

# Estágio GOLP: “Modelling short pulse laser-solid interaction”

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**Objetivo:** Modelar a interação do Titânio com um pulso laser de intensidade na ordem de  $10^{15} \text{ W/cm}^2$  e duração de 50fs

**Ferramenta:** MULTI-fs. Código em Fortran adaptado do MULTI-IFE precisamente para estudar pulsos na ordem dos femto-segundos



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## Hydrodynamic simulation of subpicosecond laser interaction with solid-density matter

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The interaction of ultrashort subpicosecond laser pulses with initially cold and solid matter is investigated in a wide intensity range ( $10^{10}$  to  $10^{17} \text{ W/cm}^2$ ) by means of the hydrodynamic code **MULTI**, which is an extension of the long pulse version of **MULTI** [R. Ramis, P. Schulze, and J. Meyer-ter-Vehn, Comput. Phys. Commun. **49**, 475 (1988)]. Essential modifications for the treatment of ultrashort pulses are the solution of Maxwell's equations in a steep gradient plasma, consideration of the nonequilibrium between electrons and ions, and a model for the electrical and thermal conductivity covering the wide range from the solid state to the high temperature plasma. The simulations are compared with several absorption measurements performed with aluminum targets at normal and oblique incidence. Good agreement is obtained by an appropriate choice of the electron-ion energy exchange time (characterized by 10 to 20 ps in cold solid Al). In addition we discuss the intensity scaling of the temperature, of the pressure, and of the density, where the laser energy is deposited in the expanding plasma, as well as the propagation of the heat wave and the shock wave into the solid. For laser pulse durations  $> 150 \text{ fs}$  considered in this paper the amount of isochorically heated matter at solid density is determined by the depth of the electron heat wave in the whole intensity range.

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### I. INTRODUCTION

The achievement of ultrashort laser pulses with durations around 100 fs and intensities exceeding  $10^{16} \text{ W/cm}^2$  has initiated numerous investigations of laser interactions with solid matter in a new regime (see, for example, the review article Ref. [1]). In contrast to long nanosecond pulses, ultrashort pulses with a high contrast between the main pulse and prepulses generate a steep gradient plasma with typical scale lengths considerably below the laser wavelength  $\lambda$ . As a consequence, a larger fraction of the laser energy can be coupled to the solid before it expands [2–4]. Recently, isochoric heating of solid aluminum to temperatures of 300 eV has been demonstrated [5]. Thus matter properties like the x-ray opacity [6] or the equation of state can be studied at very high densities. Another important aspect is the study of the electrical conductivity in the transition regime from the solid state to the plasma state [7–10]. As examples for practical applications we mention the generation of ultrashort x-ray pulses [11] to study rapid changes of material properties [12] or material processing on a very fine spatial scale by means of interaction with ultrashort laser pulses [13–15]. At very high intensities the appearance of the harmonics of solid targets is also an important issue [16,17].

The coupling of the ultrashort laser pulse to the dense target is a complex process. It involves the absorption of the laser pulse in the steep gradient plasma, whose expansion cannot be neglected unless the intensity is very low or the pulse extremely short, the propagation of an electron heat wave propagating into the solid, and the generation of a shock wave as a consequence of the high pressure. Hydrodynamic codes are a useful tool for a consistent description of these processes provided the laser intensity is not too high. At high laser intensities ( $S_2$ ) collisionless and relativistic

effects become important. For this situation kinetic simulations are appropriate [18–24]. Recent particle in cell (PIC) simulations including collisions [25] indicate that the validity range of hydrodynamic simulations goes up to  $S_2 \lambda^2 \sim 10^{17} (\text{W/cm}^2) \mu\text{m}^2$ .

In this paper we present a comprehensive study in the regime that can be described by means of a hydrodynamic code. For this purpose we use the one-dimensional hydrodynamic code **MULTI** [26], which is based on a one-fluid two-temperature model including electronic heat conduction and multigroup radiation transport. For the equation of state (EOS) and the radiative opacities tabulated steady state values are utilized [27,28]. This code had been developed to simulate laser plasma experiments with longer (nanosecond) pulses. In order to cope with the physics of short pulse interaction, the code was modified at three essential points: (1) light propagation in steep gradient matter, (2) modeling of the electron collision frequency, and (3) utilization of separate EOS's for the electrons and the ions.

