Взаимодействие лазерного излучения экстремальной интенсивности с веществом в ультрарелятивистском режиме

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02.03.2023

Outline

- Extreme lasers and plasma

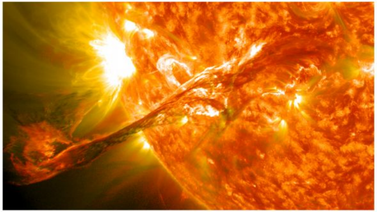
  what can be done?
- Acceleration of matter with lasers

  sailing with light
- Radiation dominated plasma

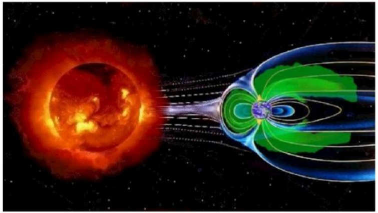
  gigagauss magnetic fields in the lab

Extreme laser-matter interaction → Plasma

Jet in the Centaurus A galaxy-X ray (Chandra)



Solar corona material is hovering in the Sun's outer atmosphere



Solar wind pressure ↔ pressure of the Earth's magnetic field

The race to extreme light intensities ... continues

Irnee D'Haenens & Theodore Harold Maiman

[Nature 187 (1960)]

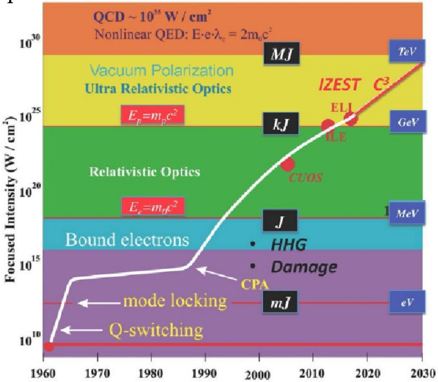
LASERs produce coherent, monochromatic artificial light, directional, amplifiable, "concentrable"in space and over time

- Current intensity record $I \simeq 2 \times 10^{22}$ W/cm^2 HERKULES, 0.3PW, 10 fs, $\sim 1\mu$m focus (CUOS)

$$I/c \simeq 3 \times 10^{13} \text{atm}$$

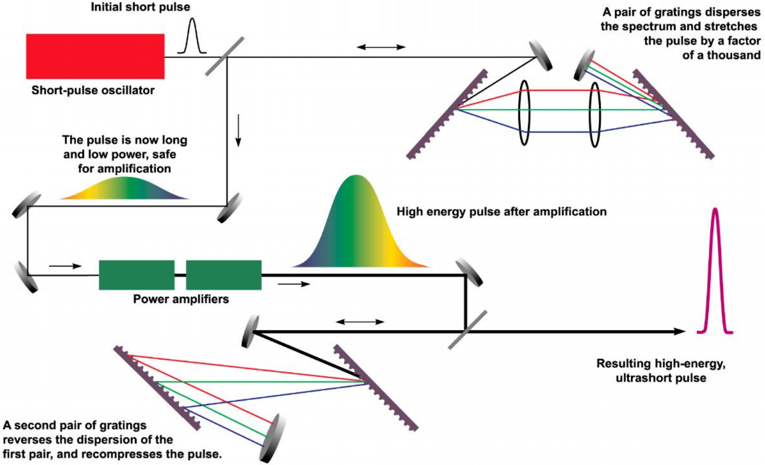
- In construction in Europe

ELI (1.5kJ/150fs) (Czechia, Hungary & Romania)
APOLLON (150J/15fs) (France)
VULKAN (300J/30fs) (UK)



Chirped Pulse Amplification - Nobel Prize 2018 in Physics

Gérard Mourou &
Donna Strickland
"... for their method of generating high-intensity, ultra-short optical pulses."
[Optics Comm. 56 (1985)]



Before the invention of lasers

Intensity of Sunlight:
$I \simeq 0.14 \mathrm{W/cm}^2$
with concentration $\simeq 10^4$
$\rightarrow I \simeq 10^3 \mathrm{W/cm}^2$ at focus

Archimedes' mirror burning Roman ships. 213 BC.

