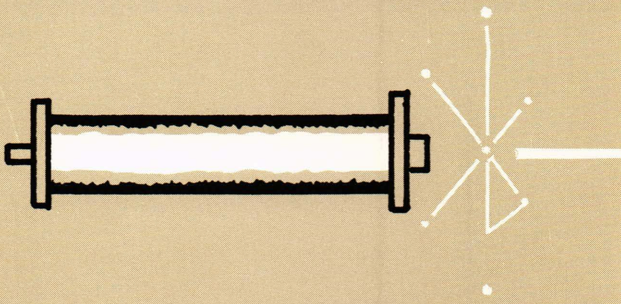
A theta-pinch plasma gun has been developed to study the interaction of a high-temperature, high-density plasma with various magnetic fields. The gun produces a doughnut-shaped puff of hydrogen plasma having an average density of 1 to 2 x 10^{15} particles per cm^3, a temperature of 350,000°K and a directed velocity of 2 x 10^7 cm/sec. A variety of techniques has been used to study the plasma including a specially developed fast far-infrared interferometer. A significant amount of the directed plasma energy can be converted into more useful transverse (random) energy by reflecting the plasma from a magnetic barrier.



R. Turner

A plasma gun is a device for producing a high-velocity slug of ionized gas. In a plasma gun, charge neutrality exists at the time of creation of the plasma, as contrasted with sources using ion or electron beams that are neutralized, for example, by injection of the opposite charge at some later time or position. Plasma guns are of interest for use in controlled thermonuclear fusion work, space propulsion, and as sources of high temperature ionized gas for fundamental plasma physics studies. The interest here is principally the development of a plasma gun for use in controlled nuclear fusion experiments.

One of the more promising approaches to controlled nuclear fusion consists of injecting a sufficiently hot and dense plasma into a magnetic field, where the plasma can be confined long enough for thermonuclear reactions to occur. One reason for favoring this approach is the belief that the problems of creating and containing a thermonuclear plasma can be better solved if the two functions are optimized separately. A disadvantage of this approach is that a plasma or charged particle injected into a static magnetic field will not be contained unless some irreversible process takes place while the plasma is in the field. Several methods for producing an irreversible reaction have been suggested and tried with varying degrees of success, such as: the collision in the containment region of two plasmas produced by counterfiring plasma guns; a randomization of the plasma by its interaction with the confining magnetic field, and short-circuiting of the polarization field produced by the plasma as it passes through the confining field.

Many different plasma guns or plasma sources have been made in the last ten to fifteen years, examples of which are the rail gun, the coaxial or Marshall gun, the conical-pinch or thetatron, the loaded titanium gun, the button source, the "T" gun, and various types using the pinch mechanism. Guns almost universally use the electric field produced by a high-voltage source to ionize the gas and use the Lorentz force (the force produced by the interaction of a current with a magnetic field) to propel the plasma. Considerable effort has gone into understanding the operation, improving the energy and density, and reducing the impurity level of the output of these guns. For high-β injection work (where β is defined as the ratio of the plasma pressure to the confining magnetic field pressure), a plasma should preferably be a dense, energetic, stable puff, well defined in time; it should be free of neutral gas and impurities (from the walls or electrodes); and, if possible, it should be created in a magnetic field geometry compatible with the confining magnetic field. Some of these conditions are mutually conflicting, and others are not possible with certain types of guns. The most serious disadvantage of most guns, however, is that a considerable amount of low-energy plasma follows the initial energetic plasma.

The coaxial gun and the conical-pinch are two of the more popular guns. In the coaxial gun a high voltage applied between two coaxial conductors ionizes the gas in this region to produce a radial current and an associated azimuthal magnetic field; the interaction between the current and magnetic field produces a force in the axial direction. In the conical-pinch gun, application of high voltage to a coil, generally a single turn, produces an azimuthal gas current and a magnetic field with

HETA-PINCH PLASMA GUN STUDIES

radial and longitudinal components that depend on the shape or flare angle of the coil. The interaction between the azimuthal current and radial magnetic field produces a force in the axial direction. In actual practice the operation of both these guns is more complicated than described.

Coaxial guns produce much higher ion energies than can be explained by the Lorentz force alone; one proposed explanation is that the energy is produced by a pinch as the plasma leaves the gun. The conical-pinch gun performance is not as critical to cone angle as the above simple analysis would indicate, and in fact some of the best results are produced with a very small cone angle; the plasma itself is a sufficiently good conductor to distort the external magnetic field and provide a radial component of magnetic field. The operation of both of these guns depends critically on the amount of gas in the chamber at the time of breakdown, the amount of preionization, and the amount of bias or trapped magnetic field. For example, the coaxial gun can be operated either in a high-directed-energy low-density mode, with a typical directed energy of 3 to 5 keV and a density of 10^{13} particles/cm^3, or a low-directed-energy high-density mode, with an energy of 200 eV and a density of $10^{15}/\text{cm}^3$ by changing the initial gas pressure in the gun. In general, however, both guns produce a plasma with a long, low-energy component that complicates confinement studies.

The work reported here has been concerned with the development of a gun based on the theta-pinch principle, using two pinch coils, suitable for: (a) high-β plasma injection studies; (b) the determination of the properties of the gun's output; (c) the interaction of its output with various magnetic fields; and (d) a comparison between the performance of the two-coil theta-pinch gun developed and the more conventional single coil conical-pinch gun.

A theta-pinch provides a good means of creating a suitable plasma provided that the plasma can be extracted from the pinch region. A theta-pinch is usually produced by the discharge of a high-voltage capacitor bank through a single-turn coil surrounding a gas at low pressure. The gas, usually hydrogen, deuterium, or helium at a pressure of 0.01 to 0.1 Torr is slightly ionized before the main discharge by either a low-energy discharge through the coil or an axial discharge along the coil axis. The capacitor discharge produces a damped oscillatory (50 to 500 kHz) current in the coil, a longitudinal magnetic field, and azimuthal electric field in the gas. If the electric field is large enough, it will break down the gas at the confining wall, where the azimuthal electric field is a maximum, and set up a circulating current in the gas; the gas current acts like a shorted secondary turn of a transformer. The sudden change of the gas at the wall from a poor to a good conductor can trap the existing magnetic field within the current ring. The amount and direction of the trapped field are critical to the later behavior of the pinch.

