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# SPACE-TIME ENERGY CONCENTRATION AND THE DESIGN OF DT FUSION MICRO-EXPLOSIONS*

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## ABSTRACT

As part of our effort to employ a plasma focus as a driver for fusion micro-explosions, we have explored many target concepts and have carried out extensive implosion calculations. Based on this work we will present some of the basic principles of micro-explosion design.

It is useful to organize this discussion in terms of the power per unit area required by various targets. Specifically, we will consider designs appropriate to $10^{14}$, $10^{13}$ and $10^{12}$ watts/cm$^2$. We will also briefly consider the possibilities of targets requiring power densities less than $10^{12}$ watts/cm$^2$ and greater than $10^{15}$ watts/cm$^2$.

## INTRODUCTION

The purpose of the present work is to understand the space-time energy concentration of the plasma focus, through theoretical and numerical studies, and to apply this knowledge to the production of electron, ion, infrared and microwave bursts in this device. Present efforts are concentrated on the determination of the power per unit area of the electron and ion bursts, the mechanism of electron burst deposition in high Z materials, and on the potential application of the electron burst and its energy deposition as a driver for fusion microexplosions. Future efforts will deal with enhancement of the ion bursts and measurement of the infrared and microwave production.

We believe that it will ultimately become possible through appropriate choices of gas mixture and pressure, and the materials and configuration of the anode center, to channel a substantial fraction of the capacitor bank energy into the desired mode of energy concentration: electron burst, ion burst, infrared burst, or microwave bursts. At present it is possible to achieve the greatest conversion efficiency in the form of electron bursts with currents of 1 MA and diameter of 1mm perhaps concentrating under conditions favoring radiation collapse to a diameter smaller than 100 microns.

An understanding of the processes involved requires application of the most advanced theoretical and experimental tools for numerical calculation and for fast space and time resolved diagnostics. This project has the potential for yielding a light, compact pulsed power source that could drive fusion microexplosions, when driven by an explosive generator. For this reason we maintain close contact with the companion project of B. Freeman and his colleagues at Los Alamos Scientific Laboratory, where the problem of driving a plasma focus with an explosive generator is under study.

One of the most popular and vigorously studied drivers for fusion micro-explosions is the laser. Energy stored in a low voltage, relatively slow capacitor bank can be used to drive flash lamps that create a population inversion, which amplifies a coherent radiation pulse via the lasing process. The amplified pulses can be directed to a target at energy densities sufficient to achieve ablative driven convergent compressions of a pellet. A 1 MJ capacitor bank can result in the pumping of a 300J Nd laser. Then a fraction of this 300J can cause ablation in a nanosecond or less of the outer surface of the target, coupling perhaps less than 10% of the laser pulse absorbed by the ablation into energy of the unablated imploded material. The efficiency of conversion of capacitor bank energy into energy of imploded material is small. It thus becomes interesting to ask if one can find a more direct and effective way of achieving the same ends of imploding DT fuel to densities and temperatures that permit significant fusion yields.

A number of ways have been devised for achieving more direct concentration of the bank energy into imploded DT fuel. A high voltage power source, (Marx generator) may be coupled through a switch to the pulse forming line of a relativistic electron beam machine. This machine can provide substantial power in relativistic electron beams reaching a current density greater than $10^7$ A/cm$^2$ in pulses of 100 ns or less. More recently means have been found to inhibit the electron flow and, as a result, achieve substantial power in accelerated ion bursts with current density that are presently as high as $10^5$ A/cm$^2$. It may prove possible

to concentrate these relativistic electron bursts or energetic ion bursts on suitable cylindrical or spherical targets to achieve the desired implosion.

Alternatively the capacitor bank may be employed to drive a large current parallel to the axis and over the surface of a thin cylindrical shell. The resulting $\vec{J} \times \vec{B}$ forces act to implode the shell in a cylindrically symmetric fashion converting the stored energy in the capacitor to kinetic energy of the imploding foil prior to its stagnation on axis. It may be possible to use the imploding shell to drive a fusion microexplosion. A number of variants of this liner implosion scheme exist including replacing the foil by a cylindrical parallel array of wires of the same mass or acceleration of a foil or pellet linearly rather than convergently. This latter possibility is known as an induction gun.

