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ePLAS Development for Jet Modeling and Applications

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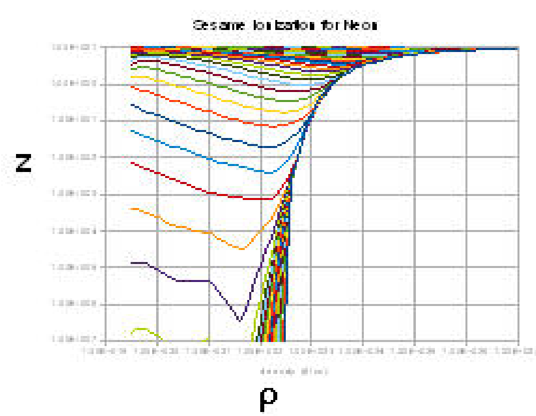

Typical Sesame Atomic Z Table data now available in ePLAS

Overall Summary

This Final Report describes completed work on improvements to the ePLAS code for the modeling of Plasma Jets under the auspices of an SBIR Phase I Grant for the period 6/17/2010 to 3/16/2011. Code enhancements developed under the Project will aid modeling efforts in support of magneto-inertial fusion. We provide an executive summary outlining the technical challenges addressed. We also list the goals set, and the technical and user facility results accomplished during the Project. A major technical accomplishment was the invention a new approach to long time scale modeling based on the implicit treatment of the electron currents. This enabled a 100-fold speed up in jet calculations. RAC suggests that much additional productive work remains to be completed in this modeling arena for Plasma Jets.

Executive Summary

ePLAS is a highly efficient implicit/hybrid simulation code, developed by RAC [http: www.researchapplicationscorp.com], enhanced through an earlier SBIR for the Laser Fast Ignition Laser Fusion community, and recently enriched by this just-completed Phase I Project devoted to the modeling of Plasma Jets. Plasma Jets are central to Magneto-inertial Fusion, but also to Plasma Thrusters and Plasma Processing. It is an exciting time for Magneto-inertial Fusion (MIF) with the Plasma Liner Experiment (PLX) now beginning at Los Alamos[2], and Field Reversed Configurations (FRCs) under study in Wisconsin[3] and at the Air Force Research Laboratory[4]. The LANL experiment will explore the feasibility of forming imploding[5] "plasma liners" that can reach high (0.1 Mbar) peak pressures upon stagnation. The liners will be formed through the merger of 30 dense ($n_{elec} \sim 10^{17}$ e^-/cm^3) high Mach number (10-35), (50-75 km/s) jets, each of 2.5-5 cm radius. Small, parallel-plate mini-railguns are being developed[6] to drive these jets. Each should operate at ~ 300 kA peak current and launch up to ~ 8000 μg of multi- Z argon, and possibly xenon. Recent experimental tests at HyperV[7] have achieved densities in the mini-railgun bore approaching 10^{18} e^-/cm^3, and densities in the jet plume exceeding 10^{17} e^-/cm^3. Ultimate success will require optimized tuning of the rails, the nozzle injecting the gases, and the careful implementation of pre-ionization.

The modeling of plasma jet production and transport[8, 9] has proven challenging and costly, due to the large space (17 by 75 cm) and time scales (11 μs) typically involved. Even with implicit field coding[10], 30 hrs of single processor time has been needed per microsecond of jet dynamics. Electron and ion emission from the surrounding conductor walls must be carefully managed to avoid anomalous penetration[9] of the magnetic fields driving plasma jets. Current re-striking[8] and pre-arcs may shield the plasma from a proper driving magnetic thrust. Ionization in sharp gradient regions of the driven plasma may subtly alter the jet resistivity, continuity and acceleration. Electron magneto-hydrodynamic (EMHD) effects[11] can account for collisionless *B*-field penetration of low density regions of the jet.

MIF jet dynamics has kinship with plasma evolution seen and modeled in earlier scenarios. The jet is like the fill plasma band in a Plasma Opening Switch (POS)[11], providing an initial short-circuit between an anode and a cathode. Typically, a 3 x 10^{13} cm^{-3} density switch plasma conducts multi-kA currents for 5 to 100 ns. Then, it "opens" the short-circuiting plasma, letting the driving B-field pass by it to a load. MIF jet plasmas are 10^4 times denser than in the POS, and must conduct 10^2 -10^3 times longer, as they are propelled by the driving B-field to coalescence with other jets, forming a liner. This liner can then serve Fusion applications.