The interaction between the circulating plasma current, j_θ, and the external magnetic field, B_z, produces a radially inward force

$$F_r = j_\theta B_z$$

If the conductivity of the gas at the wall is high enough to prevent the diffusion of the external magnetic field, the force will cause the current ring to implode radially inward. And if the current ring remains stable during the implosion, the un-ionized gas ahead of it will be compressed and heated. Compression ratios of 10 to 100, which increase the original density of $10^{15}/\text{cm}^3$ to 10^{16} to $10^{17}/\text{cm}^3$, and energies of up to several keV have been achieved in this manner. The details of the compression and heating mechanisms are complicated and are discussed in detail elsewhere.[1]

The Theta-Pinch Gun

The plasma is produced in the theta-pinch gun by rapidly increasing the field of a magnetic mirror geometry, as in a standard theta-pinch, and is ejected by distorting the mirror field in such a way as to produce a longitudinal force. Two one-turn coils with independently controlled capacitor banks provide the desired field configuration.

Two versions of the gun have been tested; the major difference between them is in the history of the magnetic field used to create and eject the plasma. In the original design both coils were energized simultaneously from identical 2.5 kJ capacitor banks that provided a symmetric mirror field oscillating at 500 kHz. The plasma was created between the coils at the start of the second half-cycle of the magnetic field as in a conventional theta-pinch. When the magnetic field reached the next maximum, the rear or breech coil was short-circuited (crowbarred); if the short-circuit were perfect, the field would then decay exponentially at a rate determined by circuit impedance and plasma resistance. A fraction of a microsecond later the front or muzzle coil was also crowbarred. The asymmetry in the magnetic field produced by these means provided the longitudinal force to eject the plasma. Because of poor performance of the crowbar switches, the force on the plasma was small and erratic and resulted in unsatisfactory gun operation. The fast changing current and the low gun inductance put severe requirements on the crowbar switches. They must operate with nearly zero voltage across them, must have an inductance that is small compared to the coil inductance (20 nH), and must have a switching jitter of less than 50 nsec. These conditions are difficult to meet with spark gap switches in which breakdown delay and jitter increase rapidly as the voltage across them is reduced below the static breakdown voltage. The problems can be eased somewhat by using high-voltage energetic pulses to trigger the crowbar switches. A more satisfactory solution, however, was to add a second slower, but more energetic, capacitor discharge (120 kHz) through the breech coil. This eliminated the need for crowbarring of either coil and permitted a wider variation in the magnetic field configuration. The plasma, however, is now created and ejected without going through the well defined initial pinch phase of the first gun.

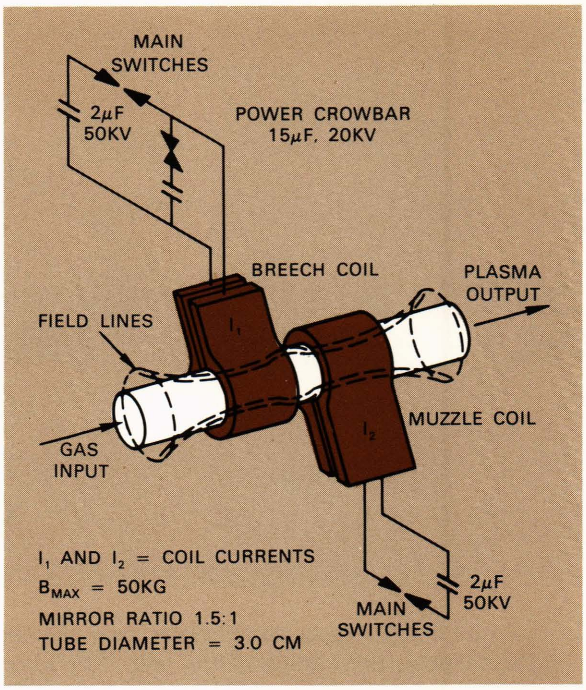


Fig. 1—Theta-pinch plasma gun.

The gun used for the results to be described is shown schematically in Fig. 1. The coils are aluminum, 3.5 cm long, with an inside diameter increasing from a minimum of 3.3 cm to 4.0 cm (cone angle, 7.6°) and are mounted 1.5 cm apart. This arrangement provides a mutual coupling between the coils of 20 percent and a magnetic mirror ratio (the ratio of the maximum to the minimum field strength) of 1.5; this mirror ratio was chosen as a compromise between the low ratio desirable for plasma stability and the high ratio necessary to provide sufficient ejection force. Each coil is connected by ten low-inductance coaxial cables and five spark gap switches to a 2μF/50 kV capacitor bank that produces a maximum field of 50 kG in 0.54 μsec. A 15 μF/20 kV capacitor, also with five spark gap switches, provides the slower (2 μsec rise time) current through the breech coil. The switches are pressurized, three-electrode, triggered spark gaps developed for 50 kV operation from a 20 kV, open-gap, Naval Research Laboratory design. Pressurization with nitrogen up to 100 psi permits variable voltage operation with a fixed 5mm gap setting. To extend the life of the switches, all capacitors are pulse-charged in 25 μsec. Because of an instability which

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[1] K. Hain and A. C. Kolb, "Fast Theta-Pinch," *Nuclear Fusion, Suppl. Part 2,* 1962, 561-569.

results in breakup of the current ring and the rapid loss of plasma to the wall during compression in the present gun, the maximum voltages are limited to 18 kV on the 2 μF banks and 13 kV on the 15 μF capacitor; this gives a total of 1600 joules of stored energy on the breech coil and 325 joules on the muzzle coil.

The timing of events in the firing cycle of the gun is adjusted to produce a single fast puff of plasma. A fast opening electromagnetic valve is used to emit a pulse of gas at a pressure of about 0.1 Torr into the region between the coils (originally at a pressure of 2 x 10^{-6} Torr), it is then preionized with a low energy 3 MHz discharge (0.02 μF capacitor charged to 20 kV) through each coil; the main capacitors are discharged 15 μsec after the preionization. The plasma output depends critically on the time between the opening of the gas valve and the discharge of the main capacitor banks; a 5 percent variation in this time changes the output from a fast, sharp puff to a broad, slower, oscillatory puff. The output also depends critically on the time between discharge of the fast and slow capacitor banks; a variation of 0.3 μsec in this time will change the energy of the output by more than a factor of two. The magnetic fields of the individual coils are shown in Fig. 2.

When the gun operating conditions are adjusted to produce a plasma output having a maximum transverse energy density, the compressional cycle is much more asymmetric than in the original gun. The implosion starts at the breech coil 1.40 μsec after the initial current and 0.3 μsec later at the muzzle coil. The implosion takes slightly longer at the breech coil, indicating that the gas density is higher there than at the muzzle coil. The major compressional effect, to be expected from the relative strength of the breech and muzzle fields, takes place at the breech coil.

