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Measurement of megagauss magnetic fields in a plasma focus device

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The magnetic field associated with the dense pinch in a plasma focus device has been measured from the Zeeman splitting of the C V, $2s$-$2p$ emission. Values of the order of 1 MG are derived, in agreement with pressure balance between the self-field due to currents in the pinch and the kinetic pressure of the plasma.

I. INTRODUCTION

The magnitude of the magnetic field has a considerable bearing on the mechanism by which a dense plasma column is transiently formed along the axis of symmetry of the plasma focus, a coaxial electrode device described by Mather.[1] There is substantial evidence to show that the Lorentz forces associated with the self-magnetic-field in the imploding sheath are responsible for the pinched plasma column. The dimensions of the boundary between the plasmas and the magnetic field and the compression of the plasma particles onto the axis of symmetry have been investigated by Morgan and Peacock[2] using nanosecond-exposure interferometry. These authors find that only 6% of the particles within the implosion volume are finally swept up, on account of the cusped, conical shape of the imploding plasma boundary. At the termination of the implosion the radius of the tight pinch is typically 0.8 mm. Morgan and Peacock point out that the modified Bennett relation

$$\bar{\beta} I^2 = 2k \sum_{e,i} N\bar{T} , \qquad (1)$$

where $N\bar{T}$ is the product of line density and average temperature, is satisfied for the dense plasma column with a value of β, the ratio of the average kinetic pressure to the total pressure, just less than unity.

The kinetic pressure $\langle n_e k T_e + n_i k T_i \rangle$ is therefore balanced by the magnetic field pressure, $B_\theta^2/8\pi$ calculated on the assumption that all the circuit current I flows in the plasma column. In this case then the self-magnetic-field at the plasma boundary must lie between 1 and 2 MG. Filippov *et al.*,[3] using a different focus geometry, have indeed deduced values of this order from the spatial anisotropy of the charged particle production arising from the fusion reactions in the focus. The results of Morgan and Peacock[2] are in good agreement with the theoretical predictions of a two-dimensional (2-D), two-fluid, numerical code developed by Potter.[4] This code, which describes the structure of the imploding current sheath, correctly predicts the amount of particles collected and derives a value for $\bar{\beta}$ equal to unity for the compressed plasma column. The numerical code has not been operated for exactly the same experimental conditions pertaining to this paper but observations over a wide range of experimental conditions show that, in terms of the plasma dynamics (rate of compression ratio, density distribution, etc.), the code simulates the experimental results within 10% up to the time of peak compression. The particle energies are less well predicted by the numerical code but are still within a factor of two of the experimental values.[2]

Alternative explanations have however been proposed to account for plasma compression in some coaxial systems. For example, Bernoulli flow of an initially low-beta ($\bar{\beta} \ll 1$) plasma has been suggested by Morozov,[5] and in practice it has been verified Newton *et al.*[6] that this "compressive flow" can be set up with the appropriate operating conditions.

The present paper describes direct measurements of the magnetic field from line profiles of the C V $1s2s\,^3S_1$-$1s2p\,^3P_{2,1,0}$ multiplet which is emitted from the dense plasma. These measurements allow us to distinguish between the high-beta pinch and such low-beta processes as particle focusing or plasma flow.

II. LINE BROADENING IN PLASMA FOCUS

In order to measure magnetic fields from line profiles it is desirable that the Zeeman splitting be of the same order or greater than frequency shifts due to thermal and mass motion and Stark broadening. The emitting ion must exist for a finite time in the plasma focus where the dense plasma parameters are $T_e \sim 2$ keV, and $n_e \sim 10^{19}$ cm^{-3}.[7] The C V multiplet at 2270.9, 2277.9, and 2277.3 Å,[8] satisfies these requirements and allows polarization measurements to be made, in the quartz ultraviolet spectral region, with readily available optical components.

Defining the dense pinch in cylindrical coordinates with the magnetic axis of symmetry, the z direction, as the cylindrical axis, then it is of some advantage to view the emission in the radial direction and orthogonal to the local direction of the poloidal field. Radial mass motion is less than that in the z direction,[7] and in addition, one has the possibility of discriminating between σ and π components of the Zeeman splitting.

