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Radiation-magnetohydrodynamic evolution and instability of conductors driven by megagauss magnetic fields

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We are pleased to report important progress in experimentally characterizing and numerically modeling the transformation into plasma of walls subjected to pulsed megagauss magnetic fields. Understanding this is important to Magnetized Target Fusion (MTF) because an important limitation to the metal liner approach to MTF comes from the strong eddy current heating on the surface of the metal liner. This has intriguing non-linear aspects when the magnetic field is in the megagauss regime as needed for MTF, and may limit the magnetic field in an MTF implosion.

Many faculty, students, and staff have contributed to this work, and, implicitly or explicitly, to this report. Contributors include, in addition to the PIs, Andrey Esaulov, Stephan Fuelling, Irvin Lindemuth, Volodymyr Makhin, Ioana Paraschiv, Milena Angelova, Tom Awe, Tasha Goodrich, Arunkumar Prasadam, Andrew Oxner, Bruno Le Galloudec, Radu Presura, and Vladimir Ivanov.

Highlights of the progress made during the grant include:

- 12 articles published, and 44 conference and workshop presentations made, on a broad range of issues related to this project;
- An ongoing experiment that uses the 1 MA, 100-ns Zebra z-pinch at UNR to apply 2-5 megagauss to a variety of metal surfaces, examining plasma formation and evolution;
- Numerical simulation studies of the 1-MA Zebra, and potential Shiva Star and Atlas experiments that include realistic equations of state and radiation effects, using a variety of tables.
- Collaboration with other groups doing simulations of this experiment at LANL, VNIIEF, SNL, and NumerEx leading to a successful international workshop at UNR in the spring of 2008.

These results are described in the next sections:

1. Experimental Results

Our main experimental work has been on the important radiation-magnetohydrodynamic (R-MHD) problem of the generation and evolution of plasma from a metal surface carrying intense current. Experimental data is greatly needed in this area, as the results of computer modeling can vary significantly.

High-current experiments to test R-MHD modeling face multiple challenges. For example, plasma can be initiated at contacts and by large electric fields, via surface processes outside the scope of R-MHD, prior to formation by ohmic heating.[1] In addition, the plasma may have strong three-dimensional features, a situation of limited interest when the validity of one-dimensional R-MHD modeling still needs to be established. Moreover, complex diagnostics may be required, as when trying to make high resolution measurements of surface plasma features inside an imploding metal liner.

We have developed deceptively simple experiments that provide a significant test of one-dimensional R-MHD modeling of plasma formation from a current-carrying metal surface. A new type of load[2] for 1-MA-class plasma initiation experiments was found to avoid plasma formation from contacts and high electric fields. It has a low-inductance (a short length) to keep the electric field below the threshold (300 kV/cm) for explosive electron emission. Moreover, it has an hourglass shape (Fig. 1) that avoids any current junction at high current density.

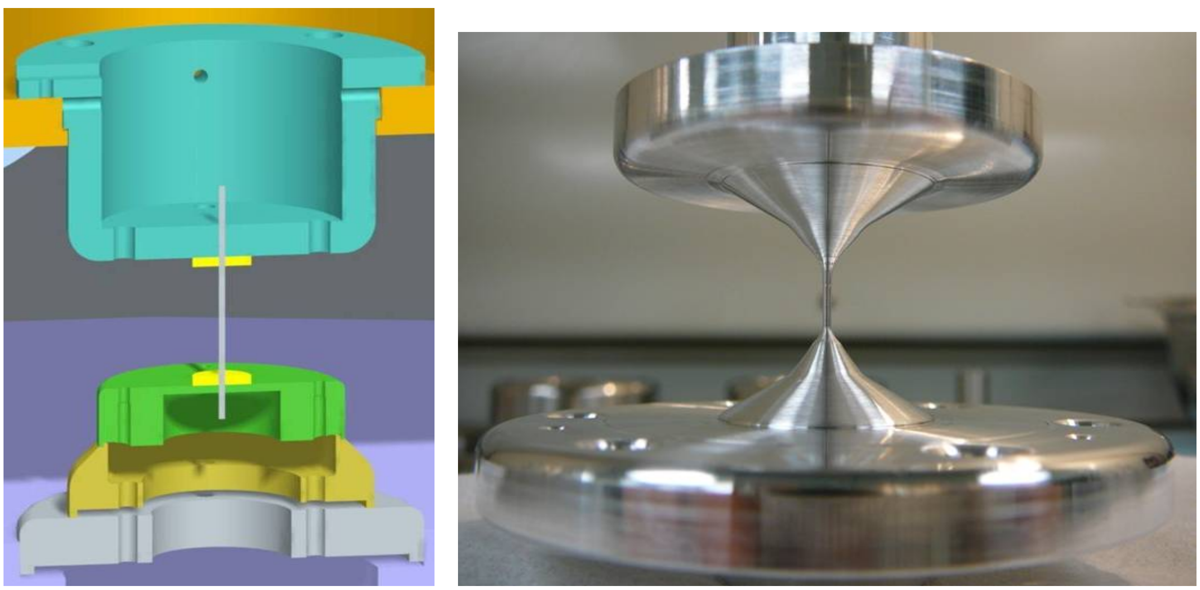

Figure 1. A conventional wire load (ProE drawing, left) and the new machined "wire" load (photo, right). The conventional wire load is made from multiple parts, while the new load is machined from a single solid piece of aluminum, and connected to electrodes via a large-diameter buried knife edge contact. The diameter of the central region of both loads is 1 mm. A variety of conventional wire loads were fielded: Wires of length 7 mm or 21 mm, with or without small, thin Teflon discs covering the wire-electrode contacts, to block plasma produced there.

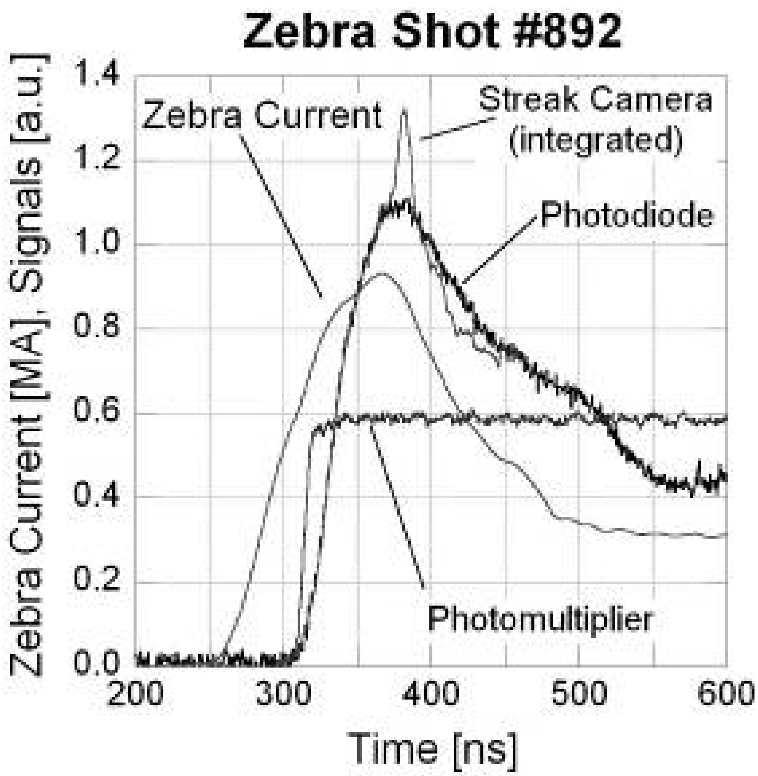

Figure 2. Zebra current and surface brightness as functions of time, for an hourglass-shaped load. Surface brightness is measured with a photodiode, a streak camera, and a photomultiplier (displayed as a positive signal here).

