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H. Sahlin, G. McFarland, R. Barlett, and R. Gullickson

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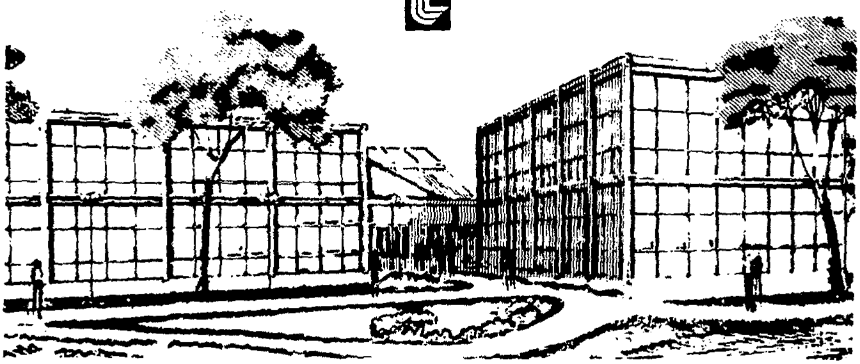

THE PLASMA FOCUS AS A PULSED POWER SOURCE*

H. Sahlin, G. McFarland, R. Bariet

University of California, Lawrence Livermore Laboratory
Livermore, California 94550

R. Gullickson

Air Force Ofc. of Scientific Research
Bolling AFB, Washington, D. C. 20332

ABSTRACT

The plasma focus is a remarkable natural phenomena that achieves significant space-time compression of both particle and field energy. Depending on the mode of operation, about 20% of the bank energy can be concentrated into the kinetic energy of a thin, dense, cylindrically convergent gas shell, or into a small-diameter, high-ν/γ relativistic electron burst and oppositely directed ion burst. The kinetic energy of the fast ions and electrons can exceed the applied voltage by a factor of greater than 100. The different modes of energy concentration by the plasma focus are presented and discussed both in terms of their role in the direct yield of the focus and for the case of a plasma focus supplemented by various fusionable targets.

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1. INTRODUCTION

The quest for pulsed fusion can be stated in the form of the "impossible problem": given *1 MJ of electrical* energy, by any means whatever obtain a DT fusion yield at least equal to this initial energy. Among the forms of pulsed power that have been suggested for driving fusion microexplosions are magnetic fields, lasers, relativistic electron beams, energetic ion beams, electromagnetic and electrostatic fields, and energetic microparticles. We will use the 1 MJ of allowed energy to charge a capacitor bank with a voltage, v, of ≥40 kV, where the bank in turn drives a plasma focus. We will show that many of the above forms of pulsed power may be produced with admirable efficiency, separately or in combination, by the plasma focus.

It is now well known that the attainment of net energy production from DT fusion at small energy input requires, in the case of inertial confinement, the use of convergent compression to super-solid density, $\rho r \geq 1$ g/cm^2, perhaps supplemented by tamping with a dense, relatively cold external shell.[1] For a tamped, inertially confined system with $\rho r < 1/4$ g/cm^2, a magnetic field strong enough to reduce conduction losses to the tamper must be present in the fuel. If the field is also required to couple burn-α's directly to the unburned fuel, then a product, Br, of 1 MG-cm is required, implying a current of 5 MA. A field of this strength is also capable of containing a solid-density cylinder of DT, 100 μm in diameter, at a fusion temperature of 10 keV, although for such a system the MHD instability time will not greatly exceed the inertial confinement time, and may be shorter than the few-ns burn time of such an uncompressed solid-density fiber.

The field coupling of burn α's is one example of the way in which strong fields may be employed to provide real-time feedback of the burn energy to drive the burning system. Other field-coupled direct-conversion modes are possible. The most straightforward example is field amplification by means of direct pdv work done by the expansion of the burn-heated fuel against the confining field.

Strong fields may also be employed to confine a plasma of less than solid density for a microinstability time, where the burn time is less than the microinstability or Bohm diffusion time. For such a system, either the density must be low enough for the microinstability time to be less than or equal to the MHD instability time, or a plasma configuration with intrinsic MHD stability must be employed. Two proposed systems are: (1) the implosion of a MHD-stable system to densities and temperatures resulting in burn times comparable to or less than Bohm-diffusion times,[2] and (2) the explosion of denser-field plasma systems to attain these same conditions.[3] The latter idea was suggested as an analogy to one of the several neutron-production modes of the plasma focus.

We have already noted that currents approaching 5 MA are desirable to facilitate direct burn-α coupling to a system having a ρr less than 1/4. A second reason for the desirability of a multi-MA current is provided by the unique current value of 1.5 to 3 MA, known as the Pease-Braginsky current.[4] For this current, a pinch after field penetration has equal and opposite classical-resistive-heating and bremsstrahlung-cooling rates, when the Bennett pinch relation, $B^2/8\pi = 2nkT$, is also satisfied. This current is nearly Z-independent; scaling is $Z/(Z + 1)$ for fully ionized high-Z plasmas. To the extent that a turbulent resistivity can be interpreted as giving rise to large-effective-Z scattering centers, this current should be insensitive to plasma turbulence.

On the other hand, Z^4 and Z^6 radiation rates, which are due to bound-free and bound-bound transitions of partially ionized impurities, destabilize the pinch toward a radiation collapse that will proceed to the point where energy demand exceeds energy supply, i.e., to the condition of exact impedance matching of the pinch to the power source. Similarly a system with initial current exceeding the Pease-Braginsky value should be unstable toward bremsstrahlung collapse until impedance match at the Pease-Braginsky current value is achieved.

