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ANNULAR PLASMAS FOR INTENSE X-RADIATION SOURCES:
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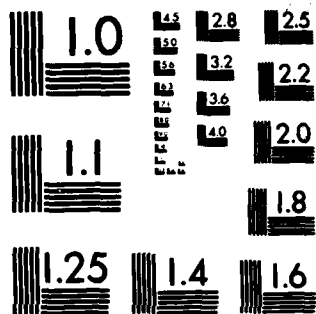
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ASSESSMENT REPORT

D. MOSHER

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EXECUTIVE SUMMARY

Plasma x-radiation sources produced with intense pulsed electrical power have been studied during the past 10 years for applications to vulnerability testing, weapon physics, condensed matter diagnosis, lithography, and x-ray lasing. The most intense of these sources are produced from the electromagnetically driven implosion of a cylindrical plasma annulus. The subsequent compression to small radius heats the radiating plasma to kiloelectronvolt temperatures.

Currently, plasma annuli are created from cages of very fine wires, cylinders of very thin foils, or supersonic gas puffs. The low masses required for these electrical loads create a variety of problems associated with a limited selection of load material atomic numbers, load fabrication, and nonuniform and asymmetric matter distributions and current flow.

The difficulties limit the utility of the x-ray sources in the following ways:

- Many materials with strong x-radiation in important spectral bands cannot be fashioned into acceptable electrical loads.
- Defective loads cause many of the infrequent generator pulses to be "duds."
- Asymmetries and instabilities, by preventing maximum plasma compression, reduce the radiation dose.

A new and disarmingly simple technique for annular plasma production developed at the Ecole Polytechnique, Palaiseau, France, appears to solve many of the source creation problems currently encountered in US Department of Defense programs.

This report evaluates the utility of the new technique by presenting:

- An historical background of plasma source development for the Departments of Defense and Energy programs
- Current US and European activities associated with plasma radiators and applications
- A simple theoretical analysis of plasma implosions to establish parameters for desirable sources
- Limitations of conventional plasma sources
- A description of the Ecole Polytechnique plasma puff system and preliminary experimental results
- A discussion of the advantages of the plasma puff source and recommendations for ONR action.



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ANNULAR PLASMAS FOR INTENSE X-RADIATION SOURCES: ASSESSMENT REPORT

During the early 1970s, research at the Naval Research Laboratory (NRL) in Washington, D.C., led to the development of intense x-radiation sources created by the discharge of terrawatt (10^{12} W) electrical pulses through fine (a few times 10^{-3} -cm diameter) metal wires. The intense electrical heating transformed the metal into a kiloelectron-volt-temperature plasma (10^7 degrees Kelvin), which radiated part of the absorbed energy as soft x-ray lines and continuum with photon energies in the 100-eV to a few-keV range.

The high atomic number plasmas were of interest to atomic physicists because of the high ionization states produced (Dozier et al., 1977). The radiator also was the most powerful laboratory source of thermal x-rays in existence (Mosher et al., 1973). Because of their intensity, exploded-wire radiation sources have applications in material science (*European Scientific Notes*, 36-12: 334 and 345 [1982]) and lithography, and as pumps (Jones and Ali, 1974) or sources (Dahlbacka et al., 1981) for x-ray lasers. The plasma sources became an important part of ongoing Defense Nuclear Agency (DNA) programs assessing the vulnerability of defense systems and components to radiation from nuclear bursts.

During the mid-1970s, researchers at NRL and Physics International Co. (PI), San Leandro, CA, demonstrated that improved coupling to the electrical generator and a higher conversion efficiency of electrical energy to radiation could be achieved by using an array of even finer wires in the form of a cylindrical cage (Stallings et al., 1976). Mutually attractive magnetic forces between the current-carrying filamentary plasmas caused them to be accelerated towards the symmetry axis. The kinetic energy of implosion gained during the 50- to 100-ns electrical pulse was then transformed to plasma internal energy and radiation on the 10-ns time scale of the collision and stagnation of the plasma filaments on

the symmetry axis.

