7. Forwarded Materials
Interaction of Ultra-Short Pulses with Matter: Prospective Applications to X-Ray Diagnostics of Plasma and Condensed Matter

Jean-Francois Eloy
CESTA

by Jean-François ELOY

We considered the time dependence of transient photoconductivity effects induced on the surface of semi-conducting materials with ultrashort EM pulses involving an associated high electromagnetic fields. By means of new relationship [1], our calculations involved the local displacement currents due to electronic transitions resulting from high EM fields effects. Our first results [2] confirm a significant variation of transient reflectivity in the hundred femtosecond range as previously reported.

The responses of a dispersive and dissipative medium or a bounded plasma to an initially localized ultrashort electromagnetic pulse have been investigated by using a Green's function technique [3, 4, 5]. Recently, an inverse symbolic method has been developed for describing space-time evolution of ultrashort electromagnetic pulses in various media. Linear analysis shows that no-wake-oscillations occur for \( v^2 / \omega_p^2 \geq 0.8 \), \( v \) being the electron collision frequency and \( \omega_p \) the plasma frequency. For the domain where \( v^2 / \omega_p^2 \approx 0.8 \), i.e. when the medium-dependent linear term of a renormalized form of the field equation is negligible, the influence of non-linearity should become relatively important, particularly for high fields.

The use of ultrashort pulses for diagnostic of fine structure inhomogeneities may offer interesting possibilities for investigations of plasmas (fusion experiments) or other media under extreme conditions. In order to apply a well-known laser time-equivalent sampling technique, we particularly consider [6] an original approach involving the implementation of X-Ray ultrashort pulses generated by either femtosecond laser interaction with a metallic target or synchrotron radiation pulse emitted by interaction of relativistic electrons beam with a periodic magnetic field.

[1] J-F Eloy,
New analytical approach of the electronic transient effects induced on semi-conducting material surfaces by different E-M masses patterns. PIERS'93, Pasadena (CA), July 1993.
[2] J-F. Eloy,

L'ATOME, DE LA RECHERCHE A L'INDUSTRIE

Origine: DEV/RIA J-F ELOY Janv. 9th, 97

329
Interaction of Ultra-Short Pulses with Matter: Prospective Applications to X-Ray Diagnostics of Plasma and Condensed Matter

by Jean-François ELOY

• OUTLINE
  - Historical Overview
  - Theoretical Considerations concerning ElectroMagnetic and Optic Ultrashort Pulses
  - Dynamic Approach of Ultrashort Pulse Effects applying a Fourier Analysis
  - New Symbolic Approach applying a Green Function Method
  - Analytical and Numerical Studies of some Cases of Ultrashort Pulse Propagations
  - Prospective Applications at Time-Resolved Diagnostics of Plasma and Condensed Matter
ULTRASHORT INTERACTION PRINCIPLE

QUANTUM MECHANICS:
PERTURBATION THEORY IN TIME

Cross Section of Electronic Transitions:

The probability to have the electronic system in the state \( \psi_n(o) \) is

\[
\frac{2|F_{mn}|^2}{1-\cos \sqrt{\frac{\Delta \omega^2}{4|F_{mn}|^{-2}} + \frac{h^2}{2}}} \frac{1}{t}
\]

where \( F_{mn} \) is an invariant operator.

Evolution in the time function for ultrashort interaction:

\( \Delta t \) tends towards zero.

the term of electronic transitions probability,

\[
\left(1-\cos \sqrt{\frac{\Delta \omega^2}{4|F_{mn}|^{-2}} + \frac{h^2}{2}} \right) t
\]

becomes, in first order:

\[ \{ t^{2/2} \} \]
RELATIVE INFLUENCE OF ULTRASHORT PULSE ON THE DAMPING TERM, $V$

$v_{ei} \rightarrow \frac{v_{ei}}{v_{em}}$

for ultrashort pulse

\[ \frac{v_{ei}}{v_{em}} \]