Thus in the discussion to follow we will be interested in plasma foci with pinch currents of 3 to 5 MA. The attainment of this current requires a focus driven by at least a 1-MJ bank and, in addition, probably requires operation at a bank voltage approaching 100 kV.[5]

2. THE PLASMA FOCUS

In its simplest form, a "plasma focus" is a small-diameter coaxial gun with a length several times its diameter and a coax separation of several cm.[6,7] The inner coax is normally the anode, and the outer coax, the cathode, is often a relatively open structure, e.g., consisting of equally spaced, small-diameter rods arranged in a cylinder parallel to the axis of the system. The open cathode structure permits gas to flow radially. The coaxial electrodes are separated at the gun breach by a cylindrical insulating sleeve of high melting temperature, such as Al_2O_3, that fits tightly around the anode and extends for several cm along this inner coax. The system is normally operated at a deuterium fill-gas pressure of from 1 to 20 Torr.

When the bank voltage is applied across the electrodes, a discharge forms between the electrodes, and across the surface of the insulator, and the resultant current sheet becomes the outer coaxial current of an inverse pinch. The magnetic pressure of this pinch lifts the current sheet from the insulator and drives it supersonically down the gun barrel at a velocity equal to the Alfvén velocity of the downstream fill gas $v = B/\sqrt{4\pi n_0 m}$, snowplowing the fill gas ahead of it. The thickness of the snowplow is a few mm, and this plasma piston is heated by the stagnation energy of the downstream fill gas and by resistive heating, and is cooled by bremsstrahlung and by dynamic gas flow parallel to the surface of the snowplowed plasma. Recent measurements show that the electron and ion temperatures of the snowplow tend to be of the order of 100 eV prior to denser pinch formation.[8]

When the current-sheet-driven snowplow reaches the end of the anode, terminating the so-called rundown phase, most of the "plasma foil"-snowplowed piston developed during rundown is fired off the end of the barrel in the Z direction. Because the mechanical support provided by the anode is no longer present, the magnetic pressure drives the current sheet in a cylindrically convergent collapse toward the axis and the snowplow in this collapse phase is supplied by the fill gas of the end of the gun. The resulting pinch still possesses significant axial gas flow and differs in this unique respect from a conventional Z pinch. Only about 20% of the gas in the collapse region is contained in the dense pinch formed by stagnation of the snowplow on-axis.[9]

Rundown and Early Collapse

During the rundown and early collapse, the energy driving the system is provided by the capacitor bank, and a well-designed system should have an effective quarter-cycle time corresponding to the slower phase of snowplow motion. During this effective quarter-cycle period, half of the bank energy will be stored inductively in the bank-gun system behind the current sheet and half of the energy will go into particle degrees of freedom. Twenty-five percent of the bank energy is present as directed plasma motion and 25% as thermal energy of the plasma, most of which is radiated away as bremsstrahlung or carried away as thermal energy of the gas flow parallel to the current sheet.

The gas dynamic flow also removes a portion of the ordered particle energy, but as a result permits a greater degree of convergent compression. Since virtually none of the rundown/snowplow particle energy is present at final pinch formation due to the gas dynamic flow parallel to the current sheet, the mechanical energy that stagnates on-axis may contain as little as 5% of the bank energy, and normally involves about 20% of the fill gas swept up during the collapse phase.

Final, Rapid Collapse

At the onset of final rapid collapse, the effective quarter-cycle time of the bank/snowplow/gas system should be reached and the half of the bank energy that goes into the field energy should be stored inductively. The ratio of the gun-pinch inductance to the bank inductance at this point should be 1/5 to 1/10, so that the inductive energy is stored primarily in the gun and concentrated around the developing pinch. During the phase of rapid collapse the cycle is driven by its own inductive energy, and just prior to pinch formation the convergently compressed snowplow plasma foil can reach velocities of from 1×10^7 to 5×10^7 cm/s and the snowplow front can begin to run away from the current sheet that drives the snowplowed plasma.[10]

Plasma-Focus Guns

A variety of plasma-focus guns are employed in practice. The Mather gun, which we have used implicitly in the foregoing discussion, is characterized by an anode with a length (ℓ) that can be several times the gun diameter (d). At the opposite extreme from the rundown-dominated Mather geometry is the collapse-phase-dominated Filippov geometry for which d is several times ℓ. Practically all work to date in the Filippov geometry has been performed in a Filippov gun with a solid cathode spaced about 10 cm above the anode rather than a more-open cathode structure that would facilitate the natural gas dynamic flow parallel to the snowplow surface.[11] In between these two extremes lies the Conrad gun, with $\ell \approx d$, where the insulator may often extend for the entire gun length. Conrad guns employ[12] an open region off the end of the anode similar to that of the Mather geometry.

Effect of Operating Conditions

The plasma focus is in first approximation a gun-independent phenomena that nonetheless exhibits significant gun-dependent features.

Two modes of operation of the plasma focus are of interest for our present purpose: (1) the so-called "high-density mode" that we have been discussing, which leads to a dense pinch plasma "wire" on-axis as a result of the convergent compression of the snowplow plasma foil, and (2) the low-density mode, which produces concentrated electron and ion bursts.

For the high-density mode the field diffusion into the snowplowed plasma is slow, and as a result the dense, field-free snowplowed plasma precedes the current sheet and its field into dense pinch formation. By lowering the gas pressure, one can make the field penetration of the snowplow take place prior to dense pinch formation and thus make the field-collapse precede the plasma shell as the axis is approached, resulting in a system similar to a plasma-filled relativistic-electron-beam diode;[13] the induced axial voltage due to the collapsing electromagnetic front can result in relativistic-electron-burst formation on-axis, and also to significant axial ion acceleration.

In the low-density mode of operation the plasma-foil current sheet plays the role of a switch for the inductive energy stored behind it. A sudden change in resistivity due to the onset of strong plasma turbulence as the plasma foil approaches the axis transforms the plasma piston from a state that is relatively opaque to the magnetic field into a state that is highly transparent to the field energy. Thus a slow build up of inductance energy is followed by a rapid release of this energy. This E-beam-like mode and its associated high-ν/γ electron and energetic-ion burst will be discussed in the next section.