For this Project, RAC proposed to employ its ePLAS code, a derivative of ANTHEM[12-14] - a veteran of POS modeling, to the mini-railgun jet problem. In its earlier form ePLAS explored Opening Switches extensively[15-19]. Here, we employed the code's implicit/hybrid nature plus newer features, to characterize and optimize the mini-railgun jets. ePLAS can use either PIC particles or a "hot" fluid for electrons emitted from a cathode. It allows for "cold" electron and ion fluids in the plasma jet background - for a variety of computational advantages. It can also treat the background ions as particles. ePLAS runs efficiently on PCs. RAC worked successfully to surmount any new difficulties imposed by the larger scales and densities for the jets. It also strove to make ePLAS broadly available to "beta testers" in the fusion community. With experience gained from jet applications, RAC now plans to extend ePLAS use to a broader range of challenges, such as the modeling of jets for Plasma Thrusters and Plasma Processing.

The wide availability of an efficient, user-friendly simulation code for plasma jet modeling will hasten the day when fusion power becomes available for the nation and the world. New jet MIF and FRC concepts found through simulation with such a model will change the energy picture dramatically. Concepts and code improvements achieved in this project will aid both the government and the commercial power industry. Byproducts of this effort will be enhanced Jet Thruster modeling capabilities and improved models for Plasma Processing. The US community of Research Universities and the National Energy Laboratories will benefit on the nearest term through access to the robust modeling capabilities embodied in ePLAS.

Goals, Accomplishments and Pertinent Activities

For this Phase I Project we proposed to explore *five technical areas for accomplishment* in jet modeling, and possible ePLAS code improvements needed to master them. We also outlined plans to disseminate our results. These technical areas were: 1. Electrode physics, 2. B-field and hydro modeling 3. Flow algorithms, 4. Variable Z, 5. Parallelism, and 6. Dissemination of results.

Below we provide a summary of our results mastering these challenges and a record of our successful efforts in the dissemination or our results.

1) Electrode physics –

Recent work[9] had indicated that high mesh resolution may be needed near the electrodes driving the Plasma Liner Experiment (PLX) jets. This was not our earlier experience with the POS[11-16]. We found, in fact, that the electrodes could be made into dense, fixed-ion[16] extensions of the fill plasma slug (jet), and that our implicit field solver would draw (or push) the needed electron flow (current) through the walls to avoid unphysical gaps. We proposed to revisit this issue for PLX jet conditions.

During phase I we began to study this electrode issue by running HyperV- like rail-gun jet problems with either external electrodes (as boundary conditions), or internal electrodes with dense shaped plasmas and fixed ions serving as the walls for the jet-accelerating guns. Each approach gave similar results for jet production, with the shaped plasmas providing more freedom in mimicking gun configurations. Figs. 1(a) and (b) below capture an ePLAS calculation of a hydrogen slug pushed along a gun bore into a larger volume. The down-gun expansion in volume was facilitated through the use of dense shaped dense plasma for both the gun walls and the void region walls beyond it. Alternatively, for Fig. 2 we used external boundary conditions at which the normal E-field was set to zero to model jet acceleration. This was equally successful.

We have not, however, reached closure on whether the external boundary conditions with the careful implementation of Child-Langmuir limits are needed at the high jet densities of interest here. So, this will receive further study. Furthermore, drifting jet ions can scrape along gun walls, so this should be given attention, as well.

