On the Control of e-Beam Parameters with Laser Plasma Accelerators

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Frontiers in Intense Laser-Matter Interactions Theory, Garching, Germany – March 1-3 (2010)

Summary

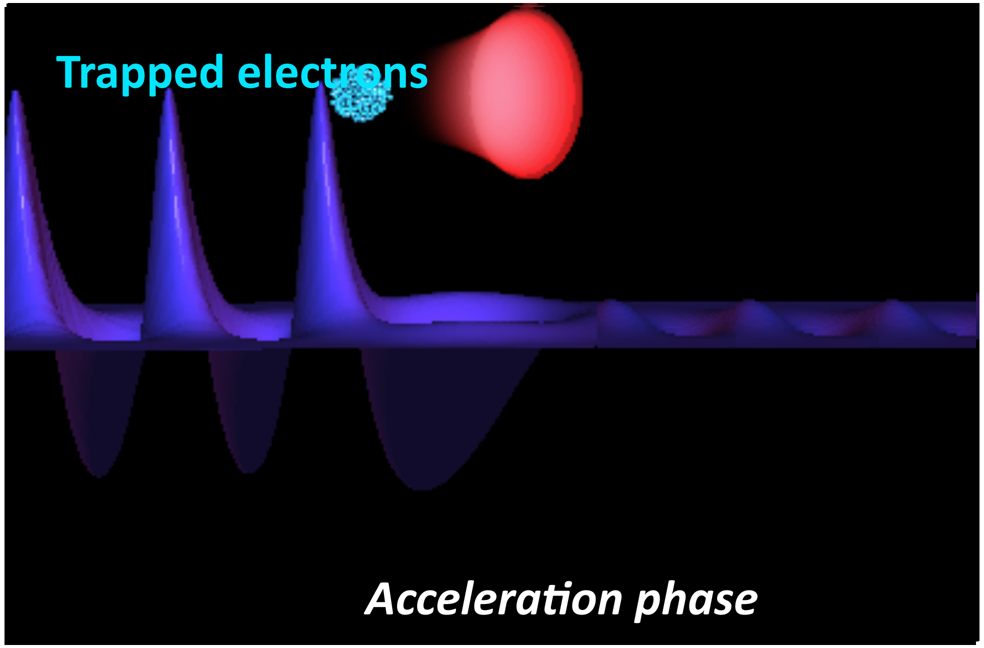
Part 1 : Controlling the e-beam parameters with two colliding laser pulses

Part 2 : Beam loading effects

Part 3 : Conclusion and perspectives

Controlling the injection

A second laser beam is used to heat electrons

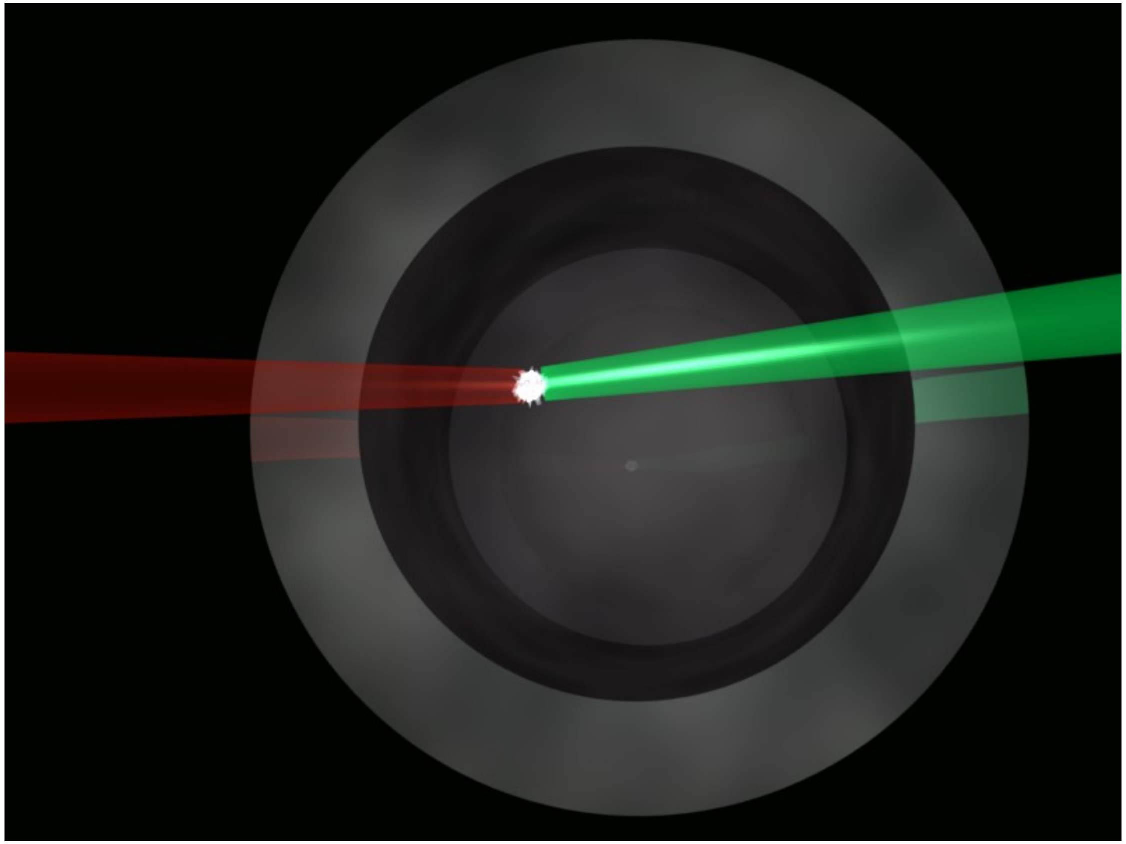


Ponderomotive force of beatwave: $F_p \sim 2a_0a_1/\lambda_0$ (a_0 et a_1 can be “weak”)

Boost electrons locally and injects them INJECTION IS LOCAL and IN FIRST BUCKET

E. Esarey *et al.*, PRL **79**, 2682 (1997), G. Fubiani *et al.*, PRE **70**, 016402 (2004),
H. Kotaki *et al.*, PoP **11** 3296 (2004), J. Faure *et al.*, Nature (2006)

Non collinear geometry



Advantages

No feedback (2 mJ of light scattered from the plasma)

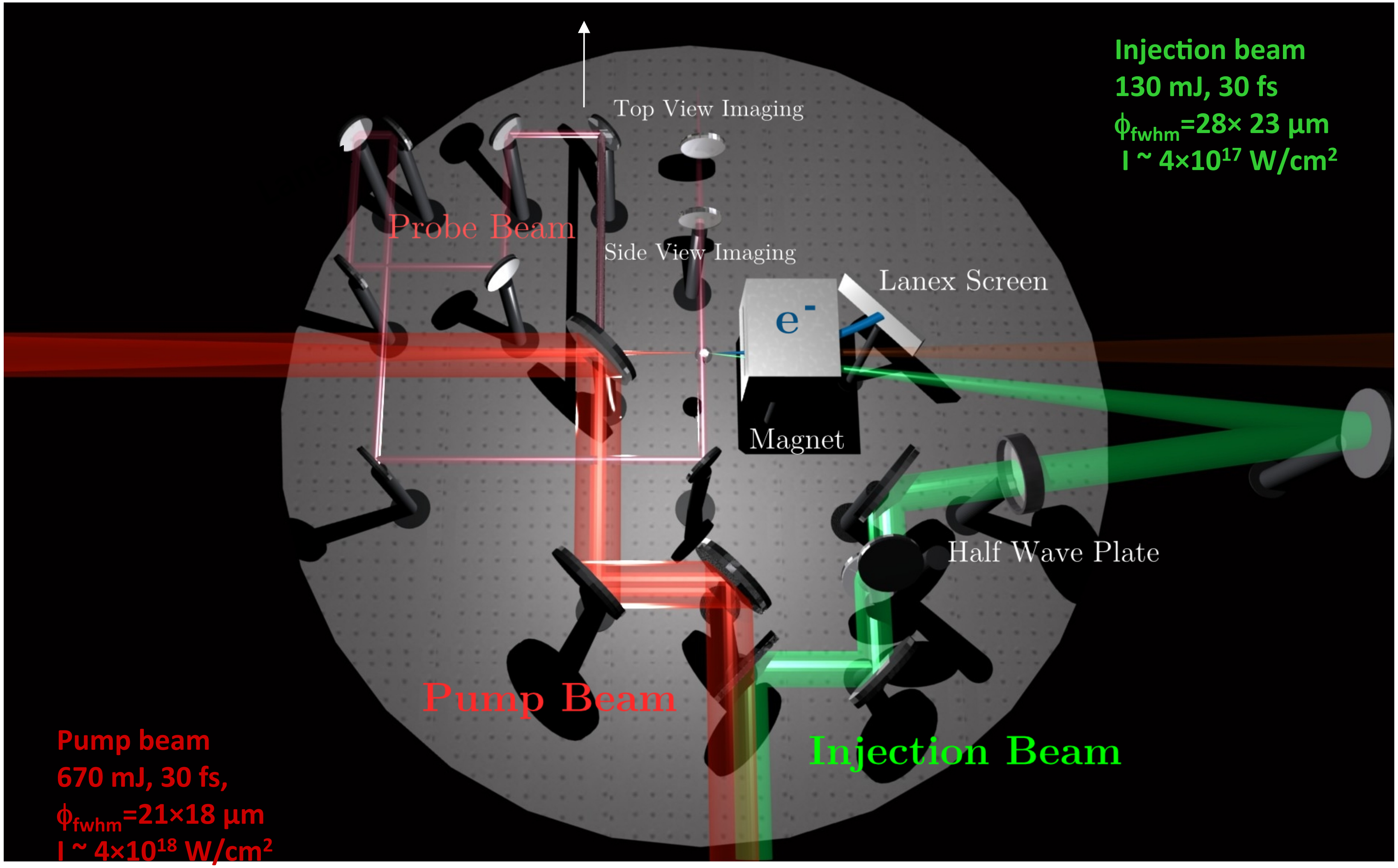
Easier access to use e-beams for applications or diagnostics

Drawbacks

- Synchronization is more critical
- Tuning the energy is more difficult

θ=4.5°. Focal spots are about 25 µm FWHM. Beam overlap occurs over $L=(w_0+w_1)/\tan(\theta)$
L ~ 600-1000 µm : not that critical + tuning still possible

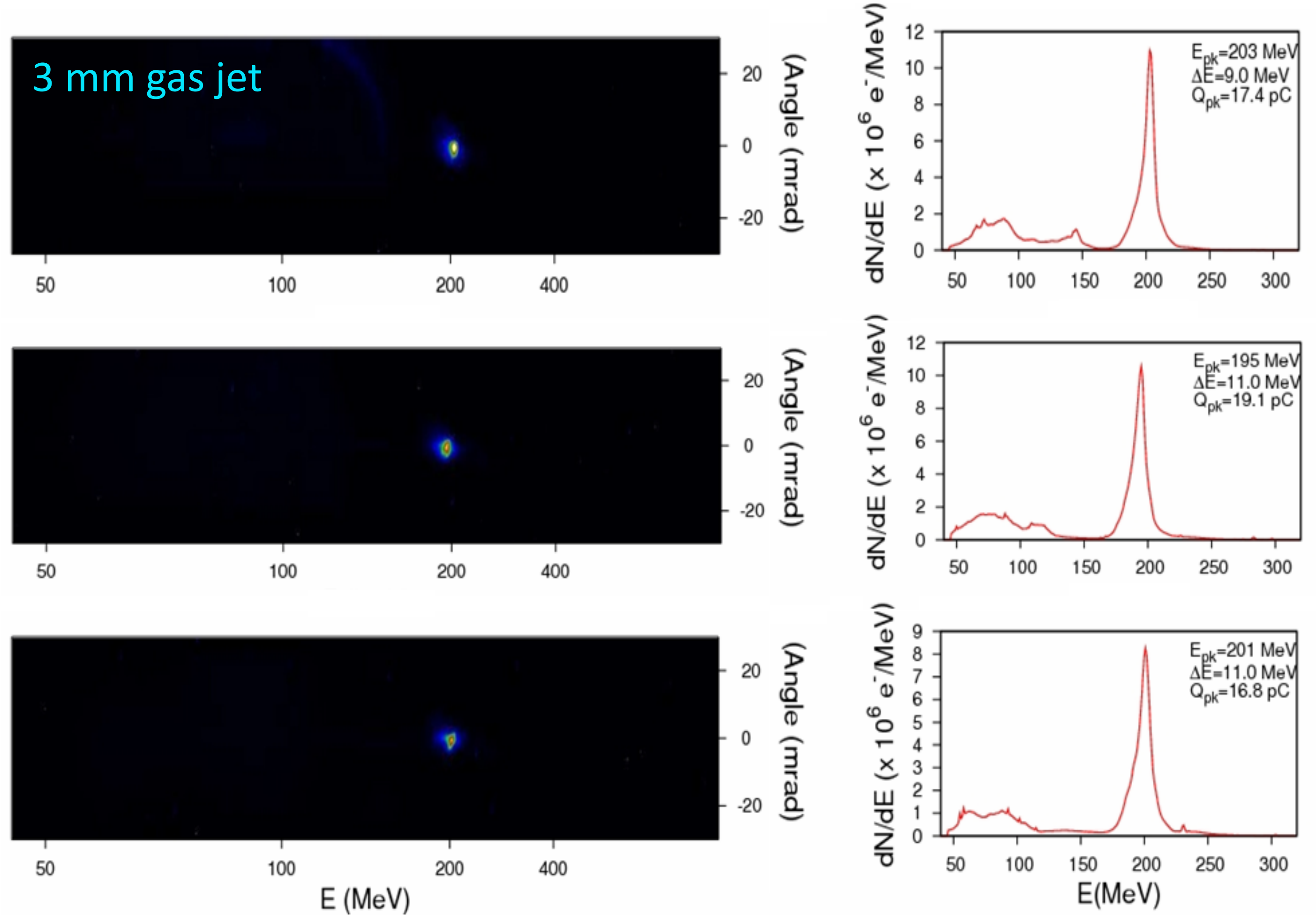
Experimental set up



Injection beam
130 mJ, 30 fs
ϕ_{fwhm}=28× 23 µm
I ~ 4×10^{17} W/cm^2

Pump beam
670 mJ, 30 fs,
ϕ_{fwhm}=21×18 µm
I ~ 4×10^{18} W/cm^2

Stable monoenergetic beams @200 MeV



Statistics (30 shots):

