

Laser wakefield electron acceleration to multi-GeV energies



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In collaboration with



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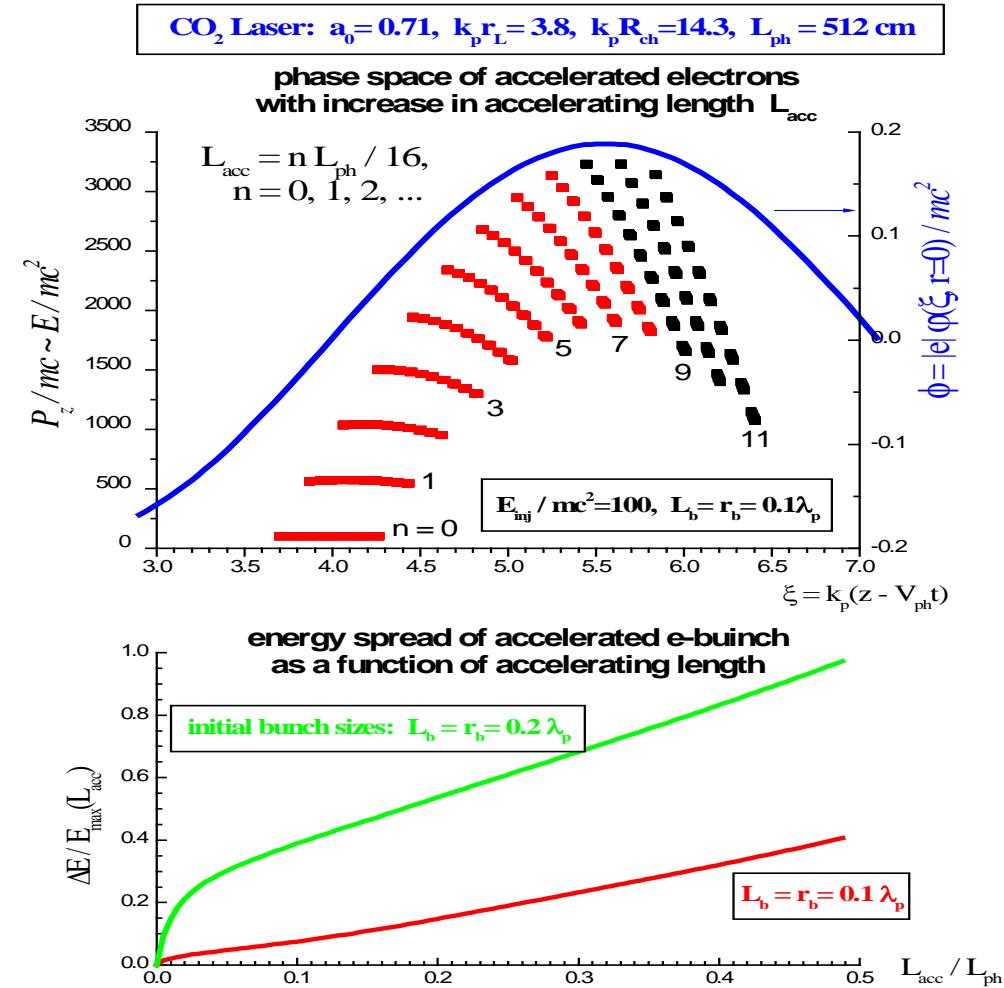
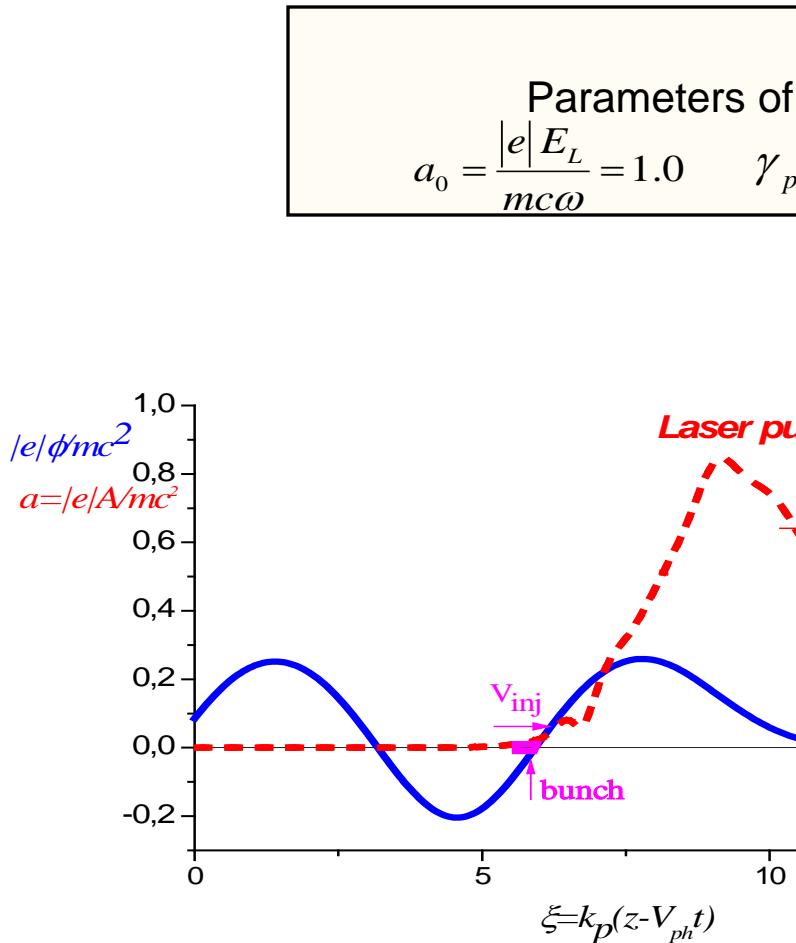
Outline

