Experimental Results from SHIVA Star Vacuum Inductive Store/Plasma Flow Switch Driven Implosions


Abstract—Using a 1313-μF, 3-nH, 120-kV, 9.4-MJ SHIVA Star capacitor bank, we have performed vacuum inductive store/plasma flow switch (PFS) driven implosions of low mass (200–400 ng/cm²) cylindrical foil liners of 2-cm height and 5-cm radius. This technique employs a coaxial discharge through a plasma armature, which stores magnetic energy over 3–4 μs and rapidly switches it to an imploding load as the plasma armature exits the coaxial gun muzzle. The current transferred to the load by the PFS has a rise time of less than 0.2 μs. With 5-MJ stored energy, we have driven fast liner implosions with a current of over 9 MA, obtaining an isotropic equivalent 2.7-TW 0.5-MJ X-ray yield.

I. INTRODUCTION

Since the early 1970’s, the Air Force Weapons Laboratory (AFWL) has been investigating the electromagnetic implosion of cylindrical plasma liners to produce high-energy-density plasmas and intense radiation pulses [1]. In 1976–1978, we achieved direct capacitor drive, 1.0–1.5-μs implosions of aluminum and aluminumized plastic liners with capacitive energy stores of 0.7–1.3 MJ, discharge currents of 7–12 MA, resulting in 0.5–1.0-TW radiation pulses, 50–200-kJ isotropic equivalent yield [2]. Anisotropy effects are expected to increase the magnitude of the radiation yield, since the optically thick pinch plasma is elongated along the observing direction. In order to scale these results to multimegajoule energies, we have investigated inductive store pulse compression techniques, including air core inductive store/fast fuse opening switch/surface flashover closure switches [3] and vacuum inductive store/plasma flow switching [4]. Plasma flow switching has the important advantage of lower voltage across vacuum/solid dielectric interface, a mechanically simpler design, and less expensive manufacture.

The plasma flow switch (PFS) technique, originally studied by Turchi et al. [5], employs a vacuum discharge through a plasma armature that stores magnetic energy for several microseconds and rapidly transfers current and energy to a load when the plasma armature exits the vacuum inductive store structure. We have investigated coaxial, cylindrical/radial, and staged vacuum inductive store geometries. In this paper, we discuss results from a cylindrical liner implosion load driven by a coaxial vacuum inductive store.

II. EXPERIMENT CONFIGURATION

During the experiments described here, the SHIVA Star capacitor bank with 5.0-MJ stored energy is discharged through a vacuum coaxial gun, accelerating a plasma armature by $J \times B$ forces, storing magnetic energy over 3–4 μs, and then rapidly transferring current and energy to a cylindrical foil liner implosion load. The geometry is illustrated in Fig. 1. The current transfer time is about 0.2 μs, which is on the order of the cylindrical implosion gap axial dimension divided by the velocity of the plasma armature as it exits the coaxial gun muzzle.

The plasma armature is created by the electrical explosion of an array of wires and its impact on a plastic barrier foil. The armature is designed so that the average areal mass density (mass per unit area) of the assembly is proportional to $1/r^2$. The armature is formed from an array of 1.8–2.0-mil (4.57 × 10⁻⁵ to 5.08 × 10⁻⁵ m) diameter aluminum wires and a stretched 400 ± 20 μg/cm² Mylar foil a distance of 0.635 cm downstream from the wire array. The mass of the assembled plasma armature is approximately 100 mg. The coaxial gun has a 7.62-cm inner radius, 10.16-cm outer radius. The distance from the gun muzzle to the Mylar foil is 6.0 cm. The discharge inductance up to the position of the Mylar foil is 19 nH; this includes the 3-nH capacitor bank/parallel-plate transmission line inductance, about 3 nH for a series 0.94-m-long.
2.125-cm²-cross-section aluminum foil safety fuse and the vacuum/solid dielectric interface, and about 13 nH for the vacuum current feed. The vacuum current feed is baffled to attenuate UV photons from the discharge and to protect the insulator from ablation and breakdown. The safety fuse absorbs energy late in the discharge and protects the SHIVA Star bank in the event of a vacuum/solid dielectric interface failure.