E = 206 +/- 11 MeV

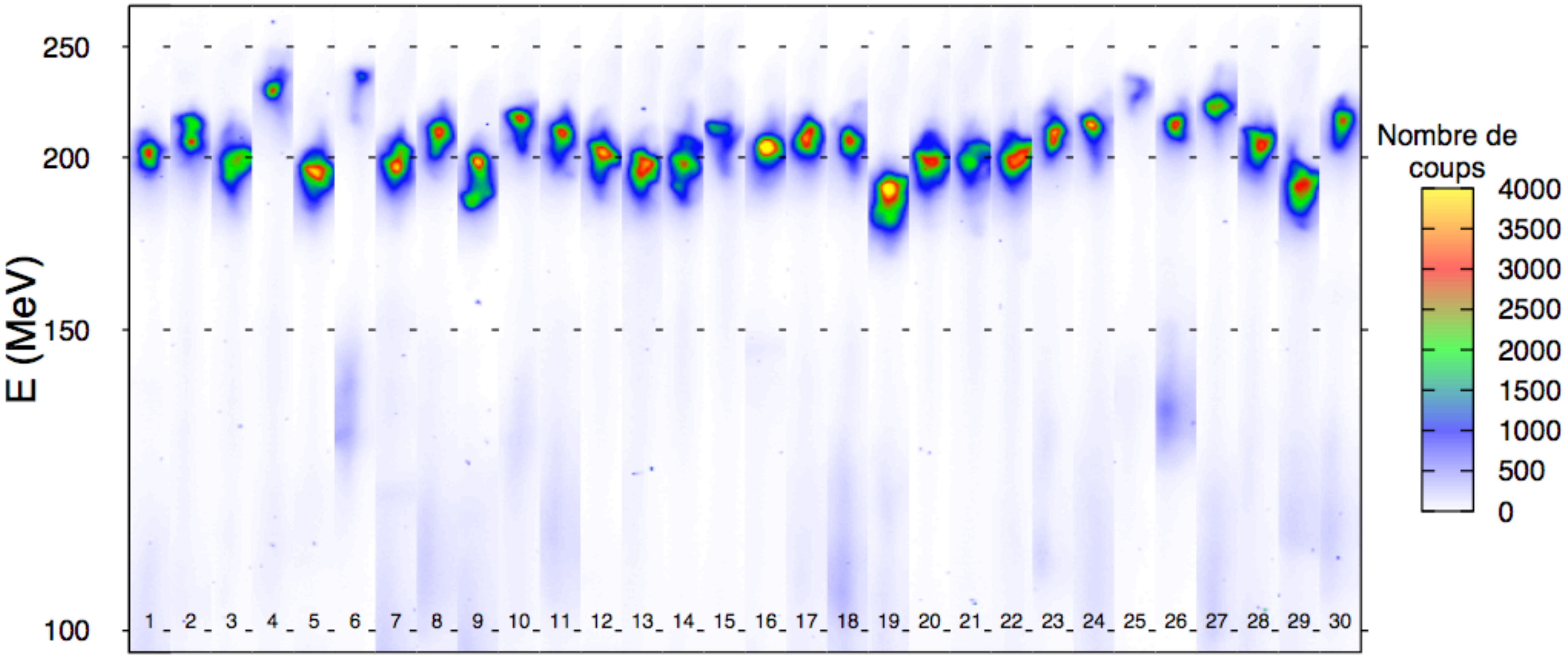
Qpk = 16.5+/- 4.7 pC

δE = 14 +/- 3 MeV

δE/E = 6%

Very little electrons at low energy, δE/E=5% limited by spectrometer

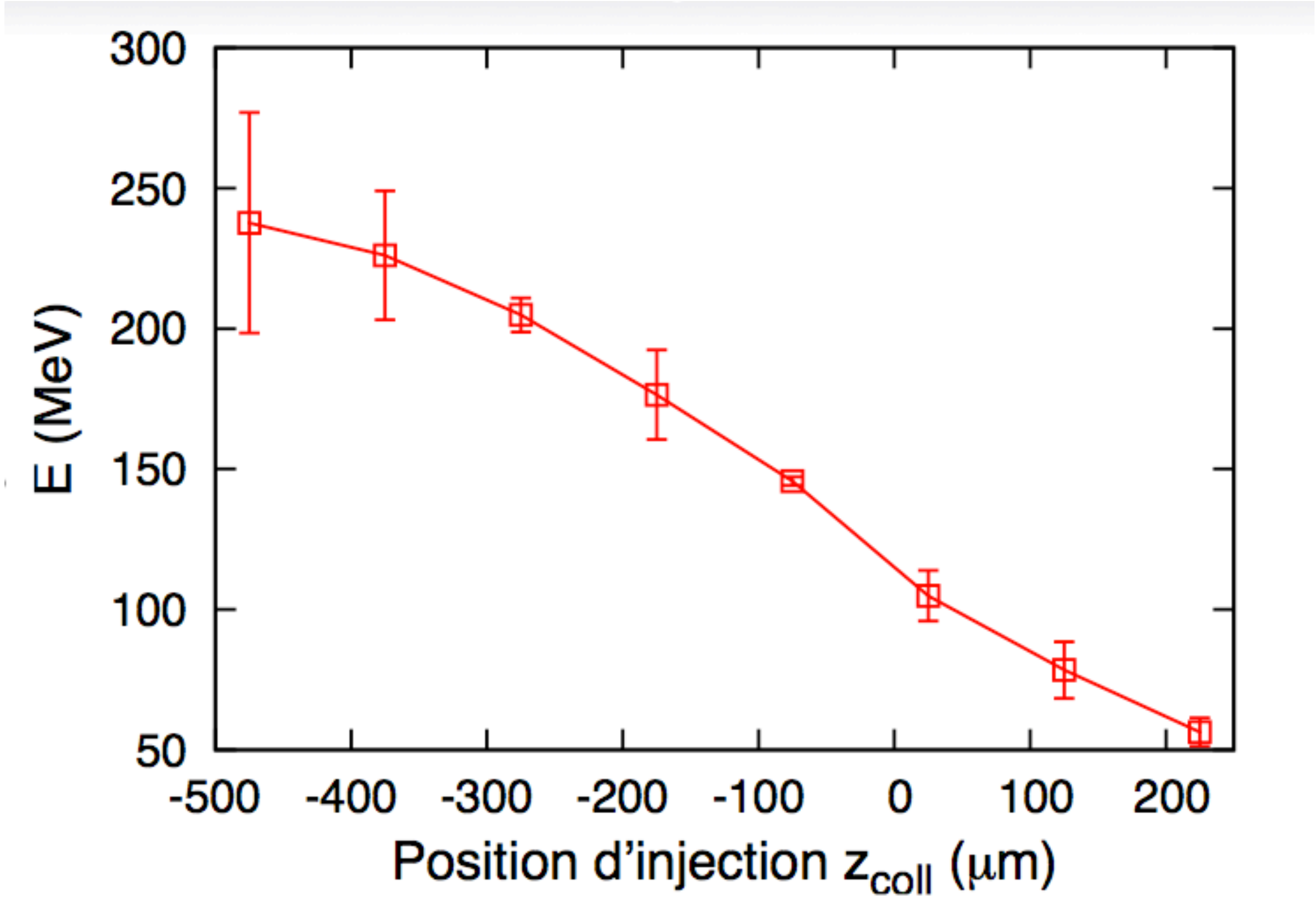
Very stable quasi-mono energetic electron beam



30 tirs consécutifs avec $a_0 = 1.5$, $a_1 = 0.4$, $n_e = 5.7 \times 10^{18}$ cm^{-3}

Nb: very few electrons at low energy
$\delta E/E=5\%$ limited by the spectrometer

Tunable energy of the e-beam



Tuning the charge & the energy spread

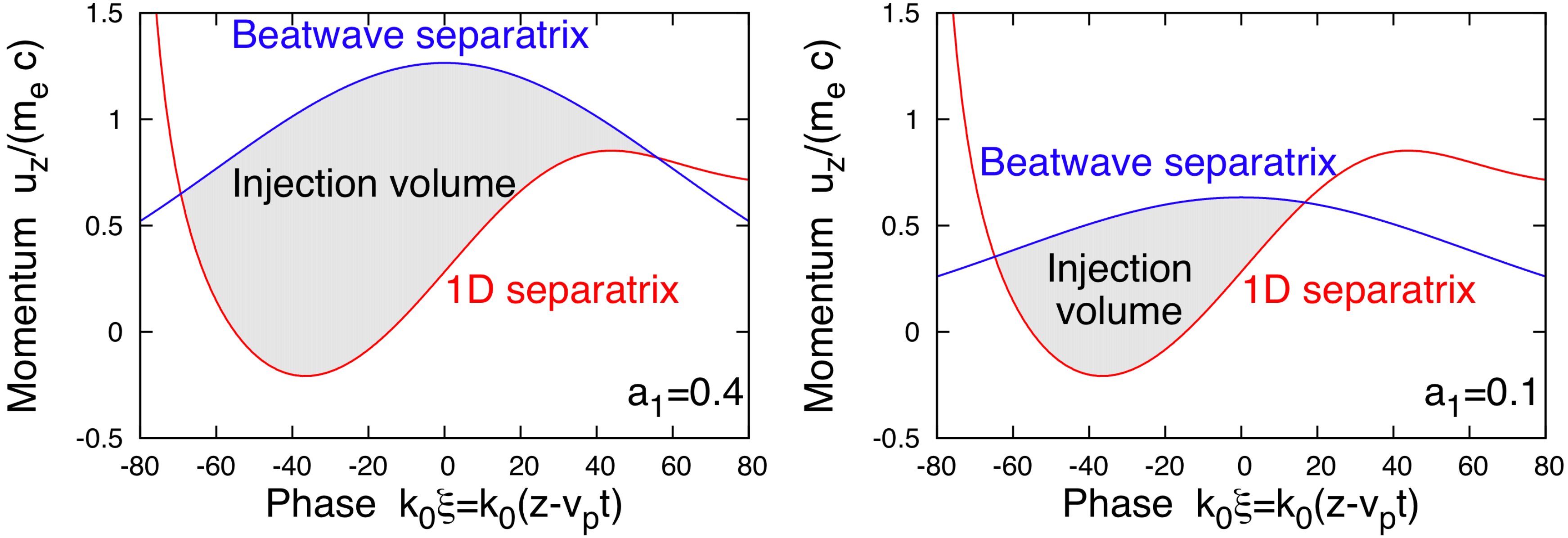
- **Charge can be tuned by**

  Controlling Heating electrons processes →Changing intensity of injection beam: smaller a_1 means less heating and less trapping

- **Energy spread can be tuned by**

  Decreasing the phase space volume V_{trap} of trapped electrons by changing a_1.

  Changing the ratio $c\tau/\lambda_p$ by changing n_e (by changing λ_p)



Evolution of injection volume with a_1 for a_0 = 2, n_e = 7.10^{18}cm^{-3}. Fields are computed for the 1D case and the beatwave separatrix corresponds to the circular polarization case.