In comparison with conventional wire loads, the novel load delays plasma formation, yields a dramatic improvement in initial surface plasma uniformity, and gives evidence of nearly one-dimensional behavior that should be amenable to numerical simulation. Recent experiments described in 2008 conferences, have shown equally good results with less expensive, more-easily machined, variations of the hourglass shape.

A second design concern was to produce conditions in which unstable modes only grow to modest amplitude[3]. Because a metal subjected to MG field responds like a fluid to the magnetic pressure, the well known z-pinch m = 0 and m = 1 instabilities can disrupt the configuration. For a given current rise time τ and peak current I, the maximum possible magnetic field is obtained by setting the instability growth time equal to the rise time, by choosing the rod radius as

$$R = \left(\frac{I\tau}{2\pi f_s} \right)^{1/2} \left(\frac{\mu_o}{\rho} \right)^{1/4},$$

where f_s is a scaling factor of order unity that multiplies the instability growth time, and ρ is the metal density. For Zebra, with f_s =1, the optimum radius is R = 0.5 mm, and the corresponding maximum magnetic field with good stability is 4 MG. This analysis was borne out by experiment, as $m = 0$ modes do not appear in the laser shadowgrams until near peak current. For example, on 1-mm-diameter loads, near the time of peak field, unstable sausage ($m = 0$) modes, driven by the curvature of the magnetic field, grow from initial microscopic surface perturbations to modulations with multi-μm amplitude. The kink ($m = 1$) instability is not observed. The experiment is amenable to one-dimensional numerical modeling up to a time near peak field, and to comparison with two-dimensional simulation thereafter.

The experimental configuration is chosen to facilitate high resolution diagnostics and comparison with numerical modeling. A 1-mm-diameter metal cylinder is driven by a fast (70-ns rise), large (990-kA peak) current pulse from the UNR Zebra generator to form a warm, dense z-pinch. The experiment has much in common with exploding wire studies, except that the skin depth of the current is small compared with the rod radius, while for thin wires the opposite is the case. Plasma forms at a higher level of magnetic field because there is more mass to heat. In most experiments the rods consisted of aluminum 1100 or aluminum 6061. Data have also been taken for additional materials and rod diameters. The current (Fig. 2) rose from 1% to 10% of peak current in 20 ns, from 10% to 90% of peak current in 70 ns, and from 90% to 100% of peak current in 30 ns. Then the current dropped back to 50% of peak in 100 ns.

The generation and evolution of plasma has been measured with time-resolved optical and laser diagnostics. Typically the central portion of the load is optically imaged to a time-gated intensified CCD camera, a streak camera, a filtered photodiode, and a photomultiplier. Another filtered photodiode and photomultiplier monitor the overall level of light in the load vacuum chamber. The laser imaging diagnostics[4,5] include shadowgraphy, schlieren, interferometry, and Faraday rotation, obtained using a 150-ps, 532-nm-wavelength laser pulse from a frequency-doubled Nd:YAG laser. On each shot, the plasma is probed by a train of 5 short laser pulses, evenly spread over a 34-ns period. The laser images have 8 μm spatial resolution. The measurements yield information on the threshold for plasma formation, the expansion of the aluminum, the temperature at the transition between optically thick and optically thin matter, and the growth of the unstable m=0 mode driven by the curvature of the magnetic field.

The novel hourglass-shaped loads respond to the current pulse in a better and qualitatively different way than conventionally mounted mm-diameter-wire loads. For conventionally mounted loads, spurious plasma formation is found to occur at the joints between wires and electrodes, and sometimes at other current joints in the vicinity. In Fig. 3 are ICCD images (5-ns exposure) timed to record light emission of the central region of 1-mm-diameter aluminum cylinders shortly after surface plasma is formed. On the left is an example with a commercially drawn 1-mm-diameter wire and conventional electrodes, while on the right is an example of a machined, 1-mm-diameter, hourglass-shaped load, where care was taken to make solid electrical contacts between Zebra and the load hardware. In this and other images, the hourglass loads show good uniformity of light emission that starts reproducibly later in time, while the drawn wires show less repeatable early light and less uniform spatial distribution of emission. The initially nonuniform emission is not well understood, but the hourglass-load data quickly assume a uniformity that one would hope to see for comparison with one-dimensional numerical modeling. The surface of hourglass loads is also most likely to represent behavior that occurs on the inner surface of an imploding liner, which is a machined surface with no electrical connections.

The surface brightness as a function of time was measured by a photodiode or sometimes photodiode arrays, a photomultiplier (PMT), and a streak camera (Fig. 2). For temperatures above 0.5 eV, visible-wavelength intensity is approximately proportional to temperature, so intensity vs. time can also be interpreted as temperature vs. time.

