KE opportunity: Compact radiation source based on a laser-plasma wakefield accelerator

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Outline of talk

• Large and small accelerators + high power lasers
• Laser driven wakes
• Ultra-short bunch electron production using wakefield accelerators
• The Advanced Laser Plasma High-energy Accelerators towards X-rays (Alpha-X) project
• Synchrotron, free-electron laser and betatron sources
• Conclusion
Synchrotrons and light sources: tools for scientists and industrialists

Synchrotron – size and cost determined by accelerator technology

Diamond

DESY undulator

undulator synchrotron

TOPS ALPHA-X
Wakefield accelerator

UCLA: Tajima + Dawson 1979

Wake behind optical pulse travels and laser group velocity

$$v_g = c \sqrt{1 - \frac{\omega_p^2}{\omega_0^2}}$$

The ponderomotive force is given by the gradient of the light pressure

$$F_{pond} = -\frac{e^2}{4m\omega^2} \frac{dE^2}{dz} = -mc^2 \frac{d}{dz} (|a|^2)$$

The electrons are pushed out of high intensity regions by the ponderomotive force

Phase velocity gives

$$\gamma_\phi = \frac{\omega_0}{\omega_p}$$

3-D plasma wave

Critical density for 800 nm: $1.75 \times 10^{21} \text{ cm}^{-3}$
Particles accelerated by electrostatic fields of plasma waves

Accelerators:

Surf a 10’s cm long microwave – conventional technology

Surf a 10’s μm long plasma wave – laser-plasma technology

\[
\gamma = 2\gamma^2 \frac{\delta n_p}{n_p} = 2 \left( \frac{\omega_0}{\omega_p} \right)^2 \frac{\delta n_p}{n_p} = 2 \frac{n_c}{n_p} \frac{\delta n_p}{n_p}
\]
Wakefield acceleration

Dephasing length: \[ L_d = \frac{2\lambda_p \gamma^2}{\pi} \] where the phase velocity gives \[ \gamma = \frac{\omega_0}{\omega_p} \]
**UK consortium:**

- Injectors (conventional and all-optical)
- Laser-plasma wake-field acceleration
- Plasma capillaries

**FEL or synchrotron source**

- Free-electron laser (FEL)
- Beam transport systems
- Diagnostics

\[ \lambda = \frac{\lambda_i}{2\gamma^2} \left(1 + a_u^2\right) \]

\[ 2\gamma^2 = 10 \rightarrow 10^7 \]

\[ \lambda = 100 \, \mu m - 2 \, nm \]
ALPHA-X project

Strathclyde:
Riju Issac, Gregory Vieux, Enrico Brunetti, Bernhard Ersfeld,
Albert Reitsma, Ranaul Islam, David Clark, Tom McCanny,
Seth Brussaard, Jinhai Sun, Jordan Gallacher, Richard Shanks,
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Lancaster U., Cockcroft Institute / STFC - ASTeC, STFC - RAL CLF,
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IST Lisbon, U. Paris-Sud - LPGP, Pulsar Physics, UTA, CAS, LBNL
FSU Jena, U. Stellenbosch, U. Oxford, LAL, U. Twente, TUE, ...

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E.U. Laserlab and EuroLEAP
TOPS laser:
1.2 J @ 10 Hz
$\lambda = 800$ nm
30 fs

**ALPHA-X beam line at Strathclyde**

**TOPS laser:**
- 1.2 J @ 10 Hz
- $\lambda = 800$ nm
- 30 fs
Modelling of Laser Wakefield Acceleration

laser pulse envelope dynamics: ponderomotive wakefield excitation, electron bunch acceleration, phase slippage, beam loading

z-v gt (units of λp)

Laser pulse envelope: electrostatic wakefield, bunch density, energy density of wakefield

