MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK

LAPLAS -
A one - dimensional code for laser plasma simulations

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Abstract

This report describes in detail a FORTRAN program called LAPLAS which was developed to support the laser plasma experiments carried out at MPQ. LAPLAS is a one-dimensional finite difference Lagrange code which solves the gasdynamical equations allowing for two temperatures (electronic and ionic). The formulation is explicit for the hydrodynamics and implicit in the energy equations. A tabulated equation of state is used.

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I) Introduction

Experiments connected with inertial confinement fusion (ICF) and related topics are being carried out at MPQ, mainly with the ASTERIX III laser. In order to achieve a thorough theoretical understanding of the processes going on in such experiments a numerical simulation code was developed [1]. This report describes in detail the FORTRAN program together with the output from a typical run.

The code is called LAPLAS (= LAser PLASma code) and solves the one-dimensional gasdynamics equations with two temperatures (electrons and ions). It includes flux limited thermal conductivity, energy exchange between electrons and ions, inverse Bremsstrahlung absorption in the corona and fast electron preheat. It uses a tabulated equation of state (EOS) from the SESAME library [4]. A hybrid scheme is chosen which treats the hydrodynamic part explicitly and the coupled energy equations implicitly. A geometry option is built in which allows the treatment of plane, cylindrical or spherical symmetric cases. There are two versions of the code: version 1 uses a totally ionized ideal gas EOS while version 2 uses the SESAME data.

II Basic equations

We have two fluids, namely electrons and ions with masses m_e and m_i, number densities n_e and n_i, temperatures T_e and T_i, and partial pressures p_e and p_i. The hydrodynamic motion is dominated by the heavy ions, so only one fluid needs to be modeled: The total mass density ρ is approximated by $n_i m_i$, the bulk velocity is $\bar{v} \cong \bar{v}_i$. The continuity equation then reads

$$\partial n_i/\partial t + \nabla \cdot (n_i \bar{v}) = 0 \qquad (1)$$

The momentum equation acquires the form

$$n_i m_i d\bar{v}/dt = -\nabla(p_e+p_i) \qquad (2)$$

with the substantial derivative $d/dt := \partial/\partial t + \bar{v} \cdot \nabla$.

The energy equations follow directly from the first law of thermodynamics. We use (1) and write

$$\rho c_v^j dT_j/dt = -T_j(\partial p_j/\partial T)_\rho \nabla\cdot\bar{v} + \rho\, dQ_j/dt \qquad (3a,b)$$

for electrons and ions $j = e,i$. Here $c_v^j := (\partial U_j/\partial T)_\rho$

is the specific heat derived from the internal energy per mass U. $\rho\dot{Q}_j$ represents the energy sources for each species:

$$\rho\dot{Q}_e = \nabla\Phi + \nabla \cdot (\kappa_e \nabla T_e) + 2\rho\omega_c (T_i - T_e) \quad , \qquad (4a)$$

$$\rho\dot{Q}_i = \qquad \nabla \cdot (\kappa_i \nabla T_e) - 2\rho\omega_c (T_i - T_e) \quad . \qquad (4b)$$

Φ is the laser energy flux coupling to the electrons only, κ_e and κ_i are the heat conductivity coefficients and ω_c is related to the electron-ion collision frequency ν_{ei} by

$$\rho\omega_c = 3\, n_e k m_e \nu_{ei}/2/m_i$$

($k = 1{,}38 \cdot 10^{-16}$ eV/K is the Boltzmann constant).

The electron density is simply given by

$$n_e = Z_{eff} n_i \qquad (5)$$

where Z_{eff} is the ionic charge.
The transport coefficients (according to Spitzer) are taken from [2]:

$$\kappa_e = \gamma_e(Z_{eff})\ 3\ k^{7/2}\ T_e^{5/2}/(4\sqrt{m_e}\sqrt{2\pi}\ e^4\ Z_{eff}\ \ell n\Lambda) \quad , \qquad (6)$$

$$\kappa_i = \gamma_i(Z_{eff})\ 3\ k^{7/2} T_i^{5/2}/(4\sqrt{m_i}\sqrt{\pi}\ e^4 Z_{eff}^4\ \ell n\ \Lambda) \quad , \qquad (7)$$

$$\nu_{ei} = 4\ \sqrt{2\pi}\ e^4 \ell n\Lambda\ Z_{eff}\ n_e / (3\sqrt{m_e}\ k^{3/2}\ T_e^{3/2}) \quad . \qquad (8)$$

$\gamma_e(Z)$ and $\gamma_i(Z)$ are given in [2], $\ln\Lambda$ denotes the Coulomb logarithm. (Actually, mean values are used: $\gamma_e = 7.$, $\gamma_i = 3.9$, $\ln\Lambda = 10.$) Accomplished by an equation of state $p(\rho,T)$, $U(\rho,T)$, the system (1) to (4) is closed.

III Lagrange coordinates

Because of the violent plasma expansion, it is very convenient to have a coordinate system which is tied to the mass of the system. In one-dimensional geometry the conservation of the mass reads

$$4\pi\rho_o \int_{r_1}^{r} r^{(\alpha-1)}\ dr = 4\ \pi \int_{R_1}^{R} \rho(R) R^{(\alpha-1)} dR \quad \text{or}$$

$$\partial R/\partial r = (\rho_o/\rho(r,t))(r/R(r,t))^{\alpha-1} \qquad \text{with} \qquad (9)$$

$R(r,0) = r, \quad \rho_o = \rho(r,0).$

$\alpha = 1$: plane geometry (foils)
$\alpha = 2$: cylindrical geometry
$\alpha = 3$: spherical geometry.

R = Euler coordinate,
r = Lagrange coordinate.

Now we choose the Euler coodinate at t = 0 as a new independent variable and transform our equations into the comoving Lagrangian system ($\underline{v}$ = 0):

$$\partial n_i/\partial t = - (n_i^2/n_i^o) r^{1-\alpha}\, \partial(R^{\alpha-1}v)/\partial r \qquad (10)$$

$$\partial v/\partial t = - \rho_o^{-1} (R/r)^{\alpha-1}\, \partial(p+q)/\partial r \qquad (11)$$

$$\partial R/\partial t = v \qquad (12)$$

$$\rho c_v^e \partial T_e/\partial t = (n_i/n_i^o) r^{1-\alpha}\, \partial(R^{\alpha-1}\Phi)/\partial r +$$

$$+ (n_i/n_i^o) r^{1-\alpha}\, \partial(R^{\alpha-1} \kappa_e (n_i/n_i^o)(R/r)^{\alpha-1}\, \partial T_e/\partial r)/\partial r + \qquad (13a)$$

$$+ 2\rho\omega_c\, (T_i - T_e) -$$

$$- T_e\, (\partial p_e/\partial T)_\rho\, (n_i/n_i^o) r^{1-\alpha} \partial(R^{\alpha-1}v)/\partial r \qquad (13b)$$

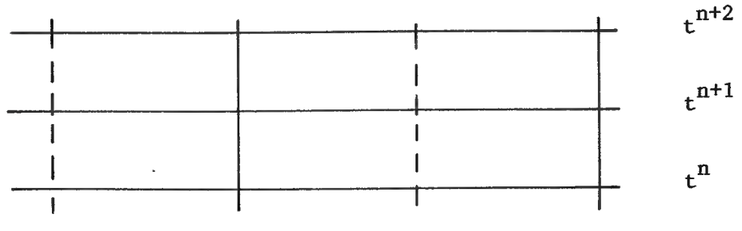
(ions analogous, insert q).

An artificial viscosity q is introduced (see [3]) which is defined by

$$q := \begin{cases} \rho \ell^2\, (\partial v/\partial R)^2 & \text{if} \quad \partial v/\partial R < o \\ 0 & \text{otherwise.} \end{cases}$$

The dimensionless viscosity length ℓ should be around 1.5 to 2.0 thus giving the shocks a thickness around 3 to 5 zones.

IV) The Richtmyer-von Neumann scheme [3]



The velocities v_j are defined at the zone boundaries R_j, whereas the temperatures and densities are defined at the center j+1/2. The time centering is at $t^{n+1/2}$. The scheme is now

$$(R_j^{n+1} - R_j^n)/\Delta t = v_j^{n+1} \quad , \qquad (14)$$

$$(v_j^{n+1} - v_j^n)/\Delta t = -\rho_o^{-1} (R_j^n/r_j)^{\alpha-1} (P^n_{j+1/2} - P^n_{j-1/2} + \qquad (15)$$

$$+ q^n_{j+1/2} - q^n_{j-1/2}) / (r_{j+1} - r_j) \quad ,$$

$$\rho^{n+1}_{j+1/2} = \rho_o (r^\alpha_{j+1} - r^\alpha_j)/((R^{n+1}_{j+1})^\alpha - (R^{n+1}_j)^\alpha) \, . \qquad (16)$$

Instead of (10) we used equation (9) which guarantees total and global mass conservation.

Boundary conditions:

The boundary conditions are formulated at the integer points j = J.

a) free surface:

$$p^n_{J+1/2} = -p^n_{J-1/2} + 2p_o \text{ for all n}$$

including an applied external pressure p_o (for instance, p_o is used to prevent an ideal gas from running away).

b) rigid wall:

$$v^n_J = 0 \quad \text{for all n.}$$

In addition for the center of a sphere: $R^n_J = 0$ for all n.

The system (14) to (16) is explicit. The time step Δt is given by the Courant-Friedrichs-Lewy stability criterion

$$c\Delta t/(R^n_{j+1} - R^n_j) \leqq 1 \qquad \text{for all n, j}$$

($c^2 = \partial p/\partial \rho$ sound velocity).

Sequence of computation:

Given the state of the hydrodynamic system at time $t = t^n$ together with the boundary conditions at $j = 1$ and $j = M$. Then equation (15) gives the new velocities $v_j^{n+1}(j=2, .., M-1)$. From the boundary conditions we infer v_1^{n+1} and v_M^{n+1}. Eq. (14) yields the new coordinates $R_j^{n+1}(j = 1, ..., M)$ and eq. (16) the new densities $\rho_{j+1/2}^{n+1}$. The solution of the implicit scheme for the energy equations finally gives $T_{j+1/2}^{n+1}$ and with the EOS $p_{j+1/2}^{n+1}$. So the new state at $t = t^{n+1}=t^n+\Delta t$ is fixed (the artificial viscosity $q_{j+1/2}^{n+1}$ is calculated from ρ_{j+1}^{n+1} and v_j^{n+1}).

V) The implicit scheme for the energy equations

1) Version 1: The ideal gas

For an ideal gas we have the EOS ($\gamma = 5/3$)

$$P_j = n_j k T_j \qquad (j = e,i) \tag{17}$$

$$U_j = P_j/\rho/(\gamma-1) = 3\ k\ T_j n_j/2\rho.$$

We immediately derive $c_V^j = 3/2\ k\ n_j/\rho$ and $T_j(\partial p/\partial T)_\rho = P_j$.
Assuming total ionization we obtain the relation

$$n_e = Z n_i$$

with the atomic number Z.
Eqs. (13) are then given by

$$\partial Te/\partial t = (2/3kn_e^o)r^{1-\alpha}\ \partial(R^{\alpha-1}\Phi)/\partial r +$$

$$+ (2/3\ kn_e^o)r^{1-\alpha}\ \partial(R^{\alpha-1}\ \kappa_e(n_e/n_e^o)(R/r)^{\alpha-1}\partial T_e/\partial r)/\partial r +$$

$$+ 2\ (m_e/m_i)\ \nu_{ei}\ (T_i-T_e) - \tag{18a}$$

$$- (2/3)\ T_e\ (n_e/n_e^o)\ r^{1-\alpha}\partial(R^{\alpha-1}v)/\partial r$$

$$\partial T_i/\partial t = (2Z/3kn_e^o)r^{1-\alpha}\ \partial(R^{\alpha-1}\ \kappa_i(n_e/n_e^o)(R/r)^{\alpha-1}\partial T_i/\partial r)/\partial r$$

$$+ 2\ Z\ (m_e/m_i)\ \nu_{ei}\ (T_e - T_i) -$$

$$- (2/3)(T_i+qZ/(n_e k))(n_e/n_e^o)r^{1-\alpha}\partial(R^{\alpha-1}v)/\partial r \tag{18b}$$

The thermal conductivities are redefined

$$\kappa_j =: \kappa_j^*\ T_j^{5/2} \qquad (j = e,i) \tag{19}$$

and expressions like $T_j^{5/2}\partial T_j/\partial r$ are replaced by $(2/7)\partial T_j^{7/2}/\partial r$.

Heat flux limitation:

The electronic heat flux is limited by an upper bound which is called the "free streaming" value. In addition, we apply a constant factor f (= parameter) and write

$$q_{max} = f n_e k T_e (kT_e/m_e)^{1/2}.$$

Redefining the electronic heat conductivity to

$$q_e = -\bar{\kappa}_e \nabla T_e = \kappa_e \nabla T_e/(1+\kappa_e \nabla T_e\ /q_{max}) \tag{20}$$

amounts to interpolating by the harmonic mean

$$1/|q_e| = |1/\kappa_e\ \nabla T_e| + 1/q_{max}.$$

So we have

$$\bar{\kappa}_e = \kappa_e\ (1 + |\kappa_e \nabla T_e|/q_{max.})^{-1} =: \xi\ \kappa_e. \tag{21}$$

An explicit numerical scheme of the diffusive equations (18) would require a much more restrictive stability criterion than the one for the hydrodynamics. Therefore an implicit scheme is chosen.

