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Enhanced Model for Fast Ignition

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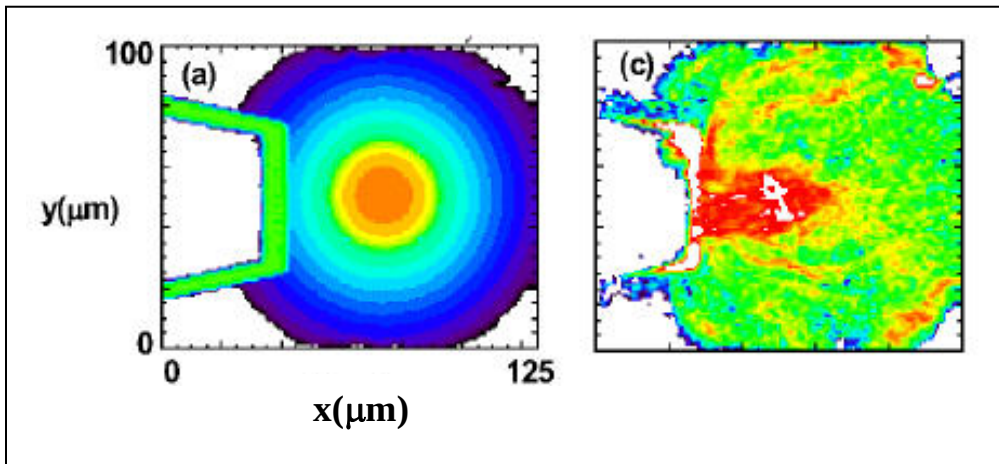
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Cone target for Fast Ignition with calculated core heating

Overall Summary

Target interactions in Fast Ignition, a significant Department of Energy initiative, have proven too difficult to model with standard plasma simulation codes due to the high densities of the compressed cores, and the complexities of the collisional, relativistic electron transport initiated by laser absorption. New Implicit/hybrid codes can properly treat this phenomenology, but their optimal form is still undergoing intense research, their application has been limited, and their development and distribution have seriously lagged the more standard but less capable techniques.

The overall objective of this project has been to further develop, refine, and extend a successful implicit/hybrid code, ePLAS, distributing it throughout the Department of Energy community, academia, and industry, so as to hasten success in achieving fusion energy via Fast Ignition.

During Phase I of this project advances were made in light absorption modeling, and fast ion generation. Early versions of the new computer simulation model were distributed to users throughout the fusion energy community for testing and near term applications.

The thrust of Phase II has been to implement and study more generalized light absorption, to provide a variable atomic number capability and associated specific heats, to implement joint fluid/particle ions, to begin to explore shock ignition, and to move toward alternate operating system and generalized graphics options, while vigorously testing ePLAS on current problems, broadening its user interface, and encouraging wider use of the code.

ePLAS continues to provide an efficient speedy means for the examination of planned and ongoing experiments in Fast Ignition. With a laptop PC a user can, typically, in 20 minutes to an hour scope the behavior of plasma components in a laser target exposed to intense short pulses.

Over the duration of this Project there has been much progress with the code. Presentations demonstrating ePLAS capabilities, and manifesting collaborations were made, or are planned for nearly all the pertinent Professional Meetings - IEEE-ICOPS, IFSA, AAC and APS-DPP - during the past 3 years. The PI has been honored for his Fast Ignition contributions by the ILE Osaka in Japan. University collaborations have continued and expanded with UCSD, OSU and LLE. There has been significant progress with export control, facilitating dissemination of ePLAS, and in the development of a company website: <http://www.reserachapplicationscorp.com>, describing RAC and ePLAS.

Much room for improvement remains. RAC continues to seek new means for new additions to ePLAS and its further dissemination for the efficient computational support of DOE Ignition initiatives.

Executive Summary

Laser Fusion is a prime candidate for alternate energy production, capable of serving a major portion of the nation's energy needs, once fusion fuel can be readily ignited. Fast Ignition may well speed achievement of this goal, by reducing net demands on laser pulse energy and timing precision. However, Fast Ignition has presented a major challenge to modeling. This project has enhanced the computer code ePLAS for the simulation of the many specialized phenomena, which arise with Fast Ignition. The improved code has helped researchers to understand better the consequences of laser absorption, energy transport, and laser target hydrodynamics. ePLAS uses efficient implicit methods to acquire solutions for the electromagnetic fields that govern the accelerations of electrons and ions in targets. In many cases, the code implements fluid modeling for these components. These combined features, "implicitness and fluid modeling," can greatly facilitate calculations, permitting the rapid scoping and evaluation of experiments. ePLAS can be used on PCs, Macs and Linux machines, providing researchers and students with rapid results. This project has improved the treatment of electromagnetics, hydrodynamics, and atomic physics in the code. It has simplified output graphics, and provided new input that avoids the need for source code access by users. The improved code can now aid university, business and national laboratory users in pursuit of an early path to success with Fast Ignition.

Goals, Accomplishments and Summarized Activities

Research Applications continued to benefit from the engaged efforts of seven professional researchers during the development of its implicit/hybrid plasma code ePLAS for Fast Ignition. Goals set for the proposed work were:

1) Implement and study direct light absorption:

Dr. Dan Barnes explored and extended for ePLAS a new implicit scheme due to G. Petrov and J. Davis¹ at NRL, which avoids the need for costly elliptic solvers in acquiring the updated B-fields. This allows for the inclusion of all the E - and B -field components. While earlier versions of the code were limited to just E_x , E_y and B_z and Cartesian geometry, the new scheme also works in cylindrical geometry. During the project an additional time step controller was engaged to assure that time steps in problems respected a Courant condition based on the light speed, particularly when the light intensity was low, as in now on-going experiments for the LLE Rochester short pulse laser. *Dr. Barnes* also examined a simplified implicit B operator to facilitate long time scale problems in which the time step greatly exceeds the Courant condition.

2) Install a variable Z (Atomic number) capability, and analytic specific heats for real materials and Equations of State (EOS):

Dr. Walt Atchison has provided new coding for ePLAS to access the public LANL SESAME EOS tables. This was accomplished using allocatable arrays in Fortran 95 to minimize memory demands. *Dr. Ron Kirkpatrick* provided analytic Thomas-Fermi

models for a set of materials, and, in particular, copper used in ongoing TITAN laser experiments by experimentalists at UCSD and General Atomics. The PI initiated extensive ePLAS changes to accommodate local cell values for Atomic Number and Atomic Mass.

3) Provide a K-alpha image reproduction capability:

Dr. Ron Kirkpatrick produced a K-alpha radiation transport package, coupled to newly extended ePLAS IDL presentation files, and initiated comparisons with data from targets exposed on the LLNL TITAN laser system.

4) Code tests on current experimental problems (Cone-Wire Targets):

Dr. Rickey Faehl beta-tested ePLAS. His recent focus was with laser-illuminated cone-headed wires in Cartesian and cylindrical geometry in support of pending UCSD experiments in Rochester. This process led to the repair of bugs at both the cylindrical centerline and at the upper problem boundary. Dr. Faehl calculated the dynamics of hot electrons driven by the lower, $\sim 5 \times 10^{18} \text{ W/cm}^2$ intensities of the LLE pulse in 1 mm long copper wires over time scales exceeding 10 ps.

The PI, *Dr. Rod Mason*, was also actively engaged in ePLAS modeling to aid ongoing studies of cone-wire experiments conducted by UCSD and General Atomic on the TITAN laser at Lawrence Livermore Laboratory²⁻⁴. Also, his recommendations from ePLAS concerning multi-cone simulations contributed to significant recent research at ILE OSAKA^{5,6}.

5) Implement joint fluid/particle ions:

The PI studied ion emission problems in short pulse laser illuminated foils. He explored both fluid and particle ion representations for this emission. Deficiencies were detected at lower densities with the particle modeling. He also planned future changes of the ePLAS coding that will ultimately permit the joint presence of both fluid and particle ions. This approach will copy portions of the formulation used for the joint modeling of fluid and particle electrons in earlier versions of the code. For the generally slow ions simplification can come from combining current contributions from local fluid and particle ion components to produce single net ion current components in the auxiliary fluid equations used for the implicit field solutions.

6) Code extensions for Shock Ignition Studies:

Shock Ignition involves the launch of strong shocks from modestly intense lasers. The PI began a tuning of ePLAS to examine the ability of hot electrons generated at such intensity to drive the needed shocks. He determined that modifications in the code's present hot electron drag routines were desirable.

7) Additions for Lightning Modeling:

Early time laser deposition can launch ionization waves in laser targets. As a test bed for such ionization studies, simple air chemistry was added to ePLAS to perform sample ionization studies, as generated by high voltage lightning strikes.

8) Explore alternate Operating Systems and alternate graphics rendering:

Dr. Dale Henderson produced a modified ePLAS version that runs under Linux. He corrected numerous FORTRAN deficiencies stemming from legacy coding. ePLAS now runs on LINUX PCs with executables created under GFORTRAN and the Commercial LINUX INTEL compilers. Particular attention has been paid to code changes permitting liberal user NAMELIST interpretations.

The *PI* implemented ePLAS under the Mac Snow Leopard OS system, rendering the graphics with the Mac version of IDL.