In addition to the pressure dependence of the focus phenomena, the addition of a small percentage of high-Z impurities (particularly in the form of inert gas, because it is not absorbed by the chamber walls) can significantly alter the focus behavior by increasing the radiative-cooling rate of the snowplowed plasma.

Gun-Dependent Phenomena

Gun-dependent behavior of the focus arises from the gun geometry, the degree of openness of the cathode, and the structure and material of the anode center. It is now known that the results obtained from a hollow-anode gun can differ significantly from a gun with a hollow anode center, and that for a solid anode center, the shape as well as the material employed can play an important role in the exact nature of the plasma focus produced by the gun.

In the past, these gun- and operating-condition dependent aspects of the plasma focus have resulted in considerable confusion in trying to obtain a consistent picture from the results of different experimental groups. The situation has been clarified considerably, and it is now possible to provide a reasonably consistent picture for the entire range of experimental phenomena observed at various centers of plasma-focus experimental research.

3. MECHANISMS FOR NEUTRON YIELD OF THE PLASMA FOCUS

At the present time it is possible to identify at least five different relatively distinct neutron-producing mechanisms in the plasma focus. These different sources of yield exhibit scaling (with bank energy E or peak current I) as E^{α} and I^{β}, where $\beta = 3$, 4, and 5, and $\alpha = 1.5$, 2, and 2.5. The mechanisms to be considered are:

1) Stagnation yield, scaling as E^2 or I^4.

2) Current-restrike heating, scaling as E^2 or I^4.

3) Beam/cold-target yield, scaling as $E^{1.5}$ or I^3.

4) Beam/hot-target yield, scaling as $E^{2.5}$ or I^5.

5) Deflagration burn, scaling as $E^{2.5}$ or I^5.

Each of these mechanisms can be emphasized or suppressed, depending on the gun and operating conditions, and each can serve as the basis of an interesting pulsed power source useful for driving appropriately designed fusion microexplosion targets.

Stagnation Yield

The most straightforward of the yield-producing mechanisms is the stagnation yield, which occurs due to compression and heating as the current-driven plasma shell stagnates by convergent self-collision to form a dense pinch. The axial dense-pinch, or "plasma wire," normally has a density (n) in the range of 3×10^{19} to 3×10^{20}, a diameter (d) of ≤ 0.2 cm, and a stagnation temperature of about 1 keV. The plasma stem persists in a relatively stable form for an effective MHD time $\tau = (r/v)f$, where r is the pinch radius, v equals $(\pi \times 10^7)\sqrt{T}$ (where v is the thermal velocity of the deuteron plasma and T is the absolute temperature of the plasma in keV), and f is a factor (with value $f = 5$) that brings the theoretical MHD time, $\tau = r/v$, into agreement with the experimentally observed value of $\tau = 10$ ns.

Since the ion equilibration time at stagnation is about 10^{-10} s, the stagnation yield should be of a relatively thermonuclear character. The yield due to this mechanism is negligible in the rundown-dominated Mather geometry but accounts for about 10% of the neutron yield in the collapse-dominated Filippov geometry.

Since the neutron yield Y is for a DT system as given by $Y = Nn\tau\langle\sigma v\rangle/4$, where N is the total number of ions in the pinch, n is the ion density, $\langle\sigma v\rangle$ is the Maxwell average-cross-section, and τ is the confinement time, we conclude that the stagnation yield is proportional to $N^2/\pi R^2 \ell$, where R and ℓ are the pinch radius and length respectively. Since the thermal energy, E_H, is $(4.8 \times 10^{-16})NT$ joules, and this energy is proportional to the inductive energy of the system, the stagnation yield should scale as the peak current I^4 or as E^2, where E is the bank energy.

The confinement time τ is inversely proportional to $\sqrt{T}$, while $\langle\sigma v\rangle$ rises sharply with T at 1 keV, and thus an increase in the stagnation temperature by a factor of two can increase the DT stagnation yield by about 30. The stagnation DT yield of a 1-MJ Filippov system should be more than 10^{14} neutrons (300 J) and be equal to 0.03% of the bank energy or about 0.15% of the snowplow kinetic energy, which in a 1-MJ Filippov system might approach 1×10^5 to 2×10^5 J, or 10 to 20% of the bank energy. Because of the temperature sensitivity, MHD calculations show that a breakeven stagnation yield could occur at the 100-MA level, corresponding to a plasma focus driven by a bank energy of about 400 MJ.[14]

Viewed as a pulsed power source, the convergent plasma shell with a thickness of 0.2 cm and velocity of 2×10^7 to 5×10^7 cm/s could have a total kinetic energy of 100 to 200 kJ and thus have a stagnation time, τ, of 4×10^{-9} to 10^{-8} s, a stagnation energy of $>10^{13}$ W, and a stagnation energy flux $>10^{12}$ W/cm^2. Such a stagnating plasma shell could provide an interesting pulsed power source for driving targets of the type recently suggested by Basov, Krokhin, and collaborators.[15]

If the stagnation of the plasma shell against a target induces the development of a turbulent resistivity due for example to radiation cooling of the electron thermal velocity relative to the drift velocity of the electrons, then about 50% of the inductive energy stored behind the snowplow can also be delivered to the target in a time τ of 10 to 25 ns, and thus under such optimal conditions nearly 50% of the bank energy can be employed to drive the microexplosion in the form of axial cylindrical or spherical targets, and the power could approach 2.5×10^{13} to 5×10^{13} W at an energy flux of 10^{13} W/cm^2. High-voltage operation will tend to increase the inductive storage relative to the stagnation energy, while operation of a focus with a low-voltage bank should have the inverse effect.

