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Development of Imploding Liner Systems for the NRL LINUS Program

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For nearly two decades, the idea of creating fusion plasmas by the implosion of cylindrical shells or liners has appealed to workers interested in high energy density systems.[1,2] A variety of schemes have been offered over the years to accomplish the adiabatic compression of plasmas at megagauss magnetic field levels by imploding liner magnetic flux compression techniques.[3-7] The two main elements of such schemes have been the implosion of an electrically conducting cylindrical liner and the creation of an initial plasma suitable for compression by the surrounding liner. Some progress has been made both experimentally and conceptually in regard to plasmas that could be
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INTRODUCTION

For nearly two decades, the idea of creating fusion plasmas by the implosion of cylindrical shells or liners has appealed to workers interested in high energy density systems.[1,2] A variety of schemes have been offered over the years to accomplish the adiabatic compression of plasmas at megagauss magnetic field levels by imploding liner magnetic flux compression techniques.[3-7] The two main elements of such schemes have been the implosion of an electrically conducting cylindrical liner and the creation of an initial plasma suitable for compression by the surrounding liner. Some progress has been made both experimentally and conceptually in regard to plasmas that could be compressed by liner implosion, but no experimental test has yet been accomplished successfully in which the energy and temperature of the magnetically-confined plasma has been increased into a significant regime by liner implosion. Considerable progress has been made, however, in developing liner implosion techniques suitable for both experimental development and eventual imploding liner fusion reactors. The principal development has been the achievement of controlled, reversible liner implosions with excellent symmetry and surface quality.[8,9] The following paper reviews some of the highlights of the development of liner implosion systems at the Naval Research Laboratory and indicates directions of future work.

EARLY WORK

The earliest work on imploding liner magnetic flux compression is associated with weapons development and the use of explosives to

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implode metal shells. The compression of trapped magnetic flux was used as a measure of the implosion of the shell whose position was otherwise difficult to ascertain.[10] Later analysis indicated the possibility of creating ultrahigh magnetic fields by this technique and efforts were made along these lines by various groups.[11,12] Some of these efforts were closely associated with the development of explosive flux-compression or magnetocumulative generators for high energy pulsed electrical power systems. With implosions driven by high explosive, magnetic fields of tens of megagauss were achieved.

Later efforts utilized electromagnetic forces, in the manner of z- or theta pinch discharges[13,14] to implode cylindrical liners and achieved peak fields of a few megagauss. In principle then, imploding liner magnetic flux compression techniques could thus be coupled to pulsed electrical power sources, allowing repetitive operation of ultrahigh magnetic field plasma compression systems. (Indeed, attempts had already been made[15] to compress plasma using imploding liners, driven by explosives; these tests indicated that considerable development, involving many explosive shots and improved initial plasma systems, would be required to achieve success.)