Dr. John Ambrosiano studied new graphics schemes based on GNUplot (including 3D data sets) and NCSA EasyViz. He initiated the development that will permit IDL Virtual Machine renderings of all ePLAS graphical output data. This should spare academic users the expense of the full IDL software.

Accomplishments and Summarized Activities

RAC's main accomplishments were outlined in the summary above. They have been outlined at recent professional meetings^{7,8,9}. Here we provide additional detail.

1) Implicit *E* & *B*-fields

The observation that an implicit *B*-field is not needed for many short pulse interaction studies promises a rewarding simplification of the coding needed for modeling of the full set of electromagnetic fields in current problems. For possible further simplification the *PI* initiated a study of the actual degree of implicitness required, i.e. the extent to which the Courant condition on light can be violated, using a laterally thin version of ePLAS. This study is still underway. In any case, with all the field components included, the auxiliary fluid equations in ePLAS can provide for the full set of required fields in the system as below:

ePLAS solves the Implicit Moment System

Maxwell's equations

$$\frac{\partial \mathbf{E}}{\partial t} = -4\pi \sum q_\alpha \mathbf{j}_\alpha + c \nabla \times \mathbf{B}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -c \nabla \times \mathbf{E}$$

Auxiliary fluid moment equations

$$\frac{\partial \mathbf{j}_h}{\partial t} = -\frac{\nabla \cdot \vec{\mathbf{P}}_h}{m_h} + \frac{n_h q_h}{m_h} \mathbf{E} + \mathbf{j}_h \times \frac{q_h \mathbf{B}}{m_h c} - \nu_h \left(\mathbf{j}_h - \frac{n_h}{n_i} \mathbf{j}_i \right)$$

$$\frac{\partial \mathbf{j}_c}{\partial t} = -\frac{\nabla \cdot \vec{\mathbf{P}}_c}{m_c} + \frac{n_c q_c}{m_c} \mathbf{E} + \mathbf{j}_c \times \frac{q_c \mathbf{B}}{m_c c} - \nu_c \left(\mathbf{j}_c - \frac{n_c}{n_i} \mathbf{j}_i \right)$$

$$\frac{\partial \mathbf{j}_i}{\partial t} = -\frac{\nabla \cdot \vec{\mathbf{P}}_i}{m_i} + \frac{n_i q_i}{m_i} \mathbf{E} + \mathbf{j}_i \times \frac{q_i \mathbf{B}}{m_i c}$$

$$+ \frac{m_e}{m_i} \left[\nu_h \left(\mathbf{j}_h - \frac{n_h}{n_i} \mathbf{j}_i \right) + \nu_c \left(\mathbf{j}_c - \frac{n_c}{n_i} \mathbf{j}_i \right) \right]$$

Plasma Physics

RAC

Thus producing the difference equations:

Which difference as:

$$\frac{\mathbf{E}^{m+1} - \mathbf{E}^m}{\Delta t} = -4\pi \sum q_\alpha (\bar{C}_\alpha \mathbf{j}_\alpha^m + C_\alpha \mathbf{j}_\alpha^{m+1}) + c \nabla \times (\bar{C}_{EB} \mathbf{B}^m + C_{EB} \mathbf{B}^{m+1})$$

← For new fields

$$\frac{\mathbf{B}^{m+1} - \mathbf{B}^m}{\Delta t} = -c \nabla \times (\bar{C}_{BE} \mathbf{E}^m + C_{BE} \mathbf{E}^{m+1})$$

For new currents →

Here:

B explicit in $\mathbf{j} \times \mathbf{B}$

$\bar{C}_x = 1 - C_x$ centers

$$\vec{\mathbf{P}}_\alpha \equiv P_{\alpha\beta\gamma} \equiv m_\alpha n_\alpha v_\beta v_\gamma + (P_\alpha + P_{\alpha\alpha\beta}) \delta_{\beta\gamma}$$

Plasma Physics

RAC

$$\frac{\mathbf{j}_h^{m+1} - \mathbf{j}_h^m}{\Delta t} = -\frac{\nabla \cdot \vec{\mathbf{P}}_h^m}{m_h} + \frac{n_h q_h}{m_h} (\bar{C}_E \mathbf{E}^m + C_E \mathbf{E}^{m+1})$$

$$+ (\bar{C}_{jx} \mathbf{j}_h^m + C_{jx} \mathbf{j}_h^{m+1}) \times \frac{q_h \mathbf{B}^m}{m_h c} - \nu_h \left(\mathbf{j}_h^{m+1} - \frac{n_h}{n_i} \mathbf{j}_i^m \right)$$

$$\frac{\mathbf{j}_c^{m+1} - \mathbf{j}_c^m}{\Delta t} = -\frac{\nabla \cdot \vec{\mathbf{P}}_c^m}{m_c} + \frac{n_c q_c}{m_c} (\bar{C}_E \mathbf{E}^m + C_E \mathbf{E}^{m+1})$$

$$+ (\bar{C}_{jx} \mathbf{j}_c^m + C_{jx} \mathbf{j}_c^{m+1}) \times \frac{q_c \mathbf{B}^m}{m_c c} - \nu_c \left(\mathbf{j}_c^{m+1} - \frac{n_c}{n_i} \mathbf{j}_i^m \right)$$

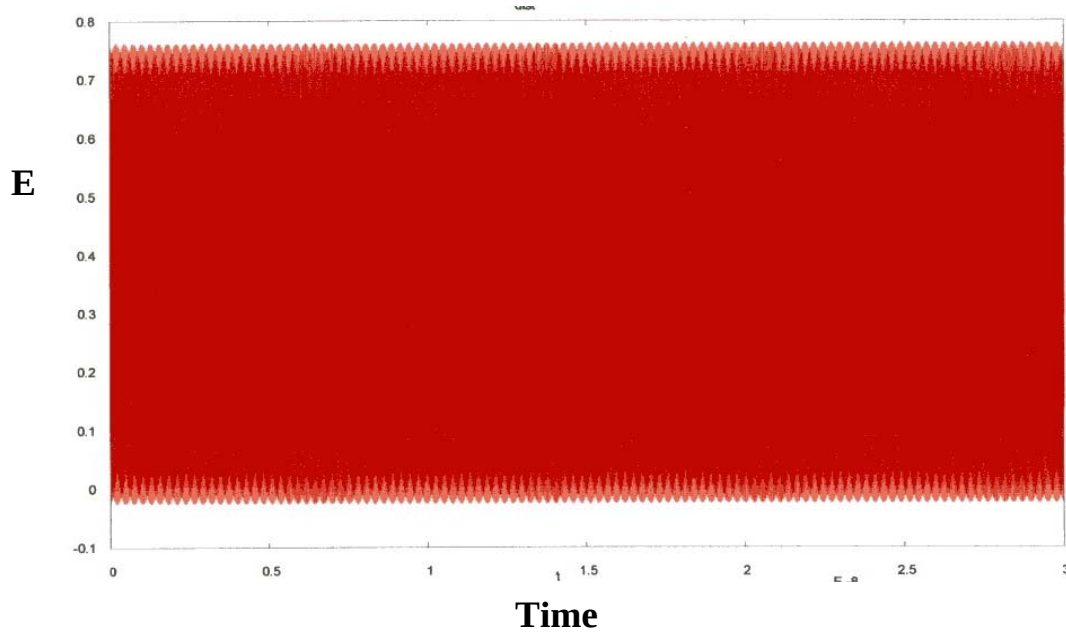
$$\frac{\mathbf{j}_i^{m+1} - \mathbf{j}_i^m}{\Delta t} = -\frac{\nabla \cdot \vec{\mathbf{P}}_i^m}{m_i} + \frac{n_i q_i}{m_i} (\bar{C}_E \mathbf{E}^m + C_E \mathbf{E}^{m+1})$$

$$+ (\bar{C}_{jx} \mathbf{j}_i^m + C_{jx} \mathbf{j}_i^{m+1}) \times \frac{q_i \mathbf{B}^m}{m_i c}$$

$$+ \frac{m_e}{m_i} \left[\nu_h \left(\mathbf{j}_h^{m+1} - \frac{n_h}{n_i} \mathbf{j}_i^m \right) + \nu_c \left(\mathbf{j}_c^{m+1} - \frac{n_c}{n_i} \mathbf{j}_i^m \right) \right]$$

Examination by *Dr. Barnes* of Petrov and Davis' explicit B-field approach¹ has been productive and shows good energy conservation for light waves, as tracked in the figure below.

Total energy

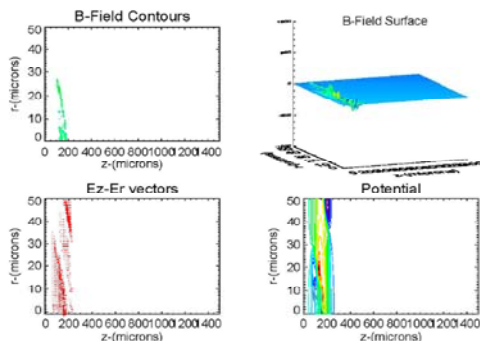


We have found that the stability and dispersion properties of this method can be greatly improved by considering the implicit E -field solve as a corrector, and following this step using a B -field and current corrections as presently the practice in ePLAS. We are now extending this method to a full polarization implicit E only version for ePLAS for Fast Ignition problems.

