IPAC13
The 4th International Particle Accelerator Conference
第四届国际粒子加速器会议
Shanghai China
12-17 May 2013
Shanghai International Convention Center

Review of Laser Wakefield Accelerators

Victor Malka

Laboratoire d'Optique Appliquée

ENSTA ParisTech – Ecole Polytechnique – CNRS
PALAISEAU, France

victor.malka@ensta.fr

Laser Plasma Accelerators : Outline

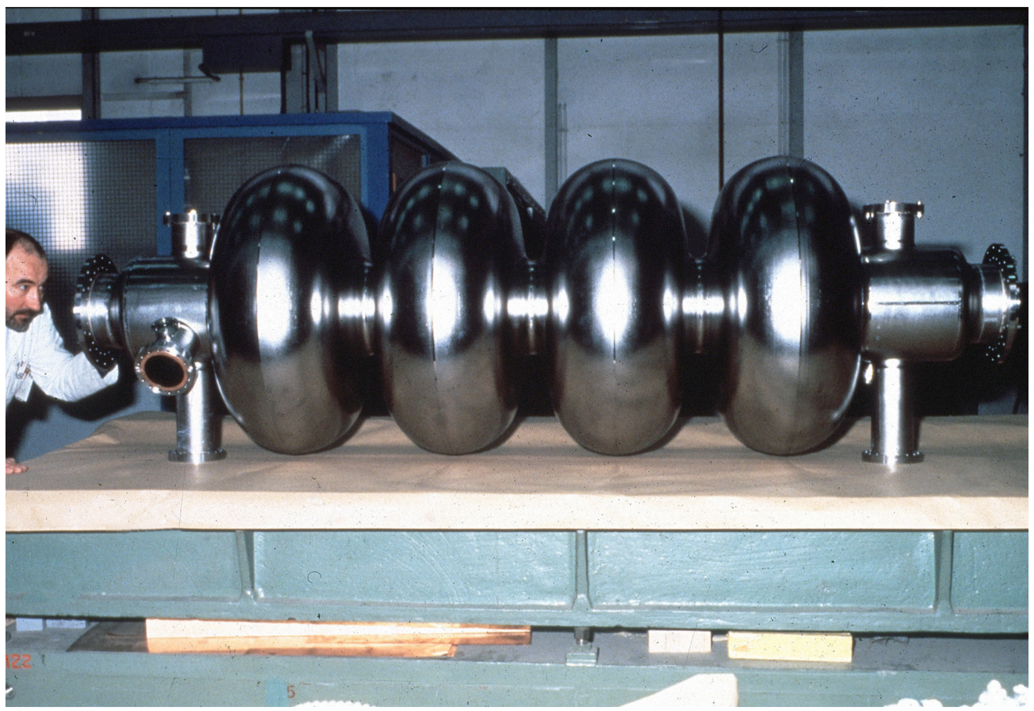
- Introduction : Laser wakefield principle and motivation
- Review of injection processes :
  - Transverse injection : Bubble/Blow out regime
  - Longitudinal injection
  - Density gradient
  - Ionization
  - Colliding
- Applications
- Conclusion and perspectives

Laser Plasma Accelerators : Outline

- Introduction : Laser wakefield principle and motivation
- Review of injection processes :
  - Transverse injection : Bubble/Blow out regime
  - Longitudinal injection
  - Density gradient
  - Ionization
  - Colliding
- Applications
- Conclusion and perspectives

High Accelerating Gradient with Laser Plasma Accelerators

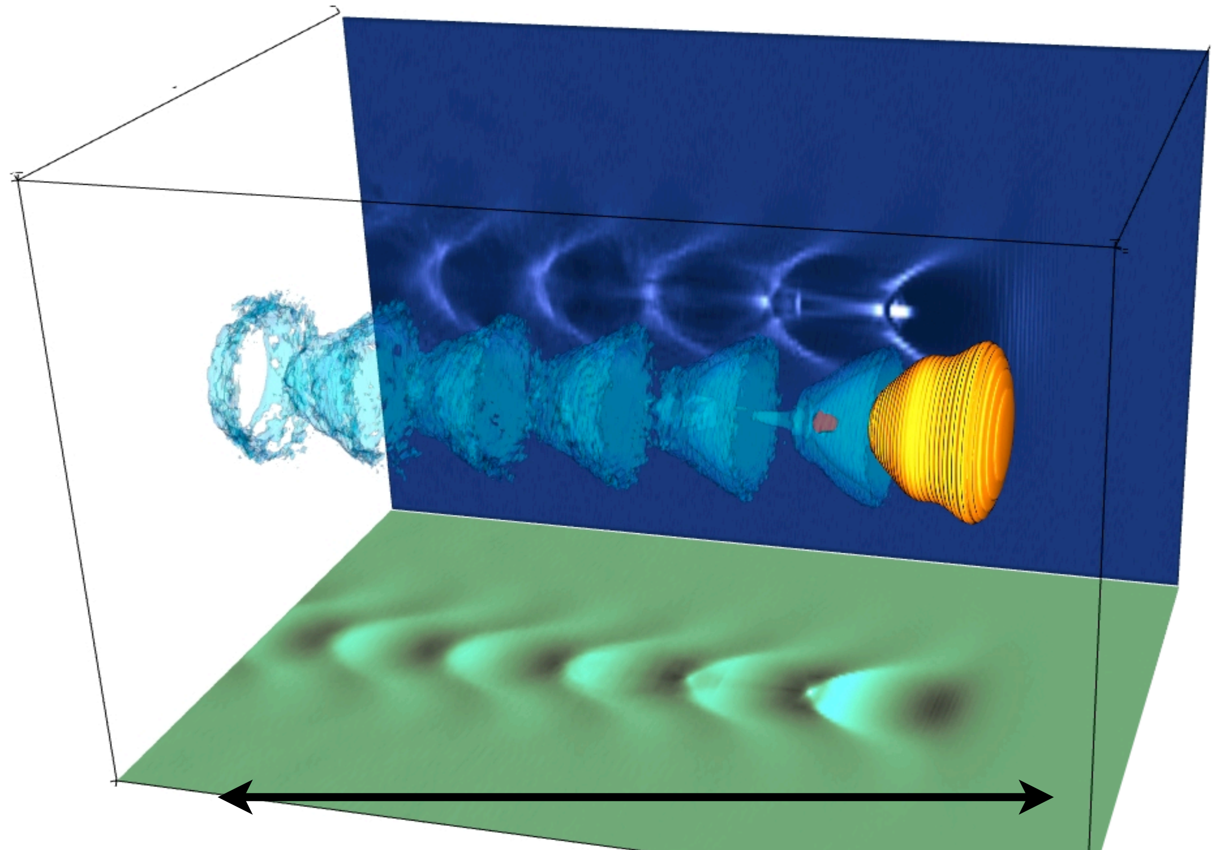
RF Cavity



1 m => 100 MeV Gain

Electric field < 100 MV/m

Plasma Cavity



1mm => 100 MeV

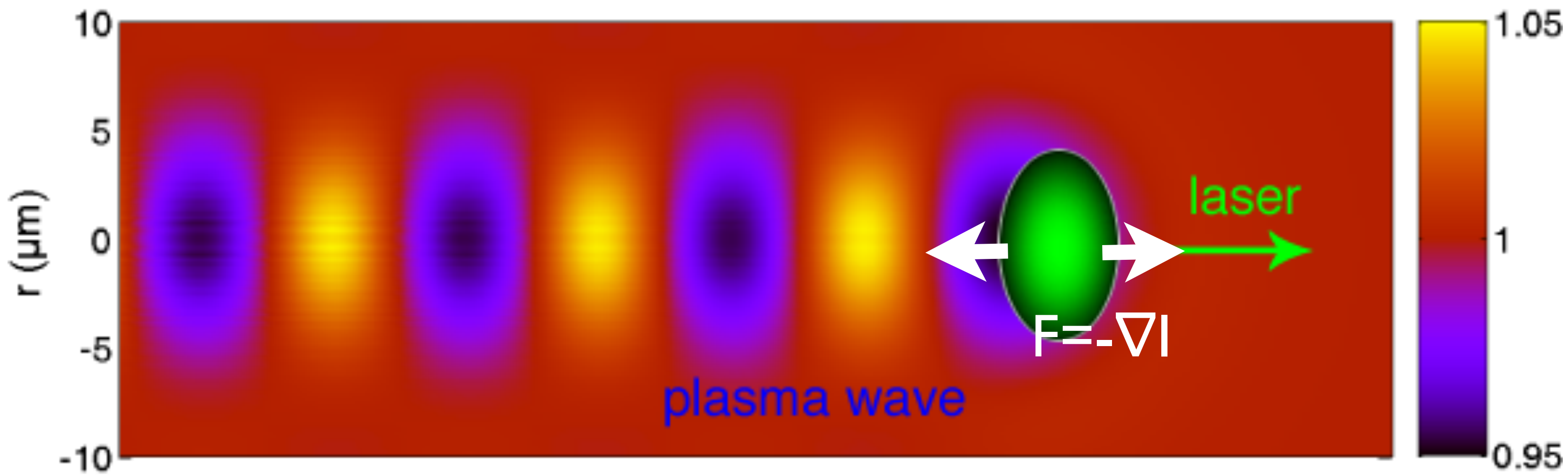
Electric field > 100 GV/m

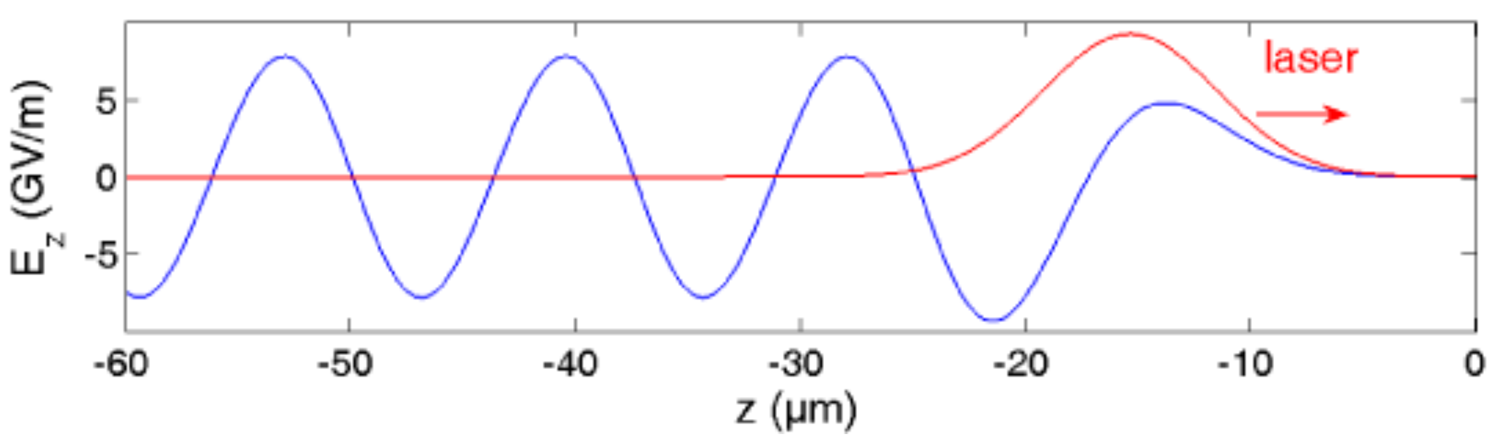
V. Malka *et al.*, Science **298**, 1596 (2002)

How to excite relativistic plasma waves ?

The laser wake field : broad resonance condition $\tau_{laser} \sim T_p/2$
=> short laser pulse

electron density perturbation and longitudinal wakefield





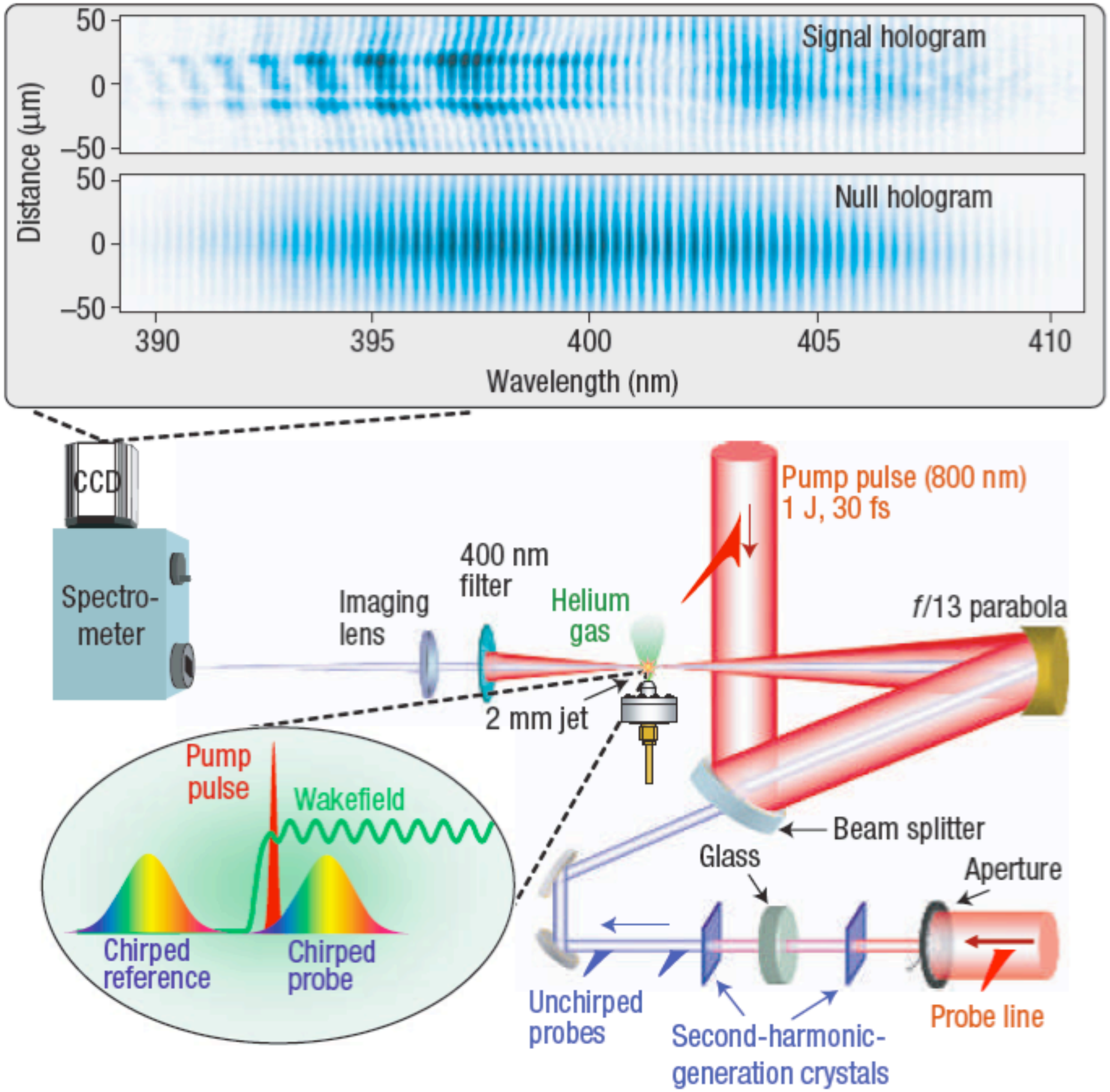
wave in the wake of a boat

E_z = 300 GV/m for 100 %
Density Perturbation at 10^{19} cc^{-1}

$v_{phase}^{epw} = v_g^{laser} \sim c$

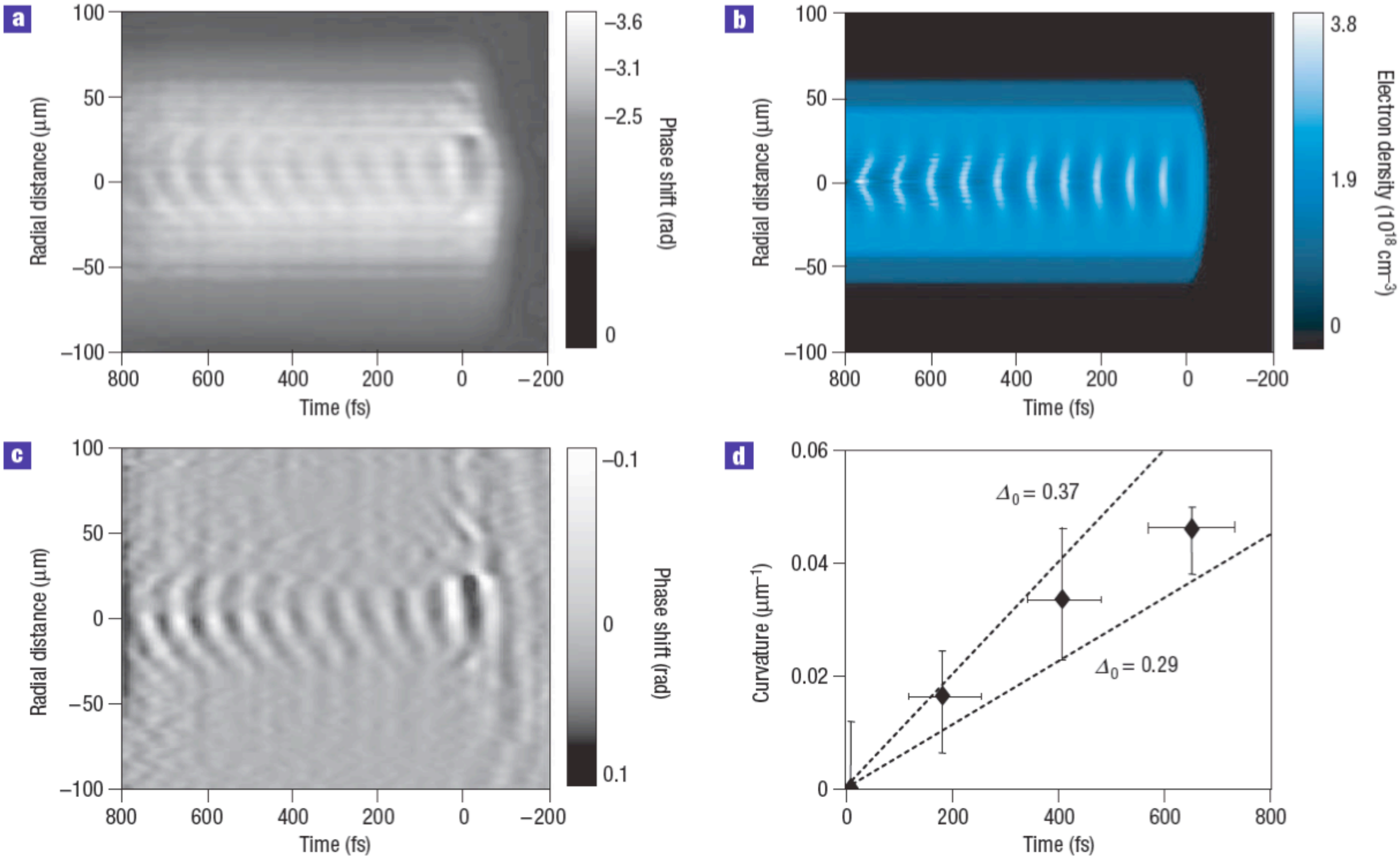
T. Tajima and J. Dawson, PRL **43**, 267 (1979)

Snapshots of laser wakefield



N. H. Matlis *et al.* , Nature Physics 2006

Snapshots of laser wakefield



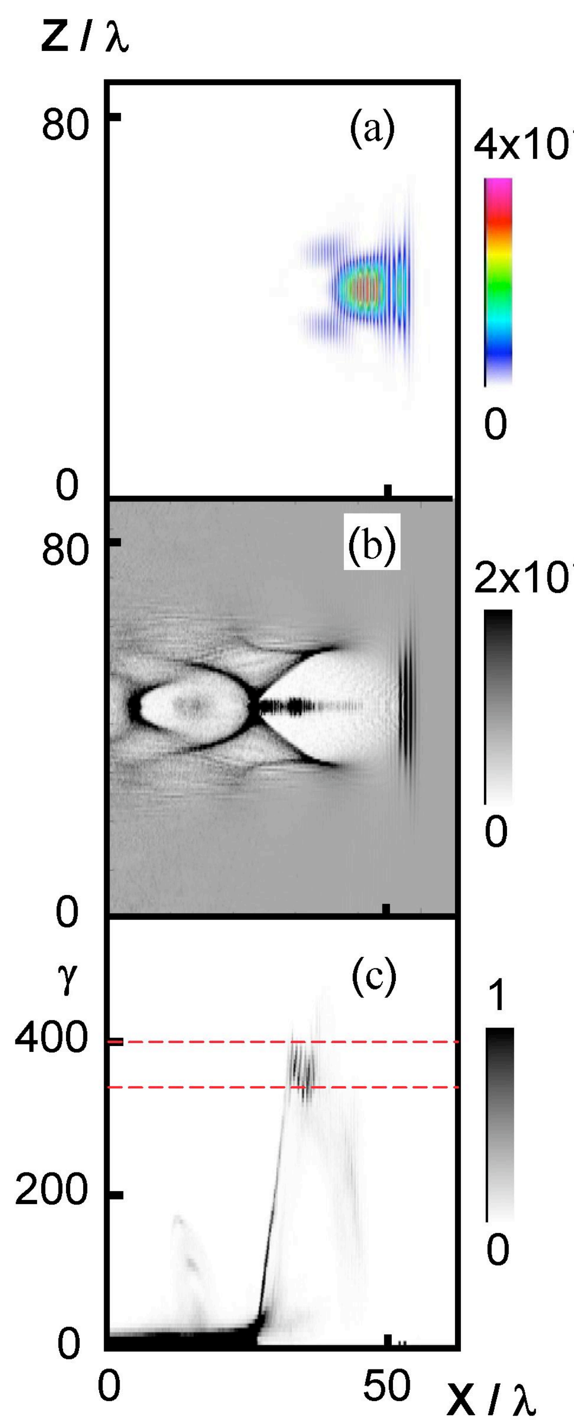
Strongly driven wake with curve wavefronts. a) probe phase profile for 30 TW at 2.2×10^{19} cm^{-3}. b) simulated density profile. d) same than a) without n_e background.

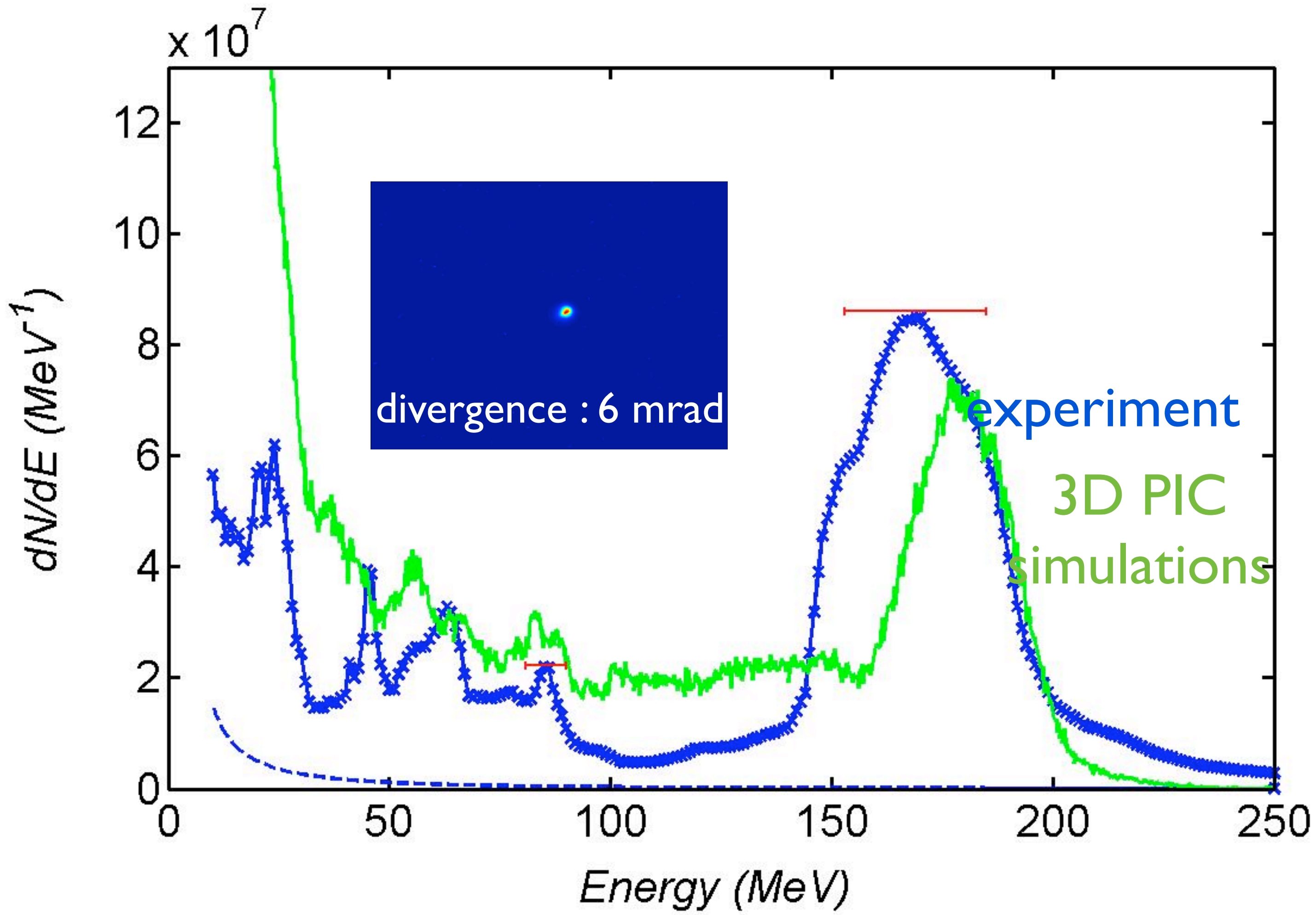
N. H. Matlis *et al.* , Nature Physics 2006

Laser Plasma Accelerators : Outline

- Introduction : Laser wakefield principle and motivation
- Review of injection processes :
  - Transverse injection : Bubble/Blow out regime
  - Longitudinal injection
  - Density gradient
  - Ionization
  - Colliding
- Applications
- Conclusion and perspectives