Giulio Parigi, 1600, Uffizi Gallery

The dawn of laser-plasma physics (1964)

THE PHYSICS OF FLUIDS VOLUME 7, NUMBER 7 JULY 1964

On the Production of Plasma by Giant Pulse Lasers

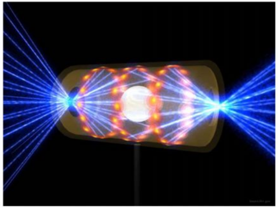
JOHN M. DAWSON
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey
(Received 10 October 1963; final manuscript received 10 March 1964)

Calculations are presented which show that a laser pulse delivering powers of the order of 10^{10} W to a liquid or solid particle with dimensions of the order of 10^{-2} cm will produce a hot plasma with temperatures in the range of several hundred eV. To a large extent the plasma temperature is held down by its rapid expansion and cooling. This converts much of the energy supplied into ordered energy of expansion. This ordered expansion energy can amount to several keV per ion. If the expanding plasma can be caught in a magnetic field and its ordered motion converted to random motion this might be utilized as a means for filling controlled thermonuclear fusion devices with hot plasma. Further, it should also be possible to do many interesting plasma experiments on such plasmas.

What can be done with lasers and plasmas?

Fusion

National Ignition Facility (NIF)



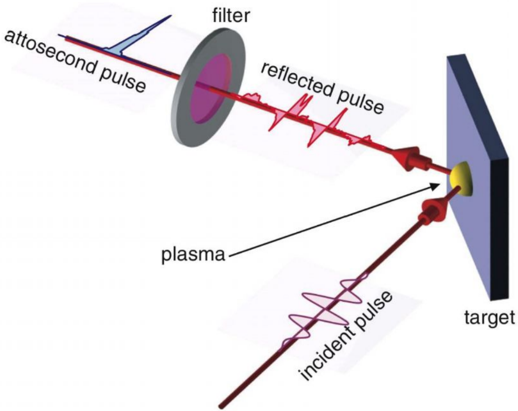
NIF Hohlraum-artistic rendering

Matter at extreme conditions

Nature Covers

What can be done with lasers and plasmas?

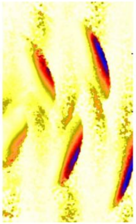
"Relativistic engineering"



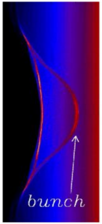
Idea: coherent control of laser-plasma dynamics (e.g. moving mirrors) to create/manipulate EM pulses (atto/zeptosecond pulses, high harmonics, ultra-high fields...)

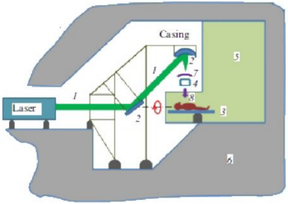
What can be done with lasers and plasmas?

Acceleration of matter



e^- bunches:
from laser-irradiated He droplet &
in the wake of a laser-pulse





p^+ bunch from laser-irradiated plasma &
optical counterpart of a classical setup of a gantry in Ion Beam Therapy

Laser Sails

22 NATURE JULY 2, 1966 VOL. 211

INTERSTELLAR VEHICLE PROPELLED BY TERRESTRIAL LASER BEAM

By Prof. G. MARX

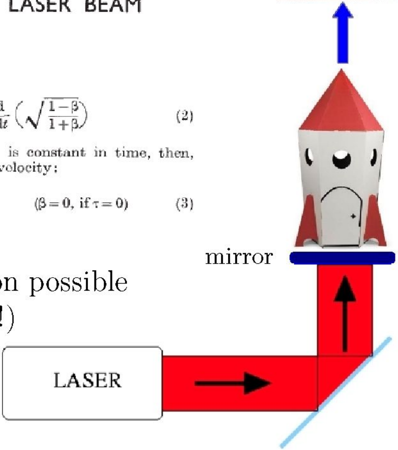
Institute of Theoretical Physics, Roland Eötvös University, Budapest

The extreme difficulties of interstellar space travel are well known[1]. It is a commonly accepted view that, apart from the technical difficulties involved, the laws of conservation of energy and momentum forbid the visiting of other planetary systems in the human life-span[1]. This article sets out to show that this is not necessarily the case. To arrive at the nearest stars in the life-span of the astronaut a relativistic velocity is needed.

