PEACEFUL USES OF ATOMIC ENERGY

Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy

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Volume 32

Controlled Fusion Devices

UNITED NATIONS

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PREFACE

More than 2,100 papers were submitted by the nations, the specialized agencies, and the International Atomic Energy Agency, which participated in the Second United Nations International Conference on the Peaceful Uses of Atomic Energy. The number of papers was thus about twice that involved in the First Conference. Provision was therefore made to hold five concurrent technical sessions in comparison with the three that were held in 1955. Even so, the percentage of orally presented papers was less in 1958 than in 1955.

In arranging the programme, the Conference Secretariat aimed at achieving a balance, allowing adequate time for presentation of as many papers as possible and, nevertheless, leaving time for discussion of the data presented. Three afternoons were left free of programme activities so that informal meetings and discussions among smaller groups could be arranged. No records of these informal meetings were made.

A scientific editorial team assembled by the United Nations checked and edited all of the material included in these volumes. This team consisted of: Mr. John H. Martens, Miss L. Ourom, Dr. Walter M. Barss, Dr. Lewis G. Bassett, Mr. K. R. E. Smith. Martha Gerrard, Mr. F. Hudswell, Betty Guttman, Dr. John H. Pomeroy, Mr. W. B. Woollen, Dr. K. S. Singwi, Mr. T. E. F. Carr, Dr. A. C. Kolb, Dr. A. H. S. Matterson, Mr. S. Peter Welgos, Dr. I. D. Rojanski and Dr. David Finkelstein.

The speedy publication of such a vast bulk of literature obviously presents considerable problems. The efforts of the editors have therefore been primarily directed towards scientific accuracy. Editing for style has of necessity been kept to a minimum, and this should be noted particularly in connection with the English translations of certain papers from French, Russian and Spanish.

The Governments of the Union of Soviet Socialist Republics and of Czechoslovakia provided English translations of the papers submitted by them. Similarly, the Government of Canada provided French-language versions of the Canadian papers selected for the French edition. Such assistance from Governments has helped greatly to speed publication.

The task of printing this very large collection of scientific information has been shared by printers in Canada, France, Switzerland, the United Kingdom and the United States of America.

The complete Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy are published in a 33-volume English-language edition as follows:

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* These papers should be read in conjunction with Paper P/1329 above, involving relativistic plasmas.

Session A-7

CONTROLLED FUSION DEVICES, PART I

LIST OF PAPERS

Review of Controlled Thermonuclear Research at Los Alamos for mid 1958

By James L. Tuck*

At this first opportunity for open scientific discussions on this subject we look forward with eagerness to exchanging experiences with others and hearing of the courses taken towards the common goal in the various laboratories of the world.

Early Development

At this laboratory, the peculiarly intriguing nature of the problem and the admirable consequences of its solution have long been recognized. Lively discussions of such matters as plasma drift in a torus and its effect on achieving a laboratory thermonuclear reaction occurred between Fermi, Kerst, Landshoff, Teller, R. R. Wilson and the writer in 1946, and an unsuccessful search for neutrons from colliding Munroe jets of metal deuterides was made at about the same time, based on an earlier paper by Ulam and the writer.

When the subject was reopened in 1951, the toroidal pinch (as proposed, with a superimposed B_z field, by the writer in 1948) was selected as the confinement geometry for initial study and it passed through the usual vicissitudes and modifications—instability, linear dynamic pinches (Columbus), rf pinches, so called B_z and wall stabilized pinches; while parallel speculations and experimental forays were made into cusped geometries (Picket Fence), spinning plasmas, shocks in axial and convergent geometries and magnetic mirrors. Our ideas and plans have undergone profound changes during the last seven years and are in process of undergoing another. As little as half a year ago, the chief obstacle to the achievement of a thermonuclear reaction via the stabilized pinch appeared to be contamination of the plasma by foreign atoms sputtered or evaporated off the walls. Doubtless this particular obstacle is still there, but in the meantime a crevasse has opened at our feet, in the form of our new experimental observations of high energy losses from the pinched plasma. If these turn out to be due to the newly predicted surface hydromagnetic instabilities, then we know how to overcome these and the outlook may be better than ever. If the losses turn out to be due to plasma oscillations, as is feared, then the outlook for the stabilized pinch as a possible reactor seems grave.

Present Requirements

The outstanding need in controlled thermonuclear research at present is for reliable quantitative observations on confined plasma, and the shortage of these can undoubtedly be blamed on the extreme mobility of plasma, the variability of gas discharges, and their sensitivity at high temperatures to impurities. It is only recently that primary measurements on the pinch effect have been made, of quality such that worthwhile derivations of other quantities from them could be made. At Los Alamos, the magnetic probe has unquestionably been the most effective measuring tool, yielding (from the pinch) plasma pressure, plasma electrical conductivity and, most recently, plasma mass. The mean temperature of the plasma, involving $(T_{\text{electron}}+T_{\text{ion}})$, has also been determined but not the much-sought-after individual components of it. Obviously, if ion temperatures could be made high enough, the trivial neutron-producing processes which bedevil us at present would also become trivial in yield, with the result that the thermonuclear yield could take its logical place as the ideal thermometer for ions.

