Introduction & Historical Overview of Plasma Wake Acceleration

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Outline

- Motivation and principle
- Laser Beat wave and Laser Wakefield
- Self Modulated Laser Wakefield
- Towards high quality electron beams in LPA
- Particle Wakefield Accelerator
- Applications
- Conclusion and perspectives

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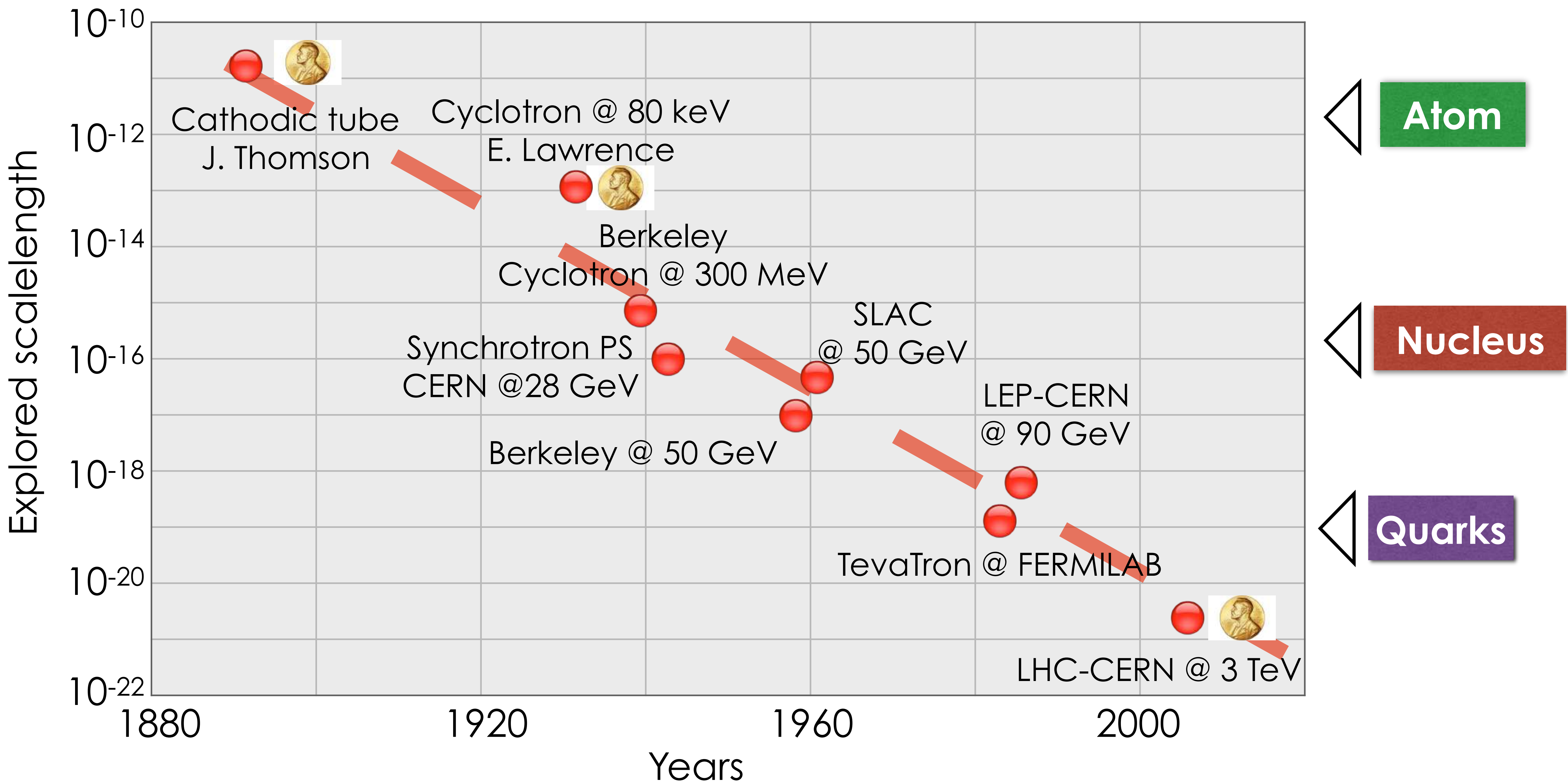
Accelerators: One century of exploration of the infinitively small



Industrial Market for Accelerators

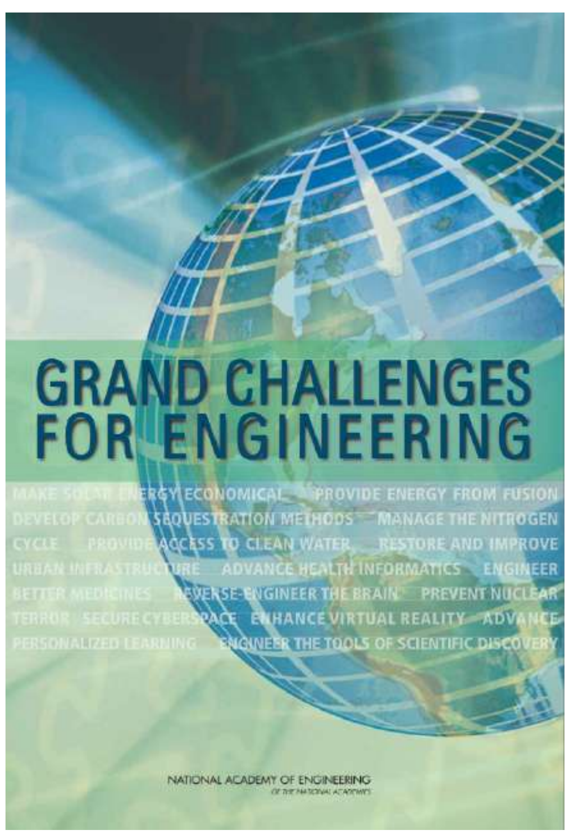
The development of state of the art accelerators for HEP has lead to :
research in other field of science (light source, spallation neutron sources…)
industrial accelerators (cancer therapy, ion implant., electron cutting&welding...)

Application	Total syst. (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**	

Compact and Cheaper High Energy Colliders a Grand Challenge for Science and Engineering in the 21st Cent.

Particle Physics Project Prioritization Panel (P5) Report 2014: Building for Discovery

« A primary goal, therefore, is the ability to build the future generation accelerators at dramatically lower cost…For e+e- colliders, the primary goals are improving the accelerating gradient and lowering the power consumption »



NAE Grand Challenges for Engineering Tools of Scientific Discovery

« Engineers will be able to devise smaller, cheaper but more powerful atom smashers, enabling physicists to explore realms beyond the reach of current technology »

Courtesy of C. Joshi

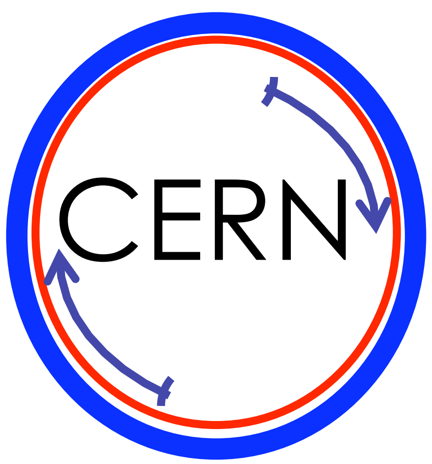
Plasma Accelerators : motivations

E-field$_{max}$ ≈ few 10 MeV /meter (Breakdown)

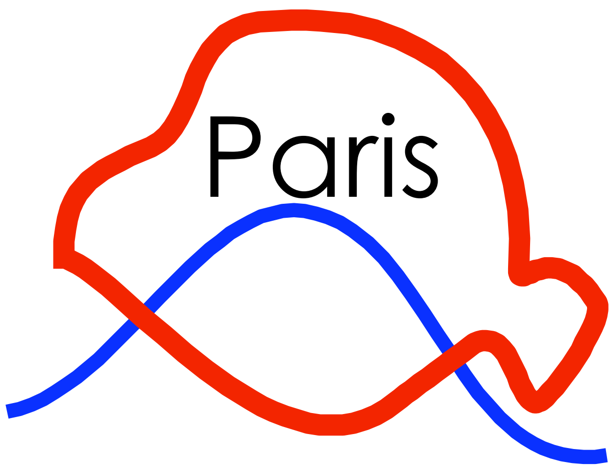
R>R$_{min}$ Synchrotron radiation

→ Energy ↗ → Length ↗ → Cost ↗

LHC
27 km



≈



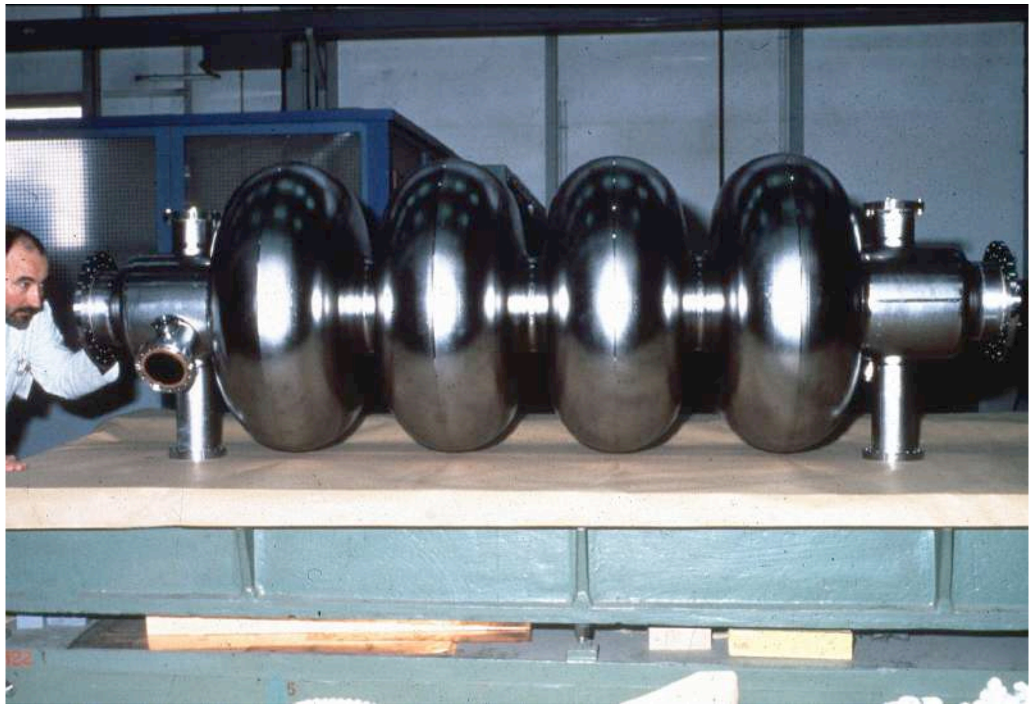
Circle road
31 km

➡ New medium : the plasma

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.

Compactness of Laser Plasma Accelerators

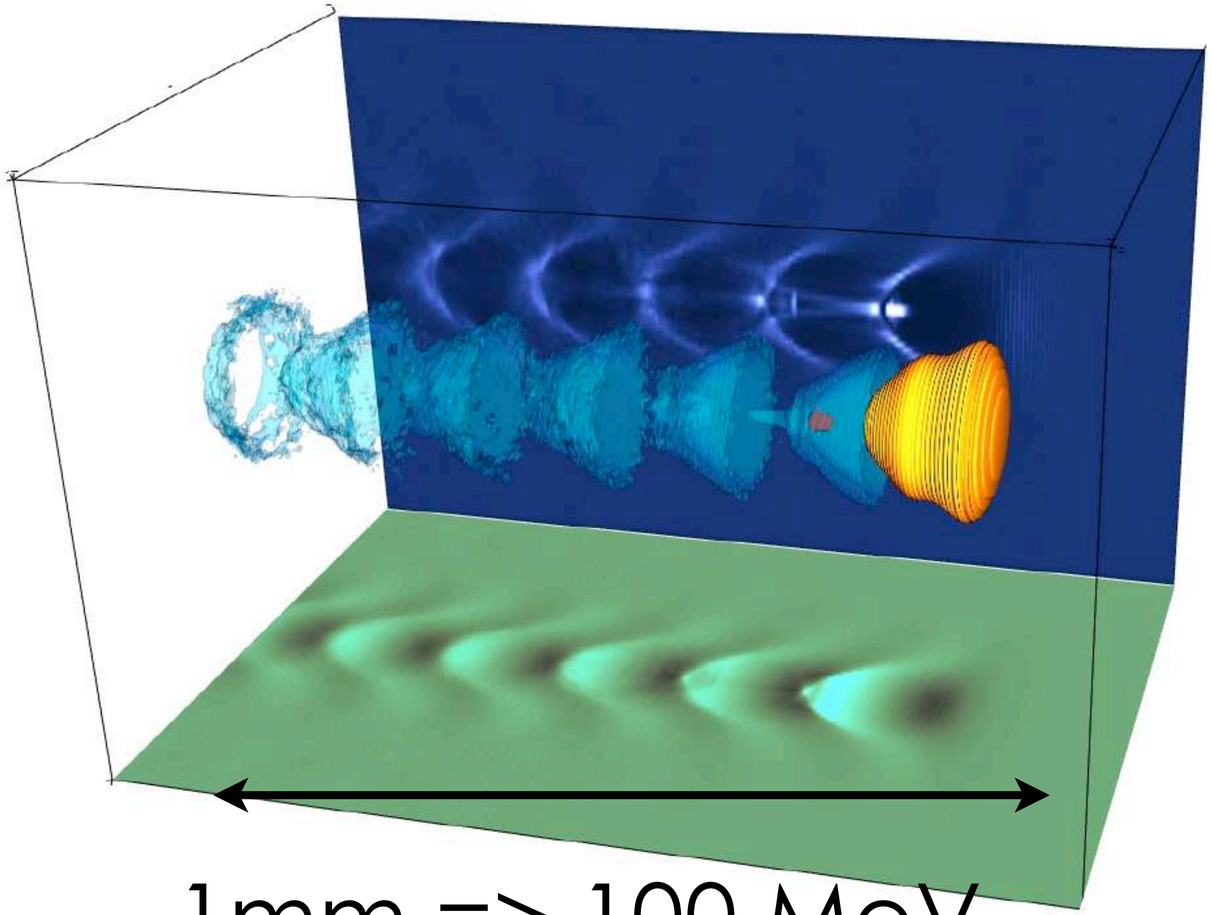
RF Cavity



1 m => 50 MeV Gain

Electric field < 100 MV/m

Plasma Cavity



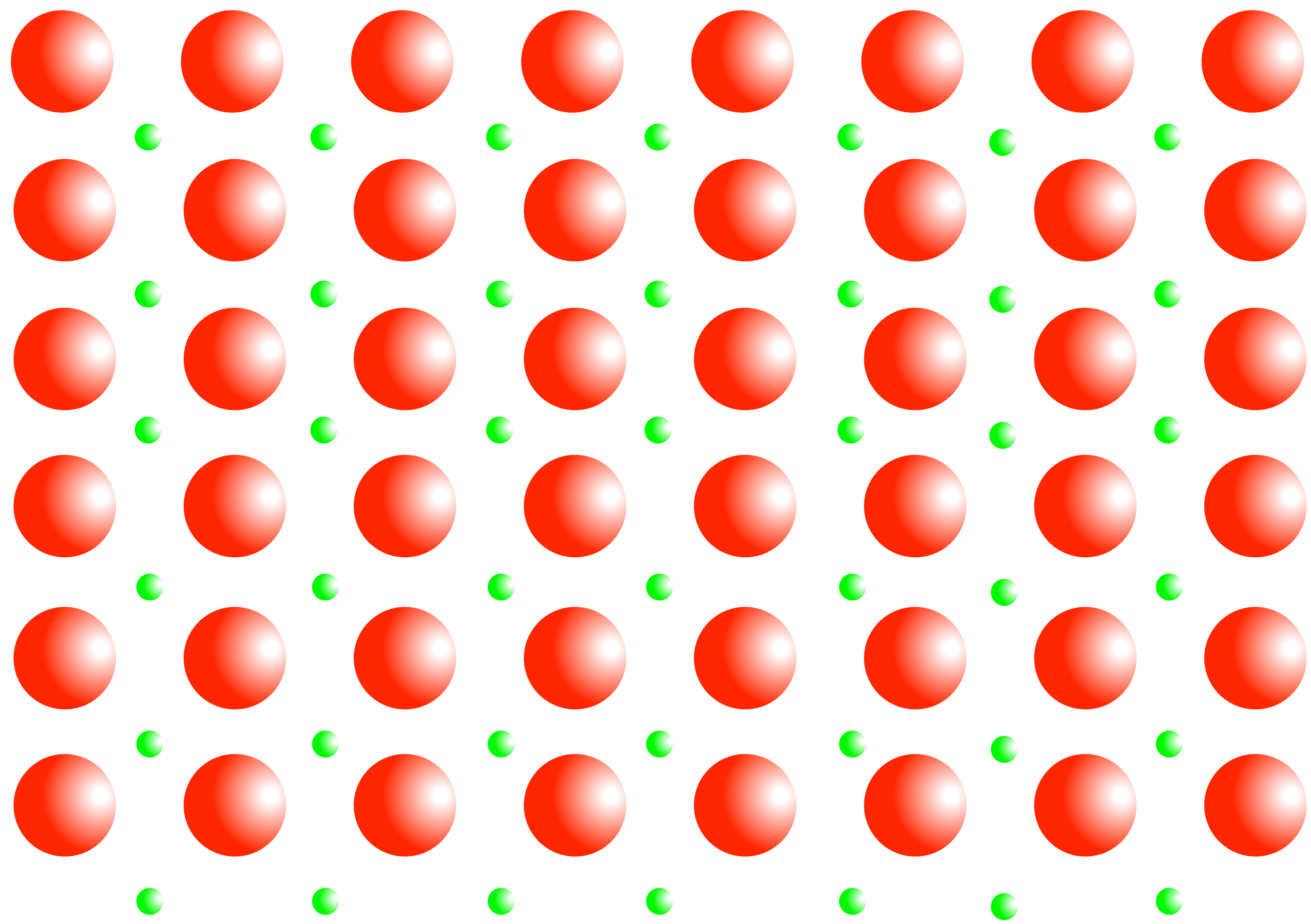
1mm => 100 MeV

Electric field > 100 GV/m

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

Why is a plasma useful ?

