RECEIVED

JAN 10 1996

LA-13025-PR

OSTI

**October, November, and
December 1994**

Table of Contents

Acronyms and Symbols, p. v

Simulation and Analysis of PEG II-25, p. 1

D. Peterson, Plasma Physics Applications

**Resistor Developments for
Atlas Marx Modules**

Fourth Quarter—94, p. 7

M. C. Thompson, Hydrodynamics and
X-Ray Physics—Atlas Project

High Energy Density Physics

Technical Quarterly

Volume III

Los Alamos
NATIONAL LABORATORY

Issue Coordination by Robert Reinovsky, Group NWT/DX-DO/HEDP
Compilation by Janet Neff, Group NWT/HEDP
Cover Photo by Henry Ortega, Group CIC-9
Edited by Hector Hinojosa, Group CIC-1
Graphic Design & Layout by Zizi Kolshorn, Group CIC-1

ABSTRACT

The High Energy Density Physics Technical Quarterly (formerly the AGEX II Technical Quarterly) publishes short technical contributions on above ground experiments that use pulsed power and laser drivers. The Quarterly is intended to provide rapid exposure of timely technical ideas and results as well as a means for documenting High Energy Density Physics progress and scientific quality for the High Energy Density Physics community. Suitable topics include experimental results, diagnostic apparatus, theoretical design, and scaling, among others. This volume is the third in a series, preceded by LALP-94-81 (Vol. I) and LA-12901-PR (Vol. II).

Contributions should be short and compact in the style of Physical Review Comments, Rapid Communications, Letters, or Review of Scientific Instruments Notes. Articles should include an abstract and should be submitted as an electronic file. Accompanying figures should also be submitted as electronic files separate from the main text file.

Authors are responsible for a modicum of peer review because the High Energy Density Physics Program Office cannot administer a full review process.

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the United States Department of Energy under contract W7405-ENG-36.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither The Regents of the University of California, the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by The Regents of the University of California, the United States Government, or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of The Regents of the University of California, the United States Government, or any agency thereof.

LA-13025-PR

UC-700

September 1995

**High Energy Density Physics
Technical Quarterly**

Volume III

**Carl Ekdahl
Program Manager**

Los Alamos
NATIONAL LABORATORY

Los Alamos, New Mexico 87545

MASTER
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *DLC*

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ACRONYMS AND SYMBOLS

ACRONYM/SYMBOL	MEANING
AGEX	above ground experiments
LANL	Los Alamos National Laboratory
MHD	magnetohydrodynamic
RVC	reticulated vitreous carbon

SIMULATION AND ANALYSIS OF PEG II-25

Darrell Peterson
Plasma Physics Applications, XPA
Los Alamos National Laboratory

Abstract

A key component in the use of pulsed power for the support of science-based stockpile stewardship is the capability to understand, computationally simulate, and design the sources provided through pulse power. Building on earlier calculation/experiment comparisons, a simulation of a recent plasma implosion experiment (Peg II25) conducted on the Pegasus II capacitor bank facility has matched the experimental results well over a variety of diagnostic measurements. Such plasma implosions show dramatic instability development, which has a strong effect on the quality (pulse width, peak power, and temperature) of the resulting soft x-ray pulse. The simulation shows a development of instabilities very similar to that seen in visible light framing camera photographs of the implosion. The current, determined self-consistently in the simulation, compares well with that measured, and differs markedly from the results one obtains from 0D to 1D models. Finally, the calculated radiation pulse in both total energy and power is in good agreement with that determined from bolometer measurements. Agreement of experiment and 2D radiation magnetohydrodynamic (MHD) simulation to this level, over a variety of very different diagnostic measurements of such experiments, is unique to the Los Alamos Athena program. Such simulations provide a good basis for understanding the radiation sources provided by plasma implosions and for designing future experiments with optimized sources.

