Cold injection producing mono-energetic, high quality, GeV electron beams

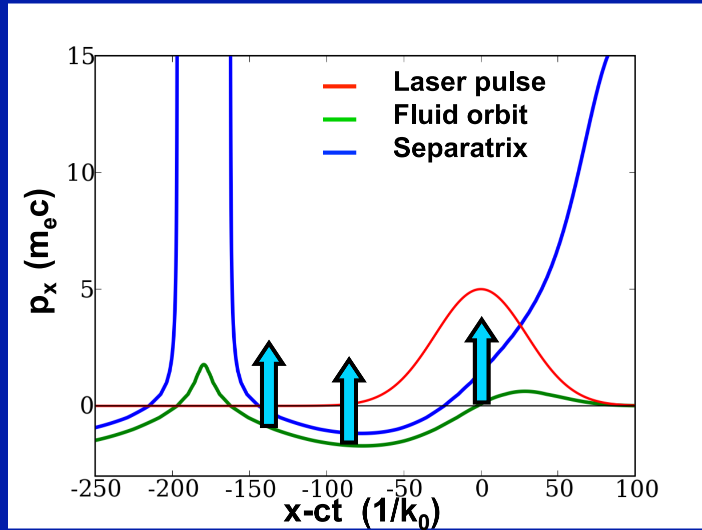
SILMI Workshop, Garching, March 2010

X. Davoine[1], A. Beck[1], V. Malka[2], and E. Lefebvre[1]

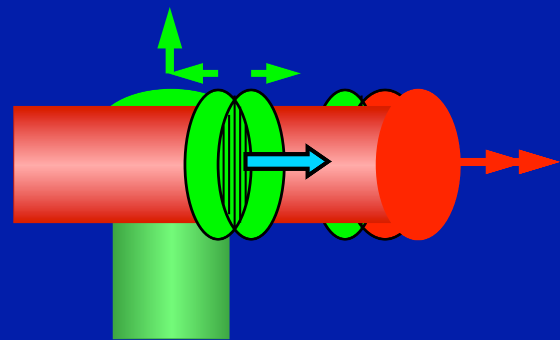
[1]CEA, DAM, DIF, 91297 Arpajon, France
[2]LOA, Ecole Polytechnique/ENSTA/CNRS, 91761 Palaiseau, France

Optical injection up to now

- Idea: use additional laser pulse(s) to provide some electrons with the necessary momentum to cross the separatrix.



- Previous work:
  - In perpendicular geometry, injection can be caused by the transverse ponderomotive force [1] or by the wake field of the 2nd pulse [2].
  - In collinear geometry, the beatwave created by 2 additional pulses colliding in the wake can lead to injection [3].
  - In collinear geometry, the beatwave created by the collision between the main pulse and an additional pulse can also inject electrons [4,5].