Plasma is an Ionized Medium => High Electric Fields



electrons plasma oscillation

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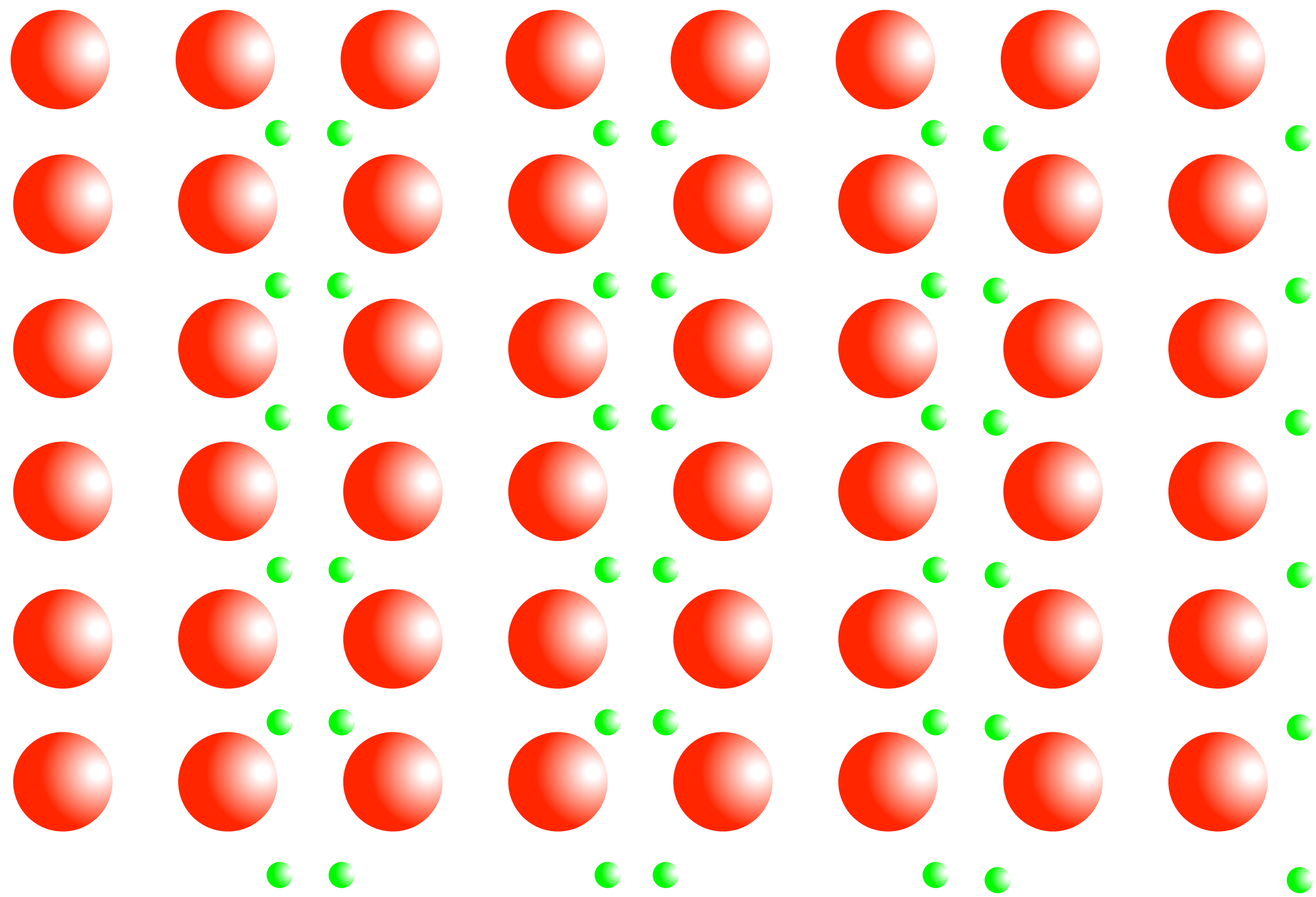

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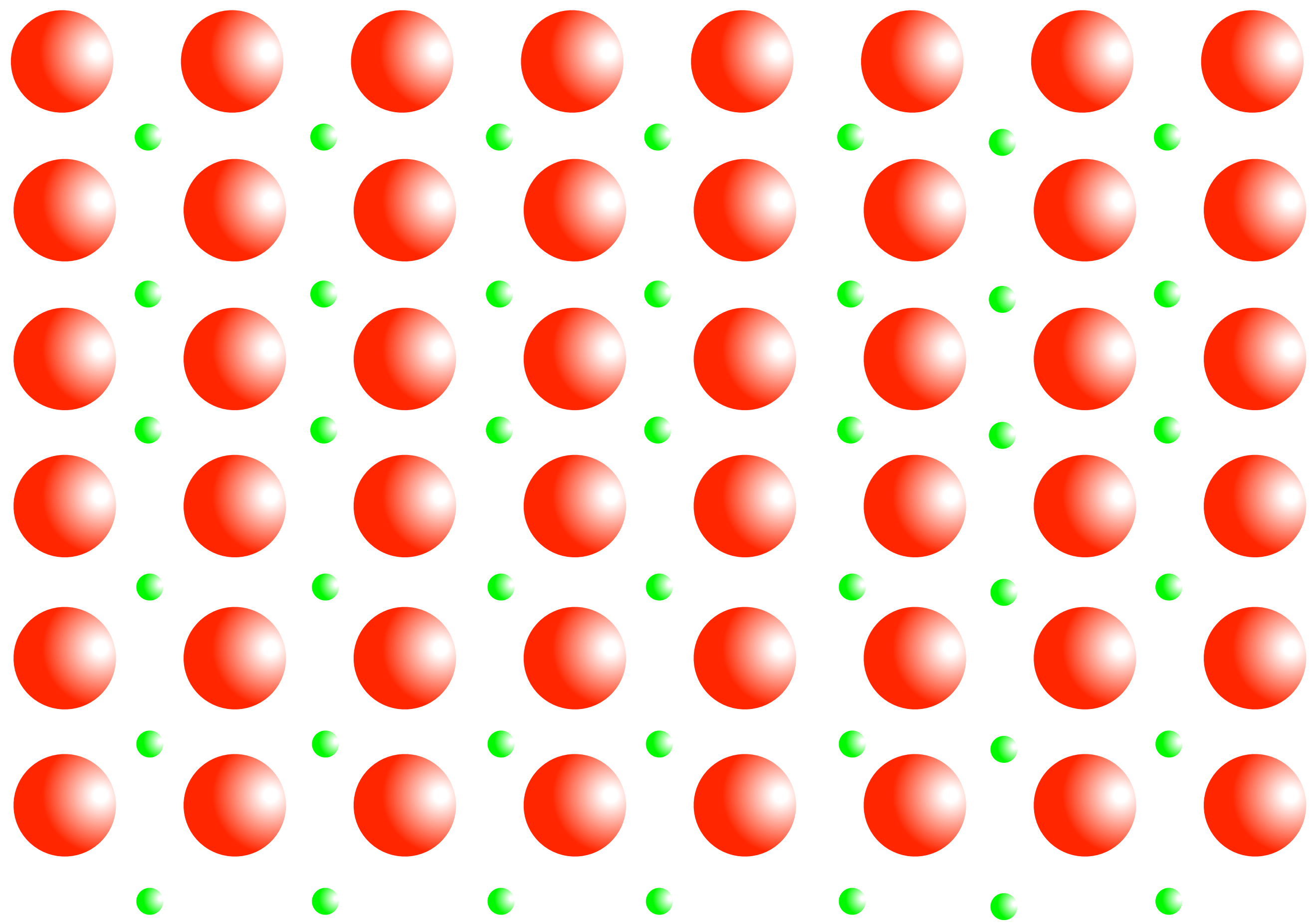

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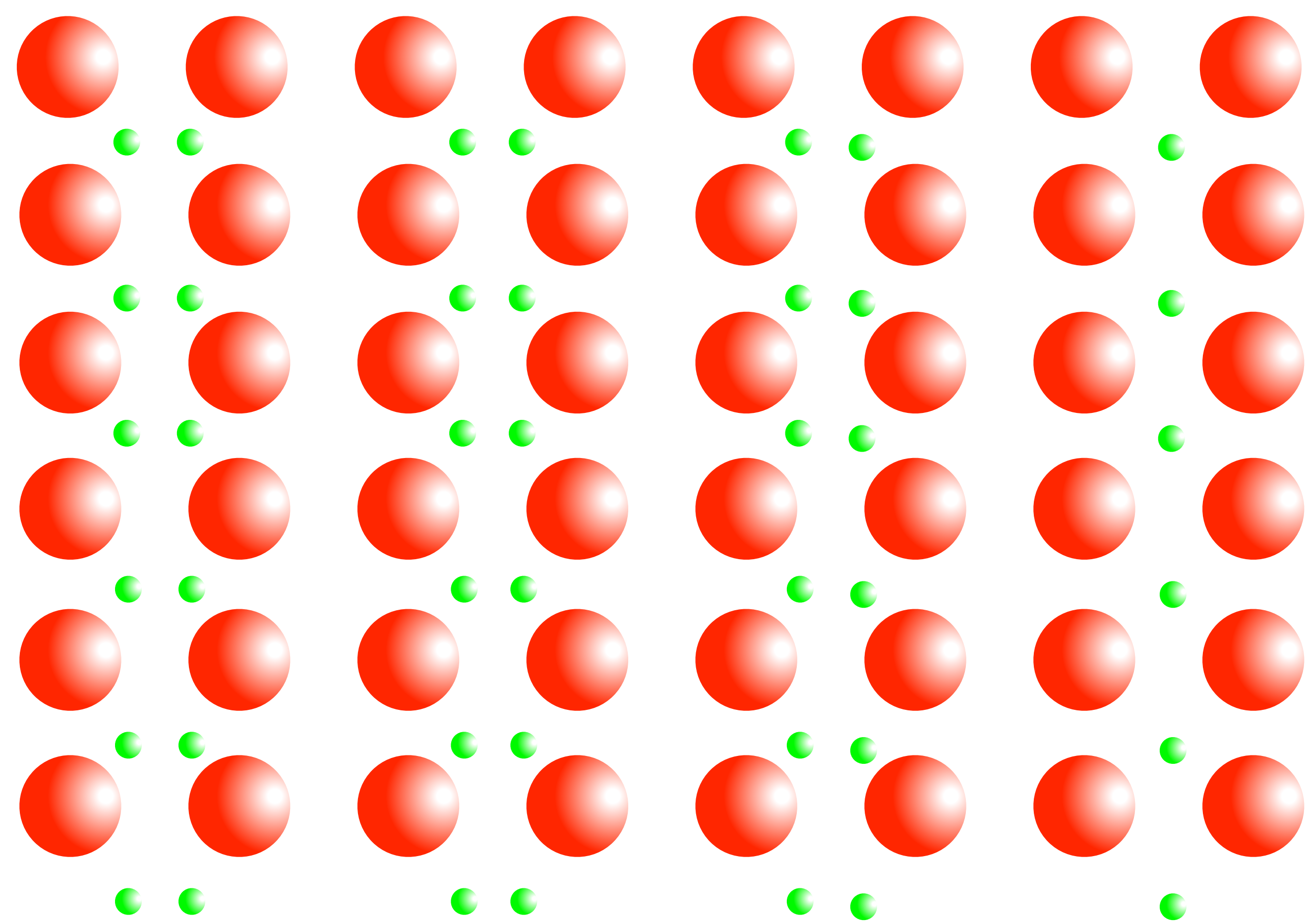

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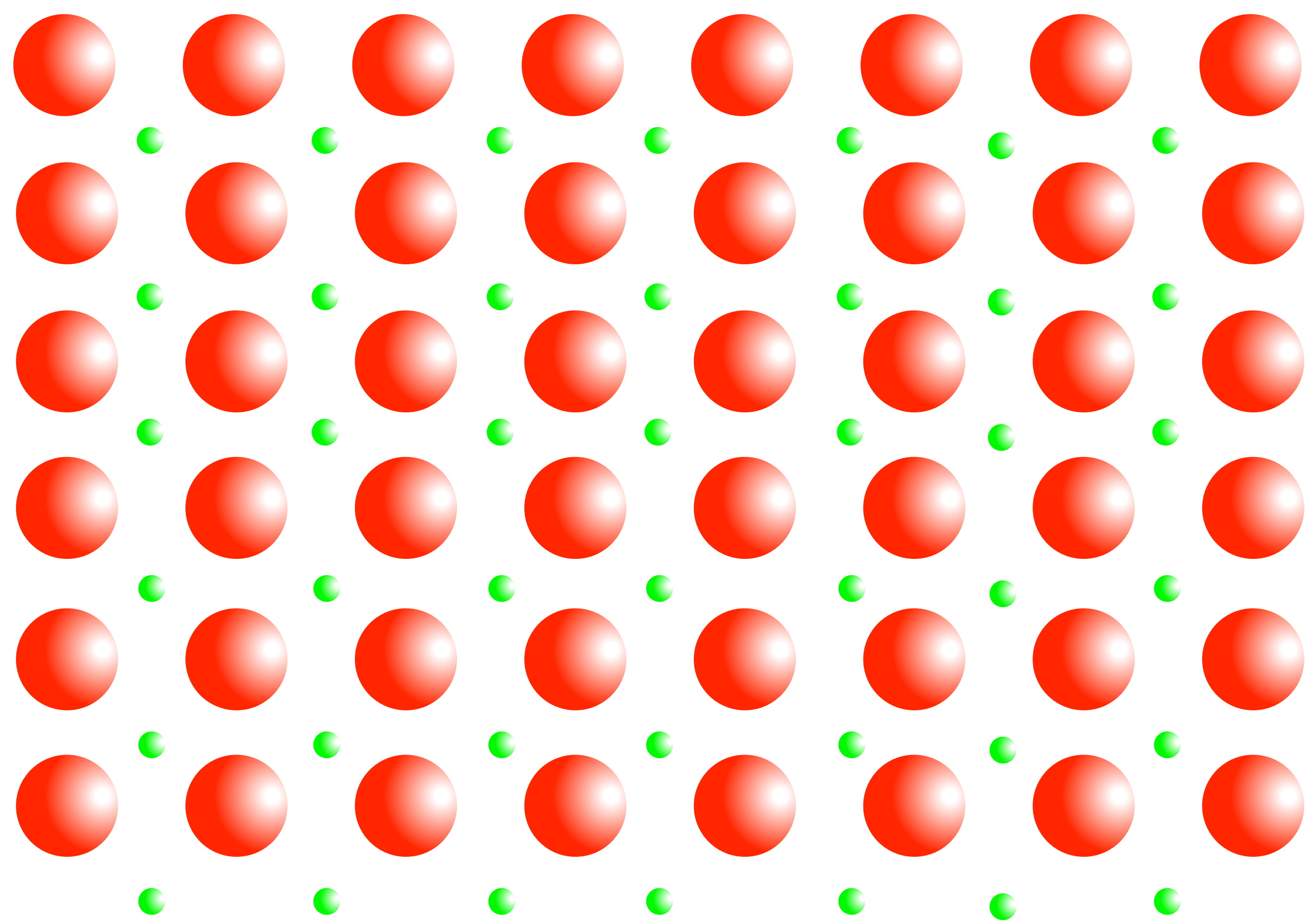

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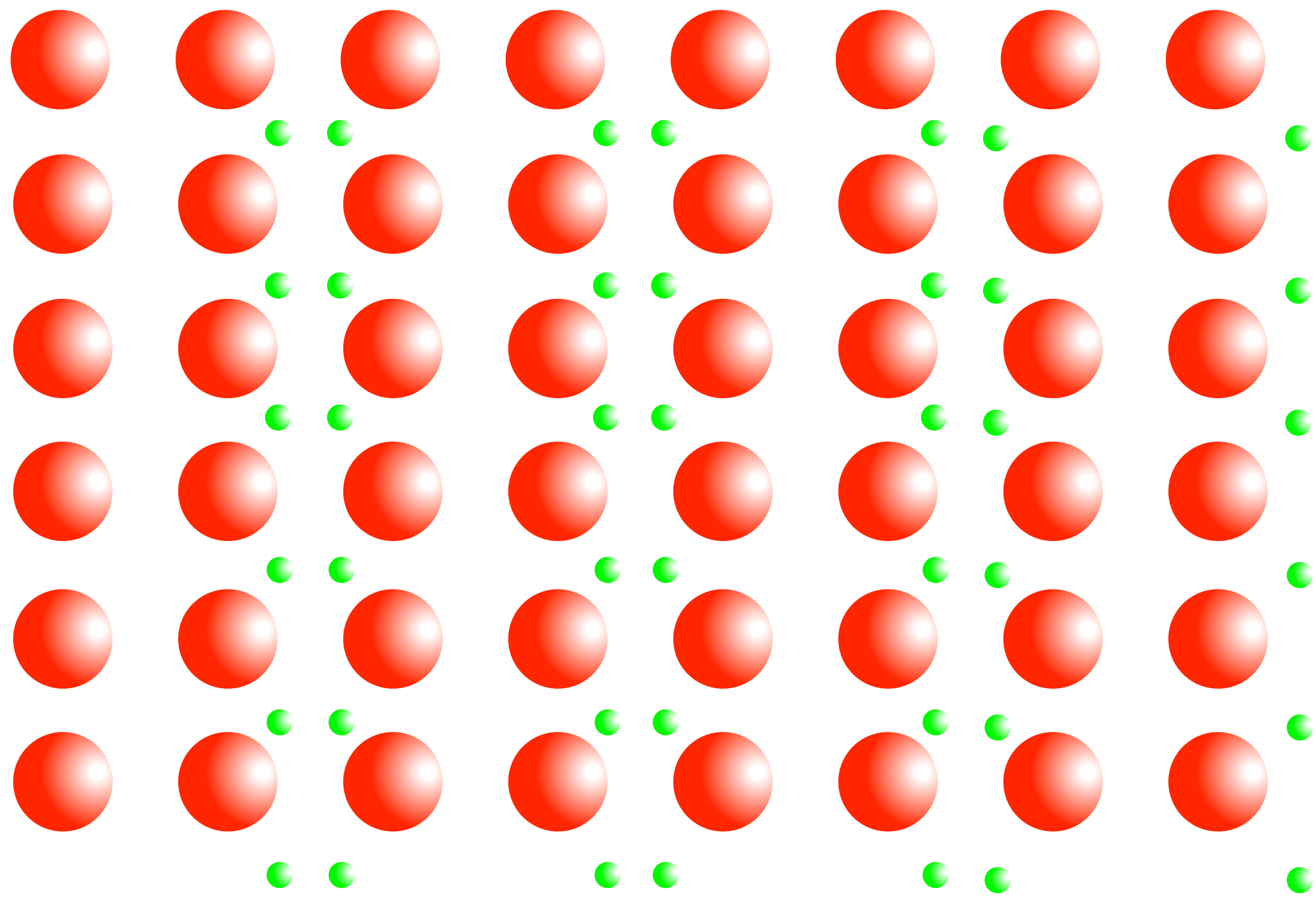

