Overview of laser-driven electron acceleration

Victor Malka

Laboratoire d'Optique Appliquée

ENSTA ParisTech – Ecole Polytechnique – CNRS
PALAISEAU, France

victor.malka@ensta.fr

3rd Topical Workshop on Novel Acceleration Techniques, Dresden, Germany, April 28-30 (2014)

Outline

- Motivation and principle
- Laser Beat wave and Laser Wakefield
- Self Modulated Laser Wakefield
- Towards high quality electron beams
- Conclusion and perspectives

Outline

- Motivation and principle
- Laser Beat wave and Laser Wakefield
- Self Modulated Laser Wakefield
- Towards high quality electron beams
- Conclusion and perspectives

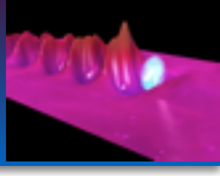
Industrial Market for Accelerators

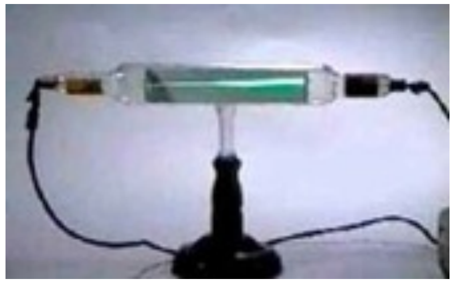
The development of state of the art accelerators for HEP has lead to :
research in other field of science (light source, spallation neutron sources…)
industrial accelerators (cancer therapy, ion implant., electron cutting&welding...)

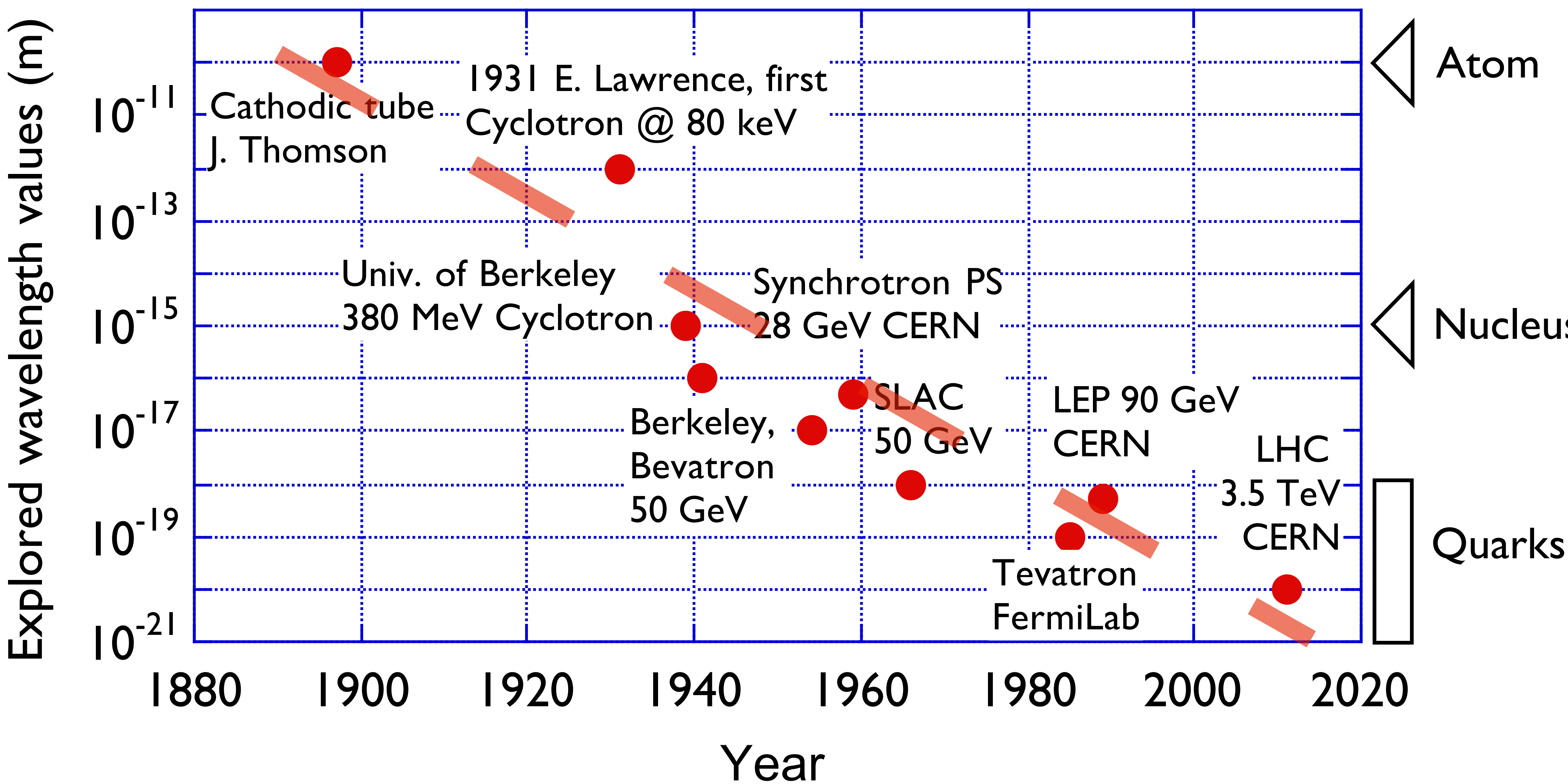
Application	Total systems (2007) approx.	System sold/yr	Sales/yr (M$)	System price (M$)
Cancer Therapy	9100	500	1800	2.0 - 5.0
Ion Implantation	9500	500	1400	1.5 - 2.5
Electron cutting and welding	4500	100	150	0.5 - 2.5
Electron beam and X rays irradiators	2000	75	130	0.2 - 8.0
Radio-isotope production (incl. PET)	550	50	70	1.0 - 30
Non destructive testing (incl. Security)	650	100	70	0.3 - 2.0
Ion beam analysis (incl. AMS)	200	25	30	0.4 - 1.5
Neutron generators (incl. sealed tubes)	1000	50	30	0.1 - 3.0
Total	**27500**	**1400**	**3680**	

Total accelerators sales increasing more than 10% per year

Accelerators: One century of exploration of the infinitively small

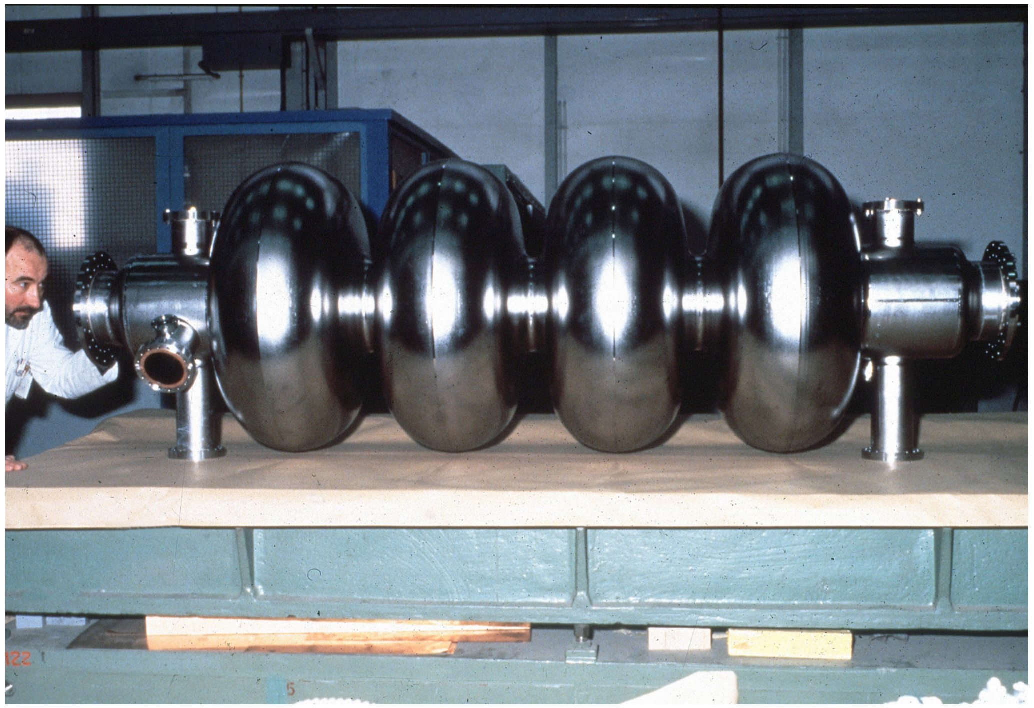






Compactness of Laser Plasma Accelerators

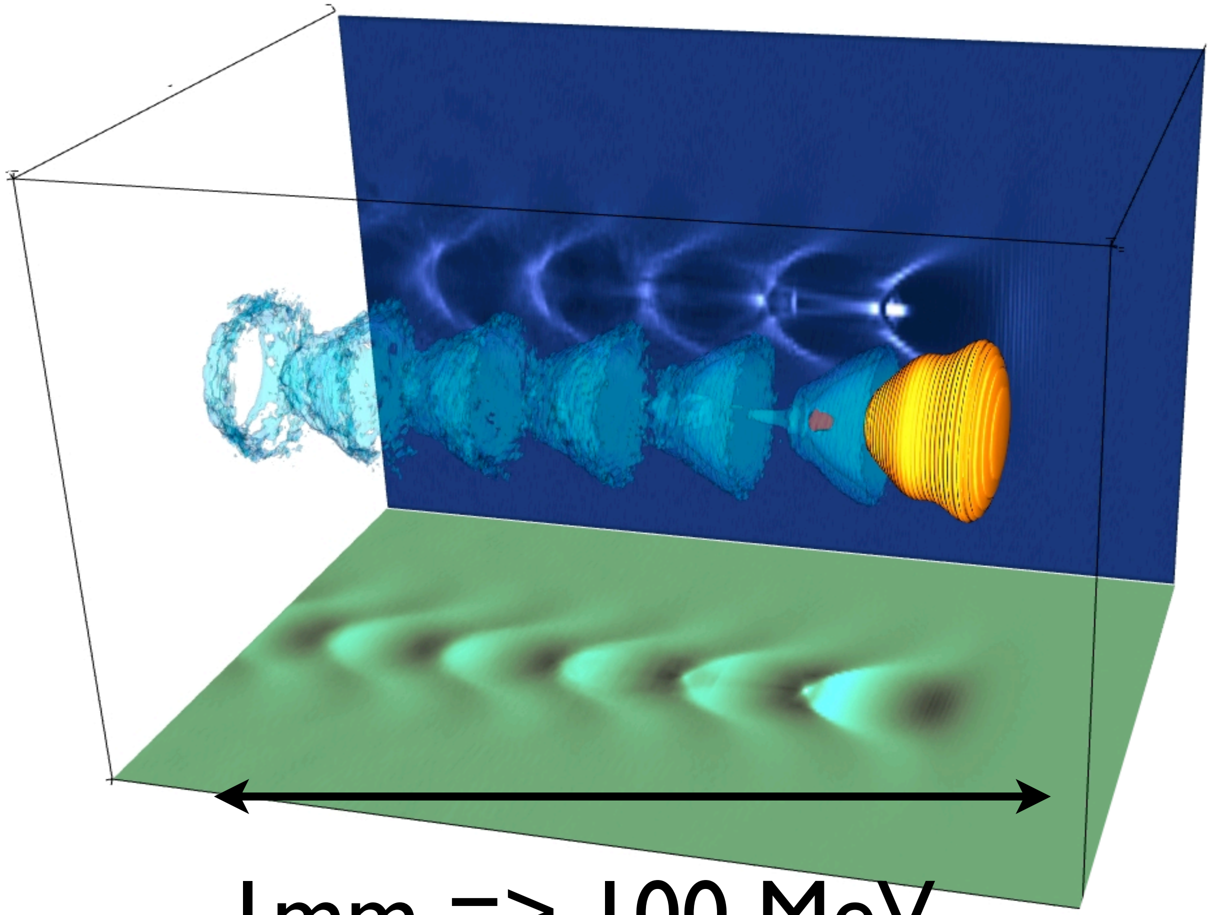
RF Cavity



1 m => 100 MeV Gain

Electric field < 100 MV/m

Plasma Cavity



1mm => 100 MeV

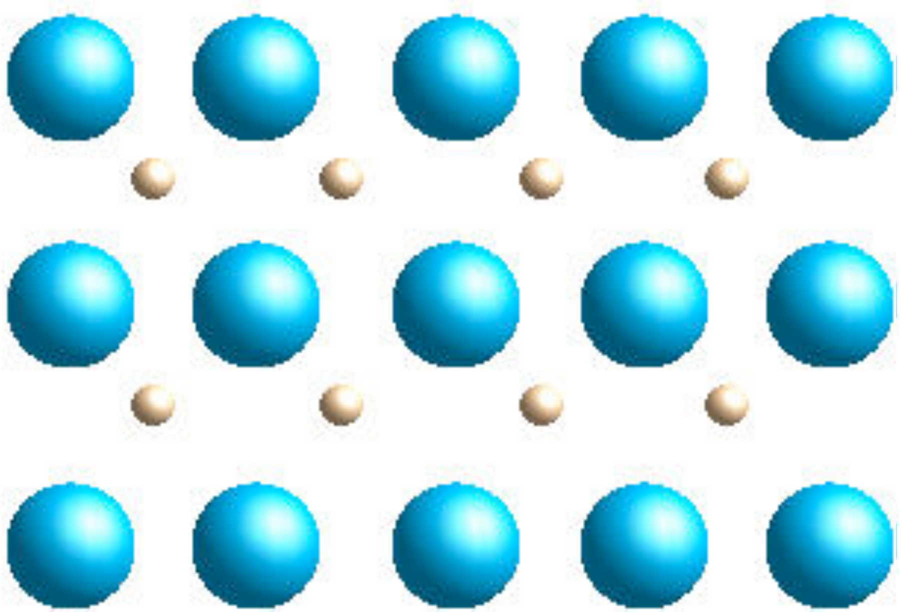
Electric field > 100 GV/m

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

1956: Coherent Principle of Acceleration in Plasmas

Superconducting RF-Cavities : E_z = 55 MVm

Plasma is an Ionized Medium => High Electric Fields



$$E_z\ (\mathrm{GV/m}) \approx \delta n/n \times \sqrt{n}$$

V. I. Veksler, "Coherent Principle of Acceleration of Charged Particles." *Proceedings of the CERN Symposium on High Energy Accelerators and Pion Physics*, vol. 1. Geneva, 1956. Pages 80–83.

1979 Relativistic plasma waves with Laser pulse

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Such a wake is most effectively generated if the length of the electromagnetic wave packet is half the wavelength of the plasma waves in the wake:

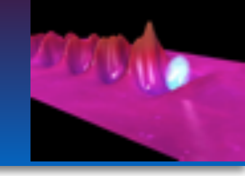
$$L_t = \lambda_w/2 = \pi c/\omega_p . \quad (2)$$

=> Laser wakefield

An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes $2\pi c/\omega_p$. The mechanism for generating the wakes

=> Laser beatwave

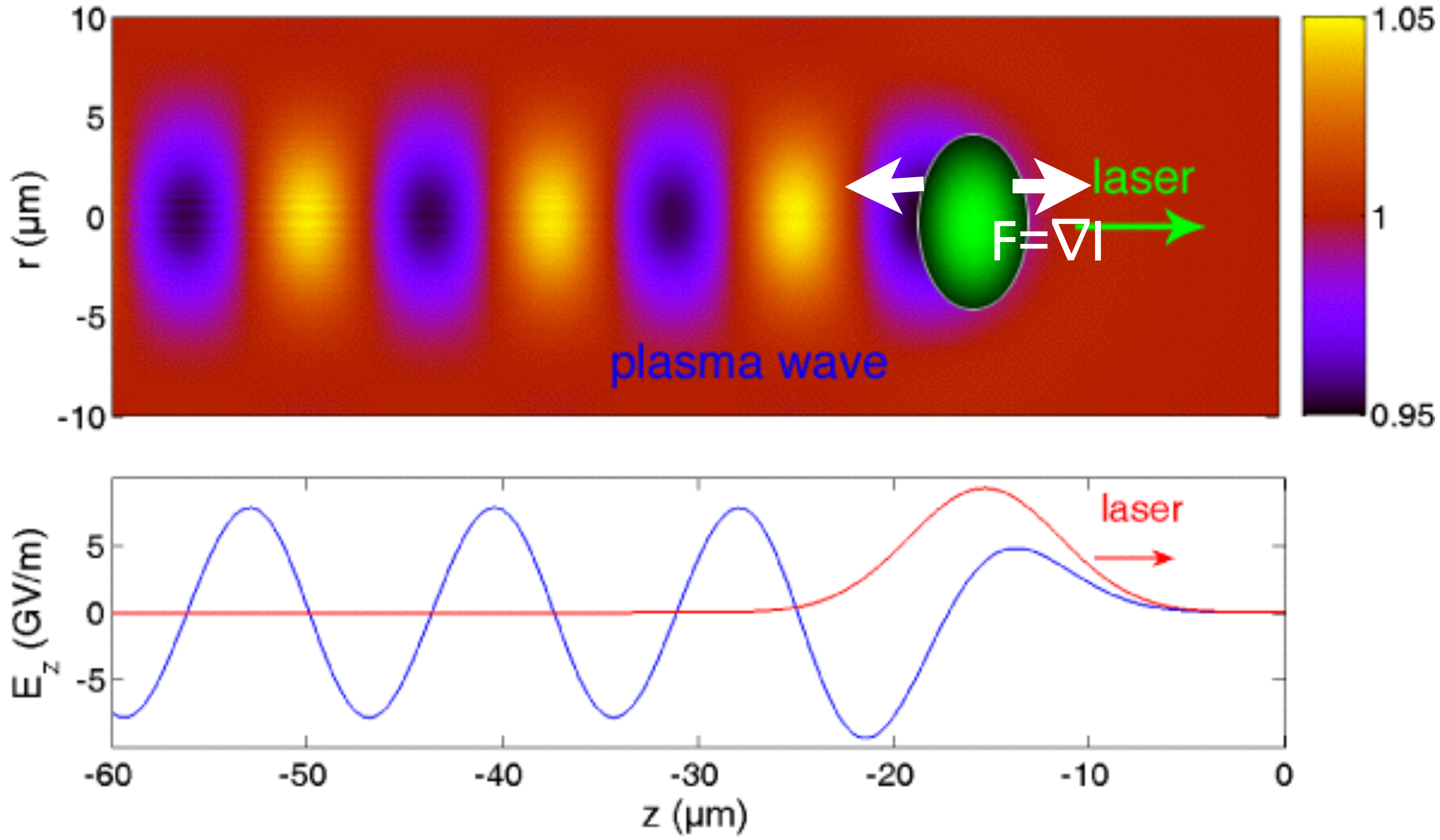
1979 How to excite a plasma wave ? the Laser Wakefield



1) 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

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

E_z = 0.3 GV/m for 1 % Density Perturbation at 10^{17} cc^{-1}

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

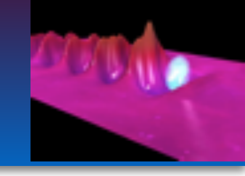
T. Tajima and J. Dawson, PRL **43**, 267 (1979)

Resonance : children are well aware....

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

my first swing experiments...

Outline



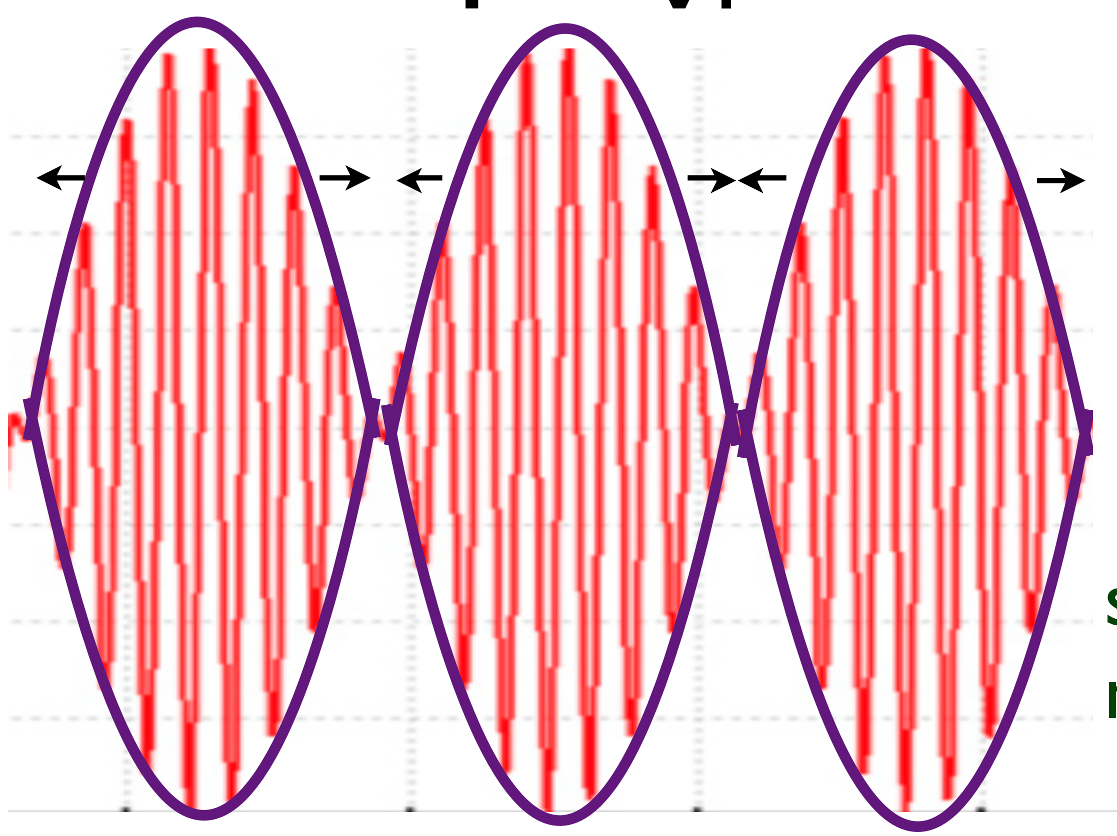
- Motivation and principle
- **Laser Beat wave and Laser Wakefield**
- Self Modulated Laser Wakefield
- Towards high quality electron beams
- Conclusion and perspectives

2) The laser beat waves : $\tau_L >> T_p$

$\omega_1, \mathbf{k}_1$

$\omega_2, \mathbf{k}_2$

$F \approx -\nabla I$



Train of short resonant pulses

\$\$\$\$!