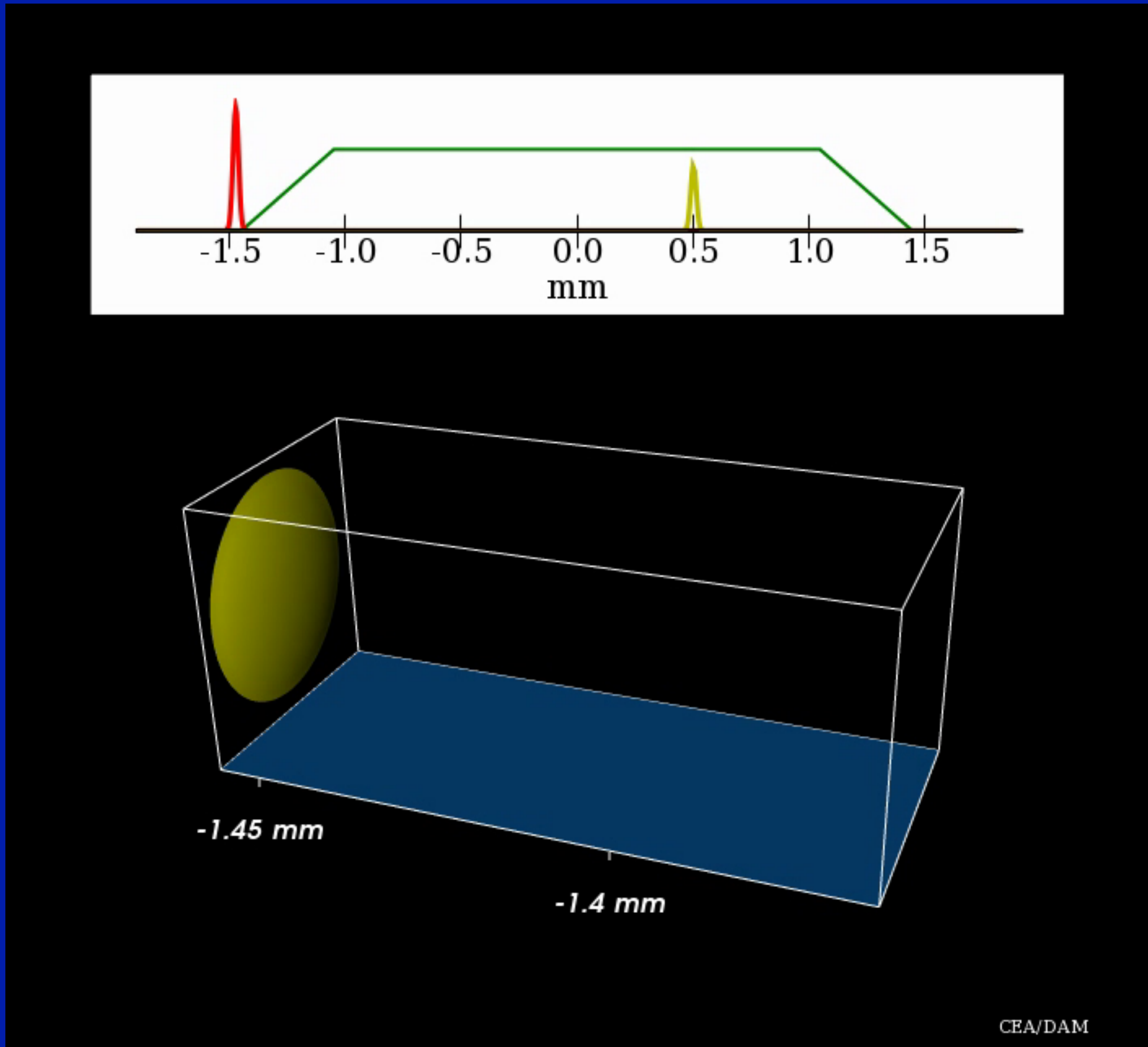
[1] D. Umstadter *et al.*, PRL **76**, 2073 (1996)
[2] R. G. Hemker *et al.*, PRE **57**, 5920 (1998)
[3] E. Esarey *et al.*, PRL **79**, 2682 (1997)
[4] G. Fubiani *et al.*, PRE **70**, 016402 (2004)
[5] H. Kotaki *et al.*, POP **11**, 3296 (2004)

'Scale-1' simulation of optical injection for LOA exp't

Pump pulse
- λ = 0.8 µm
- 30 fs
- 3.1×10^{18} W/cm^2

Plasma
- 2.9 mm long, two 400 µm density ramps
- Electron density 7×10^{18} cm^{-3}
- Collision @ 475 µm before center of gas jet

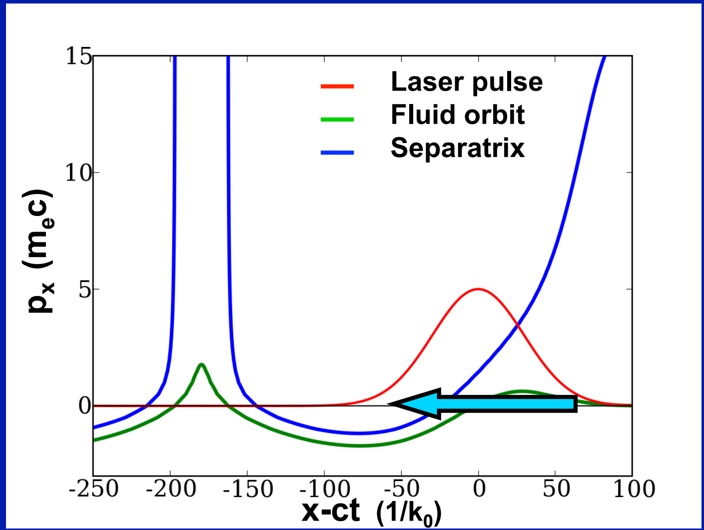
Injection pulse
- λ = 0.8 µm
- 45 fs
- 3.5×10^{15} W/cm^2



X. Davoine *et al.*, Phys. Plasmas **15**, 113102 (2008)

Cold injection principle: no momentum gain [1]

