1.2 x 10^6 km^2

1.4 x 10^3 W/m^2 x 7 x 10^5 km^2 = 1 petawatt
Who needs plasma?

Observations of intense laser interaction with, and radiation from, individual electrons

Mike Downer
University of Texas-Austin
Collective Properties of Plasmas:
concepts you do NOT need to know about for this lecture

- $\omega_p$: Plasma frequency
- $\lambda_D$: Debye length
- $\Lambda$: Plasma parameter
- $\delta$: Magnetization parameter
- $\nu$: Collision frequency
Physics you will need to know about for this lecture:

\[ \vec{F} = m\vec{a} \]

where

\[ \gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2} \]

and \( m_0c^2 = 0.51 \text{ MeV} \)
Laser Radiation & Electron Acceleration

Stationary Electrons $\rightarrow$ Electrostatic Fields

Steady Currents $\rightarrow$ Magnetostatic Fields
(electrons moving at constant velocity)

Accelerating Electrons $\leftrightarrow$ Electromagnetic Radiation

Cerenkov Radiation

Inverse Cerenkov Accelerator

Any process that generates radiation may be inverted to accelerate charged particles
I will discuss 2 types of experiments

I. Direct Laser Acceleration (DLA) of electrons
- Thomson, Compton scatter and synchrotron radiation

II. Radiation from accelerated electrons
- Thomson, Compton scatter and synchrotron radiation

selected experiments are illustrative, not comprehensive
I. Direct Laser Acceleration of Electrons in Vacuum?

**Good idea**
Modern lasers provide unprecedented accelerating fields (larger than SLAC)

**Dumb idea**
EM waves wiggle the electron sideways; they don’t accelerate it linearly

\[ \vec{F} = m\vec{a} \]
\[ e\vec{E} = m_0 \frac{d\vec{v}}{dt} \quad \text{and} \quad \vec{E} = E_0 e^{ik_0z - i\omega t} \]

\[ \therefore \frac{d\vec{v}}{dt} = \frac{e}{m} E_0 e^{ik_0z - i\omega t} \]

\*Neglecting \( \vec{v} \times \vec{B} \) and relativistic effects

\[ \text{SLAC} \]
Lawson-Woodward Theorem: Mathematical proof that DLA is a dumb idea?


The net energy gain of an electron interacting with an electromagnetic field in vacuum is zero.

The theorem assumes that:
(i) the laser field is in vacuum with no walls or boundaries present,
(ii) no static electric or magnetic fields are present,
(iii) the region of interaction is infinite,
(iv) ponderomotive effects (nonlinear forces, e.g. $\mathbf{v} \times \mathbf{B}$ force) are neglected.
Exploit $\mathbf{v} \times \mathbf{B}$ force at “relativistic” light intensity to accelerate electrons longitudinally?

**Good idea**

Light pressure pushes particles forward

**Dumb idea**

Electron trajectories become complicated, even chaotic $\Rightarrow$ poor $\text{e}^-$ beam quality

\[ \bar{F} = ma \]
\[ eE + \frac{v}{c} \times B = m \frac{dv}{dt} \]

Radiation losses are high
Two laser beams intersecting in vacuum can accelerate an electron longitudinally.

1/2 wavelength behind:
- electron **decelerates**
- sub-micron phasing is essential

- transverse field components cancel
- longitudinal field components add
- electron **accelerates**

- accelerating phase moves at $\frac{c}{\cos \alpha} > c$
- electron can’t keep up!

**intersection point moved at** $c/\sqrt{2}$

**phase slippage**

- Low Energy ($\gamma < \gamma_c$)
- High Energy ($\gamma >> \gamma_c$)
Direct Laser Acceleration in vacuum requires microstructured cavities to manage phase slippage


Ez ~ 1 GeV/m estimated below damage threshold

- Ez << E, low overlap with electron beam ⇒ low efficiency
- Experimental results had to wait 9 years
Laser acceleration in vacuum was first demonstrated in 2005