Point (1), Maxwell's equations are now solved explicitly on a high resolution mesh, whereas the original **MULTI** code a WKB approximation (resulting in Beer's law) was used. Point (2) refers in the first place to the collisional absorption of laser light in the interaction layer, but also to the energy exchange between electrons and ions and to the thermal conductivity which is important for the propagation of the electron heat wave into the dense target. The material state ranges from cold solid to hot ideal plasma, involving quite different physical regimes. Whereas in the plasma regime the electron collision frequency  $\nu$  is based on Coulomb collisions and thus  $\nu \propto T^{-3/2}$ ,  $\nu$  is determined in the cold solid regime by the interaction between electrons and lattice vibrations (or phonons) and is therefore proportional to the temperature of the heavy particles ( $\propto T$ ) [29]. By interpolating

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**Artigo de Referência:** Detalha a base matemática do **MULTI**, baseado na adaptação da hidrodinâmica às interações adicionais observadas experimentalmente

# Progresso:

1. Simulação no Deucalion para as condições apresentadas à direita ( $T_i$  - 800nm - 50fs -  $1e15 \text{ W/cm}^2$ )
2. A simulação é uni-dimensional, e obtém-se valores para a densidade, temperatura iônica, temperatura eletrónica, posição, velocidade ...
3. Pretende-se processar e analisar os dados do ficheiro fort.11

```
GNU nano 2.9.8
=====
parameters
  ideo=1, xmin=0.0, texit=2.5e-12,
  ileft=0, iright=0,
  alphal=0.0, alphar=0.0, betal=0.0, betar=0.0, itype=0, tau=0.
  iradia=1, ihydro=1, iheat=0, model=0, zmin=0.1, flf=1.0e6,
  nsplit=5,
  dtmin=1.0e-18, dtinit=5.0e-15, dtmax=5.0e-13,
  dtvar=0.05, dttevar=1.0e12, dttivar=1.0e12, dtbreak=2.0, dtf=
  texit=2.0e-12, nextit = 100000000,
  dt_aout=1.0e0, ns_aout=1,
  dt_bout=1.0e99, ns_bout=1,
  irad_left=1, irad_right=1, nreduce=1
/
&layer
  nc=200,
  thick=1.0e-5,           ! 100 nm = 1e-5 cm
  r0=4.5,                  ! Ti ~solid density g/cc
  te0=0.025, tio=0.025,   ! ~room-T in eV
  zonpar=1.0,
  material='Titanium'
/
&material
  name='Titanium',
  zi=22, ai=47.867,
  eeos_file='Titanium.i304',
  ieos_file='Titanium.i305',
  z_file='Titanium.ZKEV',
  planck_file='Titanium_PLANCK',
  ross_file='Titanium.ROSS',
  eps_id=1
/
&pulse_wkb
  inter=-1,               ! from left
  wl=0.8,                  ! microns (800 nm)
  pimax=1.9e20,             ! 1e15 W/cm^2 = 1e22 erg/s/cm^2
  pitime=5.0e-14,           ! 50 fs FWHM
  itype=1,                  ! sin^2 envelope
  delta=1.0
/
```

fort.12: Parâmetros da simulação

```
GNU nano 2.9.8
=====
subroutine ascii_output
step= 1 time= 0.500000E+14
| i x v rho te ti depo
1 -0.222754E-11 -0.141708E+04 0.449975E+01 0.124291E+01 0.132484E+00 0.307907E+26
2 0.598095E-07 0.461341E+03 0.450005E+01 0.259313E-01 0.257114E-01 0.800000E+00
3 0.100000E-06 0.140208E+01 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
4 0.150000E-06 0.699555E-05 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
5 0.200000E-06 0.277710E-10 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
6 0.250000E-06 0.568826E-16 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
7 0.300000E-06 0.116476E-21 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
8 0.350000E-06 0.238337E-27 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
9 0.400000E-06 0.489743E-33 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
10 0.450000E-06 0.109424E-38 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
11 0.500000E-06 0.205922E-44 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
12 0.550000E-06 0.422250E-50 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
13 0.600000E-06 0.865837E-56 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
14 0.650000E-06 0.177543E-62 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
15 0.700000E-06 0.364058E-67 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
16 0.750000E-06 0.746512E-73 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
17 0.800000E-06 0.153975E-78 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
18 0.850000E-06 0.313855E-84 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
19 0.900000E-06 0.643632E-89 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
20 0.950000E-06 0.131979E-95 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
21 0.100000E-06 0.270627E-101 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
22 0.105000E-06 0.555933E-107 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
23 0.110000E-06 0.111739E-112 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
24 0.115000E-06 0.233311E-118 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
25 0.120000E-06 0.470851E-124 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
26 0.125000E-06 0.961084E-130 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
27 0.130000E-06 0.201174E-135 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
28 0.135000E-06 0.412515E-141 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
29 0.140000E-05 0.848576E-147 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
30 0.145000E-05 0.173459E-152 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
31 0.150000E-05 0.355665E-158 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
32 0.155000E-05 0.729362E-164 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
33 0.160000E-05 0.149546E-169 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
34 0.165000E-05 0.306644E-175 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
35 0.170000E-05 0.628794E-181 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
36 0.175000E-05 0.128936E-186 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
37 0.180000E-05 0.264388E-192 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
38 0.185000E-05 0.542137E-198 0.450000E+01 0.250000E-01 0.250000E-01 0.800000E+00
```

fort.11: Output da simulação

# Progresso:

1. Visualização dos resultados obtidos a partir de um script em python (matplotlib e numpy)
2. Comparação com os dados de simulações com códigos alternativos (Med103)
3. Comparação com os dados experimentais e constatar exatidão do MULTI-fs para Titânio

