Laser driven plasma wakefield: progation effects

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Propagation effects play an important role in LPA

- The ultra-high intensity required fo laser wakefield is usually achieved inside a small volume
- Acceleration of electrons to ultra-high energies requires to maintain a high acceleration gradient over a long distance

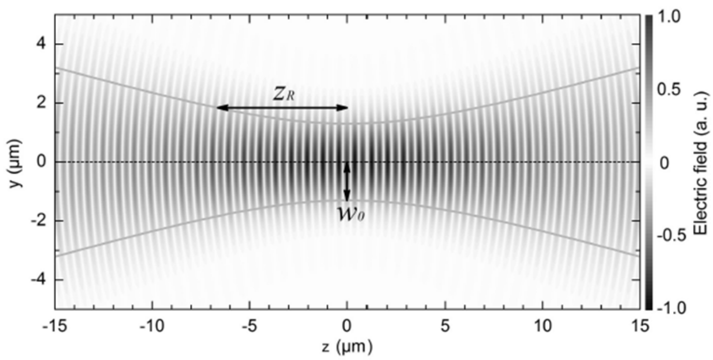
- Ultra-intense laser beams interact with matter and give rise to non linear effects, which usually grow with propagation distance

Outline

- Laser plasma acceleration characteristics (reminder)
  - Description of laser and plasma wave
  - Electron acceleration parameters
- Optimization of interaction length to achieve the maximum energy gain
  - Laser guiding by grazing incidence reflection
    - Guiding properties
    - Plasma wave excitation
  - Optical guiding in plasmas
  - Longitudinal density gradient
  - Staging

Laser propagation in vacuum

- Ultra High Intensity, larger than ~10^{18} W/cm²
- The beam has to be focused w_0
- Typical volume small $w_0^2 Z_R$ ~10µmx10µmx300µm



Electric field amplitude described with Gaussian distributions

- $$\mathbf{E}(r,z,t) = E_L \frac{w_0}{w(z)} \exp\left[-\frac{r^2}{w^2(z)}\right] \exp\left[-2\ln(2)\frac{(z-ct)^2}{c^2\tau_0^2}\right] \times \Re\left\{\exp\left[i\omega_0 t - ik_0 z - ik_0\frac{r^2}{2R(z)} + i\psi_g(z)\right]\mathbf{e}_\perp\right\}$$
- Transverse waist $w(z) = w_0\sqrt{1+\left(\frac{z}{z_R}\right)^2},$
- Rayleigh length $z_R = \pi w_0^2/\lambda_0$

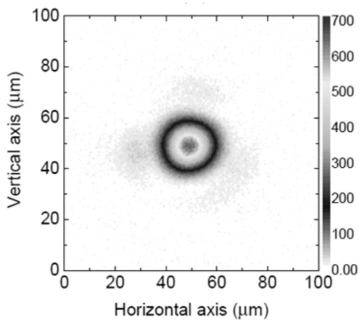
Energy, waist, and duration can be measured experimentally

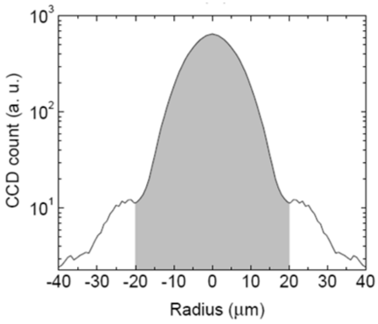
laser energy $\mathcal{E}_L$ and pulse duration τ_0.

- Laser power $P = 2\sqrt{\frac{\ln(2)}{\pi}}\frac{\mathcal{E}_L}{\tau_0} \simeq \frac{\mathcal{E}_L}{\tau_0}.$
- Intensity $I_L = c^2\varepsilon_0\langle\mathbf{E}\times\mathbf{B}\rangle = \frac{c\varepsilon_0}{2}|\mathbf{E}|^2,$
- Peak intensity $I_0 = \frac{2P}{\pi w_0^2} \simeq \frac{2\mathcal{E}_L}{\pi\tau_0 w_0^2}.$
- Laser strength parameter ***a***
  - ***a*** ~ eA/mc² (normalized laser vector potential)
  - Peak value $a_0 \sim 8.5\times10^{-10}\,\lambda_0[\mu m]\,I_0^{1/2}[Wcm^{-2}]$
  - Quasilinear regime $a_0 \sim 1$, or weakly relativistic regime

Example of energy distribution in the focal plane

- UHI beam with adaptative correction
- Grey area = 84 % of energy in the focal plane
- Good beam quality in the focal plane

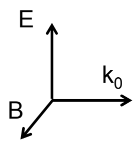


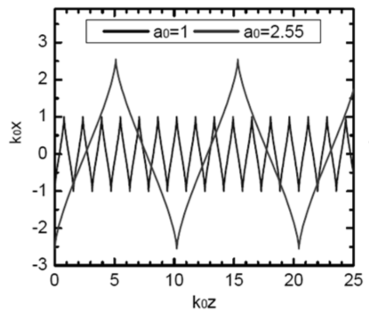


Ju et al., Phys. Plasmas 20, 083106 (2013)

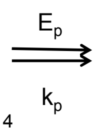
The plasma is used as a transformer

- For I_L~10^{18}W/cm², |E| ~ 10^{12}V/m: why don't we use the laser field directly?