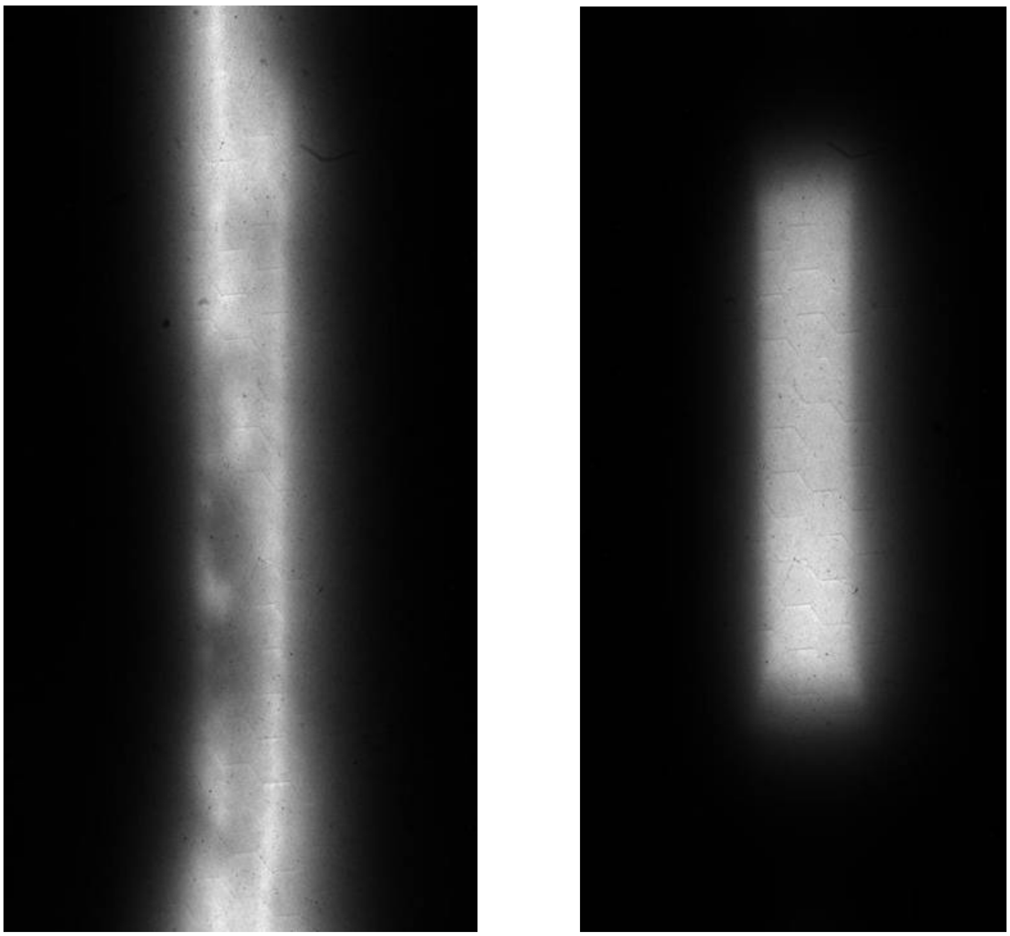

Figure 3. Time-gated (5-ns gate) intensified CCD camera images of a conventional wire load (left) and a new machined load (right), both driven by the 1-MA, 100-ns Zebra generator. The conventional wire load (shot 878) comprised a 21-mm-long (vertical dimension) Al 1100 wire (without Teflon disks on the contacts). The right photo is the emission from a load (shot 891) that was machined from Al 6061. The glowing central 7-mm length is connected, above and below, to conical sections that are dark. Both loads are 1 mm in diameter (horizontal dimension). The light emission from the new load is markedly more uniform than from the conventional wire load.

The data in Fig. 2 suggest little influence by line radiation, because the streak camera (unfiltered) and the photodiode (narrow-band-pass filtered) view very different spectral regions but show excellent agreement for measured intensity vs. time, except near peak intensity where the streak camera had a blemish on its photocathode and gave incorrect readings. For this and other hourglass loads, the PMT saturates almost immediately when plasma light begins. The photomultiplier is a sensitive detector of bulk metal heating or plasma formation: it has 10,000-times greater gain than the photodiode, and saturates almost immediately when light begins. With hourglass loads using good electrical connections, the PMT starts at the same time as the photodiode, suggesting that no precursor type of plasma breakdown has occurred before the uniform surface ionizes and becomes a plasma.

The shadowgrams show an opaque object with a well defined surface that expands uniformly in radius until near peak current. Radius measured by emitted light on streak photos and ICCD framing pictures agree well with the laser measurements (Fig. 4).

The optical system shown in Fig. 5, designed and built by graduate student T. Awe, allows the surface plasma to be viewed at two times on a single discharge, separated by 27 ns (Fig. 6). The results show that some amount of non-uniform emission occurs at the beginning of plasma formation, but as time progresses the hour-glass type loads become increasingly uniform. These data were obtained using an easier-to-machine version of hourglass loads termed “barbells”.

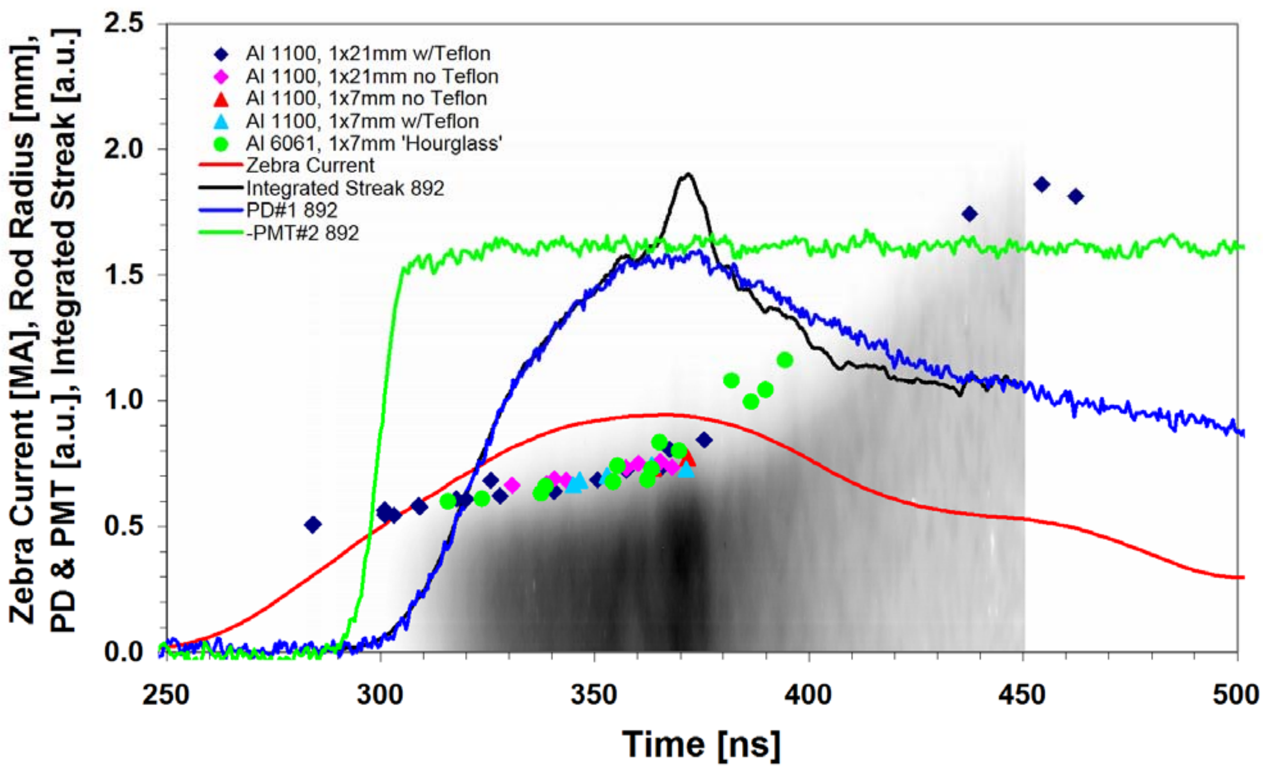

Figure 4. Streaked self-emission & laser shadowgrams show consistent plasma expansion.