In the code we denote the indices j-1/2 with J, j+1/2 with J+1 and so forth. By central difference δf_j or $(\delta f)_j$ of a quantity defined at j we mean

f(j+1/2)-f(j-1/2). The evaluation of some expression f at the intermediate time $t^{n+\theta} := t^n + \theta\Delta t$ is abbreviated by

$$[f]^{n+\theta} := \theta \cdot f^{n+1} + (1-\theta) \cdot f^{n}.$$

($0 \leqq \theta \leqq 1$, $\theta = 0$ is fully explicit, $\theta = 1$ means fully implicit, stability requires $1/2 \leqq \theta \leqq 1$). Then eq. (18) reads (TE := T_e, TI := T_i)

$$\begin{aligned}(TE^{n+1}_{j+1/2} - TE^{n}_{j+1/2}) \,/\, \Delta t = {} & \alpha_1 \,(\delta F_{j+1/2})^n + \\ & + \alpha_2 \,[\delta(\sigma_e \delta TE^{7/2})_{j+1/2}]^{n+\theta} \\ & - \alpha_3 \,[(n_e)_{j+1/2}/(TE_{j+1/2})^{3/2}\,(TE-TI)_{j+1/2}]^{n+\theta} \\ & - \alpha_4 \,[(TE\; n_e)_{j+1/2}\,\delta(R^{\alpha-1}v)_{j+1/2}]^{n+\theta}\end{aligned} \qquad (22a)$$

with $F := \Phi R^{\alpha-1}$

$$\sigma_e := \xi\, n_e R^{2(\alpha-1)}/(n_e^o r^{\alpha-1})$$

$$\alpha_1 := 2/(3\, kn_e^o)\;\alpha/\;(r_{j+1}^{\alpha} - r_j^{\alpha})$$

$$\alpha_2 := 4\kappa_e^*/(21 k n_e^o)\alpha/(r_{j+1}^{\alpha} - r_i^{\alpha})/\Delta r$$

$$\alpha_3 := 2(m_e/m_i)\nu_{ei}^* \quad (\nu_{ei} =: \nu_e^* {}_i n_e / T_e^{3/2})$$

$$\alpha_4 := 2\alpha/(3n_e^o)/(r_{j+1}^{\alpha} - r_j^{\alpha}) \;.$$

Furthermore, $\Delta r = r_{j+1} - r_j$ and $r^{\alpha-1}\Delta r$ is replaced by $(r_{j+1}^{\alpha} - r_j^{\alpha})/\alpha$. Analogously, for the ions (22b).

2) Version 2: Tabulated EOS:

Due to the history of this code version 2 is written in a way that it appears as a correction to version 1 without changing the structure of the implicit energy routine.

Some comments on the EOS tables in advance: The SESAME data we have access to so far only contain one temperature, so we have to decompose the pressure $p = p_e + p_i$ and the internal energy by some reasonable assumption. We assume the ions to be still an ideal gas. (In future, two temperature tables of SESAME will be available)

The electronic pressure at temperature T_e then becomes

$$p_e = p_s(\rho, T_e) - n_i k T_e$$

where $p_s(\rho, T_e)$ is the SESAME interpolated value. An analogous treatment for the internal energy gives the specific heat for the electrons:

$$\rho c_V^e = \rho\,(\partial U_s/\partial T)_\rho - 3\, kn_i/2$$

We now define the correction factors which arise due to the EOS being different from an ideal gas:

$$RC := ((2m_i/3k)\,(\partial U_s/\partial T)_\rho - 1)/Z_{eff} \qquad (23)$$

$$PT := ((1/kn_i)(\partial p_s/\partial T)_\rho - 1)/Z_{eff} \qquad (24)$$

For an ideal gas (= version 1) we have RC = PT = 1, $Z_{eff} = Z$.
Eq. (13a) then reads

$$\begin{aligned}\frac{\partial T_e}{\partial t} = {} & \frac{1}{RC}\frac{1}{Z_{eff}}\frac{2}{3kn_i^o}\frac{1}{r^{\alpha-1}}\frac{\partial}{\partial r}\left(R^{\alpha-1}\Phi\right) + \\ & + \frac{1}{RC}\frac{1}{Z_{eff}}\frac{2}{3kn_i^o}\frac{1}{r^{\alpha-1}}\frac{\partial}{\partial r}\left(R^{\alpha-1}\kappa_e\frac{n_i}{n_i^o}\left(\frac{R}{r}\right)^{\alpha-1}\frac{\partial T_e}{\partial r}\right) + \\ & + \frac{1}{RC}\,2\,\frac{m_e}{m_i}\,\nu_{ei}\,(T_i - T_e) - \\ & - \frac{PT}{RC}\,\frac{2}{3}\,T_e\,\frac{n_i}{n_i^o}\,\frac{1}{r^{\alpha-1}}\,\frac{\partial}{\partial r}\left(R^{\alpha-1}v\right)\end{aligned} \qquad (25a)$$

and for the ions

$$\frac{\partial T_i}{\partial t} = \frac{2}{3kn_i^o}\,\frac{1}{r^{\alpha-1}}\,\frac{\partial}{\partial r}\left(R^{\alpha-1}K_i\,\frac{n_i}{n_i^o}\left(\frac{R}{r}\right)^{\alpha-1}\frac{\partial T_i}{\partial r}\right) + \tag{25b}$$

$$+ 2\,Z_{eff}\,\frac{m_e}{m_i}\,\nu_{ei}\,(T_e - T_i) -$$

$$- \frac{2}{3}\left(T_i + \frac{q}{kn_i}\right)\frac{n_i}{n_i^o}\,\frac{1}{r^{\alpha-1}}\,\frac{\partial}{\partial r}\left(R^{\alpha-1}v\right).$$

Now we see that all the corrections can be put into the coefficients $\alpha_1 \ldots \alpha_4$ provided we formulate the equations with n_i instead of n_e. The information about Z_{eff} of course is hidden in the EOS. A first crude estimate is given by the relation

$$Z_{eff} = U_s(\rho,T_e)/(3kT_e/2m_i) - 1 \quad \text{for } Z_{eff} \leq Z \tag{26}$$

(This will be improved in the future).
One problem with the tabulated EOS is interpolation. We found it most adequate to interpolate linearly in the logarithms which gives correct values for the ideal gas. In cases where they are not explicitly needed, negative pressure values are being suppressed. The target density ρ_o is calculated from the tables by finding the density where the pressure vanished at given initial temperature.

VI) Solution of the implicit difference scheme

The system (22a,b) must be solved for $TE^{n+1}_{j+1/2}$ and $TI^{n+1}_{j+1/2}$. To this end, the nonlinear parts are linearized:

a) The heat conduction term

$$\left(TE^{7/2}\right)^{n+1}_j = \left(TE^{7/2}\right)^n_j + \frac{7}{2}\,TE_j^{5/2}\,\underbrace{\left(TE^{n+1}_j - TE^n_j\right)}_{=:\,w^e_j} + \cdots$$

$$\bar\alpha_2\left[\delta\left(\sigma_e\,\delta TE^{7/2}\right)_{j+1/2}\right]^{n+\theta} = \tag{27a}$$

$$= \bar\alpha_2\left[(\sigma_e)_{j+1}\left(TE^{7/2}_{j+3/2} - TE^{7/2}_{j+1/2}\right) - (\sigma_e)_j\left(TE^{7/2}_{j+1/2} - TE^{7/2}_{j-1/2}\right)\right]^{n+\theta} =$$

$$= \bar\alpha_2\,\theta\Big((\sigma_e)^{n+1}_{j+1}\left\{(TE^{7/2})^n_{j+3/2} - (TE^{7/2})^n_{j+1/2} + \tfrac{7}{2}\left(TE^{5/2}\right)^n_{j+3/2} W^e_{j+3/2} - \tfrac{7}{2}\left(TE^{5/2}\right)^n_{j+1/2} W^e_{j+1/2}\right\} -$$

$$- (\sigma_e)^{n+1}_j\left\{(TE^{7/2})^n_{j+1/2} - (TE^{7/2})^n_{j-1/2} + \tfrac{7}{2}\left(TE^{5/2}\right)^n_{j+1/2} W^e_{j+1/2} - \tfrac{7}{2}\left(TE^{5/2}\right)^n_{j-1/2} W^e_{j-1/2}\right\}\Big) +$$

$$+ \bar\alpha_2(1-\theta)\Big((\sigma_e)^n_{j+1}\left\{(TE^{7/2})^n_{j+3/2} - (TE^{7/2})^n_{j+1/2}\right\} - (\sigma_e)^n_j\left\{(TE^{7/2})^n_{j+1/2} - (TE^{7/2})^n_{j-1/2}\right\}\Big),$$

$$\bar\alpha_2 := \alpha_2/RC\,.$$

b) The relaxation term

We define $$F(n_i, TE, TI) := \frac{n_i\,(TE - TI)}{TE^{3/2}}\,.$$

Then we have

$$F_{TE} := \frac{\partial F}{\partial TE} = n_i\,\frac{\frac{3}{2}\,TE^{1/2}\,TI - TE^{3/2}}{TE^3}$$

$$F_{TI} := \frac{\partial F}{\partial TI} = -\frac{n_i}{TE^{3/2}}$$

$$F_{n_i} := \frac{\partial F}{\partial n_i} = (TE - TI)/TE^{3/2}\,.$$

The linearized relaxation term then can be written

$$\bar\alpha_3\Big(\theta\Big\{F^n_{j+1/2} + \left(F_{TE}\right)^n_{j+1/2} W^e_{j+1/2} + \left(F_{TI}\right)^n_{j+1/2} W^i_{j+1/2} + \tag{27b}$$

$$+ \left(F_{n_i}\right)^n_{j+1/2}\left((n_i)^{n+1}_{j+1/2} - (n_i)^n_{j+1/2}\right)\Big\} + (1-\theta)\,F^n_{j+1/2}\Big),$$

$$\bar\alpha_3 := \alpha_3\,Z_{eff}/RC\,.$$

C) The work term

$$\bar{\alpha}_4 \Big(\theta \Big\{ (TE)^n_{j+1/2} + W^e_{j+1/2} \Big\} (n_i)^{n+1}_{j+1} \Big\{ (R^{\alpha-1})^{n+1}_{j+1} V_{j+1} - (R^{\alpha-1})^{n+1}_{j} V_j \Big\} + \tag{27c}$$

$$+ (1-\theta) (TE)^n_{j+1/2} (n_i)^n_{j+1/2} \Big\{ (R^{\alpha-1})^n_{j+1} V_{j+1} - (R^{\alpha-1})^n_j V_j \Big\} \Big) ,$$

$$\bar{\alpha}_4 := \alpha_4 \, \bar{Z}_{eff} \, \frac{PT}{RC} .$$

Some remarks

The laser flux appears only in the lower time level n, the same is true for the heat flux correction ξ. When calling the energy rountine the new values R^{n+1}_{j+1} and $n^{n+1}_{j+1/2}$ are already known, the old ones are stored. The new velocities v^{n+1}_{j+1} are known, too. Strictly speaking, they are centered between n and n+1 (cf. eq. (14)) and only enter as v_{j+1}. This underlines the hybrid character of the code. RC and PT are evaluated at the old time level n.

The linearization casts the scheme into the following form:

$$-A^e_{j+1} w^e_{j+2} + B^e_{j+1} w^e_{j+1} - C^e_{j+1} w^e_j + G^e_{j+1} w^i_{j+1} = D^e_{j+1} , \tag{28a}$$

$$-A^i_{j+1} w^i_{j+2} + B^i_{j+1} w^i_{j+1} - C^i_{j+1} w^i_j + G^i_{j+1} w^e_{j+1} = D^i_{j+1} . \tag{28b}$$

A, B, ... are the coefficients of the linearized system of equations and are known at time level n. The unknowns are
$w^k_j = (TK)^{n+1}_j - (TK)^n_j$, K = E,I, k = e, i.
The coefficient matrix has a multi-diagonal structure and is solvable by Gauss elimination. We write (24) as

$$\sum_{m=j}^{j+2} H^{j+1}_m \, \Delta\vec{X}_m + \vec{D}_{j+1} = \vec{0} . \tag{29}$$

with

$$H^{j+1}_j := \begin{pmatrix} -C^e_{j+1} & 0 \\ 0 & -C^i_{j+1} \end{pmatrix}$$

$$H^{j+1}_{j+1} := \begin{pmatrix} B^e_{j+1} & G^e_{j+1} \\ G^i_{j+1} & B^i_{j+1} \end{pmatrix}$$

$$H^{j+1}_{j+2} := \begin{pmatrix} -A^e_{j+1} & 0 \\ 0 & -A^i_{j+1} \end{pmatrix}$$

$$\vec{D}_{j+1} := \begin{pmatrix} -D^e_{j+1} \\ -D^i_{j+1} \end{pmatrix} , \qquad \Delta\vec{X}_\ell := \begin{pmatrix} w^e_\ell \\ w^i_\ell \end{pmatrix} .$$

A recursive solution is obtained by the ansatz

$$\Delta\vec{X}_j = E_j \, \Delta\vec{X}_{j+1} + \vec{F}_j \tag{30a}$$

with

$$E_j := \begin{pmatrix} {}^eE^1_j & {}^eE^2_j \\ {}^iE^1_j & {}^iE^2_j \end{pmatrix} , \qquad \vec{F}_j := \begin{pmatrix} {}^eF_j \\ {}^iF_j \end{pmatrix} .$$

Inserting eq. (30) into eq. (29) gives by comparison with $\Delta\vec{X}_{j+1}$:

$$E_{j+1} = -\left(H^{j+1}_j E_j + H^{j+1}_{j+1} \right)^{-1} H^{j+1}_{j+2} \tag{30b,c}$$

$$\vec{F}_{j+1} = -\left(H^{j+1}_j E_j + H^{j+1}_{j+1} \right)^{-1} \left(H^{j+1}_j \vec{F}_j + \vec{D}_{j+1} \right) .$$

In our special case eqs. (30) are analytically solvable. From (30b) we obtain

$$\left(-C^e_{j+1} \, {}^eE^1_j + B^e_{j+1} \right) {}^eE^1_{j+1} + \left(-C^e_{j+1} \, {}^eE^2_j + G^e_{j+1} \right) {}^iE^1_{j+1} = A^e_{j+1}$$

$$\left(-C^e_{j+1} \, {}^eE^1_j + B^e_{j+1} \right) {}^eE^2_{j+1} + \left(-C^e_{j+1} \, {}^eE^2_j + G^e_{j+1} \right) {}^iE^2_{j+1} = 0$$

$$\left(-C^i_{j+1}\,{}^iE^1_j + G^i_{j+1}\right){}^eE^1_{j+1} + \left(-C^i_{j+1}\,{}^iE^2_j + B^i_{j+1}\right){}^iE^1_{j+1} = 0$$

$$\left(-C^i_{j+1}\,{}^iE^1_j + G^i_{j+1}\right){}^eE^2_{j+1} + \left(-C^i_{j+1}\,{}^iE^2_j + B^i_{j+1}\right){}^iE^2_{j+1} = A^i_{j+1}\,.$$

