Laser Plasma Wakefield Acceleration: Concepts, Tests and Premises

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Summary

Part 1 : Laser plasma accelerator : motivation

Part 2 : Laser plasma accelerator as booster

Part 3 : Laser Plasma accelerator as injector : Production of monoenergetic electron beam

Part 4 : New scheme of injection : toward a stable, tuneable and quasi monoenergetic electron beam.

Part 5 : Conclusion and perspectives
Classical accelerator limitations

\[ E \text{-field}_{\text{max}} \approx \text{few } 10 \text{ MeV /meter (Breakdown)} \]
\[ R > R_{\text{min}} \text{ Synchrotron radiation} \]

\[ \text{Energy} = \text{Length} = $$$ \]

LEP at CERN

27 km

\[ \approx \]

PARIS

31 km

New medium: the plasma
Why is a Plasma useful?

- Superconducting RF-Cavities: $E_z = 55$ MV/m
- Plasma is an Ionized Medium $\rightarrow$ High Electric Fields
How to excite Relativistic Plasma waves?

The laser wake field

$\tau_{\text{laser}} \approx T_p / 2 \Rightarrow \text{Short laser pulse}$

Electron density perturbation

Laser pulse

$F \approx -\text{grad} \ I$

Phase velocity $v_{\text{epw}} = v_{\text{laser}} \Rightarrow \text{close to} \ c$

Analogy with a boat

Are Relativistic Plasma waves efficient?

$E_z \sim \sqrt{n_e}$

$E_z = 0.3 \text{ GV/m for 1% Density Perturbation at } 10^{17} \text{ cc}^{-1}$

$E_z = 300 \text{ GV/m for 100% Density Perturbation at } 10^{19} \text{ cc}^{-1}$
Relativistics microelectronic devices

Courtesy of W. Mori & L. da Silva

Time = 0.74 [ps]

100 μm
Plasma cavity

1 m
RF cavity
Interaction and dephasing lengths

\[ L_{\text{Deph.}} = \lambda_p \gamma^2 \]

\[ \Rightarrow L_{\text{deph.}} = (\lambda_0/2)(n_c/n_e)^{3/2} \]

Diffraction limited

\[ L_{\text{acc.}} = \pi Z_R \]

Guiding: channel or relativistic

\[ \Delta W_{\text{diff.}} \ [\text{MeV}] \approx 580 (\lambda/\lambda_p)/(1+a_0^2/2)^{1/2} P \ [\text{TW}] \]

\[ \Delta W_{\text{ch}} \ [\text{MeV}] \approx 60 (\lambda_p/w_0) P \ [\text{TW}] \]

W. P. Leemans et al., IEEE 24, 2 (1996)
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Accelerating & focusing fields in Linear RPW

- Small Laser amplitude $a_0=0.5$
- Homogeneous plasma

![Electron density and pulse diagram](image-url)
Accelerating & focusing fields in plasma channel

- Small Laser amplitude $a_0=0.5$
- Parabolic plasma channel
Accelerating & focusing fields in NL RPW

- Large Laser amplitude $a_0=2$
- Homogeneous plasma

Electron density

relativistic shift of $\omega_p$
Three Injection schemes

Before the pulse

Low energy => Low charge

High Energy => Short Bunch

Low energy

Laser
$\tau_{\text{bunch}} = 200$ fs
Injecting the LOA e-beam @ $\tau_{\text{bunch}} = 30$ fs, 170 MeV
3 GeV, 1% energy spread e-beam

- $E = 9 \ J$
- $P = 0.15 \ PW$
- $a_0 = 1.5$
- Parabolic channel:
  - $r_0 = 47 \ \mu m$
  - $n(r) = n_0 \ (1 + 0.585 \ r/r_0)$
  - $n_0 = 1.1 \times 10^{17} \ cm^{-3}$

3.5 GeV, with a relative energy spread FWHM of 1% and an unnormalized emittance of 0.006 mm.
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Laser plasma injector

Scheme of principle

Experimental set up
Energy distribution improvements: The Bubble regime

Charge in the peak: few 100 pC
According to absolute calibration of scintillator*

At LOA

Several groups have obtained quasi monoenergetic e beam but at higher density ($\tau_L > \tau_p$)

*Y. Glinec et al., in preparation, NB
Quasi monoenergetic e-beam: 14 groups

At Lundt
Mangles et al. PRL (2006)

At LBNL
Laser plasma injector: GeV electron beams

\[ w_0 = 20 \mu m \quad \tau = 30 \text{fs} \quad P = 200TW \quad \lambda = 0.8 \mu m \quad a_0 = 4 \quad n_p = 1.5 \times 10^{18} \text{cm}^{-3} \]

Courtesy of UCLA & GOLP groups

LOA

Laser plasma injector:

+ good efficiency: $E_{\text{e-beam}}/E_{\text{laser}} \approx 10\%$

+ simple device

+ sub 30 fs duration: ideal as injector

+ with channel: GeV range is obtained\(^1\) with moderate laser power*

*But since the efficiency is conserved a compromise between charge and energy must be found

- Stability not yet demonstrated!