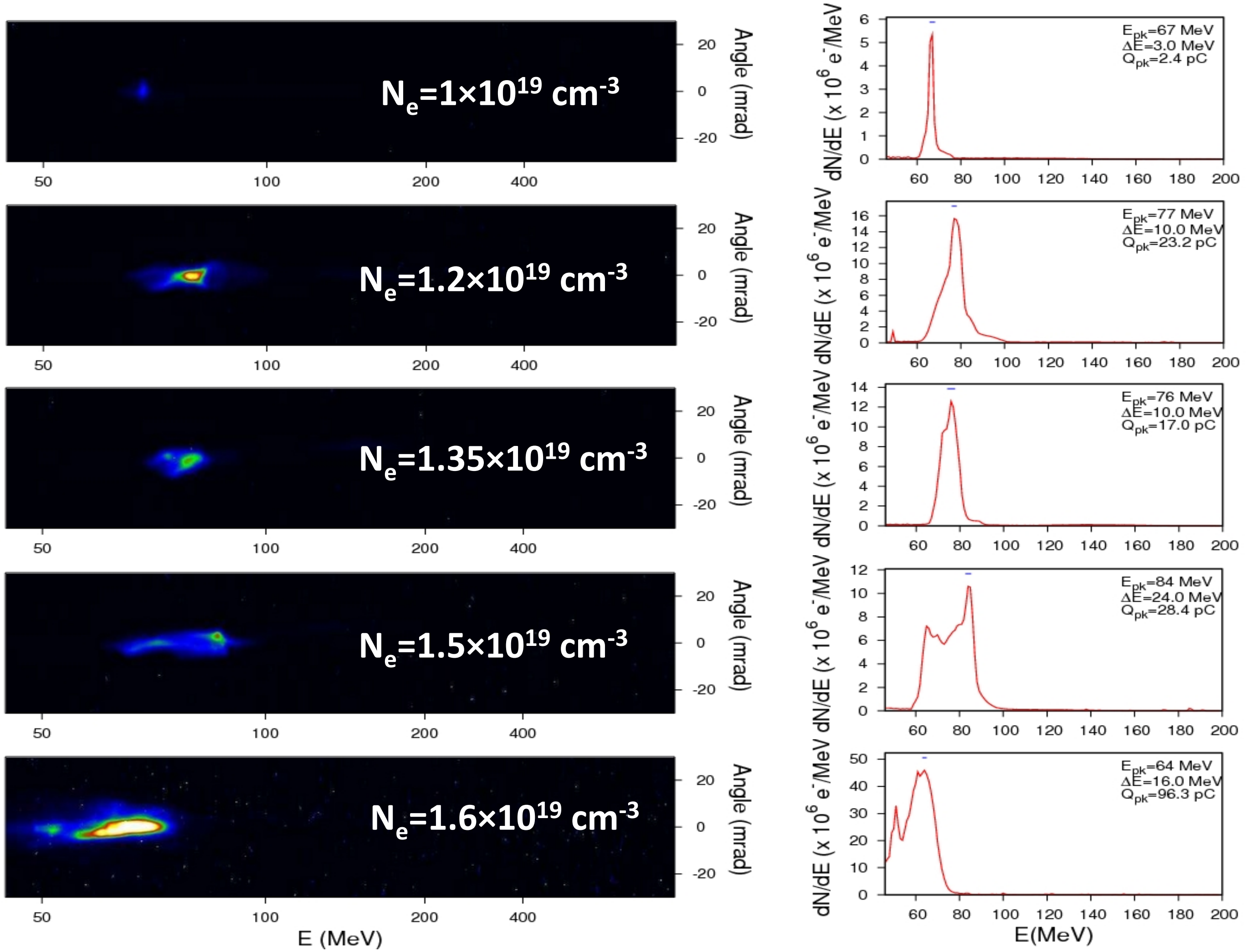
In practice, energy spread and charge are correlated:

Decreasing a_1 decreases the charge but also V_{trap}, and in consequence the energy spread

Tuning the charge and the energy spread with the plasma density

2 mm
gas jet

Increasing pressure



E=67 MeV
ΔE=3 MeV
Q_{pk}=2.4pC

E=77 MeV
ΔE=10 MeV
Q_{pk}=23.2pC

E=76 MeV
ΔE=10 MeV
Q_{pk}=17pC

E=64 MeV
ΔE=24 MeV
Q_{pk}=25.4pC

E=64 MeV
ΔE=16 MeV
Q_{pk}=96pC

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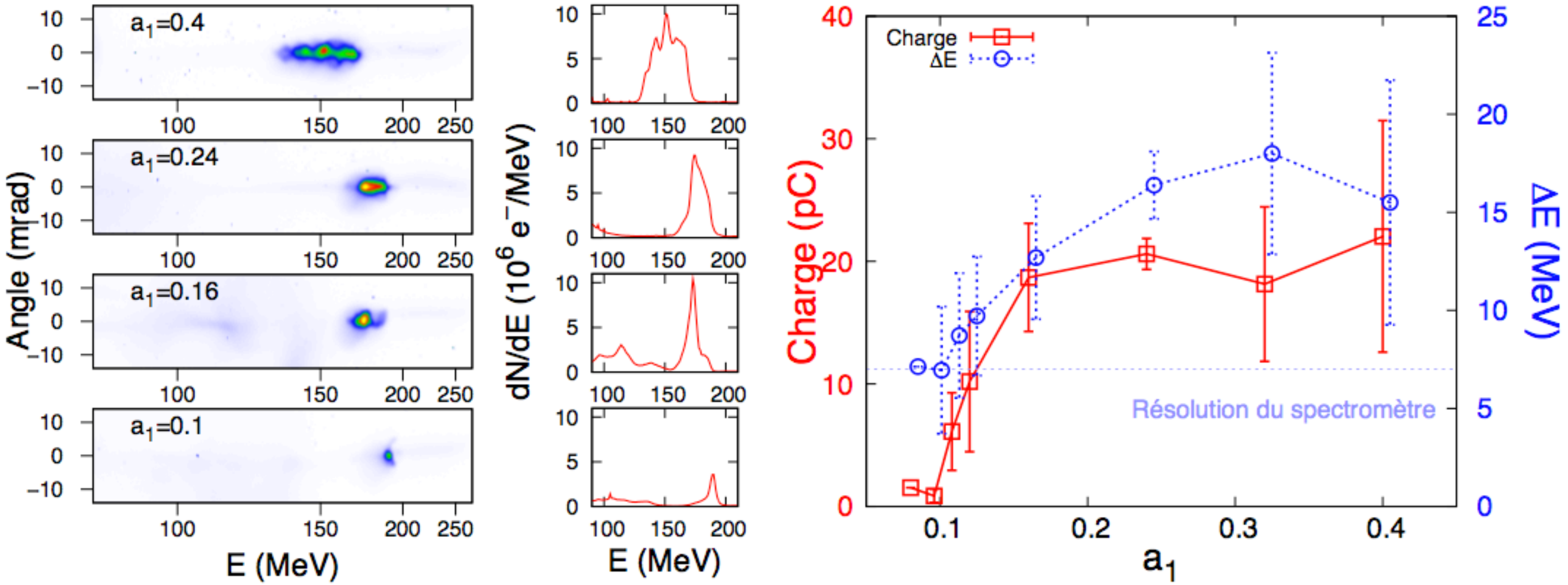
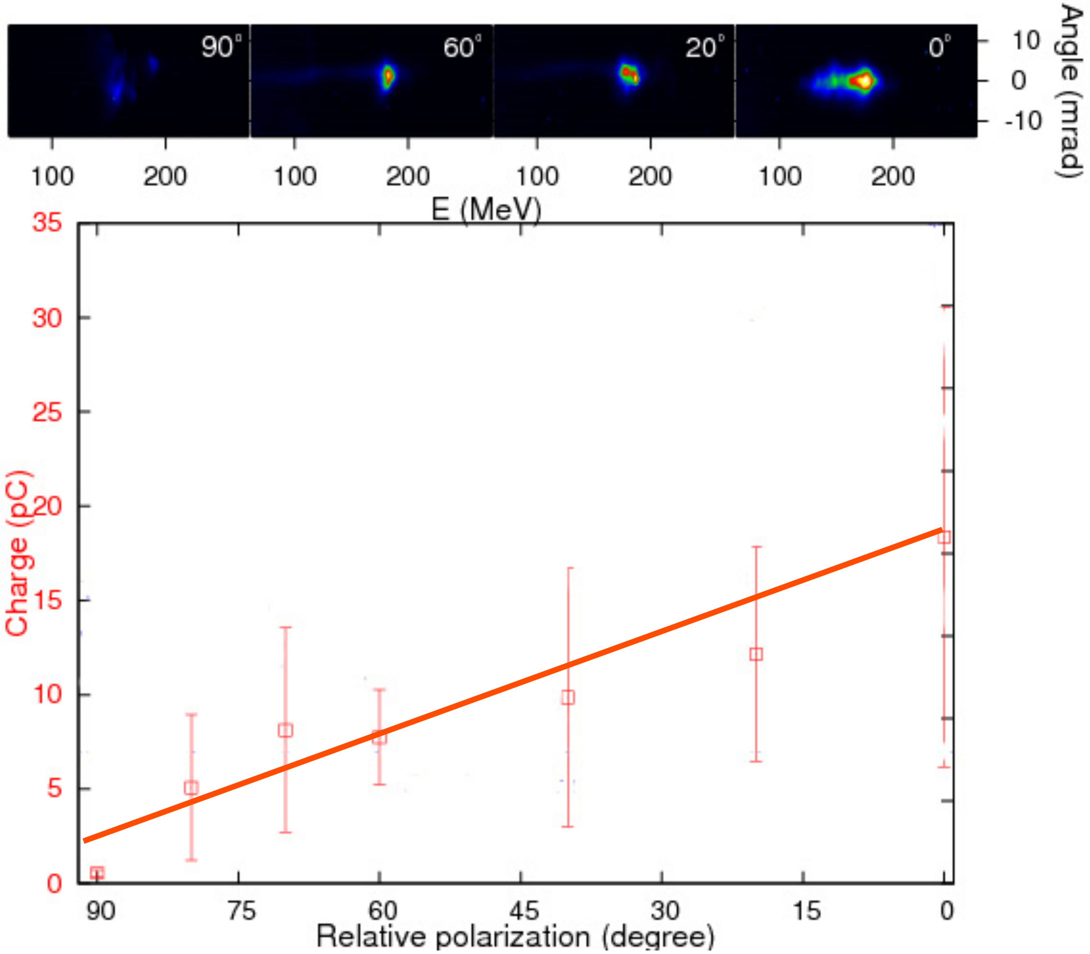
Tuning the charge and the energy spread with injection beam intensity a_1



Charge from 60 pC to 5 pC, ΔE from 20 to 5 MeV

C. Rechatin et al., Phys. Rev. Lett. 2009

Tuning the charge with the polarization angle



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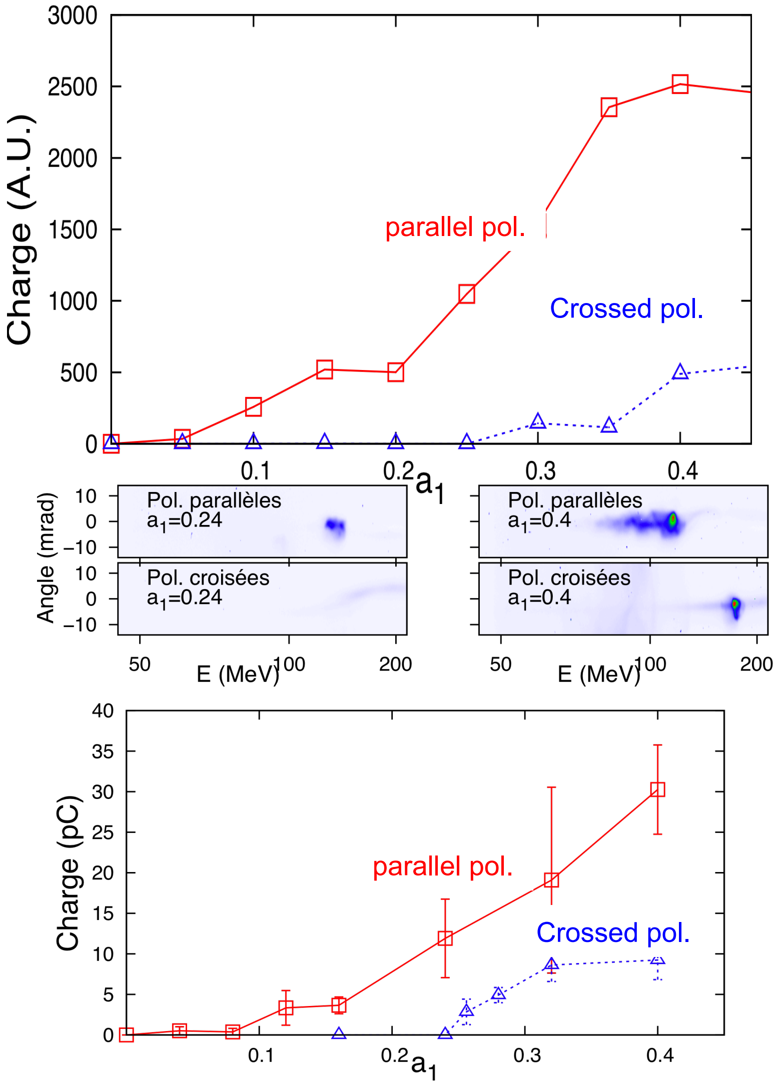
Summary of charge for II & ⊥ Polarization