- Injection mechanism:
  Let electrons phase slip in the wake so they can cross the separatrix with little longitudinal momentum



- How can we help electrons 'tunnel through' the ponderomotive potential?
  ➲ Collision with a counter-propagating pulse: creation of an EM beatwave

$$F_{bw} = \frac{1}{\gamma} k_0 a_0 a_1 \sin(2k_0 x)$$

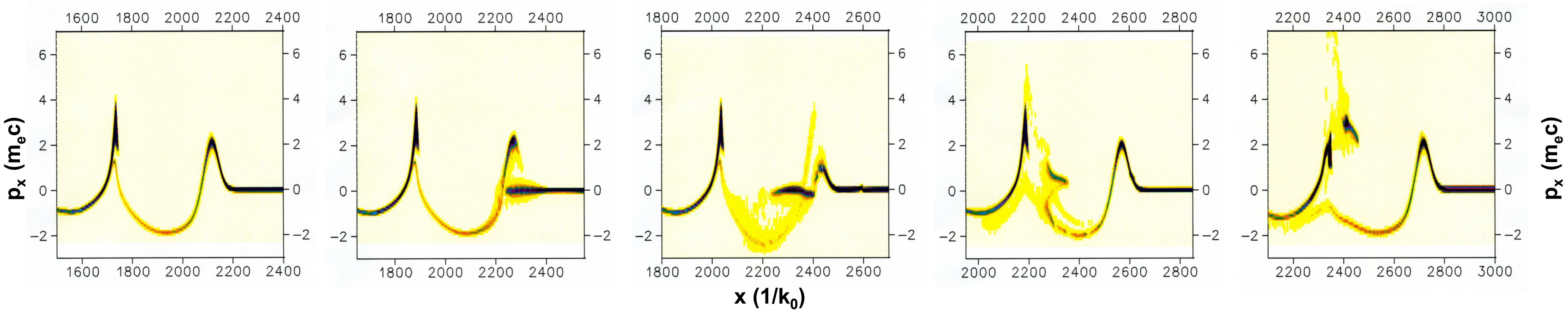
- Electrons are trapped in the static and $\lambda_0/2$ long beatwave buckets
  – Electron longitudinal motion is frozen while the pulse propagates
  – They slip backward in the wake
  – They are injected without momentum gain

[1] X. Davoine *et al.*, PRL **102**, 065001 (2009)

A cold injection example in 2D

- Simulation parameters:
  - Main pulse:
    - λ_0=0.8 µm ; a_0=4 ; 30 fs ; w_0=18 µm ; circular polarization (4.2 J)
  - Colliding pulse:
    - λ_1=0.8 µm ; a_1=0.2 ; 63 fs ; w_1= 5 µm ; circular polarization
  - Plasma:
    - $n_{e0} = 2.5\ 10^{-4}\ n_c = 4.4\ 10^{17}\ cm^{-3}$
    - parabolic density: $n_e(r)=(1+r^2/R^2)n_{e0}$ with R = 27 µm

- Phase space plot during the pulse collision (only electrons near the axis are plotted)

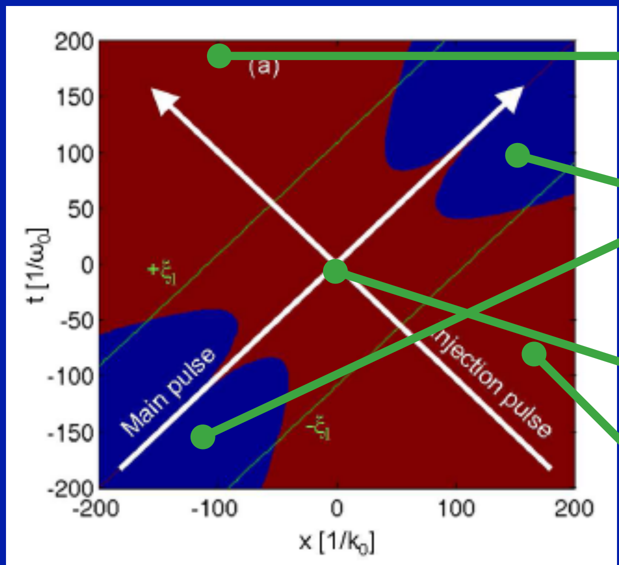


A simple 1D model

- Condition 1
  To effectively freeze the electron longitudinal motion, the beatwave force should be larger than the main pulse ponderomotive force:

$$\chi \equiv \frac{F_b/\sin(2x)}{|F_p|} = \frac{\tau_0^2 \tilde{A}_1}{2\ln(2)\,|x-t|\,\tilde{A}_0} > 1$$

