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TITLE: ANTHEM: A TWO-DIMENSIONAL MULTICOMPONENT SELF-CONSISTENT HYDRO-ELECTRON TRANSPORT CODE FOR LASER-MATTER INTERACTION STUDIES

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ANTHEM
A TWO-DIMENSIONAL MULTICOMPONENT SELF-CONSISTENT HYDRO-ELECTRON TRANSPORT CODE FOR LASER-MATTER INTERACTION STUDIES

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Abstract

The ANTHEM code for the study of CO_2-laser-generated transport is outlined. ANTHEM treats the background plasma as coupled Eulerian thermal and ion fluids, and the suprathermal electrons as either a third fluid or a body of evolving collisional PIC particles. The electrons scatter off the ions; the suprathermals drag against the thermal background. Self-consistent E- and B-fields are computed by the Implicit Moment Method. The current status of the code is described. Typical output from ANTHEM is discussed with special application to Augmented-Return-Current CO_2-laser-driven targets.

I. CODE OUTLINE

At 10^{15} W/cm^2 intensities roughly all the energy deposited in targets by CO_2 lasers goes directly into long range suprathermal electrons. These penetrate the dense collisional target material normally, and spread laterally in the collisionless corona through self-consistent B-fields, while scattering off ions and E-fields at the interface with the collsional pellet core. To serve a useful purpose, the energy in the suprathermals must be transferred to a much larger number of thermal electrons, which can then drive a pellet implosion either directly or indirectly. Presumably, this conversion process can be managed efficiently with the aid of the self-consistent fields in a carefully engineered target. However, most earlier target design work has been done with codes in which the suprathermal modeling has been done with multi-group diffusion. This simple modeling is of questionable value in coronal regions where flux limiters must be imposed, and where the suprathermal transport may be strongly influenced by the B-fields. To improve this situation we have embarked on the development of ANTHEM - a hybrid PIC fluid transport model for the self-consistent transport of the electrons in evolving pellets of arbitrary collisionality.

In ANTHEM we deal with a three component collisional plasma. The ions and thermal electrons are treated as fluids; the suprathermals are managed as either an additional fluid or as collisional PIC particles. The thermals and superthermals flow through the moving ion background under the influence of collisions and self-consistent fields. The fluids are modeled by donor-cell[1] Eulerian hydrodynamics, with FCT corrections that make the treatment second order in space. The PIC suprathermals undergo Rutherford scattering off the ions by the model suggested by Dawson and Shanny[2], and experience Coulomb drag against the background thermal electrons. Thermal collisions with the ions are treated implicitly, allowing many scatterings in a time step. Self-consistent E- and B-fields are determined by the Implicit Moment Method[3], permitting time steps much larger than the local plasma period. Thus, the governing time step for calculations becomes a Courant condition on the fastest electrons. As modeling alternatives, options exist in ANTHEM (a) to treat the suprathermals as a second electron fluid, or (b) to supress the suprathermals and deposit the energy directly in the thermals. The addition of a PIC mode for the ions is also contemplated.

The code is written for both x-y cartesian and r-z cylindrical geometry[4]. Laser light is tracked in along the x or z-axis to the first cell exceeding critical density. There the energy is deposited, forcing the emission of the suprathermal particles. Typically, two are emitted per cycle per source cell. Usually, the emission is directed towards the laser in a 20° cone characterizing resonance absorption. For more general tests, the cone can have any angle, or the emission can be reduced to a monoenergetic beam towards the target. In the fluid suprathermal mode, the emission temperature and drift velocity are specified at critical, and the suprathermal density is simply increased as laser deposition proceeds.

At present the code can be initialized to examine (i) foils, (ii) shells, or (iii) CO_2 ARC targets[5], as shown in Fig. 1. The ARCs are under scrutiny as micro-Z-pinches that may be Joule-heated and B-field compressed as a result of the return thermal currents needed to supply the suprathermal emission.

