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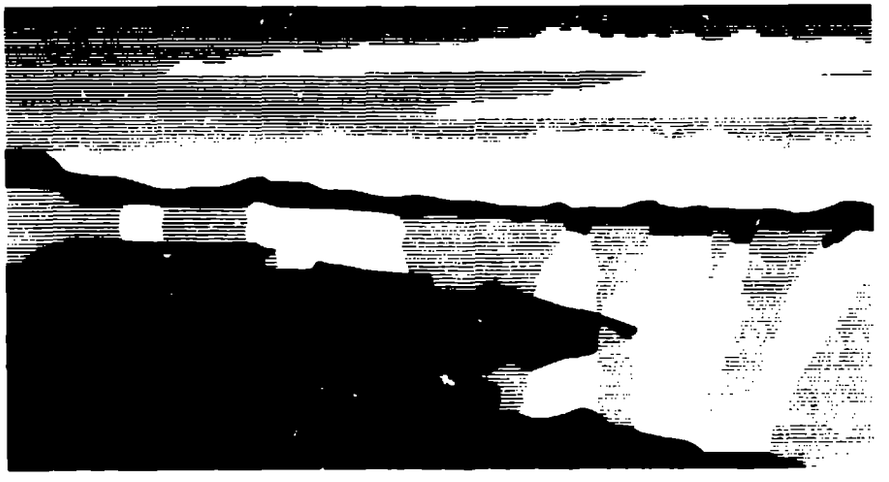
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LOADS FOR PULSED POWER CYLINDRICAL EMPLOSION EXPERIMENTS

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ABSTRACT

Pulse power can be used to generate high energy density conditions in convergent hollow cylindrical geometry through the use of appropriate electrode configuration and cylindrical loads. Cylindrically symmetric experiments are conducted with the Pegasus-II inductive store, capacitor energized pulse power facility at Los Alamos using both precision machined cylindrical liner loads and low mass vapor deposited cylindrical foil loads. The liner experiments investigate solid density hydrodynamic topics. Foil loads vaporize from Joule heating to generate an imploding cylindrical plasma which can be used to simulate some fluxes associated with fusion energy processes. Similar experiments are conducted with "Procyon" inductive store pulse power assemblies energized by explosively driven magnetic flux compression.

I. INTRODUCTION

Cylindrical loads for Los Alamos pulse power experiments of the Athena Program are supplied by the Target Fabrication Staff of the Materials Technology: Polymers and Coatings Group of the Materials Science and Technology Division. The technologies that have been developed to support fabrication of laser driven inertial confinement fusion (ICF) targets which include foams, foils, membranes, films, electroplated coatings, precision machining, precision assembly and specialized characterizations, are also used to fabricate loads for the pulsed power program, components of pulsed power diagnostic instruments and components of plasma opening switch experiments. A brief description of the pulse power facilities, pulse power experiments and the loads used in the experiments follows. Fabrication of the major components used to assemble loads for the principal types of pulse power experiments is described in detail.

II. PULSE POWER FACILITIES

The electrical configuration of the Los Alamos Athena Program pulse power facilities, Pegasus-II and Procyon, in the load region, in simplest terms, is that of a large diameter coaxial transmission line with a thick walled hollow center conductor, a geometry known as a coaxial gun.[1] Hollow cylindrical conducting loads are inserted as a short section of thinned wall, reduced diameter center conductor near the end of the coaxial line. The line may be either hard shorted or, depending upon the experiment, open circuit until shorted dynamically during a pulse power event. As the transmission line is energized, current in the load interacts with the current induced magnetic field rising in the vacuum dielectric region separating the inner and outer conductors. The thin wall hollow cylindrical load is unable to withstand the resultant force and is imploded either as a condensed phase liner or as a vaporized foil plasma, depending upon the original mass of the load, electrical drive conditions and experimental configurations.[2]

Pegasus-II employs a 4.3 MJ, 860 μF capacitor bank, a two-stage Marx bank, which can be charged to 90 kV. Several MA (I<15 MA) can be delivered to a load in a typical circuit configuration of nominally 30 nH and 0.5 mΩ. Each half of the machine consists of four, radially arrayed parallel modules. Explosive detonator actuated solid dielectric switches are driven by a common firing unit to discharge the capacitors through fuse assemblies that open near peak current from the bank at approximately the quarter cycle time of the load circuit. The fusing precludes ringing and prevents potentially damaging voltage reversal of the capacitors after maximum transfer of energy to the series storage inductance of the load circuit.

