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LASNEX: PONDEROMOTIVE FORCE ALGORITHM

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LASNEX: PONDEROMOTIVE FORCE ALGORITHM

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Abstract

The new algorithm used to calculate the ponderomotive force in LASNEX is discussed. The algorithm is shown to be identical with the corresponding analytic expression when the WKB solution for the fields in a plane-parallel medium is used. LASNEX calculations performed to check the ponderomotive force algorithm are described.

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LASNEX: PONDEROMOTIVE

FORCE ALGORITHM

The method of calculating the ponderomotive force in LASNEX has recently been modified. The new algorithm was obtained by demanding that momentum be conserved and by using the well-known WKB (geometrical optics) solution for wave propagation in a plane-parallel medium such that $\epsilon(\omega, r) = \epsilon(\omega, x)$. The full analytic expression for the ponderomotive force (the gradient of the radiation stress tensor) reduces exactly to the new LASNEX prescription for cylindrical geometry (as in LASNEX) using the WKB solution for the fields.

The algorithm for the ponderomotive force, F_p^{LASNEX} , in LASNEX in terms of the light intensity, I , and the real part of the dielectric function, ϵ , may be written as follows:

$$\left(F_p^{\text{LASNEX}}\right)_\alpha = - \frac{\partial}{\partial x_\alpha} \left[(1 - \epsilon) \frac{I}{2c\epsilon^{1/2}} \right] - \frac{\partial}{\partial x_\beta} \Pi_{\alpha\beta} \quad (1)$$

where $\Pi_{\alpha\beta} = \frac{I\epsilon^{1/2}}{c} (\hat{I} \cdot \hat{\alpha})(\hat{I} \cdot \hat{\beta})$ and c is the speed of light. $\hat{I}$ is a unit vector in the direction of the radiation energy flux. $\hat{\alpha}, \hat{\beta}$ are unit vectors in a given coordinate system. For the configuration illustrated in Fig. 1, $\hat{I}$ and $\underline{\Pi}$ become

$$\hat{I} = \hat{r} \sin\theta + \hat{z} \cos\theta \quad (2)$$

and

$$\underline{\underline{\Pi}} = \frac{I\epsilon^{1/2}}{c} \begin{bmatrix} \sin^2\theta & \sin\theta \cos\theta \\ \cos\theta \sin\theta & \cos^2\theta \end{bmatrix} = \begin{bmatrix} \Pi_{rr} & \Pi_{rz} \\ \Pi_{zr} & \Pi_{zz} \end{bmatrix} \quad (3)$$

In practice the second term in eq. (2) is handled by differencing the r and z momentum components of each light ray across a zone rather than actually forming $\Pi_{\alpha\beta}$. One quarter of the momentum difference is given to each zone vertex.

The analytic expression for the ponderomotive force is given below, in terms of the radiation stress tensor, $\underline{\underline{P}}_R$, generalized to include the effects of absorption¹

$$\underline{\underline{F}}_p = -\underline{\nabla} \cdot \underline{\underline{P}}_R$$

where

$$\underline{\underline{P}}_R = \frac{1}{4\pi} \left\{ \epsilon_{\text{real}} \underline{\underline{E}}\underline{\underline{E}} + \underline{\underline{B}}\underline{\underline{B}} \right\} - \frac{1}{2} \langle E^2 + B^2 \rangle \underline{\underline{I}} \quad (4)$$

and $\underline{\underline{E}}$ and $\underline{\underline{B}}$ are the laser field quantities. $\langle \rangle$ indicates time average, $\underline{\underline{I}}$ is the unit tensor. The WKB solution for wave propagation in a plane-parallel medium² yields an expression for $\langle E^2 \rangle$ in terms of the vacuum field quantity, E_{vac} .

$$\langle E^2 \rangle = \langle E_{\text{vac}}^2 \rangle / \epsilon^{1/2} \quad (5)$$

¹ Thomson, Max, Estabrook, PRL, 35, 663 (1975).

² Ginzburg, The Propagation of Electromagnetic Waves in Plasmas, Pergamon Press, Oxford, 1970, p. 227.