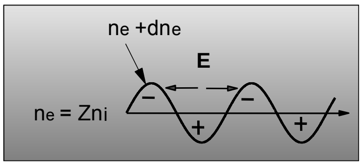


- Single electrons wiggle in the transverse laser field
- In a plasma, the action of the ponderomotive force leads to a plasma wave (time average)



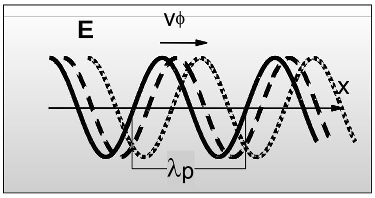
Longitudinal electric field associated to a plasma wave

Accelerating fields > 100 GV/m



- Space charge field
- Plasma wavelength

  $\lambda_p[\mu m] \sim 33\ (n_e[10^{18} cm^{-3}])^{1/2}$



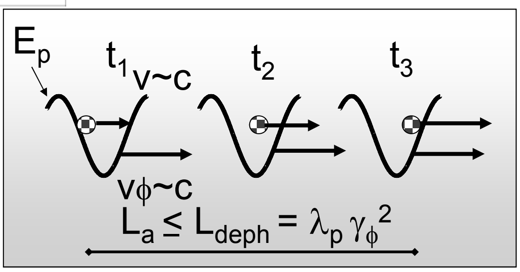
- Relativistic wave:

phase velocity of the order of the laser group velocity

$$E(GV/m) = 96\ \left[n_e(10^{18} cm^{-3})\right]^{1/2} \frac{dn_e}{n_e}$$

$$v_g = \frac{\partial \omega}{\partial k} = c\sqrt{1 - \frac{\omega_p^2}{\omega^2}},$$

Dephasing length for accelerated electrons



- Energy gain

  $\Delta W = e\ E_p\ L_a$

$\gamma_\phi = \lambda_p / \lambda_0$

- $\Delta W \sim n_e^{-1}$
  - $\mathbf{E_p \sim n_e^{1/2}}$
  - $\mathbf{L_a \sim n_e^{-3/2}}$

n_e	$10^{17} cm^{-3}$	$10^{19} cm^{-3}$
γ_ϕ	100	10
L_a	1 m	1 mm
ΔW_{max}	20 GeV	200 MeV

B. Cros,

Linear vs NL regime of LPA

- 2 main regimes:
  - quasilinear regime

$$k_p^2 r_L^2/2 > a_0^2/\gamma_\perp \qquad a_0^2 \sim 1$$

$$\gamma_\perp = (1 + a_0^2/2)^{1/2}$$

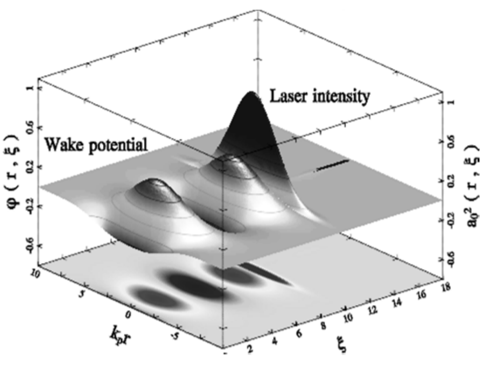
  - bubble or blowout regime

$$k_p r_L \lesssim 2\sqrt{a_0} \qquad a_0^2 > 1$$

Importance of transverse structure to define these regimes

$$a = a_0 \exp(-r^2/r_L^2 - z^2/4L^2).$$

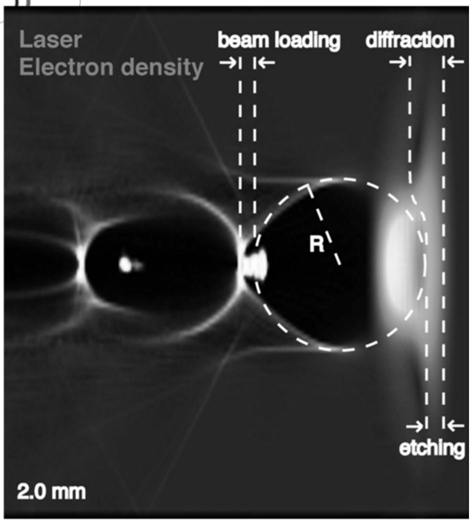
Laser wakefield: quasilinear regime



- Ponderomotive force ~ gradient of laser energy
- Independent control of transverse and longitudinal fields
- Accelerating structure sine wave: λ_p~10-100μm
- Accelerating field: 1-100 GV/m

It is necessary to inject electrons produced by an external source

Non linear wakefield with self-injection



- Compression and self-focusing of the pulse
- Expulsion of electrons: creation of a bubble (ions)
- Electrons self-injected at the back of the bubble by accelerating and focusing fields
- Injected electrons modify the back of the bubble (beam loading)
- Generation of betatron radiation

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W. Lu PRSTAB, 10, 061301 (2007), A. Pukhov et al, Appl. Phys. B 74, 355 (2002)

3 main mechanisms to control electron acceleration distance

- Laser diffraction: typically the Rayleigh length
- Pump depletion: length over which half of the laser energy is transferred to the plasma wave
- Dephasing length: distance over which electrons outrun the plasma wave and enter a decelerating phase

B. Cros, CAS November 2014

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Scaling laws in the different regimes

	a_0	w_0	Dephasing length L_d	Laser depletion length L_{pd}	Relativistic factor of plasma wave γ_p	Electron energy gain over Ld $\mathcal{E}_e/m_e c^2$
Linear	<1	λ_p	$\frac{\omega_0^2}{\omega_p^2}\lambda_p$	$\frac{\omega_0^2}{\omega_p^2}\frac{c\tau_0}{a_0^2}$	$\frac{\omega_0}{\omega_p}$	$a_0^2\frac{\omega_0^2}{\omega_p^2}$
1D Nonlinear	>1	λ_p	$4a_0^2\frac{\omega_0^2}{\omega_p^2}\lambda_p$	$\frac{1}{3}\frac{\omega_0^2}{\omega_p^2}c\tau_0$	$\sqrt{a_0}\frac{\omega_0}{\omega_p}$	$4a_0^2\frac{\omega_0^2}{\omega_p^2}$
3D Nonlinear	>2	$\frac{\sqrt{a_0}}{\pi}\lambda_p$	$\frac{4}{3}\frac{\omega_0^2}{\omega_p^2}\frac{\sqrt{a_0}}{k_p}$	$\frac{\omega_0^2}{\omega_p^2}c\tau_0$	$\frac{1}{\sqrt{3}}\frac{\omega_0}{\omega_p}$	$\frac{2}{3}a_0\frac{\omega_0^2}{\omega_p^2}$

