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The ePLAS Code for Ignition Studies

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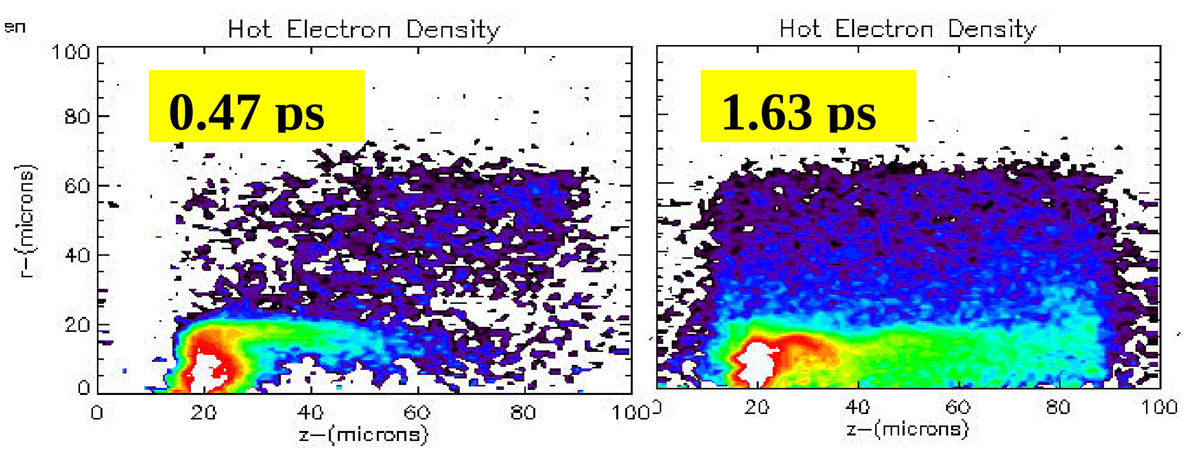

Simulated short pulse driven hot electron transport in a 20 μm radius gold wire with an H_2 exterior cylinder

Overall Summary

This Final Report describes completed work on improvements to the ePLAS Code for ignition studies under the auspices of an SBIR Phase I Grant for the period 6/17/2011 to 3/16/2012. Code enhancements developed under the Project will aid modeling efforts in support of Inertial Confinement Fusion (ICF). 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. Major technical accomplishments during this project include the addition of tabular SESAME equations of state to ePLAS, a DT burn capability, K_α imaging, improvements in electron and ion Fast Ignition modeling, Shock Ignition modeling and improvements for calculations on the ion hydrodynamic time scale.

Executive Summary

ePLAS is a highly efficient implicit/hybrid simulation code, developed by RAC [http://www.researchapplicationscorp.com], enhanced through an earlier SBIR[1] for the Plasma Jet community, and now enriched by this just-completed Phase I effort devoted to Ignition Studies. This Phase I worked to refine ePLAS for the mastery of both Fast and Shock Ignition physics, but also to prepare capabilities to resolve problems unexpectedly arising with classical ignition. This is an exciting time for ICF research. In 2009/10 various technical reviews[2,3] helped to establish pertinent community needs. These included: the use of short pulse picosecond lasers for the heating of pre-compressed thermonuclear fuel, i.e. Fast Ignition (FI), and, alternatively, the provision of a final intense laser pulse in Direct Drive for Shock Ignition (SI) of the fuel. The original overall plan was to achieve conventional ignition in hohlraums on the National Ignition Facility (NIF), and then, possibly, to employ these alternate schemes to improve efficiency. However, even conventional ignition is now presenting unexpected challenges

During the tenure of this Phase I effort for Ignition Research a 4 beam 10 TW short pulse capability, the Advanced Radiographic Capability (ARC) was available at the Lawrence Livermore National Laboratory (LLNL). Also, the smaller TITAN laser regularly provided target data for short pulse foil and cone/wire experiments. At Los Alamos the TRIDENT Laser facility was yielding valuable short-pulse fast-ion generation and interaction results. Sandia National Laboratory was employing short pulse lasers as diagnostic elements, and potential heating sources. The OMEGA-EP laser at the Rochester Laboratory for Laser Energetics (LLE) regularly shot 2-10 kJ pulses of up to 10 ps duration for target interaction experiments. In Japan at the Osaka Institute for Laser Engineering (ILE) cone targets for short-pulse heating was showing early progress and neutron output enhancement. A more energetic FIREX-II laser was also promised. Work at Osaka had involved nested cones for short pulse energy delivery to a target. The High Power Energy Laser Research Facility (HIPER) in Europe could supplement the Rutherford Appleton Laboratory's short pulse laser. Short pulse experiments were planned in China. France continued to complete its long pulse Laser Mega Joule facility (LMJ), where short pulse capabilities may be added. Experiments at all these facilities required effective predictive and backup modeling of both observed and expected short-pulse laser-matter interactions. These laser facilities created an intense demand among National Laboratory, Commercial and University researchers for simulation codes providing guidance for the control of HEDLP experiments involving Fast Ignition.

Shock Ignition has been explored theoretically at Rochester and the Naval Research Laboratories (NRL). Experimental elements of SI can be explored on OMEGA at LLE, in Osaka and with the LMJ in Bordeaux. But SI cannot be fully pursued on the NIF until that laser is reconfigured to do Polar Direct Drive, an event that may not occur for four more years, and until Livermore has achieved ignition with indirectly driven hohlraum capsules.