By Maxwell's equations

$$\epsilon \langle E^2 \rangle = \langle B^2 \rangle \quad (6)$$

as the permeability, μ , is infinitesimally different from unity for a plasma in thermodynamic equilibrium.³ The light intensity is just the energy flux of the radiation $\frac{E^2}{4\pi} c\epsilon^{1/2}$. Thus

$$\frac{\langle E^2 \rangle}{8\pi} = \frac{\langle E_{vac}^2 \rangle}{8\pi\epsilon^{1/2}} = \frac{I}{2c\epsilon^{1/2}} \quad (7)$$

Finally if eq. (4) is evaluated for the configuration shown in Fig. 1, choosing $\mathbf{B}$ to be directed into the page and $\mathbf{E} = |\mathbf{E}| (\hat{z} \sin\theta - \hat{r} \cos\theta)$, using eqs. (5), (6), and (7), one obtains the identity between the analytic expression for the ponderomotive force and the new LASNEX algorithm.

$$\mathbf{F}_p = \mathbf{F}_p^{LASNEX} \quad (8)$$

LASNEX calculations were carried out to check the new ponderomotive force algorithm. First, the momentum deposited in the material by the laser light was examined for one-dimensional configurations in which laser light was incident upon a slab of hydrogen. In a time, Δt , the total light momentum crossing a surface with area, A , due to a normally incident laser beam with power, P , and cross sectional area, A , also is the following:

$$\left(\begin{array}{c} \text{Total light} \\ \text{momentum} \end{array} \right) = \left(\frac{I}{c^2} \right) A c \Delta t = P \Delta t / c \quad (9)$$

where $\left(\frac{I}{c^2} \right)$ is the light momentum density.

³ Ibid, p. 27.

In the LASNEX examples, we checked to see that the net change in the light's momentum from its entry into the slab to its exit using eq. (9) was exactly balanced by the increase in the momentum of the material due to the ponderomotive force. This type of calculation was done for normal incidence as well as for various angles of incidence. In the latter case, the separate r and z components of the momenta were resolved. For non-normal incidence and complete reflection, the net momenta of the light is only in the direction normal to the surface as the ray path is symmetric about the normal. However, when absorption occurs in the case of non-normal incidence, there is a tangential component of the light momenta deposited. This type of momentum deposition is due to the second (tensor) term in the ponderomotive force algorithm, eq. (1). The proper treatment of this tensor aspect of the ponderomotive force is a very important attribute of our algorithm. In all cases each component of the light momenta exactly equalled the momenta deposited in the material as it should. In addition, these one-dimensional calculations were done for both possible orientations, i.e. allowing either the r or the z coordinate to move while the other is held fixed.

Other one-dimensional calculations were performed in which light was shined through underdense slabs with either uniform density or two linear density ramps back to back. For these cases the net momentum deposition by the light into the material was zero up to round-off error as it should be.

Finally the actual magnitude of the ponderomotive force for normal incidence upon a linear density gradient assuming 100% reflection at the

the critical density was compared with the analytical result given in the paper by Lindl and Kaw⁴, in their Fig. 1. The oscillatory character of the force is, of course, not present for our algorithm. However, if a spatial average of the analytical result is taken, the two forces compare quite well. See Fig. 2. The LASNEX algorithm does give a larger positive force (acting in the direction of the beam) because the WKB swelling factor over-estimates the field at the critical density. Figure 2 illustrates the nature of the approximation made to the ponderomotive force by the newly implemented algorithm. Each point on the graph in Figure 2 corresponds to a LASNEX zone in the test calculation. However, the zones in this test calculation are approximately an order of magnitude smaller than the zones typically employed by LASNEX users. Therefore, agreement with a spatial average of the theoretical curve is exactly what is desired.

⁴ Lindl and Kaw, Phys. Fluids 14, 371-7 (1971).

Figure 1

Typical LASNEX configuration showing light intensity vector
and corresponding field vectors.

Fig. 1

Figure 2

Ponderomotive force for normal incidence as a function of distance from the plane of reflection. LASNEX ponderomotive force values and a spatial average of the analytic curve are also shown. The laser wavenumber is k ; $a \left[\approx \frac{1}{n} \frac{dn}{dz} \right]$ is a measure of the density gradient.

- LASNEX force
- + Estimated spatial average of analytic curve

Fig. 2

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