electrons plasma oscillation

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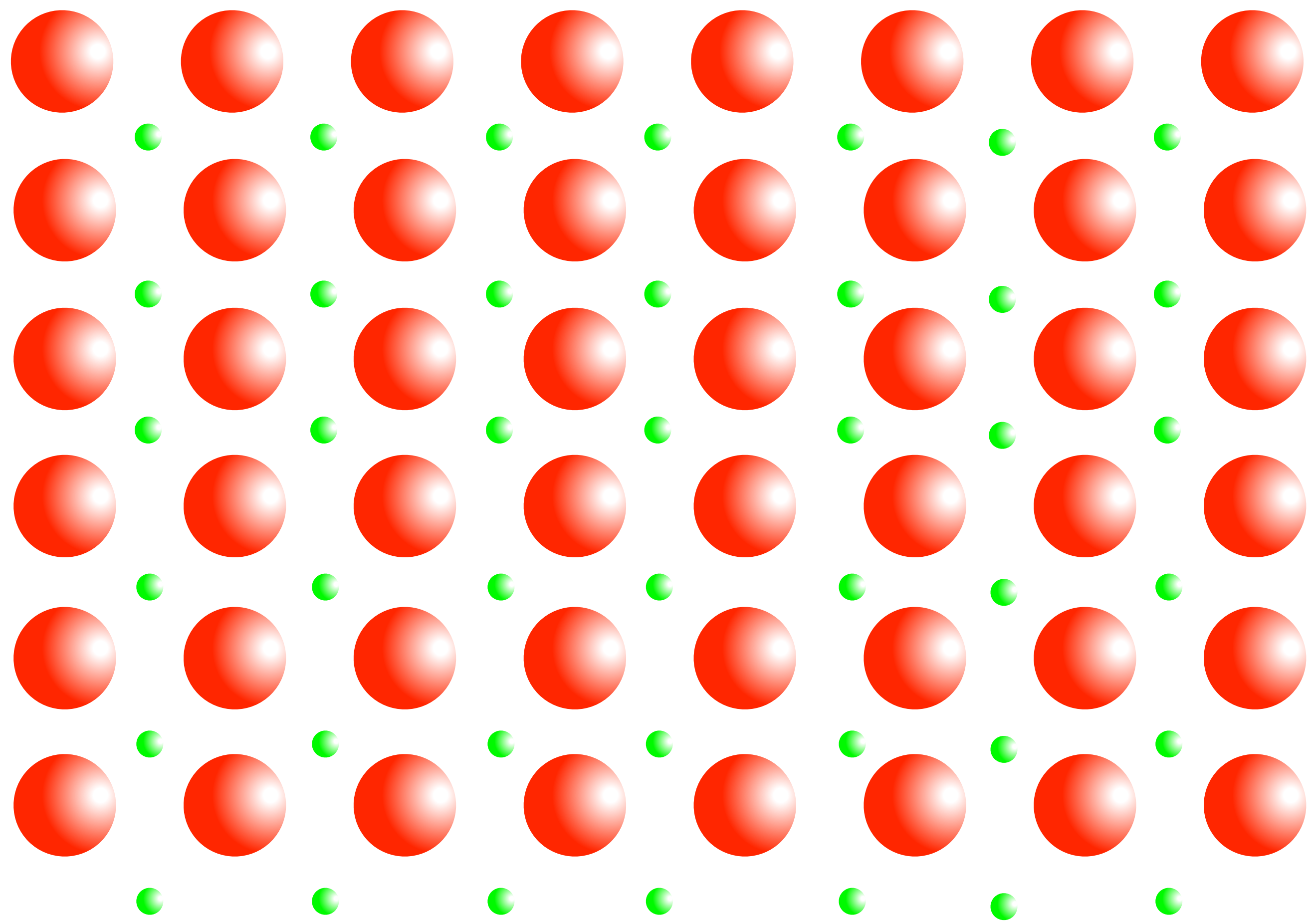


electrons plasma oscillation

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

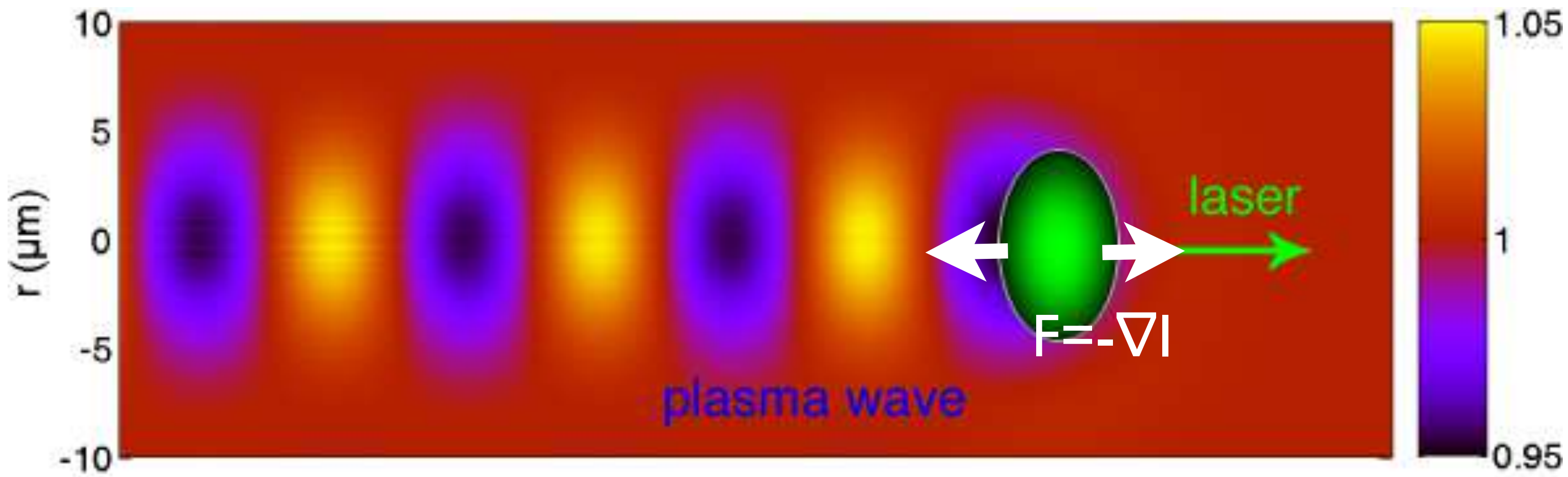
=> Laser beatwave

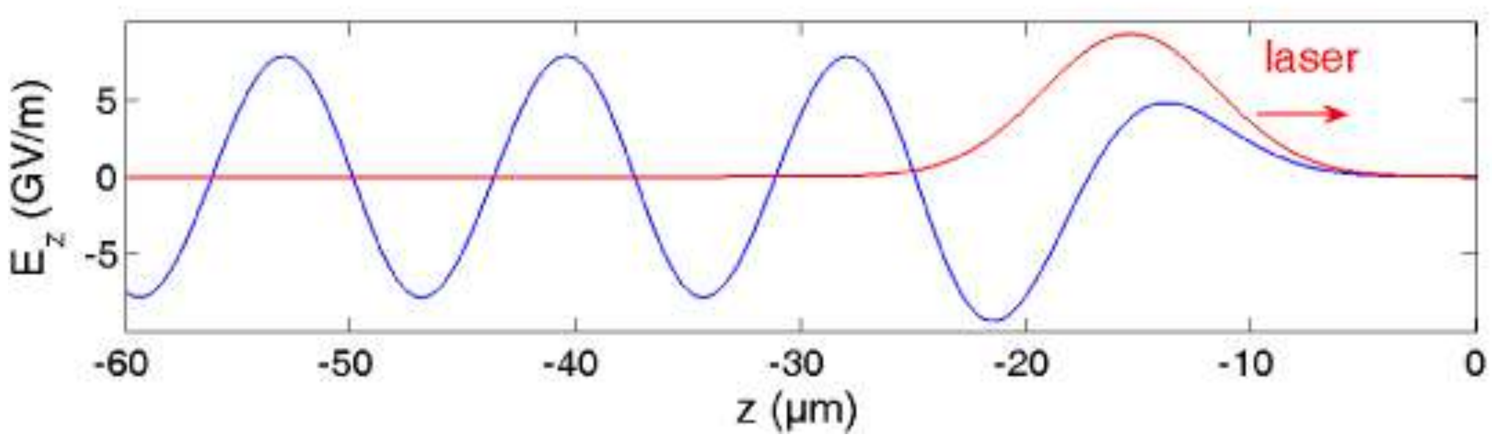
The linear wakefield regime: GV/m electric field

The laser wake field : broad resonance condition

$\tau_{laser} \sim \pi/\omega_p$ with $\omega_p \sim n_e^{1/2}$ i.e. $\lambda_p \sim 1/n_e^{1/2}$

electron density perturbation & longitudinal wakefield





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

wave in the wake of a boat

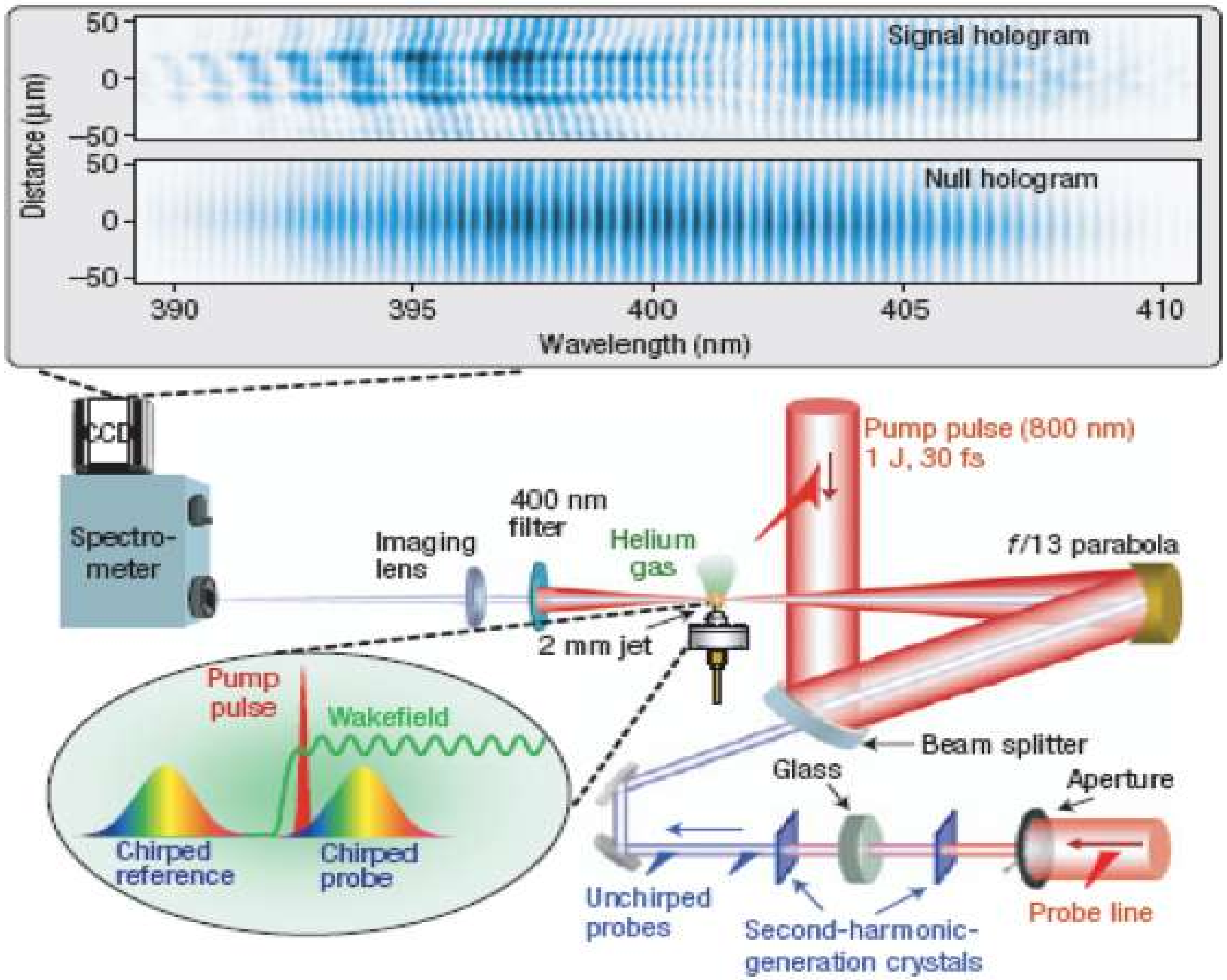
$$E_z\ (GV/m) \approx \delta n/n \times \sqrt{n}$$

Linear wakefield : E_z = 1 GV/m for 1 % density Perturbation at 10^{18} cc^{-1}

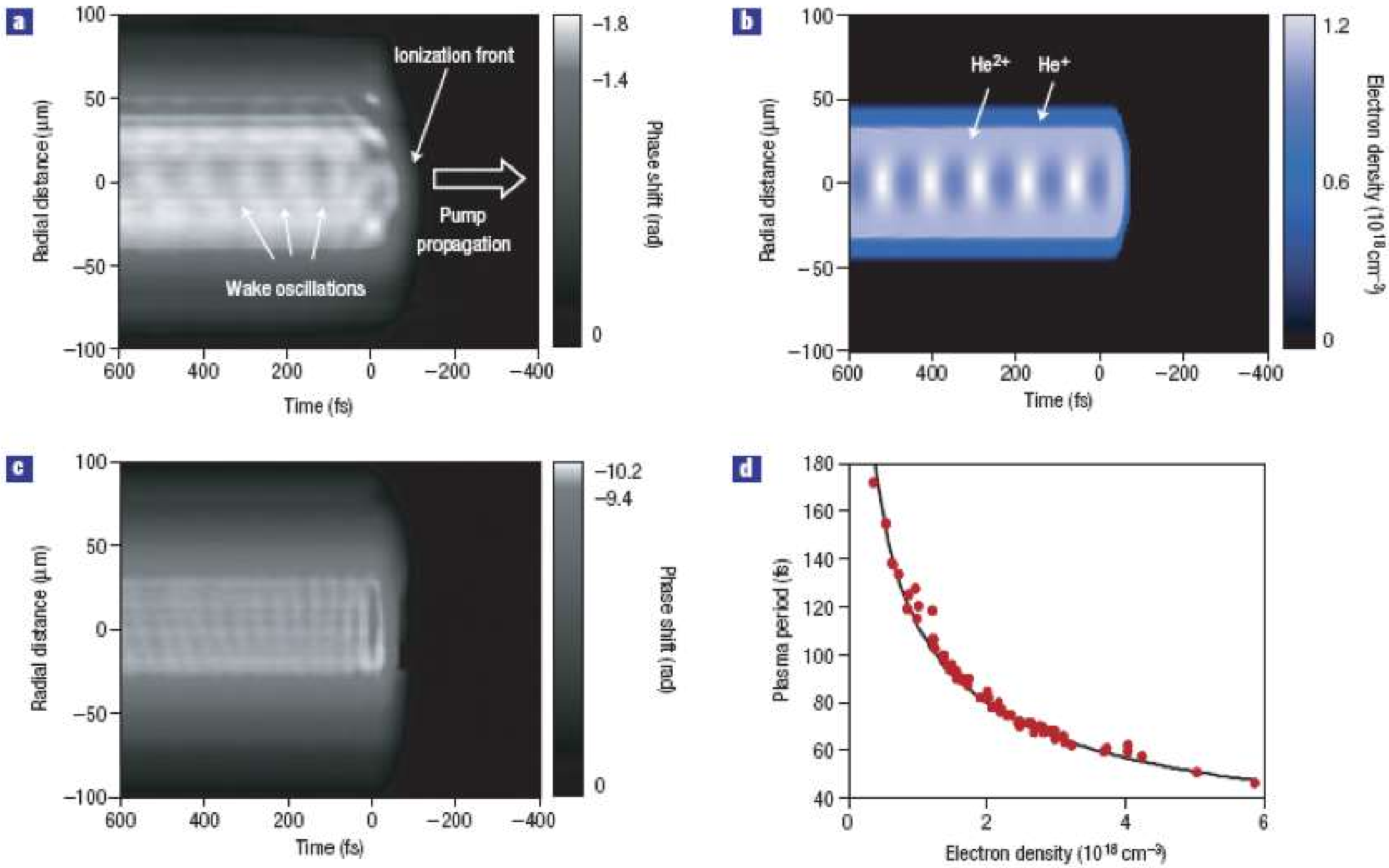
T. Tajima and J. Dawson, PRL **43**, 267 (1979)

Accelerated electrons in LWF

Snapshots of laser wakefield



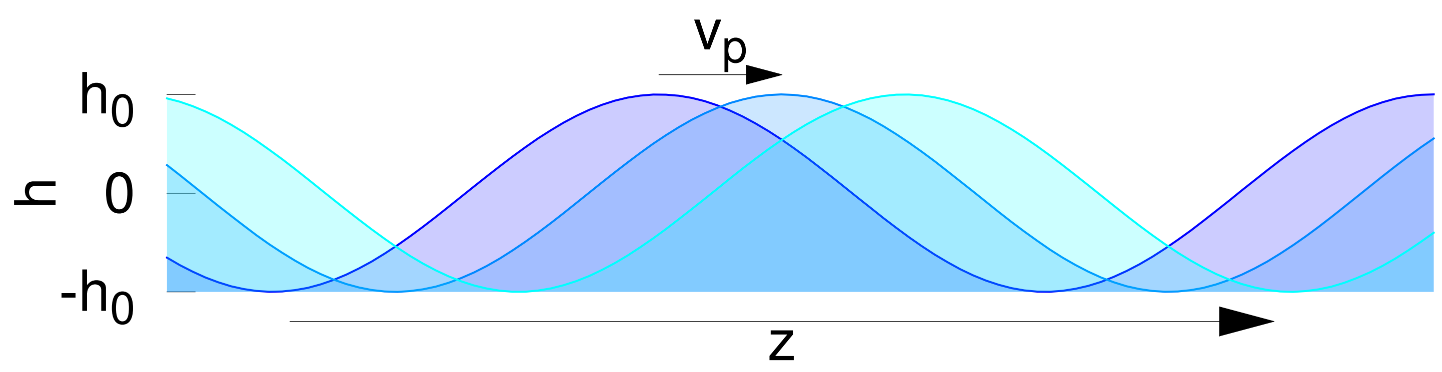
N. H. Matlis *et al.* , Nature Physics 2006



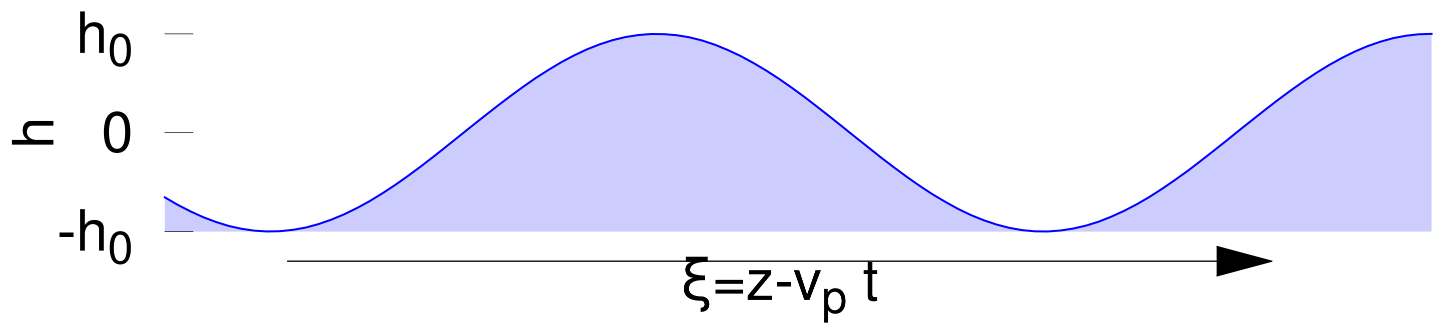
Small amplitude wakes with flats wavefronts. a) probe phase shift 10TW, 30 fs at $0.95x10^{19}cm^{-3}$. b) Simulated wake density profile. c) same than a) at $5.9x10^{19}cm^{-3}$. d) wake period versus n_e.