Before considering the results and their interpretation, it is necessary to discuss briefly the various contributions to line broadening of the C V multiplet. Stark broadening parameters for neutral helium have been tabulated by Griem,[9,10] and for our experimental conditions where the frequency shifts $\delta\omega \ll \omega_{pe}$ the electron plasma frequency, then broadening of the 2270.9-Å component can be described in the isolated-line electron impact approximation. A simple scaling for He-like C V is

$$\delta\lambda^{s}_{1/2,1/2} \propto \lambda^2 Z^{-2} n_e\, \omega(0)\ , \tag{2}$$

where $\omega(0)$ is the half-intensity half-width of the neutral line and Z is the core charge on the ion. This scaling leads[10] to a dispersion width (full width at half-intensity) of 1.04 Å at an electron density of 2×10^{19} cm^{-3}.

The ion energies in the radial direction and the spatial density distribution during the dense pinch phase have been measured in the focus from line profiles in the x-ray region,[7] from laser beam scattering,[11] and from laser interferometry.[2] Using these results and scaling the thermal energies of the ions with their charge/mass ratio gives the relation

$$E(Z/M) = 1.5 Z^{2.1}/M\ , \tag{3}$$

which yields 3.67 keV for the maximum, radial ion temperature of the C V ions. Since the half-intensity wavelength spread due to thermal effects is given by

$$\Delta\lambda^{D}_{1/2} = \frac{7.16\lambda}{10^7}\left(\frac{T_i}{\mu}\right)^{1/2}\ , \tag{4}$$

where T_i is in eV, λ in Å, and μ is the mass in atomic units; then the full half-intensity width due to thermal motion, at a temperature of 3.67 keV, is 3 Å.

Temporal variations in the values of T_i and n_e during the dense pinch phase can be as much as a factor of 2 and will result in uncertainties in the overall broadening, due to Stark-thermal effects, of about 50%. Since the density and temperature values quoted above are close to a maximum in the constricted pinch and since the measurements in this paper encompass also the earlier implosion when both T_i and n_e will be less, a mean full half-intensity width to the Voigt profile of ~2 Å is indicated. This broadening is of the same order or less than the expected Zeeman shifts, given by

$$\Delta\lambda_z = gK\lambda^2 H \tag{5}$$

where g is the Landé splitting factor, $K = 4.7\times10^{-5}$ cm^{-1}G^{-1}, and λ is in cm. For magnetic fields H of the order of 10^6 G the Zeeman splitting can amount to several angstroms.

This is illustrated in Fig. 1 where the spectral intensities of the magnetic quantum transitions which contribute to the overall intensity of the C V $1s2s\,^3S$-$1s2p\,^3P_2$ component are calculated for field values between 10^5 and 2×10^6 G. Above 8×10^5 G, the Zeeman splitting exceeds the thermal-Stark broadening.

The effect of frequency shifts due to mass motion of the plasma boundary is likely to be more serious than thermal-Stark broadening. Velocities in the radial direction of 3×10^7 cm sec^{-1} have been observed,[7] which will give rise to a wavelength shift in the 2270.9-Å line of ± 4.5 Å. The effect of mass motion is included in the calculation of

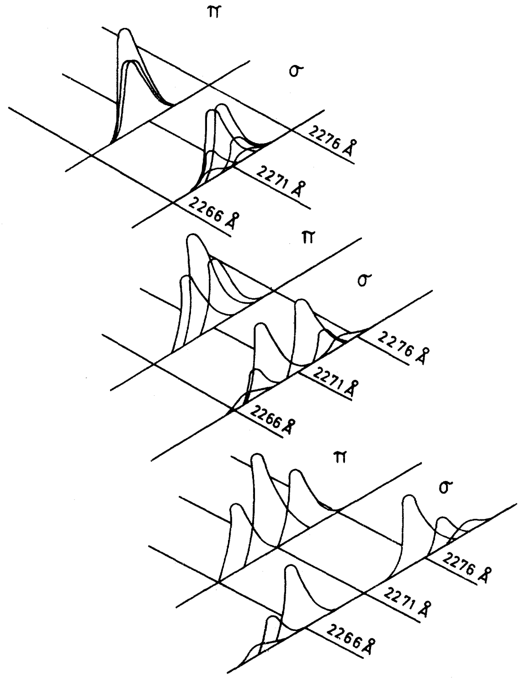

FIG. 1. Calculated profiles of $2s\,^3S_1$-$2p\,^3P_2$, C V emission orthogonal to the local magnetic field direction. Three sets of profiles are shown for magnetic field values, from top to bottom, of 0.1, 0.8, and 2 MG. The profiles of the individual Zeeman components are broadened due to thermal-Stark effects. The ion temperature is assumed to be 1 keV and the electron density, 2×10^{19} cm^{-3}. Mass motion of the plasma is neglected.

the position and intensities of the magnetic quantum transitions in Fig. 2, and its magnitude can readily appreciate by comparing the π component splitting at the lowest field values in Figs. 1 and 2. The wavelength spread due to mass motion is seen to be of the same order as the Zeeman splitting and mixes the two orthogonally polarized σ and π components close to the line center. Fortunately, it is still possible to deduce the magnitude of the magnetic field from the total extent of the broadening and from the fractional polarization particularly of the far wing of the line profile on its high-frequency side.

