Applications of laser-driven beams
(with a focus on electrons)

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**Motivation: X-ray tumour diagnosis**

**Clinical evidence:**
Primary tumours of up to approx. $10^6$ cells have generally not metastasized. Local tumor therapy might be successful.

**Strategy**
- Early tumour diagnosis (while diameter is below 1 mm)
- Local non-invasive radiation therapy using various beam types and treatment techniques.

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**Gordon Steel, Basic Clinical Radiobiology, 2002**

F. Pfeiffer et al., PMB 52, 6923 (2007).

Phase-contrast tomography of a rat brain
Phase-contrast CT allows excellent soft-tissue discrimination

conventional CT

phase contrast CT

Slices through a mouse thorax using equal radiation dose.

(F. Pfeiffer)
Phase Contrast Imaging

Modulation of the phase much stronger than absorption

Refractive index: $n = 1-\delta-i\beta$

Requirements:
- sufficient degree of spatial coherence
- a high resolution detector
Brilliance = \frac{\text{photons}}{\text{mm}^2 \cdot \text{mrad}^2 \cdot s \cdot 0.1\% \text{ bandwidth}}

transv. emittance
(=phase space area)

long. emittance

High photon flux

Low divergence

Small bandwidth

Small source size
Elektronen- und Röntgenquellen

CALA/

Stefan Karsch

brilliance

$[\text{ph/ (sec mm}^2\text{ mrad}^2 0.1\% BW)]$

peak brilliance of laser driven sources

undulator

deflecting magnet

average brilliance of laser driven sources

rotating anode 100 kW, Bremsstrahlung

costs (size)

$[\text{M€ (meter)}]$
„Wiggly“ electron X-ray sources: Ingredients: relativistic electron beam +

- **Undulator radiation**, FEL
  - 100's eV - keV
  - $\lambda_u \approx 1\text{cm}$

- **Betatron radiation**
  - keV – 10's keV
  - $\lambda_b \approx 500\mu\text{m}$

- **Thomson scattering**
  - 10's keV - MeV
  - $\lambda_l \approx 1\mu\text{m}$

\[ \lambda_{x-ray} = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right) \]

\[ \lambda_{x-ray} = \frac{\lambda_l}{4\gamma^2} \left(1 + \frac{a_0^2}{2} + \gamma^2 \theta^2 \right) \]
Ingredient No.1:

Electron beams

A. Popp, M. Heigoldt, S.W. Chou et al.

Source: Kent Nishimura/Getty Images North America (2009)
Plasma acceleration: prediction and reality

Volume 43, Number 4
PHYSICAL REVIEW LETTERS
23 July 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density $10^{18}$ W/cm$^2$ shine on plasmas of densities $10^{18}$ cm$^{-3}$ can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

2006:

40 TW laser pulse
1 GeV, 30 pC
$3 \times 10^{18}$ W/cm$^2$
$n_e = 4.3 \times 10^{18}$ cm$^{-3}$
$L_{\text{acc.}} \approx 1$ cm

Stable beams by using stagnant flow gas cell

**ATLAS 60**
1.5 J on target
25 fs
Gas cell
peak energy \( \sim 500 \text{ MeV} \)
total charge \( \sim 100 \text{ pC} \)

**ATLAS 25**
0.85 J on target
37 fs
Capillary
peak energy \( \sim 200 \text{ MeV} \)
total charge \( \sim 30 \text{ pC} \)

\[ \rightarrow \text{Blowout regime, continuous trapping} \]

Osterhoff, SK et al., PRL 101, 085002 (2008)
cut-off energy

130 mbar = $6.4 \times 10^{18}$ cm$^{-3}$

A. Popp et al., in preparation

3d PIC simulation (OSIRIS) by J. Vieira

$n_e = 3.4 \times 10^{18}$ cm$^{-3}$
High-charge 0.5 GeV beams from a 1.5J, 60 TW laser
Halo at highest energy hints at 4:1 betatron-laser resonance and resonant excitation
Emittance measurement by direct imaging of electron beam inside the source:

Normalized emittance: $0.14 \, \pi \, \text{mm mrad}$

RMS beam size in Ce:YAG crystal after 30 x magnification by the lenses

![Diagram of beam path and magnification](image-url)
Temporal characterization by coherent TR spectroscopy