Subsequent experiments at the Sandia National Laboratories (SNL) and the Air Force Weapons Laboratory (AFWL) in Albuquerque, NM, indicated that more symmetric, uniform, and tightly convergent implosions could be achieved by distributing the metal mass in a cylindrical shell rather than a cylindrical cage of discrete wires (Baker et al., 1978). SNL experiments and computer modeling indicated that the radiation produced from annular plasma implosions might be useful for driving small deuterium and tritium bearing pellets to thermonuclear ignition. Along with laser and ion beam drivers, that inertial confinement fusion (ICF) concept became part of the military applications programs of the Department of Energy's Office of Inertial Fusion.

Unfortunately, distributing the required 10^{-4} to 10^{-3} g of matter into a few-centimeter-diameter cylinder several centimeters long means that the shell must be very thin (as low as 100 angstroms). Techniques for making and handling such foils have yet to be developed for most materials of interest. With this problem in mind, researchers at PI and Maxwell Laboratories, Inc. (MLI), developed annular supersonic nozzles that form a puff-gas annulus of the required mass (Smith et al., 1982). Recently, puff-gas plasmas driven by 3.5-MA discharge currents have been imploded with the 10-terrawatt (TW) BLACKJACK 5 generator at MLI to produce intense argon K-line spectra (Clark et al., 1982).

Simple Modeling of Plasma Implosions

In an annular plasma implosion, most of the radial collapse occurs late in the pulse near the maximum of the current I (Figure 1). A decrease in I at late times due to dL/dt loading (where L is the instantaneous inductance of the annulus in the cylindrical return current wall) occurs when the load collapses to small radius. At earlier times, the load looks like a fixed inductance characterized by radius R_0 . The final imploded radius, R_f , will

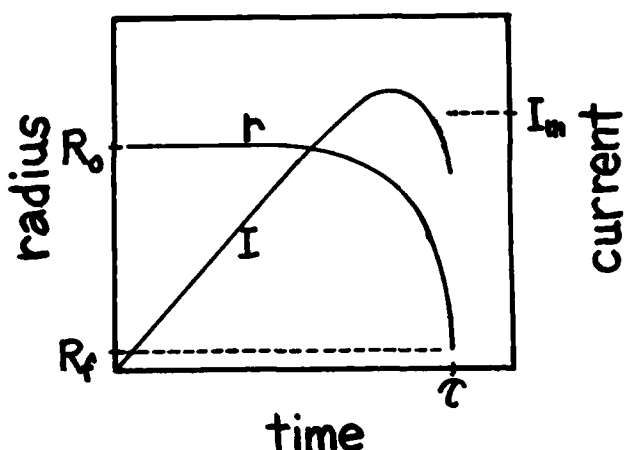


Figure 1. Implosion time history.

be comparable to the annular thickness of the plasma during implosion. With these observations, the kinetic energy transferred to the plasma is easily calculated from conservation of electrical energy.

The instantaneous power into the load is

$$IV = I(L\dot{I} + \dot{L}I) \quad (1)$$

where V is the voltage across the load and the dot indicates a time derivative. The total energy accumulated in the load as a function of time is then

$$\begin{aligned} E &= \int IV dt \\ &= \frac{1}{2} LI^2 + \int \frac{1}{2} (\dot{L} I^2) dt \quad (2) \end{aligned}$$

The first term on the right-hand side of equation (2) is the instantaneous magnetic energy stored in the moving inductor; the second is the kinetic energy, K , of the imploding load.

During most of the radial run-in, the current does not change greatly from the value I_m , so that the integral in equation (2) can be approximated by

$$K \approx \frac{1}{2} I_m^2 \Delta L \quad (3)$$

where ΔL is the total change in L experienced during the run in. For plasma length l in cm and ΔL in nH,

$$\Delta L = 2l \cdot \ln(R_0/R_f) \quad (4)$$

so that for I_m in amperes and K in joules,

$$K \approx 10^{-9} l \cdot \ln(R_0/R_f) I_m^2 \quad (5)$$

The implosion time, τ , can be calculated by integrating the equation of motion with the experimental $I(t)$ and a particular value of m (annulus mass in grams per centimeter) until the implosion radius, R_f , is reached. The experimentally observed implosion time is determined from a sharp decrease in the current and the peak of the emitted x-ray signal. Comparison of the theoretical and experimental values of τ can be used to estimate m . With I in amperes and the other parameters in cgs units:

$$r \frac{d^2 r}{dt^2} = 1 \times 10^{-2} I^2(t)/m \quad (6)$$

which must be integrated numerically unless I is constant in time. If I is treated as constant and approximately equal to I_m during the run-in, the equation for K can be recovered by integrating equation (6) in the form

$$\frac{1}{2} m r \frac{d}{dr} \dot{r}^2 = 10^{-2} I_m^2 \quad (7)$$

Equation (6) can also be used to estimate the collapse time τ . From dimensional arguments and numerical solution (Mosher, 1978), τ is given to within 30% by

$$\tau^2 = 600 m R_0^2 / I_m^2 \quad (8)$$

For a high energy implosion, τ is about 100 ns, R_0 is about 1 cm, and I_m is about 3 MA--so m is about 0.2 mg/cm. Distributed in a foil with a density of 5 g/cm³, the thickness would be about 10^{-5} cm. Small generators require foils as much as a factor of 10 thinner. The technological problems associated with the fabrication and mounting of

such thin foils have led to the use of annular arrays of fine wires and annular gas puffs to achieve the required masses.

There are two energy sources for radiation emission from imploded plasmas. First, as the annulus stagnates on the axis of symmetry, K is converted into internal energy and radiation on the interaction time scale $t_i \approx 2R_f/v_f$, where v_f is the final implosion velocity given by $\frac{1}{2}mv_f^2 = K/1$. Typically, v_f is about $3R_o/\tau$, and about one-third of the electrical matched load energy, E_m , is converted to implosion kinetic energy (Mosher, 1978). This indicates a substantial power multiplication from the electrical input, P_e , to stagnation heating, P_s :

$$\frac{P_s}{P_e} \approx \frac{K/t_i}{E_m/\tau} \approx \frac{R_o}{2R_f} \quad (9)$$

Equation (9) demonstrates that almost one order of magnitude power multiplication might be achieved in implosions with large radial compressions.

The conversion efficiency of kinetic energy to radiation depends on the interaction (stagnation) time and the imploded mass, as shown by a crude conservation of energy equation.

$$K \approx U + P_r \cdot t_i \quad (10)$$

Here, U and P_r are the internal energy and radiated power. Both quantities depend sensitively on plasma temperature, the equation-of-state model, and the radiation transport model used. A proper treatment of energy balance requires the use of sophisticated radiation hydrodynamics computer codes.

In very high current discharges, additional radiation may be emitted by the z-pinch formed after stagnation. That component of the radiation lasts for the duration of the current pulse with ohmic heating balancing radiation losses. This is the primary heating mechanism in single exploded-wire

discharges. However, because the ohmic heating is limited to the generator electrical power, no enhanced radiation associated with power multiplication can be achieved. For properly configured imploded plasmas, stagnation of kinetic energy is the major power source for radiation.

Much of the x-radiation is emitted in the form of thermally excited K series lines from highly ionized states. Thus, the researcher can choose the desired photon energy range for strong emission by selecting a material with characteristic K-lines in that spectral region. K-line x-radiation in the 1.5- to 5-keV range has been studied experimentally by using wire arrays of aluminum and titanium and noble gas puffs. L and M series lines in this photon energy range can also be excited by appropriate choice of higher atomic number materials (Dozier et al., 1977). All these sources are strong emitters in the 100-eV to 1-keV regime, where densely packed lines merge into a continuum (Riordan et al., 1981).

Because strong line emission requires thermal excitation, the highest photon energies emitted can be only a few times the plasma electron temperature. The largest pulsed power generators currently used to drive imploding plasma loads (about 10 TW) create few-keV plasmas and can thermally excite lines up to 5 keV. Empirical scaling indicates that higher photon energy excitation requires an electrical power that increases roughly as $(h\nu)^2$ for a given radiated power.

