MHD MODELING OF CONDUCTORS AT ULTRA-HIGH CURRENT DENSITY*

S. E. Rosenthal, M. P. Desjarlais, R. B. Spielman, W. A. Stygar, J. R. Asay,
M. R. Douglas, C. A. Hall,
M. H. Frese[i], R. L. Morse[ii], and D. B. Reisman[iii],
Sandia National Laboratories, PO Box 8500, Mail Stop 1194

Abstract

In conjunction with ongoing high-current experiments on Sandia National Laboratories' Z accelerator we have revisited a problem first described in detail by Heinz Knoepfel [1]. Unlike the 1-Tesla MITLs of pulsed power accelerators used to produce intense particle beams, Z's disc transmission line (downstream of the current addition) is in a 100-1200 Tesla regime, *so its conductors cannot be modeled simply as static infinite conductivity boundaries*. Using the MHD code [2,3] MACH2 we have been investigating the conductor hydrodynamics, characterizing the joule heating, magnetic field diffusion, and material deformation, pressure, and velocity over a range of current densities, current rise-times, and conductor materials. Three purposes of this work are (1) to quantify power flow losses owing to ultra-high magnetic fields, (2) to model the response of VISAR [4] diagnostic samples in various configurations on Z, and (3) to incorporate the most appropriate equation of state and conductivity models into our MHD computations. Certain features are strongly dependent on the details of the conductivity model. Comparison with measurements on Z will be discussed.

I. INTRODUCTION

The development of very high current drivers has reopened a concern first voiced by Knoepfel [1] in which electrical losses at high current density were described. Later calculations by Singer and Hunter [5] extended Knoepfel's predictions to include losses due to mechanical work. Baker and Hussey [6] reexamined Singer's calculations and confirmed those results. Later Allshouse [7] used LASNEX [8], a 2-D RMHD code, to model conductor responses at the high current density levels predicted on next-generation drivers. Most recently, Reisman [9] and Stygar and Spielman [10] have examined the importance of model details and experiments on the prediction of electrical losses at high current densities.

The Z accelerator permits, for the first time, the possibility of detailed measurements of the losses in conductors at current densities as high as 10 MA/cm. Simultaneously, improvements in the tabulated values of the resistivities of several elements allows greatly improved calculations of the losses in conductors. This information has gained added importance with plans to build larger pulsed-power drivers having current densities approaching 10 MA/cm. Clearly, before proceeding to build such drivers, we must learn whether loss mechanisms exist that fundamentally limit the current density in a conductor.

Treating the magnetic diffusion as a linear problem with constant resistivity shows that diffusion and corresponding Joule heating would be significant at current densities in the 1-10 MA/cm range. Considering an assumed functional dependence of resistivity on heat energy [1,5,11] provides a simplified description of nonlinear magnetic diffusion, providing a pessimistic upper limit of losses that scale with the cube of the current density. In this paper we describe our effort to study diffusion and heating consistently with a MHD code using electrical conductivities that are accurate over the wide range of densities and temperatures important for this problem. Such conductivity information has not previously been available for use in a MHD calculation.

II. MODEL DESCRIPTION

A. *Brief Description of MACH2*

The MACH2 Code solves the time-dependent magnetohydrodynamics (MHD) equations for on block-structured grid composed of arbitrary hexahedrals. The code is of the ALE (Arbitrary Lagrangian-Eulerian) variety which allows the grid to move independently of the magnetofluid. The physical processes included in the model are diffusion, Lagrangian hydrodynamics, and advection. Details of the algorithms are provided in references 2 and 3.

The geometrical domain is block structured which allows for the modeling of complex geometries. MACH allows for numerous boundary conditions in the 2-D plane which are specified by the user. An important feature is that new EOS/conductivity/opacity models are easily implemented.

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[i] NumerEx, Inc, Albuquerque, NM
[ii] University of New Mexico, Albuquerque, NM
[iii] Lawrence Livermore National Laboratory, Livermore, CA

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14. ABSTRACT

In conjunction with ongoing high-current experiments on Sandia National Laboratories Z accelerator we have revisited a problem first described in detail by Heinz Knoepfel [l]. Unlike the I-Tesla MITLs of pulsed power accelerators used to produce intense particle beams, zs disc transmission line (downstream of the current addition) is in a 100-1200 Tesla regime, so ifs conductors cannot be moaeled simply as static iqfinite conductivity boundaries. Using the MHD code [2,3] MACH2 we have been investigating the conductor hydrodynamics, characterizing the joule heating, magnetic field diffusion, and material deformation, pressure, and velocity over a range of cutrent densities, current rise-times, and conductor materials. Three purposes of this work are (1) to quantify power flow losses owing to ultra-high magnetic fields, (2) to model the response of VISAR [4] diagnostics amplesin variousc onfigurationso n Z, and (3) to incorporate the most appropriate equation of state and conductivity modelsi nto our MHD computations.C ertain features are strongly dependent on the details of the conductivitym odel. Comparisonw ith measurementosn Z will be discussed