$\omega_1 - \omega_2 = \omega_p$

linear growth rate

$\delta(t) = 1/4\ a_1 a_2 \omega_p t$

=> homogenous plasmas

saturation : relativistic, ion motion

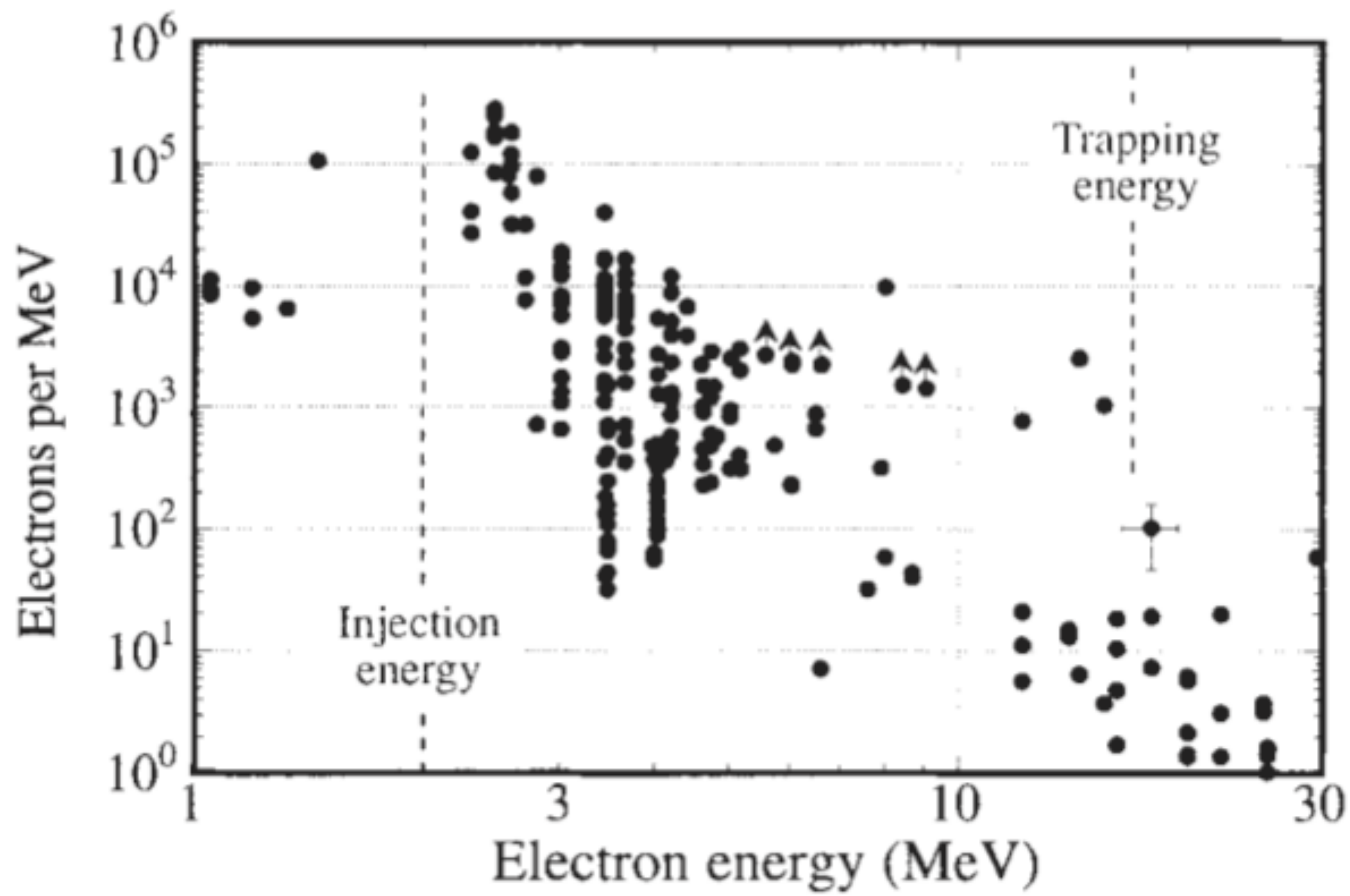
Optical demonstration by Thomson scattering :

Clayton *et al.* PRL 1985, Amiranoff *et al.* PRL 1992, Dangor *et al.* Phys. Scrypta 1990

Chen, Introduction to plasma physics and controlled fusion, 2nd Edition, Vol.1, (1984)

1992-1994 Accelerated electrons in LBWF

The 2-MeV electrons are accelerated up to ≈ 28 MeV
Electron spectra indicate an E_{field} of ≈ 2.8 GV/m



M. Everett *et al.*, Nature 1994

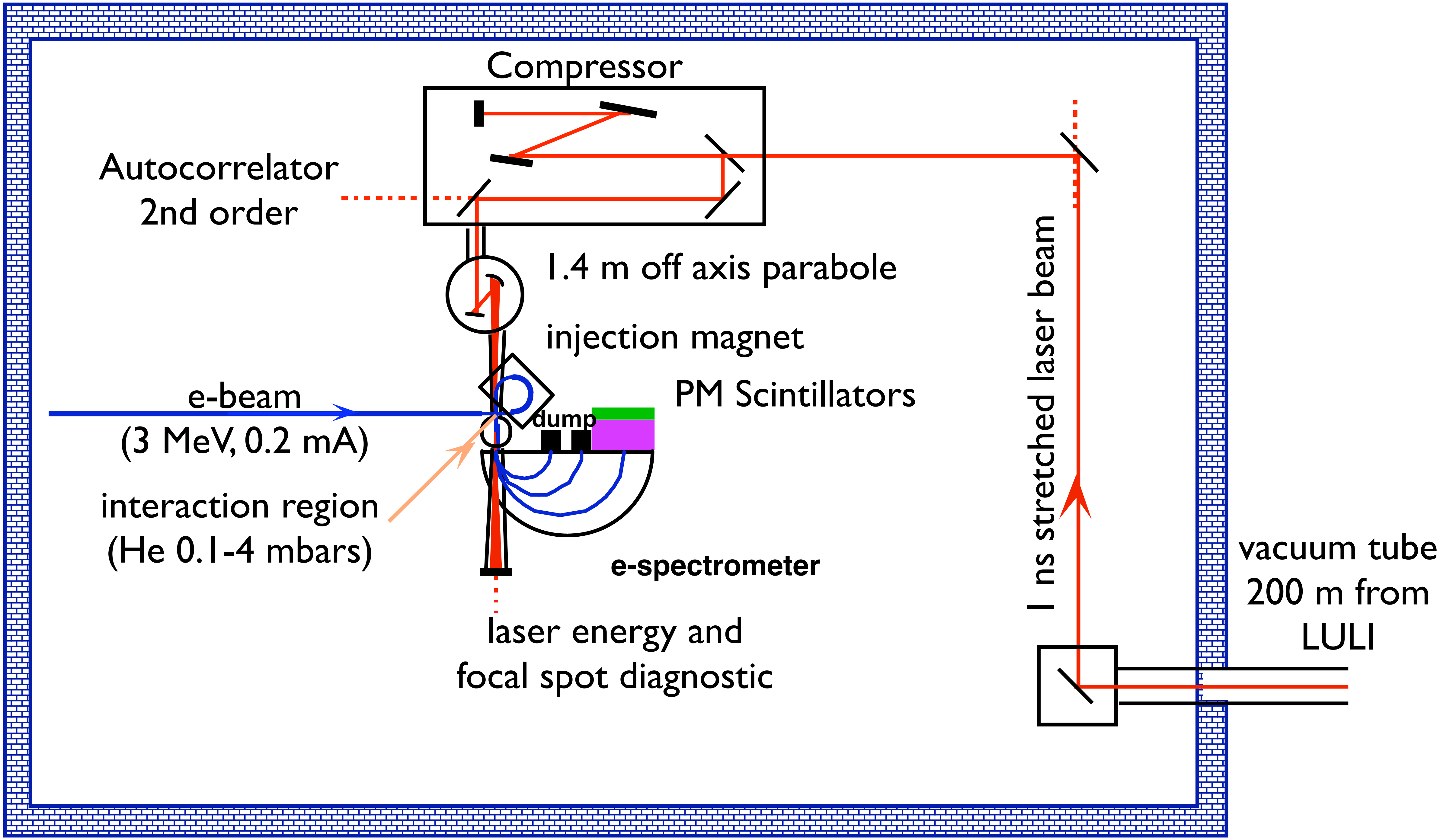
Electron gain demonstration Few MeV's:

Kitagawa *et al.* PRL 1992, Clayton *et al.* PRL 1993, N.A. Ebrahim *et al.*, J. Appl. Phys. 1994, Amiranoff *et al.* PRL 1995

1998 Accelerated electrons in LWF

LULI/LPNHE/LSI/IC

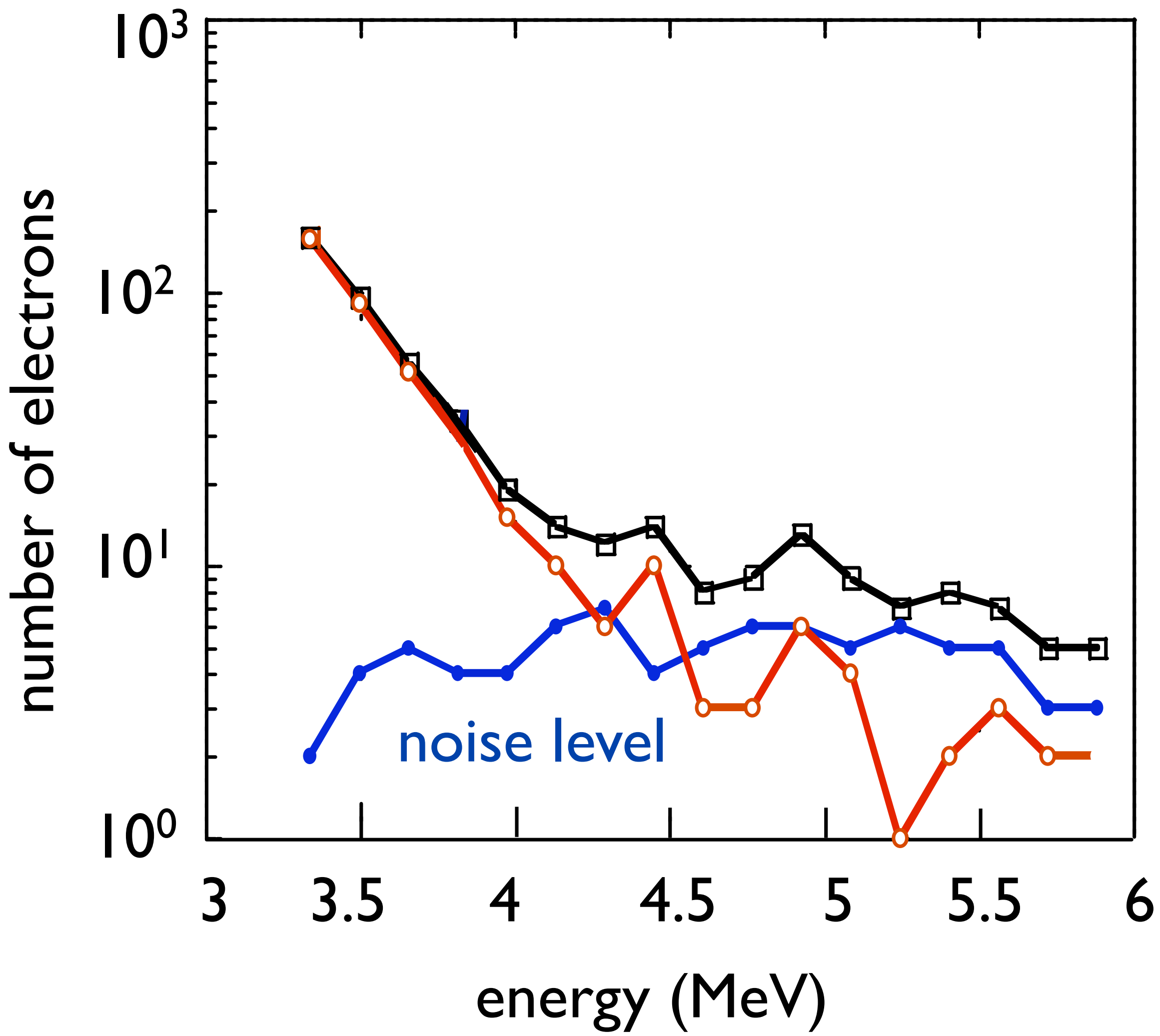
Electron spectra indicate an E_{field} of ≈ 1 GV/m



1998 Accelerated electrons in LWF

LULI/LPNHE/LSI/IC

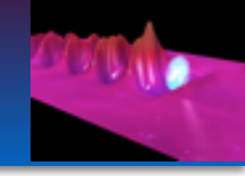
The 3-MeV electrons are accelerated up to ≈ 4.5 MeV
Electron spectra indicate an E_{field} of ≈ 1.4 GV/m



2.5 J, 350 fs, 10^{17}W/cm^2, 0.5 mbar of He

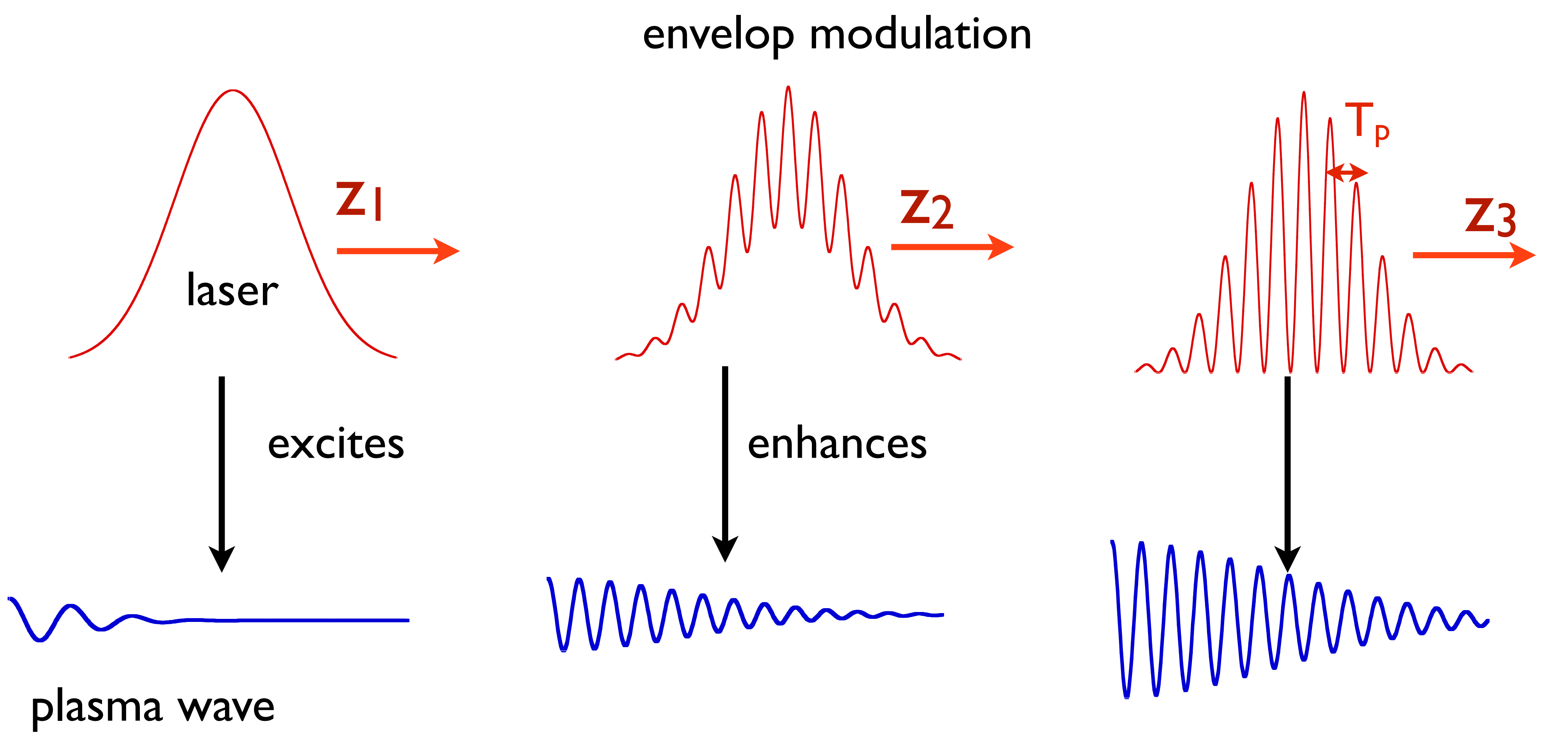
F. Amiranoff *et al.*, PRL 1998

1992 How to excite a plasma wave: The SMLWF



Self modulated laser wakefield scheme : $c\tau_{laser} >> T_p$

(Andreev *et al.*, Antonsen *et al.*, Sprangle *et al.* 1992)

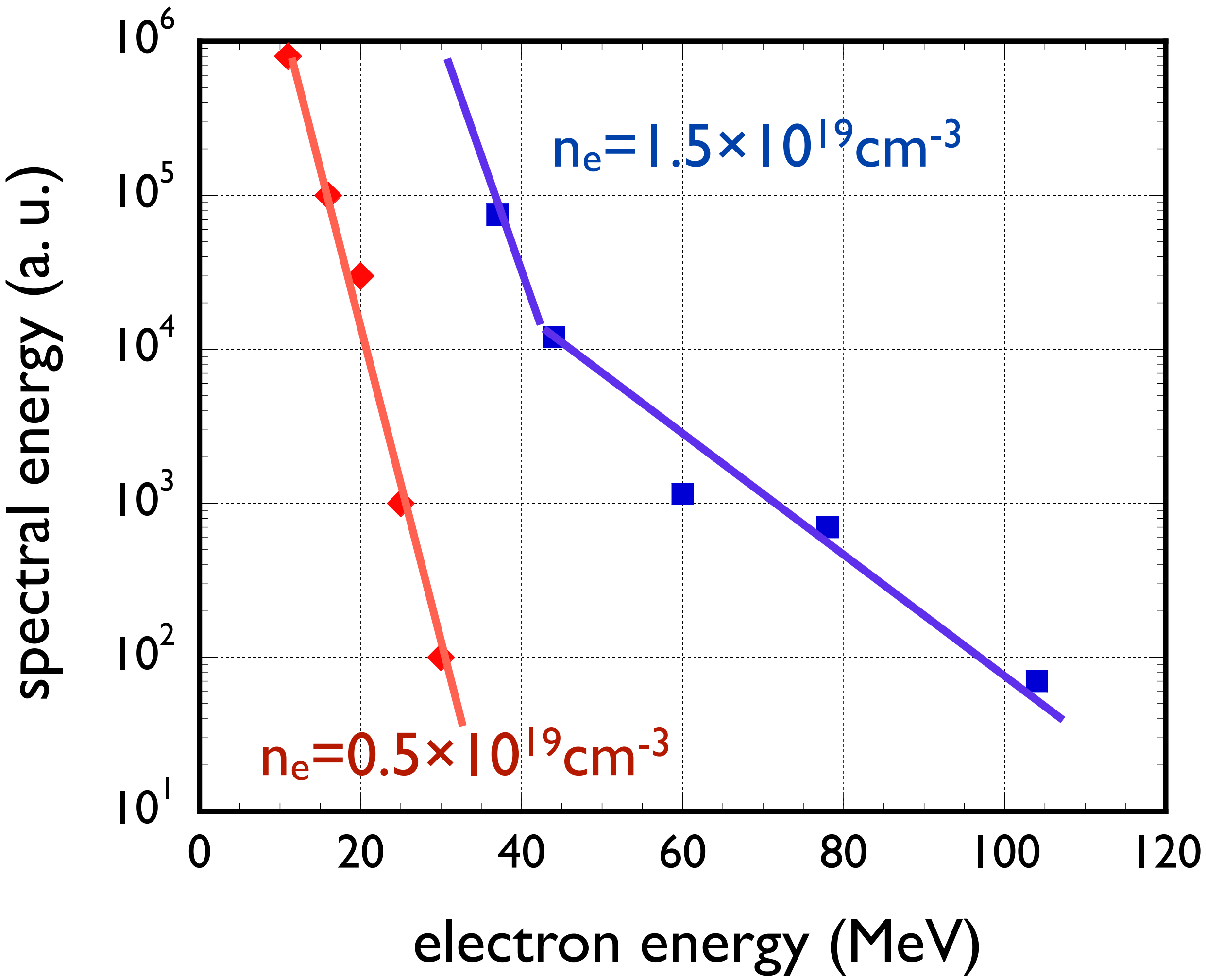


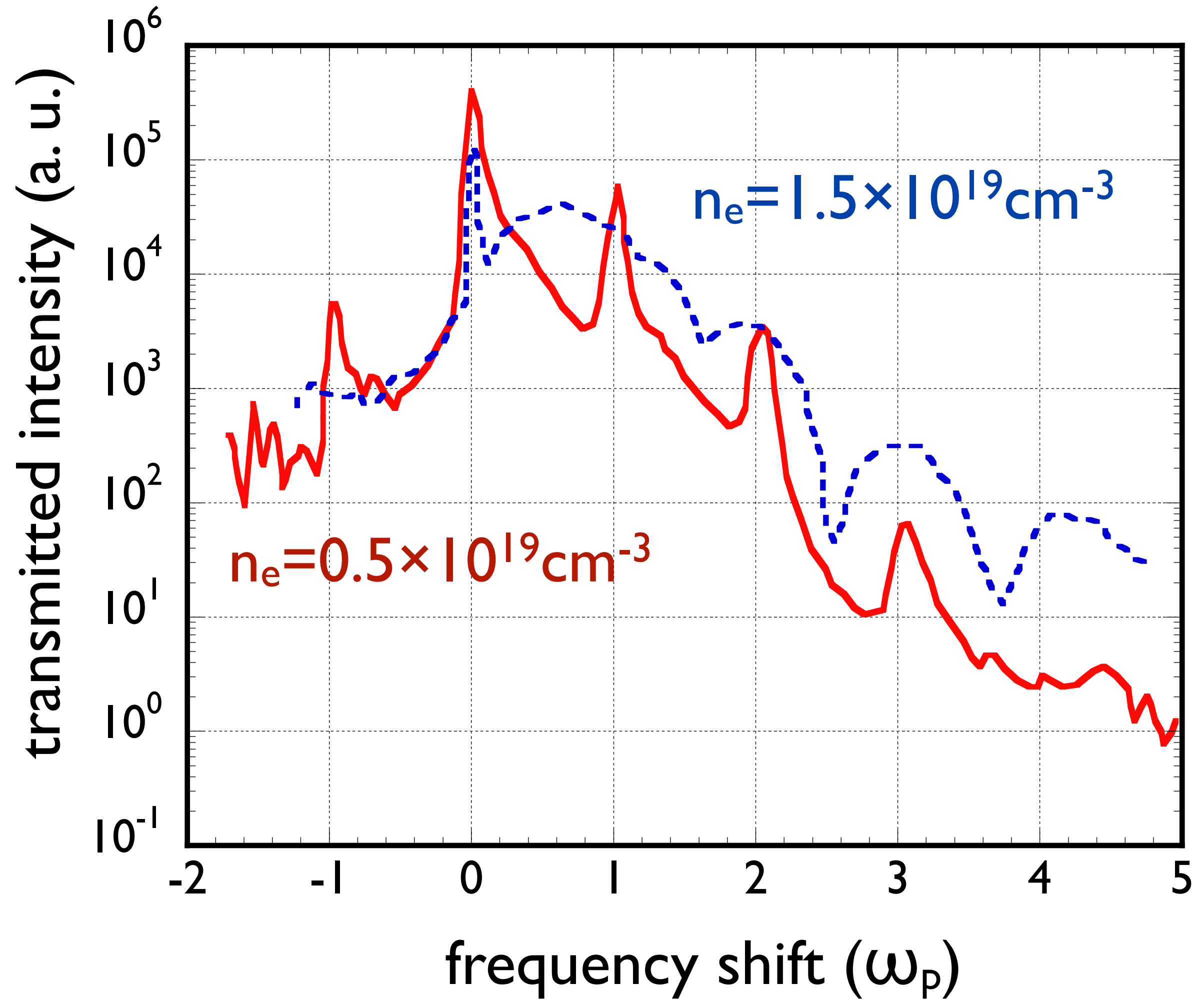
$P_L > P_c(GW) = 17\ n_c/n_e$ then wavebreaking can occur

Outline

- Motivation and principle
- Laser Beat wave and Laser Wakefield
- **Self Modulated Laser Wakefield**
- Towards high quality electron beams
- Conclusion and perspectives

1995 Relativistic wave breaking (RAL/IC/UCLA/LULI)





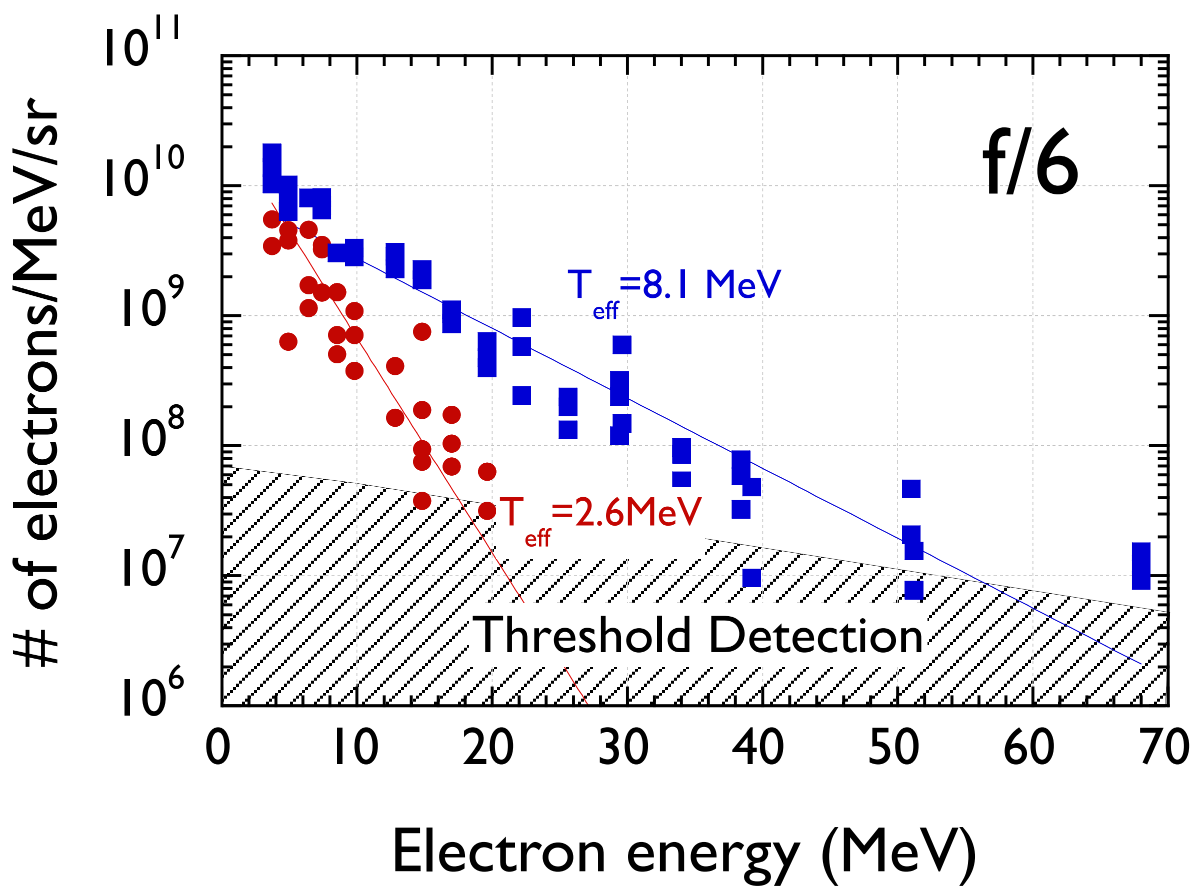
Multiple satellites : high amplitude plasma waves
Broadening at higher densities
Loss of coherence of the relativistic plasma waves