- Motivation and some history ...
 - *e-bunch energy spread in LWFA with external injection*
 - *e-bunch compression and acceleration*
 - *minimal energy spread at different injection schemes*
- Laser wakefield electron acceleration in guiding structures to high (TeV) energies
 - *multistage acceleration (first accelerating stage)*
 - *wakefield generation and electron acceleration with low energy spread (loading effect)*
 - *emittance growth at broken cylindrical symmetry*
- Conclusions and perspectives

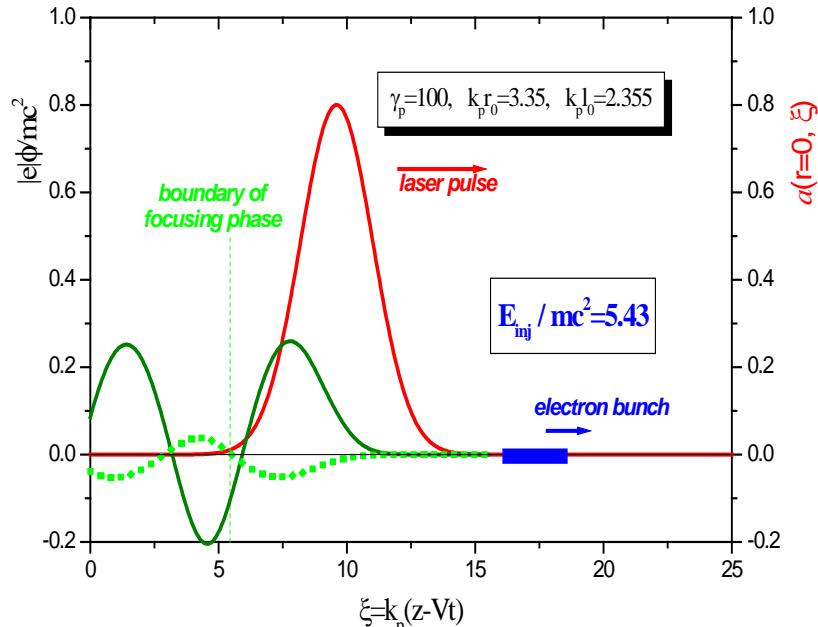
Motivation and some history ...

