# Measurements on an Experimental Induction Plasma Accelerator

**DAVID B. MILLER**

**University of Michigan**
**Ann Arbor, Mich.**

**An experimental arrangement is described which electromagnetically generates and accelerates ionized gas by inductive coupling between the circuit and the gas. Measurements are made of energy coupled from the circuit to the plasma and of energy, momentum, and velocity of the accelerated gas. Energy on the order of 20 to 40 j is transferred to the plasma; this represents about 5 to 10% of the energy available for transfer, and $\frac{1}{3}$ to $\frac{1}{2}$ of this appears as energy of directed motion of the gas. The gas velocities measured 10 cm beyond the acceleration coil are in the range between $0.5 \times 10^4$ and $1.5 \times 10^4$ m/sec, whereas the corresponding momenta are from 2 to 11 gm-cm/sec-cm$^2$ of flow. High speed photographs of the radial compression of the plasma within the coil indicate that this radial compression is influential in determining the ultimate operating characteristics of this type of accelerator. Suggestions are made concerning improvement of efficiency.**

FOR MANY years studies have been made of systems in which energy is transferred from a circuit to an ionized gas by induction. An early description and analysis of continuously driven, induction, or electrodeless discharges was given by Thomson (1),[1] and the theory and use of such discharges have received frequent attention since Thomson's publication (2–4). Transient inductive discharges have recently been given considerable study in the controlled thermonuclear reaction effort as a means of both generating and containing a very high temperature plasma (5–8). In these experiments ionized gas is both heated and radially accelerated by the induced electromagnetic field within cylindrical coils.

By proper use of the field geometry in cylindrical coils, acceleration parallel with the coil axis, as well as in the radial direction, can be achieved. Thus, the induction geometry can be used as a plasma accelerator and therefore potentially as a plasma propulsion device.

Two basic types of induction accelerators have been studied. One form involves an array of coils which supports a moving field, or traveling electromagnetic wave; the velocity of propagation is generally caused to increase as the wave travels through the structure, and plasma within the coil array is swept along by this moving field. The operation is closely analogous to an induction electric motor. Thonemann, Cowhig, and Davenport (9) were perhaps the first to demonstrate motion of ionized gas within such a traveling wave structure; Marshall (10) studied a system of this form for injection into thermonuclear devices, and at the present time a number of laboratories are working on traveling wave devices for propulsion purposes.

The other basic form of induction accelerator involves the electromagnetic field generated by time-changing currents in a single coil; this is therefore a stationary field device, and axial acceleration depends on a fringing or diverging field shape being generated by the coil. Petschek and Janes (11) and Blackman (12) have described experiments in which shock waves have been produced by a single, circular coil, and Josephson (13) has briefly described a shock generating structure employing a several-turn, conically shaped coil. The theory of plasma acceleration by stationary fields has been developed by Morozov (14) and by Klein and Brueckner (15); in both instances the acceleration field was assumed to be generated by a circular (i.e., very short) coil. Bostick (16) was perhaps the first to suggest that these stationary field systems could be employed in the propulsion application.

The accelerator reported in this paper is of the stationary field, or single-coil, variety. The coil is single turn and cylindrical in shape. In choosing the ratio of length to diameter for this coil, a compromise had to be made between a very short coil (such as treated by Janes, Blackman, Morozov, and Klein and Brueckner), which yields a strongly diverging field shape but influences only a very small volume of gas, and a very long coil that encloses quite a bit of gas but would not present a strong radial magnetic field component to much of the gas. The 10-cm diam by 10 cm long coil employed in these experiments was felt to present a reasonable compromise between these two extremes.

Qualitative understanding of the operating principles of this accelerator can be gained by hypothesizing that ionized gas is present within the coil at zero time and letting the coil current begin to rise from zero at this instant. The electric field induced by the time changing magnetic field causes current to flow in the gas, especially on its surface, thereby preventing the magnetic field from penetrating into the ionized gas. The pressure due to the unbalanced external magnetic field then compresses the plasma. Since, however, this compression takes place in a diverging field geometry, compression is not uniform with axial position, a diverging nozzle is in effect created, and the net result is that the gas is forced axially out of the coil region.

