Laser-Plasma Accelerators:
Riding the Wave to the Next Generation X-Ray Light Sources

Félicie Albert, LLNL
with Dan Burns, Los Gatos HS
Outline of today’s talk

• What are particle accelerators and how do they work?

• Making X-rays with particle accelerators

• Miniature particle accelerators using lasers and plasmas: laser wakefield accelerators

• Making x-rays with laser wakefield accelerators

• Some applications
What are particle accelerators?
Particle accelerators are big machines

CERN (Geneva)
Large Hadron Collider

Paris

27 km circumference
31 km circumference
What are particle accelerators used for?

- Fundamental Discoveries
- Medical Applications
- Industry
- National Security
Particle accelerators use charged particles

Elements: what constitutes ordinary matter around us

- Hydrogen, Oxygen ($\text{H}_2\text{O}$)
- Oxygen ($\text{O}_2$)
- Nitrogen ($\text{N}_2$)
- Carbon (C)
- Copper (Cu)
Particle accelerators use charged particles

**Elements:** what constitutes ordinary matter around us

- Hydrogen, Oxygen (H₂O)
- Oxygen (O₂)
- Nitrogen (N₂)
- Carbon (C)
- Copper (Cu)

**Atom:** smallest form of matter that retains the properties of an element

A one carat diamond has $10^{22}$ carbon atoms!
Particle accelerators use charged particles

This is an atom

- **Proton**: subatomic particle with positive charge
- **Neutron**: subatomic particle with no charge
- **Electron**: subatomic particle with negative charge
Particle accelerators use charged particles

This is an atom

- **Proton**: subatomic particle with positive charge
- **Neutron**: subatomic particle with no charge
- **Electron**: subatomic particle with negative charge

In a particle accelerator, particles will go up to the speed of light. That's 300,000 km per second – about 10 million times the speed of a car on the freeway!
How do they work?
One use of particle accelerators is to make X-rays
X-rays are like visible light

..... But you cannot see them
Electromagnetic waves are waves that

- Carry energy
- Travel through empty space or air at the speed of light
- We characterize them by their wavelength
The electromagnetic spectrum

<table>
<thead>
<tr>
<th>RADIATION TYPE</th>
<th>Radio</th>
<th>Microwave</th>
<th>Infrared</th>
<th>Visible</th>
<th>UV</th>
<th>X-ray</th>
<th>Gamma Ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAVELENGTH (m)</td>
<td>$10^3$</td>
<td>$10^{-2}$</td>
<td>$10^{-5}$</td>
<td>$0.5 \times 10^{-6}$</td>
<td>$10^{-8}$</td>
<td>$10^{-10}$</td>
<td>$10^{-12}$</td>
</tr>
</tbody>
</table>

FREQUENCY: low to high

SCALE: 
- Human body
- Bee
- Sewing needle
- Cell
- Molecule
- Atom
- Proton
Examples of X-ray images
How to make X-rays with a particle accelerator

A particle changing direction emits radiation along its path
How to make X-rays with a particle accelerator

A particle changing direction emits radiation along its path.

Magnets are used to change the particle’s path.
### Radiation Types

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>Wavelength (m)</th>
<th>Frequency</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>$10^3$</td>
<td>Low</td>
<td>Building</td>
</tr>
<tr>
<td>Microwave</td>
<td>$10^{-2}$</td>
<td></td>
<td>Human</td>
</tr>
<tr>
<td>Infrared</td>
<td>$10^{-5}$</td>
<td></td>
<td>Bee</td>
</tr>
<tr>
<td>Visible</td>
<td>$0.5 \times 10^{-6}$</td>
<td></td>
<td>Needle</td>
</tr>
<tr>
<td>UV</td>
<td>$10^{-8}$</td>
<td></td>
<td>Cell</td>
</tr>
<tr>
<td>X-ray</td>
<td>$10^{-10}$</td>
<td></td>
<td>Atom</td>
</tr>
<tr>
<td>Gamma Ray</td>
<td>$10^{-12}$</td>
<td>high</td>
<td>Proton</td>
</tr>
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**Magnetizm**

- **Electron**
- **Magnets**
- **X-rays**

0.01 m
To understand how particle accelerators make X-rays...
Let’s get some help from Albert Einstein
Einstein’s Special Theory of Relativity
Einstein’s Special Theory of Relativity
Einstein’s Special Theory of Relativity
Einstein’s Special Theory of Relativity
Einstein’s Special Theory of Relativity
Einstein’s Special Theory of Relativity
What we see

Electron

Magnets

0.01 m
What the electron sees:

Electron

What we see:

Electron

1. What we see: Magnets
   - N S N S N S N
   - S N S N S N S
   - 0.01 m

2. What the electron sees: Magnets
   - N S N S N
   - S N S N S
   - 0.000 001 m
   - 10,000 times smaller
What the electron sees

Electrons

Magnets

What we see

Not quite the wavelength of X-rays yet!

