Title: The Implicit Hybrid/PIC Code ANTHEM

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ABSTRACT

Recent inventions in pulse power switching, fast laser-driven thermonuclear ignition, and short pulse radiography have demanded a dramatic increase in the capabilities of plasma simulation tools. Multi-fluid, multi-component, fluid and kinetic models are needed for plasmas spanning thousands of Debye lengths and thousands of plasma periods. Such plasmas manifest both dense and tenuous regions, including or excluding magnetic fields and collisional resistivity. The problems of interest can dwell in a transition regime with limits traditionally treated by resistive MHD and/or collisional particle-in-cell (PIC) methods. The ANTHEM implicit hybrid simulation model is under development to meet these challenges. This presentation will outline its past and current features, and review results typical of short-pulse laser applications.

INTRODUCTION

Since the earliest days of laser fusion research, the modeling of hot electron transport has been a significant challenge. CO$_2$ lasers in the mid-70s and early 80s delivered up to 10 kJ in the Los Alamos Helios facility to a target critical surface at $10^{19}$ electrons/cm$^2$. A good fraction of this energy was deposited by collisionless resonance absorption, but the paucity of available electrons resulted in the emission of a hot electron component [1] at 100s of keV and even meV levels. The blow-off of the low-density plasma from the critical surface imparted too low a momentum transfer to drive effective direct-drive implosions. The hot electrons (suprathermals) could penetrate a capsule and preheat it [2]. It was briefly held that the hot electrons might be absorbed in a hohlraum wall for indirect drive, or insulated by a vacuum layer that would exclude their preheat action. Efforts were also made to transport the hot electrons through foils, leading to the backside emission of fast ion. These fast ions might then carry out the principal deposition on a capsule containing DT fuel scheduled for compression. A comprehensive hot electron transport model was needed to check these theoretical possibilities.

Early efforts along these lines were a one-dimensional, multi-group diffusion-based hot electron transport scheme [3,4], and a 2-D “Double-Diffusion” model [5]. The latter two-component model first tracked laser light along the mesh and up to the critical surface. There, the light was absorbed, converting cold electrons (density $n_c$) into hot electrons ($n_h$) at a specified temperature, recommended by experiment, and in a number sufficient to represent the absorbed energy. These “hots” then diffused away from their source under a scattering rate based on this temperature. Likewise, cold electrons at the background temperature diffused up to the deposition point to supply the hot emission upon conversion. The cold background was also locally heated by hot electron deposition. The hot and cold electron flux

* This work was supported by the U.S.D.O.E.
was determined from momentum equations allowing scattering of fixed background ions. The electron inertial terms were neglected, so the scheme was limited to finite background plasma densities, and a flux-limiter was needed to avoid electron runaway in the near-vacuum around a laser target. Similarly, the displacement current in Maxwell’s equations was neglected, leaving Ampere’s Law and Faraday’s Law to update the electromagnetic fields. For incident 1.06 µm light at 10^{16} W/cm^2 this scheme predicted the generation of megagauss B\_z magnetic fields after 20 ps, surrounding the laser spot from \( \nabla n_h \times \nabla n_c \) sources (essentially thermoelectric) in the x-y plane of electron motion. Surprisingly, at that time “double-diffusion” also predicted the development of 0.5 MG fields of opposite polarity on the back side of the same foil, arising as the hot electron arrived there and diffused away from the center line along the back surface.