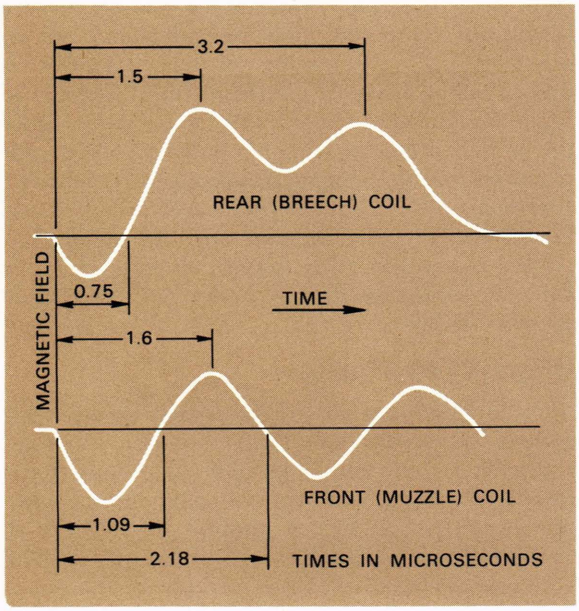

Fig. 2—Magnetic field of theta-pinch coils.

Plasma Motion in a Longitudinal Magnetic (B_z) Field

A magnetic field is generally necessary to confine the plasma as it moves from the gun to a suitable confinement region. Fortunately, the deformation of the field produced by the plasma provides a ready means for studying it. Of three different guide field configurations studied, the longitudinal or B_z field proved to be the most suitable for the following reasons. It is the most compatible with the magnetic field of the gun; the magnetic perturbations can be interpreted quantitatively; it is the easiest to build; and it is about as efficient a transfer field as the best of the other fields. For these reasons, the results to be described have been restricted to those obtained with it. The experimental arrangement of the gun and the guide field are shown in Fig 3.

The one-meter-long guide field of 0 to 5 kG (normally parallel to the gun field at the time the plasma was ejected) oscillated at a frequency of 600 Hz and was essentially constant during the plasma transit time. The field was produced by a capacitor discharge (38 μF/15 kV) through a solenoid wound on a stainless steel coil form (0.16 mm thick, 17 cm in diameter). The resistivity of stainless steel is high enough to permit the flux of the slow solenoidal field to diffuse through it, but small enough to prevent the high-frequency plasma perturbations from forcing the flux back out, and so it acts as a flux conserver.

Magnetic Loop Measurements and Analysis

Single turn loops around the 10-cm-diameter vacuum wall provide a very useful means for studying the average plasma behavior without perturbing it. The following properties of the diamagnetic component of the plasma, the component that perturbs the magnetic field, can be determined as a function of time and position with a series of loops along the guide field: velocity and shape; transverse energy per unit length and total transverse energy (assuming the B of the plasma is known); average particle density, for an assumed plasma cross-sectional area; and the sum of the ion and electron temperatures.

When properly adjusted, the gun produces a

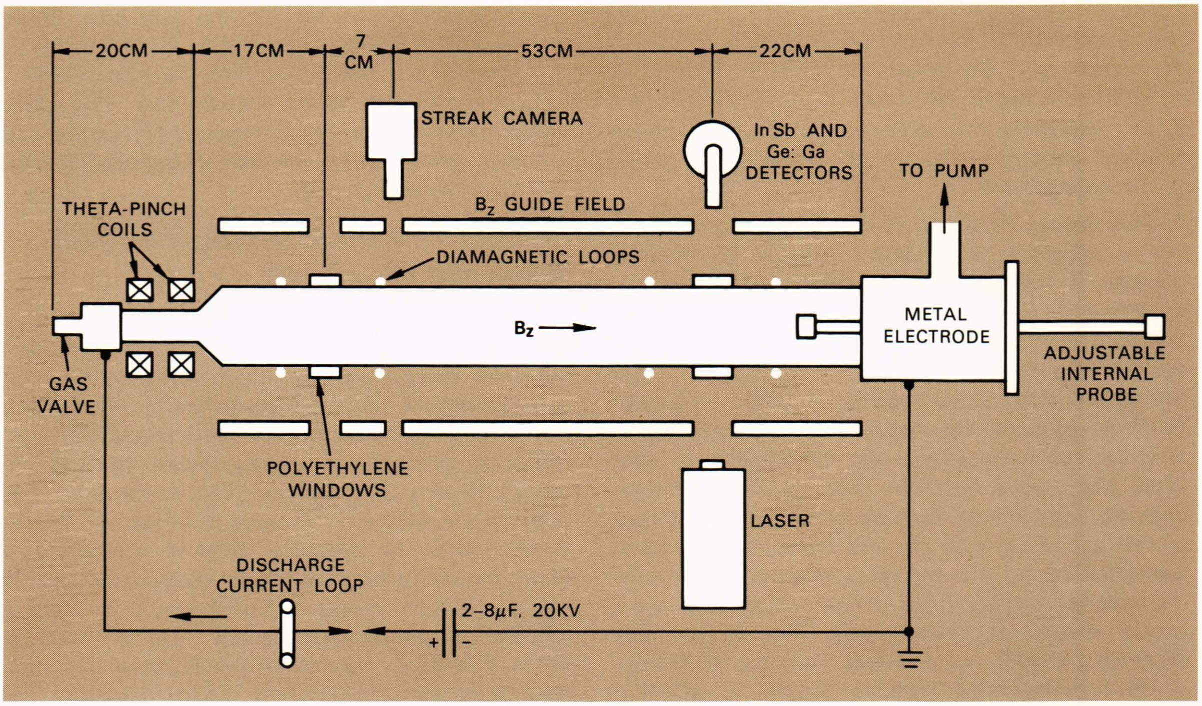

Fig. 3—Longitudinal (B_z) magnetic field experimental arrangement.

single diamagnetic puff of plasma, for either a parallel or anti-parallel direction of the guide field, even though both the breech and muzzle fields go through zero repeatedly. These results differ in several respects from those obtained in other gun experiments. The peak of the puff moves at a constant velocity of 2 x 10^7 cm/sec or with a directed energy of 210 eV per ion. Slightly higher velocity puffs can be obtained by reducing the volume of gas in the gun, but at the expense of a lower total energy.

The transverse energy density decays almost exponentially, with a time constant of 0.7 μsec for the first 20 to 25 cm of travel and with a time constant of 2 μsec during the remaining distance. Some loss of energy density results from longitudinal expansion of the puff (described below). The total transverse energy in the puff, however, also drops a considerable amount—from 11 joules near the muzzle to 3.8 joules at a point 70 cm away. Some loss is due to radiation cooling; the initial high loss rate, however, most likely results from a fast growing instability that permits particles to reach the wall. The slower loss rate, but one that is still many times the classical diffusion rate, is most likely due to smaller scale instabilities in the plasma. Understanding the nature and mechanisms for this latter type of loss is one of the most important present problems in the field of controlled thermonuclear fusion research. At the muzzle, the puff is 6.5 cm long, measured between the half-amplitude points, and during the first 40 cm of travel its length increases roughly exponentially (with τ = 1 μsec) to 20 cm; it then continues to expand at a much slower rate (τ = 7 to 9 μsec). The initial expansion appears to result from the ions that have been preferentially heated in the transverse direction, transferring energy to the longitudinal direction (the ion collisional relaxation time is 0.5 μsec for the assumed plasma conditions at the muzzle) and from the difference in initial longitudinal velocities of the particles. Since the puff contains a trapped magnetic field that closes around the plasma, the axial expansion will continue until an equilibrium condition is established between the plasma and the field. The slower expansion rate agrees closely with the calculated diffusion time of the trapped field due to plasma resistivity.