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

Injection criteria : the surfer experiences

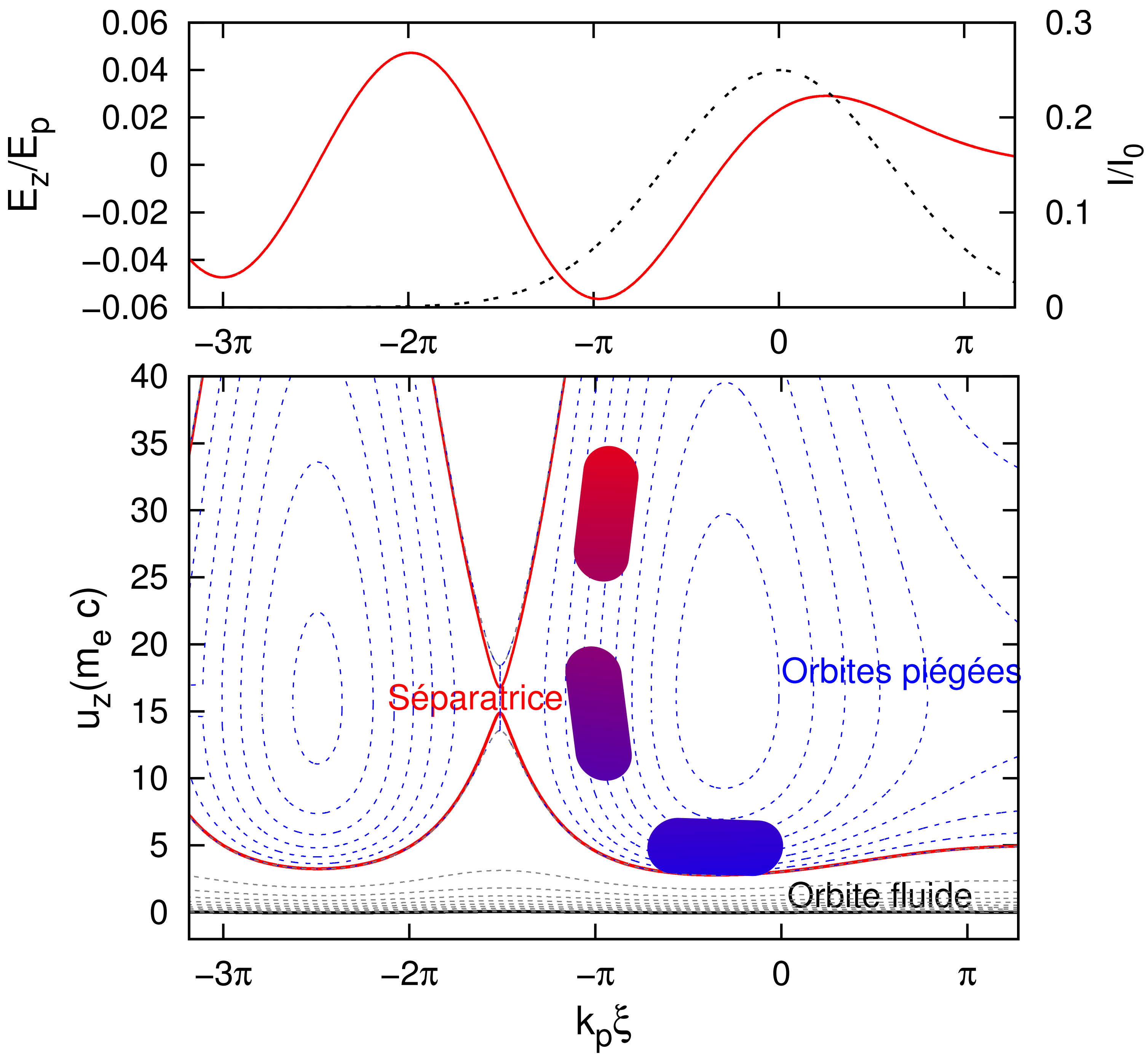


in the terrestrial reference frame
$h = h_0 \cos(z - v_p t)$



in the wawe reference frame
$h = h_0 \cos(\xi)$

1 D maximum energy gain : W_{max}: eE_pL_{deph}



In plasma wave :

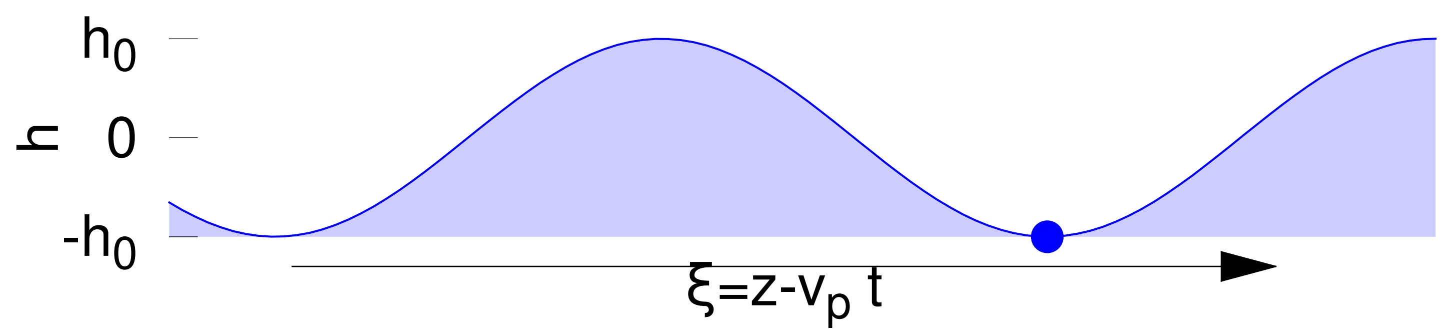
- E field is not homogenous
- Volume is phase space is conserved
- very small initial volume

external injection :

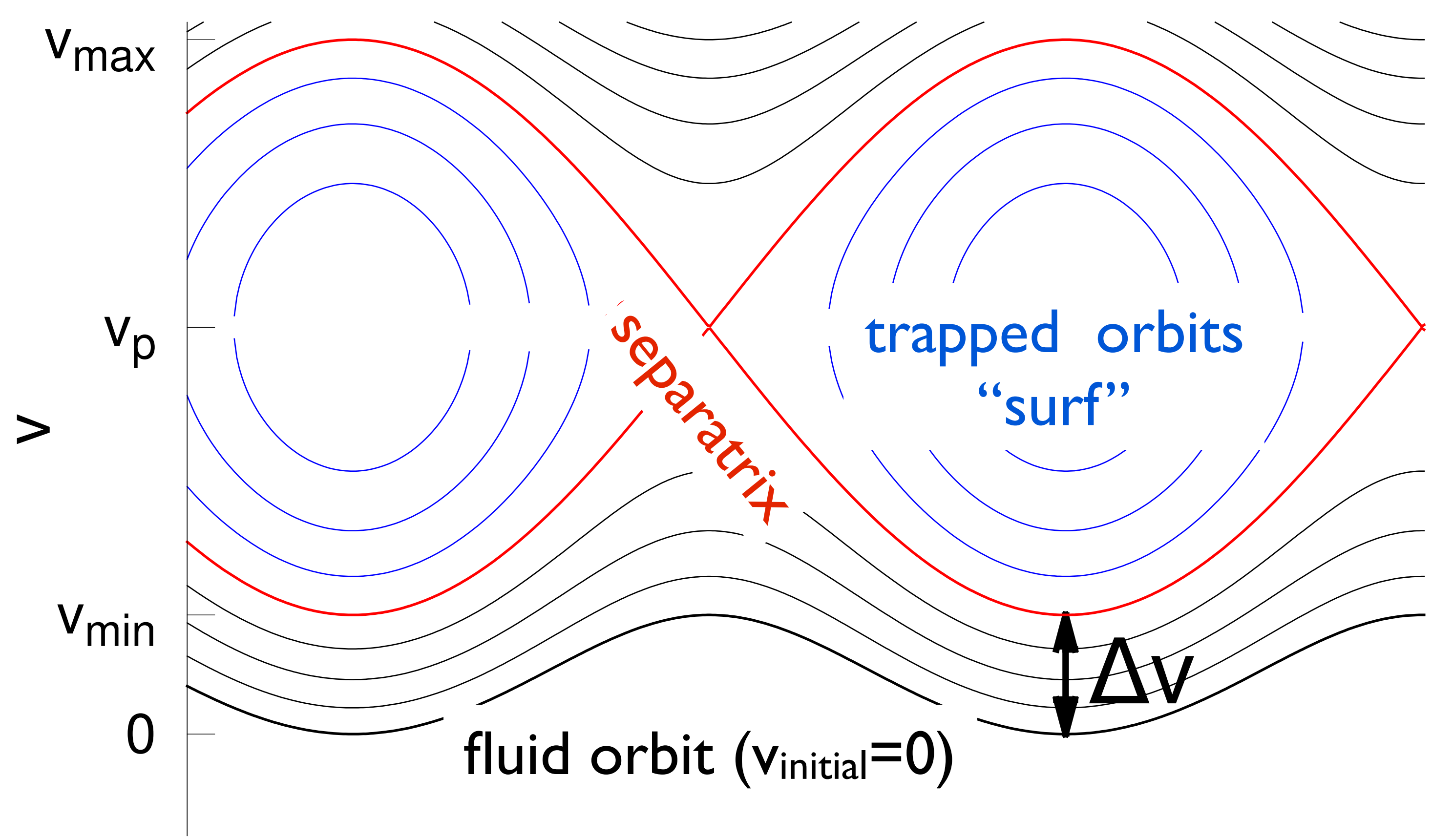
- Size≈ μm
- Length≈ μm (fs)
- Synchronization ≈ fs
- Controle ?

=> very challenging with conventional accelerator

Injection criteria : the surfer experiences



phases space (ξ , v-v_p)



conclusions :

- trapped orbits allow higher energy gain
- One needs to transmit enough velocity ΔV

Trapping energy : analogy electron/surfer

surfer with enough initial velocity

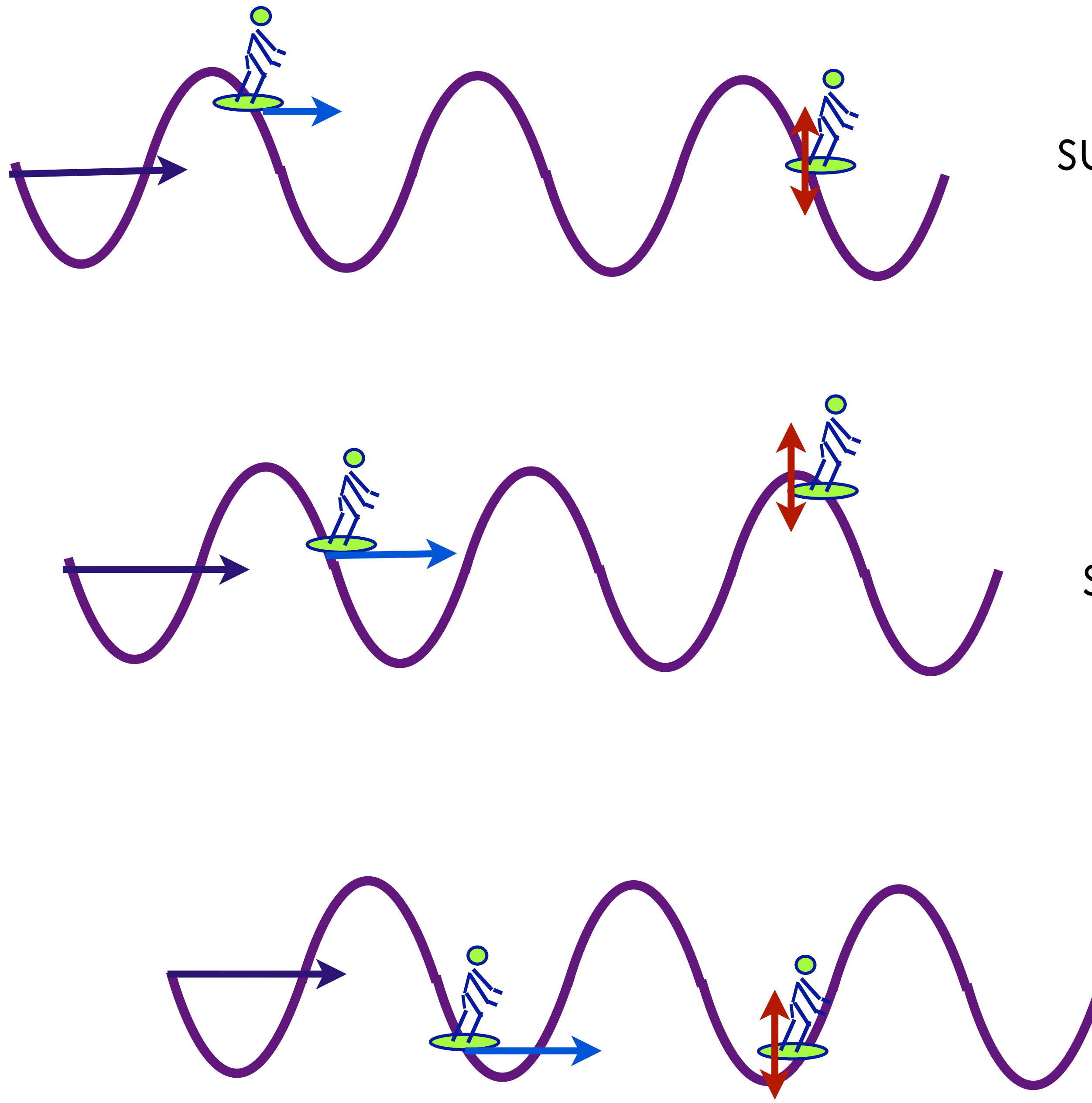
surfer initially at rest

surfer with enough initial velocity

surfer initially at rest

surfer with enough initial velocity

surfer initially at rest



Trapping energy : analogy electron/surfer

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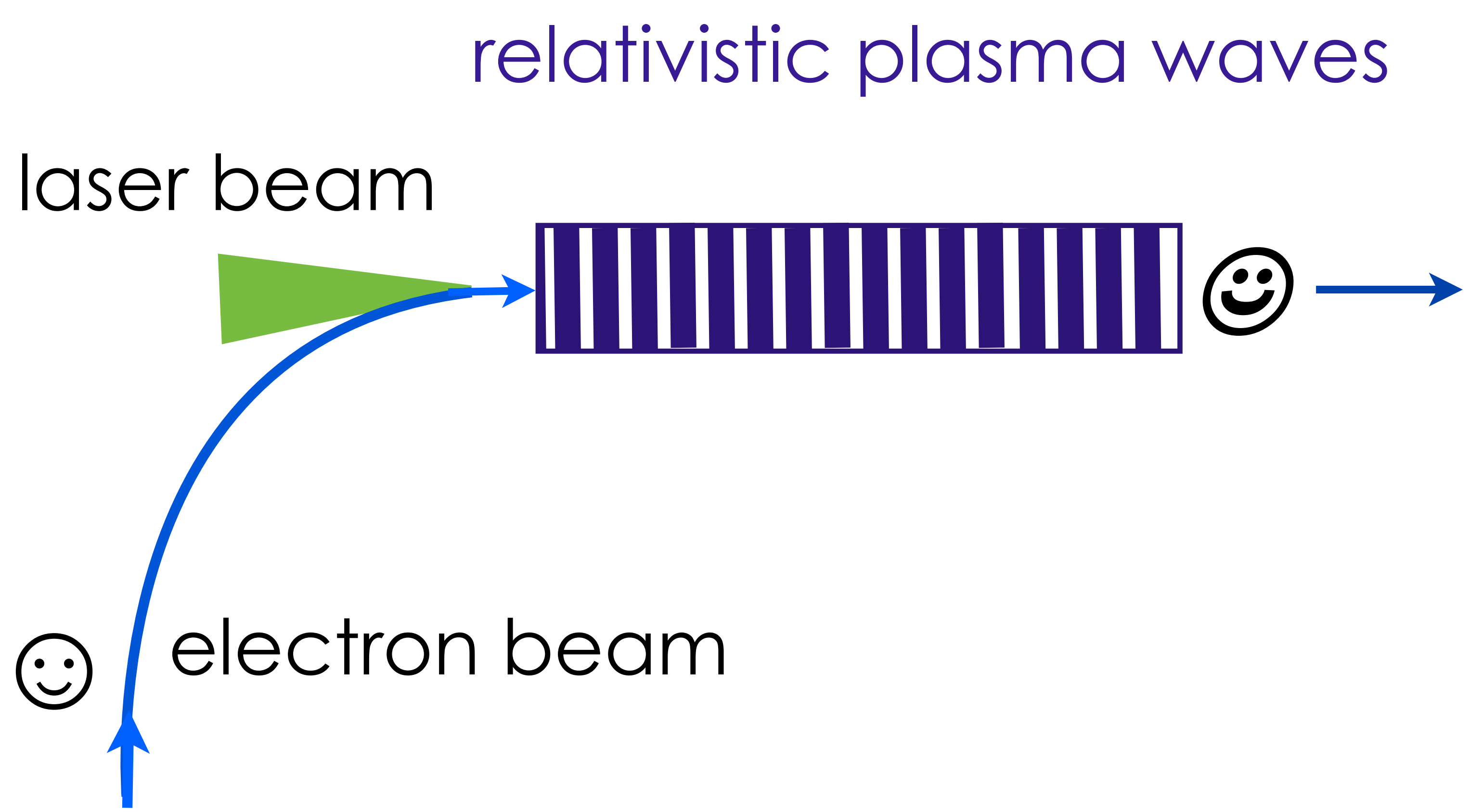
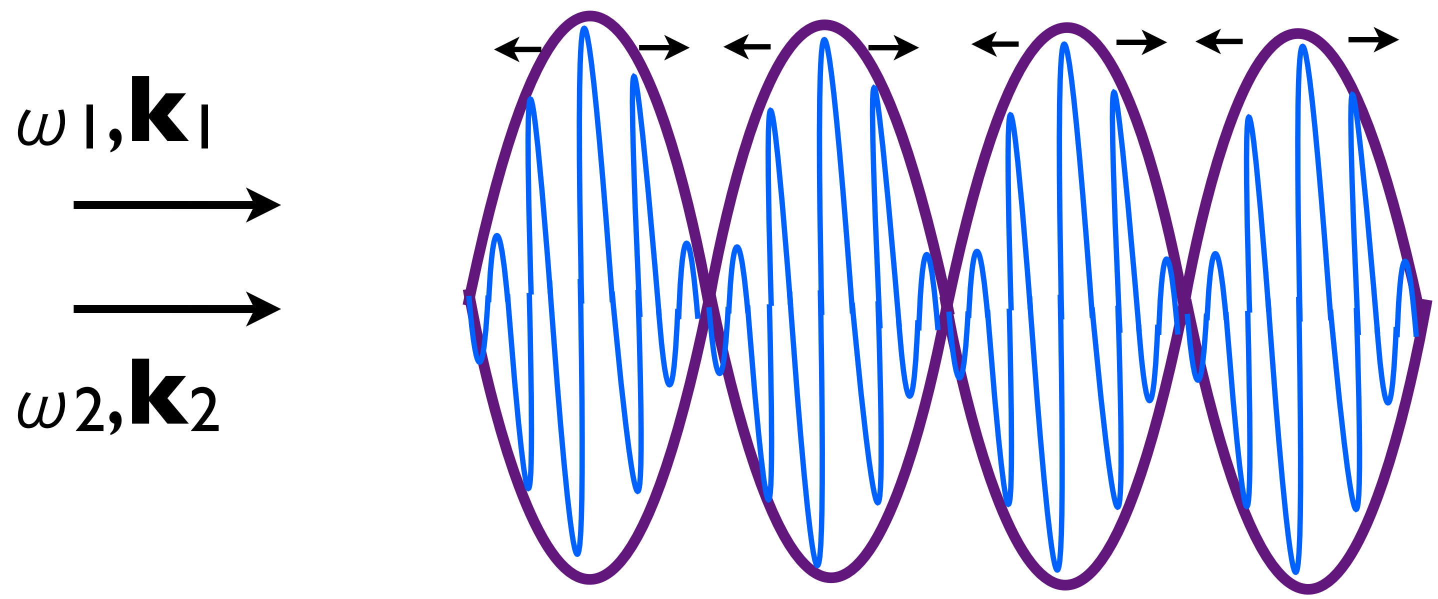
External injection of e- in laser driven wakefield