Limitations of the diffusion treatment for the two electron components encouraged the development of a PIC treatment for, at least, the hottest electrons. In [6] particle (PIC) electrons were launched in 1-D into a returning fluid of cold electron with inertia. The ions were still fixed. The returning electron fluid obeyed Braginskii’s equations and included thermal conduction. The emitted “hot” particle electrons underwent Rutherford scattering against background ions, and drag against the thermal electrons. Only electrostatic fields were needed, and these were calculated by a novel artificial reduction or “dilation” of the electron charge, which permitted a stable explicit calculation of the electric field at time steps much larger than the physical plasma period of the background electrons. This was sufficient to rapidly establish a steady state, in which the incident and return currents were nearly equal, with the E-field set in the high density background plasma by resistivity, and in low-density regions by momentum balance in the hot component, i.e. \( E = -\nabla P/n_e \)). In [7] this lead us to note that the momentum equations for hot and cold electrons could be used with Ampere’s Law to solve implicitly for a predicted E-field prevailing at the end of each computational time step. Hot particle electron trajectories could then advanced through this “implicit moment” field.

This Implicit Moment [8] approach to particle simulation was subsequently formalized in a study applied to the simple two-stream instability. Here, the collisionless electrostatic coupling of counter-streaming beams was well and stably modeled with large time steps, i.e. \( \omega_p \Delta t = 40 \), with \( \omega_p \) the plasma frequency. A careful study of the addition of collisional effects was provided in [9, 10]. An alternate “Direct Implicit” scheme, which avoided the use of moment equations was introduced by Friedman et al. in [11]. Brackbill and Forslund first extended the Moment Method to 2-D with all species treated as particles in [12]. Then, in [13] Wallace et al. used this scheme to render an implicit particle simulation of the thermoelectric B-fields surrounding a laser spot in cylindrical geometry. They deposited CO\(_2\) light on a hydrogen foil at \( 2 \times 10^{19} \) electrons/cm\(^3\) peak density (i.e. at twice critical) in these simulations. Mason and Cranfill in [14] showed similar B-fields, but calculated for a peak density of \( 4 \times 10^{24} \) electrons/cm\(^3\), using the ANTHEM hybrid/implicit scheme. They showed the retention of hot electrons near the target surface, due to the resistive, and absorptive properties of the background plasma. They reported results for both particle and fluid modeling of the hot electrons. Refs. [14 and 15] spell out details of the 2-D implicit/hybrid ANTHEM model.

After 1985 CO\(_2\) lasers were largely rejected as ICF drivers. Neodymium Glass laser light (1.06 µm) was frequency tripled to drastically reduce its hot electron production in laser-
matter interactions. Hot electrons became, it was hoped, a non-issue, in ICF. Consequently, the use of ANTHEM was redirected to the modeling of fast Plasma Opening Switches (POSs) for Pulse Power. In these switches a low density plasma \(10^{12}-10^{15} \text{ electrons/cm}^3\) initially fills a small portion of transmission line. When a megavolt potential is suddenly applied across the electrodes of this line, a pulse of magnetic field traveled down it, and up to the surface of the filling plasma. On penetrating that surface, the magnetic field gradient drives an intense surface electron flow, working to shield the plasma interior. This electron stream is drawn from the cathode electrode and rapidly becomes relativistic in the plasma. Ultimately, after several tens to hundreds of nanoseconds of “conduction time,” this electron current fully penetrates the plasma of the POS, and Pulsed Power could continue down the line. Implicit/hybrid simulation is perfect for this situation. The filling background plasma is centimeters, and, therefore, thousands of Debye lengths, \(\lambda_D\), in extent. The time scale for opening can be thousands of plasma periods, \(\tau = \omega_p^{-1}\), particularly when at the higher plasma fill-densities that are desired for near microsecond switch conduction times. So, pragmatically, explicit PIC simulation requiring \(\omega_p \Delta t < 0.2\) and \(\Delta x < \lambda_D\) can only be used for the lowest densities, and few-nanosecond switches. Implicit hybrid simulation with ANTHEM proved ideal for longer time scales [16-19]. The background plasma could be treated as an ion fluid plus a “cold” electron fluid component, while the shielding electron emission stream was treated as a second electron fluid, or as emitted particles. Modeling features of the code specific to POS switches are collected in [19]. Reference [20] characterized important characteristics of electron magneto-hydrodynamics (EMHD), whereby B-field can penetrate collisionless plasmas along a direction perpendicular to density gradients. Additional calculations predicted that multiple internal electrodes could be floated inside a POS (see Fig. 1) to permit switch opening to higher impedance loads [21,22].