Imploded Plasma Radiator Research

Department of Defense imploded plasma research for nuclear weapons effects simulation is carried out on the 5-TW PITHON generator at PI and the 10-TW BLACKJACK-5 device at MLI. Researchers use a variety of puff gas and wire array loads. From the theory, the implosion energy increases as the square of the current, so both devices have particularly low output impedances (below 1 ohm) for single-module, coaxial transmission line generators. In recent years, DNA has concentrated on devel-

oping these soft, intense x-ray sources to supplement the hard x-radiation provided by electron beam bremsstrahlung. To this end, the imploded plasma source has been designed into an environmental simulator for vulnerability testing of entire navigational satellites.

PI and MLI are marketing lower power devices with imploded plasma loads as laboratory x-ray sources for research and commercial applications. The devices have conversion efficiencies of 1% (compared with 0.01% for conventional rotating anode sources)--efficiencies comparable to those of the few synchrotron sources in the world that radiate in the x-ray regime. In smaller laboratories, the plasma radiators can therefore act as x-ray sources for spectrographic studies, flash radiography, x-ray microscopy, crystal diffraction, and extended x-ray absorption fine structure. The PI group has used a PIXI pulser (7.5-kJ energy storage) to produce 150 J of neon K-line radiation in a 20-ns pulse which, in collaboration with the MIT Lincoln Laboratories, was used for microlithography exposures (Dahlbacka, 1981). Submicron resolution was obtained from exposed photoresist in an environment thousands of times less clean than required in present semiconductor assembly lines.

Department of Energy research with imploded plasma radiators continues at SNL. Experiments on the PROTO-II generator have concentrated on the use of meticulously fabricated plastic and metal foil annuli to produce radiation pulses of the shortest possible duration. Current plans call for foil implosions to be conducted on the PBFA II device now in design and construction. This 100-TW generator will consist of 36 pulsed-power modules terminated in a single disc line feeding an imploded load radiator. X-radiation as a driver for thermonuclear pellet implosions will be studied. Preliminary experiments and analyses concerning this concept also have been carried out by researchers at PI in collaboration with the Lawrence Livermore National Laboratory.

A multimegajoule capacitor bank at AFWL is used to drive imploding annular foils over larger distances and longer time scales than available with transmission line generators. Large radiation yields have been achieved in the AFWL SHIVA experiment, and applications to Departments of Defense and Energy programs have been proposed.

Imploded plasma radiation sources are used for radiation effects simulation research at the Commissariat a l'Energie Atomique (CEA)--Direction des Applications Militaires (DAM) center at Valduc, Is sur Tille, France. Multiple wire array experiments are conducted on the SIDONIX-1 generator with about 130-kJ stored and 1.2-MA currents delivered to the loads in a 60-ns pulse.

The ANGARA-5 system under development at the Kurchatov Physical Institute in Moscow is a multimodule concept similar to PBFA II. The program director, Leonid Rudakov, has moved ICF-related research away from particle beams and toward radiating plasma implosions. However, the prototype module is not performing to specifications, and there is some doubt that the full system will ever be built. Radiating plasma implosions have been investigated on a variety of smaller devices in the USSR during the last decade, but only the basic physics has been documented.

A capacitively driven gas puff system under the direction of A.E. Dangor at Imperial College, London, uses a 9- μ F bank of 25-kV capacitors to implode 5-cm-diameter annuli for basic dynamics studies. As with the Ecole Polytechnique effort described below, eventual development of laboratory x-ray sources for materials studies and lithography are envisioned.

Plasma Source Limitations

Gas-puff systems now in use have several drawbacks associated with the need to use materials that are gases at room temperature. The selection of atomic numbers for gases is small, so the ability to choose the spectrum is limited. Even the best nozzle designs suffer from annular divergence and a change in gas density with distance from

the nozzle. Because the implosion time depends on the density and annular radius, it is difficult to achieve simultaneous implosion along the plasma length with puff-gas loads. The spread in collapse times results in nonuniform emission along the plasma length and in an increase of the x-ray pulse duration. Special gas-transmitting electrodes opposite the nozzle are needed to limit the back reflection of molecules into the vacuum space. If improperly configured, gas reflected outside the annulus can divert the current, thereby shorting out transfer of electrical energy to the load. Electrodes that allow the gas to pass through freely, such as a grid of fine wires, may introduce implosion asymmetries because of localized return currents. Finally, radio frequency excitation or some other form of plasma preionization may be required for optimal coupling of the generator to the annular load and symmetric implosion. Adding a preionizer makes the gas-puff system substantially more complex.