THE PLASMA FOCUS

The plasma focus has some similarity to all of these schemes and is in effect a convergent magnetic shock tube that provides concentration of energy stored in a capacitor bank into plasma kinetic and field energy in the conventional high pressure mode of operation (Mode I), or into accelerated ion bursts and electron bursts in a low pressure mode of operation (Mode II). These electron bursts have exceeded the current densities achieved with conventional relativistic electron beam machines by at least an order of magnitude.

One popular form of the plasma focus is the co-axial or Mather gun. Co-axial electrodes are separated by a gap of almost one-inch; the inner electrode is the anode and the outer electrode, the cathode, often consists of many parallel bars that permit outward radial flow of the fill gas. The electrodes are separated at the breech of the gun by an insulating sleeve that extends for several inches along the anode. The electrodes are connected to a transmission line and through switches to the capacitor.

The focus fill gas is often hydrogen or deuterium in the pressure range of 1-10 Torr. Operation of the plasma focus begins by closing the switches to apply the bank voltage across the insulator separating the anode and the cathode. First there is a brief period of low current resistive flow between the electrodes through the fill gas. Then breakdown occurs along the breech insulation or between the electrodes at the end of the insulator or in a combination of these two modes. The current begins to increase at a rate of the order of $10^{12}$ A/sec. Resulting $\vec{J} \times \vec{B}$ forces drive

this current down the gun barrel and the current sheet snowplows the fill gas ahead of it to build up a region of shocked gas which reaches a constant axial velocity. Due to the radial flow permitted through the open outer electrode, this region of shocked gas can achieve a constant thickness. Energy is converted from capacitive storage into inductive energy storage behind the moving plasma. In a well designed system, peak current and zero capacitor bank voltage are reached as the snowplowed plasma reaches the end of the gun. At this point the inductance of the gun and of the transmission plates, capacitors, and switches are roughly equal, and one-half of the bank energy is stored behind the snowplow. One-half of the bank energy has gone into kinetic energy and thermal energy of the plasma that has escaped radially, as well as the moving plasma that is about to be fired off the end of the gun, and thus is energy unavailable for the subsequent energy concentration process.

In an interesting variant of the focus, a foil is placed over the end of a pair of coaxial electrodes like those of the focus except the outer electrode or cathode is closed. In this system current flows through the foil connecting the electrodes and results in the same type of inductive energy storage as the plasma focus but with less energy loss to matter degrees of freedom. The mass of the foil is chosen so that the magnetic pressure behind the foil can push the foil out of the way as peak current is reached. This permits rapid convergent collapse of the field energy toward the axis where large induced axial electric fields cause the formation of a relativistic electron burst.

The moving plasma in the focus has the virtue that the snowplowed plasma plug is self-created thus permitting a high repetition rate. As the plasma flies off the end of the gun the inductive energy stored in the gun can be used for a radial convergent collapse.

In Mode I or high pressure focus operation the collapsing field energy drives the fill gas that is present off the end of the gun towards the axis to form a snowplowed cylindrically convergent plasma shell with a length of about 2 cm. The collapse velocity of this plasma shell reaches 20-30 cm/μsec as the shell approaches the center of convergence at the axis. Only about 10% of the gas contained in the cylindrical volume at the end of the gun (with a diameter equal to that of the anode and a length of about 2 cm) actually reaches the final stage of convergence on axis. The remaining 90% flows away in the axial direction at velocities that can reach 100 cm/μsec as the moment of final convergence is reached.

The stagnation of this field driven snowplow on axis results in a pinch with a temperature of 1 kV and a density of $5 \times 10^{19}$ for the pinch column whose diameter is 1-3mm. This stagnation of the plasma shell on axis results in a small neutron yield that, in the Mather geometry, is less than 1% of the total neutron yield. Guns that have a diameter exceeding their length are known as Filippov guns. In the Filippov geometry the rundown phase is quite short and the convergent collapse phase dominates. The plasma stagnation on axis in the Filippov geometry results in 10% or less of the total neutron yield.