Plasma Oscillations

If the amount of gas in the region between the coils is increased above that for which the most energetic output results, the puff will lengthen and oscillations will appear on the magnetic loop signals, as shown in Fig. 4. Similar oscillations, in the case of pinch experiments, have been explained[2]

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[2] G. B. F. Niblett and T. S. Green, "Radial Hydromagnetic Oscillations," *Proc. Phys. Soc.* **74**, Dec. 1959, 737-743.

as the result of the plasma concentrated in a thin annulus, oscillating between an internal trapped magnetic field and the external confining magnetic field. The analysis has been extended to show that for hydrogen, the density n in particles/cm^3 is equal to

$$1.5 \times 10^{16} \frac{g^2 \tau^2 B^2}{A},$$

where A is the plasma cross-sectional area in cm^2 (derived from probe and photographic data), τ is the period of oscillation in microseconds (typically 0.3 to 1 μsec), B is the external magnetic field in kilogauss and g is the plasma shape factor.[3, 4] The factor g varies from 1 for a plasma concentrated in a thin annulus to 1.4 for a plasma with the maximum density on the centerline. The oscillations provide an easy means of obtaining an estimate of the plasma density; at 23.6 cm from the gun, the density derived by this technique is 2×10^{15}/cm^3.

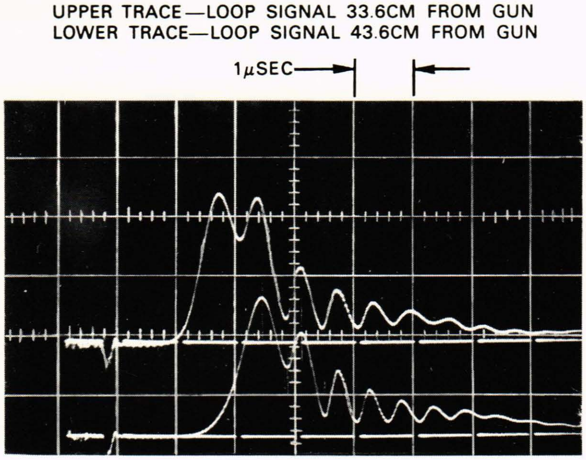

Fig. 4—Magnetic loop oscillations in a B_z field.

The determination of plasma density from plasma oscillations, as previously described, has been made for a plasma having radial motion only and has assumed it oscillates as a solid body. If the analysis is to be applicable to the output of a gun, the oscillations detected at various positions along the puff must be in phase. However, the available data indicate that the plasma is a much more complicated structure than the model assumes; and other types of plasma motion are conceivable that can produce oscillatory loop signals. The plasma may, for example: split into rings, the result of finite resistivity; form vortices; consist of two or more puffs of different velocity; or rotate or oscillate about an axis at right angles to the guide field direction, the result of the opposing directions of the trapped and the guide fields. The oscillations may result from wave motion in the plasma or from an instability. Certain of the conditions necessary for a drift-type instability at the ion cyclotron frequency are satisfied by the puff: azimuthal currents are present, which exclude the guide field and support the trapped field; high radial gradients in the particle density and the magnetic field are present at both the inner and outer radii of the plasma annulus. Because of the uncertainties as to the nature of these oscillations, they have been studied in detail.

The results of a series of measurements indicated that the gun most often operated in such a mode that the plasma density could be derived from the oscillations on the loop signals. Occasionally the gun puts out a puff for which the analysis is not applicable. The oscillations on adjacent loops are not in phase and in some cases only a part of the puff is oscillating at any time. The oscillations on the two magnetic loops of Fig. 4 are in phase near the beginning of the puff, but are out of phase near the end of the puff where the frequency is higher. The oscillations tend to approach an upper frequency limit which appears to be due to the fact that a significant amount of plasma extends from the main puff to the wall. In this case, the wall sets the boundary condition on the oscillation with the result that the original analysis is no longer applicable.

Plasma Photography

Side-on streak photographs of the puff moving along the guide field and end-on framing pictures of it leaving the gun and entering the guide field were made. They were used to determine the stability of the puff during the critical transition region between the gun and the guide field, the relationship between the light from the puff and the corresponding magnetic loop signal, and the presence of a luminous precursor to the main puff.

The light from a fast puff, at 24.3 cm from the gun, was insufficient for streak photography; most of the radiation is in the ultraviolet region. To add luminosity to the puff, a background of argon at a pressure of 2×10^{-4} Torr was added. Figure 5 is a typical streak picture of a fast puff under these conditions; the puff is photographed through a narrow vertical slit and moves from right to left as seen in the photograph. The shape of the puff determined from such streak photographs and magnetic loop signals are in agreement. The light starts 0.4 μsec after the start of the magnetic loop signal; the maximum diameter of the puff derived

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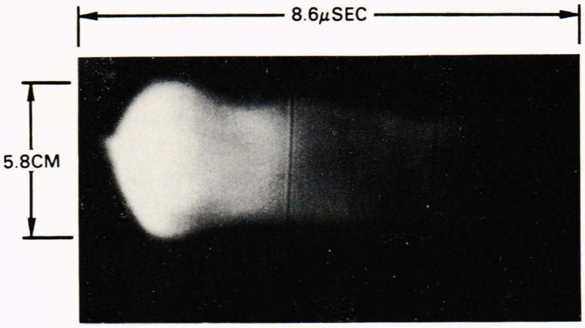
[3] J. B. Taylor, *Proceedings of a Conference on Theoretical Aspects of Controlled Fusion Research,* TID-7582, Gatlinburg, Tenn., Apr. 27-28, 1958.

[4] H. A. Bodin and B. McNamara, "Radial Oscillations of a Plasma Cylinder with Arbitrary Density Distribution," *Plasma Phys.* **9**, 1967, 505-509.



PHOTOGRAPH MADE SIDE-ON OF A FAST HYDROGEN PLASMA PUFF MOVING THROUGH AN ARGON BACKGROUND OF 2×10^{-4} TORR AT 24.3CM FROM THE GUN

Fig. 5—Streak photograph of a fast puff in an argon background.

from the streak picture occurs 0.3 μsec after the maximum loop signal. Part of the difference in time between the two measurements results from the plasma perturbing the magnetic field ahead of its actual position as it moves along the tube, and part from the time required to ionize the argon. While the puff is stable, it appears to have some filamentary structure associated with it. The addition of the argon in the tube at this low pressure had negligible effect on the loop signals. However, the addition of less than one percent of neon or nitrogen to the initial gas, pulsed into the gun to increase the visible light, almost eliminated the loop signals. This clearly indicates that the actual gun output has a low impurity level.