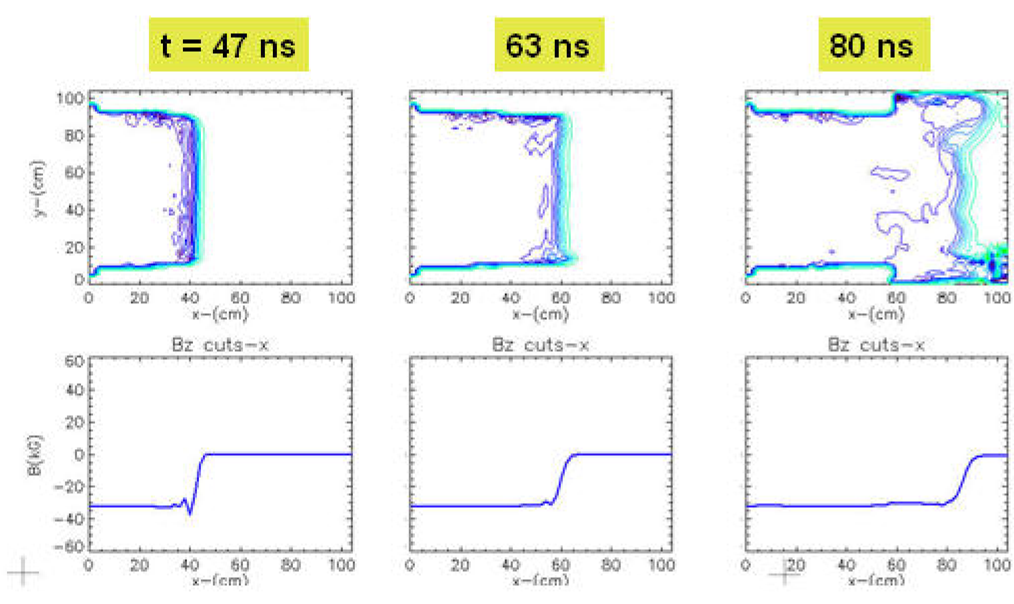

Fig. 1(a). *B*-field penetration along a wide rail gun, opening into a void. Here, we have used a reduced proton mass (for computational speed-up with explicit electron hydrodynamics). Top: 2-D *B*-field penetration, Bottom: the B-field along a central cut with a left-side drive value of 3.2 T. The overall scenario represents the electrodes with high density internal plasmas out to 60 cm. These open into a mildly larger void at greater x values.

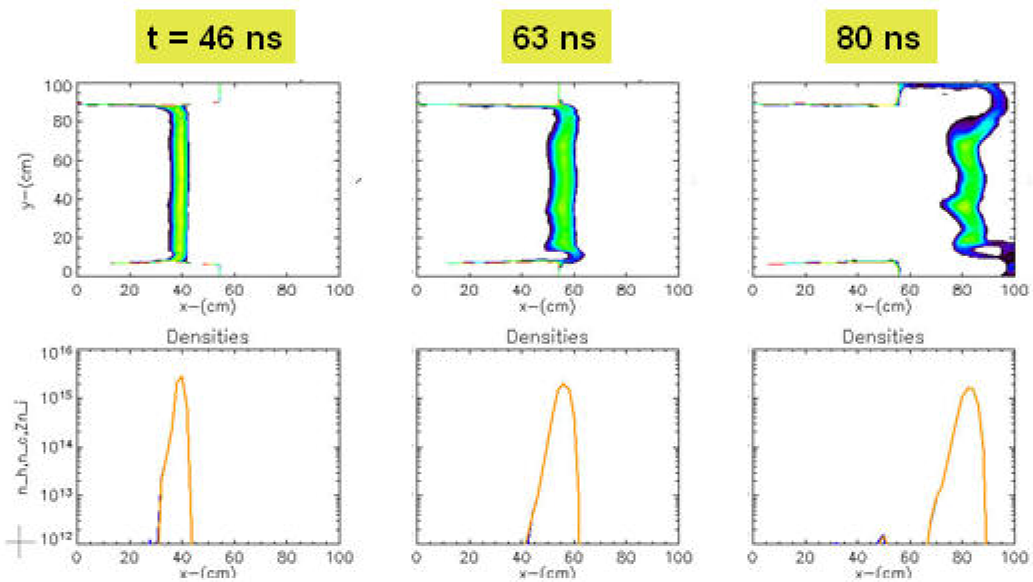

Fig. 1 (b). Jet density evolution with the shaped electrode walls.

