[3]E. Yablonovitch, Appl. Phys. Lett. 23, 121 (1973).
[4]S. A. Akhmanov, R. V. Khoklov, and A. P. Sukhorukov, in *Laser Handbook*, edited by F. T. Arecchi and E. O. Schulz-Dubois (North-Holland, Amsterdam, 1972), Vol. 2, Chap. E3.
[5]G. H. McCall, private communication.
[6]L. M. Goldman, J. Soures, and M. J. Lubin, Phys. Rev. Lett. 31, 1184 (1973).
[7]N. Bloembergen, Opt. Commun. 8, 285 (1973).
[8]N. N. Il'ichev, V. V. Korobkin, V. A. Korshunov, A. A. Malyutin, T. G. Okroashvili, and P. P. Pashinin, Pis'ma Zh. Eksp. Teor. Fiz. 15, 191 (1972) [JETP Lett. 15, 133 (1972)].
[9]E. Yablonovitch and N. Bloembergen, Phys. Rev. Lett. 29, 907 (1972).
[10]This lens is manufactured by Laser Optics Inc., Danbury, Conn.
[11]Yu. P. Raizer, Zh. Eksp. Teor. Fiz. 48, 1508 (1965) [Sov. Phys. JETP 21, 1009 (1965)].
[12]L. V. Keldysh, Zh. Eksp. Teor. Fiz. 47, 1945 (1964) [Sov. Phys. JETP 20, 1307 (1965)].
[13]E. Yablonovitch, to be published.

Observation of the Stability Window in the Fast-Toroidal-Pinch Experiment

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A fast toroidal pinch with very small aspect ratio (2.6) is operated to test tokamak configuration. A narrow stability window appears between $q = 1.3$ and 1.5. In the stable region the energy loss from the plasma is mainly governed by the decay of the plasma current, which, in the present case, is controlled by the external circuit. In the unstable region, the energy-loss rate observed under clean vacuum conditions is found to agree approximately with the calculated growth rate of the kink mode.

The application of θ-pinch techniques to tokamak discharges is one of the most powerful and efficient ways to improve both the β and density values obtained in usual tokamaks which are limited by the relatively small input power of Joule heating. A symmetric toroidal pinch (STP) system has been constructed to check the theoretical and technical β limit of tokamaks. Since the θ-pinch techniques are well established and simple, similar experimental efforts have been reported previously.[1,2]

In order to improve the β value of a tokamak with circular cross section, the aspect ratio A and the safety factor q should be as small as possible. The reduction of A is limited for technical reasons, and too small a value of q leads to violent magnetohydrodynamic instability. In this Letter, the study of the relation between the growth rate of the instability and the q value is reported. When various factors are optimized, it is found that a lower technical limit of A is about 2.6 in the case of the STP.

A schematic drawing of the STP system is shown in Fig. 1. The major dimensions and parameters are indicated in Table I. In order to cancel the field error generated by the tab of the induction coil, which is the primary winding for inducing the plasma current, a double-copper shell structure is adopted. The operating time sequence of the STP system is shown in Fig. 2.

Figure 3 shows typical wave forms of the toroidal field and the plasma current, and also the negative one-turn voltage induced by the decay of the primary current. The toroidal field B_t and the primary current I_z are crowbarred simulta-

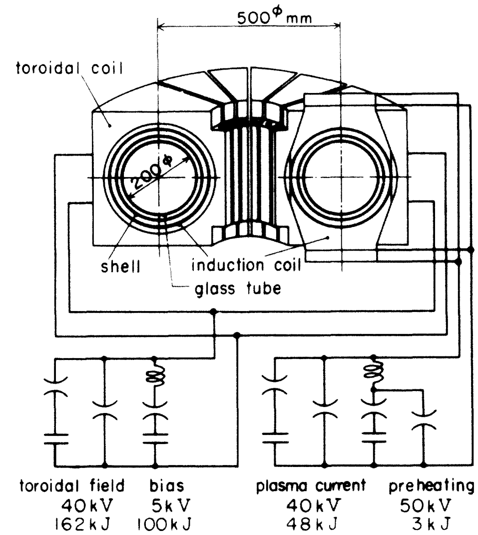

FIG. 1. Schematic drawing of the STP system.