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D. B. Miller, Member ARS, formerly Assistant Research Engineer, Plasma Engineering Laboratory, Electrical Engineering Dept., University of Michigan, is now Research Engineer, Missile and Space Vehicle Dept., General Electric Co., Philadelphia, Pa. Manuscript received Aug. 9, 1961. This work was supported by the Air Research and Development Command, USAF, under Contract No. AF 19(604)-4557.

[1] Numbers in parentheses indicate References at end of paper.

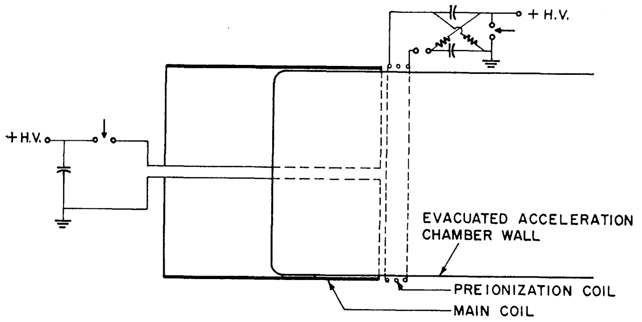

**Fig. 1** Cross-sectional view of stationary field induction accelerator

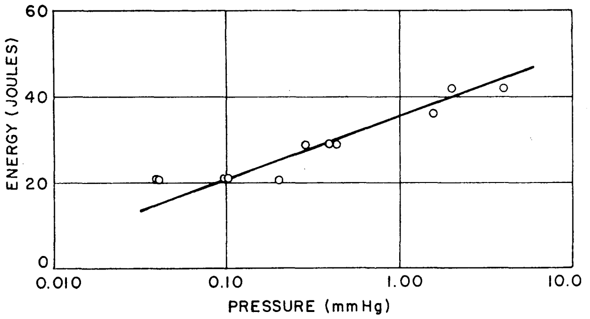

**Fig. 2** Energy transferred from the circuit to the plasma by the eleventh half cycle; helium

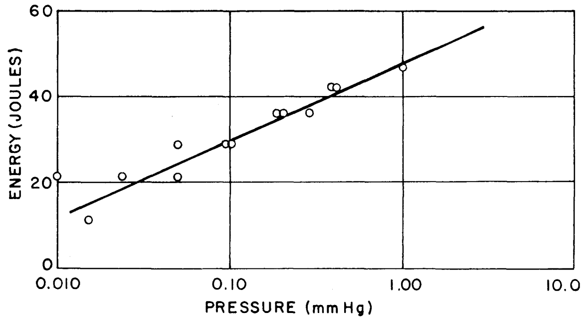

**Fig. 3** Energy transferred from the circuit to the plasma by the eleventh half cycle; argon

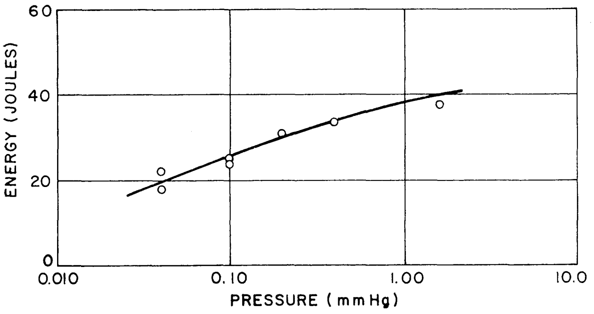

**Fig. 4** Total energy in the stream; helium

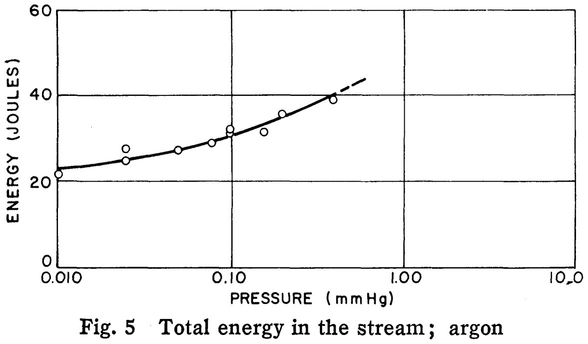

**Fig. 5** Total energy in the stream; argon

## Experimental Apparatus

The experimental coil is mounted over a cylindrical Pyrex vacuum chamber in such a manner that the end of the vacuum chamber is in the central plane of the coil, as shown in Fig. 1; by this geometry, complications due to acceleration in both directions out of the coil are avoided.

