Laser driven plasma waveguides for tabletop synchrotrons

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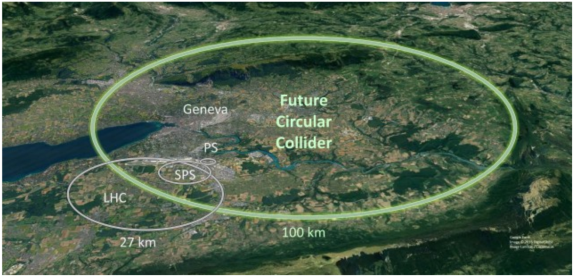
Why new technology?

Size

LHC - 27 km $\Longrightarrow$ 14 TeV,
FCC - 100 km $\Longrightarrow$ 100 TeV,
SLAC - 3 km $\Longrightarrow$ 42 GeV electrons.

RF breakdown

Cavity damage at $\sim$ 100 MV/m



CERN

Why new technology?

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Energy doubling

With 85 cm plasma channel - 42 GeV $\rightarrow$ 85 GeV.

SLAC

Why new technology?

Energy doubling

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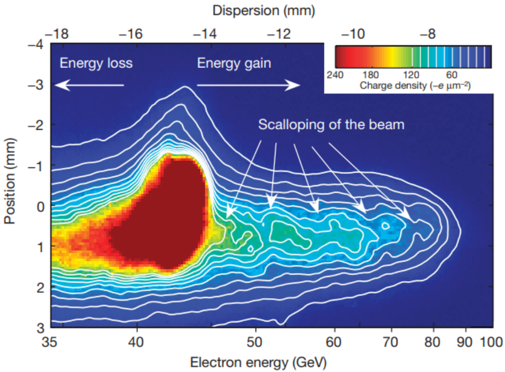

Ian Blumenfeld et al, Nature (2007).

Why new technology?

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Energy doubling

With 85 cm plasma channel - 42 GeV $\rightarrow$ 85 GeV.

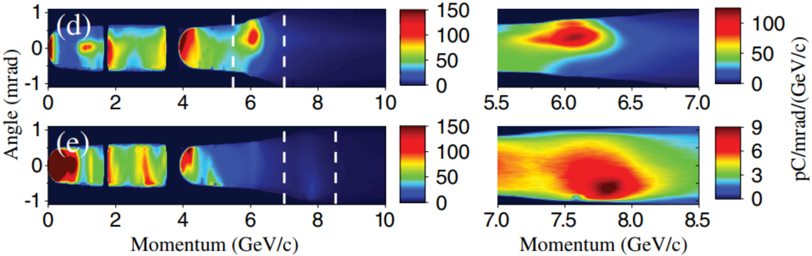
Standalone acceleration

LWFA - 0 $\rightarrow$ 7.8 GeV in 20 cm channel.

Why new technology?

Standalone acceleration

LWFA - 0 → 7.8 GeV in 20 cm channel.



AJ Gonsalves et al,Physical review letters (2019).

Laser parameters

Requirements

High intensity ultrashort laser pulse focused into small area over a large distance.

- Intensity: $I_0 > 10^{17}$ W/cm^2
- Length: $\tau < 50$ fs
- Focus: $r_0 < 100\ \mu$m
- Distance: $d > 10$ cm

Normalized vector potential

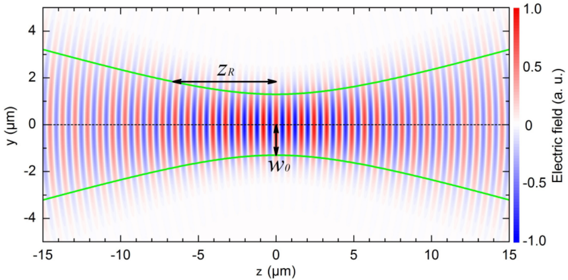
$$a_0 = \frac{eA_0}{m_e c}$$

$$a_0 = 0.86\lambda[\mu\mathrm{m}]\sqrt{I_0[10^{18}\mathrm{W/cm^2}]}$$

Laser parameters

Gaussian beam

$$I(r,z) = I_0\left(\frac{w_0}{w(z)}\right)^2 exp\left(\frac{-2r^2}{w(z)^2}\right)$$



Ju, Jinchuan. PhD Thesis (2013).