In order to bring this into play, there has been a direct effort at Los Alamos to produce an identifiable thermonuclear reaction, without regard for reactor implications. Whether this has been achieved is still indeterminate: of the five experiments producing neutrons, Scylla looks probable as a thermonuclear source and is supported by a measurement of the neutron energy distribution, Columbus II neutrons have an energy anisotropy so small as to raise difficulties in interpretation by trivial processes, Columbus S-4 neutrons seem well correlated with a new instability and therefore appear suspect, as do the Perhapsatron S-4 neutrons on account of a much larger energy anisotropy. Ixion neutrons seem to be of two kinds, trivial ones associated with sheath breakdown and less determinate ones in a kind of tail of indefinite extent.

Obviously, the control of thermonuclear fusion depends on answers to problems in basic plasma physics. For example, are the high plasma losses observed in the pinch a characteristic of all confined

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systems? Until such questions are answered, the technological problems of a fusion reactor are surely far away. What engineering design for a thermonuclear reactor would survive an increase in plasma diffusion rate by an order of magnitude?

As a matter of fact, some of the highly impulsive schemes—Columbus and Picket Fence—might survive such an increase but, for the time being, at Los Alamos we hope to steer clear of any large machine, keeping to a course of fairly basic plasma physics research in which practice and theory are intimately associated, around numerous modest-scale experiments.

In magnitude, our effort engages the activities of fifty-one people, including twenty-four physicists, the rest being engineers, technicians and secretariat. The staff is divided into two groups under the leaderships of Dr. K. Boyer and Dr. J. A. Phillips.

THEORETICAL

Stability

The theories of an infinite-conductivity pinch stabilized by an axial field—Kruskal and Tuck,[1] Rosenbluth,[2] and Colgate[3] in the USA, Artsimovich[4] and Shafranov[5] in the USSR, and Tayler[6] in the UK—have become largely supplanted in our minds by the energy principle treatment[7] by Suydam[8] of the same geometry with diffuse boundaries between axial stabilizing field B_z and confining field B_θ. In this treatment the sign of δW, a function of the displacement, is the criterion for stability. The study was carried out by noting that the special character of the Euler-Lagrange equation of the variational principle permits one to evaluate δW for a *minimal* displacement (i.e., a displacement which satisfies the Euler-Lagrange equation) for general configurations of plasma and field, without obtaining a detailed solution to this equation. If a minimum for δW exists, such a procedure will find this minimum. However, certain configurations exist for which δW is unbounded below (hence unstable) and it has not been shown that the above procedure will identify such cases. Thus a condition has been found which is *necessary*, but has not been shown *sufficient* for stability. It is

$$\frac{8\pi}{B_z^2}\left(\frac{dp}{dr}\right)+\frac{r}{4}\left(\frac{1}{\mu}\frac{d\mu}{dr}\right)^2 > 0$$

where $\mu = B_\theta/rB_z$ and p = plasma pressure. This imposes restrictions on the radial gradient of density in the pinch, such that it seems unlikely that a stable pinch with unidirectional B_z and B_θ exists. However, and here we differ from the older Rosenbluth criterion, stability is aided by an external-to-the-pinch reversed B_z and B_θ. Much importance is attached to this prediction, for although it adds complications to a thermonuclear reactor based on a pulsed B_z-wall stabilized, toroidal pinch (Pephapsatron) it revives hopes for a continuous rf pinch using cyclic B_z and B_θ magnetic fields, to which we shall return in the conclusions. A computation of a stable configuration with thick boundaries and reversed B_z has also been reported by Rosenbluth.[9]

A pinch current and plasma distribution has been found by Longmire[10] (see also Bickerton[11]) which is stationary and in equilibrium with pressures and diffusion, assuming isothermal plasma and ignoring Joule heating. It is unlikely to be observed in the laboratory since it is unstable by the Suydam criterion above, but has didactic value for the light it throws on the compensation of the outward diffusion current $-D\nabla n$ by the inward drift cE/B.

Ixion Geometry

The axial magnetic field–radial electric field, spinning plasma geometry (as variously proposed by Lloyd Smith,[12] Shipley,[13] Luce,[14] Baker[15] and Gow[16]) with the addition of magnetic end mirrors, is known here as Ixion. A mathematical analysis of the motion[17] predicts a strong enhancement of the mirror confinement. In such a device, collisions are by virtue of the Larmor energy since the rotation does not lead to collisions and, for ions created non-adiabatically in the system (as, for example, by ionization), the Larmor energy is approximately the same as the drift energy, $\frac{1}{2}mc^2(B/E)^2$. Thus, for example, with $E = 10$ esu/cm and $B = 2000$ gauss, the Larmor energy is 25 kev which is quite adequate for thermonuclear purposes. The current through such a device in equilibrium would of course ideally be zero, and the plasma confinement time diffusion-dominated. A plasma current does arise, however, by virtue of interaction between the rotating plasma and neutral atoms, either originally present or returning from the walls, as well as by virtue of a differential drift, between ions and electrons, due to the centrifugal force. In order, then, to achieve the long confinement time appropriate to a reactor, plasma drifting to the walls must be disposed of by some kind of diverter (*cf.* Stellarator) action and, to minimize the centrifugal drift, the radius must be large.

The initial formation of the rotating plasma also presents a problem as follows. The displacement current which flows in setting up the rotation has a magnitude corresponding to the enormous dielectric constant $4\pi nmc^2/B^2$, i.e., of order of 10^6 amp. This current, in flowing to the electrodes, would produce local space charges (sheaths) which would screen out the applied electric field from the bulk of the plasma unless arrangements are made for a ready supply of electrons and ions at the appropriate electrodes.