Electron

Magnets

0.01 m

0.000 001 m

10,000 times smaller

Radiation Type

Radio

Microwave

Infrared

Visible

UV

X-ray

Gamma Ray

Wavelength (m)

$10^3$

$10^2$

$10^{-5}$

$0.5 \times 10^{-6}$

$10^{-8}$

$10^{-10}$

$10^{-12}$

Frequency

Low

High

Scale

Not quite the wavelength of X-rays yet!
What the electron sees and emits

0.000 001 meters
What the electron sees and emits

0.000 001 meters

How we see it

10,000 times smaller
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**What the electron sees and emits**

- 0.000 001 meters

**How we see it**

- 10,000 times smaller

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X-rays!
Synchrotrons and X-ray free electron lasers

- **Electron**
- **Magnets**
- **X-rays**

**Photo:** Argonne National Laboratory

**Synchrotron**

**Photo:** SLAC National Laboratory

**X-ray Free Electron Laser**
X-rays wavelengths are small enough to “look” at molecules and atoms.

2 Hydrogen atoms + 1 Oxygen atom = Water molecule
X-rays wavelengths are small enough to "look" at molecules and atoms.

2 Hydrogen atoms + 1 Oxygen atom = Water molecule

But this happens very quickly! About 10 femtoseconds.
X-rays wavelengths are small enough to "look" at molecules and atoms

2 Hydrogen atoms + 1 Oxygen atom = Water molecule

One femtosecond is 0.000 000 000 000 001 seconds [one quadrillionth]
A femtosecond is to a minute what a minute is to the age of the universe (14 billion years)

In one second, light almost has time to go to the moon

In one femtosecond, light barely has time to cross the width of human hair
To make movies of these molecules we need "fast" x-rays

“fast” x-ray

“slow” x-ray
What are big X-ray machines missing?

Several X-ray wavelengths

Slow

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<tr>
<td>Power</td>
<td>$10^3$</td>
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Photo: Argonne National Laboratory
What are big X-ray machines missing?

X-ray Free Electron Laser

One X-ray wavelength
Fast

<table>
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Photo: SLAC National Laboratory
How to accelerate particles on a smaller scale?
By using lasers and plasmas to do laser wakefield acceleration

A regular particle accelerator

A laser plasma accelerator

3 km

1 meter

Photo: SLAC
By using lasers and plasmas to do laser wakefield acceleration

A regular particle accelerator

A laser plasma accelerator

Accelerating electrical field is 1000 times stronger
What is a laser?

- **Light**
- **Amplification by**
- **Stimulated**
- **Emission of**
- **Radiation**

Light bulb

Many colors in all directions

Laser

One color in one direction
A laser can separate electrons from ions in an atom to form a plasma.
In a plasma, ions are much heavier than electrons and move around faster.
Electron plasma wave

Wake behind a boat
Electron plasma wave

Wake behind a boat

Plasma wave behind a laser

Width of human hair

Nuno Lemos, LLNL
Electron plasma wave

Wake behind a boat

Plasma wave behind a laser

Width of human hair

Nuno Lemos, LLNL
What can electrons do in a plasma wave?

Surf's up! Electrons will ride the plasma wave to gain speed:
we just created a particle accelerator
Trapped electrons surf on the plasma wave to gain energy

Just like surfing, laser wakefield acceleration requires good synchronization.
It is not always easy ....
Lasers we use at LLNL for laser wakefield acceleration
How to make X-rays with a laser wakefield accelerator
Remember how X-rays are made with a particle accelerator...
Remember how X-rays are made with a particle accelerator...

There are no magnets in a plasma but the electron will use the wave to wiggle.
Remember how X-rays are made with a particle accelerator...

There are no magnets in a plasma but the electron will use the wave to wiggle.
Laser pulse

Electron plasma wave
Width of human hair
Trapped Electron

Laser pulse

Electron plasma wave

Width of human hair
Betatron

X-ray beam

Width of human hair

Trapped Electron

Laser pulse

Electron plasma wave

Betatron X-ray beam

Width of human hair
Laser wakefield acceleration can produce X-rays just like the big machines but on a much smaller scale.
Laser wakefield acceleration can produce X-rays just like the big machines but on a much smaller scale.

Synchrotron

Several X-ray wavelengths
Slow

Photo: Argonne Nat. Lab

X-ray Free Electron Laser

One X-ray wavelength
Fast

Photo: SLAC

Laser wakefield

Several X-ray wavelengths
Fast

Photo: LLNL
Some applications of X-ray light sources from laser wakefield acceleration
X-rays for radiography

Radiography -> X-rays in -> X-rays out
Radiography of biological objects with X-rays from laser wakefield accelerators

Chrysoperia carnea
Wenz et al, Nat. Comm [2015]

Trabecular hip bone sample
X-rays for absorption spectroscopy

Intensity vs. Wavelength: X-rays in 

Sample: X-rays out 

Intensity vs. Wavelength: X-rays out
X-rays for diffraction

X-rays in

sample

X-rays out
Pump-probe experiments

Intensity vs. Wavelength for X-rays in

Intensity vs. Wavelength for X-rays out

Sample in the middle
Pump-probe experiments

Laser in at Time 0 ($T_0$)

sample
Pump-probe experiments

Laser in at Time $0$ ($T_0$)

X-rays in at $T_0 + T$

Intensity

Wavelength

Sample
Pump-probe experiments

Laser in at Time $0 \left( T_0 \right)$

X-rays in at $T_0 + T$

sample

X-rays out

- Intensity vs. Wavelength
- Intensity vs. Wavelength
X-rays have small wavelengths to “look” at molecules and atoms

2 Hydrogen atoms + 1 Oxygen atom = Water molecule
What we’ve learned today

• What are particle accelerators and how do they work?

• Making X-rays with particle accelerators

• Miniature particle accelerators using lasers and plasmas: laser wakefield accelerators

• Making x-rays with laser wakefield accelerators

• Some applications
Laser plasma accelerators will revolutionize these fields

- Fundamental Discoveries
- Medical Applications
- Industry
- National Security
The ultra high intensity lasers world map
What we’ve learned today
What we’ve learned today
What we’ve learned today
What we’ve learned today
Collaborators


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