In the case of ARC targets, the energy deposition and suprathermal emission take place at the end of the rod. Then the suprathermals are slowed by the drag, so that a fraction of their energy is directly transferred to the thermal electrons. Superthermals that are dragged to zero speed are destroyed, while the local thermal density is increased. A slowed suprathermal will not be destroyed unless the local thermal density exceeds twice the suprathermal density. This avoids the down-conversion of suprathermals at the coronal edge of a pellet. The code couples the thermal temperature to the ion temperature at the ion-electron rate given by Braginskii[6], and calculates simple bremsstrahlung energy loss from the thermal electrons - limited to a local blackbody rate in each cell.

As energy is deposited in the various components, they begin to move. The superthermal particles stream from the emission site towards the laser. The thermal electron and ion fluids then expand into the surrounding vacuum. Care has been taken to assure that an adiabatic expansion into the vacuum does, indeed, cool the fluids. The use of FCT techniques[7] to provide a second order spatial treatment, and the advection of entropy (instead of total or internal energy) to guarantee adiabatic flow in expansions has proven successful in this regard.

When the drag, scatter and fields are set to zero, the various fluids move with independence. Simple perfect gas equations of state are employed for the electrons and ions. At present only a single ion species is allowed. The ion Z, A and mass can be chosen as desired. For $Z = A = 1$, $m_e = m_i$ and $T_i = T_e$ the ions (as a test) move in superposition with the electrons. At the physical mass ratio the electron fluid moves out $(m_i/m_e)^{0.5}$ times faster than the ion fluid. With scatter "on" the electrons and ions expand together at $\sqrt{2}$ times the ion thermal speed; however, electrons at the leading edge of the expansion will leak (diffuse) ahead of the front, as scattering becomes too infrequent to contain them. Then, with the E-field "on" even [illegible] electrons are bound to the ions, i.e. within a Debye length, usually [illegible] smaller than a cell size. Finally, with the inclusion of B-field the electrons can "slip" relative to the ions, such that $\nabla\cdot j = 0$ leaving the net charge density undisturbed, but laterally transporting heat[8]. This final effect may have profound effect on target design; it is fundamental to the enhanced ion emission employed in fast ion targets.

In ARC targets the hot electrons bounce off the expanding ion sheath at the end of the rod and run down its exterior towards the disk base. A B-field arises from $\nabla n \times \nabla T$ effects, and convects down the rod with the suprathermals. This field largely insulates the rod from the flowing suprathermals. Later the field increases further due to the global circulation of outgoing coronal suprathermals and returning thermals in the outer surface material of the rod.

Enlarged time steps are permitted for the calculations due to the implicitness of the model. The scattering is made implicit by relaxing the future (m+1)-level electron velocities towards the ion velocity in the Lagrangian phase of the donor-cell hydrodynamics calculations; see Ref. 9. Implicit fields are found by combining the expressions for the (m+1)-level currents (from time-integrating the momentum equations - with simple differencing for the convective terms) with the fourth Maxwell equation for $\partial E/\partial t$. The resultant vector expression is solved for $E^{(m+1)}$ in terms of B. The curl of this E expression, thru Farady's law gives an equation to be matrix solved for $B^{(m+1)}$, completing the system. Divergence[10] of the predicted densities from the actual densities achieved (following the particle pushing and the FCT hydrodynamics) is avoided by a Poisson solve on the densities correcting the electrostatic part of $E^{(m)}$. Details will be given elsewhere[11].

II. CODE STATUS

ANTHEM bridges the collisionless transport regime analysed with VENUS[12] and the dominantly collisional regime explored with Double-Diffusion[13]. The status of the code is as follows: All the physics elements discussed thusfar are in place, with the exception of the matrix solve for B. At present B is calculated explicitly from Faraday's law (with an artificially reduced value for the speed of light); this will soon be rectified. Tests of the code with these elements in concert are under way - with application to the ARCs. The inclusion of Righi-Leduc terms[14] in the thermal conduction, and a particle ion treatment -- for certain applications, is under consideration. ANTHEM can stand alone in the calculation of electron transport in target elements that avoid high compression

III. TYPICAL OUTPUT (and figure captions)

Figure 1 shows a sketch of the CO_2 ARC target that, in part, motivated development of ANTHEM.