The Procyon explosively driven system is an assembly of magnetic flux compression generator, storage inductor and coaxial gun load section.[1] The MK-IX flux compression generator is initially energized by a ~475 kA current from a 1500 μF, 36 kV switched Marx bank. The coaxial MK-IX generator is burned axially to amplify current as flux

is driven into the storage inductor.[3] The storage inductor incorporates an explosively formed fuse opening switch which is detonated near peak current from the generator of 21 MA (18MJ), measured in the storage inductor. Detonator actuated closing switches then connect the storage inductor to the coaxial gun load section. The Procyon system is designed to drive 1 MJ z-inch plasma experiments. Current commuted to a load has exceeded 15 MA, current rise time at the load is a few μs, and the entire Procyon event occurs in ~500 μs.

III. PRINCIPAL PULSE POWER EXPERIMENTS

Three principal experimental topics predominate in the Athena Program pulse power activities. Liner experiments have been limited to the Pegasus-II facility. Well behaved liner drive utilizing a liner design described below has been established. Liner experiments can usually be described as applications of the predictable dynamics of the driver liner acting upon experimental target assembly designed to investigate cylindrically symmetric shock effects at up to 300 kb. Load foil implosion experiments are conducted at the Pegasus-II facility and with Procyon assemblies. The experiments are intended to generate black body radiation at soft x-ray energies by stagnating radially accelerated plasma ions originating from vaporized cylindrical load foil material. Current experiments address the efficiency of the radiation generating processes, theoretical models, perturbations and plasma instabilities. Direct drive load foil implosions experiments refer to pulse power events in which the current rise time is determined by circuit values and an electrically conducting cylindrical load foil is vaporized by Joule heating at the maximum current it can sustain as a condensed phase, independent of the current potentially available from the pulse power facility. Plasma opening switch experiments incorporate a shunt plasma in the power flow channel, between the pulse power source and the load, designed to operate for an appreciable fraction of the circuit determined current rise time. The opening switch is intended to delay current to the load until late in the quarter cycle. Current rise time at the load is then decreased, rate of rise ($\dot{I}$) increased, both being determined largely by opening switch operation as opposed to circuit parameter values. Current is then commuted to the load at a magnitude well in excess of the threshold value required to vaporize a typical foil load, to thereby generate a more energetic implosion. Plasma opening switch experiments are conducted on both of the pulse power facilities and may or may not include a dynamic load consisting of a plasma derived from a vaporized cylindrical load foil. The alternative is normally a static load comprised of a heavy wall hollow metal cylinder. or a solid rod, that remains in a condensed phase and present a single valued impedance throughout a quarter cycle of the pulsed power event.

A. Liner Implosion Experiments

Liner experiments are a fairly recent addition to the Los Alamos Athena Program activity, the first event occurring in April 93. This followed identification of several hydrodynamic issues that appeared amenable to a new series of experiments to be conducted at the Pegasus-II facility. The first issue was to demonstrate adequate liner drive performance. An aluminum liner was designed to accelerate to a velocity of 3 mm/μs while remaining in contact with a pair of copper glide plane electrodes for a radial distance of 8 mm. Shock magnitude of 300 kb was predicted upon collision of the liner with a cylindrical target structure of a smaller diameter than the aperture in the glide planes. Drive conditions require only a third of the voltage capability of the Pegasus-II bank (32 kV) at about half the nominal current capability (5 MA) which offered some operational merits.