NIR (InGaAs) spectrometer
Visible (Si) spectrometer
THz (pyro.) spectrometer

0.4–1.1 μm
1.1–1.9 μm
1.7–7.0 μm or 5.5–25 μm

ATLAS Laser
collimating OAP
gas cell
double tape drive
transition radiation
Si wafer
lens
outside vacuum

electron spectrometer
electron bunch
lanex screen
pressure 70 mbar, density $3.7 \times 10^{18}$ cm$^{-3}$

8 mm gas cell, smooth spectrum 5.1 fs FWHM

12 mm gas cell, modulated spectrum 3.9 fs FWHM
Stable acceleration by forced injection

Colliding pulse injection (J. Faure et al., Nature 444 (2006))

Down-ramp injection (Gonsalves et al., Nat Phys 2071 / DOI:10.1038 (2011))
Stable electron acceleration: Shock-front injection into supersonic nozzle

**Gas target**
supersonic Laval nozzle with 0.75 – 1.5 mm exit diameter

Density ratio: 1.6
Transition: ~ 5 µm
Plasma wavelength: ~ 20 µm

tuning the electron energy: move blade to move injection point

Medium-charge (30-100 pC), low-energy (-100 MeV) beams with narrow energy spread
Ingredient No.2:

Electron deflection
Larmor radiation (see e.g. Jackson) of an accelerated charged particle:

Radiation power: \[ P_R = \frac{e^2}{6\pi\varepsilon_0 m_0^2 c^3} \left( \frac{d\vec{p}}{dt} \right)^2 \]

Angular distribution: \[ \frac{dP_R}{d\Omega} = \frac{e^2}{16\pi^2 \varepsilon_0 m_0^2 c^3} \left( \frac{d\vec{p}}{dt} \right)^2 \sin^2 \Psi \]

(Hertzian dipole)

Find relativistic invariant form of Larmor formula:

Transform time: \[ dt \rightarrow d\tau = \frac{1}{\gamma} \, dt \] and four-momentum: \[ \left( \frac{dP_\mu}{d\tau} \right)^2 \rightarrow \left( \frac{d\vec{p}}{d\tau} \right)^2 - \frac{1}{c^2} \left( \frac{dE}{d\tau} \right)^2 \]

\[ P_R = \frac{e^2 c}{6\pi\varepsilon_0 \left( m_0 c^2 \right)^2} \left[ \left( \frac{d\vec{p}}{d\tau} \right)^2 - \frac{1}{c^2} \left( \frac{dE}{d\tau} \right)^2 \right] \]
Deflection in magnetic field: $\Delta E/dt=0$

\[
P_R = \frac{e^2 c}{6\pi \varepsilon_0 (m_0 c^2)^2} \left(\frac{dp}{d\tau}\right)^2 = \frac{e^2 c \gamma^2}{6\pi \varepsilon_0 (m_0 c^2)^2} \left(\frac{dp}{dt}\right)^2
\]

\[
\frac{dp}{dt} = p\omega = p \frac{v}{R}; \quad E = pc; \quad \gamma = \frac{E}{m_0 c^2}
\]

\[
P_R = \frac{e^2 c}{6\pi \varepsilon_0 (m_0 c^2)^4} \frac{E^4}{R^2}
\]
average rest frame:

lab frame:
spontaneous synchrotron radiation spectrum:

radiation beam sweeps past observer during

\[ \Delta t = \frac{2R}{c\beta \gamma} - \frac{2R}{c} \sin \left( \frac{1}{\gamma} \right) = t_e - t_\gamma \approx \frac{4R}{3c\gamma^3} \]

\[ \log N \]

\[ \log E \]

...which leads to a critical radiation frequency

\[ \omega_{\text{crit}} = \frac{2}{\Delta t} = \frac{3c\gamma^3}{2R} \]

and a spectral energy density:

\[ \frac{dN}{d\varepsilon / \varepsilon} = \frac{3\sqrt{3\varepsilon \gamma^4 I_b}}{8\pi\varepsilon_0 R \omega \hbar} \xi \int_\xi^\infty K_{5/3}(\xi) d\xi, \quad \xi = \frac{\omega}{\omega_{\text{crit}}} \]
periodic deflection:

“identical“ emission at each turning point

Spectrum is enhanced at wiggling frequency!
X-ray spectrum is influenced by:

- Electron energy and bandwidth
- Wiggling field strength and number of oscillations
- Observation direction and solid angle
- Wiggling period

\[
\lambda_{x-ray} = \frac{\lambda_{u,b,l}}{2(4^*)\gamma^2} \left(1 + \frac{a_0^2}{2} + \gamma^2\theta^2\right)
\]
Thomson backscattering, $E = 70$ MeV
$\lambda = 800$ nm

Collimated, monochromatic e-beam, 25 period, flat-top optical undulator
Thomson backscattering, $E = 70$ MeV
$\lambda = 800$ nm

Collimated, monochromatic e-beam, 30 fs laser pulse
Thomson backscattering, $E = 70$ MeV
$\lambda = 800$ nm

Divergent (2.2 mrad), monochromatic e-beam, 25 period, flat-top optical undulator
Thomson backscattering, \( E = 70 \text{ MeV} \)
\( \lambda = 800 \text{ nm} \)

Divergent, monochromatic e-beam, 30 fs laser pulse
Undulator radiation

In collaboration with:

F. Grüner Group (HHU)
U. Kleineberg Group (LMU)
1. Undulator radiation (with F.Grüner et al. & Kleineberg et al.)

Electron spectra:

**ATLAS 60**
- 1. 5 J on target, 26 fs
- ~500 MeV peak energy
- ~100 pC total charge

Higher electron energies and high-efficiency X-ray multilayer mirrors enhance high-energy photon production

- Requires multi-GeV electrons to reach energy range for human diagnosis.
- May become valuable source radiation biology studies
2

- Betatron radiation
Betatron emission

\[ \lambda_{x\text{-ray}} = \frac{1}{3K \gamma^2} \lambda_\beta, \quad \lambda_\beta \approx \sqrt{2 \gamma \lambda_p} \approx 300 \, \mu m \]
Results extremely important for:

- Designing future accelerators
- Compact X-ray source (Thomson, Compton, Betatron, or FEL)
- Applications (chemistry, radiotherapy, medicine, material science, ultrafast phenomena studies, etc...)

First X rays betatron contrast images

S. Fourmaux et al., Opt. Lett. 36, 13 (2011)


E. Esarey et al., Rev. Mod. Phys. 81, 1229 (2009)
S. Corde et al., Rev. of Modern Physics 85, 1 (2013)

Courtesy of K. Krushelnick

HELL Experimental Platform - Detailed Used Requirements Workshop
Institute of Physics of the Academy of Science, Praha Czech Republic, January 28 (2014)
Are these beams any good for applications?
Single-shot phase contrast imaging
Betatron radiation source characteristics

**spectrum**

- Peaks at 5.5 KeV

**source size**

- Best fit 1.7 µm

assuming a 5-fs pulse duration, this infers a peak brilliance of $2 \times 10^{22}$ ph/(s$^2$mm$^2$mrad$^2$ 0.1% bandwidth)
Tomography: Line projections and Radon transform:

Parametrize each point on ray by a direction unit vector $\omega$, distance to rotation center $t$ and longitudinal position $s$:

$$f(x) = f(\omega t + s\omega^\perp)$$

Then the Radon transform yields a representation of the object function $f$ in the variables $t$ and $\omega$:

$$Rf(t, \omega) = \int_{x \cdot \omega = t} f(x) \, dx = \int_{-\infty}^{\infty} f(\omega t + s\omega^\perp) \, ds$$
Tomography:

- Projections are $(n-1)$-dim. distribution functions representing the line integrals of the $n$-dim. density distribution along each ray path.
- The set of projections under different angles $\alpha$ constitute a sinogram:

\[ f(\bar{x}) \]

\[ Rf(t, \omega) \]
Reconstruction: Inversion of Radon transform:

Overlapping backprojections

2 angles

360 angles

Filtered backprojection formula:

\[ f = \frac{1}{4\pi} R^\# \frac{d}{dt} (\text{Rf}) \]

\[ H(y) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{f(x)}{y-x} \, dx \]
The intensity distribution on the detector is a result of wavefront distortions introduced by phase object. The Transport of Intensity Equation relates sample thickness to measured intensity distribution:

\[ T(\vec{r}) = -\frac{1}{\mu_{\text{poly}}} \times ln \left( F^{-1} \left\{ \frac{F(I(\vec{M}\vec{r}))}{I_0} \left( 1 + \frac{R\delta_{\text{poly}}}{M\mu_{\text{poly}} |\vec{k}|^2} \right) \right\} \right) \]
The transport-of intensity-equation (TIE) relates the edge-enhanced image at the detector (a) to the phase map of the insect (b)

\[
T(r) = -\frac{1}{\mu_{poly}} \times \ln \left( F^{-1} \left\{ \frac{F(I(Mr))}{I_0} \right\} \right)
\]

\[
1 + \frac{Rd_{poly}}{M\mu_{poly} \cdot |k|^2}
\]

Tomographic reconstruction of 2-D projections yields cuts through sample (edge enhancement (a) and phase images (b,c))
3D rendering of the fly (with S. Schleede, F. Pfeiffer et al., TUM)

J. Wenz et al., submitted to Nat. Photonics

- Demonstrates suitability for high-resolution imaging (well below 1 mm) for an all-optical source
- Photon energies for human diagnosis require 10J-class laser, long scan times.
Bone Tomography

- Trabecular/cancellous bone - intricate spongy internal structure
- Efficient distribution of mechanical stress throughout bone volume
- Very high surface area to volume ratio – site of intense bone remodelling

by courtesy of S.P.D. Mangles
X-rays produced on Astra Gemini are ideal for imaging these bone samples.
Tomographic 3D reconstruction of human trabecular bone

Projection at 1 degrees

Sinogram

Degrees

20 40 60 80 100 120 140 160 180
Tomographic 3D reconstruction of human trabecular bone

- Voxel size: $4.8 \times 4.8 \times 4.8 \, \mu m$
  - Limited by geometric magnification
  - Resolution $\approx 50 \, \mu m$
- Total scan time 4 hours
  - @ 10 Hz laser operation this image could be achieved in 3.6 seconds
- Total dose $\approx 40 \, mGy$
  - Potential for in-vivo studies
- Data quality already suitable for studies of osteoporosis

by courtesy of S.P.D. Mangles
Thomson scattering radiation

K. Khrennikov, J. Wenz + L. Veisz group et al.
Experimental setup

**Driver:** 1.2 J, 28 fs, $4.2 \times 10^{19} \text{ W/cm}^2$ \( (a_0=4.4) \)

**Colliding pulse:** 0.3 J, 28 fs, $1.8 \times 10^{18} \text{ W/cm}^2$ \( (a_0=0.9) \)

Electron beam size at interaction point decreases from 30 µm at 15 MeV to 17 µm at 45 MeV
Hard X-Rays recorded with an intensified camera

a) 30MeV electrons 15keV photons
   Colliding pulse on
   Colliding pulse off

b) 50MeV electrons 42keV photons

c) 70MeV electrons 83keV photons
Thomson scattering ($a_0=0.9$)

Shock-front injected e-beams:
Electron energy (red – averaged)

X-ray energy
(red – averaged; white – expected (SPECTRA 9.0))

DAQ failure

single shots

Electron energy [MeV]

X–Ray photon energy [keV]
X-ray energy matches expectations from electron energy

nominal $a_0=0.9$
(for perfect collision)

$$\lambda_{x-ray} = \frac{\lambda_l}{4\gamma^2} \left( 1 + \frac{a_0^2}{2} + \gamma^2\theta^2 \right)$$
Undulating with plasma fields

Laser-induced charge separation in nano-elements

Laser absorption similar to Brunel heating

Resulting e-static field: \( E = E_{\text{las}}(R_{\text{wire}}/r)^{1/2} \)

Periodically arranged wires:

\[ \Rightarrow \text{imposed period } \lambda_u \]

\[ \Rightarrow \text{transverse spacings control strength} \]
Undulating with plasma fields

