### Table of Contents

<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
<th>Page #</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Introduction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overview</td>
<td>J. S. Thompson</td>
<td>6</td>
</tr>
</tbody>
</table>

**Scientific Programs**

### Experiments

- Stabilization of plasma instability in implosions of "star"-like wire arrays  
  - V. Ivanov  
  - 9
- Ablation and implosion dynamics in linear wire arrays  
  - V. Ivanov  
  - 11
- Dynamics of mass transport and magnetic fields in low wire number array z-pinches  
  - V. Ivanov  
  - 13
- Experimental studies of planar wire arrays and comparison with cylindrical arrays on 1 MA zebra generator and possible applications to ICF research at the SNL  
  - V. Kantsyrev  
  - 15
- Radiative properties of implosions of combined planar wire arrays and X-pinches composed from different wire Materials on 1 MA Z-pinch generator at UNR  
  - A. Safronova  
  - 17
- Dynamics of laser-plasma expansion in an external magnetic field  
  - R. Presura  
  - 19
- Laser magnetized plasma interactions for the creation of isochorically heated solid density warm matter  
  - R. Presura  
  - 21
- Effect of sheared flow and on-axis wire on wire array z-pinch dynamics  
  - R. Presura  
  - 23
- Energy deposition in solids by laser pulses: acoustics and material ablation  
  - D. Atherton  
  - 25
### Table of Contents

<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
<th>Page #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explosion of palladium wires saturated with hydrogen and deuterium</td>
<td>T. Darling</td>
<td>27</td>
</tr>
<tr>
<td>Photodetachment studies of Atomic and Molecular Anions</td>
<td>A. Covington</td>
<td>29</td>
</tr>
<tr>
<td>High-Pressure Infrared Absorption Spectroscopy of Polymers</td>
<td>R. Kraus</td>
<td>31</td>
</tr>
<tr>
<td>Progress in Resonant Ultrasound Spectroscopy (RUS) studies of phase transformations and microstructural effects in solids</td>
<td>T. Darling</td>
<td>33</td>
</tr>
<tr>
<td>Developments of laser targets and operations of the target fabrication laboratory</td>
<td>N. Renard-Le Galloudec</td>
<td>35</td>
</tr>
<tr>
<td><strong>Simulation &amp; Theory</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activities of theory/simulation group of high energy density physics with ultra-intense laser pulses</td>
<td>Y. Sentoku</td>
<td>40</td>
</tr>
<tr>
<td>Relativistic collision model for large density scale plasmas</td>
<td>Y. Sentoku</td>
<td>42</td>
</tr>
<tr>
<td>Proton acceleration by laser-plasma interaction: energy increase and beam control</td>
<td>E. d'Humieres</td>
<td>44</td>
</tr>
<tr>
<td>Generation of keV solid-density plasma with untrashort laser pulses</td>
<td>Y. Sentoku</td>
<td>46</td>
</tr>
<tr>
<td>Full scale integrated simulation of fast ignition</td>
<td>Y. Sentoku</td>
<td>48</td>
</tr>
<tr>
<td>The importance of EBIT data for Z-pinch M-shell W plasma diagnostics</td>
<td>A. Safronova</td>
<td>50</td>
</tr>
<tr>
<td>Investigation of Global MHD instabilities in multispecies Z-pinch plasma</td>
<td>V. Sotnikov</td>
<td>52</td>
</tr>
</tbody>
</table>
## Table of Contents

<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
<th>Page #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinear dispersion of resonance extraordinary wave in a plasma with strong magnetic field</td>
<td>V. Sotnikov</td>
<td>54</td>
</tr>
<tr>
<td>Investigation of nonlinear dynamics of flute mode instability in finite beta plasma in support of Z-pinch and laboratory astrophysics experiments</td>
<td>V. Sotnikov</td>
<td>56</td>
</tr>
</tbody>
</table>

### Facilities & Operations

#### Leopard Laser Facility

<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
<th>Page #</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTF's laser program progress in 2006</td>
<td>P. Wiewior</td>
<td>60</td>
</tr>
<tr>
<td>Leopard laser's PILC and test systems</td>
<td>S. Samek</td>
<td>64</td>
</tr>
<tr>
<td>Leopard laser command system</td>
<td>V. Nalajala</td>
<td>66</td>
</tr>
<tr>
<td>Leopard pulsed power system commissioning</td>
<td>B. Le Galloudec</td>
<td>68</td>
</tr>
<tr>
<td>Refurbishment and activation of the Phoenix laser target chamber at the NTF</td>
<td>N. Renard-Le Galloudec</td>
<td>70</td>
</tr>
</tbody>
</table>

#### Zebra Accelerator Facility & Tomcat Laser

<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
<th>Page #</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTF infrastructure development 2006-2007</td>
<td>S. Batie</td>
<td>73</td>
</tr>
<tr>
<td>NTF infrastructure development</td>
<td>S. Batie</td>
<td>75</td>
</tr>
<tr>
<td>Wire loads for the NTF Zebra accelerator 2006-2007</td>
<td>S. Batie</td>
<td>77</td>
</tr>
<tr>
<td>Wire loads for the NTF Zebra accelerator</td>
<td>S. Batie</td>
<td>79</td>
</tr>
<tr>
<td>Zebra accelerator operations 2006-2007</td>
<td>S. Batie</td>
<td>81</td>
</tr>
<tr>
<td>Zebra accelerator operations 2005-2006</td>
<td>S. Batie</td>
<td>83</td>
</tr>
</tbody>
</table>
# Table of Contents

<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
<th>Page #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental assistance on Zebra and Tomcat</td>
<td>B. Le Galloudec</td>
<td>85</td>
</tr>
<tr>
<td>Outreach Activities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NTF's Outreach activities for 2006</td>
<td>N. Renard-Le Galloudec</td>
<td>87</td>
</tr>
<tr>
<td>Staffing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Employee listing</td>
<td></td>
<td>90</td>
</tr>
<tr>
<td>Publications &amp; Presentations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Listing</td>
<td></td>
<td>92</td>
</tr>
</tbody>
</table>
Introduction
Nevada Terawatt Facility Annual Report 2006/07
Overview

J. S. Thompson

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The Nevada Terawatt Facility has made significant progress towards establishing strong scientific research programs, managing an operational research facility and completing the development of major research capabilities at the Nevada Terawatt Facility. We have demonstrated our ability to operate the 2 TW (Zebra) accelerator as a scientific facility and our capability to build a 100 TW class laser (Leopard). Our computer cluster is fully functional and has 86 nodes and 18.6 Tbytes of memory. Research groups have continued and enhanced strong collaborations with scientists at NNSA laboratories and initiated experimental investigations with research groups in the Physics Department at the University of Nevada, Reno and the Atmospheric Physics program at the Desert Research Institute. The research programs have stressed graduate education, and the number of successful graduate students in the program continues to improve. The operations and scientific staff emphasized working in a safe environment, and we continue to coordinate our operations with the University’s EH&S department. The University also instituted a card lock access system and automatic locking gate for the Sage Building, where the Nevada Terawatt Facility is located, to restrict access to non-University employees.

Scientific Programs:

This report contains abstracts from each of the research groups supported by the Nevada Terawatt Facility. There are five experimental research groups and two groups in theory and modeling supported by the Cooperative Agreement. Two experimental groups are using Zebra to study the physics of wire arrays from the pre-pulse or initiation phase to stagnation. One experimental group uses Zebra to generate magnetic fields for laser generated heating and plasma shock studies. This group has been able to synchronize the 100 TW laser (Leopard) with the Zebra accelerator. The materials science group has studied materials under static high pressures and investigated non contact methods for sensing phase changes in materials. They have also developed new wires for wire array studies using Zebra. The fifth experimental research group has prepared a target chamber for experiments utilizing Leopard, and has worked with a nanofabrication company to produce novel laser targets for enhanced generation of x-rays and ions.

There are two groups specializing in theory, simulation and modeling. One group specializes in PIC simulations and has studied novel laser targets, techniques for laser-driven isochoric heating of material and concepts for fast ignition in laser fusion. The other group specializes in hybrid simulations of plasmas and has investigated plasma instabilities and dynamics of two component plasmas.

Graduate and undergraduate students are fully engaged in each of these research activities. I anticipate that two students will graduate with Ph.D. degrees in 2007 and we should reach a steady state of three to five Ph.D. degrees completed per calendar year within the next two years.

Facilities:

Zebra Accelerator:

The Zebra accelerator was transformed into an operational scientific research facility in 2006. We performed 372 scientific shots on Zebra in 2006 and have completed 100 scientific shots through the
first quarter of 2007. The engineering and operations group has streamlined the shot to shot turnover procedure and is able to shoot scientific loads on an average of two to four times per day. This group has also standardized the design of shot hardware and established a procedure for designing and manufacturing hardware on a timeline based on the schedule for experimental group’s access to Zebra. The engineering group has also developed a suite of core diagnostics for the Zebra accelerator that they operate and maintain for the experimental research groups.

**Leopard Laser:**

The Leopard laser is a silicate and phosphate glass rod and disk amplified system designed to provide 100 TW of energy at the fundamental wavelength. In 2006, the components of the laser were designed, tested and installed in the laser bay. All of the components, including flashlamps, were tested at the NTF before being installed in the amplification chain. The laser’s design specifications were met in early 2007 when the full amplified energy of the laser, 30 J, was compressed to 300 fs by a grating compressor. The synchronization and master clock for firing Leopard and Zebra has been completed and coupled operation should begin in mid-April of 2007. The Leopard laser should come on line as a research facility by the end of 2007 with the delivery of an adaptive optics system, and a beam monitoring and master operations control system that will be contracted with external vendors.

**Cheetah Laser:**

The Nevada Terawatt Facility has contracted with Amplitude Technologies for delivery of an ultra fast laser in the summer of 2007. The laser will deliver 250 mJ of 800 nm light in a pulse duration of less than 25 fs at 10 Hz. The system is upgradeable to 1 J per pulse. This laser will operate on the master clock and will be able to be synchronized with Zebra and Leopard. Experimental programs are under development and include pulse probe experiments with Zebra and or Leopard, ultra fast laser plasma studies and fast chemical dynamics.

One area of facility improvements that has not been given sufficient attention during the development of the research facilities has been the building HVAC in the research bays. We will be addressing this issue during 2007 and should be able to provide a research environment with a stable temperature in a range conducive to faculty, staff and experimental equipment.

**Outreach and Recruiting:**

The faculty and staff of the Nevada Terawatt Facility have actively participated in outreach activities to K-12 schools through University and College initiatives in 2006. Several hundred students have toured the facility and seen wire loads shot on Zebra, and the experimental data from the shot. The response of the students and teachers participating in this activity has been overwhelmingly positive.

The Nevada Terawatt Facility needs to recruit and graduate high quality Ph.D. students for our research programs, and to meet our commitments to our sponsors. One of the research faculty members has been assigned the responsibility of developing a recruitment plan, and implementing the plan in the 2007-08 academic year. This faculty member will also be responsible for tracking and reporting on graduate students’ progress toward completing their degrees. This activity will not be supported by direct costs to the sponsoring agency.

**Acknowledgements:**

This report would not have been completed without the dedication and creativity of Ms. Geraldine Ferguson, Ms. Celia Ranson and Dr. Emmanuel d’Humieres. This work was supported by the US Department of Energy under Cooperative Agreement DE-FC52-06NA27616.
Experiments
Stabilization of plasma instability in implosions of “star”-like wire arrays

V. V. Ivanov¹, V. I. Sotnikov¹, A. Haboub¹, A. L. Astanovitskiy¹, A. Morozov, S. D. Altemara¹, C. M. Thomas¹, S. Batieⁱ, V. Nalajala¹, B. Jones², C. A. Coverdale²

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Z-pinches produce powerful x-ray radiation, which have been applied to fusion research and high energy density plasma physics [1,2]. Cylindrical and double nested wire arrays produce energy ~1.8 MJ and power >280 TW in 20-MA z-pinch [1,2]. Recently linear wire arrays were tested and have demonstrated a high x-ray yield [3].

In this paper implosions in “star”-like loads were investigated in the first time. Triple and quadruple “star”-like loads were compared with nested, linear, and cylindrical arrays. It was found that in “star”-like loads implosion is directed along the radial wire rows cascading from wire to wire. Smoothing of MHD instability during cascade implosion provides high peak power of radiated soft x-rays.

Figure 1 presents a scheme and image of the triple 24-wire Al array. The implosion dynamics and x-ray yield were investigated by the five-frame laser probing with a pulse duration 150 ps, an optical ICCD camera, filtered PCDs/XRD, a Ni bolometer, and time integrated and time-gated pinhole cameras [4].

Figure 2 shows the power of the radiated soft x-ray pulse measured from the XRD with 6-μm Kimfol filter and Ni bolometer for various loads. Triple loads are compared with nested double arrays and cylindrical 16-mm loads. Triple arrays produce 2-3 times more power than cylindrical arrays and ~30% more than double nested arrays. Multiframe shadowgraphy showed that high efficiency of triple loads correlates with the low level of MHD instability. Figure 3 presents implosion in 4-wire cylindrical array (a), 8-wire double array (b), and 12-wire triple array (c) with the same azimuthal symmetry. Implosion in the cylindrical array, Fig. 3(b) is inhomogeneous and non-symmetrical [5]. Implosion in the double array, Fig. 3(b) begins on edge wires. A magnified image (d) shows strong plasma instabilities. In
triple arrays implosion also starts on the edge wires and cascades to the center like in linear arrays [6]. Fig. 3(c) presents the last phase of implosion in the triple array. Imploding plasma is concentrated in three columns moving to the center. Pictograms (1) and (2) give a direction of laser probing in shadowgrams (b) and (c). The magnified image (e) in Fig. 3 shows that plasma instabilities in triple array are smoothed after collision with other wires.

Figure 4 presents a two-frame shadowgram of implosion in the quadruple array (12 wires, 12 μm, 36μg/cm). A plasma column with a smooth leading edge is formed on the last wire of the radial row.

Instability grows on the back edge of the plasma column. Smooth leading edge and precision timing of imploding plasma columns produces a stable 9-12-ns soft x-ray pulse with the peak power ~0.4 TW. The x-ray pulse from quadruple arrays is more stable than in other tested loads. Figure 5 presents shot to shot variation in quadruple 24-wire array (red squares), 12-wire array (blue squares), 24-wire triple arrays (red triangles), 12-wire triple arrays (blue triangles) and 16-wire double arrays (green circles). Quadruple “star”-like arrays demonstrate the best stability, presumably because of the low level of the MHD instability. A higher level of MHD instabilities could explain a fall of soft x-ray power in the light load (19-25 μg/cm). Shadowgrams show that the magnetic Rayleigh-Taylor instability breaks the moving plasma columns in light “star”-like loads before they reach the array axis.

Quadruple wire arrays were compared with triple, linear and compact cylindrical loads (with diameters 3, 8, and 16 mm) and showed 10-20% more power of soft x-ray radiation in the Zebra generator. Experiments were carried out with different configurations of “star”-like loads. X-ray power increases in loads with better azimuthal symmetry and in the compact loads with smaller diameter. Other materials, like stainless steel and Ni also showed a high x-ray yield in “star”-like configuration.

“Star”-like loads with decreased mass produce the highest power of the K-shell x-ray pulse despite a decrease in the soft x-ray yield. Two-frame shadowgraphy shows that the speed of implosion and kinetic energy is larger in light loads. This can explain the effective production of K-shell radiation.

In conclusion, “star”-like loads present the most powerful source of soft and K-shell x-ray radiation in the Zebra generator. Imaging diagnostics show that high efficiency in the soft range correlates with smoothing of MHD instabilities.

6. V.V. Ivanov et al., Phys. Plasmas, to be published.
Ablation and implosion dynamics in linear wire arrays

V.V. Ivanov¹, V.I. Sotnikov¹, A. Haboub¹, G.E. Sarkisov², R. Presura¹, T.E. Cowan¹

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Wire array Z-pinches are effective radiators of powerful x-ray pulses, which are applied to fusion research and other areas of dense plasma physics [1]. Recent experiments have demonstrated that linear wire arrays produce high x-ray yields [2].

In this paper the detailed implosion dynamics in linear wire arrays was investigated at the 1-MA Zebra generator [3]. Optical diagnostics of the z-pinch plasma included five-frame laser probing and a time-gated ICCD camera. The x-ray diagnostics includes photoconductive detectors (PCDs), an x-ray diode (XRD), a Ni bolometer, time-gated and time-integrated cameras and spectrometers [4].

The experiments showed that cylindrical and linear wire array z-pinches pass through the same basic stages of ablation and implosion [3,4]. In the ablation phase, plasma streaming from wires has an axially periodic structure. Due to faster ablating of material, breaks arise first on the two outer edge wires. Extended “fingers” of trailing material are seen at the stagnation stage. At the stagnation stage imploded plasma produces a z-pinch on the axis and this pinch radiates the main portion of x-ray radiation.

The implosion bubbles arise in breaks on the wires like in cylindrical arrays [4,5]. Bubbles indicate a burnout of edge wires and the beginning of the implosion phase. The speed of the leading edge of bubbles >2.5·10⁷ cm/s was measured from two-frame shadowgrams. The formation of bubbles is similar to formation of bubbles in cylindrical wire arrays but interferometry also shows a difference. In linear arrays the phase shift in the wire breaks was <0.4 fringes compare to the phase shift ~3-4 fringes and n~10¹⁹ cm⁻³ in cylindrical arrays. Current in the linear array moves with the bubble front and does not switch back to the plasma on the edges.

Figure 1 presents implosion in the 8-wire linear array. Two wire gaps near the edges were enlarged for clear viewing of details of the implosion. In Fig. 1 (a) the plasma bubbles from the edge wire hit the next wire in the array. The Alfvén speed in the plasma column is <<V_{plasma} therefore bubbles produce a shock. Kinetic energy, converted to the energy of the shock, breaks the core in the plasma column. In Fig. 1 (b) a part of the wire plasma column without the core begins moving to the next wire in the array. MRT instabilities are seen in moving plasma in Fig. 1 (c). Plasma moves to the center of the array cascading from wire to wire.

Investigation of the ablation and implosion phases showed also significant difference between cylindrical and linear arrays. In linear arrays, the ablation begins on the edge wires subjected to the largest mutual magnetic field. At the time that plasma bubbles arise on the edge wires other wires remain in the ablation phase and are still at the initial positions. Bubbles hit the next wire’s plasma column in the array. Interaction of the shock with the core-corona structure leads to the acceleration of plasma and the plasma column begins evolution toward to the next wire. In cylindrical arrays...
the typical scale of perturbations (0.4-0.5mm) increases in axial size and merges to form a spatial wavelength ~ 4x the initial axial period. In linear arrays the character axial scale is lost every time when collision of bubbles with the next wire takes place. This prevents generation of large scales in the spectrum of MHD perturbations.

The observed plasma distribution and directions of ablating plasma depend on the configuration of the mutual magnetic field in the wire array. Ablating plasma does not reach the axis of the array if the central gap is enlarged. Figure 2 shows ICCD images from the equidistant array and from the array with the enlarged central gap. Figure 2(a) shows the equidistant array, 20 ns after the beginning of the current pulse. Radiating plasma columns are seen in all inter-wire gaps of the wire array. Figure 2(b) presents the array with the enlarged central gap, 10 ns after the beginning of the current pulse. The central gap in this array is free of plasma.

Figure 3 presents five frames of the gated x-ray pinhole camera (a-e), two frames of the laser shadowgraphy (g,h), and the timing diagram (f). The shadowgram (g) and x-ray frames (b,c) show the off-axis precursors at 25-35 ns before the beginning of the main x-ray pulse. In Fig. 3(g) the implosion begins in the edge wire and plasma bubbles moves to the next wire. The precursor merges to the plasma column of the near axial wire in Fig. 3(h). Hot plasma spots arise in the x-ray image Fig. 3(d). The x-ray image in Fig. 3(e) shows the moment when plasma and the majority of current are concentrated in two inner wires. Radiation of these two plasma columns produces a 10-ns sub-keV prepulse in the diagram Fig. 3(f). The main x-ray pulse arises when two plasma columns collapse to the pinch on the axis of the array. The equidistant arrays produce ~2 times larger peak power. X-ray yields in arrays with enlarged central gap were smaller in 5-10% compare to equidistant arrays.

In linear arrays, bubbles snowplough material between wires, bringing kinetic energy and current to the next plasma column. Cascade implosions can produce a preheating of the imploding plasma. The mechanism of rescaling of perturbation observed in linear arrays can be relevant to nested wire arrays.

Dynamics of mass transport and magnetic fields in low wire number array z-pinches

V. V. Ivanov¹, V. I. Sotnikov¹, G. S. Sarkisov², T. E. Cowan¹, S. N. Bland³, B. Jones², C. A. Coverdale², C. Deeney², P. J. Laca¹, A. L. Astanovitskiy¹, A. Haboub¹

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Progress in z-pinch physics research has established the wire array z-pinch as the most powerful laboratory source of soft x-ray radiation [1]. Z-pinch physics has provided new directions for fusion studies, dense plasma and radiation physics, laboratory astrophysics, and other areas of science. Recent experiments have demonstrated a broad radial mass distribution during implosion in wire arrays at the 20-MA Z facility [2] and at 1-3 MA facilities. “Bubbles” in plasma streams formed at the start of implosion have been observed at different pulsed power generators [2,3].