A "diagnostic pin cylinder" was used throughout the first series of experiments to measure shock magnitude and implosion symmetry. Shock sensors consisted of radially oriented optical fibers with carefully positioned ends. Shock heating of the fiber end results in emission of a measurable burst of black body radiation[4] Intensity can provide a measurement of pressure. Multiple positions of 20 optical pins at each event of the original liner characterization series has provided both implosion symmetry and liner velocity measurements. Triggered Marx x-ray generators have been used to acquire instantaneous radiographic indication of liner position and shape.[5] X-ray diagnostics were developed throughout the original experimental series to now include three axis radiographic capability and multiple flash x-ray generators. The experiments also typically include optical imaging instruments to measure liner motion and a host of Pegasus-II system monitoring instruments. Spatial resolution of the liner position sensing instruments is 80 μm or greater for either static or dynamic measurements.[6] At the conclusion of the original liner drive characterization experiments any implosion asymmetry was less that the limit of spatial resolution. Liner velocities have been within +/-20% of expected values. Unresolved common timing issues, trigger signal propagation delay and instrument calibrations appear to be responsible for most of the observed variations in the measurements as opposed to real variability in liner dynamics.

A current series of liner experiments is designed to measure size and velocity distributions of fast moving particle ejecta originating from the collision of the driven aluminum liner with a less massive thin wall hollow coaxial aluminum target cylinder.[7] The ejected particle flux from the inside surface of the target cylinder is collimated by a 180° narrow slit in a third hollow coaxial cylinder. Triggered axial optical holography is being developed to measure quantity and distribution of ejecta passing through the bore of the collimator cylinder.

1. Liner design. Pure aluminum is preferred as a driver liner material due to a unique combination of density and resistivity.[2] And unalloyed aluminum is selected for the Pegasus-II liner design. The liner is a right hollow cylinder 4.8 cm outside diameter, 2 cm in height. Wall thickness is 0.04 cm. The liner cylinder height is extended beyond the designed active height for fabrication and assembly conveniences. Large flanges are designed at each end of the cylinder to act as low impedance current joints when the liner is inserted into the mating electrodes of the Pegasus-II facility. Hollow cylindrical copper glide planes are inserted into the bore of the liner at each end and bolted to the liner flanges. The distance between the glide planes determines the active length of the liner. The glide planes provide a 0.8 cm wide annular electrical contact surface for the wall of the liner at each end to ride against as it is imploded. The glide plane contact surfaces are inclined 8° to insure contact is preserved as the liner is accelerated. A rectangular notch is designed into the outer diameter of each glide plane contact surface to cut the active liner free, squarely, upon first contact just as the elastic limit of the aluminum is reached early in the implosion event.[8]

The pin cylinder used in the original liner drive characterization series of experiments was designed to be supported on axis by a single three spoke structure bolted to a liner flange. The concentric target cylinder and collimator cylinders of the ejecta experiments are each designed to be supported at both ends by dielectric bushings of low x-ray opacity attached to the glide planes. LE Phenolic was selected to support the target cylinder and black Delrin the collimator cylinder. Simple arrays of 12, 20 and 150 μm diameter wires are designed into the collimator cylinder to first assist in axially locating the depth of focus of the holographic system and then to calibrate the hologram for measurement of ejecta size distribution.

2. Liner fabrication. Pegasus-II driver liners are machined from lengths of 4 inch diameter 1100 series aluminum rod to which a larger diameter 1100 series plate has been attached by full penetration vacuum e-beam welding at one end. The addition of the plate is to provide sufficient diameter and thickness for the larger of the two current joint flanges. Machining is done on a precision Hardinge lathe using high speed steel tooling. Several fixtures have been designed and fabricated for use during liner machining to provide rigid support and to transfer reference surfaces as the part is re-grasped in the lathe. Tolerances are specified as +/-0.001 cm for important dimensions, twice that value for others. All dimensions are measured and documented upon part completion. Surface finish of the liner inside surface is measured using a Federal profilometer; 25 μm rms average being typical.