The first and third as well as the second and forth equation form two systems for the unknowns ${}^eE^1_{j+1}$, ${}^iE^1_{j+1}$ and ${}^eE^2_{j+1}$, ${}^iE^2_{j+1}$. Analogously, eq. (30c) is treated to obtain ${}^eF_{j+1}$ and ${}^iF_{j+1}$. We are left with the following system of recursion formula:

$$\alpha_2 = \frac{C^e_{j+1}\,{}^eE^2_j - G^e_{j+1}}{B^e_{j+1} - C^e_{j+1}\,{}^eE^1_j} \qquad \alpha_3 = \frac{C^i_{j+1}\,{}^iE^1_j - G^i_{j+1}}{B^i_{j+1} - C^i_{j+1}\,{}^iE^2_j}$$

$$\alpha_4 = \frac{C^e_{j+1}\,{}^eF_j + D^e_{j+1}}{B^e_{j+1} - C^e_{j+1}\,{}^eE^1_j} \qquad \alpha_5 = \frac{C^i_{j+1}\,{}^iF_j + D^i_{j+1}}{B^i_{j+1} - C^i_{j+1}\,{}^iE^2_j}$$

$$\alpha_6 = \frac{A^e_{j+1}}{B^e_{j+1} - C^e_{j+1}\,{}^eE^1_j} \qquad \alpha_7 = \frac{A^i_{j+1}}{B^i_{j+1} - C^i_{j+1}\,{}^iE^2_j}$$

$${}^eE^1_{j+1} = \frac{\alpha_6}{1-\alpha_2\alpha_3} \qquad {}^iE^1_{j+1} = \frac{\alpha_3\alpha_6}{1-\alpha_2\alpha_3}$$

$${}^eE^2_{j+1} = \frac{\alpha_2\alpha_7}{1-\alpha_2\alpha_3} \qquad {}^iE^2_{j+1} = \frac{\alpha_7}{1-\alpha_2\alpha_3}$$

$${}^eF_{j+1} = \frac{\alpha_4+\alpha_2\alpha_5}{1-\alpha_2\alpha_3} \qquad {}^iF_{j+1} = \frac{\alpha_5+\alpha_3\alpha_4}{1-\alpha_2\alpha_3}\,.$$

The boundary conditions at j = 1 determine ${}^eE^1_1$, ${}^eE^2_1$, ${}^iE^1_1$, ${}^iE^2_1$ as well as ${}^eF_1$ and ${}^iF_1$. The recursion gives the remaining quantities for $2 \leq j \leq M$. The boundary values at j = M fix w^e_M and w^i_M and eq. (30a) all w^e_j, w^i_j $(1 \leq j \leq M-1)$.

Boundary conditions:

At j = 1 and j = M we prescribe

$$\nabla T_e = \nabla T_i = 0 \qquad (31)$$

In cylindrical or spherical geometry this is a consequence of the symmetry at the center. In all other cases, it corresponds to the requirement that no heat leaves the system.

a) j = 1

From (30a) we have

$$w^e_1 = {}^eE^1_1\, w^e_2 + {}^eE^2_1\, w^i_2 + {}^eF_1$$

$$w^i_1 = {}^iE^1_1\, w^e_2 + {}^iE^2_1\, w^i_2 + {}^iF_1$$

Condition (31) means $w^e_1 = w^e_2$ and $w^i_1 = w^i_2$
It follows

$${}^eE^1_1 = 1, \quad {}^eE^2_1 = 0, \quad {}^eF_1 = 0$$

$${}^iE^1_1 = 0, \quad {}^iE^2_1 = 1, \quad {}^iF_1 = 0.$$

b) j = M

Eq. (31) gives $w^e(M+1) = w^e(M)$ and $w^i(M+1) = w^i(M)$.
From (30a)

$$(1 - {}^eE^1_M)\, w^e_M - {}^eE^2_M w^i_M = {}^eF_M$$

$$-\,{}^iE^1_M\, w^e_M + (1 - {}^iE^2_M)\, w^i_M = {}^iF_M$$

with the result

$$w^e_M = D_1 / D, \quad w^i_M = D_2 / D \quad \text{where}$$

$$D: = (1-{}^eE^1_M)\cdot(1-{}^iE^2_M) - {}^eE^2_M\,{}^iE^1_M$$

$$D_1: = {}^eF_M\,(1-{}^iE^2_M) + {}^iF_M\,{}^eE^2_M$$

$$D_2: = {}^iF_M\,(1-{}^eE^1_M) + {}^eF_M\,{}^iE^1_M\,.$$

VII) Meaning of the variables used in LAPLAS:

1) COMMON block:

E02 (322)	Electrons per Debye sphere
DIVUO (322), V(322), Y(322), ZEI (322), ENE (322)	Auxiliary arrays, needed for subrountine FLUG
VELO (322)	velocity v
VELOV (322)	v at old time level
WACHM (322)	Mach number
R (322)	Euler coordinate
HR (322)	" " at old time level
RL (322)	Lagrange coordinate
RHO (322)	electron density / critical density at j
RHO1 (322)	" " " at j+ 1/2
RHO1V (322)	RHO1 at old time
RHOI (322)	ion density / critical density at j+1/2
RHI (322)	" " at j
RHOIV (322)	RHOI at old time
TE (322)	electron temperature
TI (322)	ion "
VIS (322)	artificial viscosity
PHI (322)	laser flux
FLUXL (322)	heat flux / flux limit
X3D (101), Y3D (101)	coordinates for 3-D plot
P (322)	pressure
E (322)	internal energy
RC (322), PT (322)	RC, PT, corrections in energy routine due to EOS
KTE (322), KRHO (322)	position of T and ρ in EOS tables
ZEFF (322)	ionic charge
ST (23)	temperature mesh in EOS
SRHO (100)	density mesh in EOS
SP (100, 23)	EOS pressure table
SEN (100, 23)	EOS internal energy table
PP (100)	auxiliary array needed in RETTEN
NR	number of mesh points in ρ (EOS)
NT	" " " " in T (EOS)
M	number of zones + 1

Further important quantities:

VVO	$(n_e/n_{cr})^{-1}$ at t = 0
VVI	$(n_i/n_{cr})^{-1}$ at t = 0
RHOTAR	target density in g/cm^3
DCR	n_{cr} critical density
PHI0	peak laser flux
S2N, S2N1	square of sound velocity at j-1/2 and j+1/2
HFLK1, HFLK2	ξ = heat flux correction
HFLL1, HFLL2	q_{max} = heat flux limit

2) Input parameters:

IEOS	controls use of EOS
CUT	value at which the pressure is cut
KETEST	controls ETEST
KITEST	controls TESTI
TAUE	time ≧ TAUE necessary for calling ETEST or TESTI
KABSO	controls ABSORP
NFE	controls fast electron creation
DELTAF	fraction of energy which goes into fast electrons
WELAE	range of fast electrons
JFL	controls flux limiting
FFL2	f - factor
THETA	θ
KYE	only version 1 : κ_e is reduced initially, restored after KYE steps
IONEN	controls FLUG
DIST	distance to detector
NZIO	after NZIO time steps spectrum is calculated
IPLO	plot
KPR	first print output
KPR1	repeated output

NZY	controls primitive plot, inactive
IPRO	profile plot at time T(IPRO)
KALP	geometry exponent α
KZEIT	maximum number of time steps
DELTA	fraction of anomalously absorbed energy at n_{cr}
WK	wave number = $2\pi/\lambda_{Laser}$
WLO	peak intensity of laser light in W/cm^2
PAN	external pressure
FOLDI	target thickness
THOO	n/n_{cr} at t = 0
TEO	electronic temperature at t = 0
TIO	ionic " " "
GAMMA	c_p/c_v adiabatic index
Z	mean atomic number of target material
FIO	mean mass " " "
ZEIT	time
ZF	factor applied to time step
IZEI1, IZEI2 ZEIFA1, ZEIFA2	multiply ZF after IZEI time steps with ZEIFA
DZMAX	maximum time step
AEND	upper bound for change per time step
KZO	controls way of fine zoning
MH	M = 2 · MH + 1 (in ZONE2)
DIKOR	coronal thickness for ZONE1
QX	q = factor for fine zoning
NPROF	controls initial target profile
AF	profile form
JP	JP points are involved
IPULS	controls laser pulse shape
TAU	half-width of laser pulse
ZEITM	total width " "
KSHOCK	controls shock treatment
VISL	viscosity length
BB	material code for SESAME-EOS

3) Output

MODELL	number of time steps
ZEIT	time
DZEIT	time step Δt
ABSORPTION	absorption of laser light (momentary)
M	number of zones + 1
MPC	location of critical density
J	zone index
X(CM)	Euler coordinate
NI/NKRIT	ion density / n_{cr}
MACH	Mach number
TI(K)	ion temperature
TE(K)	electron temperature
HFL/FLL	heat flux / flux limit
NDEB	number of particles per debye sphere
J(cgs)	mass flow
SCHUB	push
I,J, EKIN, ETH, Q, EL	1. line: kinetic, thermal, total energy related to absorbed laser energy EL 2. line: same data for accelerated part of the target only
HYDRODYN. WIRKUNGSGRAD	hydrodynamic efficiency η
TOTALE ABSORPTION	total absorption till t
IMPULS1	total momentum/momentum of rear part of the target
IMPULS2	total momentum/momentum of front part of the target
SCHWERPUNKTGESCHW.	center of mass velocity V_{CM}
EFF. DRUCK	mass * $V_{CM}/\Delta t$
ABLATION	ablation rate
OPT. TRANSMISSION	optical transmission

VIII) Short description of the subroutines

1) GET

Fetches the EOS data from disk (→ RETTEN, ARR, include data segment!), determines the target density and stores the logarithms of the EOS tables. For instance, the pressure is stored as log P (log ρ, log T). Ideal gas tables are created to compare with version 1. Entries smaller than CUT are replaced by CUT (however, there is a version which keeps negative pressures).

2) INTP

Interpolates the EOS data linearly in the logarithms. Corrections PT and RC are calculated as well as ZEFF. Derivatives are exact for the ideal gas case because of the linear nature of the EOS, for example

$$(\partial p/\partial T)_\rho = (p/T)\ (\partial \log p\ /\partial \log T)_\rho .$$

The search in the EOS tables is facilitated by using the information which lies in the logarithm of the temperature.

3) TIME

Controls the time step according to the explicit stability criterion

$$DZ = \mathrm{Min}\ (DZ_j)$$

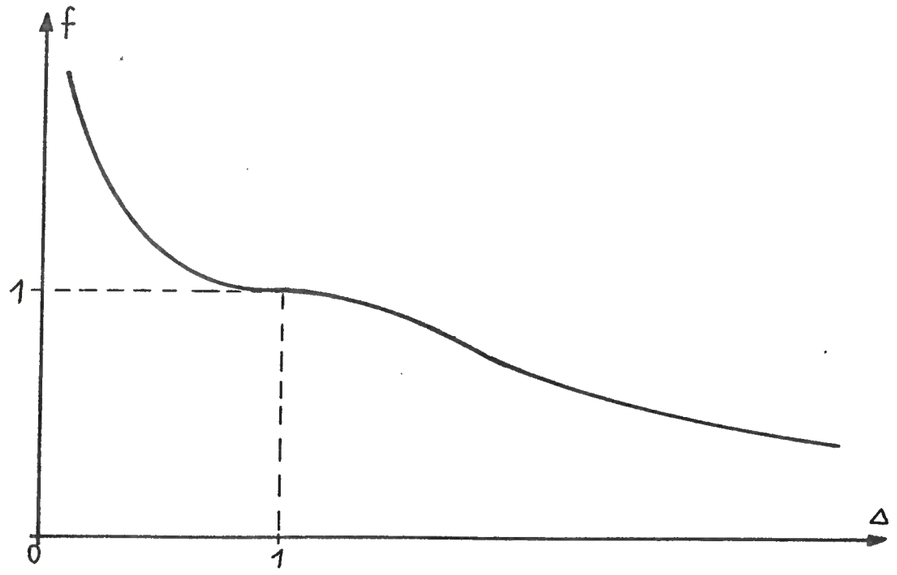
$$DZ_j := \frac{|R_{j+1} - R_j|}{S_{j+1}} \qquad (S_j = \text{sound velocity}).$$

The factor ZF is introduced to manipulate DZ, for example: The run begins with ZF = 0.05. After IZEI1 = 20 steps it is multiplicated by ZEIFA = 5 and after IZEI2 = 500 steps it is multiplicated by ZEIFA2 = 2. So the final ZF = 0.5, the intermediate ZF = 0.25 corresponds to the more stringent stability condition for strong shocks.

For accuracy reasons, an additional automatic time step control is applied in version 2. The maximum relative change DELMAX of all pressures and temperatures per timestep is calculated and the timestep adapted to allow DELMAX not to exceed a given value AEND. To this end, the time factor ZF is multiplied by the funtion

$$f = \begin{cases} (1-(\Delta-1)^2) \ /\ (1-(\Delta-1)^3) & \text{for } \Delta > 1 \\ 1 - (1-\Delta)\ \log \Delta & \text{for } \Delta < 1 \end{cases}$$

with Δ: = DELMAX / AEND. The actual value of *AEND* is around 0.5.



4) ENERG

Implicit solution of the energy equations (see section VI).

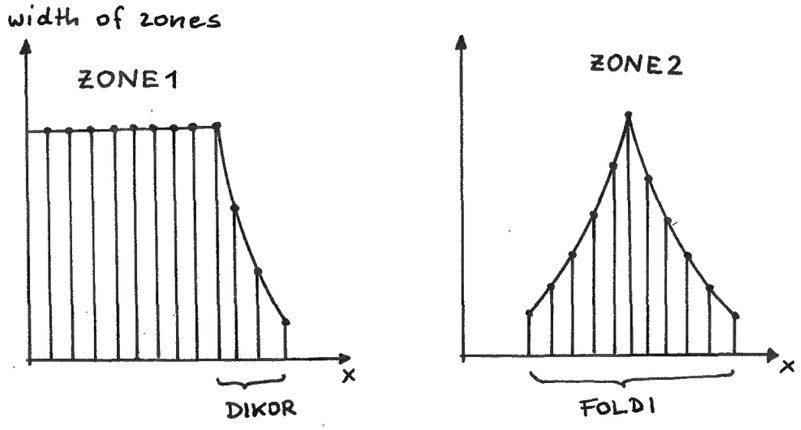
5) ZONE1, ZONE2

Determine the spatial mesh. ZONE1 causes fine zoning only at the front side (to laser) while ZONE2 causes a symmetric fine zoning on both sides of the target. The width of the zones increases geometrically: a, qa, q^2a ..., $q^{n-1}a$, with a = width of the first zone and q > 1. The sum over the first n zones is $s_n = a(q^n-1)/(q-1)$. ZONE1: Given a fixed number MH of

zones in corona thickness DIKOR, we have a = DIKOR·(q-1)/(q^{MH}-1). If q ≅ 1 and q^n >> 1, an approximation for the total number of zones M is

$$M \cong MH + (FOLDI / DIKOR - 1)/(q-1).$$

ZONE2 distributes MH zones into each half of the target.