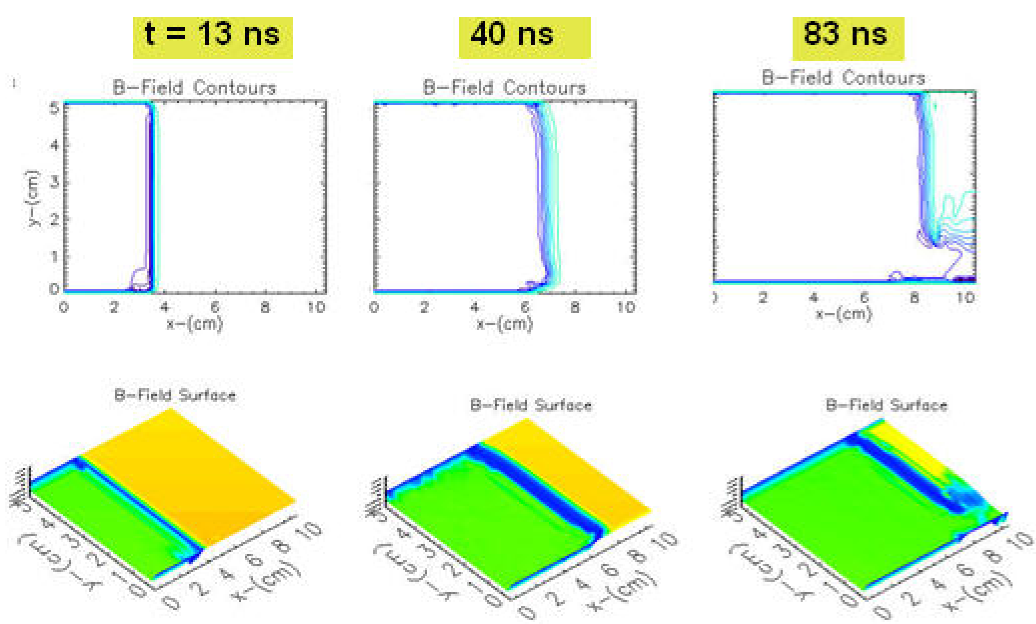

Fig. 2 (a). Evolving B-field contours and surface plots with the use of external electrodes for 10^{16} e^-/cm^3 Z = 1 argon jets for a 5 cm gun bore.

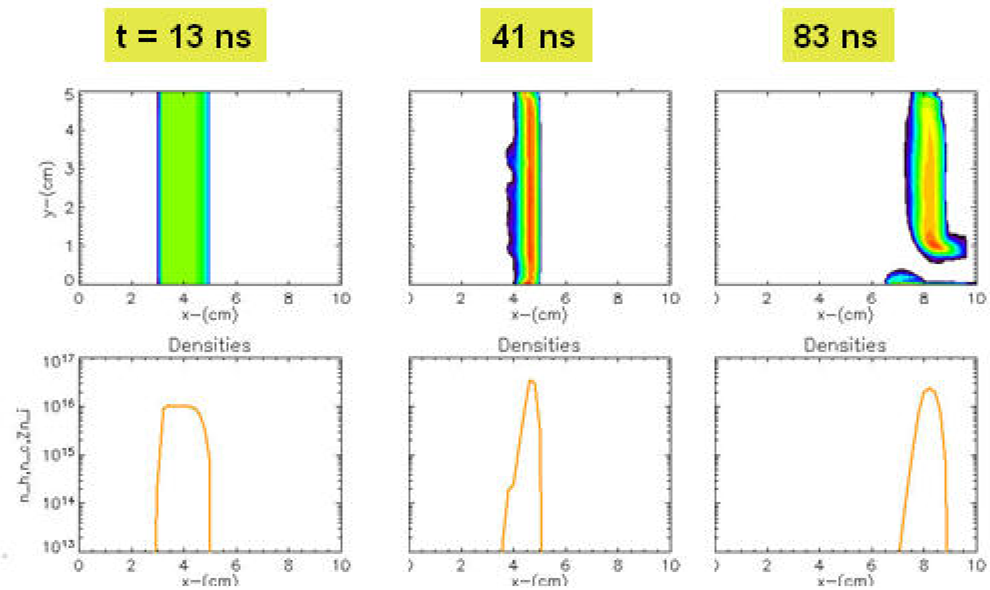

Fig. 2 (b). Density evolution of the argon jets in the gun using external electrodes, 10^{16} e^-/cm^3 density and a narrower gun bore.

2) The *B*-Field and implicit electron hydro modeling –

In standard usage prior to this Project, the ePLAS *B*-fields were obtained by the implicit moment method[12-14]. This approach avoids numerical instability from plasma waves, when cells are much larger than a Debye length. However, it usually retains electron inertia, thereby limiting calculations to a maximum time step that is set by the electron Courant condition. This can seriously extend the total time needed for global modeling. Alternatively, pure hybrid electron treatments can greatly accelerate studies, in which the ion dynamics is central. This can be the situation for jets.