The modeling of short-pulse interactions represents a serious challenge for the Fast Ignition community. To be useful, a simulation code must track laser light propagation to a target, and model light absorption generating relativistic “hot’ electrons out of “cold” collisional background electrons. It must follow the resultant net electron and ion motion through self-consistent, evolving *E*-fields and *B*-fields. It should determine the temperature of background ions and their ultimate approach to thermo-nuclear burn conditions. Additionally, sophisticated simulation codes are needed to aid and hasten the invention and design of Fast Ignition ICF targets. Recent experiments, pursued primarily for near-term insight, used cones to deliver short-pulse light axially to surfaces neighboring compressed fusion fuel. However, foils generating fast ions for FI are also under study, and new creative target designs are in demand. Evaluating the current and new ideas requires a comprehensive simulation model that can scope out the possibilities with efficiency and ease of use. ePLAS provides such capabilities. The driving, final laser pulse for SI presents related challenges in hot electron generation, transport and deposition. These challenges can also be well managed by ePLAS. These were the major issues during our Phase I work.

In the summer and fall of 2011 the certified NIF laser began complete target experiments with its full 192 beams delivering as much as 1.6 MJ to hohlraum containing cryogenic targets and 50-50 DT fuel. These targets did not ignite as expected[4]. Only $\sim 6 \times 10^{14}$ neutrons were observed, while $\sim 10^{17}$ were expected from a properly tuned shot. Since then the Livermore effort has been strongly committed to achieving that required “tuning.” ePLAS can help with this tuning.

ePLAS (formerly ANTHEM[5-9]) was the first code to model hot electron transport and related B-fields in support of Tabak et al.’s charter paper[10] on Fast Ignition. ePLAS establishes a target, and tracks laser beams to its surface. It calculates self-consistent electric and magnetic fields that arise for the counter-flow of heated electrons from the laser spot and related return currents. It includes the effects of ponderomotive forces. The code accounts for collisions between the various electron and ion components in the target. ePLAS is an Eulerian model, describing the plasma and field dynamics relative to a fixed background mesh. Its implicit electromagnetic field solver uses the Implicit Moment Method[6-8] to determine advanced *E*- and *B*-fields allowing for greatly reduced demand for cycles and meshing, and thus for extremely efficient calculations on PCs. ePLAS is a hybrid code, i.e. it tracks the various plasma components as either fluids or particles. The code has been used for greater understanding of foil[11,12], wire[13], cone[14,15] and nail targets[16]. With previous support it was enhanced to model particle ion blow off from foils[17], and ion time scale plasma jet[18] dynamics.

ePLAS has been granted EAR99 status by the Dept. of Commerce, permitting distribution to most users without a license. It has been restructured with allocatable memory, so as to permit varied mesh size and particle numbers in most applications with no need for the source code. The code's graphical output can be readily rendered by commercial graphics software, most typically IDL from EXELIS or MATLAB developed my Mathworks. ePLAS runs on PCs, Linux machines, and Macs.

The wide availability of an efficient, facile simulation code for Ignition problems will hasten the day when fusion power becomes available for the nation and the world. New target concepts found by the community through significant simulations with this code will change the energy picture dramatically. Concepts and code improvements achieved in the ePLAS development process are already serving the community. During this Projcet US Research Universities[13] and the National Energy Laboratories[19] benefitted in the through access to the robust laser-matter modeling capability embodied in ePLAS.

Goals, Accomplishments and Pertinent Activities

For this Phase I Project we proposed to explore *six technical areas for accomplishment* in Ignition modeling, and to provide ePLAS code improvements needed to master them. These technical areas were: 1. Equations of State, DT/DD burn and K-alpha modeling, 2. Hot electron modeling for Fast Ignition, 3. Ion modeling for Fast Ignition, 4. Improvements for Shock Ignition studies 5. Adaptations for near term NIF ignition improvements and finally, 6. Code utility upgrades: a GUI, parallel computing, and the Cloud.

Below we provide a summary of our Phase I results in tackling these challenges, and a record of our successful efforts in the dissemination of our results.

1) Equations of State, K-alpha, DT/DD burn, and K-alpha modeling –

For Phase I we provided a basic DD, DT burn package with IDL plotting diagnostics giving burn rates and neutron output as functions of time and of space in a target. We also provided simplified Fermi-Thomas equations of state (EOS), and access to the tabular SESAME tables. Typical Sesame results for the varying atomic number Z of lithium are, for example:

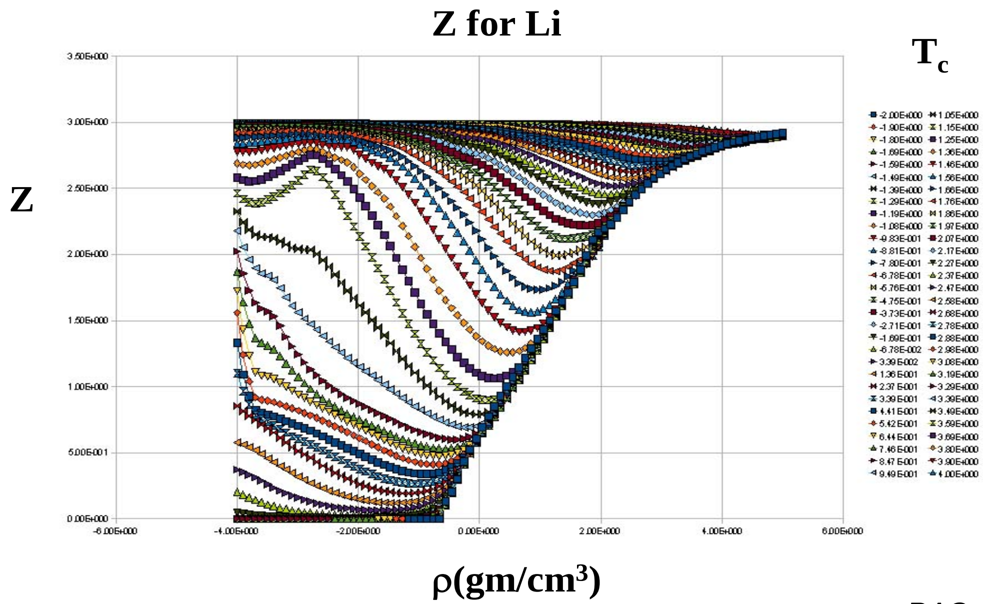

Fig. 1. Atomic number $Z(\rho,T_c)$ for lithium according to Sesame.