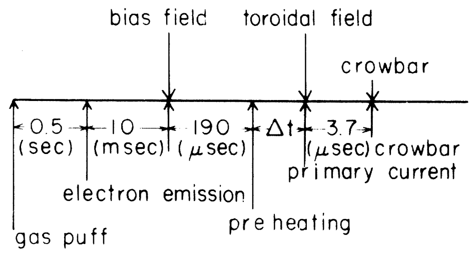

FIG. 2. Operating sequence of the STP system. The delay time Δt between the start of preheating and the main discharge is varied from 4 to 20 μsec.

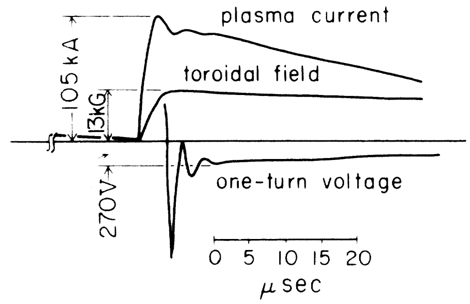

FIG. 3. Typical wave forms of plasma current I_p, toroidal field B_t, and negative one-turn voltage around the torus.

neously at 4 μsec after the start of both circuits. It is noted, however, that the plasma current becomes maximum at 3 μsec. This indicates that the plasma current depends strongly on the resistivity during the compression stage. Indeed, the maximum plasma current observed is only about half the value expected for zero resistivity. After crowbar, however, the inductive voltage drop $L_p dI_p/dt$ of the plasma current becomes equal to the observed negative one-turn voltage within the accuracy of measurement, provided the value of L_p is calculated with a uniform current distribution. Therefore, the resistive voltage drop I_pR_p of the plasma is very small compared with $L_p dI_p/dt$. From the above facts, the simple circuit equation shows that the decay of the plasma current results mainly from dissipation in the external circuit resistance. This is confirmed by the observation that the decay rate $1/\tau_I = -I_p^{-1} \times dI_p/dt$ of the plasma current is independent of the operating condition except for the case when the base pressure is extremely high. The large difference between the decay times of the plasma current and the primary current (Table I) can be ascribed to the resistive behavior of the plasma current during the compression stage. The filling pressure of D_2 gas is usually chosen to be 1.2×10^{-2} or 6×10^{-3} Torr, because operation at higher pressure excites violent oscillations of the magnetic axis during the compression stage. Figure 4 shows typical data obtained from a magnetic probe signal. It is seen that the plasma current-density distribution becomes approximately uniform at 10 μsec. In accordance with the current distribution, streak photographs taken after crowbar through the horizontal perforations do not exhibit the definite plasma structures which are usually seen in a linear θ pinch. From the outward expansion speed of the plasma in the case of no plasma current, the plasma temperature is roughly estimated to be 100–400 eV.

About 8 μsec after the beginning of the main discharge, it is seen in Figs. 3 and 4 that transient behavior disappears from the signal traces

TABLE I. Major dimensions and parameters of the STP system.

Major radius R (glass torus)	25 cm
Minor radius of glass torus	9.7 cm
Aspect ratio of the torus	2.55
Max. toroidal field B_t	13 kG
Rise time of B_t	4 μsec
Decay time of B_t	350 μsec
Max. primary current I_z	400 kA
Rise time of I_z	4 μsec
Decay time of I_z	170 μsec
Max. one-turn voltage around the torus	24 kV
Max. bias field	1.3 kG
Max. preheating plasma current I_{ph}	30 kA
Decay time of I_{ph}	12 μsec

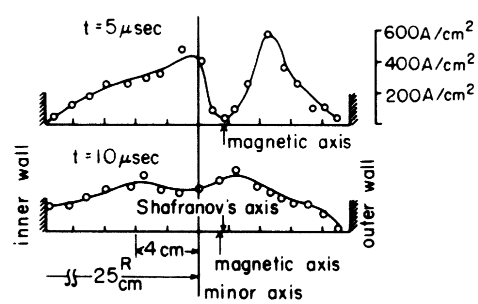

FIG. 4. The distribution of the plasma current density, obtained from a magnetic probe. Here, t is the time time from the start of the main discharge. For the case shown, $B_t = 9$ kG and the filling D_2 pressure is 1.2×10^{-2} Torr.

of one-turn voltage, plasma current, and magnetic probe. The plasma is in equilibrium, since the position of the measured magnetic axis approximately agrees with that calculated by Shafranov's formula.[3] Under such circumstances, the energy-loss rate of the plasma can be deduced from diamagnetic measurements. The minimum discriminating flux change $\Delta\Phi/\Phi$ of the diamagnetic loop used here is less than 1/200. Therefore, the maximum error which arises in the poloidal β_p does not exceed 30% in the case when the safety factor q at the surface of the plasma is 1.5.