In research done at the University of Nevada, Reno in collaboration with the Sandia National Laboratory, Albuquerque, and Imperial College, London, an important step has been made in the understanding of fundamental processes involved to wire array implosions. Using multi-frame laser probing techniques in the 1-MA Zebra generator, measurements of the microscopic origins of mass flow instabilities and current distribution were performed [4]. A short probing laser pulse provides instant images of the fast moving plasma. It is shown that the mass transport during the implosion is realized by plasma “bubbles” arising on breaks in the wires. Interferometry reveals that the leading edge of the bubbles brings material from wires to the axis during the implosion. The speed and acceleration of material during the implosion was measured. It was shown for the first time, that current flows through the wire gaps, and current in jets that extend from the bubbles to the precursor formed on axis.

The experiments were carried out on the 1-MA Zebra generator. Plasma diagnostics include five-frame laser probing of the z-pinch in three directions [5]. Four frames of the shadowgraphy cover two probing directions. The third probing direction includes shadowgraphy, Faraday rotation diagnostics, an interferometer, and schlieren diagnostics all at one temporal location. A short 150-ps laser pulse provides instant images of the fast moving plasma on CCD cameras. Temporal profiles of the x-ray pulses were recorded with filtered photoconducting detectors (PCDs). The experiments were carried out with 2 cm tall, 1.6 cm diameter Al wire arrays.

The early stage of the implosion phase in an Al 8-wire array is presented in Fig 1. The arrows labeled (1) show

![Fig. 1. Two-frame shadowgrams (a, b) and (c, d) from two shots in Al 8-wire arrays. The delay between frames is 7 ns.](image-url)

development of the implosion bubble from the wire break. Bubbles in the plasma streams suggest a burnout of the wire cores and the beginning of the implosion phase, as suggested in [8]. In the 8-wire arrays, breaks...
on the wire arise ~30 ns before the start of the x-ray pulse, are seen in Fig. 1(e). Fig. 1(c, d) highlight the development of the bubbles.

Interferograms show that the leading edges of the bubbles deliver material from the wire to the axis. This leading edge can accrete ablated plasma filling the array before the beginning of implosion stage. A significant portion of the plasma resides in these structures. The plasma density on the leading edge of the bubbles is \( n_e > 10^{19} \text{ cm}^{-3} \). The plasma density inside the large bubbles is \( n_e < 8 \cdot 10^{17} \text{ cm}^{-3} \).

The average radial speed of the leading edge of bubbles during 7 ns, as measured from the shadowgrams on the same probing direction, is plotted in Fig. 2(a) as a function of the initial radial size \( \Delta r \)

of the bubble. The speed of the material was measured to be \( 2 \cdot 3.5 \cdot 10^{14} \text{ cm/s} \) in the 8-wire arrays and \( 2 \cdot 6 \cdot 10^{14} \text{ cm/s} \) in the 4-wire arrays. An acceleration of \( 2.5 \cdot 10^{15} \text{ cm/s}^2 \) was measured in these same wire arrays in the beginning of bubbles movement. Large variation of the speed is seen on the diagram in Fig. 3(a). Bubbles exhibit an initial rapid acceleration, followed by a near constant velocity implosion. Bubbles snowplough ablated material and accretion of material could decelerate the leading edge of bubbles. The leading edge of the bubbles brings material to the axis of the array with a speed 200-500 km/s and produces a shock during collision with the plasma column on the axis.

Complementary images of wire array implosion in two probing diagnostics are presented in Fig. 3. The shadowgram in Fig. 3 (a) shows a collision of the bubbles with the precursor. The Faraday diagnostic show that a significant part of current flows in plasma on the initial position of the wire in the beginning of implosion. The Faraday effect in Fig. 3 (b) shows that later current switches from the implosion mass, to the precursor plasma column in at the beginning of the x-ray pulse.

![Fig. 3. The shadowgram (a), the Faraday image (b), and the timing diagram (d) of the implosion in the Al 4-wire array (shot 541). The arrow in diagram (d) presents a temporal position of the frame, (1) is the current pulse, and (2) is the x-ray pulse. Diagram (c) presents outlines from leading edges (1,2) and the precursor (3) from the appropriate rectangles 1,2, and 3 in the shadowgram (a).](image)

Observed dynamics are similar in the implosion of 4-32 wires that leads to the assumption that this physics can be applied qualitatively to larger generators. Implosion bubbles become smaller and more regular in 24-32-wire arrays. Similar plasma implosion mechanisms as those were also observed at the MAGPIE generator with optical streak photography and XUV framing images [4].

Experimental Studies of Planar Wire Arrays and Comparison with Cylindrical Arrays on 1 MA Zebra Generator and Possible Applications to ICF Research at the SNL


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An enhancement of energy conversion of the pulsed power source into the radiation from the z-pinch plasma, and shaping of radiation pulses from a compact (in comparison with a cavity dimension) driver is critical for the Z-pinch driven Inertial Confinement Fusion (ICF). A new load, planar wire array, placed in the center of the z-pinch chamber, may be a possible path to resolving these issues [1]. Experiments were performed on the UNR 1 MA, 100 ns Z-pinch generator Zebra with planar arrays from Al, Cu, brass, Mo, and W. Planar arrays have shown a very short rise-time of the radiation peak: sub-keV rise was 7-8 ns (Al and Cu), and the keV rise was in 2-3 ns for Al. Total radiation yields have been measured up to 24 kJ from Mo double arrays [2] and up to 18-19 kJ from Mo and Cu single arrays (25-30% from energy delivered to z-pinch load) [3]. It exceeds the inductive energy change at least by a factor of 4-5 [3]. An observed strong small scale plasma inhomogeneity indicates a enhanced resistivity of such a plasma as a possible energy coupling mechanism [1, 3]. A scaling of arrays performance with width, material, mass, wire numbers, inter-wire and row gaps was studied [3].

It was found that hot spots in planar arrays play a key role not only in a final array implosion but also during an early plasma formation [3] (Fig. 1).

Fig. 1. Shot #810, brass planar wire array. \( N_w=10, \Phi_w = 10.9 \, \mu \text{m}, \Delta=1\, \text{mm}, \, M=80 \, \mu \text{g/cm}. \) Load current (gray dash line) and responses of XRD (5 \, \mu\text{m} kimfoil filter-dashed/point line), and PCD (8 \, \mu\text{m} Be filter-solid line) detectors. At the bottom is positions of MCP time-frames. Inserted are MCP x-ray time-gated images taken along axis 90° to the array plane in \( h\nu>3 \, \text{keV} \) (top row) and \( h\nu>1 \, \text{keV} \) (bottom row). Frames duration is 2 ns, interframes intervals ar 3, 3, 3 and 6 ns. The plasma column length is 20 mm. Anode is at the top.

A comparison with cylindrical arrays demonstrated that planar arrays...
radiate high peak power and comparable yields in the x-ray region [3]. The physics of single planar arrays implosion is different from low-number wires cylindrical arrays. Multiple hot spots appear 20-30 ns before implosion along the wires near the central axis when several central wires surrounded by coronal plasma were not imploded yet. This result shows that the current flows through most of the wires long before the implosion [3]. Number of hot spots clusters increases as avalanche during a ns-scale implosion stage. No evidence of a quasi-uniform precursor plasma column formation (as for cylindrical arrays*) was observed for single planar arrays in 1 keV x-ray images. X-ray pulse shape is close to single planar arrays, except for the presence of tens of ns long, “base-prepulse” in a sub-keV (>0.2 keV) region, that may be useful for x-ray radiation pulse shaping. The maximum Te> 1300 eV (higher than in X-pinches!) at Ne ~ 5x10^19 cm^-3 was observed for Mo single planar arrays in hot spots clusters [3].

Implosion of double planar arrays is characterized by the presence of a nascent plasma column with a smaller number of hot spots, what is different from single planar or cylindrical arrays. The wire rows in double planar array imploded to the z-pinch load central axis independently before stagnation stage [2] (Fig. 2).

Fig. 2. Shot #487, Al double planar array. N_w=10, Φ_w = 10 μm, Δ_w=6mm Δ_s=1mm, M= 80 μg/cm. Load current (wide red line) and responses of XRD (5 μm kimfoil filter-blue line), and PCD (8 μm Be-thin red line) detectors. At the bottom are the positions of MCP time-frames. Inserted are MCP x-ray time-gated images taken along to the array plane in hν>3 keV (top row) hν>1 keV (bottom row). Frames are 6 ns, interframes interval is 10 ns. The plasma column length is 20 mm. The anode is at the top.

Dynamics of planar arrays implosion provided wide capability to shaping an x-ray pulse by changing arrays geometry and wires material. Even very compact planar arrays (width smaller than 5 mm) imploded powerfully, e.g. planar arrays can be much more compact than usually used cylindrical arrays (single or nested arrays with the same mass). It is can be very useful for ICF and other applications.

The implosion of compact Al cylindrical arrays (with interwire gap d ~ 1mm) lead to larger total energy yields E_T than from conventional low wire number (with interwire gap d >>1mm) Al cylindrical arrays (12-14 kJ vs 6-10 kJ) [3]. At the same time, compact Al cylindrical arrays showed radiation parameters close to planar Al arrays: demonstrated the larger maximum E_T 12-14 kJ vs 10-12 kJ, and just 10-20% longer x-ray pulses rise time [3]. Does enhanced resistivity play a similar role?

The possibility of application of planar wire arrays to ICF will depend on the scaling of soft x-ray power as a function of load current, array width, mass, wire material. The joint experiments on the SNL Saturn facility (6 to 10 MA) have been planed in 2007 to study scaling of planar array performance with a current.

Radiative Properties of Implosions of Combined Planar Wire Arrays and X-pinches Composed from Different Wire Materials on 1 MA Z-pinch Generator at UNR

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High-z cylindrical wire arrays (such as tungsten wire arrays) have been studied extensively on the 20 MA SNL-Z generator at Sandia National Laboratories (SNL) since 1998 when it was shown that they could reach very high x-ray powers, ~200 TW, and x-ray energies, ~2 MJ [1]. Since then different wire materials (such as Al, Ti, Fe, Mo, W etc) as well as different load configurations (such as nested wire arrays) have been investigated at the SNL-Z facility to study implosion dynamics and radiation output for inertial confinement fusion (ICF) and other high-energy density applications (see, for example, Ref. [2] and the references therein). Recently, we found that planar wire arrays (PWAs) imploded on 1 MA device radiate significant peak power and represent a new and very promising source of x-ray with a lot of potential applications including ICF [3]. Then, it is very important to study radiative properties of such loads. In particular, the radiative properties of PWA and X-pinches composed from two wire materials, Mo (mid-z) and Al (low-z) will be analyzed in this work.

Experiments with X-pinches and PWAs discussed in this paper were performed on Zebra generator with a current of 1 MA and a rise-time of 100 ns at UNR. The loads were composed of Al 5056 and Mo wires arranged in the anode-cathode gap of 20 mm. Alloy wires Al 5056 which contain 95% Al and 5% Mg were used to study opacity issues and to produce opacity-free lines available for K-shell diagnostics. Recently, we have studied for the first time also combined X-pinches with Mo and W wires and they have shown advantages in their applications for M-shell W diagnostics [4]. In present X-pinch experiments two wires were mounted at the angle of 31° to the central axis. In PWA experiments, the Z-pinch load consisted of several wires (from 10 to 15) mounted in a single linear row with a 1mm gap at the center of the discharge chamber. In combined Mo PWAs two wires of the primary Mo material were replaced with two Al wires at periphery (Al/Mo/Al) or with two Al wires at the center (Mo/Al/Mo). The list of configuration, number of wires, composition, wire diameters and masses of loads analyzed in this work is given in Table 1 below [5].

Table 1.

<table>
<thead>
<tr>
<th>Shot</th>
<th>Type of load</th>
<th>N of wires composition</th>
<th>Wire φ (µm)</th>
<th>Mass of load (µg)</th>
<th>Al mass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>466</td>
<td>X-Pinch</td>
<td>Mo/Al</td>
<td>99/99</td>
<td>931</td>
<td>59</td>
</tr>
<tr>
<td>467</td>
<td>X-Pinch</td>
<td>Al/Mo</td>
<td>99/50</td>
<td>931</td>
<td>59</td>
</tr>
<tr>
<td>789</td>
<td>Planar</td>
<td>Al/Mo/Mo</td>
<td>152/62/15</td>
<td>93/16</td>
<td>20</td>
</tr>
<tr>
<td>802</td>
<td>Planar</td>
<td>Al/Mo</td>
<td>157/62/15</td>
<td>140/13</td>
<td>13</td>
</tr>
<tr>
<td>803</td>
<td>Planar</td>
<td>Al/Mo</td>
<td>7.9/15/7.9</td>
<td>139/13</td>
<td>13</td>
</tr>
<tr>
<td>825</td>
<td>Planar</td>
<td>Al/Mo</td>
<td>7.9/19.8/7.9</td>
<td>154/21</td>
<td>21</td>
</tr>
</tbody>
</table>

In Fig. 1 x-ray film and pinhole images and positions of the lineouts for the implosion of the Mo/Al/Mo PWA are shown. Time integrated x-ray pinhole images were recorded with the resolution of 220 µm with two different sets of filters that cover the region λ < 10.3 Å and at λ < 4.4 Å. In softer x-rays (at λ < 10.3 Å) the emission region is much larger in size (mm-scale) than in harder x-rays. All x-ray spatially resolved spectra considered in this paper were axially resolved spectra recorded through the 0.5 mm slit on the BIOMAX film by a convex crystal spectrometer with a KAP crystal
This crystal collects both L-shell Mo (3.5–5.3 Å) and K-shell Al and Mg (6.5 – 9.2 Å). In particular, the strongest and most diagnostically important K-shell lines of Al and Mg are the He-like lines (Heα lines, Al1 and Mg1, respectively; the Heβ, A13) and H-like lines (Lyα lines, Al2 and Mg2, respectively). The strongest and most diagnostically important L-shell Mo spectral features are Ne-like lines (3A–3G) as well as Na- and F-like lines. In Fig. 2, x-ray spectra from the Mo/Al/Mo PWA lineouts (see Fig. 1, bottom) show the presence of L-shell Mo and K-shell Al radiation. Note that no K-shell Mg lines were observed. Modeling of the L-shell Mo spectrum from N3 (black line) gives $T_e=1000$ eV and $n_e=9\times10^{20}$ cm$^{-3}$. Modeling of the K-shell Al spectra indicates a variation of the plasma parameters for different lineouts (black lines): a) N2: $T_e=390$ eV, $n_e=7\times10^{20}$ cm$^{-3}$, b) N3: $T_e=340$ eV, $n_e=9\times10^{20}$ cm$^{-3}$, c) N5: $T_e=420$ eV, $n_e=3\times10^{20}$ cm$^{-3}$ [5].

The implosions of combined Mo and Al X-pinches produce dense plasmas (Al/Mo X-pinch in particular) that primarily concentrate near the cross-wire point in the middle of the anode-cathode gap. Modeling of L-shell Mo radiation gives a much higher $T_e$ than from K-shell Al and Mg radiation (~900-1200 eV vs 300-480 eV). The K-shell Al radiation spreads towards the anode where it is emitted from the hot spots along the wires of the Al/Mo X-pinch, or toward the cathode where it is emitted from the plasma column on the axis for the Mo/Al X-pinch. The L-shell Mo radiation spreads to the anode/cathode much less effectively than...
Explosive plasma expansion in an external magnetic field occurs in a variety of physical systems, from arcing in magnetically insulated transmission lines to space and astrophysical events. Examples include; supernova explosions in the interstellar magnetic field, the interaction of solar coronal mass ejections with planetary magnetospheres, artificial plasma releases in the Earth’s magnetosphere, and high-altitude nuclear explosions. An experiment was performed to extend a previous study [1] to ion times ($t \approx 1/\Omega_i$, the ion gyrofrequency).

In this experiment (Fig. 1), the plasma wind was created by ablation of a solid CH$_2$ target with the short pulse laser Tomcat (4 J in 5 ps at 1 μm wavelength and irradiance $I \leq 10^{16}$ W/cm$^2$). An azimuthal magnetic field with flux density $B \leq 60$ T was generated by high current discharges of the pulsed-power generator Zebra (0.6 MA maximum current with 200 ns rise time) in a reusable short-circuit load. The plasma and magnetic field were characterized with multi-frame laser shadow and schlieren imaging and magnetic probes, respectively. Two configurations of the Zebra load were used to investigate the plasma-field interaction in the plane of the magnetic field lines and perpendicular to it, without changing the line of sight of the laser diagnostics.

![Fig. 1. Experimental set-up.](image)

In the fluid regime, this configuration is favorable to the onset of the Kelvin-Helmholtz instability. An estimate of the instability growth rate yields a value in...
agreement with the observations. However, pending precise measurement of the plasma parameters at the boundary, kinetic instabilities cannot be ruled out.

The frontal region of the plasma-field interface becomes unstable as well (Fig. 4). A flute-type mode grows faster than the ion gyroperiod. The flute tips propagate with practically constant velocity. The schlieren images show a density decrease at the front indicating that plasma flows through this boundary across the magnetic field. This effect may be relevant to the impulsive penetration of the solar wind across the magnetopause, as well as to the arcing observed in magnetically insulated transmission lines.

Three-dimensional simulations were made with an ideal magnetohydrodynamic (MHD) model. It is assumed that initially 2 J of laser energy are deposited in a disc 0.1 mm thick with 0.5 mm diameter forming a fully ionized plasma with $T \approx 350$ eV and no directed velocity. The magnetic field distribution is identical to that used in experiment. The simulations describe well the formation of a diamagnetic cavity, the dynamics of the plasma plume during the interaction with the magnetic field, and the onset of instabilities at the plasma-field interface. The growth rate of the Kelvin-Helmholtz instability is similar to that observed in experiment.

![Fig. 3. Mass density evolution during the plasma expansion across magnetic field, as predicted by a 3D-MHD simulation. The axes are in mm; the horizontal is the radial direction with the target at right and the conducting rod at left, and the vertical is the direction of the current flow.](image1)

![Fig. 4. Sequence of schlieren images of a plasma plume expanding across $B \approx 30$ T, recorded at 14 ns and 21 ns after the laser pulse.](image2)

Two-dimensional particle in cell simulations (Fig. 5) strongly suggest that the flutes propagating across the magnetic field become polarized and continue to propagate by $E \times B$ drift with constant velocity.

![Fig. 5. Evolution of a plasma flute (electron density represented) propagating across a magnetic field. For comparison, the case without field is also shown. The plasma propagates along the magnetic field gradient.](image3)

Collisional particle-in-cell simulations predict that solid density matter irradiated with a short pulse high intensity laser can be heated to keV temperatures by applying an external magnetic field [1]. The role of the magnetic field is to restrict the radial diffusion of the hot electrons accelerated by the laser field. The requirement for this confinement is that the gyro-period be less than the collision time. This reduces the radial diffusion of the hot electrons long enough to couple to the cold electrons which in turn couple to the ions [2].

To test these predictions, an experiment is being developed at the Nevada Terawatt Facility, taking advantage of the coupled Tomcat/Leopard – Zebra facility [3]. The 100-TW class Nd:glass laser Leopard is currently in the commissioning phase [4]. Energy up to 29 J was measured at the output of the amplifier chain. Low energy pulses were transported by free propagation, compressed to 0.9 ps, and used for tests on target. Currently the laser operates at 1TW and the contrast is \( \sim 2 \times 10^6 \). To transport higher energy pulses to the compressor, a telescope will be installed in the beginning of April 2007. After tests, the short pulse high intensity laser beam will be transported to the Zebra vacuum chamber. With lens focusing \((f/10)\), intensity on target \( I > 2 \times 10^{17} \text{ W/cm}^2 \) will be available.

In preparation for the integrated experiment, multi-megagauss magnetic fields were produced with the fast pulsed power generator Zebra \((I_{\text{max}} \approx 0.6 \text{ MA}, \tau_{\text{rise}} \approx 200 \text{ ns})\) [5]. A relatively uniform magnetic field with flux density \( B \approx 2 \text{ MG} \) was generated with two-turn helical coils, and up to \( B \approx 1.2 \text{ MG} \) with horseshoe coils. The field was measured with differential Faraday rotation [6] and results are shown in Fig. 1. Laser shadow imaging was used to investigate the target status and the breakdown mechanism of the coils. The horseshoe coils survived the current maximum by at least 100 ns (Fig. 2 b-d) and the debris was negligible. Survivability tests with CH laser targets and Si targets placed inside horseshoe coils showed no significant
plasma formation on the target surface even after the current peak (Fig. 2 b-d).

The synchronization between a short pulse laser and Zebra was developed previously [3] and tested during an experiment with the laser Tomcat (5 J, 5 ps, \( I \approx 2 \times 10^{16} \text{ W/cm}^2 \)). The jitter of Zebra was reduced to 15 ns r.m.s. (from 50 ns r.m.s. typical), to make sure that every shot will yield data.

