A PASSION FOR EXTREME LIGHT: UNIVERSITY of SALAMANQUE
For the Greatest Benefit of Human Kind

Presented by
Prof. Gérard Mourou
Nobel Prize for Physics, 2018
LE Big Bang se produisait il y a 14 milliards d’années. Cependant, il fallut 380.000 ans à la lumière pour se libérer de la soupe primordiale des particules.

Mais cette lumière était incohérente.
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A LIGHT BULB,
Incoherent Photons are radiated outwards
This is a laser! Coherent Light

1. Very directional, small amount of divergence
2. Monochromatic: one wavelength, (one color).
Laser can emit very short bursts of light.
Red Blood Cell: 10 fs
Incoherent Light
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The light is coherent, like marching soldiers
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Components of the first ruby laser

- Power supply
- Switch
- Polished aluminum reflecting cylinder
- 100% reflective mirror
- Quartz flash tube
- Ruby crystal
- 95% reflective mirror
- Laser beam

Diagram:
- Flashlamp
- Ruby rod
- Mirror
- Mirror (partially-reflecting)
- Output beam
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Slowing down atoms
2018

1960
1 eV

Theodore Maiman
(July 11, 1927 – May 5, 2007)
Quantum Optics

\(\mu eV – peV\) Temp. = \(10^{-8} K\)

K Slowing down atoms to cm/s

2018

Atomic Molecular Optics

* cold atoms
* metrology
* atom optics
* condensed-matter physics
* quantum information science
* chemistry

Theodore Maiman

(July 11, 1927 – May 5, 2007)
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Quantum Optics
\(\mu eV – peV\) Temp = 10^{-8} K
Slowing down atoms to cm/s

1960 1eV
Theodore Maiman
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Relativistic Optics
GeV - TeV
Accelerating particles to C

2018

Atomic Molecular Optics
* cold atoms
* metrology
* atom optics
* condensed-matter physics
* quantum information science
* chemistry

Relativistic and Ultra-relativistic Optics

* accelerator physics
* nuclear physics
* cosmology
* NL QED
* general relativity
* extradimension physics
How Extreme is Extreme?

1 PW is 1000 times the total power in the global grid, for $10^{-15}$ s!
How Much Pressure Does a PW Laser Exert?

1 PW/1μm spot size corresponds to $10^{23}$ w/cm$^2$

That is the equivalent of the pressure of 10 million Eiffel Towers on the tip of your finger!!

Seriously extreme!
Petawatt Laser Provides
A 10-1000J Uniform wave front in
Phase and Amplitude
Chirped Pulse Amplification (CPA)


1. A short light pulse from a laser

2. The pulse is stretched which reduces its peak power

3. The stretched pulse is amplified

4. The pulse is compressed and its intensity increases dramatically

A short light pulse from a laser is sent through a Bragg grating pair, which stretches the pulse and reduces its peak power. The stretched pulse is then amplified by an amplifier. Finally, the pulse is compressed by another Bragg grating pair, resulting in a dramatic increase in intensity.
Extreme light Laser is capable to produce,
1. the largest peak power,
2. the largest temperature,
3. the largest pressure,
4. largest acceleration,
5. the largest field.

It is a universal source of High Energy Particles and Radiations
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CPA: A Universal Source of High Energy Particles and Radiations

- 50 GeV – attainment of highest energies
- Electron acceleration TeV
- Proton and ion acceleration TeV
- X-rays, gamma rays MeV
- High field science, ultra-relativistic optics

$10^{23}$ W/cm$^2$
Laser Exploration: From Atomic to Sub-Atomic

**ATOMIC**
- molecules
- atoms
- $10^{-10}$ m

**SUB-ATOMIC**
- nuclei
- protons
- electrons/quarks
- $10^{-14}$ m
- $10^{-16}$ m
- $\leq 10^{-18}$ m

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**Extreme light ultra high intensity roadmap**

- **QCD ~ $10^{35}$ W/cm² - nonlinear QED:** $E \cdot e \cdot \lambda_c = 2m_0c^2$
- **Ultra relativistic optics:** $E_q = m_pc^2$
- **Relativistic optics:** $E_0 = m_0c^2$
- **Bound electrons**: chirped pulse amplification (CPA)

- **1eV**
- **1MeV**
- **1GeV**
- **1PeV**
Extreme Light Infrastructure - ELI

The Largest Civilian Laser Infrastructure
Initiated and Coordinated (PP) by, G. Mourou (EP)
ELI (Delivery Consortium) W. Sandners

Czech Republic
Hungary
Romania
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**Extreme light roadmap and ultra high intensity shortcut**

- **Nonlinear QED:** $E \cdot e \cdot \lambda_c = 2m_0 c^2$
  - $P = E / T$
  - $1 \text{TeV}$

- **Ultra relativistic optics:** $E_q = m_p c^2$
  - Short cut $1000 \text{J} - 1 \text{fs}$
  - $1 \text{GeV}$

- **Relativistic optics:** $E_0 = m_0 c^2$
  - $XCELS - ELI$
  - $1 \text{MeV}$

- **Attosecond physics (bound electrons):**
  - $\lambda^3$
  - $\text{CUOS}$

- **Light materialisation**
  - CPA: Eye surgery, Micromachining
  - $1 \text{eV}$