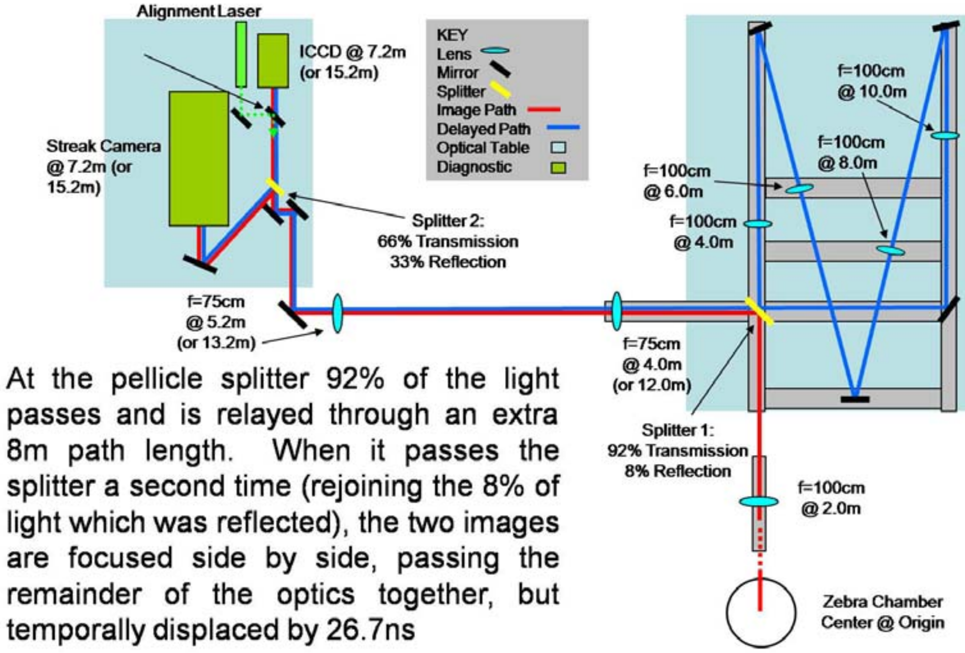

Figure 5. Optical system to deliver two images with different path lengths (time difference of 26.7 ns) onto a single-frame (5-ns) ICCD camera.

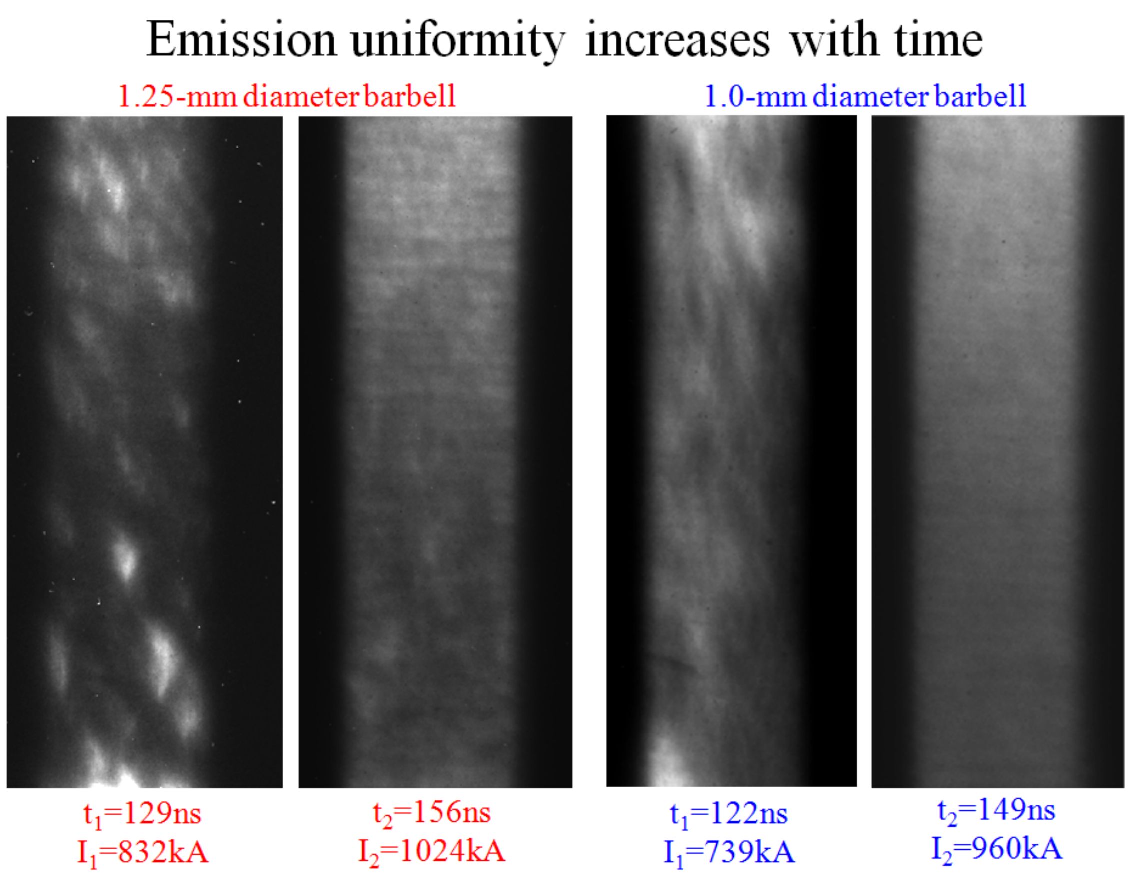

Figure 6. Double-frame ICCD camera pictures using optical system shown in Fig. 5.