Introduction

From its inception, one of the important goals of the foil implosion soft x-ray source development program at Los Alamos (previously designated the Trailmaster program, now a part of the High Energy Density Physics program) has been to simulate such implosions using a 2D radiation magnetohydrodynamic (MHD) code from the standard X-Division production library. Detailed simulations are important for two reasons. First, we desire to have a scientific understanding of these implosions (as opposed to using engineering experience as the primary guideline for designing foil implosion experiments). This understanding will allow the Athena community to design experiments that will produce results desired by the weapons design community for stockpile stewardship. Such scientific understanding of the implosion and radiation processes will also ensure that the foil implosion x-ray sources are well understood and characterized. Second, the use of XDivision codes in this analysis provides vitality to code development and use, and provides an important connection to the physical measurements from the implosion experiments. Thoroughly analyzing and simulating the implosion experiments exercise the important steps of understanding and reconciling state-of-the-art diagnostic results coupled to large-scale computations.

Direct-drive experiments (with no intervening pulse-sharpening switch) on the original Pegasus I bank and on the upgraded Pegasus II bank are particularly well suited for such work. Although the coupling of bank energy to the foil is not optimal, the

simplicity of the system allows diagnosis of the implosion and measurement of the associated electrical parameters so that they may be compared directly to calculations with a minimum of ad hoc assumptions. A number of successful comparisons have been achieved (unique, as far as the author is aware). The development of instabilities with extremely complicated, nonlinear, magnetically driven Rayleigh-Taylor modes has been observed in both experiment and simulation. Results from 2D simulations have explained timing and features within the radiation pulses (as measured by x-ray diodes) as well as the overall pulse width. Simulations have provided a good match to spectrometer measurements and an explanation for the unusual spectral shape. The correlation of the current and voltage measurements, as they are affected by 2D instabilities, with the final radiation pulse has been explored. Such unexpected results as the beginning of the radiation pulse occurring at peak current (rather than current minimum as 1D results show) and the production of more radiation energy (though at a lower power) than is seen in 1D calculations have been explained by 2D calculations.

A relatively recent experiment in this series has provided a dramatic comparison between experiment and simulation, and is the subject of this report. Experiment Peg II25, fired April 1, 1994, on the Pegasus II bank, imploded an 8440Å-thick, 2cm-high, 5cm-radius freestanding cylindrical aluminum foil with an approximate mass of 14.3 mg over an implosion time of about 2 ms using a peak current of about 5 MA. Particularly good measurements using current diagnostics, bolometry, and visible light framing camera pictures (among other things) were obtained in this experiment. The bolometry indicated a record yield (for Pegasus II) of radiated energy in excess of 250 kJ.

Current and Bolometry Measurements

In Fig. 1 a comparison is shown of the drive current and the measured radiation power for the PEG II-25 experiment with the same quantities calculated by a 2D simulation. The 2D calculation uses a self-consistent circuit model coupled to a 2D radiation MHD Eulerian load. The calculation begins after the foil has been vaporized and is in the plasma state, but has traveled only a small distance (0.1 cm) toward the axis from the original 5cm radius. At this time a random perturbation in the density of the expanded plasma is imposed in the 2D simulation and the calculation proceeds with a rapid development of instabilities, cascading from short to long wavelengths, and final thermalization on-axis and a resultant radiation pulse. The development of magnetically driven Rayleigh-Taylor instabilities determines the shape, duration, and peak power of the final radiation pulse, but cannot be seen in the shape of the current pulse until shortly before peak current. At this time the current waveform begins to deviate from that expected for an unperturbed (1D) implosion, peaking earlier and at a lower maximum current, with a less steep descent and a different minimum current than seen in 1D calculations. In addition, the radiation pulse begins to appear at the peak of the current with a long pulse width and different (larger) total energy than would be seen for an unperturbed implosion. In the unperturbed case, the very short, high power radiation pulse is virtually coincident with the final minimum current dip. The close match of the simulation and the

experiment can be seen in Fig. 1. The radiation pulses have been scaled to fit on the axis used to plot currents, but are in the proper relationship to each other. Total energies (integrating the two curves) are similar and the peaks of the radiation pulses are 0.83 TW (experiment) and 0.76 TW (calculated). As can be seen, the pulse widths and shapes are in close agreement

Fig. 1. Current (solid line) and radiation power (dotted line) as measured in the Peg II25 experiment. The radiation power has been scaled to fit within the y-axis. Also shown are the calculated current (dot-dash line) and radiation power (dashed line, scaled by the same factor as the experimental power). Peak powers for the radiation are 0.83 TW (experiment) and 0.76 TW (simulation).