Implicit E with explicit B gives similar results for $\Delta t < \Delta x/c$, while skipping elliptic solves

Implicit B-Field

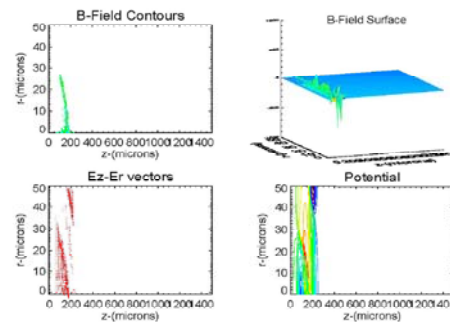
ipetr=0 case:
 icy= 5000 r= 2.33E+00 dr= 4.68E-04 31 19 11 iph= 38649
 cycle limit - icymax - reached, stopping
 dump 1 made at cycle 5000 nrec= 92
 no. hots source into system= 42940
 no hots remaining in system= 38649
 hots too light 4291, hots escaped 0
 hots destroyed by drag 1369
 CP: 1387.328s System: 0.000



Plasma Physics

New Explicit B-field

ipetr=1 case:
 icy= 5000 r= 2.33E+00 dr= 4.68E-04 24 9 11 iph= 38300
 cycle limit - icymax - reached, stopping
 dump 1 made at cycle 5000 nrec= 92
 no. hots source into system= 42960
 no hots remaining in system= 38300
 hots too light 4660, hots escaped 0
 hots destroyed by drag 1486
 CP: 1400.156s System: 0.000

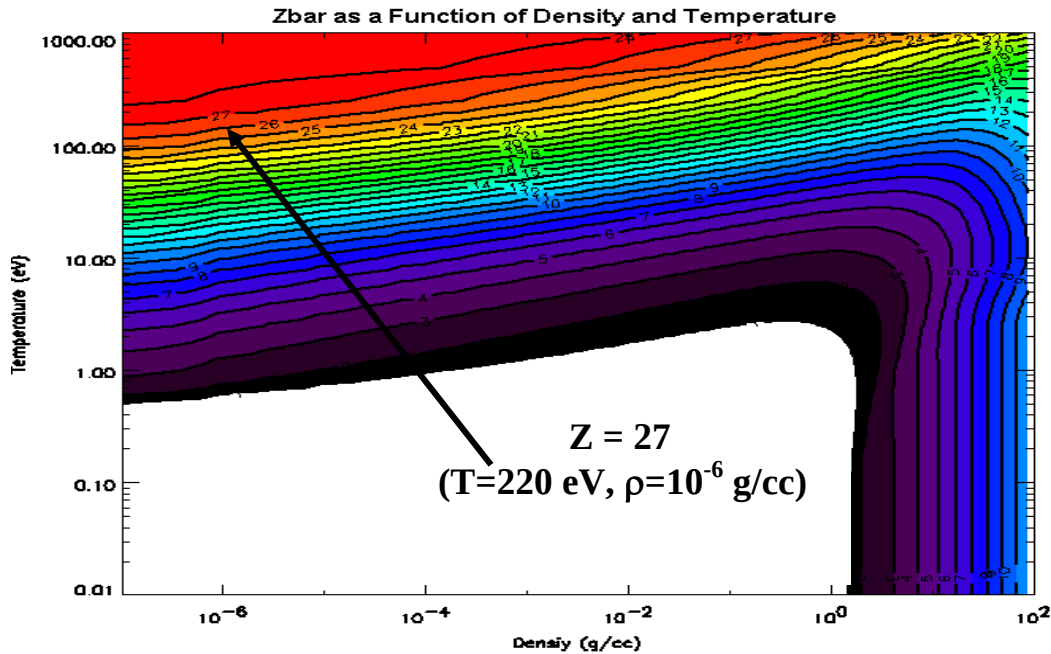


RAC

RAC also continues to study the use of simplified implicit operator with a greatly simplified stencil to advance the B-field as well. This will allow application when the time step greatly exceeds the Courant condition for light.

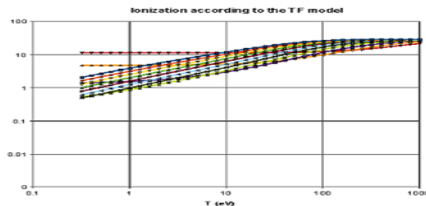
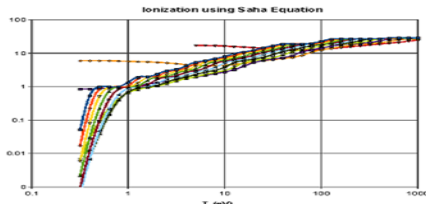
2) Variable Z

Dr. Atchison has provided coding for access to SESAME table data and analytic equations of state. This now promises to give a much better match between simulations and experiment for the temperatures achieved by cold background electrons in wire experiments. Energy transfer to ionization can bring the predicted temperatures down from ~ 700 eV to nearly 200 eV. For Cu ePLAS takes, for example, tabular values from the SESAME $Z(\rho, T)$ data below:



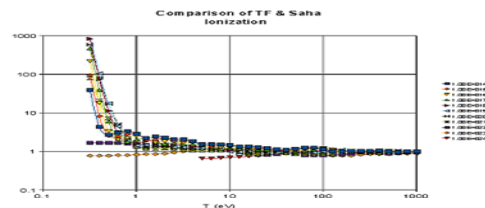
Alternatively, Dr. Kirkpatrick has been developing various analytic ionization models.

Ionization Models

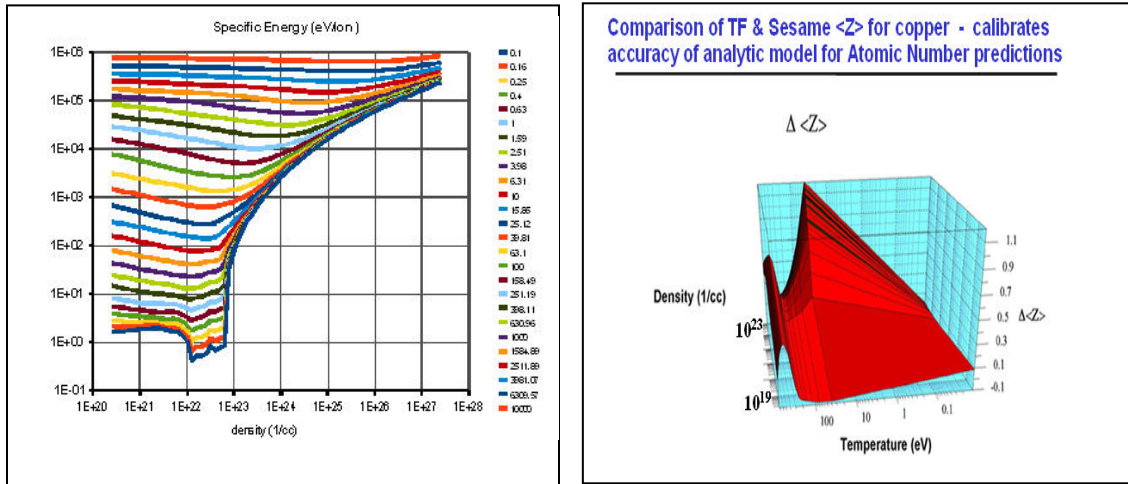


The Thomas Fermi Model compares favorably with $\langle Z \rangle$ based on Saha equation for temperatures above 1 eV.

Our crude partition functions used in Saha may be partly responsible for the differences, but the data-based Saha ionization should be more accurate above 1 eV.

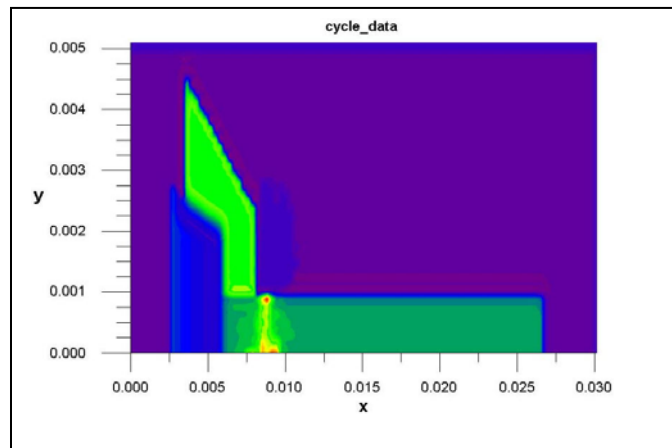


He has also provided an analytic Fermi-Thomas model to supplement the SESAME tabular data in ePLAS, and is completing work on an alternate routine based on the Saha Equation. Comparisons between the various approaches appear below to the right.



Evaluations of effects from the EOS choices have been made by *Dr. Faehl* in application to recent experiments on the Titan and OMEGA-EP lasers.