W. Lu PRSTAB, 10, 061301 (2007)

Energy gain in a laser plasma accelerator

$\Delta W = e\,E_p\,L$

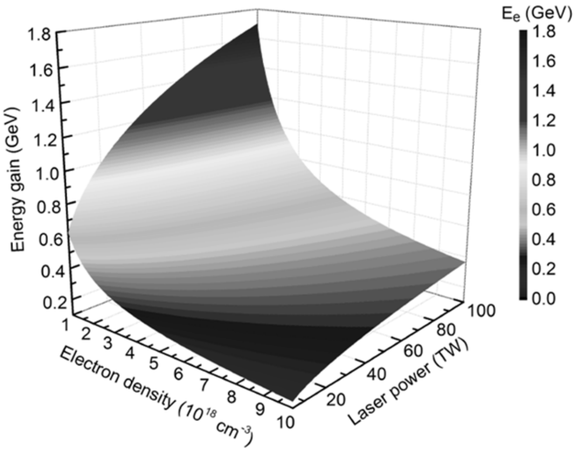
- The length of acceleration is determined by either
  - The Rayleigh length
  - The dephasing of electrons entering a decelerating phase of the plasma : **$L_{deph} \propto 1/\,n_e^{3/2}$**
  - The damping of laser energy **$L_{am} \propto 1/\,(a_0^2\,n_e^{3/2})$**
- Optimum length: $L_{deph} \sim L_{am}$ and $a_0 \sim 1$

$\Delta W \propto 1/n_e$

- **To increase energy gain requires**
  - To lower electron density
  - To increase interaction length

While maintaining $a_0 \sim 1$

Energy gain over the dephasing length in the 3D NL regime



- Large energy gains can be achieved for low electron density and large laser power

$$\mathcal{E}_e[\mathrm{GeV}] \simeq 1.7 \left(\frac{P[\mathrm{TW}]}{100}\right)^{1/3} \left(\frac{0.8}{\lambda_0[\mu\mathrm{m}]}\right)^{4/3} \left(\frac{1}{\rho_e[10^{18}\ \mathrm{cm}^{-3}]}\right)^{2/3}$$

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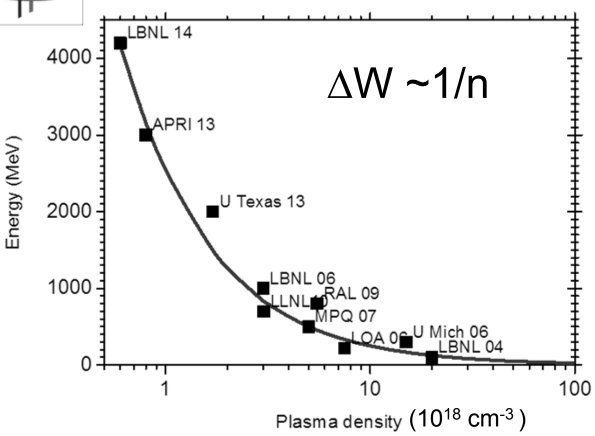
Increased electron energy achieved at lower plasma density and higher power



Experimental results follow the scaling law for energy gain

In the NL regime, with self-injection

Above GeV for PW lasers
APRI13: 2 gas jets
LBNL14: Largest gain, with external guiding

- But …..lowering the plasma density eventually stops self-injection

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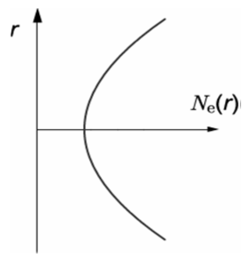
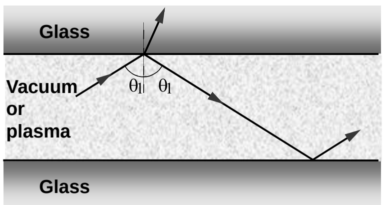
Laser guiding to overcome the limitation due to laser diffraction

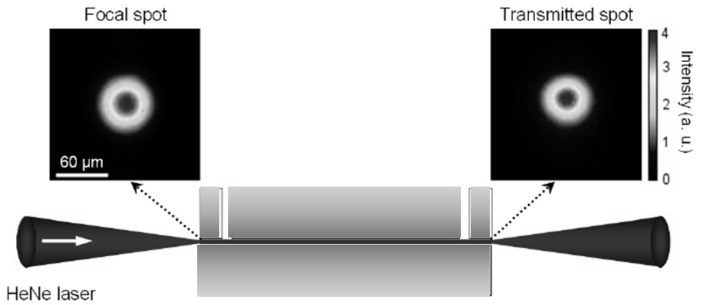


- **Plasma channel:** transverse variation of density yields refractive index profile
- A parabolic plasma channel can guide a Gaussian beam with a constant spot size $w_0 = w_m$, where w_m depends on the curvature of the channel
- Plasma channels detailed in S. Hooker talk



- **Glass capillary tube**: Losses are finite, but small if close to grazing incidence
- Can couple 98% of Gaussian into EH_{11} if w_0 = *0.645 Rcap*

Guiding in capillary tubes at low intensity corresponds to theory



Rcap/w0=1.47, Lcap=3cm, $Tr_1 = C_1 \exp(-2L_{cap}/L_1^l) \simeq 94\%$.