Typical output from our test runs with ANTHEM is presented in Figures 2 to 6. Figure 2 collects results from 1-D tests of the collisional and E-field capabilities of the code. More details will be given in Ref. 9. The results are for illumination producing 35 keV suprathermals at critical, as marked by the vertical fiducial lines in the frames (a) thru (f). Frames (a) and (b) show an initial 5 μm gold foil expanding with near symmetry due to suprathermals that have readily penetrated to the to the rear, i.e. left side. The electric fields contain the suprathermals within the foil material, forcing the hot density n_h to match the ion charge density Zn_i in the corona and producing the front and rear low density regions of fast ion blowoff. Scatter and drag have been suppressed for this case. Frame (c) gives corresponding results for the same illumination when scatter is added. The hot density is still lower by an order of magnitude on the rear side at 5.8 ps. The frame (e) phase space plot for suprathermals shows a symmetric population of the positive and negative regions of velocity sp and, again, most of the electrons confined to the right. Finally, frames (d) and (f) show a much further reduction of the electron penetration when the drag is turned on.

Figure 3 shows our success thusfar in resolving difficulties associated with expansion of the fluids into a vacuum. Frames (a) and (c) show the evolution of density and temperature using the usual advection of internal energy. A spike appears at the leading edges of the temperature profiles for both the material initially to the left and for the foil at 950 μm. Frames (b) and (d) show the improved profiles with entropy advection. In all four frames the exact solution for a right-moving expansion is shown. The exact solution still tends to lead the computed one.

Figure 4 show the 2-D r-z evolution of ions in the ARC target expanding from an initial 10 keV condition. The sharp corners near the nose of the ARC have been smoothed as the expansion proceeds and a temperature spike has developed at the interface between material expanding from the disk and that from the rod. Also, a trench in the center of the foil is visible due to its rapid right and left expansion. In the neighborhood of the rod the trench is missing.

Figure 5 shows results of a 5 ps calculations with suprathermal emission from the cap of the ARC. E-fields reflect the elctrons back into the cap material. The phase plot in (a) demonstrates the closed u-x loop created by this process. The loop does not, in fact, return exactly on itself, due to the present first order formulation of the field solution. A second order in time improvemnt to the code will be required to repair this deficiency.

Figure 6 show a fluid calculation of the hot electron transport. For this run the fields were suppressed. Electrons at 10 keV were generated along the starred line at the nose (cap) of the ARC. Scattering and drag were on. The upper and right boundaries were taken as mirrors. The suprathermals spread up and around the target and down its length to the disk. For this run the rod walls were thick enough so that the scatter and drag were sufficient to keep these electrons excluded from the interior of the rod.