This same tabular data can be rendered with IDL to show an interesting Z trough.

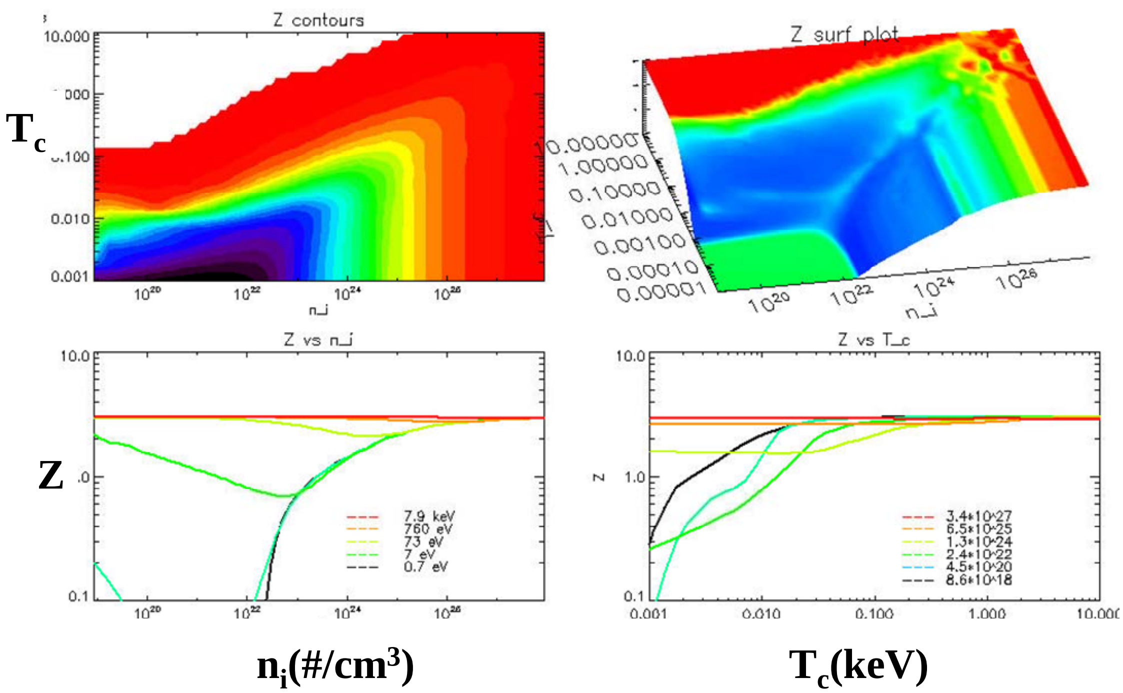

Fig. 2. The lithium EOS, showing a Z trough below 100 eV and 10^{24} ions/cm^3.

In comparison calculations[20] for laser driven fast lithium ions with fixed vs. variable ePLAS has shown similar ion expansions, but with delayed edge expansions over a 6.5 ps period.

To help model ongoing experiments, we enhanced our K-alpha plotting package. The ePLAS K-alpha package for ePLAS renders images that can be directly compared to experiment, as in Fig. 3. A schematic of a typical view point used is:

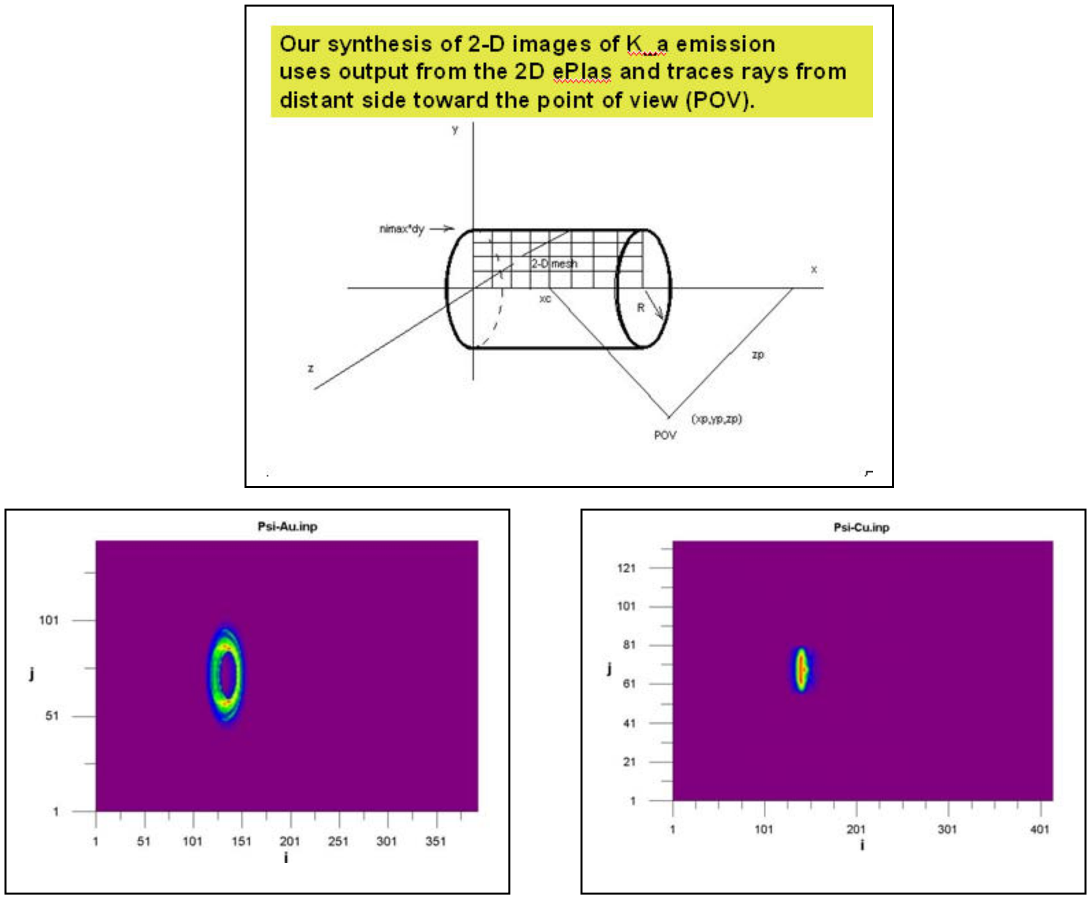

Fig. 3. Typical K-alpha images for the gold cone and copper wire.

RAC will continue to test and refine the new ePLAS K-alpha imaging capability for availability to users with ongoing experiments

2) Hot electron modeling for Fast Ignition -

To help certify ePLAS as an aid to Fast Ignition, we applied the code to transport problems for hot electrons in foil and wire-like targets with lateral material interfaces providing varied Z (and resistivity) values[21]. For a 3 x 10^{19} W/cm^2 20 μm radius red light Gaussian laser beam striking a solid hydrogen wire surrounded by a conical vacuum region with a gold straw beyond it, we have found that over the interval of 1.17 ps the hot electrons which were launched at the critical density (as shown in Fig. 4), became confined largely to the wire, which, in turn, became surrounded by a thermo-electric *B*-field.

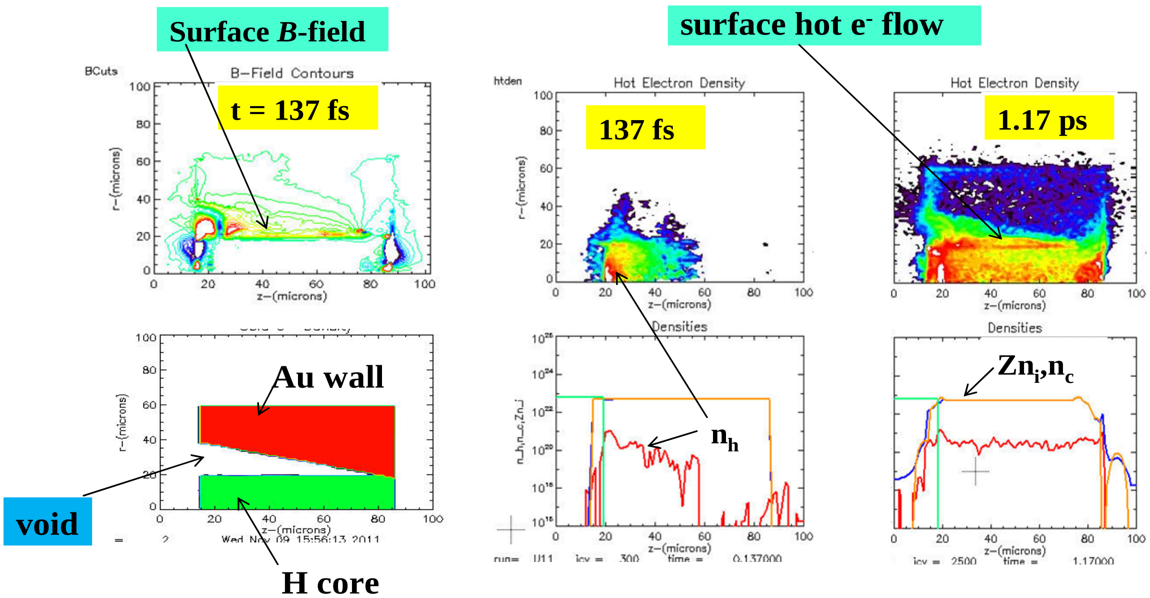

Fig. 4. Short pulse generated hot electrons in a hydrogen wire.

This calculation with voids was possible with ePLAS, while generally impossible for conventional hybrid codes, because of its special retention of both electromagnetic displacement and electron inertial terms. When, alternatively, we modeled a gold wire simply surrounded by a hydrogen straw[21] (of lower resistivity) the hot electrons were again confined to the wire if *B*-fields were retained in our calculations – see Fig. 5.