Lcap : typically 1-10 cm, scalable to ~1m
Rcap: from 25μm to 500μm

Veysman et al., JOSAB, 27 1400 (2010)

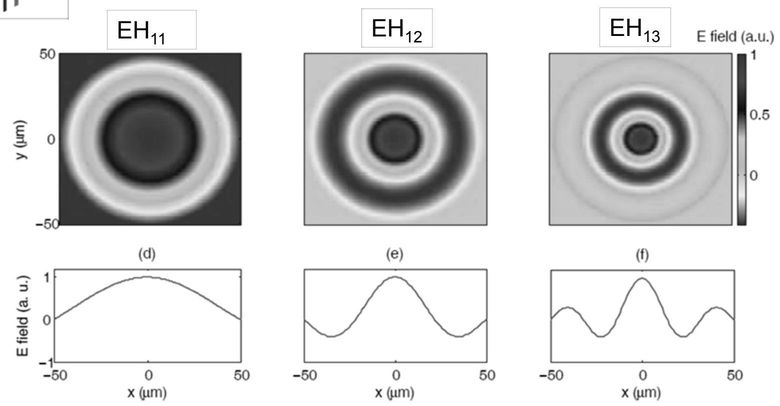
Eigen mode characteristics

- Solving Maxwell equations with capillary boundary conditions gives hybrid modes solutions (quasi transverse EM modes)
- For the mode EH_{1m}, the field amplitude

$$E_{1m}(r,z,t) = \mathcal{J}_0(k_{\perp m} r) \exp(-k_m^l z) \cos[\omega_0 t - k_{zm} z]$$

B. Cros *et al*. *Phys Rev. E*. **65** 026405 (2002)

Field distribution in the transverse plane for the 3 first modes



➡ For Rcap=50µm

Eigen mode characteristics

➡ For the mode EH_{1m}, the field amplitude

$$E_{1m}(r,z,t) = \mathcal{J}_0(k_{\perp m} r)\exp(-k^l_m z)\cos[\omega_0 t - k_{zm} z]$$

is multiplied by 1/e over the characteristic damping length

$$L^l_m = \frac{1}{k^l_m} = \frac{2k^2_{zm}R^3_{cap}}{u^2_m}\frac{\sqrt{\varepsilon_r - 1}}{1+\varepsilon_r}$$

Eigen value

Dielectric function of the wall

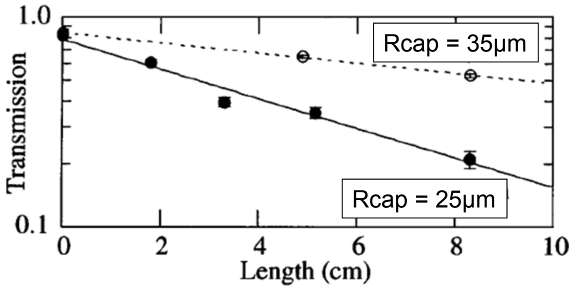
Group velocity:

$$k_{\perp m}{}^2 = k_0{}^2 - k_{zm}{}^2$$

$$v_{gm} \cong c\sqrt{1 - \frac{k_{\perp m}{}^2}{k_0{}^2}}$$

r 201 $k_{\perp m} = u_m / R_{cap}$

Damping length increases with the cube of capillary radius



Ld = 31cm

Ld = 11cm

Z_R ~ 0.1cm

Monomode guiding demonstrated experimentally for I ~10^{16} W/cm²

Dorchies et al., PRL 82, 4655 (1999)

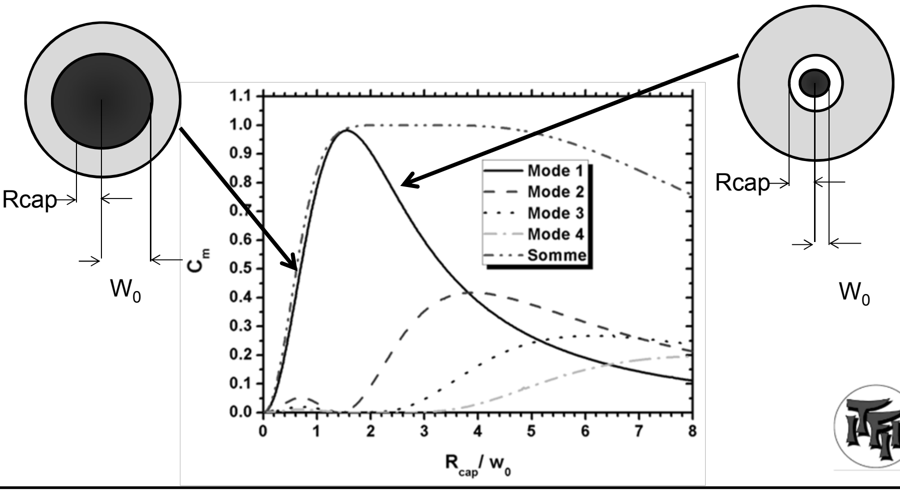
Parameters of the 9 first modes

- Mode properties for Rcap = 50μm and laser wavelength 0.8μm

Mode number m	Eigen value u_m	Damping length L^l_m (cm)	Group velocity v_{gm}/c	Transverse flux at the wall $\mathcal{F}^{max}_m$ (10^{-5})
1	2.404826	91.7	0.99998	2.034
2	5.520078	17.4	0.9999	4.604
3	8.653728	7.1	0.9998	7.2011
4	11.79153	3.8	0.9995	9.8049
5	14.93092	2.4	0.9993	12.4113
6	18.07106	1.6	0.9989	15.0189
7	21.21164	1.2	0.9985	17.6272
8	24.35247	0.9	0.9981	20.2359
9	27.49348	0.7	0.9975	22.8449