Reasonable values for q are 1 < q < 1.1, q ≠ 1!
(Attention: the combination of high f and q kills the energy conservation presumably because the centering is bad).

6) ETEST, TESTI

Check energy and momentum (only for α = 1) balance, ETEST forms the sum of kinetic and thermal energy of all zones and compares with the absorbed laser energy. Hydrodynamic efficiency: = (kin. + thermal) energy of backward moving part of the target / total energy of the target.

7) ABSORP

Describes the absorption of laser light by inverse Bremsstrahlung absorption in the corona and anomalous absorption at the critical density. A fraction δ* of the anomalously absorbed energy may be used to create fast electrons which penetrate the target many times.

a) Inverse Bresmstrahlung absorption
The laser light is collisionally absorbed when penetrating the corona to the critical density and back. The absorption coefficient is given by Johnston and Dawson [5].

b) Resonance (anomalous) absorption
The fraction δ (= parameter) of the incoming laser flux is to be absorbed. To avoid numerical roughness, the energy is coupled into three cells around the location of the critical density. A weighting factor σ ensures the distribution of the energy to be correctly centered and coupled in smoothly.

c) Fast electrons
The fraction δ* (= parameter) of the anomalously absorbed energy goes into fast electrons. In our model they are associated with an energy flux $\phi \sim e^{-x/d}$ where x is the Lagrange coordinate and d the range. This flux is reflected each time it hits a wall. At the creation ($x = x_c$) it runs into the target only. After reflection at the rear side (x = 0) it penetrates to the front side (x = a), is reflected and so on:

$$\varphi_1 = \varphi_1^\circ e^{-\frac{x}{\alpha}}, \quad \varphi_1^\circ = \varphi_c^\circ e^{-\frac{x_c}{\alpha}},$$
$$\varphi_2 = \varphi_2^\circ e^{-\frac{(a-x)}{\alpha}}, \quad \varphi_2^\circ = \varphi_1^\circ e^{-\frac{a}{\alpha}},$$
$$\varphi_3 = \varphi_3^\circ e^{-\frac{x}{\alpha}}, \quad \varphi_3^\circ = \varphi_2^\circ e^{-\frac{a}{\alpha}},$$
$$\varphi_4 = \varphi_4^\circ e^{-\frac{(a-x)}{\alpha}}, \ldots$$

The sum is

$$-\varphi_1 + \varphi_2 - \varphi_3 + \varphi_4 - \cdots = \sum_{n=1}^{\infty} (-)^n \varphi_n =$$
$$= -e^{-\frac{x}{\alpha}} + e^{-\frac{a}{\alpha}} e^{-\frac{(a-x)}{\alpha}} - e^{-\frac{a}{\alpha}} e^{-\frac{a}{\alpha}} e^{-\frac{x}{\alpha}} + e^{-\frac{a}{\alpha}} e^{-\frac{a}{\alpha}} e^{-\frac{a}{\alpha}} e^{-\frac{(a-x)}{\alpha}} - \cdots$$
$$= e^{-\frac{(a-x)}{\alpha}} e^{-\frac{a}{\alpha}} \left(1 + e^{-\frac{2a}{\alpha}} + e^{-\frac{4a}{\alpha}} + \cdots\right) - e^{-\frac{x}{\alpha}} \left(1 + e^{-\frac{2a}{\alpha}} + e^{-\frac{4a}{\alpha}} + \cdots\right)$$

$$\Rightarrow \varphi(x) = \varphi_c^\circ e^{-\frac{x_c}{\alpha}} \left(1 - e^{-\frac{2a}{\alpha}}\right)^{-1} \left(e^{-\frac{2a}{\alpha}} e^{\frac{x}{\alpha}} - e^{-\frac{x}{\alpha}}\right).$$

It remains to add the "main part"

$$\varphi_0(x) = \begin{cases} \varphi_c^{\circ} e^{-\frac{(x_c - x)}{\alpha}} & \text{for} \quad x \le x_c \\ 0 & \text{for} \quad x_c < x \le a \end{cases} .$$

In total we have

$$\phi(x) = \varphi(x) + \varphi_0(x) .$$

Case $\delta^* = 1$, $x_c \cong a$:

i) $d \ll a \rightarrow \phi(x) \cong \varphi_0(x)$, exponential decay.
ii) $d \gg a \rightarrow \phi(x) \cong \varphi_c^{\circ} x/a$, uniform heating of the target.

8) FLUG (only for $\alpha = 1$)

Calculates the ionic velocity distribution function dF/dv as recorded with a detector at a distance D. We assume the velocity profile to be nearly frozen in after termination of the laser pulse. Then it follows

$$dF/dv = n_i dR/dv = n_i^{\circ} dr/dv.$$

The detector records the ion current $I_i(t)$. This is derived from the following consideration: A target zone of Lagrange thickness Δr passes the detector in the time

$$\Delta t = t_2 - t_1 = D/v - D/(v+dv/dr\ \Delta r) = D\Delta v/(v^2+v\Delta v).$$

In the limit $\Delta r \rightarrow 0$ we have

$$I_i = q_i n_i^{\circ}\ dr/dt = q_1 n_i^{\circ}\ dr/dv\ v^2/D \sim dF/dv.$$

(q_i = mean ionic charge, v = D/t).

9) PULS

Defines laser pulse shape. Four different options are possible: sine square pulse, box pulse, pulse with prepulse and calculated pulse (Uchiyamacode).

10) RANDPL, D3PLOT, LINPL, PLOTPV

Create plot output, specific for Garching's computer installation.

The MAIN program solves the hydrodynamic equations and does the input/output operations.

There is an additional subroutine calculating the radiation pressure (only with $\alpha = 3$, RADPR) which is normally not included (see [6]). Version 1 of the code is available without GET and INTP but can be generated equally well by version 2 with the option IEOS = 0.

IX) Output of a typical run

A very important diagnostic for analyzing the results of a code is an adequate graphic output. LAPLAS produces on request a maximum of eleven pages plot output: Page one repeats the input parameters, page 2 plots density, pressure, electronic and ionic temperatures in Euler coordinates at selected times given on the top (= input). On page 3 we see: pulse profile, energy balance, effective pressure, hydrodynamic efficiency and center-of mass velocity versus time. Page 4 enlarges the front profiles at a certain time (=input). Pages 5-8 cover the whole time history of temperature, density, pressure and ionic charge in 3-D plots. By choosing the Lagrange coordinate as radius all structures are nicely resolved. A linear plot of the density profile compared with the initial one follows on page 9. Finally, the motion of some selected mass elements in the log p - log ρ plane is shown on pages 10 and 11. The print output is described in section VII.

```
C ================================================================C
C                                                                C
C                                                                C
C                                                                C
C                                                                C
C   LLL                    PPPPPPP                               C
C   LLL                    PPPPPPPPP                             C
C   LLL                    PPP     PPP                           C
C   LLL                    PPP     PPP                           C
C   LLL                    PPPPPPPPP                             C
C   LLL                    PPPPPPP                               C
C   LLL          AAA       PPP      LL          AAA      SSSSSSSS  C
C   LLL         AA AA      PPP      LL         AA AA     SS        C
C   LLLLLLLLLL AA   AA     PPP      LL        AA   AA    SSSSSSSS  C
C   LLLLLLLLLL AA AAA AA   PPP      LLLLLLLL AA AAA AA         SS  C
C   LLLLLLLLLL AA     AA   PPP      LLLLLLLL AA     AA  SSSSSSSS  C
C                                                                C
C                                                                C
C                                                                C
C ================================================================C
C ================================================================C
C    LASER PLASMA CODE          MPQ  MAY  1983        VERSION 2    C
C ================================================================C
C                                                                C
```

EINGANGSDATEN RES166
****

PARAMETER FUER ENERGIE - UND IMPULSTEST :
KETEST= 1
KITEST= 1
TAUE = 6.00E-13

PARAMETER FUER LASERENERGIEEINKOPPLUNG :
KABSO = 1

PARAMETER FUER SIMULATION FUER ENERGIEDEPOSITION VON"SCHNELLEN ELEKTRONEN"
NFE = 0
DELTAF= 1.00E-02
WELAE = 1.0000E-04

PARAMETER FUER ZUSTANDSGLEICHUNG :
IEOS = 1
CUT = 1.0000E-10

PARAMETER FUER ENERGIESATZ (WAERMELEITUNG) :

JFL = 1
FFL2 = 3.0000E-02
THETA = 7.5000E-01
KYE = 1

PARAMETER FUER IONENFLUGZEITSPEKTRUM :
IONEN = 0
DIST = 1.4000E+02
NZIO = 2400
IPLO = 0

PARAMETER ZUR STEUERUNG DER DATENAUSGABE :
KPR = 1
KPR1 = 200
MWRITE= 81
NZY = 1000000

FOLIEN UND LASERDATEN :
KALP = 1
KZEIT = 90000
DELTA = 5.0000E-01

WLO = 2.0000E+14 SPITZENINTENSITAET IN W PRO CM**2
PAN = 0.0000E+00 KONSTANTER TEST-DRUCK IN DYN/CM**2
WK = 4.7781E+04

FOLDI = 1.0000E-04
RHOO = 1.1964E+03

TEO = 3.0000E+02
TIO = 3.0000E+02

GAMMA = 1.6667E+00

Z = 1.3000E+01
FIO = 2.7000E+01

DCR = 6.4472E+20

MATERIAL : ALUMINIUM

BERECHNETE TARGETDICHTE : 2.6753E+00

PARAMETER FUER ZEITSCHRITTSTEUERUNG :
ZEIT = 0.0000E+00
ZF = 1.0000E-03
IZEI1 = 50
IZEI2 = 200
ZEIFA1= 1.00E+00
ZEIFA2= 1.00E+00
DZMAX = 1.00E-12
AEND = 3.00E-01

PARAMETER FUER FINE ZONING :
KZO = 0
WENN KZO = 1: -> NUR FRONT FINE ZONING
WENN KZO = 0: -> FRONT UND REAR FINE ZONING

MH = 40
DIKOR = 1.00E-04
QX = 1.05E+00

PARAMETER FUER ANFANGSPROFIL DES TARGETS
NPROF = 0
AF = 3.00E+00
JP = 5
PARAMETER FUER LASER EIN - UND AUSSCHALTVORGANG (LASERPULSFORM)
IPULS= 1

IPULS=1: SINUSQUADRAT
IPULS=2: RECHTECK
IPULS=3: JODLASERPULS MIT VORPULS
IPULS=4: GERECHNETER PULS(UCHIYAMACODE TAU452)