The coil is constructed of 0.022-in. copper sheet and is connected through a three-element, triggered spark gap to a 37.5 $\mu$f capacitor bank consisting of five G.E. Type 14F609 capacitors. The total circuit inductance is 0.128 $\mu$h, and the inductance of the coil is 0.0696 $\mu$h. All tests to be described were run at 9 kv charging voltage, which gives a maximum current of $1.06 \times 10^5$ amp. This current generates a vacuum magnetic field of 1.04 weber/m$^2$ at the center of the coil.

A three-turn preionization coil, located adjacent to the main coil (as shown in Fig. 1) and driven by a pair of 0.012 $\mu$f, 25 kv capacitors in a Marx doubling circuit, is used to initiate the ionization process at the beginning of each pulsing of the electrical system. The frequency of this preionization circuit is 1.56 Mc/sec.

The vacuum chamber can be evacuated down to about $5 \times 10^{-5}$ mm Hg. It was pumped down and refilled to the desired pressure with the test gas before each shot. In the experiments to be described, both helium and argon were employed, and successful operation of the accelerator (i.e., ionization of the gas) could be achieved for pressure above about $10^{-3}$ mm Hg.

## Experimental Results[2]

The experiments to be described can be divided into two parts. The first group comprises a series of independent but related measurements, which together allow calculation of an overall energy balance for the stationary field accelerator. Specifically, energy transferred from the circuit to the plasma, energy in the flowing plasma, and momentum and velocity of the plasma are measured; these latter two quantities together give energy of directed plasma motion. These three independently measured but related energies are then compared, and the extent to which they agree then indicates reliability of the several measurements. It should be emphasized that a set of independent measurements of this sort should, whenever possible, be performed when carrying on plasma accelerator diagnostics because of the inherent difficulties in executing any single measurement technique. In addition to the energy balance measurements, time resolved studies of the radial plasma motion are included.

The total energy transferred from the circuit to the plasma during a pulse is measured by comparing the transient capacitor voltage behavior with and without plasma. The capacitor voltage is a damped sinusoid, and plasma is created and accelerated out of the coil each half cycle. By comparing the capacitor voltage at the beginning of any half cycle with and without plasma, the energy that has gone from the circuit into the plasma can be calculated up to the instant of measurement. An R-C voltage divider across the capacitors was used with a Tektronix Type 541 oscilloscope, triggered from the same pulse that triggers the spark gap switch, to measure the capacitor voltage wave form. Although approximately 15 half cycles could, with care, be observed during a pulse, plasma was never observed beyond about the eighth half cycle. Consequently the comparison measurement was made at the beginning of the eleventh half cycle, since it was felt that negligible energy was transferred from the circuit to plasma after that time. The results of this energy measurement are shown in Figs. 2 and 3. Since, initially, energy in the amount of approximately 1500 j is stored in the capacitors but a maximum of only about 500 j of this appears in the field of the coil, it

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[2] These results have been selected from Ref. 17, which also includes additional experimental results and theoretical analysis pertaining to the induction accelerator.

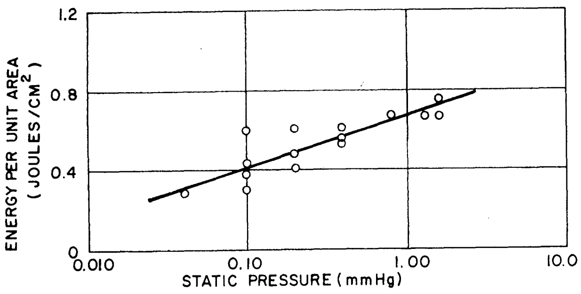

Fig. 6 Energy at center of stream; helium

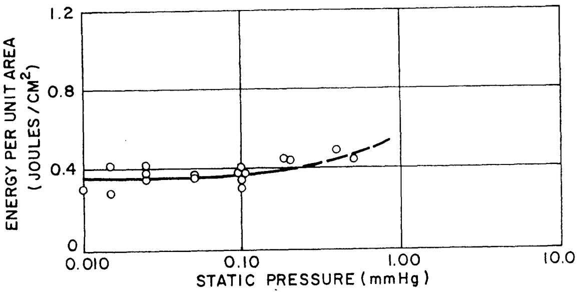

Fig. 7 Energy at center of stream; argon

can be said from Figs. 2 and 3 that something on the order of 5 to 10% of the available energy is transferred to the plasma.