The implosion load is a 5-cm-radius 2-cm-tall 200–400-μg/cm² aluminized Formvar seamless cylindrical foil. In the experiments to date, this foil has a concave bow of about 1-mm amplitude (due to the Formvar surface tension). According to 2-D radiation magnetohydrodynamic (MHD) calculations [6]–[8], this is an important limitation on the implosion performance. The bowing is a large initial perturbation for driving an m = 0 instability.

The electrodes within the initial radius of the cylindrical foil have 2-cm-diameter holes at their center for axial radiation diagnostic access. We have performed experiments with closed and with partially open outer conductors below the coaxial gun muzzle (at the same axial position as the cylindrical implosion electrode gap). The partially open outer conductor design is used only when radial diagnostic access is desired. The implosion electrodes are formed by the muzzle end of the coaxial gun electrode and an electrode 2 cm beyond the muzzle which is not initially electrically connected to the coaxial gun outer electrode. After plasma armature switching, this more distant (lower) implosion electrode is electrically connected to the coaxial gun outer electrode.

In the initial experimental design, the lower implosion electrode consisted of radial vanes from the 5-cm initial foil radius to a 9.52-cm outer radius with a 0.64-cm gap between this electrode outer radius and the axial extension of the 10.16-cm radius outer electrode of the coaxial gun. This design was to allow unrestricted plasma flow from the switching region while trapping the discharge magnetic field. In this design, the experimental transfer efficiency of current to a 200-μg/cm² 5-cm-radius implosion load was 40–50 percent, with the remainder of the current diffusely distributed in the switching region. For very massive loads at the 5-cm radius, the current delivery improved substantially. (The initial results from this experimental series were reported by Baker et al. [4] at the 1985 IEEE Pulse Power Conference.) These results were in substantial agreement with the subsequent 2-D MHD code predictions obtained by Buff et al. using the MACH2 computer code [6]–[8]. Numerical simulations with MACH2 predicted that using a more restrictive outflow boundary condition would greatly increase current delivery to lower mass implosion loads. We accomplished this by making the lower electrode solid out to a 7.62-cm radius while retaining the radial vane structure at larger radii. Two-dimensional MHD calculations of PFS-driven plasma liner impulsions for our approximate experimental parameters were also reported by Lindemuth [9]. In those calculations, he emphasized implosion performance as a function of initial radius. His results agreed qualitatively with the results of Buff et al. [8].

III. RESULTS

With this change to a more restrictive outflow geometry, we obtained the current delivery illustrated in Fig. 2. The ratio of current delivered to the initial load radius is 80–100 percent of the total current for a 200-μg/cm² implosion foil. This is a factor of 2 improvement over previously reported results. These results were achieved with the solid coaxial outer electrode and a solid axial extension. We have yet to perform a series of experiments with the restrictive outflow geometry and a partially open outer conductor.

The experimental diagnostics included Rogowski current probes, capacitive voltage probes, small single-turn magnetic probes (with approximate cross-sectional areas of 10⁻⁶ m²), and an array of X-ray vacuum photodiodes. The current and magnetic probes were calibrated after installation in the discharge chamber, but prior to installation in the transmission line of the SHIVA Star capacitor bank. The B-dot probes were calibrated in situ by discharging a small capacitor through the load in the discharge chamber prior to the installation of the wire and foil arrays. The accuracy of the probe calculation is estimated to be ±10 percent. The Rogowski and voltage probes were located slightly outside the solid dielectric insulator/vacuum interface. The Rogowski coils monitored the load current, while the magnetic probes monitored the current at a number of locations in the discharge geometry (Fig. 1). The experimental curves of Fig. 2 show the total current, the muzzle (gun) current, and the current adjacent to and outside the initial foil radius (where the probe is at 5.5-cm radius). The peak current was 12.2 ± 1.2 MA with a rise time of 3.3 μs. The current delivered to the initial foil radius exceeds 9.4 MA,
assuming that the current is azimuthally symmetric, at a
time approximately 3.75 $\mu$s after the start of the current
flow. The current rise time at the initial foil radius is less
than 0.2 $\mu$s.