Strathclyde
ALPHA-X all-optical injection experiments on ASTRA

10^{18} \text{Wcm}^{-2} \text{ in 25 mm spot}

a_0 \sim 0.7 - 1

800 nm

350 - 540 mJ

40 fs

F/16 mirror

n_e \sim 2 \times 10^{19} \text{cm}^{-3}

\gamma = 2 n_c \frac{\delta n_p}{n_p n_p} = 175

\delta \gamma \approx 3\%

\tau \sim 5 - 10 \text{ fs}

I \sim 5 \text{ kA}

Few fs duration electron bunch

Imperial/RAL/Strathclyde

S. Mangles et al.

Nature 2004
LBNL - Oxford campaign (ALPHA-X) team: GeV beams from capillary


Pre-formed plasma channels – Spence & Hooker (PRE 2001)
Acceleration to 1 GeV in 33 mm long pre-formed plasma channels

5% shot-to-shot fluctuations in mean energy

\[ E = 0.48 \text{ GeV} \pm 6\% \]

and an r.m.s. spread <5%.

12TW (73fs) - 18TW (40fs)

\[ E = (0.50 \pm/-0.02) \text{ GeV} \]
\[ \Delta E = 5.6\% \text{ r.m.s.} \]
\[ \Delta \theta = 2.0 \text{ mrad r.m.s.} \]
\[ Q = 50 \text{ pC} \]
\[ \text{Laser } \sim 1 \text{ J} \]

\[
\gamma_{\text{max}} = 2 \frac{n_c}{n_p} \frac{\delta n_p}{n_p} = 1750
\]

Wakefield - undulator experiment
Electron and optical spectra

Strathclyde, Jena & Stellenbosch

Jena: JETI laser

TOPS ALPHA-X

**ALPHA-X: Measured electron and radiation spectra**

- Jena: JETI laser
  - $N_{\text{ph}} \approx 300,000$ photons
  - $Q = 28 \text{ pC} @ 65 \text{ MeV}$
  - $\varphi = 2 \text{ mrad}$
  - $\delta \lambda / \lambda = 55 \text{ nm (FWHM)}$
  - Visible: $B = 6.5 \times 10^{16}$ ph/sec/mrad²/mm²/0.1%BW

$$\frac{\delta \gamma}{\gamma} < 0.5 \left[ \left( \frac{\delta \lambda}{\lambda} \right)_{\text{measured}}^2 - \left( \frac{\varphi \gamma}{\varphi} \right)^2 - 1 / N_u^2 \right]^{1/2}$$

Sets an upper limit to total energy spread ($\approx 1\%$) and emittance ($1 \pi \text{ mm mrad}$)


**TOPS ALPHA-X**
Predicted Synchrotron radiation and SASE FEL for Strathclyde undulator

matched beam
SASE FEL

SASE FEL

matched beam
SASE FEL

Photon Flux [Photons/0.1% BW]

Photon energy [eV]

3x10^{12}
2x10^{12}
1x10^{12}
0
350
400
450

synchrotron radiation

Peak Brilliance: \(2.97 \times 10^{25}\) photons/sec/mrad²/mm²/0.1% b.w.

Photon Flux [Photons/0.1% BW]

Photon energy [eV]

1.5x10^5
1.0x10^5
5.0x10^4
0.0
350
400
450

Photon flux into 200 µrad

Synchrotron:

\(\sigma/\gamma = 0.1\%\)

\(I_{pk} = 12\) kA

\(\varepsilon_n = 1\) \(\pi\)mm mrad

\(N_u = 200\)

\(\tau_e < 10\) fs

Peak Brilliancy \(B = 3 \times 10^{25}\) ph./sec/mrad²/mm²/0.1% b.w. for 10 Hz

Average brilliance \(B = 2.5 \times 10^{11}\)

With laser improvements: 1 kHz: rep rate:

average brilliance \(B > 10^{13}\)

FEL: \(B > 10^6\) times higher

TOPS
ALPHA-X

IOP London 2009
Predicted SASE FEL Power growth

\[ E = 1 \text{ GeV} \]
\[ Q = 100 \text{ pC} \]
\[ I_{pk} = 30 \text{ kA} \]
\[ \varepsilon_n = 1 \pi \text{ mm mrad} \]
\[ \delta\gamma/\gamma = 0.1\% \]
\[ \beta = 0.5 \text{ m} \]
\[ \rho = 0.0065 \]
\[ E_{ph} = 422 \text{ eV} \]
\[ B_{pk} = 6 \times 10^{31} \text{ phot/sec/mm}^2/\text{mrad}^2/0.1\% \text{ BW} \]