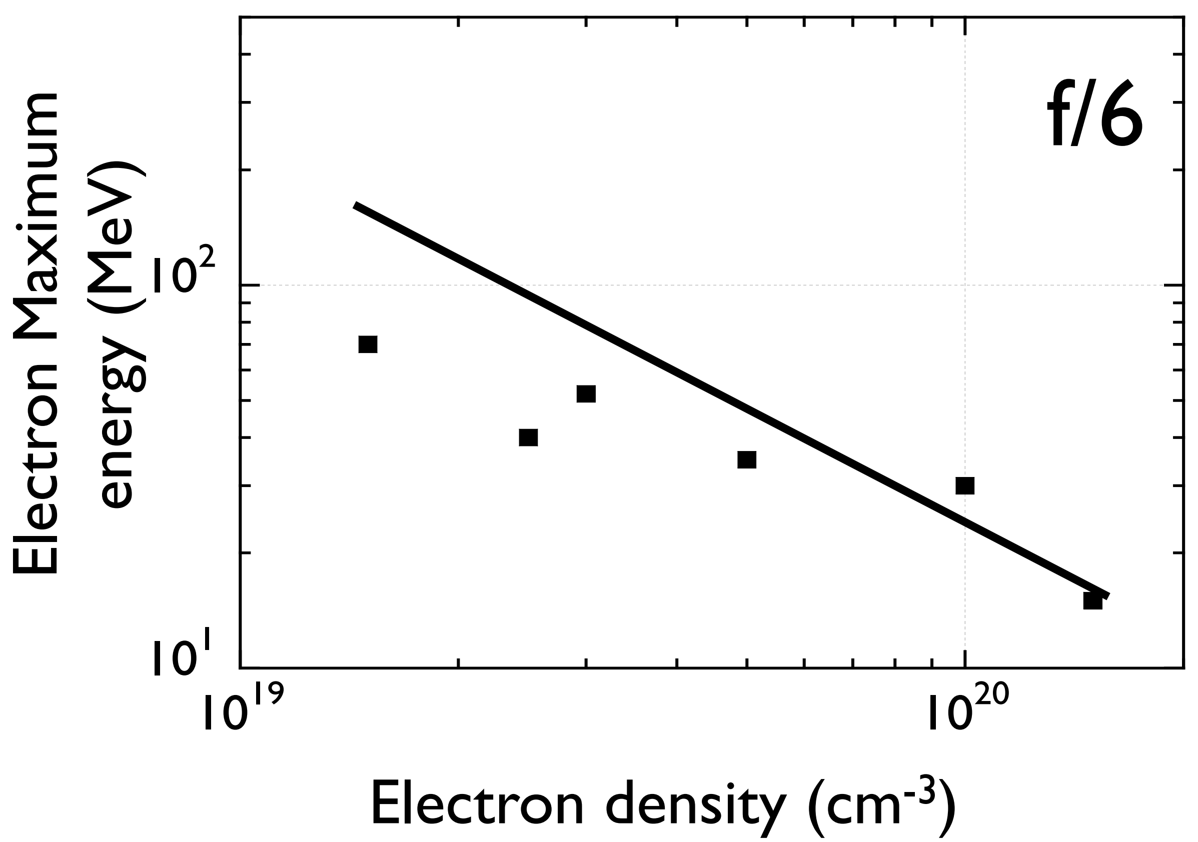
A. Modena *et al.*, Nature (1995)

2001 SMLWF with 10 Hz laser

Spectra : E_{max} increases when n_e decreases

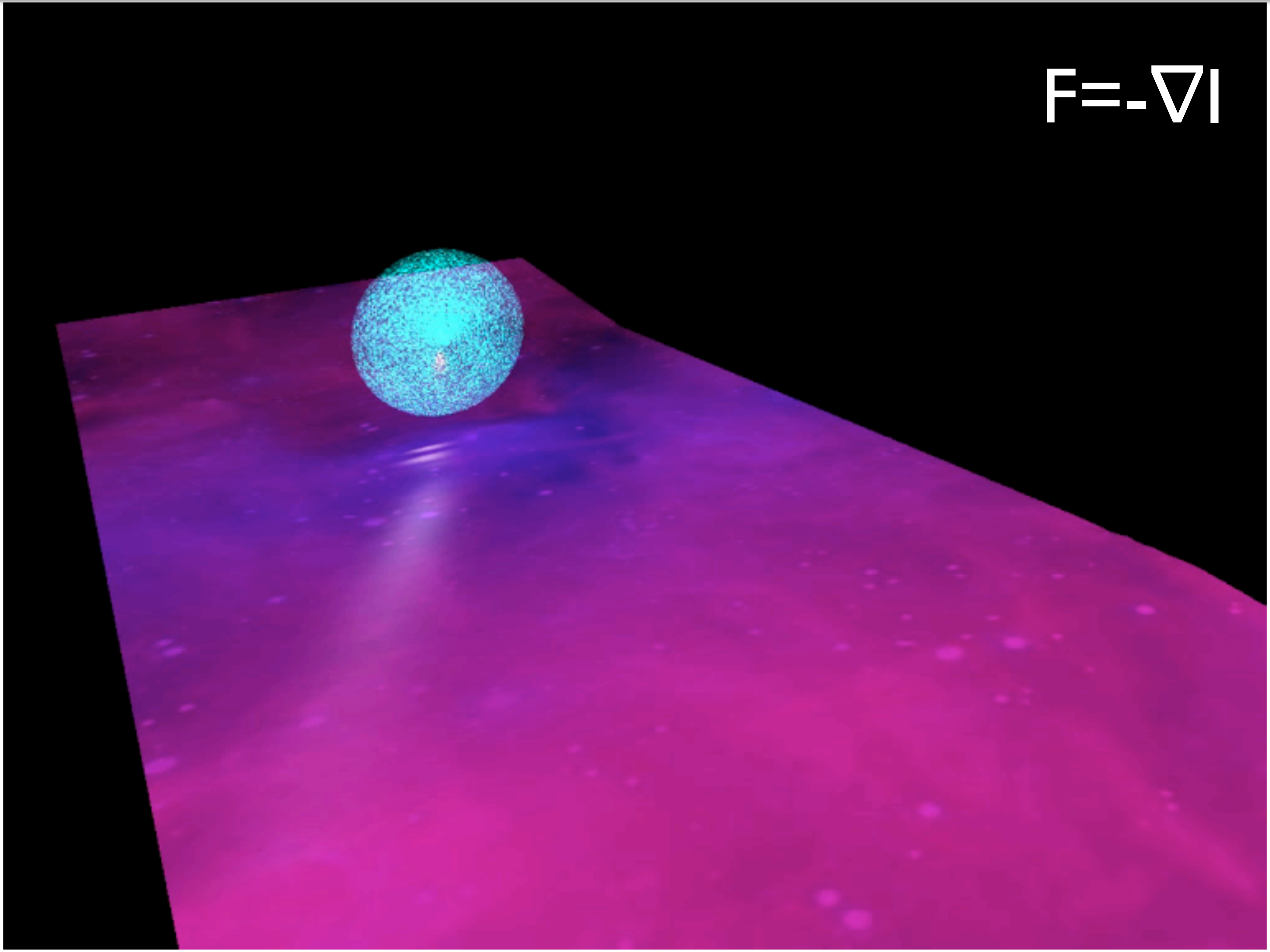
Parameters: $n_e=5\times10^{19}cm^{-3}$ & $1.5\times10^{20}cm^{-3}$, τ_L=35fs, E=0.6J, $I_L= 2\times10^{19}W/cm^2$





V. Malka et al., Phys. of Plasmas **8**, 6 (2001)

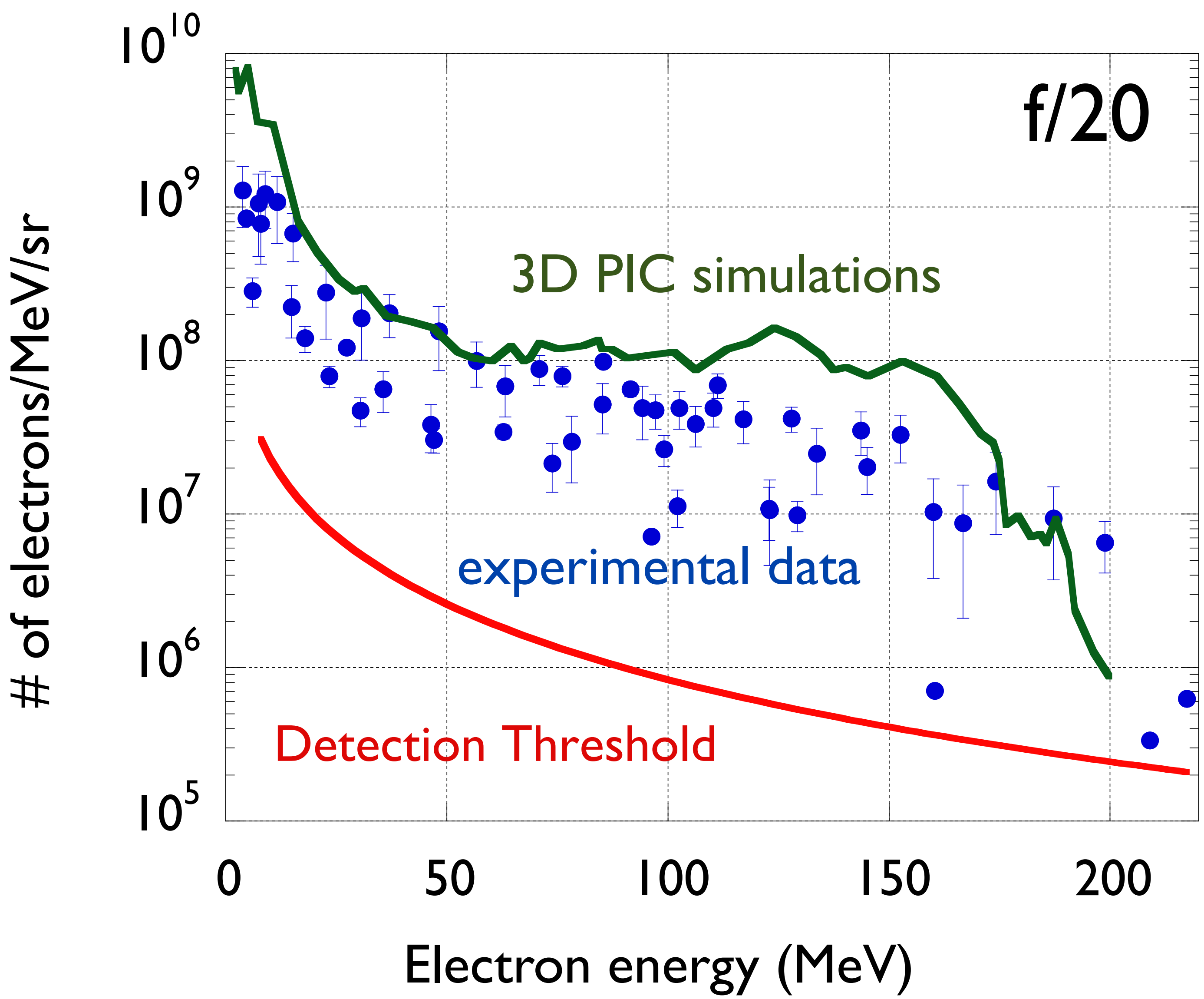
The Forced laser wakefield



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

2002 The Forced Laser Wakefield

Parameters: n_e=1.5×10^{19}cm^{-3}, τ_L=35fs, E=0.6J, I_L= 1×10^{18}W/cm^2 with $k_p w_0$>1



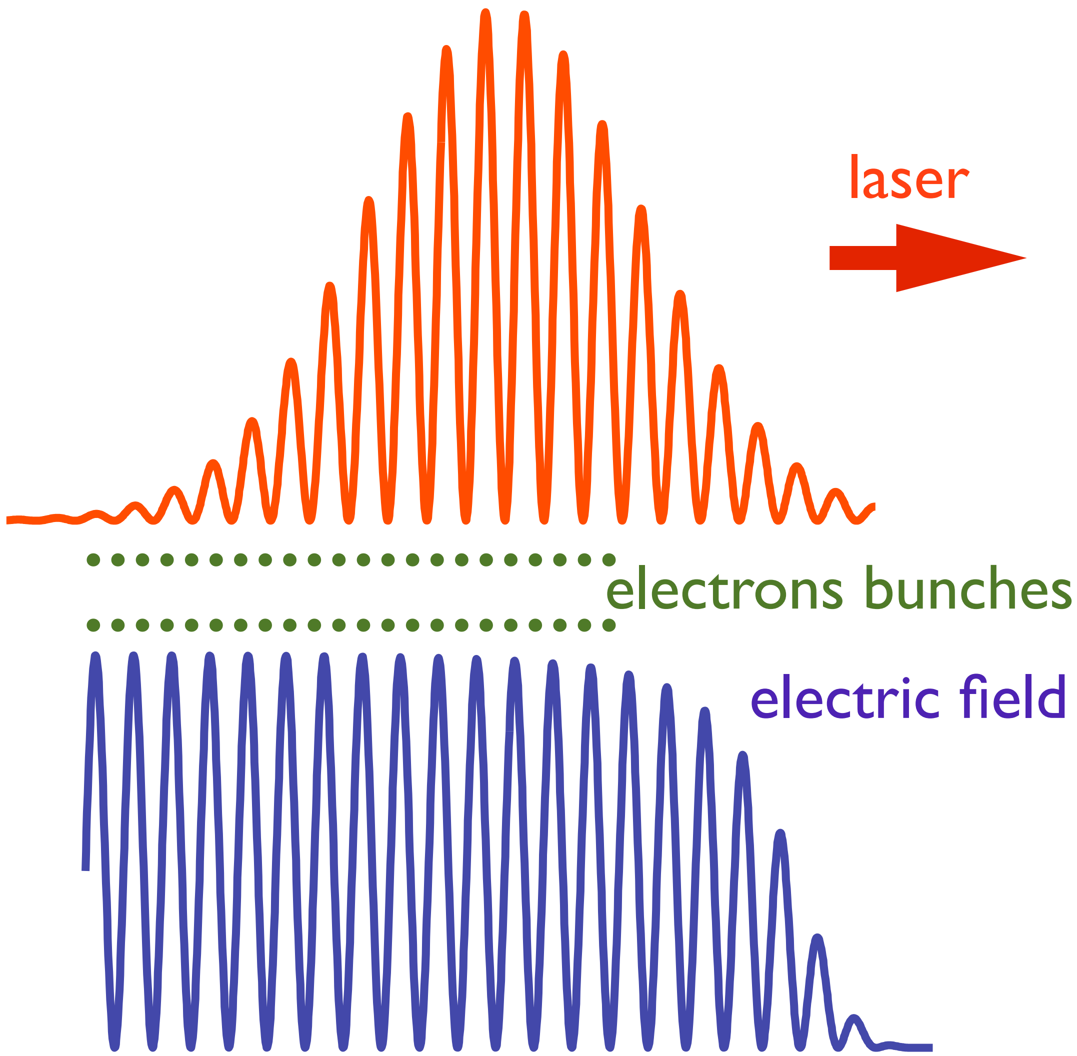
V. Malka *et al.*, Science **298**, 1596 (2002)

Outline

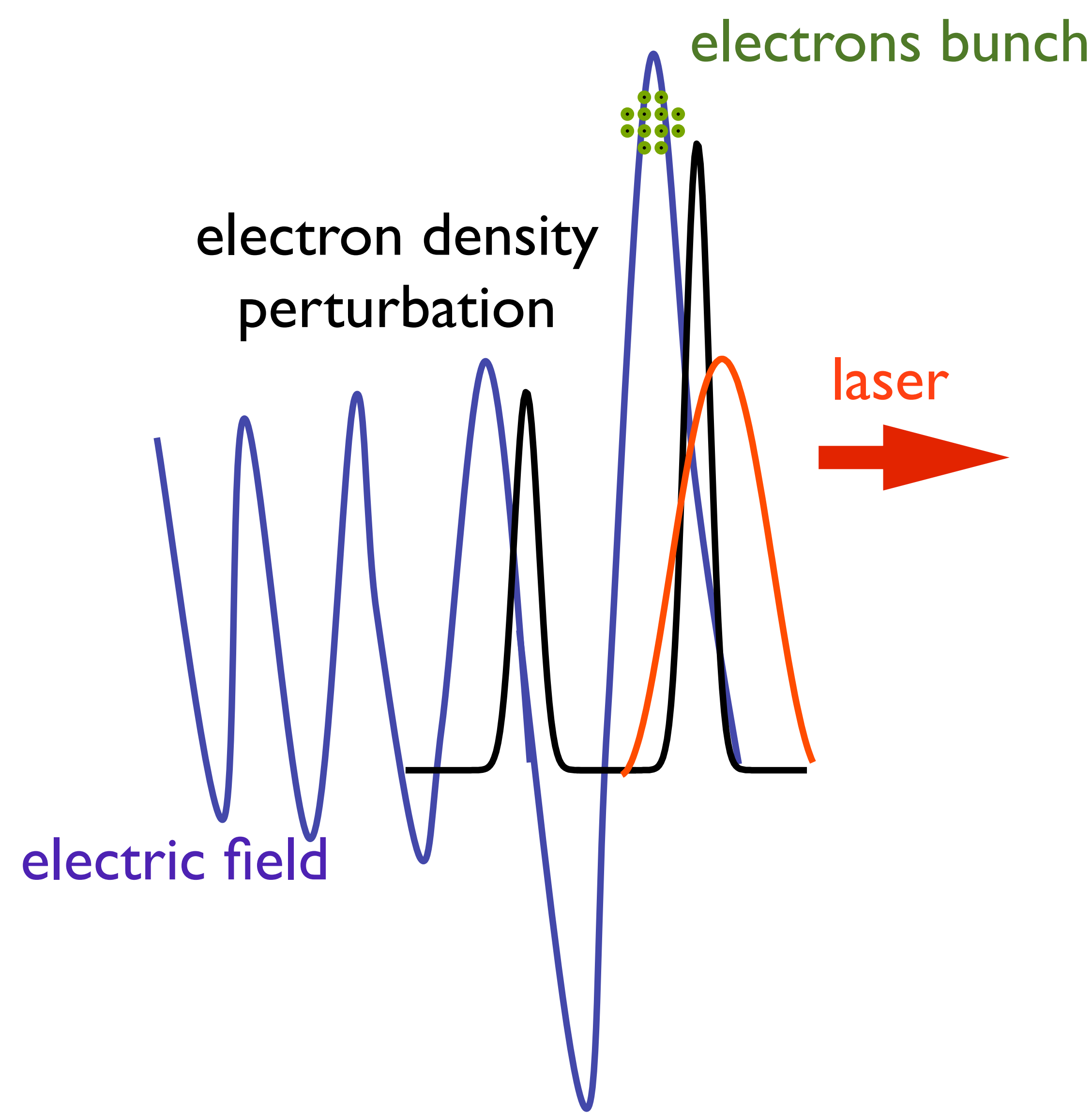
- Motivation and principle
- Laser Beat wave and Laser Wakefield
- Self Modulated Laser Wakefield
- Towards high quality electron beams
- Conclusion and perspectives