Collision attenuation factor

with: $\omega_e \tau_{relax} \approx 1$

following the relationship:

\[ \frac{v_{emuc}}{v_{ei}} = \frac{\left(\frac{t_{emuc}}{\tau_r}\right)^2}{1 + \left(\frac{t_{emuc}}{\tau_r}\right)^2} \]

cea-dam

Origine: ELOY Jean-François
CEA/CESTA

Date: Jan. 15th, 97
THEORETICAL CONSIDERATIONS concerning Ultrashort Pulse Interaction with Matter

In the soft X-frequency range, the usual expression of index is given by:

\[ n = (1 - \delta - i \beta) \]

where \( \beta = \frac{\mu}{4 \pi} \lambda \)

with \( \mu = \) absorption coeff and \( \delta = f(\lambda^2) \)

Considering the Maxwell Equation equivalent to Ampere Law:

\[ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \]

or

\[ \nabla \times \mathbf{H} = \sigma \mathbf{E} + \varepsilon \frac{\partial \mathbf{E}}{\partial t} \]

where \( \mathbf{J} \), or \( \sigma \mathbf{E} \rightarrow \rightarrow \) current of conduction due to free carriers

and \( \frac{\partial \mathbf{D}}{\partial t} \), or \( \frac{\partial \mathbf{E}}{\partial t} \rightarrow \rightarrow \) drift current due to the bounded carriers

With a phase representation of field:

\[ \nabla \times \mathbf{H} = j \omega \varepsilon \mathbf{E} + (\sigma + \omega \varepsilon^*) \mathbf{E} \]

Knowing the high Electrical and Magnetic Fields associated with ultrashort X-Ray Pulse, our approach takes mainly into account, the generation of localized currents

L'ATOME, DE LA RECHERCHE A L'INDUSTRIE

Origine : DEVRIA J-F ELOY

Jan. 18th, 97
OVERSHOOT PHENOMENA INDUCED BY HIGH E-FIELDS

Mean Free Path of Electron:
\[ l = \frac{v_m \cdot \Delta t}{\alpha} \]
If: \( \Delta t = 10^{-13} \text{s} \), \( \Delta l = 10^{-6} \text{m} \).

cea-dam

Origine: ELOV Jean-François
CEA/CESTA

Date: Jan 15th, 97
Overshoot Velocity of Electrons due to High E-M Field

\[ m^* (\frac{\partial v}{\partial t} + v \frac{1}{T}) = qE \]

when \( E_s > \) overshoot electric field, \( E_{no} \)

cea-dam

Origine: I BLOV Jean-François
CEA/CESTA

Date: Jan. 15th, 97
SLAC/DESY International Workshop on the Interaction of Intense Sub-picosecond X-Ray Pulses with Matter
Stanford, Jan. 23-24, 1997

Overshoot Features of Various Materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>Overshoot field $E_{no}$ (V/m)</th>
<th>Thermal velocity $v_s$ (m/s)</th>
<th>Coefficient $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>$101 \cdot T^{1.55}$</td>
<td>$0.015 \cdot T^{-0.87}$</td>
<td>$2.57 \cdot 10^{-2} \cdot T^{0.66}$</td>
</tr>
<tr>
<td>AsGa</td>
<td>$3.4 \cdot 10^5$</td>
<td>$10^5$</td>
<td>4</td>
</tr>
<tr>
<td>SiC</td>
<td>$2-3 \cdot 10^8$</td>
<td>$2 \cdot 10^5$</td>
<td>(?)</td>
</tr>
</tbody>
</table>

Origine: ELOY Jean-François
January 23th, 97
For the Analytical Studies of ULTRASHORT PULSE PROPAGATION and INTERACTION, we have the use of:

- Traditional Approach of spectral representation of signals by using Fourier Analysis

- Alternative of Representations:
  - Gabor time-localization: "window function" technique or the "short-time Fourier Transform" (STFT)
  - Wavelet Transforms: variable frequency window; example: Gaussian double derivative profile

- Original Approach:
  - Inverse Symbolic Method using Green's function in case of time-space localized sources
Analytical and Numerical Studies of Ultrashort Pulse Propagation and Interaction at CESTA/IEMUC Group