Measurement of Plasma Density by Far-Infrared Laser Interferometry

An independent measurement of plasma density was desired to check the value of $2 \times 10^{15}/\text{cm}^3$ derived from plasma oscillations. This density is above the cut-off frequency of available microwave interferometers, and a simple transmission experiment at a wavelength of 3 mm confirmed that the plasma was indeed opaque. On the other hand, the plasma is too thin to produce a satisfactory interference pattern using near-infrared or visible wavelengths. An interferometer that was suitable for these higher densities, operating in the far-infrared at frequencies above the plasma cutoff, was developed. The interferometer and the experimental results are described in detail.[5]

The Mach-Zehnder interferometer, laser, and plasma apparatus are shown in Fig. 6; the interferometer was positioned to look through the plasma at two positions 17 and 77 cm from the gun. A 75-μm Mylar beam splitter at the laser divided the output radiation of an HCN or H_2O laser source into two beams, one passing through the plasma and the second external to it providing a reference signal. The beams were recombined at the second beam splitter, with the phase and attenuation of the reference leg being adjusted to provide cancellation of the two beams in the absence of the plasma. The interference signal

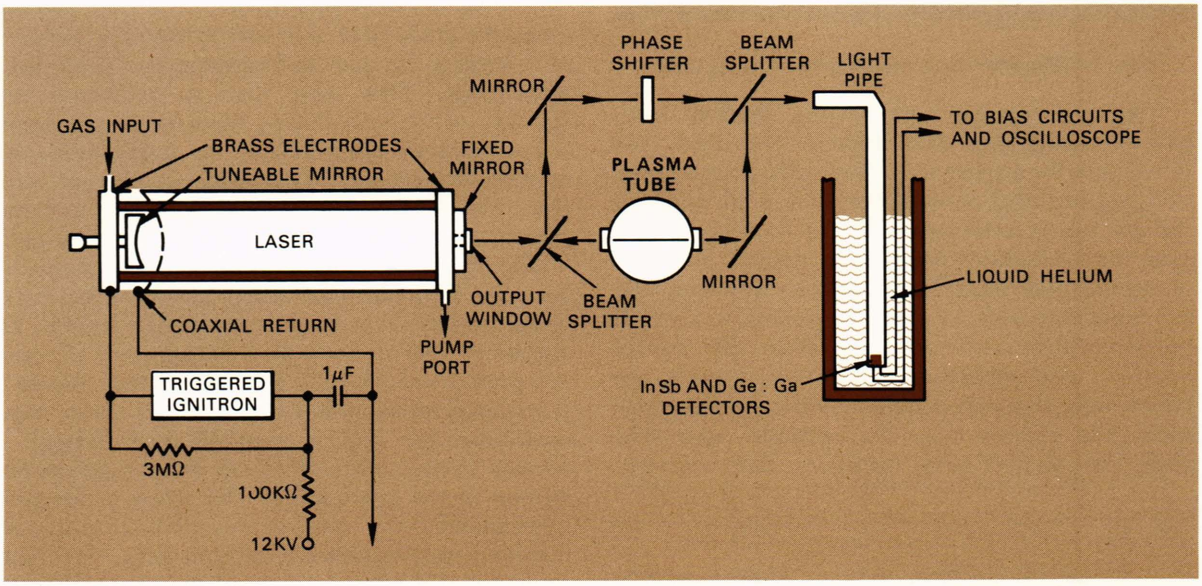


Fig. 6—Mach-Zehnder far-infrared laser interferometer.

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[5] R. Turner and T. O. Poehler, "Far-Infrared Laser Interferometry for Electron Density Measurements," *J. Appl. Phys.* **39**, Nov. 1968, 5726-5731.

produced by the change in phase of the beam passing through the plasma was detected with a fast detector cooled to 4.2°K. The same laser configuration and exciting current were used for both the HCN and H_2O lasers. Because of the high electrical noise level associated with the plasma gun and the short duration of its output, pulsed operation of the laser was used. The HCN laser emits two strong lines at 337 and 128 μm; the H_2O laser emits a variety of lines from 4 to 220 μm; however, the strong lines within the range of the detector used are segregated in time and give rise to an emission pulse with three main peaks. The first peak consists mainly of 48 μm, the second 79 μm, and the third 119 μm radiation. A particular wavelength was synchronized to illuminate the plasma as it passed a viewing window. An InSb photoconductor was used to detect the 337 μm HCN radiation, and a gallium-doped germanium detector was used to detect the H_2O radiation and the 128 μm HCN radiation. Both detectors were operated to have a response time of approximately 0.1 μsec.

The result of an absorption measurement made 17 cm from the muzzle with horizontally polarized 337 μm radiation ($E \parallel B$) is shown in Fig. 7. The magnetic loop signal, the lower trace, is representative of the plasma shape at a point 5 cm, or 0.3 μsec, later than the laser measurement. When allowance is made for this time difference, it can be seen that the absorption began with the increasing magnetic loop signal, reached the 50 percent point near the peak of the loop signal, and was complete after the peak. Part of this apparent absorption is no doubt caused by refraction and diffraction of the beam by the plasma that reduces the energy reaching the detector, and part is caused by a reflected energy loss. However, the indications are that there is a region in the energetic portion of the plasma with a density of up to 5 x $10^{15}/cm^3$. The complete absorption in the tail indicates that a region of high density, but cold plasma, follows the main energetic plasma. A similar absorption result was obtained 77 cm from the gun.

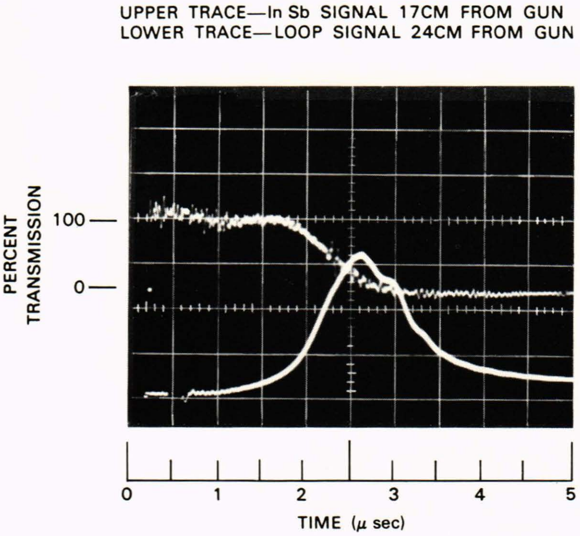

Fig. 7—Plasma absorption of 337 μm radiation.