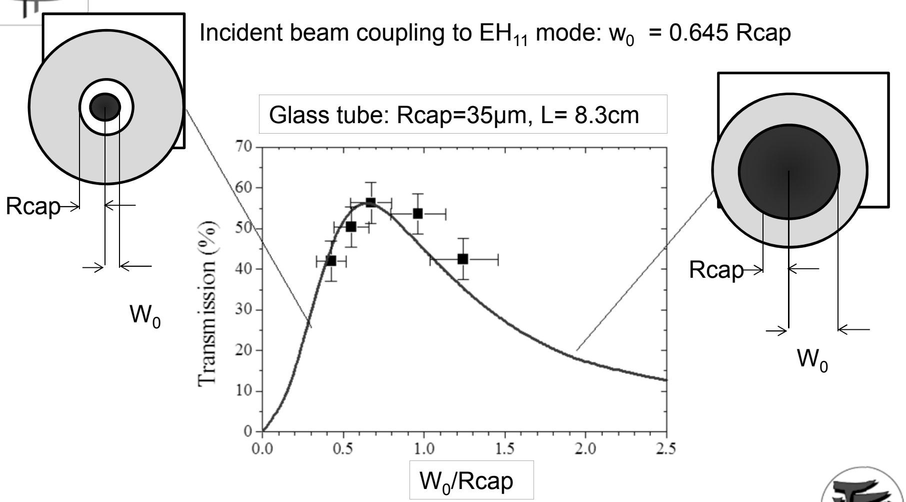
Mode coupling for a Gaussian beam

Incident beam coupling to EH_{11} mode: $Rcap/w_0 = 1.5$



Measured coupling in glass capillary tubes

Incident beam coupling to EH_{11} mode: $w_0 = 0.645$ Rcap

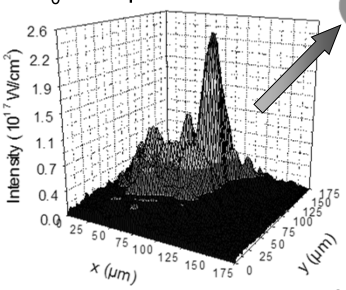


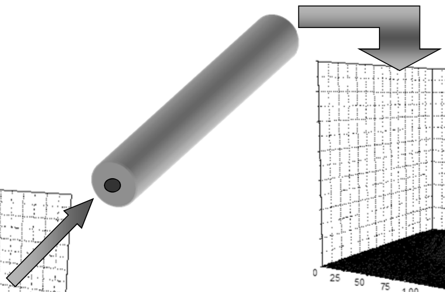
Dorchies et al., PRL 82, 4655 (1999)

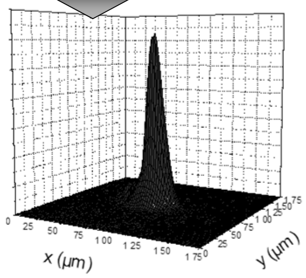
Monomode output at high intensity (filtering)

Capillary tube: radius 25 µm, L = 12 cm

Input:
4.2 J @ 0.5µm
400 fs
w_0 = 20 µm







Output:
I ~10^{17} W/cm^2
T ~ 30%

B. Cros, et al. Physica Scripta **T107**, 125 (2004).

Monomode EH_{11} guiding is preferable for LPA

- Maximum group velocity

  $v_g \approx c$

- Minimum damping factor

  $L_d^{-1} \approx 2.4^2\ \lambda^2/Rcap^3$

- Smooth gradient of transverse field

  $E(r) \propto J_0(2.4\ r/Rcap)$

- Single mode excitation

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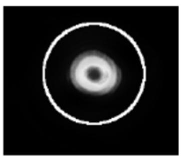
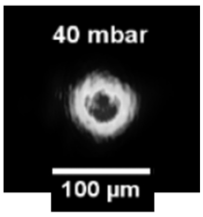
Intense laser guiding in gas filled capillary tube