Visible Light Framing Camera Photos

Visible light framing camera photographs (developed for the implosion experiments by Hank Oona) have been used on a number of experiments to observe the development of instabilities in the imploding plasmas. In Fig. 2a-d, comparisons have been made between framing camera photos (above) at four times during the implosion, and density contours (below) from the 2D calculation. The photos show visible light emitted by the imploding plasma and reveal the structure and dynamics of the pinch. The view is side-on to the aluminum plasma cylinder. The plasma is about 10 cm in diameter (left to right) in the first photo (Fig. 2a) and the full 2cm height from bottom to top electrode can be seen. The vertical black rectangles are return conductor vanes and the dark hemisphere in the lower right is a magnetic probe projecting from the lower electrode. Examination of the edge of the imploding plasma cylinder shows the classic spike-and-bubble pattern from Rayleigh-Taylor instabilities arising from a light fluid (the magnetic field) accelerating a heavy fluid (the plasma cylinder). Horizontal striations can be seen in Figs. 2a and 2b showing the cylindrical nature of

Fig. 2. Framing camera visible light photographs (above) from the experiment and density contours (below) from the 2D simulation for four times during the implosion, (a) $t = 1.32$ ms, (b) $t = 1.48$ ms, (c) $t = 1.65$ ms, and (d) $t = 1.82$ ms. The view is side-on to the aluminum cylinder with an initial diameter of 10 cm (left to right) and a height of 2 cm (top to bottom). Dark regions at the top and bottom of each photo are the electrodes, and two return conductor vanes obscure part of the view in the photos. Also, seen in the photos is a dark hemisphere region where a magnetic probe obscures part of the view near the lower electrode on the right side.

the instabilities and facilitating the determination of the instability wavelength dominant at these times.

At this time we cannot generate equivalent visible light "photos" from the calculated densities and temperatures in the 2D simulation, so we make comparison here only with densities. The position, wavelength, and amplitude of the instabilities seen in the density contours from the calculation can be compared with similar information from the framing camera photos. The four times shown in Fig. 2 correspond to $t = 1.32, 1.48, 1.65,$ and 1.82 ms in Fig. 1. In Fig. 2a, the instabilities have developed from very small scale wavelengths to about $\lambda = 0.33$ cm (six wavelengths across 2 cm) and the amplitude of the instabilities is still relatively small. In Fig. 2b, the dominant instability is now closer to $\lambda = 0.5$ cm (seen most clearly at the left edge of the photograph) and the amplitude is appreciable. The calculated density in Fig. 2b shows a similar development. By $t = 1.65$ ms in Fig. 2c, spike material has been left behind at both electrodes with two bubble regions and a single spike near the center (again, most clearly seen on the left edge). The calculated densities show a similar pattern. Near the upper electrode, a fast growing bubble region is beginning to penetrate through the plasma shell with a spike region immediately below the bubble. Two smaller spike regions near the lower electrode are merging and a somewhat slower developing bubble region is beginning to form that will press inward somewhat later than the top bubble. An effect from the instabilities can be seen by this time in the current waveform in Fig. 1, which has peaked and the increased inductance from the penetrating bubbles is causing the current to decline (in unperturbed calculations the current continues to rise at this time). In Fig. 2d at $t = 1.82$ ms, the bubble located near the top electrode has accelerated material to the axis and the radiation pulse has begun. Spike material in the center now extends in an "angel wing" shape (partially obscured by return conductor vanes in the photo) and a second bubble region is pressing material near the lower electrode to the axis where it will also contribute to the radiation pulse.

Conclusions

Although much remains to be done in simulating and analyzing foil implosions and many issues have not been addressed (for example, the 3D nature of the implosion), the example shown here illustrates the capability of simulating in detail the development of large scale, complex MHD features culminating in current and radiation profiles. This example shows very close correlation with the results seen in an experiment. Such agreement, over a wide range of different diagnostics, between experiment and simulation, is unprecedented in radiation MHD 2D simulations. The capability developed within the Athena program is thus a firm basis for not only understanding such implosions, but also for developing a design and predictive capability for the use of such sources in the High Energy Density Physics effort in nuclear weapons science-based stockpile stewardship.