Fig. 1. Multi-Gap POS. A floating internal electrode establishes a second plasma gap, allowing opening to larger loads. The numbers indicate features described in the patent [22].

In the early 90s interest in suprathermal electrons was again ignited by the prospect of using ultra-powerful lasers to heat the fuel of a pre-compressed target. ANTHEM was used in Tabak et al. ’s paper introducing the Fast Ignitor concept [23, Fig. 7], where it predicted that 200 MG B-fields would be seen near the surface of a target compressed to \(10^{24} \text{ electrons/cm}^3\)
and heated over 1 ps by a glass laser (1.06 \textmu m) delivering 10^{20} \text{ W/cm}^2. When ponderomotive force was added to the model, Mason and Tabak subsequently showed [24] that this force could provide a push on the electrons at the target surface leading to the generation of 2 Giga-gauss magnetic field. The polarity of these front-side fields was reversed to those seen from the thermoelectric effect. In 2000+, interest in short-pulse “Fast Ignition” continues to grow, with the aim of reducing the energy, timing and symmetry demanded for success with the National Ignition Facility (NIF). This, in turn, calls for plasma simulations that can stably manage the absorption of laser energy by the target plasma, while accommodating its transport and absorption at both high and low densities, as provided by ANTHEM.

THE ANTHEM MODEL

ANTHEM [14,15] is presently a two-dimensional Eulerian model that can track two electron components, and one ion component. Each of these components can be either a fluid or a set of collisional PIC particles. The electron fluids suffer classical scatter against the background ions, and drag against each other [16]. Similarly, the electron particles can undergo Rutherford scattering and drag against background electrons [7,9]. Generally, we have used the hot electron component to follow relativistic electrons [24] emitted from a conducting cathode in pulsed power problems, or to track energetic emission from near the critical surface under laser illumination. The second cold electron component, plus the ion component represent the background plasma. The electromagnetic fields are determined implicitly through the Moment Method [8]. That is, we use a set of auxiliary fluid equations at each computational time-step to predict time-advanced sources of current in an implicit solution of Maxwell’s equations. These auxiliary equations retain electron inertia. Thus, for a single auxiliary electron fluid we would have

$$\frac{m_e}{\partial t} \frac{\hat{e} \hat{n_e}}{\partial \vec{v}_e} = -\nabla \cdot \vec{P} - e_n(\vec{E} + \vec{v}_e \times \vec{B} / c) - m_e \nu_{ei} n_e (\vec{v}_e - \vec{v}_i)$$, \hspace{1cm} (1)

with \( \vec{P} \) containing both static and dynamic “pressure” terms, \( \nu_{ei} \) a scattering rate against ions, and \( \vec{v}_i \) the ion velocity. This is combined with Ampere’s and Faraday’s Laws, i.e.

$$\frac{\partial \vec{E}}{\partial t} = -4\pi e (Zn_i \vec{v}_i - n_e \vec{v}_e) + c \nabla \times \vec{B}$$, \hspace{1cm} (2)

$$\frac{\partial \vec{B}}{\partial t} = -c \nabla \times \vec{E}$$ \hspace{1cm} (3)

Their use leads to an elliptic system for a single magnetic field component, say \( B_z \), and two electric components, \( E_x \) and \( E_y \). The electric fields are derived algebraically from the auxiliary moment equations, once \( B_z \) is known. With centered differencing, for example:
\[ B_z^{(m+1)} = B_z^{(m)} - c \Delta t \vec{\nabla} \times \vec{E}^{(m+1/2)} \] (4)

and

\[ \vec{E}^{(m+1)} = \vec{E}^{(m)} - 4 \pi e \Delta t \left( Z n_i \vec{v}_i - n_e \vec{v}_e^{(m+1/2)} \right) + c \Delta t \vec{\nabla} \times \vec{B}^{(m+1/2)} \] (5)