When unpolarized radiation was used, much less absorption, particularly in the tail of the plasma, was measured. Kubo and Inuishi,[6] using microwave radiation at 35 GHz, observed that in a steady plasma the attenuation of the horizontally polarized ($E \parallel B$) signal was greater than the attenuation of the vertically polarized signal ($E \perp B$). They attributed the excessive attenuation to scattering by a turbulent plasma. The similarity of results indicates that the wake of the puff may also contain turbulent plasma. Additional measurements, however, are desirable to confirm this fact.

Because of the high absorption, interferometer measurements were not possible at the 337 μm wavelength. However, there was little plasma absorption at the shorter H_2O wavelengths (48, 79, and 119 μm) and interference measurements could be made readily. The interference fringes or phase shift produced by a plasma can be unambiguously interpreted if the density changes in a known fashion from a known reference density. For this reason the phase shift measured from the time of zero magnetic loop signal, when there is no plasma in the tube, up to the maximum loop signal, during which time it can be assumed that the density is increasing monotonically, provided the most reliable measurement of density. The phase shift is a function of path length through the plasma and the density distribution along the path. For the results reported here, a uniformly distributed plasma with a path length of 5 cm at the 17-cm window and 4 cm at the 77-cm window has been assumed.

At 17 cm from the gun and at the 79 μm wavelength, a phase shift of 6π radians was measured, representing a density of 1.7 x $10^{15}/cm^3$. A phase shift of about 2π radians was observed at the 48 μm wavelength, indicating a density of 1.0 x $10^{15}/cm^3$; the signal level of this measurement was such, however, that its accuracy was poor. At 77 cm from the gun, 4π radians of phase shift were measured at 79 μm for a density of 1.4 x $10^{15}/cm^3$. At a wavelength of 119 μm, 6π radians of phase shift

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[6] U. Kubo and Y. Inuishi, "Enhanced Microwave Scattering by Plasma Instability in a Magnetic Field," *J. Phys. Soc. Japan* **25**, Dec. 1968, 1688-1693.

were measured for a similar density of $1.4 \times 10^{15}/\text{cm}^3$. Figure 8 shows a typical interference measurement at the 77 cm position in which the plasma puff was illuminated with 119 μm radiation, along with the related magnetic loop signal. The interference fringes produced by the main plasma puff and by the tail of the plasma can be clearly seen.

The plasma densities measured with the interferometer are in good agreement with the results obtained from plasma oscillation data. When the absorption and interference data are combined with internal magnetic probe and plasma oscillation data, an estimated radial density profile, as shown in Fig. 9, can be derived for two positions along the guide field.

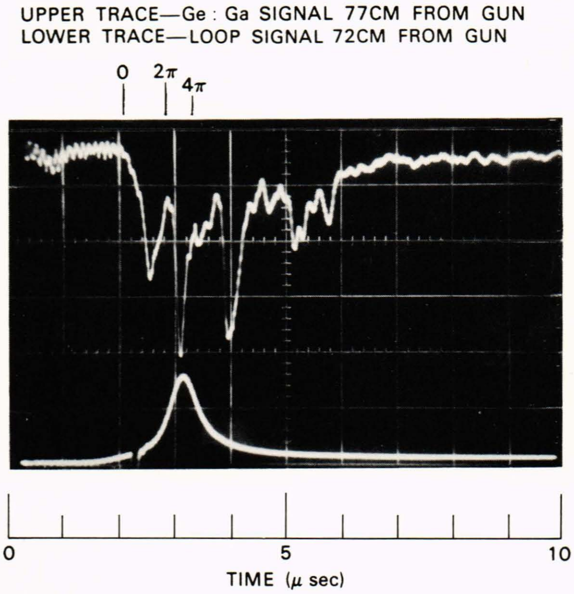

Fig. 8—Interference measurement at 119 μm.

Ion Probe Measurement of Plasma Density

An ion probe was used to make an additional independent measurement of the puff density and to determine if the gun produced any plasma with high directed energy but little transverse energy. The probe consisted of a small reentrant collector inside a Faraday cage that, in turn, was covered with a small aperture.[7] Several large pumping ports, shielded from the main plasma stream, were provided in the side of the Faraday cage. The internal collector was biased negatively to collect positive ions. The probe was calibrated in a steady-state plasma up to a density of $10^{12}/\text{cm}^3$.

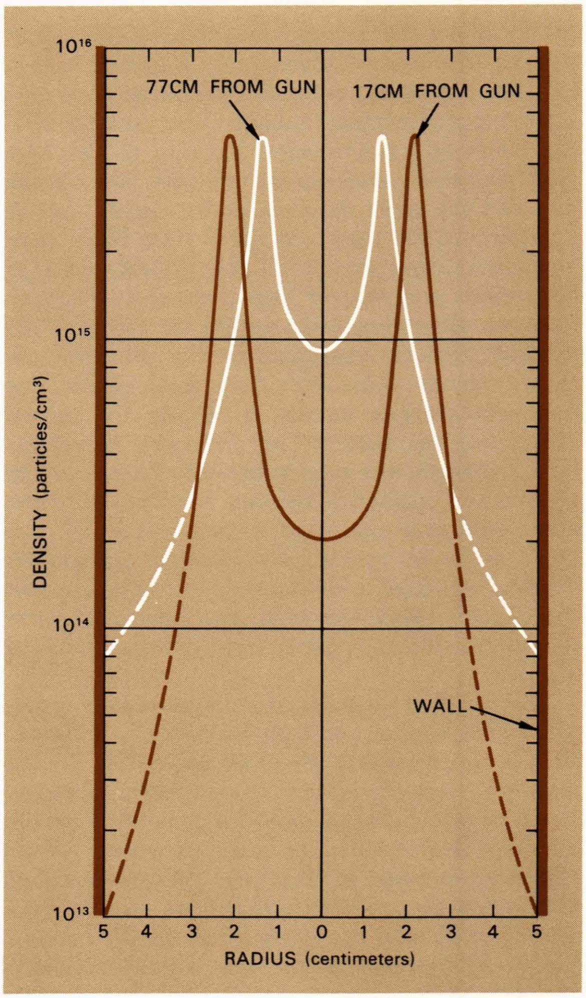

Fig. 9—Radial plasma density.