Resistor Developments for Atlas Marx Modules Fourth Quarter—94

M. Clark Thompson
Hydrodynamics and X-Ray Physics, P-22—Atlas Project
Los Alamos National Laboratory

Abstract

The Atlas pulsed power machine uses resistors in two critical circuit locations. In the first application, series resistors limit voltage reversal on the capacitors while simultaneously limiting fault currents to nondestructive levels. Secondly, shunt resistors across the transmission line limit oscillations between the Marx's and the transmission line. A novel resistor material, reticulated vitreous carbon (RVC), is being investigated for use in one or both of these applications. Initial test results have exceeded Atlas design requirements, and nearly full-scale tests are underway.

The fundamental function of the Atlas machine is to transfer stored energy from a capacitor bank into a research load. The current pulse is delivered to the load by a set of Marx modules radially positioned around a disk-like transmission line system with the load in the center of the disk. The capacitor bank is distributed around the disk as modular units or modules, formed to facilitate both construction and operational maintenance. The bank capacitance and the unavoidable inductance between the bank and the load form a fundamental performance limitation (rise time and peak current) of the machine. A secondary effect of this parasitic inductance is the potential for a resonance that can significantly overstress the capacitor bank by current reversal during ringdown and high peak voltage spikes in the insulation systems. Resistive components are designed in to damp these otherwise resonant networks.

There are two system resistors in the Atlas circuit designed to protect the Marx capacitors and transmission-line insulation. One resistor is a shunt element designed to damp the relatively high Q resonance formed by the Marx bank inductance and the disk transmission-line capacitance. The second resistor is a series current-limiting element that is distributed in the Marx module structures. This series resistor is an integral part of the transmission line system, shown in Fig. 1. It uses a relatively thin rectangular form (56 × 46 × 2.5 cm) in 12 locations in a module transmission-line scheme (240 series resistors total in the Atlas machine). It will serve as the limiter to fault currents through Marx components and system voltage damping. Though this conservative approach requires more total energy be amassed in the capacitor bank, it will provide a more predictable and economical operation for Atlas users, and with the reduction of reversal on the capacitors, will allow use of more compact, higher energy density capacitors.¹

Fig. 1. Cross section of the Atlas Marx bank and transmission line. Series RVC resistors are shown between each pair of capacitors. The shunt resistor is shown as originally designed using a liquid resistor.

Both resistors have high current, high energy-density requirements that are not well served by the conventional electronic resistive component industry. The base Atlas design calls for electrolytic resistors that are a common solution to resistance in large, high energy, pulsed power applications. The advantages of these liquid resistors is their inherent ability to absorb high energy and the ability to tailor the required resistance to the application over a broad range of resistivities via solution concentration and type. The most significant disadvantage of the liquid approach is the liquid itself. The liquid resistor could offer potential leaks of this conductive medium into the machine insulation system that could have catastrophic results.

It is with these thoughts in mind that we search for new resistive media or techniques. We have found a unique material for the series resistor and possible adaptation for the shunt device that is carbon in a different form. We intend to use reticulated vitreous carbon (RVC) foam² blocks for the series resistor elements. There are at least two manufacturers of the material and it can be formed to our needs. For the series resistor the blocks will serve as a resistive transmission line on the back side of the Marx modules providing the lowest inductance practical. As this component is directly in the current path to the load, parasitic inductance has a significant impact on the rise time of the Atlas machine.