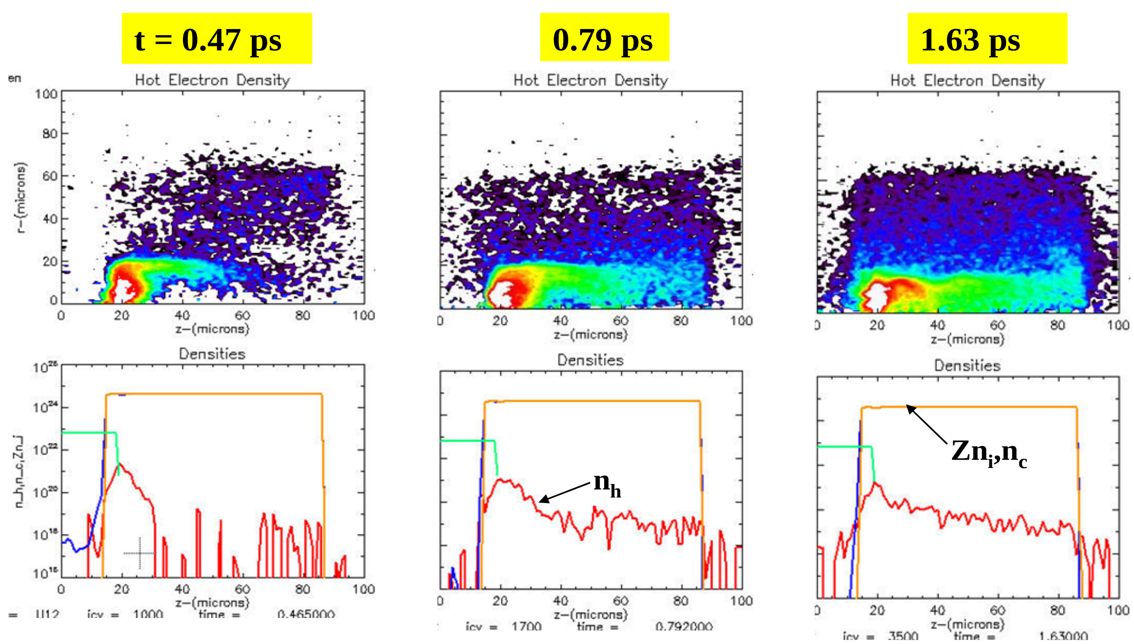

Fig. 5. Hot electrons confined by resistive B-fields at the Au/H_2 material interface

However, subsequent ePLAS calculations showed that these hot electrons were rapidly released into the surrounding straw when the *B*-fields at the gold/hydrogen interface were suppressed (but with *E*-fields retained). These results were consistent with earlier Rutherford Appleton Laboratory (RAL) findings[22], and RAC discussed this at the recent ICOPS12 meeting in Edinburgh[21].

3) Ion modeling for Fast Ignition -

For possible future application to fast ion driven ignition, under this Phase I Grant we revisited and compared the particle ion vs. fluid ion capabilities of ePLAS. For a simple laser driven foil problem both modes were shown to give similar ion expansions[20]. While the particle mode has the advantage of capturing non-equilibrium effects, it can significantly noisier, unless sufficient ion particles are employed.

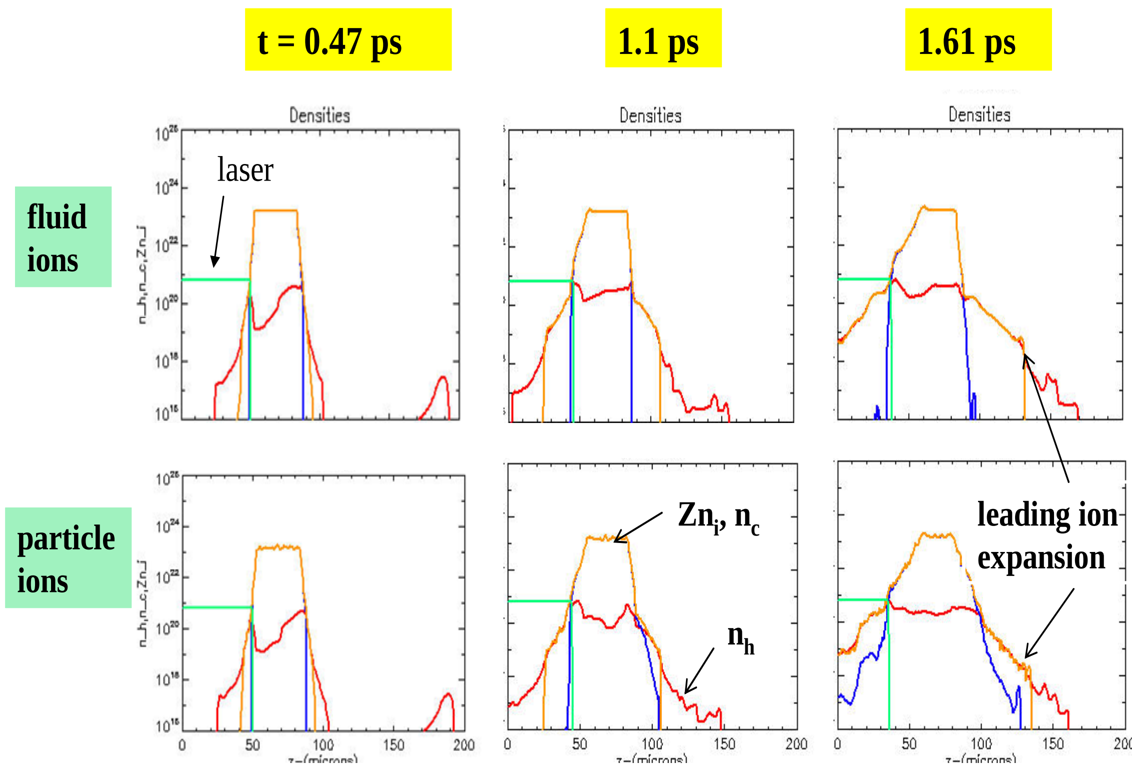

Fig. 6. Comparison of laser driven fast fluid and particle ions.

For the Fig. 6 calculations sufficient ion particles (10^3/cell) were, in fact, used, so that the particle and fluid ion density profiles (orange) were smooth down to 10^{18} ions/cm^3. A detailed examination shows the particle ions running out somewhat faster than the fluid ions, possibly because of lost collisionality in the leading edge of the particle expansion, as captured in the phase space plots of in Fig. 7.