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B. Geometries

The geometry for the simulations corresponds to the disc/coaxial load configuration shot on the Z high-current-density power flow experiments. The inner coax had a 6-mm inner conductor diameter and a 12-mm outer-conductor diameter (See Fig. 1). The length of the

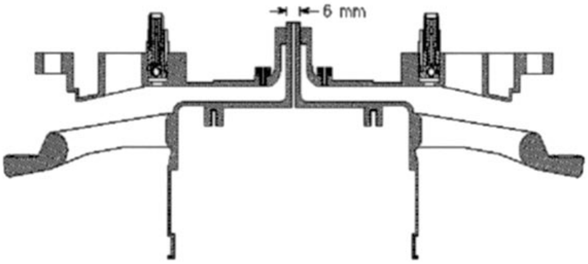

Figure 1. A drawing of a coaxial load that is used to develop high current densities. The locations of the B-dot current monitors and the VISAR probes are shown.

coaxial section was 1 cm. The conductor material for the experiment was 304L stainless steel. We have also considered only a portion of the disc for a simpler geometry.

III. ELECTRICAL CONDUCTIVITY MODEL

The fidelity of our MACH2 calculations depends largely upon an accurate knowledge of the material resistivities over a wide range of temperatures and densities. Of particular importance for these simulations is the regime defined by temperatures below a few eV and densities below solid, especially in the vicinity of the metal-insulator transition. In recent years, DeSilva and colleagues [12] have performed numerous experiments with Cu, Al, and W wires with particular emphasis on this regime. It is clear that the commonly used Lee-More [13] and SESAME (Rinker [14]) resistivities, developed for higher density and temperature applications, are not very accurate in this parameter range, often differing from the data by several orders of magnitude. We have recently developed a modified Lee-More algorithm that smoothly blends into the standard Lee-More results outside of this regime, but is modified in such a way as to give good agreement with the experimental data of DeSilva. The nature of the modifications is such that reasonable electrical conductivities can be estimated for materials for which extensive data do not yet exist. This modified Lee-More algorithm is used to generate SESAME format conductivity tables for use in MACH2.

New tables have been generated for stainless steel, tungsten, iron, aluminum, and copper. A set of constant-temperature conductivity curves for copper is shown in Fig. 2. The discrepancy between previously available conductivities and data is quite large for densities below solid.

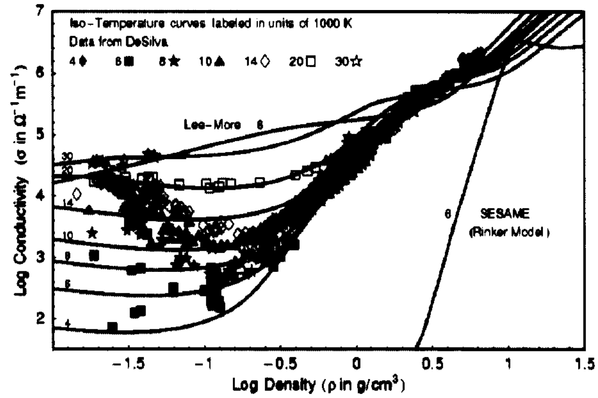

Figure 2. A subset of constant-temperature conductivity curves from our modified Lee-More model, with data, for copper. Also shown are the 6000K curves for both the original Lee-More and Rinker models.

Figure 3 illustrates the effect of using overly-resistive conductivities in a MACH2 simulation of a copper disc. Ablated material, too resistive to be trapped by the magnetic field, extends 0.5 mm into the original vacuum gap. This density corresponds to an electron density of up to 10^{22} cm^{-3}, presenting a serious limitation to power flow.

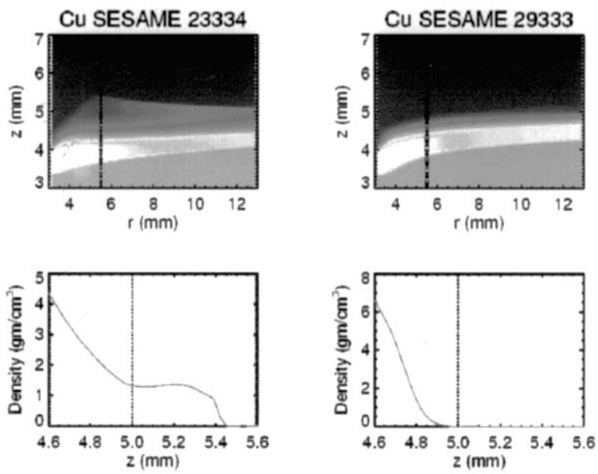

Figure 3. z-r snapshots (first row) and corresponding axial lineouts (second row) for the lower conductor of a copper disc between r = 3 and 13 mm. Rinker resistivities were used in the simulation on the left, and our new model on the right.