SMLWF / FLWF (ps/fs) :multiple/single bunch

SMLWF: ωpτ>>1

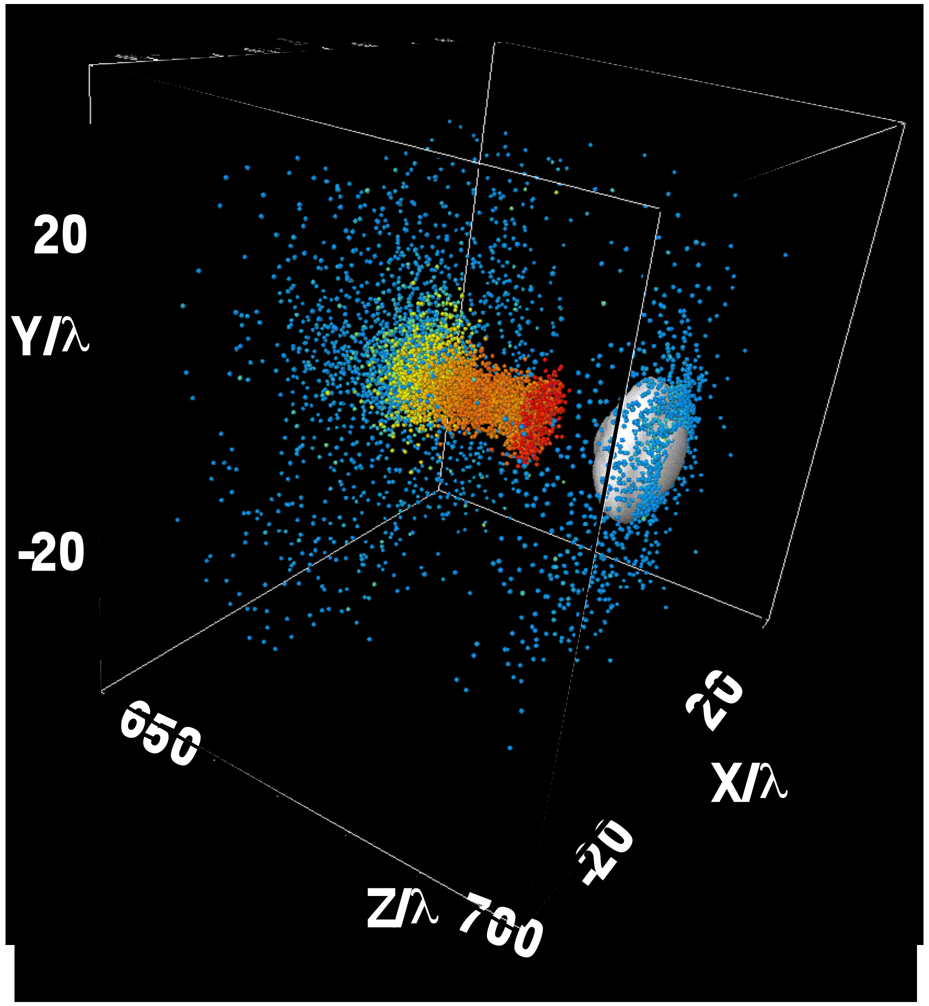


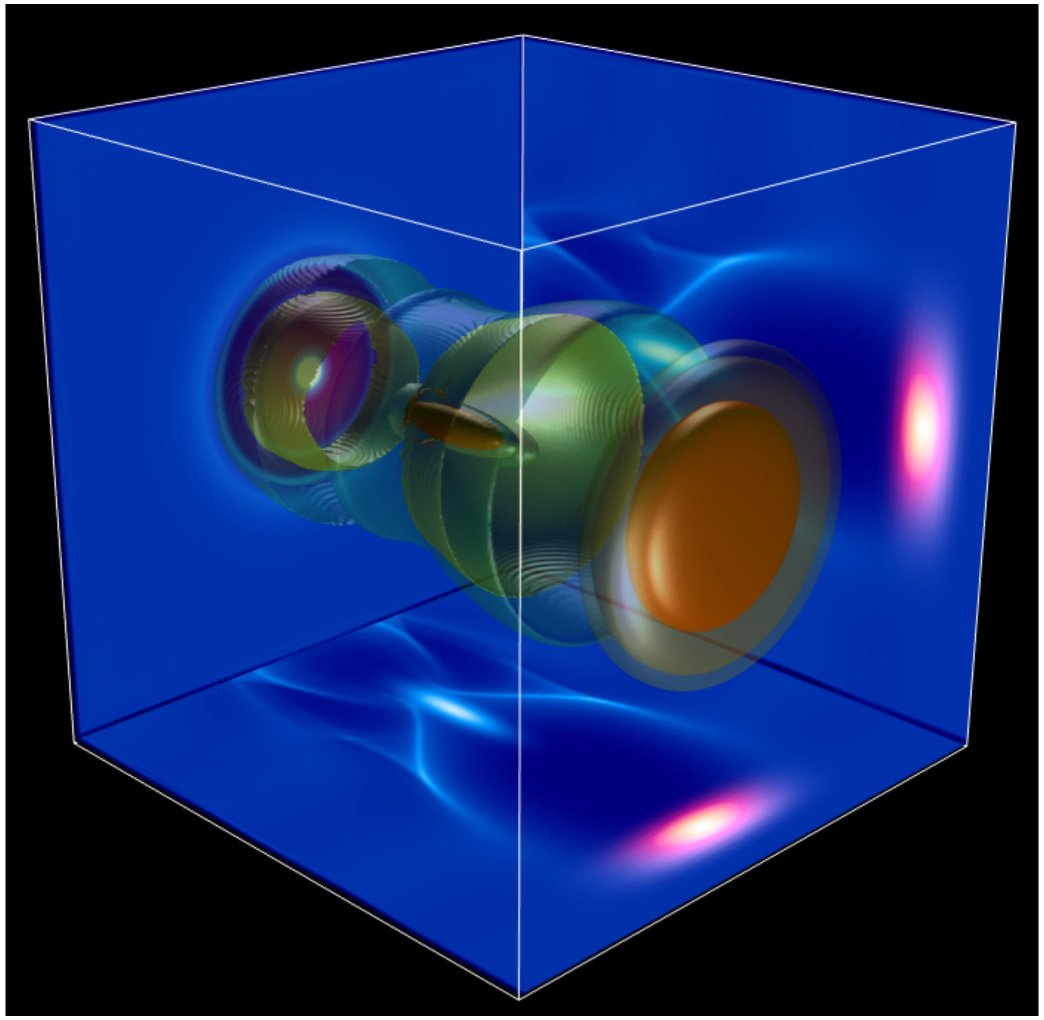
FLWF: ωpτ≈1



V. Malka *et al.*, Europhysics News, April (2004)

2002 The Bubble regime : QM energetic electron beam



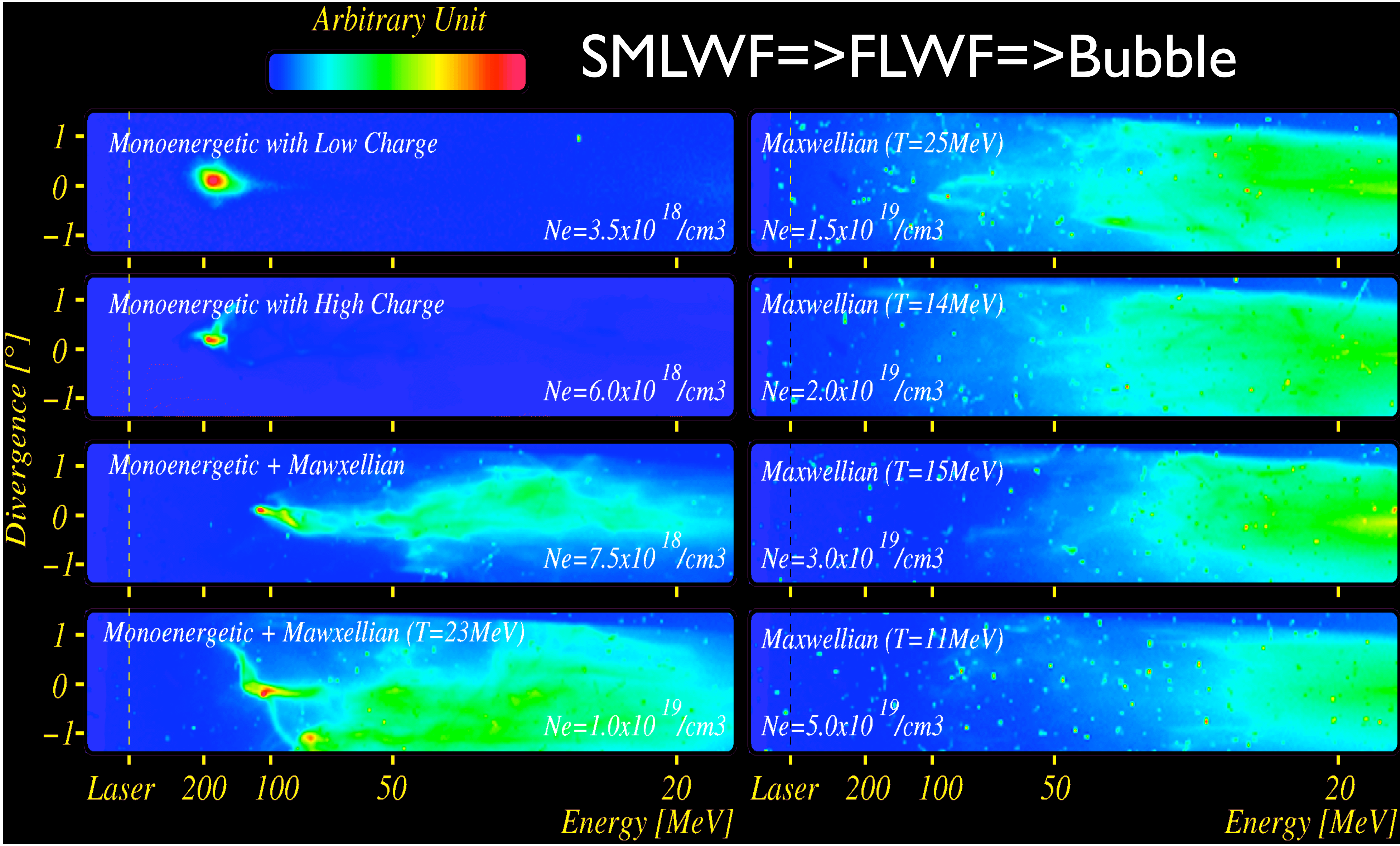


VLPL, courtesy of A. Pukhov

Golp, courtesy of L. Silva

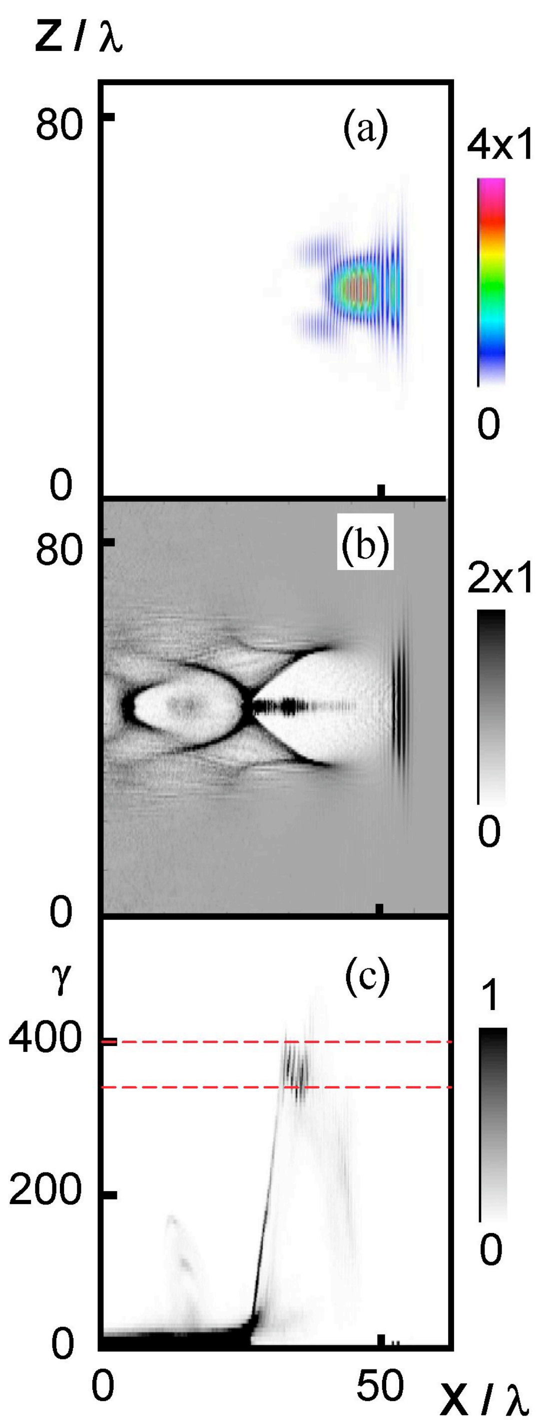
A. Pukhov & J. Meyer-ter-Vehn, Appl. Phys. B, **74** (2002)

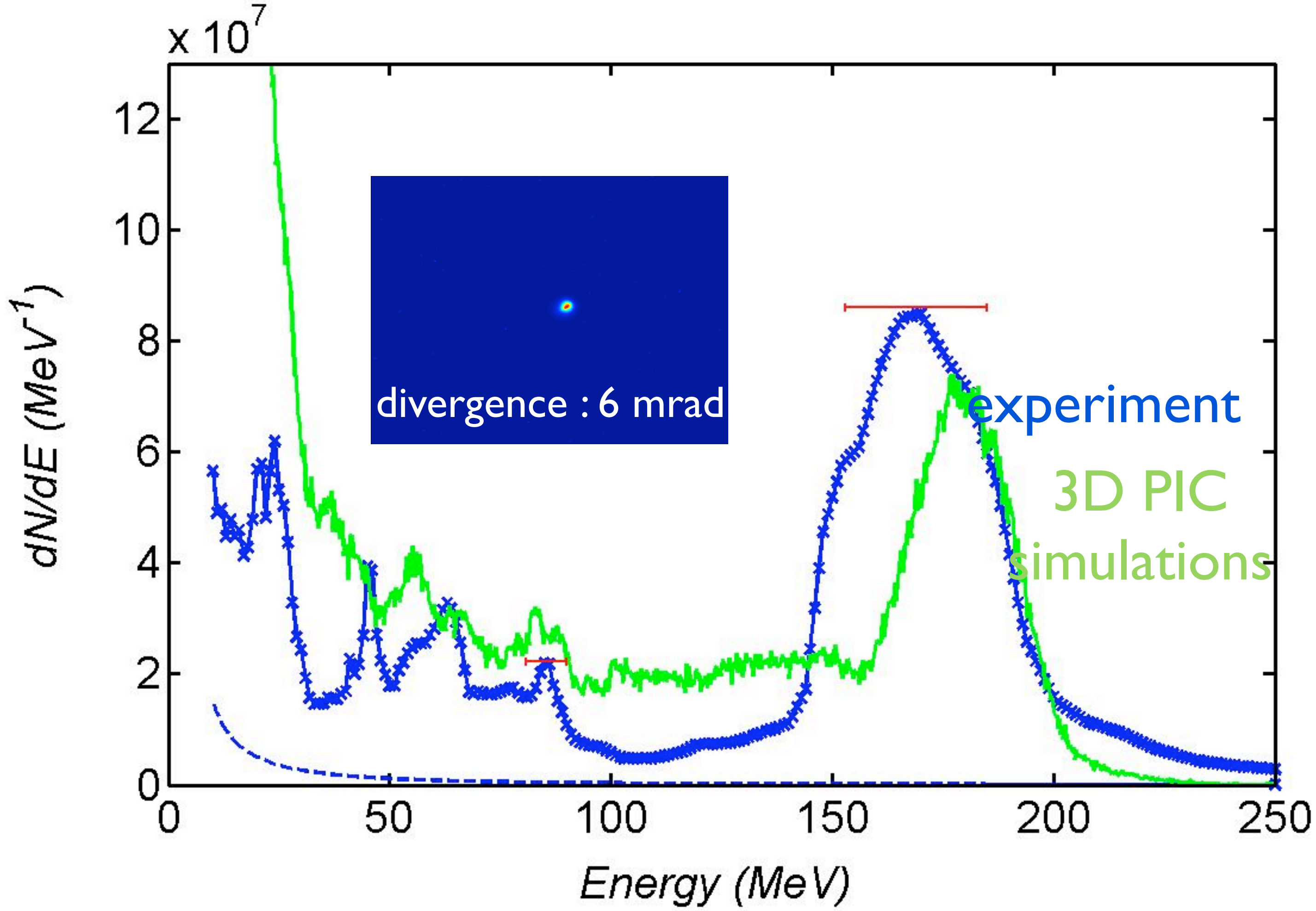
2005 Bubble regime: distribution quality improvements



V. Malka *et al.*, Phys. of Plasmas **12**, 5 (2005)

2005 The Bubble regime : theory/experiments





Experimental parameters : E=1J, τ_L=30fs,
λ_L=0.8µm, I_L=3.2×10^{19}W/cm^2, n_e=6×10^{18}cm^{-3}

J. Faure *et al.*, Nature **431**, 7008 (2004)

2005 The Dream Beam

Monoenergetic beams of relativistic electrons from intense laser–plasma interactions

S. P. D. Mangles[1], C. D. Murphy[1,2], Z. Najmudin[1], A. G. R. Thomas[1], J. L. Collier[2], A. E. Dangor[1], E. J. Divall[2], P. S. Foster[2], J. G. Gallacher[3], C. J. Hooker[2], D. A. Jaroszynski[3], A. J. Langley[2], W. B. Mori[4], P. A. Norreys[2], F. S. Tsung[4], R. Viskup[3], B. R. Walton[1] & K. Krushelnick[1]

[1]*The Blackett Laboratory, Imperial College London, London SW7 2AZ, UK*
[2]*Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK*
[3]*Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK*
[4]*Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA*

High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

C. G. R. Geddes[1,2], Cs. Toth[1], J. van Tilborg[1,3], E. Esarey[1], C. B. Schroeder[1], D. Bruhwiler[4], C. Nieter[4], J. Cary[4,5] & W. P. Leemans[1]

[1]*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA*
[2]*University of California, Berkeley, California 94720, USA*
[3]*Technische Universiteit Eindhoven, Postbus 513, 5600 MB Eindhoven, the Netherlands*
[4]*Tech-X Corporation, 5621 Arapahoe Ave. Suite A, Boulder, Colorado 80303, USA*
[5]*University of Colorado, Boulder, Colorado 80309, USA*

A laser–plasma accelerator producing monoenergetic electron beams

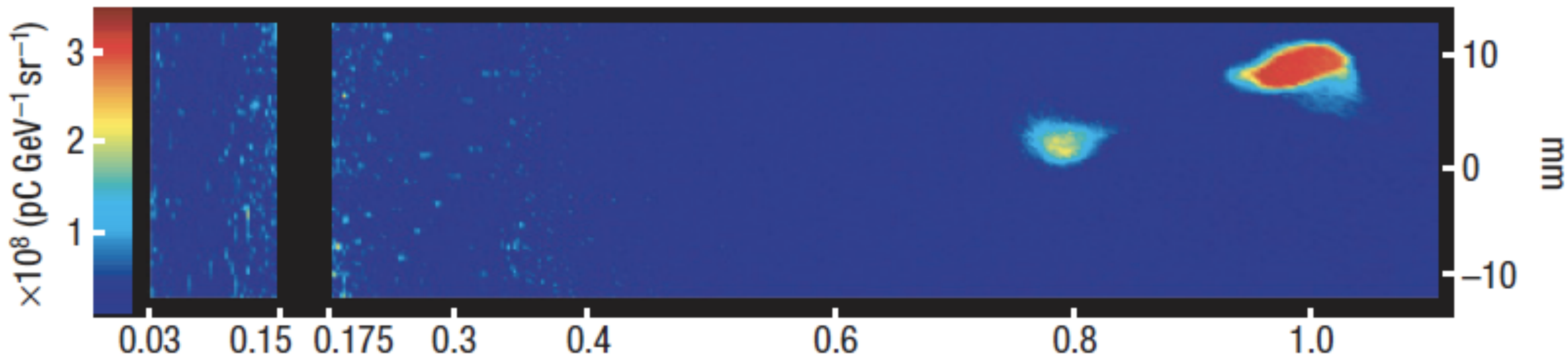
J. Faure[1], Y. Glinec[1], A. Pukhov[2], S. Kiselev[2], S. Gordienko[2], E. Lefebvre[3], J.-P. Rousseau[1], F. Burgy[1] & V. Malka[1]

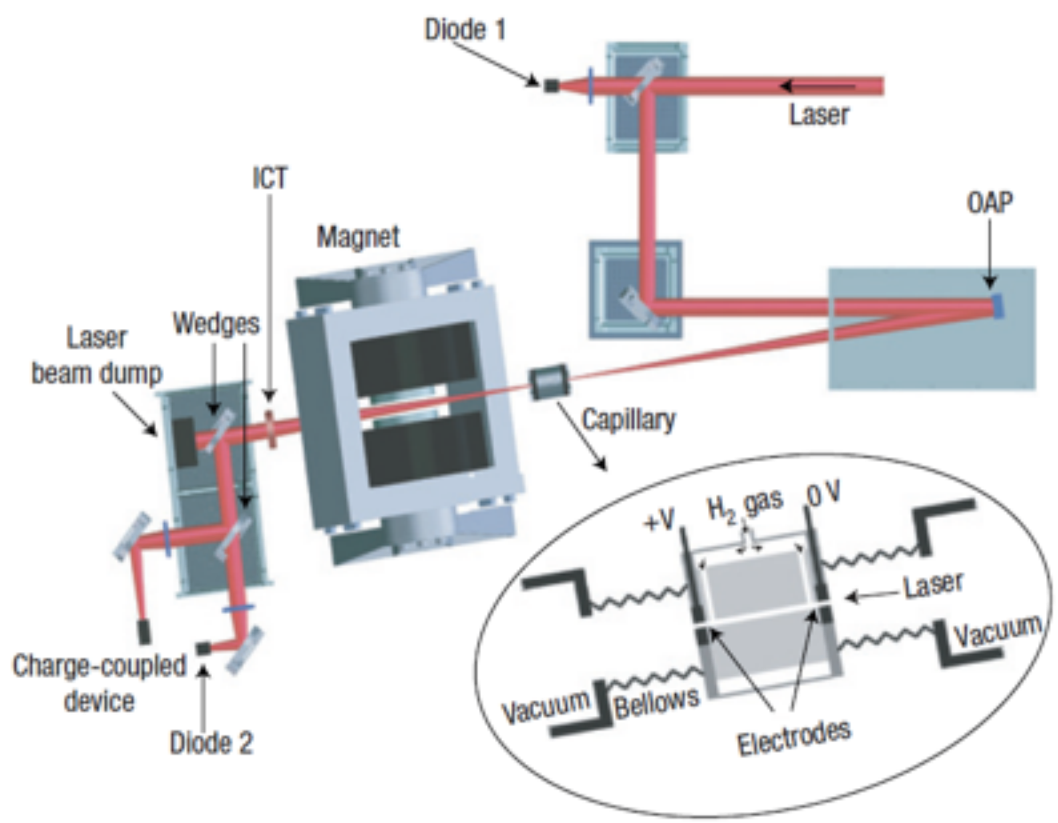
[1]*Laboratoire d'Optique Appliquée, Ecole Polytechnique, ENSTA, CNRS, UMR 7639, 91761 Palaiseau, France*
[2]*Institut für Theoretische Physik, 1, Heinrich-Heine-Universitat Duesseldorf, 40225 Duesseldorf, Germany*
[3]*Département de Physique Théorique et Appliquée, CEA/DAM Ile-de-France, 91680 Bruyères-le-Châtel, France*

Some reports on quasi monoenergetic electron beam

Name	*Ref.*	*Year*	*Lab*	*Energy (MeV)*	*DE/E*	*Charge (pC)*	*N*	I_{18}	*t*	*Remarks*
Mangles	Nature	2004	RAL	73	6	22	20	2,5	1,6	
Geddes	Nature	2004	L'OASIS	86	2	320	19	11	2,2	channel
Faure	Nature	2004	LOA	170	25	300	6	3	0,7	
Hidding	PRL	2006	JETI	47	9	0,32	40	50	4,6	
Hsieh	PRL	2006	IAMS	55		336	40		2,6	
Hosokai	PRE	2006	U.Tokyo	11	10	10	80	22	3	preplasma
Miura	APL	2005	AIST	7	20	0,004	130	5	5,1	
Hafz	PRE	2006	KERI	4	93	200	28	1	33,4	
Mori	PRE	2006	JEARI	20	24	0,8	50	0,9	4,5	
Mangles	PRL	2006	LLC	150	20		20	5	1,4	