In my January visit to the Laboratoire de Physique des Milieux Ionisés (Labo. PMI) at the Ecole Polytechnique in Palaiseau, France, Dr. Henri Doucet, the laboratory director, described a new approach to the production of annular loads that may solve most or all of the above difficulties.

Research at the Ecole Polytechnique

The Ecole Polytechnique is one of the *grandes écoles* from which the French state recruits most of its top staff. The Labo. PMI, employing about 30 researchers, is a group of the Centre National de la Recherche Scientifique (which controls the cream of most basic science in France) and receives additional funds from the CEA. The facilities of the Labo. PMI include a two-beam, 400-J, phosphate glass laser for laser-matter interactions research, magnetic-multipole plasma confinement systems for the study of waves and turbulence, devices to study negative ion production for tokamak plasma heating by neutral injection (*European Scientific Notes*, 36-12:348 [1982]), a high-impedance intense relativistic-

electron beam (IREB) generator for free electron laser studies, and a low-impedance IREB device called GAEL. Doucet is beginning a fundamental study of plasma implosions for x-ray source development using GAEL--a 2-ohm, 500-kV, 50-ns generator with 8-kJ electrical energy storage. The annular plasma puff system was developed for that study.

The Plasma-Puff System

Doucet's objective is to generate cylindrically symmetric annuli with low enough mass to be driven by a 250-kA machine and with the right atomic number for x-ray diagnosis. Aluminum is ideal because the K-lines lie above the absorption band of simple vacuum transmission windows but are low enough in energy to be thermally excited by the electrical energy available. Fabrication of aluminum-foil cylinders with sufficiently low mass was clearly beyond the resources of the Labo. PMI. Instead, the desired annular plasma is generated with the equipment shown in Figure 2.

The foil holder, hub, and slit-defining plate are constructed from stainless steel, and the witness plate is copper. The slit plate is mounted in the door of GAEL's vacuum diode, the foil holder is outside the door, and the witness plate is within the device. The annular plasma is therefore puffed into the interelectrode gap of GAEL. The whole assembly is pumped through the diode vacuum manifold.

The 2-mm-wide, 5- μ m-thick aluminum foil annulus is vaporized by discharge of a 7- μ F, 25- to 30-nH capacitor system charged to 15 kV. With a low-inductance, command-triggered switch (that resembles a rail gap separated by a dielectric flashover board), and a 30- to 35-nH (including the foil support) strip-line feed, the electrical circuit had a ringing period of about 3.5 μ s. Foil vaporization occurs about 0.5 μ s after switch closure (just before the first quarter-period maximum), when about 160 kA flows through the circuit.

Experimental Results

The work has just begun and mea-

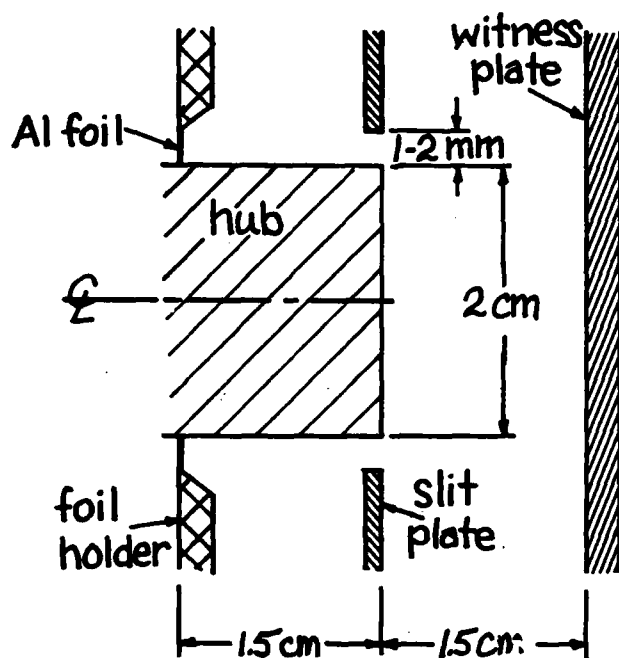


Figure 2. The plasma puff assembly.