PIC simulations (1D)

≠ Injection threshold

3-5 less charge

=> Good agreement with experimental data

=> Stochastic heating and plasma wave inhibition

C. Rechatin *et al.*, **NJP11,** 013011 (2009)

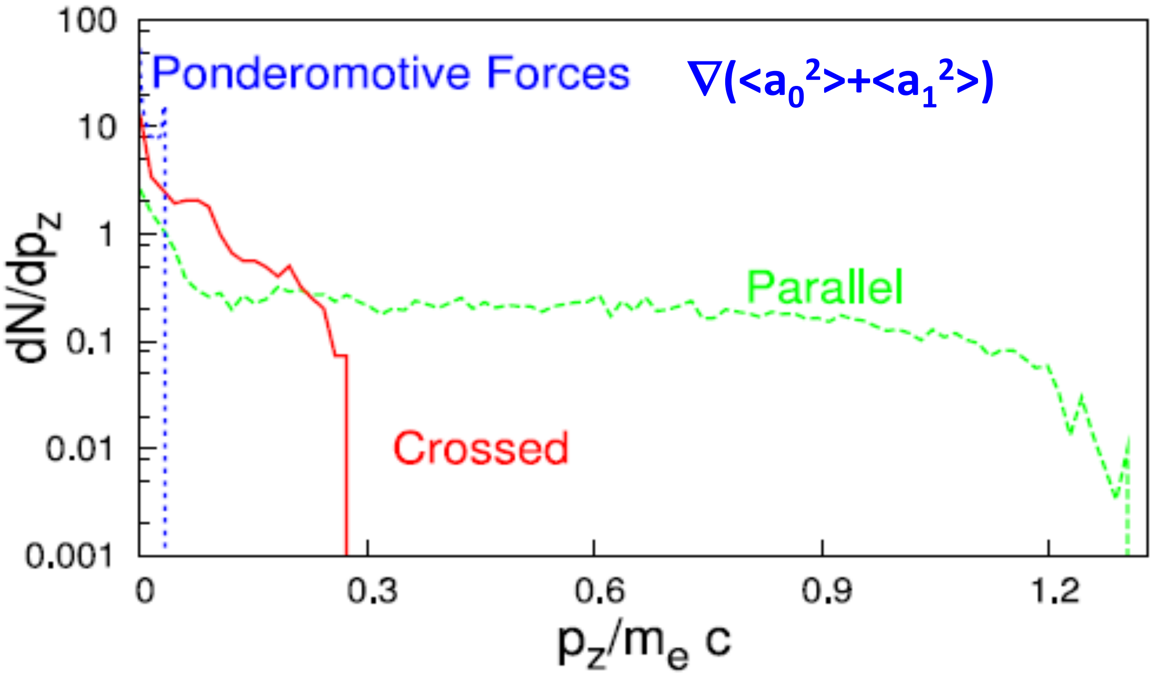
V. Malka *et al.*, **Phys. Plasmas** (2009)

Stochastic heating with cross-polarized laser pulses

electrons in : - the superposition of two laser fields
- in vaccuum

$a_0=2$

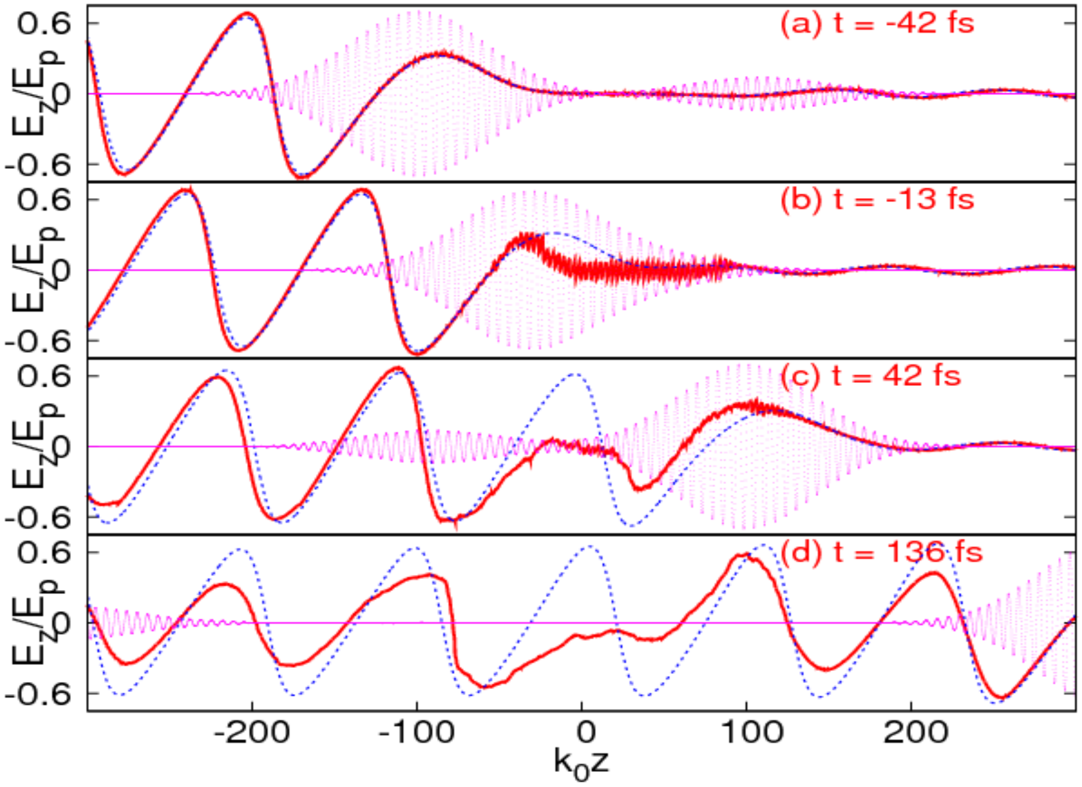
$a_1=0.4$



- **For orthogonal polarization: stochastic heating is still present ($a_0>1$, p_z component)**
- **For linearly polarized lasers, the stochastic heating mechanism is more efficient**

Parallel polarizations: beatwave & wake inhibition:

1D PIC, parameters :a_0=2, a_1=0.4, τ=30 fs, n_e=7 10^{18} cm $^{-3}$



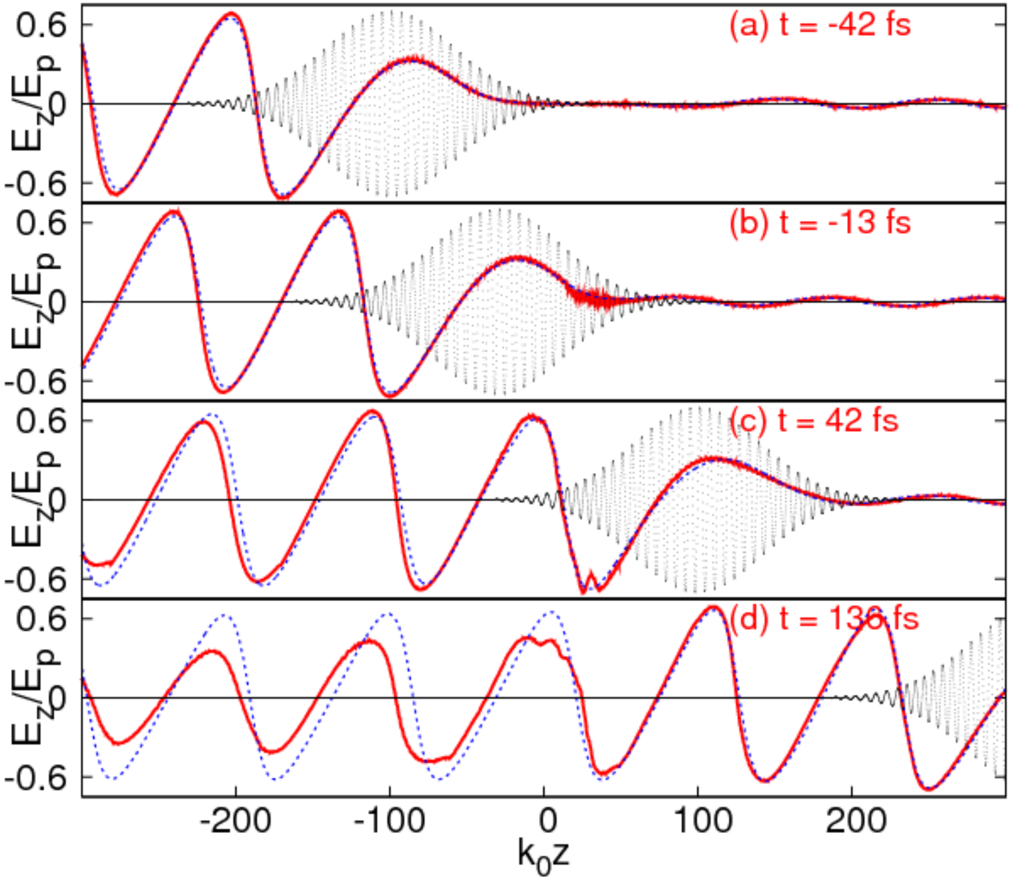
The beatwave prevents a large scale collective oscillation and thus the plasma wave excitation :

=>The wakefield is inhibited at the collision position.

=>Trapping is more difficult

Orthogonal polarizations: no beatwave, no wake inhibition:

1D PIC, parameters :a_0=2, a_1=0.4, τ=30 fs, n_e=7 10^{18} cm $^{-3}$



Crossed polarization:

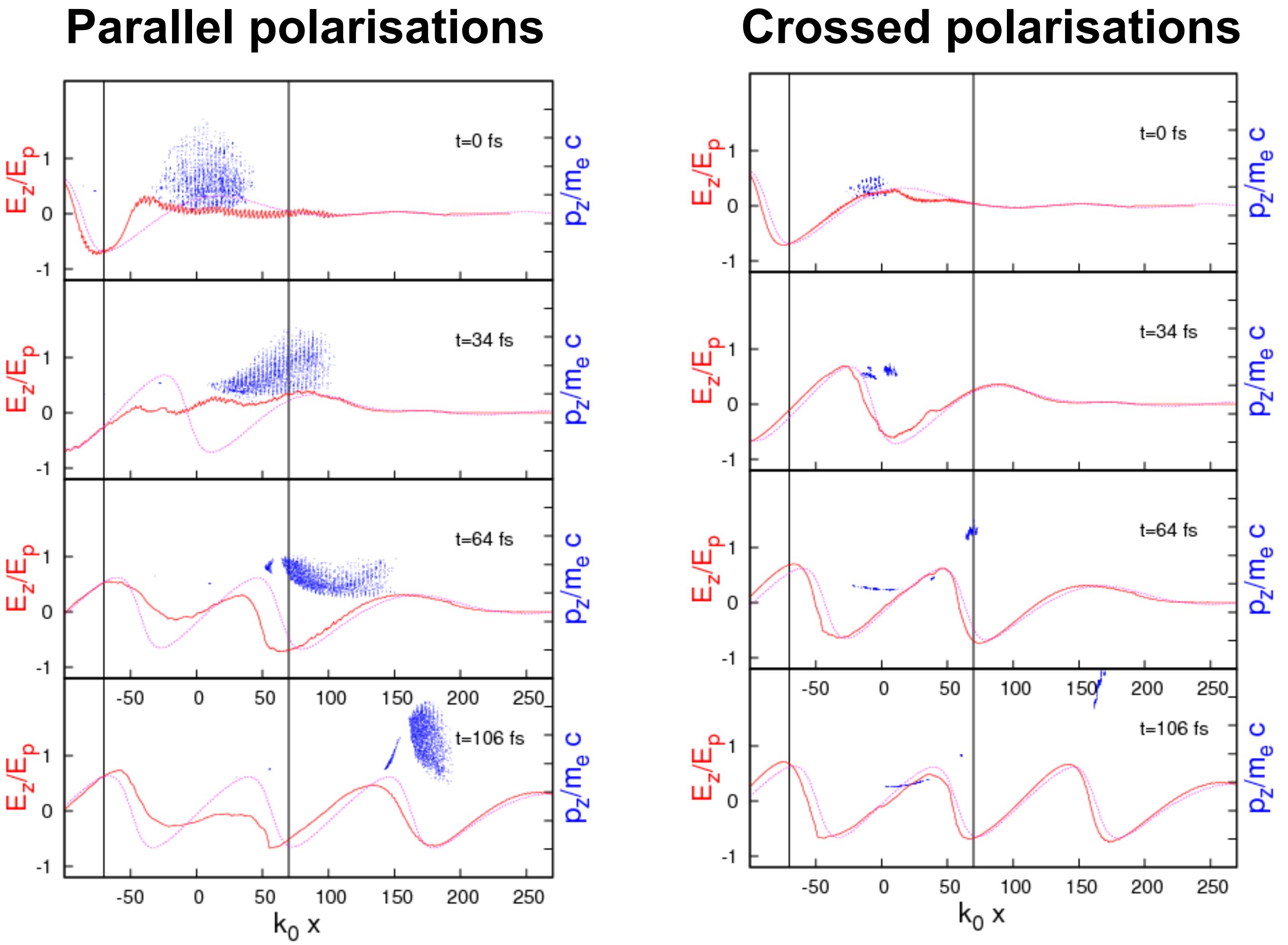
=>no beatwave

=>no wake inhibition

=>Trapping is easier

C. Rechatin *et al.*, **Physics of Plasmas 14,** 060702 (2007)

Electron dynamic: case of parallel and crossed polarisations

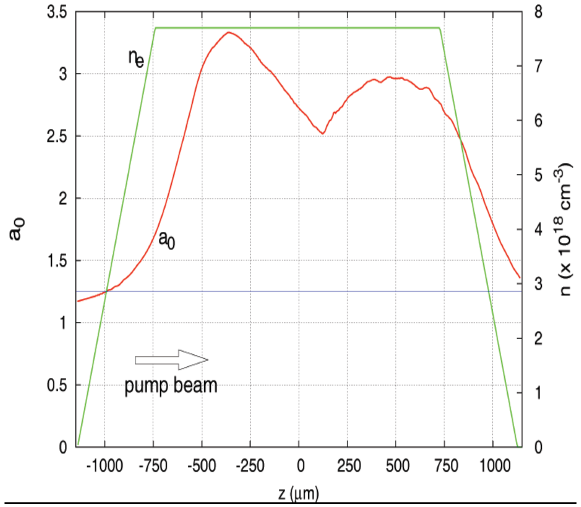


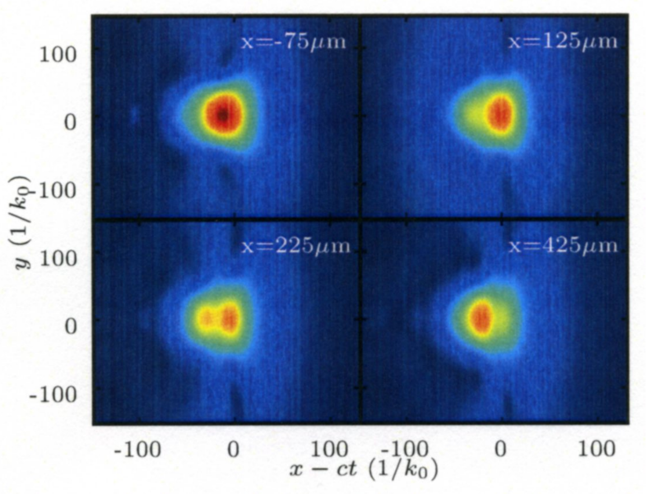
V. Malka et al., **Phys. of Plasmas 16,** 056701 (2009).

3 D PIC simulations results

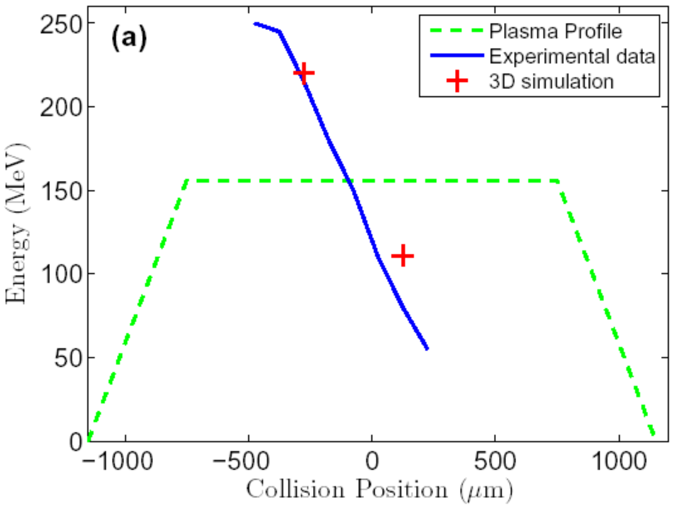
3D PIC simulations feature of laser evolution is needed to predict precisely experimental data.

Evolution of laser Amplitude and Shape





Energy evolution



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

Summary

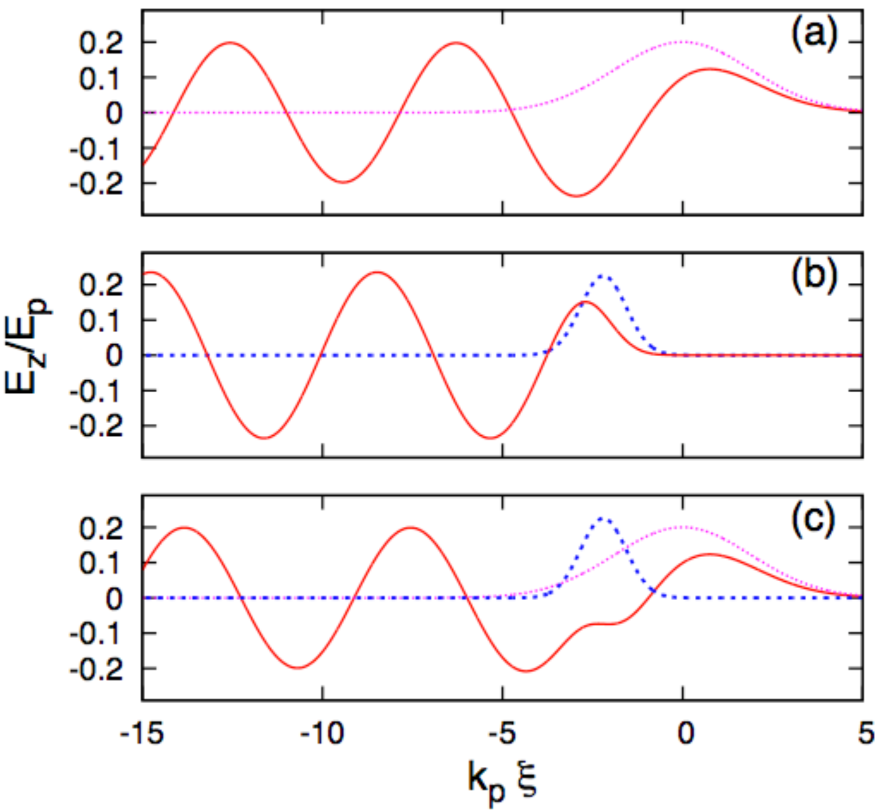
Part 1 : Controlling the e-beam parameters with two colliding laser pulses

Part 2 : Beam loading effects

Part 3 : Conclusion and perspectives

Beam Loading : Linear regime

Parameters: n_e=1.5 10^{19}cm^{-3},τ =35fs, E=0.6J, I=2 10^{18} W/cm^2



Laser wakefield

n_e=7 10^{18}cm^{-3},τ = 30fs, a_0 = 0.5

E-beam wakefield

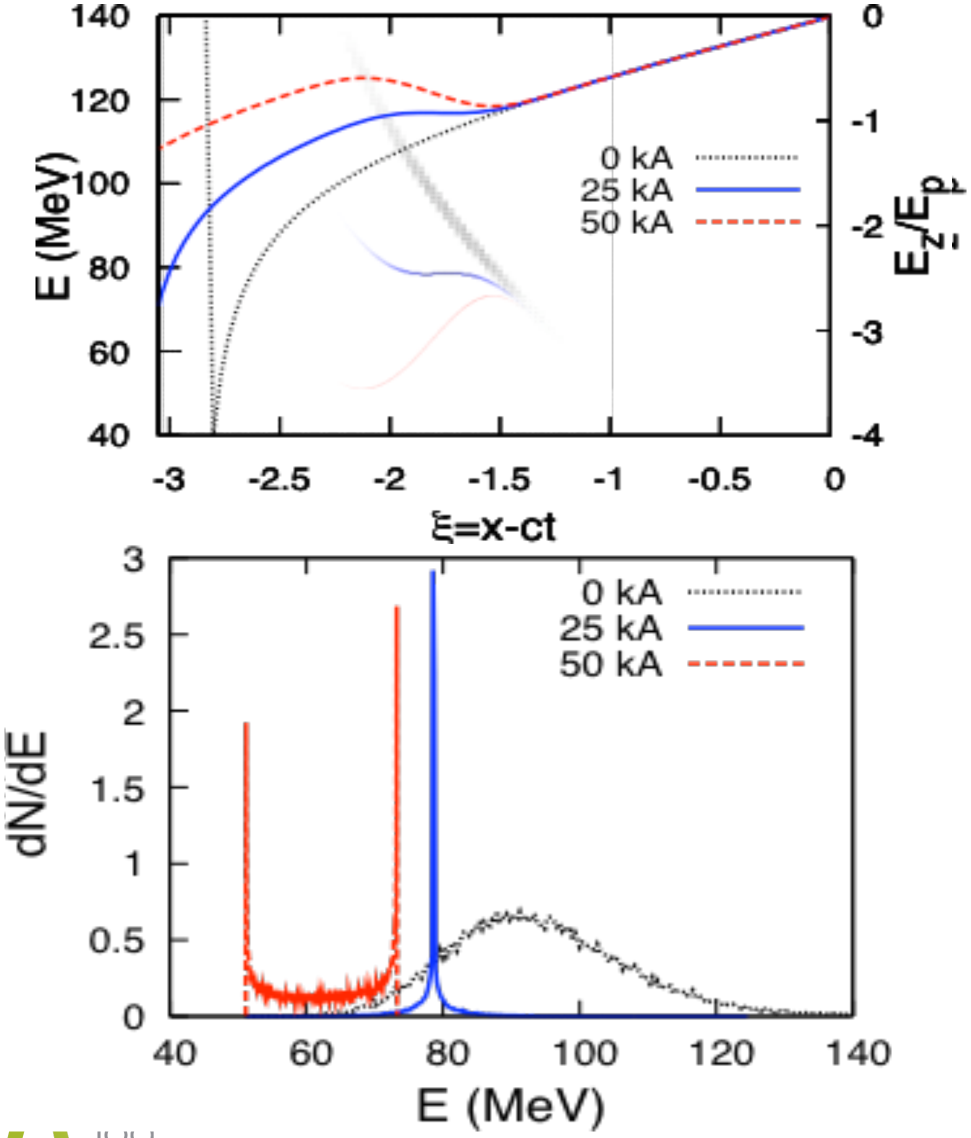
n_b/n_e=0.11, τ = 10fs, d_{FWHM}=4μm (Q=7pC)

The end of the bunch experiments a modified wakefield (less accelerated electrons)

