Laser-plasma wakefield particle acceleration at CUOS*

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Focused Intensity / Wcm$^2$

- $10^{10}$: Atomic matter
- $10^{15}$: Plasma
- $10^{20}$: Relativistic Plasma
- $10^{25}$: "QED Plasma"
- $10^{30}$: Non-linear QED

Energy levels:
- 1 eV
- 1 MeV
- 1 GeV
- 1 TeV

- QED Critical field
- electron quiver energy
- Plasma
- Electron Bunch
- Laser Pulse
- Laser pulse
- γ-photon
- Pair production
- Electron beam

- CURRENT RECORD (HERCULES)
HERCULES laser

- Chirped Pulse Amplification Ti:Sapphire
- 808 nm central wavelength
- Peak power 300 TW (9 J in 30 fs)
- ASE intensity contrast $10^{-8}$
- With Cross-Wave Polarization
  ASE intensity contrast $10^{-11}$
- 0.1 Hz repetition rate
- 4 inch beam successfully focused to $2 \times 10^{22}$ Wcm$^{-2}$

V Yanovsky et al, Optics Express 16, 2109 (2008)
Laser Wakefield Acceleration

Surfing electrons on an electric wave!
LASER WAKEFIELD ACCELERATION

Surfing electrons on an electric wave!

~10 µm for present experiments
Laser Wakefield Acceleration

Surfing electrons on an electric wave!

Maximum energy gain (limited by dephasing)

$$\Delta T = \frac{2}{3} a_0 \frac{n_c}{n_e} m_e c^2$$

Experiments now routinely demonstrate GeV energies in a cm-scale plasma accelerator

i.e. 100 GeV/m accelerating gradient

TeV - ILC - 31 km

TeV - 50 stage LWFA - 100 m

>1000 papers since Y2000
Wakefield based photon sources

Betatron radiation

Electrons in 3D wake structure oscillate with frequency

\[ \omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}} \]

- Esarey PRE (2002)
- Rousse, Ta Phuoc
- Corde et al PRL (2011) x2
- Plateau et al PRL 2012
- Albert et al PRL (2013)

HERCULES: PEAK Brightness comparable to 3rd generation synchrotron

Spatially coherent - phase contrast X-ray imaging possible
Gas jet/gas cell/two stage gas cell

- HERCULES: Energy stability, pointing stability, divergence and energy spread all improved using 2-stage cells

3D printed variable length two stage gas cell

Normalized transverse emittance <π mm mrad

(1st stage ionization injection - Pak PRL 2010, McGuffey ibid)
LWFA Electron Beam Probing of Relativistically Expanding Strong Magnetic Field

Electron beam probes magnetic field generated by ultrafast laser on metal foil surface

- HERCULES laser split into a LWFA driver to generate electrons and a tightly focused pump of a solid density Aluminum target
- Strong ($10^4$ Tesla) magnetic field generated expanding at close to c
- $B$ generated by rapid expansion of current along surface of metal

Schumaker et al PRL 110, 015003 (2013)
Collimated, High-Energy Positron Measurements

Scaling with Z and d consistent with a two-step process (Bremsstrahlung + Bethe-Heitler)

Overall positron yield: $3 \times 10^7$ e$^+$
Overall lepton yield: $3 \times 10^8$ (secondary e$^-$/e$^+$)
Positron density: $2 \times 10^{14}$ cm$^{-3}$
Lepton density: $2 \times 10^{15}$ cm$^{-3}$
Intensity: $10^{19}$ erg s$^{-1}$ cm$^{-2}$
Divergence: 3 mrad

Image Plates integrated over 10 shots

G. Sarri et al., PRL 110 255002 (2013)
LWFA at a kHz ($\lambda^3$ laser, 1 TW)

- Feedback-optimized electron beam with genetic algorithm
- Plasma wave structure is reproducible (stable)
- **Laser phase manipulated to coherently control plasma dynamics**
- Order of magnitude improvement on peak charge and divergence of LWFA
- Ultrafast electron diffraction possible

He et al., Nat. Commun. 6 7156 (2015).
Strong field QED: An opportunity to push boundaries

- This may be important for the next generation of ultra powerful lasers

- For $10^{22} \text{Wcm}^{-2}$, $a_0 \sim 100$, particles accelerated to $\gamma \sim a_0$

- 4.5 GeV - $\gamma \sim 10^4$

Colliding laser-electron beam geometry

$\chi_e = \frac{||F_{\mu\nu}p^\nu||}{mcE_{cr}}$

$\chi_\gamma = \frac{||F_{\mu\nu}\hbar k^\nu||}{mcE_{cr}}$

$\chi \sim 10^{-5} \gamma a_0$

(vid SLAC E144 collaboration - $\gamma \sim 10^5$, $a_0 \sim 1$)
Colliding an electron beam with a laser pulse

\[
\frac{d^2N}{d\omega_0 d\omega d\Omega} \propto \omega_0
\]

30 fs, \(\gg 10^{21} \text{ Wcm}^{-2}\)

LWFA driver pulse

Focusing paraboloid

Supersonic gas jet

Focusing paraboloid

\(\text{At 0.5 GeV, } 10^{21} \text{ Wcm}^{-2} \ldots\)

- Multi photon Compton Scattering: Photon source with peak brightness comparable to 4th generation light source (\(10^{29} \text{ photons mm}^2 \text{ mrad}^2 / 0.1\%\text{bandwidth}\))

\(\text{At 5 GeV, } 10^{22} \text{ Wcm}^{-2} \ldots\)

- Transition to strong field QED regime: electron-positron pair cascade
- nonlinear / manybody QED

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cf SLAC E144 collaboration chi~0.4

Bell and Kirk PRL 2008
Fedotov et al PRL 2010
Bulanov et al PRL 2010
Sokolov PRL 2010
Nerush et al PRL 2011
Bulanov et al Phys Plasm. 2012
Blackburn et al PRL 2014
Ji etal PRL 2014
Summary

• Laser Wakefield Acceleration capable of producing ~GeV electrons on a table-top with good transverse emittance

  • But - energy spread and shot-to-shot stability still poor comparable to current LINACS

  • Excellent timing stability and ultrashort duration allow range of pump-probe experiments on a “tabletop” system

  • Experiments at high repetition rate demonstrate that poor stability is not inherent to plasma dynamics

  • Colliding laser - electron beam geometry at high intensity should allow us to access nonlinear QED physics not accessible on particle accelerators!