measurements on the plasma puff are meager. After a capacitive discharge (GAEL has not yet been fired into this load), the witness plate shows a ring of deposited aluminum well contrasted against the copper. The deposited ring has sharp inner and outer edges, a thickness and radius about the same as the foil annulus and slit, and appears to have uniform density distribution in azimuth. This seems to indicate collimation over the few centimeter lengths desired for imploding loads. On one shot I observed, the slit plate was not installed. In that case, the witness plate showed a sharp inner edge and a fuzzy outer region with decreasing deposited density on a radial scale of several centimeters.

On some shots, the witness plate was removed, and Faraday cups (small charge-measuring devices) were placed downstream from the slit. The plasma puff velocity determined by the relative timing of two Faraday cups separated by a 1-cm axial distance was in the 1- to

2-cm/ μ s range. Some early shots with a single Faraday cup 50-cm downstream showed a 7- μ s dead time followed by a 2- μ s spike with a long (>10 μ s) tail at about 10% of the peak level. The fastest ions were therefore moving at a respectable 7 cm/ μ s, but there is not yet information about whether most of the mass was in the spike or the slower tail. Assuming that half of the mass blows off in the direction of the witness plate and that the fuzzy deposited radial distribution on the shot without a slit characterized plasma spreading from the source, the results indicate annular atomic densities in the 10^{17} cm^{-3} regime.

Because of uncertainties in the voltage across the load, Doucet can only state that the electrical dissipation in the foil is in the 10- to 100-J range. One can estimate that about 50 J are needed to ionize the full mass of aluminum. A comparable energy is required to heat the vapor to a 1-eV plasma state for which the sound speed is the observed 1 to 2 cm/ μ s. The high velocities inferred from single Faraday cup measurements on some shots are not so easily understood. Magnetic acceleration of any significant fraction of the mass leads to velocities of less than 0.1 cm/ μ s. Doucet suggests that on the anomalous shots, the current flow in the aluminum may have time to filament so that a small fraction of the mass is heated to higher temperature. If that were the case, only about 1% of the matter could be accelerated to the high velocities observed. One would then have expected an apparent azimuthal asymmetry on the witness plates. Doucet hopes to symmetrize the current flow by using lower inductance capacitors, thereby decreasing the time to peak current. The witness plate images themselves are difficult to understand. The slitless image indicates aluminum blowing off into a substantial solid angle, yet the sharp edges of deposited annuli with the slit in place do not indicate dispersion.

Evaluation and Recommendations

Taken at face value, the results of

the preliminary experiments are exciting. The technique opens the way for plasma puffs from foils of any metal with the corresponding choice of characteristic spectra. The results indicate unexpectedly good collimation and azimuthal symmetry, so very uniform plasma implosions may be possible. Because the materials are condensable, they should stick to solid, cylindrically symmetric electrodes, thereby eliminating the need for transmission grids and the associated induced implosion asymmetries. Even if some material reflection occurs, the plasma puff is short in duration and can be synchronized with the pulsed power generator so that filling of the vacuum region and subsequent current diversion can be avoided. The Faraday cup signals indicate that there may be enough ionization to make a separate preionizer unnecessary. Best of all, the hardware and associated pulsed power system are simple and inexpensive.

Incorporating a plasma puff capability into the United States' imploded-plasma experimental programs may represent an important advance in radiation source development. I recommend that the Office of Naval Research encourage the reproduction of Doucet's results within the Department of Defense's pulsed power community by communicating interest to DNA and NRL. The Radiation Effects Division of DNA guides x-ray source development for the Department of Defense. The NRL Plasma Physics Division has many facilities on which a test rig can be mounted. Personnel from the Condensed Matter Physics Branch are expert in x-radiation measurements. As important contributors to x-ray source development and weapons effects research, NRL scientists can evaluate the utility of the plasma source for meeting the Department of Defense's objectives.

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