Limitation of the accelerated charge
Influence on energy and energy spread

T. Katsouleas 87 *et al.*, M. Tzoufras *et al.*, Phys. Rev. Lett.,101 (2008)

Beam Loading (NL regime) : Observables



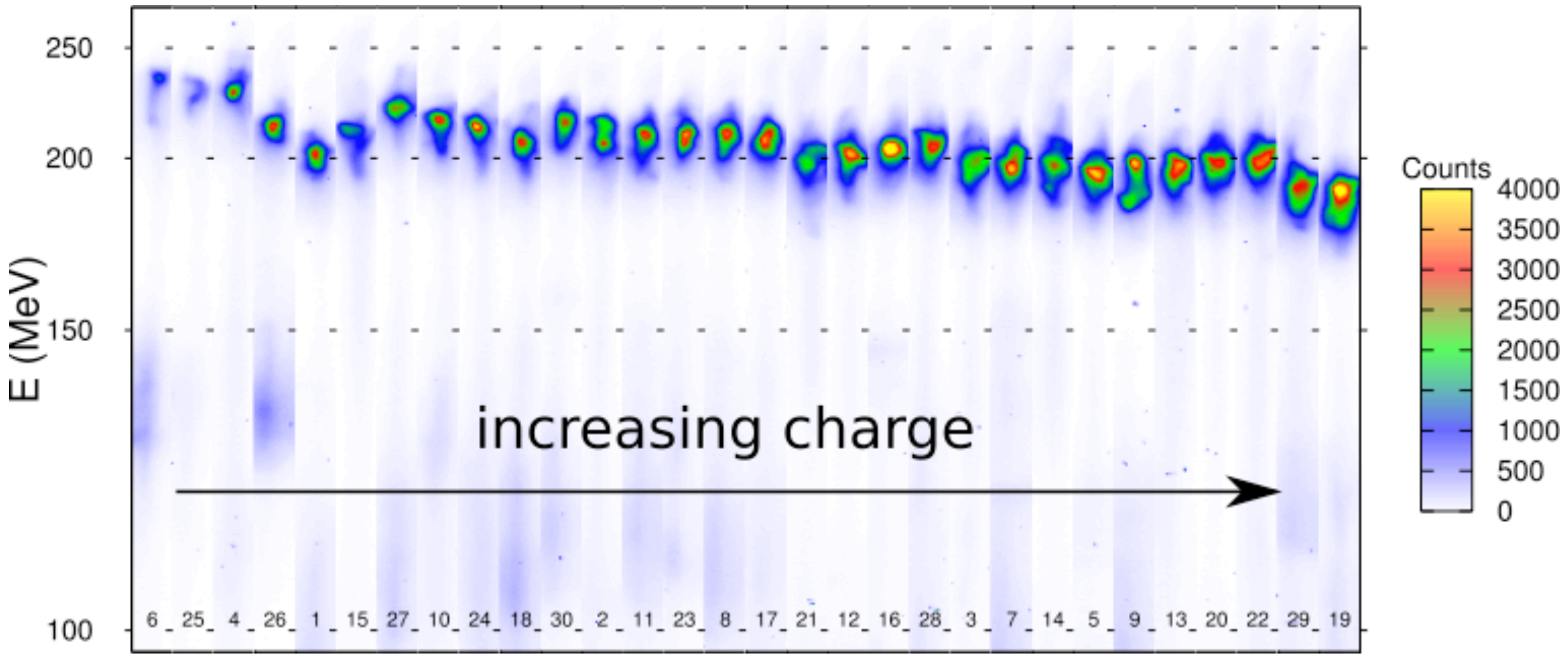
Low charge
=> Energy spread important

Optimal charge
=> Flat E-field
=> Low energy spread

High charge
=> End of the beam decelerated
=> High energy spread

Observables : correlation charge / energy spread and energy

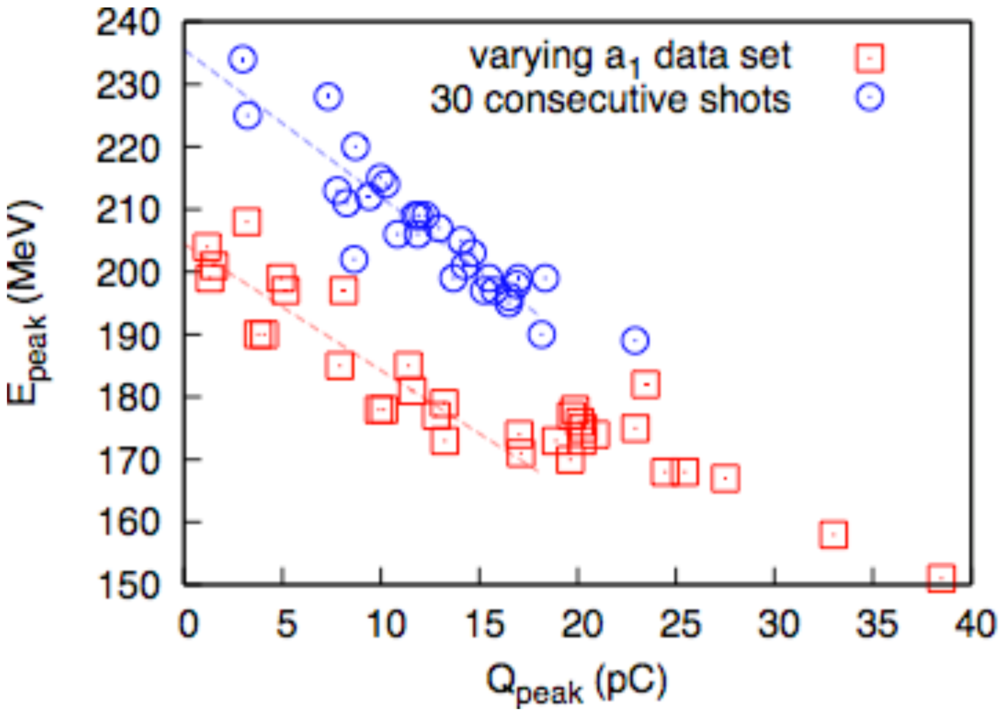
Clear correlation between charge and energy

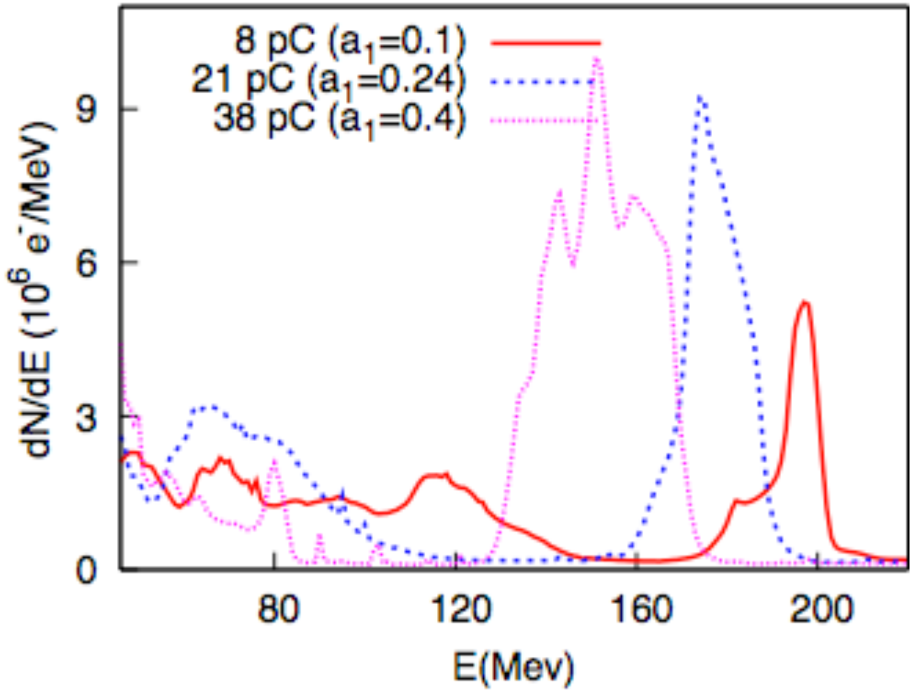


Correlation !

Clear correlation between charge and energy

A varying a_1 data set gives a broader charge variation



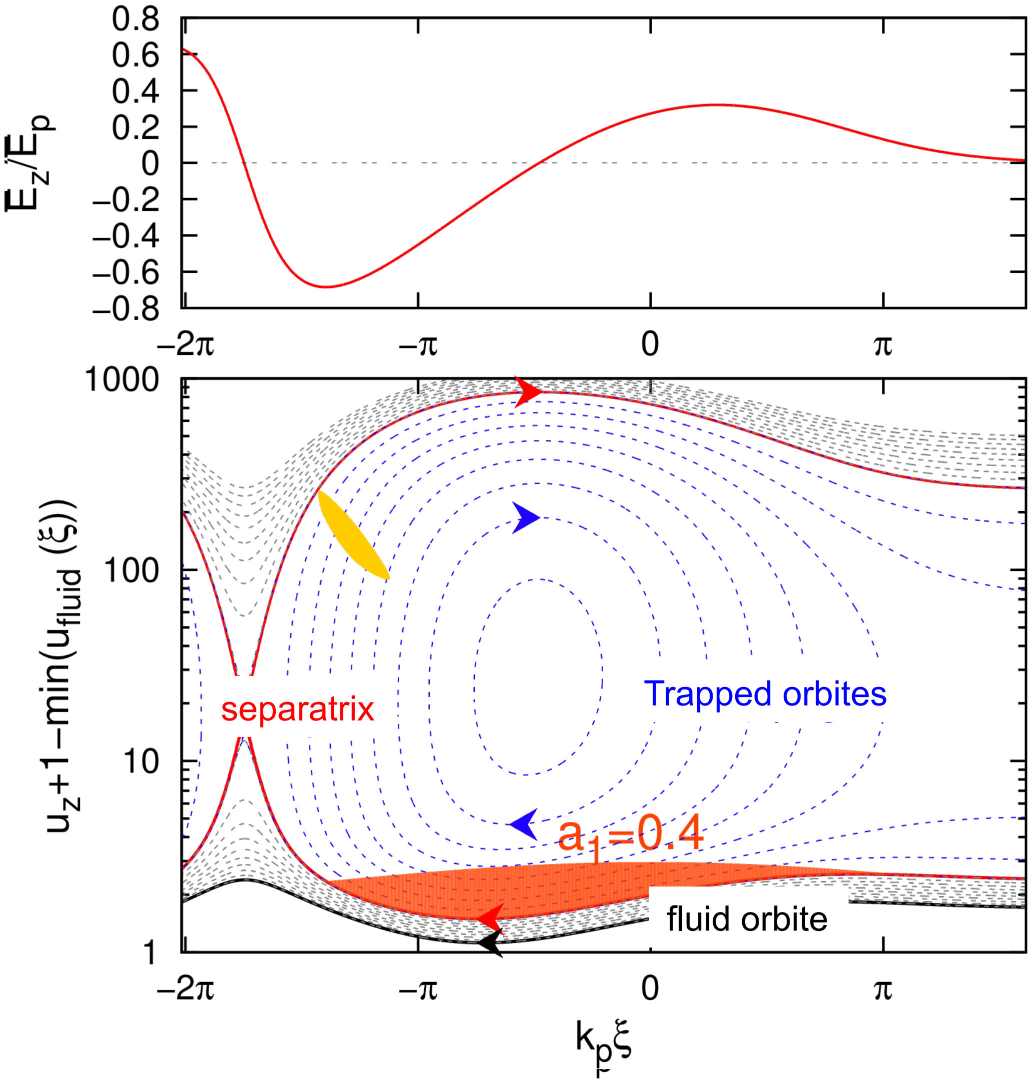


Both data sets give a decelerating field per charge of : 1.6 $GV.m^{-1}.pC^{-1}$

High energy cut-off and low energy cut off are shifted

Is it only due to beam loading effects?

Injection volume effect on electrons energy



When a_1 increases:

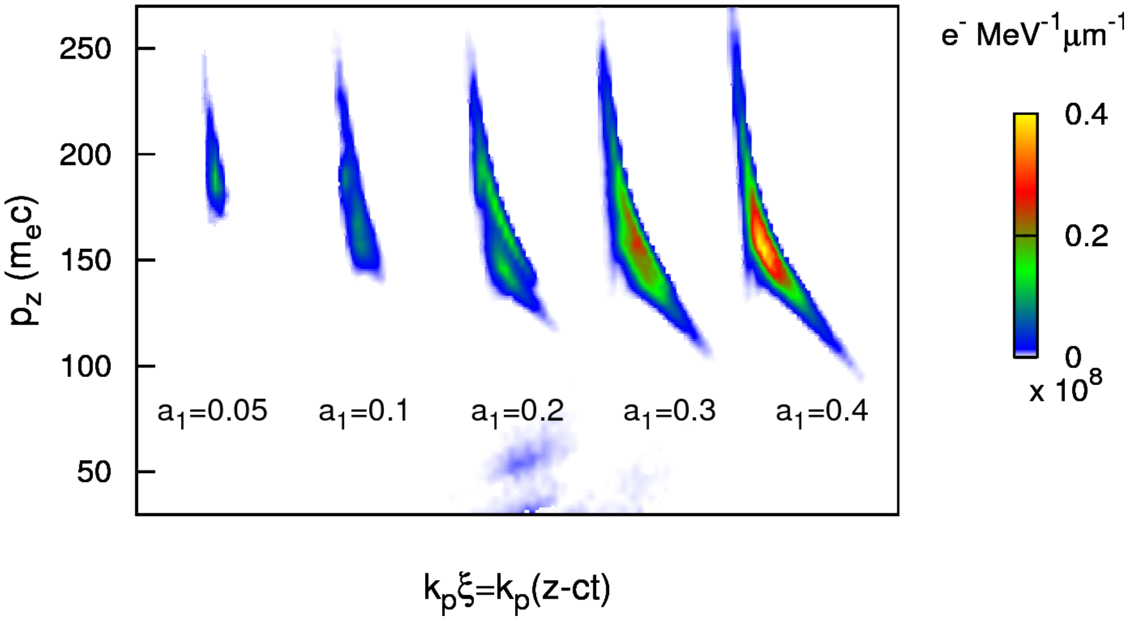
- Electrons are more heated during the collision
- They are trapped far away from the speratrix (i.e. lower E field)
- They are less accelerated

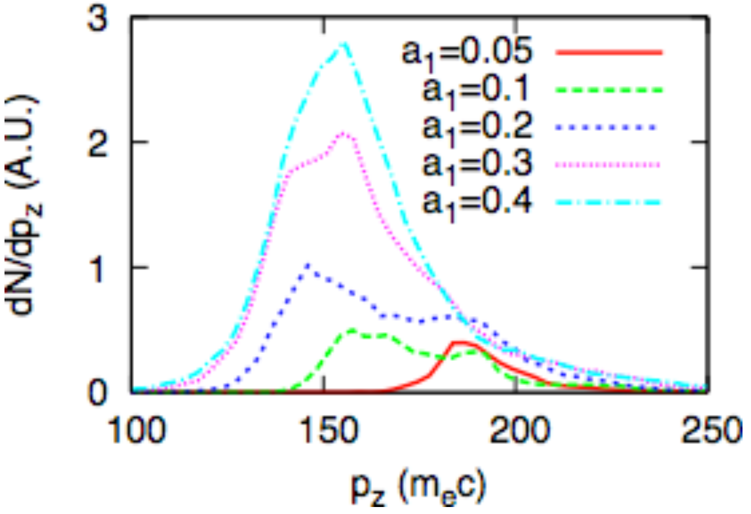
Both effects will decrease the electron energy