Contoured values of $Z(x,y)$ from the FT EOS for cu targets with gold cones appear as:



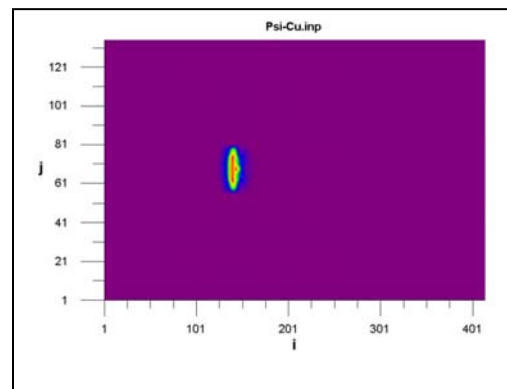
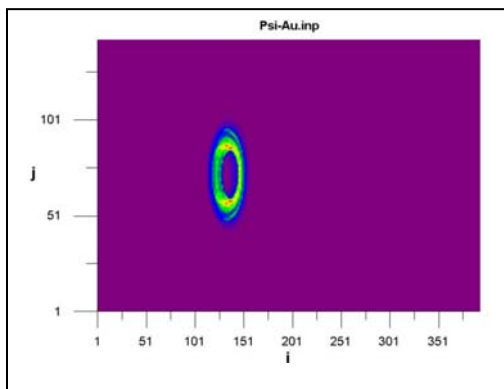
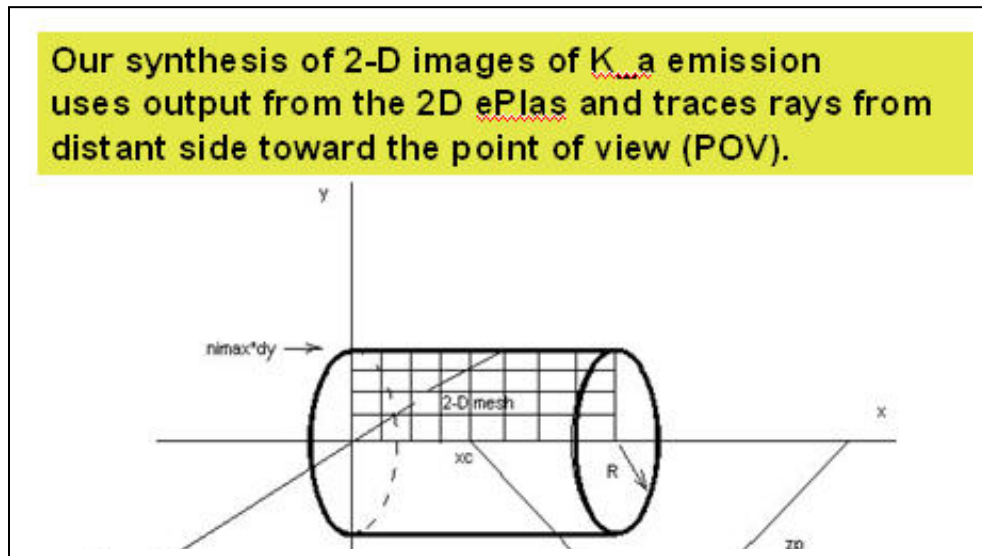
Here the lighter green yellow and red indicate regions of higher Z due to higher background temperatures. Such plots will be compared for different modeled shot conditions.

Dr. Kirkpatrick and the *PI* also plan to implement simple routines using simple thermonuclear cross sections ($\langle \sigma v \rangle$) to develop neutron diagnostics for near term Fast Ignition experiments.

3) K-alpha Image Modeling

In response to GA (R. Stephens) and LNLL (M. Key) requests, *Dr. Kirkpatrick* is also gathering information needed to synthesize the K-alpha emission from laser targets. For targets thin to K-alpha this involves calculating the source function throughout the target and a corresponding 2-D map.

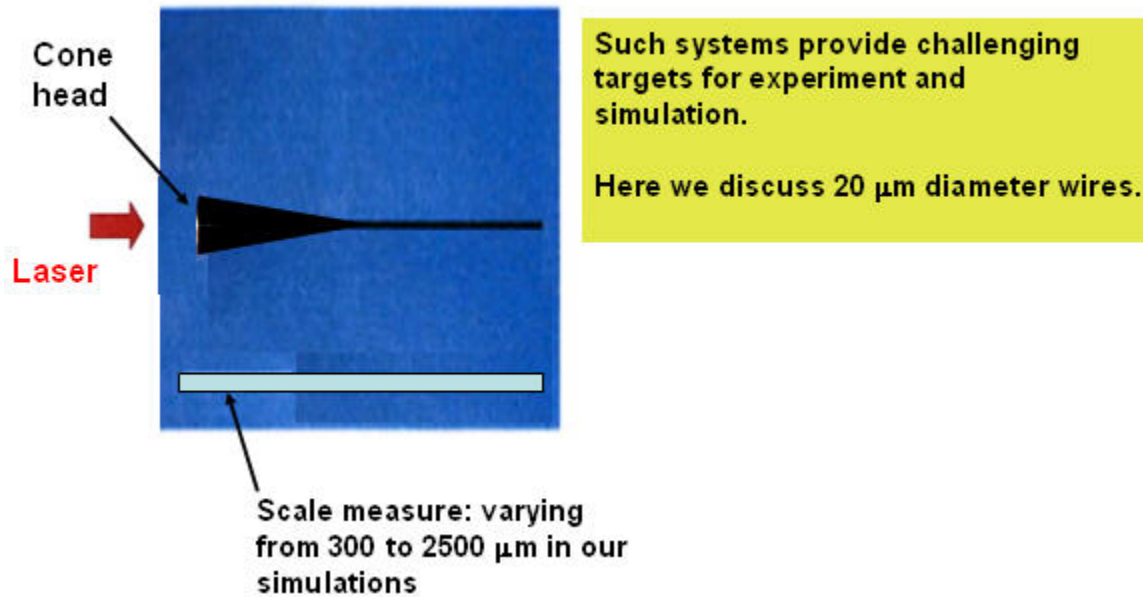
Dr. Kirkpatrick's new K-alpha package for ePLAS renders images that can be directly compared to experiment. A schematic of the view point used appears next.



Typical images for the gold cone and copper wire appear above. RAC will test and refine the new ePLAS K-alpha imaging capability for availability to users with ongoing experiments.

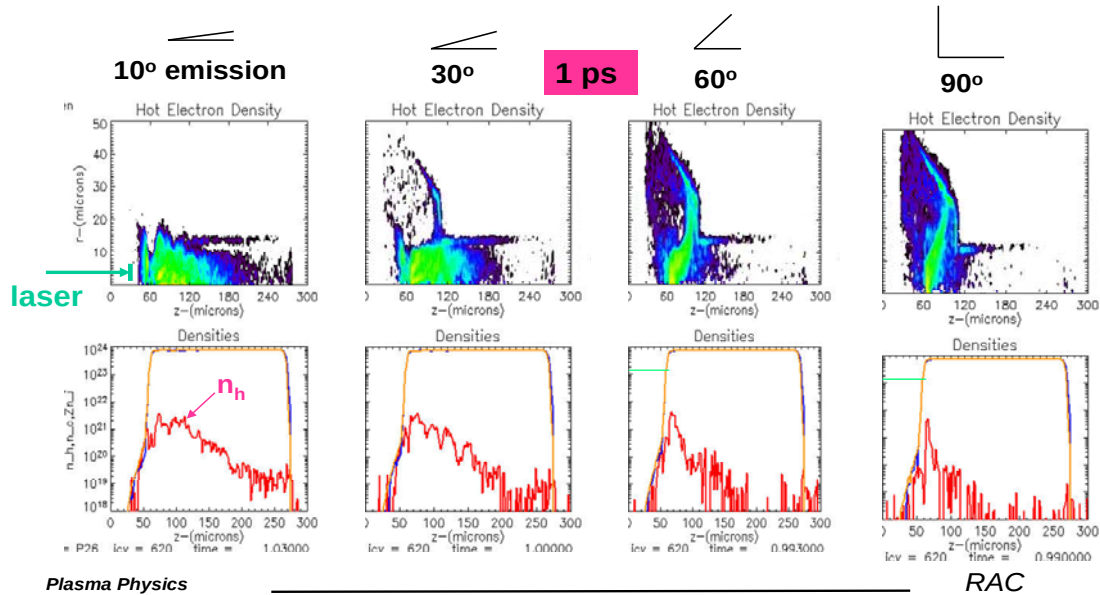
4) Code Tests and Applications (Cone Wire Targets)

Plentiful recent short pulse laser matter interaction studies have involved lasers driving hot electrons in foils or wires, and accompanying K-alpha measurements to diagnose the resultant electron transport and heating. Schematically, such targets, equipped with a cone, possibly of copper or gold appear as:



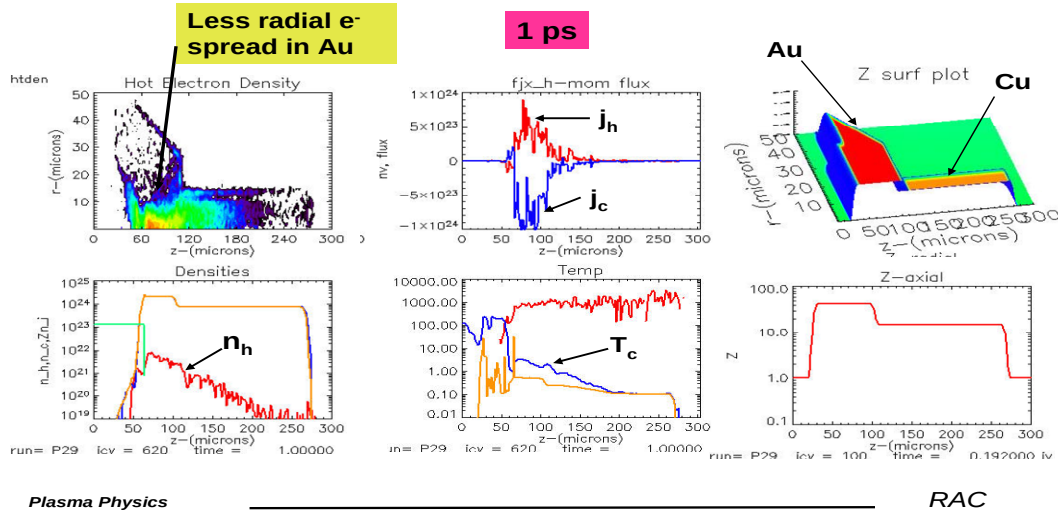
Beta-testing has uncovered hidden deficiencies in the boundary conditions, particularly in cylindrical geometry. Higher resolution studies allowed for better application to recent cone-wire experiments on the TITAN LLNL laser. Experimental comparisons with ePLAS modeling on the depth of hot electron penetration are now abundant^{3,4,10}. Thus, for different assumed angular emission of hot electrons we calculate, for example:

Nail/wire hot e⁻ penetration is sensitive to *assumed* electron emission angle from the laser source



Tests with of transport and heating in wires with variable Z are also underway.

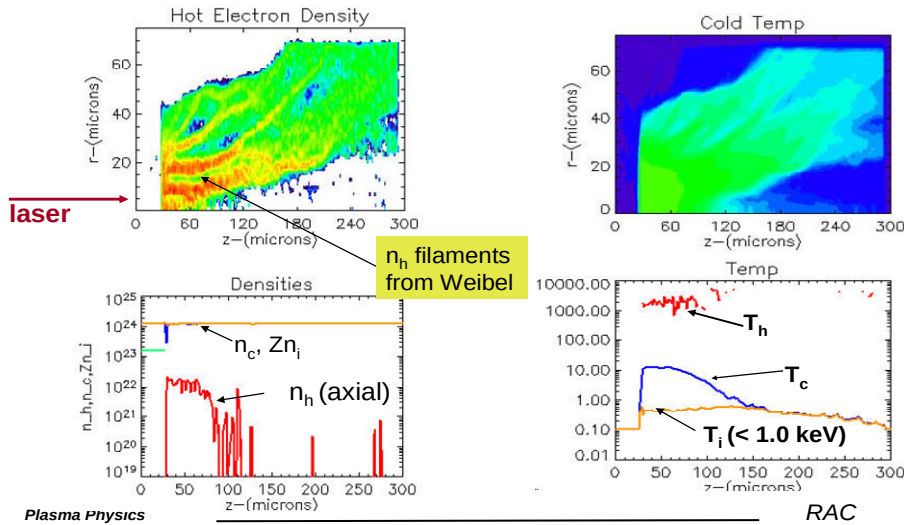
Transport studies through variable Z show:



Dr. Faehl has been conducting detailed studies of the alternate use of particle vs. fluid modeling for the hot electrons. He is reviewing the effects of the presence of pre-plasma at high laser intensities, and developing optimal criteria for the conversion of heated fluid electrons to particles near target surfaces.

The *PI* has testing ePLAS in foil illumination simulations. For the recent (Sept. '09) Short Pulse Laser Matter Workshop⁷ in Pleasanton, CA, he compared hot electron transport in high (50 g/cm^3) and low (5 g/cm^3) density foils, seeing at the lower density.

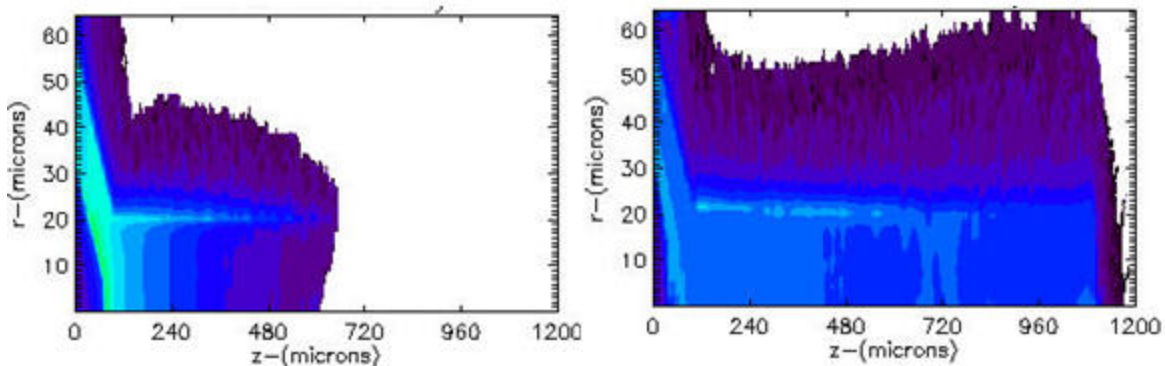
**If the background is reduced to only 5 g/cm^3
filamentation is worse and ion heating reduced**



Dr. Faehl has recently conducted ePLAS simulations^{11,12} in conjunction with the UCSD group tracking penetrating fluid-modeled hot electrons under $4.8 \times 10^{18} \text{ W/cm}^2$ intensity illumination onto a gold cone attached to a copper wire showing hot electron wire penetration, as depicted below:

**Contours of Hot Electron fluid
2.73 ps after start of laser pulse**

**Contours of Hot Electron fluid,
13.3 ps after start of laser pulse.**



These plots show quite clearly that the hot electrons tend to lodge in the conical area, (lighter blue contours) and along the wire surface near the laser deposition point – the later tendency attributed to capture by surface thermoelectric magnetic fields. Hot

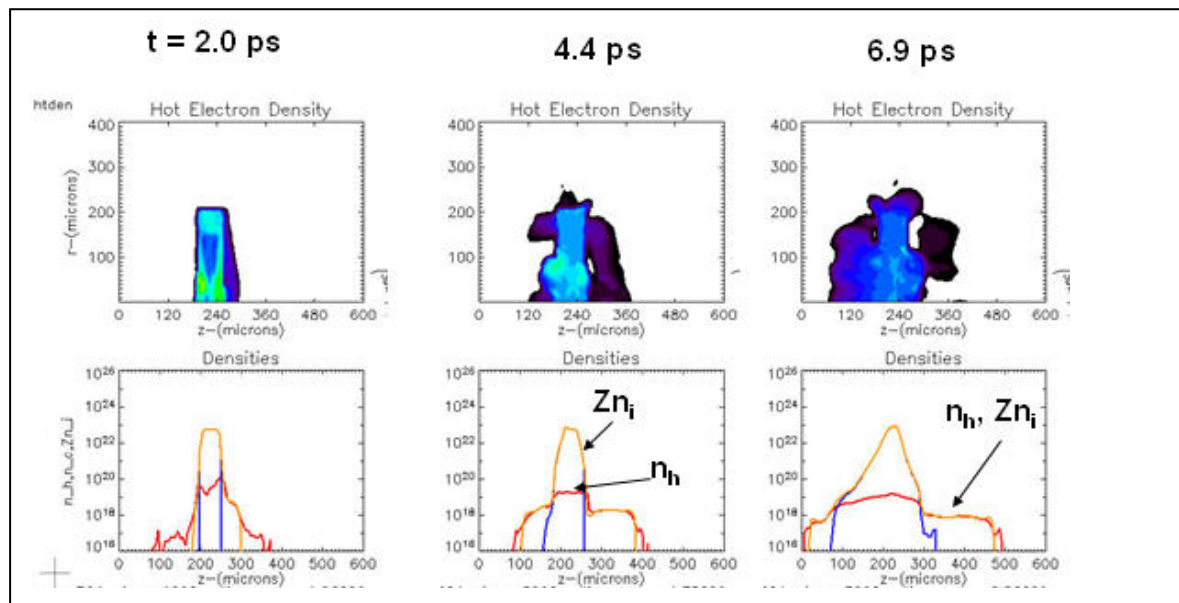
electron penetration in the body of the wire depends on its resistivity and this is set by the local temperature for cold “background” electrons, and the degree of ionization. In the simulation shown the Atomic number Z was fixed at 15, and a perfect gas EOS was used for the copper.

5) The Fluid/Particle Ion Option

The presence of both ion component representations (fluid and particle) in a single simulation will allow for accurate ion emission studies from high density gradient target surfaces. ePLAS code now has both fluid and particle ion initial setup capabilities, separate advancement schemes for each type of component, and particle ion phase plot capabilities under IDL. Work is under consideration for the future simultaneous presence of the two ion types, and their joint presence in calculating the implicit E & B -fields.