- Condition 2
  All this is effective if the main laser amplitude is not too small (say > 0.1)



Low ponderomotive force, wakefield

Ponderomotive force dominates

Beatwave force freezes motion

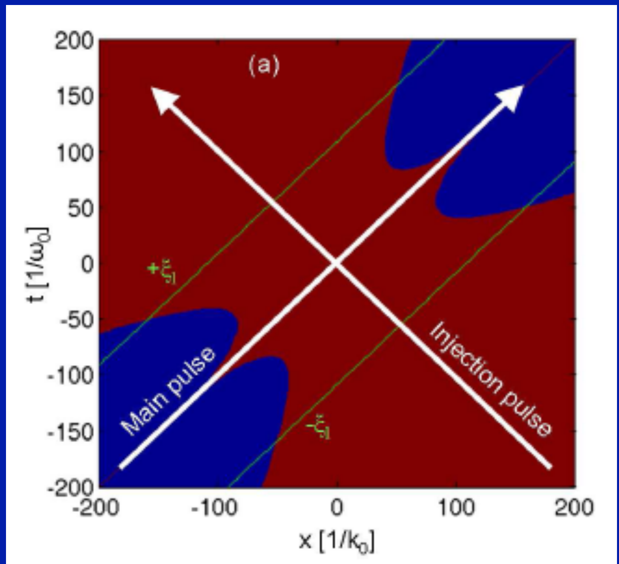
Low ponderomotive force, fresh plasma

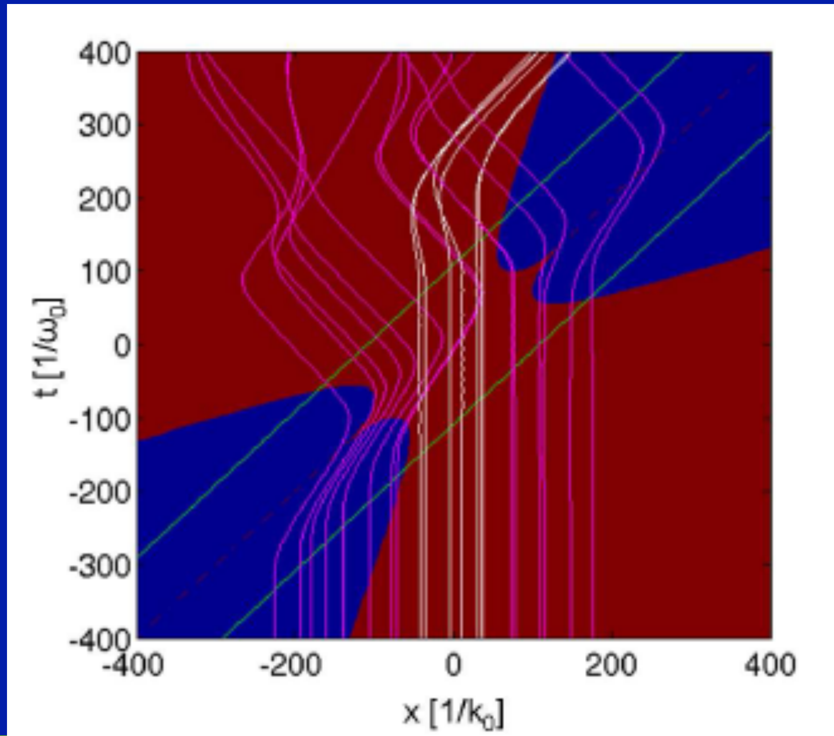
A simple 1D model

- Condition 1
  To effectively freeze the electron longitudinal motion, the beatwave force should be larger than the main pulse ponderomotive force:

$$\chi \equiv \frac{F_b/\sin(2x)}{|F_p|} = \frac{\tau_0^2 \tilde{A}_1}{2\ln(2)\,|x-t|\,\tilde{A}_0} > 1$$