The Modified Lee-More conductivity tables are a vast improvement. Accurate electrical conductivities provide us with a prerequisite for meaningful simulations in our parameter regime. We can explore the qualitative nature of energy absorption by the conductor; *e.g.*, is significant plasma evolution into the gap expected? Quantitative comparisons can be made with experiment, leading to refinements in other areas of the simulation model that might be deficient.

IV. SIMULATIONS OF Z SHOT 315

The MACH2 calculations show the preferential heating found in the regions of highest current density. Careful examination of the calculations reveals significant diffusion of magnetic field into the conductor as well as conductor motion (and density increase) driven by the gradient of the magnetic pressure. Because of the dependence of losses on current density nearly all of the dissipation occurs in the inner coaxial region of the load.

The top of Fig. 4 shows a snapshot of the azimuthal magnetic field at the time of peak current. Below in Fig. 4 is the profile taken along the line indicated at z = 10 mm. One can see the usual 1/r dependence of the field in the vacuum gap ($3 < r < 6$ mm), and the diffusion that occurs into the metal, to the left at r = 3mm, and to the right at r = 6 mm. The lineal current density is roughly 10 MA/cm at r = 3 mm, and 5 MA/cm at 6 mm.

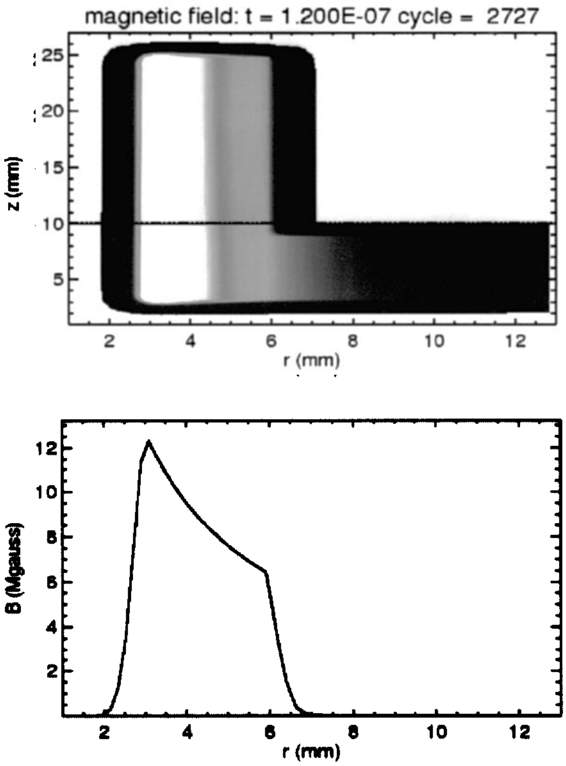

Figure 4. Mach2 simulation results for shot 315; 4a) The azimuthal component, B_Θ, of the magnetic field at the time of peak current in grayscale contours. 4b) The profile of $B_\Theta(r)$ at z = 10 mm (along the line indicated in 4a).

Profiles of mass density along the z = 10 mm line show in Fig. 5 the different degrees of compression corresponding to 10 MA/cm near r = 3 mm, and 5 MA/cm at 6 mm. Also note the lack of mass in the original gap. Finally, figure 6 shows the Joule heating rate, maximum at the inner coaxial surface, extending into the metal by 1 mm. More radial resolution is needed to capture the actual peak near 2.8 mm.

Using reasonably accurate resistivity information, the MHD simulations can now provide a meaningful description of our high-current density problem. An important conclusion has emerged from this ongoing effort: negligible conductor material enters the gap, even at the highest current density considered. Ablative material in the 2-4 eV temperature range is sufficiently conductive (200-600 μΩ-cm) to be held against the solid conductor by the magnetic pressure for the time of the pulse.

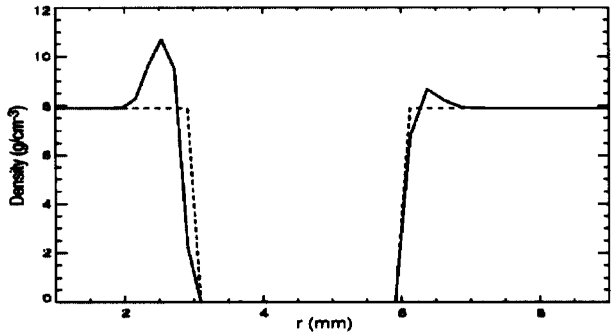

Figure 5. A radial profile of the conductor mass density (taken along the line indicated in Fig. 4a). Dashed curve is at t = 0, solid curve is at time of peak current.

