Short Pulse Laser Interactions with Matter

Paul Gibbon
Forschungszentrum Jülich

Part I

Introduction to Short Pulse Laser Physics

❶ Introduction: Historical Background

- Progress in technology
- Multiphoton Physics
- Single-Electron Interaction with Intense Electromagnetic Fields
- Nonlinear Wave Propagation
- Metal Optics
- Long Pulse Laser-Plasma Interactions (ICF)
- Femtosecond Lasers

Web site for lecture handouts

`www.fz-juelich.de/zam/splim`

CENTRAL INSTITUTE FOR APPLIED MATHEMATICS (ZAM)

COMPLEX ATOMISTIC MODELING AND SIMULATION

- ZAM Homepage
- Atomistic Modeling
- Group Members
- Recent Publications
- Computational Methods
- Simulations of Liquids
- Laser-Plasma Interactions
  - PEPC
  - BOPS
  - SPLIM
    - Lectures
    - Download
    - Wave-envelope
- Quantum Chemistry
- Teaching
- Guests
- Events
- Internals

> Laser-Plasma Interactions > SPLIM

SPLIM Repository

This web page contains supplementary material for the book "Short Pulse Laser Interactions with Matter". This material is provided for teaching and research purposes only, and includes:

- Lectures based on the book,
- Documentation for numerical models described in Chapter 6.
- Program downloads .

Laser technology progress: chirped pulse amplification

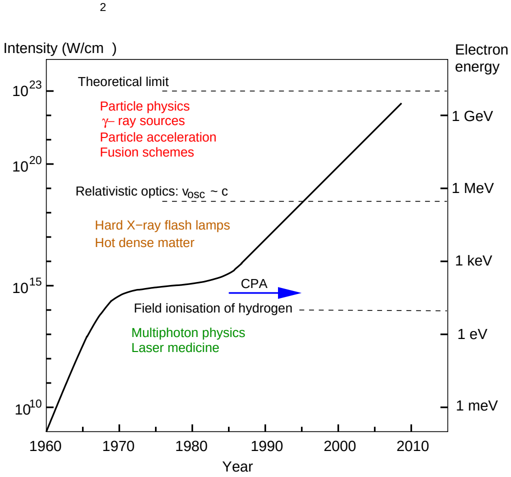


Figure: Progress in peak intensity since the invention of the laser in 1960.

What kind of physics does this field involve?

Contributory fields are numerous and diverse:

- laser physics
- atomic physics
- plasma physics
- astrophysics
- nuclear & elementary particle physics

Many theoretical models have roots in these more classical areas.

Extreme conditions: violent science

- Ordinary matter — solid, liquid or gas — rapidly ionized when subjected to high intensity irradiation.
- Electrons released are then immediately caught in the laser field
- Oscillate with a characteristic energy which then dictates the subsequent interaction physics.
- Continual challenge to both theoreticians and experimentalists.

Prehistory

- Multiphoton physics
- Single-electron interaction with intense EM fields
- Nonlinear wave propagation
- Metal optics (Drude model)
- Long pulse laser-plasma interactions (ICF)

Multiphoton physics

- Standard lasers (0.25 μm – 13.4 μm): cannot observe the photoelectric effect on normal material because $\hbar\omega \ll I_p$.
- Higher intensities in the 1960s and '70s (Fig. 1) led to possibility of *multiphoton* ionisation:

$$n\hbar\omega = I_p.$$

- Electron absorbs n photons of moderate energy (eg laser photons with $\hbar\omega \approx$ eV)

Electrons in intense electromagnetic fields

- Volkov (1935): electron 'dressed' by field
- Schwinger (1949): radiated power
- Invention of laser (1960): theoretical works on electron dynamics
- Figure of merit q:

  $$q = \frac{eE_L}{m\omega c}, \tag{1}$$

  e = electron charge, m = electron mass, c = speed of light; E_L = laser electric field strength; ω = light frequency.
- Ostriker & Gunn (1969) – electron dynamics in vicinity of pulsars:

  $$q \sim 100$$

Nonlinear wave propagation

- Plasmas can support large-amplitude, nonlinear waves.
- Early works by Akhiezer & Polovin (1956) and Dawson (1959)
- Numerous studies on the behavior of:
    - large-amplitude Langmuir (electrostatic) waves
    - propagation of high-intensity electromagnetic radiation in plasmas
- Tajima and Dawson (1979) proposed 'laser electron accelerator' – fresh wave of interest in wave propagation, including from members of the particle accelerator community.

Drude model of metal optics

- Atoms in a metal share a limited number of ‘valence’ electrons, forming a conduction band – Drude (1906)
- These carry current and heat through the material.
- For an element with mass density ρ and atomic weight A, free electron density is given by:

  $$n_e = N_A Z^* \rho / A$$

  where N_A is Avogadro’s constant and Z^* is the number of valence electrons per atom.