Current-Restrike Heating

Toward the end of the 10-ns stable-dense-pinch period, $m = 0$ instabilities can become pronounced, causing a local $I\dot{L}$ voltage that can accelerate electrons to a drift velocity exceeding the thermal velocity, and thus cause the amplification of Langmuir turbulence. Because of the 1-keV ion temperature, ion damping will not inhibit the growth of these space-charge waves until they reach an amplitude that significantly affects the resistance of the plasma wire. Laser scattering and other measurements indicate an increase in resistance by a factor of 100 to 1000 in a dozen inverse plasma periods, and thus the $m = 0$ instabilities can trigger a very abrupt decrease in the current due to the resulting turbulent resistivity. This has the consequence that the field diffuses rapidly into the plasma wire, heating it toward an explosive state while, at the same time, large axial fields are induced that will act to restrike the current on-axis as an energetic electron beam and will also accelerate ions in the opposite direction. The so-called repinch reported in many previous focus studies may in fact actually be sudden axial heating due to this restrike current, an interpretation suggested by the most recent measurements.[16]

The axial heating of the plasma pinch due to restrike on-axis causes a "relatively thermonuclear" contribution to the yield that should scale as I^4.

Beam/Hot-Target and Beam/Cold-Target Yields

In addition, accelerated ions colliding with the hot, relatively dense plasma targets will produce a beam/hot-target yield that scales as I^5. The sum of the reheating thermonuclear yield and the beam/hot-target yield are responsible for something like 10% of the neutron yield in both the Filippov and Mather geometries although the two effects cannot be fully disentangled from available experimental measurements.

The range of the ions accelerated because of the axial restrike can be greater than the length of the dense pinch, and thus a beam/cold-target contribution arises from the collision of the accelerated ions with the low-density fill gas beyond the end of the focus pinch. The accelerated ions also create a plasma due to charge exchange with the background gas that is dominated by ions in the 10- to 14-keV range near the peak of the charge-exchange cross section. It is interesting to note that this process should also result in the production of a relatively directed beam of neutrals.

The yield for the Mather geometry is dominated by this beam/cold-target mechanism that should exhibit I^3 scaling, while the contribution from the beam/cold-target mechanism in the Filippov geometry is small, resulting in perhaps 10% of the yield. It is worth noting that Mather geometry studies reported recently by Bernard show a $E^{1.7}$ or $I^{3.3}$ scaling,[17] where E is the bank energy and I is the pinch current.

The small contribution of the beam/cold-target yield in the Filippov geometry may be an artifact resulting from the use of closed cathodes that tend to inhibit the natural axial gas dynamic flow. If this is the case, a large beam/cold-target contribution would result in the Filippov geometry if the cathode were a more open structure or were spaced a greater distance above the anode. The large axial ion burst produced in the Conrad geometry tends to support this point of view.

Deflagration Burn

Experimental studies of the dense-plasma-pinch explosion indicate that in addition to being triggered by $m = 0$ instabilities, the plasma wire tends to disintegrate first near the anode. This is probably due both to the fact that the pinch develops first at the anode and that the anode center can be a source of high-Z impurities that can enhance radiative cooling and thus act to introduce a turbulent state by cooling the electron thermal velocity below the drift velocity that is at the same time tending to be increased by induced voltage due to $I\dot{L}$ of the pinch, and to increase classical resistivity, which varies as $T^{3/2}$ and increases as a result of radiation cooling.

Due to both the restrike heating and heating by the magnetic-field energy that diffuses into the plasma, the dense pinch rapidly explodes to a density a factor of 100 lower than that of the dense pinch, to a diameter of 0.5 to 1 cm, and at the same time the plasma temperature of 10 to 20 keV is produced. During this process, about 50% of the inductive energy or 25% of the bank energy can be transformed into particle energy in the form of ion and electron acceleration, and plasma heating. In high-density-mode operation with a closed-cathode Filippov gun, plasma heating is dominant over particle acceleration, and the heated lower-density plasma is transiently contained for a microinstability time or Bohm diffusion time.

We have shown previously[18] that the yield in this case will tend to scale as $Y = 10^{21}(fE_b)^{2.5}(F(T)/(T^3 \ell r)) \propto I^5$, where T is the temperature in keV, r is the pinch radius in cm, ℓ is the pinch length in cm, f is the fraction of the bank energy that goes first into inductive energy and then subsequently into plasma heating ($f_{ideal} \rightarrow 1/4$, $f_{experimental} \rightarrow 1/8$), E_b is the bank energy in MJ, and where the Maxwell average-cross-section $\langle\sigma v\rangle$ has been expressed in the form F(T) 10^{-16}. The optimum value of $F(T)/T^3$ occurs at about 8 keV.

The I^5 scaling in this case arises because: (1) as for the stagnation yield, the Nn product in the expression for thermonuclear neutron yield is proportional to I^4, and (2) the Bohm diffusion confinement time is proportional to R^2B/T, and B = 0.2 I/R (for I in amperes), thus introducing an additional factor of I. This deflagration-burn scaling law predicts a DT-burn yield (for E_b = 1 MJ and = 1/8) of 28,000 J and implies that breakeven could result for a bank energy as low as 25 MJ. This I^5 deflagration-burn yield is dominant in high-pressure mode, closed-cathode Filippov geometry, contributing about 70% of the total neutron yield, while in the Mather geometry it accounts for only about 10% of the total neutron yield.

It is important to note that for fixed bank energy the parameter available for increasing the yield is primarily the rℓ product. If this product could be reduced by a factor of 100, then breakeven at the 1-MJ level might be obtainable. In effect the operation of a plasma focus in the low-pressure mode enhances the efficiency of conversion of the 50% of the inductive energy that goes into electron and ion acceleration relative to that that goes into plasma heating.

Thus by low-pressure operation, one can approach 25% conversion of the bank energy into electron and ion burst production, and for such low-pressure operation the accelerated ions become strongly concentrated in a small-angle cone along the axis.[18,19] By appropriately configuring the anode center, one can vary the fraction of the energy going into ion acceleration relative to that going into electron acceleration substantially from that specified by the simple space-charge-limited condition: $I_i = (m_e/m_i)^{\frac{1}{2}} I_e$, where I_i is the ion current, I_e is the electron current, m_i is the mass of the ion, and m_e is the mass of the electron.