6.3 x 10^{12} coherent photons per pulse
Synchrotron radiation from an ion channel wiggler: betatron radiation

- Wiggler motion – electron deflection angle $a \sim (p_x/p_z)$ is much larger than the angular spread of the radiation $\vartheta = (1/\gamma)$

$$\gamma >> a_u >> 1$$

- Only when $k$ & $p$ point in the same direction do we get a radiation contribution.
- Spectrum rich in harmonics – peaking at $h_{crit} \approx \frac{3a_u^3}{8}$
- Radiation rate $W \propto \gamma^2$ therefore only emission at dephasing length $L_d$
X-ray generation in a plasma wake

Strong radial forces cause synchrotron or betatron oscillations of electron beam

Restoring force given by Gauss law: \[ F = -\frac{1}{2} m \omega_p^2 r_\perp \]

Oscillation at the betatron frequency: \[ \omega_b = \frac{\omega_p}{\sqrt{2} \gamma_e} \]

Emitted synchrotron radiation viewed in the lab frame

\[ \lambda_h = \frac{h \lambda_\beta}{2 \gamma_e^2} \left( 1 + \frac{a_u^2}{2} + (\gamma_e \phi)^2 \right) = \frac{h \pi c}{\omega_p \gamma_e^{3/2}} \left( 1 + \frac{a_u^2}{2} + (\gamma_e \phi)^2 \right) \]

\( h \) – harmonic number
\( h_{\text{crit}} \) - maximum intensity at harmonic \[ h_{\text{crit}} \approx \frac{3a_u^3}{8} \]

Undulator/wiggler deflection parameter \[ a_u = \gamma_e k_\beta r_e = \frac{\sqrt{2} \gamma_e \pi r_e}{\lambda_p} \]
Betatron radiation: simulations for capillary

\[ a_u = \gamma k r_e = \sqrt{2\gamma_e \pi r_e} \frac{\sqrt{2}}{\lambda_p} \]

\[ n_{\text{crit}} \approx \frac{3a_u^3}{8} \]

\[ \Omega \approx \text{few mrad and } 10^9 \text{ x-ray photons} \]
Where do we stand with plasma-wakefield accelerator based sources

★ brilliance of a wakefield based incoherent radiation source

figure from http://www.xfel.eu
Synchrotron, betatron and FEL radiation peak brilliance

\[ I(k) \sim I_0(k)(N+N(N-1)f(k)) \]

- \( \lambda_u = 1.5 \text{ cm} \)
- \( \varepsilon_n = 1 \pi \text{ mm mrad} \)
- \( \tau_e = 10 \text{ fs} \)
- \( Q = 100 - 200 \text{ pC} \)
- \( I = 25 \text{ kA} \)
- \( \delta \gamma / \gamma < 1\% \)

FEL: Brilliance 5 – 7 orders of magnitude larger
The **Scottish Centre for the Application of Plasma based Accelerators: SCAPA**

A SUPA initiative to develop and apply ultra-compact accelerators and radiation sources
Conclusions

• Laser driven plasma waves are a useful way of accelerating charged particles and producing a compact radiation source: 100 – 1000 times smaller than conventional sources
• Some very good properties: sub 10 fs electron bunches potentially shorter (< 1 fs?) and high peak current (up to 35 kA?), \( \varepsilon_n < 1 \pi \text{ mm mrad}, \delta_{\gamma/\gamma} < 1\%? \).
• Slice values important for FEL - potentially 10 times better. Wide energy range, wide wavelength range: THz – x-ray
• Good candidate for FEL – coherence & tuneability
• Betatron radiation – towards fs duration gamma rays
• Still in R&D stage – need a few years to show potential
• Challenges: rep rate, stability, energy spread and emittance, higher charge and shorter bunch length, beam transport
• Synchronised with laser – can combine radiation, particles (electrons, protons, ions), intrinsic synchronisation
• Compact light source for every university or 5\(^{th}\) Generation light source?
Thank you