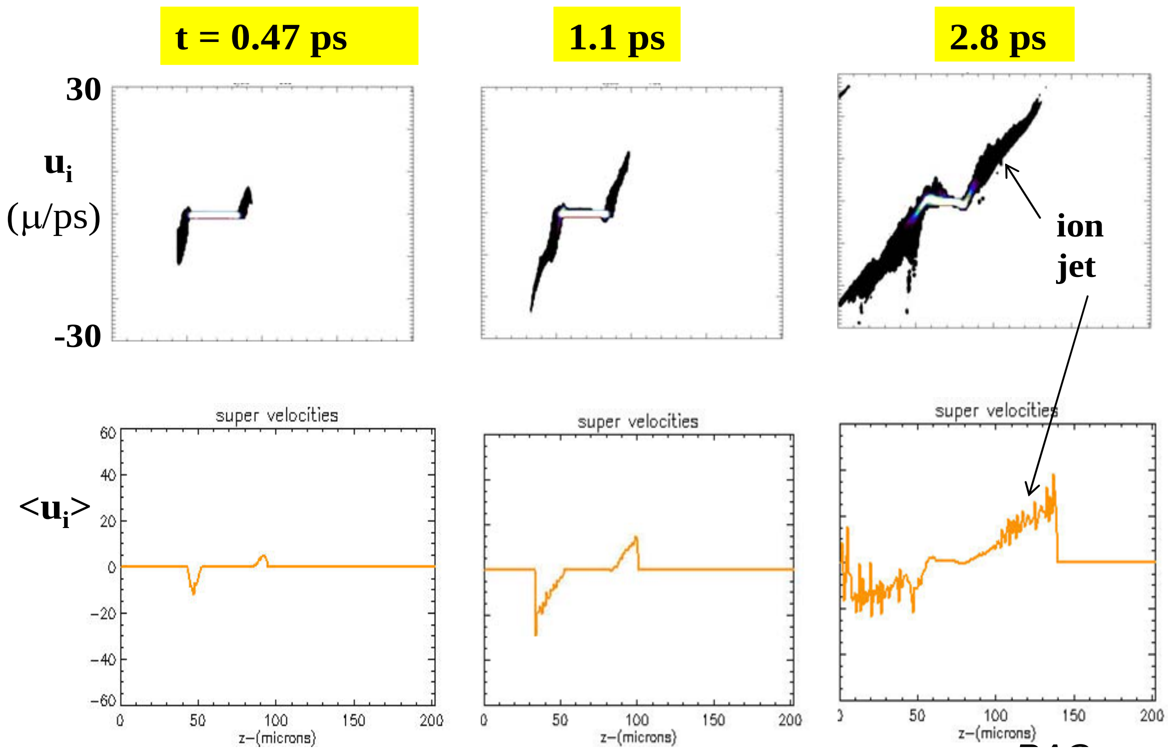

Fig. 7. Ion phase-space motion for the foil expansion problem.

In future work ePLAS will be further improved to facilitate particle ion studies of the evolution of ion mixtures, as in the imploding DT fuel in NIF capsules.

4) Improvements for Shock Ignition studies -

Shock Ignition has become a serious alternative for the initiation of thermonuclear burn following the long pulse target compression for direct drive fusion. With SI, a moderately intense (~8 x 10^{15} W/cm^2) late-time final pulse is subsequently used to launch a final shock in the compressed fusion fuel of an ICF target. It is possible that this concept offers greater timing control for final heating at lower total energy demand. However, the dynamics and absorption of mildly hot (~35 keV) electrons generated by the final pulse is a concern. Will these hot electrons transport properly to the compressed fuel? Will they electrons properly absorb? During this Project ePLAS was adapted to begin to examine such phenomenology.

The ePLAS density and temperature predictions[23] over 528 ps for shock generation under SI are shown next in Fig. 8. A ~8 x 10^{15} W/cm^2 1.06 μm laser (green curve) deposits near the 10^{21}/cm^3 critical density point, generating ~35 keV hot electrons (red curve), which couple to the background cold electrons (blue) and ions (brown/yellow). At late times the ion and cold electron temperatures tend to merge. The top frames show that the cold electron and ion densities are nearly equal, with a shock-like density jump near x = 170 μm.

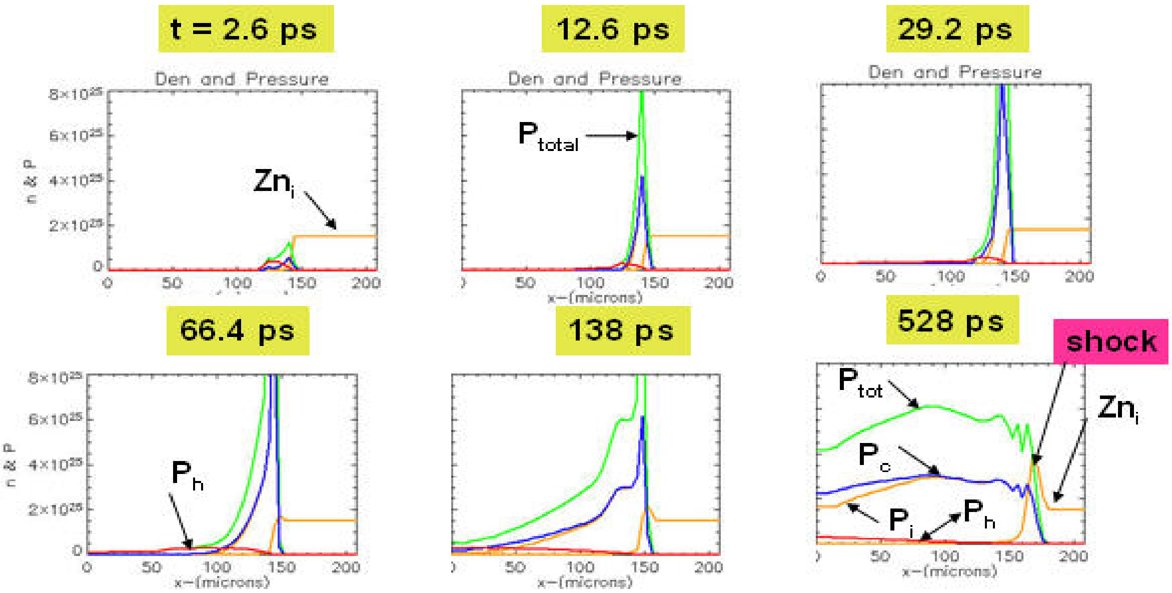

Fig. 8. ePLAS calculated shock driven by a final 8 x 10^{15} W/cm red laser pulse.