⇒Need of PIC simulations to conclude

Simulations without Beam loading effect
Change of injection volume only

3D PIC simulations with experiment parameters (300 μm acceleration)
with $p_z > 12 m_e c$ are treated as test particle : no beam loading



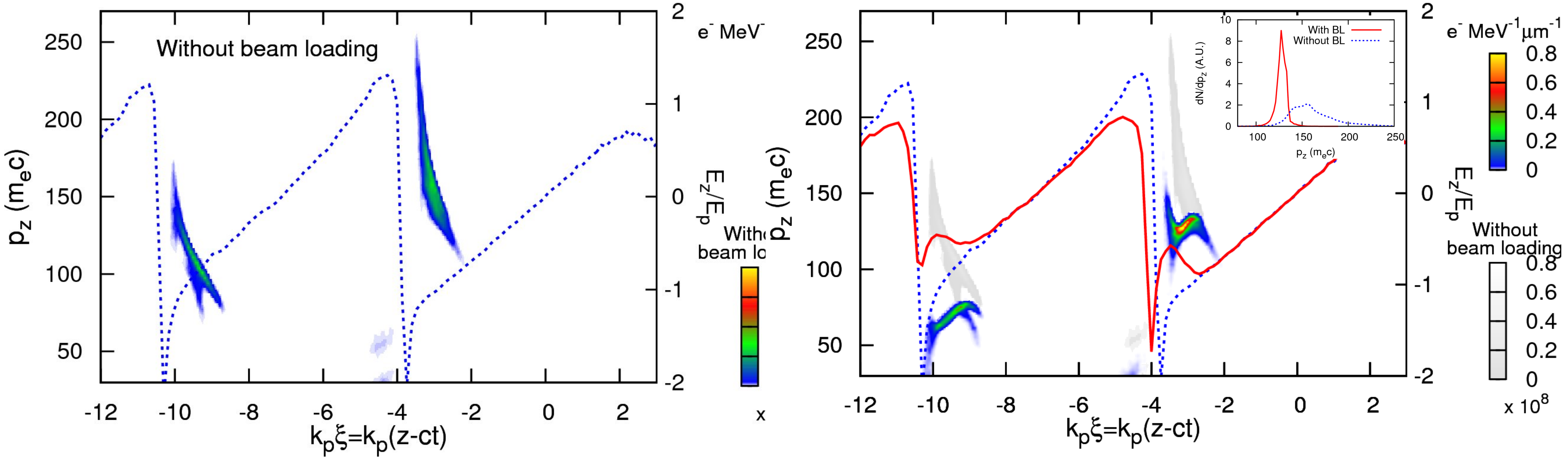


Same high energy cut-off
Decrease of low energy cut-off

Beam loading effects

3D PIC simulationsof the experiment with and without beam loading

$a_1=0.3$, $Q_{peak}= 48pC$



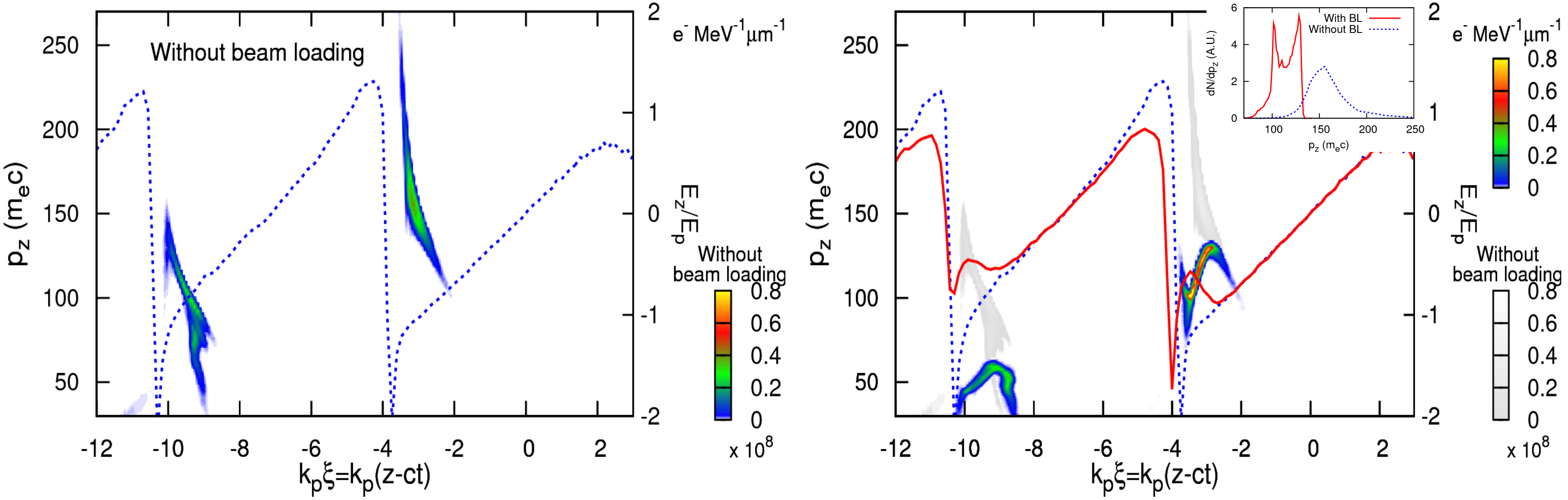
Only changes the high energy cut-off => BL improves the energy spread

Experiment : 0.8 GV.m^{-1}.pC^{-1}, simulations : 1 GV.m^{-1}.pC^{-1}

Beam loading only : over an optimal loads

3D PIC simulations of the experiment with and without beam loading

a_1=0.4, Q_{peak}= 72pC

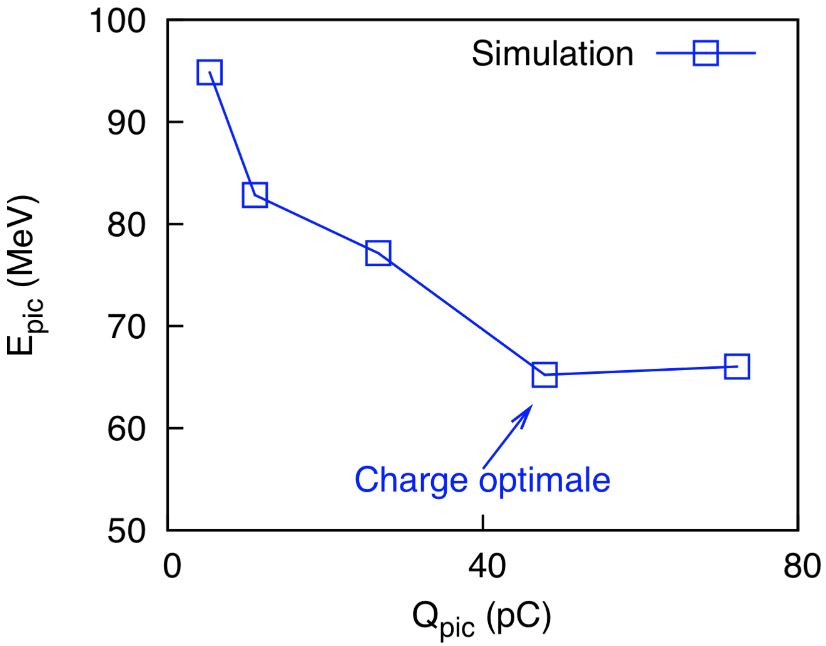


Leading electrons have the highest energy : BL deteriores the energy spread

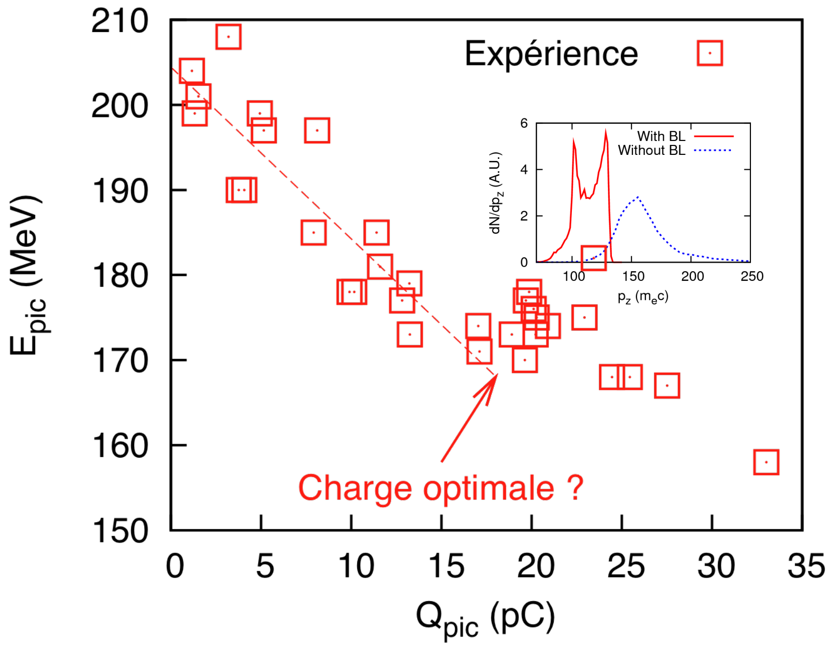
Optimal load : 20-40 pC

Measurement of the optimal charge

Behaviour for optimal charge : experiments/simulations



Simulations PIC : Q_{tot} ~ 50 pC



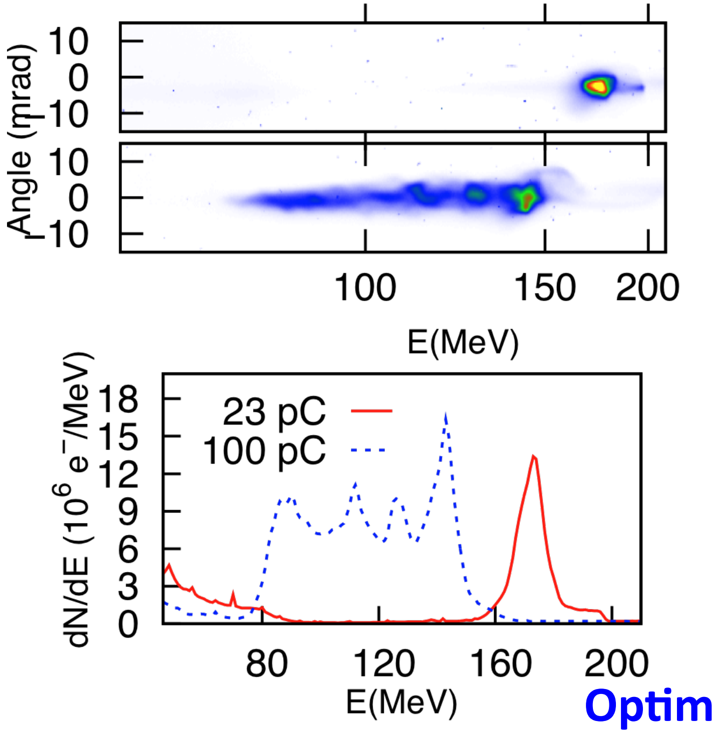
Expériences PIC : Q_{tot} ~ 20 pC

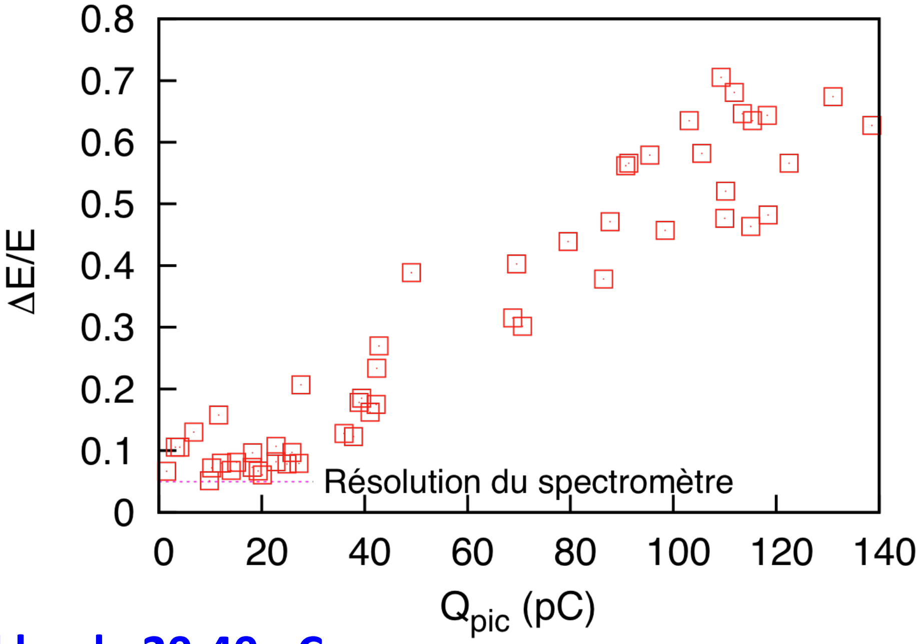
Optimal load : 20-40 pC

Optimum charge and energy spread

For an charge less than the optimum :
an increase of the charge will increase ΔE due to the increase of the injection volume
& a reduction of ΔE due to beam loading effect