So, in our Phase I effort we sought *and found a new way* to incorporate the economy of a hybrid treatment, while retaining the full electromagnetic displacement current as well as any electron MHD effects[11]. This *super-implicit MHD*[20] approach keeps the real electron mass, and calculates the full electromagnetic field dynamics in voids with no need for the introduction of artificial resistivity. Very simply, we update the two fluid implicit moment equations[12] for the *E*- and *B*-fields, *but accept the resultant electron fluid current predictions as real*. We can make the usual subsequent current correction[12] for the true ion currents following the true ion motion, but make no such correction for the electrons. The electrons can thereby, in effect, cross many cells per cycle. The resultant speed up in calculations is enormous, in the ratio of the square root of the ion to electron mass. In Figs. 3 and 4 we show results from this super-implicit MHD method for the full passage of an argon plasma jet across a 20 cm test area (of extra wide bore) and over 2 μs, requiring less than 300 computational cycles, and less than 3 minutes on a 2 GHz PC. In the future RAC plans to refine this new super-implicit method, and continue to exercise it for Jet modeling.

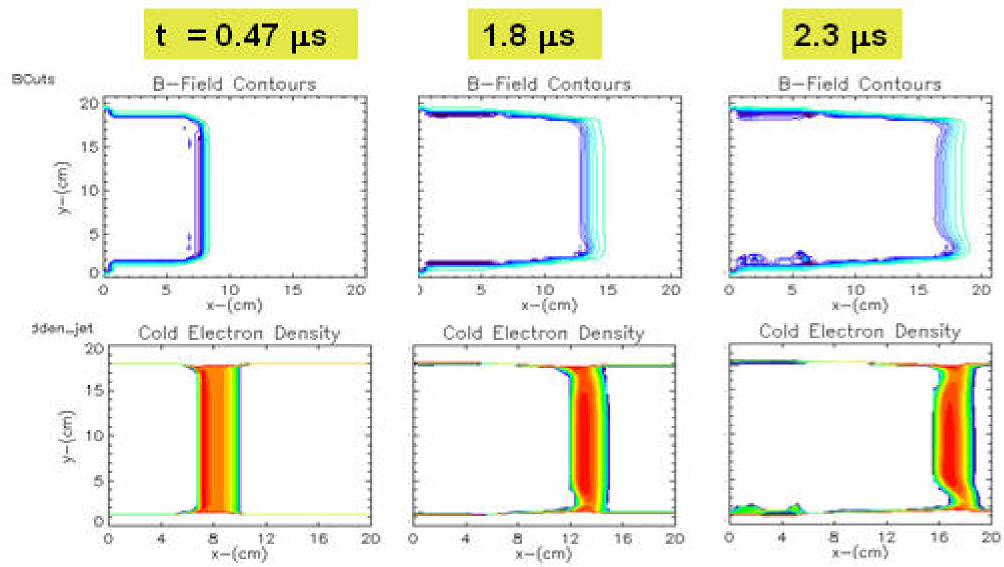

Fig. 3. Long term (μ-secs) calculation with new implicit electron currents and fluid ions. The fill plasma is singly charged argon at an initial electron density of 5 x 10^{16} e^{-}/cm^{3}.