In the case of a foil implosion, the energy is mostly kinetic just prior to stagnation. In the case of the focus the kinetic energy at the time of snowplow stagnation on axis is only a few percent of the bank energy, and 25% of the bank energy is still stored inductively in the magnetic field surrounding the pinch. The neutron yield occurs 10-100 ns after stagnation on axis over a period of 30-50 ns, during which time a substantial fraction of the inductively stored energy undergoes rapid conversion into thermal energy of the plasma and into directed energy of accelerated ions and electrons. This sudden energy conversion process is the key to plasma focus behavior. It is not well understood but appears to be some sort of equipartition process operating, which takes place with constant efficiency over a wide variety of operating conditions. The end point reached, of sharing the energy between particles and fields, is apparently the same in all cases.

Mode II operation favors production of energetic electron and ion bursts. Operation at low pressure and the presence of a few percent of high Z impurities favor this mode. Perhaps the most important and least understood factor that determines whether Mode I or Mode II is achieved is the nature of the initial breakdown. Some evidence exists in our work at Lawrence Livermore Laboratory as well as in the results of several other plasma focus groups that axial striking along the insulator favors Mode I operation and radial striking of the initial current sheet favors Mode II operation. This point is in urgent need of detailed study. Nonetheless, there is some relatively weak evidence that radial striking of the current sheath leads to Mode II operation <u>at all operating pressures</u>.

In Mode II operation, shortly after convergent collapse begins, the magnetic field behind the snowplow begins to leak through the "crack" where the snowplow joined the anode to form a magnetic bubble inside the snowplow. It may be that high Z anode material mixes into the plasma at the intersection of the collapsing plasma shell and the anode. The high Z ions increase the resistivity causing field diffusion to out-run the snowplowing in the contaminated regions. The field that penetrates inside the snowplow collapses toward axis with velocity exceeding the snowplow velocity

by an order of magnitude. The field also expands in the axial direction and the magnetic pressure of the field bubble results in effect in an extension of the anode by about 2 cm so that Mode I pinching is moved out along the axis. The plasma shell in effect wraps around the donut-shaped magnetic bubble. The larger $\dot{B}$ associated with this field penetration induces several hundred kV axial fields that can accelerate both electrons and ions. However acceleration of electrons in the field filled region is inhibited by this self-magnetic insulation and thus the electron current appears as a hollow relativistic electron burst at the front of the collapsing field bubble. Evidence supporting this picture comes from holograms obtained on single pinches by V. Gribkov's group at the Lebedev Institute in Moscow [1].

When the small diameter relativistic electron burst formed at the collapsing front of the magnetic bubble impinges on the anode center, a plasma of anode material is evolved. The partially ionized high Z plasma can result in a radiation rate that cools this region of plasma faster than it is heated by the combined effects of resistive heating and adiabatic compression. This results in pinching that is isothermal or even refrigerating, preventing the attainment of pressure balance between the matter and the magnetic field so that radiative collapse takes place. This collapse continues until limited in some way. Alternatively the radiation rate can become equal to the rate of flow of the magnetic field energy into the collapse region and the pinch is arrested. Steady state conversion of coherent magnetic field energy flowing into the collapse region into incoherent radiation leaving this region take place. In the case of low Z materials at the anode center complete ionization of the anode plasma will result.

The temperature of the plasma can become high enough for the plasma to be collisionless in which case the relativistic electron burst can drive large amplitude plasma oscillations. Scattering off these self-created plasma oscillations can generate infrared radiation. In this case the flow of the plasma oscillations out of the collapse volume combined with the energy carried away by infrared radiation at the surface of the collapse volume can result in the cooling required for the collapse to take place. In addition, syncrotron radiation due to orbiting of electrons in the strong self field of the beam and Cherenkov radiation resulting from the fact that the relativistic electron velocity exceeds the energy velocity of light in the plasma may contribute to the cooling. These latter two mechanisms have been pointed out to me by Arno Steiger of this laboratory.