- **Focused intensity (W/cm²):**
  - $10^{30}$
  - $10^{25}$
  - $10^{20}$
  - $10^{15}$
  - $10^{10}$

- **Year:**
  - 1960
  - 1970
  - 1980
  - 1990
  - 2000
  - 2010
  - 2020
  - 2030

**Equations:**

- $P = E / T$
- $E_q = m_p c^2$
- $E_0 = m_0 c^2$
Micromachining: Long pulses vs. short pulses

With femtosecond pulses, thermal diffusion is suppressed, so a minimum volume is ablated.
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High Precision Micro Machining
A femtosecond (fs) laser will cut the material without damaging it
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CPA femtosecond lasers revolutionised ophthalmology
24 million eye operations since 2001!
Ophthalmology of High Intensity
CUOS University of Michigan

Low energy, short duration pulses focused to small spot size \(I=\frac{E}{t \cdot A}\)

Three dimensional surgical patterns created by contiguous micro-cavitations

Limited adjacent tissue effects and no disruption of the tissue surface

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CPA femtosecond lasers revolutionised ophthalmology
24 million eye operations since 2001!
High Intensity Corneal Transplant Laser Surgery
CUOS University of Michigan

~ 45,000 transplants/yr in US

Mechanical instruments, such as trephines create full thickness transplants that require extensive suturing, long healing times

Femtosecond lasers can create complex shapes, permitting self-locking and partial thickness transplants
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Extreme light ultra high intensity roadmap

- **QCD ~** $10^{35}$ W/cm² - nonlinear QED: $E \cdot e \cdot \lambda_c = 2m_0c^2$
  - 1PeV
- **Ultra relativistic optics** - $E_q = m_pc^2$
- **Relativistic optics** - $E_0 = m_0c^2$
- **Bound electrons**
  - Chirped pulse amplification (CPA)
  - OPCPA
- **Mode locking**
- **Q-switching**

Focused intensity (W/cm²)

- $10^{30}$
- $10^{25}$
- $10^{20}$
- $10^{15}$
- $10^{10}$


Light materialisation

- 1PeV
- 1GeV
- 1MeV
- 1eV

Projects:
- ELI
- XCEL
- APOLLON
- CUOS
- LLNL PW
A surfer riding down the face of a wave is accelerated by energy of the wave

**Giant wakefield acceleration in gas and solid**

Tajima et Dawson (1979)
Giant wakefield acceleration

Tajima et Dawson (1979)

- Laser pulse
- Plasma
- Supersonic gas jet
- Electrons
- Plasma wave
- High Energy beam
  \( \text{GeV/cm} \)
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Synchrotron SOLEIL  3GeV
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**Extreme light roadmap and ultra high intensity shortcut**

- **Nonlinear QED**: $E \cdot e \cdot \lambda_c = 2m_0 c^2$
  - $P = E/T$
  - 1 TeV

- **Ultra relativistic optics**: $E_q = m_p c^2$
  - Short cut 1000J-1 fs
  - $\lambda^3$
  - 1 GeV

- **Relativistic optics**: $E_0 = m_0 c^2$
  - 1 MeV

- **Attosecond physics (bound electrons)**

- **Mode locking**
  - CPA Eye surgery, Micromachining

- **Q-switching**

- Timeline:
  - 1960
  - 1970
  - 1980
  - 1990
  - 2000
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  - 2020
  - 2030

**Light materialisation**
Low Hanging Fruits
Low Hanging Fruit: High Energy Proton Generation

GeV Proton Generation
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RELATIVISTIC PROTON ACCELERATOR
for
TRANSMUTATION

Projet MYRRHA
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**CPA in Nuclear Medicine**

**Proton therapy**

Extreme light technology will be tens of times more compact, more precise and less expensive.

**Nuclear therapy**

Radionuclides are used to implant radioactive pellets directly into a tumour.

**Nuclear diagnostics**

When a scanner needs a radioisotope, extreme laser acceleration in the clinic would make this fast and safer.
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CPA Mitigating Nuclear waste
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NUCLEAR TRANSMUTATION CONCEPT

Example of fission reaction of MA

Np-237
(T_{1/2}=2.14\text{Myr.})

Fission reaction

Neutron

Mo-102
(T_{1/2}=11\text{min.})

β-ray

Ru-102
(stable)

Tc-102
(T_{1/2}=5\text{s})

β-ray

Cs-133
(stable)

I-133
(T_{1/2}=21\text{hr.})

Xe-133
(T_{1/2}=5\text{d})

β-ray

Note: 10% or less of FPs are Long-lived ones.

High energy neutrons (> 1\text{MeV}) are suitable for fission reaction.

Nobel NSF
Space Debris

Millions of orbital debris are cluttering space
SPACE DEBRIS - A state of emergency!

4x 7,000 tons = 28,000 tons!!!

How much is that?
We have put the equivalent of over 4 Eiffel Towers into space!
Space Debris

Millions of orbital debris are cluttering space
Debris identification: Laser Induced Breakdown Spectroscopy
In conclusion, extreme light is capable of generating the largest fields, largest accelerations, the largest temperatures and the largest pressures.

It carries the best hopes and opportunities for the future of science and society.
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The best is yet to come!
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Outlook for Laser-Particle acceleration TeV

- Microwave cavity
- Laser wakefield Visible 100m