BREMSSTRAHLUNG FROM DENSE PLASMAS*

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Bremsstrahlung radiation in the optical and x-ray regions of the spectrum has been observed during the magnetic compression of a shock-preheated deuterium plasma in a magnetic mirror geometry. In earlier experiments,[1] streak camera observations of the shock velocities during the initial stages of the discharge and the subsequent adiabatic compression together with measurements of the field strength led to the conclusion that electron temperatures of about 8×10^6 °K and densities of the order 10^{17} cm^{-3} might be expected during the first half-cycle of the discharge for field strengths of about 100 000 gauss. Under such conditions the thermal bremsstrahlung radiation in the soft x-ray region should be sufficiently strong to be detected photographically. Since the x-ray flux depends exponentially on the electron temperature, such measurements should yield reasonably good estimates of the temperatures. Because the bremsstrahlung intensity also depends on the square of the density it is necessary to observe two regions of the spectrum to determine both N_e and T_e. The density is best determined from the intensity in the optical portion of the spectrum because this only varies with $T_e^{-1/2}$ since the factor $\exp(-h\nu/kT_e)$ in the bremsstrahlung spectral distribution is essentially unity.

The x-rays were detected by photographing the plasma through a 5-mil beryllium window which effectively transmits radiation with an energy above 1.6 kev. The tube was viewed axially through one of the magnetic mirrors and the solid angle was limited by a constriction in the quartz tube so that x-rays which might be generated by electrons striking the tube wall would not reach the central region of the film. The film was also partially shielded by a thick perforated foil used to support the thin beryllium window. In Fig. 1

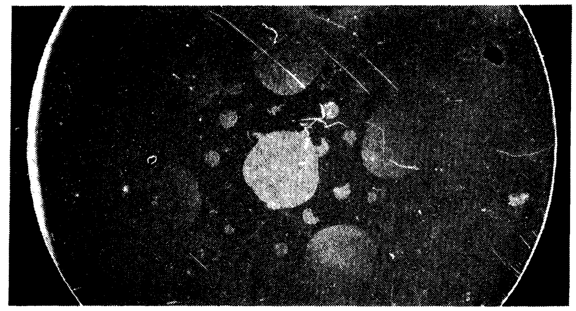

FIG. 1. X-ray photograph of a compressed deuterium plasma: $H = 200\,000$ gauss, $N_e = 7 \times 10^{16}$ cm^{-3}, $T_e = 8 \times 10^6$ °K.

it is seen that the central hole which views the axis of the plasma cylinder has the highest exposure and the film density falls off radially. The observed film density corresponds to $E = 0.3$ erg/cm^2 of incident x-ray energy at the film[2] which was placed 30 cm from one of the magnetic mirrors.

The continuous intensity in the visible region was measured with an $f/3$ streak camera with known transmission characteristics and exposure time, and also with a monochromator at 3800 A using a calibrated photomultiplier. A streak spectrograph with a time resolution of 10^{-7} second showed a continuum with a flat spectral distribution and no spectral lines of either deuterium or impurities during the compression cycle.

These experiments were performed under two different conditions in which the maximum field between the magnetic mirrors was 125 000 gauss and 200 000 gauss, respectively. The field was varied by varying the capacitance at constant voltage (15 kv). The other experimental parameters were: capacitance, 400 μf and 940 μf; maximum current, 2×10^6 amp and 3.2×10^6 amp; ambient pressure, 300 microns D_2; tube length, 20 cm; tube diameter, 2 cm i.d.; coil (steel) diameter, 3.5 cm; mirror ratio 2/1; and the final diameter of the plasma as determined with the streak camera was 2-3 mm. The plasma was first preionized by a 10^9-watt, 6-Mc/sec, 20-kv discharge producing a magnetic field with an amplitude of 10 000 gauss. A low-inductance, 0.8-μf auxiliary bank of seven capacitors was used for this purpose. For the case of the highest field only one discharge of the main condenser bank was required to x-ray photograph the plasma and at the lower field, ~20 discharges were necessary. The electron temperature during the early stages is determined by shock processes which are independent of the capacitance and maximum field strength but depend on the geometry, initial voltage, and ambient pressure, which were held constant. This serves to indicate that the x-ray emission is associated with the high final field and plasma pressure and not with the starting voltage.