ZEITM=FUSS ZU FUSS PULSLAENGE= 6.00E-10

PARAMETER FUER SCHOCKBEHANDLUNG :
KSHOCK= 1
VISL = 1.50E+00

MODELL= 3327 ZEIT= 1.000E-09 S DZEIT= 5.624E-13 S ABSORPTION= 5.844E-01 M = 81 MPC= 25
JOB:RES166

J	X (CM)	NI/NKRIT	MACH	TI (K)	TE(K)	HFL/FLL	HFL	NDEB	J(CGS)	SCHUB	P(MBAR)	V(CM/S)
1	2.189E-01	-6.096E-04	8.644E+00	3.813E+05	1.865E+07	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	-1.3E-02	2.9E+08
2	1.564E-01	6.096E-04	6.373E+00	3.813E+05	1.865E+07	-5.1E-01	-6.3E+17	2.4E+03	4.5E+03	1.2E+00	1.3E-02	2.1E+08
3	1.325E-01	1.670E-03	5.517E+00	9.003E+05	1.858E+07	-4.6E-01	-1.1E+18	1.7E+03	9.9E+03	2.1E+00	3.6E-02	1.8E+08
4	1.168E-01	2.673E-03	4.943E+00	1.323E+06	1.851E+07	-4.5E-01	-1.5E+18	1.4E+03	1.4E+04	2.7E+00	5.8E-02	1.7E+08
5	1.047E-01	3.663E-03	4.515E+00	1.706E+06	1.844E+07	-4.5E-01	-2.0E+18	1.2E+03	1.8E+04	3.0E+00	7.9E-02	1.5E+08
7	8.633E-02	5.690E-03	3.858E+00	2.414E+06	1.827E+07	-4.5E-01	-2.9E+18	9.9E+02	2.3E+04	3.5E+00	1.2E-01	1.3E+08
9	7.165E-02	7.640E-03	3.326E+00	3.033E+06	1.808E+07	-4.6E-01	-3.9E+18	8.5E+02	2.7E+04	3.5E+00	1.6E-01	1.1E+08
11	5.890E-02	9.502E-03	2.852E+00	3.570E+06	1.785E+07	-4.8E-01	-4.9E+18	7.5E+02	3.0E+04	3.4E+00	2.0E-01	9.4E+07
13	4.698E-02	1.104E-02	2.371E+00	3.972E+06	1.756E+07	-4.9E-01	-5.5E+18	6.9E+02	3.0E+04	2.9E+00	2.3E-01	7.8E+07
15	3.467E-02	1.138E-02	1.817E+00	4.027E+06	1.721E+07	-5.5E-01	-6.0E+18	6.6E+02	2.5E+04	1.9E+00	2.3E-01	5.9E+07
17	2.171E-02	1.238E-02	1.191E+00	4.180E+06	1.664E+07	-5.9E-01	-6.6E+18	6.1E+02	2.0E+04	1.2E+00	2.4E-01	3.0E+07
19	9.519E-03	1.614E-02	9.726E-01	5.154E+06	1.279E+07	-9.3E-01	-9.3E+18	3.2E+02	2.0E+04	8.7E-01	2.5E-01	2.5E+07
21	3.164E-03	3.490E-02	6.292E-01	5.182E+06	6.549E+06	-6.5E-01	-5.1E+18	8.4E+01	2.8E+04	8.3E-01	2.8E-01	1.2E+07
23	-1.055E-03	5.454E-02	2.101E-01	4.009E+06	4.358E+06	-4.0E-01	-2.6E+18	3.7E+01	3.0E+04	5.9E-01	2.9E-01	3.2E+06
25	-4.254E-03	7.781E-02	-2.855E-01	2.956E+06	3.046E+06	-2.0E-01	-1.1E+18	1.8E+01	2.7E+04	3.5E-01	2.9E-01	-3.6E+06
27	-6.846E-03	1.054E-01	-9.525E-01	2.157E+06	2.182E+06	-1.4E-01	-6.3E+17	9.3E+00	1.9E+04	1.2E-01	2.7E-01	-9.4E+06
29	-8.622E-03	1.878E-01	-1.994E+00	1.287E+06	1.290E+06	-7.9E-02	-3.1E+17	2.9E+00	1.1E+04	2.4E-02	2.6E-01	-1.3E+07
31	-9.327E-03	6.834E-01	-4.856E+00	5.122E+05	5.123E+05	-2.6E-02	-1.1E+17	3.2E-01	-2.0E+03	2.0E-04	2.5E-01	-1.5E+07
33	-9.420E-03	8.138E+00	-1.657E+01	1.018E+05	1.018E+05	-4.4E-03	-5.0E+15	2.6E-02	-5.5E+04	3.4E-02	2.3E-01	-1.5E+07
35	-9.429E-03	6.961E+01	-1.277E+01	1.285E+04	1.285E+04	-6.7E-04	-6.1E+13	1.5E-03	-1.3E+05	8.7E-02	2.2E-01	-1.5E+07
37	-9.433E-03	1.070E+02	-1.033E+01	1.406E+03	1.406E+03	0.0E+00	0.0E+00	5.4E-05	-1.9E+05	1.3E-01	2.0E-01	-1.5E+07
39	-9.436E-03	1.036E+02	-1.073E+01	1.917E+03	1.917E+03	0.0E+00	0.0E+00	1.0E-04	-1.6E+05	1.1E-01	1.8E-01	-1.5E+07
41	-9.443E-03	1.019E+02	-1.096E+01	1.971E+03	1.971E+03	0.0E+00	0.0E+00	1.1E-04	-1.5E+05	1.0E-01	1.6E-01	-1.5E+07
43	-9.447E-03	1.009E+02	-1.175E+01	1.800E+03	1.800E+03	0.0E+00	0.0E+00	1.0E-04	-1.4E+05	9.5E-02	1.4E-01	-1.5E+07
45	-9.452E-03	9.895E+01	-1.209E+01	1.842E+03	1.842E+03	0.0E+00	0.0E+00	1.1E-04	-1.3E+05	8.8E-02	1.2E-01	-1.5E+07
47	-9.456E-03	9.695E+01	-1.303E+01	2.034E+03	2.034E+03	0.0E+00	0.0E+00	1.3E-04	-1.3E+05	8.5E-02	1.1E-01	-1.5E+07
49	-9.460E-03	9.447E+01	-1.234E+01	2.220E+03	2.220E+03	0.0E+00	0.0E+00	1.5E-04	-1.2E+05	8.1E-02	9.4E-02	-1.5E+07
51	-9.464E-03	9.202E+01	-1.762E+01	2.407E+03	2.407E+03	0.0E+00	0.0E+00	1.7E-04	-1.2E+05	8.1E-02	8.0E-02	-1.5E+07
53	-9.467E-03	9.010E+01	-1.549E+01	2.632E+03	2.632E+03	1.1E-05	1.4E+11	1.9E-04	-1.2E+05	8.2E-02	7.1E-02	-1.5E+07
55	-9.470E-03	8.874E+01	-1.782E+01	2.809E+03	2.809E+03	0.0E+00	0.0E+00	2.1E-04	-1.2E+05	8.3E-02	6.2E-02	-1.5E+07
57	-9.473E-03	8.685E+01	-2.176E+01	2.882E+03	2.882E+03	0.0E+00	0.0E+00	2.1E-04	-1.3E+05	8.4E-02	4.8E-02	-1.5E+07
59	-9.476E-03	8.523E+01	-9.990E+00	2.991E+03	2.991E+03	2.4E-05	3.8E+11	2.2E-04	-1.3E+05	8.3E-02	4.0E-02	-1.5E+07
61	-9.478E-03	3.488E+01	-8.139E+00	3.415E+03	3.415E+03	3.9E-05	7.7E+11	2.6E-04	-1.3E+05	6.5E-02	3.2E-02	-1.5E+07
63	-9.480E-03	8.405E+01	-1.014E+01	4.115E+03	4.115E+03	6.7E-05	1.8E+12	3.4E-04	-1.3E+05	8.6E-02	2.5E-02	-1.5E+07
65	-9.483E-03	8.295E+01	-1.030E+01	4.665E+03	4.665E+03	2.7E-05	8.6E+11	4.0E-04	-1.3E+05	8.8E-02	2.4E-02	-1.5E+07
67	-9.484E-03	8.155E+01	-1.510E+01	4.972E+03	4.972E+03	2.4E-05	8.3E+11	4.4E-04	-1.3E+05	8.9E-02	2.1E-02	-1.5E+07
69	-9.486E-03	7.953E+01	-1.524E+12	5.107E+03	5.107E+03	0.0E+00	0.0E+00	4.5E-04	-1.3E+05	8.9E-02	1.5E-02	-1.5E+07
71	-9.488E-03	7.498E+01	-1.524E+12	5.127E+03	5.127E+03	2.1E-05	3.0E+11	4.2E-04	-1.4E+05	9.2E-02	1.2E-02	-1.5E+07
73	-9.490E-03	6.511E+01	-1.524E+12	5.435E+03	5.435E+03	-2.3E-05	-9.9E+11	4.0E-04	-1.5E+05	9.9E-02	1.0E-02	-1.5E+07
75	-9.491E-03	6.318E+01	-7.654E+01	5.452E+03	5.452E+03	1.3E-04	6.4E+12	3.9E-04	-1.5E+05	1.0E-01	6.5E-03	-1.5E+07
77	-9.493E-03	3.839E+01	-1.524E+12	6.739E+03	6.739E+03	0.0E+00	0.0E+00	4.5E-04	-1.5E+05	1.0E-01	4.7E-03	-1.5E+07
79	-9.505E-03	4.330E+00	-1.069E+02	7.015E+03	7.015E+03	8.2E-05	9.3E+11	9.6E-04	-3.6E+04	2.1E-02	3.0E-03	-1.5E+07
81	-9.621E-03	4.110E-01	-5.291E+01	1.470E+04	1.470E+04	0.0E+00	0.0E+00	0.0E+00	-2.3E+03	1.3E-03	6.5E-04	-1.5E+07

I= 1 J= 80 EKIN=6.0560E-01 ETH=1.7435E-01 Q=9.5995E-01 EL=3.1437E+11 ERG
I= 24 J= 80 EKIN=7.6902E-02 ETH=1.7316E-02 Q=9.4218E-02 EL=3.1437E+11 ERG
HYDRODYNAMISCHER WIRKUNGSGRAD= 1.0956E-01 TOTALE ABSORPTION= 5.238E-01

IMPULS1= 2.8811E-02 IMPULS2= 2.9665E-02 SCHWERPUNKTGESCHW.(CM/S)=-1.458E+07

PT =
1.00250E+00 1.00377E+00 1.00433E+00 1.00470E+00 1.00499E+00 1.00520E+00 1.00538E+00 1.00553E+00 1.00566E+00 1.00576E+00
1.00585E+00 1.00591E+00 1.00593E+00 1.00592E+00 1.00592E+00 1.00596E+00 1.00593E+00 1.00572E+00 1.00593E+00 1.00486E+00
1.01032E+00 1.00925E+00 1.00621E+00 1.00143E+00 9.95905E-01 1.10545E+00 1.05965E+00 9.97118E-01 9.82519E-01 8.35294E-01
6.10491E-01 7.04256E-01 8.94424E-01 9.92172E-01 2.78724E+00 3.00564E+00 2.83283E+00 2.84553E+00 2.88138E+00 3.03168E+00
3.24650E+00 3.41411E+00 3.55949E+00 3.60951E+00 3.64958E+00 3.70931E+00 3.82049E+00 3.91538E+00 4.01607E+00 3.77360E+00
3.61691E+00 3.41339E+00 3.37019E+00 3.14593E+00 2.98745E+00 2.69474E+00 2.42931E+00 2.37249E+00 2.37593E+00 2.39556E+00
2.58216E+00 2.80336E+00 3.02099E+00 3.89664E+00 3.93809E+00 4.75439E+00 4.17587E+00 4.43000E+00 3.49567E+00 3.14012E+00
2.18132E+00 2.07649E+00 1.56707E+00 1.04977E+00 3.02461E-01 3.53828E-02 1.95476E-01 2.21242E-01 3.94475E-02 3.03298E-01

RC =
9.90602E-01 9.97325E-01 1.00084E+00 1.00347E+00 1.00578E+00 1.00782E+00 1.00974E+00 1.01163E+00 1.01352E+00 1.01541E+00
1.01735E+00 1.01938E+00 1.02143E+00 1.02360E+00 1.02640E+00 1.03071E+00 1.03458E+00 1.09541E+00 1.08799E+00 1.16896E+00
1.17748E+00 1.25158E+00 1.32146E+00 1.75812E+00 1.76260E+00 1.20168E+00 1.31693E+00 1.46169E+00 2.45513E+00 2.09253E+00
1.43995E+00 1.56817E+00 1.55193E+00 7.27811E-01 8.34990E-01 8.63186E-01 9.44813E-01 9.91591E-01 1.03658E+00 1.05854E+00
1.07375E+00 1.09365E+00 1.13061E+00 1.16304E+00 1.17992E+00 1.20374E+00 1.23711E+00 1.24101E+00 1.24345E+00 1.15180E+00
1.14657E+00 1.13867E+00 1.13293E+00 1.11861E+00 1.10911E+00 1.09191E+00 1.07765E+00 1.06987E+00 1.06532E+00 1.06143E+00
1.05591E+00 1.04350E+00 1.02178E+00 1.02030E+00 1.00486E+00 9.91079E-01 9.58955E-01 9.46580E-01 8.74903E-01 8.33762E-01
6.89611E-01 5.95589E-01 6.17959E-01 5.56368E-01 7.08933E-01 4.50056E-01 2.98966E-01 2.54420E-01 3.45280E-01 1.17184E+00

ZEFF =
1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01
1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01
1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01 1.30000E+01
1.04626E+01 5.04764E+00 2.43195E+00 1.33232E+00 1.29965E+00 1.25926E+00 1.11717E+00 1.06623E+00 1.02573E+00 1.00748E+00
9.91365E-01 9.72313E-01 9.42234E-01 9.20196E-01 9.14009E-01 9.08600E-01 8.96799E-01 9.03815E-01 9.11694E-01 9.23573E-01
9.34331E-01 9.49494E-01 9.62174E-01 9.80132E-01 9.92077E-01 1.01396E+00 1.03161E+00 1.04331E+00 1.05395E+00 1.06222E+00
1.07358E+00 1.09187E+00 1.11613E+00 1.11828E+00 1.13243E+00 1.14432E+00 1.17137E+00 1.18281E+00 1.25398E+00 1.29701E+00
1.48167E+00 1.61465E+00 1.59359E+00 1.69348E+00 1.80092E+00 2.78635E+00 4.23934E+00 4.73510E+00 3.66134E+00 3.52158E+00

KRHO =
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 3 5 9 16 26 26 25 25 24 24
24 24 24 24 23 23 23 22 21 20 20 19 19 19 19 19 19 19 18 18 18 18 18 18 18 18 17 17 17 17 16 15 15 14 14 10 8 4 2 0

KTE =
18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 17 17 16 16 16 15 15 14 14 14 14 14 13 12 12 10 9 8 4 4 4 4 4 4
4 4 4 4 4 4 4 4 4 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 6 6 6 6 7 8

FOLIEN- UND LASERDATEN JOB:RES166 GESAMTRECHENZEIT(1/100 SEK)= 9171

****

LASERINTENSITAET=2.000E+14 W CM-2 TOTALE ABSORPTION= 5.238E-01 F-FAKTOR= 3.00E-02

FOLIENDICKE= 1.000E-04 CM ANZAHL DER MASSENSCHALEN= 80 ZONING-PARAMETER= 1.05E+00

KERNLADUNGSZAHL= 1.300E+01 ATOMMASSE= 2.700E+01

ABLATION=1.715E-01 OPTISCHE TRANSMISSION =0.000E+00 HYDRODYNAMISCHER WIRKUNGSGRAD= 1.096E-01

MAXIMALTEMPERATUR AN KRITISCHER DICHTE= 6.933E+07 K

EINGANGSDATEN :
****

ENERGIE -UND IMPULSTEST
KETEST= 1
KITEST= 1
TAUE = 0.60E-12

SCHNELLE ELEKTRONEN
NFE = 0
DELTAF= 0.10E-01
WELAE = 0.1000E-03

ENERGIESATZ
JFL = 1
FFL2 = 0.3000E-01
THETA = 0.7500E 00
KYE = 1
KABSO = 1

IONENFLUGZEITSPEKTRUM
IONEN = 0
DIST = 0.1400E 03
NZIO = 2400
IPLO = 0

DATENAUSGABE
KPR = 1
KPR1 = 200
MWRITE= 81
NZY = 1000000

FOLIEN UND LASERDATEN

KALP = 1
KZEIT = 90000
DELTA = 0.5000E 00
WLO = 0.2000E 15
WK = 0.4778E 05
FOLDI = 0.1000E-03
RHOO = 0.1196E 04
TEO = 0.3000E 03
TIO = 0.3000E 03
GAMMA = 0.1667E 01
Z = 0.1300E 02
FIO = 0.2700E 02

MATERIAL = ALUMINIUM

ZEITSCHRITTSTEUERUNG
ZEIT = 0.0
ZF = 0.1000E-02
IZEI1 = 50
IZEI2 = 200
ZEIFA1= 0.1000E 01
ZEIFA2= 0.1000E 01
DZMAX = 0.1000E-11