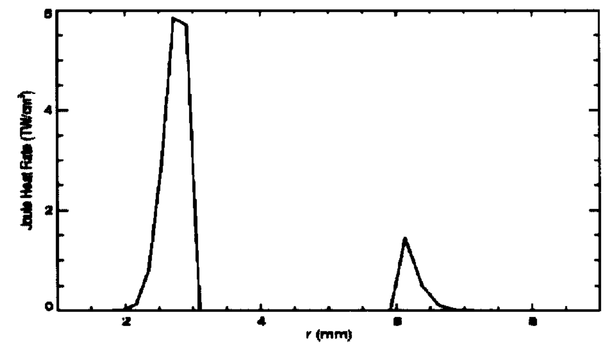

Figure 6. A radial profile (taken along the line indicated in Fig. 4a) of the Joule heating rate at time of peak current.

Quantitative comparisons with experiment are at an early stage, so far showing mixed agreement. Applying the magnetic field corresponding to the measured load current waveform as a boundary condition at the simulation disc inlet (r = 13 mm) yields good agreement between energy loss measured on Z shot 315 and calculated with MACH2 for the first 80 ns of the pulse. After this time the loss inferred from shot 315 current measurements diverges from the simulation with greater loss by a factor of 2 at peak current. We believe our new resistivity function to be reasonably accurate, so other possible sources of the discrepancy are being investigated from both the experimental and simulation sides.

V. SIMULATIONS OF VISAR SAMPLES

In the disc geometry we considered the magnetic diffusion into a thick (2 mm) sample of iron. The MACH2 simulations show hydrodynamic pressure resulting from the applied magnetic pressure on the conductor surface, using our new conductivity model and SESAME EOS for Fe. The hydro pressure runs ahead of the magnetic pressure, exhibiting structure indicative of the α–ε phase transition in iron. For comparison the simulation was repeated using a constant resistivity (9.8 μΩ-cm) to show the effect of nonlinear diffusion. Because the Fe resistivity at solid density increases by more than a factor of 10 for a temperature rise of only 700 degrees K the magnetic diffusion is significantly greater than one would predict from constant resistivity at room temperature solid density.

Results for current density of 5 MA/cm show that the increased diffusion requires a sample thickness greater than the maximum allowed to maintain isentropic compression. Phase information is also lost.

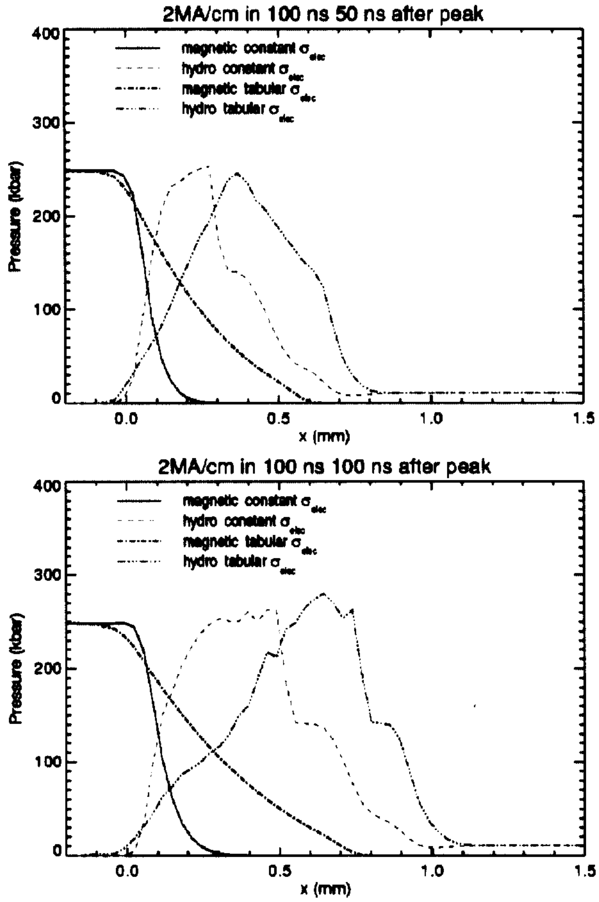

Figure 7. Profiles of magnetic and hydro pressure 50 ns (top), and 100 ns (bottom) after peak applied field.

VI. CONCLUSIONS

New, accurate conductivity tables for a variety of materials have enabled us to begin interesting inquiries into the behavior of conductors under ultra-high pressures associated with 1-10 MA/cm. Results indicate that ablation of conductor material into the power flow gap is insignificant and should not prevent efficient current conduction at these high densities.

Meaningful hydrodynamic simulations can be done of isentropic compression experiments that rely on magnetic diffusion at ultra-high current densities.

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