4. LOW-DENSITY-MODE OPERATION

In low-density-mode operation of the plasma focus, electron and ion acceleration are optimized, and as much as 25% of the bank energy can go into production of short rise-time ($\tau < 0.1$ ns), high-current ($I = I_{pinch}$), small-diameter ($d \leq 0.1$ cm) electron and an ion beams, with particle energy exceeding the applied voltage by a factor of at least 100.

In this mode of operation the plasma focus becomes a natural, self-regulating, miniature plasma-filled diode, similar in some respects to diodes described in recent work on relativistic electron-beam machines.[13]

The primary difference between low-density-mode (LDM) and high-density-mode (HDM) operation is that in the HDM the current interruption occurs after dense pinch formation, while in the LDM it occurs before pinch formation. Thus for LDM operation the magnetic field collapses into a low-density plasma having the density of the fill gas, while in the HDM the field undergoes anomalous diffusion into the stem of the dense plasma pinch.

It is helpful conceptually to think of the behavior of the HDM as analogous to the current-interruption and subsequent restrike of an exploding wire, where the dense plasma pinch of the focus plays the role of a plasma wire. In the case of the LDM, the current-sheet-driven snowplow enters the rapid-pinch phase as a plasma shell, and the current interruption and subsequent restrike on-axis are similar in a number of respects to effects in experiments with gas-filled exploding tubes.[20]

A number of important differences exist between the exploding-plasma-wire and exploding-plasma-shell modes of the plasma focus and the analogous conventional exploding-wire and exploding-tube experiments. First, the transfer of capacitive energy to inductive energy is complete prior to the explosion phase in the plasma focus, and thus the current restrike is driven entirely by the fast storage of inductive energy rather than by the bank voltage typical of the case of conventional exploding wire. This has the consequence that the current restrike in the plasma focus is a high-ν/γ relativistic electron beam rather than an ultrahigh-ν/γ nonrelativistic current like that existing prior to current interruption.

The primary virtue of high-ν/γ relativistic electron beams over ultrahigh-ν/γ nonrelativistic currents is that relativistic electrons can more readily penetrate into a region of space where no currents existed initially, and if the field of the high-ν/γ beam is also able to penetrate into the new region then one achieves in effect a very fast switch of field energy into an initially field-free region where, for example, one might wish to place a fusionable target. The price paid for the nonrelativistic current interruption and relativistic restrike in the focus is that 50% of the initial bank energy goes into directed plasma motion and plasma heating, and thus the inductive energy of the pinch is only 50% of the initial capacitor-bank energy.

Current-Interruption and Turbulence

The current-interruption in the case of the plasma focus is due to the development of strong turbulence because of a cross-over in the electron thermal and drift velocities, and, in the case of highly symmetric development of the turbulence, the resistivity can change by two or three orders of magnitude in about 12 inverse plasma periods, resulting in current interruption in 0.1 ns or less. For asymmetric turbulence nucleation, the current-interruption time can become a nanosecond or more (the time required for development of turbulence at a point to spread to the entire cross section of the plasma wire or cylindrical shell structure).

A high-power pulsed CO_2 laser could be employed to advantage in this process, since the laser could be used to nucleate symmetric turbulence at a desired location and time. Experiments indicate[21] that a CO_2-laser pulse of greater than 100 J in a time less than 100 ns approaches the magnitude required to trigger the turbulence, and that 1- to 10-kJ pulses in ≤20 ns might be particularly effective for this purpose.

The onset of the state of strong turbulence can result either from (1) the acceleration of the electrons carrying the current to a drift velocity greater than their thermal velocity due to induced voltage arising from pinching, or by $m = 0$ instabilities that reach values large enough to cause electron runaway, or (2) by cooling of the electron thermal velocity below the drift velocity, e.g., by enhanced radiation losses due to the presence of high-Z impurity atoms. Since the turbulence in turn may act to enhance the high-Z radiation rate in a dense plasma, the cooling process could be quite rapid and the energy required to increase the ionization state of high-Z impurities might also contribute to the cooling process.[22]

Experiments indicate that the current interruption tends to occur in LDM operation at the anode and at the location of $m = 0$ instabilities. The interruption at the anode is probably a result of: (1) high-Z ions from the anode surface that can cool the electron drift velocity and (2) the fact that the pinching occurs first at the anode surface.

Production of Electron and Ion Bursts

To provide a simple model of the production of the electron and ion burst, we assume that the current interruption takes place over a cylindrical shell of length $\Delta\ell$, and as a result the field diffuses rapidly through this portion of the shell to enter the low-density plasma inside the collapsing plasma shell. The velocity of collapse of the plasma shell near the axis is 1×10^7 to 5×10^7 cm/sec, and the experimental average rate of field diffusion toward the axis of the system after current interruption is at least a factor 10 greater ($v = 5 \times 10^8$).

This rapid collapse of magnetic flux upon current interruption induces a large axial voltage across the length $\Delta\ell$, and at the same time the flux transport through the plasma shell causes the shell to rapidly heat and explode. The outer half of the shell proceeds outward into the field, while the inner half proceeds inward toward the axis at a velocity less than that of the field front. Thus a natural plasma-filled diode develops, where the anode of this diode is the focus anode and the cathode is the unemploded end of the plasma-shell snowplow.