FINE ZONING
KZO = 0
MH = 40
DIKOR = 0.1000E-03

QX = 0.1050E 01

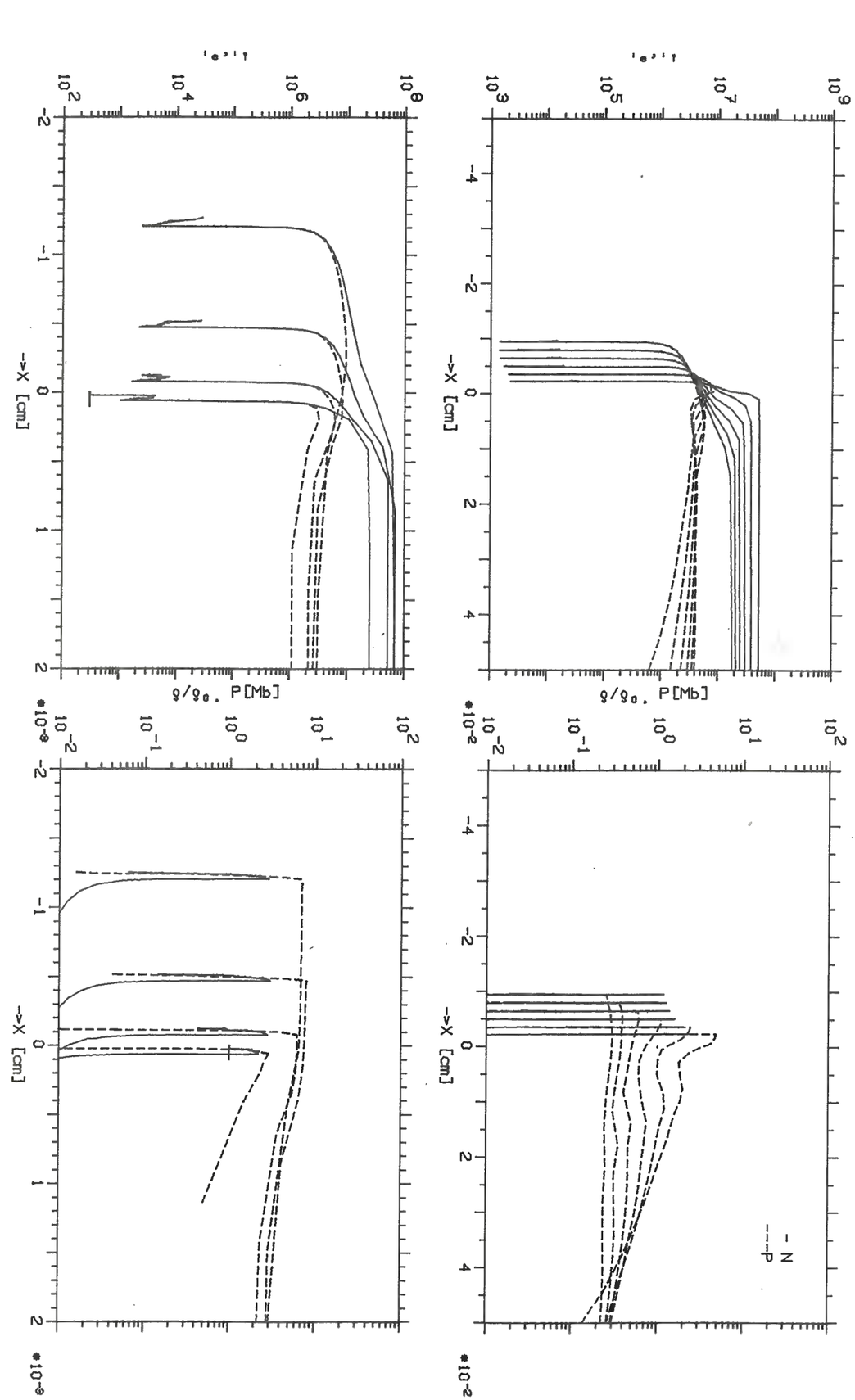
ANFANGSPROFIL
NPROF = 0.0
AF = 0.30E 01
JP = 5

LASERPULSFORM
IPULS = 1
IPULS = 1 : SINUSQUADRAT
IPULS = 2 : RECHTECK
IPULS = 3 : JODLASER MIT VORPULS
IPULS = 4 : GERECHNET (UCH TAU452)

ZEITM = 0.60E-09

SCHOCK
KSHOCK= 1
VISL = 0.15E 01

ZUSTANDSGLEICHUNG
IEOS = 1
CUT = 0.10E-09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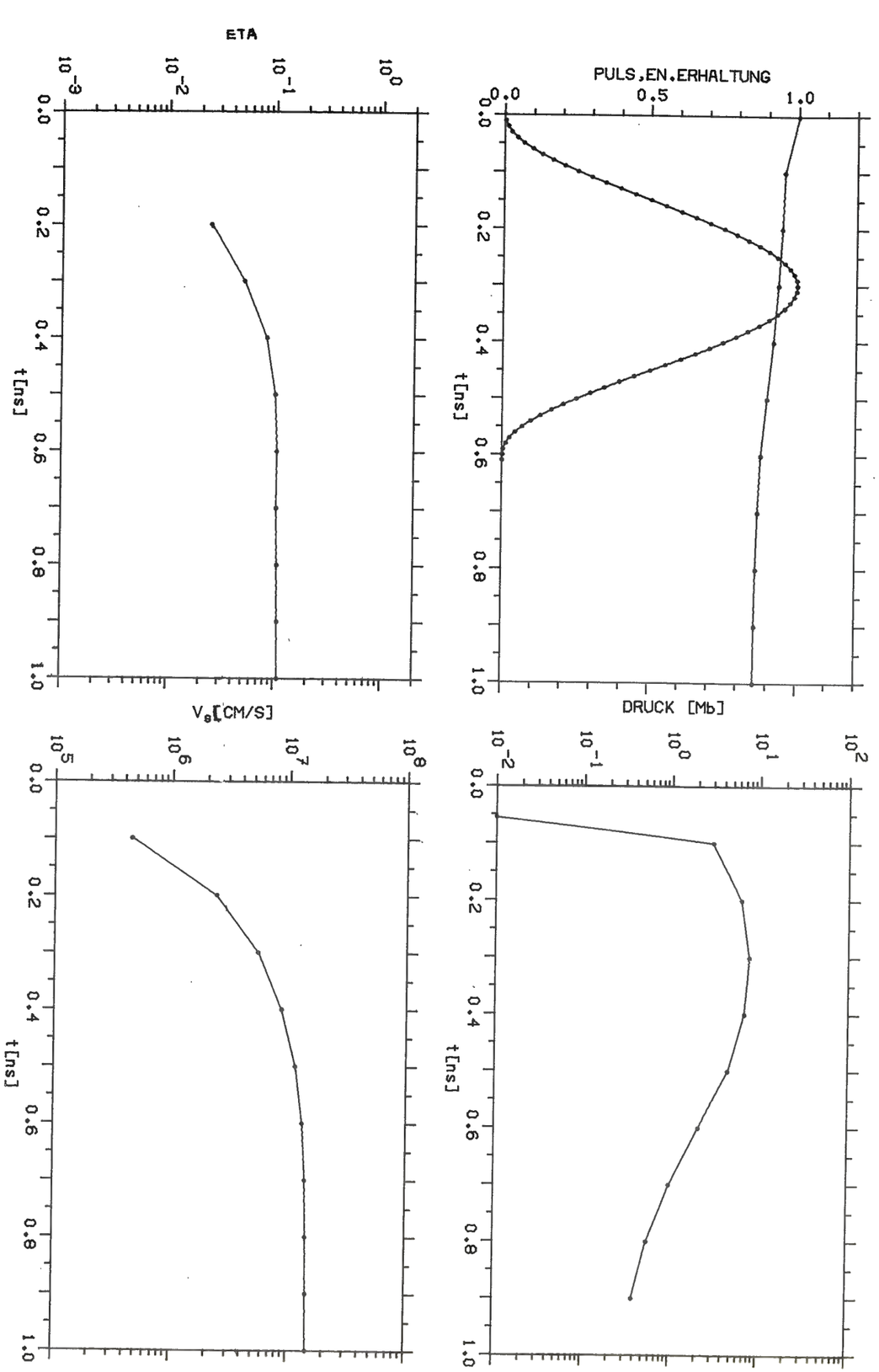
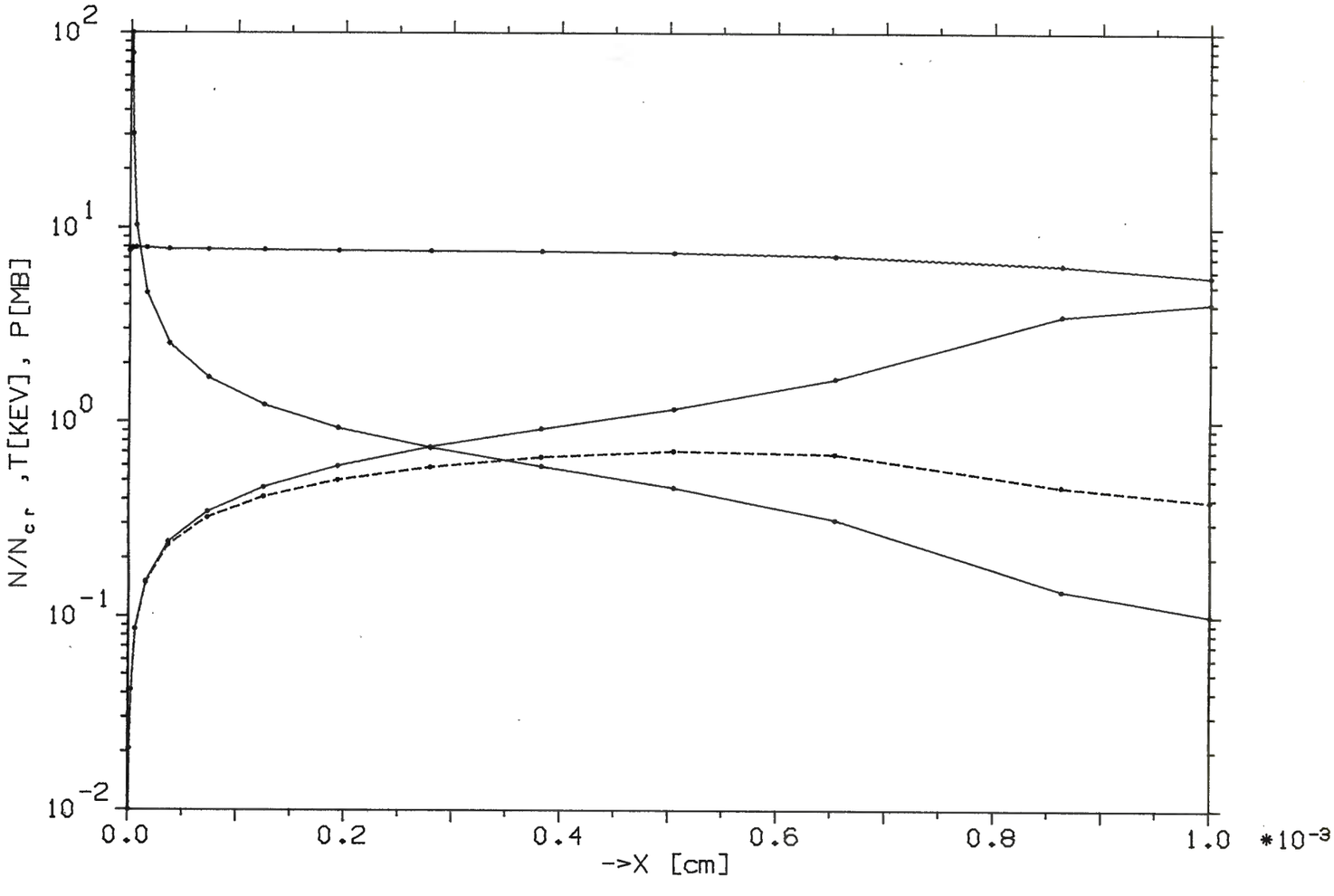
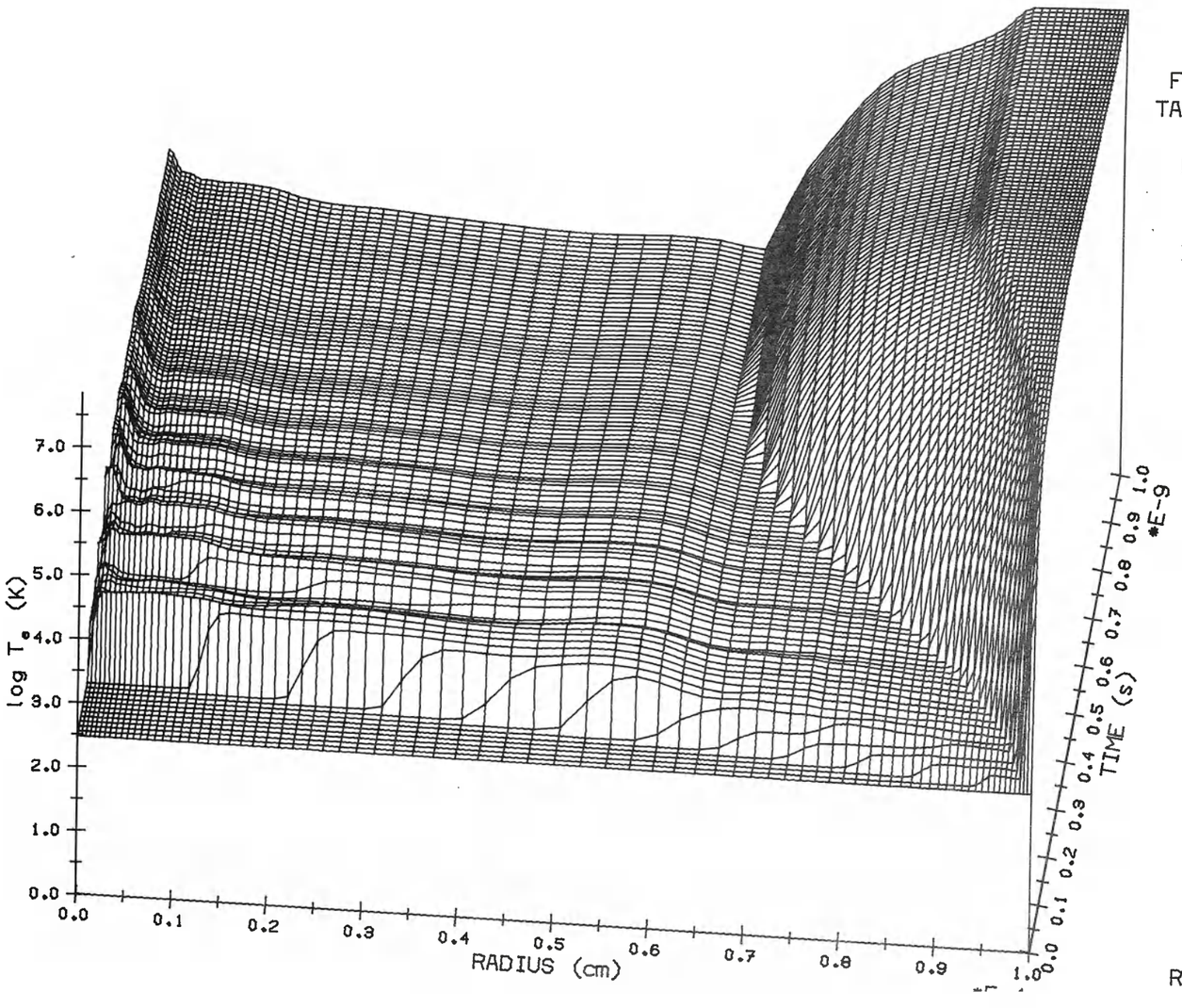
->X [cm]
ϱ/ϱ₀. P[Mb]
- N
---P