Runaway

Runaway is the term given to the production of an accelerated directed velocity in some components of the plasma by an applied electric field. A theory of immediate runaway in a fully ionized plasma of temperature T in a strong electric field has been given by Dreicer.[18] It turns out that the critical electric field E_c required to produce such runaway is small and proportional to the ratio, density/temperature. For example, at particle density $n = 10^{15}$ cm^{-3} and $\frac{3}{2}kT$ = 100 ev, $E_c = 8$ volt/cm. The theory has now been extended to the more difficult case of weaker electric fields,[19] where only part of, say, the electron distribution runs away immediately. These theories do not take into account the excitation of plasma oscillations by the runaway which, it seems superficially obvious, will reduce the runaway to some extent.

The pressure balance equation much used in the laboratory has also been modified by Dreicer as follows:

$$\frac{B^2(r)}{8\pi}+P_{rr}(v)+\int_{R_w}^{r}\frac{B_\theta^2}{4\mu r}dr+\int_{R_w}^{r}\frac{P_{rv}-P_{\theta\theta}}{r}dr = \frac{B^2(R_w)}{8\pi}+P_{rr}(R_w),$$

where r, θ, z are cylindrical coordinates, R_w is the radius of the outside wall, B is the magnetic field, $B^2 = B_z^2+B_\theta^2$, and P_{rv}, $P_{\theta\theta}$ are elements of the momentum flow tensor,

$$P_{\theta\theta} = nkT+nmv^2(B_v/B)^2,$$

$$P_{rr} = nkT.$$

Here, v is the electron drift velocity parallel to B; the mean square random thermal speeds are assumed to be equal in the θ and v directions.

The new term,

$$\int_{R_w}^{r}(nmv^2/r)(Bz/B)^2dr,$$

is the centrifugal force due to electron runaway. The question now arises, how much the very encouraging values for nkT deduced experimentally in this laboratory have been exaggerated by the neglect of this term. We shall return to this in the discussion.

Oscillations

The literature on plasma oscillations is voluminous, and we mention among the early contributors, the names of J. J. Thomson,[20] Tonks and Langmuir,[21] Landau,[22] Bohm and Gross,[23] and Vlasov.[24] More recently, the subject of the excitation of plasma oscillations has been reported on by Akhiezer and Faynberg,[25] Akhiezer and Polovin,[26] Luchina,[27, 28] Gordeyev,[29] and, very recently in the USA, Bunemann.[30, 31] These papers discuss the excitation of plasma vibrations by an electron beam or drift in an applied electric field, and they show that by a co-operative space charge interaction (without collisions) between ions and electrons, somewhat resembling bulk Helmholtz instability, the electron and ion oscillations can grow. Experimental confirmation of this process comes in an entirely different connection, namely the so-called double-beam traveling wave tube,[32, 33] in which amplification of space charge waves occurs by interaction between electron streams of differing velocities. (The identity of these two processes was pointed out by Bunemann.)

We now propose still another process for the excitation of plasma oscillations, depending on two-body interactions between ions and electrons as follows.[34] For a plasma consisting of ions of density n_0 cm^{-3} and of electrons, both at temperature T, an electric field E_a has induced a displacement of the electron velocity distributions in the x direction as a whole, so that the electric velocity distribution is symmetrical about a point v_x (henceforward called v). The so-called dynamical friction force[35] between the electron and ion distributions has been calculated on the above model by Dreicer.[18]

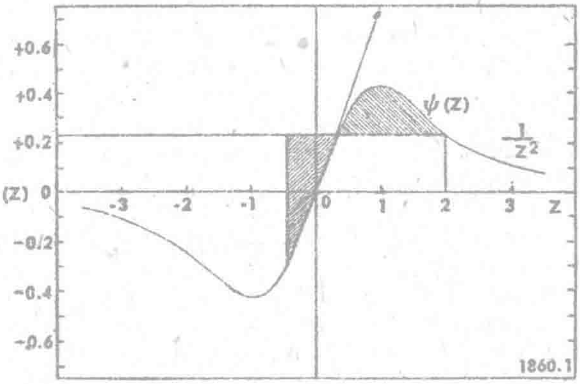

Figure 1. Dynamical friction for displaced Maxwell distribution. Straight line section through origin, $L_{z\to 0}\psi(z)$, leads to $T^{\frac{3}{2}}$ law of conductivity

Figure 1 gives the form of the function $\psi(z)$ where the dynamical friction is treated as giving a fictitious electric field of magnitude $E_c\psi(z)$; the abcissa, z, is the ratio: drift velocity/mean thermal speed. At the maximum on the curve, $\psi(z)E_c = 0.425$.

For drift speeds larger than the mean thermal speed, we see that the slope of the dynamical friction curve becomes negative, in fact $\psi(z) \propto z^{-2}$ for large z. For an applied electric field, E_a, we write down the equation of motion of the electrons, taking into account the drag force:

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x} = \frac{e}{m}[E_a-E_s-E_c\psi(z)]$$

where E_s is the restoring space charge field related to the electron density n by:

$$\frac{\partial E_s}{\partial x} = 4\pi(n_0-n)$$

and the equation of continuity is

$$\frac{\partial n}{\partial t}+\nabla\cdot(n\mathbf{v}) = 0.$$

We discuss a small sinusoidal modulation in the drift velocity, which oscillates with the characteristic plasma frequency, $\omega_p = (4\pi ne^2/\mu)^{\frac{1}{2}}$, where μ is the reduced electron mass.