Scheme of principle of the first experiments :



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

$F \approx - \nabla I$



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

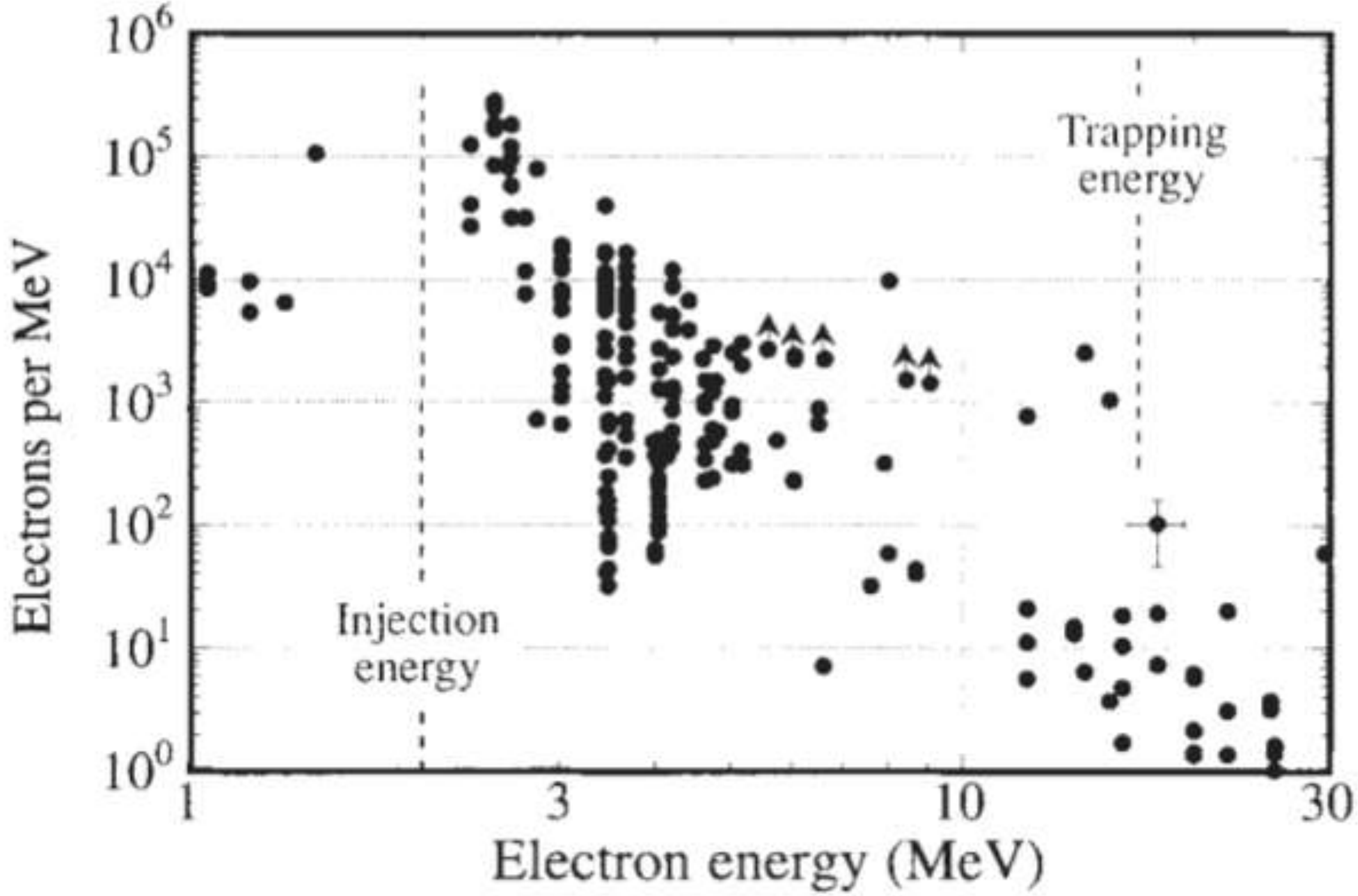
Optical demonstration by Thomson scattering :

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



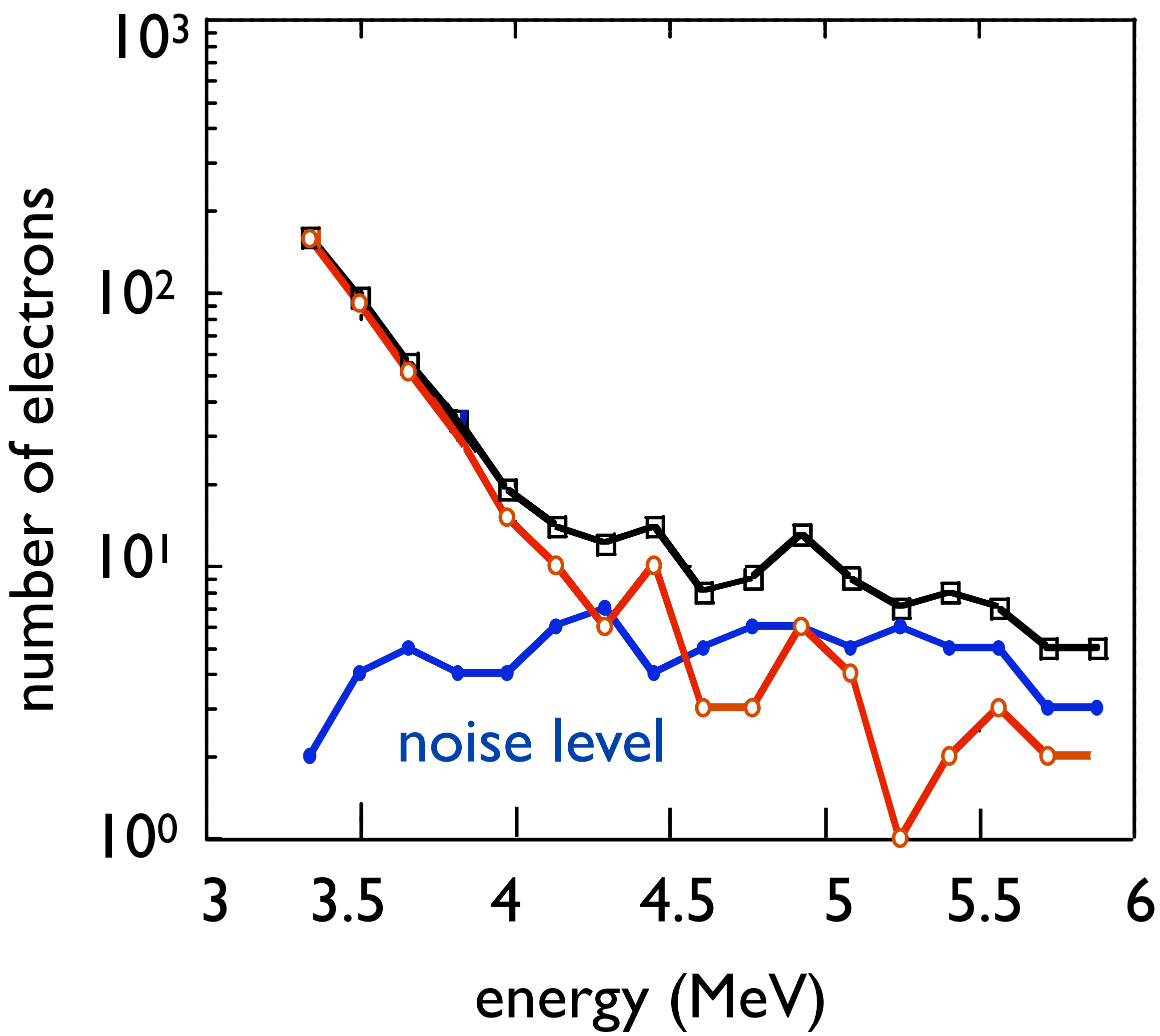
M. Everett *et al.*, Nature 1994

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

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

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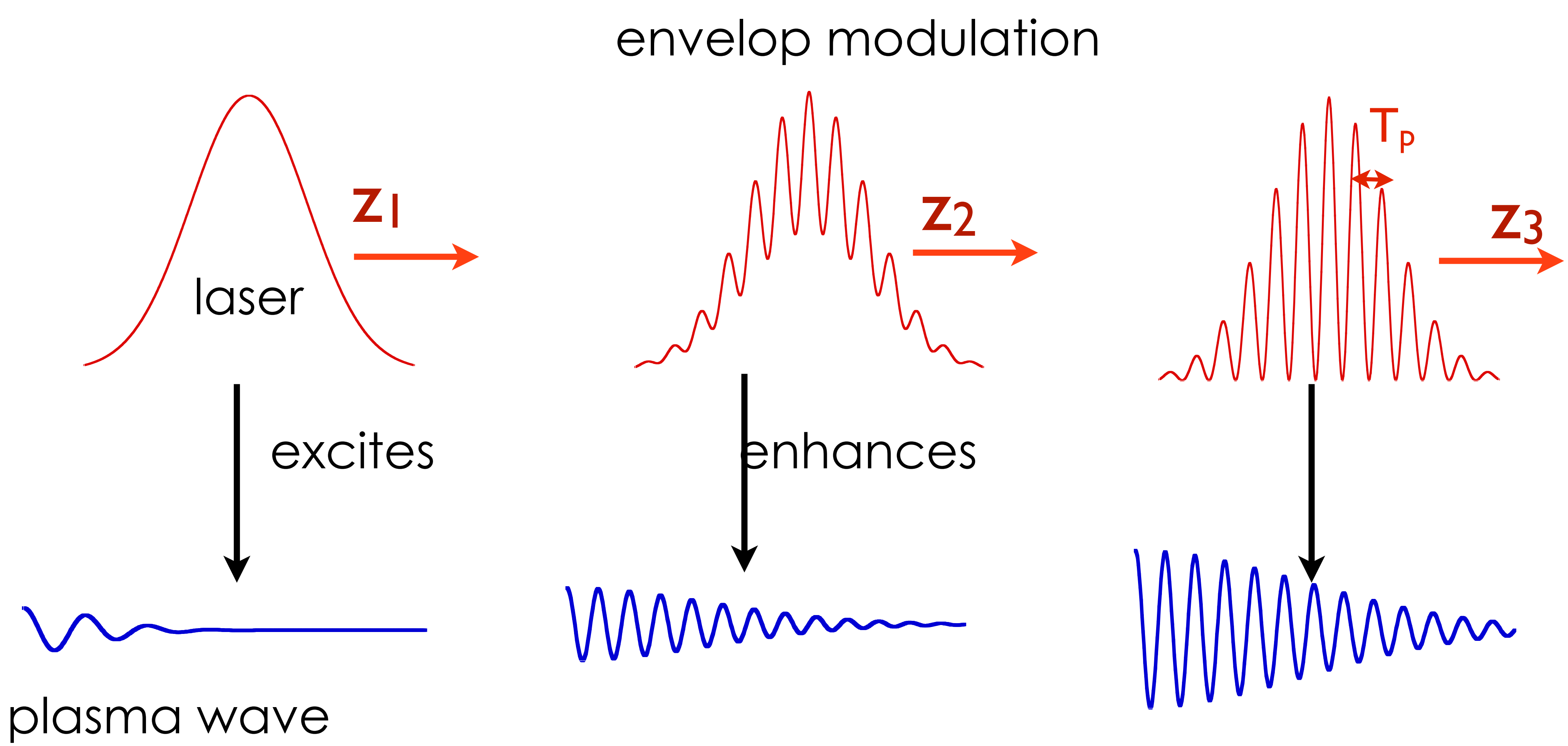
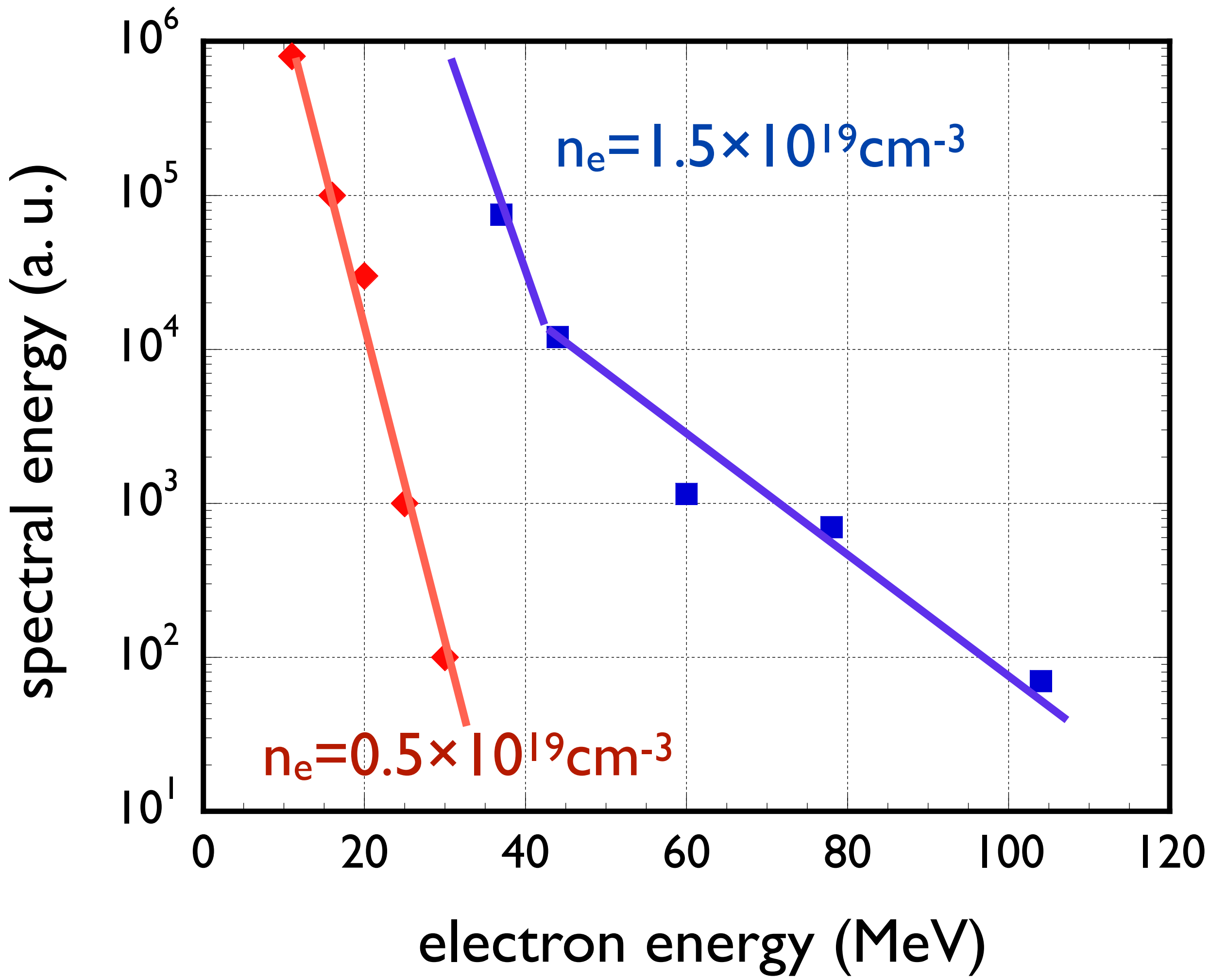
1992 How to excite a plasma wave: The SMLWF

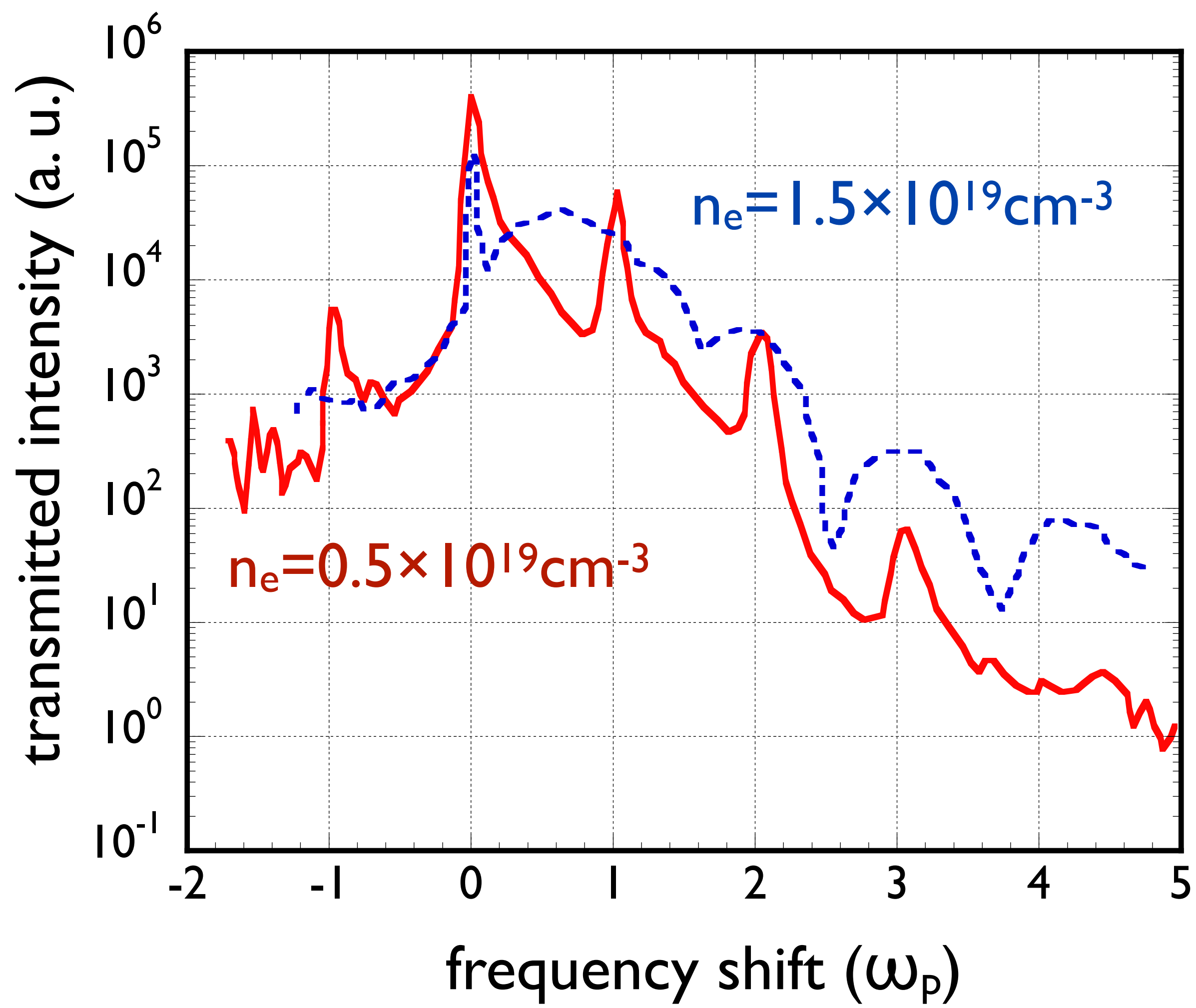
Self modulated laser wakefield scheme : $c\tau_{laser} >> T_p$
(Andreev *et al.*, Antonsen *et al.*, Sprangle *et al.* 1992)