Input focal spot
I_{max} 2x10^{17}W/cm²

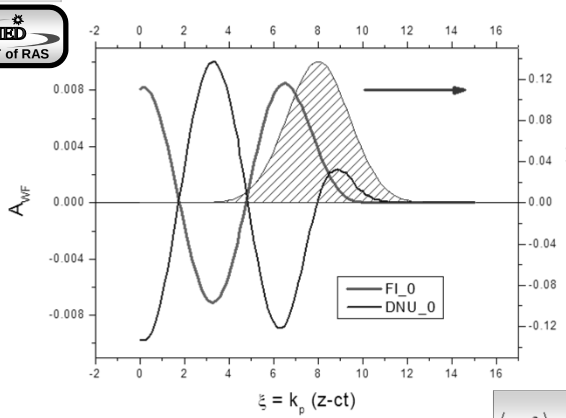


Lcap 7 cm,
Rcap 50µm



Guiding quality close to monomode for pressure < 100mbar and a_0~1

Modification of the laser pulse spectrum during propagation



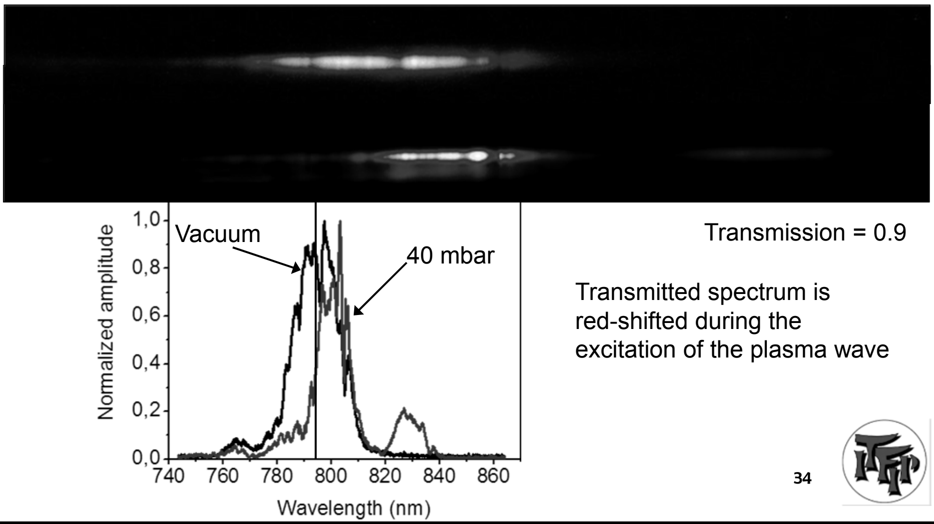
During the creation of the plasma, the pulse propagates in a rapidly varying medium and its spectrum is modified

$$\left\langle \omega^2 \right\rangle_{out} - \omega_0^2 = -\frac{\omega_0^2}{4\pi\varepsilon_{out}} \int_V \mathbf{E}_{p,\max}^2 d^3\mathbf{r}$$

Andreev & Chegotov, JETP 101, 56 (2005)

Excitation of a plasma wave over a long distance with capillary guiding

Input: Imax = 6.1 10^{17}W/cm^2, Rcap=75 µm, L= 71.8 mm,



Transmission = 0.9

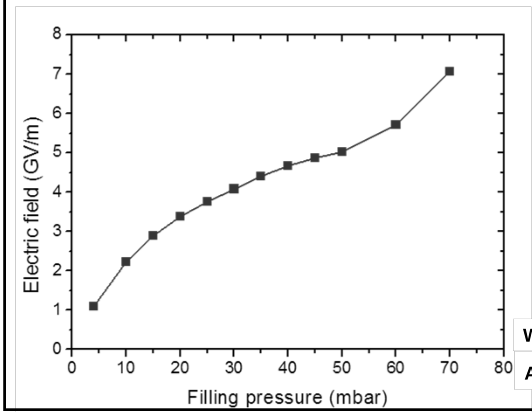
Transmitted spectrum is red-shifted during the excitation of the plasma wave

LPA in the linear regime

Input laser

Output laser

Capillary tube Rcap ~ 50 µm, L = 8 cm, filled with hydrogen
Laser intensity ~ 10^{17} W/cm^2 - 4 TW



- Accelerating field in the range (1-10 GV/m) over a long distance (8 cm)
- Measured by optical diagnostic, excellent agreement with simulation

Wojda et al. Phys. Rev. E 80, 066403 (2009)

Andreev et al. New J. Phys. 12 (2010) 045024.

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B. Cros, CAS November 2014 36

Optical guiding in plasmas

- Phase velocity $v_\varphi = c/\eta$
- Refractive index for a large amplitude wave and a low density plasma

$$\eta_r(r) \simeq 1 - \frac{\omega_{p0}^2}{2\omega^2}\frac{n(r)}{n_0\gamma(r)}$$

- Guiding is achieved when the refractive index decreases radially (similar to optical fibers)
- Possible when the plasma density has a minimum on axis
- In a plasma channel, for $a^2 \ll 1$:

Relativistic optical guiding — Preformed plasma channel

$$\eta_r \simeq 1 - \frac{\omega_{p0}^2}{2\omega^2}\left(1 - \frac{a^2}{2} + \frac{\Delta n_p}{n_0} + \frac{\delta n}{n_0}\right)$$

Self-channeling & self-modulation of laser pulses

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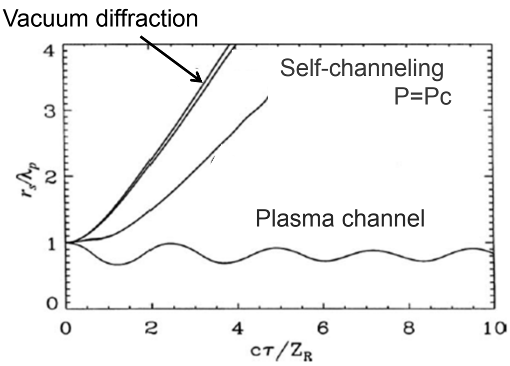
Optical guiding in the conditions of resonant wakefield excitation

Evolution of laser spot size as a function of propagation (condition of resonant wakefield)

Sprangle et al. PRL 69, 2200 (1992)



- Diffraction is counteracted by a decrease of the refractive index away from the axis
- Self-channeling occurs for high enough power and density, P > Pc ~ **17$(\lambda_p/\lambda)^2$**
- A parabolic density profile is ideal to guide a Gaussian laser pulse (See S. Hooker talk)

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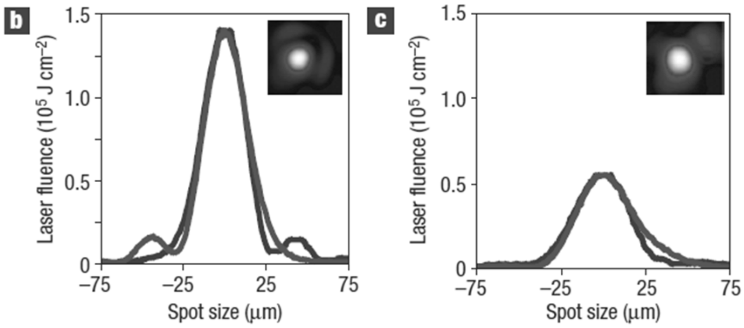
Example of guiding in plasma channel for a 40 TW laser