▪ e-bunch energy spread in LWFA

Electron bunch injection into LWFA at the maximum of accelerating field

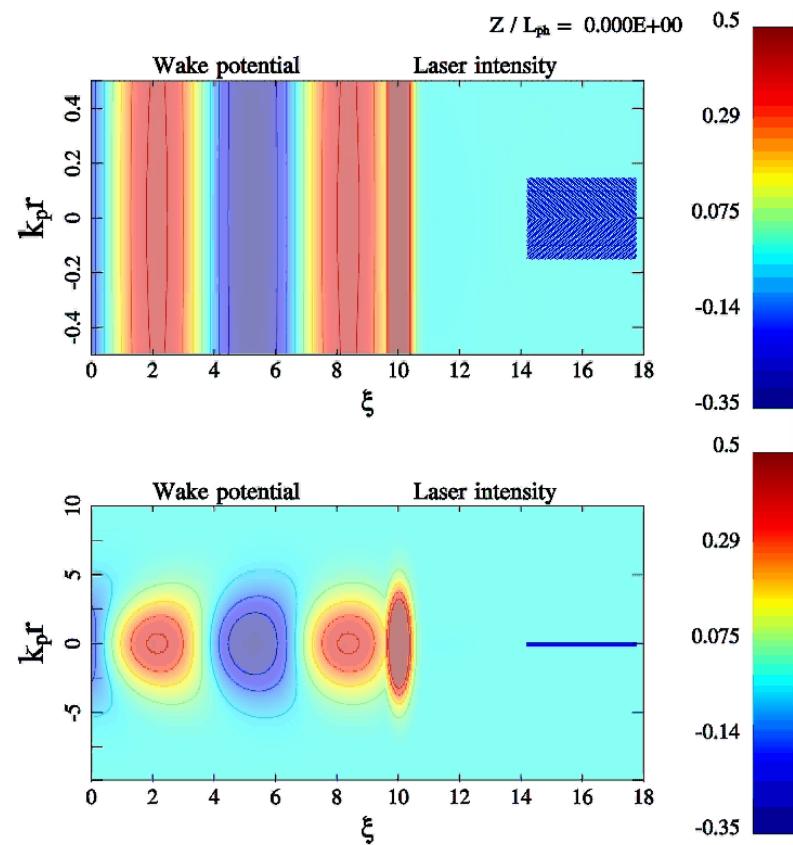


Electron Bunch Injection in Front of the Laser Pulse



For the velocity of injected electrons

$$u_{inj} = c \sqrt{1 - m^2 c^4 / E_{inj}^2} < v_{ph} \quad :$$



$$\frac{\Delta E}{mc^2} = 2\gamma_{ph}^2 k_p L_b \left\{ \left(\frac{d\varphi}{d\xi_{inj}} - \frac{d\varphi}{d\xi} \right) + \frac{k_p L_b}{2} \left(\frac{d^2\varphi}{d\xi^2} - \frac{d^2\varphi}{d\xi_{inj}^2} \right) \right\}$$

$$\frac{L_b}{L_{b0}} = \frac{1 - \beta}{\beta - u_{inj} / c} \quad \beta = v_{ph} / c$$

Long low-energy electron bunch will be trapped and compressed in the wakefield

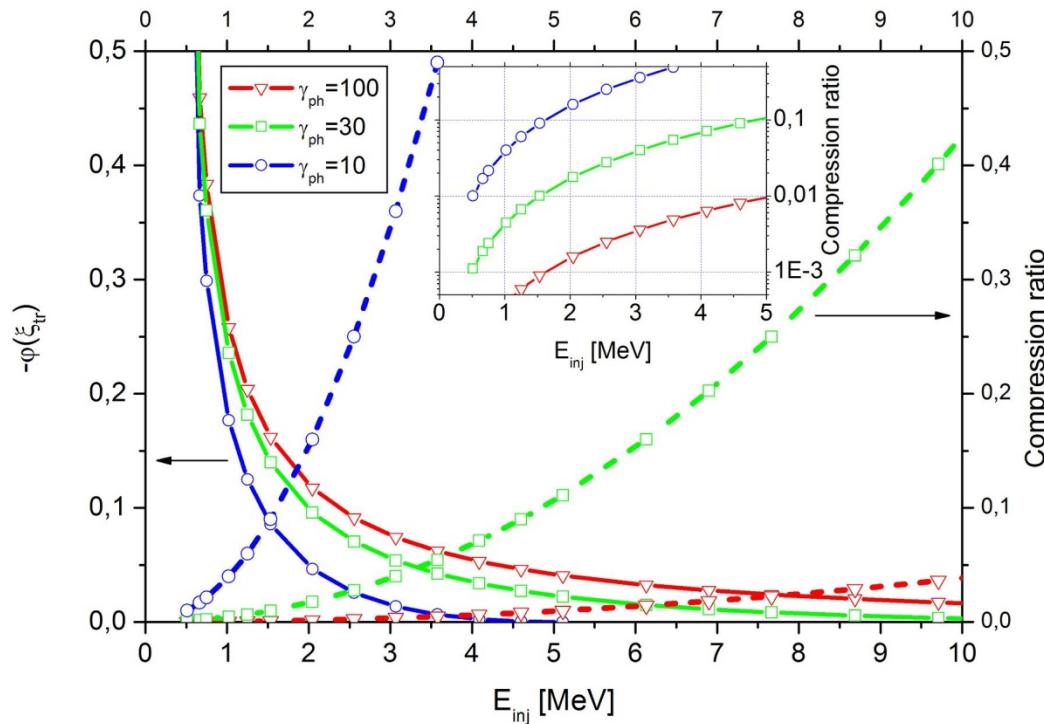
Electron Bunch Injection in Front of the Laser Pulse

trapping and compression

bunch injected in front of the laser pulse can be trapped and compressed in the wake field, if the condition

$$-\varphi(\xi_{tr}) = E_{inj} / mc^2 - \left[(1 - \gamma_{ph}^{-2}) (E_{inj}^2 / m^2 c^4 - 1) \right]^{1/2} - 1 / \gamma_{ph}$$

is fulfilled in the focusing phase of the wakefield



$$\frac{L_{b,rms}}{L_{b0}} \approx \frac{c - V_{ph}}{V_{ph} - u_{inj}} \approx \frac{E_{inj}^2}{\gamma_{ph}^2 m^2 c^4}$$