Radiation collapse of the type described here could cause a beam with an initial diameter of 1mm to reach a limiting diameter of 100μ in a time as short as $10^{-11}$sec. The very large axial fields

induced during this collapse process could cause axial ion acceleration producing a burst consisting of $10^{10}$-$10^{11}$ accelerated protons or deuterons with energies of 1-25 MeV. Accelerated protons and deuterons with energies of 2-5 MeV and perhaps up to 10 MeV have in fact been observed in our experiments at Lawrence Livermore Laboratory. The high rate of radiation out of the collapse volume acts as a strong resistive drag on the electrons and thus may prevent the electrons from reaching the multi-MeV energy achieved by the ions. This point is also borne out by an experiment where the total radiated energy above 1 MeV is quite small in low pressure operation and nonexistent in operation at high pressure.

Operating at good impedance matching at full bank capacity we will be able to produce electron bursts with I = 1.6 MA, current densities $>10^9$ A/cm$^2$, with pulse width of $\tau \leq 10$ ns, carrying energy of 25,000 to 50,000 J. According to my estimates this is sufficient to drive a $6 \times 10^{-6}$gm large aspect ratio target that has a maximum theoretical yield of 0.8 MJ, i.e., a yield that could exceed the 300-500 kJ stored in the capacitor bank.

At the Lebedev Institute, V. Gribkov has observed a number of shots in which a 1 ns, 1 kJ Nd laser pulse was fired at the location where the plasma-focus-produced electron burst strikes the anode. With appropriate timing of the laser pulse relative to the time of electron burst production by the focus, the neutron pulse length of the focus was decreased in width by a factor of 10 (i.e., T = 5ns instead of T = 50ns) but the magnitude of the neutron yield was not changed. Previously, he had reported observing anomalous deposition of the focus-produced electron burst in the aluminum-coated copper anode center. In one region of operation the electron burst production occurs after pinch formation and the pinch is able to preheat the anode center to permit anomalous deposition. In another mode of operation, interruption of the current sheet and electron burst production occur early in time so that a laser pulse is required to preheat the anode center in order to obtain anomalous deposition. The anomalous deposition process was characterized by sudden termination of the hard bremsstrahlung simultaneous with the abrupt turn-on of strong non-thermal infrared radiation production in the wavelength range 1-10μ. This sudden change in the nature of the radiation indicates that scattering of fast electrons off high Z atoms is suddenly replaced by scattering off large amplitude plasma oscillations. In order to achieve this state, it is necessary for the plasma to become hot enough to decrease the classical collision frequency to a value equal to or less than the plasma frequency. In near solid density plasmas, a matter temperature of about 1 kV is required before anomalous stopping can take place.

The Filippov focus is operated in the Soviet Union with a block of aluminum mounted on the center of the cathode vacuum wall so that plasma squirted down the axis as the focus forms impinges on this aluminum block. In each shot aluminum is evaporated from the block and distributed throughout the system. The aluminum probably deposits on the insulator and also deposits on the anode center where, after about 100 shots, it reaches a steady-state value.

In previous work, Gribkov [1] observed that pinching to a diameter of about 1 cm was followed by a steady-state period of about 100 ns followed by strong turbulence and explosive rupture of the current sheet in a ring about 1 cm away from the focus anode. The current restructured in the form of a relativistic electron beam to focus on axis at the anode with a beam diameter of about 1mm. The deposition of the electron burst at the anode center launched a strong shock into the $D_2$-fill gas on axis resulting in neutron production.

