Direct laser acceleration of electrons in the corrugated plasma waveguide

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Laser wakefield acceleration has made GeV electrons available in a compact setup using terawatt lasers.

40 terawatt, 40 femtosecond laser pulse

Electric discharge plasma waveguide

GeV electron beams from a centimetre-scale accelerator

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Laser wakefield acceleration has made GeV electrons available in a compact setup using terawatt lasers. 40 terawatt, 40 femtosecond laser pulse ~30 picoCoulombs of ~1 GeV electrons

GeV electron beams from a centimetre-scale accelerator

W. P. LEEMANS1**, B. NAGLER1, A. J. GONSAVES2, Cs. TÓTH1, K. NAKAMURA1, C. G. R. GEDDES1, E. ESAREY1**, C. B. SCHROEDER1 AND S. M. HOOKER2
Laser wakefield acceleration has made GeV electrons available in a compact setup using terawatt lasers.

But:

This is inherently nonlinear- you need terawatt lasers to do wakefield acceleration.
The SLAC structure is a TM-mode microwave waveguide with periodic structure to phase-match acceleration.

A linear process:
There's no minimum microwave power
The SLAC structure is a TM-mode microwave waveguide with periodic structure to phase-match acceleration. 'slow-wave' structure wave phase velocity < c

EM propagation & particle accel.

There is a maximum power, though.
The SLAC structure is a TM-mode microwave waveguide with periodic structure to phase-match acceleration.

50 GeV in 3.2 km

\[50 \times 10^9 \text{ V} / (1.7 \times 10^7 \text{ V/m}) = 2 \text{ miles}\]

Solution: use ‘milder’ fields over longer distance

Internal breakdown (lightning!) and self-destruction if wave fields are greater than \(~ 10^7 \text{ Volts/m}\)

Bunch Cloud

EM propagation & particle accel.

‘slow-wave’ structure
wave phase velocity < c
Another solution: replace the copper tube with a (much smaller) tube made of plasma!

Now, instead of megawatt microwave klystrons:

You can accelerate with terawatt OR gigawatt optical lasers!
This might seem a little crazy

Bunch of relativistic electrons

Wheee!

But...
We've already done the hardest part: making the plasma tube

Terawatt, femtosecond laser pulse

Microstructured plasma waveguide

1 mm

Ultrahigh-Intensity Optical Slow-Wave Structure


PRL 99, 035001 (2007)
Our simulations show we can get good acceleration gradients with modest lasers.

Radially-polarized femtosecond laser pulse

The structured plasma can phase-match direct acceleration

Relativistic electron bunch

Direct Acceleration of Electrons in a Corrugated Plasma Waveguide

A. G. York* and H. M. Milchberg
J. P. Palastro and T. M. Antonsen

PRL 100, 195001 (2008)
Our simulations show we can get good acceleration gradients with modest lasers.

The structured plasma can phase-match direct acceleration.

Radially-polarized femtosecond laser pulse

Relativistic electron bunch

Even small lasers would give big acceleration gradients:

- 1.9 TW: >80 MeV/cm
- 30 GW: >10 MeV/cm (over many centimeters)
Our simulations show we can get good acceleration gradients with modest lasers.

Radially-polarized femtosecond laser pulse

The structured plasma can phase-match direct acceleration

Relativistic electron bunch

Acceleration depends on electron injection:
Total charge and efficiency seem promising. In our 2 TW drive-beam simulations:

About 40 pC of charge can fit in each “bucket”

Each “bucket” absorbs about 1% of the drive pulse energy.

Palastro et al., PRE 77, 036405 (2008)
How we made the plasma tube:

Cluster Jet (Ar, H$_2$, N$_2$)

Spatially modulated 500mj 100ps Nd:YAG laser pulse

Periodically Modulated Plasma Waveguide

Diffractive optic to shape the waveguide creation pulse

Axicon

1.5cm

Breakdown in atmosphere, mm-scale corrugations

We have a lot of control over the shape and density of the plasma tube.
How we made the plasma tube:

Breakdown in argon clusters, 100's μm-scale corrugations

We have a lot of control over the shape and density of the plasma tube.
Cluster Jet (Ar, H\(_2\), N\(_2\))

Periodically Modulated Plasma Waveguide

Spatially modulated 500mj 100ps Nd:YAG laser pulse

Diffractive optic to shape the waveguide creation pulse

Axicon

Small corrugations are crucial if we're going to extend this technique to ion acceleration.
We've demonstrated terawatt guiding in these tubes*. They're corrugated optical waveguides!

100mj 50-70fs
Ti:sapphire laser pulse
(delayed ~2ns relative to YAG pulse)

Spatially modulated 500mj 100ps Nd:YAG laser pulse

Diffractive optic to shape the waveguide creation pulse

Periodically Modulated Plasma Waveguide

Axicon

Cluster Jet (Ar, H$_2$,N$_2$)

13 µm

So far we've demonstrated guiding of a linearly polarized laser pulse.

We need to guide a **radially** polarized pulse (a TM waveguide mode) for effective acceleration.

*PRL 99, 035001 (2007)
In the lab, it looks like this:

- Use a ‘Ring Grating’ (RG)-a transmissive diffraction grating lithographically etched into a fused silica disk
- Image the RG through an axicon to the line focus
- Creates a modulated plasma spark that evolves into a modulated channel
- Different ring gratings give us different modulation periods

The ring grating

100ps pulse

Pulse images the RG from 60cm upstream
Second method - tailored cluster flow

Modulated Plasma Waveguide

60 fs transverse interfer. probe

100ps Nd:YAG laser pulse

Ar or N₂ Cluster Jet

Axicon

60fs Ti:Al₂O₃ laser pulse

1.5 cm

330µm

1030 µm
Cluster flow can be tailored to make extremely small features in the plasma channel.