Plasma wave

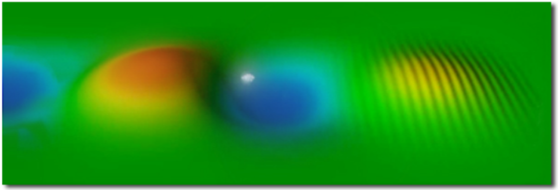


Photo - Sean C. Fulton, Graphic - Berkeley lab

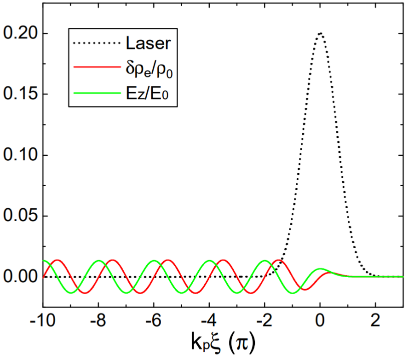
Plasma wave

- For $a_0 \ll 1$: Weak plasma oscillations
- For $a_0 > 2$: Bubble regime

Ponderomotive force

Expels electrons from high intensity region,

$$F = -m_e c^2 \nabla (1 + \frac{a_0^2}{2})^{\frac{1}{2}}$$



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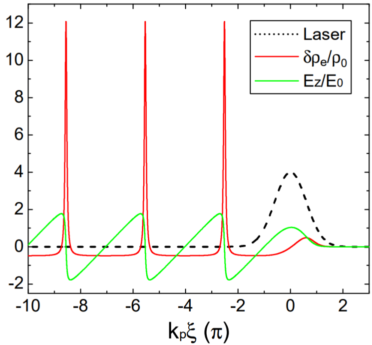

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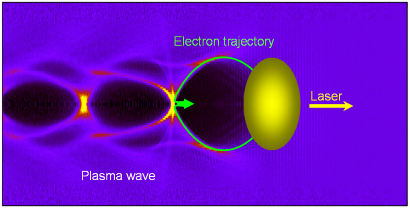

Ju, Jinchuan. PhD Thesis (2013).

Ponderomotive force

Expels electrons from high intensity region,

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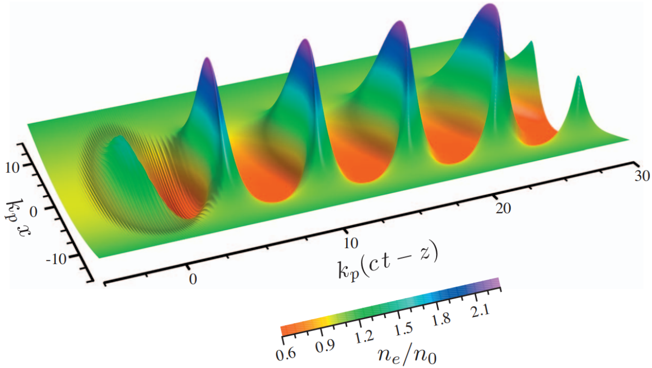
Bubble regime

Spherical cavity void of free electrons.

Bubble regime



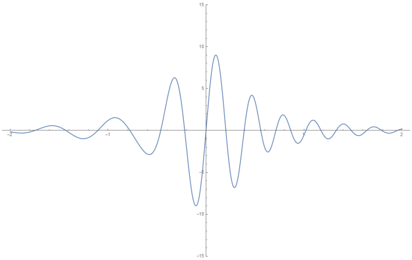
E. Esarey, C.B. Schroeder, W.B. Leemans, Reviews of modern physics (2009).

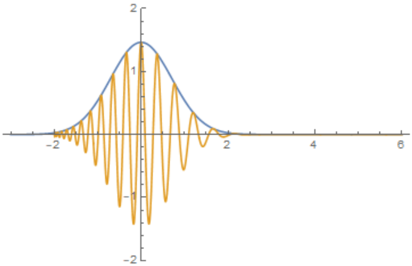
Dispersion

- Ti:Sapphire laser - 800 $\pm$ 300 nm $\rightarrow$ temporal stretching.