2006 GeV electron beams from "cm scale" accelerator





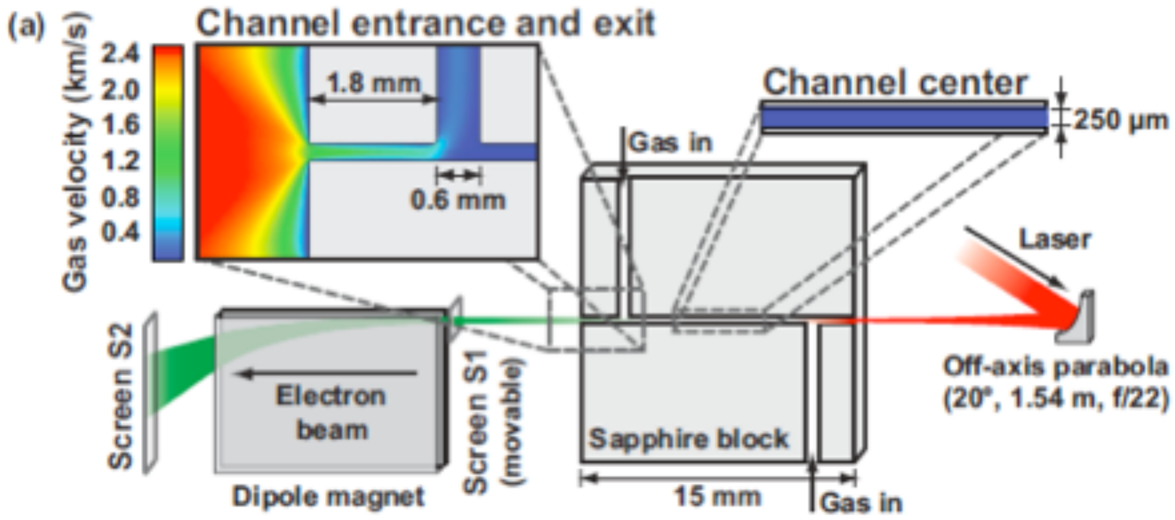
310-μm-diameter channel capillary

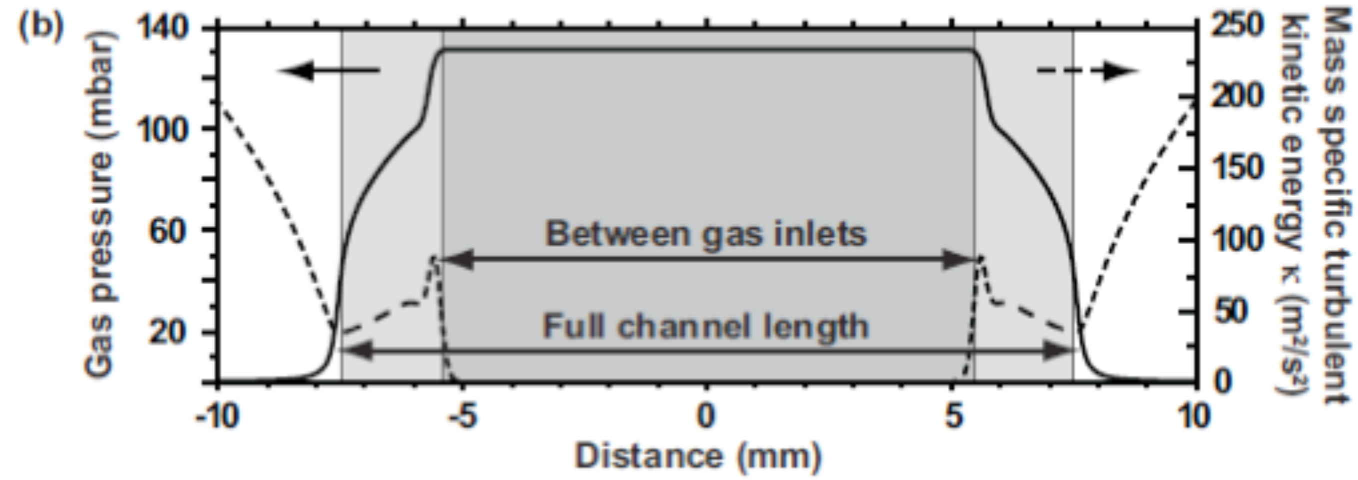
P = 40 TW

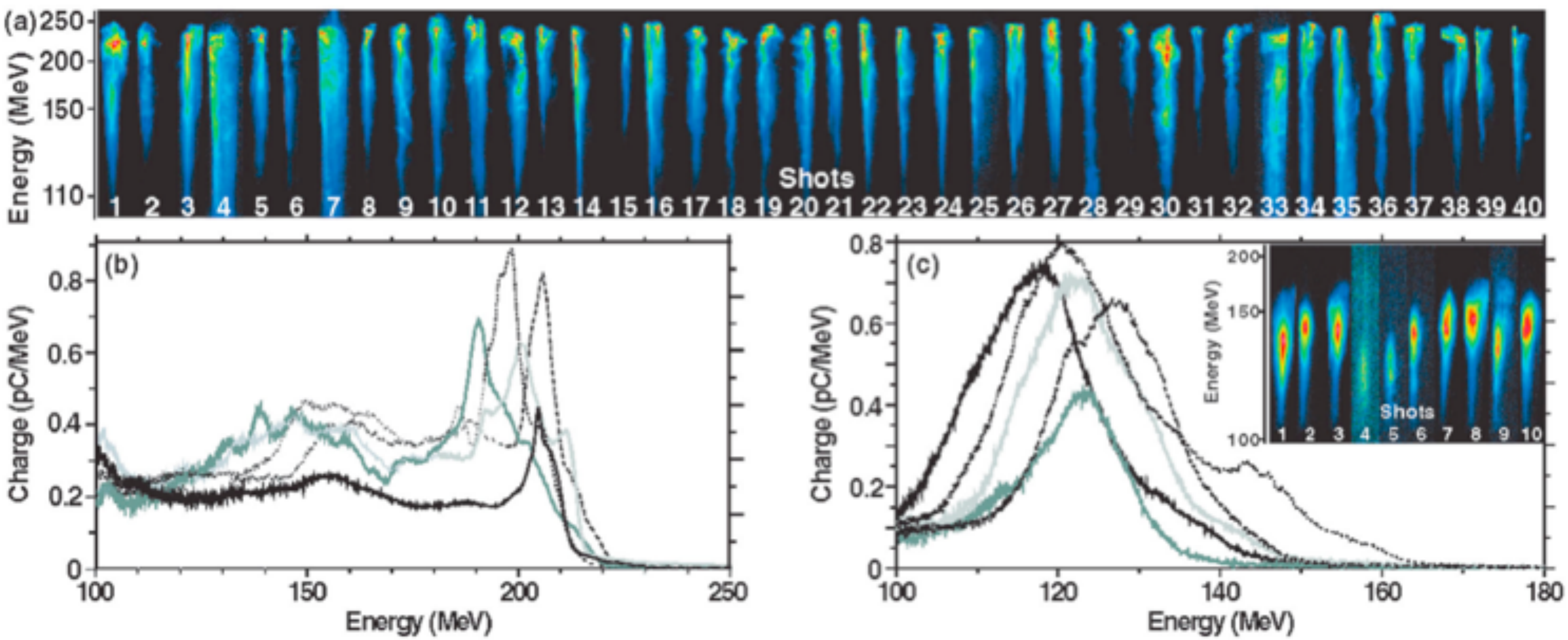
density 4.3×10^{18} cm^{-3}

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

2009 Gas cell experiments at MPQ



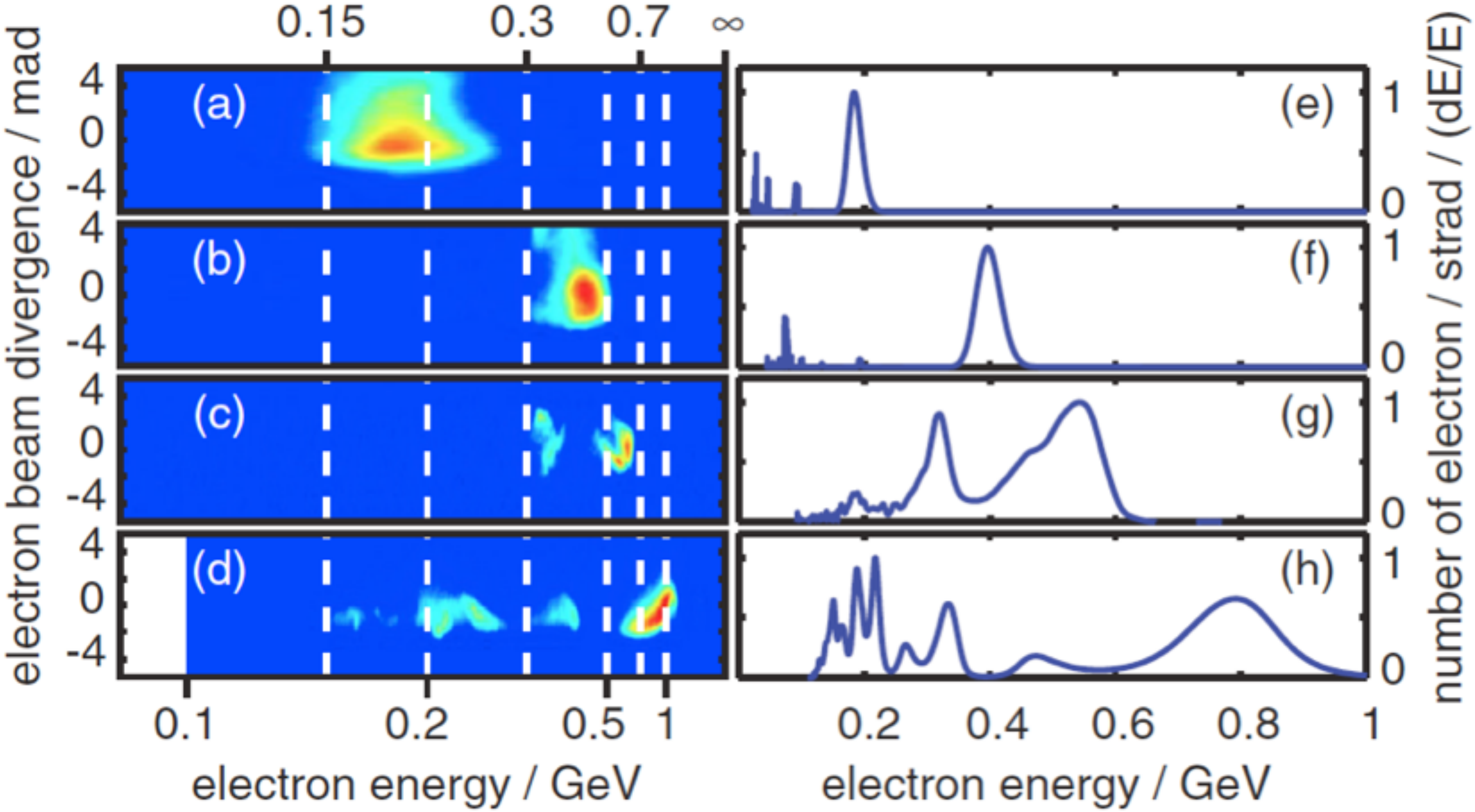




Laser : 20 TW
1cm gas cell target
0.8J, 40 fs, a_0=0.9
n_e=7x10^{18}cm^{-3}
Stable e-beam :
10 pC
220 MeV
Div = 2 mrad
DE/E = 8%

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

2009 GeV electron beams from "cm scale" accelerator



Astra Gemini laser RAL :

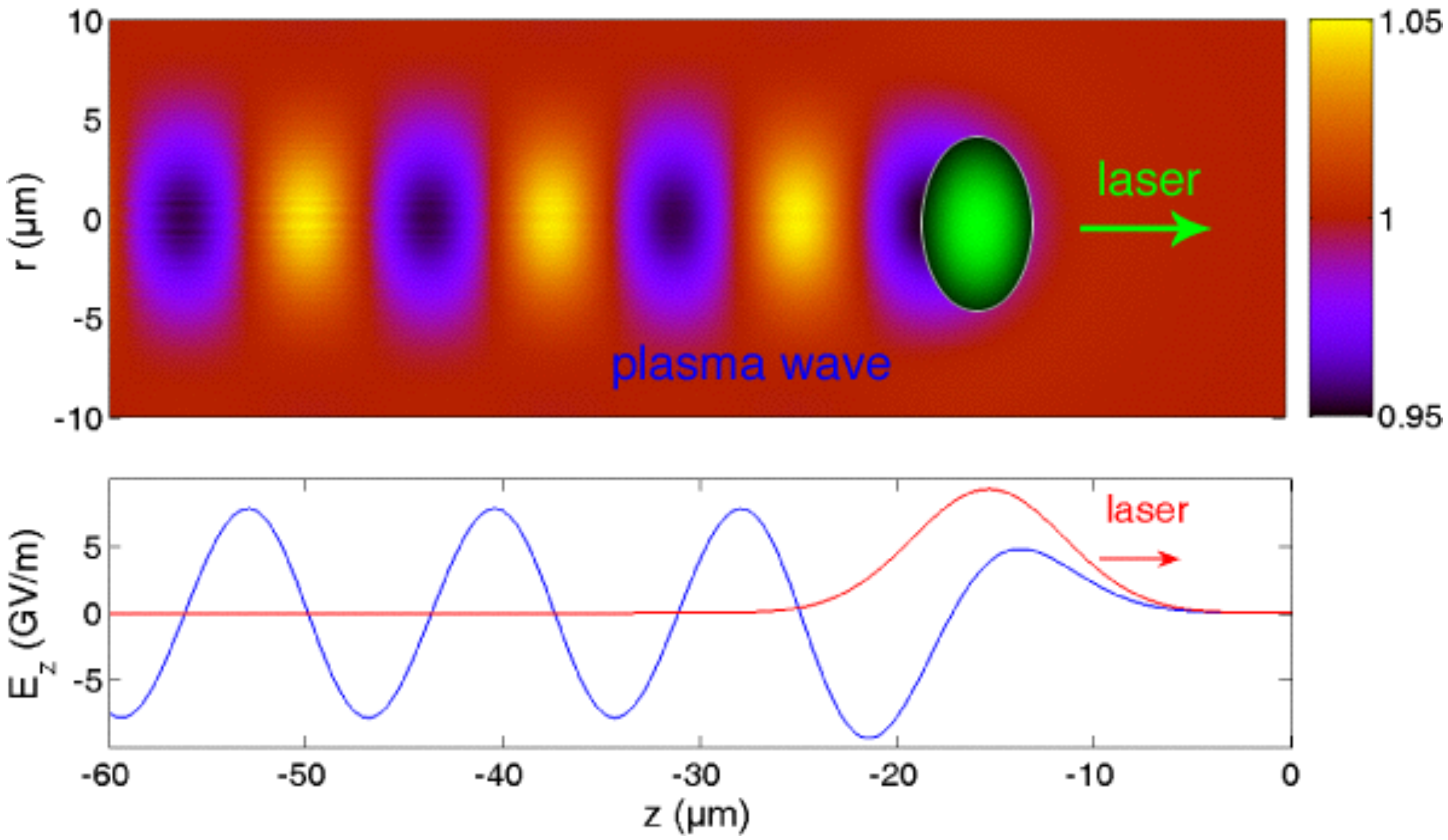
11J, 55fs, a=3.9, 1cm gas jet target, density 5.7×10^{18} cm^{-3}

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

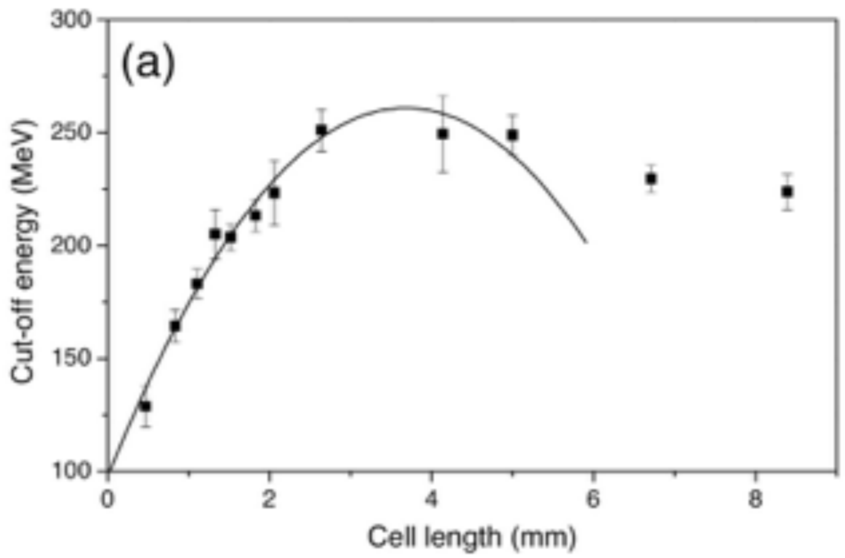
S. Kneip *et al.*, Phys. Rev. Lett. 103, 035002 (2009)

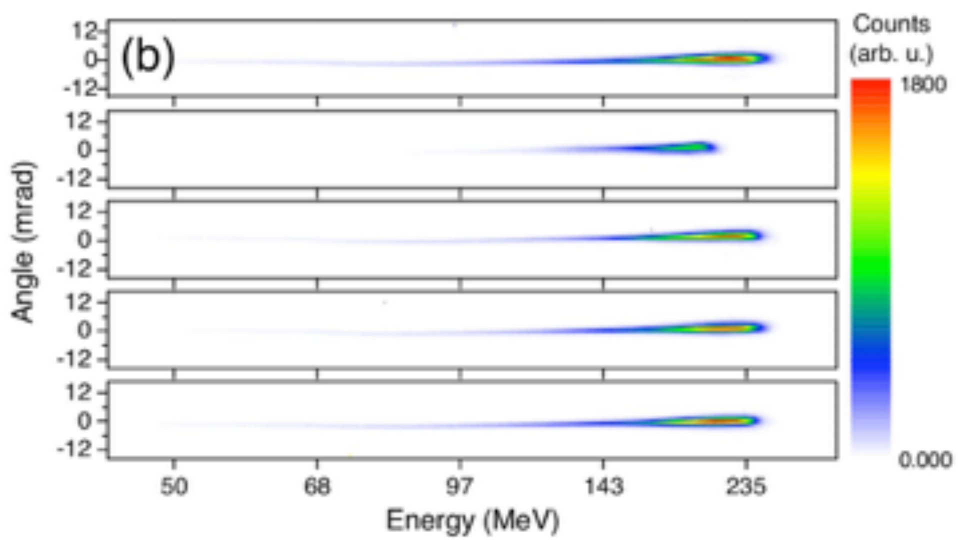
2013 Longitudinal injection

Two different self-injection mechanisms take place :



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



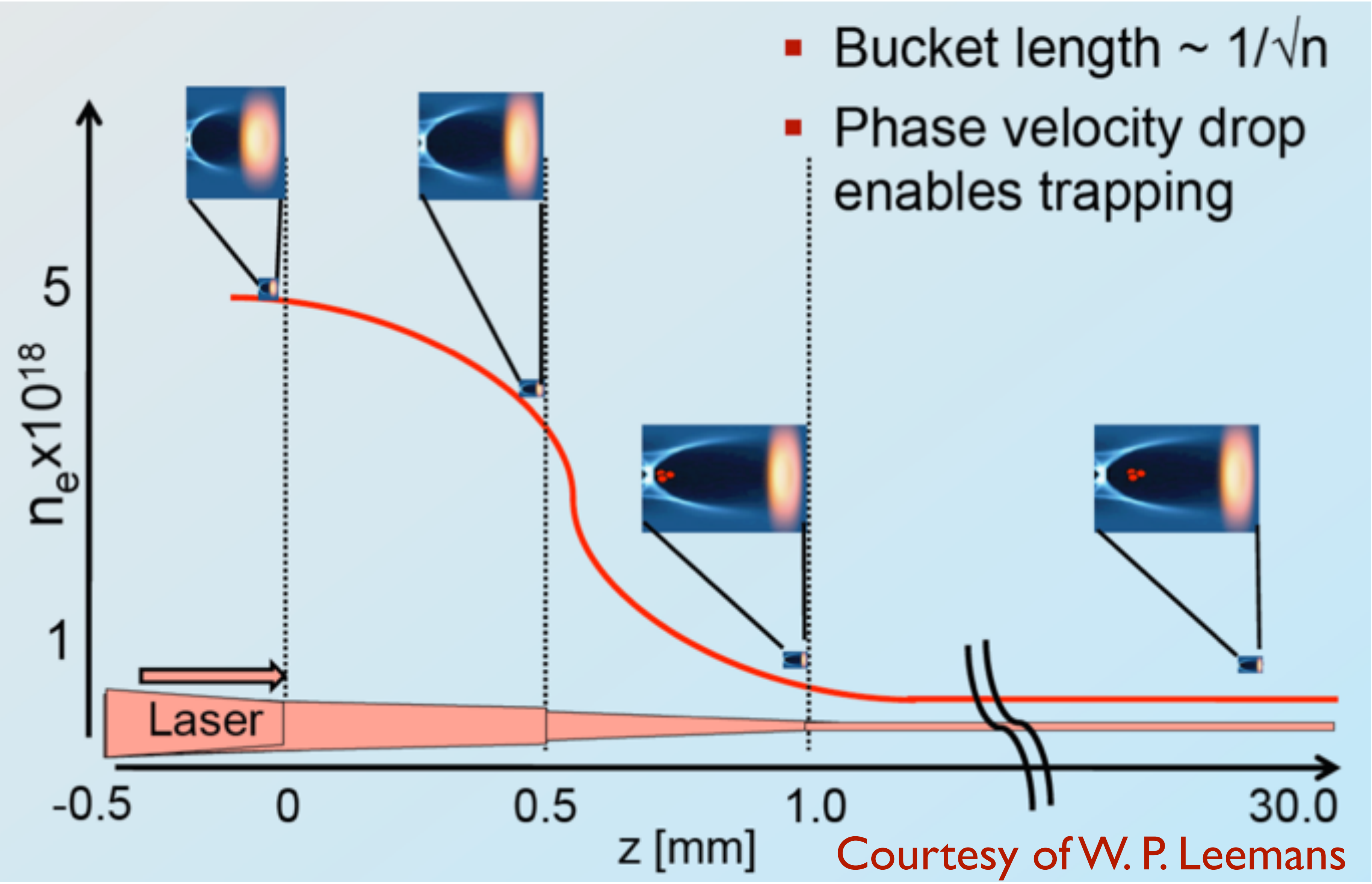


longitudinal injection improves
- the stability of the electron beam

and
- reduces the divergence of the electron beam

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

2005-2008 Density ramp injection



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

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

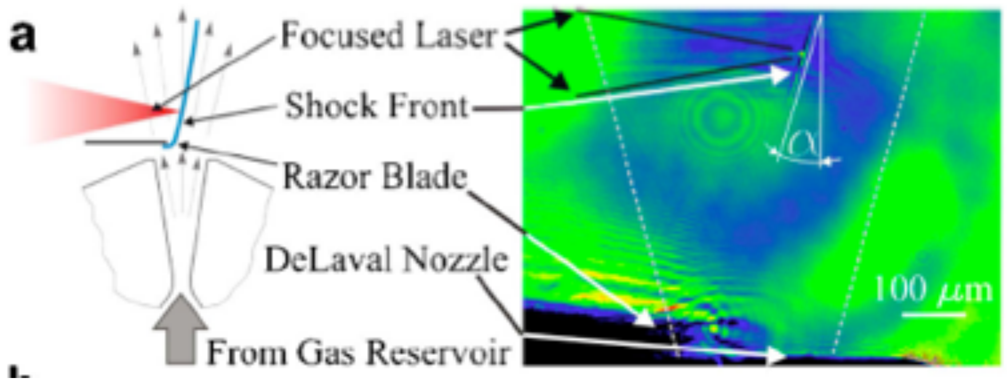
which depends on z through on density

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

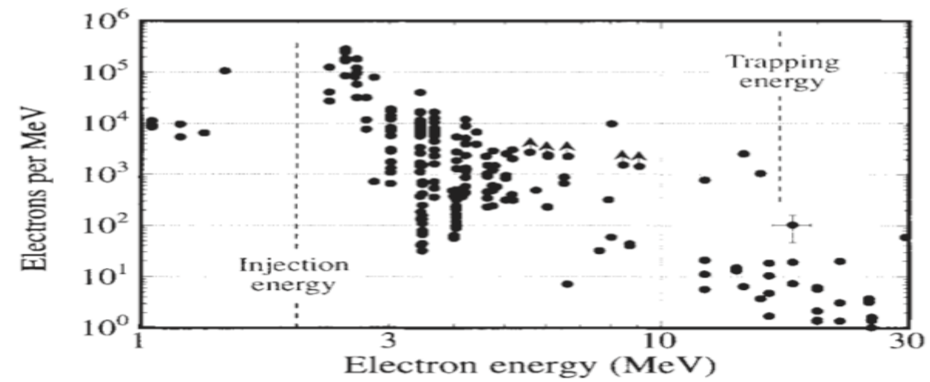
For a downward density, the wake phase velocity slow down facilitating electrons trapping

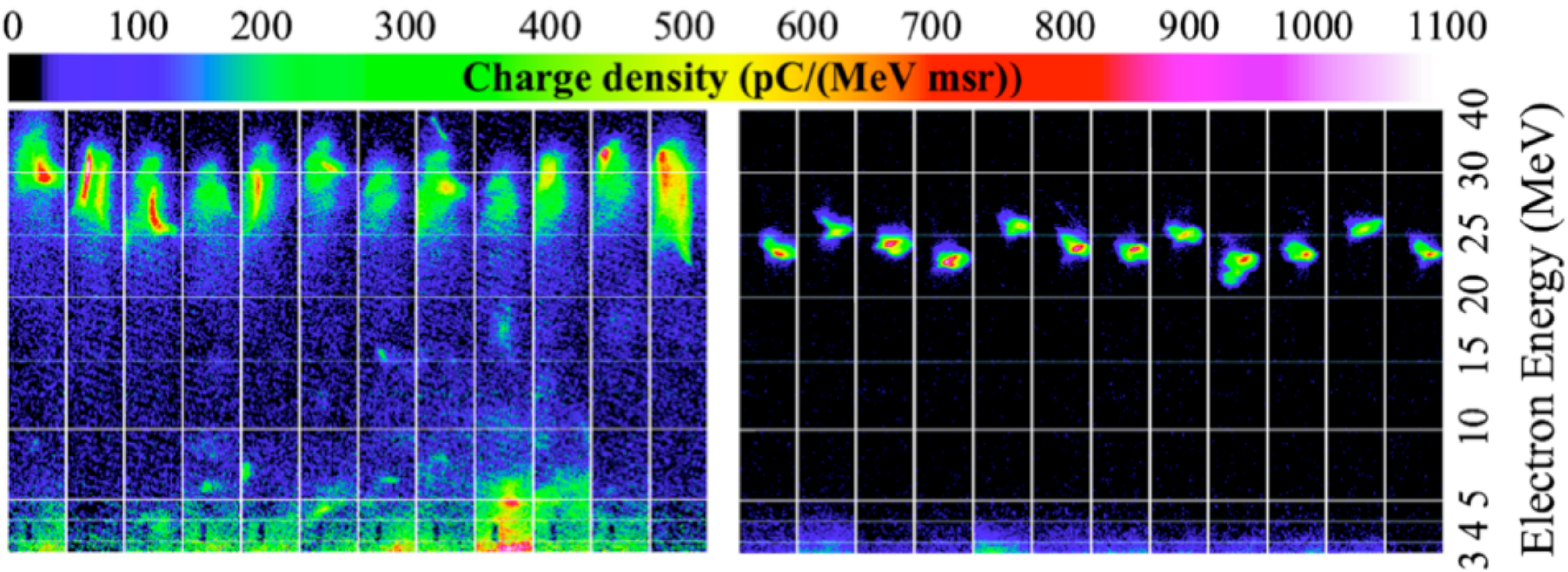
S. Bulanov *et al.*, PRE **58**, R5257 (1998), H. Suk *et al.*, PRL **86**, 1011 (2001), T.-Y Chien *et al.*, PRL **94**, 115003 (2005), T. Hosokai *et al.*, PRL **97**, 075004 (2006), C. G. R. Geddes *et al.* PRL **100**, 215004 (2008), J. Faure *et al.*, Phys. of Plasma **17**, 083107 (2011)