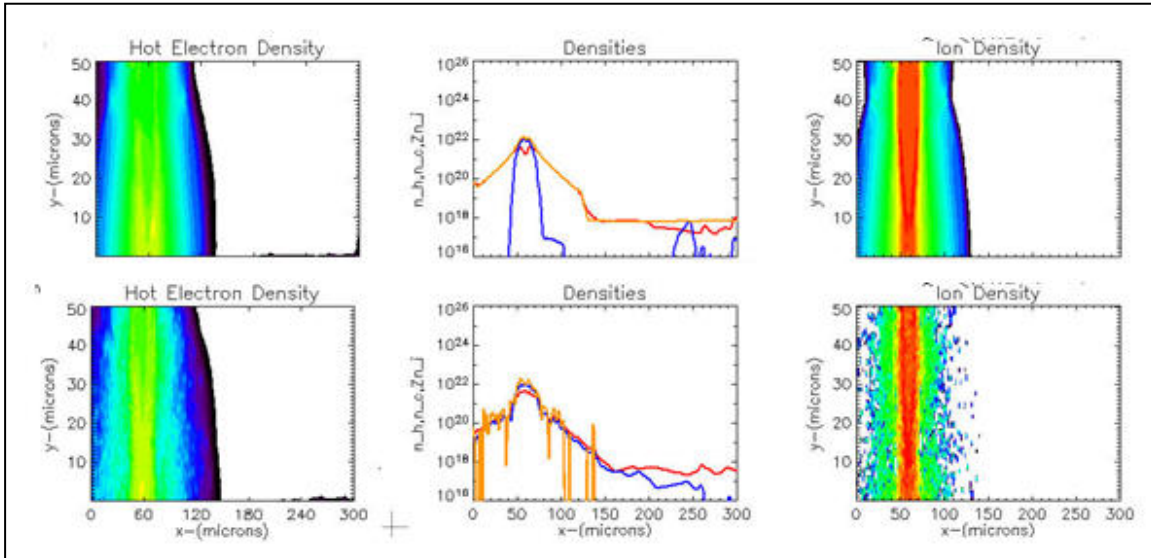
The range of hot electrons from short pulse lasers may prove too great to couple effectively to the background cold electrons and ions of a laser pellet’s thermonuclear fuel. Fast ions, driven by the hot electrons, may couple more suitably. The particle-in-cell modeling of such ions can be inefficient, since many particles may be needed to manage the large density range from solid to ion jets encountered. Fluid ion modeling demands fewer resources, but lacks the spectral information that may be crucial to tune the coupling. A combined treatment would be useful, in which the background foil is treated as fluid, while the accelerated ions are modeled as particles. For the present project RAC has compared¹³ the relative utility of the two present ion modes, and initiated planning toward the future addition of a separate second ion component, much as there are now two separate electron components in the code.

Typical fluid ion simulations of a solid hydrogen foil show us, for example:



Here, the top row shows the calculated contours for hot electrons driving the expansion over 6.9 ps from the 10 μm radius laser spot at the left. Clearly, hot electrons spread to fill the whole foil, but first along the foil surfaces. The bottom row captures the hot electron density (red), cold e^- density (blue), and ion density (yellow/brown). The fast ion blow-off coupled to the ions, but at only 10^{18} particles/ cm^3 , is clearly evident from $z = 300$ to $500 \mu\text{m}$. These determinations required 24 minutes of 2.1 GHz single processor time on a laptop PC.

Below we collect recent results comparing irradiated solid hydrogen foil expansions at 1ps.



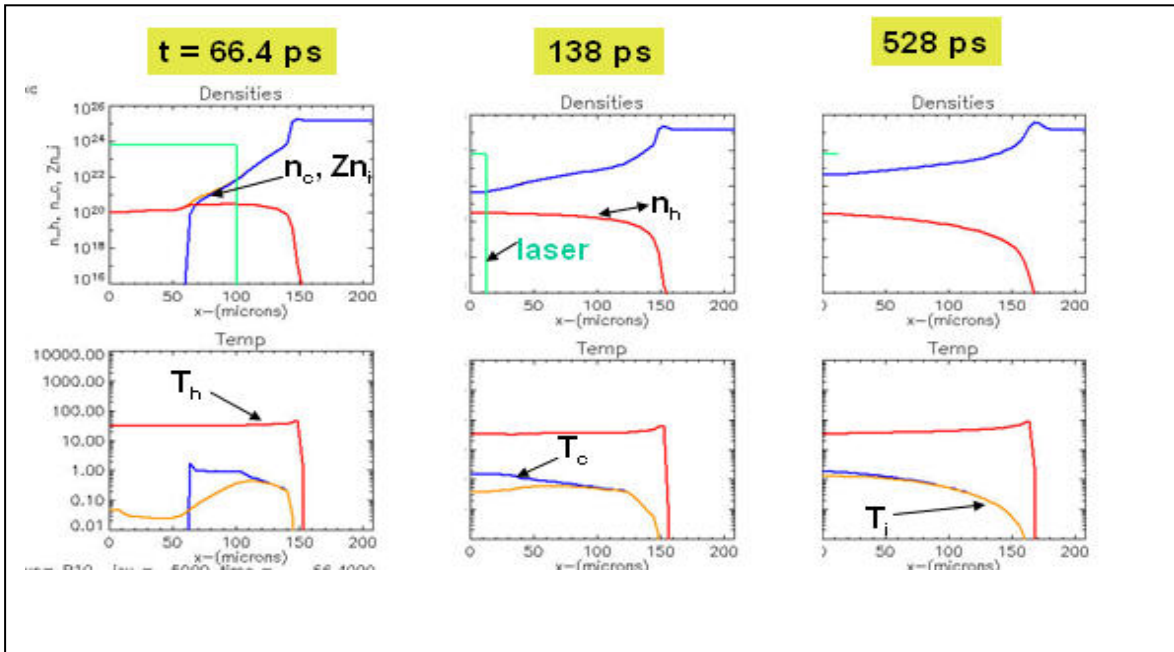
The laser illuminates the lower left 10 μm Δy band (Cartesian geometry). A fluid is used for the ions in the upper set of frames; the resultant ion contours (upper right) are smooth and most extended at the base. Alternatively, modeling with particle ions (lower frames) the recorded ion density is jagged at the lowest densities. Generally, the two calculations give very similar results. However, the cold electron density (in blue) expands laterally in the particle ion case, but not when the ion fluid is employed. This behavior warrants further study. Most significant, perhaps, is that no particle ions are seen below $10^{18}/\text{cm}^3$ densities. Initially, only 10^3 particle ions were used per cell, limiting the lowest density that could be modeled. But more ions would have stressed both machine storage, and the time for calculations. Drs. Mason and Faehl have worked to optimize such tradeoffs, and to provide options for both sufficient particle ions near the surface of a foil, and background fluid ions for its interior, where the ion velocity spectrum matters less.

6. Improvements for Shock ignition studies

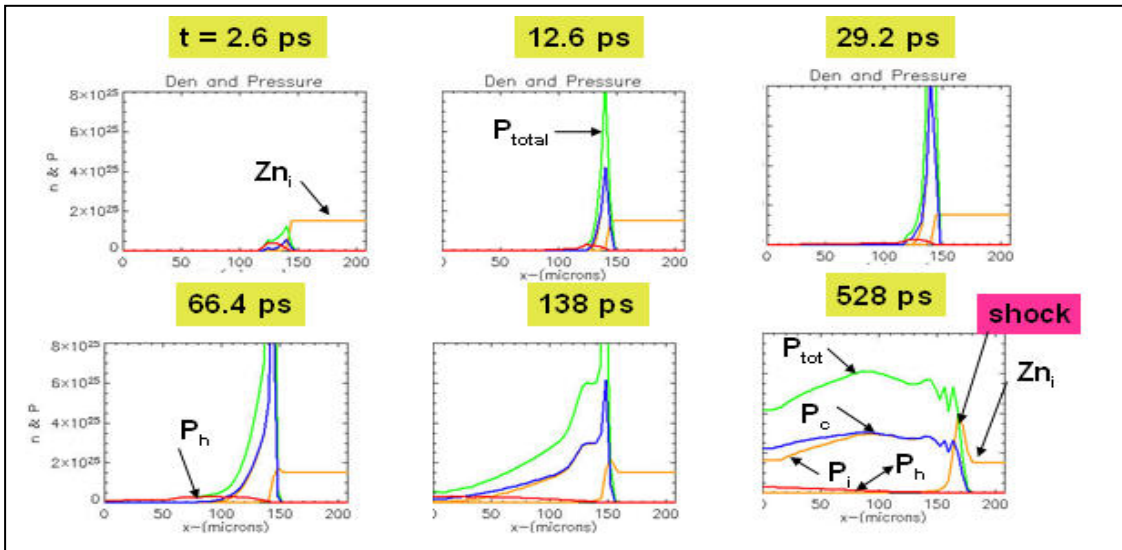
Shock Ignition (SI) has recently become a serious alternative for the initiation of thermonuclear burn following longer pulse fusion target compression for HEDLP. With SI a moderately intense ($\sim 8 \times 10^{15} \text{ W}/\text{cm}^2$), late-time, final pulse is used to launch a final shock in the 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. The

dynamics and absorption of mildly hot (~ 35 keV) electrons generated by the final pulse is a concern. Will they transport properly to the compressed fuel? Will they properly absorb? ePLAS has begun to examine such phenomenology¹⁴.