The Bubble regime : theory/experiments

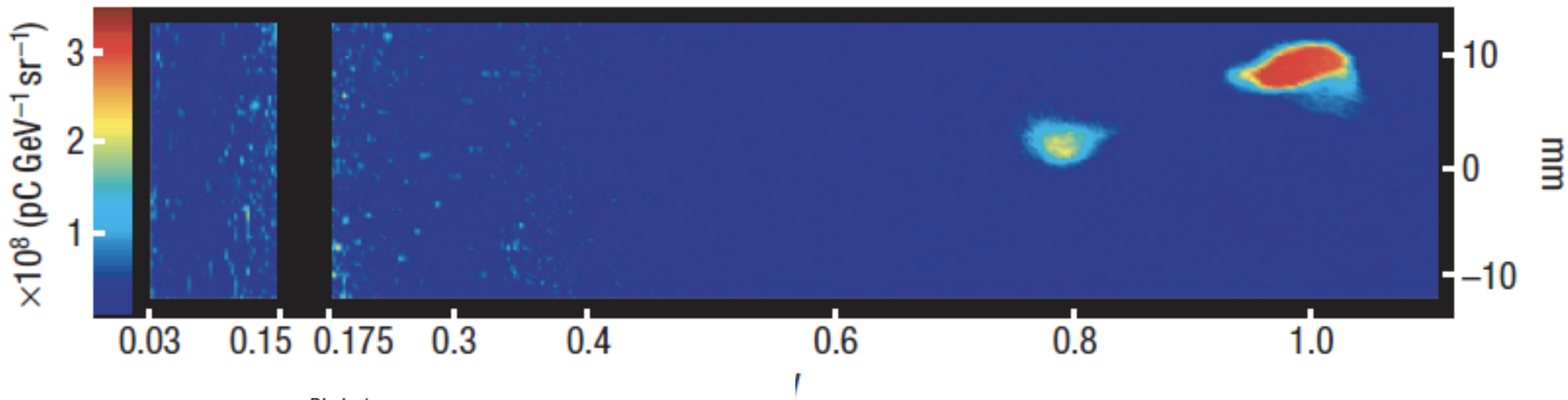


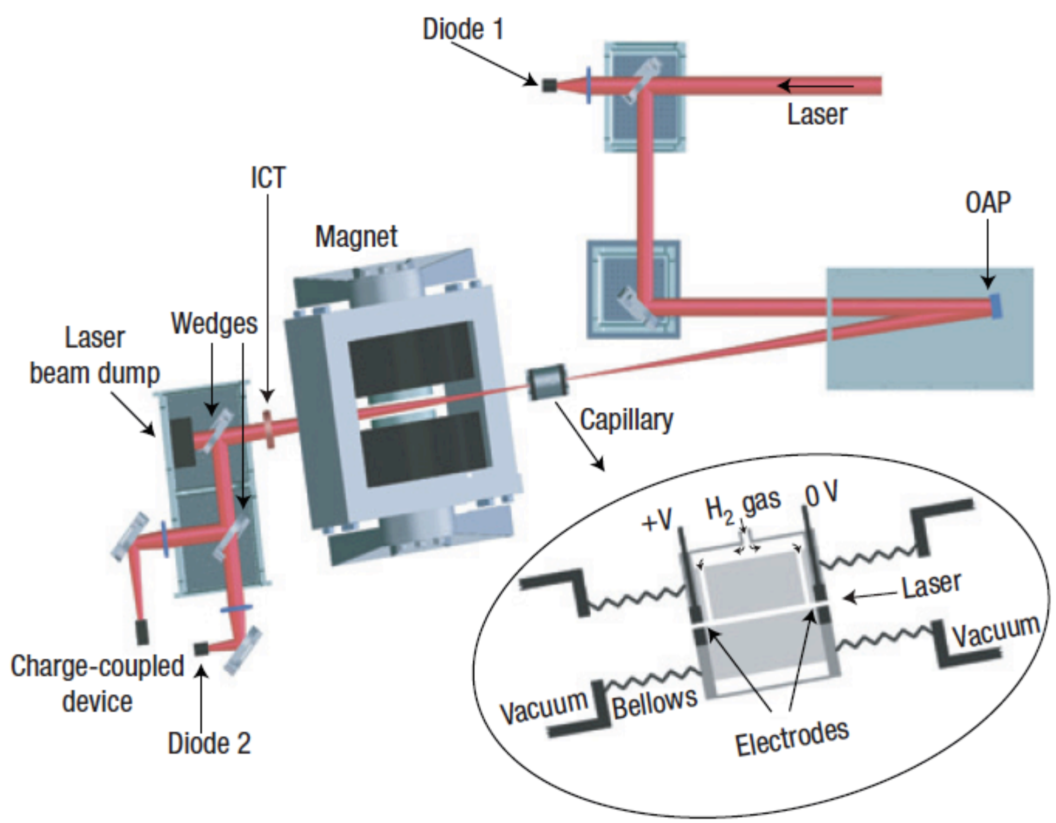


Experimental parameters : E=1J, τ_L=30fs,
λ_L=0.8µm, $I_L=3.2\times10^{19}$W/cm^2, $n_e=6\times10^{18}$cm^{-3}

S. P. D. Mangles *et al.*, C. G. R. Geddes *et al.*, J. Faure *et al.*, «Dream Beam», Nature **431** (2005)

GeV electron beams from “cm scale” accelerator





4 cm length capillary discharge

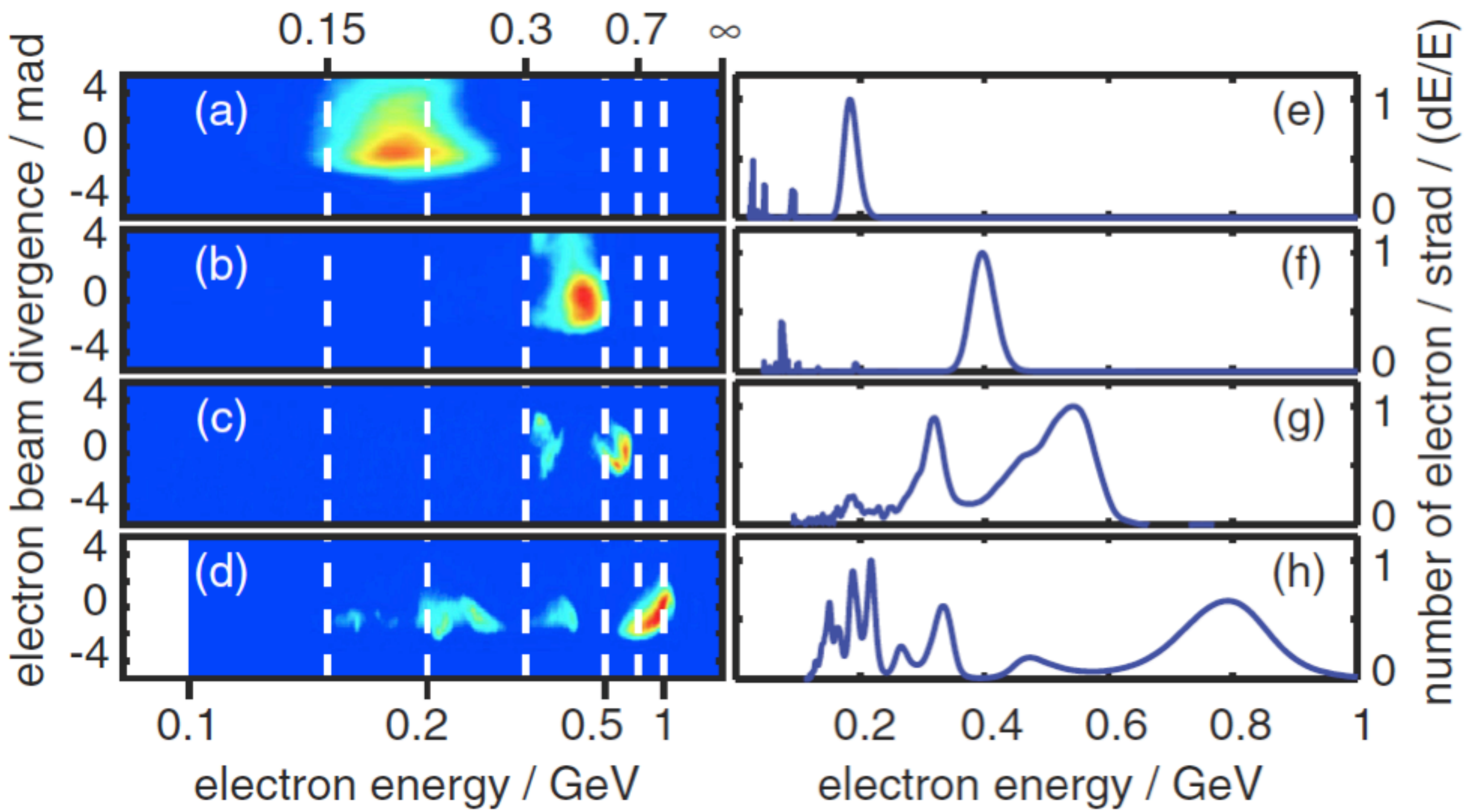
310-µm-diameter channel capillary

P = 40 TW, density 4.3×10^{18} cm^{-3}

1 GeV, 2.4 % relative energy spread, 30 pC

W. Leemans *et al.*, Nature Physics, september 2006

GeV electron beams from "cm scale" accelerator



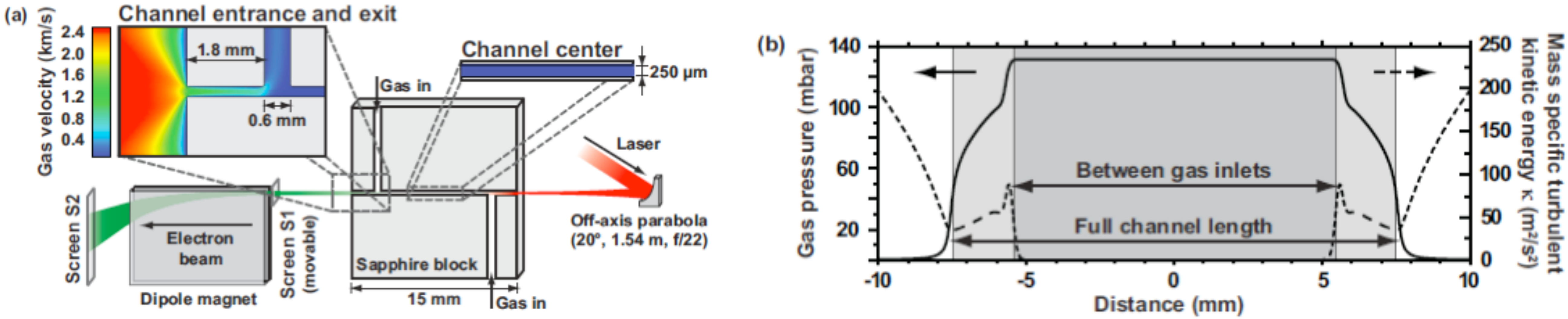
Astra Gemini laser RAL :

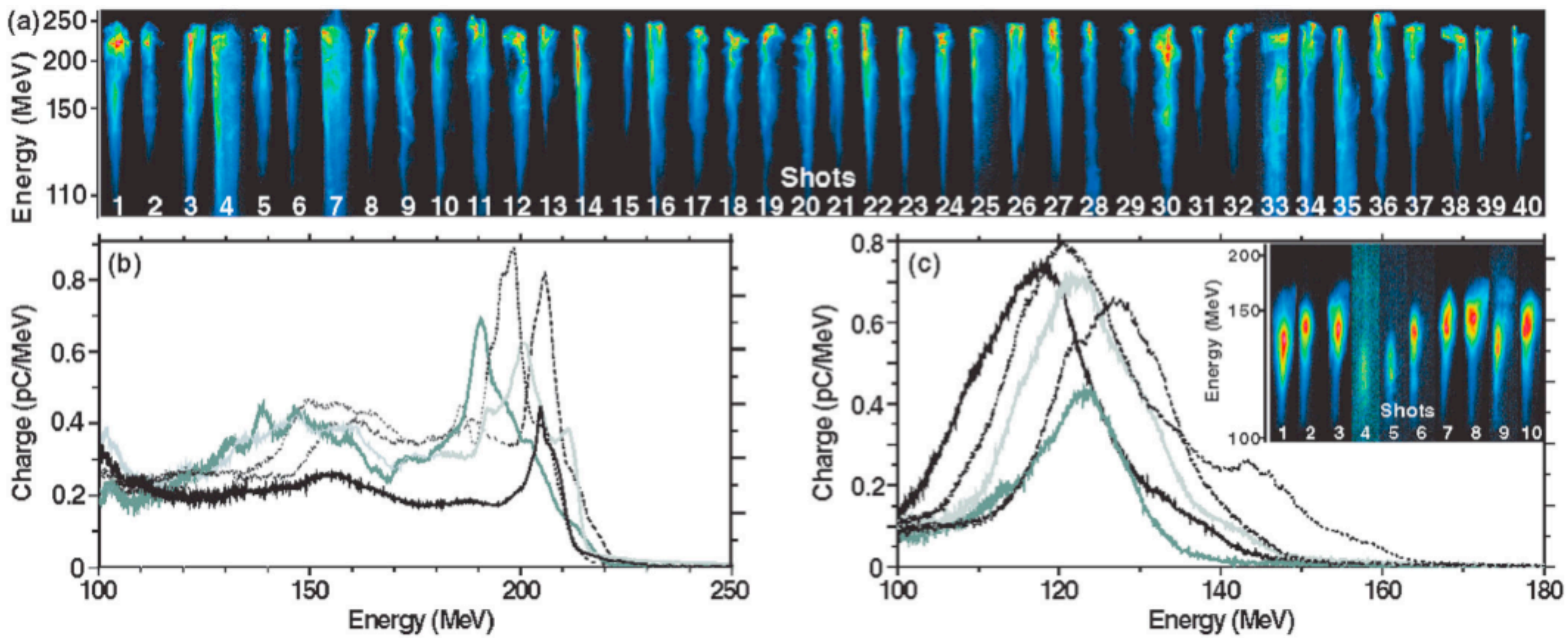
11J, 55fs, a=3.9, 1cm gas jet target, density 5.7×10^{18} cm^{-3}

0.8 GeV, >ten % relative energy spread, 300 pC

S. Kneip *et al.*, Phys. Rev. Lett. 103, 035002 (2009)

Gas cell experiments at MPQ





Laser : 20 TW

1cm gas cell target

0.8J, 40 fs, a_0=0.9

n_e=7x10^{18}cm^{-3}

Stable e-beam :

10 pC

220 MeV

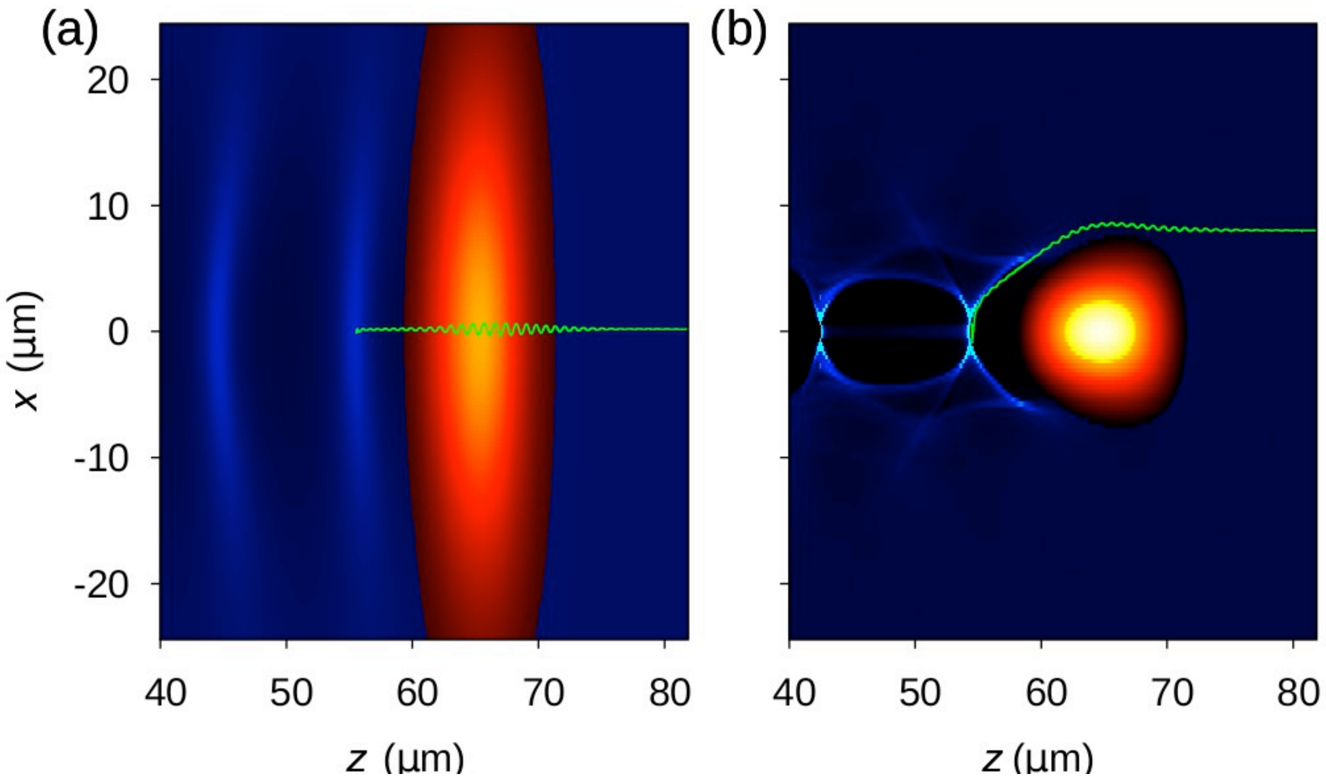
Div = 2 mrad

DE/E = 8%

J. Osterhoff et al., PRL 101, 085002 (2008)

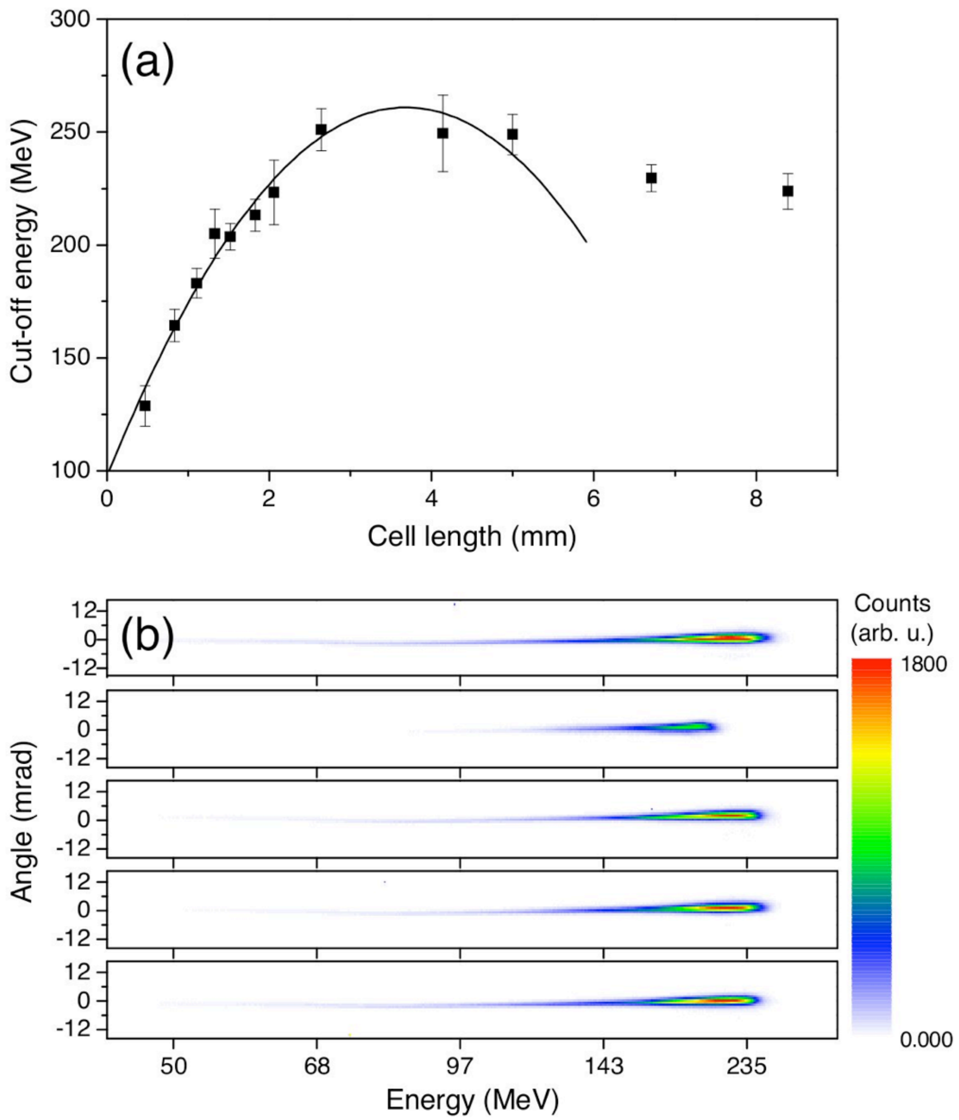
Longitudinal injection

Two different self-injection mechanisms take place :



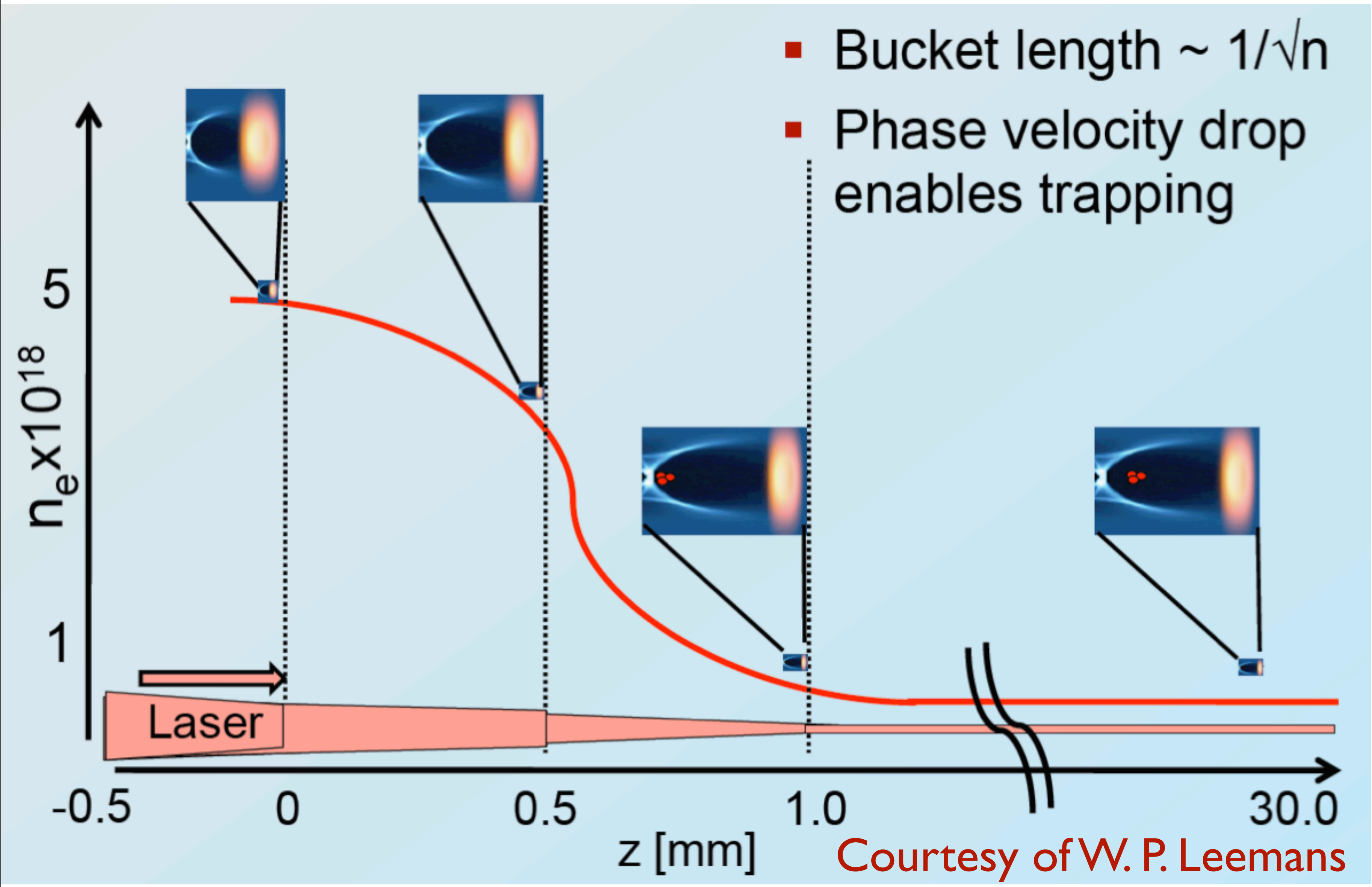
longitudinal injection improves
- the stability of the electron beam
and
- reduces the divergence of the electron beam

- At lower plasma density transverse injection is prevented
- Only one bunch is injected (longitudinal injection)



S. Corde *et al.*, Nature Communications (2013)

Density ramp injection : principle



$$v_p/c = \left(1 + \frac{\zeta}{k_p}\frac{dk_p}{dz}\right)^{-1}$$

where, $\zeta = z - ct$ and $k_p(z)$

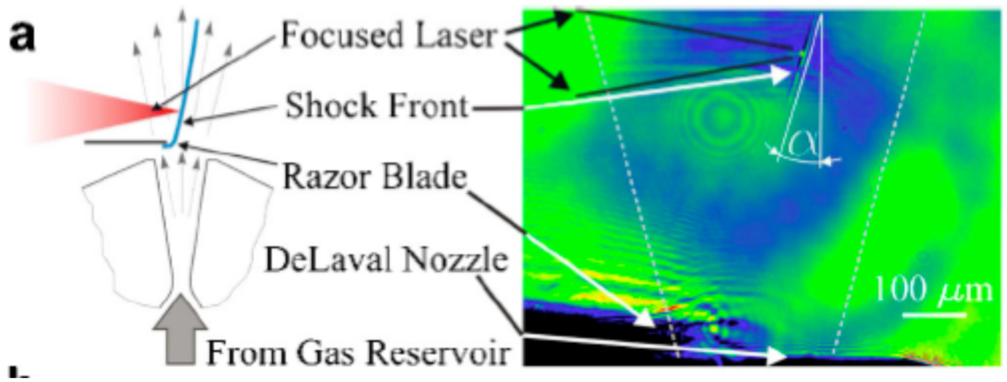
which depends on z through on density

$$\frac{k_p}{dz} = \frac{k_p}{2n_e}\frac{dn_e}{dz}$$

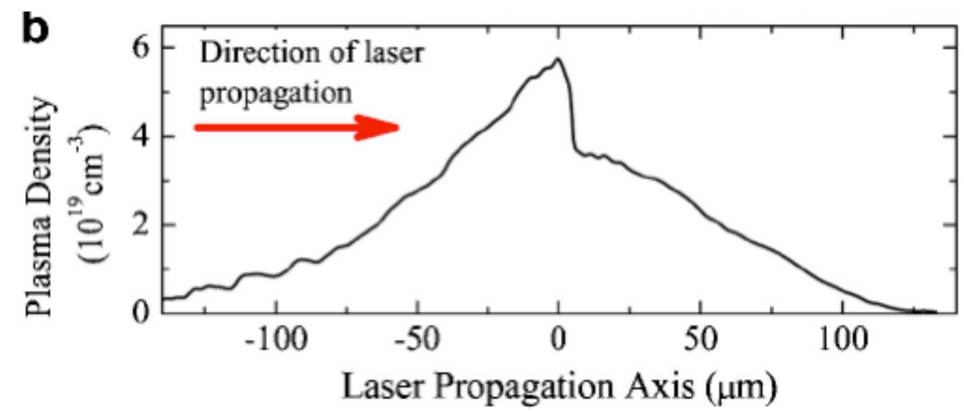
For a downward density, the wake phase velocity slow down facilitating electrons trapping