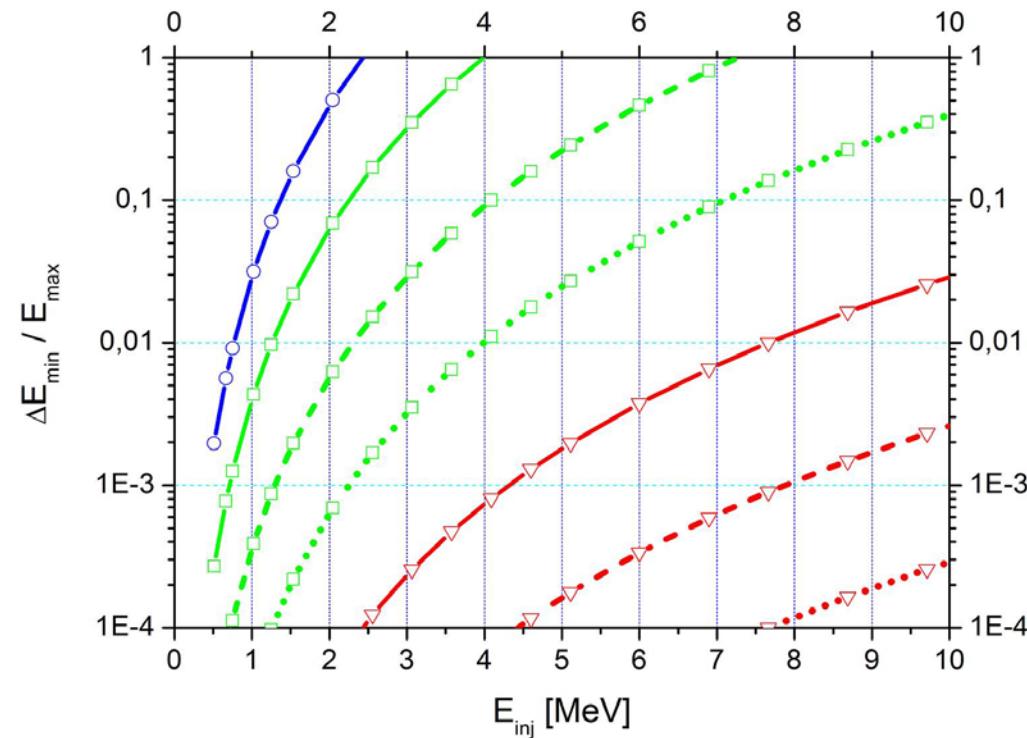
Electron Bunch Injection in Front of the Laser Pulse

energy spread at the end of acceleration

$$E_{\max} \cong 2 \gamma_{ph}^2 mc^2 \varphi_{\max}$$

$$\frac{\Delta E_{\min}}{E_{\max}} \cong \frac{1}{2} (k_p L_{b,rms})^2 \cong 2\pi^2 \gamma_{ph}^{-6} \left(\frac{E_{inj}}{mc^2} \right)^4 \left(L_{b0} / \lambda_0 \right)^2$$

$$\frac{\Delta E_{\min}}{mc^2} = \gamma_{ph}^2 (k_p L_{b,rms})^2 \left| \frac{d^2 \varphi}{d \xi_{\max}^2} \right|$$



$\gamma_{ph} = 100$, 30, and 10 marked by triangles, squares and circles respectively, and for three initial bunch lengths $L_{b0} = 100$, 30, and 10 μm (solid, dashed and dotted lines respectively) for the laser wave length $\lambda_0 = 1 \mu m$

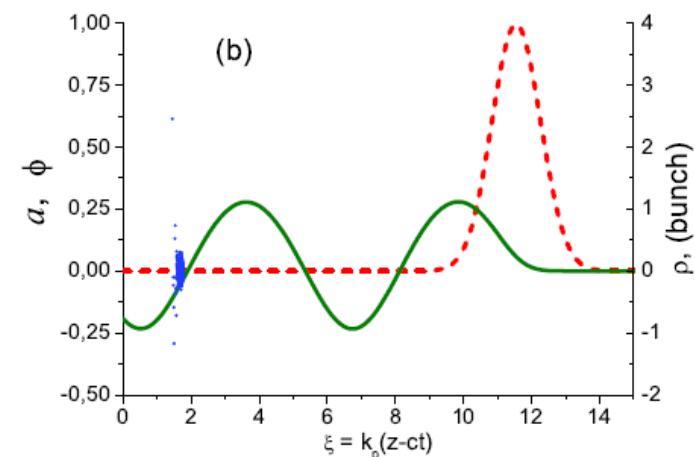
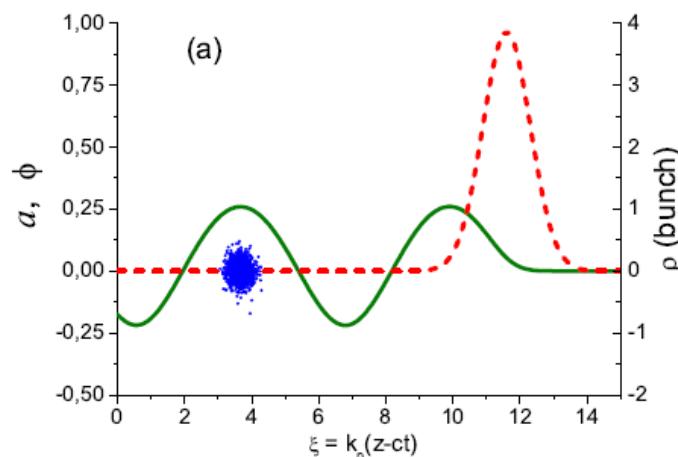
Motivation and some history ...