INITIAL NRL LINUS ACTIVITIES

As indicated above, the concept of using magnetic flux compression to create and confine a high temperature, high density fusion plasma had been suggested and discussed by several authors. It had, however, fallen into disfavor, in part because of the success of other techniques (e.g., theta pinches driven by fast capacitor banks) but, more importantly, because of the difficulty of conceiving and demonstrating liner implosion flux compression techniques that could extrapolate to controlled repetitive situations required for fusion power reactors. Some new enthusiasm, however, developed at IAE Kurchatov, based on electromagnetic liner implosion and MHD conversion of liner material energy after neutron-induced vaporization subsequent to thermonuclear burn.[16] After discussions between E. P. Velikhov of IAE Kurchatov, and R. A. Shanny of NRL, theoretical and numerical calculations of imploding liner fusion techniques were performed at NRL[17,18] within a program called LINUS. Initial experiments with metal liners imploded in the manner of a theta pinch using a 50 kJ capacitor bank (SUZY I) were performed at NRL by dePackh, Okada, Young, and others.[19] (These experiments included some tests with lithium liners that were quite spectacular since the hot lithium fragments would break out of the sealed container after implosion and react with the surrounding air.) Development of higher energy systems was initiated by dePackh, et al, including work on a homopolar generator with liquid metal brushes, superconducting inductive-opening switches, and a new fast capacitor bank (SUZY II) to provide liner implosions at the 500 kJ level. After the retirement of dePackh in 1972, the work on homopolar generators, and inductive opening switches was continued by Robson, Turchi, Ury, and others. With the completion of the SUZY II capacitor bank, the electromagnetic implosion of solid cylindrical shells was continued by Turchi, aimed at the demonstration of large radius-ratio implosions (20-30:1) of adequate symmetry and quality to achieve megagauss magnetic fields. In parallel with the experimental efforts, theoretical and numerical studies were continued by Boris and Winsor on modeling liner implosions, and by Barcilon, Book, Cooper and Winsor on the rotational stabilization of Rayleigh-Taylor modes in liquid liner implosions[20,21] following the suggestion of Shanny. The initial scheme for liner-plasma compression was a simple, long cylindrical liner and plasma, following work at IAE Kurchatov. Later, Robson proposed[22] the use of two imploded, opposing rings to compress a spindle cusp plasma (the "flying cusp") and Turchi suggested a cusp-ended theta pinch to restore basically cylindrical liner motion and allow a reversible liner-plasma compression cycle.[23]

SOLID LINER EXPERIMENTS ON SUZY II

As indicated above, the initial purpose of the liner implosion experiments using the 540 kJ SUZY II capacitor bank was to demonstrate the use of electromagnetic driving techniques to achieve liner implosions of interest to the LINUS program. For cylindrical implosions to increase the temperature of a plasma from 100 eV to 10 keV, a radial compression ratio of 30:1 is necessary. To achieve peak plasma densities on the order of 10^{19} cm^{-3}, (so that the free-streaming axial plasma loss from a system only a few tens of meters long would be tolerable during a Lawson time), it is necessary to attain peak magnetic fields of a few megagauss. A computer model for a cylindrical liner implosion driven by the SUZY II bank was developed which treated the liner implosion in terms of the coupling of the driver coil (primary) and liner (secondary) circuits, including resistance (that varied with dissipation), the crowbar switch operation, and plastic deformation-work in the liner during implosion. Parameters were varied to optimize performance in terms of rate-of-rise of mechanical stress in the liner, implosion speed, and peak magnetic field attained. Best results were predicted for aluminum liners 7.0 cm long (equal to driver coil length), 1.0 mm thick and about 30 cm in diameter. Experimentally, good results were indeed achieved. Implosions through radial compressions of up to 28:1 with excellent symmetry and quality were obtained. Implosion speeds up to 1400 m/sec and magnetic fields of 1.4 Mgauss were measured.

While the initial goals of the experimental program were well satisfied by these results, the long-term prospects with such implosions for success in a fusion breakeven experiment were less heartening. First of all, the nonexplosive driving technique did not prevent the explosion of liner material as shrapnel, subsequent to peak compression. This explosion appears to be associated with irreversible changes in the liner during implosion, particularly strain-hardening of the initially annealed aluminum and elastic-plastic buckling of the cylindrical shell as its perimeter is decreased. In contrast to explosively-driven implosions, in which sufficient energy is transferred to internal states of the metal to change its phase into a liquid, the electromagnetically imploded liners (in the speed range of the SUZY II experiments, at least) remain in the solid state. The severe strain in the liner material, however, associated with large radius-ratio implosion, puts the material considerably into the plastic range. As the liner material is forced past itself, dislocations and other imperfections are multiplied making it impossible for the liner to reverse its motion to return to its original geometry. This irreversibility is further enhanced by the folding of the liner shell onto itself rather than simply thickening (elastic-plastic buckling).