Drude model: conductivity

- Electrical conductivity of a metal:

$$\sigma_e = n_e e^2 \tau / m_e$$

where τ is the *collision* or *relaxation time*.

- Ohm's Law:

$$\mathbf{j} = \sigma_e \mathbf{E}$$

- Resulting AC conductivity:

$$\sigma(\omega) = \frac{\sigma_e}{1 - i\omega\tau}. \tag{2}$$

Drude model: dielectric constant

- Combine $\sigma(\omega)$ from Eq. (2) with Maxwell's equations to get *complex dielectric constant*:

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega(\omega + i\nu)},$$

where

$$\omega_p^2 = 4\pi n_e e^2 / m_e$$

is the *plasma frequency* of the valence electrons, and $\nu \equiv \tau^{-1}$ is their collision frequency.

Long pulse interactions: Inertial Confinement Fusion (ICF)

- Principle: micrometer-sized pellet filled with DT fuel compressed to enormous densities by many laser beams focused symmetrically onto its surface
- Pellet shell material ablates radially outwards, pushing the fuel inwards via rocket effect
- Fuel implodes, reaching densities $\rho \sim 500 - 1000$ gcm^{-3} and temperatures T of 10 keV (10^7 degrees Kelvin)
- Laser fusion became official in 1972 (previously classified): paper in Nature by Nuckolls *et al.*

Requirements for ICF

- Aim to satisfy *Lawson criterion* for thermonuclear confinement:

$$nT\tau > 10^{15} \ \text{keV s cm}^{-3}. \tag{3}$$

- Target must release fusion energy before it blows apart
- – leads to requirement for the *areal fuel density* $\rho R \geq 0.3$, where R is the final capsule radius
- 'Hot spot' scenario: hot, low density core surrounded by cold, high density fuel
- Laser driver energy $\sim$ 1MJ
- Facilities currently being built: NIF, Livermore, USA; LMJ, Bordeaux, France

ICF issues relevant to short pulse interactions

- Hydrodynamics – ion motion, target expansion (prepulse physics)
- *Coronal* processes – Fig. 2:
  - parametric instabilities – Raman and Brillouin scattering
  - resonance absorption - kinetic wave-particle interactions
  - fast electron generation & heating: 'suprathermal' temperature T_H given by:

    $$T_H \simeq 14\,(I\lambda^2)^{1/3}\ \mathrm{keV},$$

    where I is the laser intensity in units of 10^{16} Wcm^{-2} and λ the laser wavelength in microns.

Coronal physics in ICF

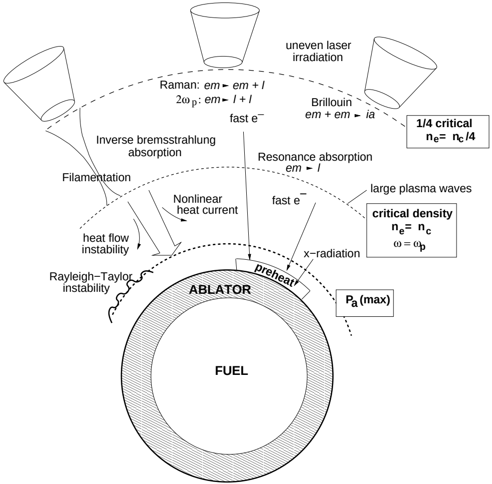
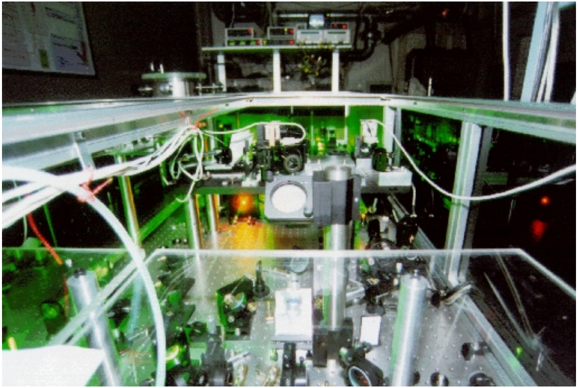


Figure: Laser-plasma interactions in the corona of an imploding micro-balloon.