800 nm, 4 ps, 0.5 mJ

30 MeV
2 ps
10 pC

This is acceleration by
“Inverse Transition Radiation”

radiation emitted by a charged particle
on crossing a dielectric boundary

No acceleration without a boundary,
as per Lawson-Woodward Theorem
Side-pumped transparent dielectric grating structure utilizes the transverse laser electric field efficiently


Projected performance:
- 1 to 10 GeV/m gradient w/o damage
- $10^6$ e-/bunch with 8% efficiency

GRAND VISION: Harness...
... micro-fabrication capabilities of microelectronics industry
... latest fs laser technology
to forge compact particle accelerators of the future
QuickTime™ and a decompressor are needed to see this picture.

courtesy R. L. Byer
DLA has been demonstrated with CO₂ lasers

**Inverse Cerenkov Accelerator**


- **gas** slows light phase velocity to match electron velocity at Cerenkov angle $\theta_c$
  - 9% energy gain demonstrated (40 → 43.7 MeV)
  - Works best for high $\gamma$ e-beams

**Cerenkov Radiation:**

P. Cerenkov, Doklady Akad. Nauk. SSSR 2, 415 (1934)

(optical shock wave)

**Inverse Cerenkov Accelerator:**

RADially POLARIZED LASER BEAM

(10.6 µm, 220 ps, 580 MW peak power)

H₂ GAS

(40 ± 0.5 MeV, 13 ps, 0.1 nC)
Inverse Free Electron Laser (IFEL)


Undulator magnet array phase-matches e-beam with copropagating laser beam.

- utilizes transverse component of E field
- \(\approx5\%\) energy gain demonstrated
- Best for low to moderate \(\gamma\) e-beams
- Synchrotron losses problem at high \(\gamma\)
**Staged Electron Laser Acceleration (STELLA)**

- STELLA demonstrated staged acceleration for the first time
- STELLA used two identical IFELs driven by BNL ATF CO$_2$ laser

Energy shift: ~ 8 MeV
Energy spread: down to 0.36%
Trapping efficiency: up to 80%

1st IFEL modulates e-beam energy ($\pm$ 0.5%)

Kimura et al., PRL 86, 4041 (01)
____________, PRL 92, 054801 (04)
PASER: Particle Acceleration by Stimulated Emission of Radiation


EXPERIMENTAL RESULTS

EXPERIMENTAL SET-UP

CO₂ LASER
0.5GW - 0.2 nsec

Accelerator
45 MeV - 5 pssec

PASER CONCEPT

Frank-Hertz Experiment (1914)
Latyscheff-Leipunsky Expt (1930)
LASER
PASER

single collision
many collisions

QuickTime™ and a decompressor are needed to see this picture.

~ 2 x 10⁶ collisions
Direct laser acceleration can (unintentionally) play a role even in laser-driven “plasma” accelerators.
SUMMARY: Part I

I) Direct Laser Acceleration of Electrons

- **visible lasers:** ITR accelerator demonstrated in 2005 (30 → 30.03 MeV)
- **CO₂ lasers:** ICA, IFEL demonstrated 1995-present (40 → 45 MeV)
- **PASER:** fundamental new concept demonstrated in 2006 (45 → 45.2 MeV)
- present in some laser-plasma accelerators
- experiments at proof-of-principle stage, but many visionary ideas

II) Radiation from Laser-Driven Electrons

- linear Thomson scatter from stationary electrons: characterizes intense laser propagation in a plasma
- nonlinear Thomson scatter: characterizes figure-8 electron orbits (1998)
- linear Thomson scatter from relativistic electron bunches
  - side-scatter (LBNL, 1996): helped open up fs x-ray science
  - back-scatter:
    1) from 200 MeV linac → bright 0.78 MeV γ-rays (T-REX, 2008)
    2) from poly-energetic LWFA beam → broadband keV x-rays (2006)
- undulator radiation (near IR) from mono-energetic (~60 MeV) LWFA beam
  - promise of future table-top synchrotrons & FELS when scaled to mono-energetic GeV electron beams from laser-plasma accelerators
II. Radiation from electrons accelerated by lasers & conventional linacs
Linear* Thomson scatter:
light scatter from free electrons