ETA
PULS.EN.ERHALTUNG
t[ns]
DRUCK [Mb]
V_s[CM/S]

T/NS= 0.300E 00





α = 1

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TARGETDICHTE = 0.268E 01
Z = 13.000
MASSENZAHL = 27.000

ZEITFAKTOR = 0.800

M = 81

q = 1.050

f = 0.030

θ = 0.750

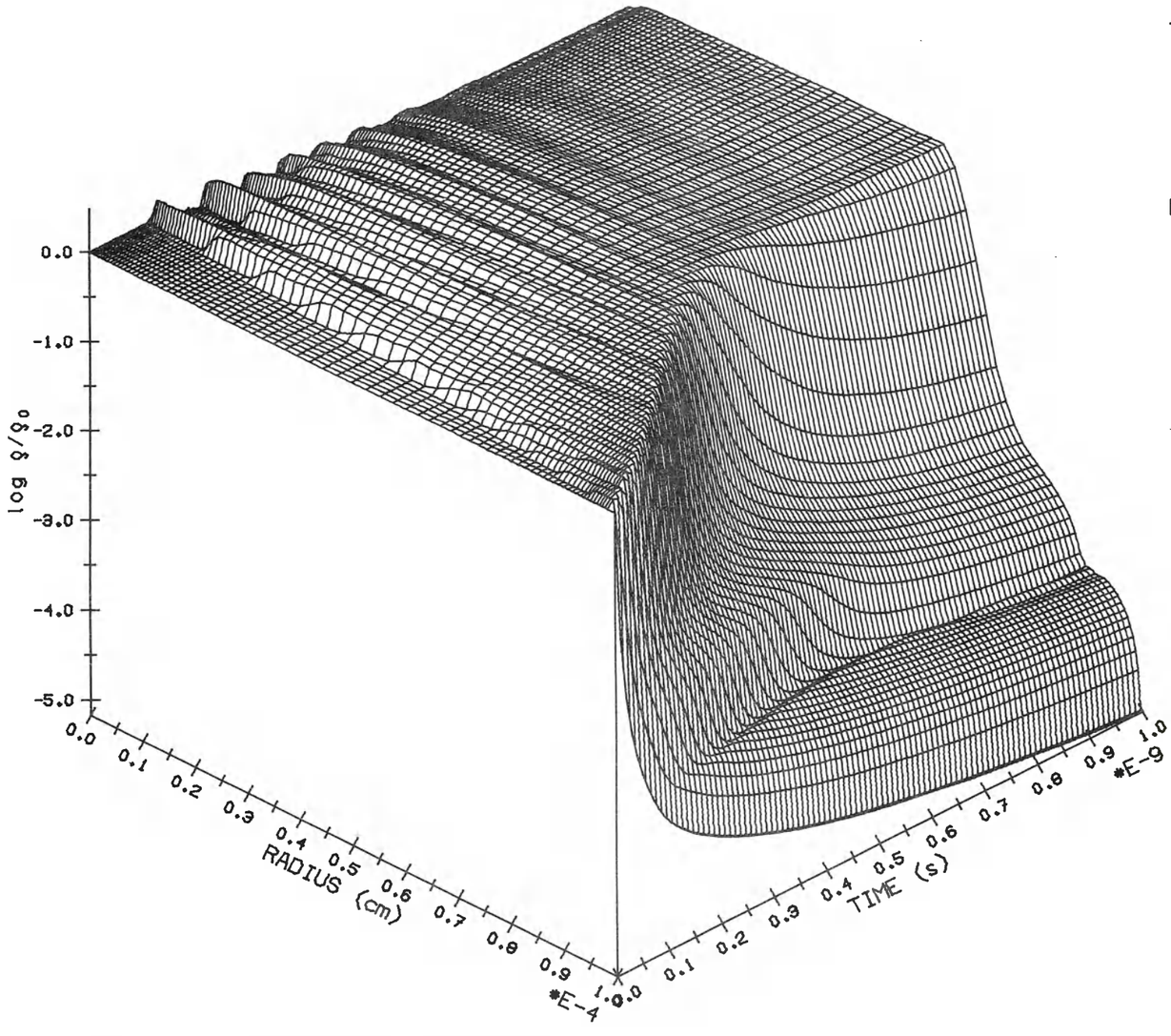
WL0 = 0.200E 15

δ = 0.500

IEOS = 1

NFE = 0
δ^* = 0.010
d = 0.100E-03

RECHENZEIT = 91.71 s



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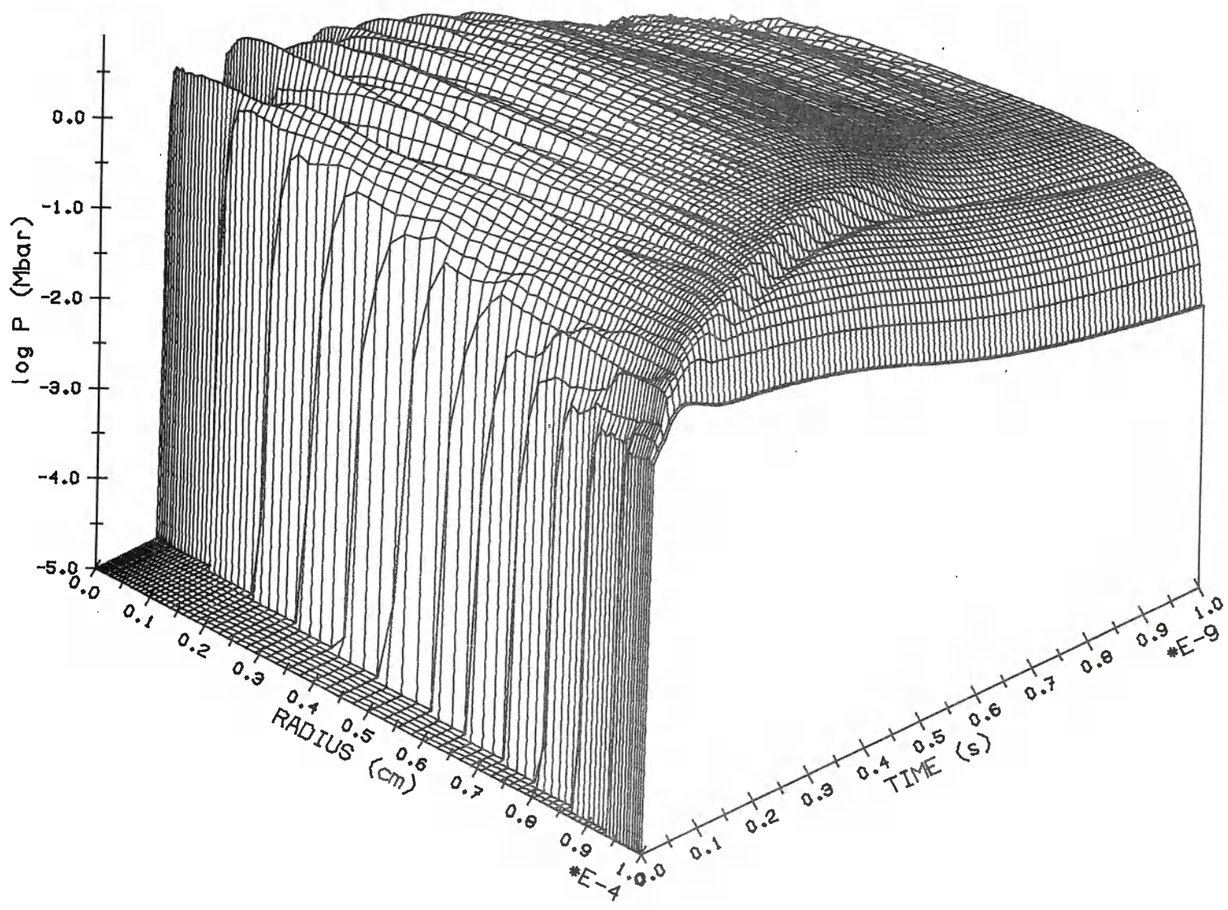