Pin cylinders from 6061 aluminum rod. glide planes from high purity copper rod, collimator cylinders from tantalum tubing and support bushings from polymer dielectrics are machined using equipment similar to that used to machine the liners. Important dimensions are measured and documented prior to liner assembly. Surface finish of 6061-T6 aluminum target cylinders, 0.02 cm wall thickness, for the ejecta experiments is specified. Parts of 10 to 30 μin rms average are machined from rod similarly to driver liners, 3 to 10 μin rms average surface finish is obtained by single point diamond turning using an air bearing spindle. A 0.04 cm wide collimating slot extending 180° of circumference is milled in the tantalum tubing using a circular carbide cutter. Fiducial wire locating holes, 120 μm and 180 μm diameter are drilled through the wall of the tantalum tubing using a miniature Hauser jig boring machine by first using a carbide end mill to generate a flat surface followed by a carbide twist drill to bore the hole.

Liner assemblies are fabricated on a rotating machine stage using a dial indicator to measure concentricity of the cylinders and, in some cases, on a stage in the field of view of an optical profile projector. The profile projector can be used to measure concentricity and other dimensions of the assembly including fiducial wire diameter. Total indicated run out of any cylinder is typically less than 0.005 cm, less than the resolution of the spatial diagnostics of the experiment.

B. Load Foil Implosion Experiments

Load foil implosion experiments attempt to symmetrically vaporize and implode cylindrical load foils while avoiding undue growth of parasitic plasma instabilities. The experiments are intended to generate sufficient plasma ion kinetic energy and ion fluence to result in significant soft x-ray fluence and black body radiation temperature upon ion stagnation near

the central axis. Typical measurements of foil implosion include optical framing camera images, optical streak camera data in some cases, filtered bolometer measurement of radiated energy in four broad bands, and similar measurements from filtered XRD channels. High resolution spectral measurements are made occasionally for improved characterization of blackbody temperature and a variety of specialized instruments have been fielded to measure specific aspects of the implosion event. The experiments include a large number of measurement channels to characterize operation of the pulse power facility of the event.

Recent direct drive load foil implosion experiments at Pegasus-II typically result in a soft x-ray fluence of up to 250 kJ, radiation pulse width of 200 ns (FWHM). The measurements include evidence of instability growth, multiple modes and off axis implosion in some cases. The Pegasus-II bank is always operated at the maximum value of 90 kV for a load foil implosion event. Direct drive implosion of a typical 12 mg foil will occur at a current in the vicinity of 5 MA, peak current may rise to 10 MA late in the event but with no further contribution to useful radiation. Load foil implosion experiments using Procyon assemblies are just getting underway.

1. Load foil design. Pegasus-II is designed to drive implosion loads that are right hollow cylinders 2 cm high and up to 10 cm in diameter. The Pegasus-II facility is built on a vertical axis; spring loaded jaws in the upper electrode grip the outer diameter of an extension of the active region of a load. Foil implosion loads are fabricated on a pair of parallel support rings, both 10 cm in diameter, one of which is grasped by the upper electrode of Pegasus-II. The lower support ring hangs by the foil in a cavity in the lower electrode of Pegasus-II. A removable core is used to mount the foil support rings during foil fabrication, transport and during any storage periods. The core is removed during insertion of the foil into the Pegasus-II facility. Procyon foil implosion loads are of the same 10 cm diameter by 2 cm high dimension, also use foil support rings and a removable core. However, procyon assemblies are constructed on a horizontal axis so both support rings require attachment to the Procyon electrodes and they are bolted into place. Provision to tension and thereby reshape the foils to some degree is included in the Procyon support system.