3.3 cm long gas filled cap discharge waveguide
Plasma density 3.2x10^{18}cm-3
Energy transmission 65%

Input Intensity 3 x 10^{18} W/cm²

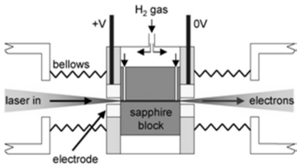
Output 1 x 10^{18} W/cm²

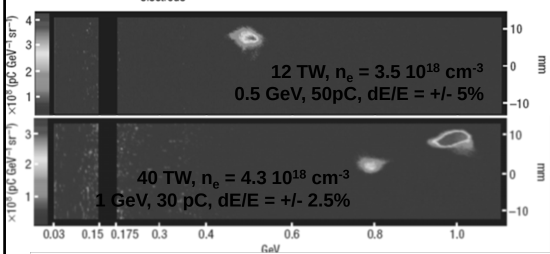


Leemans et al. Nature **Physics 2, 696 (*2006*)   Berkeley+guiding Oxford**

Plasma channel extends the acceleration length in the regime of self-injection

L = 33 mm, diam 310μm
r spot (1/e²) = 25 μm
Laser LBNL 40fs, 1.6J





- Electron bunch with an energy of the order of 1 GeV achieved over a length of 3.3 cm
- Longer than dephasing length, the complex pulse evolution has to be taken into account

Leemans et al. Nature **Physics 2, 696 (*2006*)   Berkeley+guiding Oxford**

Outline

- Laser plasma acceleration characteristics (reminder)
  - Description of laser and plasma wave
  - Electron acceleration parameters

- Optimization of interaction length to achieve the maximum energy gain
  - Laser guiding by grazing incidence reflection
    - Guiding properties in vacuum
    - Plasma wave excitation
  - Optical guiding in plasmas
  - Longitudinal density gradient
  - Staging

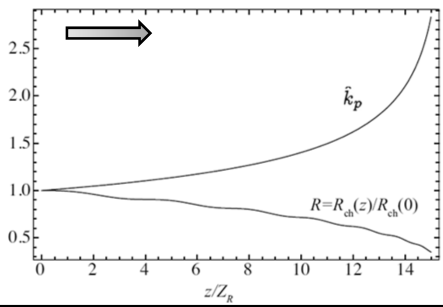
Density tailoring to overcome dephasing

- In the weakly relativistic regime ($a^2 < 1$)

dephasing length << depletion length

- Efficiency can be increased by extending the dephasing length

- Spatial density tailoring (or plasma tapering) consists in changing the plasma density along the propagation direction to prevent phase slippage between electrons and plasma wave



Normalized plasma frequency and channel radius as a function of distance for phase locking the accelerating force

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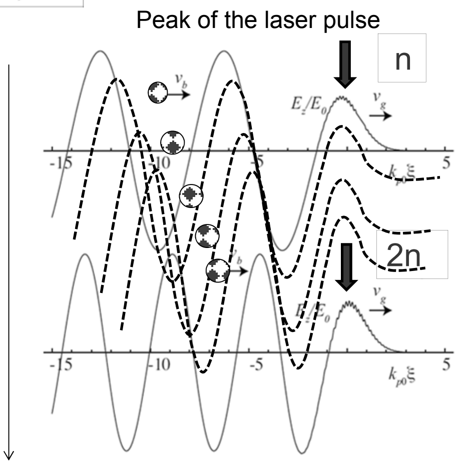
Rittershofer et al. PoP 17,063104 (2010)

Use of density tapering to achieve optimal acceleration



- The phase velocity of the plasma wave increases with distance from behind the pulse for increasing plasma density.
- By increasing the plasma density the phase of the accelerating field seen by the electron is made constant
- The process stops when particles catch-up the laser

Sprangle et al. Phys Rev E 63, 056405 (2001); Rittershofer et al. PoP 17 063104 (2010)

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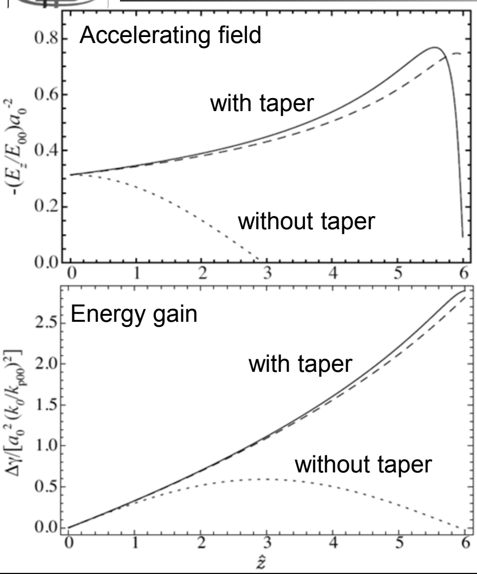
Density tapering in a plasma channel increases energy gain



- Estimation of accelerating field and energy gain; self-focusing neglected
- a_0=0.4, w_0=95μm, n_{e0}=2x10^{17}cm^{-3}, matched channel, initial electric field 2.2 GV/m.
- with taper over 60cm ΔW=2.1GeV
- without taper 0.4GeV

)14 Rittershofer et al. PoP 2010

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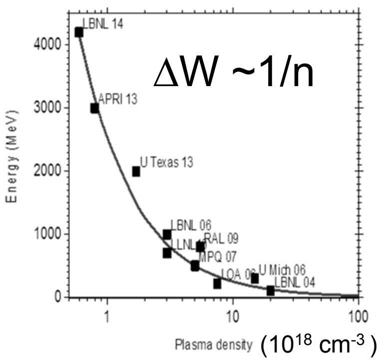
What's next?