The effect of the negative slope of $\psi(z)$ is to introduce a negative damping, and we find the growth constant for small electron oscillations to be $4eE_c\epsilon T/mv_0^3$ where v_0 = mean drift velocity. A numerical example of the growth constant for the following values of the parameters: plasma density $n = 10^{16}$ electron/cm^3, temperature $T = 100$ ev, $z \equiv 2\epsilon T/mv_0 = 2$, $v_0 = 10^9$ cm/sec, $E_c = 90$ volt/cm, $E_a = 19$ volt/cm, $\epsilon = e/300$

$= 1.6 \times 10^{-12}$, is $\omega_g = 7 \times 10^7$. We see that the growth is such that large amplitudes could develop in a few microseconds.

For identification, we shall refer to this as the violin-string mechanism (the mechanism is closely analogous to the setting into vibration of a string by the nonlinear friction of the bow).

For the large oscillations, we must refer to the limit cycle of the nonlinear equation, the maximum downward excursion of the velocity for $z = 2$ being obtained by equalizing the two shaded areas, from which we see that the amplitude can become large enough to move the particles against the field in the peaks.

The external manifestation of the process as described might be a small increase in plasma resistance (but not enough to bring it above the $\frac{3}{2}$ power law value) and an increase in the Maxwellization rate—*cf.* Langmuir's paradox.[36] These longitudinal oscillations do not radiate but numerous cross-coupling possibilities for transition into radiative modes exist—as for example via the fluctuating electron centrifugal force in moving along curved magnetic field lines. For the violin-string mechanism, the critical value of the z parameter is 1, but it has not yet become clear how large the fraction of the electrons having $z > 1$ must be for growing waves to exist. The ratio z is, of course, a critical parameter for the other mechanism also, for which still larger growth rates have been predicted, so there is some doubt which of these will be dominant for the plasma oscillation phenomena concerned.

A theoretical analysis[37] has also been made of the economics and stability of the plasma confinement process, variously called *electrostatic*[38] or *inertial*[39] in which electrons are inwardly projected over the surface of a sphere, the resultant turning point near the center forming a space charge well for positive ions. It turns out that a modest thermonuclear reaction might conceivably be maintained in a few mm^3 in this way, for experimental purposes, but no economic thermonuclear reactor seems to be possible from this geometry in the electronic form. However, an alternative arrangement,[40] with the ion and electron roles reversed, and which technically we do not know how to construct, looks quite promising.

EXPERIMENTAL

(The order is in historical sequence of development)

Columbus II [41]

This is a high power linear pinch apparatus with the following properties: *tube*—diameter, 10 cm; length, 30 cm; material, Mullite; *condenser*—capacity, 25×0.8 μf; voltage, up to 100 kv; peak current, 800 ka; time to current peak, 2.2 μsec. The condensers (Fig. 2) are at the periphery of a low inductance transmission line connected to the discharge tube by a single eight-plate subdivided vacuum spark gap.[42] At 50 kv tube voltage, the neutron pulses from this machine, of duration ~ 1.5 μsec, contain 3×10^8 neutrons per pulse for zero B_z and 2×10^7 for 200 gauss B_z.[43] The yield at large B_z has proved to be susceptible of improvement