Transverse Phase Shift

Nitrogen cluster target @ -150 deg C

Argon Cluster target @ 22 deg C

Radial Electron Density

50 μm

200 μm

600 μm

Abel Inversion

9*10^{18} \text{ cm}^{-3}
at wall

~3*10^{18} \text{ cm}^{-3}
on axis

~3*10^{18} \text{ cm}^{-3}
on axis

5*10^{18} \text{ cm}^{-3}
at wall

~2*10^{18} \text{ cm}^{-3}
on axis

(200 consecutive shot average)
Conclusions

• Optical-frequency linac with no damage threshold
• Simple, unoptimized model shows strong acceleration
• Plasma structures are under control
• Need radial polarization: diffractive optics?
• Need an injector: solid target? wakefield acceleration?
• Extension to ions needs study
Guiding in corrugated hydrogen plasma channels

- H₂ jet cryogenically cooled to enhance clustering
- Electron densities of \( \sim 1.5 \times 10^{18} \text{ cm}^{-3} \) on axis and \( \sim 3 \times 10^{18} \text{ cm}^{-3} \) at channel wall for a delay of 1 ns

Waveguide generation pulse energy and alignment controls modulation features
Why use a 100ps laser pulse and clusters?


• The far leading edge of the 100ps beam disassembles / ionizes the clusters, leaving a cold plasma that the remainder of the pulse heats.
• Much more efficient than heating an unclustered gas (for same average Z in a plasma, 3x-10x less pump energy required)
Our next project: generating a radially polarized femtosecond-scale, multi-millijoule pulse.

Radially and azimuthally polarized beams generated by space-variant dielectric subwavelength gratings

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Received August 16, 2001

We present a novel method for forming radially and azimuthally polarized beams by using computer-generated subwavelength dielectric gratings. The elements were deposited upon GaAs substrates and produced beams with a polarization purity of 99.2% at a wavelength of 10.6 μm. We have verified the polarization properties with full space-variant polarization analysis and measurement, and we show that such beams have certain vortex-like properties and that they carry angular momentum. © 2002 Optical Society of America

Corrugated guide: simple estimates of dephasing lengths and acceleration gradients

Estimate acceleration gradients using index modulation toy model:

One full dephasing cycle

n1 > n2

Accelerating-phase region: low index

Decelerating-phase region: high index

λ = 800nm

\[ N_{e1} = 3 \times 10^{18} \text{ cm}^{-3} \]

\[ N_{e2} = 6 \times 10^{18} \text{ cm}^{-3} \]

\[ w_{ch} = 12 \mu m \]

\[ p = 1, \ m = 0 \]

\[ L_{d1} = \sim 260 \ \mu m \]

\[ L_{d2} = \sim 165 \ \mu m \]

For \( P = 1 \) TW, \( E_z = 0.55 \) GV/cm, giving an effective gradient of 77 MV/cm (14% “efficiency”)

This is a linear process with no threshold.

1 mJ regenerative amplifier alone

\[ P = 20GW \rightarrow \text{Effective accel. gradient: } 11 \text{ MV/cm} \]
So, what's the gradient? A toy model:

Model this real waveguide:

Simplified density modulation:

As this simplified waveguide:

Accelerating-phase region: low plasma density (high index)

Decelerating-phase region: high plasma density (low index)

The driving wave speeds up and slows down in successive portions of the modulation so that the acceleration in the first part is not completely cancelled by deceleration in the second part.

Energy gain per cycle:

\[ \Delta U \approx -e(E_{z1}L_{d1} - E_{z2}L_{d2}) \approx -eE_0 ad \quad \text{where} \quad a < 1 \]
Laser Acceleration of Relativistic Electrons Using the Inverse Cherenkov Effect

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(Received 23 May 1994)

A 580-MW peak power, radially polarized CO\textsubscript{2} laser beam ($\lambda = 10.6$ $\mu$m) focused by an axicon accelerated 40-MeV electrons by $\approx 3.7$ MeV over a 12-cm interaction length (31 MeV/m), using the inverse Cherenkov effect in which a gas is used to slow the light wave. This represents the first direct observation of acceleration using this effect and demonstrates the effectiveness of the radially-polarized–axicon-focused geometry. The observed energy gain agrees with model predictions.

580-MW peak power gave 31 MeV/m.

10 TW peak powers are now routine, but neutral-gas phase matching limits peak intensities for ICA.
A more realistic model: FDTD simulations*

Plasma density vs. r and z

A more realistic model: FDTD simulations*

Plasma density vs. r and z

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A more realistic model: FDTD simulations

Plasma density vs. r and z

A more realistic model: FDTD simulations

A more realistic model: FDTD simulations*

Plasma density vs. r and z

One full dephasing cycle

Accelerating-phase region: low index

Decelerating-phase region: high index

$\lambda = 6.4 \, \mu m$

$N_{e1} \approx 0.5*10^{17} \, cm^{-3}$

$N_{e2} \approx 0.5*10^{18} \, cm^{-3}$

$w_{ch} \approx 40\mu m$

$t_{pulse} \approx 300 \, fs$

Accelerating field $E_z$ seen by a relativistic electron vs. propagation distance

Net gain!

(\~3\% “efficiency”, room for optimization)

Simulation includes:
- Plasma dispersion
- Finite pulse duration
- Leakage effects
- Cylindrical coordinates