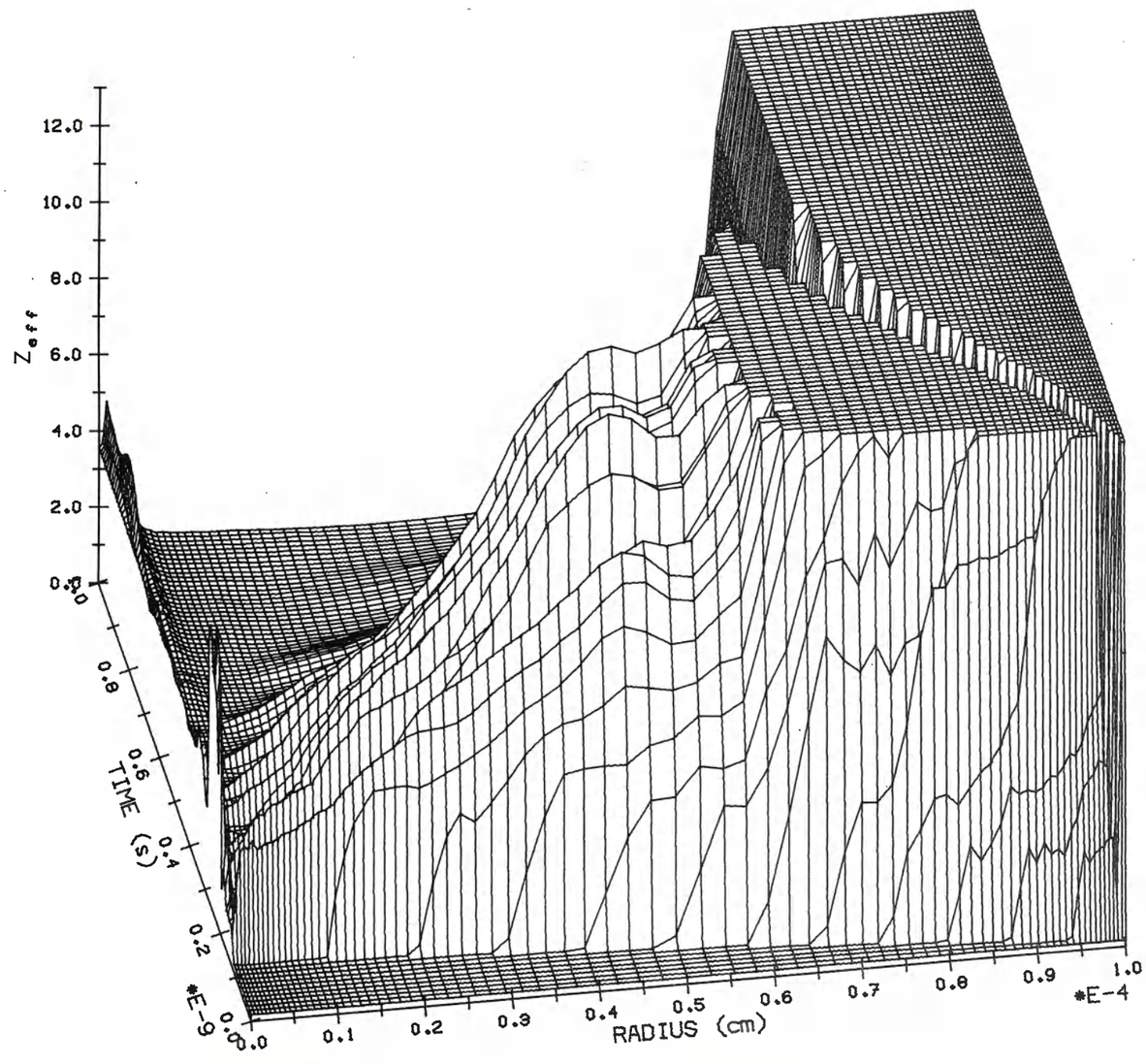
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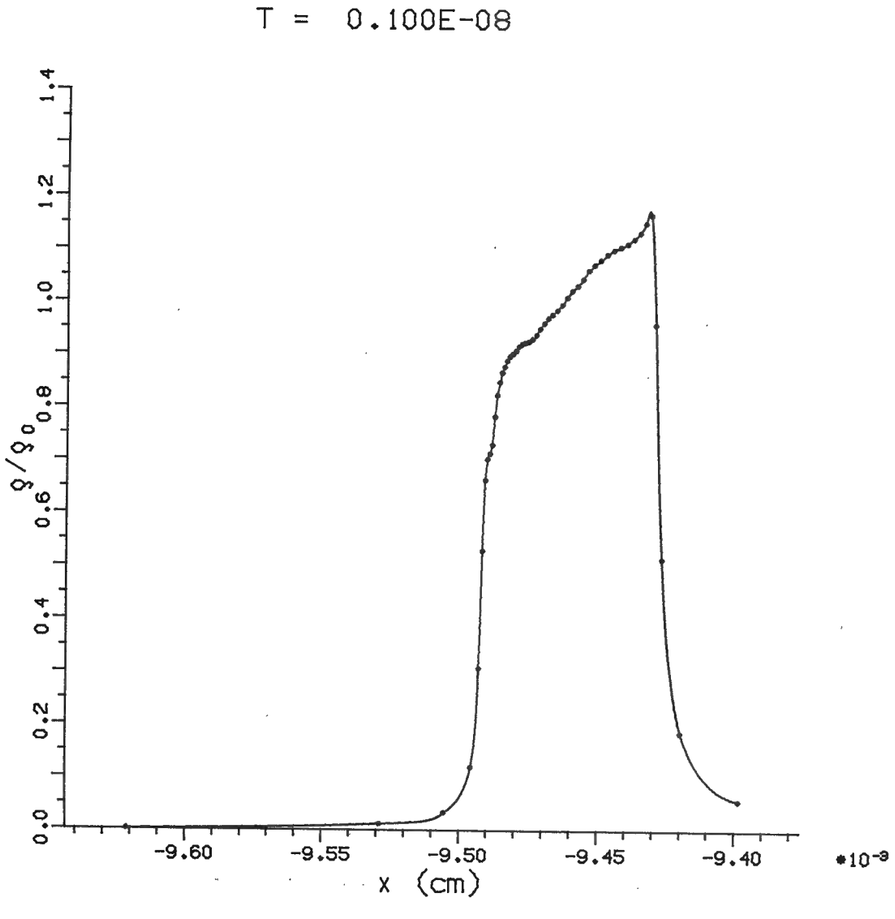
0.0
Z_{eff}
0.0
0.2
0.4
0.6
0.8
TIME (s)
*E-9
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
*E-4
RADIUS (cm)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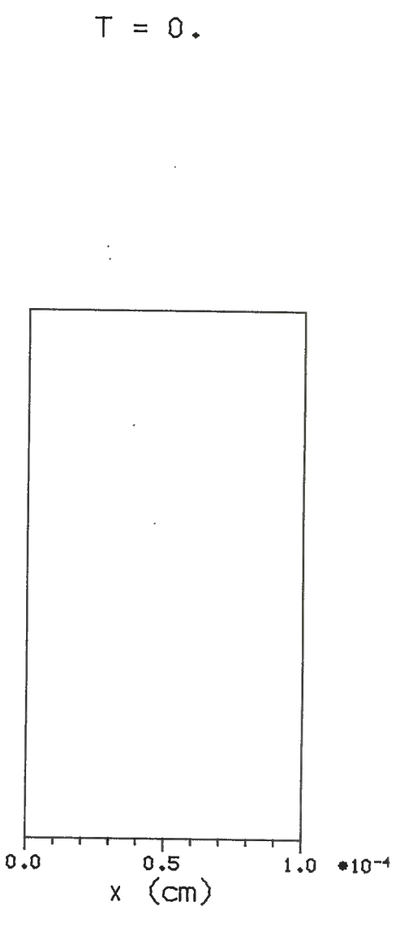
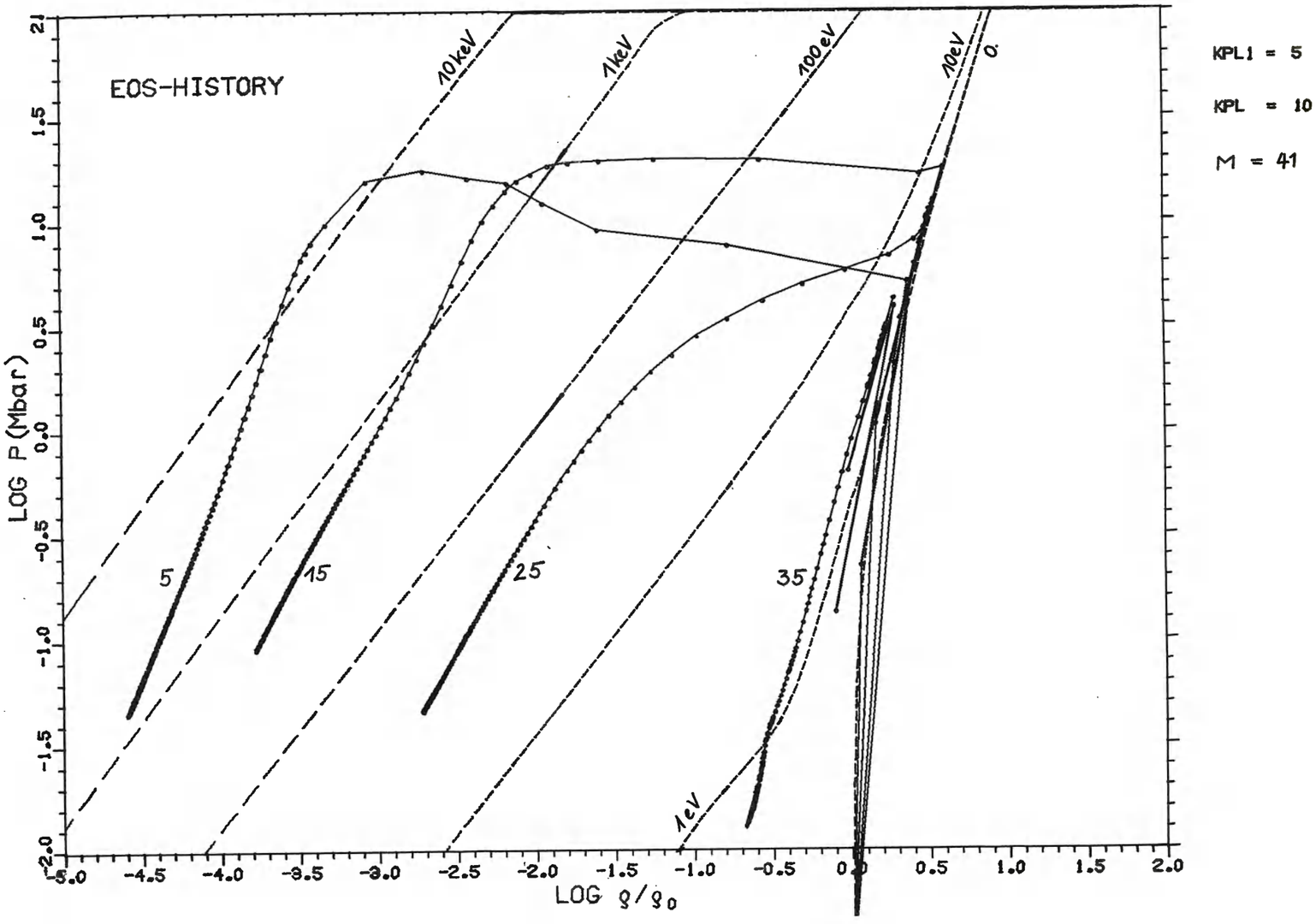
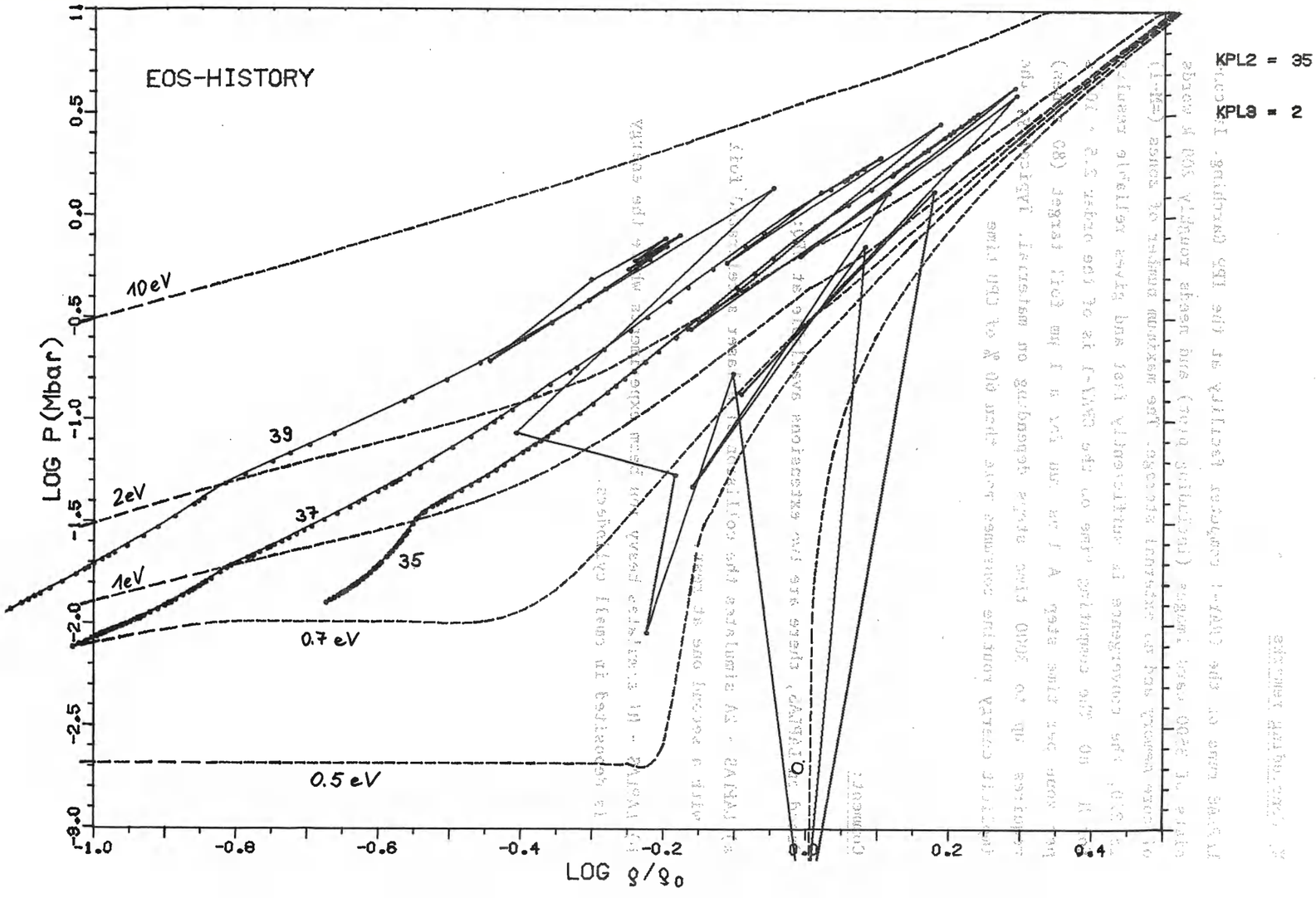
0.2
0.4
0.6
0.8
1.0
1.2
1.4
-9.60
-9.55
-9.50
-9.45
-9.40
*10-9
X (cm)


T = 0.
0.0
0.5
1.0
*10-4
X (cm)


EOS-HISTORY
10keV
1keV
100eV
10eV
0.
1eV
5
15
25
35
LOG P (Mbar)
LOG ϱ/ϱ0
KPL1 = 5
KPL = 10
M = 41


EOS-HISTORY
10eV
2eV
1eV
0.7 eV
0.5 eV
39
37
35
LOG P (Mbar)
LOG ϱ/ϱ0
KPL2 = 35
KPL3 = 2

X) Concluding remarks

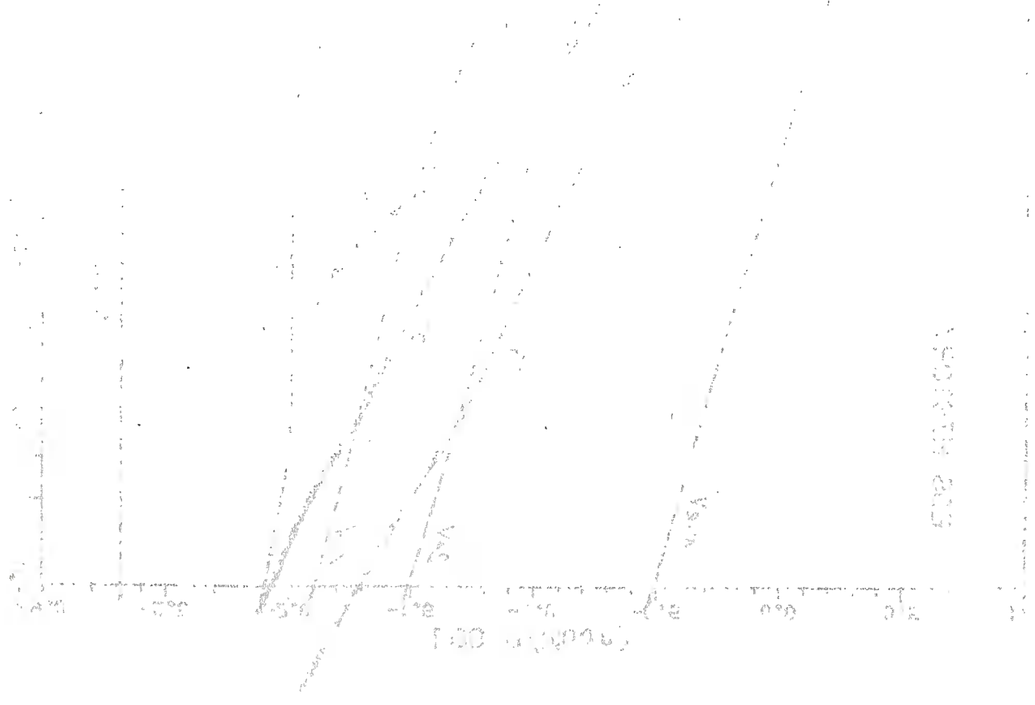
LAPLAS runs on the CRAY-1 computer facility at the IPP Garching. It consists of 3500 card images (including plot) and needs roughly 200 k words of core memory and no external storage. The maximum number of zones (=M-1) is 320, the convergence is sufficiently fast and gives reliable results for M 80. The computing time on the CRAY-1 is of the order $2.5 \cdot 10^{-4}$ s per zone per time step. A 1 ns run for a 1 µm foil target (80 zones) requires up to 3000 time steps depending on material. Typically, the implicit energy routine consumes more than 60 % of CPU time.

Comment:

Based on LAPLAS, there are two extensions available at MPQ:

a) LAPLAS - 2A simulates the collision of a laser accelerated foil with a second one at rest.

b) LAPLAS - HI simulates heavy ion beam experiments where the energy is deposited in small cylinders.



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