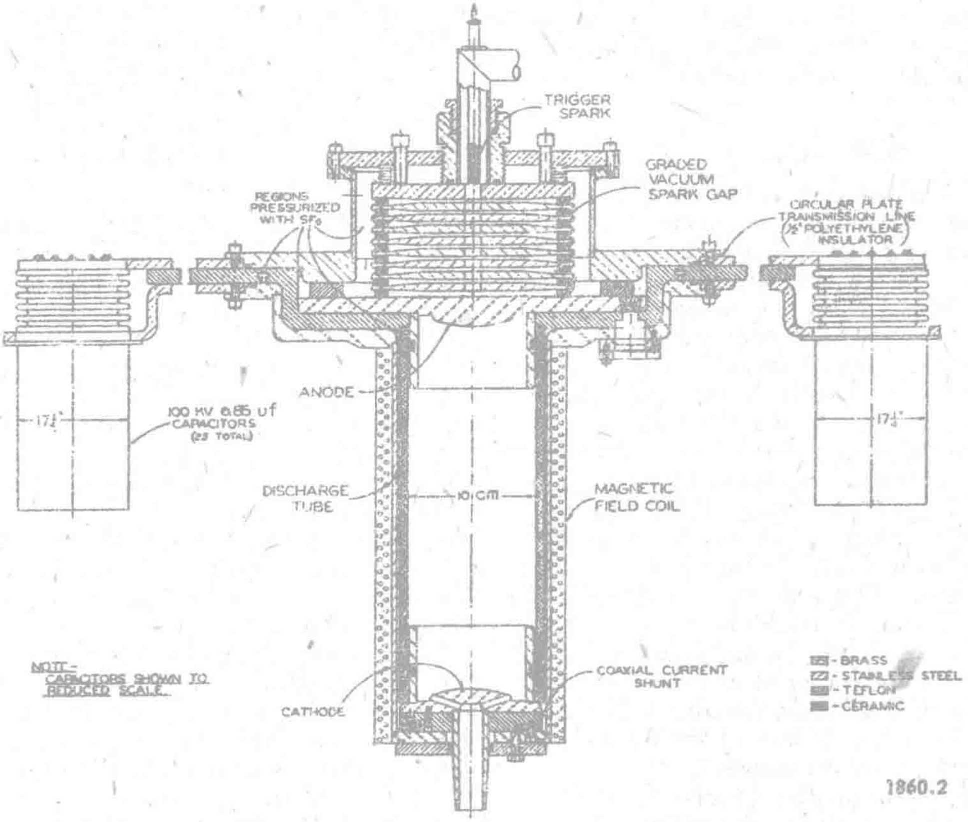

Figure 2. Columbus II apparatus, schematic

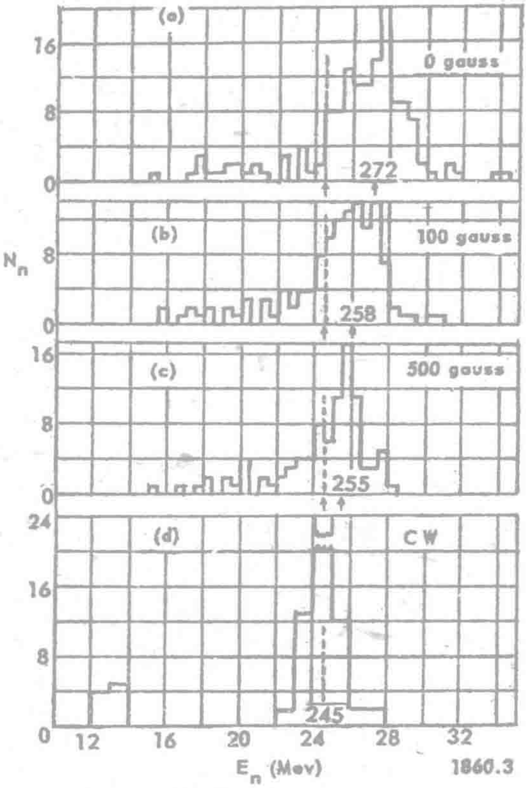

Figure 3. Columbus II neutron energy distributions

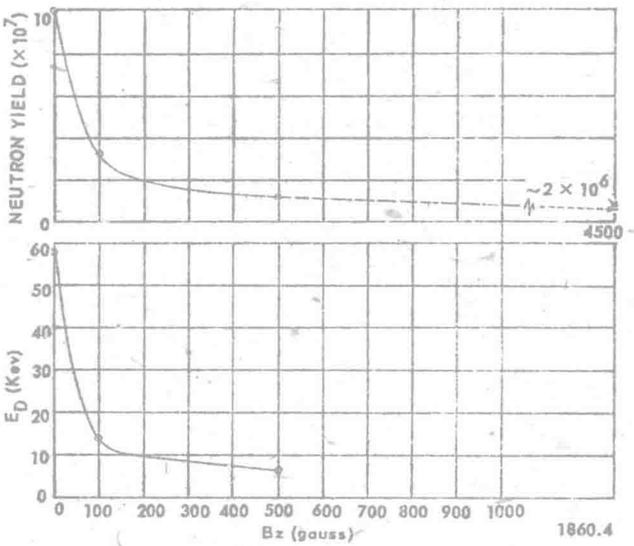

Figure 4. Columbus II neutron yield and energy anisotropy as functions of axial magnetic field B_z

by a conditioning treatment of the tube, together with a reduction of tube voltage from 50 to 40 kv. Nuclear emulsion measurements of the neutron energy distributions have been obtained up to 500 gauss B_z. Results of such measurements are shown in Fig. 3.

Neutron Yield

The neutron yield falls with increasing B_z (Fig. 4), at first sharply and then more slowly. The neutron energy anisotropy also falls from the value (expressed as the energy of deuterons moving towards the cathode, assumed to react with stationary deuteron) of 57.5 kev at $B_z = 0$ to 7.2 kev at $B_z = 500$ gauss. Equivalent deuteron radial velocities appear from nuclear emulsion studies in other experiments to be lower than the velocities towards the cathode. If we assume that the primary neutron source is, in reality, monoenergetic and centered on the peak of the observed smooth neutron energy distribution, we can proceed to calculate the current of deuterons (having the appropriate energy from the observed center-of-mass velocity) incident on stationary deuterons at the compressed pinch density consistent with the observed yield. At low B_z, this gives a reasonable answer, e.g., at $B_z = 0$ and deuteron drift energy 57.5 kev, deuteron current $\sim 10^3$ amp. However, at high B_z, say 500 gauss, and deuteron drift energy 7 kev, the deuteron current is 6×10^5 amp; this is absurd, both on energetic grounds and also because it is larger than the total tube current $\sim 5 \times 10^5$ amp. (These currents are not dissimilar but it should be remarked that a fraction of the tube current—nearly all of it in a torus, where the net plasma momentum is zero—is carried by the electrons.) In speculating on the origin of these high B_z neutrons, none of the usual instability characteristics are present, voltage signatures or sharp neutron peaks, and the discharge is conventionally stable in the $m = 0$ mode.

A simple explanation, in terms of a general thermonuclear reaction throughout the pinch, can likewise be excluded since it is not energetically possible for the whole plasma to have the required drift velocity. Some process is needed which would increase the deuteron–deuteron relative velocity in a small fraction of the plasma while maintaining in it the 4.1×10^7 cm/sec drift towards the cathode. At first sight, a Fermi-type mechanism, i.e., acceleration by reflections between moving magnetic discontinuities, might seem the most likely but in such a case more neutrons from deuterons moving away from the cathode should be observed. Ordered motion of the required kind can be imagined in a shock moving toward the cathode, as proposed by Phillips (the neutrons are known to be emitted uniformly along the pinch except in the vicinity of the anode). Another suggested process is a constriction moving towards the anode and having in it an increased B_z. The conservation of flow through such a constriction involves acceleration of the deuterons into the constriction, accompanied by conversion of longitudinal motion into Larmor energy by the increased B_z field, the required relative velocities being thus produced without calling on a collision process. Future experiments with the Columbus II apparatus involve a search for a relation between neutron pulse length and tube length, and a further attempt to apply the magnetic probe. The latter has so far proved too fragile, both mechanically and electrically.