- by Fourier Analysis
- by Symbolic Green Function Method
Analytical and Numerical Studies of Ultrashort Pulse Propagation and Interaction at CESTA/IEMUC Group

by Fourier Analysis
ULTRASHORT PULSE INTERACTION

New approach involving transient phenomena as:
- overshoot
- stark effects

Drift currents are depending on time: for a planar EM wave, linearly polarized, we can write:

\[ J_{ei} = q \cdot N_{ei} \cdot v_e \cdot E(t) \]

where \( N_{ei} \) : density of intrinsic carriers (impurities)

Then:
\[
\frac{\partial N_{ei}(t)}{\partial t} = \frac{\nabla \cdot J_{ei}}{q} = \frac{1}{q} \left( \frac{\partial J_{ei}}{\partial z} \cdot \frac{\partial J_{p}}{\partial z} \right)
\]

We can integrate this following expression:

\[
N_n(t,z) = \int_{z_0}^{z_{100nm}} \int_{0}^{100nm} \frac{\partial^2}{\partial t \cdot \partial z} (J_{ei}(t)) \cdot dz \cdot dt
\]

Therefore, transient conductivity is given by:

\[
\sigma(t) = \frac{N_n(t) \cdot q^2 \cdot \tau_e}{m_e} \cdot \frac{1 + \Gamma \omega \cdot \tau}{1 + (\omega \cdot \tau)^2}
\]
SURFACE ULTRASHORT E-M PULSES EFFECTS

LOCAL TRANSIENT CURRENT DENSITY

Gaussian double derivative pulse namely D.S.G.

\[ f(t) = cfa \cdot (cfb - cfn \cdot t^\alpha) \cdot \exp\left[-s \cdot (t/\text{cft})^\beta\right] \]

where: \( cfa = 1 \); \( cfb = 1 \); \( \text{cft} = 10^{-12} \)

Numerical values:

- \( \text{cfn} = 4 \)
- \( \beta = 4 \)
- \( s = 1 \)
- \( \alpha = 4 \)

Convolution product profile: \( \sigma(t) \otimes E(t) \)

cea-dam

Nous préparons l'avenir

DT/PE

Origine: Eloy Jean-François

Date: 22/3/93
TRANSIENT SURFACE REFLECTIVITY INDUCED BY EM ULTRASHORT PULSE

depth: 1000Å; with Overshoot considerations

\[ E_0 = 10 \text{ e/m}^3; E_s = 10^8 \text{ V/m}; \tau = 10^{-10} \text{ s}; v_s = 10 \text{ m/s} \]

\[ \omega_0 = 10^{11} \text{ Hz} \]

relaxation time: \( 10^{-11} \)

\[ R_s \]

Origine: ELET Jean-François
CEA/CESTA

Date: Jan. 15th, 97
Analytical and Numerical Studies
of Ultrashort Pulse Propagation and Interaction at
CESTA/EMUC Group

by Symbolic Green's Function Method
PURPOSES FOR USING A SPACE-TIME APPROACH

For Ultrashort Pulse Interaction

» consider individual electrons,
» avoid classical approach in the frequency domain (for ultrashort time, frequency have no meaning)
» study the propagation and interaction in the time domain
» tentative to use of a time operator:
  "time derivative"
  such as: \( \omega \leftrightarrow -j \frac{\partial}{\partial t} \)

and then "time second derivative"
such as:
\[
\left( \frac{-\omega^2}{\nu^2} \right) \leftrightarrow \frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial t^2} \left( \frac{1}{\nu^2} \right) = \frac{\partial^2}{\partial t^2}
\]
with \( \nu \): collision frequency
EQUATION OF WAVE PROPAGATION
For a monochromatic continuous wave,

Case of a dense plasma:

\[ \nabla^2 \psi - \frac{n^2}{c^2} \frac{\partial^2 \psi}{\partial t^2} = 0 \]

where:

\[ n^2 = 1 - \frac{\omega_{pl}^2}{\omega (\omega - j v)} \]

with:

\[ \omega_{pl}^2 = \omega_p^2 + 3 v_e k^2 \]