are combined, using for example \( E_{x,y}^{(m+1/2)} = (E_{x,y}^{(m+1)} + E_{x,y}^{(m)}) / 2 \), with

\[ n\vec{v}_e^{(m+1)} = n\vec{v}_e^{(m)} - \frac{\nabla \cdot \vec{P} \Delta t}{m_e} - \frac{e n_e \Delta t}{m_e} \left( \vec{E}^{(m+1/2)} + \vec{v}_e^{(m+1/2)} B_z/c \right) - n_e \Delta t \vec{v}_e \left( \vec{v}_e^{(m+1/2)} - \vec{v}_i \right) \] (6)

to acquire a prediction for the future electric fields \( E_{x,y}^{(m+1)} \) in terms of \( B_z^{(m+1)} \), in turn providing the elliptic equation for \( B_z \). The level-(m) data is obtained from the real fluids or particles at the end of each time step. The last term in Eq. (6) provides the scatter against background ions. Generally, we use the two electrons components. Only the colder one exhibits significant scattering. They add, of course, to produce the net electron flux \( n_e \vec{v}_e \) used in Eqns. (5) and (6). Attempts to draw a return-current through this scattering can result in large resistive electric fields and a barrier to the penetration of the hot electrons. The heating of the background electrons lowers their Spitzer resistivity. Flux-limited thermal conduction is included to spread this heating effect. Once heated, the resistivity can “bleach” out of the background plasma, lowering its barriers to hot electron penetration. During each time step, \( \Delta t \), laser light is tracked in across the mesh, and deposited with exponential decay over distance by inverse-bremsstrahlung, and dump-all (representing the principle short pulse mechanism) in the neighborhood of the critical density. Laser absorption results in the generation of the hot electron component at an energy determined from prior full-particle PIC simulations.

**SPECIAL FEATURES**

The code does careful accounting of current flow across the cell walls. This eliminates the need for an additional elliptic equation solution to correct the E-field divergence. However, the predicted currents from Eq. (6) may differ from the true currents determined from the transport of real fluids or particles. ANTHEM uses the difference between the predicted and true current as a source term, correcting the E-fields in the next computational cycle [8]. This could be iterated to bring the two sets of currents into greater accord at the end of each cycle. But this has not been found necessary. The Implicit Moment Method has blended well with our treatment of individual components as fluids. For relativistic electron fluids we have used Mosher’s [25] formulation of the fluid equations. A most crucial feature is that we shift from updating the velocities to updating the relativistic momenta, \( \vec{p}_{h,c} \), under the \( E \)-fields and pressure gradients. This, of course, restricts all velocities, \( \vec{v} = \vec{p}/\gamma \), to less than \( c \), the speed of light, with \( \gamma \) representing the component’s Lorentz factor. This can, of itself, be a restraint on the flow of return current to the laser-heating site. Mosher’s formulation forces certain isotropic constraints on the electron pressure,
which may prove unrealistic in practice. This has encouraged us to consider the Direct Implicit Method [11], which avoids the need for a pressure calculation, for the relativistic components in future versions of the code. Ponderomotive effects are included as a force on the cold background electrons, and on hot emission electrons of the form, \( F_{h,c} = -\left(\omega_p^2/2\right) V I \), in which \( I \) is the laser intensity, and \( \omega_p^2 = 4\pi e^2 n/m_0 \gamma \) with \( m_0 \) the electron rest mass [24].