Increased electron energy is achieved at lower plasma density and higher power

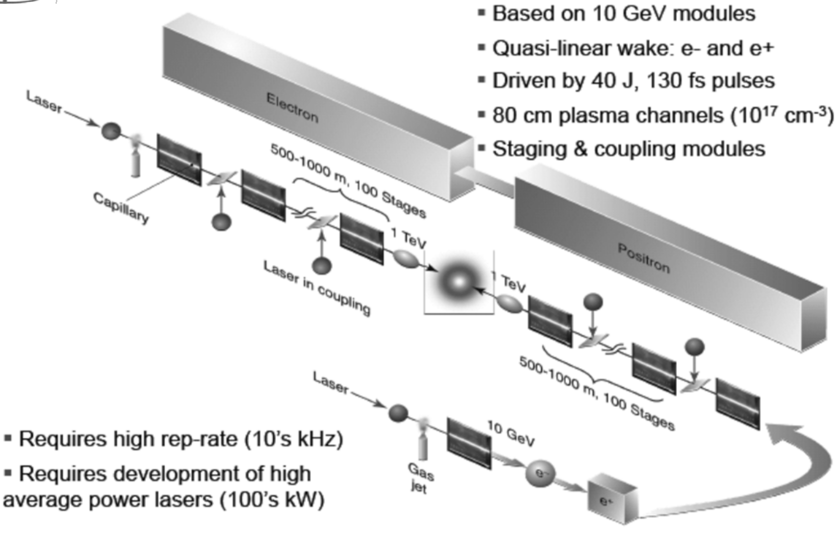
Lowering the plasma density eventually stops self-injection

Dephasing sets the maximum acceleration length in the quasilinear regime

- Staging can be used to provide fresh laser and plasma,.... and a new set of issues

Laser plasma collider concept

- Based on 10 GeV modules
- Quasi-linear wake: e- and e+
- Driven by 40 J, 130 fs pulses
- 80 cm plasma channels (10^{17} cm^{-3})
- Staging & coupling modules



- Requires high rep-rate (10's kHz)
- Requires development of high average power lasers (100's kW)

Leemans & Esarey, Physics Today, March 2009

Challenges for a multi-stage LPA

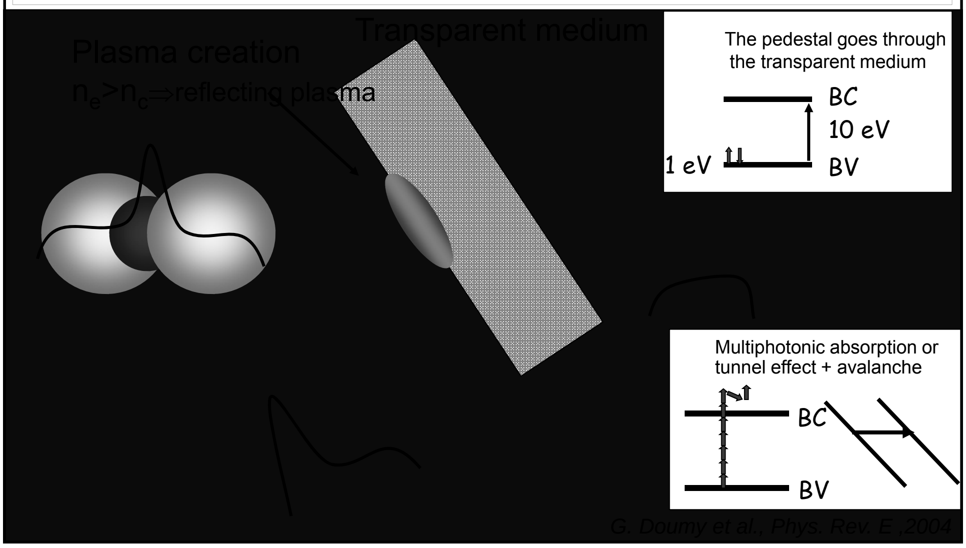
- Improve the performance of **laser systems**:
  - Beam quality, reliability , stability
  - Average power (10Hz à 10kHz)
- **Plasma stages** in the quasi linear regime to control transverse and longitudinal fields:
  - provides control of beam dynamics
  - electron or positron beams
  - meter scale plasma sources need to be developped at low density
- **External injection** schemes
  - beam transport and shaping need to be developped for electron and laser beams
- Design through European collaboration

The preservation of a high average gradient requires compact laser coupling

- The large power (~PW) and large spot (~100μm) require several meters to focus laser beams into plasma stages:
- Plasma mirrors are promising schemes for compact coupling
  - Currently used for temporal contrast improvement
  - Innovative, high repetition rate schemes are being developped (metallic tape or liquid jet)

Plasmas mirrors :*ultra –fast optical switches*

Courtesy of P. Monot, CEA-Saclay



Summary

- LPA currently produce electron bunches of extremely short duration (<10fs), up to several GeV, achieved by operation at lower density
- Laser guiding and increased laser energy should produce electron bunches in the ~10 GeV range in one stage (ex: BELLA project in the USA or APOLLON 10 PW in France)
- Staging is the next milestone for the development of LPA
- Very active and motivating field of research:
  - involving laser, plasma and accelerator physics,
  - several facilites under development,
  - need for students, researchers and engineers