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

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



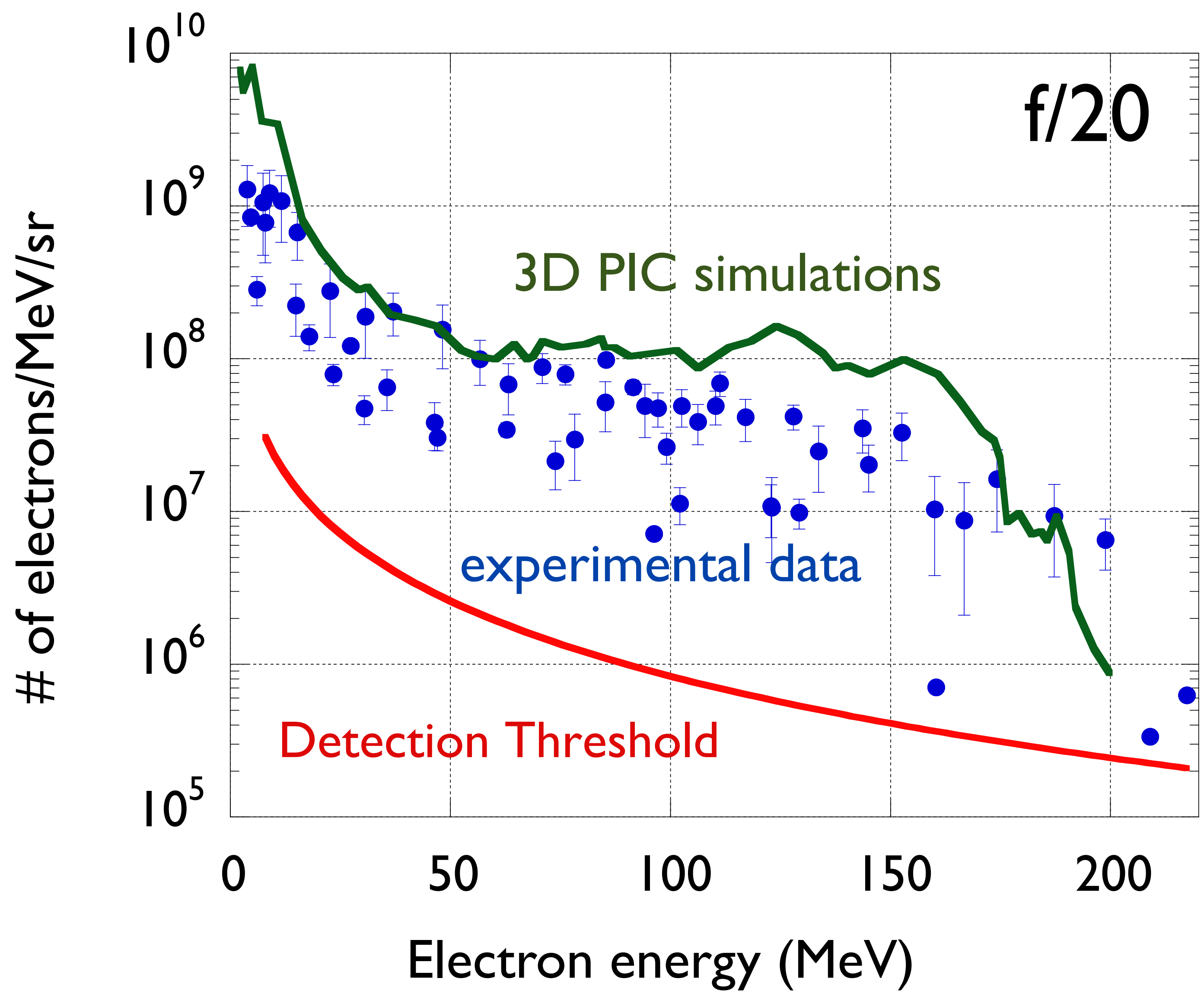


Multiple satellites : high amplitude plasma waves
Broadening at higher densities
Loss of coherence of the relativistic plasma waves

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

2002 The Forced Laser Wakefield: the NL regime

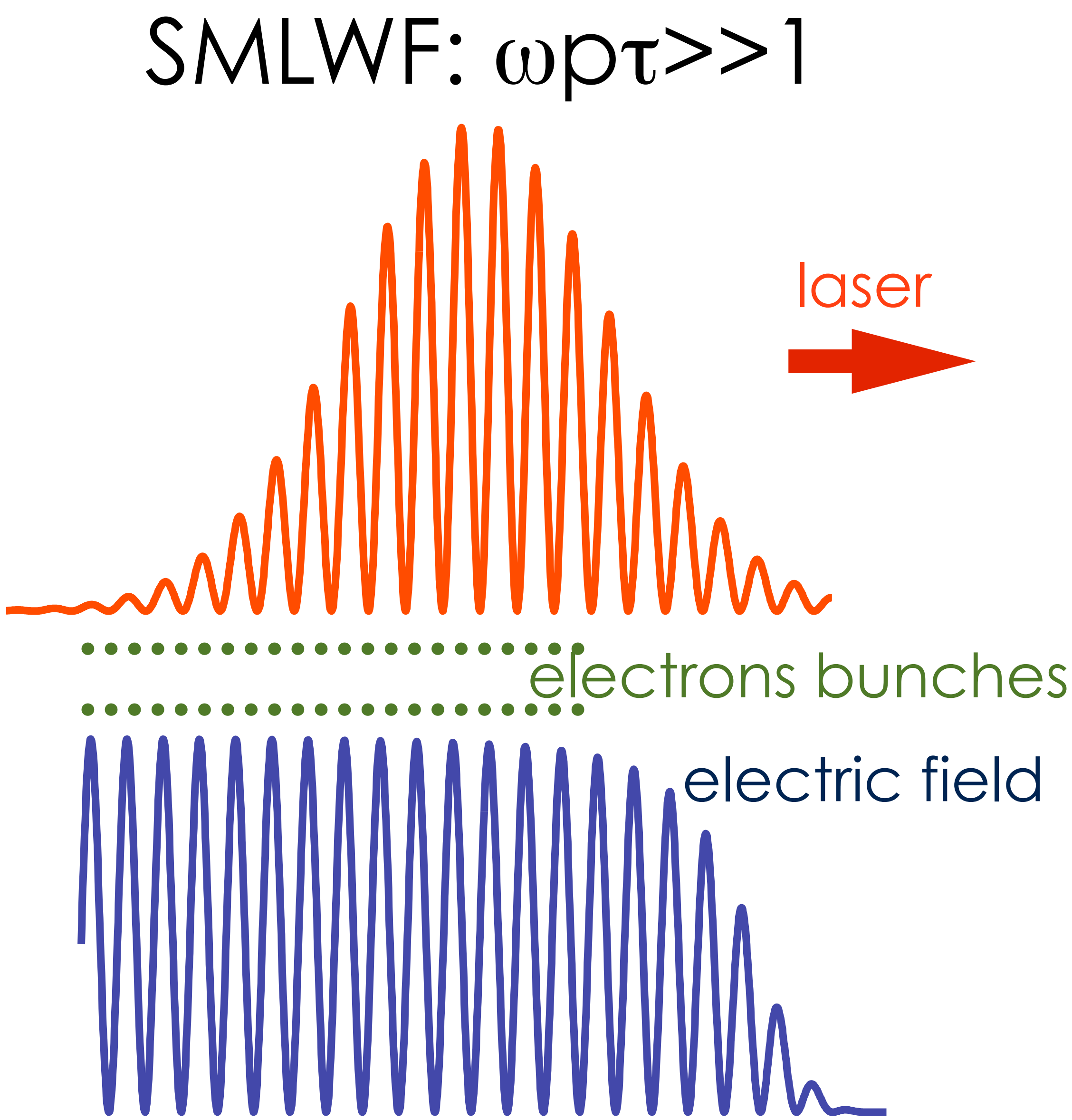
Parameters: $n_e=1.5\times10^{19}cm^{-3}$, $\tau_L=35fs$, E=0.6J, $I_L= 1\times10^{18}W/cm^2$ with $k_p w_0>1$

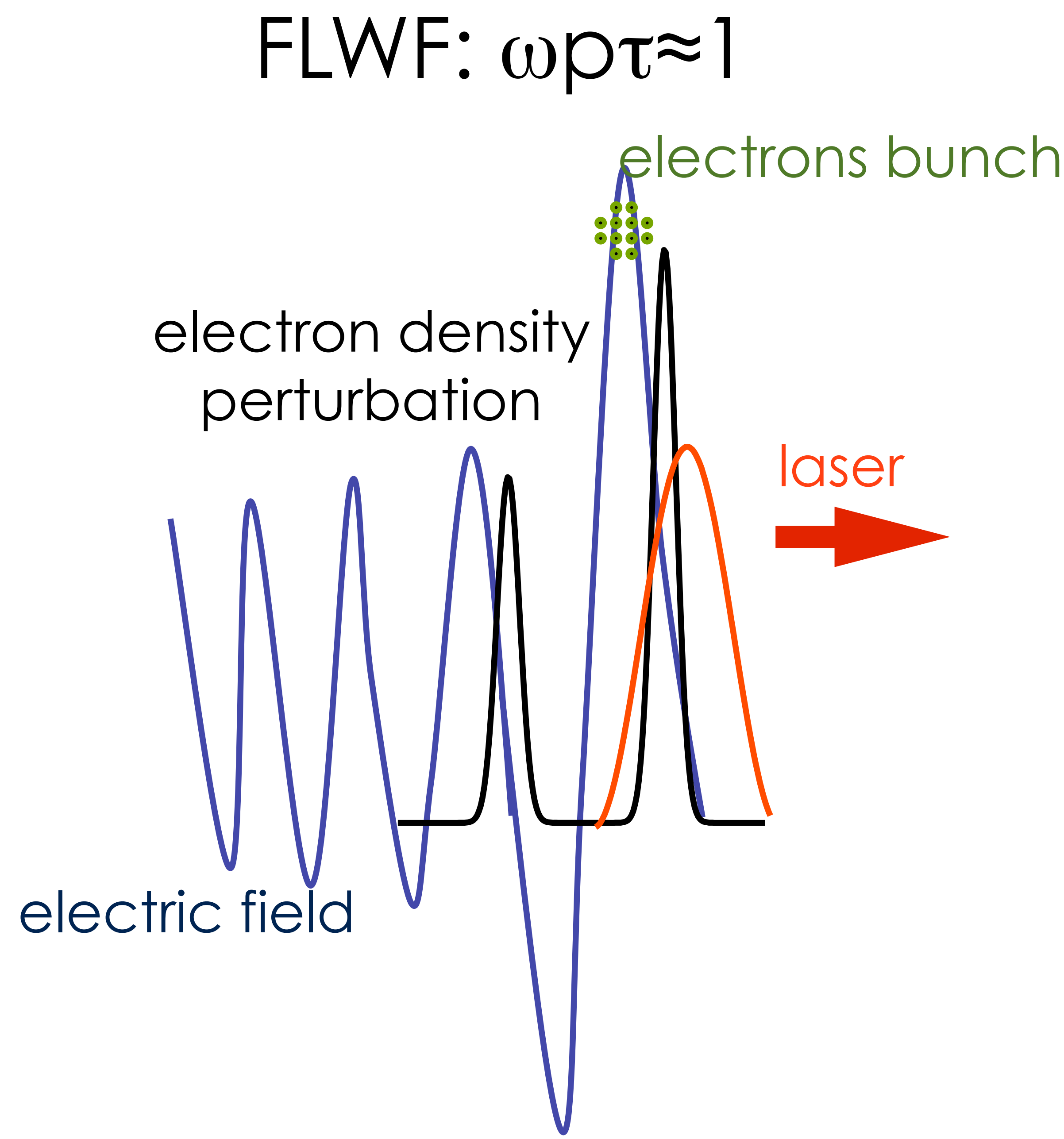


V. Malka *et al.*, Science **298**, 1596 (2002)

*CARE project

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





V. Malka, Europhysics News, April (2004)

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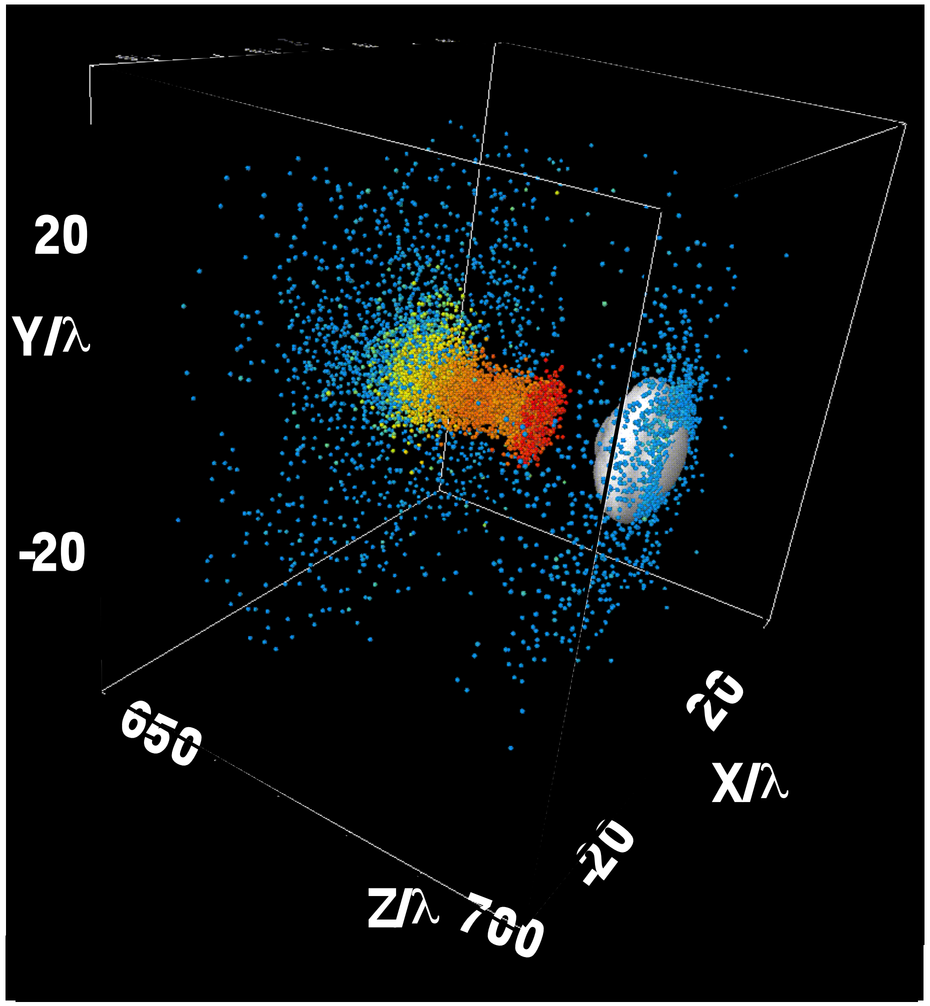
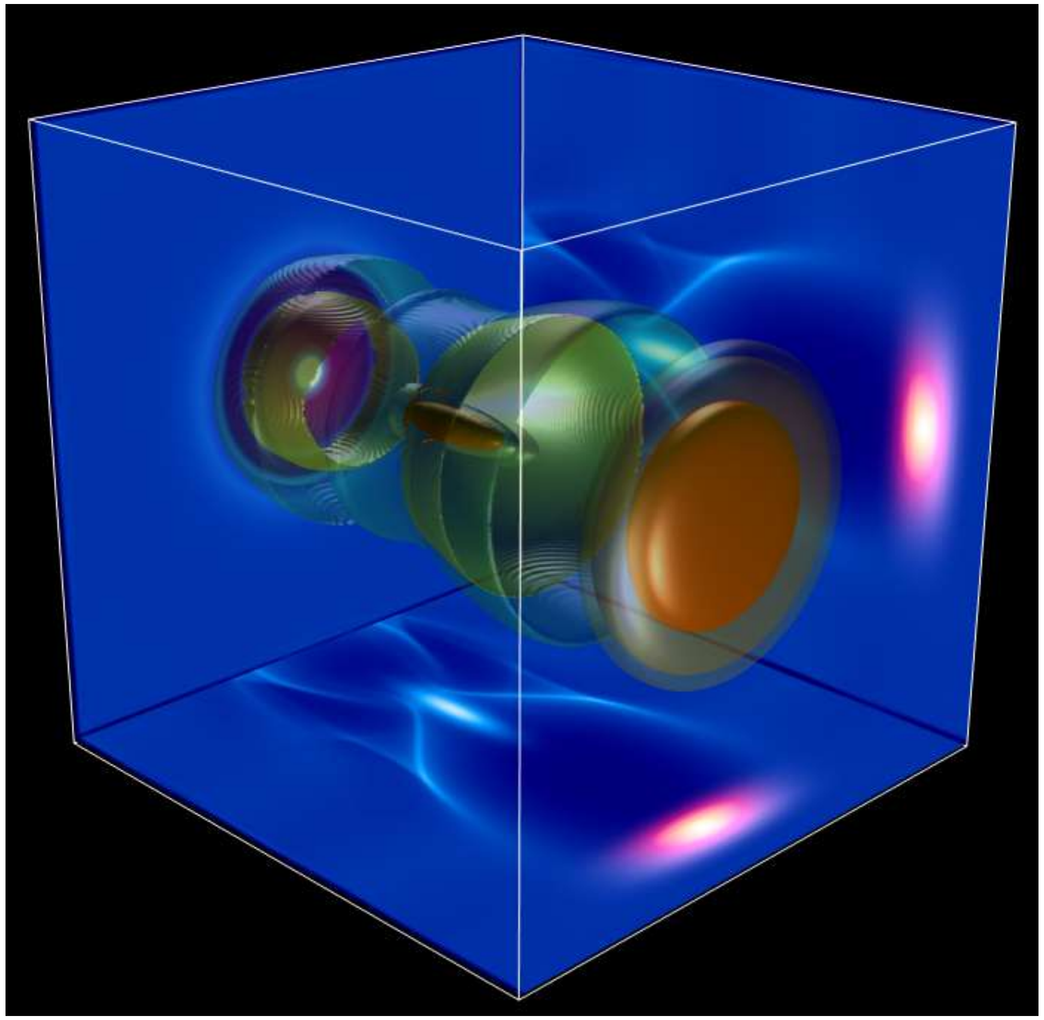
2002 The Bubble regime : QM energetic e-beam