Over the range of field values given in Fig. 1, the intensities and frequency shifts of the σ and π components are calculated in the weak-field approximation which is strictly only valid for values less than 1×10^6 G. However, the weak-field approximation holds good for higher field values if attention is restricted, as in this work, to the high-frequency side of the ${}^3S_1$-${}^3P_2$ component.

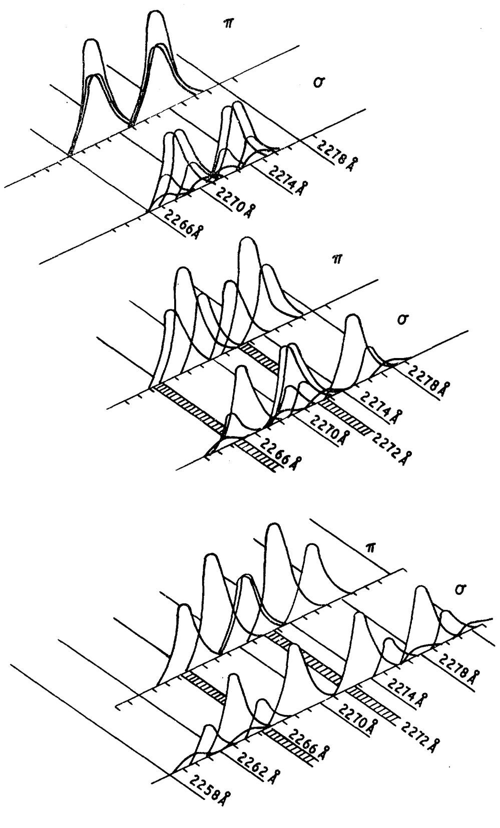

FIG. 2. Calculated profiles of $2s\,{}^3S_1$-$2p\,{}^3P_2$ C V emission orthogonal to the local magnetic field direction. Three sets of profiles are shown for magnetic field values, from top to bottom, of 0.1, 0.8, and 2 MG. Mass-motion shifts correspond to a velocity of $\pm2.5\times10^7$ cm sec^{-1} orthogonal to the axis of symmetry in the plasma focus device. The profiles of the individual Zeeman components are broadened due to thermal-Stark effects. The ion temperature is assumed to be 1 keV and the electron density, 2×10^{19} cm^{-3}.

III. EXPERIMENTAL ARRANGEMENT

The profiles were scanned on a shot-to-shot basis through a quartz-stack polarizer, using a photomultiplier and normal-incidence monochromator arrangement with a time resolution of 8 nsec and a wavelength resolution of 0.85 Å. The emission from the $2s$-$2p$ multiplet was enhanced by adding 2.5% ethylene by volume to deuterium at a total pressure of 2.1 Torr. The radiation cooling time for this ethylene-doped deuterium is $\lesssim 1$ μsec as compared with the considerably shorter time $\tau_p \sim 0.04$ μsec for which the pinch is sustained. Therefore, in the doped-gas condition, the pinch dynamics is unlikely to be seriously altered.

The emission was accepted from a plasma cross section 4 mm long in the axial direction and only 0.01 mm in radial extent at the axis of symmetry. The line of sight is orthogonal to this axis and to the local direction of the B_θ magnetic field. Assuming azimuthal symmetry, i.e., only poloidal field, the Zeeman components of the emission should therefore be plane-polarized, as in Fig. 1, in directions transverse (π) and parallel (σ) to the axis of symmetry.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

A wavelength scan of the $1s2s\,{}^1S_1$-$1s2p\,{}^3P_{2,1,0}$ multiplet extended to about 10 Å to the high-frequency side of the 2270.9-Å line center. The output signals from the photomultiplier are shown in Fig. 3. At some tens of angstroms removed from the C V multiplet, e.g. at 2256 Å [Fig. 3(b)] the background signal is due initially to photon continuum and neutron emission. The contribution from neutron bombardment of the photomultiplier is shown by the steep rising edge of the signal in Fig. 3(a) where the entrance slit to the spectrometer is occulted by a metal shutter. The leading edge of the signal in Fig. 3(a) is identified with the rise in the neutron flux since its time of flight corresponds to the neutron velocity. The bulk of the later "neutron" and background signals, Figs. 3(a) and 3(b) respectively, is probably due to hard x rays from nonthermal processes and possibly also $(n, n'\gamma)$ reactions at the chamber walls. This background is entirely reproducible from shot to shot and the C V line emission appears as an additional signal in front of this background when the appropriate wavelength range is scanned [Figs. 3(c)–(f)].