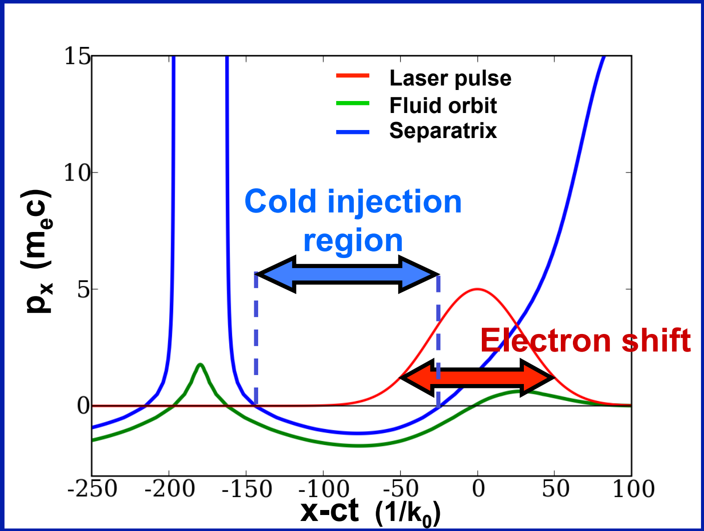
- Condition 2
  All this is effective if the main laser amplitude is not too small (say > 0.1)





Additional conditions of occurrence

- The separatrix must cross the p_x=0 axis.
  - cold injection "region": region where the separatix is under the axis p_x=0.



- The cold injection region must be long enough to extend to the back of the main pulse.
  - Electron phase shift due to the beatwave occurs only where the main pulse exists.

- Wake inhibition [1] due to pulse collision must be kept low.
  - The collision region (where pulses overlap) must be much smaller than the wakefield bucket.

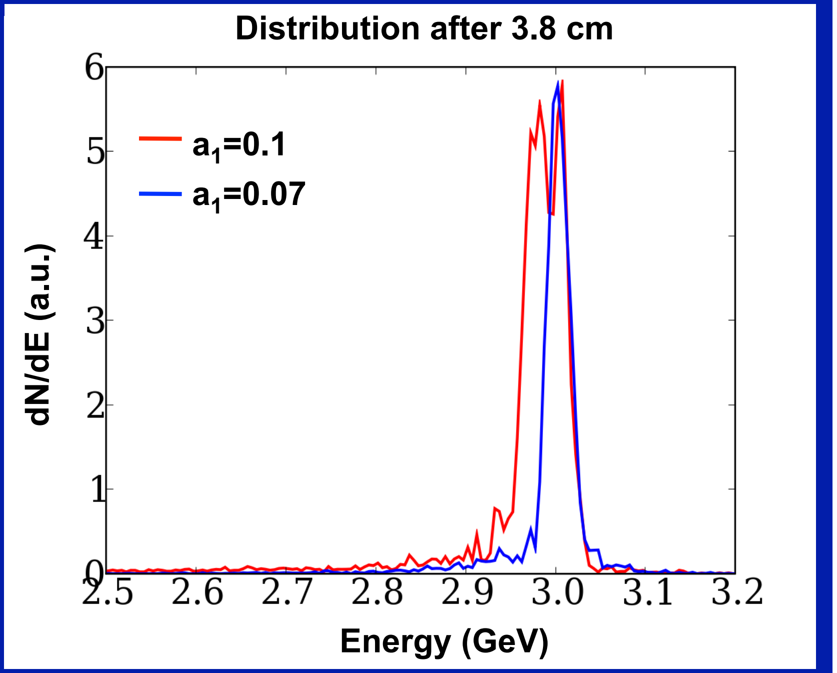
[1] C. Rechatin *et al.*, POP **14**, 060702 (2007)

Application: production of a 3 GeV bunch with 1% ΔE/E

- Cold injection provides high beam control at high energy:
  - Use of low plasma density (below the self-injection threshold)
  - Injection at the back of the "bubble" for larger dephasing length

- Main pulse: λ_0=0.8 μm ; a_0=4 ; 30 fs ; w_0=18 μm ; circular polarization (4.2 J)
- Injection pulse: λ_1=0.8 μm ; a_1=0.1 ; 30 fs ; w_1=15 μm ; circular polarization
- Plasma: n_{e0} = 2.5 10^{-4} n_c = 4.4 10^{17} cm^{-3}; $n_e(r)=(1+r^2/R^2)n_{e0}$ with R = 27 μm

- Beam parameters obtained (2D): 3 GeV, 50 pC, rms ΔE/E = 1 %
  - with a_1=0.07:
    - 28 pC
    - rms ΔE/E = 0.45 %
    - Normalized rms emittance: 8.1 mm mrad
    - rms duration: 4.8 fs