\( v_e \): electron thermal velocity
\( k \): plasma wave number
\( \omega_p \): plasma frequency
\( = N q^2/m_e \varepsilon_0 \)
\( v \): collisional damping
FOR A TIME DEPENDENT PROBLEM

Case of a Cold Plasma with Collisions:

Equation of wave propagation is expressed by:

\[ \nabla^2 \Psi - \frac{n^2}{c^2} \frac{\partial^2 \Psi}{\partial t^2} = 0 \]

with

\[ n^2 = 1 - \frac{\omega_p^2}{\omega (\omega - j\nu)} \]

where \( \omega_p \): plasma frequency = \( N q^2 / m_e \varepsilon_0 \)

\( \nu \): collisional damping

in case of ultrashort EM pulse study, how avoid the frequency aspect??
TIME-SPACE DESCRIPTION
BY GREEN'S FUNCTION METHOD

Substituting of \( \phi \leftrightarrow -ja/\partial t \)

in

\[
\nabla^2 \phi - \frac{\mu^2}{c^2} \frac{\partial^2 \phi}{\partial t^2} = 0
\]

This equation of wave propagation becomes:

\[
\nabla^2 \phi - \frac{1}{c^2} \frac{\partial}{\partial t^2} \left[ 1 + \frac{\omega_p^2}{\partial (\partial + \nu)} \right] \phi = 0
\]

For \( \nu = 0 \), we recognized the equation of Klein-Gordon

\[
\nabla^2 \phi - \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} - \frac{\omega_p^2}{c^2} \phi = 0
\]

which describes a purely dispersive medium.
TIME-SPACE DESCRIPTION VIA A GREEN'S FUNCTION METHOD

In case of dissipative medium:
Considering a source function: \( \delta(R) \delta(t-t_0) \)

in 3-D, the Green's function becomes:

\[
\nabla^2 G - \frac{1}{c^2} \frac{\partial G^2}{\partial t^2} - \frac{\omega_p^2}{c^2} \frac{1}{\partial t} \frac{\nabla^2 G}{\partial t} = -4\pi \delta(R) \delta(t-t_0)
\]

We can separate the terms representing the influence of dispersive and dissipative parts.

cea-dam

Origine: ELOP Jean-François
CEA/CESTA

Date: Jan 15, 97
SECOND STEP IN TIME-SPACE DESCRIPTION VIA A GREEN'S FUNCTION METHOD

In case of dissipative medium:

Considering the "new frequency" of oscillation:

\[ \omega_p^2 \frac{v^2}{1 - \frac{v^2}{a^2/\delta t^2}} \]

corresponding to \( \omega_p \) for \( v = 0 \)

This new oscillative frequency can be related formally to the plasma frequency \( \omega_p \) by

\[ \frac{\partial^2}{\partial t^2} \leftrightarrow -\frac{\omega_p^2}{1 - \frac{v^2}{a^2/\delta t^2}} \]

the symbolic relation:

\[ \frac{\partial^2}{\partial t^2} \leftrightarrow -\omega_p^2 + \frac{v^2}{\delta t^2} \]

from which it follows:

\[ \frac{\partial^2}{\partial t^2} \leftrightarrow -\omega_p^2 + \frac{v^2}{\delta t^2} \]

cea-dam

Origine : ELC7 Jean-François
CEA/CESTA

Date : Jan. 15th, 97

IEMUC
GREEN'S FUNCTION METHOD APPLIED TO A DISPERSIVE & DISSIPATIVE NON-RESONANT MEDIUM

After use of the second time operator, the Green's function becomes:

\[ \nabla^2 G - \frac{1}{c^2} \frac{\partial G}{\partial t} - \frac{1}{c^2} \left( \omega_p^2 - \nu^2 \right) G = \frac{v}{c^2} \frac{\partial}{\partial t} G = -4\pi \delta(R) \delta(t-t_0) \]

To solve this equation, it is convenient to introduce the transformation: \( G = U e^{-\Omega(t-t_0)} \)

\[ \nabla^2 U - \frac{1}{c^2} \left( \frac{3}{c^2} - \frac{\nu^2}{2} \right) U - \frac{1}{c^2} \left( \omega_p^2 - \frac{5}{4} \nu^2 \right) U = -4\pi \delta(R) \delta(t-t_0) \]