VLPL, courtesy of A. Pukhov

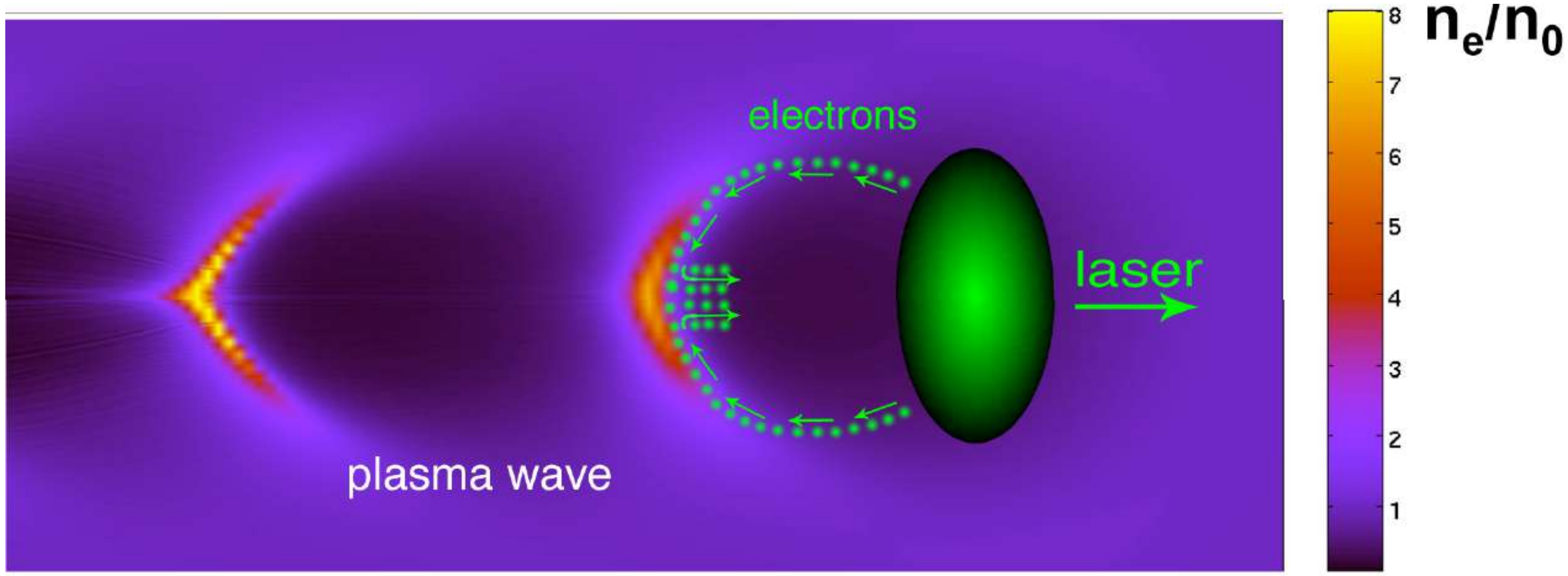


Golp, courtesy of L. Silva

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

Bubble/blow-out regime : principle

Highly non-linear regime : self-injection

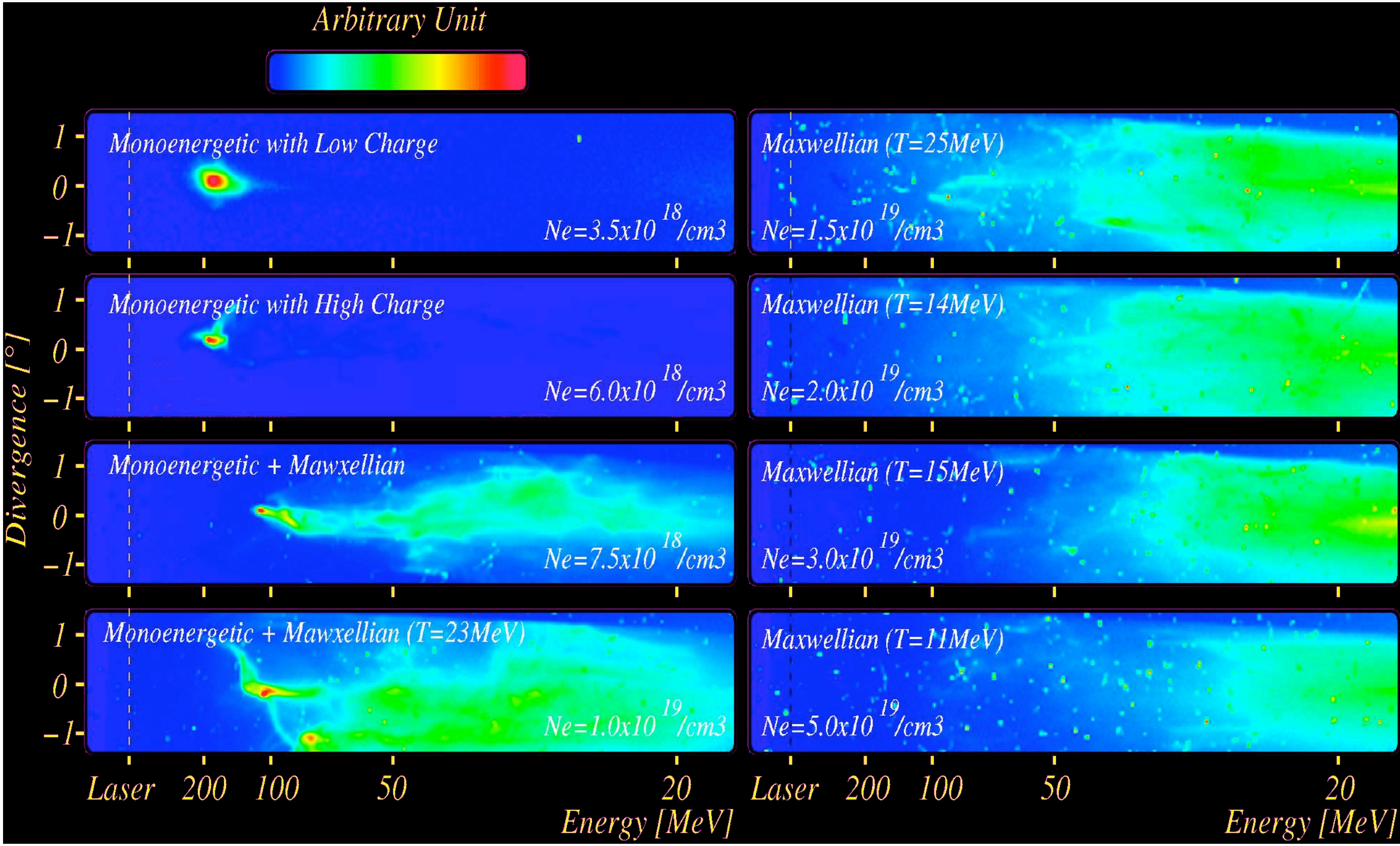


localized self injection in the bubble/blow-out regime

surfing behind a wake boat

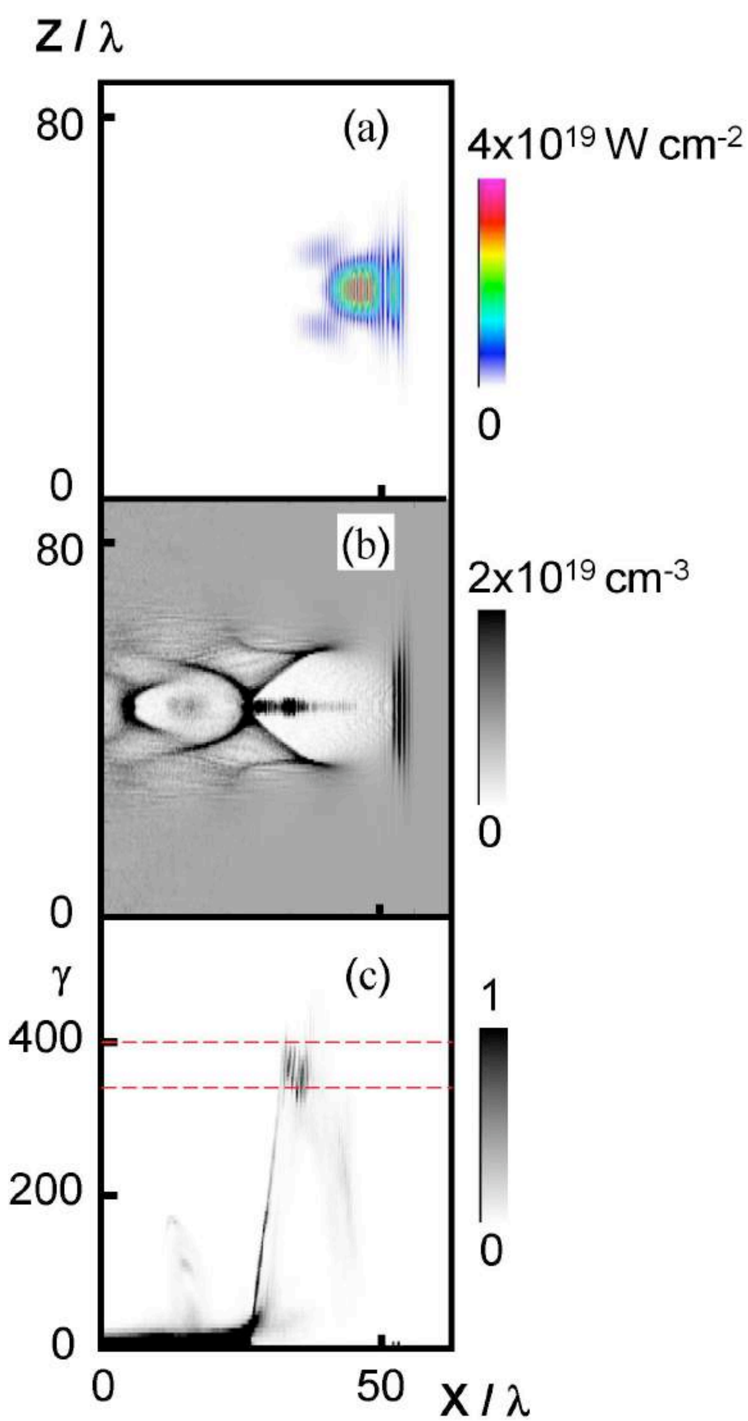
A. Pukhov & J. Meyer-ter-Vehn, Appl. Phys. B **74**, 355-361 (2002),

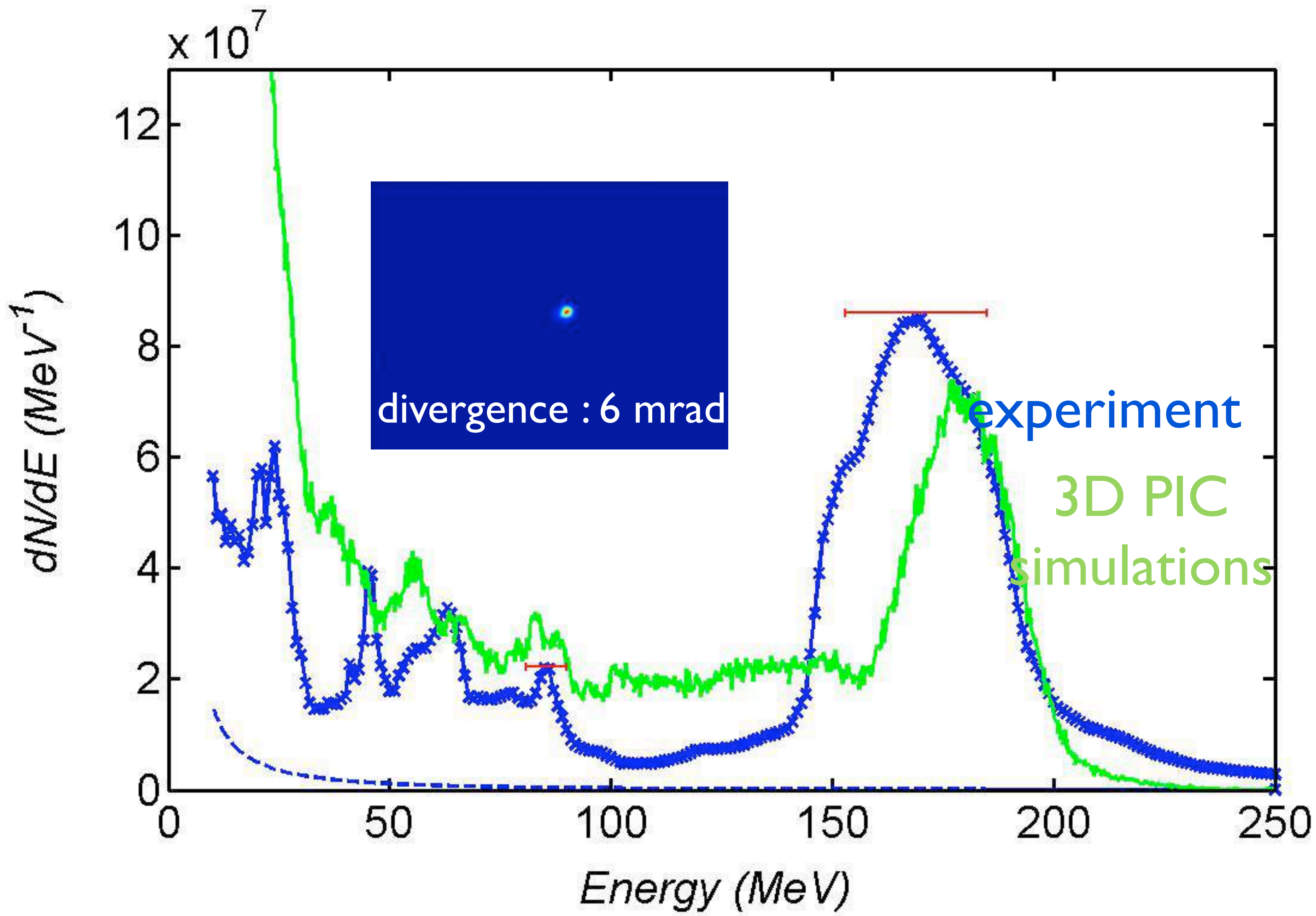
2005 Transitions SMLWF/FLWF/Bubble



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)

2004 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]

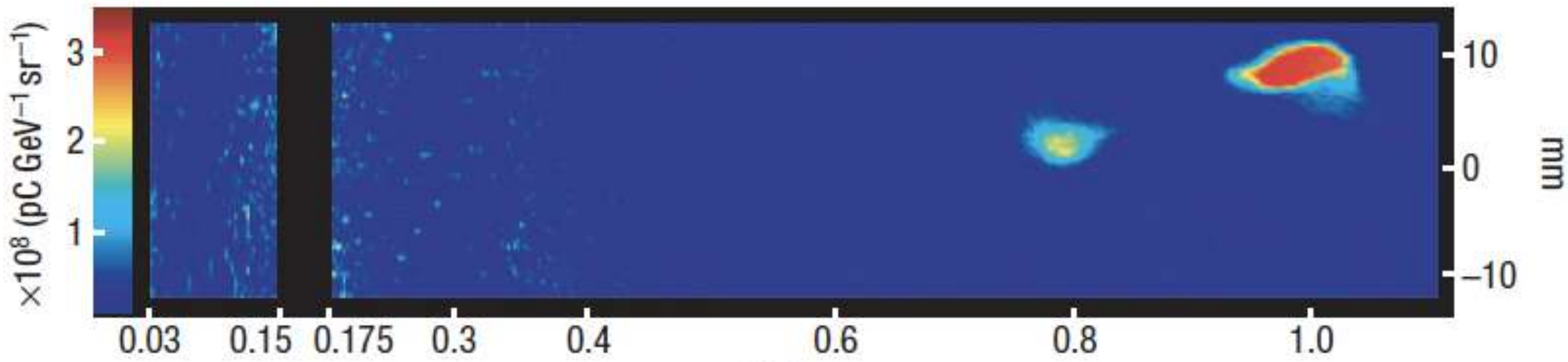
[1]*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA*
[2]*University of California, Berkeley, California 94720, USA*
[3]*Technische Universiteit Eindhoven, Postbus 513, 5600 MB Eindhoven, the Netherlands*
[4]*Tech-X Corporation, 5621 Arapahoe Ave. Suite A, Boulder,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

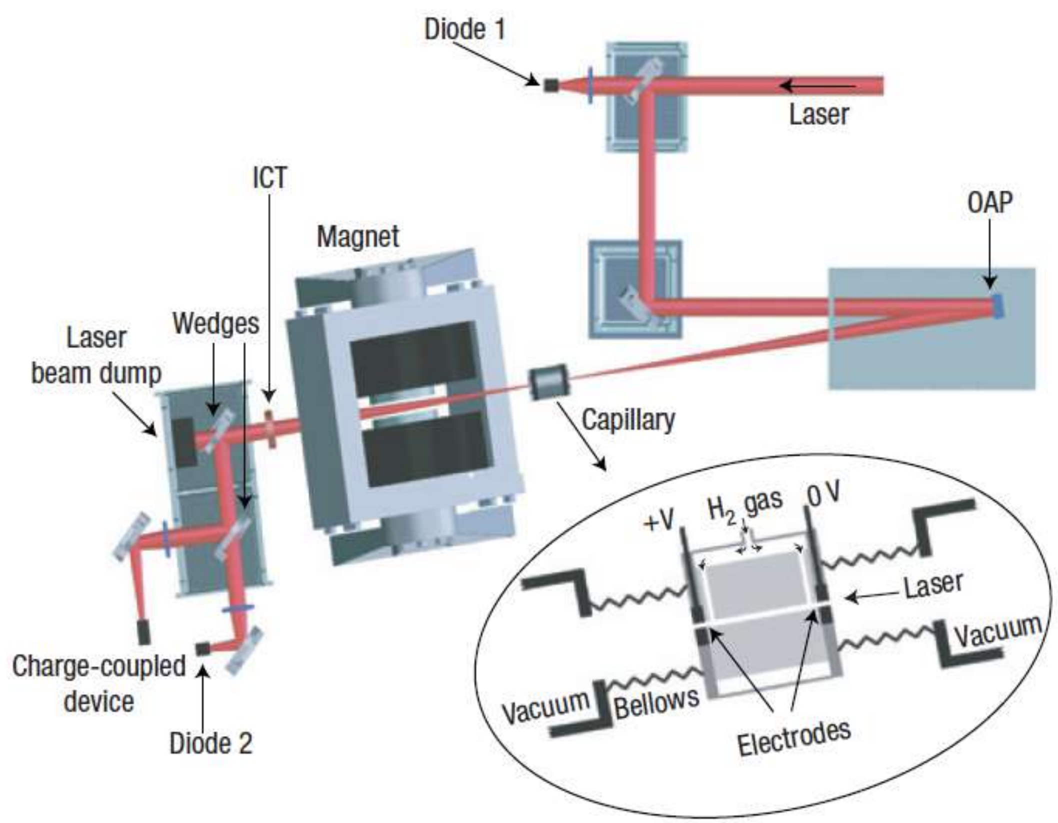
A laser–plasma accelerator producing monoenergetic electron beams