As a result of sustained operation of the focus with the aluminum block in place, Gribkov has seen and made detailed holographic study of a second mode of operation that had previously been reported by Filippov. In this mode, when the snowplow reaches a diameter of the order of 10 cm, the magnetic field breaks through by rapid diffusion in the layer of high Z plasma present where the snowplow and current sheet intersect the anode. The magnetic field that has penetrated collapses radially at a rate about 10 times greater than that of the snowplow motion, and at the same time the penetrating field expands axially forming a magnetic bubble inside the snowplow that prevents further pinching in the region near the axis. Farther out along the axis the pinching can proceed and so the current sheet closes around the end of the expanding magnetic bubble to produce a conventional plasma focus pinch several cm above the anode, i.e., beyond the "magnetic bubble extension" of the anode center. The magnetic energy of the bubble drives a restrike of the current along axis as a relativistic electron burst. Five frame holography has been used to show this detailed development.

Alternative approaches to pulsed fusion include the liner implosion work at the Naval Research Laboratory (NRL) in Washington, D.C. and the Air Force Weapons Laboratory in Albuquerque, New Mexico. Relativistic electrons and energetic ions are produced with relativistic e-beam machines at NRL and at Sandia Laboratory in Albuquerque and plasma-focus-like foil switch has been developed at Physics International. I believe that this type of foil focus, in conjunction with an explosive generator and a high gain large aspect ratio target, may provide the best way of scaling the plasma focus system to 5MJ. Conceptually, all these methods can be described by considering electrical energy delivery along a coaxial

transmission line from a capacitor bank or from an inductive energy storage device. The foil switch and the focus, as well as the liner implosion, have been described earlier in this section.

In the case of a relativistic electron beam machine, the power source is normally a relatively high-voltage fast array of capacitors known as a Marx generator on the coaxial transmission line in the pulse forming region. In the case of the relativistic e-beam machine, closure of the switch connecting the power source to the pulse forming line launches an electromagnetic wave or "displacement current snowplow." In the coaxial region, this wave propagates to the end of the center coax and then undergoes rapid collapse toward the axis inducing large electric fields that cause formation of a relativistic electron burst in the "diode region" near the axis.

The principle difficulty in the foil focus, the cylindrical foil, or to a lesser extent the plasma focus, is the danger of restrike across the insulator separating the anode and the cathode during the relatively long period of energy concentration on axis. In the case of the relativistic e-beam machine, the strategy is to beat alternate breakdown paths by shortening the total time from switch closure to electron burst formation. In all cases, unwanted breakdowns can be avoided by hiding the insulators from ultraviolet radiation or by using the self-magnetic field of the current to provide magnetic insulation against breakdown-via-electron currents. Such a strategy will ultimately be defeated by ion currents because much stronger fields are required to provide the appropriate magnetic insulation. Good magnetic insulation probably results in energy loss through microwave generation and thus magnetic insulators will no doubt prove to have a maximum efficiency less than 100%.

All of the schemes mentioned above are capable of producing power concentrations of the type required to drive fusion microexplosions ($10^{12}$-$10^{14}$watt/cm$^2$). Where one opts for relativistic electron beam generation, it is necessary to have anomalous electron stopping or to permit the power density to be deposited in a volume comparable with that achieved with lasers, i.e., in a depth comparable with the collisionless depth $\Delta = c/\omega_{pe}$. At power densities exceeding $10^{13}$watt/cm$^2$, lasers tend to generate relativistic electrons, becoming, in effect, another kind of relativistic e-beam machine. Although it is too early to be sure, high-power energetic-ion bursts will probably have the same problems at comparable power densities because the slowing of fast ions couples energy strongly into electrons. It therefore appears desirable for fusion microexplosions to have targets that can have significant gain when driven by power densities in the region $10^{12}$-$10^{13}$watts/cm$^2$.

At the Centre d'Etudes de Limeil, a plasma focus operated in the Mather geometry has obtained a maximum DD neutron yield of $10^{12}$ in a 340 kJ, 50 kV system [2]. The neutron scaling law established in their laboratory is $Y \alpha I^{3.3}$. This yield is due primarily to accelerated ions directed away from the anode, and centered in a cone with a half-angle of about 15°. They have shown that in their 340 kJ system, the entire current can be carried for a brief period in an ion burst of several hundred kV ions. Current densities of accelerated ions of 200,000 A/cm$^2$ have been achieved, a value larger than that achieved with any other existing source of several hundred kV protons.