Columbus S-4 [44–46]

This is a medium power linear pinch machine having a *tube*—diameter, 13 cm; length, 61 cm; material,

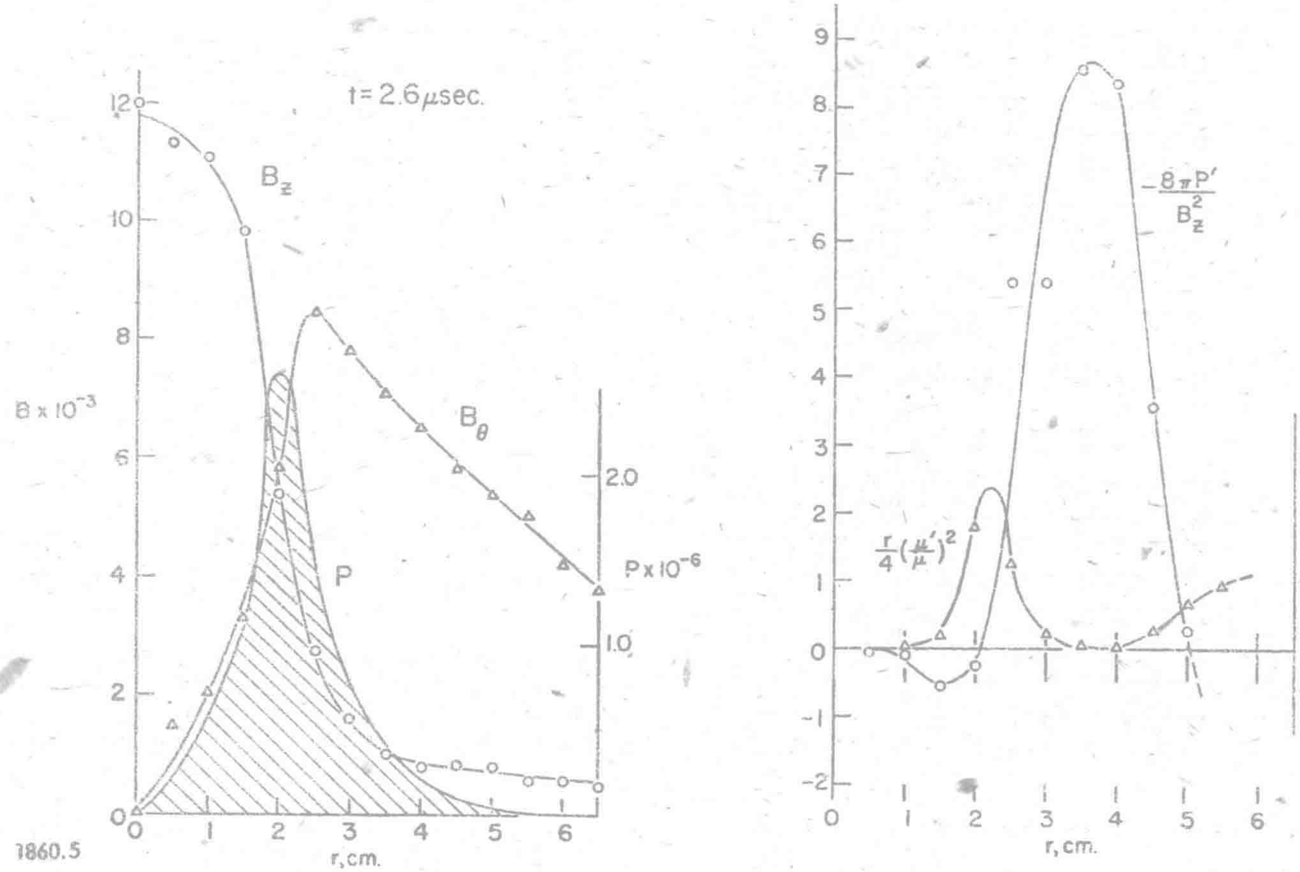

Figure 5. Columbus S-4 radial distribution of pressure and magnetic field strength B_z, B_θ and pressure (left) showing so-called hollow pressure distribution and (right) Suydam stability criterion for the foregoing: unstable between 2.5 and 5 cm

alumina (Mullite); *condenser*–capacity, 75 μf; voltage, 20 kv; peak current, 250 ka; time to current maximum, 6 μsec.

Light Emission

This apparatus has been used in a series of fundamental studies of the pinch, and from it have come most refined and reproducible observations. Important, in the achievement of cleanliness from impurities and reproducibility of operation, has been a conditioning of the tube by repeated discharges, with monitoring of the emitted impurity light and gas formation. In the clean state, the total visible light is $<1\%$ of that emitted from normal tubes, and no marked emission of gas into the pumping system is observed after a 250 ka discharge. Remaining changes in the performance from one discharge to the next were traced to fluctuation in pressure due to pumping instability, and were eliminated by a gas flow control servo operated from a Pirani gauge. In the final state, readings of B_θ and B_z (except when instabilities are present) are reproducible to within a few percent.