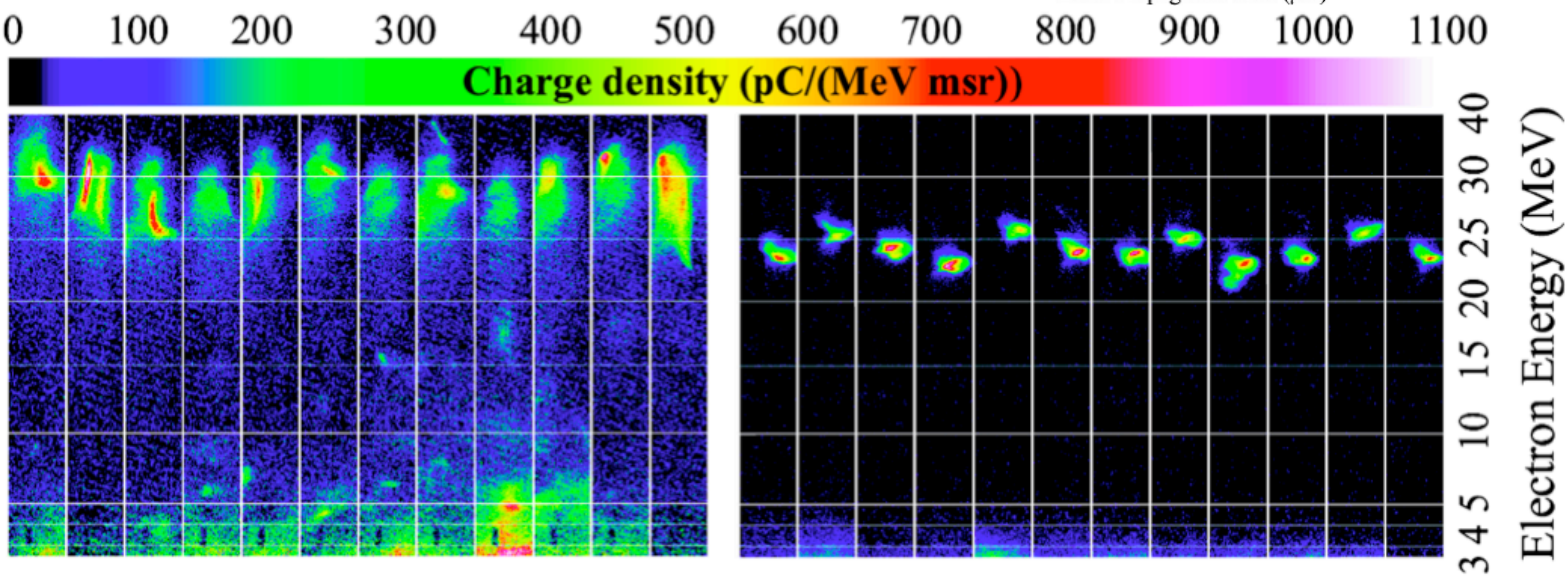
S. Bulanov *et al.*, PRE **58**, R5257 (1998), H. Suk *et al.*, PRL **86**, 1011 (2001), T.-Y Chien *et al.*, PRL **94**, 115003 (2005), T. Hosokai *et al.*, PRL **97**, 075004 (2006), C. G. R. Geddes *et al.* PRL **100**, 215004 (2008), J. Faure *et al.*, Phys. of Plasma **17**, 083107 (2011)

Sharp density ramp injection : shock in gas jet



=>



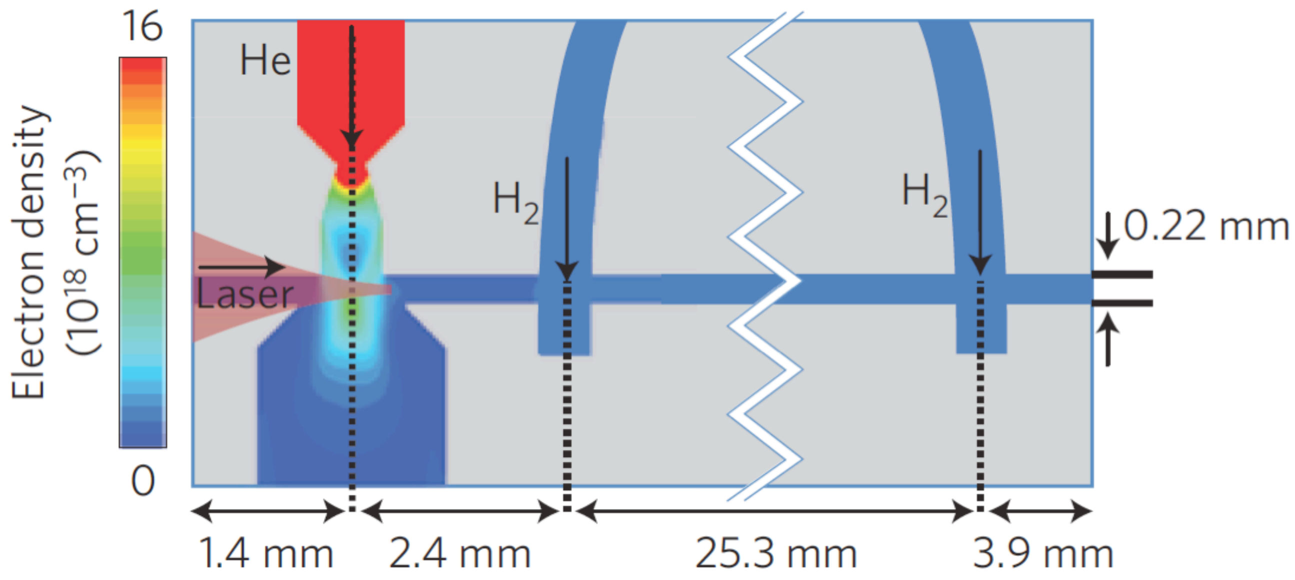


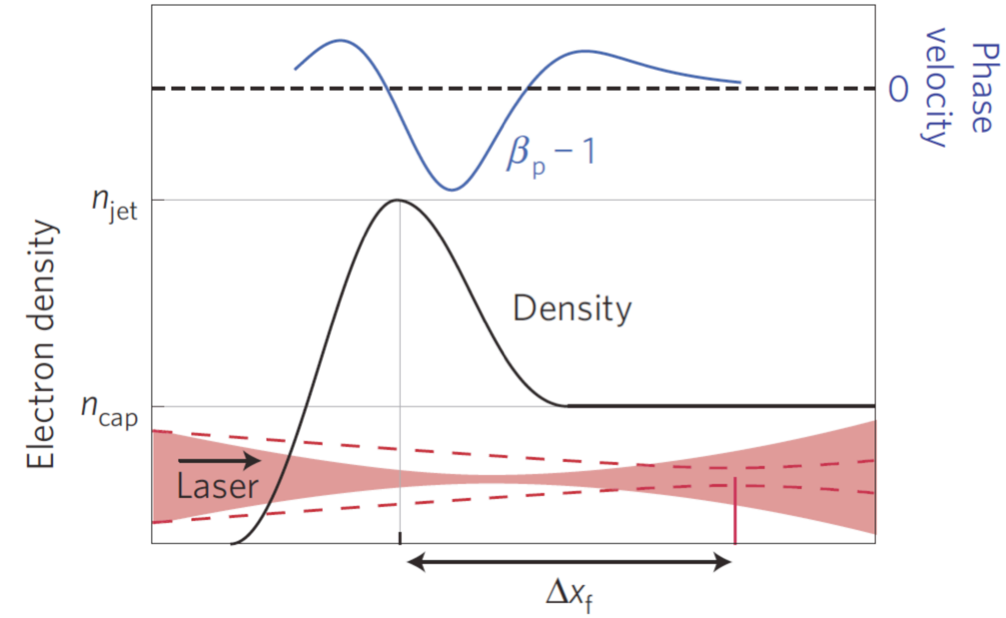
(a) Self injection

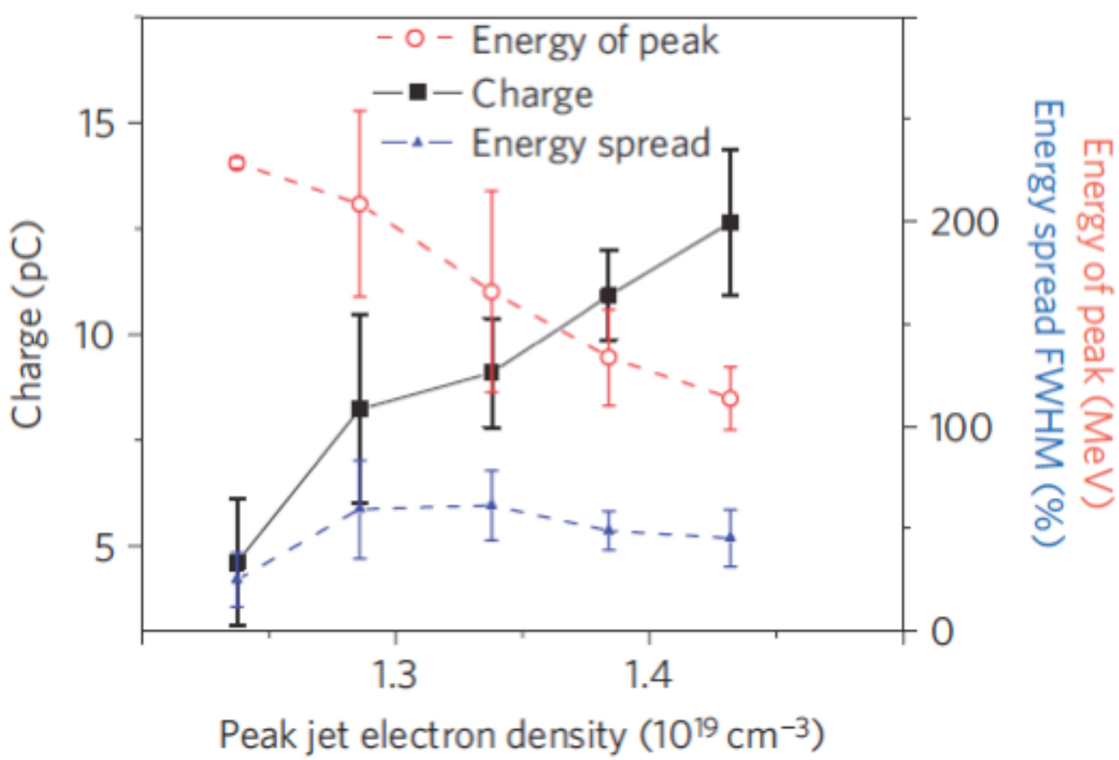
(b) Injection at density transition

K. Schmid et al., PRSTAB 13, 091301 (2010)

Density ramp + phase velocity control





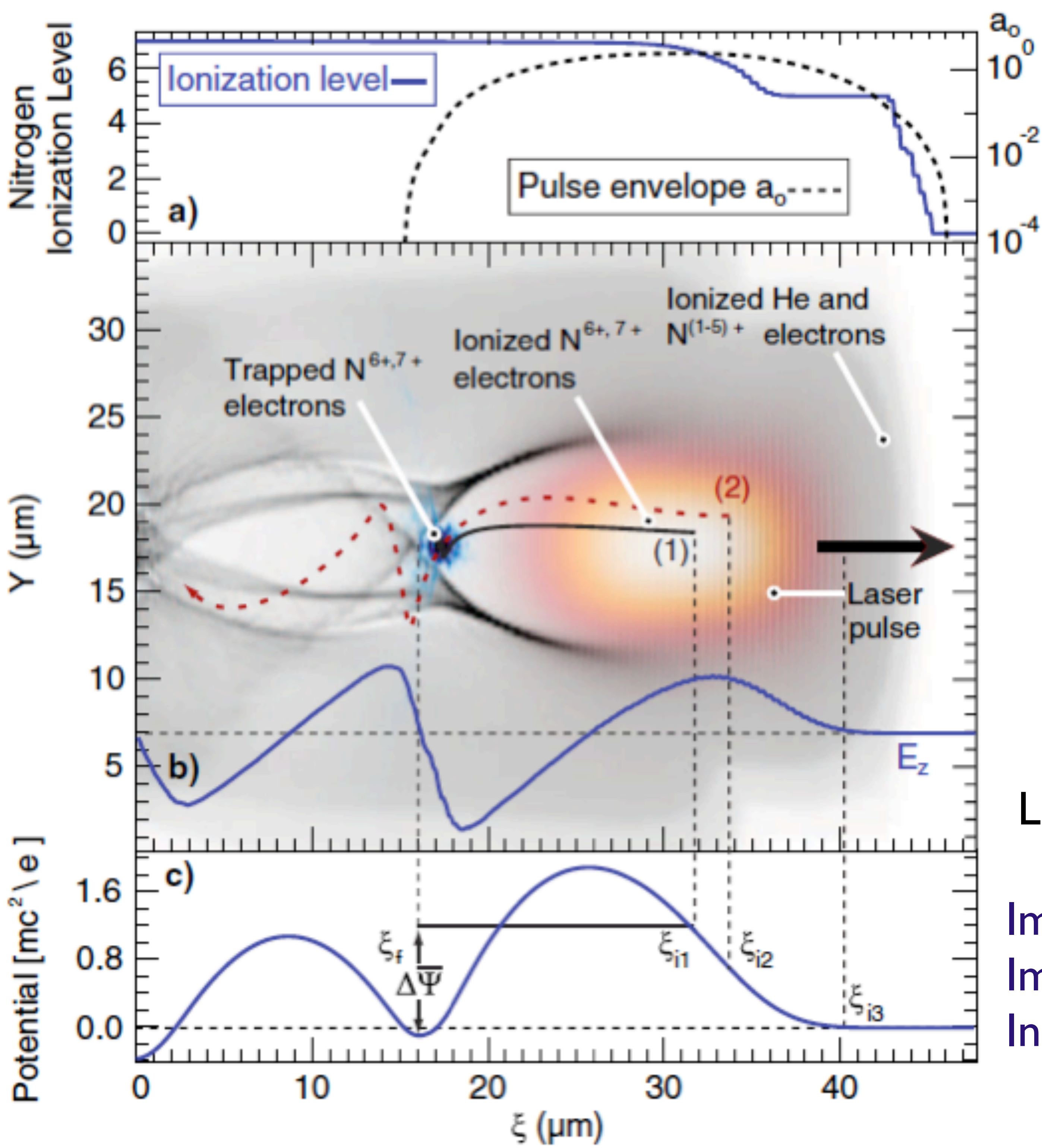


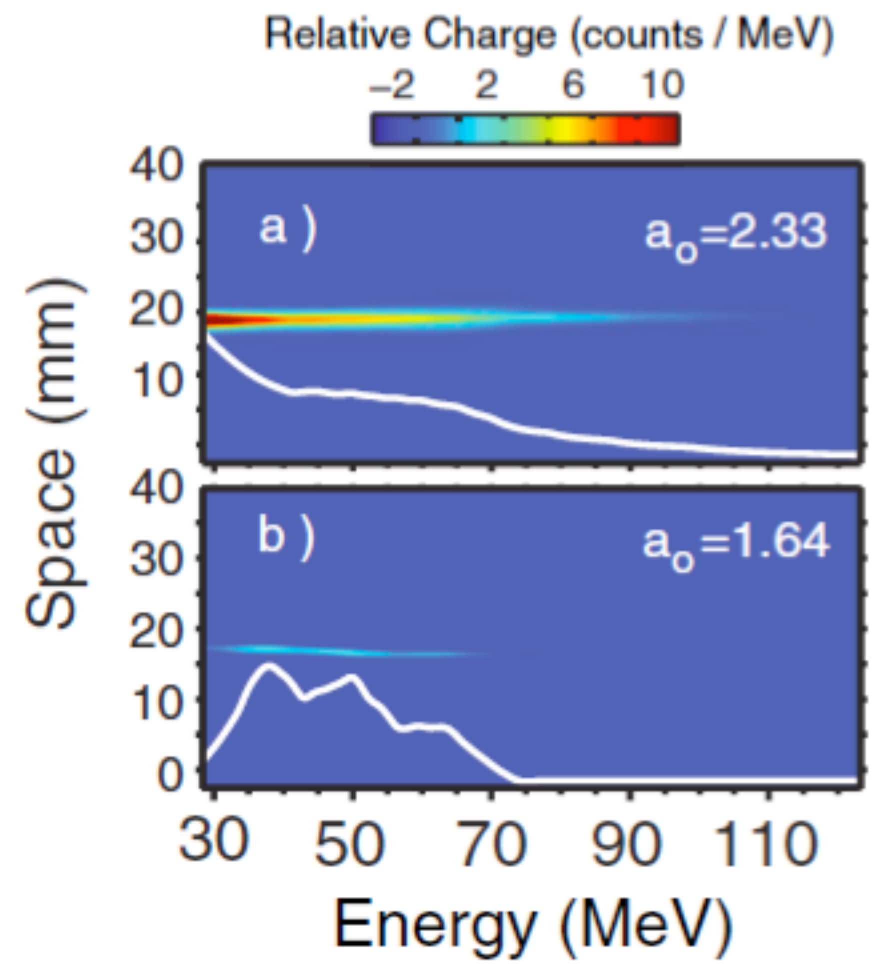
Laser : 20 TW
0.8J, 40 fs, a_0=0.9
n_e=7x10^{18}cm^{-3}

Stable e-beam :
1-10 pC
100-400 MeV
Div = 2 mrad
DE/E> a few %

A. J. Gonslaves *et al.*, Nature Physics, August 2011

Ionization Induced Trapping



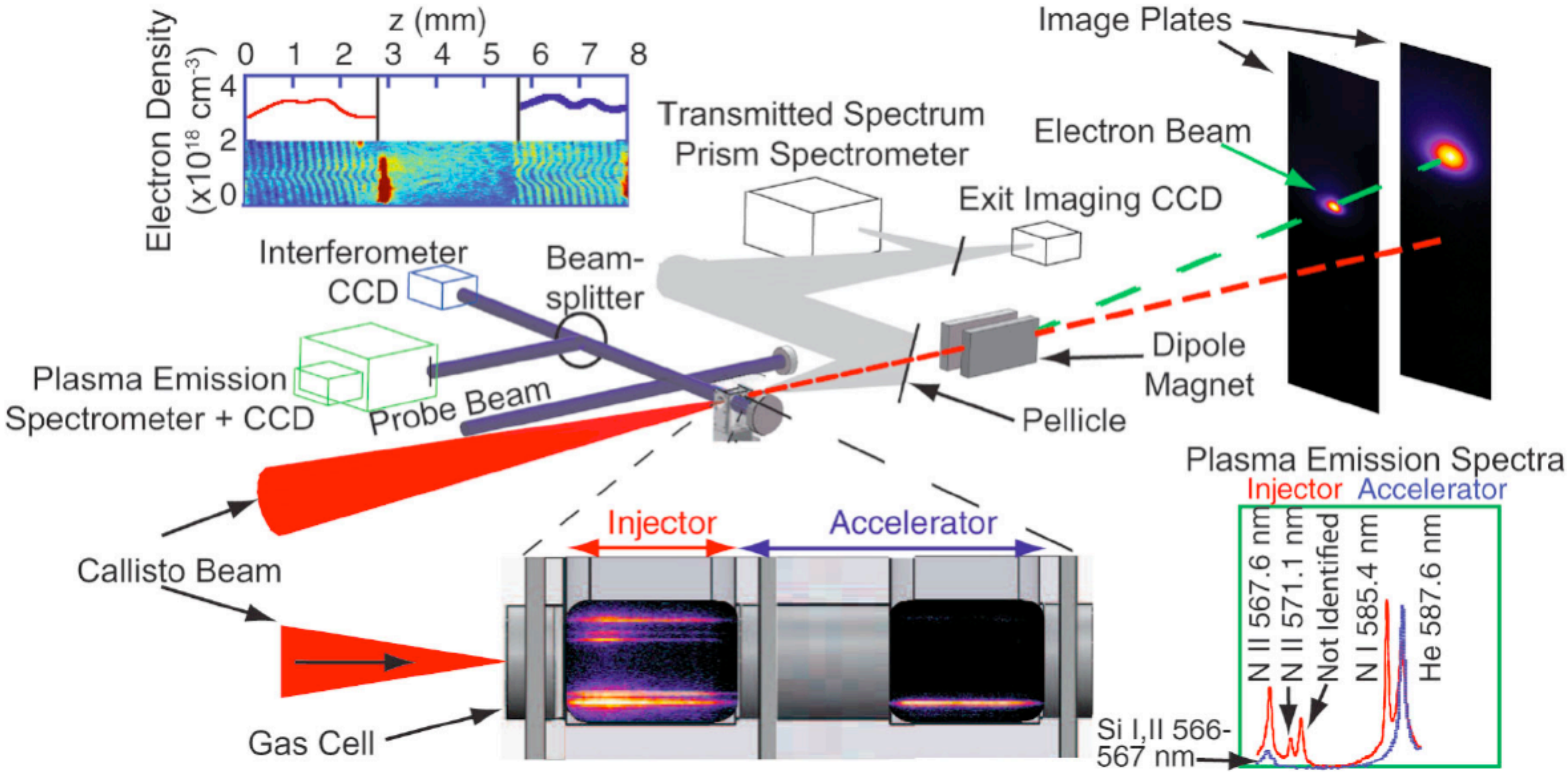


Laser: 10 TW, 0.8J, 45 fs, $a_0 \approx 2$, $n_e = 1.4\times10^{19}\,cm^{-3}$

Improve the energy spread at low laser intensity
Improve the stability
Increase the charge

A. Pak et al., PRL 104, 025003 (2010), C. McGuffey et al., PRL 104, 025004 (2010)

Ionization Induced Trapping : two stage plasma accelerator

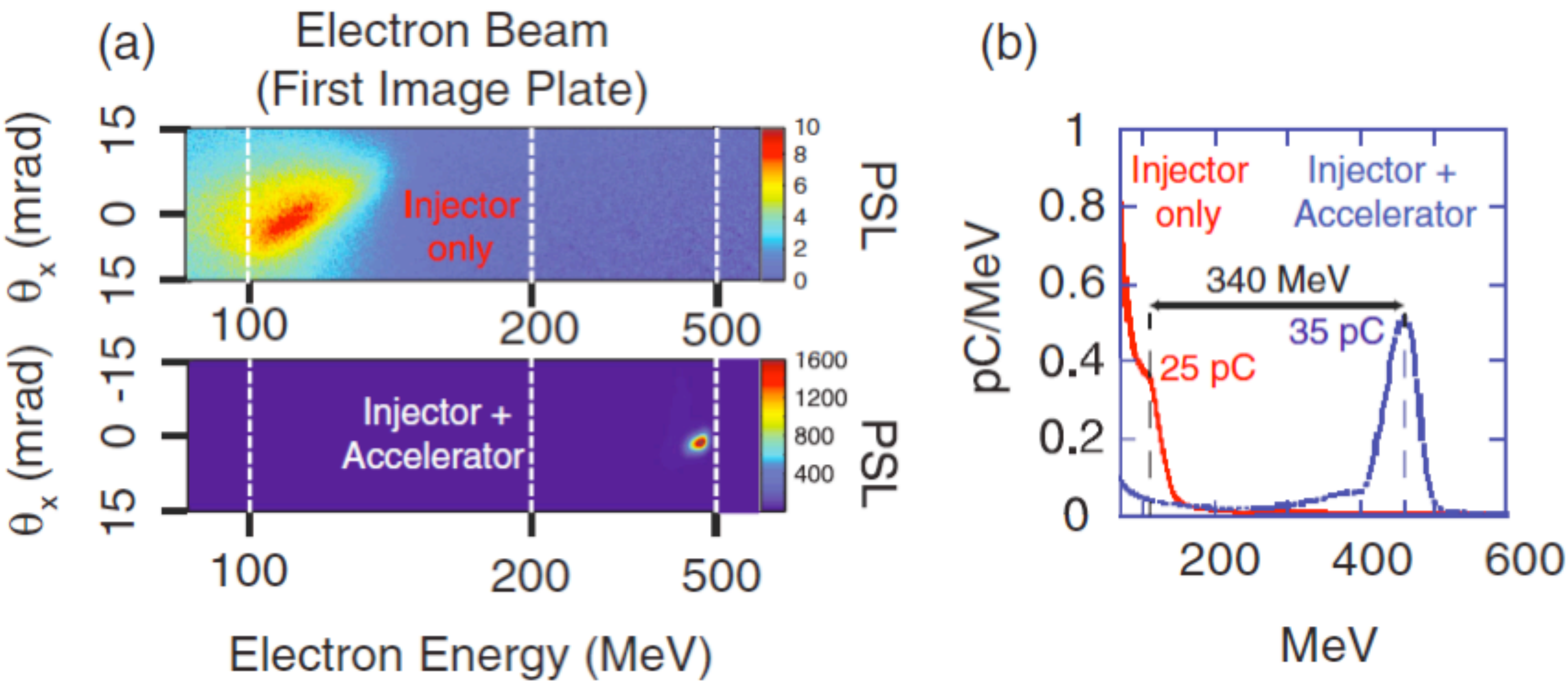


Laser : 30-60 TW, 60 fs, a_0=2-2.8, n_e=3x10^{18}cm^{-3}

35 pC, 460 MeV, div = 2 mrad, DE/E>5%

B. B. Pollock et al., PRL 107, 045001 (2011)

Ionization Induced Trapping : two stage plasma accelerator



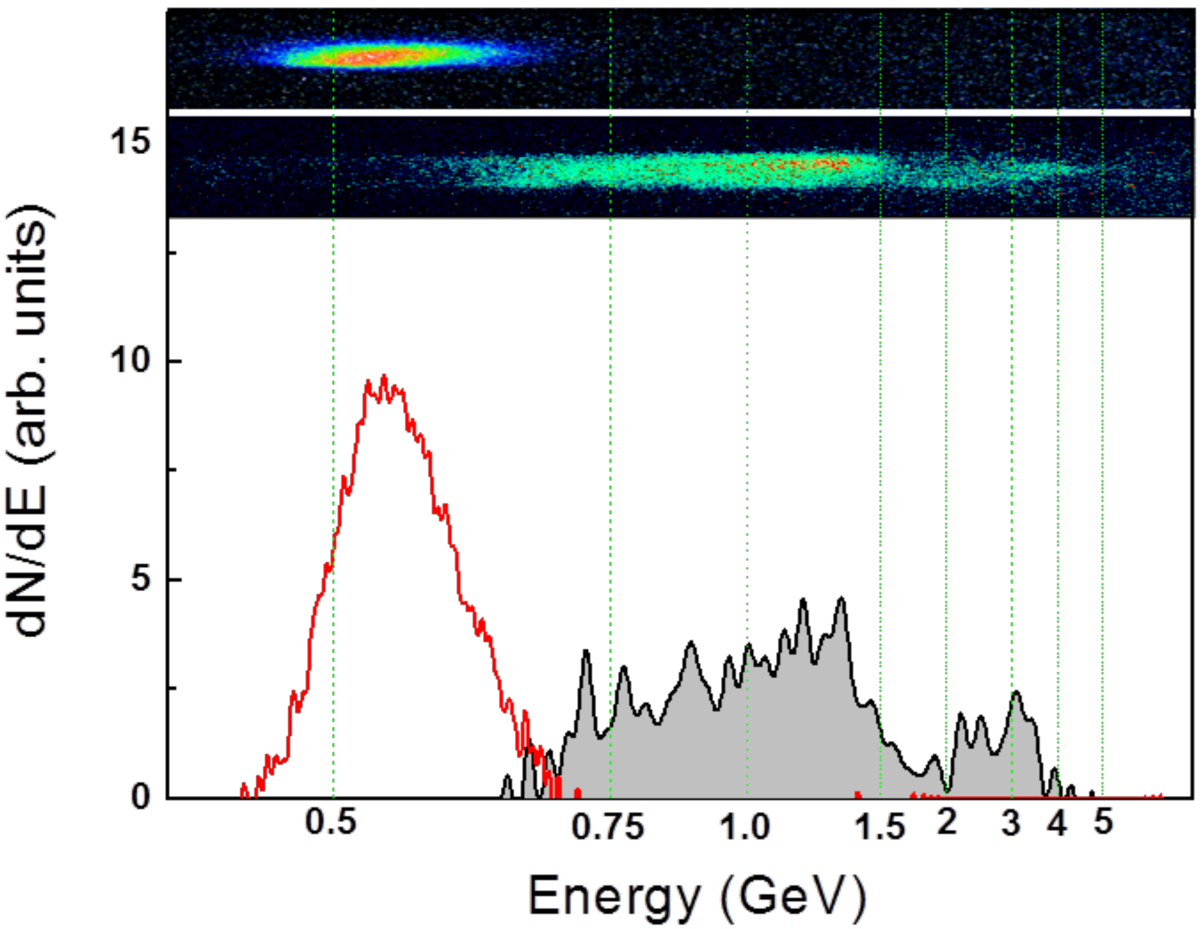
Laser : 30-60 TW, 60 fs, a_0=2-2.8, n_e=3x10^{18}cm^{-3}