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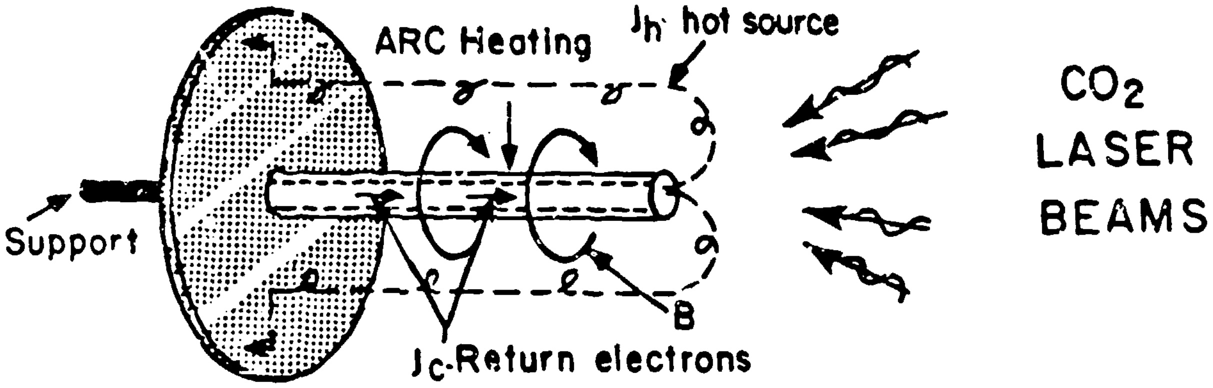
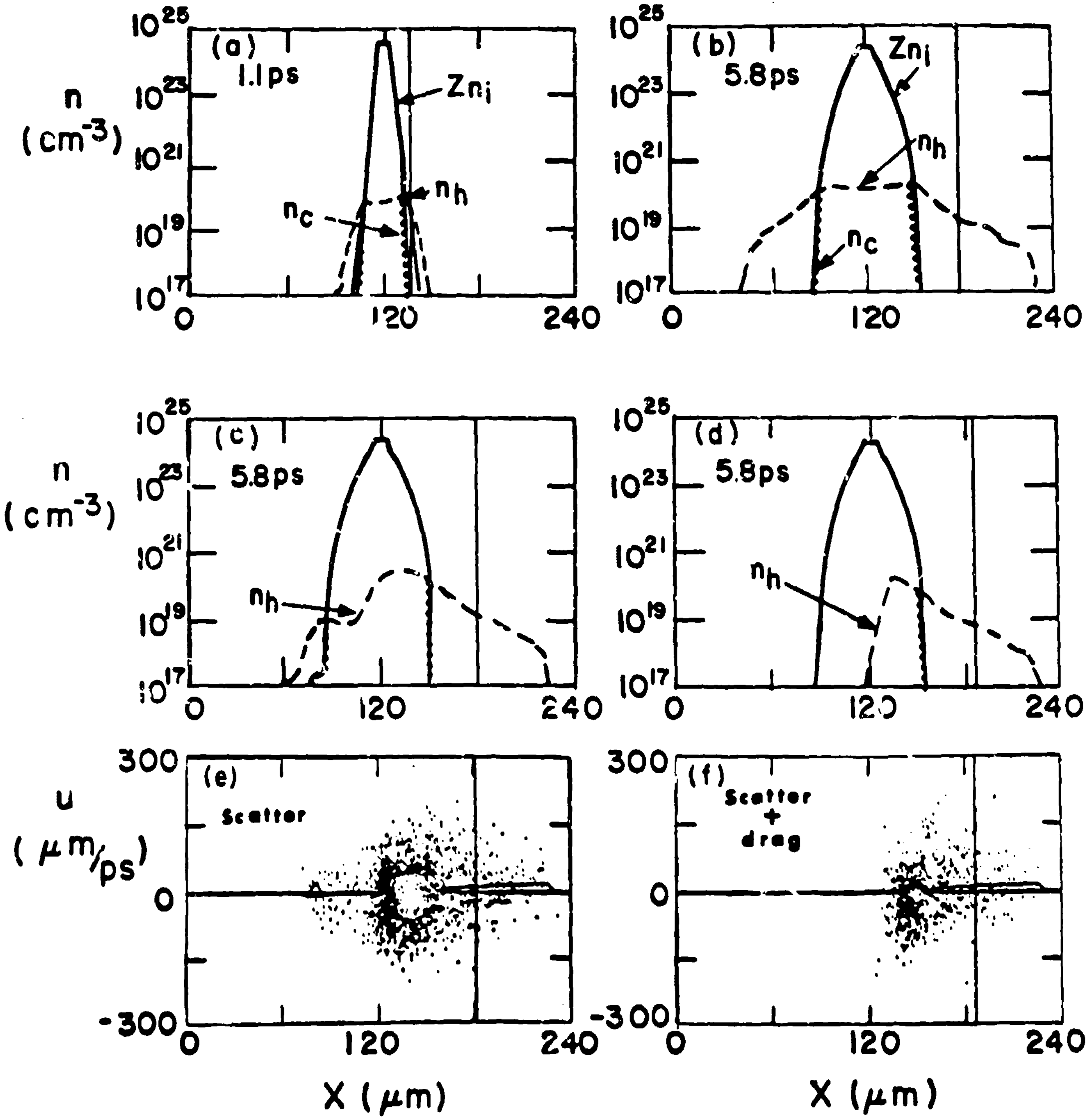