The mean value of the electron density from the photographic and photoelectric measurements are $N_e = 7\times10^{16}$ cm^{-3} and 4×10^{16} cm^{-3} for the two field strengths using a Gaunt factor[3] of 3.35 in the visible region. The electron temperatures were 8×10^6 °K and 5.5×10^6 °K, respectively, using a Gaunt factor of 0.6 for the x-ray region. Any uncertainty in the temperature is mainly due to errors in the film sensitivity. Since T_e depends on log$E$, these errors are not large. The relative values of N_e for the two field strengths were obtained from the optical measurements and the relative values of T_e were obtained from the number of x-ray exposures needed for the lower field experiment.

The electron-electron relaxation times calculated in the usual way are $\sim10^{-8}$ second for the above conditions, which is short compared to the compression time (~5 μsec). The observed final density and volume show that about 5% of the initial plasma was contained and heated. The measured confinement time and particle loss also agree quite well with the theoretical expectations for the magnetic mirror geometry. These observations imply that the ratio β of the plasma pressure to the pressure associated with the maximum field is $\beta\sim0.1$. No x-rays were observed through an aluminum window which transmits x-rays above 8 kev, as expected if the radiation is of thermal origin.

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[1]A. C. Kolb, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958 (United Nations, Geneva, to be published), 31 P/345; Bull. Am. Phys. Soc. Ser. II, 4, 118 (1959).

[2]The spectral sensitivity of the DuPont Type 502 x-ray film was estimated from the data given in H. S. Seeman, Rev. Sci. Instr. 21, 314 (1949) and from the spectral response curves provided by DuPont.

[3]W. J. Karzas and R. Latter, Rand Report RM-2010-AEC, ASTIA Document No. AD-156046, 1958 (unpublished).

HEATING AND CONFINEMENT OF A PLASMA BY A MAGNETIC FIELD OF EXTERNAL ORIGIN AND WITH A SHORT RISE TIME*

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Figure 1 shows the basic cylindrical configuration in which a fully ionized plasma is heated and confined by a magnetic field that is suddenly induced by a current in an external conductor. It is assumed that the initial plasma temperature and the rise time of the magnetic field are such that the initial skin depth is small compared with the plasma radius. A good separation between the magnetic field and the confined plasma may be retained in a time interval small compared with the decay time $R^2\mu\sigma$. During such a small time interval the plasma may be manipulated using the "magnetic piston" effect at the plasma boundary. It will be shown that this can be done if the linear ion density N_i is large enough. Furthermore, it appears that heating by translational relaxation with a good separation between field and plasma requires that an additional lower limit condition on N_i is satisfied.

The basic cylindrical configuration of Fig. 1 was proposed by Colgate[1] under the name of "collapse." This concept is incorporated in the Scylla configuration,[2] where magnetic mirrors are placed at the ends of the tube to prevent excessive particle loss. Unaware that this work was going on, we gave the name "punch" to the configuration of Fig. 1 and to related configurations.

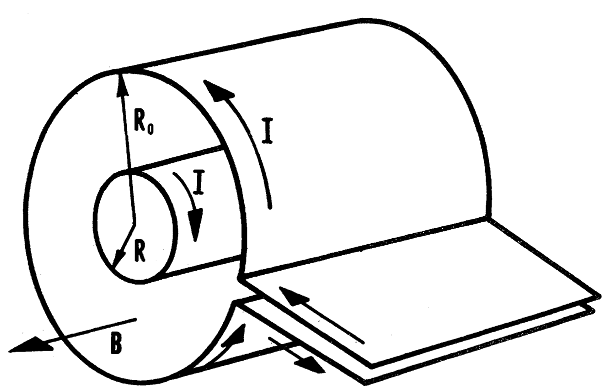
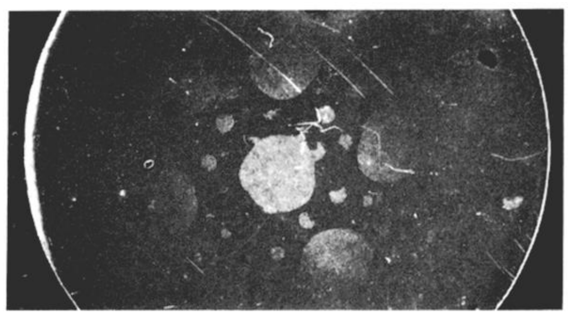


FIG. 1. Basic cylindrical punch configuration showing the magnetic field and the currents in coil and plasma.



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