2010 Sharp density ramp injection : shock in gas jet



=>



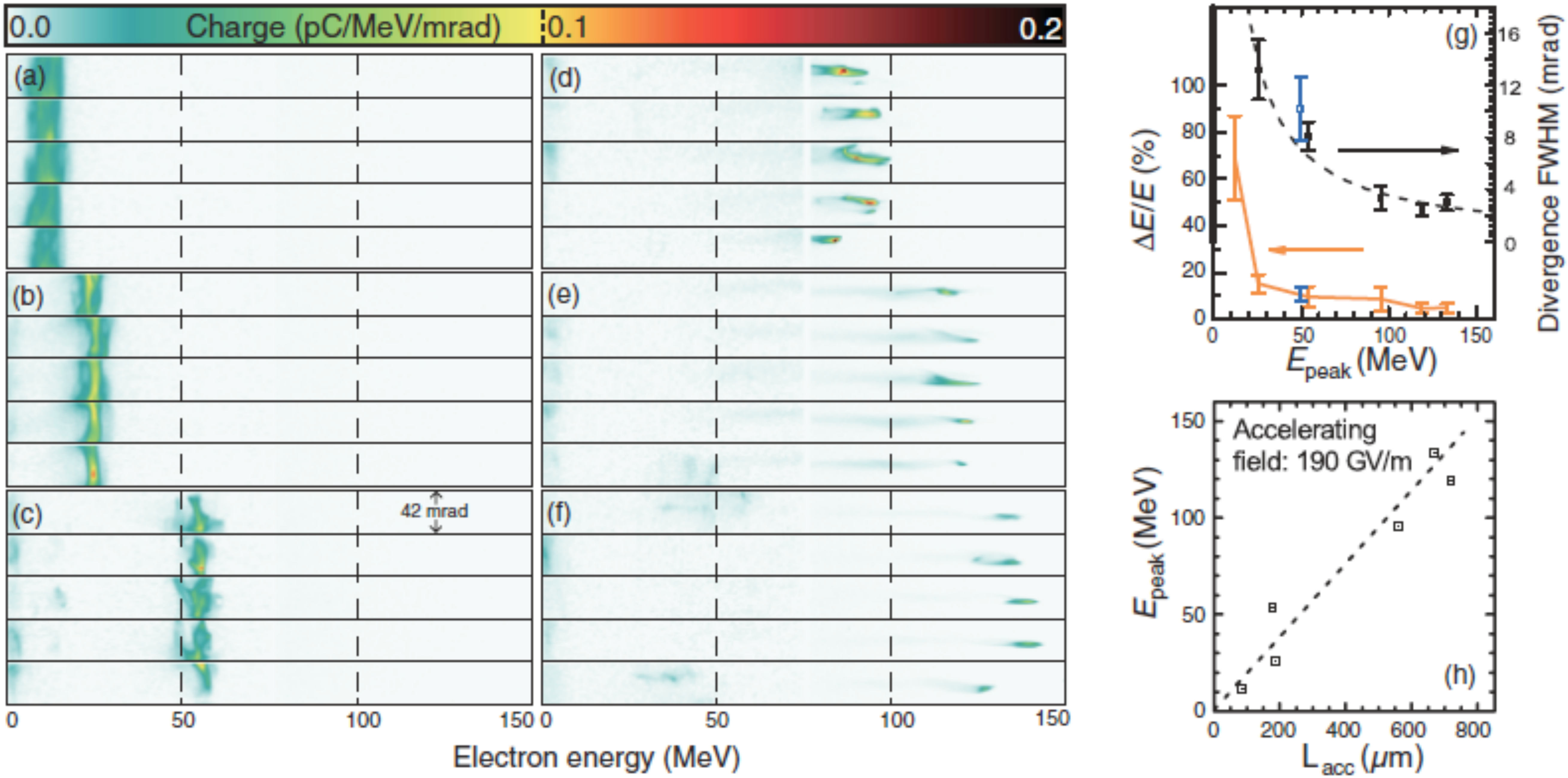


(a) Self injection

(b) Injection at density transition

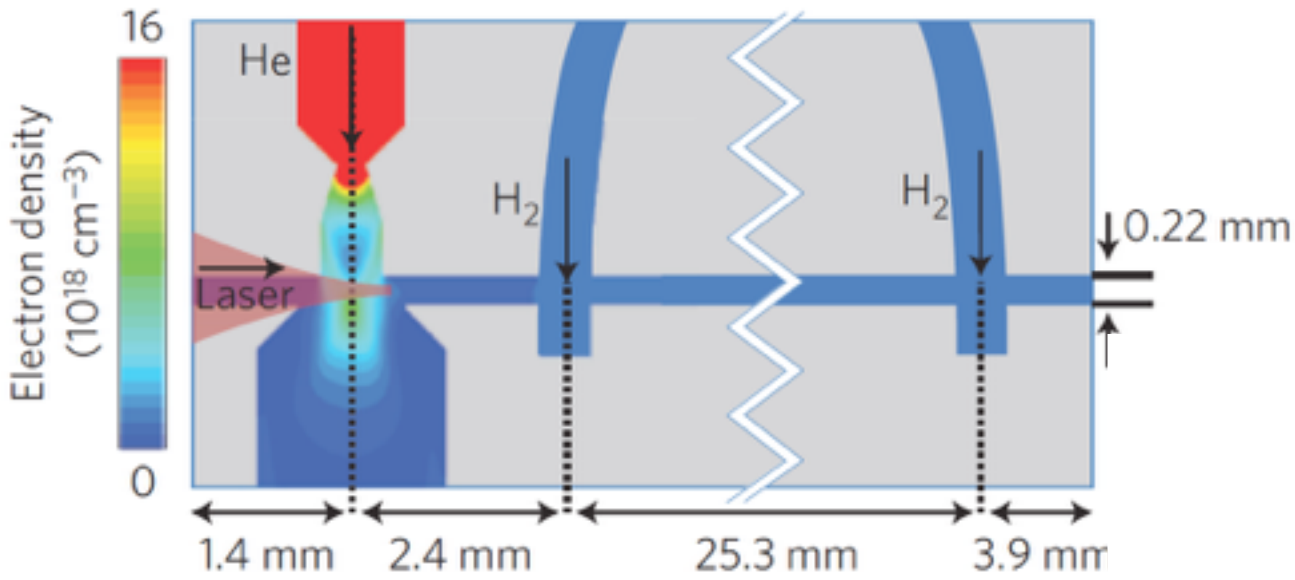
K. Schmid et al., PRSTAB 13, 091301 (2010)

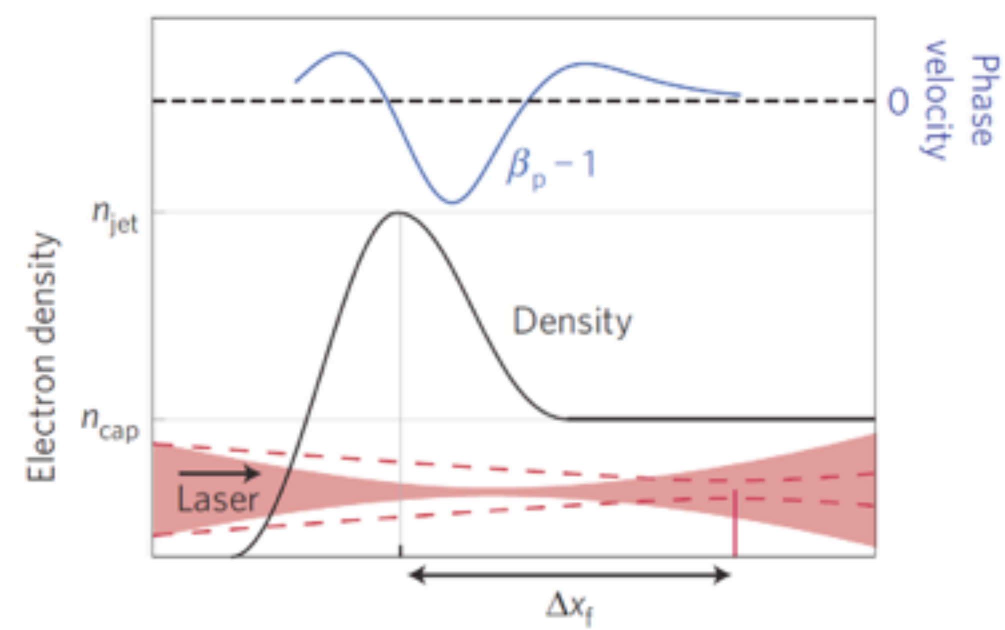
2013 Shock front injection

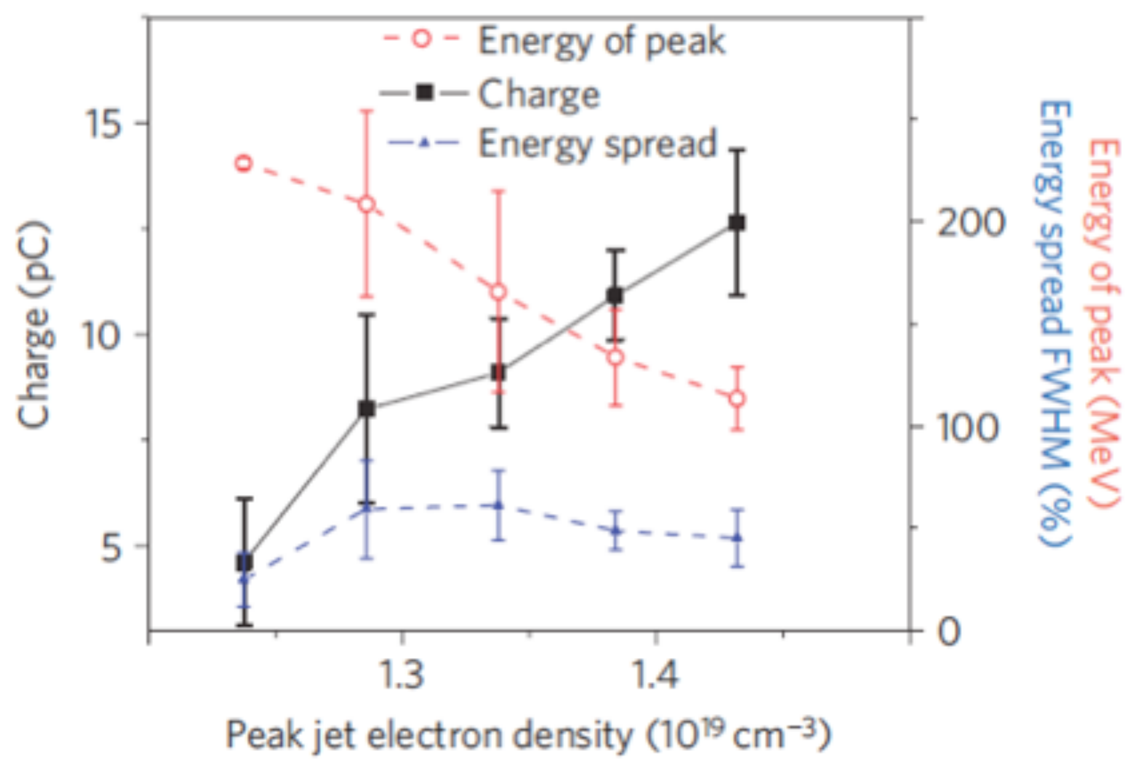


A. Buck *et al.*, PRSTAB 13, 091301 (2010)

2011 Density ramp + phase velocity control





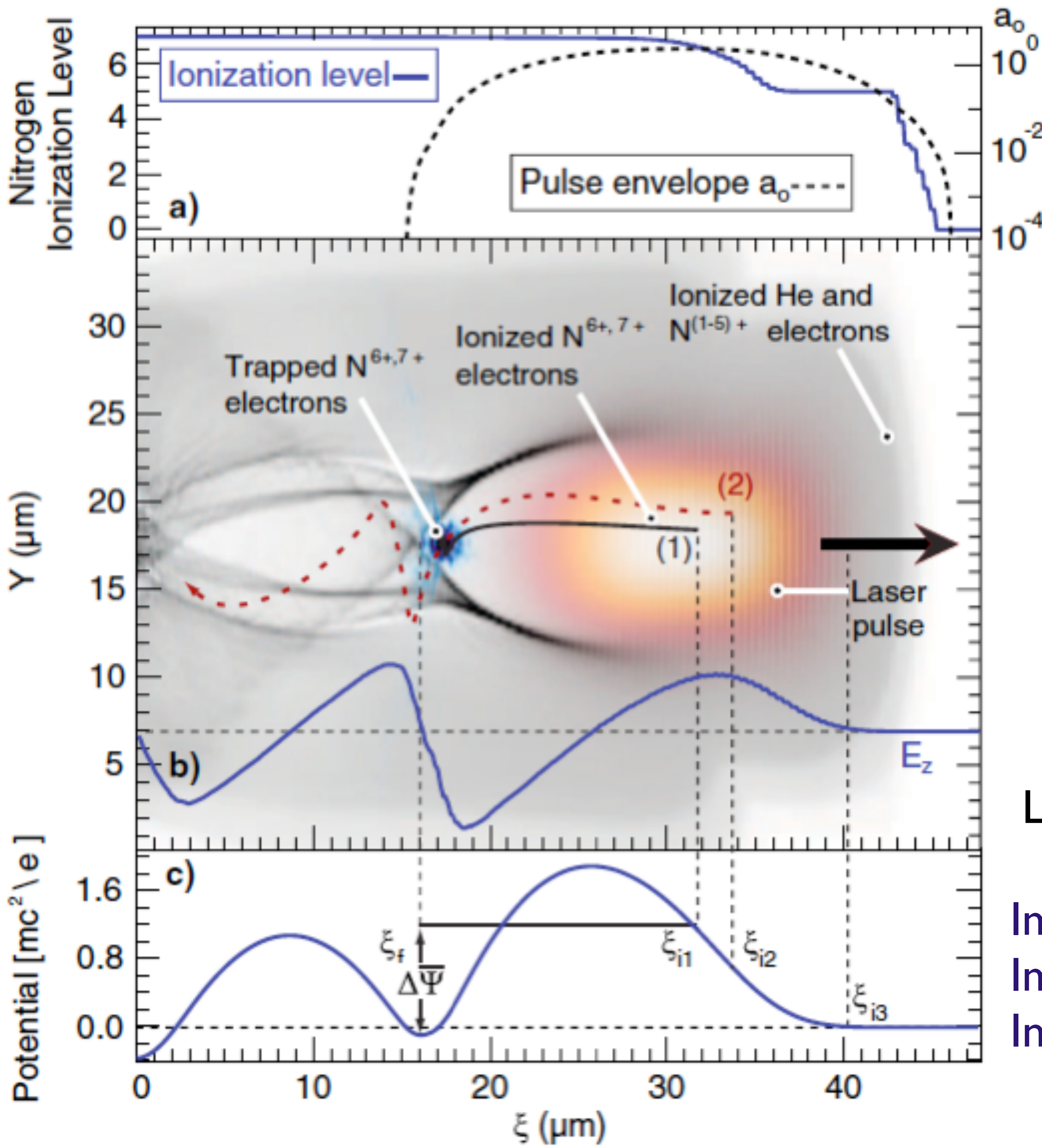


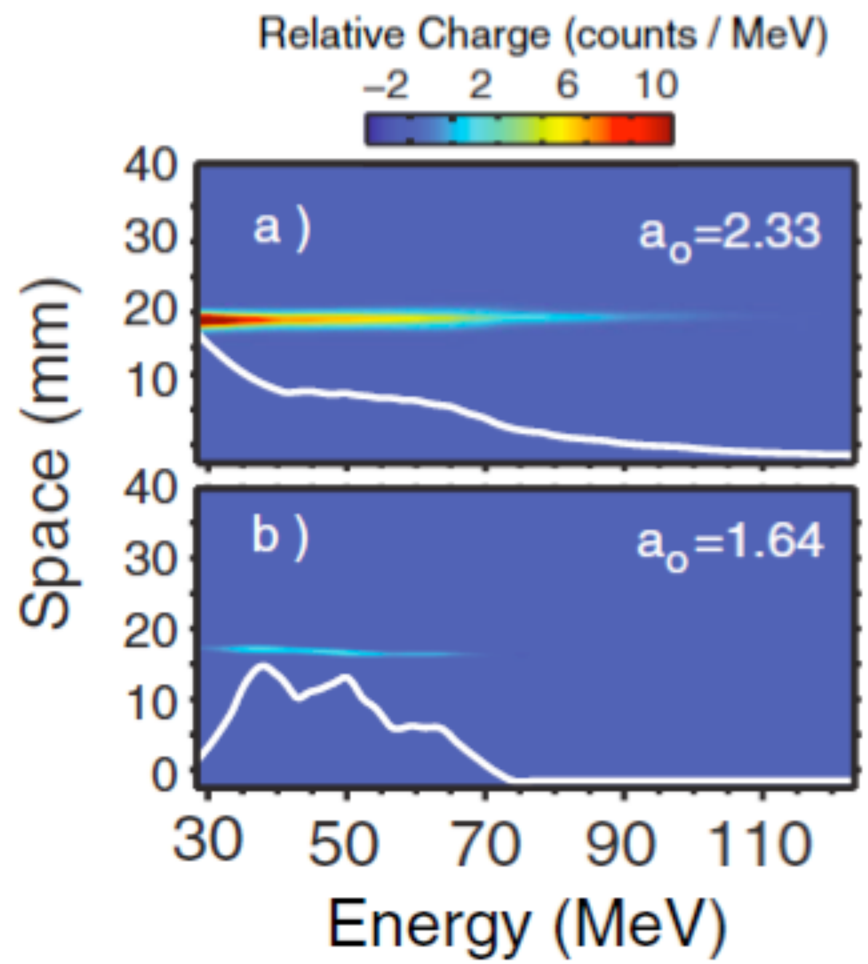
Laser : 20 TW
0.8J, 40 fs, a_0=0.9
n_e=7x10^{18}cm^{-3}

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

2010 Ionization Induced Trapping



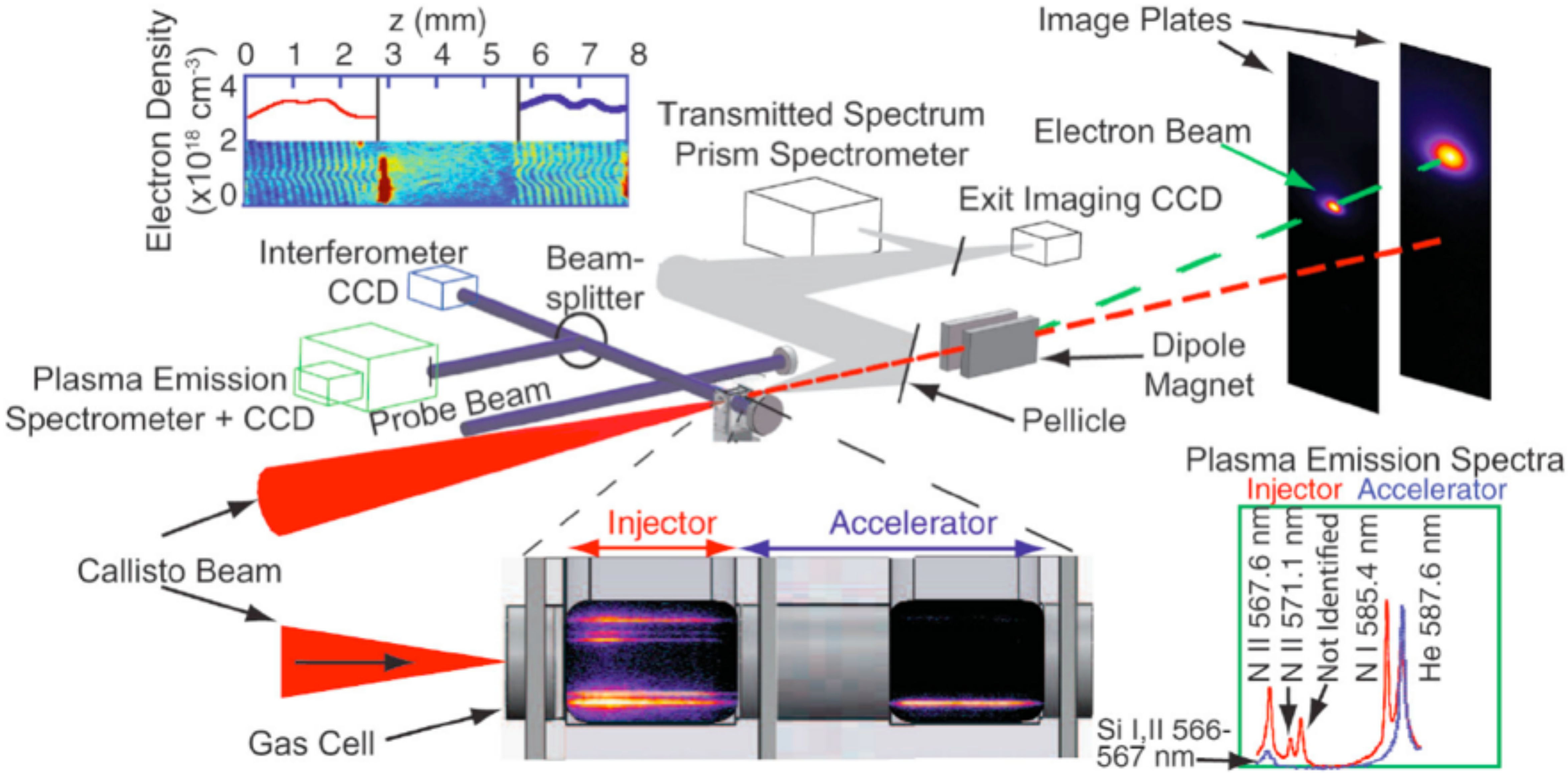


Laser: 10 TW, 0.8J, 45 fs, $a_0 \approx 2$, $n_e = 1.4 \times 10^{19} cm^{-3}$

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)

2010 Ionization Induced Trapping : 2 stage plasma acc.

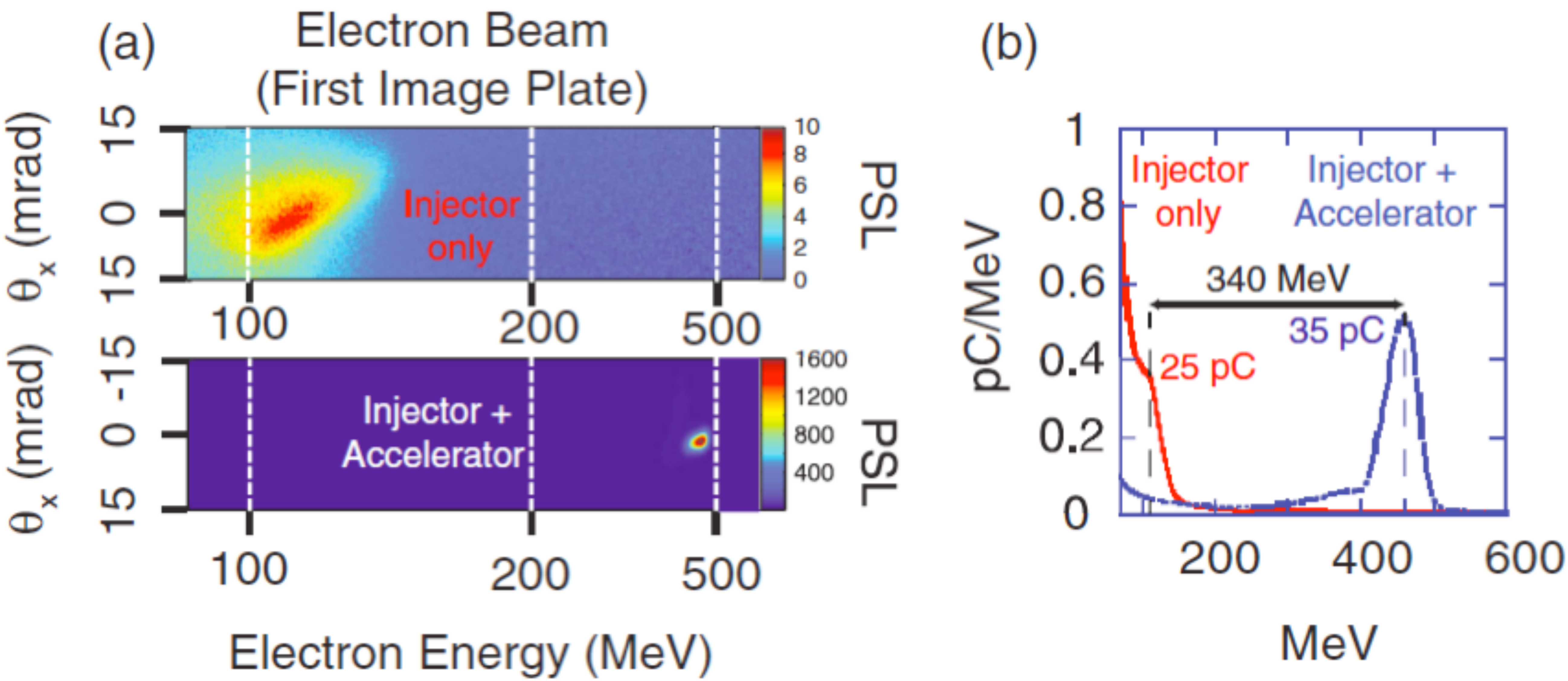


Laser : 30-60 TW, 60 fs, a_0=2-2.8, n_e=3x10^{18}cm^{-3}

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

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

Ionization Induced Trapping: 2-stage plasma accelerators



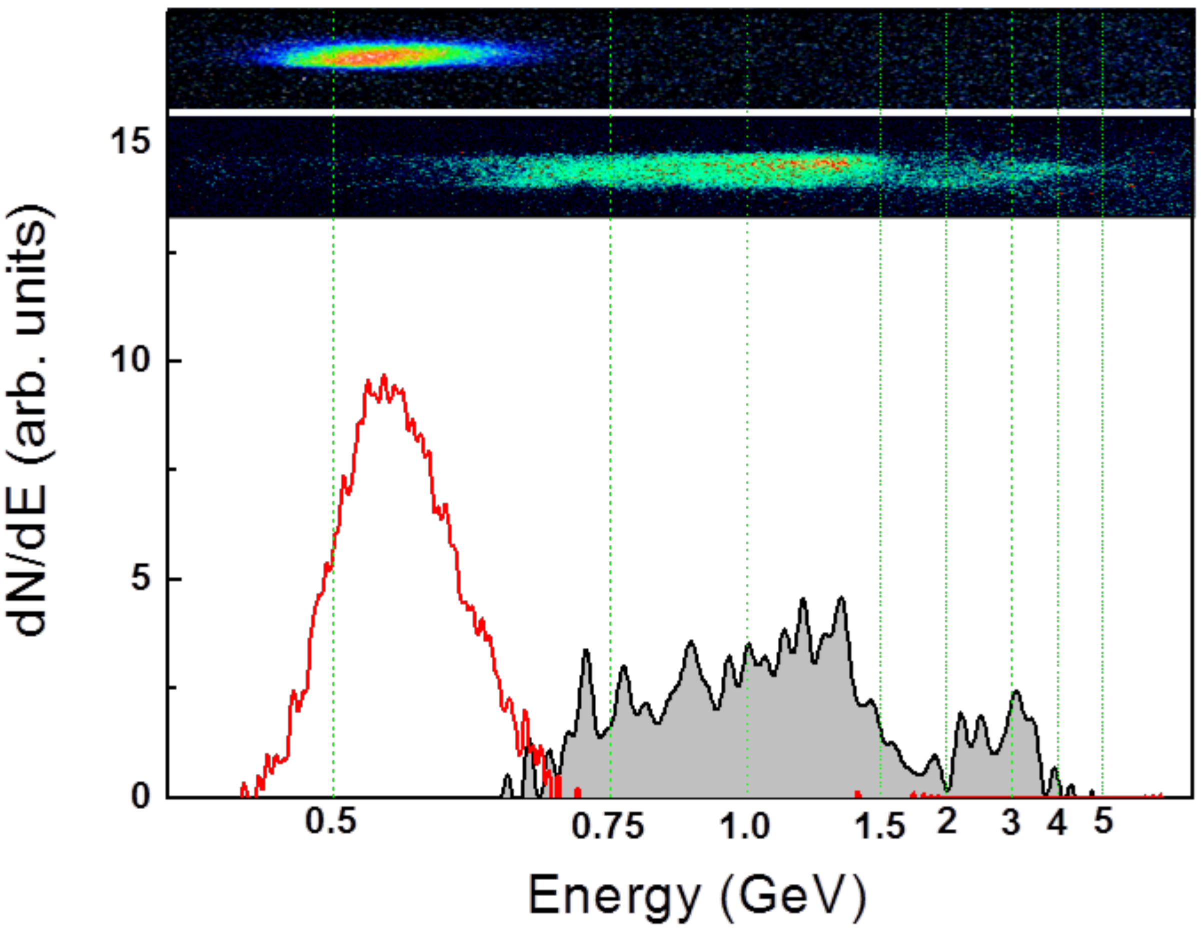
Laser : 30-60 TW, 60 fs, a_0=2-2.8, n_e=3x10^{18}cm^{-3}