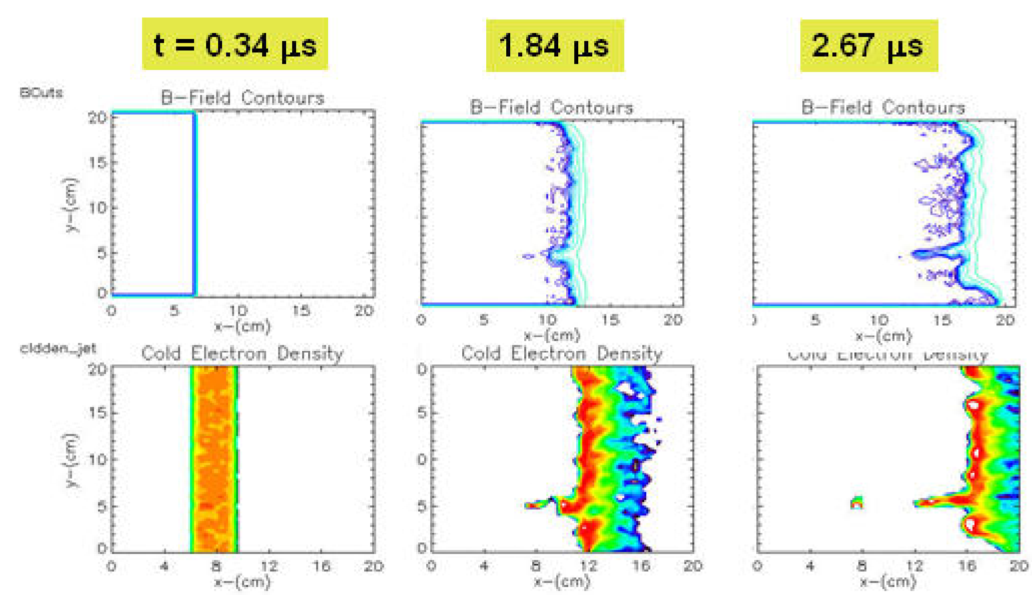

Fig. 4. Calculation for Fig. 3 conditions, but with particle ions.

3) Flow algorithms –

This Phase I Project emphasized that both fluid and particle modeling options were available in ePLAS for the treatment of the separate plasma components. We had indicated that a fluid electrons treatment would require less computer resources than corresponding electron particle modeling, and we had planned to compare the relative merits of particle and fluid electrons.

As the work proceeded, however, we realized that ion *particle* modeling with jets would be more important, since particle ion interactions could be crucial to an accurate picture of jet merger, and jet interaction with a background neutral atmosphere. Thus, we initiated argon jet studies with both fluid and particle ions, with comparative results shown in Figs. 3 and 4 (above). Figure 5 (below) shows a history of the evolution of particle ions in phase space. In the future RAC hopes to revisit the ePLAS option to use a second electron component, but the emphasis will be on further enhancements of the code's particle ion capabilities, and the addition of an improved particle ion collision capability.

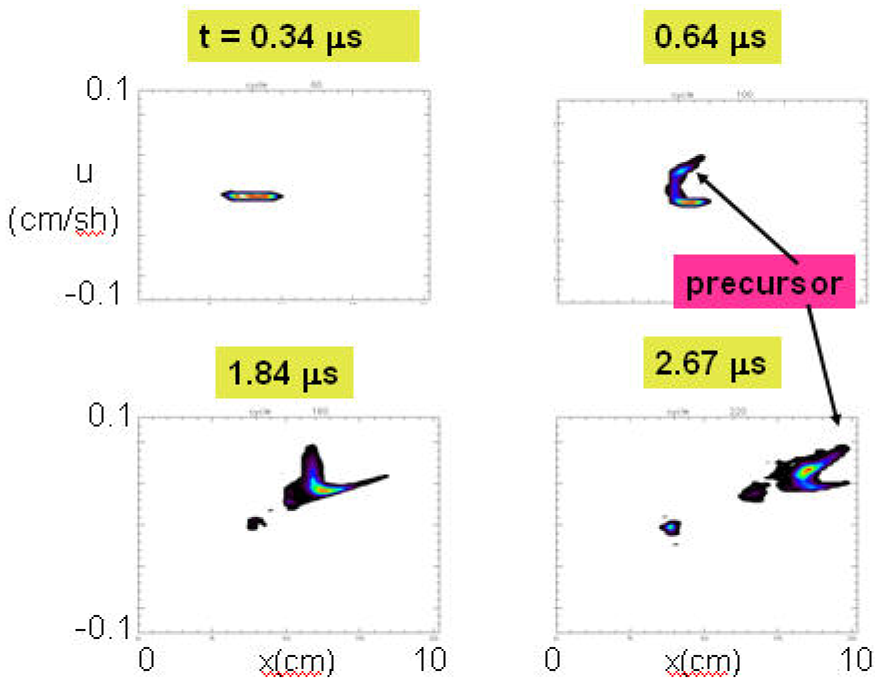

Fig. 5. Particle density in the ion (u,x) phase space, with precursor jet evident.

The merger of jets is a most important goal for HEDLP. In Fig. 6 we show preliminary ePLAS calculations of two jets launched from two parallel rail guns.