In a large plasma focus, the current prior to interruption can be several MA and the plasma density on-axis for LDM operation may be 10^{16} to 10^{17} ion/cm^3. The induced voltage will cause the plasma cathode to emit a hollow, cylindrical electron beam. The Alfvén limiting current (I) for such a beam is $1.7 \times 10^4\ \beta\gamma R/\Delta$, where $\beta = v/c$, $\gamma = 1/\sqrt{1 - \beta^2}$, R is the beam radius, and $\Delta \geq c/\omega_p$, where c is the speed of light, ω_p is the electron plasma frequency, and v is the electron drift velocity. For $n = 10^{16}$, where n is the electron density on-axis, Δ is 5.3×10^{-3}; and if $R = 0.1$, then $I = 3 \times 10^5\ \beta\gamma$, and thus restrike of a current of several MA is not possible unless $\beta\gamma$ becomes 1 or more.

The beam emitted from the plasma cathode will have a high ν/γ, e.g., $\nu/\gamma = 100$, and thus will collapse due to its self-magnetic-field in a distance d, where $R/d = \nu/\gamma$. Consequently the beam emitted from plasma cathode will self-pinch to the axis, forming a virtual cathode, and because of this self-magnetic insulation effect the ions in the natural plasma diode will be accelerated and can achieve a current substantially greater than $I_i = (m_e/m_i)^{\frac{1}{2}} I_e$. The ion acceleration will continue until the ions in the anode plasma are sufficiently depleted to produce a radial electric field strong enough to compensate for the self-field of the high-ν/γ electron beam, permitting it to propagate to the anode and achieve restrike of the current as a relativistic electron burst. The explosion of the plasma shell simultaneously proceeds to higher Z causing the distance between the anode and the plasma cathode to grow with time and results in both a continuous depletion of ions and a source of relativistic electrons.

The natural plasma diode differs from that of a conventional relativistic-electron-beam-machine diode in that it is much smaller and thus can produce shorter and smaller-diameter electron bursts. It also differs from a plasma-filled diode in the unique fashion that the distance between the plasma cathode and the focus anode grows with time rather than decreasing. The growth of the anode/virtual-cathode gap due to sequential explosion of the plasma shell could result in continuous acceleration of ions away from the anode. At present, the rate of propagation of the virtual cathode away from the plasma-focus anode due to progressive explosion of the plasma shell cannot be judged from existing experiments, and 2-D computer simulation is essential to follow the complex detail of the natural plasma diode. Experimental measurements indicate that most of the ions inside the pinch region can be accelerated to an energy of 300 keV to 1 MeV for 18-kV operation of a plasma focus and a fraction of the order of 10^{-3} of the accelerated ions can reach an energy of 5 MeV,[23] or 220 times the applied voltage.

Ion Acceleration versus Electron Acceleration

From recent results of Nardi et al.[24] it may be concluded that operation of a focus with a hollow anode favors ion acceleration over electron acceleration, presumably because the fill gas inside the anode provides a nondepletable ion source. For the case of very-low-pressure operation the ion current in the diode can probably be held down to the fraction $\sqrt{m_e/m_i}$ of the electron current, and thus 25% of the bank energy and 50% of the inductive energy can go into production of the small-diameter relativistic electron burst, while for the case of higher pressure and a hollow anode a major fraction of this 25% bank-energy fraction might go into ion acceleration.

Further experiments are required to determine the range of ratios of accelerated-ion energy to accelerated-electron energy that are possible in the natural-plasma-focus based plasma-filled diode. If the ratio of the energy of the accelerated ions to the applied potential proves to be ≥25 for higher-voltage plasma-focus operation, then it will be possible to produce substantial bursts of multi-MeV ions for 50- to 100-kV plasma-focus operation and the resulting ion source or a convergent array of such ion sources becomes an excellent candidate for ion implosion of pellets, which appears possible at powers as low as 30 TW, and the power required for target implosion with multi-MeV protons can probably be reduced as low as 1 TW.

5. APPLICATION OF THE PLASMA FOCUS TO PULSED FUSION

We will consider here in simple terms several of the applications in which a plasma focus at the 1-MJ level might be used to drive fusion microexplosions.

The coupling of an intense energy flux to a target is so complex that sophisticated computer calculations (supplemented by experiments, to normalize the codes) are required for the detailed study of microexplosion targets. However, a number of one-dimensional parameter studies of simple targets driven by laser, electron-beam, ion, and magnetic-field pulsed-power sources have been reported,[25] and the results of these studies can be used to supplement back-of-the-envelope calculations, to permit us to make reasonably realistic estimates of the parameters to be used for particular target concepts.

In making such estimates, one must avoid gross violation of several "rules of thumb" that arise from two-dimensional considerations, such as the development of Taylor instabilities.[26] The relevant conventional wisdom dictates that a convergence ratio of greater than 30, i.e., a cylindrical compression greater than 900 or a spherical compression greater than 2.7×10^4, is to be avoided, since efforts to exceed such a value are likely to be frustrated by inevitable imperfections in the target and the uniformity of the pulsed power source. A second practical constraint dictates that, to avoid catastrophic Taylor-instability problems during the acceleration phase of an implosion, the distance R over which a material of thickness ΔR is accelerated should be limited to the range $0.2 \geq (\Delta R/R) \geq 0.1$.

While these rules of thumb should be taken seriously, they should not be taken <u>too</u> seriously until they have been adequately subjected to experimental test, and it is worth noting that a multi-kJ plasma focus with Filippov geometry substantially violates both the convergence and $\Delta R/R$ constraints in the course of its normal operation. Serious suggestions have been published to the effect that $\Delta R/R$ values as small as 0.01 may be viable.[15,27]

The several target concepts for the plasma focus to be outlined in this section have been chosen by supplementing back-of-the-envelope calculations with the published results of 1-D parameter studies and keeping in mind the convergence and $\Delta R/R$, 2-D constraints. Our purpose here is to illustrate several classes of ideas rather than to provide specific target-design details. Specific computational studies of certain of the targets are in progress, in preparation for experimental tests. However we feel that the back-of-the-envelope approach, combined with input from published 1-D parameter studies and the use of realistic 2-D constraints, can produce useful values for target parameters, despite the present limited understanding of the physics of high-energy-density plasmas.