For \( \Omega = \frac{1}{2} \nu \), we obtain the simplified equation:

\[ \nabla^2 U - \frac{1}{c^2} \frac{\partial^2 U}{\partial t^2} - \frac{1}{c^2} \left( \omega_p^2 - \frac{5}{4} \nu^2 \right) U = -4\pi \delta(R) \delta(t-t_0) \]

which reveals a particular solution when:

\[ \nu^2 = \frac{5}{4} \omega_p^2 \]
SPHERICAL LASER PLASMA MEDIUM

illuminated by a spherical δ-type source

The spherical shell surface of the plasma plays the role of an EM source
SLAC/DESY International Workshop on
the Interaction of Intense
Sub-picosecond X-Ray Pulses with Matter
Stanford, Jan. 23-24, 1997

PROPAGATION OF AN E.M. WAVE
IN A PLASMA ILLUMINATED BY AN
δ - TYPE ULTRASHORT PULSE PACKET

For \( \omega_p > \frac{5}{4} \nu^2 \)

the field penetrates into the plasma \((R < R_o)\)
as indicated by the solution of the Klein-Gordon type
propagation equation expressed by:

\[
U = \frac{\delta(t-t_0, R/c)}{R} \cdot \frac{\sqrt{\omega_p^2 - \frac{5}{4} \nu^2}}{c \sqrt{(t-t_0)^2 - (R/c)^2}} J_1 \left( \sqrt{\omega_p^2 - \frac{5}{4} \nu^2} \sqrt{(t-t_0)^2 - (R/c)^2} \cdot \phi \right)
\]

Penetrating
part 1

backscattered
oscillating
part 2

On a spherical shell surface \((R = R_o)\), will remain
(for \( t > t_0 \)) a backscattered oscillating field

cea-dam

Origine: KEK, Jean-François
CEA/CESTA

Date: Jan. 15th, 97
Over the past twenty five years, ultrafast studies has been conducted in the visible and the infrared domain in the single-cycle limit. The field has been very successful and has reached a high level of maturity.

The Question is: is it possible in the next few years to extend time-resolved studies in the picosecond and femtosecond in the X-ray regime? The answer is certainly YES.

Taken from G. Mourou
ICFA Workshop
January 96
PLASMA DIAGNOSTICS RESEARCH

Cut-off densities

INTERACTION of
X/LASER RADIATIONS
with
DENSE PLASMAS

INTERACTION of
a Terahertz RADIATION
with
COLD PLASMA

log $[N_c \text{ (cm}^{-3}\text{)}]$

log $[\lambda \text{ (nm)}]$

$\omega_c \sim 28 \text{ THz}$
SLAC/DESY International Workshop on the Interaction of Intense Sub-picosecond X-Ray Pulses with Matter
Stanford, Jan. 23-24, 1997

[Diagram of experiment setup]

cea-dam

Origine: ELET Jean-Françale
CEA/CESTA

Date: Jan. 15th, 97

cea-dam

Origine : LEGY Jean-François
CEA/CESTA

Date: Jan. 15th, 97
Bunching of X-Rays for Generating Ultra-short Pulse Trains

Jean-François Eloy
CESTA
• SLAC/DESY International Workshop on the Interaction of Intense Sub-picosecond X-Ray Pulses with Matter

STANFORD, January 23-24, 1997

Bunching of X-Rays for Generating Ultra-short Pulse Trains

by Jean-François ELOY

• Principle of the Optical Pulse Compression

• Temporal Property of X-Ray pulses generated:
  – by Laser-Matter Interaction
  – by Relativistic Electrons with Periodic Magnetic Structure

• Original Layout for bunching of X-Rays Pulses
title: Bunching of X-Rays for Generating Ultra-short Pulse Trains
by Jean-François ELOY

The optical pulse compression is currently accomplished [1, 2] in two steps: 1) frequency sweep is impressed on the pulse by passing through a stretcher to provide an additional bandwidth, 2) the pulse is compressed by using a dispersive delay line involving a grating pair in a parallel diffraction position [3]. The interaction of laser beam with matter or relativistic electrons with periodic magnetic device as an "undulator" or wiggler are able to generate an instantaneous frequency of X-ray pulse increasing with time [4]. Therefore, this technique of pulse compression can be used in the X frequency range by using an assembly of grating pairs to stretch and compress successively the X-ray pulse. We propose an original layout for bunching and pulse-shaping X-rays generated by these types of interaction.