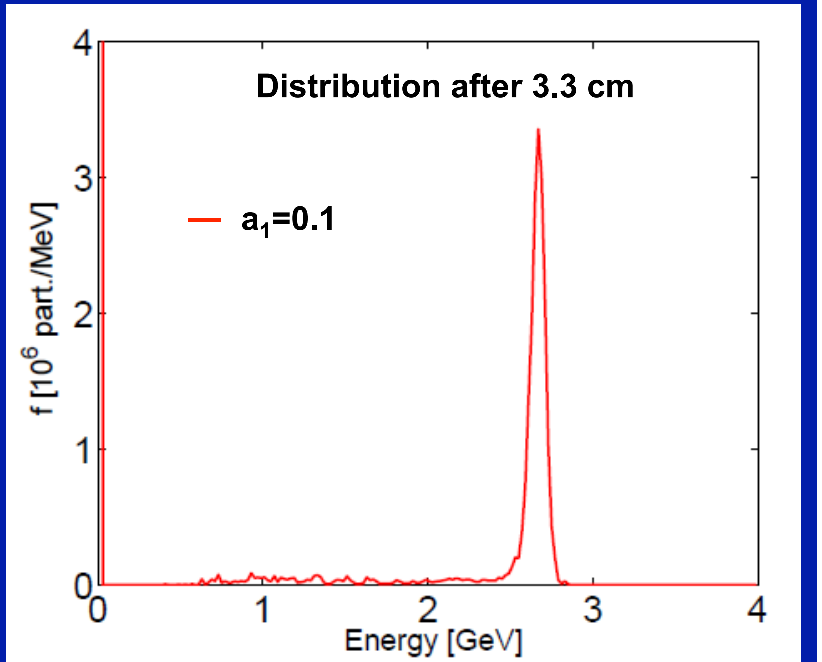


Application: production of a 3 GeV bunch with 1% ΔE/E

- Cold injection provides high beam control at high energy:
  - Use of low plasma density (below the self-injection threshold)
  - Injection at the back of the "bubble" for larger dephasing length

- Main pulse: λ_0=0.8 μm ; a_0=4 ; 30 fs ; w_0=18 μm ; circular polarization (4.2 J)
- Injection pulse: λ_1=0.8 μm ; a_1=0.1 ; 30 fs ; w_1=15 μm ; circular polarization
- Plasma: $n_{e0} = 2.5\ 10^{-4}\ n_c = 4.4\ 10^{17}$ cm^{-3}; $n_e(r)=(1+r^2/R^2)n_{e0}$ with R = 27 μm

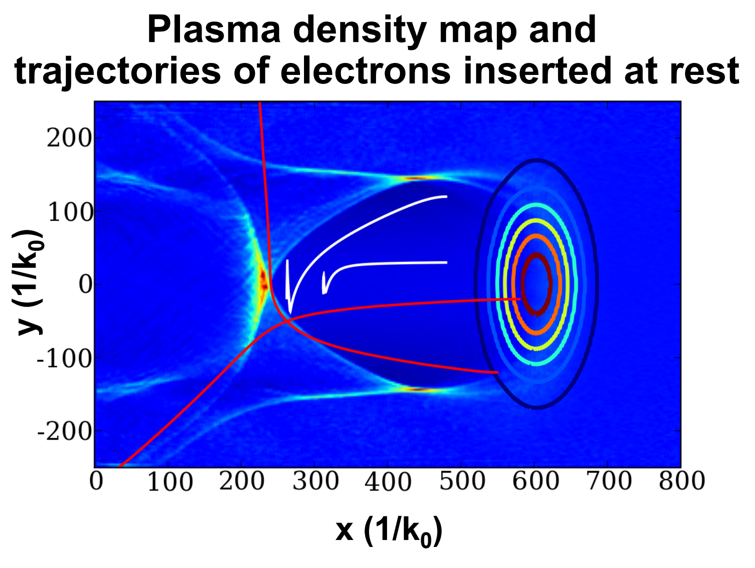
- Beam parameters obtained
  - quasi-radial 3D code:
    2.7 GeV, 59 pC,
    rms ΔE/E = 2.2 %