Emission of H_β light occurs in a brief flash, falling to zero for the main duration of the discharge. Si^{II} 4128 Å line intensity, used as an indication of wall impurities, does not appear until the second half cycle.

Behavior of Current Sheath

The magnetic probe measurements show (Fig. 5) that the currents flow in a well developed sheath in the initial stages (0–3 μsec), with a good r^{-1} dependence for B_θ, indicating negligible currents outside the sheath. From the equation for static hydromagnetic pressure balance,

$$\frac{B_z^2}{8\pi}+nkT=\frac{B_\theta^2}{8\pi}+\int_{r_w}^{r}\frac{B_\theta}{r}dr,$$

we evaluate nkT. At 2.5 μsec, this is peaked at the radius of the current sheath and falls to zero on the axis. This hollow nkT distribution has been predicted for some time to occur as a consequence of the accumulation of the swept-in gas at the sheath (snow plow effect) and its joule heating, but was never observed in earlier experiments with smaller diameter tubes. It turns out to have important consequences for the interpretation. Figure 5 also plots the two sides of the Suydam inequality from which we see that the pinch is unstable for radius >2.5 cm. After three or four microseconds, the azimuthal symmetry of the pinch is generally lost, in a manner depending on the magnitude of the initial B_z stabilizing field. For low B_z, a helical deformation is found, such as would be predicted for $m = 1$ instability. Higher B_z fields effectively eliminate such gross motions but a "fluttering" motion of the plasma boundary appears: correlation studies, of the signals from sets of closely spaced magnetic probes, indicate this motion to be turbulent in nature with related motion limited to regions of 1–2 cm extent. Figure 6 shows magnetic probe traces of the B_θ signal as the fluttering boundary reaches the probe radius set at 4 cm, together with the neutron signal. This figure also gives the signal from a probe oriented to detect radial components of the magnetic field. Such probes detect the onset of instability sensitively. Neutrons are emitted from Columbus S-4 in a characteristic long pulse coinciding with fluttering and seen only when the clean state is achieved and fluttering is present. It seems reasonable to attribute the fluttering and the neutrons to the boundary layer instability of the kind predicted by Suydam.

Figure 6. Columbus S-4 neutron emission coincident with fluttering of plasma boundary: Top – B_r, showing onset of fluttering; middle – neutron emission; bottom – B_θ at 4 cm radius: B_z = 1000 gauss; trace speed, 3 μsec per division

Microwave Radiation

Observations made with a microwave detector,[47] at $\lambda = 3$ cm, in the axial and radial directions show (1), an intense pulse of radiation in the first microsecond, (2) a quiet period 1 to 3 μsec and (3) a burst of radiation correlated in time with the fluttering. As the pressure balance calculations are extended to later times, the sheath which was well defined at 2.5 μsec, becomes intermixed at a discouraging rate so that, at 6 μsec, the distributions are found to correspond to j_θ and j_z current densities uniform across the tube.

Carrying the probe observations to the end of the first half current cycle resulted in the observation of entrapped currents in the pinch. Such currents have been reported before[48, 49] and occur in a theory of imperfect sheath formation.[50] At the time when the total tube current has reached zero, approximately one third of the original maximum current $\sim 6 \times 10^4$ amperes may still be flowing in the axial region, and back along a thin region adjacent to the wall. The phenomenon is, of course, due to the appreciable diffusion time for the internal currents to reach the exterior, together with the conductivity at the wall of some of the expanded gas in the pinch, which effectively screens the interior from the reversal in the applied voltage. Such reversed current distributions have some practical interest; a sufficient increase in the reversed current leads to a reversal of B_θ. Suydam's criterion for stability can be met by a reversal in B_θ, and a stable pinch configuration involving reversed B_θ has been deduced by Tayler.[6]

Conductivities

Returning to the plots of B_θ and B_z versus radius—using $\nabla \times \mathbf{B} = 4\pi \mathbf{j}$, we can derive $\mathbf{B}$ and $\mathbf{j}$. From three plots separated in time, using $c\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$, we determine $\mathbf{E}$, the electric field at all points. Knowing $\mathbf{B}$, $\mathbf{j}$ and $\mathbf{E}$ at all points allows the evaluation of the parallel and perpendicular conductivities, $\sigma_\parallel$ and $\sigma_\perp$. Figure 7 shows the results obtained for a discharge at 60 μ deuterium pressure, 200 ka peak, $B_z = 2000$ gauss.

Highly peaked currents, J_θ and J_z, at intermediate times indicate a well developed sheath. Note that E_θ is small at the wall (it should extrapolate to zero at 7.2 cm for conservation of B_z flux). The parallel conductivity is seen to rise with time, reach a maximum (at $t = 1.8$ μsec and $r = 3.5$ cm) of 800 mho cm^{-1}, and subsequently decline to a uniform lower value of ~ 150 mho cm^{-1}. The perpendicular conductivity is not plotted in Fig. 7 as its value within the experimental error turns out to be zero, except at the same point in space and time as the maximum in $\sigma_\parallel$, where it reaches the value 20 mho cm^{-1}.

Plasma Inertia

These parallel conductivities correspond to electron temperatures of 12 ev for 800 mho cm^{-1} and 5 ev for 150 mho cm^{-1}. In the Fig. 7 plots of pressure versus radius, an anomalous plasma pressure is observed which alternates between the inside and outside of the current sheath. Suspecting that this was due to an inertia term, a careful plot of radius versus time revealed a small sinusoidal oscillation during the contraction (Fig. 8).