▪ e-bunch energy spread in LWFA

Electron bunch injection into LWFA at the maximum of the WF potential

The compressed length of the trapped bunch can be estimated through the wakefield potential at the phases of injection and trapping:

$$L_b = \frac{1}{2} k_p L_{b0}^2 \frac{|\partial^2 \phi(\xi_m)/\partial \xi^2|}{\partial \phi(\xi_{tr})/\partial \xi}$$

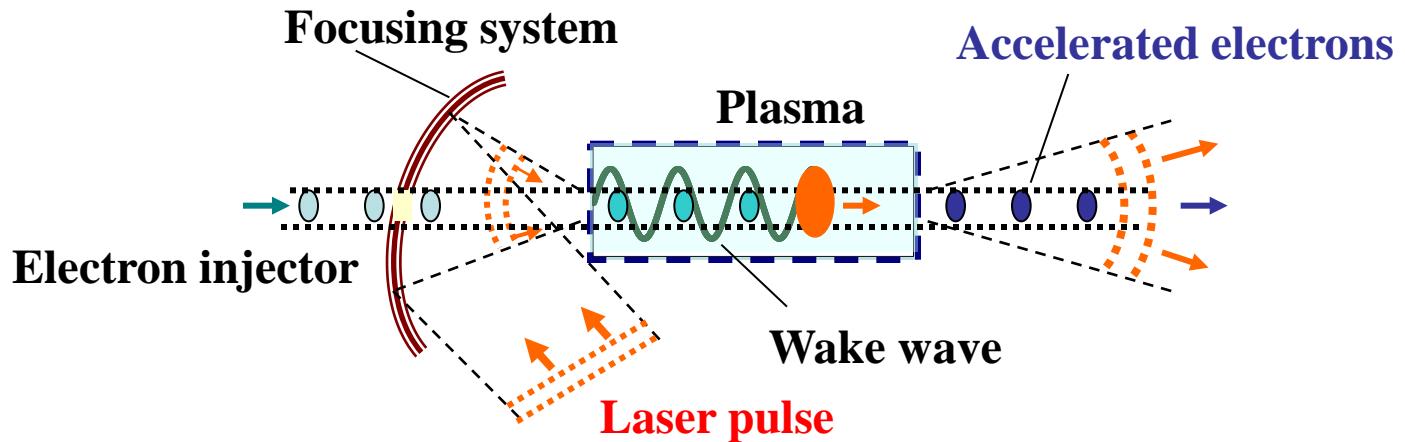


$$\frac{\Delta E}{mc^2} = 2\gamma_{ph}^2 k_p L_b \left\{ \left(\frac{d\varphi}{d\xi_{inj}} - \frac{d\varphi}{d\xi} \right) + \frac{k_p L_b}{2} \left(\frac{d^2\varphi}{d\xi^2} - \frac{d^2\varphi}{d\xi_{inj}^2} \right) \right\}$$

Laser Wakefield Electron Acceleration

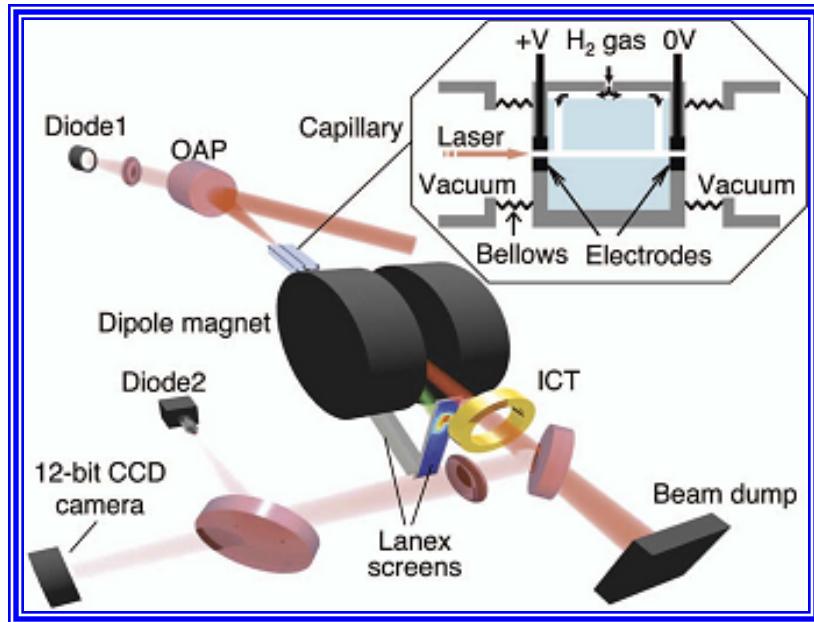
to high (TeV) electron energies, high quality bunches

- *In guiding structures:* $L_{acc} \approx (10 - 100) \times L_R \approx 1m$
- *Staging techniques:* $\sim 10 \text{ GeV per stage}$