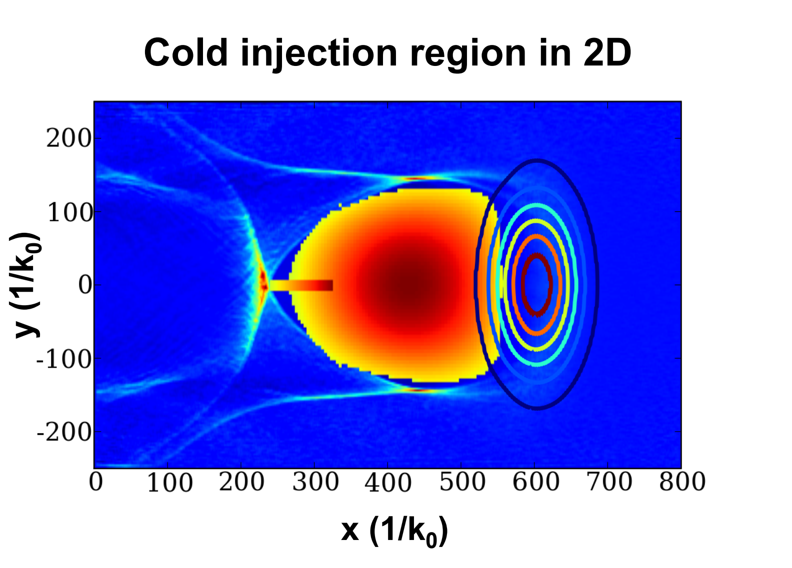


2D view of the cold injection region

- Main pulse: λ_0=0.8 µm ; a_0=4 ; 30 fs ; w_0=18 µm ; circular polarization
- Plasma: n_{e0} = 2.5 10^{-4} n_c = 4.4 10^{17} cm^{-3}; $n_e(r)=(1+r^2/R^2)n_{e0}$ with R = 27 µm

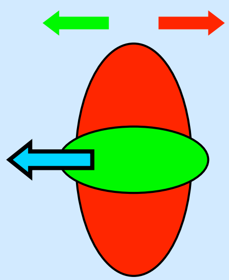
- In 2D, transverse effects have to be taken in account.
- 2D quasi-static wake fields are obtained from the simulation.
  - Electron trajectories can be calculated from the fields : where can electrons be injected and still be trapped in the bucket?



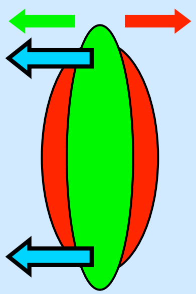


The bunch longitudinal density can be tuned

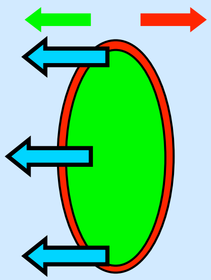
- Injection near the axis
  - Forward bunch position
  - a_1=0.2 ; 60 fs ; w_1= 5 µm

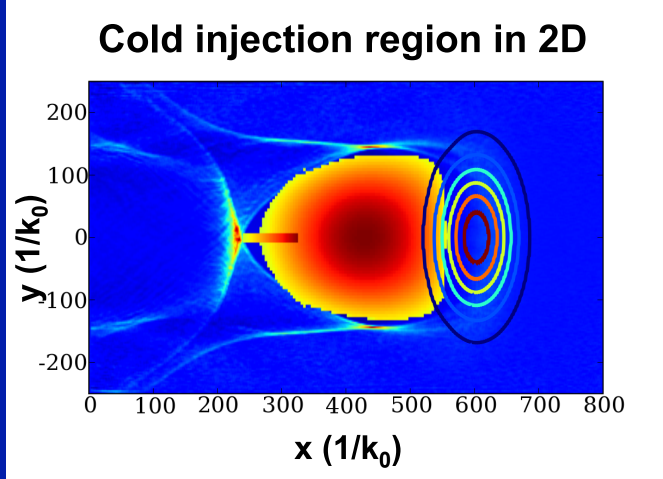


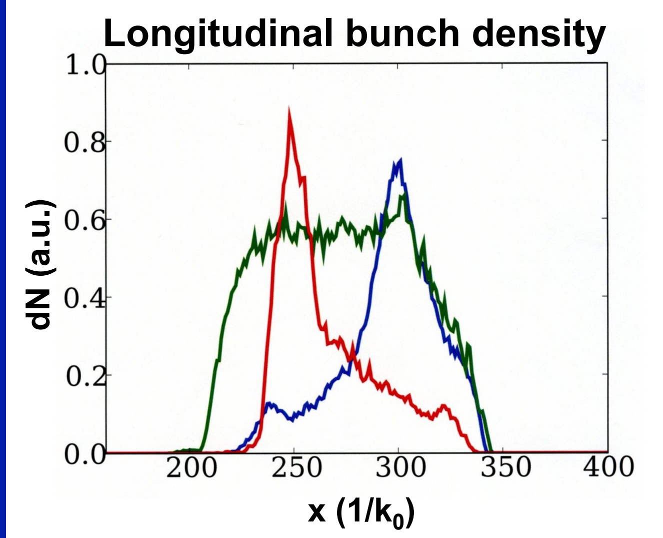
- Injection off-axis
  - Backward bunch position
  - a_1=0.2 ; 30 fs ; w_1= 15 µm