2D/3D/CIRC PIC

Laser system
- Pulse duration: 30 fs
- Pulse energy: 0.7 J

Wires configuration
- Diameter: 0.4 \(\mu\)m
- Period: 24 \(\mu\)m
- Transverse spacings: 11 \(\mu\)m

LPA electron beam
- Emittance: 0.2 mm.mrad
- Energy: 200-600 MeV
- Energy spread: 1 %

I. Andriyash et al., Nat. Communications, 5736 (2014)

Undulating with plasma fields

*Varying electron energy*
Energy: 200 / 400 / 600 MeV

*Undulator emission*
Photon energy: 12 / 47 / 106 keV
Brightness: 0.5 / 2 / 4.5×10²³ s.u.
Angular sizes: 0.85×1.7 mrad

*Laser plasma nanostructured SR source*
- Quasi-monoenergetic collimated spectrum
- Tunability $\lambda_u, \varepsilon_e$
- Brightness $\sim \gamma_b^2$
- Source brightness level $10^{23}$ s.u.
- Interaction length $\approx 1$ mm
Particle therapy with laser accelerated protons

- **Favorable energy loss relation** (Bragg-peak) for heavy particles
- **Precise tools ask for precise handling and online monitoring**
- **Average power well matched and no need for low energy spread** (match bandwidth to tumor profile, e.g. with pulsed magnet gantry)

First step: Dose controlled radiobiology

No significant difference between pulsed and continuous proton radiation (measured for sensitive head/neck SKX cell line repair activity after 24h)

Dose stability and online control for each point below 10%

A laser-driven nanosecond proton source for radiobiological studies

by courtesy of J. Schreiber

• radiate 2-7 Gy (“lethal”) dose in one single ns pulse
• dose response curve from a single shot
• low laser energy (400 mJ, in principle 10 Hz)
• low background radiation
  • thick foils: few microSv / shot
  • DLC: 1-2 microSv / 50 shot
Low divergence from nm DLC foils

ATLAS @ MPQ, 0.5 J, 30 fs

J. Bin et al., On the small divergence of laser-driven ion beams from nanometer thick foils, Physics of Plasmas 20, 073113 (2013)

by courtesy of J. Schreiber
Next steps: animal irradiation and scaling

by courtesy of U.Schramm

- Pulsed solenoid (energy selection and focusing demonstrated)
- Proton scaling at PW laser level

![Diagram showing laser-target interaction and energy selection](image)

- Pulsed solenoid (energy selection and focusing demonstrated)
- Proton scaling at PW laser level

![Graph showing max proton energy vs. laser power](image)

(clinically relevant energies)

![Graph showing On-Axis B-Field vs. time](image)

(arrival of laser pulse)

(scaling T. Kluge et al., PRL 107, 205003 (2011))
Setup for mouse ear irradiation

- **Faraday-cup**
- **Ionization chamber**
- **Collimator with scintillating screen**
- **Camera**
- **Magnetic electron spectrometer**
- **Mouse holder with radiochromic films**
- **JETI-laser pulses**
- **Gas jet**

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focusing</td>
<td>F/13</td>
</tr>
<tr>
<td>Beam diameter</td>
<td>13 µm</td>
</tr>
<tr>
<td>Intensity</td>
<td>$8 \times 10^{18}$ W/cm²</td>
</tr>
<tr>
<td>Gas jet length</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>Electron density</td>
<td>$1 \ldots 2 \times 10^{19}$ cm⁻³</td>
</tr>
<tr>
<td>Max. rep. rate</td>
<td>1 Hz</td>
</tr>
</tbody>
</table>
Setup for mouse ear irradiation
Peak brilliance (assuming 5fs duration) [photons/(s mm$^2$ mrad$^2$ 0.1 % bandwidth)]

<table>
<thead>
<tr>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undulator</td>
<td>$1.3 \times 10^{17}$</td>
</tr>
<tr>
<td>Betatron</td>
<td>$2 \times 10^{22}$</td>
</tr>
<tr>
<td>Thomson</td>
<td>$0.02 \ldots 1.5 \times 10^{19}$ (from 5 KeV to 40 keV)</td>
</tr>
</tbody>
</table>

Average brilliance scales with duty cycle ($5 \times 10^{-15}$) times the repetition rate...

⇒ rep-rated laser development!