Energy in the moving plasma stream is measured by means of a calorimetric collector that intercepts a portion of the stream. This calorimeter consists of a flat piece of 0.005-in. copper sheet that is mounted in the stream on an insulated support. Its temperature is measured by a thermocouple. By using a collector that samples on a diameter of the vacuum tube across substantially the entire stream, the total energy in the flow can be measured. The results of this total flow energy measurement, taken for a cross section of the stream 3.5 cm beyond the end of the coil, are shown in Figs. 4 and 5. Reasonably good agreement is obtained between these measurements of total energy in the stream and the previously described measurement of total energy transferred from the circuit (Figs. 2 and 3). Thus, it would appear that radiation from the plasma before it reaches the calorimeter and energy carried by particles that are reflected off the calorimeter are not significant in comparison with the stream energy that is transferred to the calorimeter.

The energy carried by the flowing plasma at the center of the stream can be measured by locating a small cross-section calorimeter on the axis of the accelerator tube. Measurements using such a calorimeter located 10 cm beyond the end of the coil give the experimental data shown in Figs. 6 and 7.

In order to compare the total stream energy with the energy in $z$-directed motion of the plasma, the results shown in Figs. 6 and 7 can be compared with velocity and momentum measurements, from which the energy in directed motion can be evaluated. Axial velocity of the gas is calculated from rotating mirror camera photographs of the shock wave that progresses down the accelerator tube each half cycle. A typical photograph from which calculations are made is shown in Fig. 8. The shock velocity is taken from the slope of the image at the point 10 cm out from the edge of the coil. (It should be noted that this point coincides with the bright area that is caused by the ballistic pendulum described below.) The gas velocity can be calculated from the shock velocity using the equations of mass, momentum, and energy continuity (18); strong shock conditions are assumed in these calculations. Experimental dependence of gas velocity (10 cm beyond the edge of the coil) on initial gas pressure is shown in Fig. 9. It should be noted from Fig. 8 that the shock and gas velocities are considerably higher at the edge of the coil than at the 10-cm station.

Simultaneously with velocity data described in the previous paragraph, momentum measurements were taken with a ballistic pendulum. This pendulum consists of a flat glass paddle the same size as the small calorimeter collector. It is suspended by a nylon arm so that its rest position is centered in the stream 10 cm beyond the edge of the coil. Momentum data taken with this pendulum are plotted in Figs. 10 and 11.

The velocity data (Fig. 9) and momentum data (Figs. 10 and 11) can now be combined in order to calculate the kinetic energy carried by the plasma due to its $z$-directed motion. The results of such calculations are shown in Fig. 12. Com-

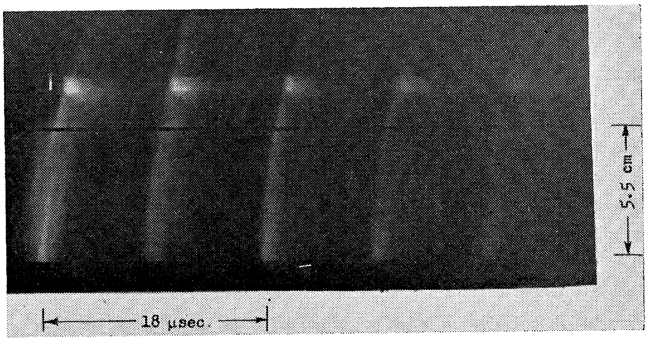

Fig. 8 Rotating mirror photograph viewing plasma through a narrow slit parallel with the flow; helium, 0.10 mm Hg

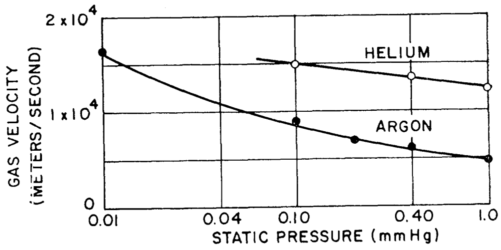

Fig. 9 Gas velocity calculated from shock velocity measurements in the induction accelerator