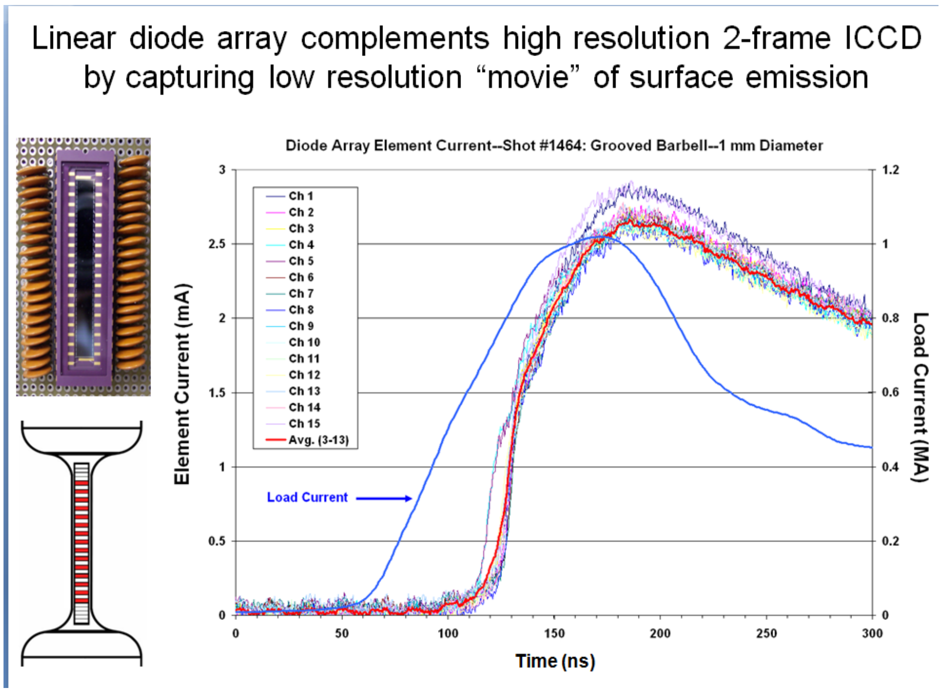

Figure 7. Linear photodiode array allows time resolved measurements of emission intensity at different locations along the aluminum rod.

These data were also confirmed by imaging the load to a linear photodiode array, as shown in Fig. 7. This diagnostic was also developed by graduate student T. Awe. As seen in Fig. 7, at early time the emitted intensity varies with axial location along the load, but as time progresses all the diode elements show about the same brightness.

To obtain the absolute surface emission intensity of watts per unit area, per unit solid angle, and per nm of wavelength, for the purpose of measuring surface temperature, the various photodiode detector systems being used must be calibrated. More work on calibrations is needed, but the estimated temperature at peak emission intensity on 1-mm aluminum rods is 15±4 eV, assuming a blackbody spectrum. A similar approach was reported recently for water-embedded wire explosions.[6] The blackbody assumption is supported by observations of the visible spectrum using a spectrograph coupled to a streak camera. No lines are found in the spectrum, which appears to be a black-body continuum. The surface-brightness temperature is also consistent with ultraviolet spectroscopy, which does show lines. For XUV photons, as opposed to visible photons, the emission is not blackbody, in accord with calculations done with the Prism-SPECT code. In the case of XUV, temperature is estimated using line ratios, and the observed temperature peak temperature is about 15 eV.

Another accomplishment in the last year of this project was a series of shots to study plasma formation on aluminum rods of different diameter. The Zebra source impedance is large enough that changing the diameter of the load does not change the current. Therefore, variation of rod diameter means that the surface magnetic field is being varied in proportion to one over radius. The results are summarized in Fig. 8.

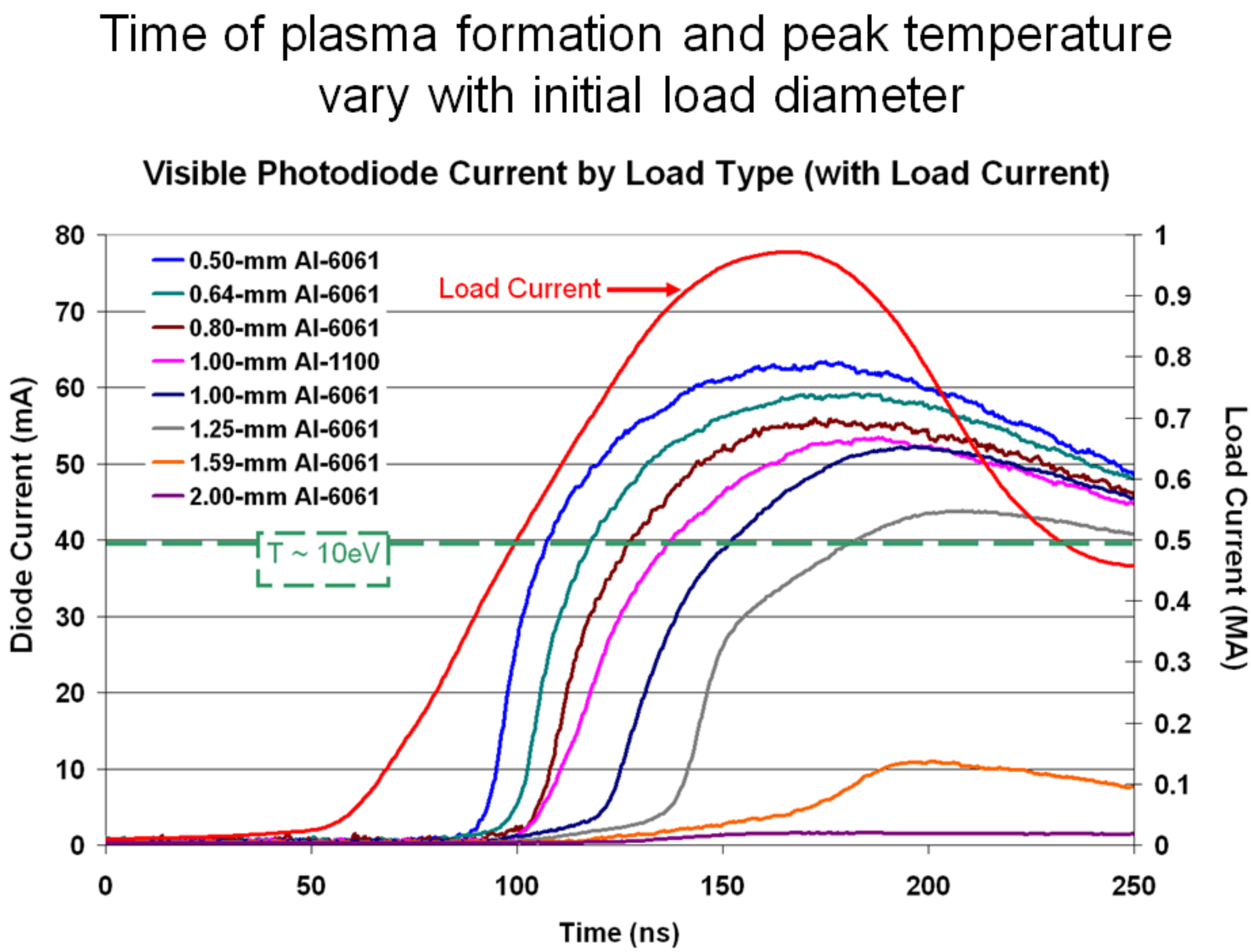

Figure 8. Variation of temperature (proportional to diode current) with time for various aluminum rod diameters.