The exact pattern of buckling will depend on the particular initial spectrum of variations in liner thickness, radius, modulus, hardness, etc. coupled with variations in the driver coil pressure. Especially important is the timescale of the implosion compared to the growth time of particular mode numbers. Thus, not only would a liner implosion event be expected to end in a shrapnel explosion, but the exact behavior of the liner and magnetic field prior to explosion would vary from shot to shot depending on the life history of the particular liner used (machining, shelf-age, etc.). For example, depending on the arrangement of the liner buckling, the electrical resistance of the liner is different so the magnetic flux diffusion is different. Collapse of metal folds onto each other also provides the possibility of spraying surface layers into the interior region and thereby contaminating possible plasma payloads. Furthermore, control of the explosion by dissipating the kinetic energy of the liner through plastic deformation-work becomes very difficult since the amount of work required to deform the liner depends on the manner in which the liner is deformed and thus on the spectrum of the elastic-plastic buckling. Since theoretical calculations had indicated that several tens of megajoules of implosion energy would be needed to achieve a fusion breakdown experiment, it was necessary to avoid the above-mentioned solid-mechanical difficulties and start with liners in the liquid state.

LIQUID LINER IMPLOSIONS ON SUZY II

The basic problem with liquid liner implosion is hydrodynamic instability, principally Rayleigh-Taylor instability as the liner material is accelerated by lower mass density fluids (either the driving magnetic field or the payload field and plasma). As mentioned briefly above, it was suggested by Shanny that rotation of the liner would stabilize the inner surface during the final stages of payload compression. The centripetal term, $-u_\theta^2/r$, could cause the pressure gradient at the inner surface to reverse direction in favor of stability; (equivalently, the direction of the effective gravity at the fluid interface would reverse direction and point into the heavier fluid). To demonstrate this stabilization technique, a hollow cylinder of liquid sodium-potassium alloy was created by rotation inside a dielectric drum inserted in the SUZY II driver coil. A slow auxilliary bank was fired which created a few hundred gauss magnetic field inside the liquid liner, (which was again 7.0 cm long, but had a thickness of 1.0 cm and an initial inner radius of 12.0 cm). The main SUZY II bank was then fired to implode the liner. In a limited series of experiments, (which were extremely cumbersome because of the conflicting demands of high voltage, high speed rotation, and alkali metal handling) both understabilized and stabilized implosions were obtained[24] in accordance with theory. It appeared therefore that it was indeed possible to exchange energy reversibly between an imploding liner and a lower mass density payload.

The remaining difficulty was to create the implosion in the first place. This was a principal concern in the SUZY II experiment since it was recognized at the outset that the initial acceleration of the liquid metal liner by the driver coil magnetic field would be subject to Rayleigh-Taylor instability. Such instability would result not only in the disruption of the outer surface of the liner but could also penetrate the liner thickness and distort the inner surface as well. Since this would prohibit a successful test of rotational stabilization of the inner surface near peak compression, a back-up experiment was suggested by Turchi in which, in a separate apparatus, the free outer surface of a hollow liquid cylinder would be replaced by a movable, gasketed-plate or stiff membrane. Motion of this plate due to a pulse of high pressure gas would cause the inner surface of the liner to implode. Rotation of the inner surface of the fluid by tangential injection would stabilize the Rayleigh-Taylor modes at the inner surface during payload compression; while elimination of the liner-driver fluid interface at the outside would eliminate Rayleigh-Taylor instability during liner acceleration. Since it would also eliminate instability during the return of the liner material after peak compression, energy could be restored to the driver system from liner kinetic energy. The reversible implosion-reexpansion cycle discussed earlier in the context of the cusp-ended theta pinch liner system[23] could therefore, in principle, be achieved as a consequence of the need to control the liner dynamics.

PISTON-DRIVEN LINER IMPLOSIONS

Although the SUZY II experiments did prove to be successful, the concept of a reversible liner implosion, based on rotational stabilization and elimination of the free outer surface in favor of a moving plate or free piston, was pursued.[25] The first apparatus to test this concept utilized a liner of water (and was hence called the water model) driven by eight circular aluminum discs displaced radially in uniform-bore channels by the pulsed action of high pressure helium. The entire assembly, including pistons, plexiglas piston block, water and surrounding helium plenum, rotated so the inner surface of the liner would be rotationally stabilized as it compressed a trapped-air payload (modeling the plasma-magnetic field payload). Not only did the system provide a reversible implosion, but the liner surface imploded four to five times before friction dissipated the energy of the initial helium gas-charge. On the basis of this success, plans were made to construct a larger, higher energy device (LINUS-0) which would implode sodium-potassium liners to compress magnetic flux.