During this Project we initiated new studies of 2D driven shock ignition[24] with ePLAS. A 100 μm wide flat pulse was applied to planar super-compressed DT for 58.8 ps (see Fig. 9).

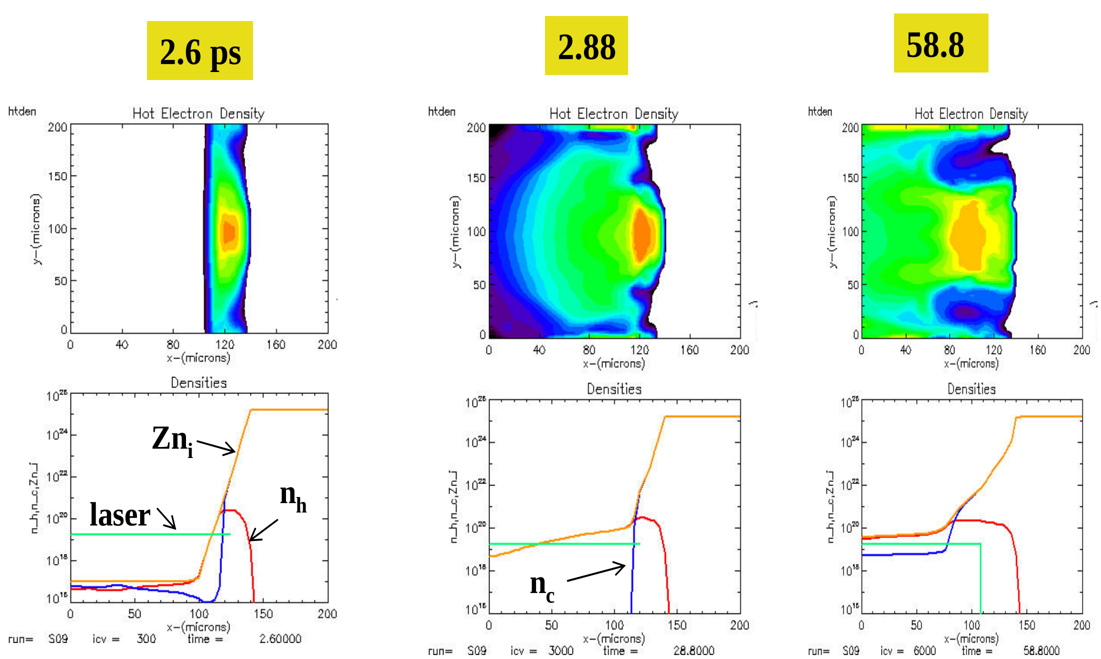

Fig. 9. Target density evolving with a finite, final beam of hot electrons.

The early time density evolution was little different from that seen with a broad pulse, but by 59 ps thermoelectric MG B-fields were seen around the hot electron beam that drives the shock (Fig. 10).

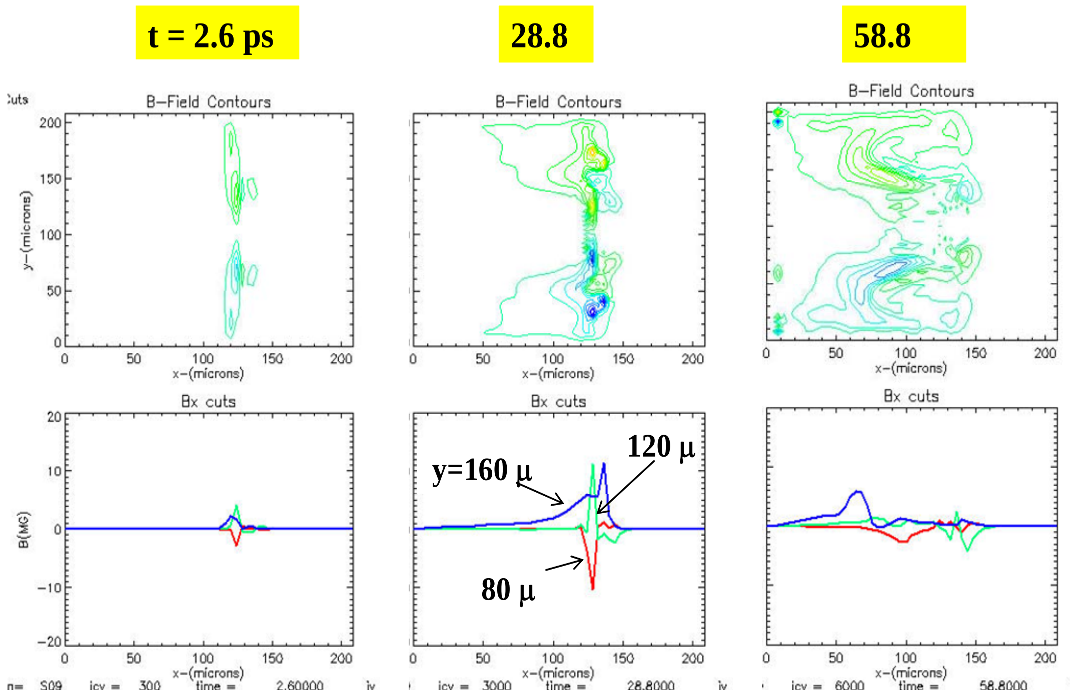

Fig. 10. Thermoelectric B-fields accompanying the hot electrons to drive Shock Ignition.