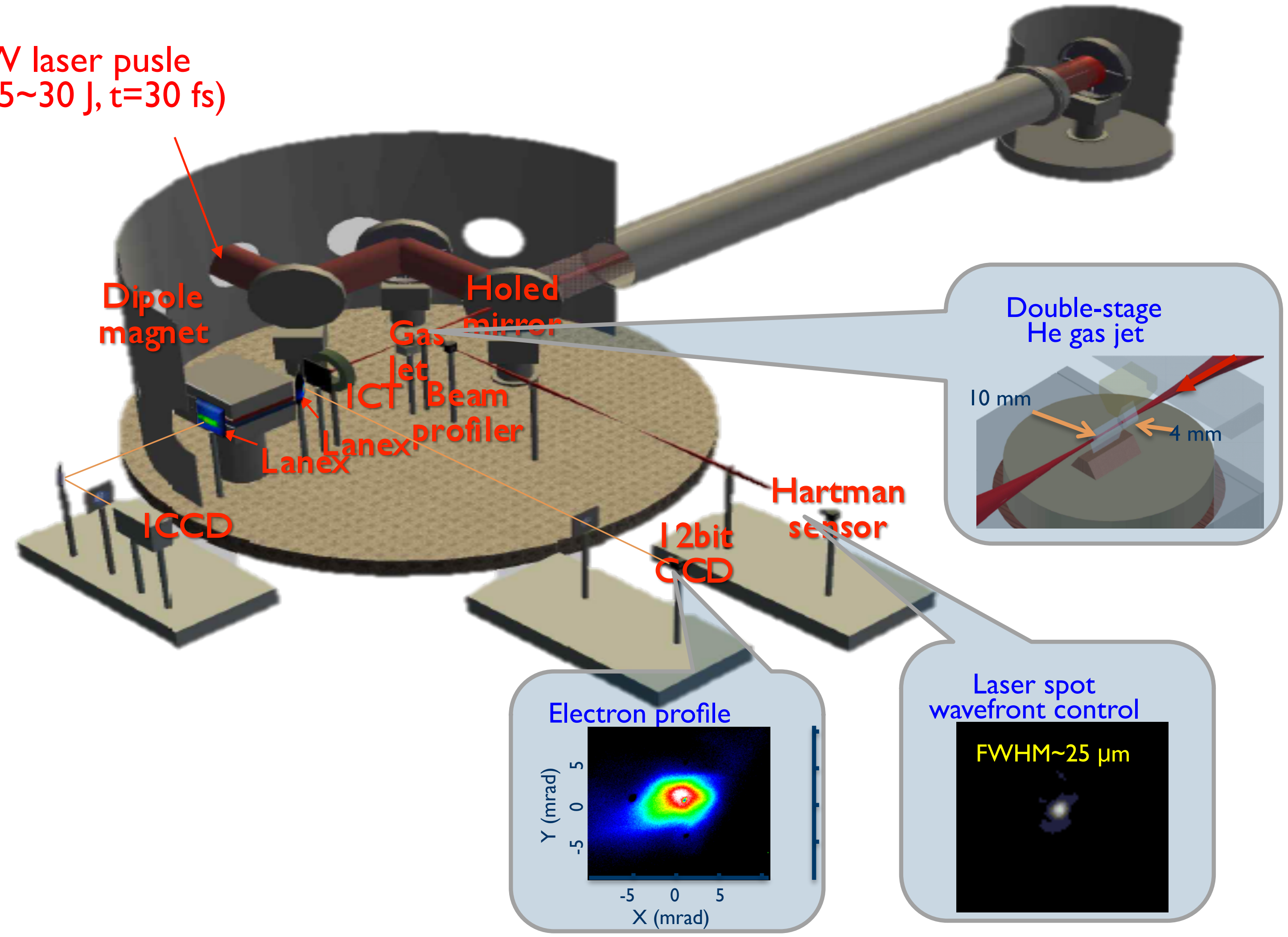
35 pC, 460 MeV, div = 2 mrad, DE/E>5%

B. B. Pollock et al., PRL 107, 045001 (2011)

Double gas jet with PW laser : 3 GeV @ GIST-APRI

Double He gas jet : $d_e = 2.1\times10^{18}$ cm^{-3} (4 mm) $d_e = 0.7\times10^{18}$ cm^{-3} (10 mm)

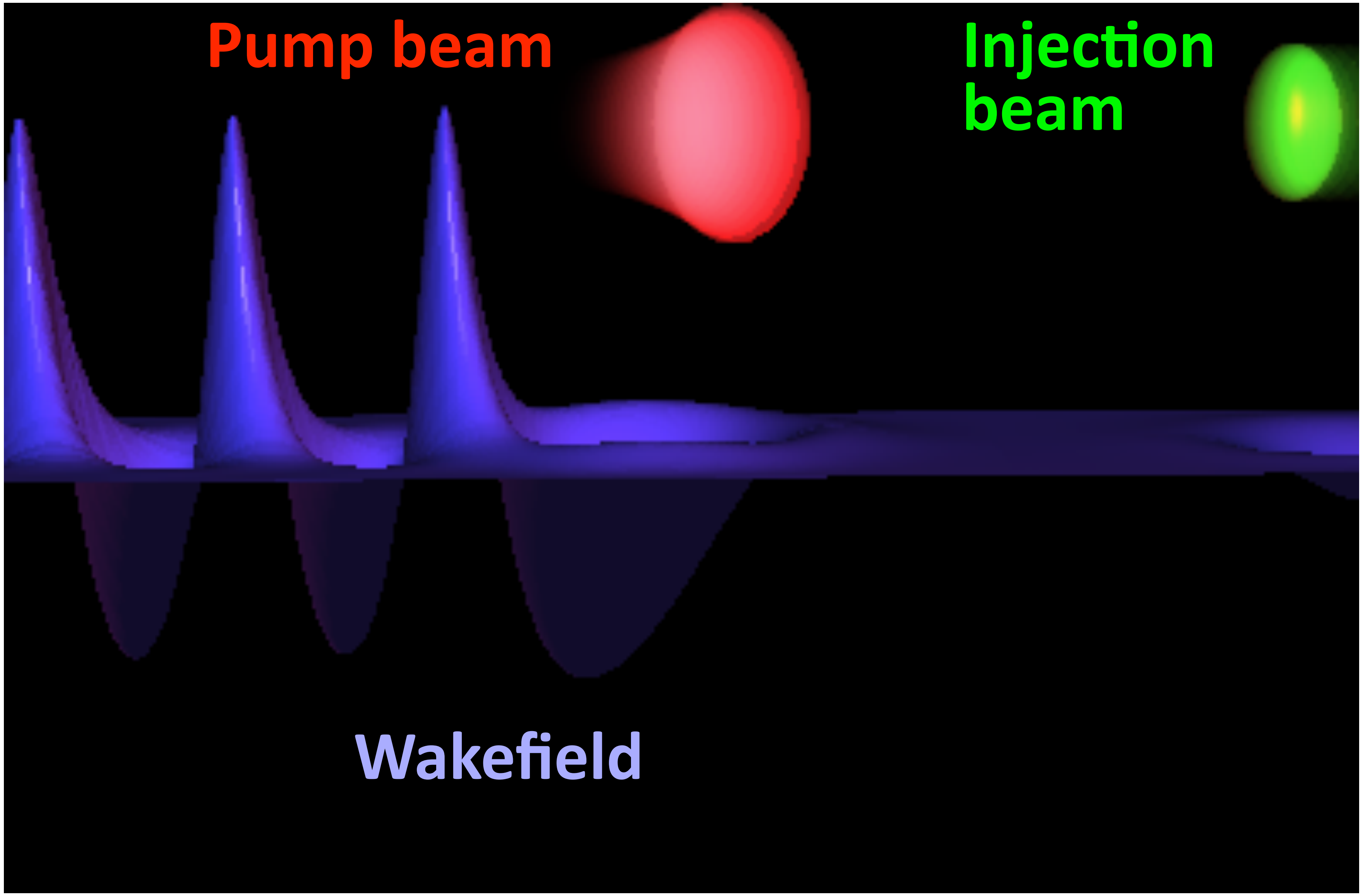




Courtesy of Hyung Taek Kim

Colliding Laser Pulses Scheme

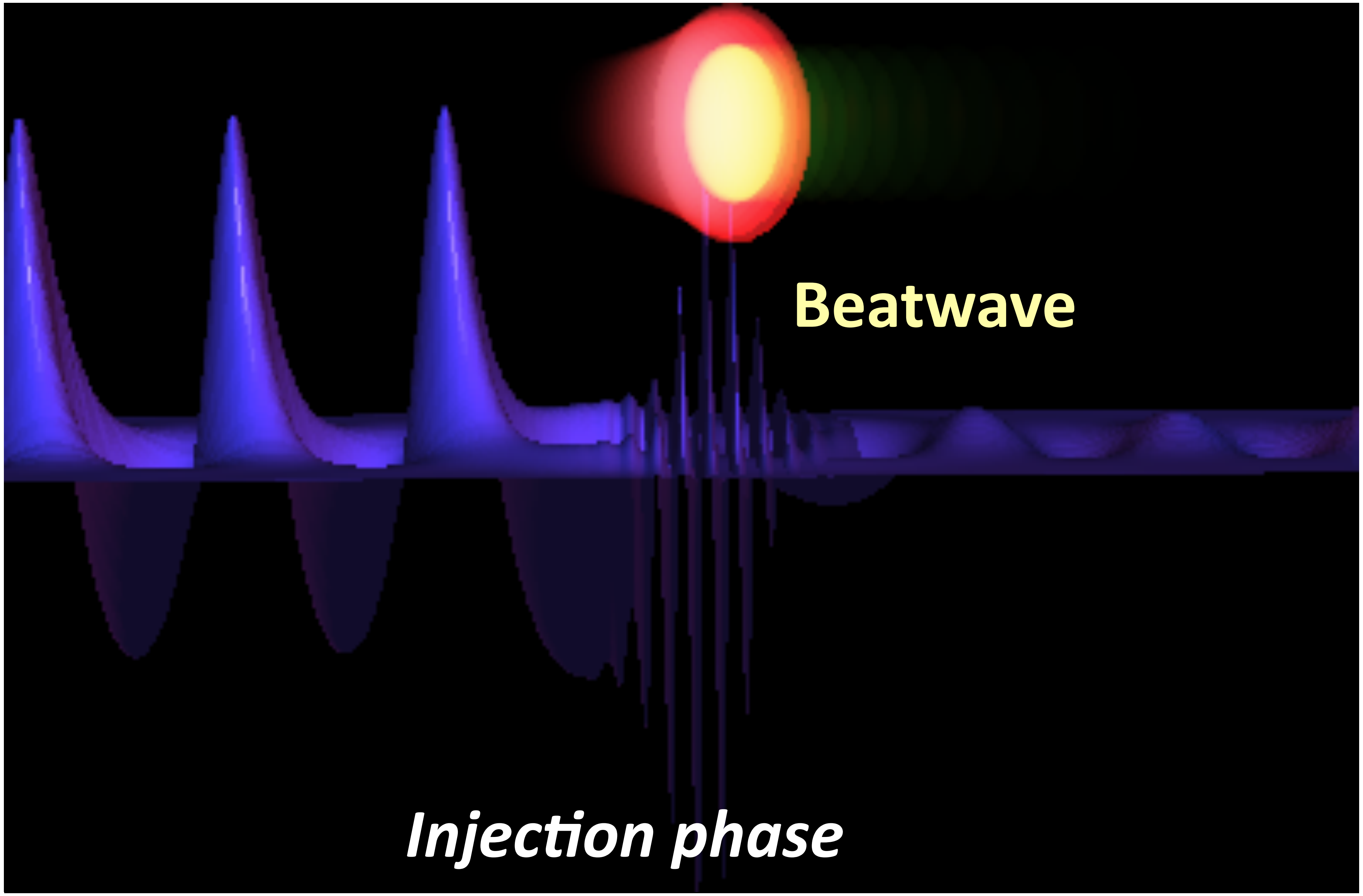
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

Colliding Laser Pulses Scheme

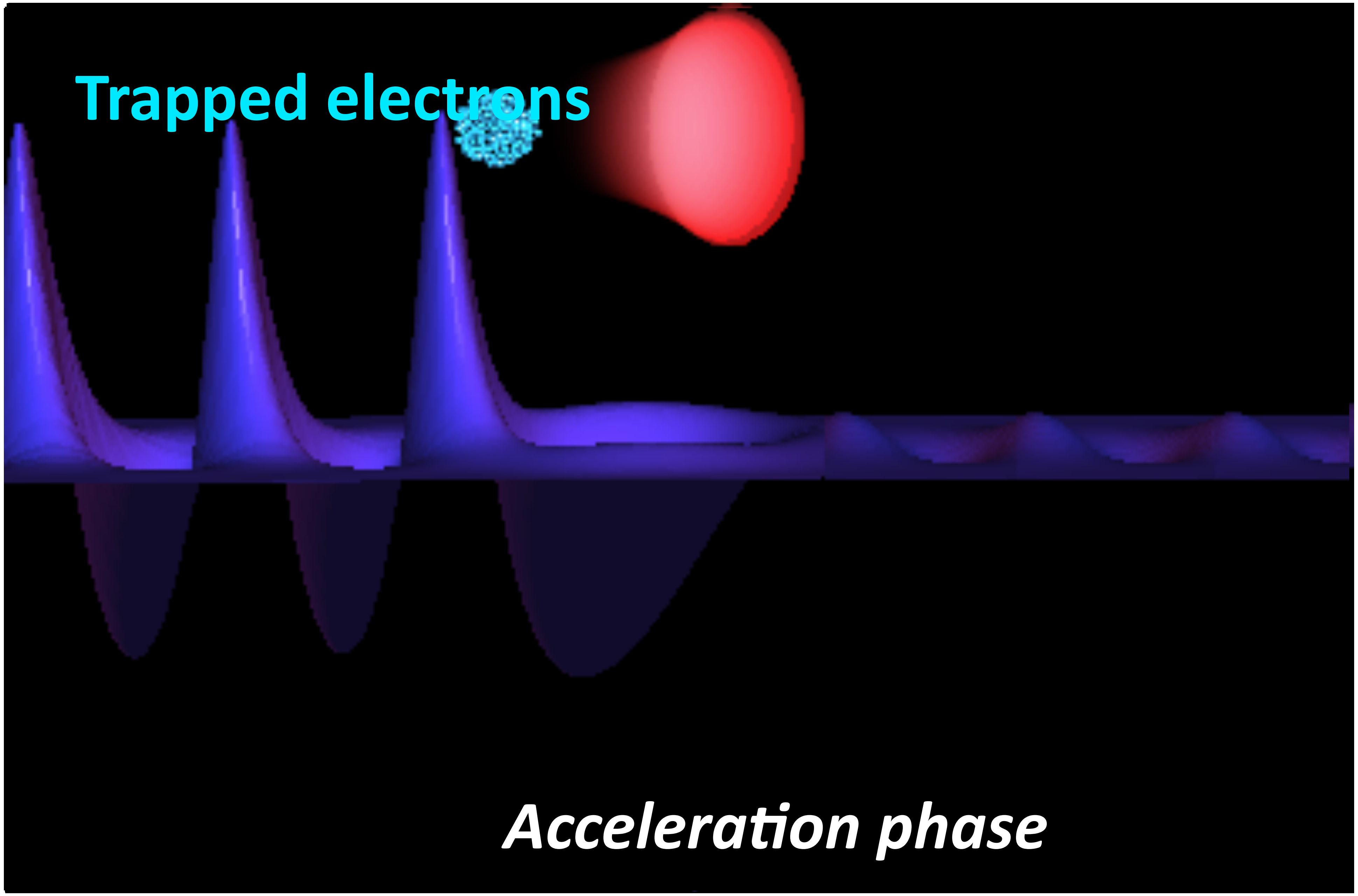
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

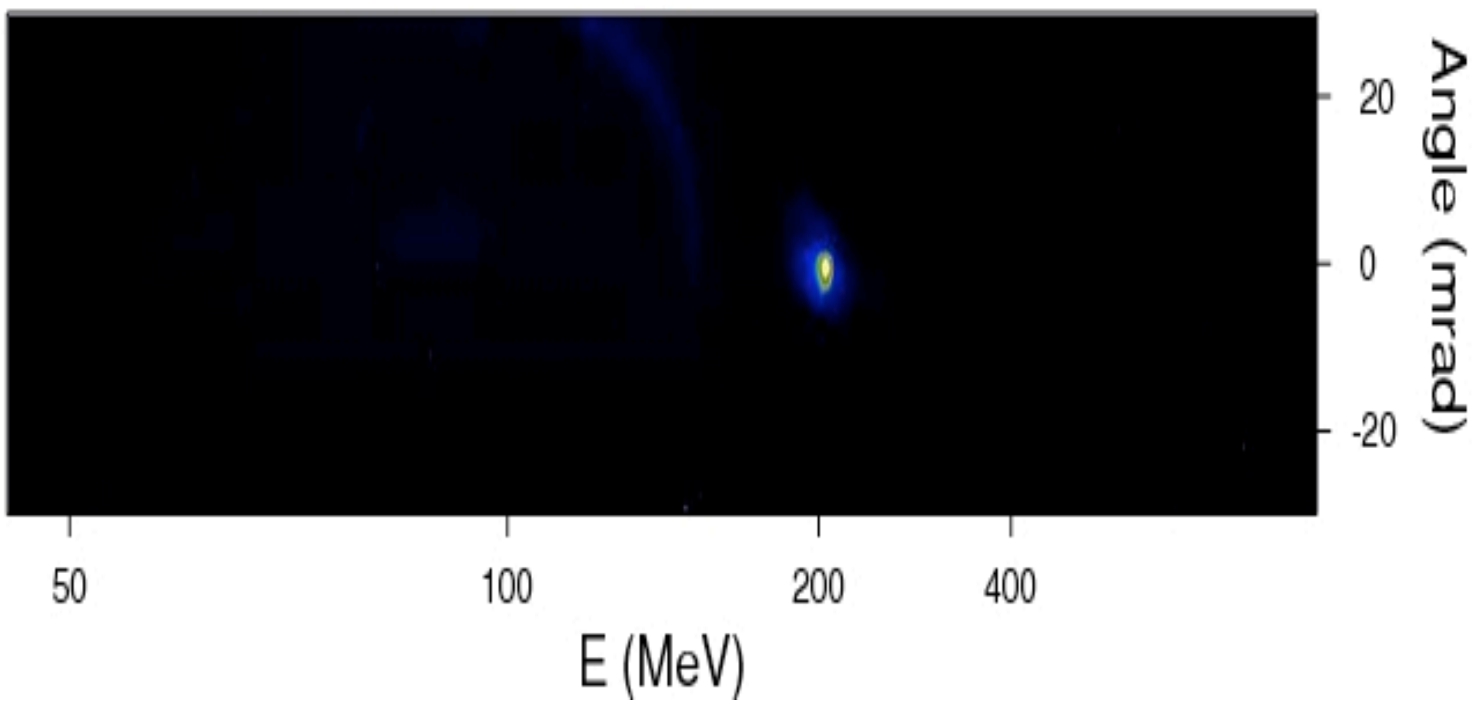
Colliding Laser Pulses Scheme

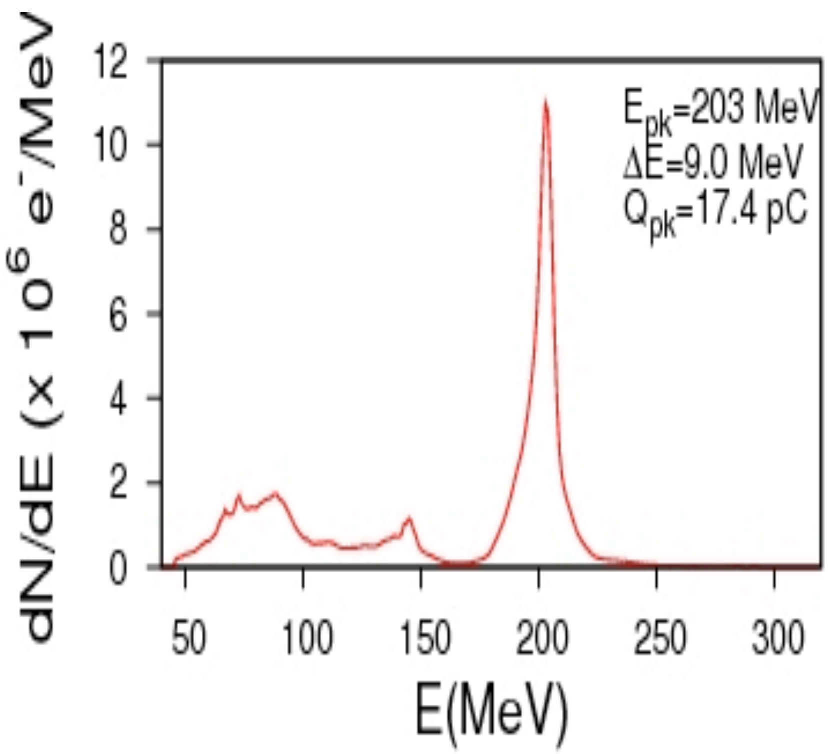
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

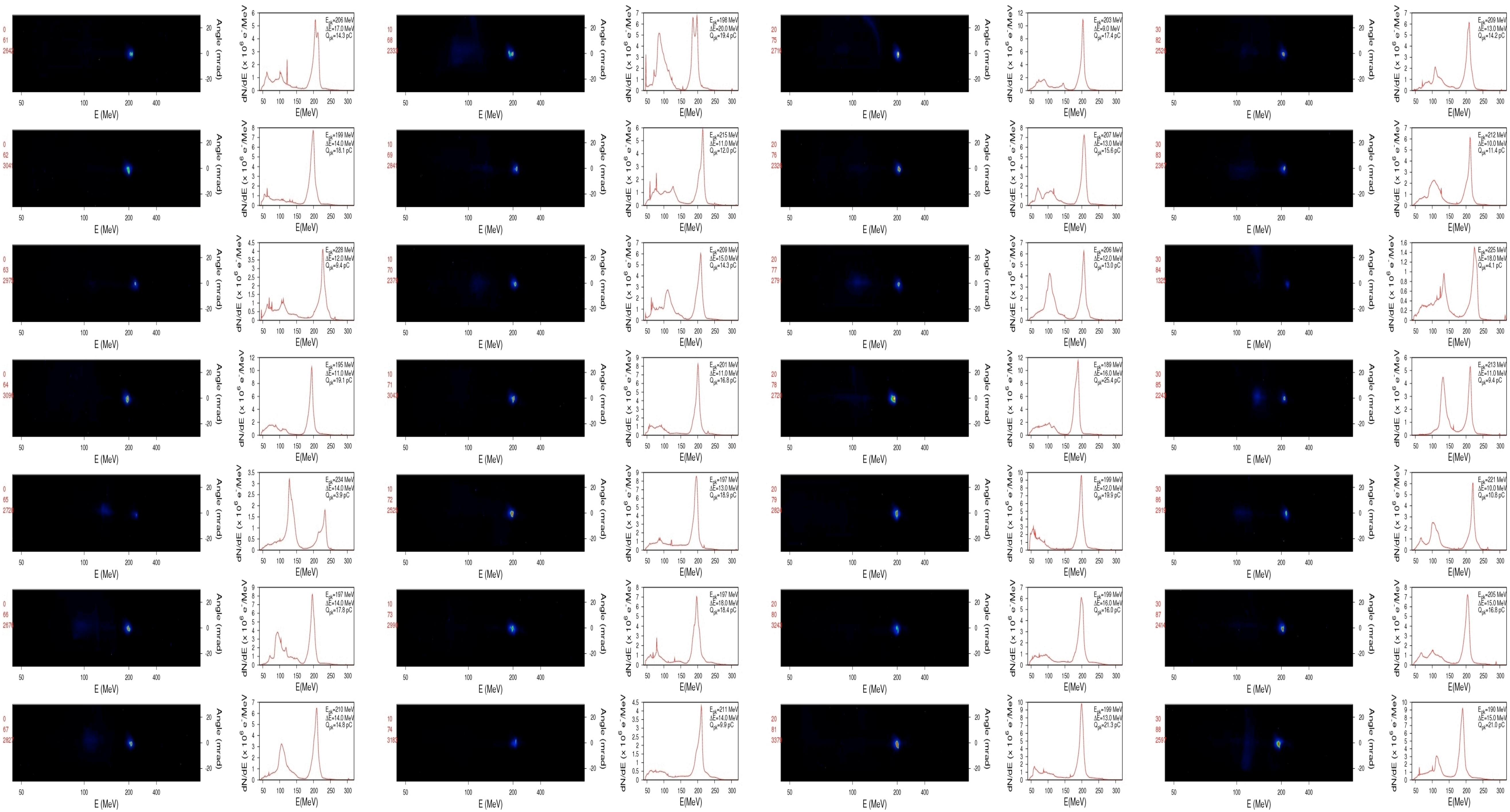
Stable Laser Plasma Accelerators



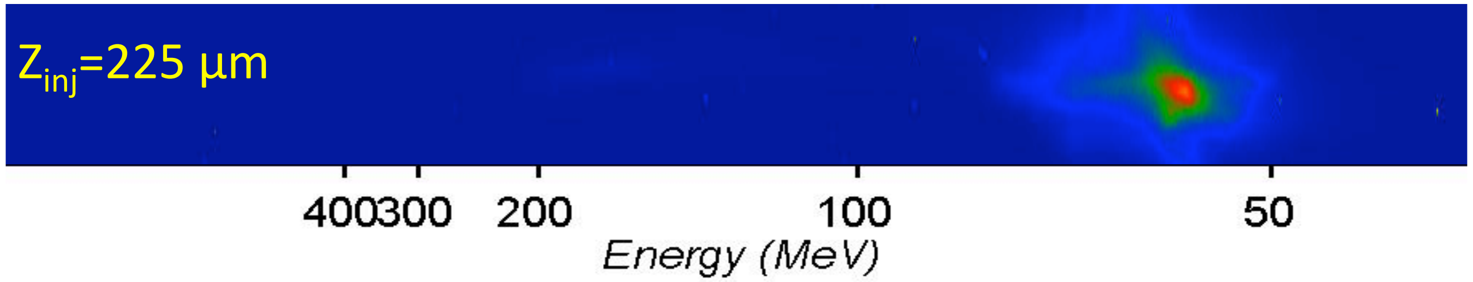


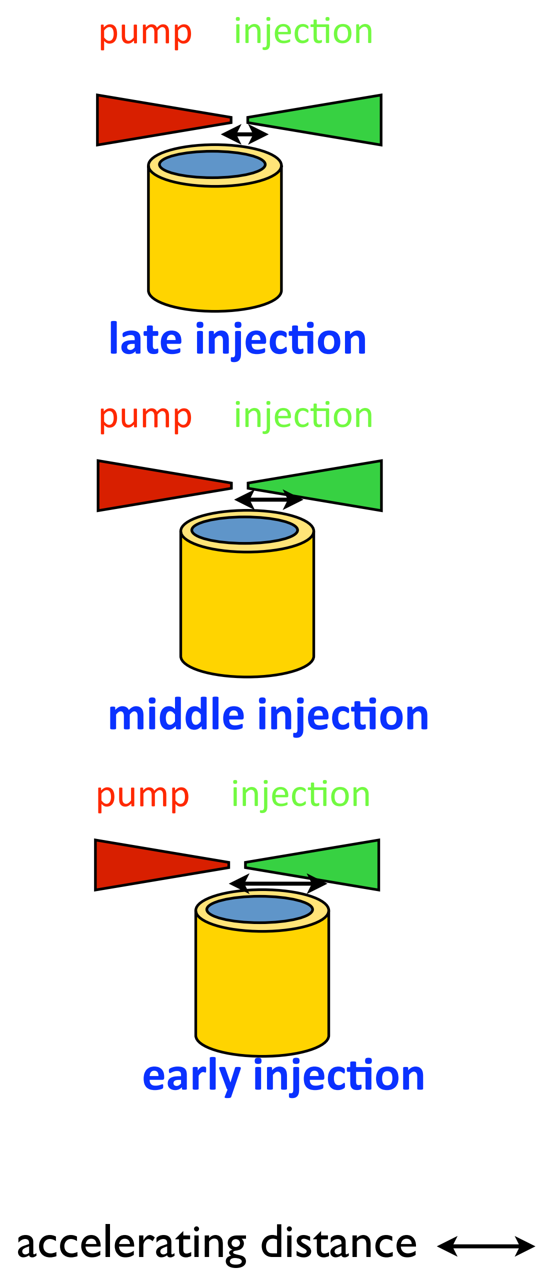
Stable Laser Plasma Accelerators

Series of 28 consecutive shots with : $a_0=1.5$, $a_1=0.4$, $n_e=5.7\times10^{18}cm^{-3}$