- Energy spread still too large for some applications: $\delta E/E \approx \text{few }\%$

* Courtesy of S. Hoocker or F. S. Tzung PRL (2004)
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External injection using another laser pulse

Counter-propagating geometry:

Plasma wave

Pump beam

Injection beam

Ponderomotive force of beatwave: $F_p \sim 2a_0a_1/\lambda_0$  
($a_0$ et $a_1$ can be “weak”)

Boost electrons locally and injects them:

INJECTION IS LOCAL IN FIRST BUCKET

Experimental set-up

- **Injection beam**
- **Pump beam**
- **Probe beam**
- **LANEX**
- **B Field**
- **Gas jet**
- **electron spectrometer** to **shadowgraphy diagnostic**

**Details**:

- 250 mJ, 30 fs, $\phi_{\text{fwhm}}=30 \ \mu\text{m}$
  - $I \sim 4 \times 10^{17} \ \text{W/cm}^2$
  - $a_1=0.4$

- 700 mJ, 30 fs, $\phi_{\text{fwhm}}=16 \ \mu\text{m}$
  - $I \sim 3 \times 10^{18} \ \text{W/cm}^2$
  - $a_0=1.2$
From self-injection to external injection

$p_{\text{self-injection}} = 1.25 \times 10^{19} \text{ cm}^{-3}$

$p_{\text{external injection}} = 10^{19} \text{ cm}^{-3}$

$p_{\text{threshold}} = 7.5 \times 10^{18} \text{ cm}^{-3}$

LOA

EPAC06, Edinburg, Scotland, June 26-30 (2006)
Optical injection by colliding pulses leads to stable monoenergetic beams

STATISTICS

Bunch charge = 15 +/- 5 pC
Peak energy = 118 +/- 7 MeV
$\Delta E = 13 +/- 2.5$ MeV
$\Delta E/E = 11 \%$
Divergence = 5.7 +/- 2 mrad
Pointing stability = 2 mrad

EPAC06, Edindurgh, Scotland, June 26-30 (2006)
Monoenergetic bunch comes from colliding pulses: polarization test

Parallel polarization

Crossed polarization
Controlling the bunch energy by controlling the acceleration length

By changing delay between pulses:
• Change collision point
• Change effective acceleration length
• Tune bunch energy

Pump beam
Gas jet
Injection beam

EPAC06, Edinurgh, Scotland, June 26-30 (2006)
Tunable monoenergetic bunches

$Z_{\text{inj}} = 225 \mu m$

$Z_{\text{inj}} = 125 \mu m$

$Z_{\text{inj}} = 25 \mu m$

$Z_{\text{inj}} = -75 \mu m$

$Z_{\text{inj}} = -175 \mu m$

$Z_{\text{inj}} = -275 \mu m$

$Z_{\text{inj}} = -375 \mu m$

Energy (MeV)

LOA
Tunable monoenergetic electrons bunches:

190 MeV gain in 700 µm: $E=270 \text{ GV/m}$

Compare with $E_{\text{max}}=mc\omega_p/e=250 \text{ GV/m}$ at $n_e=7.5\times10^{18} \text{ cm}^{-3}$
Conclusions / perspectives

SUMMARY
• Optical injection by colliding pulse: it works!
• Monoenergetic beams trapped in first bucket
• Enhances dramatically stability
• Energy is tunable: 20-300 MeV
• Charge up to 50 pC in monoenergetic bunch
• $\delta E/E$ down to 5 % (spectrometer resolution), $\delta E \sim 10-20$ MeV

PERSPECTIVES
• Combine with waveguide: tunable up to few GeV with $\delta E/E \sim 1$ %
• Multi/single stage accelerators
• Stable source:
  extremely important
  accelerator development
  light source development
Applications (material science, radiotherapy, chemistry etc...)

EPAC06, Edindurgh, Scotland, June 26-30 (2006)
Parameter designs Laser Plasma Accelerators

**ELI : > 100 GeV**

\[ a_0 = 4 \]

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<th>P(PW)</th>
<th>( \tau ) (fs)</th>
<th>( n_e ) (cm(^{-3}))</th>
<th>( W_0 ) (( \mu )m)</th>
<th>L(m)</th>
<th>E(J)</th>
<th>( Q(nC) )</th>
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**Golp and UCLA Group**
Electron beam energy and laser power evolution
Towards an Integrated Scientific Project for European Researcher: ELI