Plasma formation (diode current above about 5 mA on the graph in Fig. 8) occurs earlier in time as the rod diameter gets smaller. There is also a monotonic increase in peak temperature as the rod diameter is reduced. These data will allow extremely useful comparisons with numerical modeling.

In conclusion,

- ✓ MIF liner physics is being cost-effectively studied by using a z-pinch configuration;
- ✓ The effect of multi-MG field with $\delta/a < 1$ is being studied with experiments on the 1-MA Zebra z-pinch;
- ✓ Hourglass-shaped loads emit the most uniform light and eliminate spurious plasma prior to bulk metal heating. Thus they should allow meaningful comparison with 1-D modeling.
- ✓ Interesting and informative comparisons with radiation-MHD models are underway (see Section 2, next).

2. Numerical Modeling

We are pleased to report that the above experimental results (Section 1) are being compared with a number of MHD code simulations, using various assumptions for the material properties. In April 2008 a fascinating workshop to compare results focused exclusively on this experiment was held at the University of Nevada, Reno. Participants included scientists from Los Alamos and VNIIEF and others who submitted results for consideration.

The MHD codes include:

- MHRDR -- LANL, UNR: MHD, Eulerian, single material;
- RAVEN -- LANL, UNR: MHD + strength, Lagrangian, multi-material w/ strength;
- MACH2 -- NumerEx: ALE, multi-material;
- UP -- VNIIEF(Russia) : Lagrangian, multi-material;
- MHD code, IPR (India), Chaturvedi: Lagrangian, multi-material; and
- ALEGRA -- SNL: ALE.

A comparison of MHRDR modeling with the experiment is made below (Section 2.2), after a brief description of the MHD modeling tools and results (Section 2.1).

2.1. MHD modeling tools and results

Both the MHRDR and RAVEN codes have been run at UNR. It has been very instructive to compare the results of the two codes, which have different approaches to solving the same set of equations. It has also been very instructive to compare the results of these two codes with those of our collaborators.

The MHRDR code created by Irv Lindemuth, who now works part time with UNR, has proven to be an outstanding tool for designing and analyzing experiments.[7] It is also a valuable teaching tool for students who can gain physical insights by doing numerical experiments. The code is a two-dimensional Eulerian code that can be used with either a Braginskii-type plasma or a material specified with standard Los Alamos SESAME tables. It can be run with a variety of physical models in one or two dimensions with up to three temperatures – ion, electron, and radiation. In particular, radiation transport using the Rosseland opacity tables can be included, which appears to be important for estimating temperature in the proposed experiments after plasma is formed near the surface.

The RAVEN code is a one-dimensional Lagrangian code from Los Alamos National Laboratory that can also model with Braginskii coefficients or SESAME tables. It is very helpful to compare Lagrangian and Eulerian codes in various situations. For example, in the Eulerian code (MHRDR), the nominal vacuum region must be represented by extremely low density material, which requires some arbitrary approximations. It is useful to compare the behavior of the vacuum interface region in the Lagrangian code RAVEN versus that in the Eulerian code MHRDR.

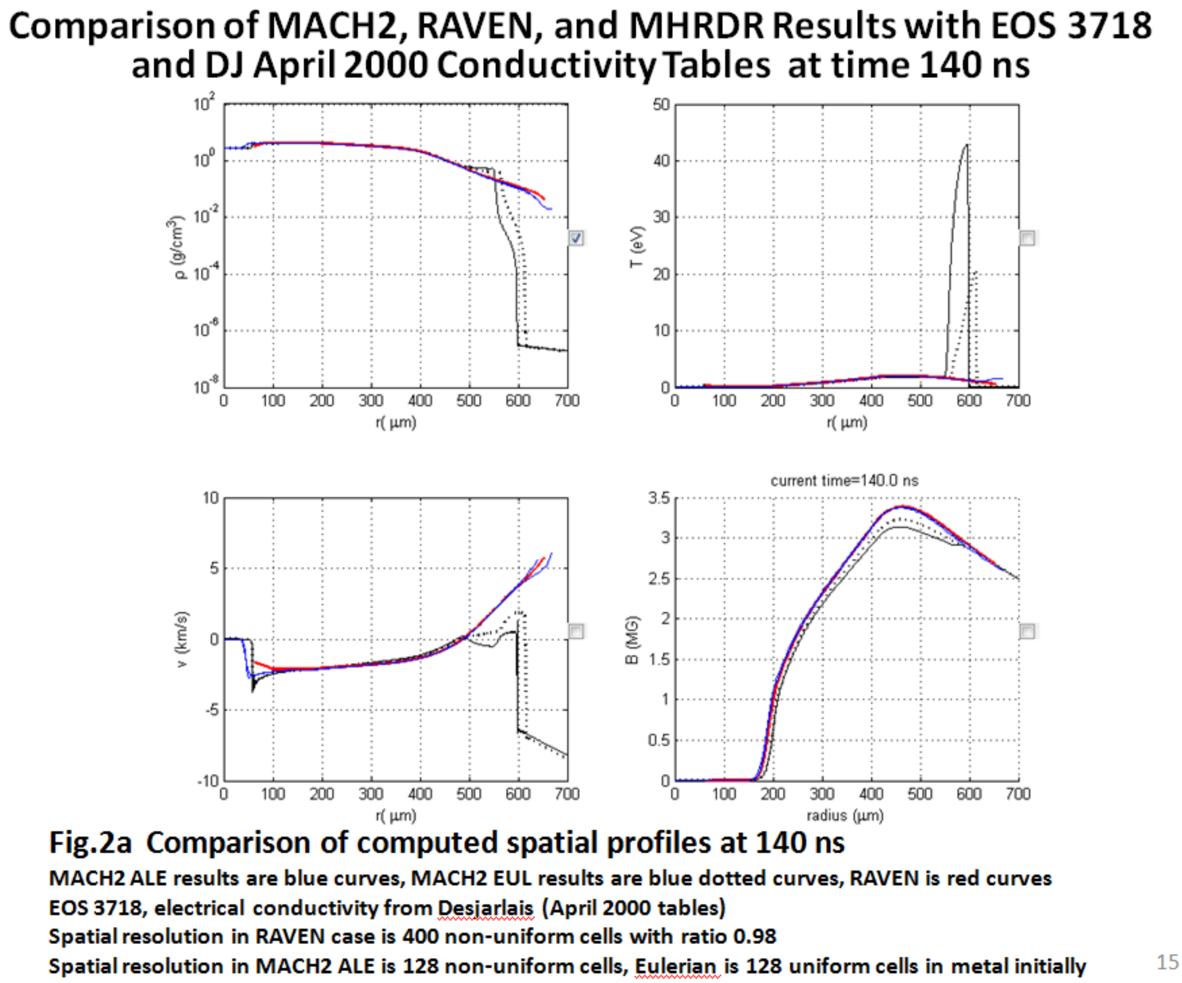

Figure 9. Comparison of code results for 1-mm aluminum rod at a time after plasma formation has occurred in the experiment.