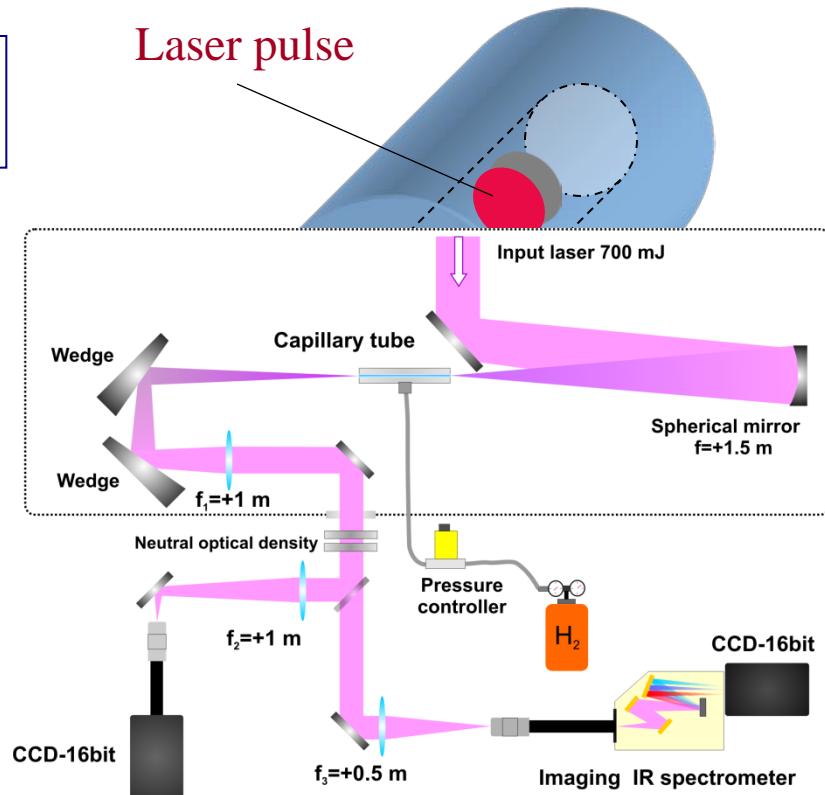
$$\tilde{E}(r) = \sum_{n=1}^{N_m} C_n J_0(k_{\perp n} r), \quad k_{\perp n} = \frac{u_n}{a} - i \frac{u_s}{k_{w\perp} a^2}$$

$$C_n = \frac{2}{[a J_1(u_n)]^2} \int_0^a E(r) J_0(u_n r/a) r dr, \quad J_0(u_n) = 0$$



Laser energy leakage:

$$I_L(z) = I_0 \exp(-z/L_D)$$



$$L_{D,n}^{-1} = \frac{u_n^2}{k_0^2 a^3} \frac{1 + \varepsilon_w}{\sqrt{\varepsilon_w - 1}}$$

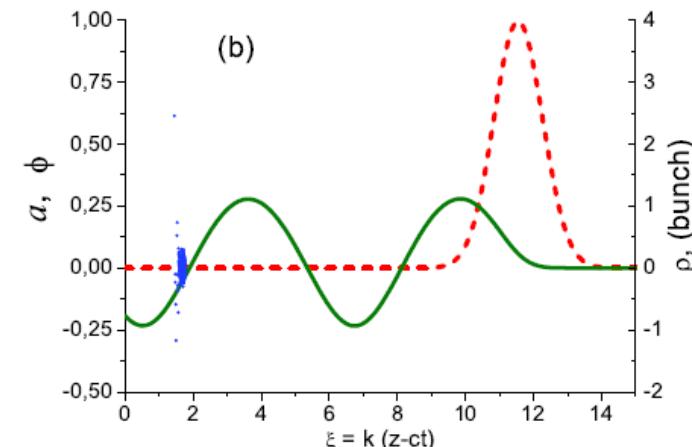
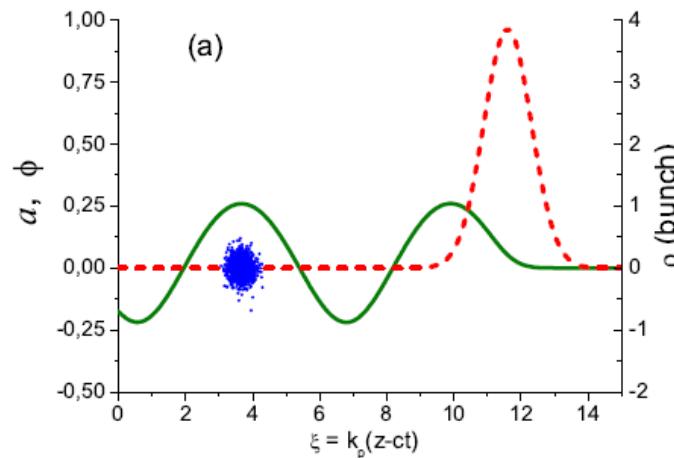
Computer simulation by the code LAPLAC

Initial energy of electrons $E_{inj} = 1.9 mc^2$ and normalized emittance $\sigma_N = 0.346 \text{ mm}\times\text{mrad}$