$$I' = -\frac{Mc^2}{2f}\frac{d}{dt}\left(\sqrt{\frac{1-\beta}{1+\beta}}\right) \qquad (2)$$

If the incoming intensity, I, is constant in time, then, by integration, the terminal velocity:

$$\frac{v}{c} = \beta = \frac{(1+2\tau)^2-1}{(1+2\tau)^2+1} \qquad (\beta = 0, \text{ if } \tau = 0) \qquad (3)$$



Idea: R. L. Forward (1964) & G. Marx (1966)

Main problem foreseen at that time: no deceleration possible

$\Longrightarrow$ no stop, no return flight (and no alien visitors!)

A scheme for deceleration and a round-trip travel to ε-Eridani was proposed by R. L. Forward

[J. Spacecraft 21, 187 (1984)]

Nobel Prize 2019 in Physics

Michel Mayor & Didier Queloz

".. for the discovery of an exoplanet orbiting a solar-type star"

[Nature 378 (1995)]

> 5300 exoplanets have been discovered and are considered "confirmed

From press-release: "With numerous projects planned to start searching for exoplanets, we may eventually find an answer to the eternal question of whether other life is out there."

- $2 \div 4 \times 10^{11}$ stars in the Milky Way
- $10^{11} \div 10^{12}$ galaxies in the Universe
- $10^{19} \div 10^{23}$ stars in the Universe
- extant civilizations (?)

The closest exoplanet to Earth (2016) Proxima Centauri b is ~four light-years away.
It would take 1.5×10^6 years to reach it at the speed of Apollo 11.

[Milky Way Galaxy, Hubble Telescope]

Efficiency of the light-sail: accelerating mirror model

Radiation pressure can be accounted for in terms of the momenta of photons

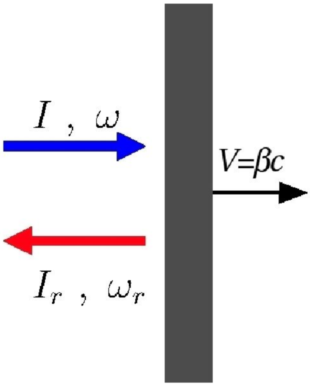
Force on the mirror and mechanical efficiency η derived from the Doppler shift and conservation of photon number N

$$I = \frac{N\hbar\omega}{\tau} \qquad \Delta\mathbf{p} = N\hbar(\mathbf{k}_i - \mathbf{k}_r) = N\frac{\hbar}{c}(\omega + \omega_r)\hat{\mathbf{x}}$$

$$\omega_r = \omega\frac{1-\beta}{1+\beta} \qquad \Delta t = \frac{\tau}{1-\beta} \qquad \frac{\Delta p}{\Delta t} = \frac{2I}{c}\frac{1-\beta}{1+\beta}$$

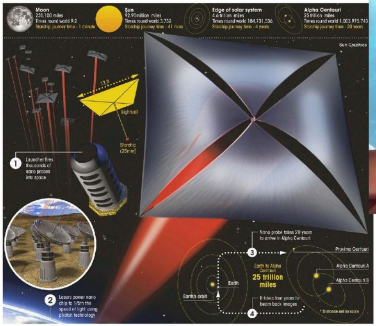
$$\eta \equiv \frac{\Delta\mathcal{E}}{I\tau} = \frac{N\hbar(\omega+\omega_r)}{N\hbar\omega} = \frac{2\beta}{1+\beta}$$

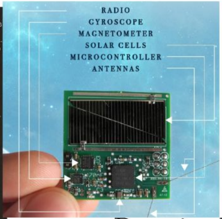
High efficiency $\eta \to 1$ but slow gain $dp/dt \to 0$ as $\beta \to 1$



τ: pulse duration
Δt: reflection time

Breakthrough Starshot: laser-boosted sails for space travel (2016)





reach α-Centauri system

accelerating $\approx$ 1000 sails ("StarChip")