Principle of Optical Pulse Compression

- **Two Steps** are necessary:

  1) Frequency sweep is impressed on the pulse by a stretcher optical device.

  2) Pulse is compressed by using a dispersive delay line involving a grating pair in a parallel diffraction position.

- Considering New Technology to make Grating for Soft X-rays, it is possible to apply the Principle of Pulse Compression in the X-Frequency Range.
Principle of Optical Pulse Compression (I)

Required Conditions of X-Rays Pulse Generation:
- Frequency sweep with time:

- Case of X-rays pulse by Laser-Matter Interaction

- Case of Relativistic Electrons Interaction with Periodic Magnetic Structure:

The FEL emission spectrum is given by:

$$\frac{dW}{d\omega \, dr} (\omega) \propto \left| \int V_x e^{i(\omega_0 t + \omega_0 \sin 2\omega_0 t)} \right|^2$$

Simulation of Temporal Profiles of X-rays spectra:
**Principle of Optical Pulse Compression**

**(II)**

**Spectral Distributions of X-rays source**

\[ \Delta t = 2 \times 10^{-13} \]

\[ \Delta \nu = 7 \times 10^{17} \]

**Hypothesis:**

If \( \Delta t = 2 \times 10^{-13} \text{ s.} \) and \( \delta \nu_n = 2 \times 10^{17} \text{ Hz.} \)

\[ \Delta t \cdot \delta \nu_n = 2 \times 10^{-13} \cdot 2 \times 10^{17} = 4 \times 10^4 \]

then

\[ \Delta \nu \cdot \delta t = 7 \times 10^{17} \cdot 4 \times 10^4 \]

**therefore, we can reach:**

\[ \Rightarrow \delta t = 57 \text{ fs} \]
First Step:

- Frequency sweep is impressed on the pulse by a "stretcher" optical device.

The first experiment of Mollenauer was using an intense optical pulse simply by passing the pulse through an optical Kerr medium. An phase change, $\delta \phi$, is impressed on the pulse such as:

$$\delta \phi = n <E^2> \omega z / c$$

where $\omega$ is the frequency, $z$ is the distance traveled in the Kerr medium, $c$ is the velocity of light.

More recently, J.P. Chambaret and co-worker (ENSTA/LOA) have designed a new concept of stretcher used in the I-R frequency range. They implemented a delay line involving a grating pair in a particular configuration.
Principle of Optical Pulse STRETCHER

Delay Function: \( \phi_e(\omega) = \phi_0 + a \omega^2 \)

where Phase Function is \( \phi_e(\omega) \)
and grating constant \( a \)

The grating pair constant is given by:
\[
a = b \frac{\lambda^3}{4 \pi c^2 d^2 \cos^2 \gamma}
\]
where \( b \) is distance between two gratings
\( d \) is the groove spacing
\( \lambda \) is the center wavelength of the pulse
\( \gamma \) is the angle normal to the input grating and
diffracted beam at \( \gamma \)
Principle of Optical Pulse Compression

(IV)

2)- Pulse is compressed by using a dispersive delay line involving a grating pair in a parallel diffraction position

Delay Function : \[ \phi_c(\omega) = \phi_0 - a \omega^2 \]

where Phase Function is \( \phi_c(\omega) \)

and grating compressor constant \( a \)

The grating pair constant is given by:

\[ a = b \frac{\lambda^3}{4 \pi c^2 d^2 \cos^2 \gamma} \]

where \( b \) is distance between two gratings

\( d \) is the groove spacing

\( \lambda \) is the center wavelength of the pulse

\( \gamma \) is the angle normal to the input grating and diffracted beam at \( \gamma \)