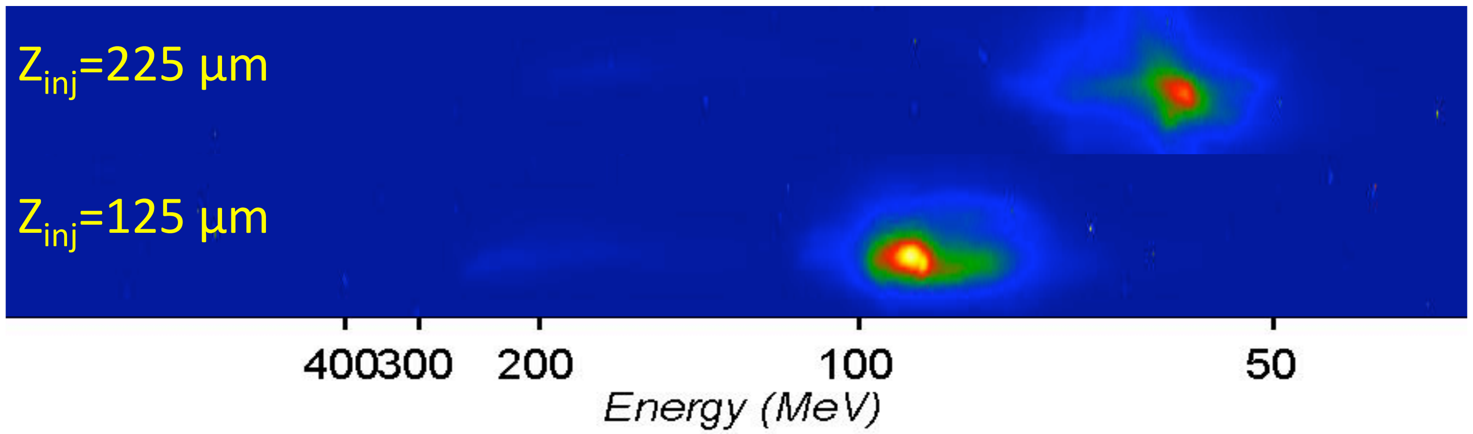
Tunability of Laser Plasma Accelerators : electrons energy

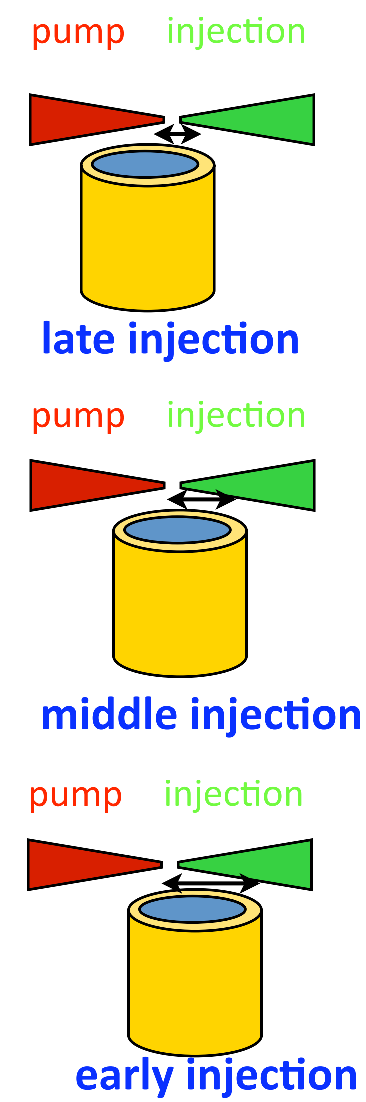




J. Faure *et al.*, Nature **444**, 737 (2006)

Tunability of Laser Plasma Accelerators : electrons energy

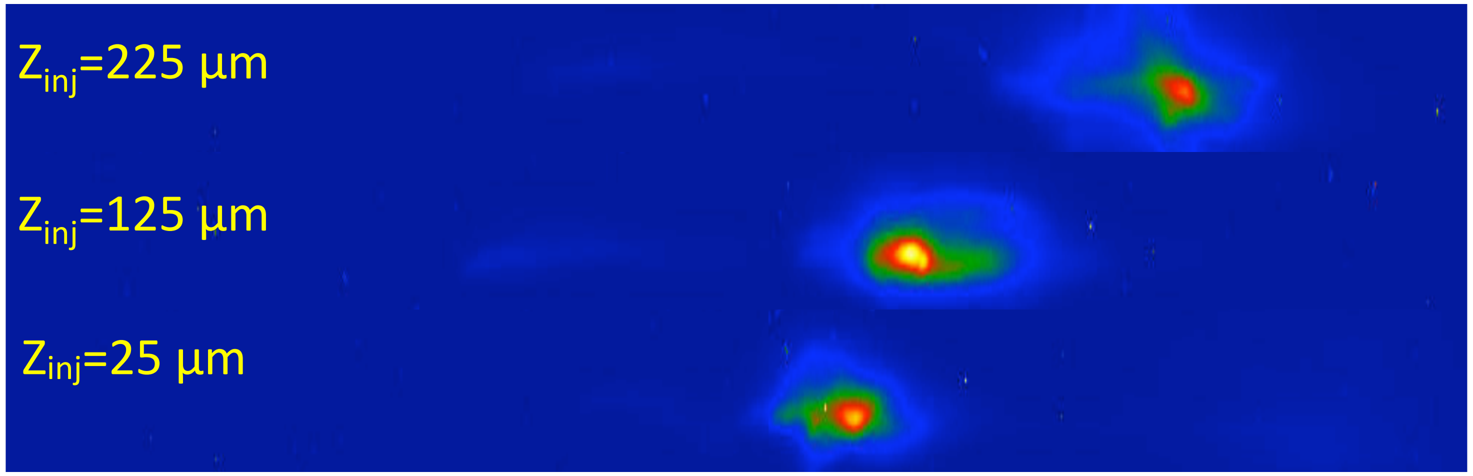


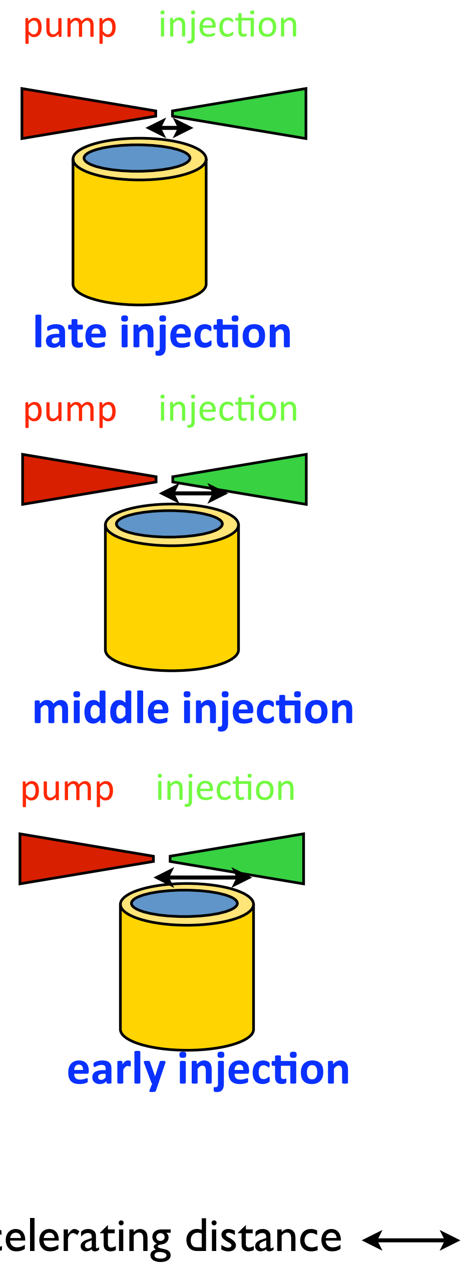


accelerating distance ⟷

J. Faure *et al.*, Nature **444**, 737 (2006)

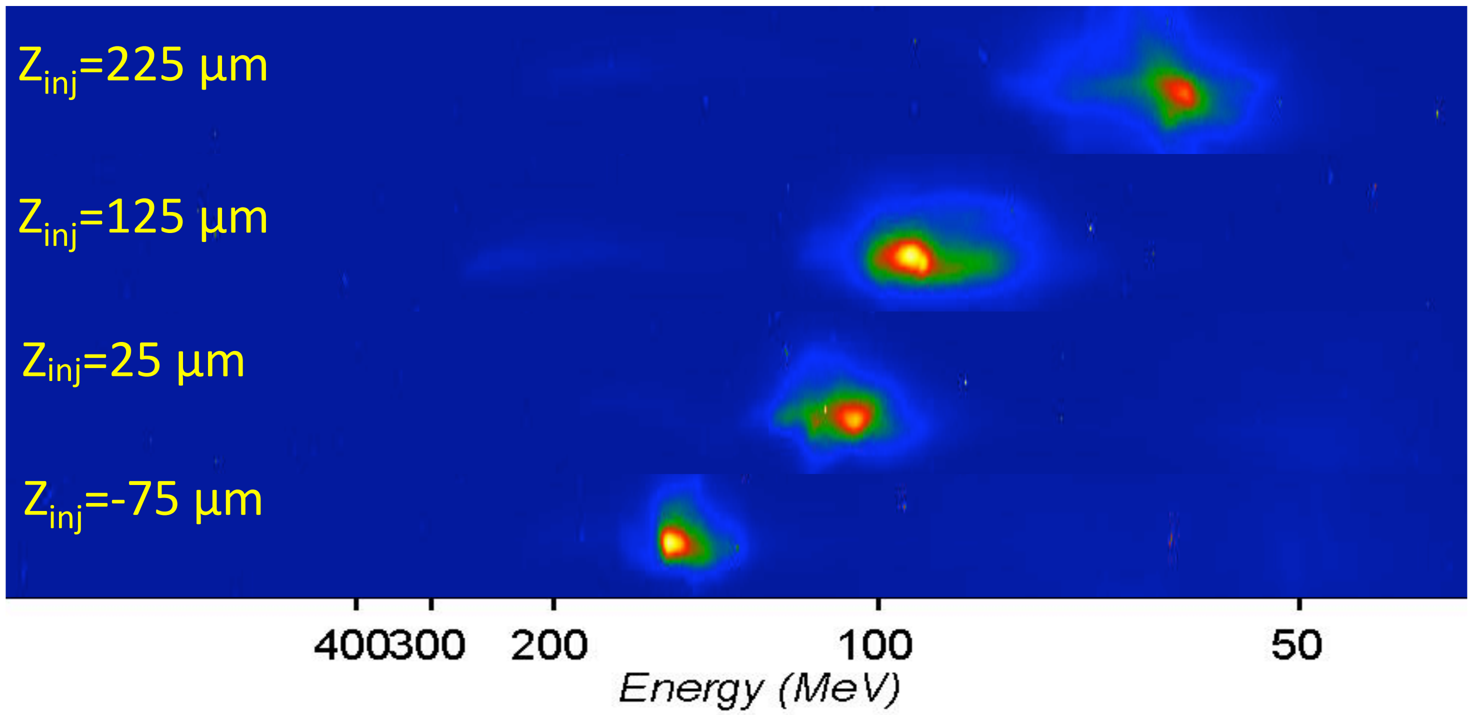
Tunability of Laser Plasma Accelerators : electrons energy

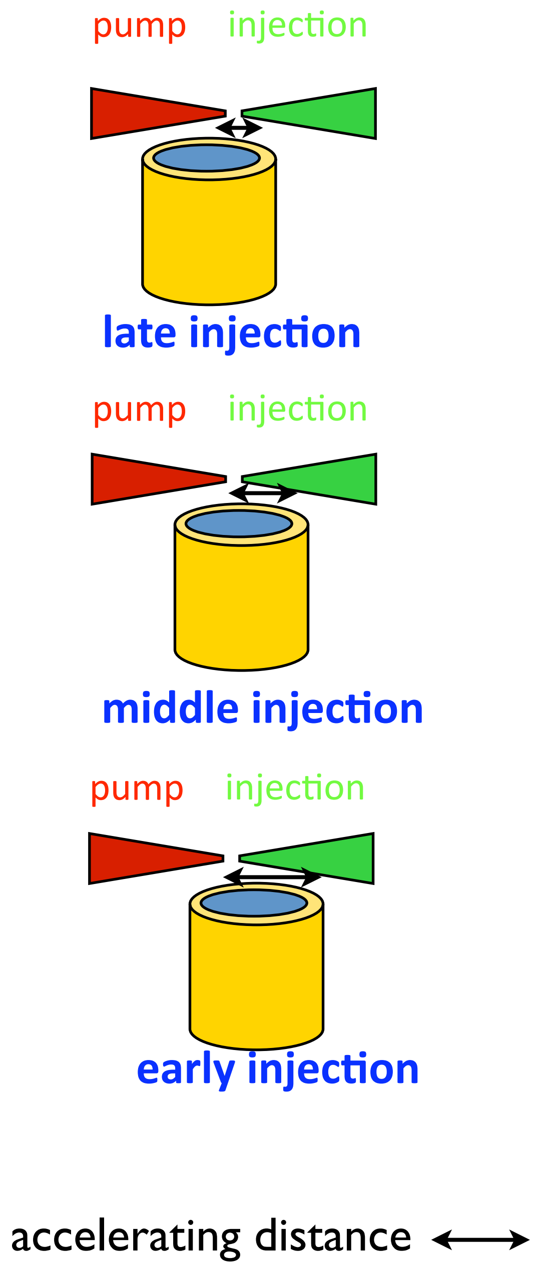




J. Faure *et al.*, Nature **444**, 737 (2006)

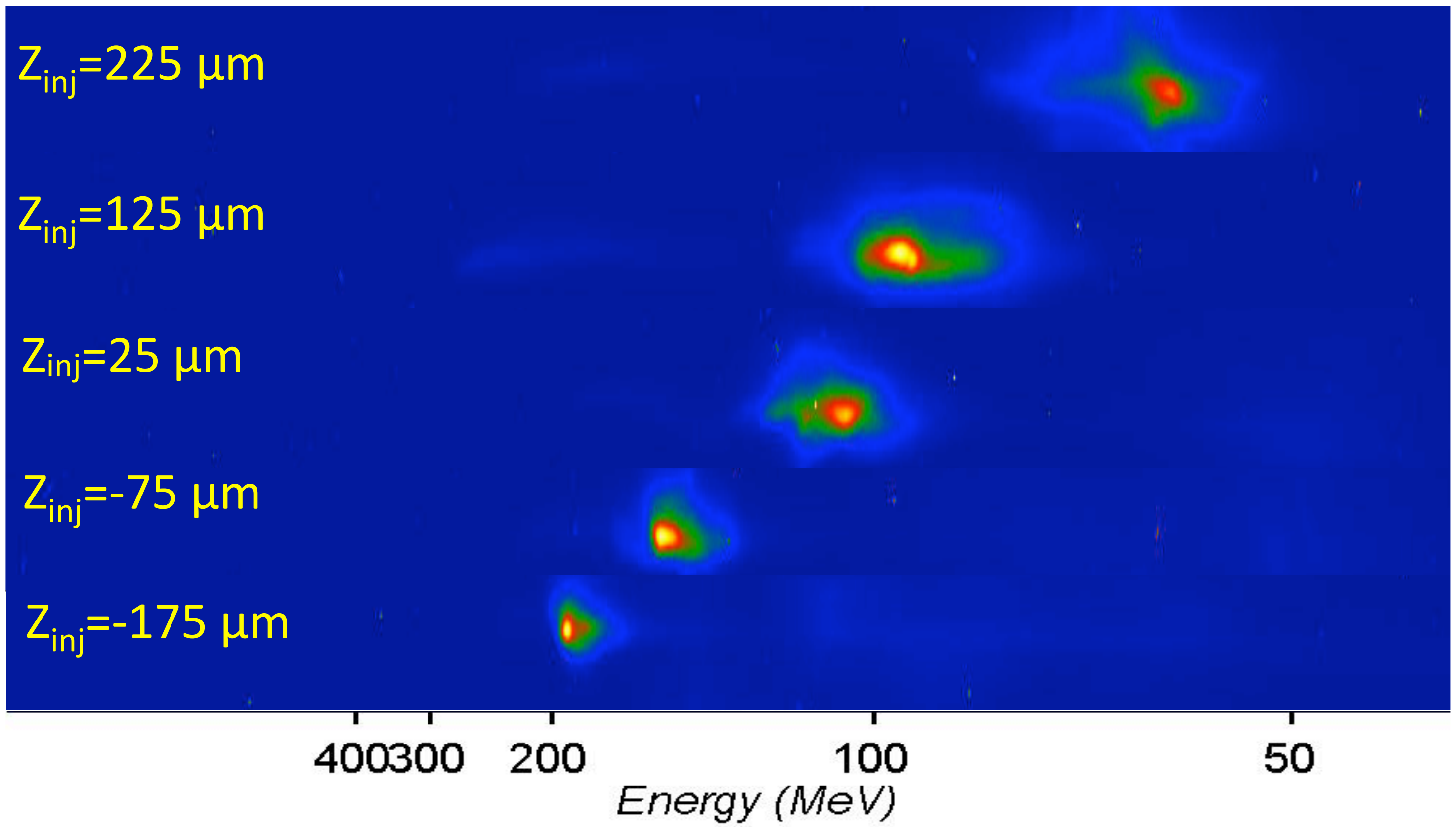
Tunability of Laser Plasma Accelerators : electrons energy