FAST IGNITOR APPLICATION

The Fast Ignitor concept [23] is an alternate approach to ICF, in which short pulse lasers are used to initiate burn at the surface of the compressed DT fuel. The aim is to avoid the need for careful timing and central focusing of final shocks, and possibly to lower substantially the energy requirements for ignition. The new approach may prove crucial should either emerging needs for more drive energy, or other difficulties render the presently planned classical nanosecond time-scale approach to ignition with the NIF impractical. Ignition is a first step towards the achievement of substantial energy and neutron outputs. For success with the Fast Ignitor, the laser energy must be efficiently deposited into megavolt electrons (suprathermal), which must, in turn, couple to the background ions within an alpha-particle range. To understand the electron fuel coupling, we have used ANTHEM to model the transport of hot electrons generated by an intense \( (\geq 3 \times 10^{18} \text{ W/cm}^2) \) short-pulse 1.06 \( \mu \text{m} \) laser into plasma targets over a broad range of densities \( (0.35 \text{ to } 10^4 \times n_{\text{crit}}) \).

We have shown [24] that: 1) the intense (30 MG to 1.5 GG) magnetic fields arise in this interaction are due to the ponderomotive push on background electrons, and tardy electron shielding, and that 2) these fields can confine the heated electrons to the surface, possibly aiding fast ignition.

Fig. 2. Magnetic fields, densities and electron flux under intense laser illumination.
Figure 2 reproduces typical ANTHEM results with fluid hot electrons. Frame (a) shows axial cuts of the magnetic field for a $3.3 \times 10^{18}$ W/cm$^2$ glass laser drive producing 700 keV electrons with 40% absorption in an initial 50 times overdense plasma. It shows a peak field of 300 MG at 340 fs directed in consistency with a central stream of hot electrons into the plasma. Frame (b) shows concomitant B-field contours. Frame (c) is the hot emission electron flux $n_{h}$, (d) gives the return flow $n_{c}$. Clearly, the hot electrons are strongly focused along the central axis of the beam through the null point in magnetic field.

ANTHEM indicates that the focusing effect grows more intense, as both the background density and the laser intensity is increased. A resultant trapping of the hot electrons near the surface can lead to energy loss though fast-ion surface emission. Such effects must be given careful consideration in capsule design for the Fast Ignitor. Frames b) and c) do not show the electron beam breakup characteristic of full-particle PIC code calculations [26] and attributed, in part, to Weibel instability [27].

**FUTURE DIRECTIONS**

Most recent calculations with ANTHEM have been run with all the plasma components in the fluid mode. This has the advantage that symmetric problems show smooth, symmetric results, unlike PIC simulations where particle statistics can warp the symmetry. However, the isotropic perfect gas in our fluid modeling lacks the structure needed to manifest Weibel instability. On the other hand, collisions in the dense plasma should be expected to suppress Weibel instability [28]. Hybrid ANTHEM simulations with particle hot electrons are planned to explore these effects.

An advantage of implicit simulation is that larger systems can be modeled. Full-particle codes are often run as periodic to emulate a larger medium. Our implicit model can be used to check the flow of hot electrons off the target front surface, and around a target’s sides to its back surface. Our early double diffusion model [5] manifested such circulating transport. Now, its significance in launching fast ions of the back side of foils is of experimental interest.

The background plasma is probably best treated as a fluid, but not as a perfect gas. Access to a tabular equation of state is desirable for real background materials. Conversion of the most energetic emerging electrons and ion to particles, is straightforward, and is planned for a future code upgrade. This should guarantee the most accurate relativistic treatment of electron stream, and any nearly collisionless effects in any generated ion beams. Reflected ion beams, bounced off ion-acoustic shocks, constitute such an effect [29]. They may account for a significant spread in the energies of ions launched by shocks crossing low-density foils [30].

Our present deposition model requires a preparatory full-particle calculation to ascertain the hot electron emission spectrum. Future efforts will be devoted to determination of both the implicit resistive return electron transport, and the laser absorption in the same calculation. A constrained return current will influence the availability of “cold” electrons for laser absorption and heating.

ANTHEM has been restricted to a single $B$-field component. This restriction must be eliminated. Avoidance of the customary coupled multiple elliptic equation formulation is certainly a goal, particularly if efficient parallelism is to be achieved.
REFERENCES