Laser scattering is employed to measure the sudden development of plasma turbulence associated with the anomalous resistivity and particle acceleration in the focus [3]. With magnetic probe measurements, they have shown that in their plasma focus system, the current flows in a substantial volume behind the current sheet rather than being concentrated in a thin layer at the back of the snowplow. This effect is also seen in the Mather geometry experiments at Frascati, but does not exist in the related low energy, low voltage plasma focus experiments in the Filippov geometry in the Soviet Union. The focus operated at Limeil employs a relatively long insulator, and relatively high voltage (40-50 kV). Apparently the current in this system does not strike axially over the surface of the insulator, but radially between the anode and the cathode just beyond the end of the insulator.

The Euratom 1 MJ plasma focus project is located at the Laboratorio Gas Ionization Frascati, Italy. The objective of the project is to scale the previous 120 kJ Filippov geometry plasma focus to 1 MJ to test the validity of neutron yield scaling law in preparation for the next step, a 10 MJ plasma focus.

The yields obtained at Frascati in the Mather geometry have currently reached $7 \times 10^{11}$, far short of the original goal. In contrast to the 120 kJ, 40 kV operation, where the yield was of a nearly thermonuclear character, they find at 1 MJ and 40 kV that the yield becomes dominated by ion acceleration even in high pressure operation [4]. It has been found that the simple model of current sheet formation at an insulator followed by snowplow motion does not apply, and that the phenomena of current sheet formation and propagation are much more complex. There is dependence on the insulator type and configuration, the energy required to ionize the fill gas, and the gas pressure; consequently, the problem of scaling to high energy is much more involved than obtaining simple MHD similarity.

In the future, work on the neutron scaling law will be pursued by concentrating on the current sheet formation and propagation.

In addition, the capacitor bank will be modified to permit 80 kV operation in an effort to increase the pinch current, and thus the neutron yield, at 1 MJ. It appears that low pressure operation at the insulator favors good current sheet initiation and lift-off, while neutron production in the pinch may be favored by higher pressure operation. By puffing gas in on axis and allowing the gas to expand toward the insulator one can produce in first approximation low insulator pressure and high pressure in the pinch region.

LARGE ASPECT RATIO TARGETS

Two key fusion projects in the Soviet Union are the relativistic e-beam project directed by L. I. Rudakov at the Kurchatov Institute in Moscow, and the laser fusion project under Basov at the Lebedev Institute in Moscow.

Rudakov has discussed the deposition of 600J of a 1000J, 30ns relativistic electron burst in a 5μ thick gold foil 3mm in diameter. This gold foil was one-tenth of a classical range thick, and it was discovered that at current densities $I \geq 10^7 A/cm^2$ the penetration of the self-field of the beam into the explosed gold foil plasmas resulted in an increased path length for the electron. This permits the energy deposition by classical collisions to take place in one-tenth the mass of target that would be required in the absence of self field penetration. The gold foil reached a temperature of 35 eV.

The gold foil was the cap of a conical hole in a lead anode block. The cones had a bore angle of 60° and the height was 3mm so that the gold capped-hole in the lead formed a conical segment of a 3mm radius sphere. The cone was filled with $D_2$ at a pressure of 150 Torr and a second foil which was 10μ thick CH was placed at a radius of 2mm [5]. The inner portion of the CH foil imploded, driving the gas in the 2mm radius conical segment of a sphere to 1000-fold compression. The velocity of the imploding CH foil was $5 \times 10^6$cm/sec and the compression was limited to 1000-fold by expansion of the lead walls of the cone. In the absence of electron conduction losses the 1000-fold compression of the $D_2$ gas in the inner region would result in a temperature of about 2 kV. Conduction losses in this low ρR system hold the temperature down to 0.5 kV and result in a negligible neutron yield.