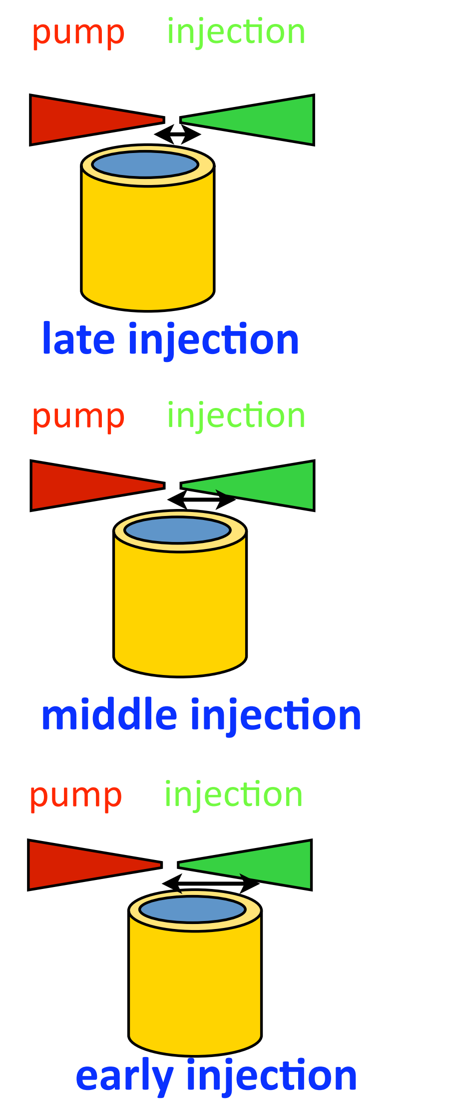




J. Faure *et al.*, Nature **444**, 737 (2006)

Tunability of Laser Plasma Accelerators : electrons energy

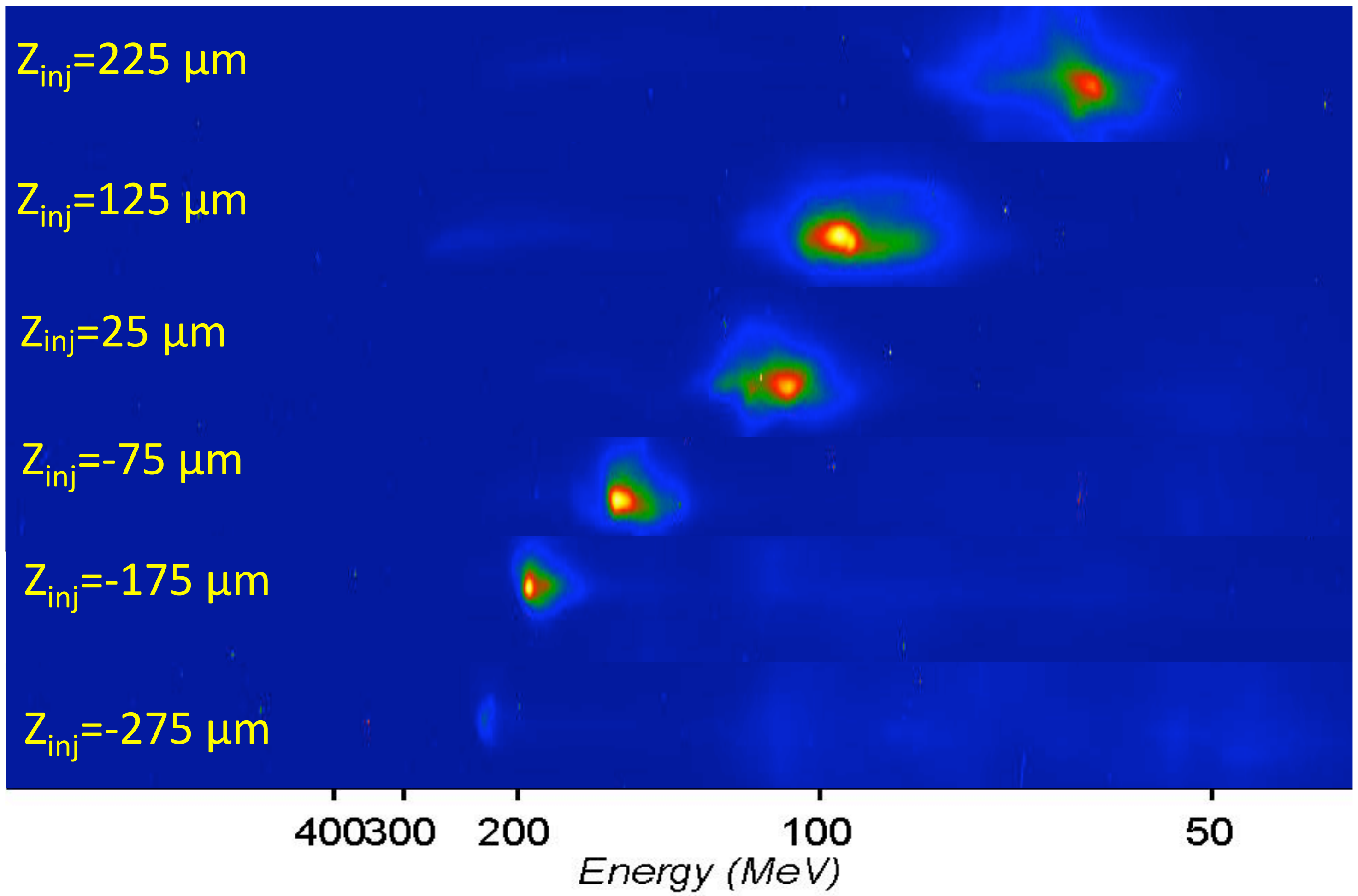


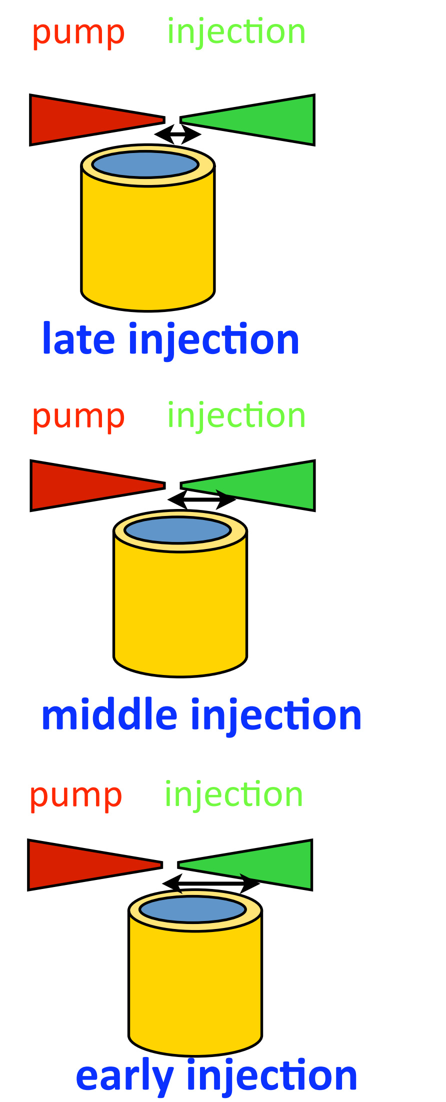


accelerating distance ⟷

J. Faure *et al.*, Nature **444**, 737 (2006)

Tunability of Laser Plasma Accelerators : electrons energy

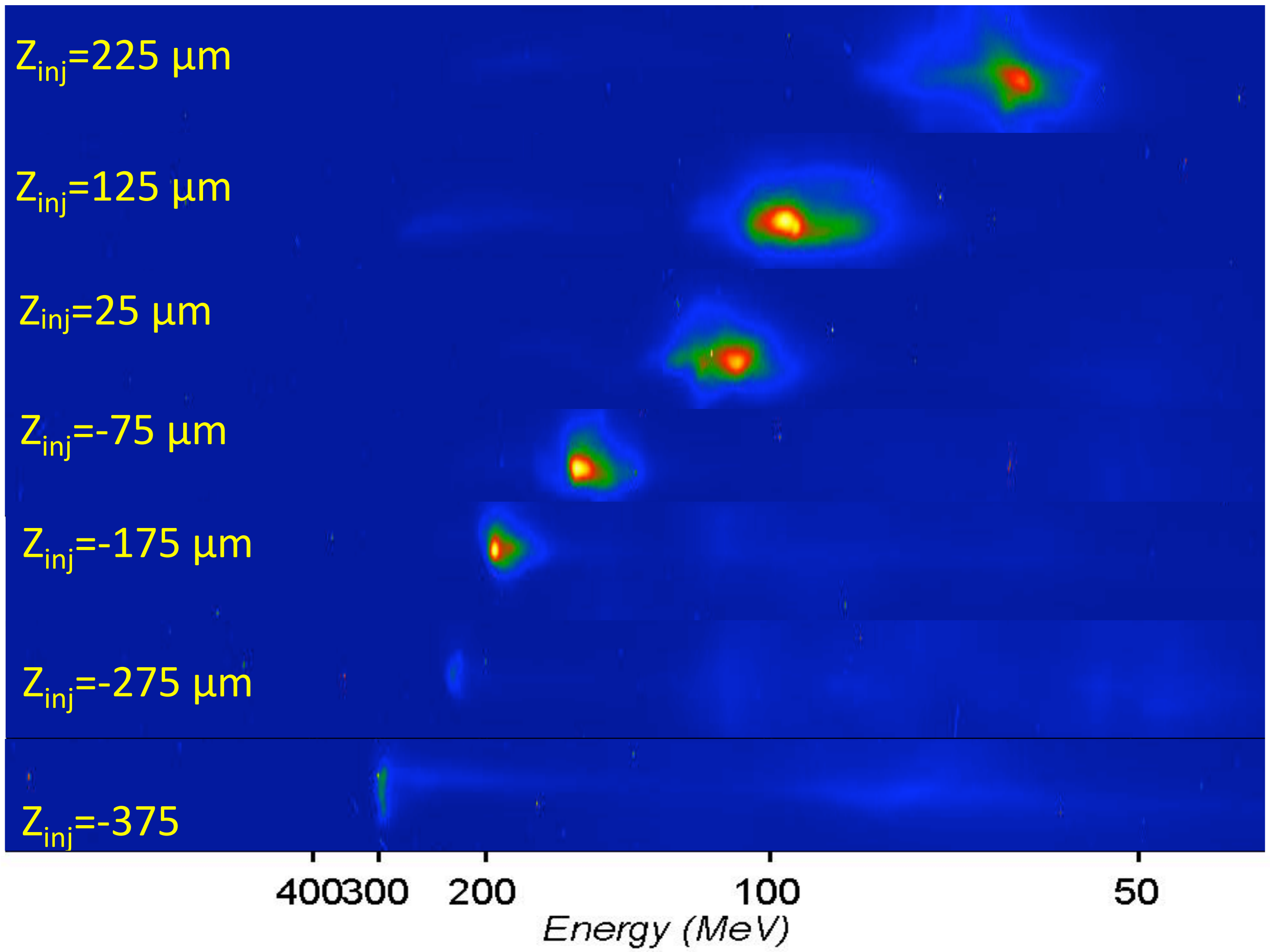


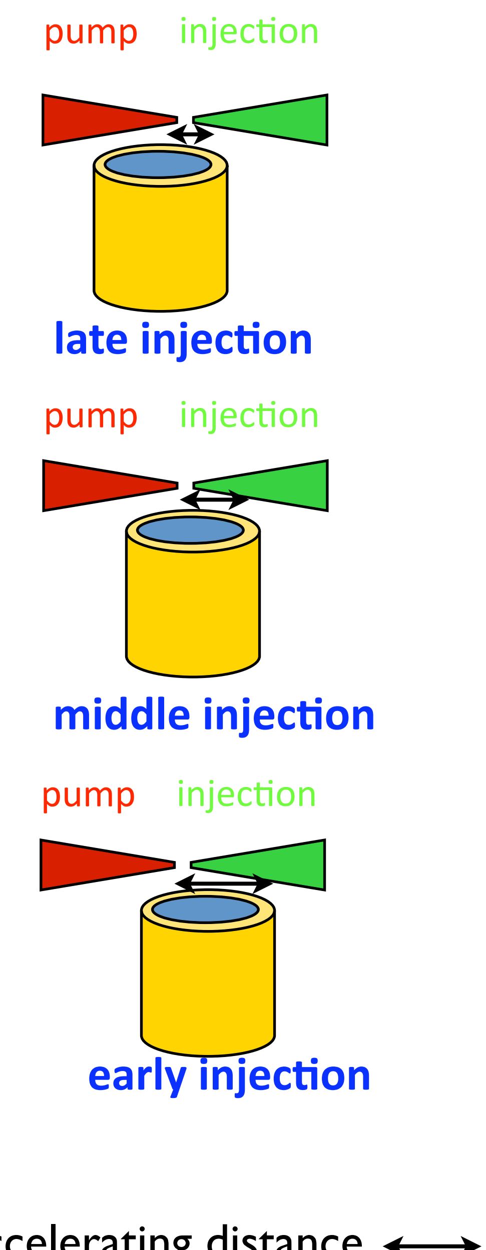


accelerating distance ⟷

J. Faure *et al.*, Nature **444**, 737 (2006)

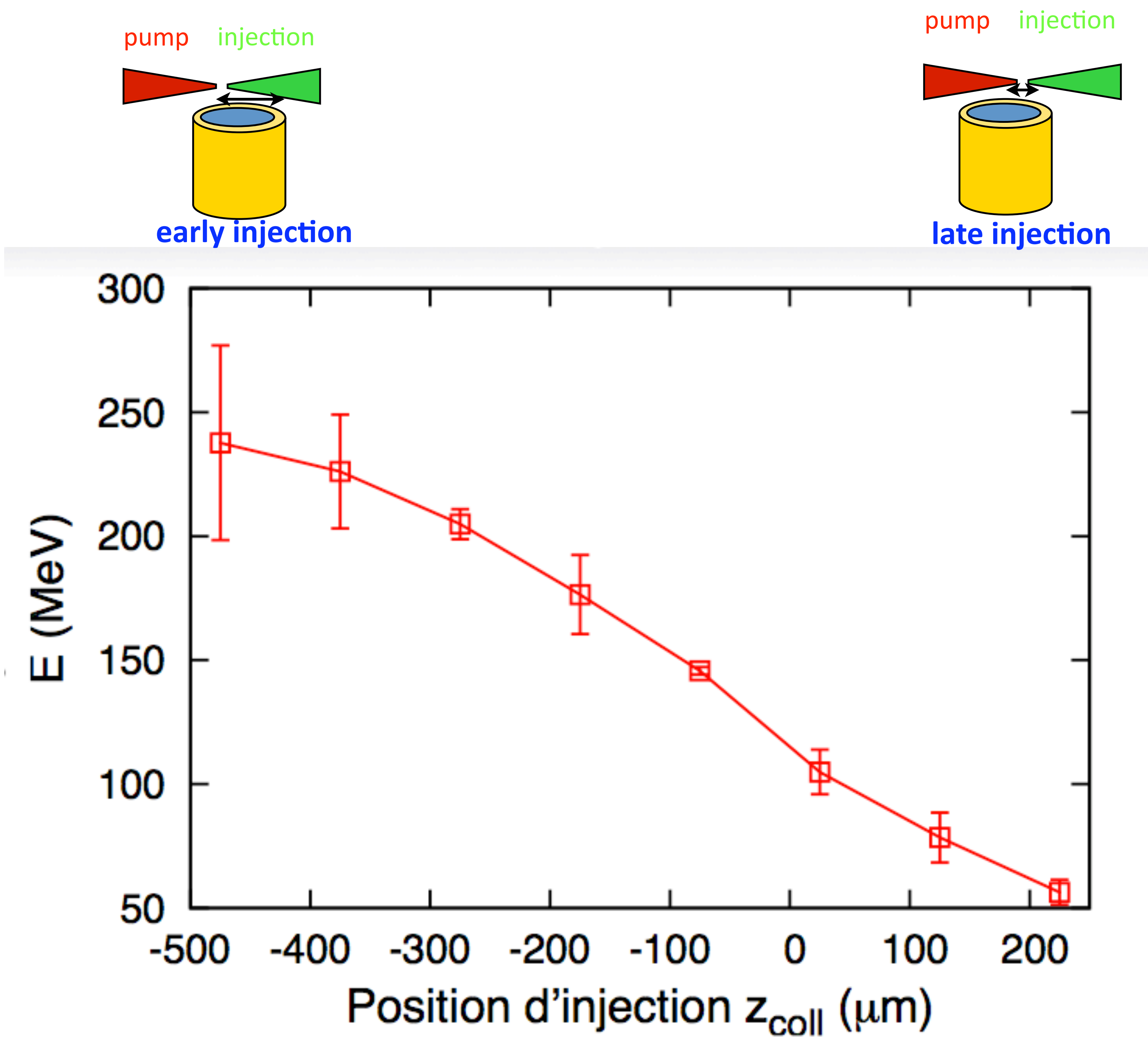
Tunability of Laser Plasma Accelerators : electrons energy



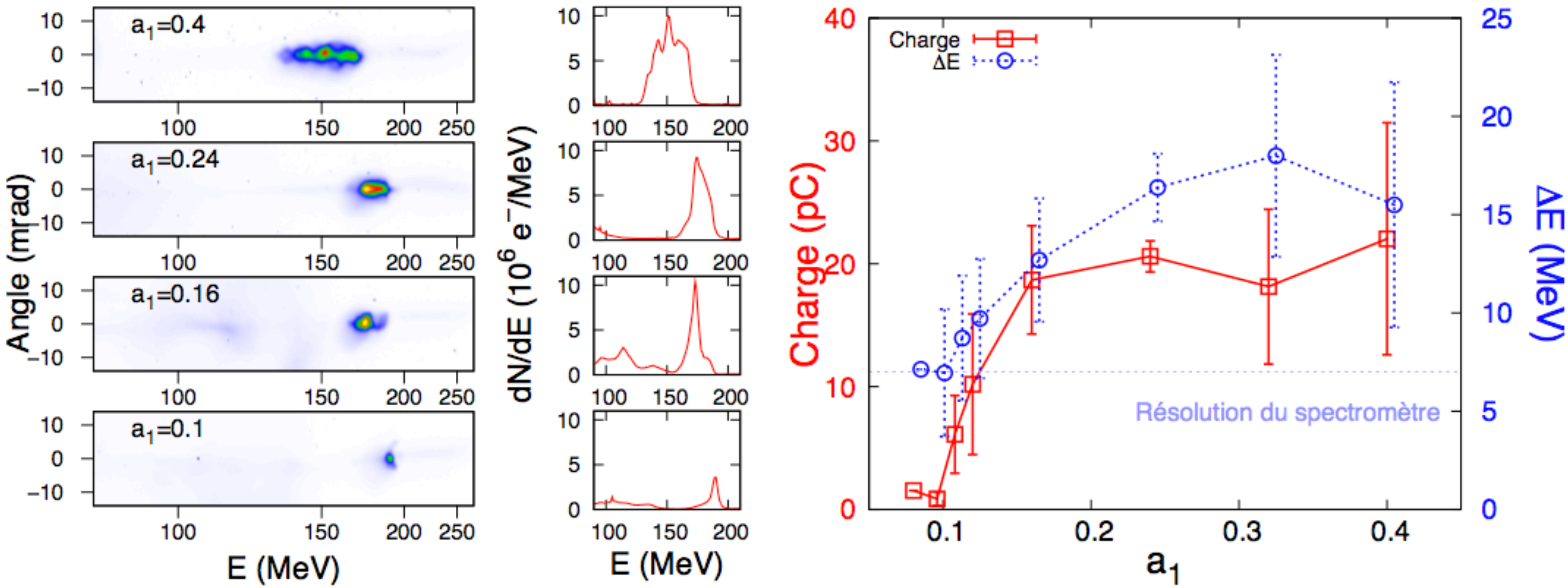


J. Faure *et al.*, Nature **444**, 737 (2006)

Tunability of Laser Plasma Accelerators : electrons energy



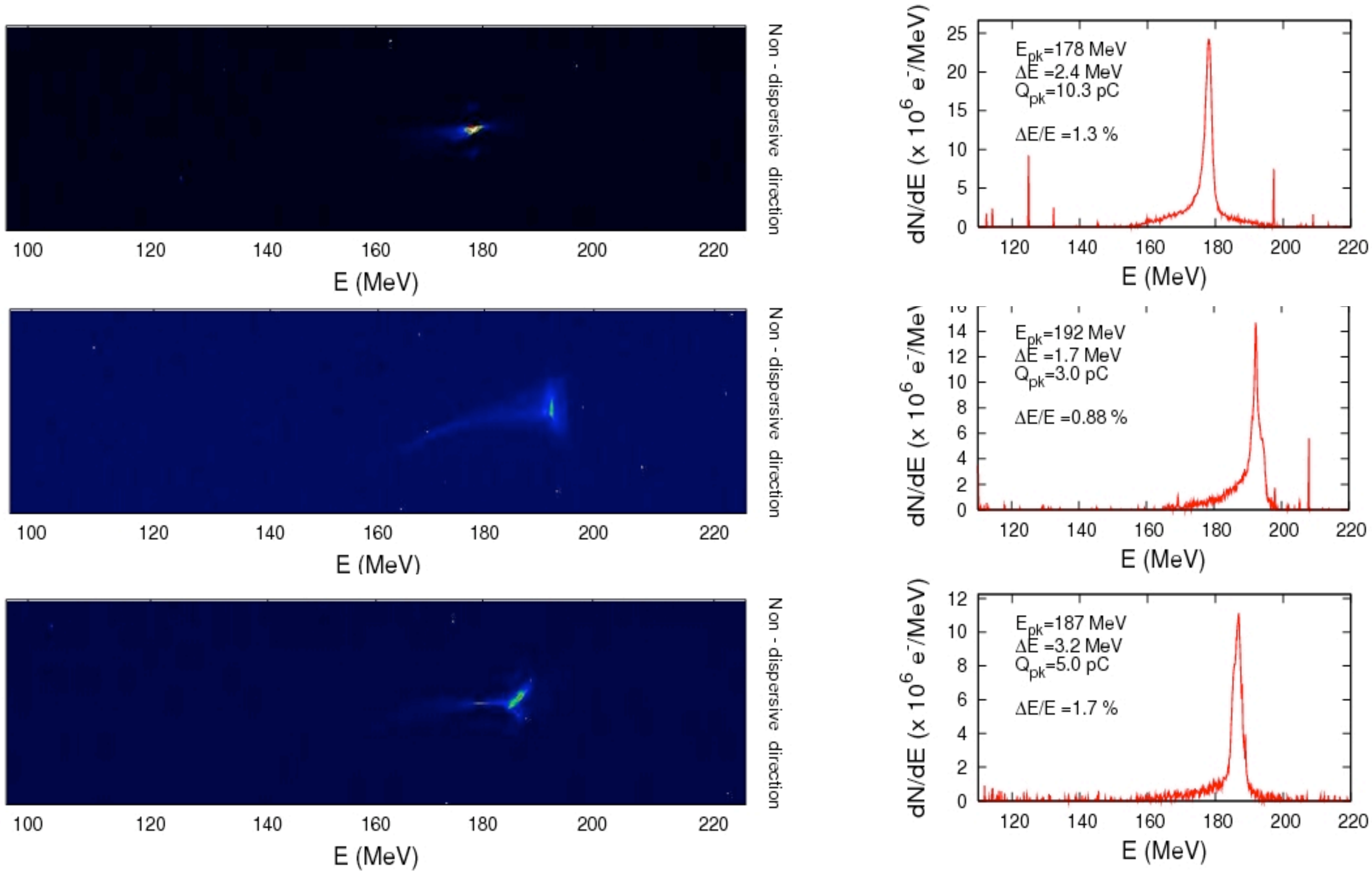
Tuning charge & energy spread with the inj. laser intensity



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

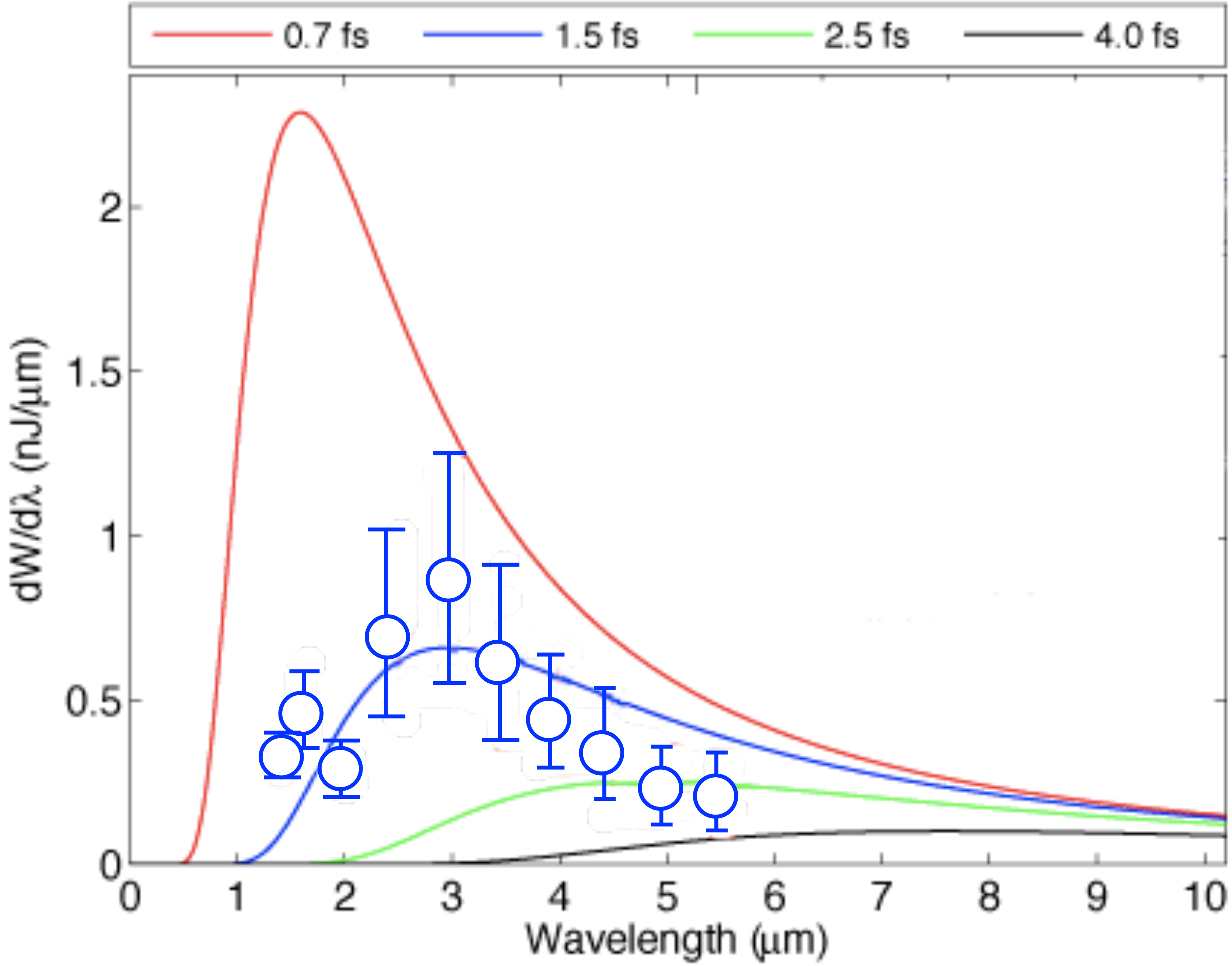
C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 164801 (2009)

1% relative energy spread



C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 194804 (2009)

1.5 fs RMS duration : Peak current of 4 kA



<u>Analytic CTR model</u>

Gaussian pulse shape

Measured e-beam :

- Charge
- Energy
- Divergence

<u>Bunch duration</u>

Peak wavelength

Peak intensity

<u>Spectral features</u>

Peak at 3 μm

Coherent

1.5 fs RMS duration : Peak current of 4 kA

O. Lundh et al., Nature Physics, **7** (2011)

A. Buck *et al.*, Nature Physics **8**, (2011)

Laser Plasma Accelerators : Outline

◉ Introduction : Laser wakefield principle and motivation

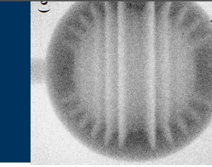
◉ Review of injection processes :

- Transverse injection : Bubble/Blow out regime
- Longitudinal injection
- Density gradient
- Ionization
- Colliding

◉ **Applications**

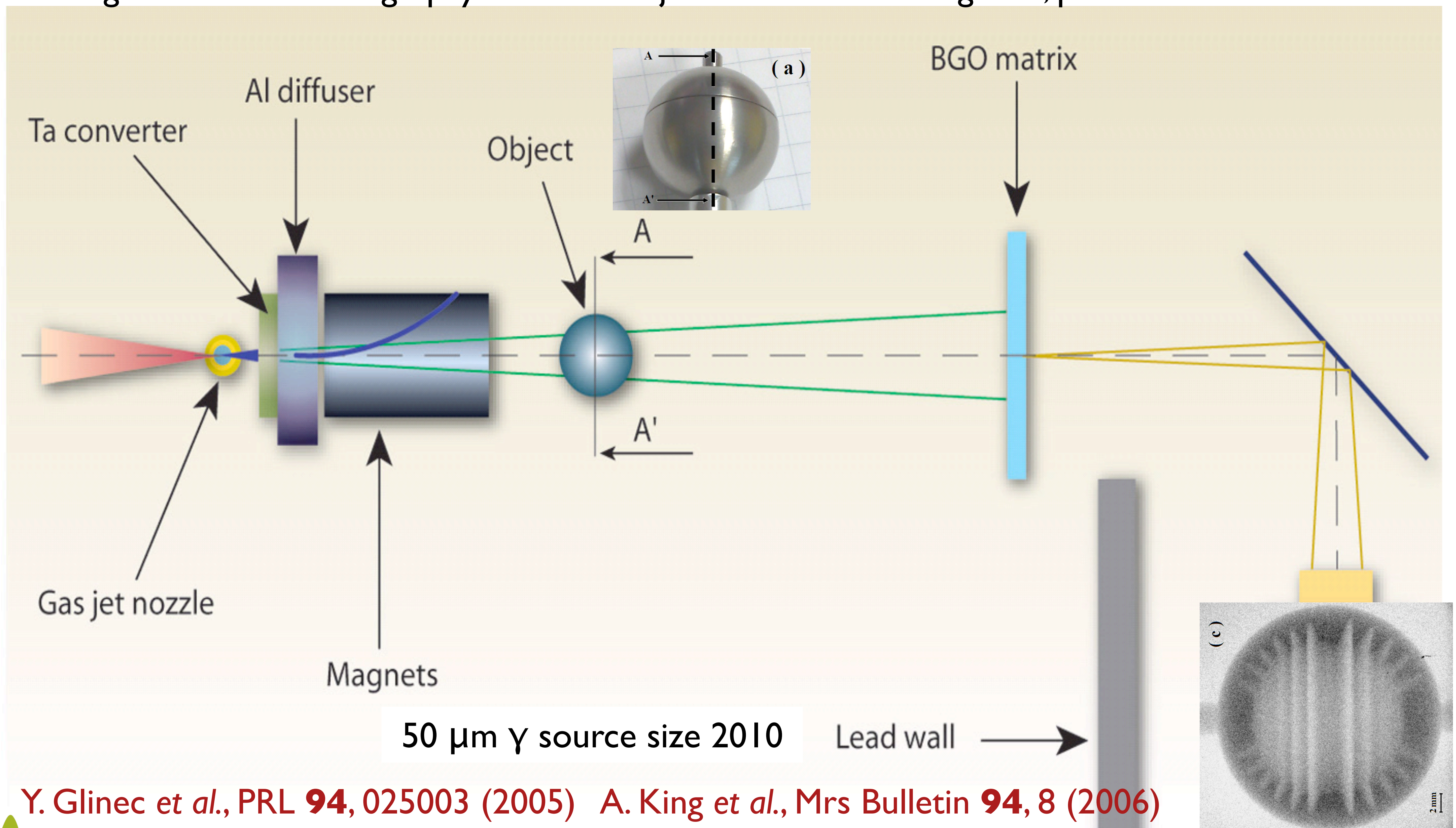
◉ Conclusion and perspectives

Some examples of applications : radiography



Non destructive dense matter inspection

High resolution radiography of dense object with a low divergence, point-like electron source