For charge greater that the optimum : Both effects will increase the energy spread

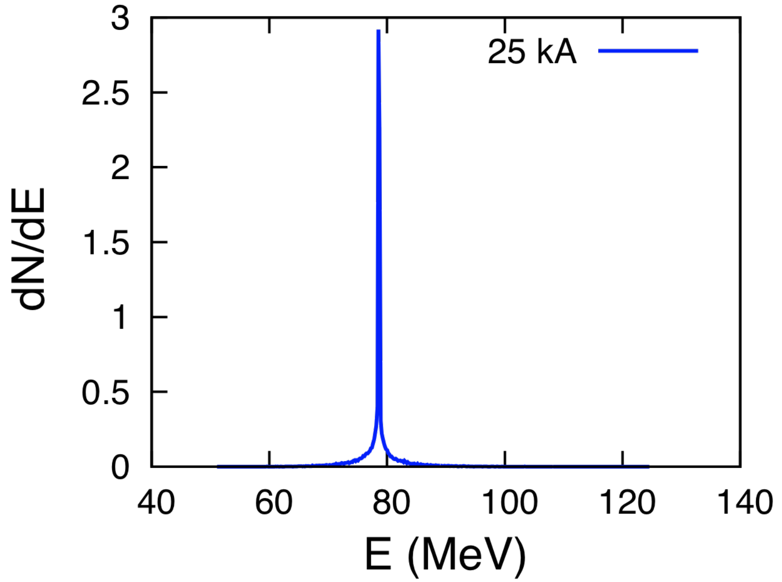




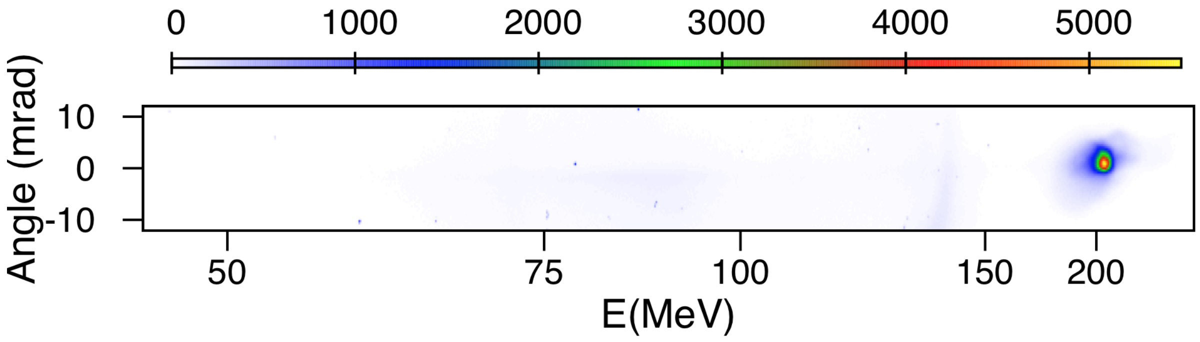
Optimal load : 20-40 pC

C. Rechatin *et al.*, Phys. Rev. Lett. 2009

What is the miminal energy spread?



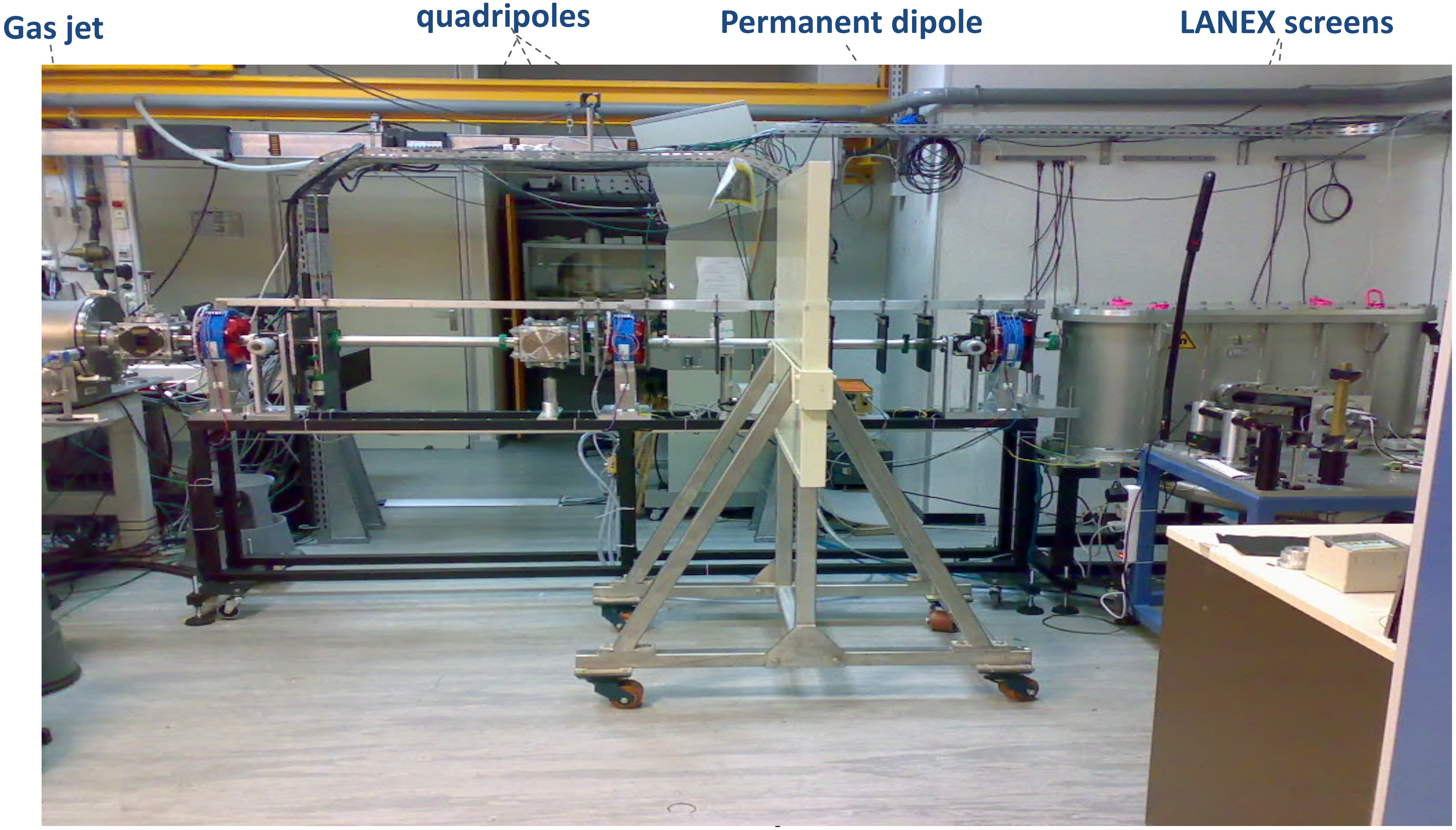
The theory predicts less than 1% energy spread for charge close to the optimam charge



Measurements limited by the Spectrometer resolution

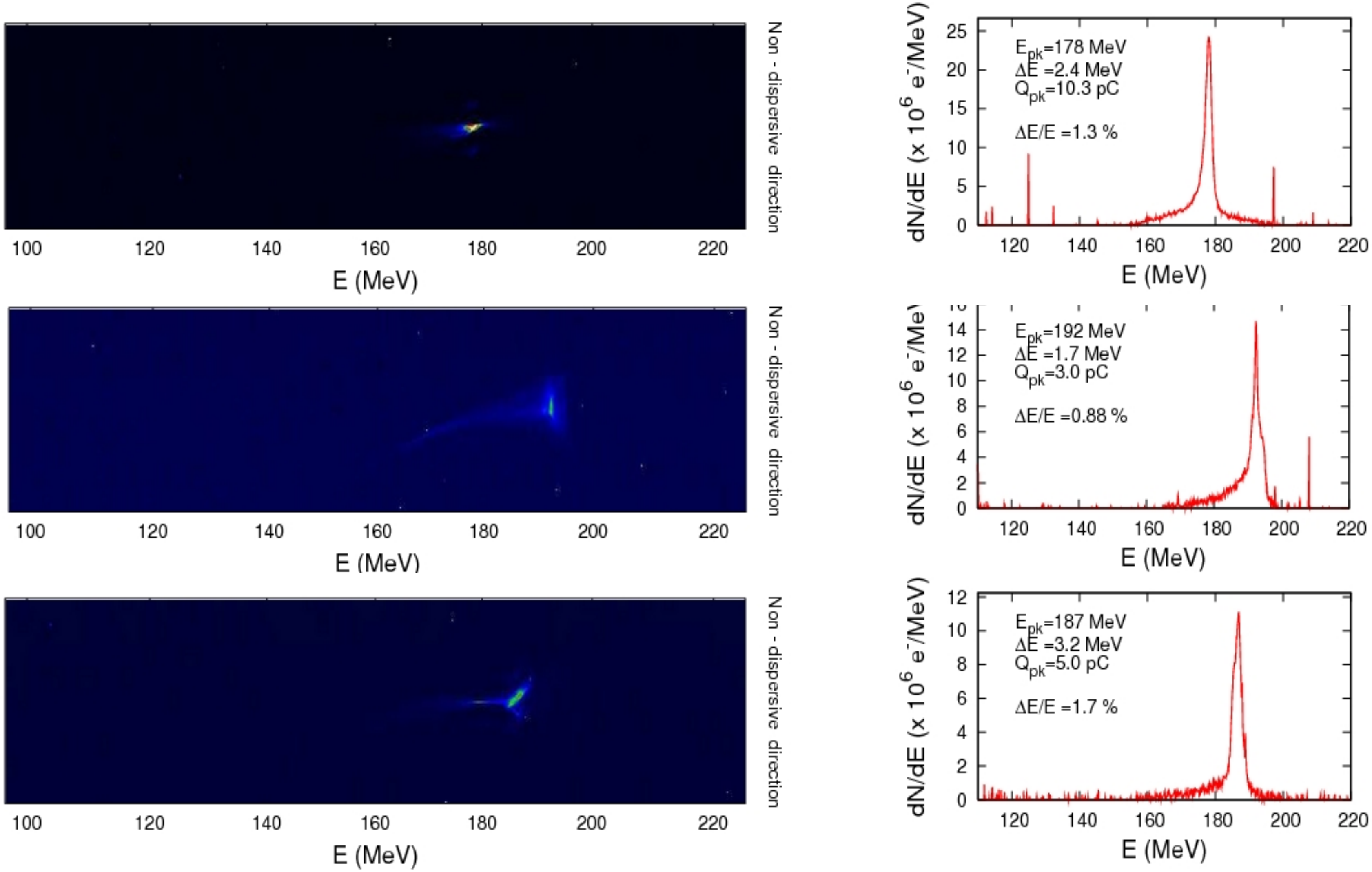
C. Rechatin *et al.*, Phys. Rev. Lett. 2009

High resolution electron spectrometer



In collaboration with A. Specka, H. Videau
LLR, CNRS, Ecole Polytechnique

1% energy spread beams



C. Rechatin *et al.*, **PRL, 102,** 164801 (2009)

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Conclusion

Accelerators point of view : Two laser beams allow the control of many e-beam parameters

- Good beam quality & **Monoenergetic dE/E down to 1 %** √
- Beam is very stable √
- Energy is tunable: 20-300 MeV √
- Charge is tunable: 1 to tens of pC √
- Energy spread is tunable: 1 to 10 % √
- Ultra short e-bunch (see O. Lundh): 1,5 fs rms √

Physics point of view : many new aspects of the interaction have been revealed :

Heating processes with crossed polarized lasers √

Inhibited plasma waves effect √

Beam loading effect : optimum charge of 20pC √

Perspectives

What Next ?

- Push energy limit (>1 GeV)
- Measure the emittance
- Increase injected charge: larger a_1 ?
- Cold injection scheme

Results extremely important for :

Designing future accelerators
Light source development for XFEL
and for applications (chemistry, radiotherapy, material science)

V. Malka *et al.*, **nature physics 4**, June 2008