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# FIELD MIXING AND ASSOCIATED NEUTRON PRODUCTION IN A PLASMA*

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A series of experiments has been performed to determine the magnitude of the internal electric fields in a preheated deuterium plasma with a trapped internal axial magnetic field $H_i$, which is compressed by a large externally generated axial field $H_e$. It has been shown that $E_\theta$ fields of several hundred volts/cm can be readily produced by the rapidly changing internal magnetic fields and result in the production of neutrons from D-D reactions.

The electric field strength in the plasma can be controlled by varying separately $(dH_e/dt)$, $H_i$, and the relative polarity of the internal and external fields. The highest $E_\theta$ fields are observed when the two magnetic fields, which are generated by separate condenser banks (the "preheater" and "main" banks) have opposite polarity. During the early stages of the compression, on the second half-cycle of the preheater and the first half-cycle of the main bank, the trapped magnetic field first increases in magnitude as the plasma radius diminishes and then decreases rapidly, reversing its direction as the two fields interpenetrate [Figs. 2(C), (E)]. Shortly after the internal magnetic field passes through zero, with $dH_i/dt \sim 10^{11}$ gauss/sec, a burst of neutrons is observed. For a trapped field of ~+10 000 gauss, which is reversed to -10 000 gauss in ~0.2 μsec, e.g., see Fig. 2(E), a kev deuteron can double its energy in about one Larmor period. Particles with energies sufficient to cause a D-D reaction can easily be produced in times of ~1 μsec by the induced electric field which transfers energy from the reversed trapped field to the plasma. The particles are confined by the external field when the internal field passes through zero since the external field from the second half-cycle of the preheater and the first half-cycle of the main bank are in the same direction and do not cancel one another.

The cancellation of a trapped reversed axial magnetic field from the first half-cycle by the penetration of an external field generated during the second half-cycle of a fast condenser discharge was first suggested by Furth[1,2] as the mechanism responsible for neutron production in other experiments.[3,4] (In these cases there was no trapped reversed field during the first half-cycle since there was no preheater field as in the present experiment.) This suggestion was based on earlier observations of Colgate[5] with rapidly oscillating axial fields (the "collapse" experiment), on field measurements of Anderson et al.[2] with inverse pinches, and also on experiments performed with the triaxial pinch.[6] The latter is a tubular pinch compressed between magnetic fields of opposite sign and neutrons are emitted near a current maximum with an isotropic energy distribution at a time of enhanced resistivity when there are rapidly cancelling reverse fields. Our experiment with axial confining fields in which the internal trapped field can be controlled lends support to the hypothesis of Furth for the trapped field origin of "second half-cycle neutrons" and does not appear to be consistent with the suggestion[7] that the energetic deuterons are produced by simple Joule and shock preheating with subsequent adiabatic compression by an external field. The cancellation of the trapped field apparently plays an essential role.

Also in this experiment the trapped field from the first half-cycle of the main condenser bank is observed to be trapped at the beginning of the second half-cycle [e.g., Fig. 2(H)] and then compressed by the rising external reversed field. This trapped field appears to be responsible for the excitation of large amplitude radial plasma oscillations observed previously[8] as well as providing a plausible mechanism for the neutron generation reported elsewhere.[3,4]

The experimental parameters employed for most of this investigation were: voltage 15 kv, capacitance 130-400 $\mu$f for the main bank and 20 kv, 1 $\mu$f for the preheater discharge; maximum current, $1.1\times10^6$ amp; maximum field, 100 000 gauss; total inductance 0.05 $\mu$h; coil inductance 0.04 $\mu$h; coil length 10 cm; coil diameter 5.7 cm i.d.; Pyrex tube 5.0 cm i.d. The electrical system is described more completely elsewhere.[8] No magnetic mirrors were used so that deuterons moving axially with energies above one kev could escape from the confining field in a few tenths of a microsecond. Therefore, the neutron generation is probably caused principally by a highly nonisotropic distribution of deuterons moving in a plane normal to the magnetic axis. The observation of neutrons with no mirror fields suggests that the presence of magnetic mirrors is not the dominant factor in the initial heating since deuterons are apparently raised to high energies in a short period of time by an induced $E_\theta$ field in the plasma.