ARC Heating
J_h hot source
CO_2
LASER
BEAMS
Support
B
J_c-Return electrons

Fig. 1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10^{23}
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(a)
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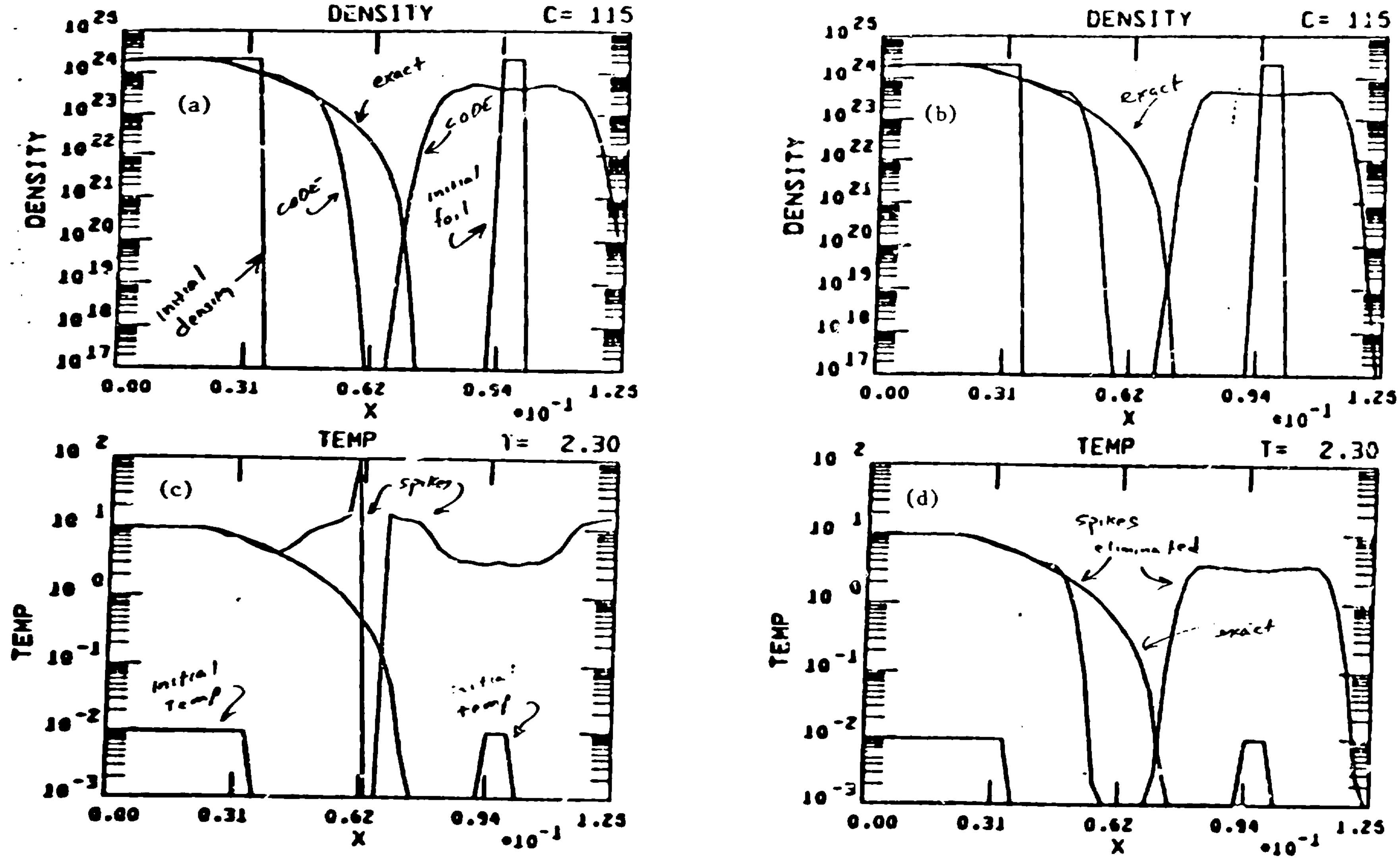
(b)
5.8ps
Zn_i
n_h
n_c
(c)
5.8ps
n_h
(d)
5.8ps
n_h
u
(μm/ps)
300
0
-300
(e)
Scatter
(f)
Scatter
+
drag
0
120
240
X (μm)
X (μm)