According to particle-in-cell simulations performed for achievable values of the parameters, with a laser intensity greater than \( 10^{17} \text{ W/cm}^2 \) and a magnetic field of the order of 1 MG, material volumes of \( 10^5 \text{ m}^3 \) can be heated for several picoseconds to temperatures of several hundred electron volts. These parameters make this technique extremely important, for example for opacity studies with numerous applications that include the radiation transport in the interiors of stars.

Based on the laser parameters available, the focus of the first phase of the experiment will be on the heating of Si. To minimize the effect of the plasma generated by the pedestal of the laser pulse, the actual Si targets (1 \( \mu \text{m} \) thick) are sandwiched between CD layers (3 \( \mu \text{m} \) and 5 \( \mu \text{m} \) thick). Homogeneous Si and CD targets with similar thickness will be used as reference. To test the shock heating, layered targets CD3-Si1-CD1-Si1-CD5 will be used (the numbers represent the thickness layer in \( \mu \text{m} \)). The complex targets were made by General Atomics. All targets are 0.6 mm squares, so that the magnetic field is practically uniform over the target surface.

In the first phase of the experiment the target heating will be assessed with time integrated measurements. To assess the effect of the external magnetic field, the measurements will be repeated with and without the field. The electron temperature and ionization balance will be inferred from x-ray spectra recorded with a von Hamos spectrograph. Such an instrument equipped with a cylindrical KAP crystal was built and used to record single-shot Al and Si spectra from laser irradiated targets (Fig. 3). In addition, the proton energy distribution will be monitored, because efficient hot electron confinement is expected to result in enhanced ion acceleration. Neutron yield measurements with scintillator-photomultiplier detectors will be developed to determine the ion (deuteron) temperature.

![Fig. 3. Aluminum x-ray spectrum recorded on a single laser shot.](image)

For the following phases of the experiment, additional diagnostics will be developed to be able to compare in detail the experimental results to simulations. These diagnostics include time-resolved (streaked) x-ray spectroscopy, chirped rear-side optical reflectivity, and frequency-domain interferometry.

Effect of sheared flow and on-axis wire on wire array z-pinch dynamics

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The presence of sheared flow has been conjectured to stabilize z-pinch instabilities [1]. Whilst the effects of a sheared flow have been tested extensively theoretically [2] and computationally [3], and invoked to explain astrophysical phenomena [4], experimental tests remain rare [5].

Conical wire arrays have previously been used to investigate in the laboratory the dynamics of plasma flows similar to astrophysical jets [6]. These experiments have been used to investigate the effects of radiation cooling on a flow, and the propagation dynamics in static ambient medium or an ambient medium with transverse motion. In contrast to such experiments, which used a jet which is ejected from the wire array, the region on the axis of the array itself is well suited to studying sheared flow effects. Supersonic (and super-Alfvénic) plasma streams converge on the array axis; these streams also have an axial (z) component to their momentum. At the axis, the momentum associated with the radial momentum is thermalized and radiated, whilst the axial component is maintained. If a static object is placed in the centre of this on-axis standing shock, it is expected that some type of shear will be formed. The implosion of the conical wire array normally produces a current carrying, unstable, non-uniform emitting column on the array axis [7]; the introduction of shear into this system would provide a simple way of investigating the effects of sheared flow stabilization.

Preliminary results [8] obtained with gated x-ray imaging (GXI) indicated that the presence of an axial flow has a definite effect on the stability of a dense z-pinch (Fig. 1). For a cylindrical array imploding on an axial wire, the precursor is \( m = 1 \) (kink) unstable. The column obtained during the implosion of a conical array does not display this instability mode.

Fig. 1. (a) Cylindrical wire array (8 \( \times \) 15 \( \mu \)m Al) with axial wire (76 \( \mu \)m Ti); 13 mm diameter, 20 mm height. (b) Two GXI frames showing the kink-unstable precursor at the cylindrical array implosion on the central wire. (c) Conical wire array (8 \( \times \) 15 \( \mu \)m Al) with axial wire (152 \( \mu \)m Ti); 20 mm height, 7.5 mm bottom (cathode) and 18 mm top diameters. (d) Two GXI frames showing the precursor of the conical array imploding on the central wire.

A second experiment was performed to investigate in more detail the effect of the central wire. The results were compared with null results (conical arrays without central wire) from a different experiment [7]. The inclusion of the axial wire significantly affected the dynamics of the conical wire array implosion. The use of spectroscopic dopants showed that there is less axial material transport with the inclusion of the central wire – indicative of some form of drag due to the central wire. Time integrated self-emission (pinhole)
imaging at $\lambda < 4.4 \text{ Å}$ shows that the on-axis wire allows the stagnated pinch to become significantly more uniform (Fig. 2). Analyzing the broad spectral range radiation measured with bolometers, it was established that the presence of the wire on axis causes an enhancement in the total energy emitted.

![Anode - Cathode](image)

**Fig. 2.** Time integrated pinhole images for the implosion of conical arrays with and without central wire. In both cases the initial arrays were made of 8 Al 5056 wires 15 \( \mu \text{m} \) thick. The array height was 20 mm, the cathode diameter 6 mm and the anode one 18 mm.

Additional experiments are necessary to investigate the mechanisms responsible for this increased emission and change in the self-emission profile. Comparison with cylindrical wire arrays with a wire on axis will allow the isolation of sheared flow stabilization from other effects of the wire axis. If the data shows that sheared flow is in fact responsible for the change in behavior then this result will be of substantial interest to both the astrophysical and laboratory plasma physics communities. If another mechanism is determined to cause this change in emission (such as the wire on the array axis altering the mean-free-path of precursor streams when they meet on the array axis) then this result would be of interest to the z-pinch community.

Energy deposition in solids by laser pulses: acoustics and material ablation

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A short laser pulse of several nS duration deposits energy in solid or liquid matter in a variety of ways. The dominant process depends on the intensity of the pulse; at very low intensities local heating occurs and the sudden local expansion launches acoustic waves into the material; at higher intensities, phase changes and the kinetic energy of released (“ablated”) particles absorbs some of the incident energy; at the highest intensities the surface material is dissociated to plasma and ejected, and the wave launched into the material may be of such amplitude that it becomes a shock wave. The plasma in the final case may even serve to partially shield the material surface by absorbing laser energy before it reaches the surface. The processes of optoacoustic sound generation, high pressure shock wave generation, ablative evaporation and plasma formation by these interactions routinely find application in science and technology. The distribution of laser energy between these various channels as a function of intensity is relevant for all these applications, but in certain regimes the ability of models to accurately describe the effects is limited by the complexity of the system. Data in these regimes also tends to be sparse.

We are on an experimental program to study the intensity regime up to ~ 10^{15} W m^{-2} with pulse durations in the range 5-8 nS. At the higher end of this range the ablated material may be described as “warm dense matter” (WDM). The interaction between the components of WDM are not so strong that a few average parameters can describe the behavior, nor so sparse that a collection of independent 2-particle interactions is adequate. This seems to be the large part of the complexity. This intensity range is insufficient in general to produce a shock wave, so the energy launched into the material may be treated as a problem in linear elasticity.

Within the last year we have acquired a small flashlamp-driven YAG laser with a nominal 50mJ/ 5-8nS pulse at 1064nm, and up to 10Hz repetition rate, as the source. We have available a 20MHz bandwidth interferometric laser vibrometer for acoustic amplitude measurements, and a 1m dual grating imaging spectrometer with a fast (~3nS) Andor iStar CCD camera to record the intensity and spectrum of light produced by the ablated material.

Our initial studies are to characterize the energy in the ablated material, which for light target elements (C, Al) produces a visible flash of light. We start with a carbon target of oriented pyrolytic graphite (OPG). This material has high purity and graphite is largely free of chemically bonded surface layers such as oxides. [1], [2]

Figure 1. Schematic diagram of initial experimental setup.
Figure 1 shows a schematic of the experimental setup. The lens L1, used to vary the spot size at the target was not used in the initial tests, so the native beam diameter of 2mm determined an intensity of $3 \times 10^{12} \text{ Wm}^{-2}$. The laser vibrometer, although tested independently, is not yet integrated into the data acquisition system. A region in the plume at position $z$ is focused by L2 onto the slits of the spectrometer. A complete spectrum from 350-700nm is recorded by the CCD camera in one exposure. The exposure time, and the time interval between the laser pulse and the exposure can be controlled with a resolution of about 3nS. The position of the target along the beam axis can be manipulated to enable the position $z$ to be scanned along the plume. In the configuration of fig. 1, we have recorded the spectrum of light from the plume, which is about 3mm long and can last up to about 10 µS, over a range of $z$ and $t$ values (where $t$ is the delay after the pulse) in ambient air atmosphere.

Possible changes due to hitting the same place on the target with many pulses have yet to be characterized. Figures 2 and 3 show the recorded spectrum at $z=0.25\text{mm}$ with a 1µS exposure started at approximately $t=0$ and $t=1\mu\text{S}$. There is clearly a continuum background (almost a blackbody at~3000K) with structures identifiable as molecular bands ($C_2$). The ratios change dramatically over time and as a function of distance $z$. The influence of the surrounding atmosphere was checked by blowing He gas into the ablation region, with the result that the molecular structure lines were suppressed relative to the continuum background. We are developing the details of the experiment so that the target can be enclosed in vacuum or some well defined atmosphere, and that the target can be manipulated so as to define the condition of the target area. A chamber has been acquired which fits these requirements and is currently being assembled. Integrating the acoustic measurements, quantifying the effects of surface modification by prior pulses, and evaluating properties of the plume such as its mass, temperature velocity, and energy content are our immediate project efforts. Fortunately at UNR physics there is an effort in theoretical support on WDM (Prof. R. Mancini) which we are learning some of the approaches to analyzing our data [3] The ultimate aim will be to determine the energy balance between the different final states as a function of laser intensity. This will necessarily lead us to the higher power laser systems in use at the NTF facility, so we are developing the apparatus with the ultimate aim of transporting it to the NTF.

Explosion of palladium wires saturated with hydrogen and deuterium

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The z-pinch pulsed power devices at the Sandia National Lab and the Nevada Terawatt Facility create a hot plasma by depositing an enormous electrical current into a thin metal wire. The plasma consists of ionized states of atoms of the wire material and electrons. Generally elemental wires are used although some alloys such as stainless steel, nichrome and various thermocouple alloys will produce plasmas with different mass ions. Large mass differences in these alloys are not found with high number ratios – for instance steel (Fe:C) has a high atomic mass ratio, 56:12, but only about 1 in 200 of the atoms are carbon.

The materials physics group is interested in the details of the phase change from solid to (liquid to plasma and the influence of microstructural differences in the solid state on the final form of the plasma. Some experiments have been performed with films of a noticeably light element, Li, deposited in a pattern on the heavy wire to attempt to trace the resultant path of those layers, but this too has only a small fraction of the total number of atoms.

There is some theoretical interest at the NTF (V. Sotnikov) in two component plasmas, but currently no experiments to examine them. The NTF Zebra source spent much of its early career at Los Alamos exploding frozen hydrogen(H) and deuterium(D) columns or “wires” as part of a fusion program. The current interest in hydrogen storage in solids suggests that a wire with a large hydrogen storage capacity would yield valuable data on two-component plasmas, perhaps relate to fusion processes and provide some information on the initiation phase of the explosion.

Palladium (Pd, M=106) has long been known to be porous to hydrogen at elevated temperatures, and is capable of holding that hydrogen when cool. Unlike titanium which disintegrates to powder upon hydriding, Pd retains its metallic integrity even at H (or D) saturation levels of about one H for every two Pd atoms. This is a large mass ratio, 106:1 (or 2), and about 34% of the atoms are hydrogen.

We have used the high temperature and pressure hydriding facility operated by Dr. Dhanesh Chandra at the Materials Engineering department at UNR to insert saturation levels of hydrogen into 20µ diameter pure Pd wires. Hydriding takes place at 400°C and 20 bar pressures with a pure H₂ source gas. We also have a D₂ source for deuteration. Thermal data for Pd hydriding suggest that the saturation H/Pd value is 0.51 mol H/mol Pd or 0.0048 grams of hydrogen per gram of palladium.

Initial experiments scheduled for June 2007 at the NTF will consist of 4 wire symmetric arrays spaced on a 12mm circle, of (1) pure Pd, (2) hydrided Pd and (3) deuterated Pd. Two sets of each composition will be fired to check for consistency. In this configuration, given the (large) size of the wire and the high atomic mass of Pd, it is possible that the Pd will not explode to a hot confined plasma column, however much of this is empirical and the resulting behavior of the hydrogen ions in the current pulse is not known. Using a smaller wire diameter in future should enable us to reach a hot 2 component plasma state. Diagnostics developed by G. Sarkisov and V. Ivanov give us information regarding electric fields and charged particle currents through a
capacitive pickup (v-dot) and also the integrated light output [1] over about a 200-1100nm wavelength range from a fast photodiode at the initiation of the plasma formation. We intend to add a diagnostic where we use a fast diode and a narrow band Hα(656.3nm) filter to detect the excess light from hydrogen.

Single wires of our pure and hydrided materials have been exploded by G. Sarkisov at Sandia National Laboratory and the light output recorded.

Figure 1. Light output differences between hydrided (red line) and pure single Pd wire shots as a function of time.

Figure 1 demonstrates that the hydrided material has a considerably higher integrated light output than the pure Pd. Further measurements are necessary to determine if this is all in hydrogen spectral lines. An estimate of the expansion velocity of the plasma can also be made, and data from several shots is shown in figure 2.

It is apparent that the velocity is generally higher for the hydrided material and that there is a clear distinction between the hydrided material and the pure Pd.

These differences lead us to suggest that in the discharge of the zebra machine at the NTF, including the v-dot data and the Hα spectral information that we will be able to detect the different arrival times of the ionic components and determine when the hydrogen recombination lines start to appear compared to the integrated light output. The influence of the hydrogen on the structure of the final state of the plasma in an exploding configuration (fine wires) will tell us if the fast ions can smooth out presently visible plume structures, and the formation of a two component Pd-H and Pd-D plasma will permit verification of modeling codes. We intend that, particularly with the use of deuterium loaded wires, neutron detectors will be available to watch for the possibility of nuclear reactions producing excess neutrons. We have also hydrided Ti films on laser target cones as a source of H atoms for ion acceleration experiments with laser pulses.

Photodetachment Studies of Atomic and Molecular Anions
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I. Introduction

The formation of a negative ion occurs when an extra electron is attached to a neutral atom or molecule. Approximately 80% of the elements on the periodic table form stable negative ions [1] and molecular anions are important in a wide variety of chemical reactions and processes [2]. In nature, anions are abundant in many rarified gaseous environments, such as the E- and D-regions of earth’s atmosphere [3]. Atomic and molecular anions also play important roles in laboratory and astrophysical plasmas where electron temperatures are of the order of the electron affinities of the neutral plasma constituents.

In the past year, we have completed measurements on a wide variety of different anions. These ions, both atomic and molecular, have been studied with a variety of different lasers and light sources in order to study both structural and dynamical properties of these highly-correlated complex targets. This paper is intended to give an overview of these measurements along with motivations for each of the studies.

II. Photodetachment Cross Sections

Attempts to accurately model low temperature plasmas require experimentally verified cross sections for processes which lead to the formation and destruction of anions. For instance, accurate Cu− collision cross sections are necessary to model the behavior of copper-vapor lasers (CVL) [4]. In addition, other ions such Fe− are thought to play important roles in the formation of transition metal oxides such FeO in astrophysical objects such as class II supernovae such as SN1987A [5]. The formation of these molecules has been proposed to come about through stimulated radiative electron attachment (RA) reaction of the form,

\[ \text{Fe} + e^- + h\nu \rightarrow \text{Fe}^- + h\nu + h\nu, \quad (1) \]

which can be followed by an associative reaction described by,

\[ \text{Fe}^- + O \rightarrow \text{FeO} + e^-. \quad (2) \]

The importance of these proposed reactions was difficult to gauge since no experimental data was available for the RA cross sections needed to calculate the rates in Eq. 1. Fortunately, photodetachment (PD) is the inverse process of radiative electron attachment, so once PD cross sections were measured, the RA cross sections could be determined via the principle of detailed balance.

Relative measurements of Fe− photodetachment cross sections were made by comparing the photoelectron yields of the unknown Fe− to Cu− [6] and C− [7], for which the cross sections are known on an absolute scale. The results of these measurements are summarized in Table I below.

Table I. Cross sections for the photodetachment of Fe− at visible photon energies.

<table>
<thead>
<tr>
<th>Photon λ (nm)</th>
<th>( \sigma(\text{C}^-) ) 1S→2S (Mb)</th>
<th>( \sigma(\text{Cu}^-) ) 1S→2S (Mb)</th>
<th>( \sigma(\text{Fe}^-) ) 1S→2S (Mb)</th>
<th>( \sigma(\text{Fe}^-) ) 1S→2S (Mb)</th>
<th>( \sigma(\text{Fe}^-) ) 1S→2S (Mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>514.5</td>
<td>13.2 ± 1.9</td>
<td>75 ± 15</td>
<td>50 ± 10</td>
<td>35 ± 7</td>
<td>3.0 ± 0.6</td>
</tr>
<tr>
<td>488.0</td>
<td>13.4 ± 2.0</td>
<td>56 ± 11</td>
<td>34 ± 7</td>
<td>22 ± 5</td>
<td>2.4 ± 0.5</td>
</tr>
</tbody>
</table>

More details of these measurements are given in Ref. [8], along with the values of the RA cross sections determined using the values in Table I.

III. Angular Distributions of Photoelectrons

In addition, the work in Ref. [8] also provided critical tests of the angular momentum transfer (AMT) theory by comparing the measured asymmetry parameter values to those predicted using the formalism developed by Fano and Dill [9] and reviewed by Manson and Starace [10]. These results indicated that at a photon energy of 1.92 eV, \( \beta = -0.65 \pm 0.09 \) for the \(^1\text{P} \rightarrow ^2\text{D}\) channel, which is significantly different than the value of \( \beta = -1 \) predicted by AMT theory for parity “unfavored” transitions. This result indicates that the configuration interaction may be playing a larger role at
photon energies closer to threshold. Other studies of photoelectron angular distributions were also carried out with higher $Z$ ions including 4$d$-transition metal and lanthanide anions. In certain cases, these studies help shed light on the type of electronic configuration that the attached electron occupies. These measurements are helpful since the energy degeneracy of $s$-, $p$-, $d$- and $f$- sub-orbitals can complicate not only the interpretation of experimental data, but also structural calculations for these many-electron-systems.

For instance, the spectral variation of the asymmetry parameter has also been studied for the photodetachment of Lu$^-$ (see Figure 1). The asymmetry parameter values (yellow circles) for the fine structure resolved $^1D_2\rightarrow^2D_3/2$ transition are plotted at photoelectron energies slightly above 2.0 eV. The spectral variation of the asymmetry parameter was fitted with the model of Hanstrop et al. [11], which is a $p$-electron specific form of the more general photodetachment model proposed by Cooper and Zare [12]. The excellent fit to a $p$-electron detachment model shown in Fig. 1 strengthens the argument presented by Eliav et al. [13] which predicted that Lu$^-$ forms in a [Xe](4$f^{14}6s^26p5d$) ground state configuration via attachment of a 6$p$-electron. To the best of our knowledge, this is the first spectral variation measurement confirming an electronic configuration predicted by theory for these highly-complex anions.

IV. Photodetachment of Lanthanide and Molecular Ions

In Figure 2, a photoelectron kinetic energy spectrum for the photodetachment of LuO$^-$ is shown at a photon wavelength of 532 nm. The experimental data points (red circles) were collected at an electron spectrometer pass energy of 10 eV and an integration time of 20 seconds per data point. The energy scale was calibrated with photoelectron peaks from Cu$^-$, which has a well known electron affinity [1]. Measurements on lanthanide anions and oxides are currently underway, and the results of recent studies of lanthanide beam production tests have also be completed [14].

Figure 1. Spectral variation of the photoelectron asymmetry parameter for photodetachment of Lu$^-$ at visible photon energies. The experimental data points (circles) are shown along with a fit to the $p$-electron photodetachment model of Hanstorp et al. (solid line) [11].

Figure 1. A typical photoelectron spectrum from the photodetachment of LuO$^-$ at a photon wavelength of 532.0 nm (2.33 eV).

Fourier-transform infrared (FTIR) absorption spectroscopy has been used to study the properties of polymers at static high-pressures. The polymer samples studied include poly (methyl methacrylate) (PMMA) [1] and poly carbonate (PC) [2-3]. These materials find application in everyday items including aircraft canopies and compact disks (CDs). These polymers can also be used as window materials in shock compression experiments. Previous experiments have shown that the optical properties of these normally transparent materials can be altered in high \( P \) and \( T \) environments [4]. Under extreme conditions, polymer related phenomena such as changes in molecular orientation, conformation, and phase transitions can be investigated using FTIR absorption-and Raman-spectroscopy based experimental techniques [5].