The ePLAS density and temperature predictions over 528 ps for shock generation in the SI scenario are shown next. A $\sim 8 \times 10^{15}$ W/cm² red laser (green curve) deposits near the 10^{21} /cm³ critical density point, generating ~ 35 keV hot electron (red, which couple to the background cold electrons (blue) and ions (brown/yellow)). At late times the ion and cold electron temperature tend to merge. The top frames show that the cold and ion densities are nearly equal, with shock-like density jump near $x = 170$ μ m.



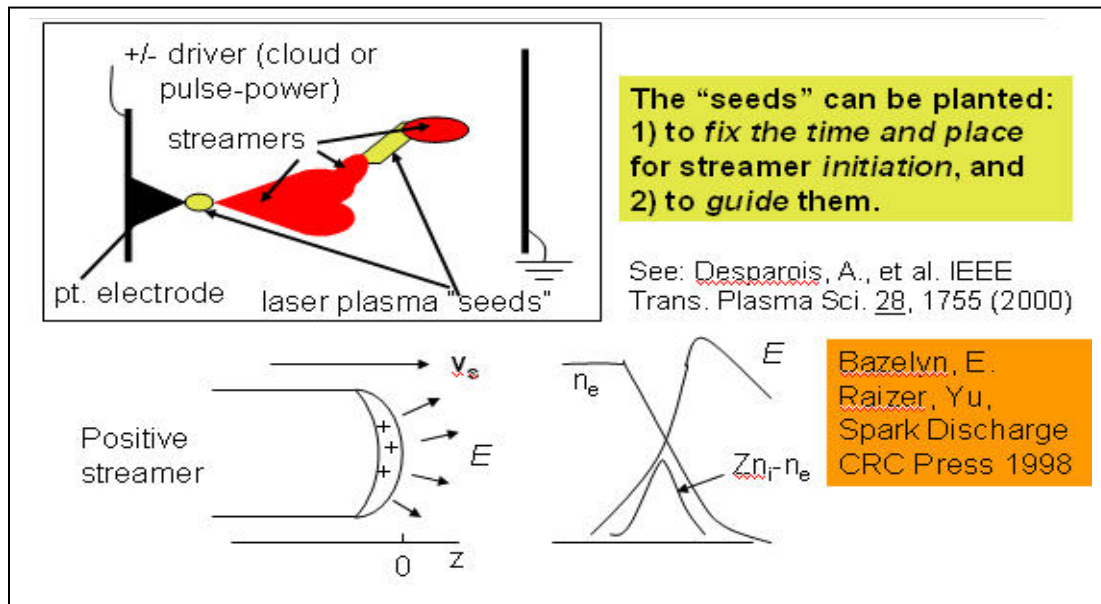
Corresponding pressure evolution over the 528 ps is given below.



There is, indeed, a pressure spike (green) at the shock, with much of the drive transferred to the cold electrons (blue). Such behavior needs further detailed computational inspection. Drs. Mason and Faehl plan to initiate further study of such FI cases, and pursue ePLAS improvements to facilitate detailed study by the broader HEDLP community. A prime candidate for study is the drag current deposition algorithm for fluid hot electrons, used above. Currently, this locally lowers the density of hot electrons, not their energy. The alternative will be considered. Also, consequences of the (more expensive) use of particle hot electrons will be examined.

7) Lightning studies

RAC has initiated lightning studies¹⁵ as an aid to developing an ionization physics capability for targets.

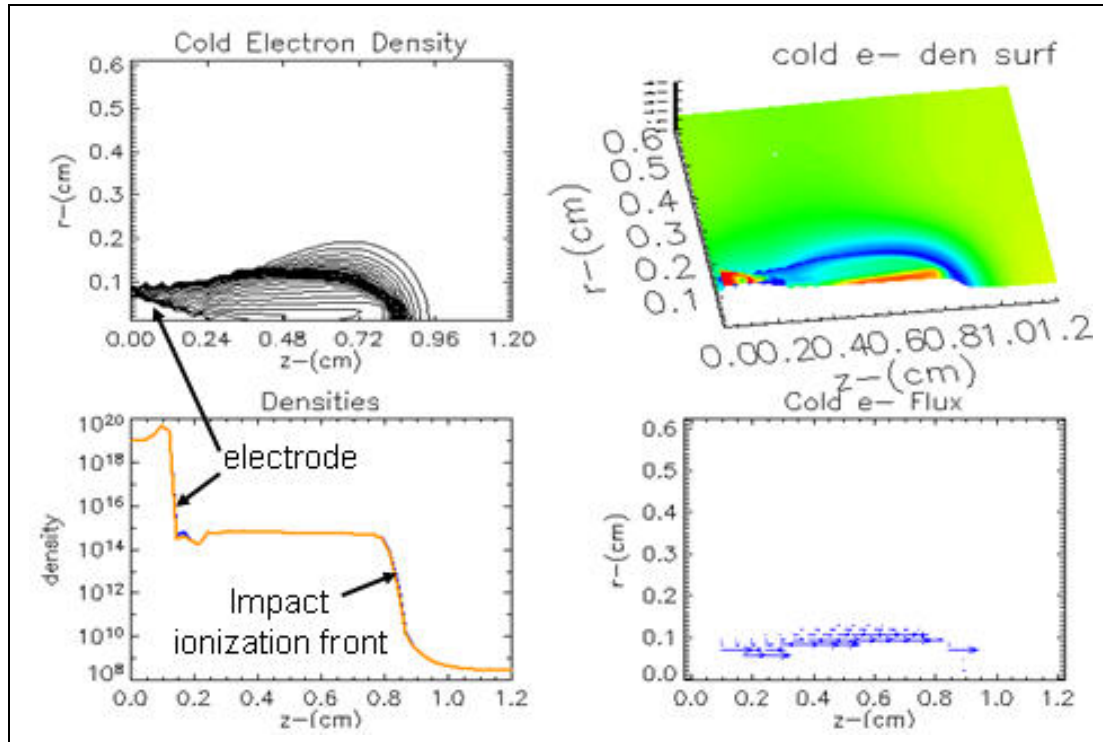


Terms have been added to the ePLAS cold electron fluid system for the creation of electrons from ionization of the background, e.g.:

$$\partial_t(Zn_i) = n_e |\vec{E}| e^{-\frac{1}{|\vec{E}|}}$$

ion impact creation, again
For N_2 ; O_2 is more complex

Thus between charged electrodes, for a negative streamer (with a cathode driving point) ePLAS finds – at 0.6 ns:



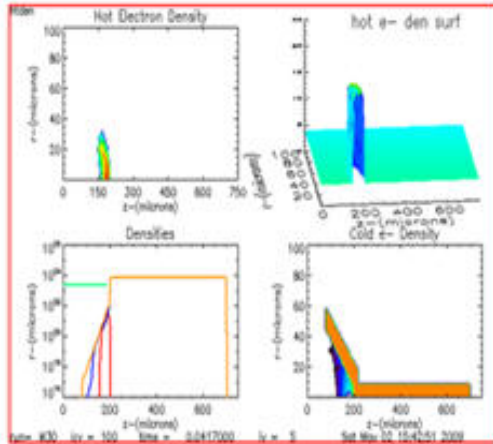
8) Allocatable memory, alternate operating systems and graphics options

Allocatable memory became a major addition to ePLAS as a result of *Dr. Henderson's* efforts. Working just with the code's executable, a user can now set the cell and particle number for problems. No recompilation of the source is needed to change these parameters. This should aid the distribution of ePLAS.

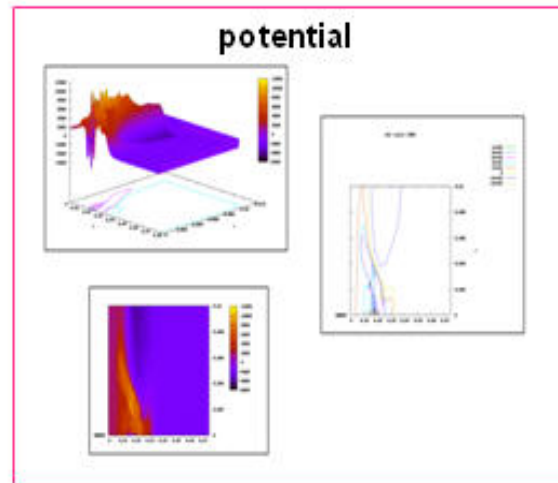
Working with LINUX, *Dr. Henderson* found that cursory use of NAMELIST input data can lead to difficulties following blank lines, comments, etc. This was true for a variety of compilers including, GFORTRAN, G95 and INTEL for LINUX. Code additions were made to ePLAS to surmount these problems. New MAKEFILES were needed, since these had been provided automatically in the Visual Studio Environment used by our INTEL windows compiler.