RVC is basically a carbonized polyurethane foam with pore densities that typically range from 10 to 100 pores per inch. The resulting density of this form of carbon is 5–15% by volume. The effective resistivity range is 0.4–0.08 Ω -cm and fits our requirements well. The process of producing RVC results in a reproducibly refined

form of carbon in a controllable density, lacking the grain boundary character of commercial bulk carbon-ceramic-mix resistors. The grain boundary of the commercial resistor is frequently the failure site in pulsed power applications where the pulse rise time is relatively fast. This fast, shock-like change in the thermal load of the microstructure of the carbon-ceramic matrix of the bulk resistive material will eventually create a macrofissure in the bulk conductive system resulting in eventual failure of the resistor. The RVC material is a continuous filament of vitreous carbon that provides an uninterrupted path for the current as in any normal conductor, thereby also distributing the instantaneous thermal shock over the entire path/bulk of the RVC volume.

We have applied electrodes to small, 4cm-long, 1cm² samples of the RVC material and pulse tested for current and energy density with results beyond the performance required for the Atlas series requirement. In our first test series, the samples repeatedly withstood over 17 kA/cm² at the electrodes and 130 J/cm³ of 15% density foam material. The Atlas requirements for current density is 8.5 kA/cm² and 23 J/cm³ for fault conditions (normal operation parameters are considerably less). Electrode application was accomplished by metal-arc spray methods with good results both mechanically and electrically. The metal-arc spray penetrated approximately 2–3 mm into the foam assuring both good adhesion and good interconnection to the filamentary carbon matrix. Sample test and Atlas-required performance are shown in Table I.

Table I. Atlas Marx bank series resistor operating conditions.

Parameter	Normal	Fault	Test Result (Oct. 94)
Current Density	3000 A/cm ²	8600 A/cm ²	17000 A/cm ²
Electric Field	820 V/cm	3300 V/cm	1400 V/cm
Energy Density	20.2 J/cm ³	23.6 J/cm ³	130 J/cm ³

The base shunt resistor design uses a pocket in the transmission plate that extends out the back side of the Marx module. This pocket allows the shunt resistor to sit in the circuit as close to the end of the transmission line periphery as possible. The volume shown accommodates the liquid resistors in an accessible package but impacts the parasitic inductance due to the necessary container size. This pocket is an inductance issue in the design of more significance than that of the series resistors. We are investigating other resistance systems that might reduce this inductive volume. One such system, shown in Fig. 2, moves the shunt volume to a vertical region between the bank and rising transmission line plate. This resistive volume produces a much reduced parasitic inductance and could be filled with a very thin sheet of the RVC carbon foam material. However, the material could be no thicker than about 1 mm for the required resistance. The foam sections could be impregnated with polyurethane to give strength to the thin sheets. The thin sheets could be manufactured in sections that plug or clamp together so that each sheet is not so long as to be unmanufacturable and fragile.

We have obtained some prototype series resistor RVC blocks that are half the final resistor width. This will allow us to test for current density and voltage withstand with half the current, a more manageable situation for our test facility at the present time. These blocks are being metal-arc sprayed here at Los Alamos National Laboratory for electroding and will undergo full power tests in early March.

Fig. 2. Single-module shunt resistor. Specifications: 1.6Ω in $5\text{-cm} \times 230\text{-cm} \times 90\text{-cm}$ dimensions. $J = 220 \text{ A/cm}^2$ for full electrode area. Energy density about 2 J/cm^3 for full volume.

REFERENCES

1. W. A. Reass and W. M. Parsons, "Capacitor Developments for Atlas Marx Modules," Los Alamos National Laboratory report LALP-94-81(November 1994).
2. Joseph Wang, Department of Chemistry, New Mexico State University, Las Cruces, NM, "Reticulated Vitreous Carbon—A New Versatile Electrode Material," *Electrochimica Acta*, Vol. 26, No. 12, pp. 1721–1726, UK (1981).

For more information:

High Energy Density Physics Program
Carl Ekdahl, (505) 667-8214, Fax (505) 665-2828

Simulation and Analysis of PEG II-25
D. Peterson, (505) 667-8967

Resistor Developments for Atlas Marx Modules
Fourth Quarter—94
M. C. Thompson, (505) 667-7555

This report has been reproduced directly from the best available copy. For more information, contact authors of individual articles.

This report is available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62,
Oak Ridge, TN 37831.
Prices are available from
(615) 576-8401.

This report is available to the public from the
National Technical Information Service,
US Department of Commerce,
5285 Port Royal Rd,
Springfield, VA 22161.