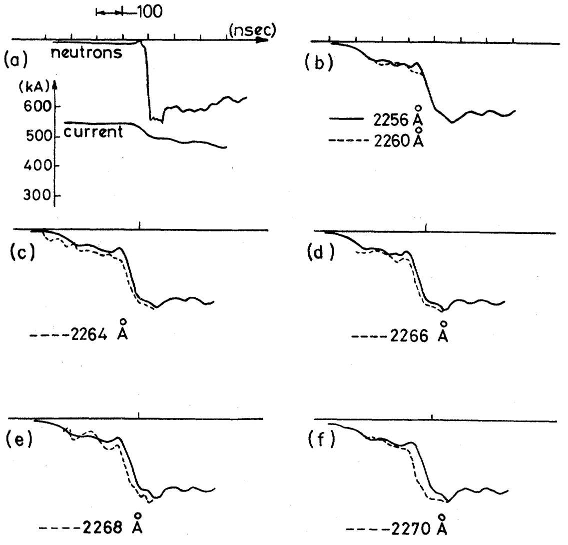

FIG. 3. Photomultiplier signals of the emission from the plasma focus device on the short-wavelength side of the $1s2s\,^3S_1$-$1s2p\,^3P_2$ transition of C V. The full lines in Figs. 3(b)–(f) represent the background noise due to photon continuum, neutrons, and hard x rays. The dashed lines in Figs. 3(b)–(f) show the additional signal due to the broadened C V $1s2s$-$1s2p$ multiplet. Figure 3(a) shows the photomultiplier signal when the spectrometer is occulted with a metal shutter and is annotated "neutrons," the time of flight of the leading edge corresponding to the neutron velocity.

The $2s$-$2p$ multiplet could be measured above the neutron and continuum noise background from about 60 nsec before the steep rise in the neutron emission. Since the neutron emission is delayed typically by 35 nsec in our experiment due to time of flight, the C V emission could be recorded for approximately 95 nsec before the leading edge of the neutron pulse shown in Fig. 3(a). Expressed in terms of the plasma dynamics, analysis of the C V emission was possible for the 40 nsec before the plasma boundary first implodes onto the axis, at t_0, and for a further 40 nsec of the subsequent phase when a tightly compressed pinch could be sustained. The intensity and time of emission of the C V multiplet, shown typically in Fig. 3, were reproducible to within 20% over 75% of the discharges. The remainder of the discharges were grossly uncharacteristic due presumably to the motion of the plasma column both laterally and axially out of the field of view of the spectrometer.

In this analysis we concentrate our attention on the high-frequency side of the $^3S_1$-$^3P_2$ member of the $1s2s$-$1s2p$ multiplet of C V. Polarization of this line emission, Fig. 4, is in contrast to that of the unpolarized continuum at 2256 Å, for example, and indicates that the frequency shifts of the line are due to Zeeman splitting. We illustrate in Fig. 4 that the line emission is essentially plane-polarized with the plane of polarization in different senses in different spectral regions of the line profile. Isolated wavelength regions show predominantly π components at the center of the line, Fig. 5, and σ components in the far wings. In order to evaluate field intensity, we have compared these results with the calculated intensity and spectral distributions of the σ and π components, such as

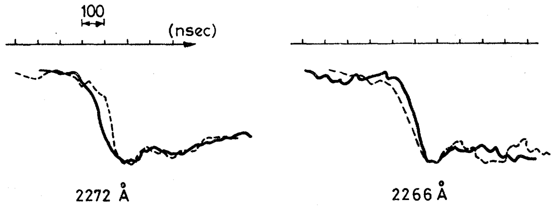

FIG. 4. Photomultiplier signals at wavelengths corresponding to the $1s2s\,^3S_1$-$1s2p\,^3P_2$ C V transition, as in Fig. 3 but showing the polarization effects: dashed line, analyzer plane of polarization parallel to the axis of symmetry of the focus device; solid line, analyzer plane of polarization perpendicular to axis of symmetry.