Historically, the standard Pegasus-II load foil consists of 4 mg of Aluminum, 2500 Å thick. For a period of several months the foil also included 1000 Å of parylene polymer on the inside surface of the aluminum. Recently, thicker foils have been investigated and foils that included fabricated perturbations of local area density. The currently favored Pegasus-II load foil has become 12 mg of Aluminum, 7500 Å thick, thereby accepting lower black body radiation temperature in favor of lessened susceptibility to implosion degradation by plasma instabilities. The initial Procyon load foil is specified to be 40,000 Å thick and has been fabricated using the same process used for Pegasus-II load foils.

2. Load foil fabrication. Cylindrical aluminum load foil fabrication is based upon a patented process developed at Los Alamos.[9,10] The foils are fabricated by physical vapor deposition (PVD) onto water soluble substrates fabricated from poly(vinyl alcohol) (PVA). Deionized water is used to dissolve 88 mole % hydrolyzed, 78,000 molecular weight PVA. Viscosity is adjusted and maintained at nominally 400 cp. A hollow cylinder fabricated from Pyrex glass tubing, 100 mm i.d. nominal, is dipped into the PVA solution and extracted at a uniform rate. The cylinder height is typically twice that of a completed load foil to minimize end effects. Commercial parting agents may be required on glass that has been used repeatedly. The polymer is oven dried at 90C for a few minutes and then peeled from the glass cylinder surfaces. The cylindrical PVA membrane removed from the inside surface is used as the foil substrate. The membrane is pulled down over the foil support rings mounted to the foil cassette core, described above, adjusted for smoothness, and then tacked to the support rings with moist contact. Small fractions of glycerol may be added to the PVA solution to increase membrane flexibility and increase shrinkage upon drying if required to obtain acceptable substrates.

Aluminum is vapor deposited by a commercial electron beam heated source in a cryopumped vacuum box coater with a typical base pressure of 10^{-6} Torr. The substrate cassette is rotated at 30 rpm throughout the process. Prior to sealing the coater, the polymer dielectric substrate is exposed to filtered nitrogen delivered through a commercial antistatic gun. This procedure is observed to reduce pinhole density in the subsequently deposited Al film. Al is evaporated at a power level to result in an accumulation rate of nominally 10 Å/s at the cylindrical substrate, measured by a calibrated quartz crystal rate monitor. Deposition occurs through an aperture (60° of arc exposed) to limit low angle of incidence artifacts. Oxygen is pulsed into the coater volume upon each kÅ of accumulation to increase foil tensile strength and to enhance surface smoothness.[11] Small witness slides are attached to a foil support ring during each deposition to provide a step for profilometer verification of film thickness. A second verification

of film thickness and a measurement of oxygen content by He RBS using a carbon witness slide is applicable to Al films less than 8 kÅ thick.

Following aluminum deposition, the PVA substrate is dissolved with water to complete the foil. Tap water is used at 60 C to promote solvation while minimizing chemical activity harmful to the metal foil. Mechanical forces are kept to acceptable levels by hanging the foil cassette in a large beaker, gently filling the beaker to a level above the top of the cassette and then draining the beaker via a tap in the bottom. The foils are soaked a few minutes during each rinse and the rinse procedure is repeated three of four times to insure removal of the PVA from the foil. The foils tend to tighten somewhat for several hours following the rinse, often reducing the occurrence of visible wrinkles. Foils that are considered unacceptable are typically cut from the support rings and the foil residue is weighed as a running check of Al mass and to insure the PVA substrate continues to be soluble in the rinse.

C. Plasma Opening Switch Experiments

Normally, the rise time of the current pulse is too slow for implosion of a low mass cylindrical load foil load to be delayed until current has approached the maximum available during a pulse power event. Switching schemes can be used to sharpen the current pulse one of which is to shunt the initial current of the rising pulse as described in the opening paragraphs of Sections III. The plasma flow switch (PFS) under development at Los Alamos was first used by the Phillips Laboratory, formerly the Air Force Weapons Laboratory.[12] The switch is based on a low mass conducting element arranged to short circuit the power flow channel between the current source and the load. Arrival of the current pulse vaporizes the conductor thereby creating a mobile conducting plasma shunt which is magnetically driven down the power flow channel towards the load position. As the switch plasma reaches, traverses and continues beyond the reduced diameter region of the coaxial center conductor mounting the load, the load slot, source current is switched to return through the load and the shunt is eliminated, the opening switch action. Timing of the switch action is determined by the coaxial barrel length, the switch plasma mass, width of the load slot, current and inductance.