To our knowledge no present target computation incorporates the effects of net charge and charge separation that we believe could have a significant bearing on target implosion. Also to our knowledge no existing computer code can presently calculate strong-field-coupled propagating burn, and there exists no adequate numerical treatment of strong turbulence that can serve as a basis for self-consistent computation of transport coefficients, although an interesting and apparently effective approach to weak and intermediate turbulence has been evolved by N. Krall and collaborators,[28] and by R. Davidson and collaborators.[29] The effect of strong turbulence on high-Z bound-bound and bound-free radiation has been universally ignored. This point was brought to our attention by Arno Steiger.[30]

We suspect that the strong turbulence effect of Langmuir collapse will tend to nucleate at the position of high-Z impurities in a low-Z plasma. If this proves to be the case, it will result in the partially ionized high-Z atom being subjected simultaneously to both the strong electron flux that can excite levels and to the strong high-frequency fields that can Stark-broaden the levels, i.e., enhance the rate of spontaneous decay. We emphasize this possibility because most of the problems of low-density approaches to fusion are reduced or rendered inoperative in high-density inertial-confinement schemes. However, radiation loss due to high-Z impurities is one problem that might be greater at high density than at low density due to the potential enhancement of radiation losses due to plasma turbulence. At present, adequate theoretical models for treating this question have not been developed.

Deflagration Burn

We have already pointed out that the stagnation energy of the HDM plasma-focus current sheet, supplemented by rapid delivery of field energy due to turbulent diffusion, could be of interest in conjunction with targets proposed by Basov et al.[15] In a previous publication[3] we have presented a target concept consisting of a spherical shell about 1/2 cm in radius, an axial fuel rod of diameter 0.02 cm, and DT or other fill gas at a pressure 1 Torr to perhaps 100 Torr. This type of target is intended for mounting at the anode center with the fuel rod contained by the shell aligned with the axis of the focus. The collapsing-current-sheet-driven snowplow of the focus forms around the spherical shell, and the focus forms on-axis just beyond the target. The stagnation of the current sheet will initiate implosion of the shell (if it is thin enough) and, by LDM operation upon focus formation, an intense axial electron burst strikes the target, penetrates the shell, and propagates along the rod, inducing a return current back along the relativistic electron path so that initially no field is present in the sphere.

By appropriate choice of gas pressure the return current can be caused to drive Langmuir turbulence, initiating the Weible instability that will cause expulsion of the return current in the form of filaments to the inside-surface-imploding spherical shell. This results in rapid transport of the field into the sphere, and the central rod can undergo perhaps a 10-fold compression before it begins to explode due to rapid field diffusion and heating caused by the turbulent resistivity. This will produce a plasma, with density about 1/10 that of solid density, that has been heated to the 8 to 10 keV temperature necessary to undergo rapid thermonuclear reaction. This low-density heated plasma is transiently contained for a Bohm diffusion time by the portion of the magnetic field inside the sphere that has not been consumed by heating of the dense plasma.

A primary objective of this target concept is to decrease the $r\ell$ product for the deflagration burn mode introduced in a previous section so that approach to breakeven conditions in a 1-MJ system may be possible. A number of relatively sophisticated effects involving coupled electrostatic- and electromagnetic-mode excitation of the cavity[3] may be of importance for a target of this type, but their discussion is deferred until this basic idea has been subjected to experimental test.

Ion Implosion

A second class of target can be illustrated by considering the example of a 1-mm diameter, thin-walled glass tube about 1 cm long and filled with DT gas at 100 atm to provide approximately 4×10^{18} DT atoms. Alternatively the DT could be present as a uniform frost layer on the inside surface of the tube. The implosion of such a target by the stagnation of the HDM current-sheet-driven snowplow plasma shell could prove interesting with either a glass- or metal-walled target of this type.

In the case of a glass-walled target and LDM operation, a Bennett-rod-like[31] restrike of the current over the surface of the target will take place when the growth of turbulent resistivity substantially interrupts the current in the collapsing plasma shell of the focus. A rod of this diameter, if it achieves operation in the Bennett mode, will drop to the virtual cathode potential, the large surface current over the rod providing natural magnetic insulation that will prevent radial electron discharge from the rod. As a consequence the exploding plasma shell of the focus surrounding the rod becomes a plasma anode from which ions are extracted and accelerated in a radially convergent fashion into the rod where they help to drive its implosion.

It may be possible to achieve in this way a convergent flux of several-MeV protons which, due to their unique energy deposition properties as noted by Maschke[32] and Mar[illegible][33] and studied systematically by Clauser,[25] have distinct advantage for imploding targets relative to other less-penetrating or more-scatterable pulsed power sources. The present idea was initially inspired by the suggestions for ion implosion by Winterberg[34] and Sudan.[35]

Return-Current Explosion

A third target concept results from the use of a thin-walled metal or glass tube a few mm in diameter and perhaps 1 cm in length that contains DT gas at a pressure between 10 and 100 atm or has a solid DT internal frost layer. This type of target placed on the axis of the focus, but spaced about 1 cm from the focus anode, will result in the following sequence of events for LDM plasma-focus operation.

First a pinch will form between the focus anode and the target tube, and inject a burst of energetic ions into the end of the tube. The snowplow will stagnate at the outer tube wall, initiating its implosion, and then a second focus will form at the end of the tubes farthest from the anode, this second pinch will inject a relativistic electron burst into the plasma that has been heated by the ions and is in the process of being heated by the wall implosion. The return current will initially be induced to flow along the relativistic-electron-beam path, but because the heated plasma provides conditions that favor development of strong turbulence, the onset of turbulent resistivity will result in expulsion of the return current from the relativistic current path.