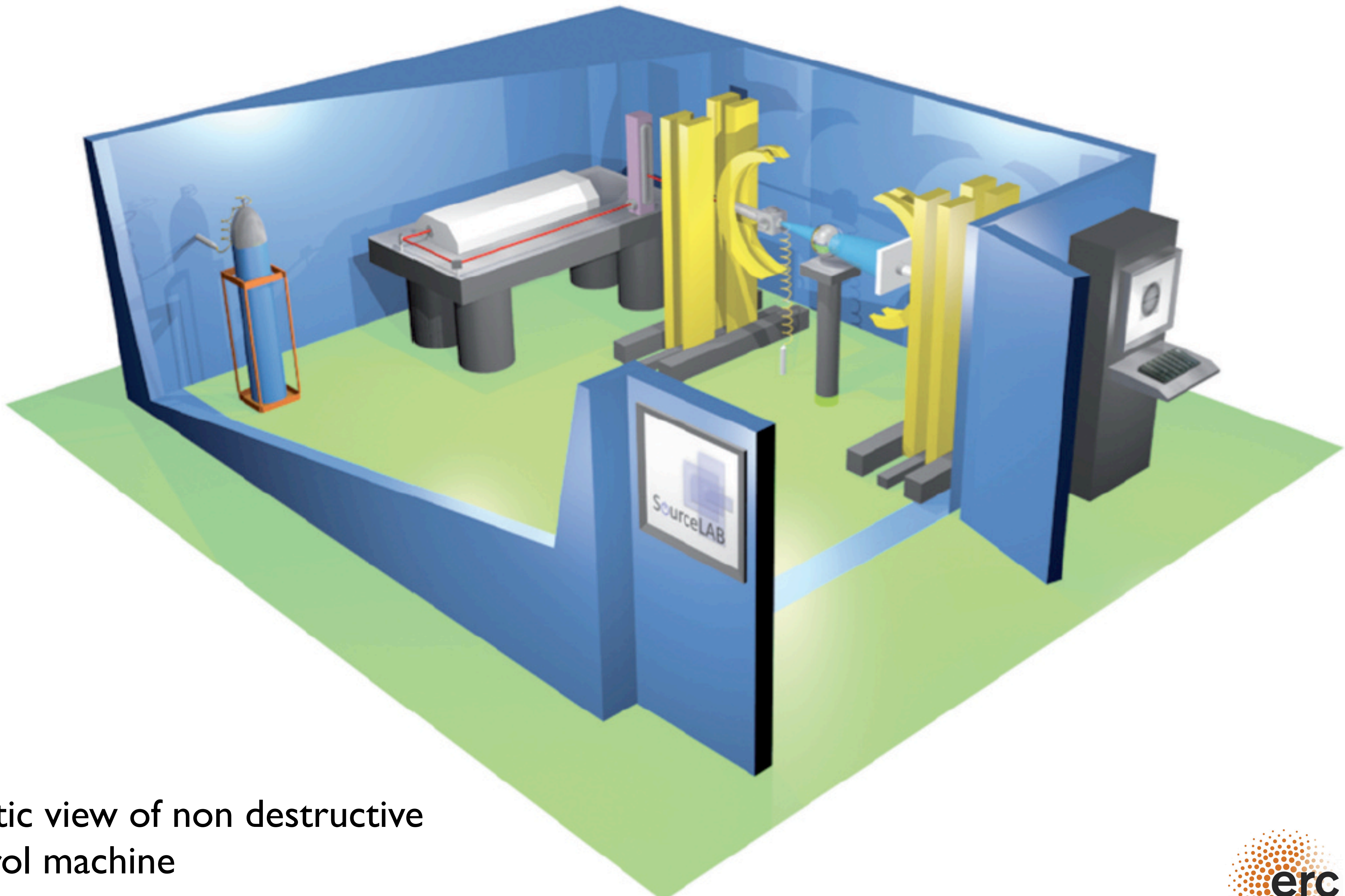


50 µm γ source size 2010

Y. Glinec *et al.*, PRL **94**, 025003 (2005)   A. King *et al.*, Mrs Bulletin **94**, 8 (2006)

A. Ben-Ismail *et al.*, Nucl. Instr. and Meth. A **629** (2010), App. Phys. Lett. **98**, 264101 (2011)

Some examples of applications : Non Destructive Control



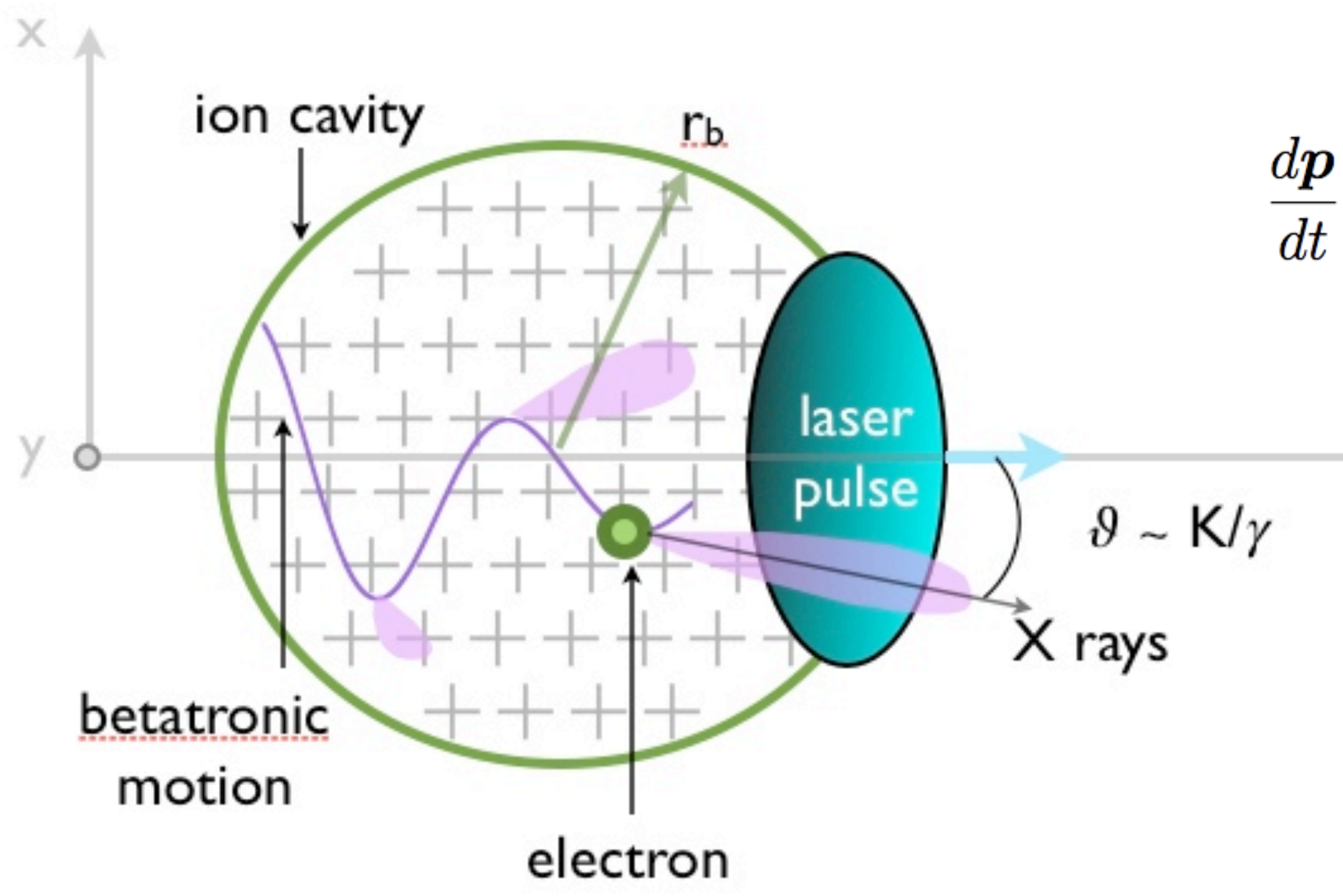
Artistic view of non destructive control machine

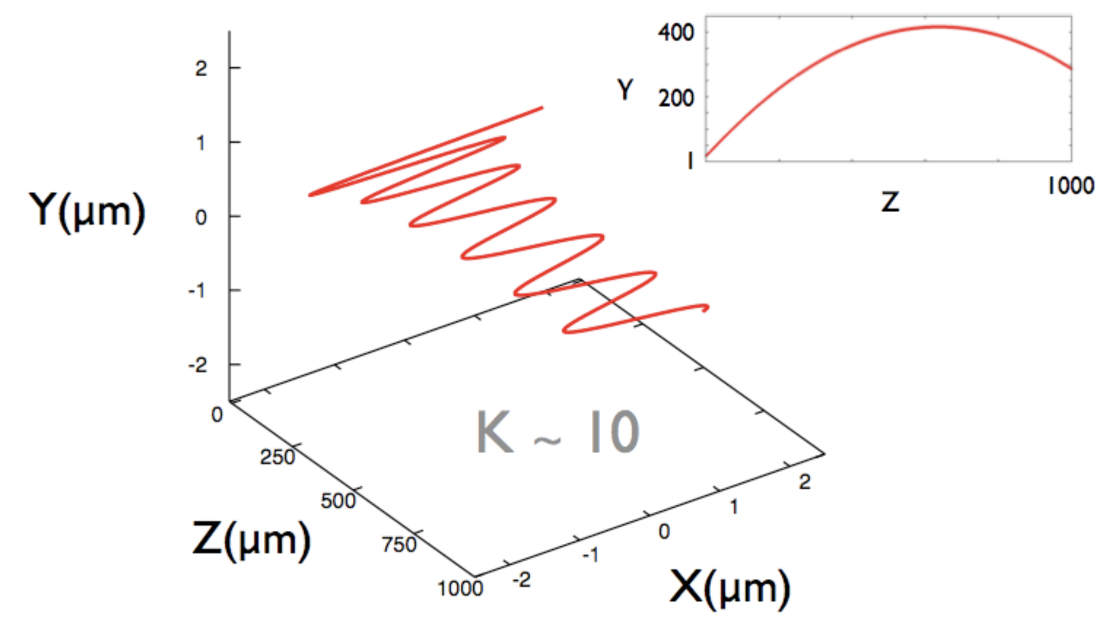
Betatron radiation properties

Transverse force

$$\frac{d\boldsymbol{p}}{dt} = \boldsymbol{F}_{\parallel} + \boldsymbol{F}_{\perp} = -\frac{m\omega_p^2}{2}\zeta\hat{\boldsymbol{z}} - \frac{m\omega_p^2}{2}(x\hat{\boldsymbol{x}} + y\hat{\boldsymbol{y}})$$

Longitudinal Force





Betatron oscillation properties:

$$\lambda_u = \sqrt{2\gamma}\lambda_p$$

$$K = r_\beta k_p \sqrt{\gamma/2}$$

$$\xrightarrow[r_\beta \sim 1\ \mu\text{m}]{\sim 100\ \text{MeV}}$$

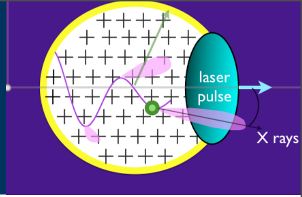
$$n_e \sim 10^{19}\ \text{cm}^{-3}$$

$$\lambda_u \sim 200\ \mu\text{m}$$

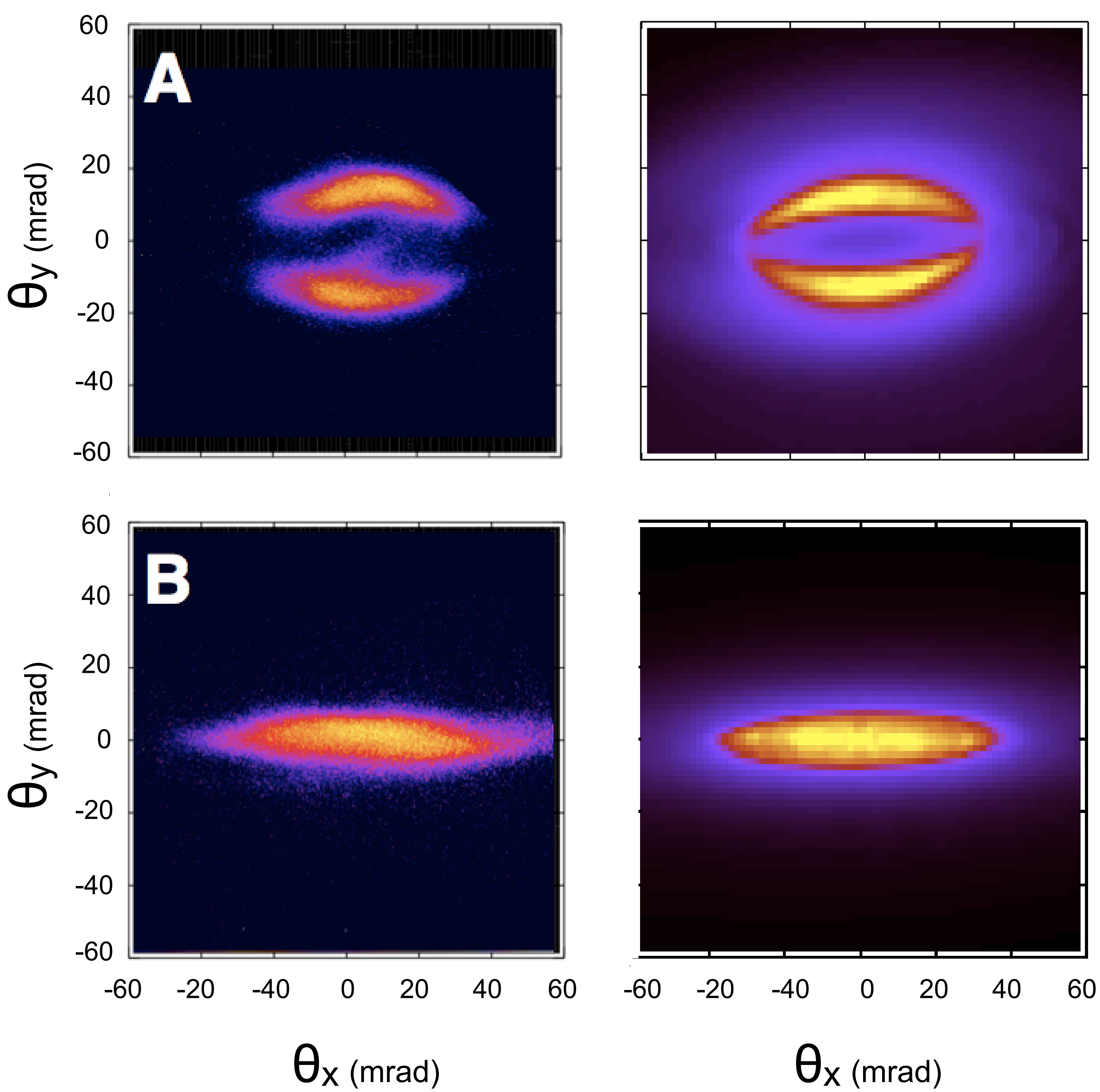
$$K \sim 5$$

A. Rousse *et al.*, Phys. Rev. Lett. **93**, 135005 (2004)

A more precise source size estimation



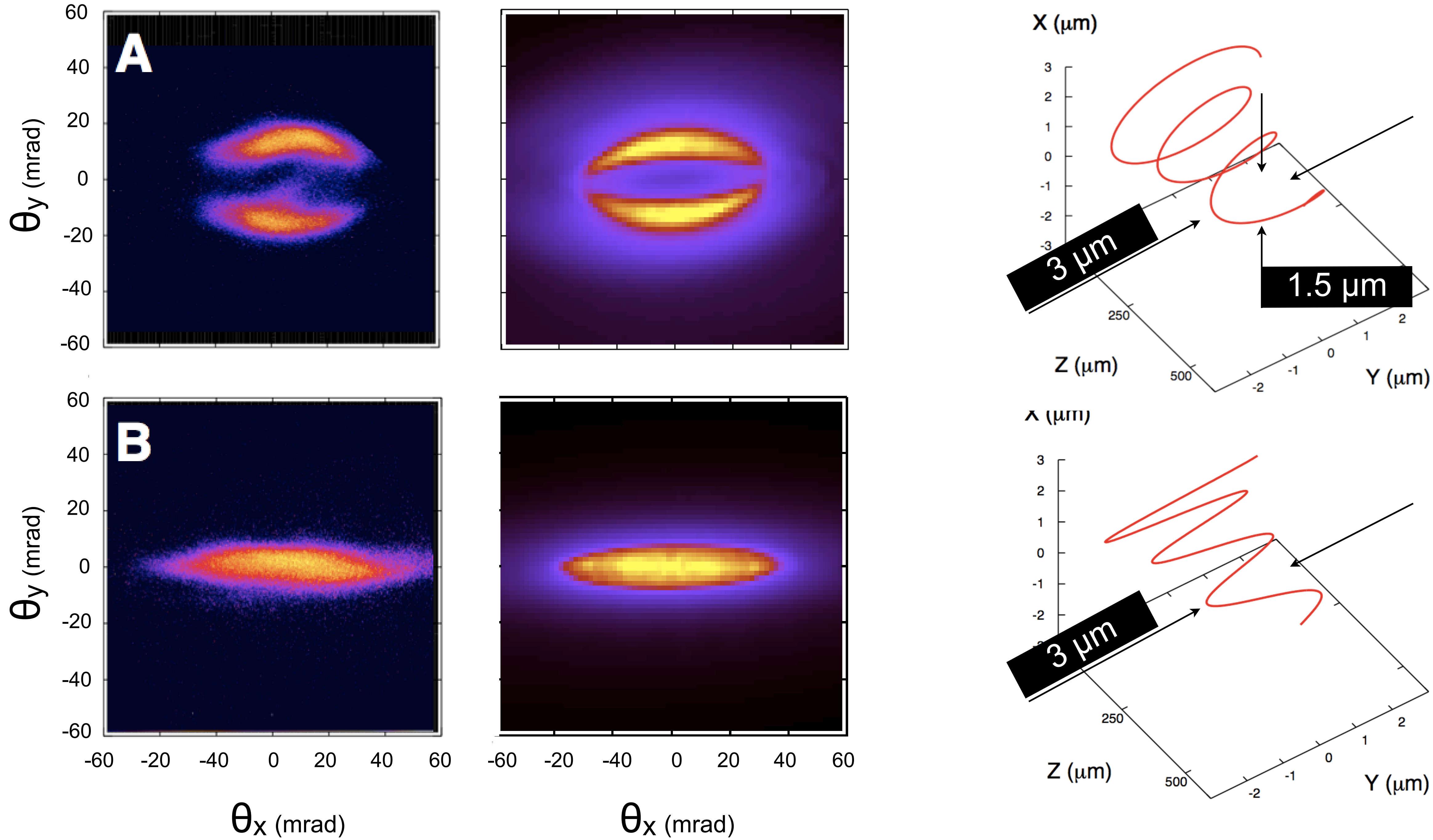
Experimental profiles | Calculated profiles | Electron orbits



K. Ta Phuoc *et al.*, Phys. Rev. Lett. **97**, 225002 (2006)

A more precise source size estimation

Experimental profiles | Calculated profiles | Electron orbits



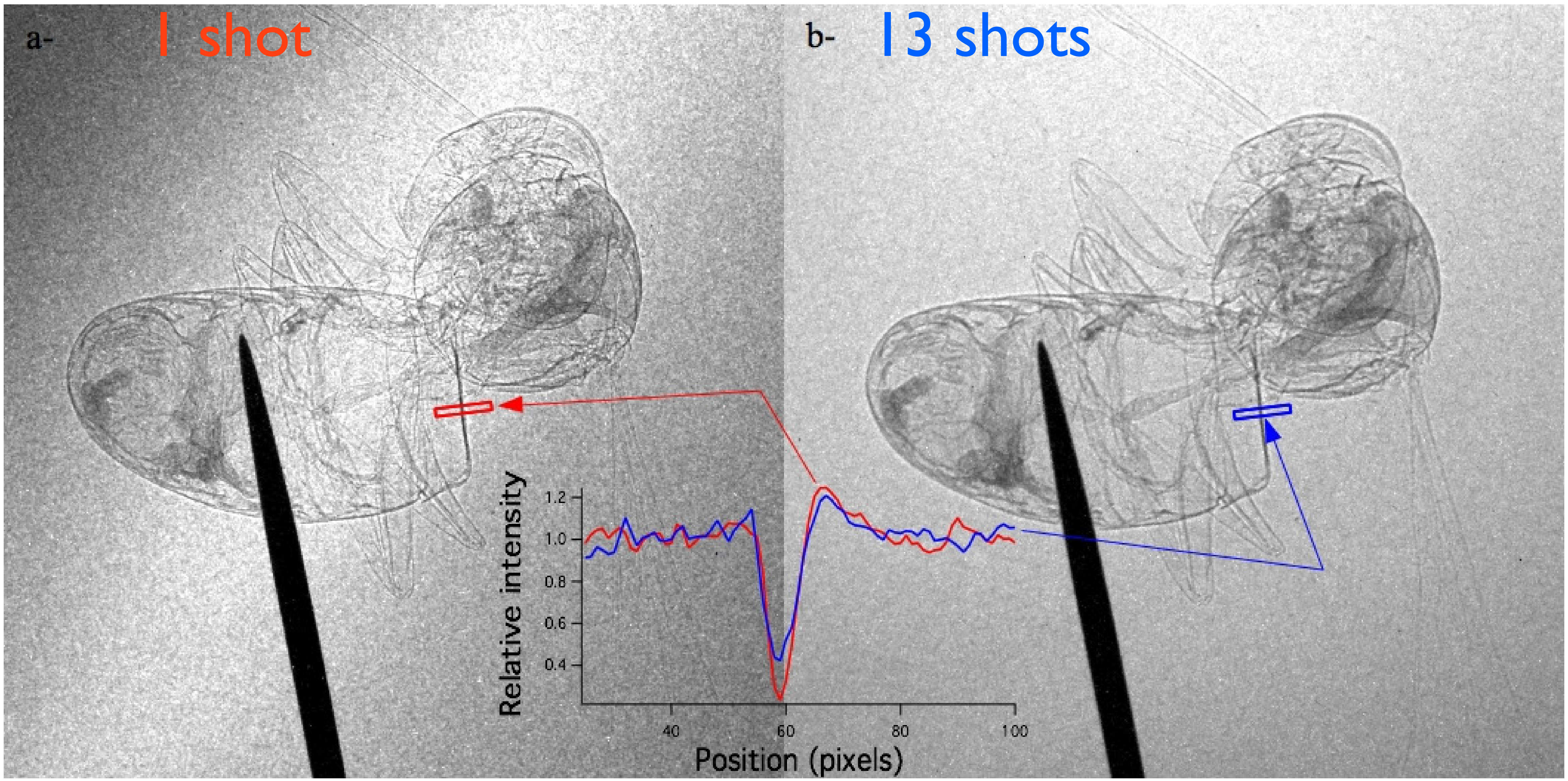
K. Ta Phuoc *et al.*, Phys. Rev. Lett. **97**, 225002 (2006)

IPAC 2013, The 4th International Particle Accelerator Conference, Shanghai China, 12-17 May (2013)

Phase contrast imaging : results

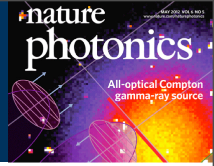
Bee contrast image :

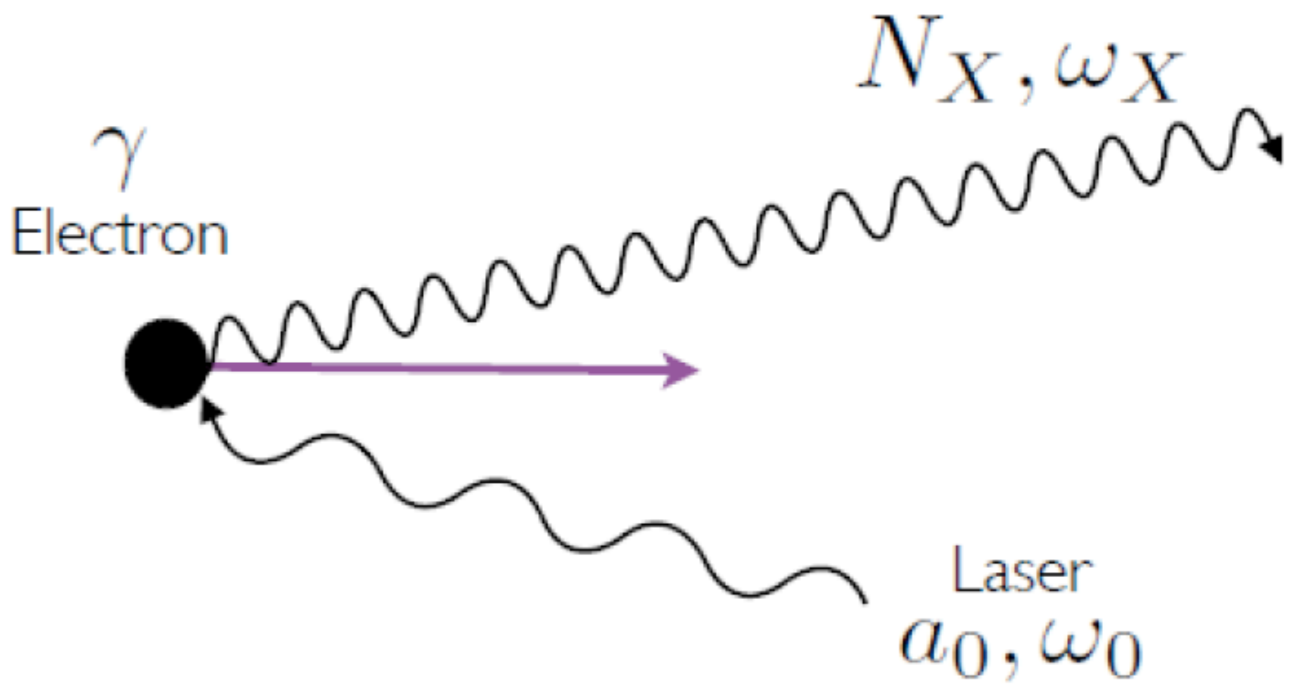
- Contrast of 0.68 in single shot.
- Very tiny details can be observed in single shot that disappear in multi shots.