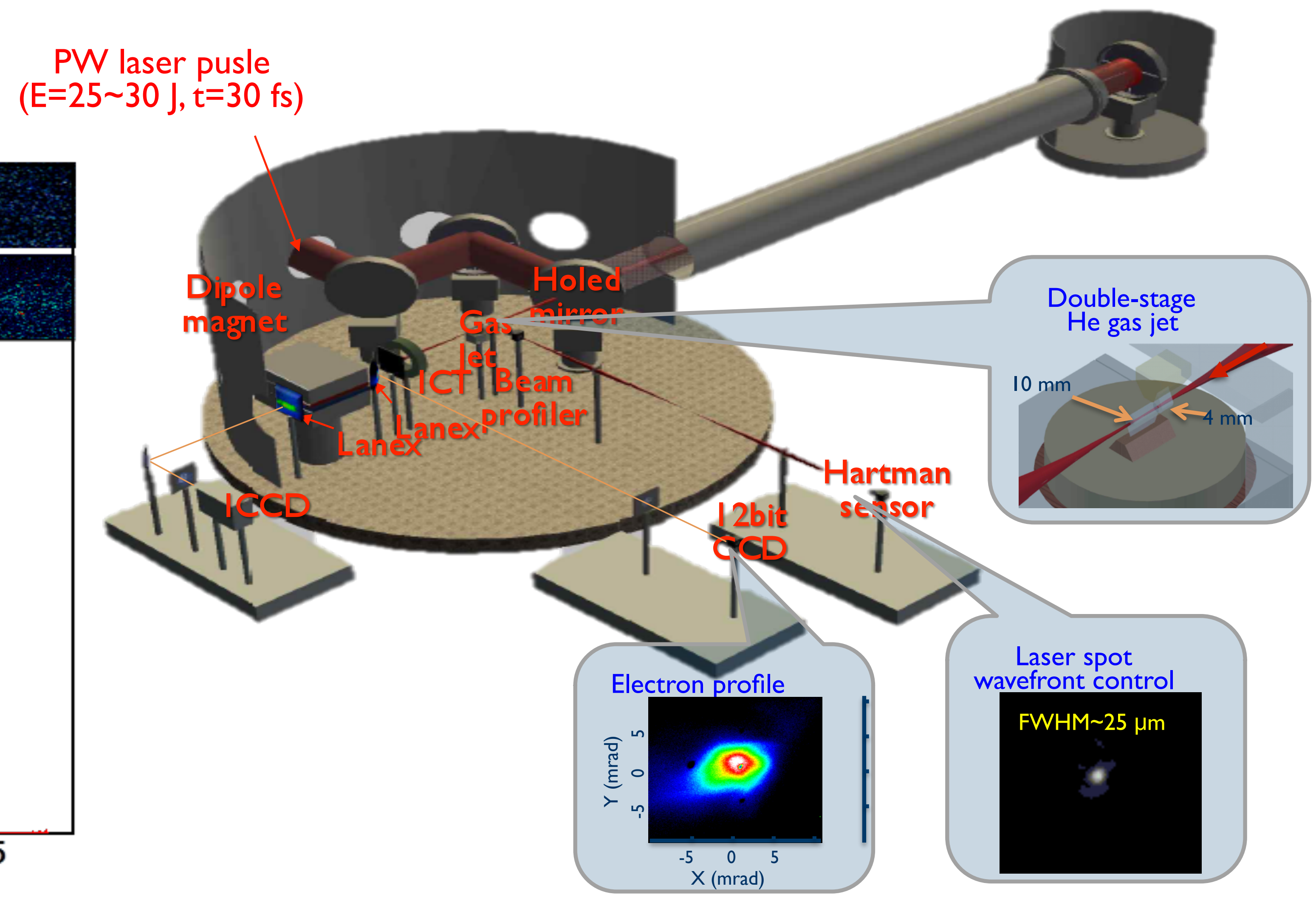
35 pC, 460 MeV, div = 2 mrad, DE/E>5%

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)

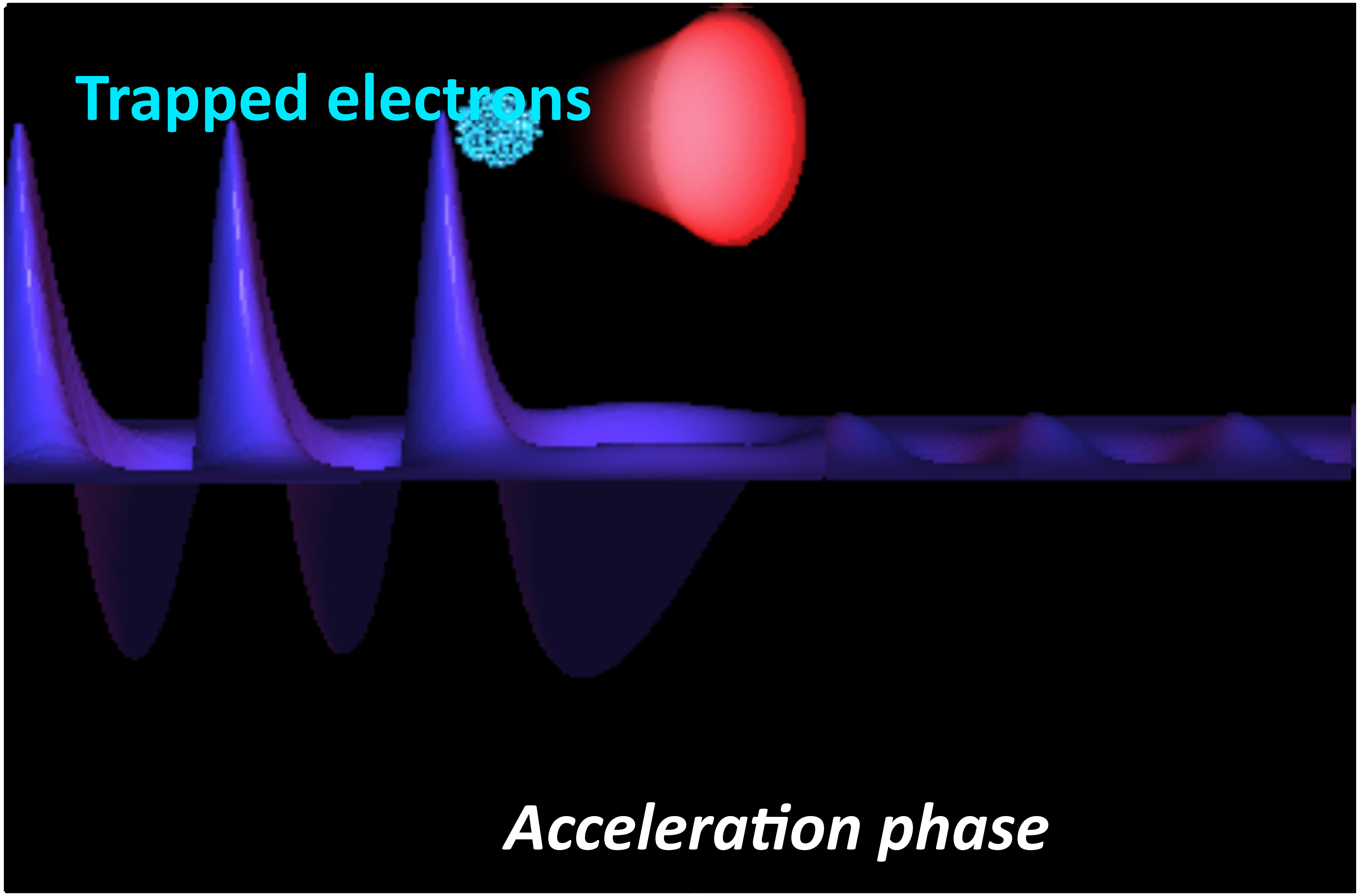




Courtesy of Hyung Taek Kim

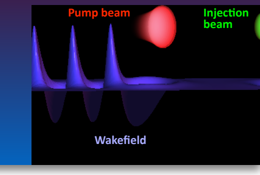
Colliding Laser Pulses Scheme

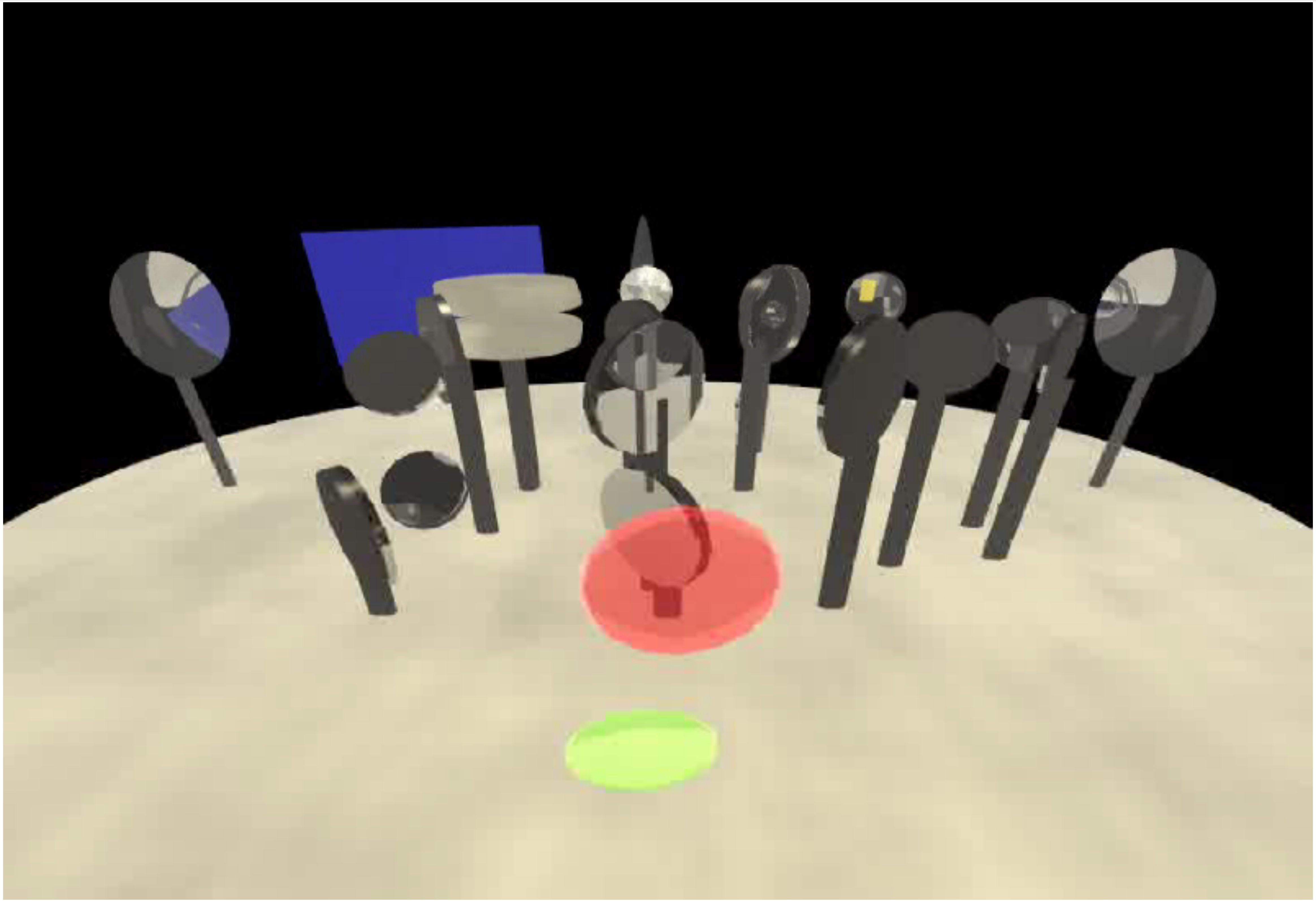
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



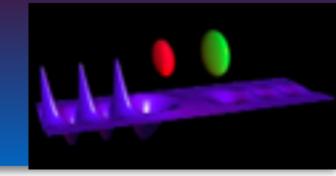
Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

The colliding of two laser pulses scheme

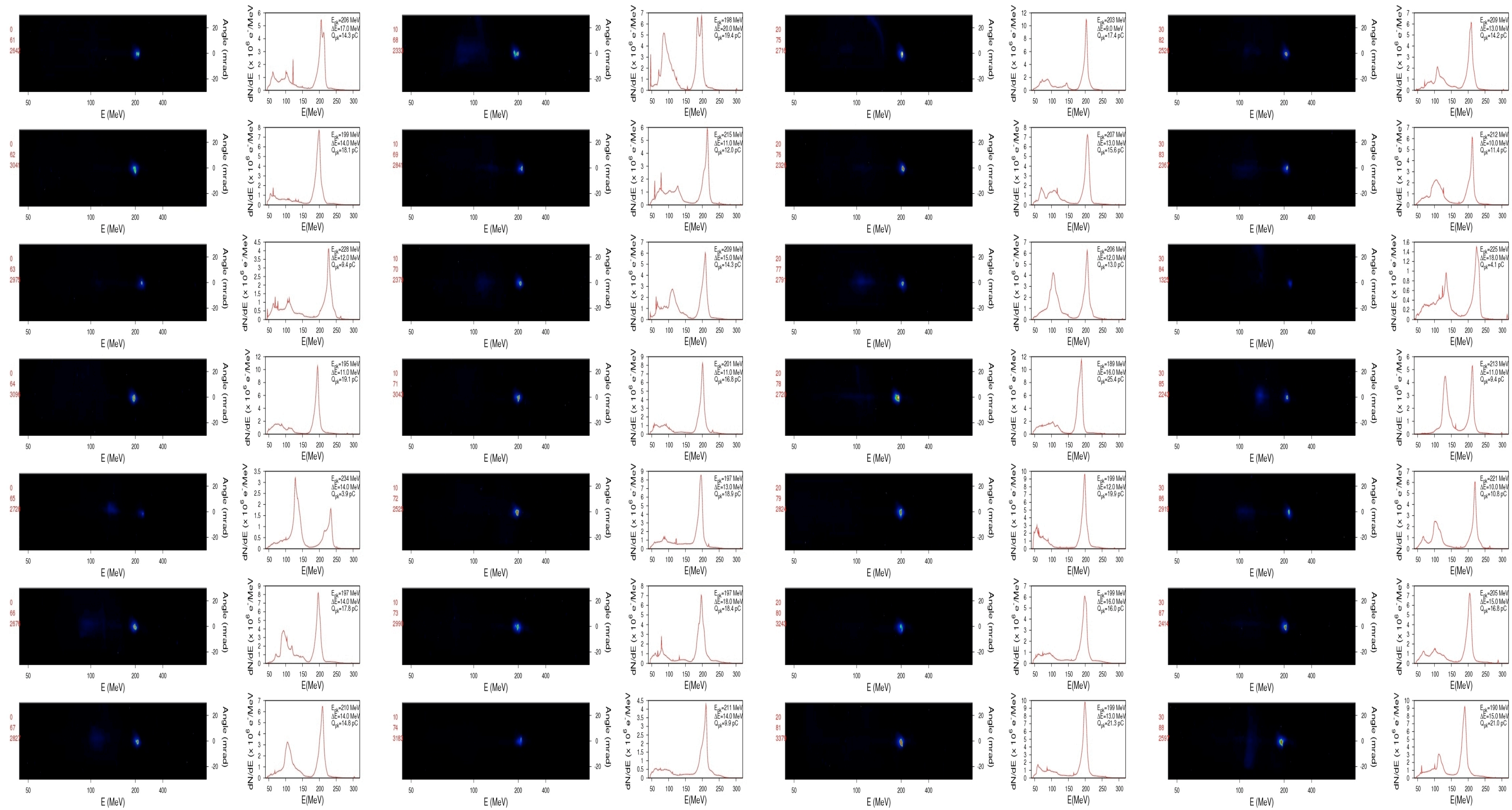




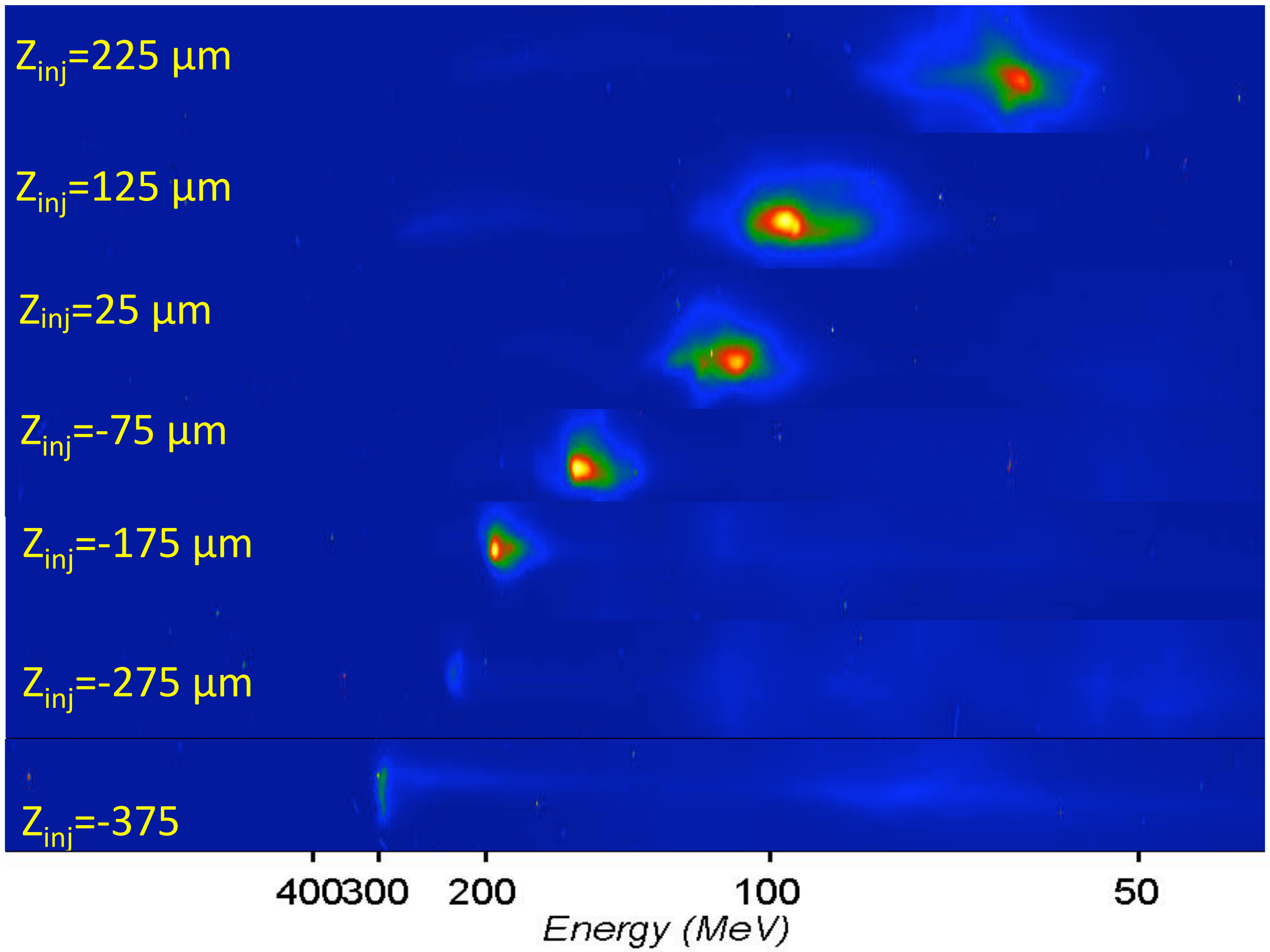
Stable Laser Plasma Accelerators

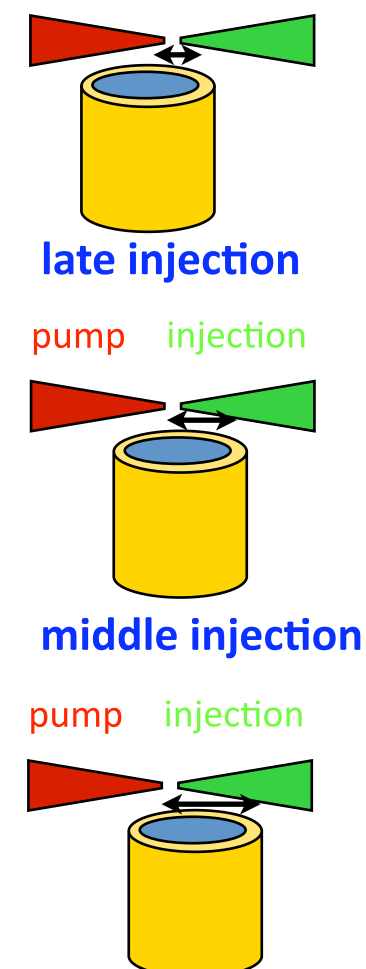


Series of 28 consecutive shots with : $a_0=1.5$, $a_1=0.4$, $n_e=5.7\times10^{18}cm^{-3}$