Let W be the total gas kinetic energy of the plasma $\beta_p \propto W/I_p^2$; then

$$\frac{1}{\beta_p}\frac{d\beta_p}{dt} = \frac{1}{W}\frac{dW}{dt} - \frac{2}{I_p}\frac{dI_p}{dt}. \qquad (1)$$

Since Joule heating after crowbar is negligible here, the energy confinement time becomes $1/\tau_E = -W^{-1}dW/dt$ and Eq. (1) is written as

$$-\frac{1}{\beta_p}\frac{d\beta_p}{dt} = \frac{1}{\tau_E} - \frac{2}{\tau_I}, \qquad (2)$$

where τ_I is the decay time of the plasma current. Evidently, the decay of the plasma current causes the additional energy loss. If the assumptions of uniform current distribution and zero resistivity are valid, it is not difficult to show that the energy-loss rate due to the decay of the plasma current becomes $2/\tau_I$. As stated previously, it is noted that in the present case τ_I is mainly determined by the external circuit resistance. Therefore, an ideal energy confinement time τ_{E0}, in which the energy-loss rate due to the decay of the plasma current is subtracted, can be defined as

$$\frac{1}{\tau_{E0}} = -\frac{1}{\beta_p}\frac{d\beta_p}{dt} \qquad (3)$$

directly from Eq. (2). In order to clarify the physical nature of the energy confinement property of the present plasma, adoption of τ_{E0} is more significant, since the artificial energy-loss rate caused by the external circuit resistance is eliminated.

In order to observe $1/\tau_{E0}$, three different initial conditions are selected. Figure 5 shows the q dependence of $1/\tau_{E0}$ measured 12 μsec after the beginning of the main discharge. Here, $d\beta_p/dt$ is obtained by smoothing the value of β_p from 8 to 16 μsec. When q is between 1.3 and 1.5 or when q is larger than 2, the observed $1/\tau_{E0}$ becomes very small and the energy confinement time τ_E is only a function of the external circuit resistance, which gives $\tau_E \simeq \frac{1}{2}\tau_I \simeq 28$ μsec. The dependence of τ_{E0} on q, shown in Fig. 5, is in agreement with the stability window pattern predicted by Shafranov.[4] It is noted that a theoretical growth rate of the kink instability[5] does not exceed the observed $1/\tau_{E0}$ by more than a factor of 2.

During the conditioning discharges, it is found that the cleaning of the vacuum chamber seems to make the plasma unstable. In order to demonstrate the stabilizing effect of bad vacuum conditions, air was admitted through an adjustable leak into the discharge tube. The observed $1/\tau_{E0}$ as a function of the base pressure is given in Fig. 6. A marked decrease of $1/\tau_{E0}$ is seen in the case of poor vacuum conditions. Further evidence of the quenching action of the instability

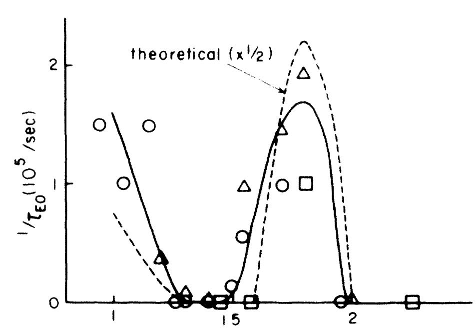

FIG. 5. The relation between $1/\tau_{E0}$ and q at the surface of the plasma. In this case, $B_t = 7$ kG and the filling D_2 pressure is 1.2×10^{-2} Torr. The β value ranges from 1 to 7.5%. Circles, 360-G negative-bias field, $\Delta t = 4$ μsec; triangles, 360-G negative-bias field, $\Delta t = 20$ μsec; squares, 360-G positive-bias field, $\Delta t = 20$ μsec.