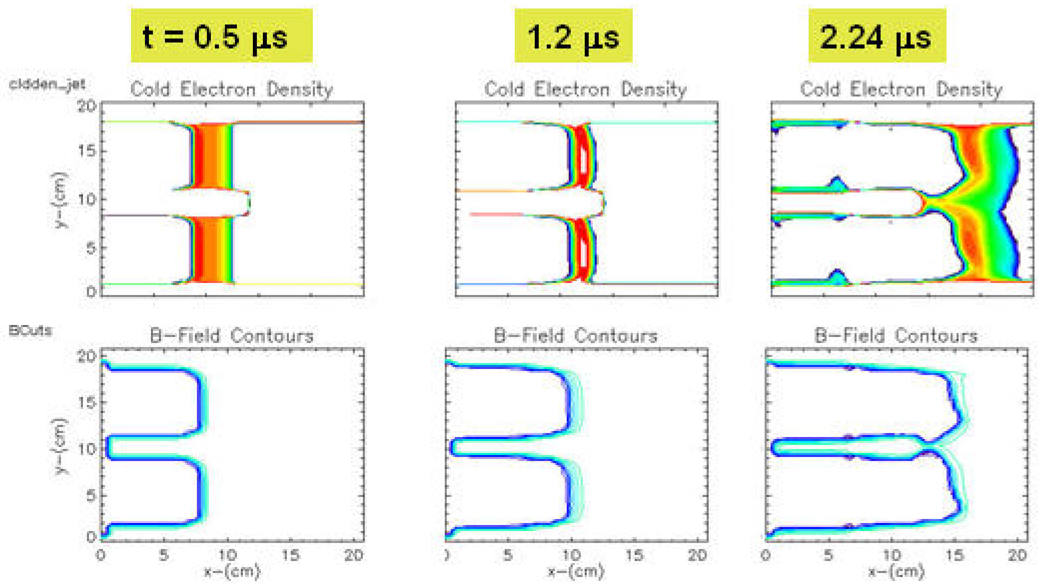

Fig. 6. Two parallel jets modeled using the ePLAS internal electrode option. The peak argon density is 10^{17} e^-/cm^3 at 1.2 μs. Note the late time tendency for jet merger.

4) Variable Z –

The atomic constitution of the jets will vary over their trajectories. During this Project RAC implemented the means to use both a Thomas Fermi analytic model, and the LANL Sesame tabular models for the equations of state (EOS) for the plasmas simulated with ePLAS. The analytic model encountered some difficulties at low jet (~2 eV) temperature; so, for these we now prefer Sesame, but other Tables, e.g. Lee-More will likely prove superior. Sample extractions from the Sesame tables are plotted in Fig. 7. We have discovered that not all the desired materials (e.g. argon) have complete tables, encouraging an optimized use of available data that will be further pursued in any future RAC effort. In Fig. 7 below we collect typical ionization data (Z) and total pressures for neon, as substitutes for argon data. Neon may, in fact, be used in the future HyperV experiments.

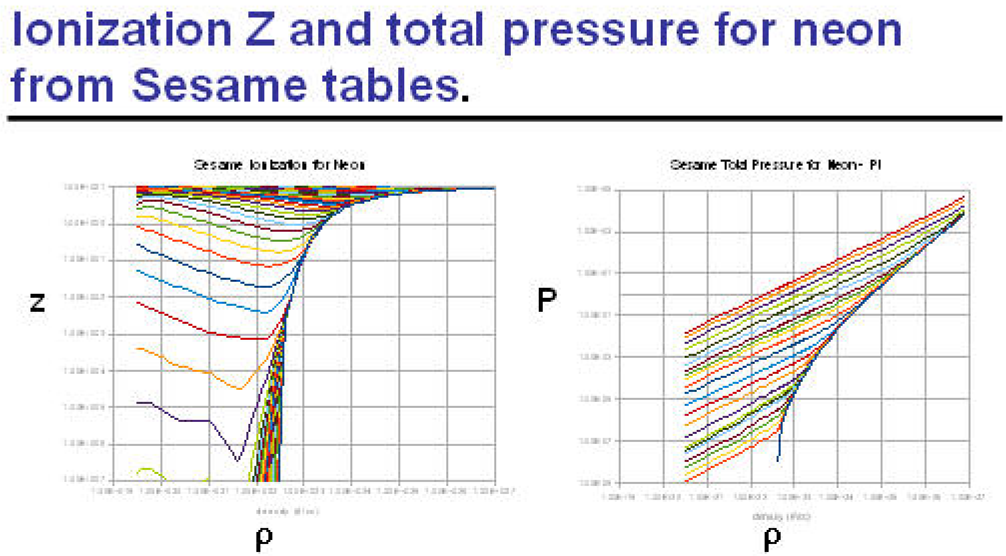

Fig. 7. Typical Sesame tabular Atomic Z and Pressure data now available in ePLAS.