This return-current explosion will propagate rapidly along the tube axis and result in a moving, induced axial field that will accelerate ions that in turn can heat the plasma in the relativistic-beam path to ignition conditions, thus favoring the development of runaway thermonuclear chain reactions on-axis that could assist or even be the primary cause of ignition. If ignition is achieved, the condition that is established results in a strong field in the target plasma that will be the analog of the gas-embedded Z-pinch ideas of Cheng[20] that favor field-coupled radial propagating burn in a system with or < 1.

Pulsed Farnsworth Microexplosion

The large electron and concentrated-energetic-ion bursts obtained from the low-density mode of the plasma focus suggest that the plasma focus could be used as an intense, pulsed ion-and-electron source for a pulsed version of electrostatic confinement originally introduced by Farnsworth and explored experimentally and theoretically by Hersch and others.[36] One version of the pulsed Farnsworth microimplosion idea[37] envisions twelve 100- to 250-kJ, 100-keV plasma-focus devices of the Filippov geometry arranged on the faces of a dodecahedron circumscribing a dielectric sphere perhaps 30 cm in diameter, with 12 small-diameter holes to permit the injection of energetic electrons and/or ions along 12 diametrical paths into the sphere.

The use of the LDM operation of the plasma focus will provide intense ion or electron sources (or both) for pulsed electrostatic confinement, and such a system operated in the ion-burst mode with a central target of the type studied by Clauser could provide a particularly interesting and relatively inexpensive means for studying ion implosion of targets with several-MeV protons or more energetic heavy ions.

Other Concepts

The target concepts discussed in this section are included primarily as an illustration of the wide range of pulsed-fusion studies that are possible with a large plasma focus through appropriate choice of operating conditions and gun design. Many other target concepts have been evolved in the course of study of the potential of the plasma focus, and no doubt important target concepts that we have not imagined will be suggested by others. This fact illustrates the versatility for pulsed-fusion studies of the relatively simple and inexpensive pulsed power source provided by a plasma focus. We believe that through use of a plasma-focus-like pulsed power source, nontrivial pulsed fusion studies will become possible at many centers of research.

LLL Target Studies

The first target studies in the L^3 Physics Department plasma-focus project have been carried out in a 60-kJ plasma-focus gun and will be continued at the 250-kJ and 500-kJ levels during the next year on a plasma-focus gun that has been designed for ultimate operation at the 1-MJ level. These target studies employ a vacuum lock mounted in the anode of the plasma focus gun to permit the target to be emplaced under operating conditions after appropriate conditioning shots have been fired. The vacuum-lock idea, and initial design, is due to John Luce.

Out of about 10 attempts, several successful shots have been achieved at 60-kJ in LDM operation with 100-μm diameter, thin-walled (2-μm) glass microballoons containing 4×10^{14} DT atoms at a pressure of 100 atm. No DT neutron yield has been detected in these early experiments. The experiments were conducted with the focus operating on D_2 and will be repeated with He^4 fill gas to facilitate detection of any DT-fusion neutrons by time-of-flight spectrometry.

The initial results showed that the focus did not form on the small target when the microballoon was mounted on a glass rod several μm in diameter extended from the vacuum lock at the anode center. However, when the microballoon was mounted on a sharpened sewing-machine needle, quite symmetric formation of the focus on the microballoons target and its mounting stem was observed in the two shots conducted in this manner to date. The current-sheet centering provided by a small-diameter metal mount may be the result of electrostatic focusing. The normal DD yield of the focus was decreased by about a factor of 4 when the metal-rod-mounted microballoon was present.

The 100-μm-diameter balloons are too small to serve as targets of the type discussed in this section. The purpose of the small balloons is to provide a diagnostic tool for studying the centering of the focus on a target. Experiments with this small diagnostic target as well as studies with other larger targets are planned for the 250- and 500-kJ level during the next year's experimental program. Computational and theoretical studies for the experiments are under way and will be reported in future publications along with experimental progress.

The problems of greatest theoretical importance to our future studies include the study of burn-α field coupling, electrostatic implosion effects, the appropriate treatment of strong turbulence, and an incorporation of the Bostick filament-annihilation process into the energy release mechanism at a target surface. One- and two-dimensional computation target studies are in progress.

6. SUMMARY

A plasma-focus device driven by a 1-MJ bank with a bank voltage of ≥40 kV provides a versatile pulsed power source for fusion microexplosion studies.

At least five distinct mechanisms for neutron yield exist in the plasma focus, and the relative contributions of the yield mechanisms may be varied by appropriate choice of operating conditions and gun geometry. For high-density-mode operation in the Filippov geometry, the collapsing plasma shell of the plasma focus can contain 10% of more of the bank energy and can serve as a 10^{13}-W power source that can be employed to implode various microexplosion targets.

Operation in the low-density mode can yield up to 25% of the bank energy in a 10- to 25-ns, fast-rising, small-diameter ($d \leq 0.1$ cm), high-current relativistic electron burst and oppositely directed ion burst. This burst may be employed in a variety of ways to heat and/or implode a microexplosion; at the same time it can serve as the source of a strong magnetic field that can contain a relatively dense plasma, act to inhibit condition losses, and serve to couple burn-α's to the system in the case where ρr is less than 1 g/cm^2. The energy of the accelerated electrons and ions can exceed the applied voltage by more than a factor 100, and an array of plasma foci arranged in, e.g., a dodecahedral pattern can serve as intense pulsed electron and/or ion source for pulsed electrostatic confinement and for ion implosion of a central target.

Preliminary experiments at 60 kJ with 100-μm-diameter, DT-filled microballoon targets have produced no detectable DT neutrons but have shown that the focus is formed well-centered on the microballoon target when the microballoon is mounted on the end of a sharpened sewing-machine needle extended from a vacuum lock at the anode center. Theoretical, computational, and experimental studies of these small microballoon targets as well as other cylindrical and spherical targets are planned for the 250-kJ and 500-kJ plasma-focus power-level during the next year.

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