Unfortunately, there exists little information on polymers at high pressure and only now are the phase diagrams of these highly useful technological materials undergoing investigation. Previous measurements using Raman spectroscopy have been carried out for PMMA [6] and PC as a function of pressure [7], and laser shock induced dynamic frequency shifts of absorption lines have been obtained with coherent Raman spectroscopy for PMMA. The infrared absorption spectra of both PMMA and PC have been measured by our group in the past year at high pressure. This information should prove useful in the analysis of experiments using ultrafast infrared absorption techniques to study shock compression of polymers [7]. To this end, we have measured the FTIR absorption spectrum of PMMA and PC at high \( P \) and room \( T \) in a diamond anvil cell (DAC).

The FTIR absorption measurements were performed using a Bruker Hyperion 2000 infrared microscope coupled to a Tensor 27 FTIR spectrometer. A 15X (0.4 NA, working distance 24 mm) reflecting condenser was used to focus the IR radiation on the sample. A liquid nitrogen cooled mercury-cadmium-telluride (MCT) detector was used to detect the infrared photons. For PC, the scans were performed with a nominal resolution of 4 cm\(^{-1}\) over the range of 800-1300 cm\(^{-1}\). For the data presented in this paper, at least 200 scans were averaged at each pressure. The results of several absorbance scans are shown at increasing pressures in Figure 1.

![Symmetric O-C-O Stretch](image1.png)

**Figure 1.** Infrared absorption spectra of PC thin film.

The diamond anvil cell used was a four post high-pressure cell (High
Pressure Diamond Optics, Tucson, AZ) designed for performing Raman and FTIR absorption measurements at moderate pressures. The culet diameter is 0.6 mm and the sample chamber was a hole of approximately 250 μm diameter drilled in an Inconel gasket. The ruby fluorescence technique was used to measure the pressure via the positions of the fluorescence peaks. Peak positions at various pressures were measured with a Renishaw Invia Raman spectroscopy microscope and samples were excited with the 488.0 nm driving line from an Argon ion laser.

The experimental data from several different IR active modes of PC are shown in Figure 2. The data was collected using PC samples of varying thickness in order to avoid saturation of certain high-intensity peaks. The data were fit to models assuming both volume independent and dependent Grüneisen parameters (solid lines in Figure 2). A summary of these fits and all of the identified IR modes is given in Table 1. Further analysis of these data is currently underway with the hopes of comparing similar bonds in PMMA and PC in order to draw more general conclusions about the behavior of these polymers at high pressures.

Table 1. Mode Grüneisen parameters for PC

<table>
<thead>
<tr>
<th>Frequency (cm⁻¹)</th>
<th>Assignment</th>
<th>γ</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>831 cm⁻¹</td>
<td>Out of plane C-H def.</td>
<td>0.0466 ± 0.001</td>
<td>-</td>
</tr>
<tr>
<td>1015 cm⁻¹</td>
<td>Symm. O=C-O stretch</td>
<td>0.0557 ± 0.00433</td>
<td>0.15496 ± 0.00265</td>
</tr>
<tr>
<td>1080 cm⁻¹</td>
<td>γ C=C-C</td>
<td>0.0615 ± 0.00586</td>
<td>0.1693 ± 0.00322</td>
</tr>
<tr>
<td>1505 cm⁻¹</td>
<td>Ring C=C stretch</td>
<td>0.0352 ± 0.00478</td>
<td>0.11732 ± 0.00356</td>
</tr>
<tr>
<td>1772 cm⁻¹</td>
<td>C=O stretch</td>
<td>0.0268 ± 0.00268</td>
<td>-</td>
</tr>
<tr>
<td>2970 cm⁻¹</td>
<td>Methyl Asymmetric C-H stretch</td>
<td>0.0950 ± 0.00625</td>
<td>0.2183 ± 0.00351</td>
</tr>
</tbody>
</table>

Similar measurements have also been started on other polymer materials including polyamides and we hope to extend these measurements to higher pressures in the near future.

Figure 2. Band maxima of active vibrational modes of PC as a function of pressure. Fits to these data were used to determine the mode Grüneisen parameters listed in Table 1.


This work was supported by the US DOE under Grant No. DE-FC52-01NV14050 at UNR.
As part of our program of studying the influence of microstructures on mechanical behavior, we have been to studying polycrystalline copper states since modification of the grain boundaries is straightforward. The overall influence of grain size is however not well quantified, particularly with respect to the RUS technique, and could certainly affect our measurements. We have completed a series of measurements where we present quantitative results on defining where polycrystal averaging fails in RUS measurements. Figure 1 shows a summary of our results, submitted for publication recently. [1]

Essentially, if we let the grain size in our samples exceed ~ 550 microns, we can no longer be sure that the physical parameters determined by RUS values really represent reasonable physical values. This work will continue with our Bi-doping of grain boundaries, where we have learned that we need to re-make and quench our samples much faster to keep the grain size small.

We are also making progress in our goal of studying the low temperature phase behavior of lanthanide metals. The construction of our cryostat system is underway and we have acquired samples of Cerium, Gadolinium and Ytterbium. Starting with Gd, we will study the influence of microstructure on a number of second-order phase transitions. Development of our tools for producing and measuring rapidly oxidizing samples like Cerium is also progressing. [2]
The study of the resonant response of wires as a way of characterizing the state of target wires in z-pinch shots has produced the apparatus developed by J. Lenz, an undergraduate student, Fig. 2. [3] The apparatus uses the vibration frequency and dissipation in a wire to study variations in mechanical states – e.g. work hardening, or defect density. With fine wires, tensioning without introducing the same problem we are trying to detect is a problem, as is the driving and detection of the vibration. The entire apparatus is vacuum compatible to remove the damping effect of air on the wires and the apparatus can scan several meters of wire, of down to 5µ, but the wire visible in the photo from the upper reel to the gauge length and EM drive is 20µ. The detector coil is not mounted here, but we intend to use the fact that the current in the wire produces the work for the vibration and therefore the impedance changes as the wire is driven into motion at the resonance frequency. This work will continue as an undergraduate project, and particularly will be used to study our H/D loaded palladium wire targets.

The work on elasticity in highly charged metals [4] will be continuing over the summer period with an undergraduate student working on a scholarship.

The development of superior configurations of measurement apparatus for RUS also is progressing. We have an energetic high school student who is working in the lab on his own time (under supervision) on a simple but potentially very efficient and robust cryogenic version of a RUS transducer stage. This effort is important as the materials effort moves toward integrating elasticity measurements with the other optical and transport measurements we are capable of carrying out in the materials lab. Figure 3 shows the present test bed for the new piezoelectric assembly. The disk transducers are attached to a copper coated kapton sheet. This makes a continuous, low inductance ground plane for both the drive and receive transducers. The kapton damps vibration and is useful at cryogenic temperatures. In the final form gravity acting on an inverted hinge will provide the light clamping force to retain the sample between the transducers. This is a very much simpler design than existing stages and will probably be implemented in the cryogenic RUS system.

Figure 4. The kapton film RUS stage.

We are maintaining a measurement interest in the elasticity of a number of materials with programmatic interests: with Dr. Dhanesh Chandra we will be examining the effects of hydrogen storage in vanadium/vanadium carbide composites and in LaNi₅ alloys, with Los Alamos we will continue research into nonlinearities in geomaterials, particularly with neutron scattering and synchrotron x-rays.

Developments of laser targets and operations of the target fabrication laboratory.

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1. Introduction

The target fabrication laboratory continues to be used by different teams for target fabrication and for student training. New conical and “pizza top” targets were developed in collaboration with NanoJems, along with closed funnels. Cutting and assembling targets brought new needs to target developments that were implemented this year in the fabrication process. In addition to gold, copper targets of different smoothness were produced. 2006 has been the first year of operations of the target fabrication laboratory. The current level of instrumentation was adequate to fabricate the targets needed by different groups. The focus of this report will be on the mass production of targets that came out of our collaboration with NanoJems. We also improved the laboratory by modifying the stalk positioner, and acquiring a used scanner for phosphor imaging plates.

2. Target Fabrication

It has now been two years since we started exploring a new way of fabricating targets at the intersection of physics and mechanical engineering. This process has seen the creation of a private company called NanoJems continuing the work started with the mechanical engineering department.

Interdisciplinary in nature, this endeavor uses silicon wafers and nanofabrication processes to mass produce targets of a given shape, or even several different shapes. We have been focusing our efforts with NanoJems on conical shapes. The following is a description of targets and their characteristics that have been successfully produced.

Gold Hemispheres:

Figures 1 and 2 illustrate the hemispherical targets fabricated by NanoJems. These Gold hemispheres have a lens diameter of 115-230 microns, a height of 12-24 microns, a radius of curvature of 100-500 microns, and a wall thickness of 10 microns.

![Fig 1. Series of hemispheres on a Si wafer (left – arrow represents 1mm). Single hemisphere (right – arrow represents 100 microns).](image1)

Each hemisphere could be lifted from the wafer and attached to a stalk.

Gold pyramids:

We developed 10 micron thick pyramids made of gold. These gold pyramids, fully released from the silicon were produced in a frame (that still had the silicon) to allow us to manipulate them without crushing the tip. Each frame was square in shape and had four pedestals like a little table with the pyramid at the center. Each of these square frames was detachable from the wafer.

![Fig 3. Wafer containing the first Au pyramids with sub-micron inside tip – arrow represents 30mm.](image2)

These pyramids had a fixed angle and 4 straight faces due to the silicon crystal structure.
The unique feature of these pyramids was their micron to sub micron sharp inner and outer tip. We then developed conical shapes in 10 micron thick gold with the same tip sharpness, and dropped the support structure. Even though it is practical and protects the target itself it also provides an escape for the electrons during the laser shots.

Gold cones:

All our gold cones were fully released from the silicon wafer, leaving a sheet of gold with targets on it that can be individually cut and mounted.

Fig 4. Au cones of varying inside angle

These targets are spaced by ~ 500 microns, yielding thousands of targets per wafer. A typical cone is ~ 200 microns at the base and 200 to 160 microns high (see schematic below).

Fig 5. Schematic of a typical cone target.

We can see that as we go up toward the tip, the angle closes. The full angle at the tip is defined from side to side and is 57 degrees on figure 5, while the opening diameter is 50 microns. Figure 6 shows how the geometry of the tip evolves toward even smaller angles as we go toward the tip.

Fig 6: Characteristics of the sharpest tips showed by the full angle as a function of the opening diameter

Note that the smallest opening diameter of ~18 microns provides a full angle at the tip of ~25 degrees. This opening diameter is of the order of or bigger than a standard focal spot obtained on lasers such as the 100TW at LULI, or the Trident short pulse laser.

In addition to conical shapes, we have been able to produce cones with flat tops and closed funnels.

Gold cone with flat tops:

Fig 7. picture of a typical conical target with a flat top.

Fig 8. Schematic of a typical cone with flat top target.

On the actual wafer, we were able to find a series of different sizes as shown in figure 9.
Gold closed funnels:

Along with the cones and flat tops, we also produced closed funnels as shown on the figure below.

The physical location of these targets did not make it easy to mount individual targets without destroying the neighboring ones. As we trained the students to cut out these targets and mount them, we defined improvements that could be made. We then developed cones out of a different material and included these improvements.

The new material we used is Copper. We successfully produced cones of different angles, wedges, open funnels, stars and octagons. All these shapes can be produced on one wafer. Figure 11 shows an example of such wafer.

Copper cones:

These cones have the same characteristics as the gold ones with the exception of the smoothness. We were able to control the smoothness to obtain either ~ 2 to 5 microns smooth, or ~ 5 to 10 microns smooth cones.

Copper wedges are also 10 microns thick and several millimeters long. They are more challenging but also more forgiving in a sense. The initial angle was measured to be 65 degrees. However, cutting and working under the microscope proved that we can adjust the angle. Figure 14 shows the initial wedge in the copper sheet before modification (left) and after cutting and modification of the angle (right).

The angle can be continuously adjusted down to at least about 28 degrees.

Almost all of these targets have been shot at Texas4, LULI, LANL, LLNL and some of the results are still under analysis. It appears however that target alignment and pointing accuracy are essential parameters to control.

We also looked at the cost of producing such targets. Keep in mind that these various targets are...
unique by their features and that no one was able to produce something similar. This makes this unique tridimensional product hard to compare. The characterization of individual targets can be done but we did not consider this in the cost analysis. We did however include target yield in the sense that the characteristics were not met for some of these targets due to current control of the fabrication process. From other vendors, we purchased targets that had several layers of different materials including a well defined dot. These were fully characterized. Even though the comparison is difficult, the individual cost of the “nanofabricated” targets is about 2.5 times less.

3. Laboratory improvements

This year we also acquired a used scanner to be able to scan imaging plates. These plates are sensitive to ionizing radiation such as x-rays and/or particles. Several laboratories now use them as detectors. They can be put under vacuum, cut into any shape to field pinhole cameras or spectrometers, and are reusable. Two types of imaging plates are available one with a protective layer and one without. These plates or phosphor screens have a size of 7.5” by 9.5” and can be purchased from Amersham Biosciences. The current resolution of the system we have available is 50microns.

We also improved the target positioner to reduce its footprint. It is a 5 degree positioner with 3 translations and 2 rotations that allows gluing a target at specific angles in two different planes.

4. Conclusion

The Laser Target Fabrication Laboratory at the NTF is fully operational and fulfilling its mission. The first year of operations shows a supplies operating budget of $2.6K excluding the nanofabricated targets, with target materials being the most expensive items. Several students have used it successfully, and some of them have been able to go to other facilities to perform experiments for which they successfully assembled targets. This work was supported by DOE/NNSA under UNR grant #DE-FC52-01NV14050, and DE-FC52-06NA27616.

Simulation and Theory
Activities of Theory/Simulation Group of High Energy Density Physics with Ultra-intense Laser Pulses

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1. Summary

Irradiation of matter with ultra-intense short laser pulses generates MeV electrons & MeV protons and can create plasmas at solid density, and temperatures of several million degrees. This extreme matter is an interesting platform of high energy density physics (HEDP), which is important to realize applications such as Laboratory Astrophysics, Fast Ignition in laser fusion, compact accelerators and compact neutron sources. Modeling of laser produced HED plasmas is a challenge because the model has to treat different time scale physics, namely, kinetic regime to collisional regime in large density scale plasmas over picoseconds. We have been developing simulation codes for HEDP. Our tools are collisional Particle-in-Cell codes, PICLS, which has the numerical dispersion free Maxwell equation solver, a full relativistic binary collision model for weighted particles, and higher order interpolation scheme for long time stability. We applied PICLS to MeV ion acceleration, laser isochoric heating, and fast ignition studies. The followings are summaries of each topic.

2. PIC modeling for HEDP

Since collisional energy transfer is an essential process in HED matter, we need to have a reliable collision model in PIC calculation. We had developed a fully relativistic energy conserving collision model for particle simulations with large density scale plasmas. Our model deals with collisions between weighted particles of arbitrary species, conserving energy perfectly in each collision while momentum is conserved on the average. We also proposed a new method to model extremely high densities. Our model is applicable to a wide range of plasmas from the cold, non-relativistic to the ultra-relativistic regime in the high energy density physics. Results were summarized as a following publication.


3. MeV proton generation

Laser-driven multi-MeV ion beams, accelerated by irradiating thin foils with intense (> 10¹⁸ W cm⁻²) short-(30 fs -10 ps) laser pulses, have unique properties such as high ion number per bunch, ultra-low emittance and short burst duration. These qualities offer the opportunity of employing these beams in many innovative applications: fast ignitor scheme in the inertial confinement fusion (ICF) concept, medical applications, dense plasma diagnostics and probing. We have investigated a new technique to improve the maximum proton energy of the laser accelerated proton beam by using ultra-thin targets [2]. We have been able to reproduce past theoretical predictions with experiments done at LULI in France, and then get a better understanding of the interaction using PICLS.

We have also conducted an experimental and numerical study of the dominant proton acceleration mechanism [4]. The so-called target normal sheath acceleration mechanism is dominant with laser parameters currently achievable. We obtained scaling laws for the accelerated proton’s maximum energy. PICLS has also been used to get a better understanding of the growth mechanisms for laser accelerated proton beams [5].

For many applications of laser accelerated ions, beam control is an essential requirement. A new and interesting technique to control the divergence and the energy spread of the proton beam has been recently developed. It consists in using an
developed. It consists in using an ultrafast laser-triggered micro-lens, which provides simultaneous energy selection and focusing of the incoming ion beam and is tunable. We used PIC simulations coupled with particle tracing and experiments to understand the focusing and energy selection mechanisms, and to study the symmetry of the expanding plasma inside the cylinder [3]. All these results give us a better understanding of how to optimize the laser accelerated proton beams for each application envisioned.


4. Laser isochoric heating

We had studied ultra-fast heating of thin plastic foils by intense laser irradiation theoretically using PICLS2d simulations. We find that the laser-generated hot electrons are confined laterally by self-generated resistive magnetic fields, heating the laser focal area beyond keV electron temperatures isochorically in a few picoseconds. Using this confinement one can excite shock waves that compress the plasma beyond solid density and achieve keV thermal plasmas before the plasma disassembles.

Such shocks can be launched at material interfaces inside the target where jumps in the average ionization state and thus electron density lead to Gigabar pressure. They propagate stably over picoseconds accompanied by multi-MegaGauss magnetic fields, and thus have a potential for various applications in high energy density physics. Results are summarized as a following publication.


5. Full scale Fast ignition simulation

For fast ignition in laser fusion, kJ energy is necessary to ignite compressed fuel before the core plasma disassembles. Ignition of compressed fuel requires the deposition of kJ energy prior to core plasma assembly. The required intensity of ignition laser light is greater than $10^{20}$ W/cm$^2$. Whether this super-intense laser pulse can produce hot electrons in an energy range conducive to efficient core heating is a critical issue in fast ignition research. We have studied the laser hole boring in corona plasmas and the laser-cone target interaction. We are the first to demonstrate a full scale cone-guiding fast ignition experiment using PICLS2d simulations. Our results show the hot electron temperature depends upon the cone target density once the pre-plasma has been blown off. The adjusted scaling of the hot electron temperature is obtained and confirmed by simulations. Core heating physics is also clarified as to the involvement of collisional processes. Drag heating between hot and bulk electrons and consequent energy cascading from the bulk electrons to the core ions are identified as the primary contributors to the core heating.

Relativistic Collision Model for Large Density Scale Plasmas

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Recent advances in the development of intense short pulse lasers have lead to exciting progress in high energy density physics (HEDP). As an example, a several µm thin foil that is irradiated by a 100 TW, sub-picosecond laser pulse reaches keV (1 keV ~ 11,000,000 Celsius) temperatures at solid density, while the electron distribution is temporarily far out of equilibrium, featuring two or more widely distinct temperatures. In modeling such extreme plasmas, both kinetic- and collisional effects on the energy transport are essential. A particular difficulty are the large density gradients between critical density $n_c$, where the laser pulse is absorbed; for a 1 µm wavelength pulse $n_c=10^{21}$ cm$^{-3}$, and solid density exceeding several hundreds of $n_c$. This means that a numerical model needs to describe the laser-plasma interaction in the low density region, as well as fast particle transport in the extremely dense target region where Coulomb collision processes are important for energy transfer. In the fast-igniter scheme of laser fusion, the density scale covers five orders of magnitude from the laser interaction region to the compressed core. Another example for a naturally occurring plasma with large density gradients is the ionosphere of our planet, in particular the polar outflow where the ion density changes by more than two orders of magnitude. Under such conditions, simulations can gain significantly from using weighted particles according to the local plasma density. While being standard practice for kinetic simulations, the use of weighted particles is less straightforward for the description of collisions. This is one topic of this project. Another difficulty arises from the extreme plasma densities in laser-solid interaction or in the fast ignition scheme. Below we will describe a method that is designed to suppress numerical instabilities. While we focus on a description of the numerical method, the implications for the physics will be discussed elsewhere.

The binary collision model for the plasma simulation is introduced by Takizuka and Abe [1]. In their model, particles are scattered by the binary collision process which conserves energy and momentum perfectly. This model is extended to the relativistic mechanics for the weak relativistic regime [2]. The details of momentum transfer in the relativistic mechanics is described there. We corrected the scattering angle of the relativistic collision of Ref. [2] to make it applicable from the non-relativistic regime to the ultra-relativistic regime.

In a situation where the plasma density varies from the under-dense region in which the laser pulse is absorbed to the more than hundred times over-dense solid it is unpractical to keep the number density per macro-particle constant because choosing a reasonable resolution in the under-dense region means an enormous number of particles in the solid. This can be avoided by using variable particle weights. This, however, has significant consequences for the binary collision model. The only available Monte-Carlo collisional model for such weighted particles available today uses a rejection method in which momentum transfer to the heavier of two colliding particles can be rejected with a probability proportional to the weight ratio between the particles [3]. We had implemented Nanbu scheme and modified the model to conserve energy perfectly. The details of our model are summarized in Ref. [4].