Fig. 2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C= 115
(a)
(b)
exact
CODE
initial foil
initial density
TEMP
T= 2.30
(c)
(d)
spikes
initial temp
spikes eliminated
exact
X
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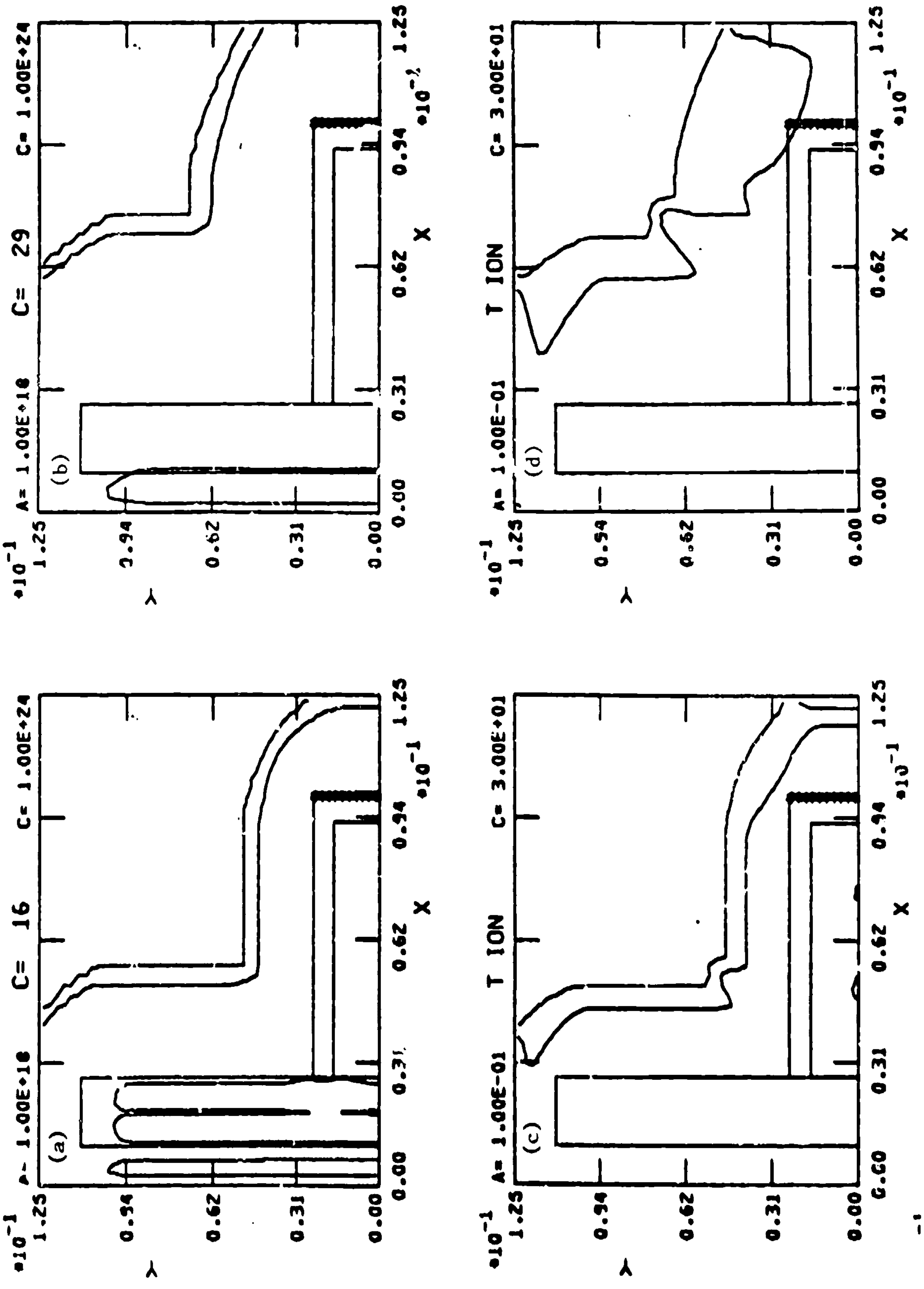
0.31
0.62
0.94
1.25