Rudakov points out that in low ρR systems the addition of high Z impurities can reduce the dominant electron conduction loss mechanism without unacceptable increase in the radiation losses. He noted that a minimum existed in the sum of the electron loss and radiation loss mechanism if

$$1 + fZ_{eff}^2 = \frac{4 \times 10^{-6}\ T_e^{3/2}}{(\rho R)_{fuel}} \quad ,$$

where $T_e$ is the electron temperature, $(\rho R)_{fuel}$ is the $\rho R$ of the fuel, $Z_{eff}$ is the charge on the high Z impurities given approximately by $Z_{eff} = 20\sqrt{T}$ where T is in keV ($Z_{eff} \leq Z$), and f is the atom fraction of high Z impurity in the fuel. In Rudakov's experiments, the addition of 7% Argon resulted in a temperature of the imploded $D_2$ of 1 keV and a neutron yield of $5 \times 10^6$. It is interesting to note that $R/\Delta R > 200$ in these experiments.

In subsequent work Rudakov and his colleagues have reported temperatures of 68-86 eV and an implosion velocity of $1.5 \times 10^7$ cm/sec. On the strength of these results, a project has been launched that will employ 48 e-beam machines to concentrate about 5 MJ energy in 30 ns onto a spherical target with a radius of about 1 cm. The implosion of this target according to the Russians requires only $10^{13}$ watts/cm$^2$.

Calculations at Lawrence Livermore Laboratory were made on the thin shell targets with the help of Bruce Freeman and John Brownell at Los Alamos Scientific Laboratory [6]. A mode of operation of the target was found which produced yields within a factor of 2 of the Soviet publication [7]. These targets required an imbedded gold layer with a mass equal to about one-half that of the main DT fuel that separated the innermosts 3-5% of the fuel from the main fuel region. During this same period Freeman and Brownell were able to show that a thin shell target whose implosion was driven by the current sheet of the plasma focus could have a yield that lay above the yield implied by extrapolation of the $I^3$-$I^5$ scaling laws of the focus and could reach breakeven for a 1 MJ focus [8].

In later discussions with Afanas'ev and Nikoliev, I learned that the mode of operation we had found was not the mode involved in the Soviet calculations. The key difference is that the imbedded gold layer had a mass equal to about 1% of the fuel and isolated the innermost 1% of the fuel from the main fuel layer. Subsequent calculations have now achieved full agreement with the published targets.

As a result of the work on thin shell large aspect ratio targets I have had many ideas for considerable improvement and sophistication of the large aspect ratio system. However, I doubt that these ideas can be profitably pursued through calculations alone. Strong experimental feedback is also required.

Our calculation of the thin shell targets has revealed a number of significant ways in which the large aspect ratio targets differ

from conventional design. These differences have been ignored in practically all studies that claim to show that the large aspect ratio targets will not work.

The key difference between the large $R/\Delta R$ targets and conventional designs is that the mass of inert material in the imploded structure is equal to the mass of the fuel in the case of the large $R/\Delta R$ targets rather than having an inert mass 100 times the mass of the fuel—a ratio typical of conventional small $R/\Delta R$ designs. The implosion rate of the large $R/\Delta R$ targets is sufficiently gentle that the layered structure of the target initially explodes into the void decreasing $R/\Delta R$ and the system recompresses to densities substantially higher than the initial density only during the final state of implosion.

The initial expansion decreases the $R/\Delta R$ and permits inhomogeneities that can never be fully eliminated to expand circumferentially thus relaxing out of existence. Such inhomogeneities in strongly driven systems grow continuously during all phases of a convergent compression and could be fatal for $R/\Delta R \geq 25\text{-}30$.