5) Parallelism –

During Phase I we explored the possibilities for ePLAS parallelism. Parallelism will be particularly desirable, should accurate physics require detailed modeling of the electron motion. For local parallelism RAC has several computers (PCs and a Mac) with multiple cores, and modern GPUs (Graphical Processor Units). While the use of GPUs initially seemed attractive, potentially being both speedy and economical, we were alerted to use more expensive GPUs capable of double precision. While we first investigated CUDA (for NVidia Company GPUs) as a parallel coding medium, we were later directed to the more versatile Open-CL, as a means for local parallelism on either GPUs or multiple cores. Alternatively, for commercial users the mature MPI (Message Passing Interface) approach is, most likely, superior. In the future RAC plans interactions with a set of talented students (as support labor) and consultants to probe GPU usage, and achieve MPI parallelism for ePLAS.

6) Dissemination of the Results –

During the Project period we described ePLAS Applications of Jet Modeling[21] for HEDLP at the APS-DPP Meeting in Chicago, Nov. 8-12, 2010, and for Plasma Thrusters[22] at the Advanced Space Propulsion Workshop, in Colorado Springs, Nov. 15-17, 2010. The PI also visited HyperV in Arlington, VA on Jan. 28, 2011 to acquire guidelines on jet modeling needs, and held related discussions with Prof. Jason Cassibry (UAH) during Jason's Los Alamos briefing on 3D jet produced liners on Feb. 8, 2011. RAC presented a Poster[20] describing its new super-implicit MHD scheme, and its recent technical Project accomplishments at the ICOPS2011 Meeting in Chicago, June 26-30, 2011.

User Facility

a. Product Development

RAC continues to improve its ePLAS MANUAL, with a Version 1a, including new input variables and defaults. Jet related collaborations were initiated with LANL and HyperV. Broader code use was encouraged. The Department of Commerce has granted ePLAS an EAR99 designation, which permits unlicensed distribution to most foreign users.

ePLAS is now distributed as a single “Zip” file that breaks into: 1) Documentation, 2) an Executable, 3) IDL “.pro” files for examination of the outputted graphical data by users owning the full IDL software, and finally, 4) the full set of Source Files for the ePLAS code.

A new Manual, Version 1a, supports the user in application of the code. The Manual introduces the code, and gives some of its history. It outlines the basic code features, and discusses code distribution for the standard Windows Professional XP OS version.

The Manual describes code operation from a much truncated basic input file, and it outlines the meaning and use of the variables in the full file. The various output features are documented. For example, when a run begins, the user immediately sees output in the black “Console” window; its initial contents are described. It also produces a printed output file, consisting principally of tables characterizing the mean output variables/cell at selected time steps. Finally, it discusses the dump file used for restarts, and the IDL output file. It gives a brief description given for the function of each of the IDL “.pro” files in rendering output. Typical output figures are collected. The Manual ends with a description of the content of each of the “.f90” source files used to build the code, plus pertinent references. Direct RAC consultations can give further guidance.

b. RAC Web Site

RAC has updated (with internal funds) a company web page outlining the features of ePLAS and describing means for accessibility. See: www.researchapplicationscorp.com.

c. Collaborations

RAC made presentations at several conferences (ICOPS[20], APS-DPP[21], and the ASPW2010[22] during the course of this Project.

Dr. Mason visited HyperV in VA in late January 2011 for discussions with Drs. S. Messer and D. Witherspoon on possible ePLAS applications to its mini-rail jets.

At company expense the *PI* recently outlined ePLAS capabilities at a CISRO Seminar[23] at the University of Western Australia.

e. Licensing

Following submission and review of ePLAS to the Dept. of Commerce for Export Control evaluation, on 7/02/2009, with CCATS #: G073276 the code was granted EAR99 status, permitting export to most foreign countries with no need for an export license.

Computer Modeling Issues

This project has dealt principally with computer code development. It involved modeling only as described in the summarized activities sections above.

Future Directions

Code development and dissemination are ongoing processes. The code's variable Z capabilities should be exercised and refined, both in its analytic and tabular forms. A second ion component is needed to enable the simultaneous tracking of both ion components, much as in the code's present electron modeling. The new super implicit scheme (implicit electron currents) for large time scale problems needs testing and refinement. More extensive free graphics, and further 64-bit PC implementation is needed for application to larger problems. Parallelism demands further study and implementation. RAC is now seeing additional support for such additions.

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