Laser driven plasma wakefield accelerators and radiation sources

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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
- Betatron gamma ray source
- Conclusion
Large accelerators depend on superconducting Radio Frequency cavities

CERN - LHC
27 km circumference

SLAC
50 GeV in 3.3 km
20 MV/m

7 TeV in 27 km
7 MV/m
Synchrotrons light sources and free-electron lasers: tools for scientists

Synchrotron – huge size and cost is determined by accelerator technology

Diamond

DESY undulator

Gamma Ray X-ray Ultraviolet Visible Infrared Microwave Radio
Particles accelerated by electrostatic fields of plasma waves

\[ E\left[\text{V/cm}\right] \approx e\sqrt{n} \]

\[ \gamma_{\text{max}} \approx \frac{2\gamma_g^2a}{3} \]

Accelerators:

Surf a 10’s cm long microwave – conventional technology

Surf a 10’s \( \mu \text{m} \) long plasma wave – laser-plasma technology
Wakefield acceleration

Dephasing length: \( L_d = 4c \gamma_g^2 \sqrt{a_0} / 3 \omega_p \), which gives a maximum energy: \( \gamma \approx \frac{2}{3} \gamma_g^2 a_0 \)
Bubble structure - relativistic regime

\[ R \approx \frac{\sqrt{a_0 \lambda_p}}{2} \]

ion bubble radius
ALPHA-X started in 2002
Advanced Laser Plasma High-energy Accelerators towards X-rays

Compact femtosecond duration particle, synchrotron, free-electron laser and gamma ray source $\lambda = 2.8 \text{ nm} - 1 \mu\text{m}$ (<1GeV beam)

electron bunch duration: 1-3 fs

Brilliant particle source: 10 MeV $\rightarrow$ GeV, kA peak current, fs duration
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 \text{ nm}

350 - 540 \text{ mJ}

40 \text{ fs}

F/16 mirror

\gamma_g \approx 10

n_e \sim 1.5 \times 10^{19} \text{ cm}^{-3}

\gamma_{\text{max}} = \frac{2 \gamma_0^2 a_0}{3} \approx 150

S. Mangles et al.
Nature 2004

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

I \sim 5 \text{ kA}

\frac{\delta \gamma}{\gamma} \approx 3\%

Few fs duration electron bunch
LBNL - Oxford campaign (ALPHA-X) team: GeV beams from capillary

Pre-formed plasma channels – Spence & Hooker (PRE 2001)

Channels manufactured using laser machining techniques – Jaroszynski et al., (Royal Society Transactions, 2006)
1 GeV beams

Acceleration to 1 GeV in 33 mm long pre-formed plasma channels

5% shot-to-shot fluctuations in mean energy

E = 0.48 GeV±6%
and an r.m.s. spread <5%.

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

E = (0.50 +/-0.02) GeV
ΔE = 5.6% r.m.s
Δθ = 2.0 mrad r.m.s.
Q = 50 pC
Laser ~ 1 J
γg ≈ 30

\[ \gamma_{\text{max}} = \frac{2\gamma_g^2 a_0}{3} \approx 2000 \]

TOPS laser: 1.1 J @ 10 Hz
\( \lambda = 800 \text{ nm} \)
30 fs

**Strathclyde: ALPHA-X beam line**

Jaroszynski et al.,
(Royal Society Transactions, 2006)
Experimental Results - energy stability

100 consecutive shots
Mean $E_0 = (137 \pm 4)$ MeV
2.8% stability

Electron Spectrometer: 200 consecutive shots (spectrum on 196 shots)
Energy spread at 130 MeV

\[ \frac{\sigma_{\gamma}}{\gamma} = 0.75\% \]

r.m.s. spread of mean energy 2.8%
Experimental Results – emittance

- Second generation mask with hole $\phi \sim 25 \, \mu m$ and improved detection system

- divergence 1 – 2 mrad for this run with 125 MeV electrons
- average $\varepsilon_N = (2.2 \pm 0.7) \pi \, mm \, mrad$
- best $\varepsilon_N = (1.0 \pm 0.1) \pi \, mm \, mrad$
- Elliptical beam: $\varepsilon_{N, X} > \varepsilon_{N, Y}$
Ultra-short pulse

Measurements at Strathclyde indicate 1-2 fs electron bunches with 1-10 pC: i.e. Multi kA peak current, with energy spread and emittance – suitable for FEL
Synchrotron radiation from an ion channel wiggler: betatron radiation

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

$\gamma \gg a_u \gg 1$

**Deflection angle** – $a_u/\gamma$

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

SCALING LAWS

- Betatron Frequency: \( \omega_\beta = \omega_p / \sqrt{2\gamma} \)
- Transverse momentum: \( a_\beta \propto \sqrt{\gamma n_e r_\beta} \)
- Divergence: \( \vartheta = a_\beta / \gamma \)
- Critical photon Energy: \( E_c \propto \gamma^2 n_e r_\beta \)
- Efficiency: \( N_{\text{phot/cycle}} = \alpha a_\beta \)

- Wavelength: \( \lambda_h = \frac{\lambda_\beta}{h 2 \gamma_e^2} \left( 1 + \frac{a_\beta^2}{2} + (\gamma_e \varphi)^2 \right) = \frac{\sqrt{3\pi c}}{h \omega_p \gamma_e^{3/2}} \left( 1 + \frac{a_\beta^2}{2} + (\gamma_e \varphi)^2 \right) \)
Gamma Ray Source demonstrated on Gemini using PW laser

$10^8$ photons between .1 and 7 MeV

Brilliance $10^{23}$ photons/(s mrad$^2$ mm$^2$ 0.1% bandwidth) is femtosecond duration pulses
Typical high energy spectra: Gemini experiment using plasma channel 85% of shots
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

1000 m² laboratory space: 200-300 TW laser and 10 “beam lines” producing particles and radiation sources for applications: nuclear physics, health sciences, plasma physics, homeland security etc.
**ALPHA-X project**

**Strathclyde (students and staff):**

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**Collaborators:** Gordon Rob, Brian McNeil, Ken Ledingham and Paul McKenna

**ALPHA-X: Current and past collaborators:**


**Current Support:**

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FIN
Thank you