A calculation of the mass density in the sheath, using the accelerations measured from Fig. 8 and the anomalous part of the pressure plot, agrees, within the experimental error, with the total mass of contained gas that would be swept in by the sheath. Subsequently this was done more simply by noting that the small oscillation frequency about the equilibrium radius of a thin heavy shell of surface density, ρ_s, under the particular external circuit conditions of B_z and I conserved, is

$$\omega_r = (B^2/4\pi r_0 \rho_s)^{\frac{1}{2}},$$

where $B = B_\theta = B_z$ is the magnetic field strength at the shell surface. An experiment to observe this oscillation frequency (Fig. 9) using a B_z probe on the axis, over a range of gas densities, confirms that the oscillation frequency varies as the square root of the gas pressure and that the B_z oscillation amplitude increases with gas pressure, as it should since the sheath velocity in Columbus S-4 is only slightly dependent on gas density at the selected operating

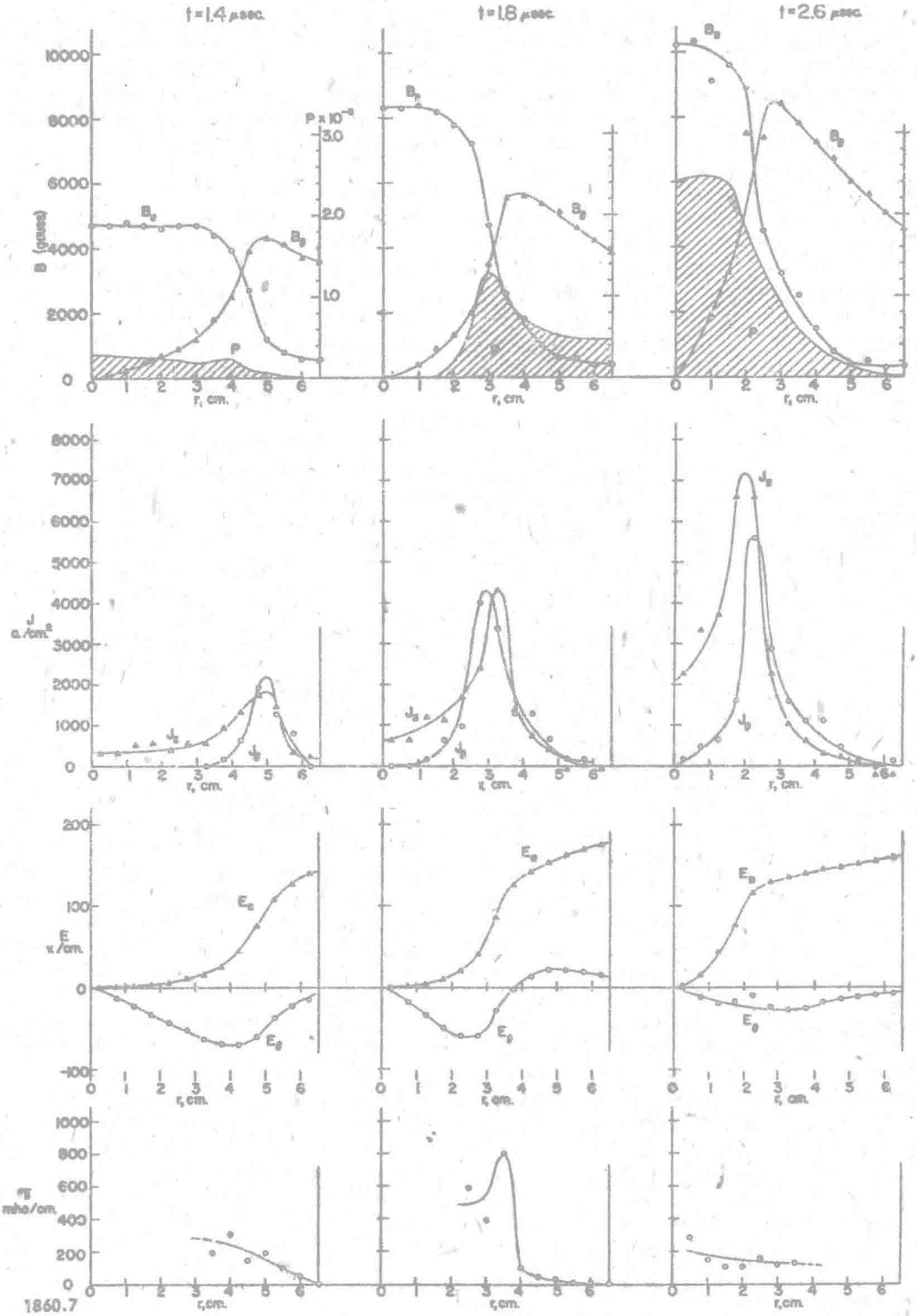

Figure 7. Columbus S-4 magnetic probe results and derived data. B_z, 1500 gauss; D_2 pressure, 60 μ Hg; potential, 14 kv; peak current 200 ka

parameters. The evaluation of ρ_s in this way fills what has been a conspicuous gap in our knowledge of the pinch—namely, the completeness of the insweeping of the initial gas filling (since Columbus S-4 is apparently free from impurities during the first half current cycle).

Temperatures

This, together with the observed dependence of ω_T on initial gas filling density, leads to the further conclusion that no significant contribution to the deuterium gas filling occurs by desorption or removal of monatomic films of deuterium from the wall, or