The radial bunch dispersion was $\sigma_{r,inj} = 1.88 \mu\text{m}$ ($k_p \sigma_{r,inj} = 0.148$, $k_p R_{rms} = 0.214$)

Longitudinal dispersion $\sigma_{z,inj} = 2.3 \mu\text{m}$ (FWHM bunch duration = 23 fs, $k_p \sigma_{z,inj} = 0.18$)

$$\varphi(\xi_{inj}) - \varphi(\xi_{tr}) = E_{inj}/mc^2 - \left[\left(1 - \gamma_{ph}^{-2} \right) \left(E_{inj}^2/m^2 c^4 - 1 \right) \right]^{1/2} - 1/\gamma_{ph}$$



At the entrance of the plasma channel, the laser pulse envelope was Gaussian in both longitudinal and transverse directions with laser wavelength $\lambda_0 = 0.8 \mu\text{m}$, amplitude $a_0 = 0.964$ and FWHM pulse duration $\tau_{FWHM} = 50 \text{ fs}$.

and waist radius $r_0 = 68.2 \mu\text{m}$

$P_L = 145 \text{ TW}$, $P_L/P_{cr} = 0.854$, at plasma density on the axis $n_0 = 1.75 \times 10^{17} \text{ cm}^{-3}$, $\gamma_{ph} = 100$.

From 1-D theory in the stationer wakefield for test particles

The compressed length of the trapped bunch can be estimated through the wakefield potential at the phases of injection and trapping:

$$L_b = \frac{1}{2} k_p L_{b0}^2 \frac{|\partial^2 \phi(\xi_m) / \partial \xi^2|}{\partial \phi(\xi_{tr}) / \partial \xi}$$

Injected RMS bunch length $k_p L_{b0} = 0.41$
Compressed bunch length $k_p L_b = 0.08$

$k_p L_{rms} = 0.07$ obtained in the simulations

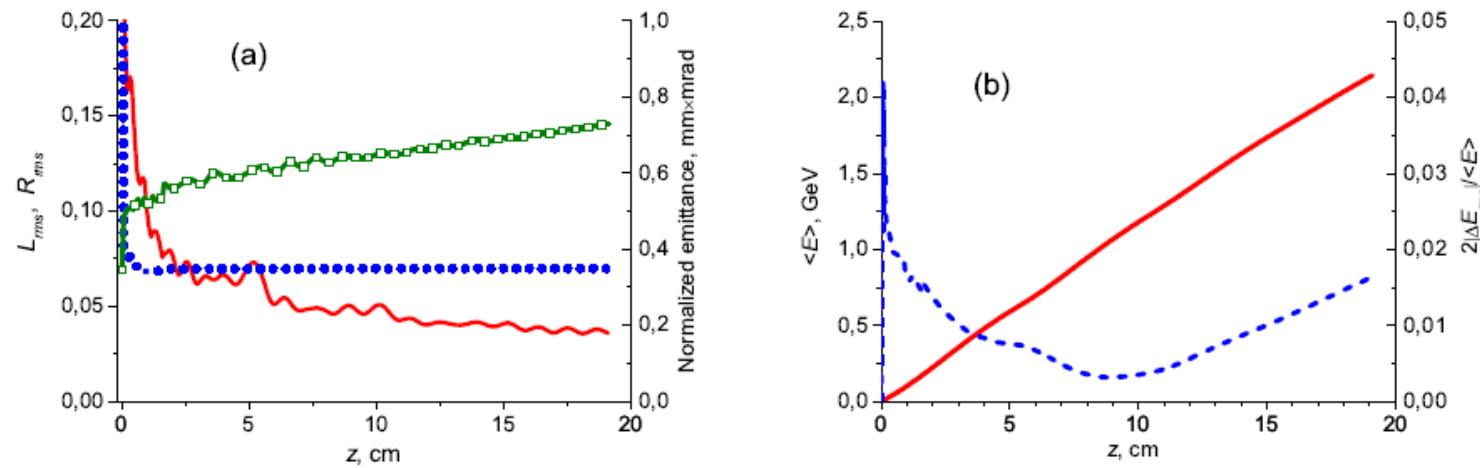
The upper estimate for the minimal electron energy spread:

$$\Delta E_f = 2\sigma_E \approx 4|e|k_p \frac{d\phi}{d\xi_f} \frac{E_{inj}^2}{m^2 c^4} \sigma_{z,inj}. \quad 2\Delta E_{rms}/\langle E \rangle \approx 0.002$$

the maximum energy of the bunch electrons at the “focusing” point is limited to the value