Chirping

Wavelength decomposition and rearrangement.





Diffraction

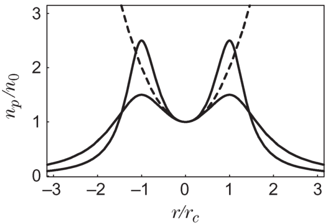
- Over $2Z_R$ is intensity constant, afterwards intensity drops.
- Bigger Z_R $\rightarrow$ better wave stability, lower peak intensity ($Z_R \propto w_0^2$).

Plasma channelling

Parabolic profile $\rightarrow$ direct change of index of refraction.

Capillary guiding

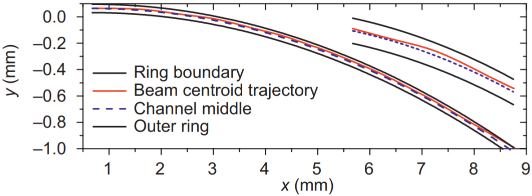
Fresnel refraction of capillary walls.



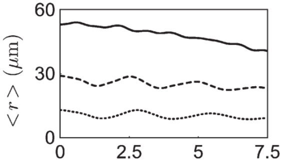
Albert Reitsma and Dino Jaroszynski, IEEE transactions on plasma science (2008).

Curved channel

- Channelling works for bending the laser pulse.



Min Chen et al, Light: Science & Applications (2016).



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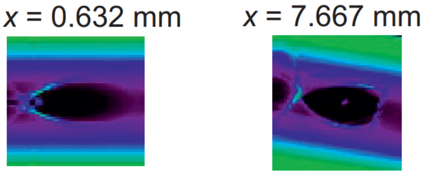
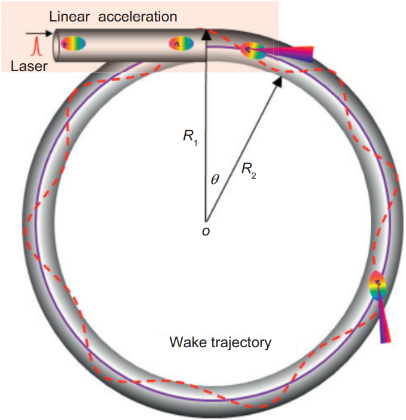


The grand plan



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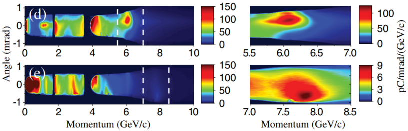
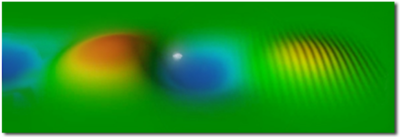
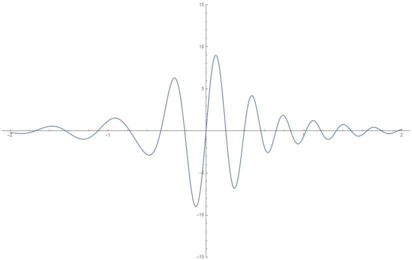
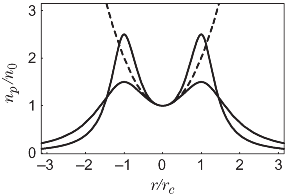
Summary


(d)
(e)
Angle (mrad)
Momentum (GeV/c)
Momentum (GeV/c)
pC/mrad/(GeV/c)
150
100
50
0
100
50
0
9
6
3
0






n_p/n_0
r/r_c

Thank you

for your attention!

References I

[1] Ian Blumenfeld et al. "Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator". In: *Nature* 445.7129 (2007), pp. 741–744.

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[3] Eric Esarey, CB Schroeder, and WP Leemans. "Physics of laser-driven plasma-based electron accelerators". In: *Reviews of modern physics* 81.3 (2009), p. 1229.

[4] AJ Gonsalves et al. "Petawatt laser guiding and electron beam acceleration to 8 GeV in a laser-heated capillary discharge waveguide". In: *Physical review letters* 122.8 (2019), p. 084801.

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