We did a series of test simulations to check our collision model. The first one is the rate of energy transfer from hot electrons to cold ions. All electrons have the same initial energy but moving to randomly distributed direction (a shell distribution in momentum space). Taking into account the shell distribution has a factor ($\pi/2$)$^{1/2}$ times faster rate than the Maxwellian distribution,
and expressing the energy by relativistic mechanics, we have the analytical exchange rate [5]. The corresponding simulation is done with the following parameters; density $10^{26}$ 1/cm$^3$, ion mass $M = 1000$, the electron initial energy was set from 2 keV to 10 MeV. A constant Coulomb log $L = 5$ is used for simplicity, and the field calculation was omitted. Results are summarized in Fig. 1. The simulation reproduces the theoretical prediction very well. This confirms that integrating microscopic collision by means of a Monte Carlo methods can give the same results as using the macroscopic quantity, like the average density/energy.

The second test is the fast electron stopping in dense plasmas. The fast electron stopping power is calculated in hydrogen plasma with a mass density 12.5 g/cm$^3$, and temperature 5 keV. Both electron-electron and electron-ion collision were included. We simulated 100 particles and make them averaged to get the stopping power. By changing the fast electron energy from 10 keV to 1 GeV, the obtained results are plotted in Fig. 2. The stopping power from NIST database is also plotted in Fig. 2 as a reference. The simulation results were compared with the Fokker-Plank simulation [Private communication with Dr. Johzaki, ILE Osaka], and the both are in very good agreement.

We discuss numerical methods for relativistic particle simulations for large density gradients. This includes an advanced Coulomb collision model for large density scale plasma in wide particle energy range. Our model has perfect energy conservation in scattering and statistical momentum conservation. This is a great advantage to simulate HEDP with fewer numbers of particles per cell, still avoiding numerical energy violation, which is critical in HEDP problems. Full relativistic description is useful for the relativistic particle transport physics in dense plasmas, like the fast ignition in the laser fusion or relativistic astrophysical jet transport in space. Benchmark simulations show the model validity in wide energy range with weighted particles.

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Proton acceleration by laser-plasma interaction: energy increase and beam control

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1. Introduction

Laser-driven multi-MeV ion beams, accelerated by irradiating thin foils with intense (> 10¹⁸ W cm⁻²) short-(30 fs -10 ps) laser pulses, have unique properties such as high ion number per bunch, ultra-low emittance and short burst duration. These qualities offer the opportunity of employing these beams in many innovative applications: fast ignitor scheme in the inertial confinement fusion (ICF) concept, medical applications, dense plasma diagnostics and probing.

2. Origin of the most energetic laser-accelerated protons and scaling laws

We have established that, for a large range of laser intensities and pulse durations, rear-surface acceleration produces the maximum energy of protons that are accelerated forward by high-intensity, short-pulse lasers from thin metal foils [1]. We have observed this experimentally in two laser intensity regimes: for high-intensity (1-6 10¹⁹ W.cm⁻²) and moderately long pulse (300-850 fs) lasers, and at a lower laser intensity (2 10¹⁸ W.cm⁻²). In other laser intensity or laser pulse duration regimes we did not explore experimentally, we have compared analytical estimates of the proton energy produced by rear-surface and front-surface acceleration to a wide range of published results. The collimation and the low emittance of the predominant RSA protons is an important advantage for potential applications that require high-quality beams such as table-top ion accelerators. We also obtained scaling laws for the accelerated protons maximum energy.

3. Beam control

For many applications of laser-accelerated ions, beam control is an essential requirement. A new and interesting technique to control the divergence and the energy spread of the proton beam has been recently developed. It consists in using an ultrafast laser-triggered micro-lens that provides tunable, simultaneous focusing and energy selection of MeV proton beams. 2D PIC simulations and new experiments were used to study the symmetry of the plasma expansion inside the laser-irradiated cylinder. The expansion is found to be very symmetrical over long time scales, in agreement with experimental observations [2].

4. Proton acceleration from laser-irradiated ultra-thin targets

We validated a regime of laser acceleration of protons, which relies on the interaction of ultrahigh contrast laser pulses with ultrathin targets, using experiments and simulations [3]. Proton beams were accelerated to a maximum energy of ~7.3 MeV from targets as thin as 30 nm irradiated at 10¹⁸ W cm⁻² µm² (1 J, 320 fs) with an estimated peak laser pulse to pedestal intensity contrast ratio of 10¹¹. This represents nearly a tenfold increase in proton energy compared to the highest energies obtainable using non contrast enhanced pulses and thicker targets (>5 µm) at the same intensity. To obtain similar proton energy with thicker targets and the same laser pulse duration, a much higher laser intensity (i.e., above 10¹⁹ W cm⁻² µm²) is required. The simulations are in close agreement with the experimental results, showing efficient elec-
tron heating compared to the case of thicker targets. Rapid target expansion, allowing laser absorption in density gradients, is key to enhanced electron heating and ion acceleration in ultrathin targets.

5. Proton acceleration from laser-irradiated micro-cones
We have investigated the interaction of high intensity lasers with micro-cones. PIC simulation results [4] show that the peak proton energy reaches 26 MeV for a $10^{19}$ W/cm$^2$, 350 fs laser, and that the pointing accuracy of the laser into the cone, by mispointing or preplasma fill conditions, is critical for maximum proton energy. Also the proton energy is relatively insensitive to the focal plane of the laser. We also compared these results with the interaction with a flat target, and with controlled pointing and preplasma conditions, the maximum energy can be tripled.

![Figure 1: Longitudinal electrostatic field measured 500 fs after the beginning of the simulation for a $10^{19}$ W/cm$^2$, 600 fs laser propagating on the axis of the cone.](image)

6. Proton acceleration from laser-irradiated gas jets
We have studied with PIC simulations, the possibility of accelerating MeV protons with laser-irradiated gas jets [5]. We investigated two regimes: low plasma densities ($< 0.05\%$ of the critical density $n_c$) and long targets for which laser wakefield acceleration of electrons is possible, and higher densities ($0.05\% n_c < n < n_s$) and shorter targets. We showed that in both regimes, proton acceleration is the result of the very strong electrostatic field set up at the back of the target by the hot electrons trapped in the laser wake. We also showed that the presence of a density gradient at the back of the target did not significantly lower the maximum proton energy as it is the case with solid targets.

7. Summary
The different applications envisioned for laser-accelerated proton beams all require different beam parameters. We were able to find new ways to increase the maximum proton energy and to control the beam divergence and energy spread. Our results give us a better understanding of how to optimize the laser accelerated proton beams for each application.

8. References
Irradiation of matter with ultra-intense short laser pulses can create plasmas at solid density and temperatures of several hundred eV, i.e. several million degrees. The lifetime of such extreme states is limited by hydrodynamic expansion, which can take not more than several picoseconds for micrometer size objects, therefore energy must be deposited rapidly and deep in the target. This principle has been demonstrated for the first time by Saemann using non-thermal electrons that were generated in the interaction of a short laser pulse with an aluminum slab, obtaining temperatures of around 300 eV in a front layer of less than 1000 Å depth at a modest relativistic laser intensity of $10^{17}$ W/cm$^2$ [1]. On the other hand, the large number of hot electrons created in Petawatt laser-matter interaction can be used to drive exploding pusher targets [2]. However to date, one has not yet achieved keV ion temperatures at solid density in sufficiently uniform volumes and for long enough times (several ps) that would be required for opacity studies of hot dense matter, small-scale pulsed neutron sources, studies relevant for inertial confinement fusion, or laboratory astrophysics. In this work we present results from two-dimensional collisional PIC simulations, PICLS2d that demonstrate a novel way to create keV thermal plasmas at compressed solid density using controlled shock waves by irradiating multi-layered thin foils with ultra-short pulses at parameters that are experimentally available today.

To do this we embed a thin layer of metal in a plastic target in the following simulation setup. The target is a slab with 5 µm thickness and 26 µm width. It consists of three layers, a 1 µm Al layer that is sandwiched by 2 µm of CD plastic on each side, as illustrated in the inset of Fig.1. The carbon C$^{12+}$ and deuteron D$^+$ densities are 20$n_e$, the Al$^{12+}$ density is 40$n_e$, resulting in a total electron density of $120n_e$ in the CD layer and 480$n_e$ in the Al. The laser pulse has an intensity of $10^{18}$ W/cm$^2$ and a 1 ps pulse duration with 30 fs rise/drop time. The laser focal spot size is 10 µm. These parameters correspond to a 1 TW laser system with a total irradiated laser energy of 1 J in the focal spot.

Figure 1 shows how energy coupling between laser generated hot electrons and the cold background electrons creates a strong pressure gradient at the interface between the Al and CD plastic layers. The ratio between the density of thermal electrons in Al and in plastic is roughly four under the present conditions, depending mostly on material parameters (note our remark about ionization earlier). The resulting electron pressure gradient drives an ion shock wave into the low-pressure plasma, compressing the density to roughly twice its unshocked value and heating the ions almost one order of magnitude hotter. The maximum shock speed in our simulation is roughly $10^3$ c so that it takes 3 ps to pass the target during which electron collisions heat the ions by an extra 10-20%. (compare below) An unusual feature of this 'ion shock', as compared to conventional hydrodynamic shocks, is that...
neither \( T_e \) nor \( T_h \) jump across the shock interface, but the ion temperature \( T_i \) does.

Figure 2 shows a snapshot of charge densities and electric field in the target, as well as ion velocity space at a time when the shock has traveled through about 1/3 of the total plastic layer. At this time the rarefaction wave that is associated with the expansion of the plastic into vacuum has reached \( x=7 \ \mu m \).

The mean-free path of the laser-heated electrons at 200 keV, as well as that of the thermal electron population (10 keV) is much larger than the Al thickness so that we can assume the electrons to be freely moving across the material interface. This means that we can view the hot electrons as an energy reservoir for the thermal energy. We also find that the electron temperature later after 1 ps is nearly constant throughout the target in \( X \)-direction.

Shock compression and heating in multi-layer targets lead to higher thermonuclear reaction rates than in comparable uniform targets. In our simulation the deuteron thermal energy jumps from several 100 eV to 3.6 keV across the shock so that the D-D fusion reaction rate increases by four orders of magnitude. The total number of neutrons is expected to \( 10^5 \) over a 30 \( \mu m \) spot in 3 ps. Shock compression thereby shifts the dominant neutron production mechanism from beam fusion in uniform targets (neutrons are generated by laser-accelerated fast deuterons from the front of the target with a few 100 keV energy and are therefore nonthermal) to thermonuclear reactions in shocked multi-layer targets. Compression factors could be further enhanced by making use of converging shocks, i.e. by embedding cylindrical or spherical metal shells in CD plastic. The key process that limits our ability to efficiently heat targets is the lateral diffusion of energy. In order to maximize the amount of laser energy coupled into hot electrons, we have to increase the laser intensity; but at the same time this leads to a higher electron temperature which increases the energy transfer time between hot and cold electrons, so that more energy is lost laterally. As an alternative way to confine the hot electrons we suggest to magnetize them with an external Megagauss field that can be generated for example by a MA z-pinch. Radiation energy losses are not included in our simulations, but we presume that most of the radiative loss originates from Al ions, and it is estimated as less than 10 mJ in laser focal spot, which is much less than the input energy 1J.

We have studied isochoric heating of thin multi-layer foils by ultra-intense laser short pulse irradiation using a two dimensional Particle-in-Cell model that includes the effects of collisions. We demonstrate a strong additional heating by ion shocks that are launched at material interfaces due to Gigabar electron pressure jumps. The ion thermal energy in such targets can exceed 1 keV at compressed solid density and a significant enhancement of the thermal neutron yield compared to uniform targets can be expected.

Fig. 2 (a) Charge density profiles and the electrostatic field at the target center observed at 1.65 ps. Only half the target is shown for symmetry reasons. (b) Ion longitudinal phase plots \( X-P_x \) at the same time with (a). Blue, green, and red color indicate aluminium, carbon, and deuteron, respectively.

Full scale integrated simulation of Fast Ignition

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In the fast ignition (FI) scheme of inertial fusion energy \cite{1}, a dense plasma core is expected to be heated by an ultra-intense laser to trigger a propagating fusion reaction. First, fuel is imploded to produce a high-density configuration without hotspot and then energy is injected to drive a small region to ignition. If the ignition energy is supplied sufficiently rapidly before hydrodynamic expansion, the hotspot can be driven to ignition conditions before it cools. If the required fuel density is 300 g/cm\textsuperscript{3} and the temperature is 10 keV, the energy delivery time is less than 3 picoseconds with 3 kJ by a petawatt laser system \cite{1}.

Recent experiments at ILE using the GEKKO laser coupled to the PW laser system have demonstrated the cone guiding concept \cite{2}. The PW laser enhances the neutron yield of two orders of magnitude and it is presumed to have heated the core up to 1 keV, based on the data of neutron yields. At this point, the details of the heating mechanism are still in debate. It is impossible to predict the heating in a scaled-up Ignition-relevant core, based on the experimental data alone. The hybrid simulations have been used to understand the transport physics in the cone-guiding fast ignition \cite{3-5}. One of problems of the hybrid simulations is how to define the input electron source. The hot electron temperature is normally assumed as the following simple ponderomotive scaling \cite{6}:

\begin{equation}
T_h = m_e c^2 \left( \sqrt{1 + a^2} - 1 \right).
\end{equation}

where $m_e$ is the electron mass, $c$ is the light velocity, and $a$ is a normalized amplitude defined as $a = eE/m_e c \omega$ with the laser frequency $\omega$. For examples, when $a = 10$, corresponds to $1.4 \times 10^{20}$ W/cm\textsuperscript{2}, $T_h \sim 4.6$ MeV. Therefore, the hot electrons produced by the ignition pulse might be much hotter than 1 MeV, which is the energy supposed to efficiently couple to the core with 300 g/cc \cite{7}.

This is the critical issue in the FI, and it is important to study the hot electron production with a realistic parameters.

This year, we had studied the cone-guiding fast ignition by the collisional PIC code. This is the simulation, which includes all the physics of the FI self-consistently except fusion reaction, namely, hot electron generation, fast ion acceleration, energy transport in large density scale coronal plasmas, and energy coupling in the core including collisional processes. We found that the electromagnetic instabilities appear around the cone target where the plasma density is less than a few hundred critical density, but no significant fields near the core area. This indicates that the core heating is mainly done by collisional processes. The dominant core heating mechanism was identified as the drag heating between hot and bulk electrons in the simulation. We also found that the hot electron temperature observed in the simulation is lower than the ponderomotive scaling of Eq. (1), after the preplasma inside cone was blown away by the strong photon pressure. The hot electron temperature scaling is revised as,

\begin{equation}
T_h = m_e c^2 (\gamma_{os} - 1) \sqrt{\gamma_{os} n_e / n_i}
\end{equation}

where $\gamma_{os}$ is the electron's relativistic factor in the laser light, $n_e/n_i$ is the cone target density normalized by the critical density. This temperature scaling, which is confirmed by our 2D simulations, indicates that hot electrons produced from the super intense ignition pulse might be tunable by changing the cone density, namely by replacing material inside the cone, for the optimal core heating. The temperature scaling is also useful to decide an input hot electrons' condition for the hybrid simulation.

The details of simulation parameters are in Ref. \cite{7}. The plasma is modeled as fully ionized hydrogen plasmas with 150 eV electron and ion temperature initially. The core
density is $2 \times 10^{25} \text{ cm}^{-3}$, which corresponds to 100 g/cc if the plasma is DT, and its diameter is 10 µm. The core is surrounded by coronal plasmas with an exponential density profile from $10^{20}$ to $2 \times 10^{25} \text{ cm}^{-3}$. The cone target with density $5 \times 10^{23} \text{ cm}^{-3}$ is placed at 25 µm from the center of core and it has 30 degree opening angle. The tip size and thickness are 10 µm and 5 µm, respectively. Inside the cone, preformed plasmas are replaced. The normalized laser amplitude is $a=10$ corresponding to the intensity $1.4 \times 10^{20} \text{ W/cm}^{2}$. The laser has a semi-infinite duration starting with 150 fs rise time with Gaussian profile. The total simulation time is about 1 ps. The input energy in the laser spot (gaussian profile of 10 µm diameter) is ~130J in 1ps, and about 85% of the energy is absorbed through the laser-cone interaction.

Figures 1 shows the quasistatic magnetic fields at 860 fs. Note here that the magnetic fields do not show up early in time, because the instability is completely dominated by collisions, but later the local plasma temperature increases, namely, the collisional effects become weaker, the magnetic fields start to grow from the instability. Nevertheless, the quasistatic magnetic filaments are localized below a few hundred critical density and never reach the core area. This density consists of the strong heating happen below 100n,. Meaning that the kinetic instability is suppressed in this high dense region, and heating is mainly the collisional processes, which are the same features observed in longitudinal modes (1D) in Ref. [9].

The maximum core temperature after about 1 ps heating is 1.5 keV for ion and 45 keV for electrons. The coupling efficiency in the area above $10^{24} \text{ cm}^{-3}$ density is 33.3% for electron and 6.4% for ion. In the core area, 13.1% (electron) and 2.4% (ion). In Fig. 2, a history of the peak energy gain in the core is plotted. We see that the rapid heating in the early time (250 – 400 fs) and also slower heating after 400 fs. The core heating at the early stage is mainly due to the resistive heating, which is saturated after the core temperature exceeds about five hundred eV (gain ~3) [9]. The later the direct collision between hot and bulk electrons becomes dominant.

Figure 2: Time history of energy gain in core region. The gain is calculated by dividing the local energy by the initial temperature 150 eV. (a) Electron energy density and (b) ion energy density at 860 fs.

The Importance of EBIT Data for Z-pinch M-shell W Plasma Diagnostics

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The first x-ray spectra of M-shell W were produced by high-density exploded–wire plasmas more than 25 years ago [1]. Then precision of the measurements of Ni-like W lines was improved in laser plasma experiments. Also tungsten wire arrays were studied extensively on the Z accelerator at Sandia National Laboratories (SNL) since 1998 when it was shown that they can produce x-ray powers up to 200 TW and x-ray energies up to 2 MJ [2]. Since then, despite an increasing number of papers about the implosions of W arrays on the SNL-Z machine and their recent applications to inertial confinement fusion, x-ray M-shell diagnostics of tungsten high energy density (HED) plasmas have not yet been developed.

We present a theoretical model of M-shell W spectra and a comparison of HEDP and EBIT data [3]. This model was benchmarked with LLNL EBIT data produced at different energies of the electron beam and recorded by crystal spectrometers and a broadband microcalorimeter. Moreover, HEDP were produced from the variety X-pinches on 1 MA Zebra device at UNR [4]. In particular, M-shell W radiation was generated by implosions of X-pinches with tungsten wires combined with the wires from other lower-Z wire material such as Al and Mo. We have found that using such combined loads provides better quality M-shell W spectra than when using only W wires [5].

Our non-LTE collisional radiative (CR) model of the M-shell W emission has about 4000 levels, and includes the ground states from all ions from neutral to bare W and a detailed structure for Cr- to Se-like W ions. Energy level structure and complete radiative coupling as well as a subset of collisional data were calculated using the FAC code developed by M. F. Gu [6]. The energies for the excited states for the transitions 3l-4l', 3l-5l'', and 3l-6l''' as well as radiative transition probabilities in Ni-like W were also determined to second order in Relativistic Many Body Perturbation Theory (RMBPT) [7-8].

<table>
<thead>
<tr>
<th>Line</th>
<th>Upper level LS</th>
<th>RMBPT 3 l (Å)</th>
<th>Ar 3 (Å²)</th>
<th>FAC 3 l (Å)</th>
<th>Ar 3 (Å²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td>3s6f 3p4 3p4 3p4</td>
<td>3.079 5.66(13)</td>
<td>3.056 5.26(13)</td>
<td>3.079 5.66(13)</td>
<td>3.056 5.26(13)</td>
</tr>
<tr>
<td>N3</td>
<td>3d6g 3p4 3p4 3p4</td>
<td>4.393 1.18(14)</td>
<td>4.393 1.35(14)</td>
<td>4.393 1.18(14)</td>
<td>4.393 1.35(14)</td>
</tr>
<tr>
<td>N4</td>
<td>3s6f 3p4 3p4 3p4</td>
<td>4.493 5.07(13)</td>
<td>4.493 5.07(13)</td>
<td>4.493 5.07(13)</td>
<td>4.493 5.07(13)</td>
</tr>
<tr>
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<td>3s6g 3p4 3p4 3p4</td>
<td>6.593 3.77(14)</td>
<td>6.593 3.99(14)</td>
<td>6.593 3.77(14)</td>
<td>6.593 3.99(14)</td>
</tr>
<tr>
<td>N7</td>
<td>3s6f 3p4 3p4 3p4</td>
<td>6.676 1.58(14)</td>
<td>6.676 1.58(14)</td>
<td>6.676 1.58(14)</td>
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</tr>
<tr>
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<td>6.144 2.37(13)</td>
<td>6.154 2.25(13)</td>
<td>6.144 2.37(13)</td>
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<tr>
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<tr>
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<tr>
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<tr>
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<td>7.930 3.97(12)</td>
<td>7.979 3.50(12)</td>
<td>7.930 3.97(12)</td>
</tr>
</tbody>
</table>

Table 1 lists the atomic data calculated for the most intense lines in Ni-like W specified in LS coupling. In particular, the spectral lines N1-N10 are allowed electric-dipole (E1) transitions, i.e. transitions of the type 3-6 (N1, N2), 3-5 (N3 and N4), and 3-4 (N5-N10). The spectral lines N11 and N12 are forbidden 3-4 electric-quadrupole (E2) transitions. The comparison of RMBPT and FAC atomic data calculated for the observable transitions in Ni-like W in Table 1 shows a good agreement.