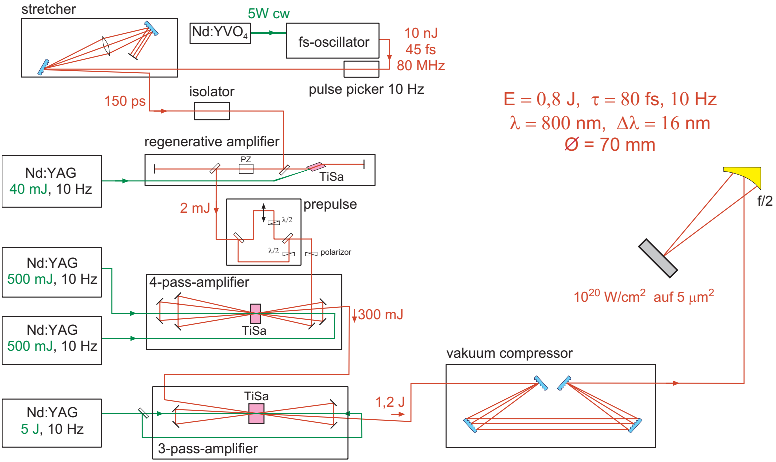
Femtosecond TW laser system: front end



Femtosecond TW laser system: components

1. *Oscillator*: produces short, low-energy pulse
2. *Stretcher*: converts fs pulse to 50–200 ps
3. *Amplifier*: increase the pulse energy by a factor of 10^7–10^9
4. *Compressor*: performs optical inverse of the stretcher to deliver an amplified fs pulse

Femtosecond TW laser system: schematic



$E = 0{,}8$ J, $\tau = 80$ fs, 10 Hz
$\lambda = 800$ nm, $\Delta\lambda = 16$ nm
Ø = 70 mm

10^{20} W/cm^2 auf 5 μm^2

Chirped pulse amplification

- Invented by Gerard Mourou and co-workers in 1985
- Way of increasing intensities beyond damage thresholds for ‘long’ pulses (100-200 ps)
- Fluence $\leq 0.16\ \mathrm{Jcm}^{-2}\tau_{ps}^{1/2}$
- – way below saturation levels of amplifying medium $\sim 1\ \mathrm{Jcm}^{-2}$ for Ti:sapphire.
- Stretcher-compressor separates pulse generation and amplification stages
- – permits standard techniques & components in amplifier chain

Oscillator

- Femtosecond laser sources are
  - *mode-locked*: output pulse is superposition of many electromagnetic waves (or laser modes)
  - *transform or bandwidth limited*:

$$\tau_p \sim 1/\Delta\nu$$

- Large bandwidth is essential to generate a short pulse.
- Example: 10 fs Gaussian pulse $\rightarrow \Delta\nu\tau = 0.44$, giving $\Delta\nu = 4.4 \times 10^{13}$ Hz, which for a central wavelength of 800 nm, translates to:

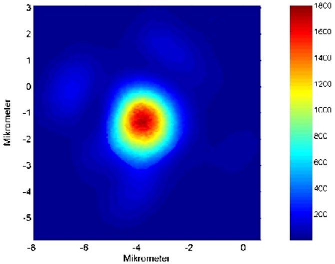
$$\Delta\lambda = \Delta\nu\frac{\lambda^2}{c} = 94\ nm.$$

Amplification & recompression

- Regenerative preamplifier – gain $\sim 10^7$
- Power amplifiers – gain $\sim 10 - 1000$
- Amplified pulse recompressed using grating pair or quadruple

Final focus

- Off-axis, parabolic mirror ($f/4 - f/2$)



- Focal spot of Ti:sapphire laser with 3 μm diameter containing more than 50% of the pulse energy.
- Peak intensity here: 4×10^{19} Wcm^{-2}.

Multi-Terawatt laser systems and laboratories worldwide

Name	Lab	Country	Type	λ (nm)	Energy (J)	τ_L (fs)	P (TW)	σ_L (μm)	I_L (Wcm^{-2})
Petawatt[a]	LLNL	USA	Nd:glass	1053	700	500	1300	–	$> 10^{20}$
VULCAN[b]	RAL	UK	Nd:glass	1053	423	410	1030	10	1.06×10^{21}
PW Mod.[c]	ILE	JP	Nd:glass	1054	420	470	1000	30	10^{20}
PHELIX[d]	GSI	D	Nd:glass	1064	500	500	1000	–	–
LULI PW	LULI	F	Ti:Sa	800	30	300	100		–
APR PW	APR	JP	Ti:Sa	800	2	20	100	11	2×10^{19}
–	FOCUS	USA	Ti:Sa	800	1.2	27	45	(1)	(8×10^{21})
ALFA 2	FOCUS	USA	Ti:Sa	800	4.5	30	150	(1)	(10^{22})
S. Jaune	LOA	F	Ti:Sa	800	0.8	25	35		10^{19}
Lund TW	LLC	SW	Ti:Sa	800	1.0	30	30	10	$> 10^{19}$
MBI Ti:Sa	MBI	D	Ti:Sa	800	0.7	35	20		$> 10^{19}$
Jena TW	IOQ	D	Ti:Sa	800	1.0	80	12	3	5×10^{19}
ASTRA	RAL	UK	Ti:Sa	800	0.5	40	12		10^{19}
USP	LLNL	USA	Ti:Sa	800	1 (10)	100 (30)	10 (100)		5×10^{19}
UHI 10	CEA	F	Ti:Sa	800	0.7	65	10		5×10^{19}