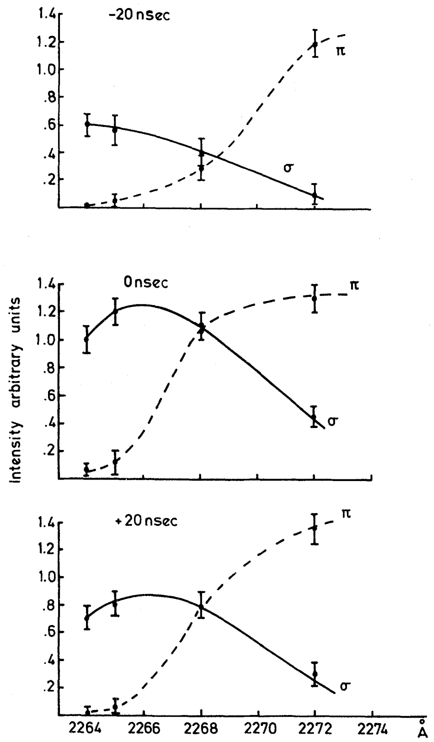

FIG. 5. Intensity of π, σ components on short-wavelength side of $2s\,^3S_1$-$2p\,^3P_2$ C V line during the plasma focus discharge. "0 nsec" refers to the time when the current sheath meets the axis of symmetry.

shown in Figs. 1 and 2, under a variety of plasma conditions.

An upper limit of 3×10^6 G is set by the isolated region of the σ component at 2266 Å, Figs. 1 and 5. This field value is also near the threshold for the Paschen-Back splitting which would cause quite a different polarization pattern from that observed in Fig. 5. A lower limit to the magnetic field is given by the observations of mainly π radiation at 2272 Å and mainly σ radiation at 2266 Å, Fig. 5. These channels, shown hatched in Fig. 2, indicate that the lower bound for the magnetic field is 0.8×10^6 G in the case where we have mass motion, and 2×10^6 G where there is no mass motion, Fig. 1.

Rapid temporal variations in the mass motion shifts just before peak compression of the pinch make it difficult to predict the actual line profile and therefore difficult to give a precise value for the field. A best estimate for the poloidal field, B_θ, is between 0.8×10^6 and 2×10^6 G.

It should be noted that for the parameters of the dense pinch the "burn through" time for C V ions is ~1 nsec.[7] The C V line profiles are therefore likely to be emitted from the outer boundary of the dense pinch which is not necessarily coincident with maximum fields in the plasma column.

V. DISCUSSION AND CONCLUSIONS

Using the results of the magnetic field measurements we can immediately comment on the validity of the low-beta "compressive flow" model,[5] for the formation of a dense plasma column in a plasma focus device. Taking into account the present interpretation of the C V line broadening, we know that in the tightly compressed plasma, $B_\theta \gtrsim 8\times10^5$ G. Also from the work of Morgan and Peacock,[2] the mean electron density and radius of the plasma are, respectively, $\overline{N}_e = 8\times10^{18}\ \mathrm{cm}^{-3}$ and $\overline{r} = 0.09$ cm. Thus with an ambient gas filling of 2.5 Torr D_2 and with an inner electrode radius of 2.5 cm, we observe experimentally for the product of density and radius

$$\langle \rho_0 r_0 \rangle \sim \langle \rho_p r_p \rangle ,$$

where the subscripts 0 and p refer, respectively, to the plasma in the interelectrode space and in the tightly compressed column. The isomagnetic condition for "compressive flow," however, requires that[5]

$$B/\rho r = \mathrm{const} , \tag{6}$$

which is clearly inadmissible in the present experiment since it would imply megagauss fields in the interelectrode space. The accumulation of plasma onto the axis of symmetry in the plasma focus device cannot therefore be due to a continuous flow of low-beta plasma from the interelectrode space.

In contrast, the magnetic field values are in good agreement with the peak poloidal field which would obtain if all the circuit current were to flow in the compressed plasma column. With a mean pinch radius of 0.9 mm and a circuit current taken from Fig. 3, $B_\theta(\mathrm{pinch}) = 1.2$ MG. The field values therefore confirm the results of Morgan and Peacock[2] that all, or nearly all of the circuit current flows in the dense plasma column on the axis of symmetry, and that a high-beta pinch is the correct model[4] to account for the formation of this plasma.

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