S. Fourmaux *et al.*, Opt. Lett. **36**, 2426 (2011)

Inverse Compton Scattering





Doppler upshift : high energy photons with modest electrons energy : $\omega_x = 4\gamma^2\omega_0$

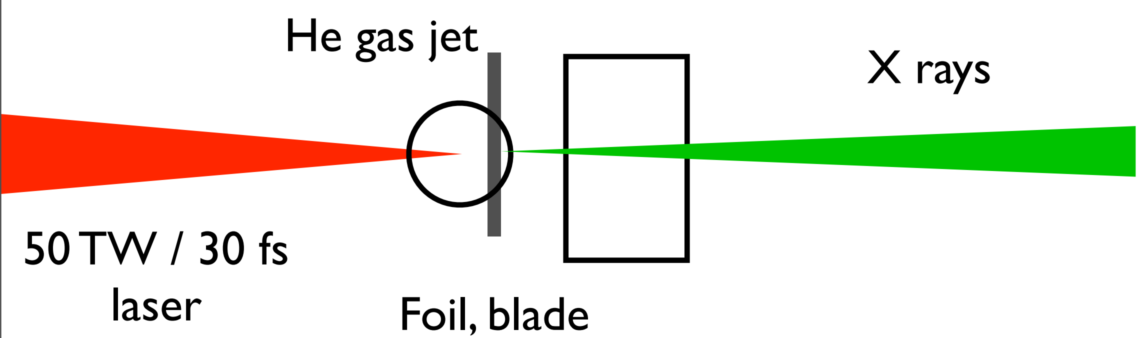
For example : 20 MeV electrons can produce 10 keV photons
200 MeV electrons can produce 1 MeV photons

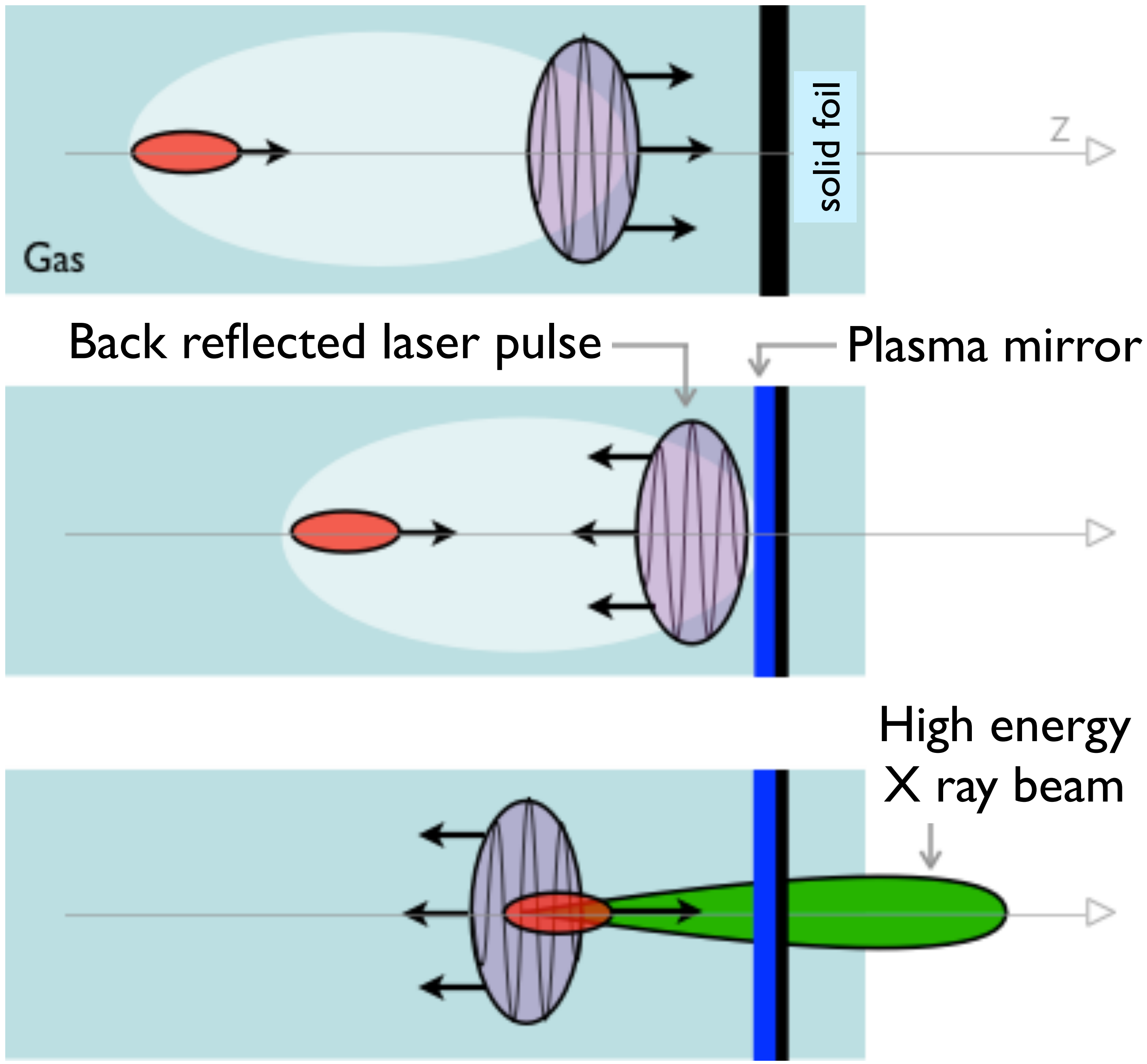
The number of photons depends on the electron charge N_e and a_0^2 : $N_x \propto a_0^2 \times N_e$

Duration (fs), source size (µm) = electron bunch length and electron beam size

Spectral bandwidth : $\Delta E/E \propto 2\Delta\gamma/\gamma, \gamma^2\Delta\theta^2$

Inverse Compton Scattering : New scheme





A single laser pulse

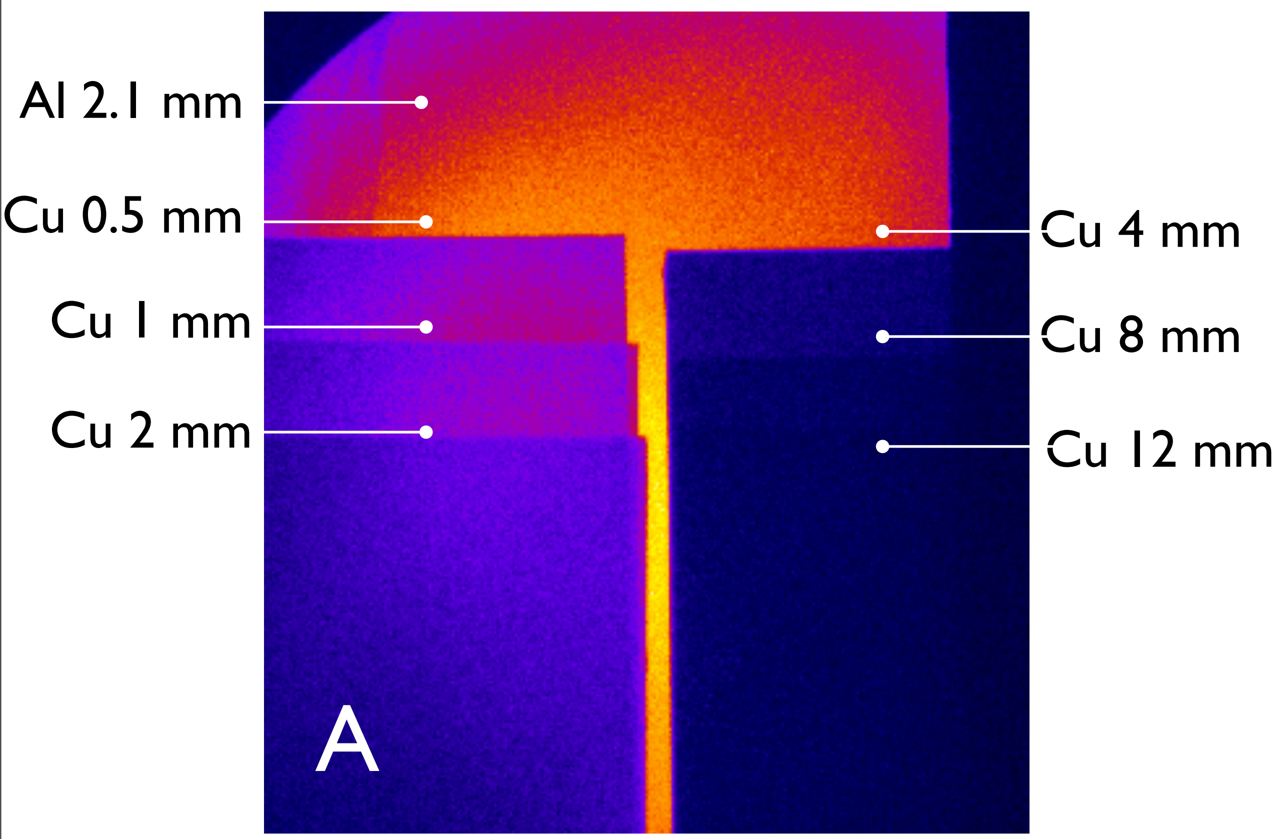
A plasma mirror reflects the laser beam

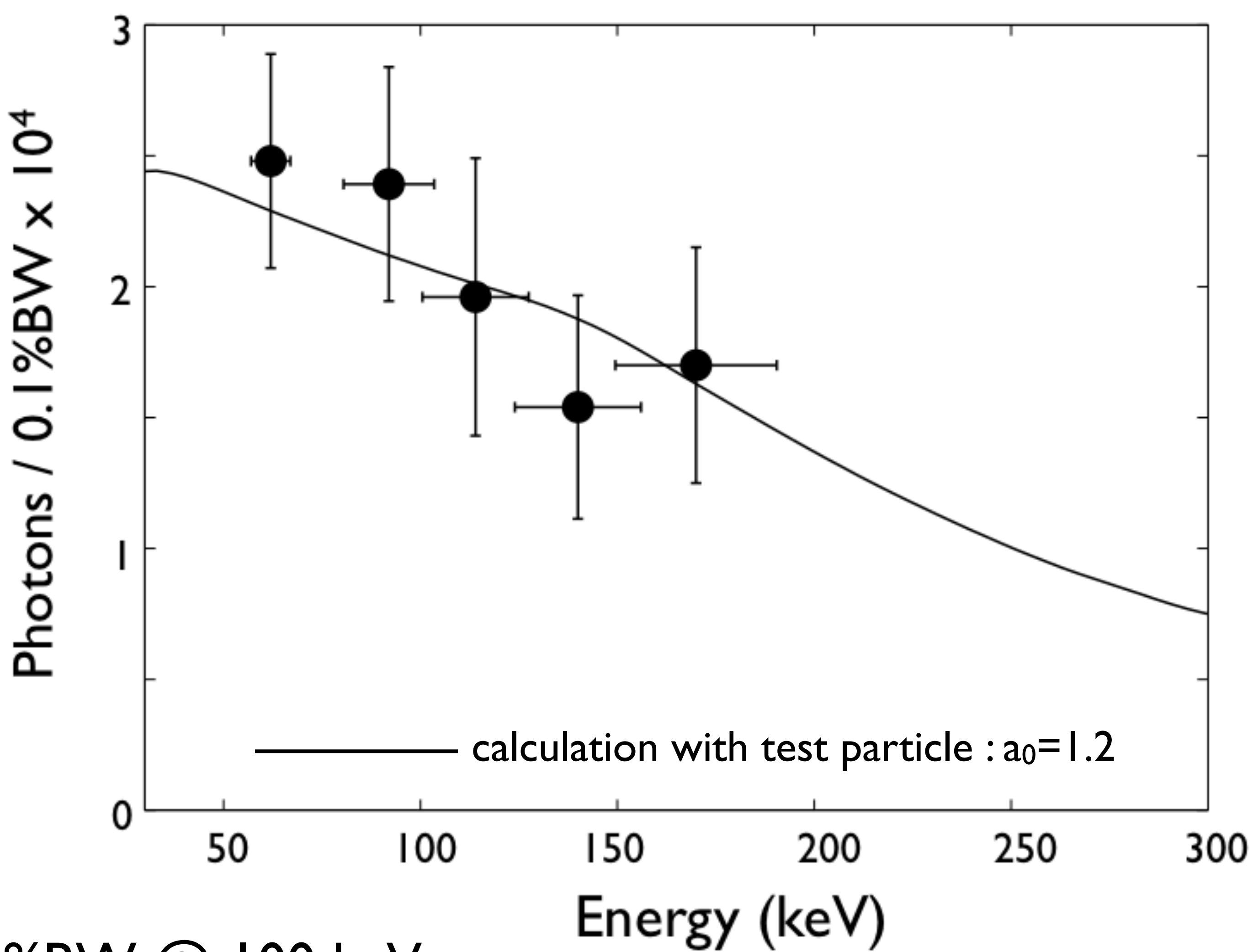
The back reflected laser collides with the accelerated electrons

No alignement : the laser and the electron beams naturally overlap

Save the laser energy !

Inverse Compton Scattering : Compton Spectra

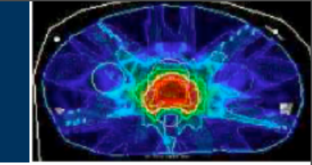


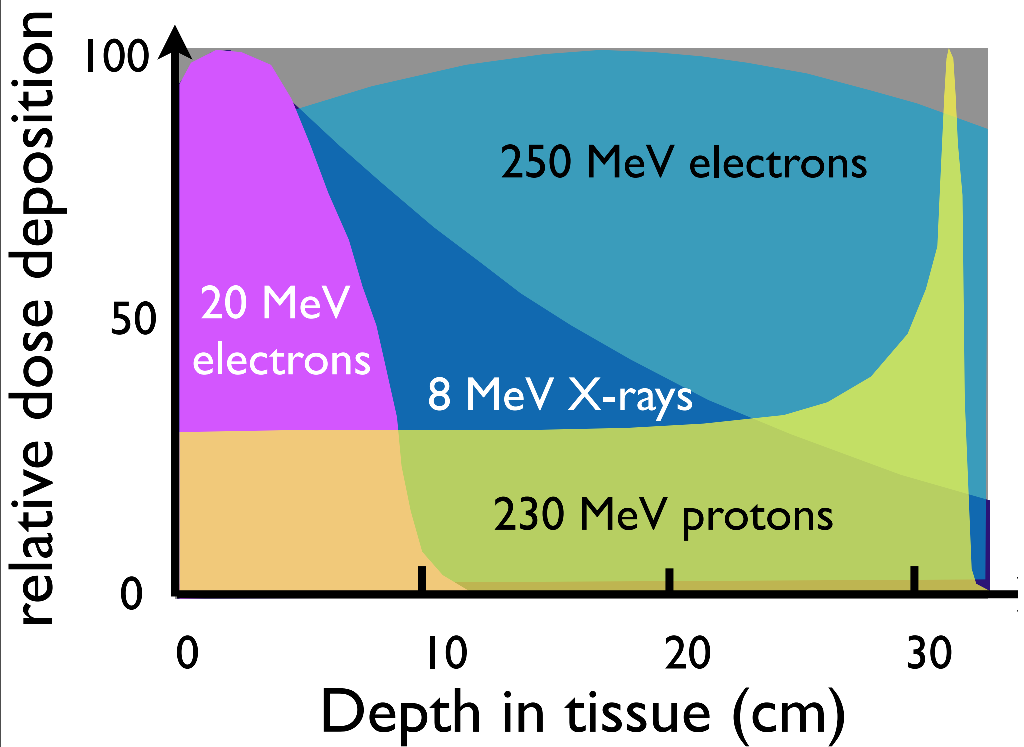


- About 10^8 ph/shot, a few 10^4 ph/shot/0.1%BW @ 100 keV
- Broad electron spectrum => broad X ray spectra
- Brigthness: 10^{21} ph/s/mm^2/mrad^2/0.1%BW @100 keV

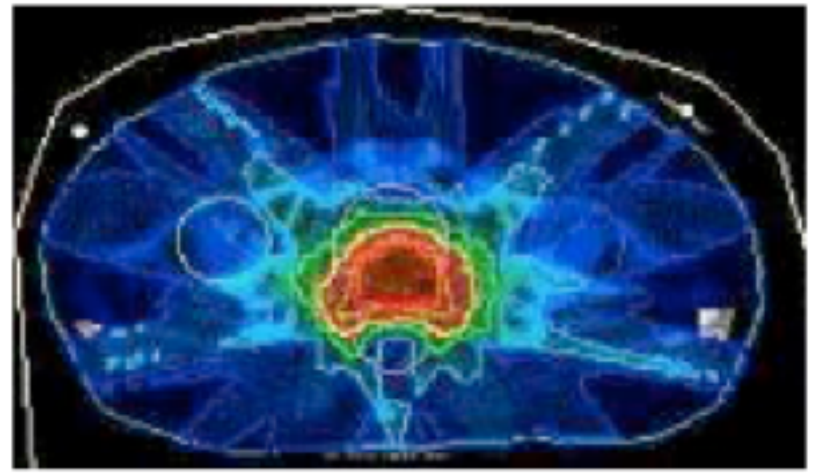
K. Ta Phuoc *et al.*, Nature Photonics **6** (2012)

Some examples of applications : radiotherapy

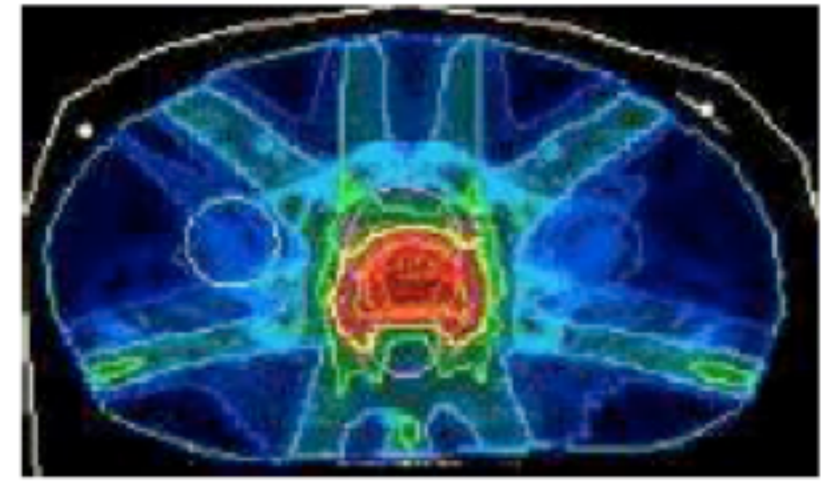




simulations of prostate cancer with 7 irradiation beams



250 MeV electrons



X rays IMRT

A comparison of dose deposition with 6 MeV X ray an improvement of the quality of a clinically approved prostate treatment plan. While the target coverage is the same or even slightly better for 250 MeV electrons compared to photons the dose sparing of sensitive structures is improved (up to 19%).

T. Fuchs *et al.* Phys. Med. Biol. **54**, 3315-3328 (2009), in coll. with DKFZ

Y. Glinec *et al.* Med. Phys. **33**, 1, 155-162 (2006),

O. Lundh *et al.*, Medical Physics **39**, 6 (2012)

Laser Plasma Accelerators : Outline

- Introduction : Laser wakefield principle and motivation
- Review of injection processes :
  - Transverse injection : Bubble/Blow out regime
  - Longitudinal injection
  - Density gradient
  - Ionization
  - Colliding
- Applications
- **Conclusion and perspectives**

Conclusions

Accelerators point of view :

- Good beam quality & Monoenergetic dE/E down to 1 % √
- Beam is very stable √
- Energy is tunable: up to 400 MeV √
- Charge is tunable: 1 to tens of pC √
- Energy spread is tunable: 1 to 10 % √
- Ultra short e-bunch : 1,5 fs rms √
- Low divergence : 2 mrad √
- Low emittance[1-3] : < π.mm.mrad √

With PW class laser : peak energy at 3 GeV √

[1]S. Fritzler *et al.*, Phys. Rev. Lett. **92**, 165006 (2004), [2]C. M. S. Sears *et al.*, PRSTAB **13**, 092803 (2010)
[3]E. Brunetti *et al.*, Phys. Rev. Lett. **105**, 215007 (2010)

Perspectives

New ideas for controlling the injection ?

Cold injection scheme[1]
Magnetic control of injection[2]
Control phase of the electric field[3]
Transverse injection scheme[4]...

New numerical code/scheme for long accelerating distance runs ?

Boost Frame, Fourier decomposition codes, moving frames
New schemes to reduce artificial cerenkhov effect and/or emittance growth, etc..

New diagnostics ?

New diagnostics such as betatron[4,5], magnetic field[6,7], interferometry in the frequency-time[8], etc...

[1]X. Davoine *et al.*, Phys. Rev. Lett. **102**, 065001(2009), [2]J. Vieira *et al.*, Phys. Rev. Lett. **106**, 225001(2011), [3]A. Lifshitz *et al.*, submitted to PRL, [4]A. Rousse *et al.*, Phys. Rev. Lett. **93**, 13 (2004), [5]K. Ta Phuoc *et al.*, Phys. Rev. Lett. 97, 225002 (2006), [6]M. C. Kaluza *et al.*, Phys. Rev. Lett. **105**, 115002 (2010), [7]A. Buck *et al.*, Nature Physics **8**, (2011), [8]N. H. Matlis *et al.* , Nature Physics 2006

Perspectives

Short term perspective (< 10 years):

Relevant applications in medicine, radiobology, material science

Compact FEL with moderate average power (10 Hz system)

Designing future accelerators

Compact X ray source (Thomson, Compton, Betatron, or FEL)

Long term possible applications (>50 years):

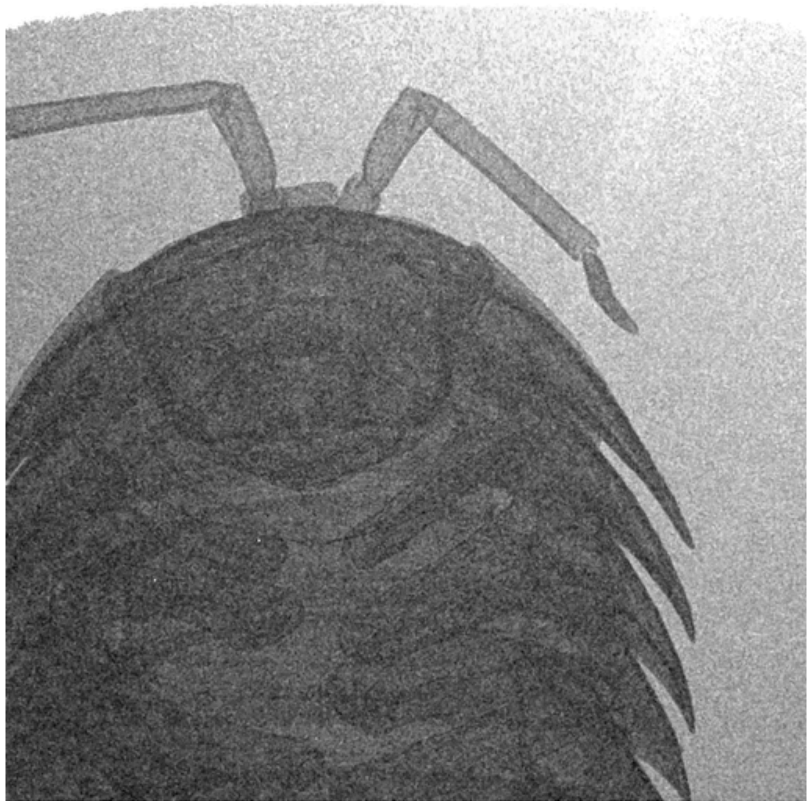
High energy physics that will depend on the laser technology evolution, on laser to electron transfer efficiency, on progress of multistage design, acceleration of positron, etc...)

V. Malka *et al.*, Nature Physics **4** (2008), V. Malka Phys. of Plasma 19, 055501 (2012)
E. Esarey et al. , Rev. Mod. Phys. **81** (2009), S. Corde et al., Rev. Mod. Phys. **85** (2013)

Perspectives

Short term perspective (< 10 years):

Relevant applications in medicine, radiobology, material science
Compact FEL with moderate average power (10 Hz system)
Designing future accelerators
Compact X ray source (Thomson, Compton, Betatron, or FEL)



Long term possible applications (>50 years):

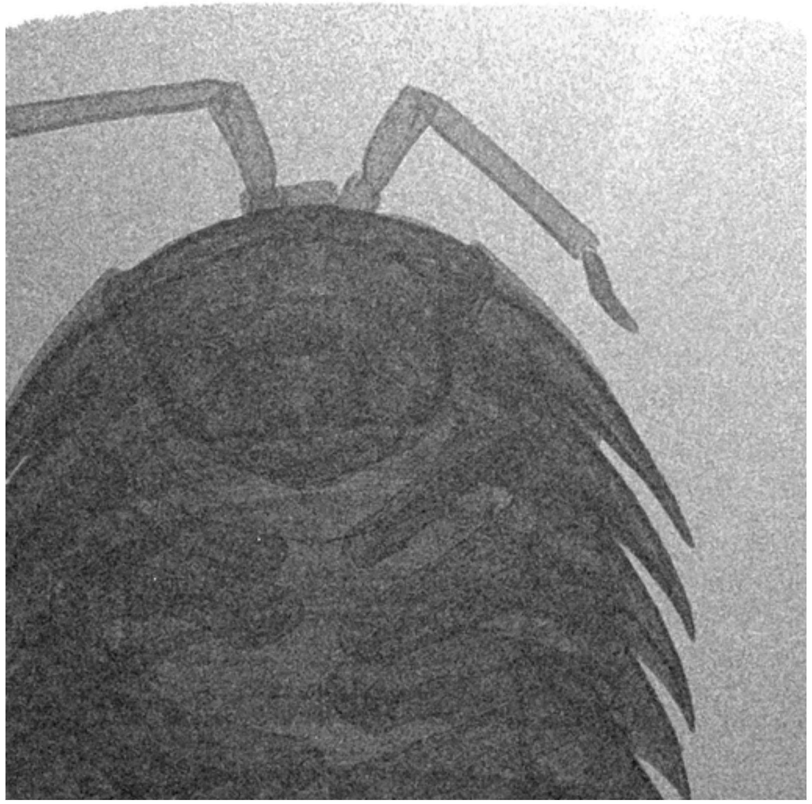
High energy physics that will depend on the laser technology evolution, on laser to electron transfer efficiency, on progress of multistage design, acceleration of positron, etc...)

V. Malka *et al.*, Nature Physics **4** (2008), V. Malka Phys. of Plasma 19, 055501 (2012)
E. Esarey et al. , Rev. Mod. Phys. **81** (2009), S. Corde et al., Rev. Mod. Phys. **85** (2013)

Perspectives

Short term perspective (< 10 years):

Relevant applications in medicine, radiobology, material science
Compact FEL with moderate average power (10 Hz system)
Designing future accelerators
Compact X ray source (Thomson, Compton, Betatron, or FEL)



Courtesy of K. Krushelnick

Long term possible applications (>50 years):

High energy physics that will depend on the laser technology evolution, on laser to electron transfer efficiency, on progress of multistage design, acceleration of positron, etc...)

V. Malka *et al.*, Nature Physics **4** (2008), V. Malka Phys. of Plasma 19, 055501 (2012)
E. Esarey et al. , Rev. Mod. Phys. **81** (2009), S. Corde et al., Rev. Mod. Phys. **85** (2013)

Acknowledgements

A. Ben Ismail, S. Corde, J. Faure, S. Fritzler, Y. Glinec, A. Lifshitz, J. Lim, O. Lundh, C. Rechatin, A. Rousse, Kim Ta Phuoc, and C. Thaury from LOA

E. Lefebvre and X. Davoine from CEA/DAM

M. Downer *et al.* from U.T., S. Fourmaux *et al.* from INRS, N. Hafz *et al.* from APRI, T. Hosokai from O.U., D. Jaroszynski *et al.* from STRATH, C. Joshi *et al.* from UCLA, M. Kalutza *et al.* from IOQE, K. Kando *et al.* from JAEA, Hyung Taek Kim *et al.* from APRI , K. Krushelnick *et al.* from CUOS, W. P. Leemans *et al.* from LBNL, Z. Najmudin *et al.* from IC, L. Silva *et al.* from GoLP, L. Veisz *et al.* from MPQ, D. Umstadter *et al.* from N. U., *etc....*

CARE/FP6-Euroleap/FP6-Accel1/EUCARD/EUCARD^2/ ANR-PARIS/ERC contracts