Dr. Ambrosiano has supplemented our traditional IDL graphical output with new renderings from GNUplot, as follows:

Traditional IDL Graphics

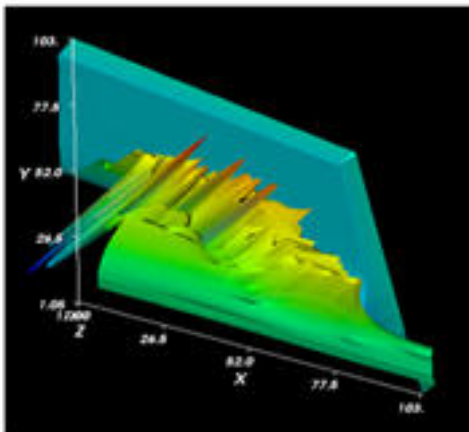


GNU plot alternatives

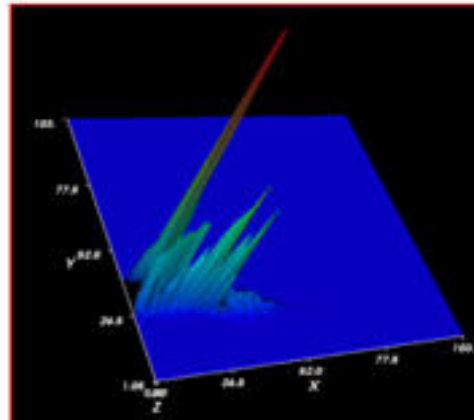


Dr. Ambrosiano has also examined free alternative graphics software from NCSA:

Potential



Hot e- density



New graphical coding has been developed for use with the IDL Virtual Machine. A typical .pro file needed to generate Virtual Machine output is shown below:

```

@pro eplasplotter_event, e
  common state, icyplt, inputfile
  common widgets, filelabel, filename_text
  widget_control, e.id, get_uval=uval
  ;Events from the File menu
  if uval eq "exititem" then widget_control, e.top, /destroy
  if uval eq "openitem" then begin
    inputfile = dialog_pickfile(/read)
    widget_control, filename_text, set_value = inputfile
  endif
  ;Events from the Edit->Properties menu
  if uval eq "propertiesitem" then begin
    desc = $
      ['0, INTEGER, 1000, LABEL_LEFT=ICYPLT:, WIDTH=12, TAG=ICYPLT', $
       '1, BASE,, ROW', $
       '0, BUTTON, OK, QUIT, TAG=OK', $
       '2, BUTTON, Cancel, QUIT, tag =CANCEL']
    form_result = CW_FORM(desc, /COLUMN, TITLE='Properties')
    icyplt = form_result.icyplt
    print, icyplt
    ;help, /structure, form_result
  endif
  ;Events from the View menu items trigger associated plots
  if uval eq "ebfldsitem" then begin
    if inputfile ne "" then begin
      ebflds_mod, icyplt, inputfile
    endif
  endif
  if uval eq "bcutsitem" then begin
    if inputfile ne "" then begin
      BCuts_mod, icyplt, inputfile
    endif
  endif

```

Presently, only densities, and E - and B -fields can be plotted in this new user-cost-free environment.

Product Development

RAC continues to improve its ePLAS MANUAL, with a Version 1a, including new input variables and defaults. Close code collaborations have continued with UCSD, and General Atomics. Broader code use is being 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. It gives an overview of how the executable can be employed using a “typical” input file – for the cone-wire problem^{3,4}.

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.

a. Publications and References

1. G. M. Petrov and J. Davis, “A two-dimensional electromagnetic field algorithm for high-intensity laser-target interactions,” *Comp. Phys. Comm.* **179**, 868 (2008).
2. R. Faehl, R. Mason, R. Kirkpatrick, F. Beg, T. Ma, M. Wei, R. Stephens, L. Van Woerkom and R. Freeman, “ePLAS model developments for short pulse interaction studies,” IEEE- ICOPS09, San Diego, CA, Poster IP4E32, 6/4 (2009).
3. R. J. Mason, R. Faehl, R. Kirkpatrick, T. Ma, M. S. Wei, F. N. Beg, M. H. Key, and R. B. Stephens, “ePLAS Modeling of hot electron transport in hot electron targets,” *J. of Phys: Conf. Series* 022047 **244** (2010).
4. T. Ma, M. Key, R. J. Mason, K. U. Akli et al., “Transport of Energy by Ultra-Intense Laser-Generated Electrons in Nail-Wire Targets,” *Phys. of Plasmas* **16**, 112702 (2009).
5. H. Cai, K. Mima, W. Zhou, T. Jozaki, H. Nagatomo, A. Sunahar, and R. J. Mason, “Enhancing the number of high energy electrons deposited to a compressed pellet via double cones in fast ignition,” *Phys. Rev. Letts.* **102**, 245001 (2009).
6. H. Cai, K. Mima, T. Jozaki, H. Nagatomo, A. Sunhara, W. Zhou, and R. J. Mason, “Collimation of relativistic laser-generated high energy electron beams via double cone target in fast ignition scheme,” *J. of Phys: Conf. Series* **244** 022030 (2010).
7. J. Ambrosiano, W. Atchison, D. Barnes, R. Faehl, D. Henderson, R. Kirkpatrick, and R. Mason, “The ePLAS implicit hybrid plasma simulation code for SPLM studies”, Short Pulse Laser Workshop, Larkspur Landing Hotel, Pleasanton, CA, September 14-15, 2009.

8. R. Mason, J. Ambrosiano, W. Atchison, R. Faehl, D. Henderson, R. Kirkpatrick, and D. Barnes, “ePLAS code improvements for short-pulse laser-matter interaction studies,” *Bull. Am. Phys. Soc.* **54**, 79 (2009).
9. R. Mason, J. Ambrosiano, W. Atchison, R. Faehl, D. Henderson, R. Kirkpatrick, “ePLAS code enhancements for short pulse laser-matter interaction studies,” IEEE-ICOPS, Virginia Beach VA, Poster 3P-64, 6/23 (2010).
10. R. Faehl, R. Mason, F. Beg, T. Ma, M. Wei, R. Stephens, “ePLAS examination of short pulse laser-wire and foil interactions,” *Bull. Am. Phys. Soc.* **54**, 79 (2009).
11. R. Faehl, R. Mason, F. Beg, T. Ma, W. Wei, T. Yabuuchi, R. Stephens, “ePLAS Model Simulations of Short Pulse Laser Target Experiments,” IEEE-ICOPS, Virginia Beach, VA, Poster 7D-4, 6/24 (2010).
12. R. J. Faehl, R. J. Mason, R. Kirkpatrick, T. Yabuuchi, F. N. Beg, R. Stephens, “Effect of pre-pulse generated plasma on short-pulse laser-cone-wire interactions,” APS-DPP, Chicago, Poster Session JP9, 11/09 (2010).
13. W. Atchison, R. J. Mason, R. Kirkpatrick, F. N. Beg, D. Schumacher, R. Freeman, M. Schmitt and K. Flippo, “Simulation of ion generation and dynamics for Fast Ignition,” APS-DPP, Chicago, Poster Session JP9, 11/09 (2010).
14. R. Kirkpatrick, R. J. Mason, R. J. Faehl, R. Betti, and A. Solodov, “Hot electron effects in laser driven shock ignition,” APS-DPP, Chicago, Poster Session NP9, 11/10 (2010).
15. W. Atchison, R. J. Mason, and J. Zinn, “ePLAS modeling of laser-induced lightning streamers,” *Bull. Am. Phys. Soc.* **54**, 201 (2009).
16. R. C. Kirkpatrick, R. J. Mason, R. Faehl, R. Betti, A. Solodov, R. Freeman, L. VanWoerkom, D. Schumacher, F. N. Beg and T. Yabuuchi, “e-PLAS electron transport modeling for laser-driven fusion, 40th Anomalous Absorption Conference, Snowmass Village, CO, June 17 (2010).
17. R. J. Mason, “Modeling of the fast ignition approach to laser fusion energy,” CSIRO Seminar, UWA, Perth, Australia, Sept. 13 (2010).

b. RAC Web Site

RAC created (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 numerous conferences (ICOPS^{2,9,11}, IFSA09^{3,6}, the AAC10¹⁶, and the APS-DPP^{8,10,12-15}) during the course of this Project. The *PI* contributed to the recent Livermore sponsored Short Pulse Laser Workshop⁶, and coauthored four papers³⁻⁶.

The *PI* was honored by ILE Osaka as a coauthor on the best paper of the year⁵ 2009 for his collaboration with ILE on Double-shell Fast Ignition Targets.

RAC continued to interact with UCSD and General Atomics, with a visit to UCSD by *Dr. Faehl* in late December 2009, and by *Dr. Mason* in June 2010. *Dr. Mason* also visited LLE in Rochester and Ohio State in March of 2010.

At company expense the *PI* recently outlined ePLAS capabilities at a CISRO Seminar¹⁷ at the University of Western Australia.

d. Techniques

The project has furthered implicit/hybrid techniques for the Fast Ignition community.

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 components, as in the code's present electron modeling. A hot fluid electron, energy dependent drag scheme is needed for improved Shock Ignition studies. More extensive free graphics and further 64-bit PC implementation is needed for application to larger problems. Parallelism needs implementation. RAC is now seeing additional support for such additions.