motion with stabilization.