5) Super-MHD extension for long time scale code operation -

Under the earlier Phase I for Plasma Jets[1] (DE-SC0004207) RAC had learned that ePLAS could be altered to calculate in a new, super-MHD manner on the ion time scale[18]. The resultant system was akin to xMHD[25] developed at Cornell University and the Sandia National Laboratory. To accomplish this, predicted electron currents in the ePLAS field solver were accepted as real, and the electron densities were acquired at the end of ion time step from the divergence of the E-field, as in a conventional hybrid code, except that displacement current and electron inertia were retained in determining predicted the currents.

This super-MHD mode of operation allowed ePLAS to track the evolution of a 5 x 10^{16} electrons/cm^3 argon plasma jet[18] over 2.7 μs, as shown in Fig. 11, while requiring only ~20 minutes of 2.9 GHz CPU time. To use this approach, only a single, cold electron component was employed. The effective Ohm's Law retained thermo-electric and Nernst effects. This should be useful in tracking the slow MHD evolution of B-fields in laser-driven target implosions.

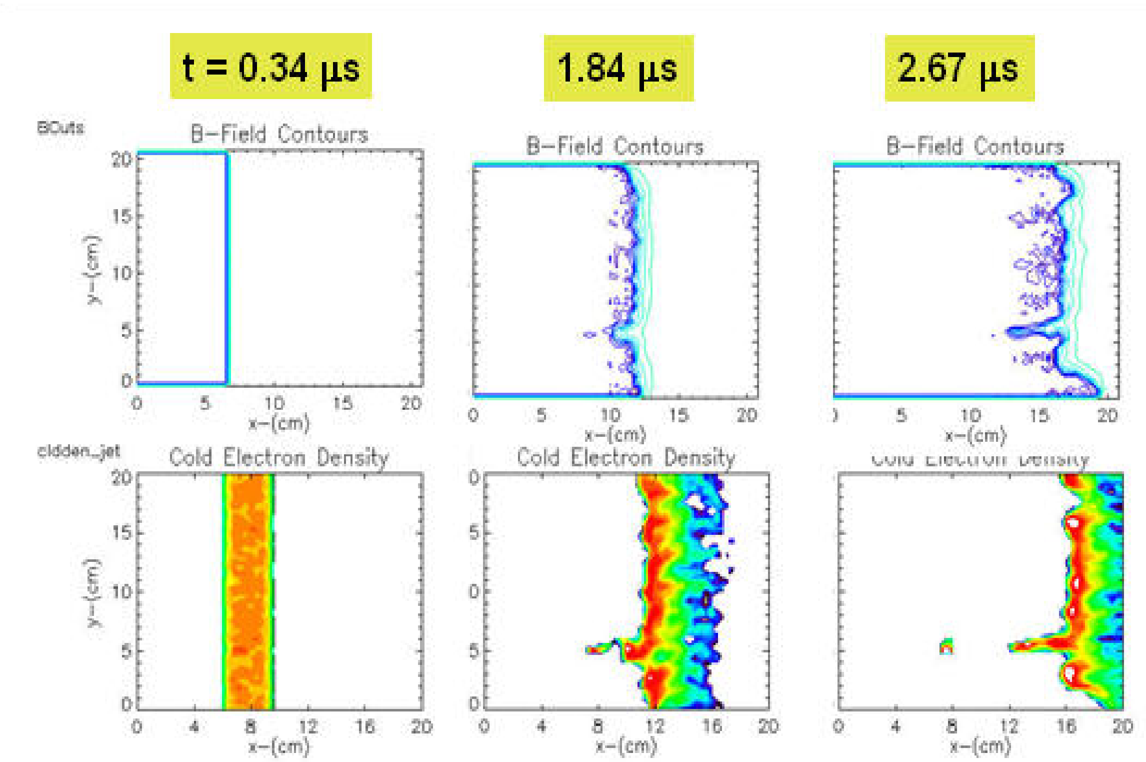

Fig. 11. Plasma jet modeling over 2.7 µsec in the new super-MHD ePLAS mode.

In the future we plan to study and adapt, if possible, this super-MHD capability for ongoing NIF target ignition studies.

6) User utility upgrades -

During this Project elements were added to the ePLAS NAMELIST input files to allow for the code's new EOS and K-alpha options, as well new target configurations, such as the voided wire/straw structures discussed above for Fast Ignition transport studies. New IDL graphical options were added to render TN burn plots over space and time. ePLAS was adapted to run on 64-bit W7 systems. Our Mac portable was converted to the new Lion OSX. Our graphical output is now regularly probed and plotted with IDL Version 8.

Initiating a parallelization effort, RAC has acquired INTEL Parallel Studio XE software and the accompanying Microsoft Virtual Studio 2010. RAC plans to install an NVIDIA Tesla C2075 computer card in our fastest Windows system, so as to enable Graphical Processor Unit (GPU) CUDA or Open-MP shared memory computing. The card's potential is 515 Gflops at 64-bit precision. [CUDA is NVIDIA Corporation's language for GPU computing.]

User Facility and Awareness

a. Product Development

RAC continued to improve the ePLAS manual during this period and added facilities for new access to the SESAME equations of state tables, use of the new DT burn capability, Fast and Shock Ignition setups, input for K-alpha imaging and for implicit field calculations on the longer ion time scale.

b. RAC Web Site

RAC updated (with internal funds) its Company Web page outlining the features of ePLAS and describing means for accessibility. See: http://www.researchapplicationscorp.com.

c. Presentations

RAC made presentations at several conferences (AAC11[26], ICOPS_11[27] and ICOPS_12[24], as well as the APS-DPP_11[28] during (and after) the course of this Project.

d. 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

The RAC team will continue to monitor activities in ICF research, and particularly on the NIF with an eye to updating ePLAS for arising new modeling demands.

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