It had been suggested by J. Marshall and by J. Hammil[26] that the piston plates would stabilize high frequency modes at the liner periphery, but low frequency modes (number less than the number of pistons) would not be stabilized. That is, the pistons could become unsynchronized and low mode number distortions of the inner surface would result. Indeed, when water models were tested with sixteen and then thirty-two pistons, gross asymmetries developed in the implosion. Without a better theoretical and experimental characterization of the growth of asymmetries (including, for example, initial perturbations in piston starting friction and Coriolis force) it is difficult to ascribe the observed asymmetries solely to Rayleigh-Taylor instability,[27] but the concern for larger machines was nonetheless real. An additional concern was the possibility of stable exchange of energy between the basic implosion oscillation and higher modes of varying individual piston positions. In the context of the high speed rotating machine, any possible mechanism for creating significant azimuthal variations of radial mass distribution is considered dangerous and undesirable.

A new piston-drive technique was therefore devised which would guarantee azimuthal symmetry. It consists of an annular piston plate surrounding the implosion chamber and displaced axially to cause the radial implosion of the inner surface of the liner.[28] Since the piston motion is parallel to the rotation vector of the machine (if the entire machine rotates) Coriolis forces on the drive mechanism are absent. With a single annular plate, azimuthal synchronization is accomplished without complicated mechanisms which are difficult to operate at high speeds and stresses. Water models based on the annular piston drive were constructed and tested, and behaved quite well. Implosion surfaces are optically smooth and can be shaped by varying the duct geometry between the piston and the free surface.[8] Radial compressions up to 30:1 have been achieved and up to thirteen oscillations of the inner surface have been measured. Rotational stabilization theory for incompressible liquid liners has been verified using annular-piston water models in which the destruction of the optical quality of the inner surface indicates the onset of Rayleigh-Taylor instability for rotation speeds below those required by theory for stability.

Two high energy density, stabilized liner implosion systems have been constructed and operated. The LINUS-0 device[29] utilizes combustion of high explosive to generate high pressure gas to drive the annular piston. The initial inner surface diameter is 30 cm and the liner length is 15 cm. Implosion speeds up to 120 m/sec have been measured to date. A half-scale version of LINUS-0, called HELIUS,[30] uses high pressure (120 atm) helium to drive the implosion and has been used to study implosions in which liner material compressibility becomes important. Loss of liner material from ports in the endwalls of the implosion chamber has also been studied on HELIUS. Both LINUS-0 and HELIUS are designed for operation with liquid sodium-potassium, but operations will continue with water to facilitate data acquisition on liner hydrodynamics.

SOME NEW DIRECTIONS

The basic thrust of the liner implosion research at NRL for the LINUS program has been the design, development and characterization of liner implosion techniques that have the required properties of safety, reproducibility and scalability for both near-term plasma compression experiments and eventual fusion reactor applications. Concepts and techniques have changed over the last several years to accommodate technical realities and capitalize on new ideas and directions. More recently, for example, the idea of tangential injection of liner material to create the necessary rotation for stabilization has been examined experimentally. The basic goal, which has been discussed for some time, is to avoid the requirement of spinning the entire implosion chamber, piston, etc. Measurements of power loss, and flow distribution on a non-imploding water model indicate that tangential injection may indeed be a useful technique. Future work is planned in which implosion of a tangentially-injected cylindrical flow will be attempted.

Of particular interest is the possibility of a plasma compression experiment using near-term LINUS technology. Examination of various candidate initial plasmas indicates that the reversed field theta pinch or compact toroid[31] is the most promising for a near-term liner compression experiment in which liquid metal liner implosion would be used to increase the energy of a plasma by adiabatic compression. Such a demonstration based on the liner implosion techniques developed at NRL would be a fundamental test for a LINUS controlled fusion reactor.

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