Neglecting $\mathbf{v} \times \mathbf{B}$ force, relativistic $\mathbf{e}^-$ mass increase, and Compton recoil

\[
\frac{d\mathbf{v}}{dt} = \frac{e}{m} \mathbf{E}_0 e^{ikz-i\omega t}
\]

Properties of $90^\circ$ Thomson scatter

\[
\mathbf{E}_{sc} = \mathbf{E}_0 \sin \phi
\]

\[
\frac{d\sigma}{d\Omega} = \left( \frac{e^2}{mc^2} \right)^2 \sin^2 \phi
\]

\[
\sigma_T = \frac{8\pi}{3} \left( \frac{e^2}{mc^2} \right)^2 = 0.665 \times 10^{-24} \text{ cm}^2
\]

J. D. Jackson, *Classical Electrodynamics, 3rd ed.*, Sec. 14.1
Intense Laser Pulse Propagation through Ionized Gas Jet

We can observe the laser pulse’s propagation path thru the plasma by imaging 90° Thomson scatter.

Gas Jet Fires
Laser Pulse Focuses, Ionizes Gas, and Scatters from free e-

vacuum Gaussian beam propagation (low intensity)
relativistically self-focused propagation (high intensity)
Relativistic self-guiding of intense laser pulse measured by linear Thomson side scatter

Axial-imaging

Side-imaging of Thomson scattered light

2.5 TW
2.0 TW
1.5 TW
1.0 TW ≈ $P_c$
0.5 TW

Exit  Gas Jet  Entrance


courtesy Don Umstadter
Nonlinear Thomson Scatter

As $a_0 \to 1$, figure-8 electron orbits develop

$k = k \hat{z}$, $E = E_0 \cos(kz - \omega t) \hat{x}$, $B = B_0 \cos(kz - \omega t) \hat{y}$

As $a_0$ increases, harmonics radiate:

$$\mathbf{j}(t) = \sum_n j_n(a_0) e^{-in\omega t}$$

each with its own intensity-dependent radiation pattern

As $a_0$ increases, harmonics radiate in intensity-dependent angular patterns

$n = 1$ thru 10  electron motion  laser field

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.
Nonlinear Thomson scatter provides direct experimental evidence for nonlinear electron orbits that underlie high-field laser-plasma interactions.

S. Chen et al., "*PRL*, 84, 5528 (2000).
Linear Thomson scatter from linearly accelerated relativistic electrons

Relativistic Electron Bunch:
\[ \gamma = \frac{E_{\text{electron}}}{m_0c^2} >> 1 \]

Terawatt laser pulse polarized out of screen

Femtosecond x-ray pulse

Electron rest energy:
\[ m_0c^2 = 0.51 \text{ MeV} \]

Lorentz transform back to lab frame

\[ h\nu_x \approx 2\gamma^2 \left( h\nu_{\text{laser}} \right) \frac{1 - \cos \Psi}{1 + \gamma^2 \theta^2} \]

Lorentz transform to e\textsuperscript{-} rest frame

\[ \gamma h\nu_{\text{laser}} \]

Thomson-scattered dipole radiation at \[ \gamma h\nu_{\text{laser}} \]

Thomson-scatter photon energy:
\[ h\nu_x \approx 2\gamma^2 \left( h\nu_{\text{laser}} \right) \frac{1 - \cos \Psi}{1 + \gamma^2 \theta^2} \]

\[ h\nu_x / h\nu_{\text{laser}} \sim 2\gamma^2 \text{ (visible } \rightarrow \text{ x-ray)} \]

• strongly forward peaked for \( \gamma >> 1 \)
The pioneering experiment was performed at LBNL


90° geometry was chosen to minimize x-ray pulse duration, at the expense of conversion efficiency.
Much of condensed matter science is based on x-ray measurements.

The past decade has seen the birth of “fs x-ray science”
Fs X-ray pulses shorter than a molecular vibrational period can probe ultrafast structural dynamics of materials


optical pump/x-ray-probe experiment

x-ray absorption in VO$_2$

x-ray diffraction from melting InSb

x-ray diffraction showing lattice vibrations in bismuth
Researchers at Lawrence Livermore have developed T-REX (Thomson-Radiated Extreme X-rays), a bright 0.78 MeV gamma-ray source.