A slug model incorporating the electrical circuit was
used to predict the motion of the coaxial armature motion.
The slug model assumes an azimuthally symmetric dis-
charge through an infinitesimally thin, perfectly conduct-
ing $1/r^2$ areal mass density (nontilting) disk or armature.
The armature is accelerated in the annular gap of the
coaxial gun by magnetic pressure (the resultant of the $J \times B$
force). This model treats the circuit as a lumped pa-
rameter $RLC$ circuit with fixed resistance $R$ and capaci-
tance $C$. The inductance $L$ and the time rate of change of
inductance $dL/dt$ are determined by an initial fixed in-
ductance and the position of the annular armature. The
simulation indicated the armature would exit the muzzle
at 3.4 $\mu$s with a current of 11.8 MA. The input parameters
of the model were 90-kV charge, 5.3-MJ stored energy,
19-nH initial inductance, and an armature mass of 99.6
mg. The 0-D slug code realistically models the time-
varying resistance of the safety fuse. A series resistance of
1 m$\Omega$ in addition to the safety fuse is used. The pre-
dicted and the observed current are shown in Fig. 3. The
small disagreement in the time behavior may be due, in
part, to the loss of the armature mass (due to armature
tilting). In other words, some mass loss will result in a
shorter time for the armature to reach the gun muzzle,
resulting in a shorter current rise time.

Bank current, voltage, and a typical X-ray vacuum pho-
dodiode trace are shown in Fig. 4. The voltage peaks at
about 4.1 $\mu$s into the current rise, and the X-ray diode
signal peaks about 4.25 $\mu$s. Notice that the voltage signal
starts to rise when the current passes its maximum at about
3.3 $\mu$s. We interpret this to mean the plasma armature
is starting to exit the coaxial gun muzzle. Inductively cor-
rected voltage at the gun muzzle and at the (changing)
armature position are overlaid on the probe voltage trace
in Fig. 5.

The X-ray signal has a double peak with the second
peak about half the amplitude of the first for the 50-
$\mu g/cm^2$ Formvar plastic filtered X-ray vacuum detector.
(Formvar has an approximate stoichiometry of C$_2$H$_4$O$_2$.)

The FWHM of this X-ray pulse is about 0.2 $\mu$s. The X-
ray photocathodes were all aluminum. The X-ray photo-
diode detectors were filtered by materials with filter re-
sponse functions covering the photon energy range from
15 eV to 3 keV. The X-ray photodiode responses and sig-
nals are shown in Figs. 6 and 7. The spectrally integrated
radiation power versus time, obtained from the deconvoluted radiation spectrum consistent with the array of signals is shown in Fig. 8.

The deconvolution technique [10]–[12] was tested for hypothetical spectra [13], as illustrated in Fig. 9. The numerical tests used AFWL and National Bureau of Standards (NBS) response functions [14], [15] for unfiltered Al photocathodes. (The AFWL response was obtained for less perfect vacuum conditions comparable to those used in this experiment.) The AFWL response was used to generate hypothetical detector signal arrays for hypothetical radiation spectra. Deconvoluted spectra were obtained for both AFWL and NBS assumed-response functions, to test the fidelity of deconvoluted spectra and the sensitivity to response function errors. For smooth hypothetical spectra, such as the radiation spectra emitted from a blackbody, the fidelity is good when one uses six or more different detector response functions covering the spectral energy range of interest [13], and when smoothing is used to avoid artificial features due to discontinuities and edges in the detector response functions [10]. The error sensitivity is linear with relative errors in detector response [13]. The spectrum obtained for this experiment indicates a peak isotropic equivalent emission power of 2.7 TW. As mentioned previously, anisotropy effects, when properly accounted for, are expected to increase the interpreted yield. The energy in the first pulse is over 0.5 MJ. The stored electrical energy is converted to radiation energy with approximately 10-percent efficiency.

We are now preparing to improve PFS-driven plasma liner implosion performance by reducing foil bowing, using gas injection snowplow stabilization [16], and op-
Fig. 7. (a)-(f) X-ray photodiode signals.

timizing foil mass and geometry guided by 2-D MHD numerical simulations.

Acknowledgment

The importance of, and the modification to, the detailed outflow boundary condition for plasma flow switching was suggested by P. J. Turchi.

References


Fig. 8. Spectrally integrated radiation power versus time.

Fig. 9. Deconvolution tests using hypothetical spectra.