M-shell W spectra produced at the LLNL EBIT-I and EBIT-II electron beam ion traps were collected in two different experiments using a crystal spectrometer and an engineering model of the x-ray
spectrometer (XRS) microcalorimeter from the Suzaku x-ray satellite mission. Earlier, we have analyzed the data from the experiments with a crystal spectrometer on EBIT-II [9]. The XRS microcalorimeter as fielded on EBIT-I recorded the spectra in a broader spectral range (from 3 to 8 Å) and with about 6 times less resolution than the crystal spectrometer. In Fig. 1 the experimental spectrum (bottom) is presented along with the modeling (top). The theoretical synthetic spectrum at the top of Fig. 1 is calculated using the non-LTE kinetic model of W with a Gaussian electron distribution function of 50 eV full width half maximum (FWHM) centered at \( E_b = 3.9 \) keV. All twelve lines Ni1-Ni12 are reproduced well by our theory.

The experimental Al/W X-pinche spectrum is shown at the top of Fig. 2. It was a planar-loop X-pinche with a 99 µm Al 5056 wire in the anode loop and a 35 µm W wire in the cathode loop. The experimental spectrum includes both K-shell radiation from Al and Mg (Al 5056 has 95% Al and 5% Mg) and M-shell radiation from W. EBIT spectra were very useful in the identification of M-shell W spectra from the implosion of combined X-pinches. The comparison of the Al/W X-pinche spectrum (Fig. 2, top) with the experimental LLNL EBIT spectrum (Fig. 2, bottom) reveals the 3-4 transitions (N5-N10) and 3-5 transitions (N3 and N4) in Ni-like W.

Modeling at an electron temperature \( T_e = 1 \) keV, electron density \( N_e = 10^{21} \) cm\(^{-3}\), and a small portion of non-Maxwellian electrons \( f = 0.03 \) describes well the most intense peaks and the ratio between 3-5 and 3-4 transitions in Ni-like W. However, more work is needed to match the intensities of higher and lower ionization stages. It is important to note that forbidden E2 transitions Ni11 and Ni12, which are present in spectra from low-density sources, are not observed in the X-pinche spectra. Work at LLNL was performed under of auspices of the DOE under contract No. W-7405-Eng-48.

Investigation of Global MHD Instabilities in Multispecies Z-pinch Plasma

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Work in progress

Investigation of multispecies plasma is important for many applications [1,2], including tokamak, laser ablated, Z-pinch, space and astrophysical plasmas. 3D hybrid simulations of multispecies plasma can provide valuable insight into the processes related to the magnetic field and current distribution, energy partition between the different ion species, and growth rates of MHD instabilities.

In the process of plasma ablation from wires in a wire array, consisting of deuterium and palladium, plasma in the precursor consists of heavy and light ions. To study the physics of the multispecies plasma in the precursor region (the region where most of the heating takes place), we use the multifluid description. This approach allows to study development of global MHD instabilities inside the precursor and identify what ion component can be responsible for support of the current in this region and as a result is associated with the magnetic field distribution inside the precursor plasma. Dependence of the growth rates of MHD instabilities from the density ratio of heavy and light ions as well as kinetic energy partition between the two plasma components will be investigated as well.

We will also present results of 3D hybrid simulations of sausage and kink instabilities in the multi-component plasma of the precursor.

In order to determine dependence of magnetic field distribution inside the current-carrying plasma of the precursor from the densities of the light (proton) and heavy (palladium) ion components, we carried out 3D hybrid simulations of two component plasma with the following setup. Inside the conducting cylinder we placed two ion components with density and magnetic field profiles, corresponding to the Bennett profile.

Simulation results for two runs

Run 1. 10% of proton density and 90% of palladium density
Run 2. 90% of proton density and 10% of palladium density
are presented below.

In Figures 1-3 distribution of magnetic field and densities of protons and heavy ions in Run 1 are presented.

Figure 1. Distribution of magnetic field inside the simulation box at the moment t = 120 (time is in dimensionless units).
It is clearly seen from Figures 2 and 3 that protons and heavy ions have different spatial distributions. Proton distribution has much larger radius in comparison with heavy ions. An important result, seen in Figure 1 is that distribution of the magnetic field tends to follow the proton distribution, i.e. it is much wider then the distribution of heavy ions. It means that protons (light ions) are the component, which is responsible for carrying current in the system. Similar result was observed in Run 2 and presented in Figures 4 (magnetic field), 5 (proton density) and 6 (heavy ion density).


The efficiency of electron acceleration by a short powerful laser pulse propagating across an external magnetic field has been investigated. The conditions for decay of the laser pulse with frequency close to the upper hybrid resonance frequency have been analyzed. It is shown that a laser pulse propagating as an extraordinary wave in a cold magnetized low density plasma takes the form of a nonlinear wave with modulated amplitude known as an envelope soliton. Also, simulation results on the interaction of an electromagnetic pulse with a semi-infinite plasma obtained with the help of an electromagnetic relativistic PIC code are discussed and comparison with the obtained theoretical results is presented. It is shown in the present work that an extraordinary wave in a cold magnetized low density plasma takes the form of a nonlinear wave with modulated amplitude or envelope soliton. This is why, under the conditions of upper hybrid resonance $\delta = 1 - \omega_{\text{th}} / \omega << 1$, both weakly nonlinear (when $\epsilon_m^2 / 32\delta^3 << 1$) as well as strongly nonlinear ($\epsilon_m^2 / 32\delta^3 >> 1$) cases of electron interaction with the wave take place ($\epsilon_m = eE_m / m\omega$, $E_m$ and $\omega$ are the amplitude and carrier frequency of the soliton wave). In contrast to a linear pulse [1] the width of a nonlinear pulse is not a free parameter any more but is defined by the effects of nonlinear contraction and wave packet broadening due to wave dispersion. The theoretical results are in agreement with the presented simulation results on the interaction of an electromagnetic pulse with a semi-infinite plasma obtained with the help of an electromagnetic relativistic PIC code [2]. The polarized electromagnetic impulse created in vacuum is transformed into an elliptically polarized extraordinary wave at the plasma boundary. The development of the ensuing modulational instability is accompanied by strong “modulation” of the broad wave packet. The short pulse is transformed into an envelope soliton with its width proportional to the inverse growth rate of the instability. The longitudinal component of the electric field of the elliptically polarized electromagnetic wave ($\epsilon_m^2 / 32\delta^3 = 1$, $v_{ph} = c$) can be used for acceleration of plasma electrons across an external magnetic field. However, the simulations show that stochastic electron heating on top of the soliton structure is observed when the threshold for parametric instability [3] is achieved ($\epsilon_m > \delta$).

The analysis of the parametric instability of a constant amplitude light wave, which propagates perpendicular to the external magnetic field such that

$$E_x = E_0 \cos \psi, \quad \psi = \omega \left( t - z / c \right)$$

has been carried out in Ref. [3]. In this case the rotation of plasma electrons perpendicular to the magnetic field in the (x,z) plane is similar the instability of a mechanical pendulum with modulated frequency [4]. Using this analogy the dispersion relation for the growth rate $\lambda$ (in the units of $\omega$) is obtained.

To model the process of resonance interaction of an extraordinary wave with a plasma we have used the electromagnetic relativistic PIC code 1D2V. The impulse formed in the vacuum region moves towards...
the plasma boundary. The wave is considered to be linearly polarized with electric field vector $E$ directed along the $x$-axis and perpendicular to an external magnetic field $B_0$. Initially, the plasma is assumed to be cold and has a step-like density profile at the boundary. The wave fields and plasma density profile depend only on the $z$ coordinate along the direction of laser pulse propagation. Ions are considered immobile.

Simulation results show that during propagation perpendicular to the external magnetic field in a low density plasma ($\omega_p/\omega_c << 1$) the wide flat-top profile electromagnetic pulse in the region of upper hybrid resonance decays into a chain of solitons due to self-modulation (Figure 1).

![Figure 1](image1.png)

**Figure 1.** Self-modulation of a long pulse propagating in the plasma at time $t = 600$ (in units of $\omega_0^{-1}$). Electric field $E_x$ is normalized to the laser pulse amplitude in vacuum $E_0$, and the $z$-coordinate is in units of $c/\omega$: $\varepsilon = 0.1$, (a) $q_p = 0.1, q_e = 0.9$; (b) $q_p = 0.4, q_e = 0.7$

The width of the solitons decreases when the plasma density is increased. To excite a single soliton, simulations of the interaction of a short pulse with an envelope-soliton-like amplitude profile with a dense plasma have been carried out. With time the main part of the pulse takes on the form of a solitary wave as shown in Figure 2.

![Figure 2](image2.png)

**Figure 2.** Excitation of a solitary wave in a dense plasma by a short laser pulse formed in vacuum, $\varepsilon = 0.1$, $q_p = 0.5, q_e = 0.65$.

The width of the soliton is decreases with increasing pulse amplitude in agreement with theoretical results.

Investigation of Nonlinear Dynamics of Flute Mode Instability in Finite Beta Plasma in Support of Z-pinch and Laboratory Astrophysics Experiments

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Flute mode turbulence plays an important role in numerous applications, such as tokamak, Z-pinch, space and astrophysical plasmas. In a low beta plasma, flute oscillations are electrostatic and in the nonlinear stage they produce large scale density structures and on top of them short scale oscillations. The large scale structures are responsible for enhanced transport across the magnetic field and the appearance of short scales leads to ion heating through ion viscosity. The nonlinear equations which describe the nonlinear evolution of flute modes, which are treated as compressible electromagnetic oscillations in a finite beta inhomogeneous plasma, have been solved numerically. Results show that inclusion of new terms associated with finite beta effects into the nonlinear system which describes the development of flute mode turbulence does not prevent formation of large scale structures and shorter scale perturbations.

Analysis of the data obtained during laboratory experiments on imploding wire arrays [1,2] has demonstrated that flute-like perturbations of density appear in the finite beta z-pinch plasma of the precursor. Moreover, these density perturbations are observed simultaneously with magnetic field perturbations directed along the pinch magnetic field. It was also observed that in the long run the perturbations evolve into large scale structures, with the wave spectrum migrating into the region of short wavelengths at the same time.

Laboratory experiments on the interaction of a plasma flow, produced by laser ablation of a solid target with the inhomogeneous magnetic field from the Zebra pulsed power generator have demonstrated the presence of strong wave activity in the region of flow deceleration [3]. The deceleration of the plasma flow can be interpreted as the appearance of a gravity-like force. The drift due to this force can lead to the excitation of flute modes. Results of such experiments are related to supernova explosions, interaction of the solar wind with the magnetopause [4] and active space experiments, such as the artificial magnetospheric releases similar to the AMPTE magnetotail release [5].

Two-fluid macroscopic equations have been derived to describe low frequency flute modes in a weakly inhomogeneous plasma with external magnetic field $B_0(x)$. As is customary in flute mode turbulence, the oscillations are taken to be uniform in the direction of the magnetic field, i.e. the wave vector along the magnetic field $k_z = 0$. The curvature of the magnetic field lines, consistent with the axial current, causes a centrifugal force on the particles emulated by the gravity-like term $g = g\hat{e}_z$, which drives the instability of the flute modes.

The nonlinear equation for density is:

$$\frac{\partial \delta n}{\partial t} = \frac{c}{e} \frac{T_c}{B_0} \frac{\kappa_y}{\kappa_x} \frac{\partial \delta n}{\partial y} + \frac{n_{0e} c}{B_0} (\kappa_y + \kappa_x) \frac{\partial \Phi}{\partial y} - \frac{n_{0e} c}{B_0} (\frac{\delta B_z}{\partial t} + \frac{c T_c}{e B_0} \frac{\delta B_x}{\partial y}) = \frac{c}{B_0} [\hat{\nabla} \delta n, \hat{\nabla} \Phi].$$

The nonlinear equation for the potential $\Phi$ can be written as:

56
To solve the nonlinear flute equations numerically, we use a pseudo-spectral spatial representation and a two-step predictor-corrector time advance. The Arakawa method is used throughout to treat the spatial derivatives encapsulated in Poisson brackets in the nonlinear terms and the viscous and biharmonic dissipations are advanced explicitly in time. Numerical results are presented in Figs. 1 - 3.

As shown in Fig. 1, linear growth of the flute mode instability is followed by robust saturation for systems with small as well as large plasma betas.

The simulations have been initialized with random density perturbations. With time these perturbations undergo exponential growth in agreement with linear theory. In the nonlinear stage the perturbations develop into large scale spatial structures, accompanied by shorter scale perturbations. The density perturbations associated with flute mode growth are plotted in Fig. 2.

Facilities and Operations
Leopard Laser Facility
NTF’s Laser Program Progress in 2006

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Abstract

NTF is currently completing the development phase of 100-TW class Nd:glass laser called Leopard (see Fig. 1). The project is established with financial support from DOE in cooperation with LLNL and other international high-intensity laser facilities. After Leopard completion, NTF will offer the unique combination of z-pincho Zebra generator with a powerful laser beam thus providing the opportunity to investigate a variety of fundamental science issues in the plasma physics field. The two major milestones were reached in 2006:

- The Tomcat laser pulse compression and coupling it to the Zebra pulsed power generator.
- Activation of the entire Leopard laser amplifier chain to the single-pass through 94 mm amplifier. The output energy of 29.4 J was measured.

Leopard Laser

We have completed standard simulations of the Leopard pulse propagation and we closed this phase of the project. The optical pass through the laser chain was simulated using a ray tracing code (ZEMAX) and a beam propagation code (Miro). While the ray tracing code is more suitable to minimize wavefront aberration and lens design, the beam propagation code includes among others the gain, B-integral and a spatial filter effect. Laser gain, pulse duration, B-integral and beam shape were optimized. Critical issues like the stray reflection amplification and the damage threshold values have been studied in detail. The extended simulation phase, including aberrations and adaptive optics, will be performed by a graduate student or post-doc in the near future.

Fig. 1: Schematics of the Leopard laser.

A milestone was reached in summer 2006, when the projected performance values were demonstrated at the femtosecond front-end. The front-end comprises a commercial fs oscillator (SpectraPhysics Tsunami), pumped by cw 10 W diode-pumped Nd:YVO₄ laser (SpectraPhysics Millenia), an Offner-type chirped pulse stretcher unit and a commercial linear regenerative amplifier (Coherent) – see Fig. 2. The regenerative amplifier is pumped by a Nd:YAG laser operating at 10 Hz repetition rate (Continuum, Powerlite).

Fig. 2: A Ti:Sapphire regen amplifier.

The system provides frequency-chirped, stretched pulses with nearly 10 nm
bandwidth and energy of 2 mJ for the injection into the flashlamp-pumped amplifiers section. The fs front-end was operated frequently in 2006 and proved itself reliable. The contrast ratio was improved to the level of $10^{-6}$ by adding an ultra fast Pockels cell at the output of the regenerative amplifier. The complete Offner stretcher unit was built in house. It converts 150 fs pulses from the fs oscillator to 1.2 ns long chirped pulses which are then amplified at irradiance well below the self-focusing threshold. During the setup of the stretcher we discovered that the large diameter convex mirror is corroded due to manufacturer error. The mirror was replaced later by the vendor.

Fig. 3: Test shot of 19 mm rod amplifier.

A 30 W cw Nd:YLF alignment laser was delivered and installed to allow for fast alignment of components without having the high intensity of a pulsed laser. With this laser a beam pointing from the front-end to the experiments can be verified later before each full energy shots.

Components of the main amplifiers were tested, modified, installed and aligned, including 6 mm, two 19 mm and 45 mm diameter rod amplifiers. Five telescopes with vacuum spatial filters have been put in place, tested and aligned. All the rod laser heads have been fired separately with a small seed pulse from the fs front-end, as well as in unison to measure the total output energy available and how it depends on the applied high voltage. Numerous mechanical and electrical modifications were made to rod laser heads obtained from LLNL. New flash lamps were ordered and installed and a new HV connection scheme was successfully implemented. Extensive work was done on the Leopard pulsed power supplies for rod amplifiers (Fig. 3). These activities were mainly driven by a safety issues and the desire to make the whole system more reliable. The test and monitoring capabilities of the system were extended by adding the capability of using dummy loads instead of the flash lamps.

One of the important milestones of NTF Laser Project was reached in March 2006, when the 94 mm diameter mixed glass disk amplifiers arrived at NTF from LLNL. A NTF technical team assembled 3 complete disk amplifiers in a LLNL clean room facility. Two amplifiers consists of six 94 mm neodymium-doped disk, four of them are phosphate and two silicate glass. One amplifier is completed with phosphate glass disks only. Mechanical modifications and additions were necessary for the disk amplifiers obtained from LLNL. The beam line in disk amplifiers is completely enclosed and filled with filtered nitrogen to ensure that no dust or water vapors can settle on the optics. Two Brewster windows were added in both ends (see Fig. 4).

Fig. 4: 94 mm disk amplifier.

A preliminary control and safety system was developed to test the ignitron switches, energy storage capacitors and the amplifier flash lamps. To test the flash lamps for amplifiers a small in-house flash
lamp test stand was developed. During the tests one flash lamp exploded and one failed to ignite. A majority of them passed all tests and were installed inside all three amplifiers. The PFN and control system of the main amplifier part consisting of one 6 mm, two 19 mm, one 45 mm and one 94 mm amplifiers were implemented in manual firing mode at the beginning and replaced by computer-controlled mode later. The system is not finish yet, but in current state of the development is able to provide full energy shot from Leopard laser. This control system allows the remote control of the power supply units, the dump system and a data acquisition system to monitor several current waveforms in parallel. The implementation of a PILC circuit improved overall efficiency and increased the flash lamp’s lifetime.

Extensive operation tests of the all amplifiers were performed. The pulsed power system was tested by discharging all the capacitors for the double-pass amplifier into dummy resistors at the full charging voltage 18 kV. Modifications in the amplifier were done to provide nitrogen flow to cool down the flash lamps and glass disks after each full energy shot. During the tests an optical damage in one phosphate glass disk was discovered. To save time and avoid delays, we decided to replace the complete amplifier and replace the damaged disk later.

In 2006 a milestone has been covered for the TW compressor called Falcon (Fig. 5). First, the compressor layout was chosen offering the best performance available. Second, the vacuum issues with the compressor chamber were finally solved.

To ensure synchronized operation of NTF’s lasers with the Zebra generator, the communication hardware for the timing system were installed and the synchronization scheme was implemented. To improve the long term stability and EMI robustness of the timing system, some critical electrical connections to the Zebra were replaced by optical fiber connections.

The optical diagnostics and control system is necessary to monitor all essential operational and beam parameters of Leopard laser with various diagnostics. It has to provide the ability to adjust the parameters as needed. Particularly important is the beam diagnostics of the output beam of the Leopard disk amplifier. Among the most important parameters are energy, power, near and far field distributions, spectrum and wavefront. Due to the lack of human resources we decided to outsource this project. A reputable company was chosen to build an optical diagnostics system for Leopard and the technical discussions have been initiated. In the meantime before delivery of this system a core optical diagnostics were implemented in the laser chain to assure the alignment quality and safe laser operation. This temporary diagnostics system includes the characterization of fs pulses from oscillator (energy, spectrum, time duration measured by FROG device, and direction and pointing of the beam), after the stretcher (energy, pulse duration, spectrum, direction and pointing), after the regenerative amplifier (the same as after the stretcher) and in many places inside the laser chain where mostly the energy and direction and pointing of the beam are monitored.

**Tomcat Laser**

The Tomcat laser pulses were successfully compressed to the time duration
on the level of 500 fs and were coupled with the firing of the Zebra pulsed power generator. A number of modifications were done to reach this milestone, including Tomcat front end improvement, new optical diagnostics suite, realignment of rod amplifier chain, vacuum beam transport line and a Falcon compressor adjustment. Synchronization with Zebra generator was implemented and temporal jitter minimized.

Fig. 6: Tomcat rod amplifiers section.

In June 2006 Tomcat laser beam was utilized for the magnetized plasma experiment. A collimated plasma flow across magnetic field was observed. Tomcat laser beam (4 J, 0.1 mm focal spot, approx. $10^{16}$ W/cm$^2$) irradiated at normal incidence a CH$_2$ target. The plasma plume expanded perpendicularly to an external magnetic field produced by the Zebra current.

In July 2006 a first compressed Tomcat laser shot on target under vacuum in the Phoenix chamber was performed.

After Tomcat experimental campaigns a need for spare parts started to be more obvious. We defined a number of crucial optical elements (including amplifiers rods) and procured them. Some small modifications for optical setup were implemented also. As a result, the user-friendliness of the Tomcat laser improved significantly and a process of transferring operational knowledge to the experimental teams begun.

Cheetah Laser

In 2006 we started a discussion about a new ultrafast laser system for NTF plasma physics science as well as for much broader interdisciplinary research conducted under auspices of University of Nevada Reno. We defined the desirable parameters of such a laser as a very short pulse duration (<30 fs), high energy (approx. 1 J), high repetition rate (10 Hz) and contrast (better than $10^{-9}$). We started a market research and discussions with potential vendors. Finally, we chose Amplitude Technology from France to build and deliver the laser system for NTF.