No significant high velocity precursor to the main puff was detected with the probe; this agrees with the results obtained from magnetic loops and also from photography. However, no reliable measurements of density were made in the main plasma puff for a wide range of apertures (25 to 1250 μm diameter) and bias voltages. The probe output was not reproducible; either no ions were collected or sufficient ions to short-circuit it were collected. Densities slightly greater than $10^{12}/\text{cm}^3$ were measured in the tail of the puff, but the results are not considered reliable. The present ion probe is unsatisfactory for measuring the high density in the main puff. The poor performance of the probe can be attributed, in part, to the fact that the plasma flow, which is supersonic (Mach 2), forms a shock wave on the face of the probe. This problem could probably be eliminated if the probe

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[7] D. E. T. F. Ashbey, T. J. Gooding, B. R. Hayworth, and A. V. Larson, "Exhaust Measurements on the Plasma from a Pulsed Coaxial Gun," *AIAA Journal* 3, June 1965, 1140-1142.

included a supersonic nozzle or skimmer ahead of the aperture. The trapped magnetic field in the plasma and the sudden perturbation of the guide field at the probe by the plasma probably also seriously affect its performance.

Axial Current Discharge Through the Plasma Puff

A further increase of the plasma gun output can be obtained by a second compression cycle. One of the easiest and most efficient ways of doing this, in terms of stored energy, is to run an axial discharge through the plasma to produce a linear Z pinch. Turbulent heating experiments at various laboratories have shown that very high electron temperatures can be achieved by this technique. Los Alamos has been experimenting with superposing a linear pinch on a plasma initially created and compressed by a theta-pinch, with the objective of producing an energetic linear pinch. Because of the manner in which the axial current was introduced in this experiment it was not possible to compress the main plasma but only the lower energy tail following it. But, even in this case, by varying the timing and current of the discharge with respect to the plasma, a qualitative estimate of the nature of the plasma following the main puff could be obtained.

A pulsed axial discharge having a current of up to 14 kA and a frequency of 30 to 90 kHz was added to the experiment. The discharge was applied between the gas valve and the vacuum system end of the guide field as shown in Fig. 3. In order that an axial current may flow, plasma must exist in the guide field from the seal to the gas valve. The time of initiation of the axial discharge and the plasma conditions in the guide field were varied over a wide range. When the discharge was run through an energetic plasma puff that has a short, low-energy tail, a linear pinch was produced during the first half-cycle of the current that trapped and compressed a portion of the B_z field. The compression was greatest near the main puff and decreased as the muzzle was approached. These results imply the presence of a low density high conductivity plasma. At the maximum compression the plasma emitted a large RF signal in the 0.6 to 3.0 GHz range which is indicative of a hot plasma. When a slow long puff that filled the B_z tube with a more nearly uniform plasma was used, the pinch did not occur until the second current half-cycle and there was only a slight flux compression and little, if any, RF signal. This implies a higher density and lower temperature plasma than in the former case.

Streak photographs with an axial current of 7 kA and three different plasma conditions, showed the plasma breaking up into two filaments and rotating about each other at frequencies up to 250 kHz; a very similar instability has been observed by Allen.[8] The rotating plasma, in all cases, quickly moved to the wall as the current approached a maximum.

The experiment demonstrated that an axial discharge along the guide field could compress and heat the plasma gun output. The amount of the axial current was limited by an instability that developed during the compression. The method used had the disadvantage that only the low energy tail of the plasma was heated. To compress the main puff while it is away from the walls—the more desirable experiment—would require hollow electrodes in the guide field and a much faster capacitor discharge.

Plasma Interaction with a Magnetic Barrier

The nature of the interaction between a high-β plasma and a magnetic mirror or barrier is fundamental to the eventual containment of such plasmas. In particular, the nature of the sheaths formed in a mirror of cusp containment geometry can be studied by observing the interaction of a dense plasma with barriers of various shapes and strength. A simplified colliding plasma blob experiment can also be performed by observing the interaction of the plasma with itself as it is reflected from a barrier.

Preliminary measurements of this interaction were made by firing the plasma along a (2 kG) guide field into a region of sharply increasing magnetic field (or barrier) located 64 cm from the gun. The barrier field had a maximum strength of 20 kG and a frequency of approximately 500 Hz, or comparable to the frequency of the B_z field.

The interaction of various plasmas—from the short, fast, energetic plasma to the longer, slower, less energetic plasma—with the barrier was measured with a variety of previously described diagnostics: magnetic loops, interferometry at the 337 μm wavelength, electric probe arrays, and high-speed photography. Magnetic loops proved to be the most useful diagnostic; little information on the plasma interaction with the barrier or of the reflected signal was obtained with the other techniques. Part of this lack of success was due to poor access to the experiment, the location of the barrier, and the long wavelength at which interferometry was made.

The magnetic barrier proved to be an efficient means of stopping and reflecting the output of the plasma gun. A 15 kG barrier reduced the magnetic

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[8] T. K. Allen, G. A. Paulikas, and R. V. Pyle, "Instability of a Positive Column in a Magnetic Field," *Phys. Rev. Letters* **5**, Nov. 1, 1960, 409-411.

loop signal at a point 20 cm beyond the barrier by as much as 90 percent. A typical set of magnetic loop signals obtained with a 10 kG barrier is shown in Fig. 10. The narrower incident plasma puff is on the left side of the trace, and the wider, reflected plasma is on the right side. The plasma was stopped at the barrier. The reflected plasma moving back toward the gun and interacting with itself to produce an increased signal can be seen at a position 53.6 cm from the gun. The reflected plasma moves back toward the gun with a velocity of less than 10 cm/μsec, compared to the incident velocity of 20 cm/μsec; or, the reflected plasma has about 25 percent of the directed energy of the incident plasma. As the plasma moved back toward the gun the loop signals from the reflected plasma increased in amplitude and in width, indicating that the energy density and total energy were also increasing. The maximum signals occurred about 30 cm from the muzzle. From this point on the loop signals decreased in amplitude and finally disappeared at a position 14 cm from the gun. At a position 33.6 cm from the gun the reflected pulse has a 20 percent greater amplitude and several times greater width than the incident puff. If an allowance is made for the normal loss of signal resulting from up to 60 cm of additional travel by the reflected plasma, then its amplitude is almost four times as large as one would expect. The reflected plasma, then, appears to interact with the plasma following it to convert some of its directed energy into transverse energy. This is in contrast to Jones and Miller[9] who in a quite similar experiment, at a lower field strength, report no change in the translational energy of the reflected plasma.