Fig. 3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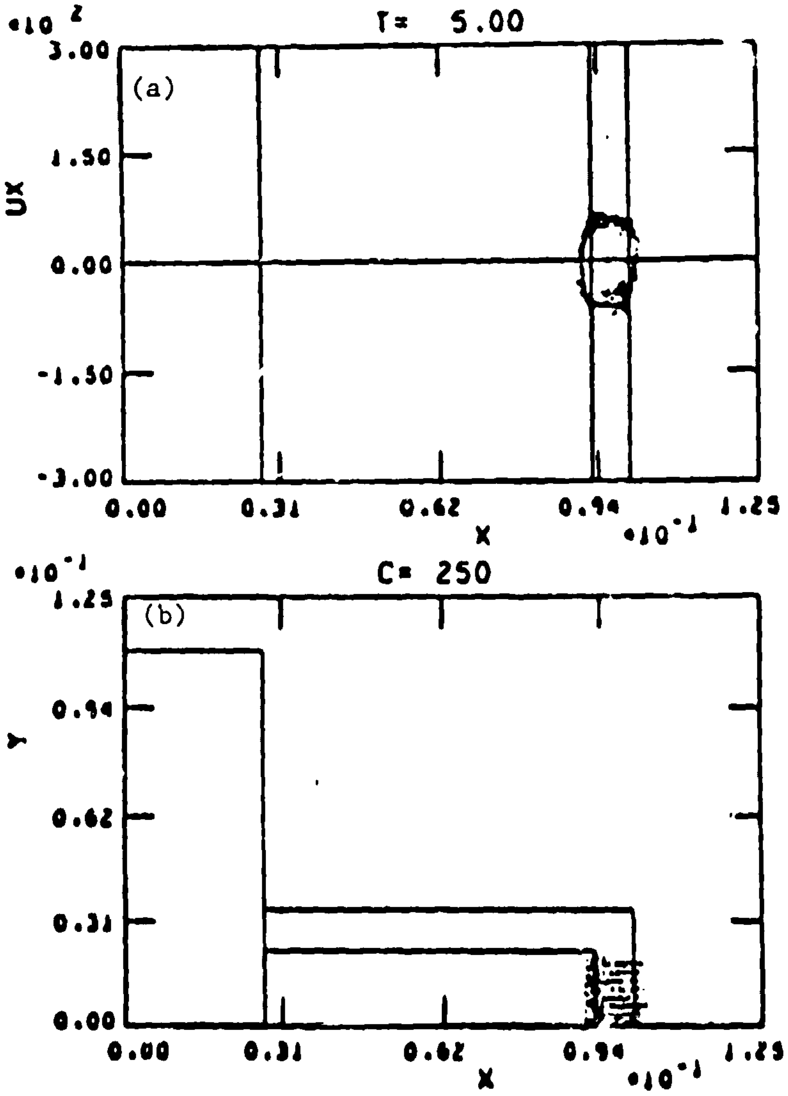
A= 1.00E+18
C= 16
C= 1.00E+24
(b)
A= 1.00E+18
C= 29
C= 1.00E+24
(c)
A= 1.00E-01
T ION
C= 3.00E+01
(d)
A= 1.00E-01
T ION
C= 3.00E+01
X
Y
*10^-1
0.00
0.31
0.62
0.94
1.25