Electron Bunch: 120 MeV ($\gamma = 235$), 10 ps, 1 nC

Terawatt laser pulse (3.7 eV, 10 ps, $a_0 = 0.05$)

Femtosecond gamma-ray pulse 0.78 MeV 10$^6$ photons

$\Psi=180^\circ$

$\Delta E/E_0 \sim 10^{-3}$
0.78 MeV gamma-rays from T-REX
CsI scintillator + micro-channel plate + CCD
Compton light sources could become the brightest $\gamma$-ray ($h\nu > 100$ keV) sources known to science

Nuclear resonance fluorescence spectroscopy & isotope-specific imaging

Laser-induced resonance fluorescence from atmospheric molecules

\( \gamma \)-ray-induced resonance fluorescence from Ir\(^{191} \) nuclei

Schumacher & Langhoff, Phys. Rev. 162, 1153 (1967)
For producing narrow-band x-rays, ultrashort, intense laser pulses are not best


Nonlinear $e^-$ orbits degrade brightness and bandwidth for short, intense pulses
Laser-Plasma Electron Accelerator

Is this a potential Thomson x-ray source?

- Gas Jet Fires
- Laser Pulse Focuses
- Ionize Gas & Make Wave
- Wave Captures and Accelerates Electrons

About 3 mm
How do laser-plasma accelerators stack up against conventional linacs as Compton x-ray sources?


\[ B_x \propto \frac{\gamma_0^2 N_e N_\lambda}{\varepsilon^2 \Delta \tau} \]

for \( \theta = 180^\circ \)

<table>
<thead>
<tr>
<th>laser-plasma accelerator</th>
<th>conventional “small” LINAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>length: ( \sim 1 \text{ cm} )</td>
<td>10 to 100 m</td>
</tr>
<tr>
<td>( \gamma_0: ) 100 to 1000</td>
<td>100 to 1000</td>
</tr>
<tr>
<td>( N_e: ) ( \sim 0.1 \text{ nC} )</td>
<td>( \sim 1 \text{ nC} )</td>
</tr>
<tr>
<td>( \varepsilon: ) ( \sim \pi \text{ mm-mrad} )</td>
<td>( \sim \pi \text{ mm-mrad} )</td>
</tr>
<tr>
<td>( \Delta \tau: ) ( \sim 10 \text{ fs}^* )</td>
<td>1 to 10 ps</td>
</tr>
</tbody>
</table>

Table-top Thomson backscatter from laser-accelerated electrons


3x10^4 photons/shot

Other observations of x-ray radiation from laser-accelerated electrons:

Counter-propagating laser = short-period undulator

- higher efficiency
- narrower bandwidth
A compact synchrotron radiation source driven by a laser-plasma wakefield accelerator

Towards a table-top free-electron laser

Kazuhisa Nakajima

Synchrotron radiation generated using an electron beam from a laser-driven accelerator opens the possibility of building an X-ray free-electron laser hundreds of times smaller than conventional facilities currently under construction.

[LWFA beams with these properties], as well as removing the need for a [electron bunch] compression stage, reduce the required undulator length to just a few metres -- dramatically improving ease of manufacture and cost [of an FEL].

...The action of SASE ...should enable operation at a level comparable to a much larger and much more expensive FEL (see Fig. 1b). Coupled with steady progress in the performance and reduction in cost of the terawatt laser systems, this has the potential to put an FEL in every major university in the world, with momentous implications for the ability of physicists, chemists and biologists to study the dynamics of the natural world at the atomic scale.
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- **Undulator radiation** (near IR) from mono-energetic (~60 MeV) LWFA beam**

** Promise of future table-top synchrotrons & FELS when scaled to mono-energetic GeV electron beams from laser-plasma accelerators
Optimizing brightness of Thomson-scattered x-rays is a 13-parameter problem


\[ B_x \propto \gamma_0^2 N_e N_\lambda \frac{\varepsilon^2 \Delta \tau}{\varepsilon^2} \text{ for } \theta = 180^\circ \]

Even the theoretical optimization problem remains incompletely solved