Fig. 7: Block diagram of Cheetah laser

This laser, called Cheetah, will arrive to NTF in the middle of 2007; will be installed and operational soon after delivery. Experimental projects for immediate use of this unique laser system are in preparation. The Cheetah laser at NTF will significantly improve our experimental capabilities and will give us a tool for study very fast processes in areas of magnetized plasma, laser-matter interactions, x-ray production, particle acceleration, chemical physics (with cooperation with UNR Chemistry Department), material science and many others.
Leopard Laser’s PILC and Test Systems

Stefan Samek, Bruno Le Galloudec, and Billy McDaniel

INTRODUCTION

A PILC system (Pre-Ionization of Low energy Circuit) was installed on the Leopard laser disk Amplifiers pulsed power. The PILC improves the Disc Amplifier efficiency and increase the lifetime of the flash lamps. We also built a test circuit allowing us to electrically test the flash lamps at low energy before a shot.

DESCRIPTION OF THE PILC SYSTEM

The PILC is applied to the 94mm amplifier circuits without additional power supplies. A small part of the energy stored in the capacitors is used to prepare the flash lamps for the main energy discharge.

Assuming that one flash lamp has the lowest resistance (close to 2 Ω), it is possible to set the value of the PILC current. The Leopard Laser pulsed power system uses 8 circuits, on each circuit 2 flash lamps are connected in series. In order to get a current ten times smaller than the main discharge a 5Ω resistor is used. A special electronic circuit was built to achieve this delayed firing order and acts as a signal splitter and time delay.

DESCRIPTION OF THE TEST CIRCUIT

An additional testing circuit was built and installed in the Leopard laser pulsed power system. The purpose of this circuit is to check the flash lamps consistency and prepare them for high-energy discharge (mainly preheat them) especially after long periods of non-use, or to test the flash lamps at low energy before a laser shot.

Fig. 3 Picture of the discharge waveform.

A trigger pulse is applied to the PILC ignitron approximately 200 µS before the main firing order. A current starts to flow in the PILC circuit; the current value is determined by the value of the resistor in series with the A-size PILC ignitron.

Fig. 4 Schematic of The Test Circuit
The test circuit is controlled manually from the control room through a computer interface. Only one PFN (Pulse Forming Network) is charged, then its power supply is disconnected and the test circuit is connected to the 94 mm amplifier PFN. At this time, the triggering pulse is applied to the test circuit ignitron allowing a few hundred amps current to flow through the flash lamps.

Fig. 4 Test Circuit

CONCLUSION

The development of these techniques ensures softer initiating conditions for firing flash lamps especially for the 94mm disc amplifier flash lamps, which are bigger, and requires more energy to work. The two systems do not require an additional high voltage power supplies, they were designed to work directly within the existing pulsed power system.

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1) K-Tech Corp, NM
Leopard Laser Command System

Vidya Nalajala, Bruno Le Galloudec, Billy McDaniel1), Patrick O’ Reilly

Introduction

The Leopard laser is composed of 4 laser heads amplifiers, two disc amplifiers, and two Faraday rotators, which are designed to operate independently or in combination. Since high voltages are required to fire the flash lamps within the laser amplifier, a remote system was designed and built to provide a safe operation. The Leopard command system (LCS) as been designed and developed to control, operate and monitor the functioning of the laser amplifiers and is controlled by a user interface programmed with Labview.

Description

The Leopard Command System controls the setup and firing sequence of the Leopard Laser. It is composed of eight subsystems coordinated by the supervision program. The communication from the program is done through a fiber optic link to two Group3 Interfaces. Group3 control is a fiber optically linked control system using distributed I/O modules called Device Interfaces (DI’s). A DI is positioned at the point to be controlled with the appropriate I/O boards added to it; the LCS system uses Digital I/O and Analog I/O type boards. Up to three I/O boards in any combination can be used in each DI. Up to 16 DI’s can be placed on each fiber optic loop coming from the supervision computer. The following figures shows the two Group3 interface that controls all laser heads interfaces as well as the pulsed power system configuration and the slow synchronization system used to fire the laser head synchronously with the 10Hz signal from the oscillator. The safety system is also connected to the LCS system.

Figure 1: Groups3 Interface 1
The computer hosting the supervision program written with Labview programming software is located in the main screen on the second floor of the Zebra laboratory. The main screen room is also the home of the Zebra Z-Pinch safety computer. From this main screen room, the operator can supervise the safety and the control of a Leopard laser shot. Figure 3 shows the Leopard Command system user interface.

Figure 3: LCS- User Interface

Work supported by DOE/NNSA under UNR grant DE-FC52-01NV14050.
Leopard Pulsed Power system commissioning
Bruno Le Galloudec, Stefan Samek, Billy McDaniel, Patrick Reilly

OVERVIEW
The Leopard laser, a 100 TW-class short-pulse laser being developed at the Nevada Terawatt Facility of the University of Nevada Reno will allow us to perform high-energy-density plasma physics experiments. The Leopard laser amplification chain is composed of Nd:glass rods and disk amplifiers donated by the University of California Lawrence Livermore National Laboratory. We refurbished and used most of the donated equipment to build the pulsed power system necessary for the Leopard laser.

There are 18 Pulse Forming Network (PFN) for the laser disk amplifier system (eight circuits per amplifier and one circuit per Faraday rotator). Each disk amplifier consists of two 52 μF capacitors connected in parallel, a high voltage fuse, an inductor, charge resistor, dump resistor and shorting relay. The PFN’s are charged using 8 kJ power supplies with a charge time of 30 Seconds from 0V To 20 kV. The circuits are discharged in parallel using an ignitron switch. The sixteen PFN’s connected to the amplifiers are discharged using two series ignitron circuits. The Faraday Rotators are switched using another set of ignitrons. The total stored energy equals 375 kJ.

GENERAL DESCRIPTION
The Leopard laser pulsed power system provides the electrical energy required to energize the flash lamps inside two 94mm Disk Amplifiers, two 94mm Faraday Rotators, two 19mm laser heads and one 45mm laser head. The power conditioning components are located within the Zebra lab on the second floor next to the main screen room and are connected to the disk amplifiers using RG-217 coaxial cables. The pulsed power system is controlled and monitored by the command system using fiber optic to minimize noise and possible ground loops. The system has its own safety interlock system. Which is linked to the command system and the Zebra safety system.

DESIGN AND INSTALLATION
We modified the original Livermore design to bring it up to date. The original power supplies were replaced by 24 kV/8 kJ rack mount power supplies from General Atomics that can operate locally or remotely. The ignitron triggering system has been replaced by Ignitron trigger boards from “GBS Elektronik”. Each board can provide a voltage of 2 kV on 4 synchronous outputs allowing us to connect both of the two ignitrons on each ignitron for more reliable triggering.

The design of the Pulse forming section was modified in order to gain some space. We replaced the previous dump system by a Ross Relay and a 1 kΩ resistor installed directly on the PFN board. We also installed the
5Ω dummy load resistor on the PFN board allowing testing of the circuits without the flash lamps by just installing a jumper cable. The parallel bank was installed on donated NOVA shelves modified to fit the room just on top of the Leopard laser room.

![Figure 3. 94mm Pulse forming network schematic.](image)

**TESTING AND COMMISSIONNING**

Before we started any high voltage testing we installed the cooling and heating systems on the ignitrons to allow them to “cook” for a few weeks. This process evaporates the mercury deposited on the anodes.

Each pulse forming network was tested by doing shots into the 5Ω Dummy loads, the voltage was increased step by step to 22 kV. The discharged current is measured for each circuit using Rogowsky coils installed in the Ignitrons cabinets. Once the tests were performed we sent the energy to the Disc amplifier installed in the laser room. Each flash lamp installed in the disc amplifier was previously tested and characterized in the flash lamp testing laboratory. The Rod amplifiers pulsed power was tested the same way.

The figure below shows the acquisition of the current on four channels (half of an amplifier) during an 18.5 kV shot. We usually measure around 4 kA on each channel for 20 kV shots.

![Figure 3. Current in one half of 94mm Disc Amplifier during a 18.5kV shot.](image)

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Refurbishment and Activation of the Phoenix Laser Target Chamber at the NTF

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From being stored outside the NTF building to being refurbished, fully equipped and qualified for vacuum, the Phoenix chamber was born to a new life. Our Phoenix target chamber came from donated equipment and was sitting outside of the building until it became clear that we were not going to get a target chamber from Lawrence Livermore National Laboratory. At that time we decided to make use of that chamber and improve its access and refurbish it.

Fig. 1 Half of the chamber as it was prepared to be refurbished

We had four 12inch ports cut out and flanges welded to it. It was thoroughly bead-blasted and electropolished after deposits from the inside were tested to insure that they were safe to remove.

Fig. 2 Gary Pettee standing next to the chamber at the NTF

After coming back to the NTF, the target chamber was painted, assembled and prepared for the first vacuum test, which it passed. To make it flexible and user friendly, we designed an optical table with a regular threaded hole pattern and a support frame to be decoupled from the chamber itself. The 3 legs of the space frame went through existing ports at the bottom of the chamber. All cutting machining and welding were done in house. The optical table was designed and ordered from Remark manufacturing.

Fig. 3 Frame for the optical table

Fig. 4 Alexey and his undergraduate students Mike and Tyler rigging the table and its support frame to install it in the chamber.
The first short pulse focused laser shot was taken on July 3rd 2006. It was then used for isochoric heating test shots until we installed the optical table inside. That optical table and its frame decoupled from the chamber itself make it more stable for optics when evacuation to shooting pressure and venting to atmosphere.

In addition to this optical table we designed posts supporting a top rail, allowing for more options to attach optics and diagnostics. All posts can be positioned almost continuously around the ring and are clamped on the optical table. A target manipulation system with three translations and one rotation stage, all motorized and controllable from outside of the chamber has been installed. The precision on the translation stages is 1.6 microns and on the rotation stage a tenth of a degree. In addition we added a manual goniometer to adjust the target angle and relax the target mounting requirements.

The target, located 10.5 inches above the optical table surface, is imaged onto a couple of viewing microscopes that have been installed outside of the chamber to visualize target movements. They were calibrated with a thin target and, the chamber cycled 5 times from atmosphere to vacuum. The target image does move when going from atmosphere to vacuum in a very reproducible way. The biggest amount of movement recorded is of the order of 400 microns on one of the microscopes directly attached to a flange compared to an average movement of 115 microns for the microscope attached to a post supporting the chamber. In the future, these microscopes will be attached to separate pedestals.

The viewing system and target manipulation system controls are installed in a screen box for EMP protection. Future work include installing flat mirrors and an Off Axis Parabolic Mirror (6 inch diameter 12 inch focal length, with 1 inch off axis), along with a focal spot imaging diagnostic, after which we will start qualifying the laser and target chamber system for shots with the Leopard laser.

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Zebra Accelerator Facility & Tomcat Laser
NTF Infrastructure Development 2006-2007

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Introduction


Central chiller system

The new Opti-Temp 10-ton chiller unit came on line in 2006, presently serving the cooling needs of the Leopard laser. The closed-loop piping is built to conveniently extend to other heat-producing equipment throughout the SAGE building as needed. Plans for 2007 include connection to the Tomcat and EKSPLA lasers, diagnostic and control screen rooms, and assorted turbomolecular pumps.

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{fig1.jpg}
\caption{Opti-Temp OTC-10A chiller, near southeast corner of UNR SAGE building. Pipe insulation is pending.}
\end{figure}

SF\textsubscript{6} reclaimer

The new reclaimer unit for sulfur hexafluoride gas (SF\textsubscript{6}) came on line in 2006. The unit cleans and recompresses the gas that is used in the fast switchgear employed on Zebra. This enables a huge savings in operations cost, as nearly all of the relatively expensive gas is saved for re-use. The reclaimer unit will effectively cover its cost, including procurement, installation and debugging, before the end of 2007. Plans are under consideration to relocate the unit, extending its controls and monitoring gauges to the Zebra control console. This would mitigate the substantial noise the unit produces in the Zebra control area.

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{fig2.jpg}
\caption{Control panel for the Enervac Gas Filter Assembly (SF\textsubscript{6} reclaimer unit), presently located adjacent to the Zebra control console.}
\end{figure}

\textbf{N\textsubscript{2} distribution}

Nitrogen distribution piping, pressure control, filtration, and exhaust piping were extended to the Leopard

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{fig3.jpg}
\caption{Control panel for the Enervac Gas Filter Assembly (SF\textsubscript{6} reclaimer unit), presently located adjacent to the Zebra control console.}
\end{figure}
laser in 2006. The finely filtered nitrogen gas is especially important to the operation and maintenance of the 94 mm disk amplifier that is presently in service. Additional laser components, including at least one additional disk amplifier, will be served by the system. Plans under consideration for 2007 include construction of a small “gas house”, in part to shade the 450L nitrogen dewar that is located outdoors.

**Vacuum pump exhaust**

An exhaust piping system that serves all rough vacuum pumps in the Zebra and Leopard labs came on line in 2006. It is constructed of schedule 40 black iron pipe, and features multiple connection ports at manifolds that are provided at strategic locations. The piping can be conveniently extended to meet other vacuum exhaust needs as they arise, eliminating the need for exhaust filtration at each unit. The likelihood of compromised indoor air quality is greatly reduced by the vacuum pump exhaust system.

**Major shop equipment**

Three major pieces of fabrication equipment were added to the NTF machine shop in 2006. These are a Ganesh 10”x 54” variable-speed milling machine (w/3-axis DRO and power knee), a Hyd-Mech 3-hp. horizontal band saw, and a Ridgid 535 pipe threading machine. The equipment has enabled a major improvement in technical support capability. The immediate utility is demonstrated especially by the new laser beam transport systems, in addition to increased machining precision for a wide assortment of mechanical parts.

Two new air compressors were purchased in 2006. One of the units presently serves most NTF laboratories, in lieu of the original building air system. This amounts to a major enhancement of reliability. The second unit will be installed in parallel, to allow redundancy and maximize the transparency of maintenance. Plans under consideration for 2007 include other needed enhancements to the air distribution system.

**Electrical utilities**

Electrical work has continued intermittently throughout most of 2006, serving the entire range of scientific and infrastructure resources that require standard electrical service.

**HVAC renovation**

Emerging from hiatus during 2006 and earlier, the HVAC renovation task is being redefined to encompass a comprehensive solution that is appropriate to all needs. The scope is planned to extend beyond the Zebra lab, to include a large adjacent space that has been known as the Leopard Laser Bay. An updated analysis and restatement of work is scheduled to begin immediately, followed by external review and recommendation. The final result will provide environmental controls that are appropriate to all equipment and human occupancy requirements.

Work supported by DOE/NNSA under UNR grant DE-FC52-01NV14050.
INTRODUCTION

Infrastructure development has progressed significantly during the 2005-2006 fiscal year. Facility upgrades completed per the defined scope of work include major improvements to the existing cluster computer facility, and new installations including the Leopard laser clean room, Falcon compressor clean room, laser flashlamp test facility, safety access control system, and nitrogen gas distribution system. Work in progress includes renovation of the original HVAC (heating-ventilating-air conditioning) system for the Zebra lab, a new central chiller system to serve NTF lab equipment, additional electrical utilities for Leopard laser support and the Zebra lab, additions to the nitrogen gas distribution system, and initial activation of the SF₆ (sulfur hexafluoride) reclamation system for the Zebra accelerator.

CLUSTER COMPUTER FACILITY

To accommodate the most recent increase in computing power, a raised floor system was installed that allows ample space for cabling, and easy access for alterations and maintenance. The sub-floor structure was selectively reinforced to assure good long-term performance under the heavy load of UPS (uninterruptible power supply) components. New electrical service was installed that includes capacity to more than double the current load at projected build-out. Heat and smoke detectors, surge protection, and an emergency shutoff switch help protect equipment. The main electrical service raceway is built to facilitate connection of a back-up generator.

LEOPARD LASER CLEAN ROOM

The Leopard laser clean room protects laser front-end components from particulate contamination. The frame is constructed from a combination of structural steel tubing, and steel strut channel. The enclosure is completed with polycarbonate panels and vinyl strip curtains. Air filtration is provided by eight HEPA (high-efficiency particulate air) fan-filter units.

FALCON COMPRESSOR CLEAN ROOM

The Falcon compressor clean room protects highly sensitive diffraction gratings and other optics from particulate and organic vapor contamination. It is constructed with a modular framing system of extruded aluminum components, polycarbonate panels, and vinyl strip curtains. Air filtration is provided by six HEPA fan-filter units, with custom-built activated carbon pre-filters.

LASER FLASHLAMP TEST FACILITY

The infrastructure team supported development of the flashlamp test facility by implementing assorted building repairs through UNR Facilities Services, and by installation of electrical service, power conditioning, the main equipment ground, portions of the capacitor rack assembly, and shrapnel shields. The infrastructure team also developed the combination safety shield/clean hood portion of the flashlamp test fixture, which includes a 16-gauge steel housing with HEPA filtration. The housing can be raised and lowered with a small electric hoist, allowing easy placement and removal of flashlamps. Essential functions of the facility are detailed in section 5.5 of the 2006 NTF Annual Report.
SAFETY ACCESS CONTROL SYSTEM

The NTF safety access control system was installed in collaboration with the UNR Facilities Services department. The system consists of magnetically operated door latches that are controlled by proximity-card readers. The card readers serve laboratories that require special access restrictions due to safety hazards. Access by individuals is granted through the secure distribution of magnetic proximity cards, each programmed according to the nature of the work to be performed, and the qualifications and training required. The local system backbone is a dedicated remote PC server, located in the Zebra lab. It is connected to the central system server at the main UNR campus via the Internet. Protocols under development among several UNR administrative units are designed to fully integrate the NTF safety access control system with similar operations across the University.

NITROGEN GAS DISTRIBUTION SYSTEM

The nitrogen gas distribution system provides, or will provide, purge gas to the Zebra load chamber, Falcon compressor, Phoenix target chamber, and Tomcat/Leopard laser beam transport systems. It also dispenses liquid nitrogen, which is used to make interference fits among metal parts at close tolerances. The system consists of a 450L dewar, located outdoors on a concrete pad, near the southeast corner of the SAGE building. Polyethylene-clad aluminum distribution piping extends into the building, and runs overhead above the first floor to branches serving assorted locations. Stop valves are located to maximize the convenience of system additions. Locking valves are located in the main supply line immediately downstream from the dewar, and at all supply terminals that are readily accessible.

ZEBRA LAB HVAC RENOVATION

Design development is nearly complete for the reactivation of the HVAC system that originally served the present-day Zebra lab. The work will include minor reconfiguration of existing ductwork and plenum spaces, addition of particulate and organic vapor filtration, and new overhead ductwork in the lab. A control system is planned that will maximize temperature and pressure stability for the Zebra lab, and for adjacent NTF labs as they are developed.

CENTRAL CHILLER SYSTEM

Installation of a 10-ton glycol-to-air chiller unit was begun during February of 2006. The unit will be located outdoors, adjacent to the nitrogen dewar noted above. Progress to date includes procurement of the chiller unit, installation of the concrete pad on which the unit will rest, pipe bollards for protection from motor vehicle hazards, hangar assemblies for coolant piping and electrical conduits, the electrical raceway for the main power supply, and concrete core drilling as applicable for the items noted above. The system design includes extendable piping loops, independently valved, that can be developed to meet future needs with zero to minimal impact on the present lab operations. The chiller unit features a precision control system that maintains high operating efficiency in parallel with a widely variable load. The immediate application will be to indirectly cool the Leopard laser rod amplifiers and their power supplies, by connection to secondary heat exchangers that are part of the laser system. Subsequent applications will be Tomcat laser front-end and rod-chain components, laser diagnostics and control room Faraday cages, many of the larger vacuum pumps associated with Zebra and laser systems, and heat-producing equipment of future experiment systems.

ELECTRICAL UTILITIES

The core electrical utility upgrade for the NTF Zebra and laser facilities is a new 225-ampere, 208-volt, three-phase electrical service. The new 42-space distribution panelboard is located near the southeast corner of the first floor of the Zebra lab. Its branch circuits serve, or will serve, support equipment for the Falcon compressor, the Leopard laser, the Phoenix target chamber, and many Zebra and general facility needs. Consistent with all new electrical raceway systems installed at the NTF, the design maximizes flexibility for future development.

Other recent electrical work includes filtered power distribution to serve the Leopard laser pulsed-power facility, additional circuits to serve the Tomcat laser front-end, work in progress on Leopard front-end power supply and utility circuits, and work in progress on the 50-ampere, 480-volt service to the central chiller.

SF₆ RECLAIMER

The SF₆ reclaimer is designed to recycle the combination conductive-media/purge gas that is utilized by the Zebra high-voltage switchgear. Once on-line, the device will provide significant cost savings for Zebra accelerator operations. Installation of the device was begun in March of 2006.

Work supported by DOE/NNSA under UNR grant DE-FC52-01NV14050.