Fig. 9 shows a comparison from several codes including MHRDR and RAVEN that was presented at the UNR workshop in April. There is far too much information to discuss properly in this report, but one of the most noteworthy general qualitative features of code comparisons can be seen in this figure.

It has been found generally that either Eulerian or Lagrangian codes give similar results for the interior of the aluminum rod, provided of course that the same material properties are assumed. However, on the edge of the rod, where density drops rapidly (note the logarithmic scale for density in Fig 9), and where aluminum changes from a solid to warm dense matter, the code predictions show considerable variation, and the formation of plasma in simulations is generally later in time than observed in the experiment. This generality should be qualified by noting that code prediction of plasma formation happens earlier in time when equations of state invoke Van der Waal loops instead of a Maxwell construction. Work remains to be done on these problems, and several papers are being prepared on this work.

2.2. Comparison of MHRDR modeling with experimental results

The outer radial boundary of the aluminum according to MHRDR simulations is given as the solid red curve in Fig. 10. The radius was defined as the location with density 1.0×10^{-4} kg/m^3. This density is roughly that at which the plasma becomes opaque to 532-nm-wavelength light (as utilized for laser shadowgrams).

It is also roughly the geometric mean of the densities around the last, steep, 4-order-of-magnitude density drop to the "vacuum density" (7.5×10^{-7} kg/m^3). So, the radius obtained is not sensitive to the choice of the edge density threshold.

Up to the time of peak current (365 ns in Fig. 10) there are small differences between the MHRDR results and experiment. This result depends significantly on material properties assumed by the numerical model, and some often-used models in recent years show significant differences. The agreement here uses resistivity by Desjarlais[8] and EOS tables recommended by Sandia National Laboratory (sesaAl 29373 and sesame 3719, respectively).

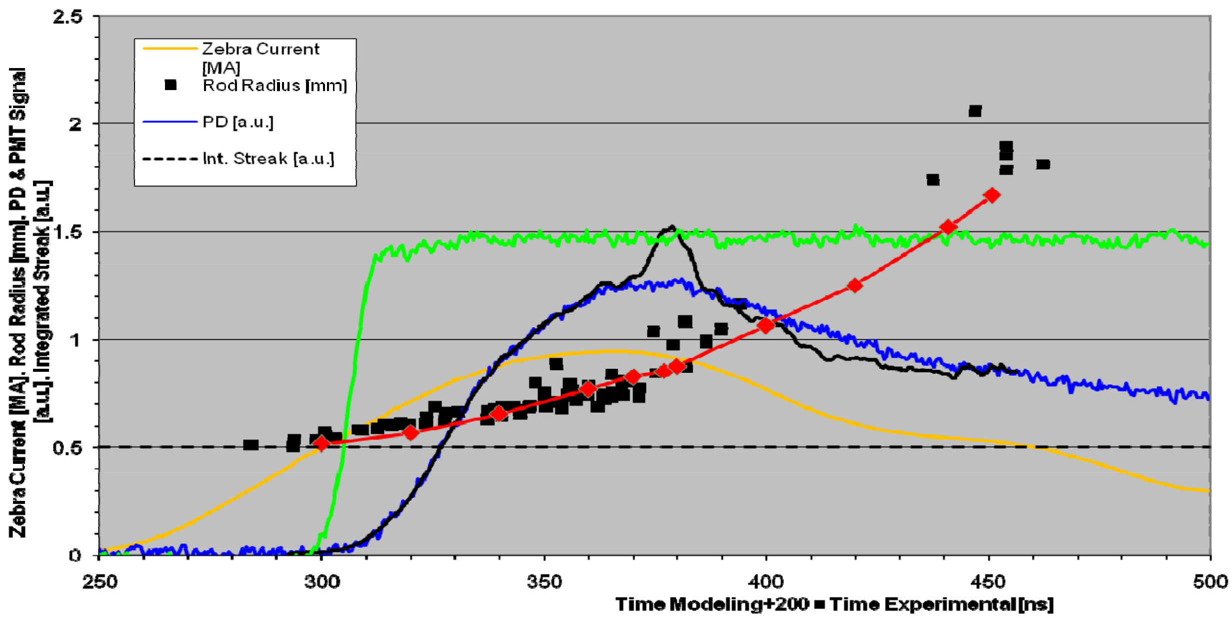

Figure 10. Comparison of aluminum radius vs. time from MHRDR modeling and experiment (shot 892, see Fig. 4). The red curve is the radius from numerical simulation. The markers represent measurements of radius by laser diagnostics. They are consistent with those (not shown) from streak and ICCD camera images. The blue, black, and green curves are the emission measured by a photodiode, a streak camera, and a photomultiplier, as in Fig. 4. The orange curve is the current vs. time. MHRDR shows plasma expansion similar to experiment.

Both the experimental data and the simulation show an increase in outward velocity shortly after the time of peak current. The increased velocity may be the result of an expanding pressure wave that has reflected from the axis and is interacting with the low-density material on the outer edge of the rod. It is presumably a coincidence that the reflected pressure wave arrives at about the same time that the surface has developed $m = 0$ modes, but this has not been established experimentally or numerically. This is another example of the kind of detail contained in the experimental data that is interesting to compare with modeling. The $m = 0$ interchange mode with wavelength small compared to the cylinder radius is as expected and has been seen in two-dimensional numerical modeling of this experiment.

3. Articles and Meeting Presentations

Our progress in this project has been documented and disseminated via the following 12 articles and 44 presentations at meetings.

Articles:

1. S. Fuelling, T.J. Awe, B.S. Bauer, T.Goodrich, I.R. Lindemuth, V.Makhin, R.E. Siemon, W.L. Atchison, R.E. Reinovsky, M.A. Salazar, D.W. Scudder, P.J. Turchi, and J.H. Degnan, *Experimental design of a magnetic flux compression experiment*, J. Fusion Energy **26**, 47-51, http://www.springerlink.com/content/e104756727450253/ (2007).
2. V. Makhin, B.S. Bauer, T.J. Awe, S.Fuelling, T. Goodrich, I.R. Lindemuth, R.E. Siemon, and S.F. Garanin, *Numerical modeling of a magnetic flux compression experiment*, J. Fusion Energy **26**, 109-112, http://www.springerlink.com/content/j5171446756074j6/ (2007).
3. T.J. Awe, R.E. Siemon, B.S. Bauer, S. Fuelling, V. Makhin, S.C. Hsu, and T.P. Intrator, *Magnetic Field and Inductance Calculations in Theta-Pinch and Z-Pinch Geometries*, J. Fusion Energy **26**, 17-20, http://www.springerlink.com/content/bj1368w783136258/ (2007).
4. M.A. Angelova, B.S. Bauer, R.E. Siemon, I.R. Lindemuth, and V. Makhin, *Sensitivity of m=0 growth to EOS and other material properties*, IEEE/Megagauss Institute Proceedings of the 2006 International Conference on Megagauss Magnetic Field Generation and Related Topics, Santa Fe, New Mexico, November 5-10, 2006, IEEE CFP06MEG-PRT, p. 161 (2007).
5. S. Fuelling, T.J. Awe, B.S. Bauer, T. Goodrich, V. Makhin, V.V. Ivanov, R. Presura, R.E. Siemon, R.E. Reinovsky, P.J. Turchi, J.H. Degnan, and E.L. Ruden, *Development of an experiment to study plasma formation by megagauss fields*, IEEE/Megagauss Institute Proceedings of the 2006 International Conference on Megagauss Magnetic Field Generation and Related Topics, Santa Fe, New Mexico, November 5-10, 2006, IEEE CFP06MEG-PRT, p. 167 (2007).
6. I.R. Lindemuth and R.E. Siemon, *The basis of Magnetized Target Fusion – A fusion primer*, IEEE/Megagauss Institute Proceedings of the 2006 International Conference on Megagauss Magnetic Field Generation and Related Topics, Santa Fe, New Mexico, November 5-10, 2006, IEEE CFP06MEG-PRT, p. 27 (2007).
7. V. Makhin, M.A. Angelova, T.J. Awe, B.S. Bauer, S. Fuelling, I.R. Lindemuth, and R.E. Siemon, *Modeling of plasma formation and evolution on the surface of Ohmically heated conductors*, IEEE/Megagauss Institute Proceedings of the 2006 International Conference on Megagauss Magnetic Field Generation and Related Topics, Santa Fe, New Mexico, November 5-10, 2006, IEEE CFP06MEG-PRT, p. 173 (2007).
8. R.E. Siemon, B.S. Bauer, T.J. Awe, M.A. Angelova, S. Fuelling, T. Goodrich, I.R. Lindemuth, V. Makhin, V.V. Ivanov, R. Presura, W.L. Atchison, R.J. Faehl, R.E. Reinovsky, D.W. Scudder, P.J. Turchi, J.H. Degnan, E.L. Ruden, M.H. Frese, S.F. Garanin, V.N. Mokhov, *The challenge of wall-plasma interaction with pulsed MG fields parallel to the wall*, IEEE/Megagauss Institute Proceedings of the 2006

International Conference on Megagauss Magnetic Field Generation and Related Topics, Santa Fe, New Mexico, November 5-10, 2006, IEEE CFP06MEG-PRT, p.155 (2007).

9. M.A. Angelova, B.S. Bauer, R.E. Siemon, I.R. Lindemuth, and V. Makhin, *Sensitivity of m=0 instability to different resistivity models*, IEEE Transactions on Plasma Science **36**, 37 (2008).

10. S. Fuelling, T.J. Awe, B.S. Bauer, T. Goodrich, A. Haboub, V.V. Ivanov, V. Makhin, A. Oxner, R. Presura, and R.E. Siemon, *A Zebra Experiment to Study Plasma Formation by Megagauss Fields*, IEEE Transactions on Plasma Science **36**, 62 (2008).

11. A.A. Esaulov, B.S. Bauer, V. Makhin, R.E. Siemon, I.R. Lindemuth, T.J. Awe, R.E. Reinovsky, K.W. Struve, M.P. Desjarlais, and T.A. Melhorn, *Radiation magnetohydrodynamic simulation of plasma formed on a surface by a megagauss field*, Phys. Review E **77**, 036404, http://link.aps.org/abstract/PRE/v77/e036404 (2008).

12. R.E. Siemon, B.S. Bauer, T.J. Awe, W.L. Atchison, M.A. Angelova, S. Fuelling, T. Goodrich, I.R. Lindemuth, V. Makhin, W.L. Atchison, R.J. Faehl, R.E. Reinovsky, P.J. Turchi, J.H. Degnan, E.L. Ruden, M.H. Frese, S.F. Garanin, and V.N. Mokhov, *The Challenge of Wall-Plasma Interaction with pulsed Megagauss Magnetic Fields*, J. Fusion Energy **27**, 235, http://www.springerlink.com/content/c01q368w00408571 (2008).

Conference and Workshop presentations:

Fusion Power Associates Annual Meeting and Symposium
Fusion: Pathways to the Future, Washington, DC, September 27-28, 2006

1. R.E. Siemon, '*Magnetized Target Fusion Pathway to Fusion*', Fusion Power Associates Annual Meeting and Symposium, Washington, DC, September 27-28, 2006.

48th Annual Meeting of the APS Division of Plasma Physics
Philadelphia, Pennsylvania, Oct. 30 - Nov. 3, 2006

2. J.H. Degnan, M. Domonkos, F.M. Lehr, J.D. Letterio, N.F. Roderick, E.L. Ruden, W. Tucker, P.J. Turchi, D. Amdahl, A. Brown, S.K. Coffey, M.H. Frese, S.D.Frese, T. Cavazos, D. Gale,T.C. Grabowski, J.V. Parker, R.E. Peterkin, Jr., W. Sommars, G.F. Kiuttu, R.E. Siemon, Paper GP1.00136, '*Progress on Liner Implosions for compression of FRC's*', presented at the 48th Annual Meeting of the APS Division of Plasma Physics, Philadelphia, PA, October 30-November 3, 2006.

3. T.P. Intrator, G.A. Wurden, R. Renneke, L.A. Dorf, M. Farrell, T.K.Gray, S.C. Hsu, A.G. Lynn, M.Gilmore, C. Grabowski, E.L. Ruden, J. Degnan, T. Awe, R. Siemon, '*Preparing to compress a Field Reversed Configuration target for Magnetized Target Fusion*', Paper CP1.00062, presented at the 48th Annual Meeting of the APS Division of Plasma Physics, Philadelphia, PA, October 30-November 3, 2006.

4. L.Dorf, T. Intrator, R. Renneke, S. Hsu, G. Wurden, T. Awe, R. Siemon, V. Semenov, ‘*Modeling FRC Formation in Field Reversed Experiment – Liner’*, Paper CP1.00065, presented at the 48th Annual Meeting of the APS Division of Plasma Physics, Philadelphia, PA, October 30-November 3, 2006.

IEEE 2006 International Conference on Megagauss Magnetic Field Generation and Related Topics, Santa Fe, New Mexico, November 5-10, 2006

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28. V. Makhin, *Numerical Modeling of Behavior of 1 mm Aluminum Wire under the Zebra 1 MA Current*, presented (oral) at UNR-Megagauss-Experiment Computational Modeling Workshop, Reno, Nevada, April 7-9, 2008.

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