4×4 m^2, 1 g to $V = 0.2c$

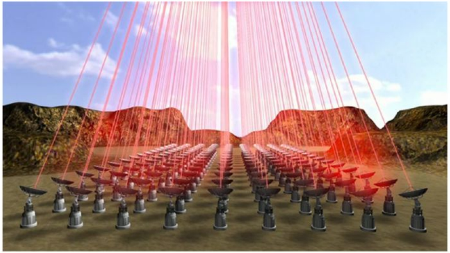
$20 \div 30$ years to compete the journey

$\approx$ 4 years for a return message to Earth

Required: power $\approx 100 \times 10^9$ Watt

acceleration time $\approx$ 10 minutes

$\Longrightarrow$ energy $> 10^{14}$ Joule



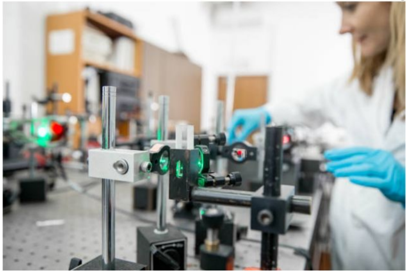
from a 1 km^2 array of 10 kWatt ground-based lasers

National Ignition Facility (USA):
10^6 Joule in 10^{-9} s (one shot/day)

[Critical analysis:
H. Milchberg, "Challenges abound for propelling interstellar probes", Physics Today, 26 April 2016]

Laser Sail as a table-top accelerator

Miniaturization in the laboratory



Laser pulse:

energy ≈ 10 J

duration $\approx 10\text{fs} = 10^{-14}$s

Sail:

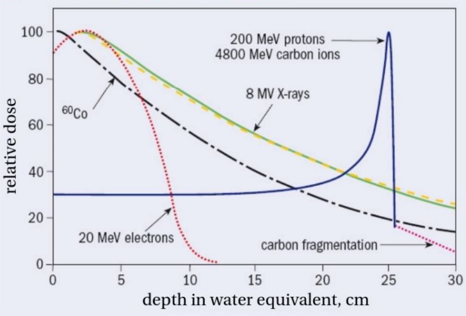
ultrathin foil

≈ 10 nm $= 10^{-8}$m

$\Longrightarrow$ it is possible to accelerate 10^{-14} g of matter (10^{14}protons) at high repetition rate (10 Hz) up to $V = 0.3c$ over 100μm $= 0.1$ mm

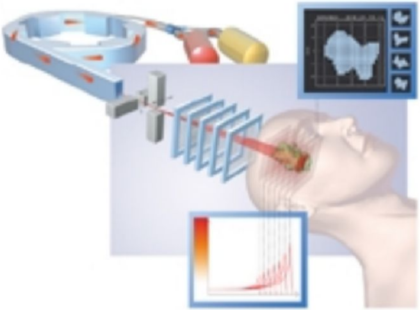
LHC at CERN:
27 km circumference

Why accelerate ions?



A beam of ions (protons, carbon ions, ...) deposits its energy in a much more localized area with respect to X-rays, γ -rays or electrons.

Depending on speed and energy, ions can reach up to 30 cm deep into the tissue.

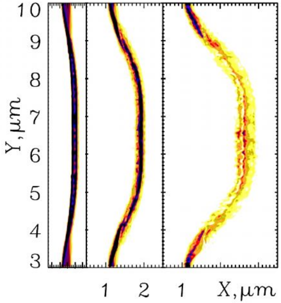


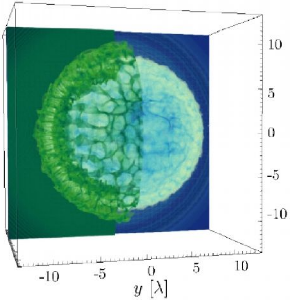
- ▷ hadrontherapy (IBT) uses ion beams to destroy in-depth located tumors
- ▷ destructive effects are particularly strong with heavy ions
- ▷ at least 150 MeV protons are needed

Current energy record with lasers is $\approx$ 100 MeV

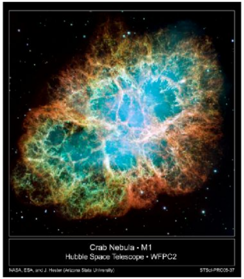
Rayleigh-Taylor instability in Light Sail acceleration