Typical observations are shown in Figs. 1 and 2. The magnetic field from the second half-cycle of the preheater is trapped on its third half-cycle if there is no rf (1 kw, 27 Mc/sec)

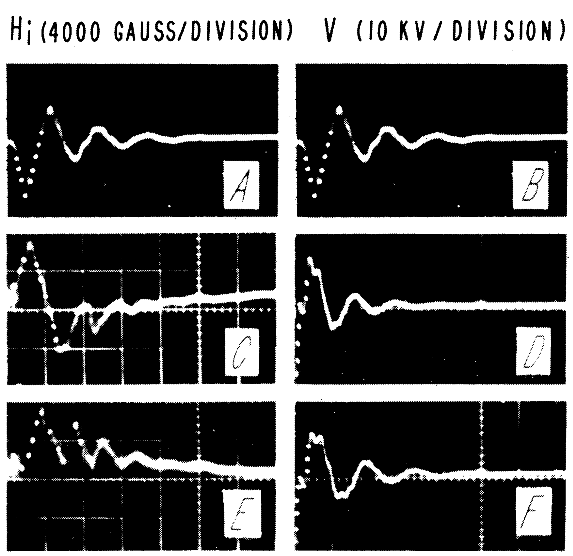


FIG. 1. Internal magnetic field $H_i$ and voltage $V$ across the coil for the preheater discharge: $A$, $B$ one atmos air (no gas current); $C$, $D$ 100 microns $D_2$ (no rf pre-excitation), $C$ shows the trapped field on the third half-cycle; $E$, $F$ 100 microns $D_2$ (rf pre-excitation), $E$ shows the trapped field on the second half-cycle. The probe is positioned at the central plane of the coil. The time scale is 1 $\mu$sec/division. The dots serve to improve the clarity in the oscillograms.

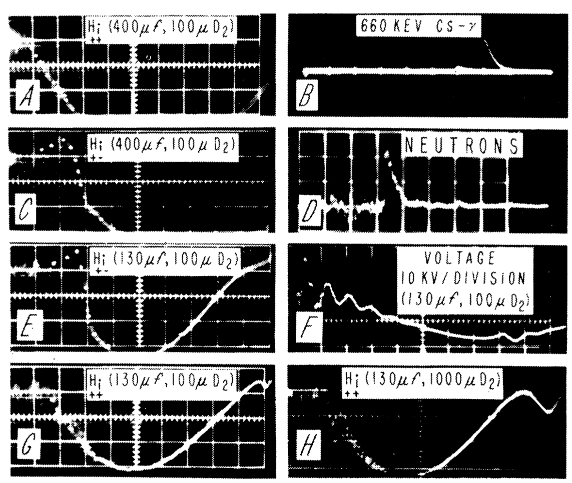


FIG. 2. Internal magnetic field $H_i$ with internal and external fields in opposite directions (+-) $C$,$E$ and in the same direction (++) $A$, $G$, $H$ showing the compression and rapid reversal of the trapped preheater field ($C$, $E$) and the trapped field from the first half-cycle of the main bank ($G$, $H$). The voltage trace $F$ corresponds to the field $E$; the modulation is due to the coupled preheater and main banks. The time of neutron emission is shown in $D$ (corresponding to $C$) and the scintillations due to cesium $\gamma$-rays are shown in $B$ for comparison. The scale for $H_i$ is 15 000 gauss/division and the time scale is 1 $\mu$sec/division. The probe was positioned on the magnetic axis at the end of the coil for $A$ and $C$ and at the central plane for $E$, $G$, and $H$.

pre-excitation [Fig. 1(C)]. With rf pre-excitation the field from the first half-cycle is trapped and on the second half-cycle the internal field [Fig. 1(E)] has a direction opposite to the field external to the plasma. The magnetic probe signal with the tube filled with air at atmospheric pressure (no ionization) is shown in Fig. 1(A) for comparison. The difference in the voltages across the coil with air (1 atmos) [Fig. 1(B)] and deuterium (100 microns) [Figs. 1(D), (F)] shows a marked effect when a plasma is created and the load inductance is reduced accordingly.

The neutrons were identified with a $BF_3$ proportional counter surrounded by paraffin and the time of emission was determined with a lead-shielded (1 cm) plastic scintillator. Additional shielding is provided by the 7.5-cm wall of the steel coil. Figure 2(B) shows the pulse shape for individual scintillations obtained using 0.66-Mev $\gamma$-rays from a cesium source, which have about the same average pulse height as 2.5-Mev neutrons. The decay time for a single scintillation is determined by the amplifier. Neutrons are observed [Fig. 2(D)] if the main bank of condensers is discharged during the second half-cycle of the preheater when the trapped field has the correct reverse polarity.[9] The neutron emission lasts for $\sim 0.2$-2 $\mu$sec which, for densities of $\sim 10^{16}$-$10^{17}$ cm$^{-3}$, corresponds to the expected scattering time for particles out the ends. If the internal magnetic field is in the same direction as the main external field [Figs. 2(A), (G)] it rises slowly in the plasma as compared to the case when the trapped field is in the opposite direction [Figs. 2(C), (E)]. After about 2 $\mu$sec the plasma radius from streak camera observations is comparable to the probe radius, and the field measured at later times is essentially the vacuum field.