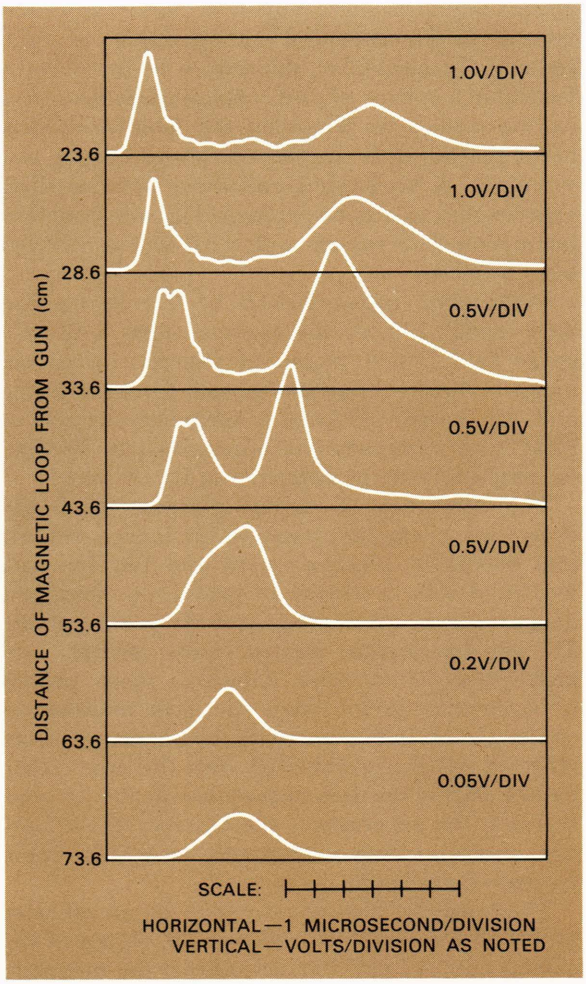

Fig. 10—Magnetic loop signals of hydrogen plasma with barrier field.

The question remains as to why the reflected pulse builds up to a maximum and then decays so quickly. There are two possibilities. One is that the reflected puff has run into cold gas just leaving the gun and dissipates its energy there. The second is that the plasma with such a high energy density develops an instability that quickly destroys it. Additional measurements are necessary closer to the gun with the present barrier and also with the barriers at different positions from the gun to clarify this problem. A second gated mirror near the gun, which permits the plasma to enter the guide field but reflects the returning plasma, is desirable. With a second barrier it may be possible to trap a high-energy plasma after several interactions with itself.

Summary and Conclusions

A small, fast, theta-pinch gun has been developed that uses the plasma heating and compression available in the standard theta-pinch as a means of improving plasma gun performance. The plasma is produced between two mirror-shaped pinch coils, each having an independent capacitor bank source. In the normal operating sequence, gas is pulsed into the region between the coils, and preionized by a low-energy 3 MHz discharge through the coils. It is compressed, heated, and ejected by the discharge of the main capacitors; the two fast banks are discharged simultaneously, while the discharge of the slower bank is adjusted to maximize the energy of the plasma output.

The gun produces a single high-β plasma puff whose characteristics are largely determined by the amount and distribution of gas within the coil region. Filling the region between the coils (≈ 50 cm^3) with gas results in a wide, slow, low-

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[9] W. B. Jones and R. D. Miller, "Generation and Motion of Plasmoids in a Magnetic Field with Mirrors," *Phys. Fluids* **11**, July 1968, 1550-1557.

energy puff that is most likely to oscillate in a "breathing mode." As the amount of gas is decreased, so that most of it is concentrated near the real coil, the puff becomes narrower, faster, and more energetic, and is more likely to develop an instability even while it is in the gun.

A typical energetic puff enters the B_z field with a trapped toroidal field of about 250 gauss and a trapped longitudinal field sufficient to exclude the plasma completely from the center of the puff. The plasma then is concentrated in an annulus 2.5 cm in radius, 1 cm thick, and about 6.5 cm long. The plasma also has an angular rotation imparted to it, while in the gun or during entry into the B_z field, that is in the same direction as the currents that exclude the B_z field and support the trapped field.

At a point 23.6 cm from the gun, the high-β component of the plasma has the following characteristics:

Average directed velocity—	up to 2×10^7 cm/sec (210 eV)
Average density	1 to $2 \times 10^{15}/\text{cm}^3$
Peak density	$5 \times 10^{15}/\text{cm}^3$
Average ion and electron temperature	35 eV
Rotational frequency	280 kHz
Total particles	3×10^{17}
Total energy (directed plus transverse)	20 J ($\approx 1\%$ of stored energy)
Impurity content	$\approx 1\%$

As the puff moves along the B_z field, the plasma increases in length, the trapped field decays, and plasma diffuses into the center and out to the wall. At the same time, the transverse energy density and the transverse energy drop almost exponentially; during the first 20 to 25 cm of travel the time constants of this decay are 0.7 and 1.2 μsec, respectively, but then increase to 2 and 5 μsec farther from the gun. The initial rate of loss can most likely be attributed to an instability produced by the high rotational speed of the plasma. The later loss of energy is due to a high, but uniform, diffusion of particles to the wall. There are no indications of a gross plasma instability at this time.

The average plasma density can be derived most easily from oscillations on the magnetic loop signals if they can be assumed to result from solid-body motion of the plasma. Extensive measurements demonstrated that the plasma puff did, in most cases, oscillate as a solid mass, particularly at the lower frequencies. Spectroscopy and far-infrared interferometry provided two additional independent measurements of the density and confirmed the results obtained from loop oscillations.

Absorption measurements at a wavelength of 337 μm can be interpreted to indicate that a small amount of dense ($n \geq 10^{16}/\text{cm}^3$) low-temperature plasma may follow very closely behind the main puff. The possibility that the observed absorption results from a lower density turbulent plasma in the tail cannot be ruled out at this time, however.

Furthermore, interference fringes observed at the 79 and 119 μm wavelengths later in the tail of the plasma show that a plasma of lower but unknown density is present. An axial discharge through the plasma in the tail of a fast puff produced significant flux compression and RF emission. The results are indicative of the presence of a hot, but low-density (10^{12} to $10^{13}/\text{cm}^3$) plasma being present.

Using only the rear coil of the theta-pinch gun provided a means of comparing the performance of the theta-pinch gun with a more conventional conical-pinch gun. The characteristics of the plasma from the two guns are very much alike; each produces a single diamagnetic puff with a trapped field. The theta-pinch gun, however, produces a plasma that is more than twice as energetic as the conical-pinch gun. This substantial increase in energy is obtained at the expense of a second coil having only 15 percent of the total stored energy. At present the output of the theta-pinch gun is limited by instabilities produced during the initial plasma compression and during the transition from the gun to the guide field. It is reasonable to assume that by proper redesign of the gun and the transition region, the energy output could be significantly increased.

A magnetic barrier proved to be a good means of stopping and reflecting the high-β puff. A 15 kG barrier in the normal guide field reduced the magnetic loop signals beyond it as much as 90 percent and reflected most of the plasma back toward the gun. The velocity of the reflected puff was approximately one-half its incident velocity. More significantly, the transverse energy of the reflected puff increased substantially above that of the incident puff. The results indicated that the plasma interacts with itself upon reflection to convert directed energy into the more useful transverse energy.

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