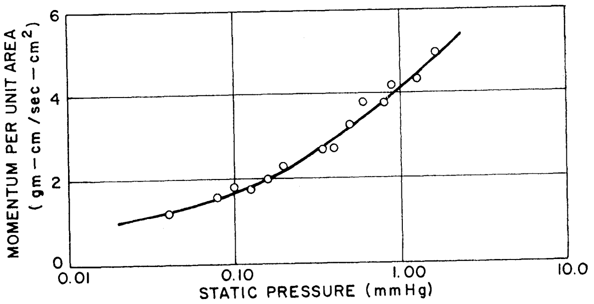

Fig. 10 Momentum carried by plasma at center of flow; helium

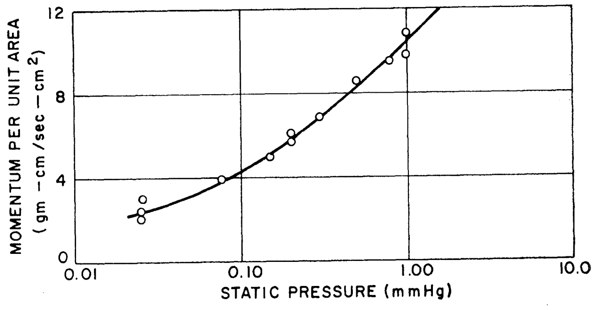

Fig. 11 Momentum carried by plasma at center of flow; argon

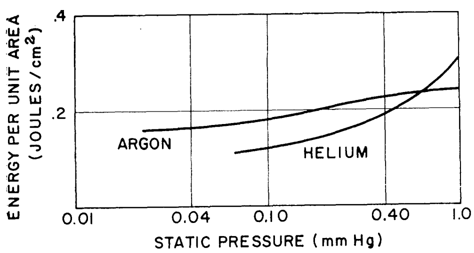

**Fig. 12** Energy in directed motion in the plasma stream; calculated from curves in Figs. 9–11

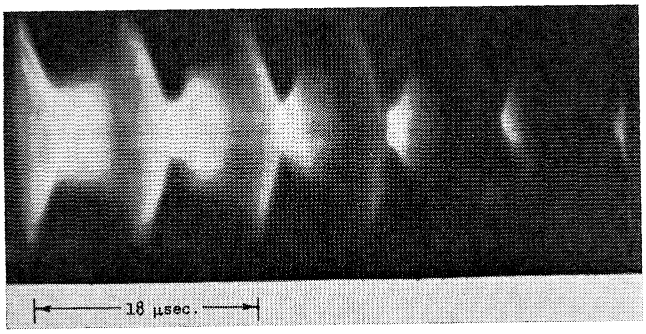

**Fig. 13** Rotating mirror photograph viewing plasma through a narrow slit transverse to the flow; argon, 0.20 mm Hg

parison of these curves with the total energy data presented in Figs. 6 and 7 indicates that the energy in directed motion is about half the total using argon and less than half for helium. It can be shown from the continuity equations that energies in thermal and directed motion behind a strong shock in helium and argon will be divided approximately equally. Thus, it appears that, in helium at least, a signicant amount of energy other than thermal energy and energy of directed motion is present; a likely form of this energy is ionization.

In order to verify the hypothesis that radial compression of the gas is an important factor in the operation of this accelerator, the rotating mirror camera was turned 90° so that streak photos of the radial plasma motion could be studied. A typical photograph for this camera orientation is shown in Fig. 13. The gas remaining within the coil is ionized and recompressed each half cycle, and a high degree of compression is achieved. The photo shown in Fig. 13 was taken viewing the plasma through a slit on the side of the acceleration chamber between the main and preionization coils (see Fig. 1). Photographic evidence of radial compression within the coil and as far as 5 cm out from the end of the coil has also been obtained, indicating roughly the volume of gas influenced by this compression process.

## Conclusions

The experiments reported in this paper indicate that ionized gas can be generated and accelerated by a stationary field induction system. The radial motion of the plasma within the coil has been shown to be an important operating characteristic of the system, and it is reasonable to state that this radial compression process is an important mechanism in the transfer of energy from the circuit to the plasma. The efficiency with which energy was transferred from the current to the plasma was generally low in these experiments. It is the belief of this author, however, that by proper coil shaping (e.g., using a tapered or cup-shaped coil so that the entire coil rather than just half of it can be filled with ionized gas) and by properly matching the frequency of the circuit with the compression rate of the plasma, efficiency can be increased significantly.

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