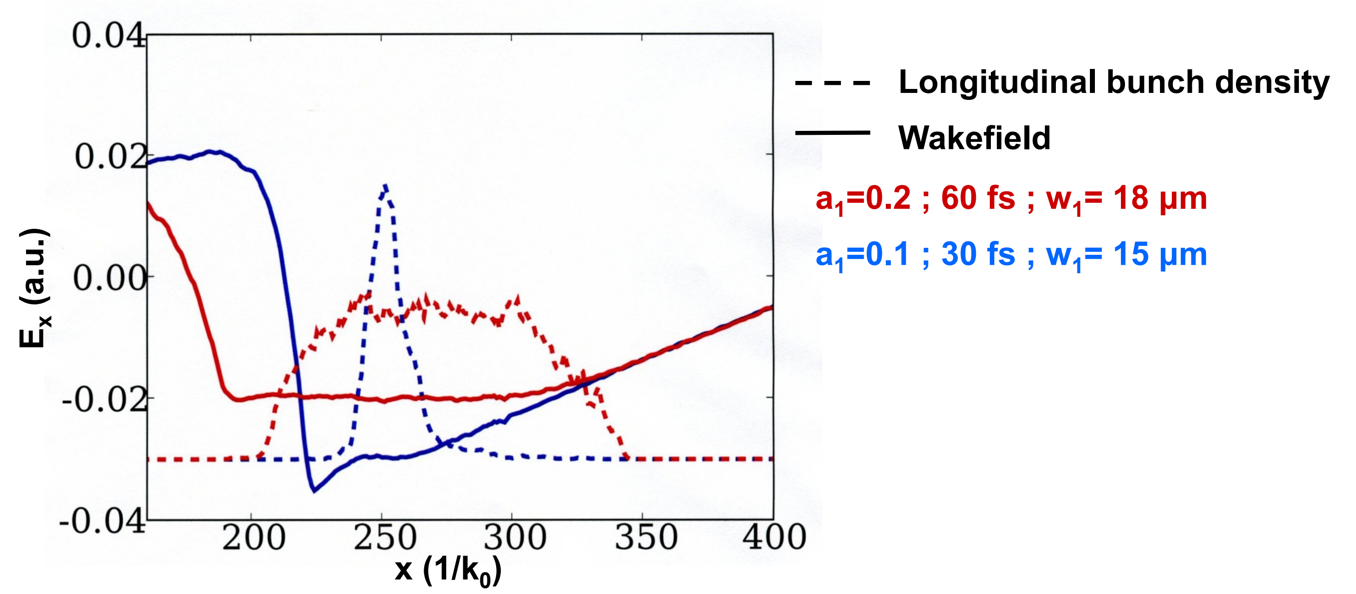
- Mixed injection
  - Longer bunch
  - a_1=0.2 ; 60 fs ; w_1= 15 µm







Cold Injection opens great perspectives for beamloading control



- The longitudinal beam density can be tuned
- Tzoufras *et al.* [1]: high beamloading with low energy spread can be achieved if the longitudinal beam density is properly tailored.

⇒ The cold injection scheme enables us to optimize beamloading and thus the electron beam parameters.

[1] M. Tzoufras *et al.*, PRL **101**, 145002 (2008)

Conclusion

- A new optical injection scheme has been presented: cold injection.
  - Longitudinal electron motion is frozen in EM beatwave during pulse collision
  - Electrons cross the separatrix due to phase slippage
  - This scheme does not rely on momentum gain
- High-quality beams can be produced
  - Low energy spread
  - High energy
  - Cold injection is an interesting feature when propagation in low-density plasma over long distance is the goal
- The longitudinal beam density can be tuned:
  - Prospect for beamloading optimization

Cold injection producing mono-energetic, high quality, GeV electron beams

SILMI Workshop, Garching, March 2010

X. Davoine[1], A. Beck[1], V. Malka[2], and E. Lefebvre[1]

[1]CEA, DAM, DIF, 91297 Arpajon, France

[2]LOA, Ecole Polytechnique/ENSTA/CNRS, 91761 Palaiseau, France