Tunability of Laser Plasma Accelerators: e-energy

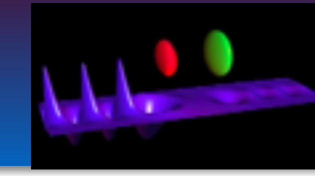


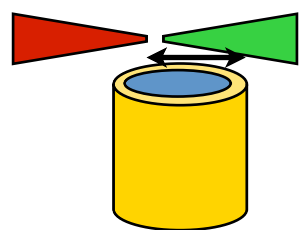


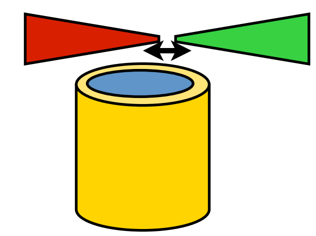
accelerating distance ⟷

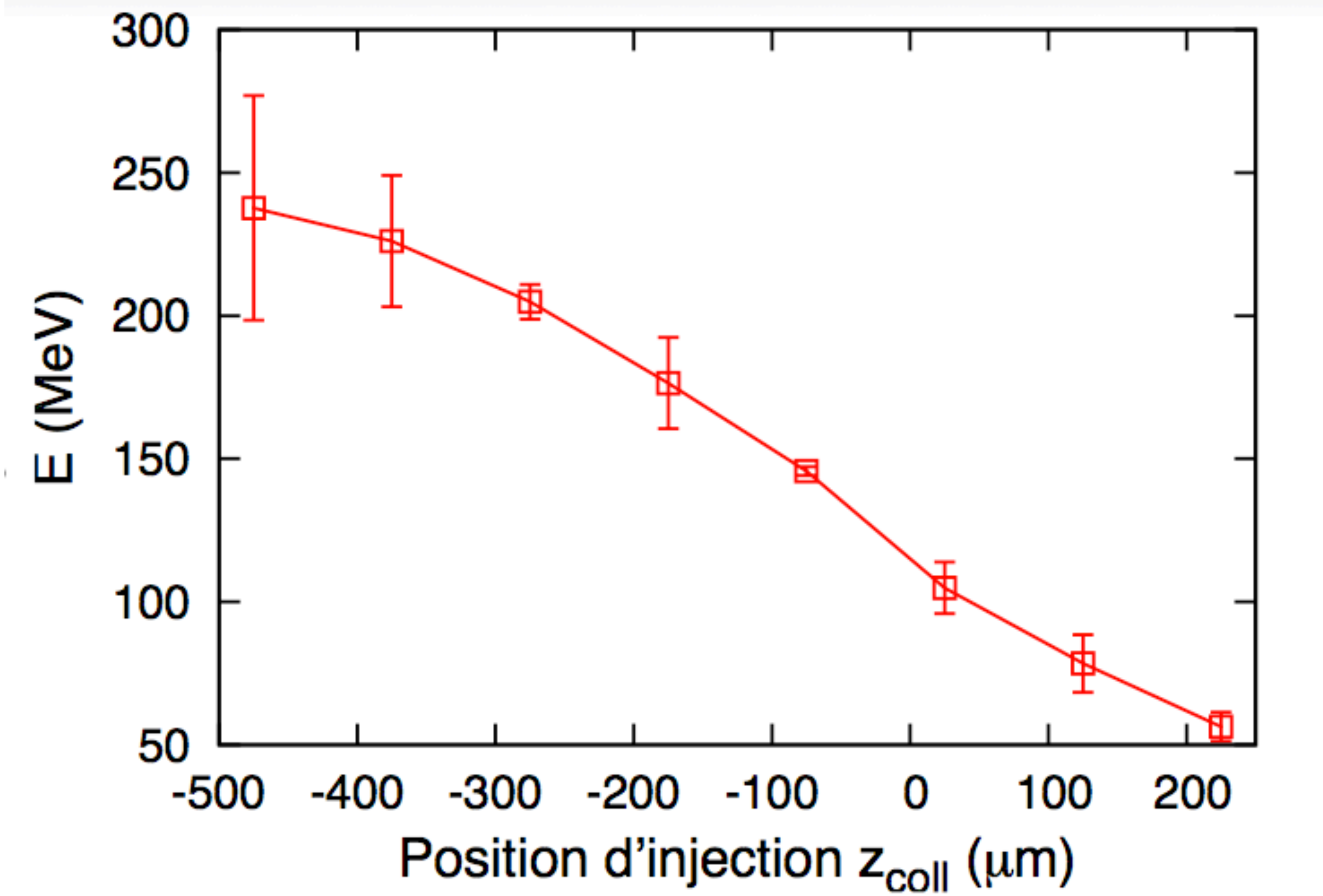
J. Faure *et al.*, Nature **444**, 737 (2006)

Tunability of Laser Plasma Accelerators : e- energy



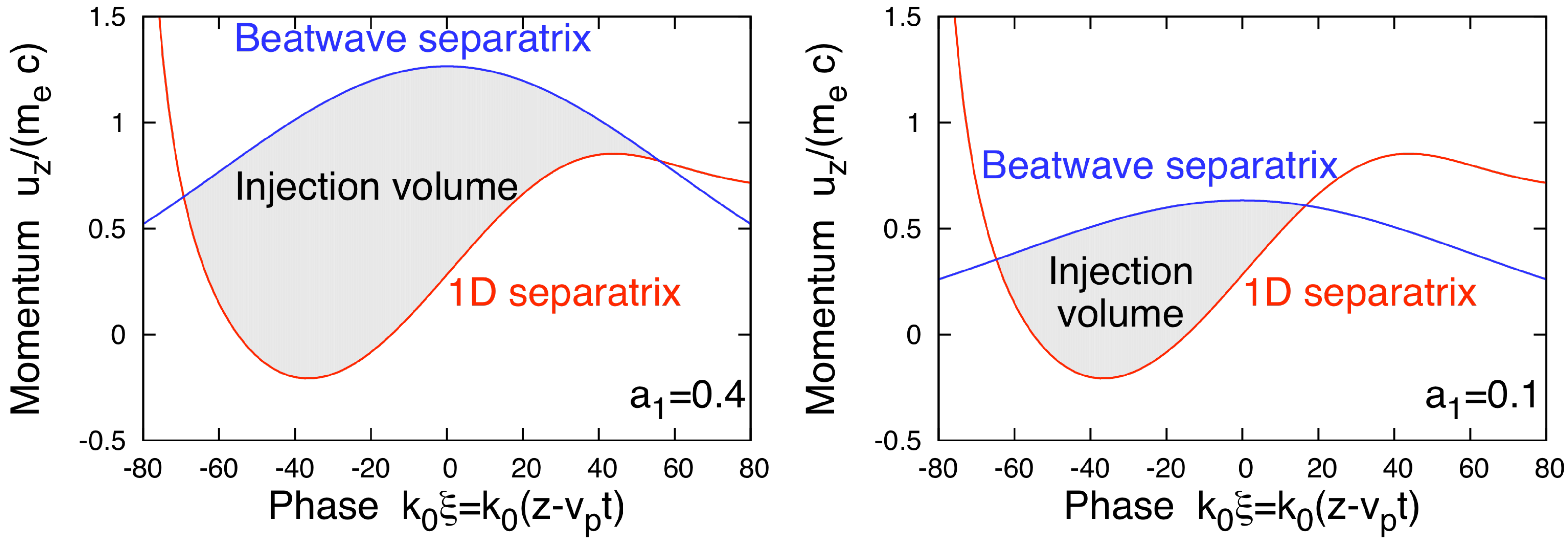






charge & energy spread controls

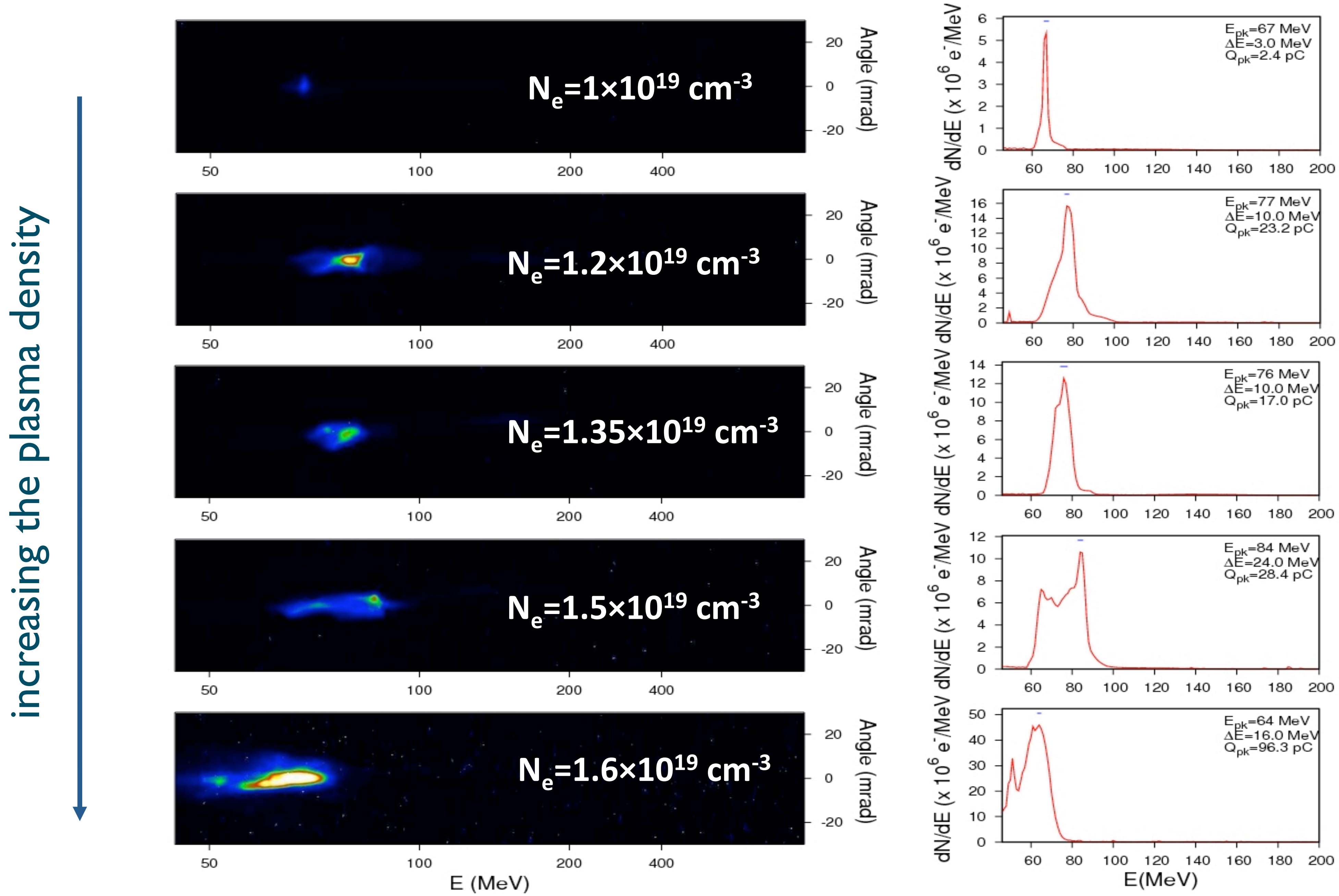
Charge : controlling electrons heating processes => smaller $a_{inj.}$ means less heating and less trapping
Energy spread : Decreasing the phase space volume V_{trap} of trapped electrons by reducing $a_{inj.}$ or by reducing $c\tau/\lambda_p$ by changing n_e (i.e λ_p)



Evolution of injection volume with a_1 for $a_0 = 2$, $n_e = 7\times10^{18}\text{cm}^{-3}$.
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 charge & energy spread with the plasma density



E=67 MeV
ΔE=3 MeV
Q_{pk}=2.4pC

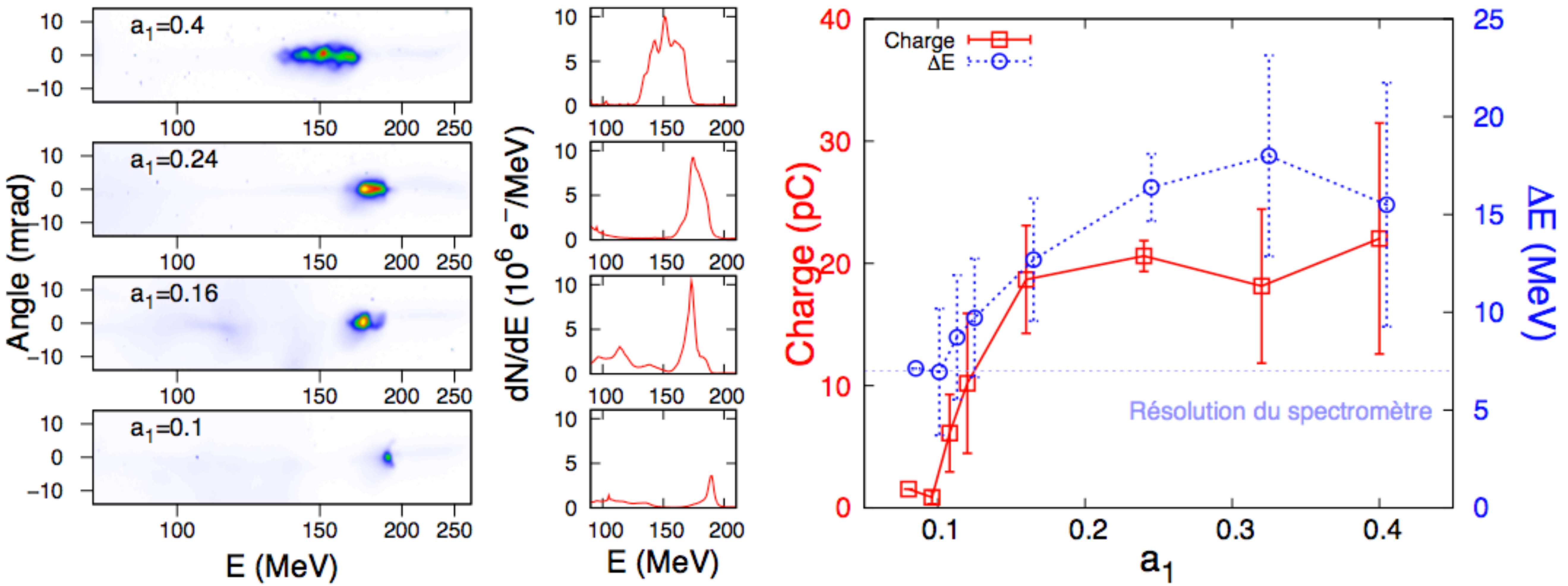
E=77 MeV
ΔE=10 MeV
Q_{pk}=23.2pC

E=76 MeV
ΔE=10.0 MeV
Q_{pk}=17pC

E=84 MeV
ΔE=24 MeV
Q_{pk}=25.4pC

E=64 MeV
ΔE=16 MeV
Q_{pk}=96pC

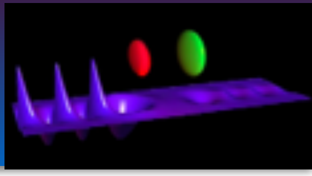
Tuning charge & energy spread with inj. laser intensity

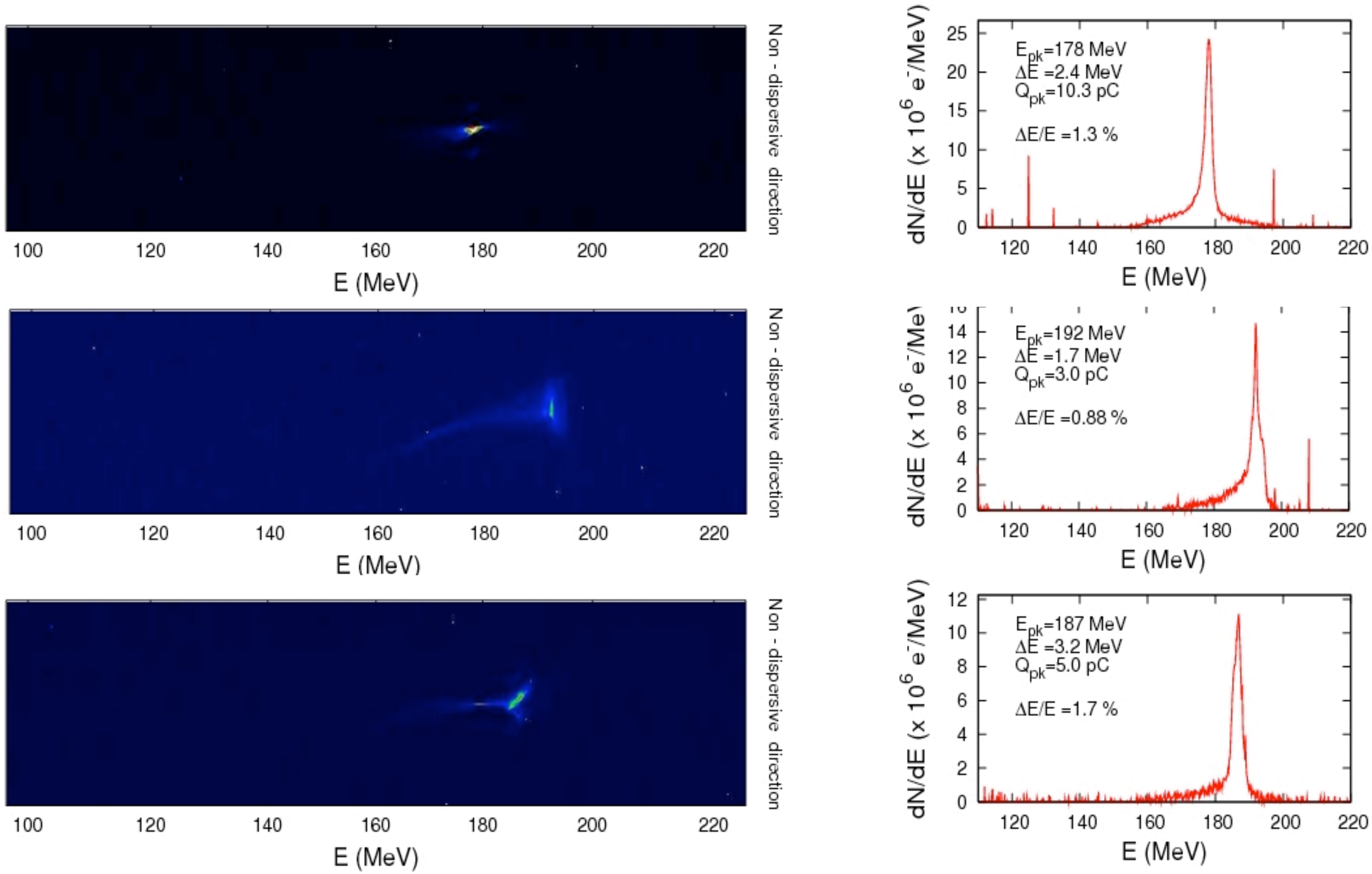


Charge from 60 pC to 5 pC, ΔE from 20 to 5 MeV

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

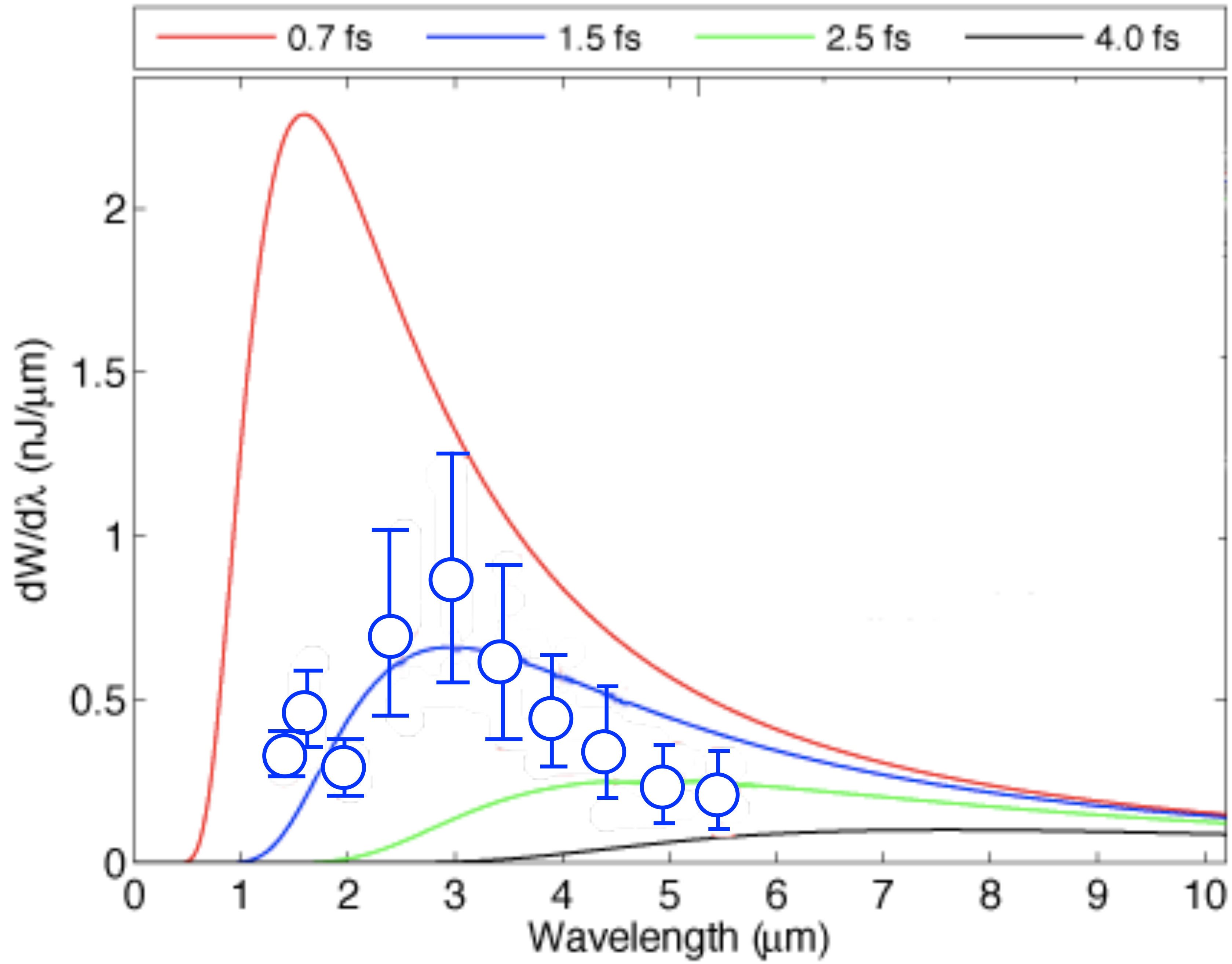
1% relative energy spread





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

1.5 fs RMS duration : Peak current of 4 kA



Analytic CTR model

Gaussian pulse shape

Measured e-beam :

- Charge
- Energy
- Divergence

Bunch duration

Peak wavelength

Peak intensity

Spectral features

Peak at 3 μm

Coherent

1.5 fs RMS duration : Peak current of 4 kA

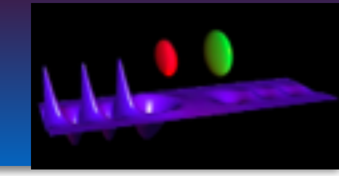
O. Lundh et al., Nature Physics, **7** (2011)

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

Outline

- Motivation and principle
- Laser Beat wave and Laser Wakefield
- Self Modulated Laser Wakefield
- Towards high quality electron beams
- 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 ?

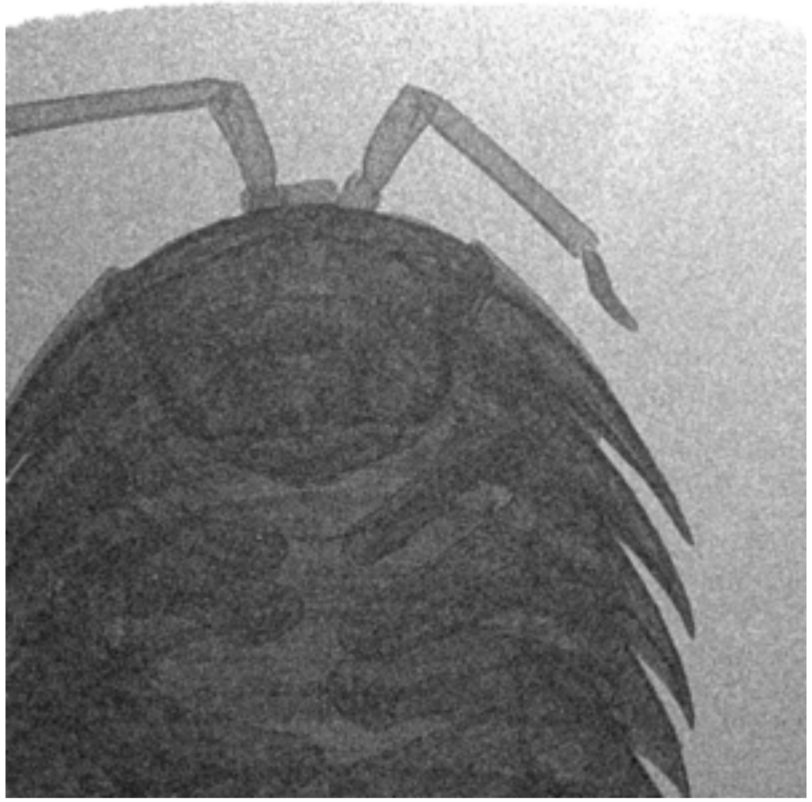
New diagnostics such as betatron[4,5], magnetic field[6,7], interferometry in the frequency-time[8], etc...

[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, radiotherapy, radiobology, material science
Compact FEL with moderate average power (10 Hz system)
Designing future accelerators
Compact X ray source (Thomson, Compton, Betatron, or FEL)
mJ-kHz laser plasma accelerators for fs electron diffraction



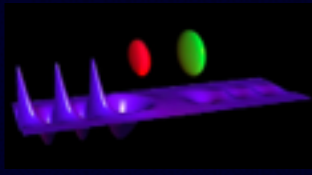
Courtesy of K. Krushelnick

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, guiding over logn distance (energy dissipation, robustness), 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.
STRATH, C. Joshi
K. Kando
Krushelnick
Lundh from LLC, Z. Najmudin
GoLP, L. Veisz
etc....

CARE/FP6-Euroleap/FP6-Accel1/EUCARD/EUCARD²/
ANR-PARIS/ERC contracts