Fig. 4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1.50
0.00
-1.50
-3.00
UX
(a)
0.00
0.31
0.62
0.94
1.25
X
*10 -1
*10 -1
C= 250
1.25
0.94
0.62
0.31
0.00
Y
(b)
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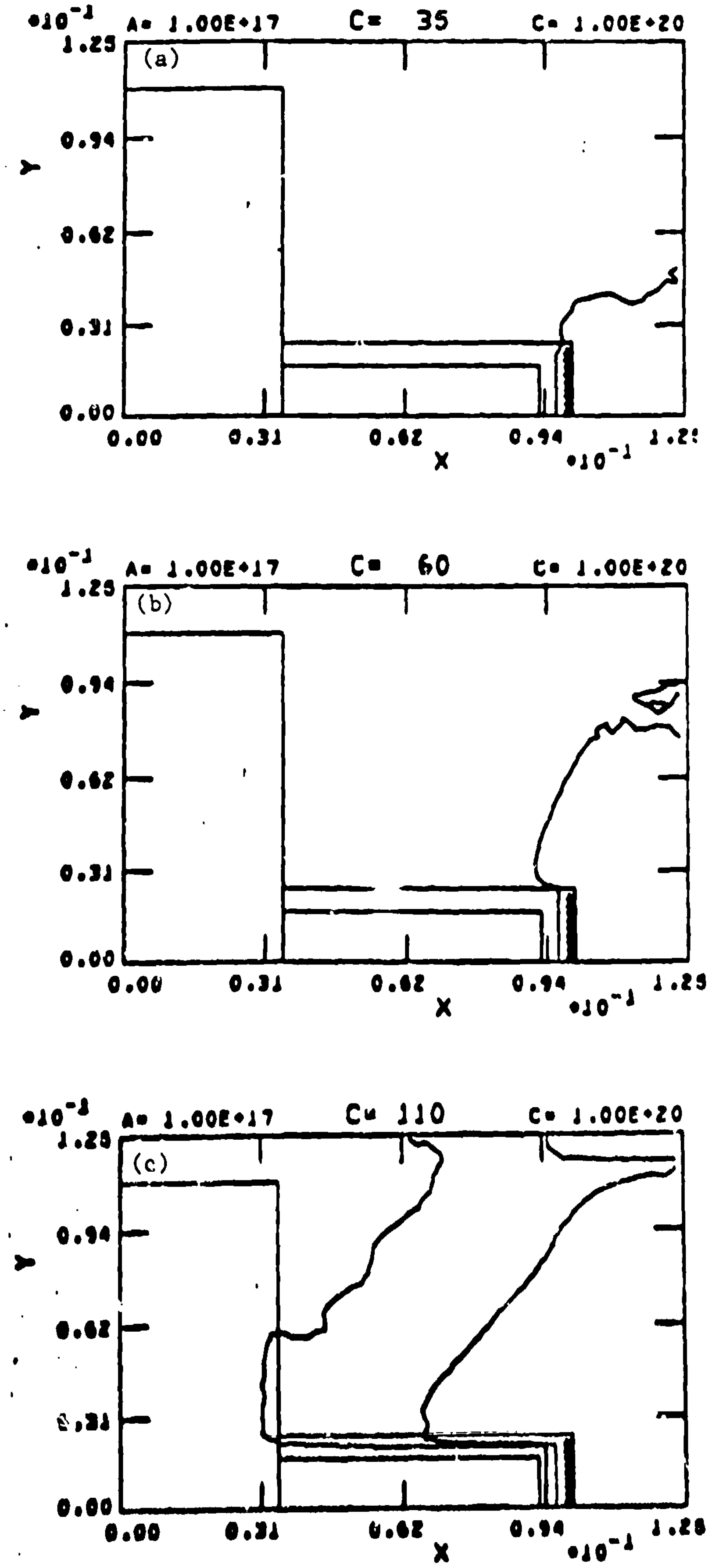
0.31
0.62
0.94
1.25
X
*10 -1

Fig. 5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0.62
0.31
0.00
Y
0.00
0.31
0.62
0.94
1.25
X
*10^-1
*10^-1
A= 1.00E+17
C= 60
C= 1.00E+20
(b)
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0.94
0.62
0.31
0.00
Y
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0.31
0.62
0.94
1.25
X
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*10^-1
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C= 110
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0.62
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0.62
0.94
1.25
X
*10^-1

Fig. 6