- ▷ a thin foil accelerated by radiation pressure is unstable
- ▷ target breaks up into net-like structures in the ion density with size $\sim \lambda$ and $\sim$ hexagonal shape





[F. Pegoraro & S. V. Bulanov, Phys. Rev. Lett. 99 (2007),
A. Sgattoni et al., Phys. Rev. E 91 (2015)]

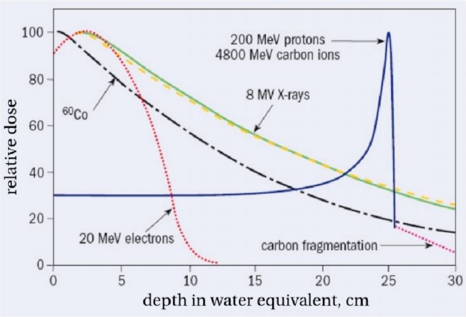


[Crab Nebula, Hubble telescope]

Interpretation:
Rayleigh-Taylor instability
(light fluid accelerates heavy plasma fluid)

Other applications of laser accelerated ions?

Suitable for any technological application, requiring an extremely localized energy deposition



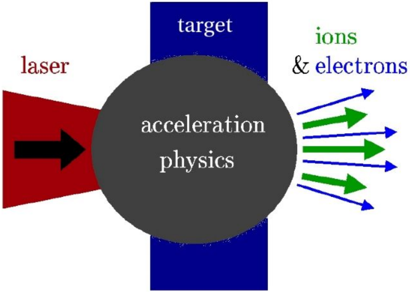
triggering of nuclear reactions

isotope production

production of warm dense matter

diagnostic of materials

ultrafast probing of electromagnetic fields



The acceleration mechanisms are of collective (cooperative, coherent) nature, based on self-consistent, nonlinear plasma dynamics (complex and difficult to control).

How to simulate relativistic plasma dynamics?

Kinetic approach

Kinetic equations for plasma distribution function

$$\frac{\partial f_{i,e}}{\partial t} + \vec{v}\frac{\partial f_{i,e}}{\partial \vec{r}} + \vec{F}_{i,e}\frac{\partial f_{i,e}}{\partial \vec{p}} = 0,$$

$$\vec{F}_{i,e} = q_{i,e}\left(\vec{E} + \frac{1}{c}\vec{v}\times\vec{B}\right),$$

Maxwell equations for the electromagnetic fields

$$\mathrm{rot}\vec{B} = \frac{4\pi}{c}\vec{j} + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}, \quad \mathrm{rot}\vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t},$$

$$\mathrm{div}\vec{E} = 4\pi\rho, \quad \mathrm{div}\vec{B} = 0.$$

Ionization dynamics

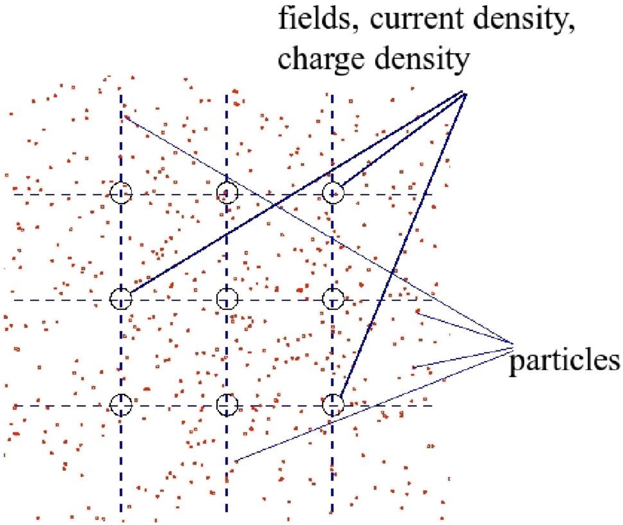
- Tunneling photoionization
- Impact ionization by electrons

Classical radiation reaction force

Numerical approach: Particle-in-Cell Method

- Particle – grid method
- Plasma is sampled by a large number of pseudo–particles
- EM fields are discretized on a grid
- The source current density is reconstructed from the particle positions and velocity

- In full 3D geometry and ovecritical plasma conditions the calculations are very expensive
- Routine use of supercomputers



Продолжение следует ...