If a large $R/\Delta R$ shell of DT is imploded numerically in the fashion appropriate to the Basov targets, one finds that the first gentle shock drives the innermost 1% or so of the shell into the void to form a low density gas, while the remainder of the shell remains relatively cool and also expands slowly into the void. Near the center of convergence the innermost 1% attains a high velocity due to convergent compression. Its stagnation carries it to a high energy density. The steep density gradient between this innermost 1% and the remainder of the fuel causes the stagnation shock to be trapped and to reverberate in the central 1% of the fuel. Unfortunately, the energy that stands to build up in this central hot spot quickly dissipates into the surrounding fuel by electron conduction. A layer of high Z material with mass of about 1% of the main fuel can cause thermal isolation of the central 1% of the fuel, resulting in a high temperature low density region with $\rho R < 0.3$, in pressure balance with the cold surroundings.

The target has the advantage of large gains at relatively modest compressions $\rho = 200$ gm/cm$^3$, driven by a long pulse $\tau = 100$ns at a low power per unit area $10^{12}$ watts/cm$^2$. The price paid for these advantages is that the minimum energy required, 1 MJ, is larger than that for schemes requiring greater power density to achieve higher final compression.

The layered structure of the target results in many shock reflections at the boundaries between materials and this causes the entire structure to ring like a bell and undergo periodic density oscillations. This feature which I call self induced dynamic stabilization may provide a natural stabilizing mechanism against

Taylor instability. This self deployment of the layered structure provided by the initial expansion of the target into the central void defines its own center and requires no levitation. I believe that this may have significant advantage over structures requiring multiple collision of many shells that are initially precentered and levitated. The high Z layer that isolates the innermost 1% of the fuel actually becomes exponentially distributed in the central fuel by diffusion during implosion and then behaves to some extent like the addition of high Z atoms in the Rudakov target.

Basov et al., have proposed a high-gain, thin-shell, high-aspect-ratio target requiring a low power per unit area to drive its implosion [9]. For example, a target with 1 cm radius R, an aspect ratio $R/\Delta R \simeq 100$ containing $10^{-2}$gm of fuel and a comparable mass of high Z material, has a yield of 1000 MJ if driven by a 100 ns, 1 MJ laser pulse that couples 20% of its energy, i.e., 200 kJ into the 2-3 x $10^{-2}$gms of imploded DT and high Z shells. Ignition is obtained by isolating about 1% of the fuel with a very thin high Z layer embedded in the fuel, this layer having a mass comparable to the isolated innermost position of the fuel, i.e., approximately $10^{-4}$gms. It is possible to study the central ignition of this target by employing a microballoon with R = 1 cm and a total inert wall mass of 1-2 x $10^{-2}$gms that contains $10^{-4}$gm of DT gas.

At Frascati, Caruso has obtained a dynamic similarity law for the implosion of such a gas-filled glass shell where the acceleration is impulsive, that is the acceleration time for the shell is short compared to its total implosion time. They have written a code to make hydrodynamic implosion calculations of the ablation-driven implosions of such a gas-filled shell and demonstrated that the similarity solution is valid. From their model they find that a gas-filled glass target with a diameter of about 500μ and a wall thickness of a few microns is dynamically similar to the Soviet 1000 MJ target if the implosions of the dynamic scale model is driven by a 100-200J Nd laser pulse. According to their calculation such a gas-filled dynamic scale model will produce a detectable neutron yield. They are currently building the Nd laser required for dynamic similarity experiments they plan to carry out with thin-shell gas-filled μ-balloons. According to their estimation, bathing each hemisphere of the target in Nd laser light diverging from a focal point outside the target will result in an ablation asymmetry of only a few percent.

It is interesting to note that recent experiments [10] on the 9-beam laser system by Basov's group at the Lebedev Institute have emphasized 1 ns, 100J Nd pulses to obtain ablation-driven compression of gas-filled thin-shell micro-balloons with wall thickness of 2.2μm and diameter of 140μm. The largest target employed in the Soviet experiments are less than a factor of two smaller in diameter than Caruso's dynamic similarity model of the 1000 MJ

Soviet target. The Soviet experiments have achieved a central density of up to 6-8 gms/cm$^3$ and a DD neutron yield of 3-5 x $10^6$ corresponding to a central temperature of the deuterium gas fuel of 0.8-1 kV.

FOOTNOTES/REFERENCES

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