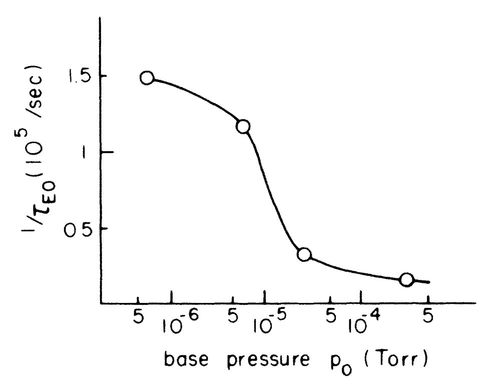

FIG. 6. $1/\tau_{E0}$ versus base pressure p_0. In this case, $B_t = 7$ kG and the charging voltage is adjusted so that q is 1.7. The filling pressure is 1.2×10^{-2} Torr.

TABLE II. Optimum stable plasma parameters obtained in this series of experiments.

Max. I_p	100 kA
Max. average β	7.4% ($q=1.3$, $\beta_p=0.85$)
Max. energy density	5 J/cm^3 (=10^{17} eV/cm^3)
Plasma temperature	< 500 eV
Max. average β_p	~ 1
Min. surface q	1.3
Plasma density	10^{14}–10^{15} cm^{-3}
Energy confinement time τ_E	~ 28 μsec
Ideal energy confinement time τ_{E0}	>100 μsec

by impurities also appears in the compression phase. In the case of a bad vacuum condition, the capacitor charging voltage needed to induce the same plasma current is reduced by 20%. Therefore, to observe the stability window, clean vacuum conditions are apparently necessary.

The optimum plasma parameters obtained in this series of experiments are listed in Table II. It is concluded that stable confinement of high-β plasma is possible where the value of q is between 1.3 and 1.5. Stable operation is also possible if q is larger than 2. In order to discuss longer energy confinement times, a power crowbar system would be necessary.

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[1]H. J. Belitz, L. Janicke, P. Noll, U. Plantikow, F. Sand, J. Schlüter, F. Waelbroeck, and G. Waidmann, in *Proceedings of the Fourth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wisconsin, 1971* (International Atomic Energy Agency, Vienna, 1972), Vol. III, p. 179.

[2]C. Bobeldijk, R. J. J. van Heijnigen, and P. T. C. van der Laan, in Proceedings of the Third International Symposium on Toroidal Plasma Confinement, Garching, Germany, 26–30 March 1973 (to be published), Paper No. G5.

[3]V. D. Shafranov, Atomnaya Energiya 13, 521 (1962) [Sov. At. Energy 13, 1149 (1963)].

[4]V. D. Shafranov, Zh. Tekh. Fiz. 40, 241 (1970) [Sov. Phys. Tech. Phys. 15, 172 (1970)].

[5]T. Amano, M. Wakatani, and M. Watanabe, J. Phys. Soc. Jap. 33, 782 (1972).

High-β Plasma Containment in the 2*X*II Mirror Device*

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High-β confinement of a hot-ion plasma has been observed in the 2*X*II magnetic mirror experiment. The maximum measured β values of 0.3 to 0.4 were near the limit predicted for mirror equilibrium in the 2*X*II mirror ratio of 1.8 to 2.3.

An attribute of mirror confinement systems is the ability to operate at high β, which allows high energy density and reduces the size of a fixed-output thermonuclear system. High-β mirror confinement has been observed in hot electron plasmas.[1] We report here containment of high-β hot-ion deuterium plasmas at measured values of β approximately 0.3 to 0.4.

The 2*X*II plasma is formed by injecting an energetic ($\overline{E}_i \simeq 2.5$ keV) deuterium plasma along a magnetic guide field. Ions that reflect off of a magnetic mirror are trapped between it and a 15-μsec-risetime gate mirror. Timing of this fast gate relative to plasma injection allows control of the trapped plasma energy. A pulsed 4.6-kG magnetic field then compresses the trapped plasma in 400 μsec and contains it in a minimum-B well. We define

$$\beta = \tfrac{2}{3}\beta_\perp + \tfrac{1}{3}\beta_\parallel = \tfrac{2}{3}nk\overline{E}/(B^2/8\pi) ,$$

as the ratio of plasma pressure to the vacuum magnetic field pressure in the absence of plasma. Here $\beta_\perp$ and $\beta_\parallel$ are the components perpendicular and parallel to the magnetic field, which are not