1. Plasma flow switch design. The historical plasma flow switch conducting element has been based upon a woven chordal array of fine wires, usually to simulate a $1/R^2$ mass grading across the vacuum dielectric of the coaxial barrel. The mass grading mimics the radial dependence of the magnetic forces acting upon the switch plasma to propagate the plasma uniformly down the coaxial barrel. Usually the switch assembly includes a uniform density polymer membrane, a "barrier film", located between the conducting element and the load slot to prevent either mass or radiation transport down the power flow channel until switch plasma initiation is well advanced. The barrier film mass appears in the switch plasma and thereby forces a compensating adjustment of the conductor film mass grading to result in the desired grading of the net switch mass. Recent Los Alamos designs have replaced the traditional wire conductors with a continuous graded Al foil conductor to provide better switch plasma uniformity, faster plasma initiation and to offer the prospect of greater variation of radial mass grading in flow switch designs. Graded Al foil based plasma flow switches with polyethylene terephthalate (PET) barrier films have been used at both the Pegasus-II facility (50 mg and 100 mg, $1/R^2$ Net) and with Procyon assemblies (200 mg, 1/R Net). More complex designs are in development. The coaxial gun of both facilities has an outer diameter of 8 inches and an inner diameter of 6 inches, therefore the desired thickness grading occurs over a radial distance of 2.54 cm.

2. Plasma flow switch fabrication. Radially graded planar aluminum switch foils are fabricated by PVD using generally similar procedures as described in the fabrication of load foils. Mass grading involves the use of sheet metal masks to intercept Al vapor in locations where foil thickness is to be reduced. Flat, smooth glass disks 9 inches in diameter are edge supported and rotated on axis in the coater to serve as a substrate for graded foil deposition. CsI or a similar water soluble ionic salt is first deposited to serve as a parting layer followed immediately by Al deposition. Al thickness control is by quartz crystal deposition monitor. Depositions on step masked witness slides precede and follow graded foil deposition to provide an average value of graded thickness obtained by profilometer measurement. A nominally 8 inch inside diameter, 1 cm wide mylar ring is centered and glued to the foil after removal from the coater, exact dimensions vary slightly between the two pulse power facilities . The glass substrate is propped at an angle in the bottom of a rectangular plastic tank. Tap water is admitted slowly to release the foil along the contact line and allow the freed portion to float on the surface. The free foil is collected from below on a stretched cloth and dried, after which it can readily be handled by the mylar ring.

PFS assemblies are completed by assembling a sequence of metal rings designed to extend the inner and outer conductors of the pulse power facility coaxial barrels. The graded Al foil and

an area of lightly pre-tensioned PET membrane supported by an oversized frame, are glued to the rings at appropriate times as the assembly proceeds, aided by precision alignment fixtures. Differences in the hardware of the two facilities require minor variations in procedure to assemble the switches. After gluing, the center section of each foil and membrane is cut out to be measured for conformance to specification.

IV. CONCLUSION

The Athena Program pulsed power activities are a part of the Los Alamos Above Ground Experiments Program, AGEX-II, under the Nuclear Weapons Technology Directorate. Pegasus-II will conduct about twenty events during the current year and about half of those will involve applications experiments using liner drive. Four Procyon events will occur in the same period emphasizing efficient generation of high radiation fluence. The Athena facilities have demonstrated remarkable reliability over the past several months and great strides have occurred in experimental diagnostics which are only perfunctorily addressed in this writing. As the shot rate increases, diagnostics continue to improve and the mission becomes a more important laboratory element, we expect to experience increasing demands regarding load complexity, quality and characterization requirements.

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