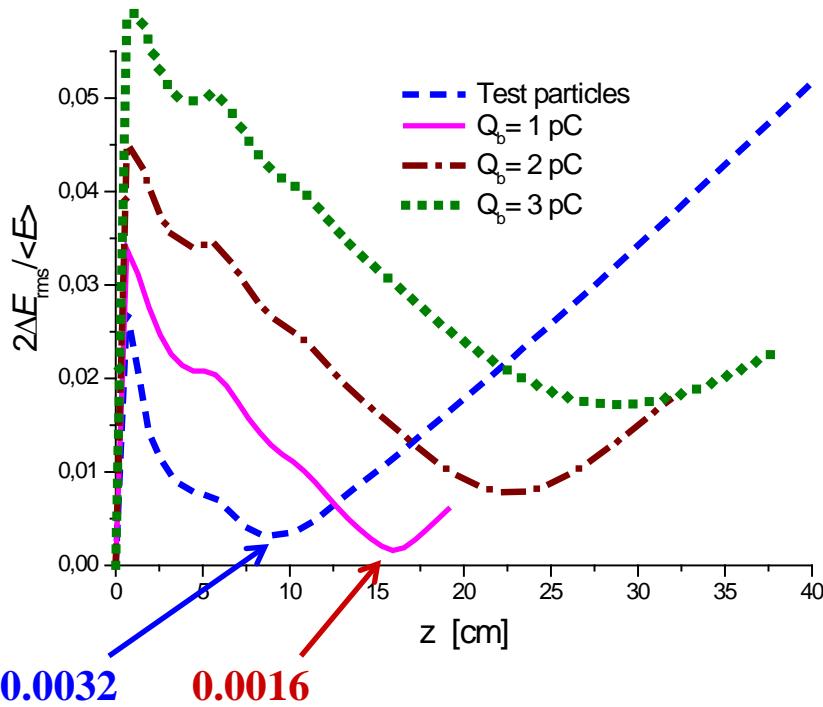
$$E_f \approx 2\gamma_{ph} mc^2 (1 - 2\gamma_{ph} |e| \phi(\xi_{df}) / mc^2)$$

How does it work in 3D modelling with allowance for the nonlinear laser and wakefield dynamics?



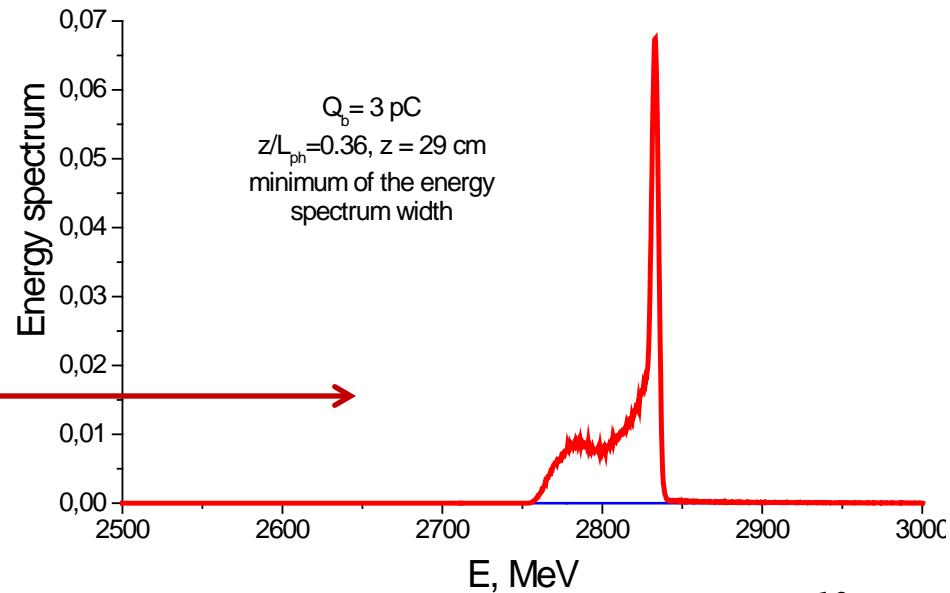
The normalized by k_p RMS bunch length (dotted line, left axis) and RMS bunch radius (solid line, left axis) and normalized emittance (line marked by squares, right axis) as functions of the acceleration length (a). The averaged energy (solid line) and the normalized RMS energy spread (dashed line) of the accelerated electron bunch as functions of the acceleration length (b).

Loading effect (self-action of the bunch charge) in the LWFA



$$N_{load} \sim n_0 k_p^{-3} = 3.6 \times 10^8 \rightarrow 60 \text{ pC}$$

Minimal energy spread for $Q_b = 3$ pC:
 $2\Delta E_{rms}/\langle E \rangle = 2\%$
 $\Delta E_{FWHM}/\langle E \rangle = 0.2\%$



Conclusion on the Laser WakeField electron Acceleration in guiding structures

- Stable and controllable laser propagation and wakefield generation over tens of Rayleigh length in guiding structures are demonstrated
- Acceleration of electrons to GeV energies in cm-scale capillaries is achieved
- Loading effect can be controlled and used to optimize electron bunch parameters for low energy spread (**but it limits the bunch charge!**)
- LWFA can provide low emittance acceleration of polarized electron bunches to high energies (*next talk*)
- *Complete analysis of the multistage acceleration that preserve high-quality electron bunches are needed to demonstrate the key element of the collider concept*

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*Thank You
for your attention!*