The experiments have been repeated using a somewhat slower preheater discharge with the following parameters: 25-30 kv, 2 $\mu$f, 330 kc/sec. The highest neutron yield was observed if the main bank was fired near the voltage maximum at the beginning of the second half-cycle of the preheater. Hard x-rays (several hundred kev) were also recorded with the scintillation counter when hydrogen was substituted for deuterium. The x-ray emission occurred during four half-cycles of the main bank when there were large voltages across the coil. The neutrons appeared at lower coil voltages. The polarity of the trapped preheater field did not seem to be a critical factor in the x-ray production.

Discussions with Dr. Harold Grad and Dr. Harold Furth have been of considerable value in the interpretation of these experiments which were carried out with the technical assistance of Mr. L. J. Melhart and Mr. T. H. DeRieux.

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[1] H. P. Furth (private communication, Geneva Conference, 1958).

[2] Anderson, Furth, Stone, and Wright, Phys. Fluids 1, 489 (1959).

[3] Elmore, Little, and Quinn, Phys. Rev. Letters 1, 32 (1958); Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958 (United Nations, Geneva, 1958), Vol. 32, p. 337, P/356.

[4] K. W. Allen and B. Niblett, Conference on Controlled Thermonuclear Reactions, Berkeley, 1959 (unpublished); W. Millar (unpublished) communicated by P. C. Thonemann; H. Hurwitz (private communication). The hard radiation reported by S. M. Osovets et al., Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958 (United Nations, Geneva, 1958), Vol. 32, p. 311, P/2225 (see Fig. 24), may originate from the same mechanism. A trapped field from an auxiliary coil was rapidly compressed and cancelled during the collapse of a plasma loop.

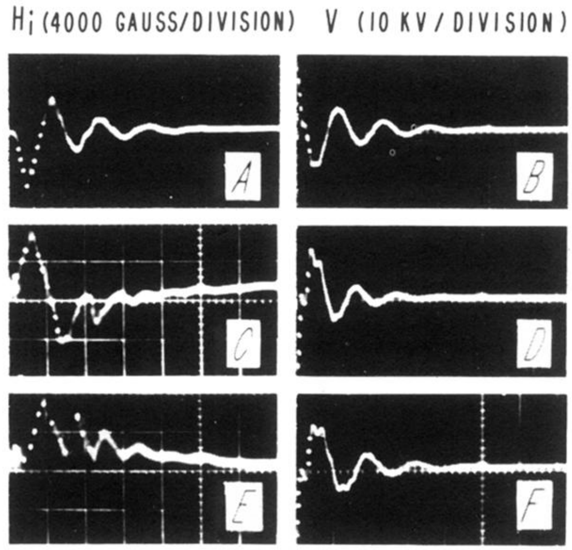
[5] S. A. Colgate and R. E. Wright, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958 (United Nations, Geneva, 1958), Vol. 32, p. 145, P/368.

[6] Anderson, Baker, Ise, Kunkel, Pyle, and Stone, Bull. Am. Phys. Soc. 4, 119 (1955).

[7] Boyer, Little, Quinn, Sawyer, and Stratton, Phys. Rev. Letters 2, 279 (1959).

[8] A. C. Kolb, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958 (United Nations, Geneva, 1958), Vol. 31, p. 328, P/345.

[9] In earlier experiments [Griem, Kolb, and Faust, Phys. Rev. Letters 2, 281 (1959)] the existence of electron temperatures of $\sim 8 \times 10^{6}$°K were inferred from an analysis of the bremsstrahlung radiation in the soft x-ray region emitted from a dense deuterium plasma confined by an externally generated magnetic field. No neutrons were observed with the scintillation counter which has a sensitivity of $1.5 \times 10^{-4}$ count/neutron. This negative result is consistent with the measured density, temperature, and volume of the plasma. No trapped reverse field was present in this case and the induced $E_\theta$ fields were too small (a few volts/cm) to generate neutrons by the mechanism discussed here.

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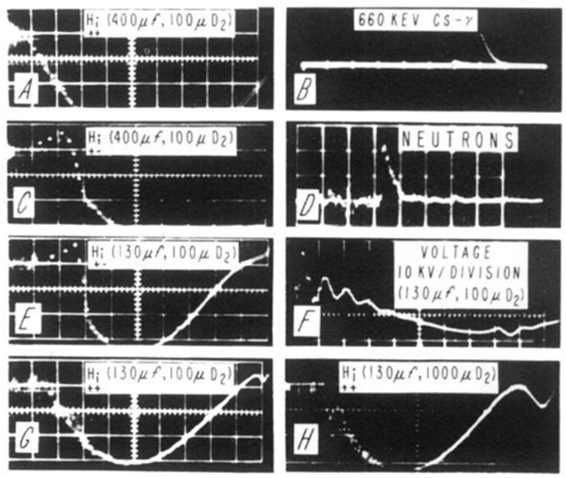


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