76
**Wire Loads for the NTF Zebra Accelerator 2006-2007**

S. Batie\(^1\), A. Astanovitskiy\(^1\), T. Adkins\(^2\), D. Macaulay\(^1\), D. Meredith\(^1\), W. Cline\(^1\), M. Johnson\(^1\), T. Jarrett\(^1\), J. Johnson\(^1\), A. Haboub\(^1\), A. Morozov\(^1\), I. Shrestha\(^1\), K. Williamson\(^1\), G. Osborne\(^1\), M. Henry\(^1\)

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**Introduction**

The basic design, manufacturing, and installation processes of Zebra wire loads remain unchanged from 2005-2006. For details of wire load development during the 2005-2006 reporting period, please see “Wire Loads for the NTF Zebra Accelerator”, S. Batie, et al, from the 2005-2006 HED Annual Report. In addition to the processes noted above, the abstract describes the background of development, and gives details of the essential components and fixtures.

**Continuing Development**

Since April of 2006, wire loads for the Zebra accelerator have been produced to meet the latest requirements specified by researchers. Among these are double, triple and quadruple nested cylindrical arrays, single and double planar arrays, and our newest 8-wire cylindrical array that features a one millimeter diameter. Certain loads are now electro-polished, such that they can accept some of the most delicate fine wires available.

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Fig. 1: Exploded view of primary wire load hardware assembly, from “Wire Loads for the NTF Zebra Accelerator”, March 2006.

Load development activities for the current period focus on fielding more interesting wire configurations, as driven by experimental results. The designs are necessarily more complex, and build on the foundation established through earlier development.

Fig 2: Backlit image of used cathode from 24-wire quadruple nested array. Remnants of fine aluminum wire cover the surface.
As the wire configurations have evolved, the assembly task has become significantly more demanding. The graduate student team has risen successfully to the challenge, and now produces a steady stream of loads to meet demand of up to four Zebra shots during a standard work day. The mechanical engineering team has steadily refined the hardware refurbishment processes and fixture systems, such that economy and efficiency continue to improve.

**Future Plans**

Load designs in progress include supplemental components for use with a new current-multiplier system that is under development for Zebra. The supplemental components build on the original load hardware design, utilizing its inherent versatility.

Work supported by DOE/NNSA under UNR grant DE-FC52-01NV14050.
Wire Loads for the NTF Zebra Accelerator

Steve Batie, Alexey Astanovitskiy, Dennis Meredith, Wade Cline, Adam Clinton, William Goettler, Michael Johnson, Brandon Seaman, Ishor Shrestha, Nicholas Ouart, Shivaji Pokala, Thomas Sant

BACKGROUND

From inception through March of 2006, Zebra wire load shots at the NTF have included 17 configurations (early tests excluded). These are single wires, X-pinches (2 geometries); cylindrical arrays of four, six, eight, twelve, sixteen, twenty-four and thirty-two wires; conical arrays of four and eight wires; and planar arrays of seven, eight, ten, twelve, and fourteen wires. Wire materials include molybdenum, tungsten, stainless steel, copper and copper-nickel alloy, and three aluminum alloys. Wire diameters range from less than 5 microns to approximately 100 microns. Specially coated wires recently developed and fielded (at the NTF) by Sandia National Laboratories (SNL) enable a novel trace method for evaluating plasma behavior.

Wire loads are prepared by researchers, graduate and undergraduate students, and engineering team members. A laboratory is dedicated to the load fabrication task that includes all necessary fixtures, wire assembly and storage apparatus, and tools. Early technical and infrastructure guidance in this area was provided by SNL. Training in load fabrication is now provided by the NTF lead mechanical engineer.

DESIGN

The primary Zebra wire load hardware design is based on the wire array hardware currently in use on the SNL-Z machine. Many features of the Zebra wire load geometry, including the A-K gap, are identical to the SNL-Z version. Some features developed by SNL for recent NTF-SNL experiment campaigns are blended into the primary Zebra hardware design. Through an iterative process, alterations have been applied that enhance convenience and conserve resources in the Zebra application. A modular design has recently been developed, enhancing the convenience of fielding different wire configurations, and allowing re-use of some of the larger and more complex component parts. Due to the reduced electrical current in the Zebra application (~1 MA, about 20 times less than SNL-Z), parts of the wire load assembly may be refurbished and used repeatedly.

NTF hardware designs are developed and documented using the Pro-Engineer CAD (computer-assisted design) software. The NTF lead mechanical engineer is primarily responsible for the creative design aspects of the NTF contributions; the student mechanical engineering team provides major support for design development and documentation.

Fig. 1 Typical Pro-Engineer models of wire array hardware assemblies (cylindrical array [left] and planar array shown).

COMPONENT PARTS

The primary Zebra wire load hardware assembly consists of five main components. These are (from left to right, below) the anode top, anode bottom, castle, castle adaptor, and mesa insert. All parts are machined from stainless steel, type 304L.

Fig. 2 Exploded view of primary wire load hardware assembly.

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1) University of Nevada, Reno
2) Ktech Corporation
Various wire holders and wire-locating inserts are used, depending on the type of load.

The “anode bottom” and “castle” help to maximize the flexibility of the load hardware system, providing a field of thin material (~0.050”) that can be machined with relative ease to meet a wide range of requirements.

ASSEMBLY AND INSTALLATION

The components are held in place for wire installation and transport to Zebra by fixturing rods (SNL design), together with a stationary assembly fixture. Following installation in Zebra, the fixturing rods are removed, leaving only fine wire between the cathode and the anode.

MANUFACTURING AND MAINTENANCE

Component parts for the Zebra wire load hardware assembly are manufactured by the UNR Physics Department machine shop. The machine shop operates a 3-axis CNC (computer-numerical control) turning center (lathe), and a 5-axis CNC machining center (mill). Each machine interfaces with the MasterCAM computer-assisted machining software. This machinery, together with highly skilled operators, has to date produced more than two hundred sets of load hardware that demonstrate remarkable accuracy and precision.

Precision EDM (electrical-discharge machining), associated mainly with the tiny slots required to accommodate fine wires, has been outsourced to three local-area vendors.

Load hardware refurbishment, repair and modification is provided by NTF technical staff, using the NTF machine shop. Load hardware provided by SNL is manufactured through a combination of capabilities internal and external to SNL.

Work supported by DOE/NNSA under UNR grant DE-FC52-01NV14050.
Zebra Accelerator Operations 2006-2007

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Format

The essential format of Zebra operations remains unchanged for 2006-2007. Section 5.9 of the 2005-2006 HED Annual Report gives information on the following topics concerning Zebra operations:

- Resource Coordination
- Experiment Campaigns
- Performance of a Shot
- Machine Turnaround
- Inspection, Maintenance and Repair
- Team Structure
- Safety Training


Major enhancements

While improvement through a wide range of technical team activities has improved productivity, the cross-training of technical personnel stands out as especially valuable for team function and effectiveness. Operations and development tasks are balanced with much greater fluidity, and capacity for Zebra shots is significantly increased. The following table shows recent changes in technical team personnel qualifications.

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<td>Core diagnostics</td>
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</table>

Fig. 1: Numbers of qualified personnel for Zebra operations.

Also highly significant for technical team effectiveness is an administrative policy that clearly identifies and supports team responsibilities. This has helped to build a culture that looks to build sustainability for the research enterprise, while delivering good service within a measured allocation of resources.

Incremental improvements

A documented framework to guide improvements in each of four main areas (to date) of NTF operations has been initiated. Included are maintenance of Zebra, lasers, and facilities infrastructure, plus Environmental Health and Safety. The framework will help ensure that all reasonably foreseeable necessities are identified and
included, leading to smoother lab operations and improved cost estimates.

Steady improvement in the coordination and performance of shots is readily observed. This extends to the coordination of Zebra shots and laser development shots, which continue in parallel. Improvements are attributed in large part to productivity gains that each team member makes from experience, together with improved communication among all interested parties.

Tangible and sustained performance improvements are clearly observed in each area shown in the bullet list at the beginning of this document.

**Results**

During the calendar year 2006, Zebra produced 371 shots. In 2007 to date, Zebra has produced more than 100 shots. Zebra load production and the technical interfaces with experimenters are increasingly streamlined, while laser and infrastructure development projects have continued in parallel. A culture of safety has developed that continuously reminds workers of the fundamental importance of maintaining a safe workplace. The gains observed during 2006-2007 set the stage for development of a highly useful, versatile, efficient and sustainable plasma research facility.

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Fig. 2: Zebra shots during March, 2007 (Courtesy V. Kantsyrev).

Work supported by DOE/NNSA under UNR grant DE-FC52-01NV14050
Zebra Accelerator Operations


INTRODUCTION

Operation of the Zebra accelerator is coordinated through a variety of resources to meet a wide range of requirements. Throughout the current fiscal year, the Zebra operations team has continued to solidify team effectiveness, while continuously identifying specific items and/or areas for further development.

RESOURCE COORDINATION

The senior managers of the NTF technical team are responsible to deliver technical support and working conditions that promote, as far as practical, the safe and reliable conduct of experiments. Technical support needs are identified, and resources are accordingly directed, through frequent communication among the senior technical managers and engineering staff. The senior technical managers also communicate frequently with the NTF director’s office, to assure that resource allocations align with the most current priority assessments.

EXPERIMENT CAMPAIGNS

An experiment campaign is a block of work time dedicated to a series of Zebra shots. A campaign is defined by approval through the NTF director’s office. Following approval, senior technical managers consult with all relevant parties, and engage an assortment of parallel activities. These include pre-campaign meetings with investigators to identify needs, evaluation/repair of existing equipment, execution of new engineering/development tasks, and development of the shot schedule. Once the campaign is begun, the technical and scientific teams promote fulfillment of the shot schedule.

PERFORMANCE OF A SHOT

The performance of each shot is coordinated and controlled by a designated shot director. The shot director verifies that all required resources, including personnel, engineering and administrative controls, and materials are in place. Specific shot support tasks are performed by qualified personnel, according to established operator procedures.

MACHINE TURNAROUND

Machine turnaround is the cycle that must be repeated to reset Zebra for subsequent shots. A single technician is dedicated to firing the machine, and to most mechanical aspects of the turnaround cycle. The data acquisition is usually addressed by a combination of engineering staff, students, and the investigator. Core diagnostics are serviced by engineering staff and students; special diagnostics (those provided by an investigator or user group) are usually serviced by the investigator, a designated technician from the user group, or a designated student. A student member of the engineering staff usually serves as safety system operator.

INSPECTION, MAINTENANCE AND REPAIR

During normal operations, key Zebra systems and components are inspected, maintained and repaired between experiment campaigns. In the event of breakdown, repairs are normally begun immediately. Shot schedule adjustments may result, according to the current priority assessment.

1) University of Nevada, Reno
2) Ktech Corporation
TEAM STRUCTURE

The Zebra operations team is composed of UNR classified and professional staff, plus external contract staff. All together, the team deploys the wide range of expertise required for Zebra operation. Operations team duties are a part-time assignment for most team members, as they are also engaged in project development. The dedicated Zebra operator addresses background Zebra development tasks during breaks in routine operation.

The major functional areas the operations team must address include management, safety, engineering and development, routine operation, and maintenance/repair. Expertise is drawn from a variety of internal personnel organizations to meet demands.

SAFETY TRAINING

All employees assigned to work in NTF laboratories are provided with training according to their work assignment. The UNR Department of Environmental Health and Safety (EH&S) provides most safety training needed by NTF employees. Some NTF lab-specific training is developed and disseminated by NTF staff. Certain specialized training, such as high-voltage safety in pulsed-power applications, has been provided by the Ktech Corporation. Advanced training in laser safety has been provided by the Laser Institute of America (LIA). The NTF Deputy Director for Operations is responsible for safety program organization.

ZEBA ACTIVITY IN 2005

In January of 2005, UNR contracted with the Ktech Corporation to provide expertise and on-site technical support for a major overhaul of the Zebra Marx generator. This provided a significant training and guidance opportunity for NTF staff, and led to useful improvements of the Zebra maintenance infrastructure.

Beginning in February, experiment campaigns began that included 169 shots for the year. Collaborators from SNL joined UNR investigators to produce valuable scientific results pertaining to a variety of plasma physics questions. Details of the scientific results are given in section 1 of the 2006 NTF Annual Report.

Work supported by DOE/NNSA under UNR grant DE-FC52-01NV14050
Experimental Assistance on Zebra and Tomcat
Bruno Le Galloudec, Vidya Nalajala, Billy McDaniel\textsuperscript{1)}, Patrick Reilly, and Travis Wright

INTRODUCTION

In 2006 three Engineers from the engineering and development group (END) were assisting experiments around the 2TW Z-Pinch Zebra and the TW laser Tomcat. Maintenance, upgrades of the machines as well as student training is also part of the service that Engineers and Technicians are providing throughout the year.

Z-PINCH AND LASER SHOTS

In 2006, 371 shots were performed with the Zebra Z-Pinch machine (1MA, 100nS). These shots were divided among different experiments on different types of loads as follows:

- Wire Arrays: 168 shots
- Planar Arrays: 87 shots
- X-Pinch: 16 shots
- Coils (Magnetized target): 25 shots
- Single wires/Shorts: 36 shots
- Atmospheric Loads: 15 shots
- MITL’S: 24 shots

The Engineering and Development team provides two Shot-Directors, two console operators and 6 safety operators for the operations on Zebra. Engineers from the team are training students from other groups for safety operation as well.

In parallel with the experimental assistance, the Engineering and Development team was working on the Leopard laser fabrication. The pulsed power system and command system were installed and successfully tested within the electromagnetic environment of the Zebra Z-Pinch.

CORE DIAGNOSTICS

Three engineers and two students from the END group are working within the core diagnostics team fielding, maintaining and retrieving data for X-Ray diagnostics. This year, one gated spectrometer, one time integrated pinhole camera and one time-integrated spectrometer were transferred to us from the Plasma Physics and Diagnostics Laboratory managed by Dr Victor Kantsyrev. Also hardware was purchased under request from Sandia National Laboratories physicists in order to build a time and position resolved spectrometer. The hardware is in house and the diagnostic will be built and tested in collaboration with the Plasma Physics and Diagnostics Laboratory group lead by Dr Victor Kantsyrev, and the Magnetized laser plasma interactions group lead by Dr Radu Presura in 2007.

Other duties performed by the Core diagnostics team are the installation and maintenance of most of the NTF instrumentation used on and around experiments as well as all the Zebra current and voltage probes. Each experiment is prepared with the principal experimentalist, fast and slow triggering signals are provided to the diagnostics and the timing is done following the information given by the experimentalists. All the schematics are provided and follow up on updates is made during the experiment. Interaction with the principal experimentalist occurs on a daily basis.

CONCLUSION

This year we were able to accomplish a larger number of shots on Zebra, which is partially due to the better organization and communication between the technical and research teams. The first tests were also done on the Leopard laser in parallel with using the Z-Pinch machine.

Work supported by DOE/NNSA under UNR grant DE-FC52-01NV14050.

\textsuperscript{1)} K-Tech Corp, NM
Outreach Activities
NTF Outreach Activities for 2006

N. Renard-Le Galloudec\textsuperscript{1), B. Pettee\textsuperscript{2)}

1) Nevada Terawatt Facility, Physics Department, University of Nevada, Reno, NV 89557
2) Ktech

Abstract

In 2006 the NTF Outreach program has included tours with the participation of faculty members, the creation of a tour handout “NTF at a glance”. The NTF has welcomed four high school students for a summer internship. In collaboration with the KEEP program we have proposed a teacher award to three colleges, the College of Engineering (Dean Batchman) the College of Education (Dean Sparkman), and the College of Science (Dean Westfall). A couple articles have been published showcasing the research we do (RT Image, medical news today) Another emerging aspect is what we could call good neighbor tours, and consist of young students (about 10-14 years old) who are interested in science and who visited the NTF with their parents.

Introduction

Currently, there are 75 staff members at NTF, comprised of 21 as faculty, 4 as post-docs, 5 as administrative, 8 Technicians, and 17 student workers. There are 20 graduate students currently enrolled and majoring in Physics at NTF. Each has a faculty advisor and participates in both the experimental and theoretical aspects of research. The graduate students are involved in collaborations with other institutions, presenting posters and contributions for conferences, and publishing research papers in various science journals.

Our undergrads students program has a total 16 enrolled, and include majors in Physics, Computer Science, Electrical Engineering and Mechanical Engineering. They, like the graduate students, are involved with projects relevant to their studies. In total, 8 students have graduated in 2005.

Outreach Activities

Activities this year have included several tours of our facility, a summer internship program, and a proposal for a teacher award.

The facility tours includes an overview of the research done and related applications; a view of our Zebra lab, Laser lab, target/load fabrication labs, data acquisition and control center, and our 48 node cluster. This is now supported by a handout highlighting these areas. The information is given by faculty and staff members that have worked with that aspect of the operations. This provides a more knowledgeable and personal presentation for the visitors.

We welcomed the KEEP program, a group of elder people and unfortunately we missed a tour of the
NTF during the Northern California Western Nevada Junior Science Humanities Symposium because transportation could not be arranged.

A selection of comments from participants of the tours include:

“...I don’t think students get to see enough of how interesting real science can be, and especially how exciting it can be to work with some of the world’s most amazing equipment. Your tour and facility bring that message through like very few others can”

“We all came away in awe of what is being accomplished in the Physics Department, and we are grateful for a glimpse of the wonders of this science. Hearing people from different parts of the world who are participating in this joint effort was fascinating.”

“...I hope to hear, one day soon, that my next surgery for my acoustic neuroma will be a non invasive procedure developed by the Nevada Terawatt Facility...”

A summer internship is another avenue of the Outreach program, in which 4 students participated in this year at NTF. Two of them took this opportunity to tour the facility with their parents.

A sixth grader from Westergard elementary school visited the NTF: “Thanks for taking me to your lab. It was so much fun, and my teacher wants me to write a report about it.” – Tony Garcia

At the beginning of 2007, not liking the format of the tours, we came up with something more participative for the students: a scavenger hunt. The first one took place on Feb 13 and included about 50 college students and a few siblings and parents. Participation from the staff was high even though this happened in the evening from 7 to 9pm.

The feedback was amazing. Here are some examples:

It was a lot more interesting than just listening.
I got to see first hand the concepts that were being talked about
We were able to interact.
I understood what was going on.
It was hands on activities and made more sense.
It helped me with real world applications.
I learned how to apply what I will be teaching to my students.
It showed me the integration of Physics into real life situations.
I learned a new career choice.
I learned interesting concepts.
Showed new opportunities in Physics.
The NTF is a neat place.
Very informative, fun, got to meet new people.
I got to learn with hands on experience.
It was cool learning what type of research our society is doing to improve our daily lives.

The opportunities available at the Nevada Terawatt Facility to be involved in research or engineering are amazing. By providing as many students as possible with this opportunity, NTF is preparing “cutting-edge” scientists and engineers for the future.

1 Michael Leverington, UNR Raggio Research Center for STEM Education
2 Esther Early, Curriculum Committee Chair, Elder College.
3 La Merne Koslawski, President, Elder College.
Staffing
## Scientific Staff

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<td>V Ivanov</td>
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## Operation & Engineering

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## Administration & Finance

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Publications and Presentations
Publications:
(** printed copies not available at this time)


Accepted for Publication


R. McKnight,, M. Carpenter and Tim W. Darling “Acoustic dissipation associated with phase transitions in lawsonite, CaAl2Si2O7(OH)2·H2O” Accepted in American Mineralogist


Submitted for Publication


Gunes Kaplan, T. W. Darling and K. R. McCall “Resonant Ultrasound Spectroscopy and Homogeneity in Polycrystals” Submitted to Journal of the Acoustical Society of America (JASA)


Presentations and Invited Talks


Y. Sentoku, “Advanced PIC simulation for high energy density physics”, Dream Beam Symposium, Max Plank Institute, Garhing, Germany. (February 28, 2007).


Y. Sentoku, “Plasma simulation for high energy density plasmas”, Osaka University, Osaka, Japan. (July 19, 2006).


Contributed Posters


V. Ivanov, T. Cowan, V. Sotnikov, A. Haboub, A. Morozov, A. Astanovitskiy, B. Le Galloudec, S. Altemara, C. Thomas, “ Dynamics of ablation stage and the beginning of the implosion stage in low wire number cylindrical, nested and linear arrays were investigated “, 48th APS DPP Meeting, Philadelphia, (October 30, 2006).


P. Leblanc, "Penumbra imaging of isochorically heated material", 21st National Conference on Undergraduate Research (NCUR 21), San Francisco, CA, April 12 - 14, 2007

D. Martinez, C. Plechaty, and R. Presura, “Magnetic Fields for the Laboratory Simulation of Astrophysical Objects”, 6th Int. Conf. on High Energy Density Laboratory Astrophysics, Houston, TX, March 11-14, 2006


V.I. Sotnikov, R. Presura, V.V. Ivanov, T.E. Cowan, J.N. Leboeuf, B.V. Oliver, “Excitation of electromagnetic flute modes in the process of interaction of plasma flow with inhomogeneous magnetic field”, 6th Int. Conf. on High Energy Density Laboratory Astrophysics, Houston, TX, March 11-14, 2006