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 fur 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*

2006 GeV electron beams from "cm scale" acc.





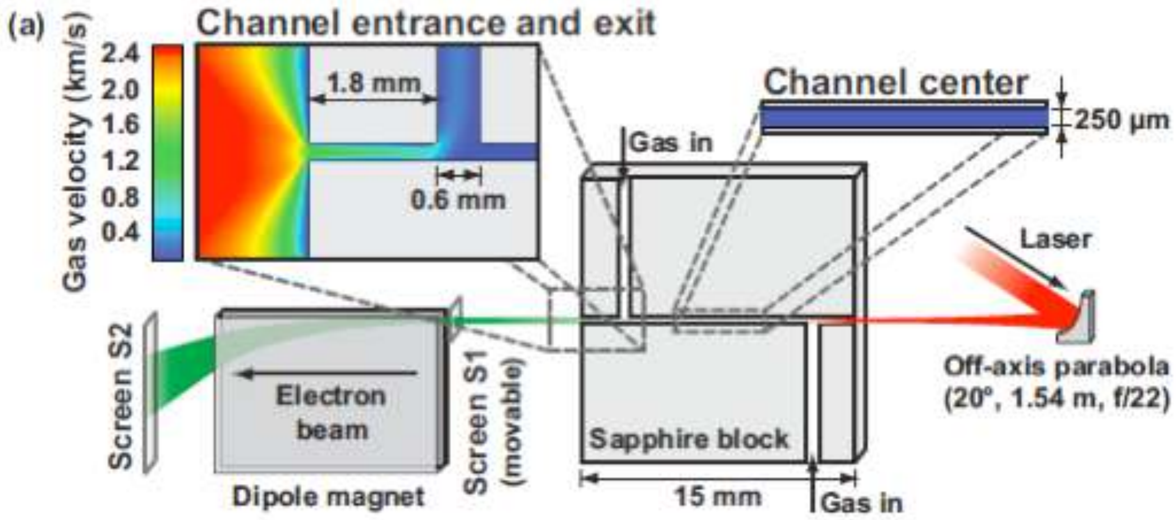
310-μm-diameter channel capillary

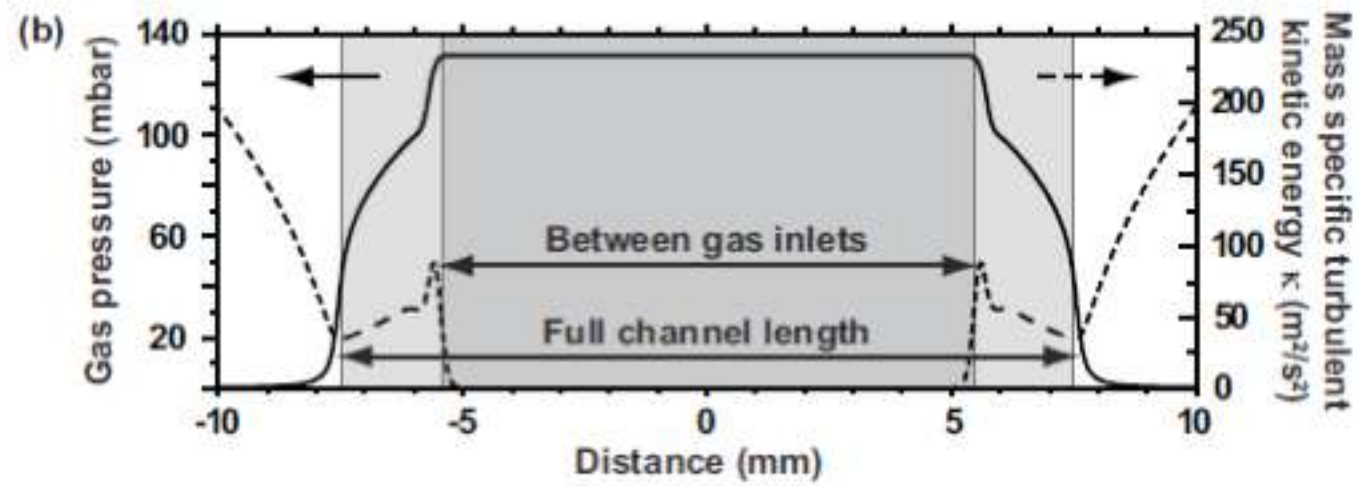
P = 40 TW

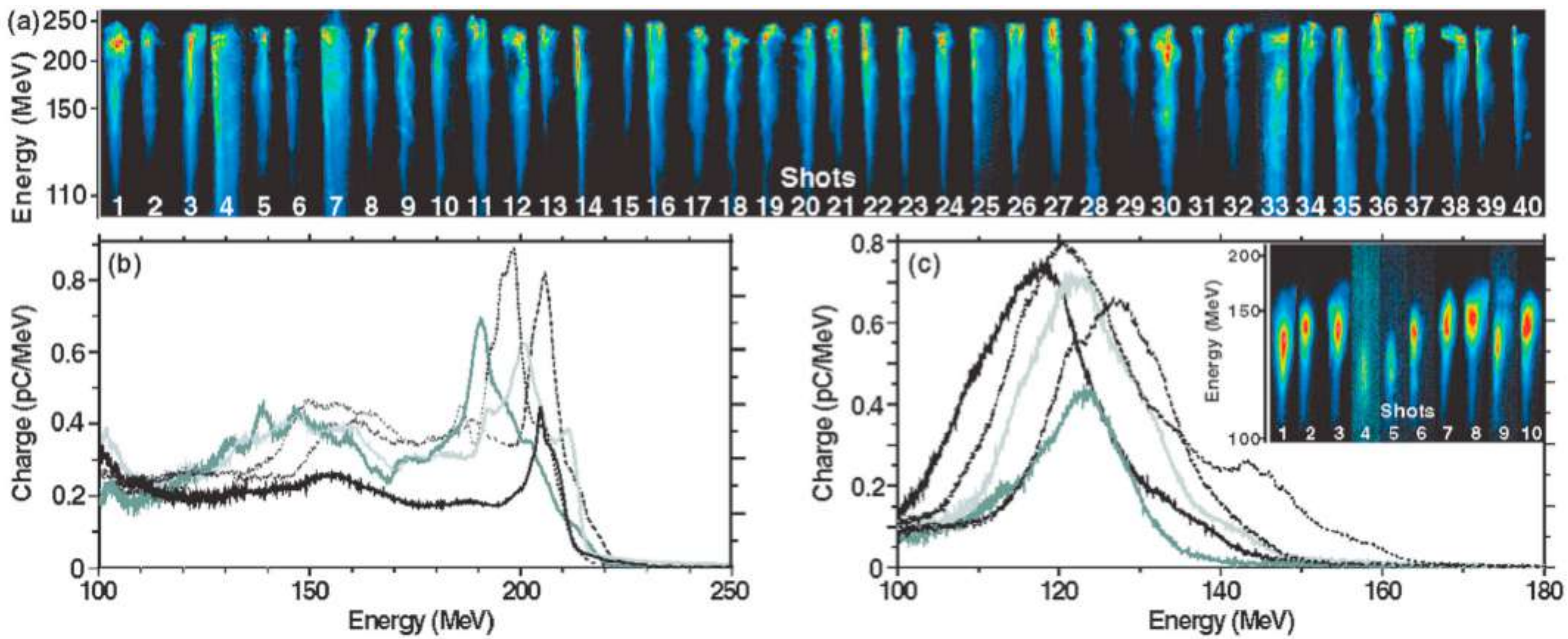
density 4.3×10^{18} cm^{-3}

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

2009 Gas cell experiments at MPQ





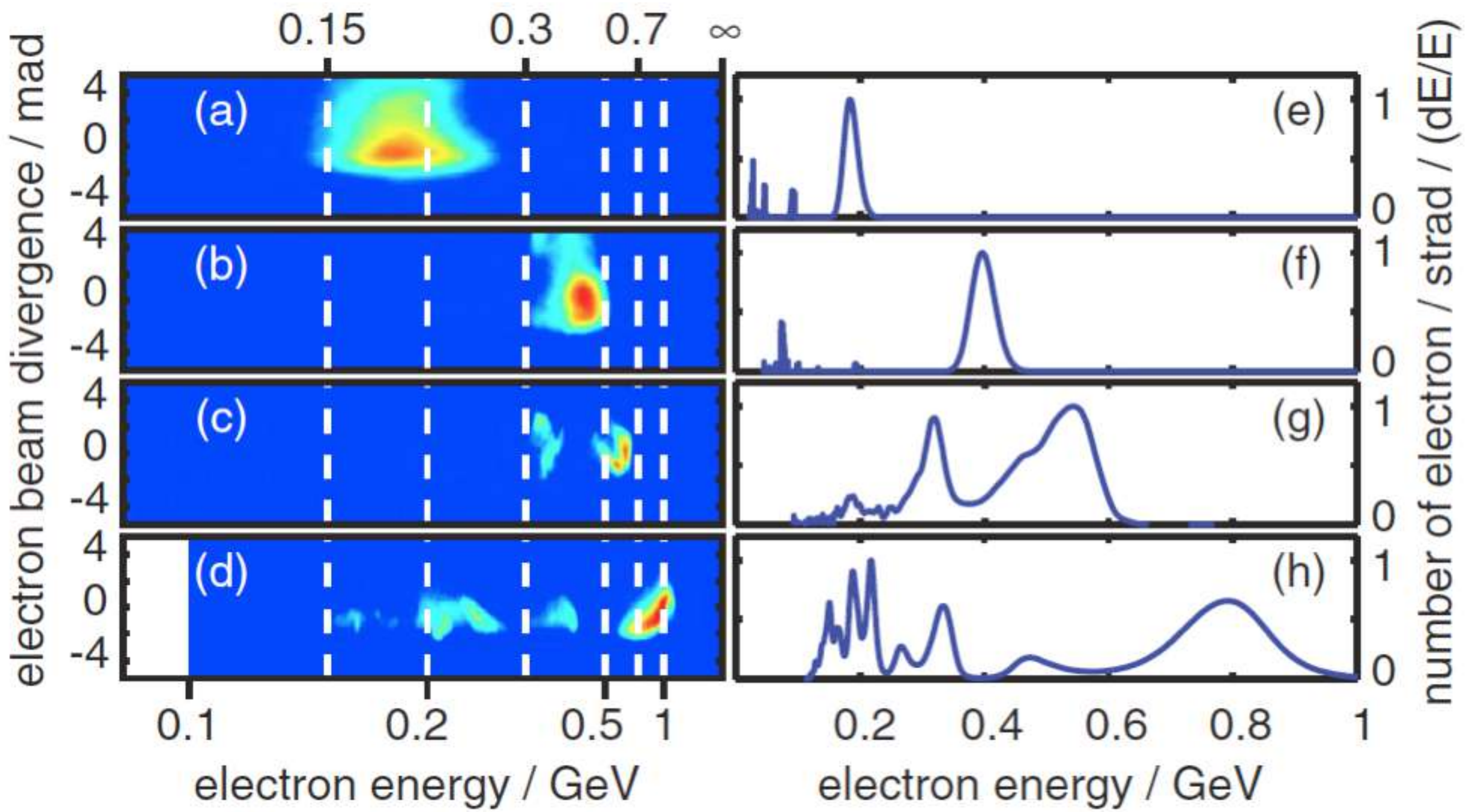


Laser : 20 TW
1cm gas cell target
0.8J, 40 fs, a_0=0.9
n_e=7x10^{18}cm^{-3}

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” acc.

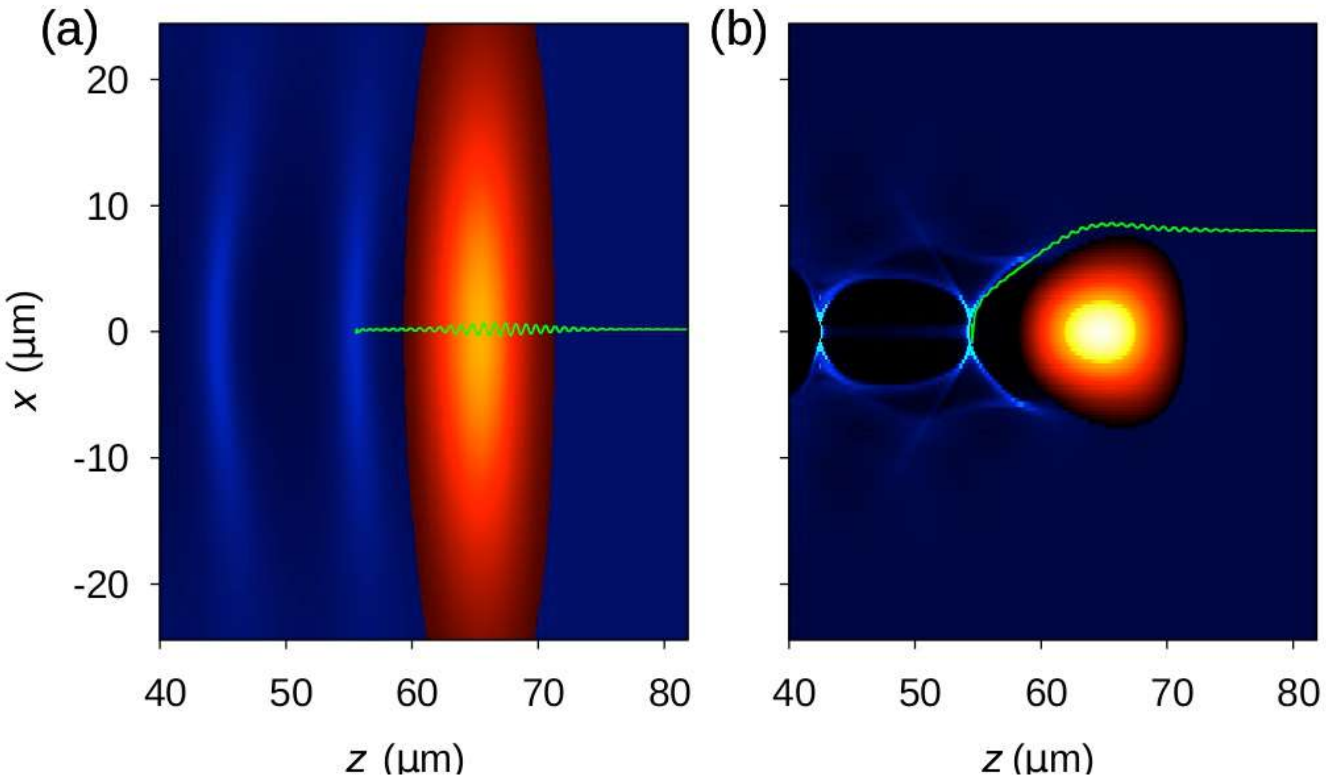


Astra Gemini laser RAL :
11J, 55fs, a=3.9, 1cm gas jet target, density 5.7×10^{18} cm^{-3}
0.8 GeV, >ten % relative energy spread, 300 pC

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

2013 Longitudinal injection

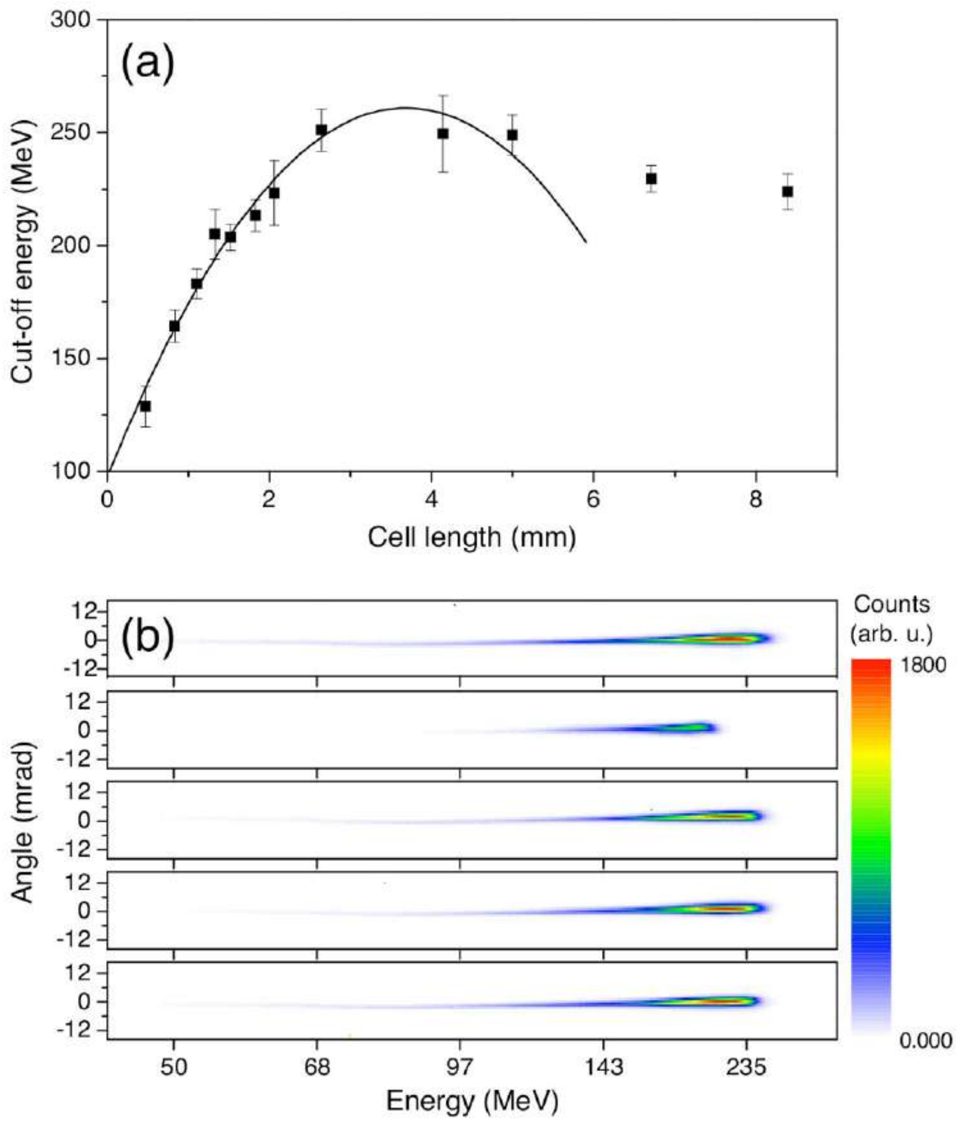
Two different self-injection mechanisms take place :



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

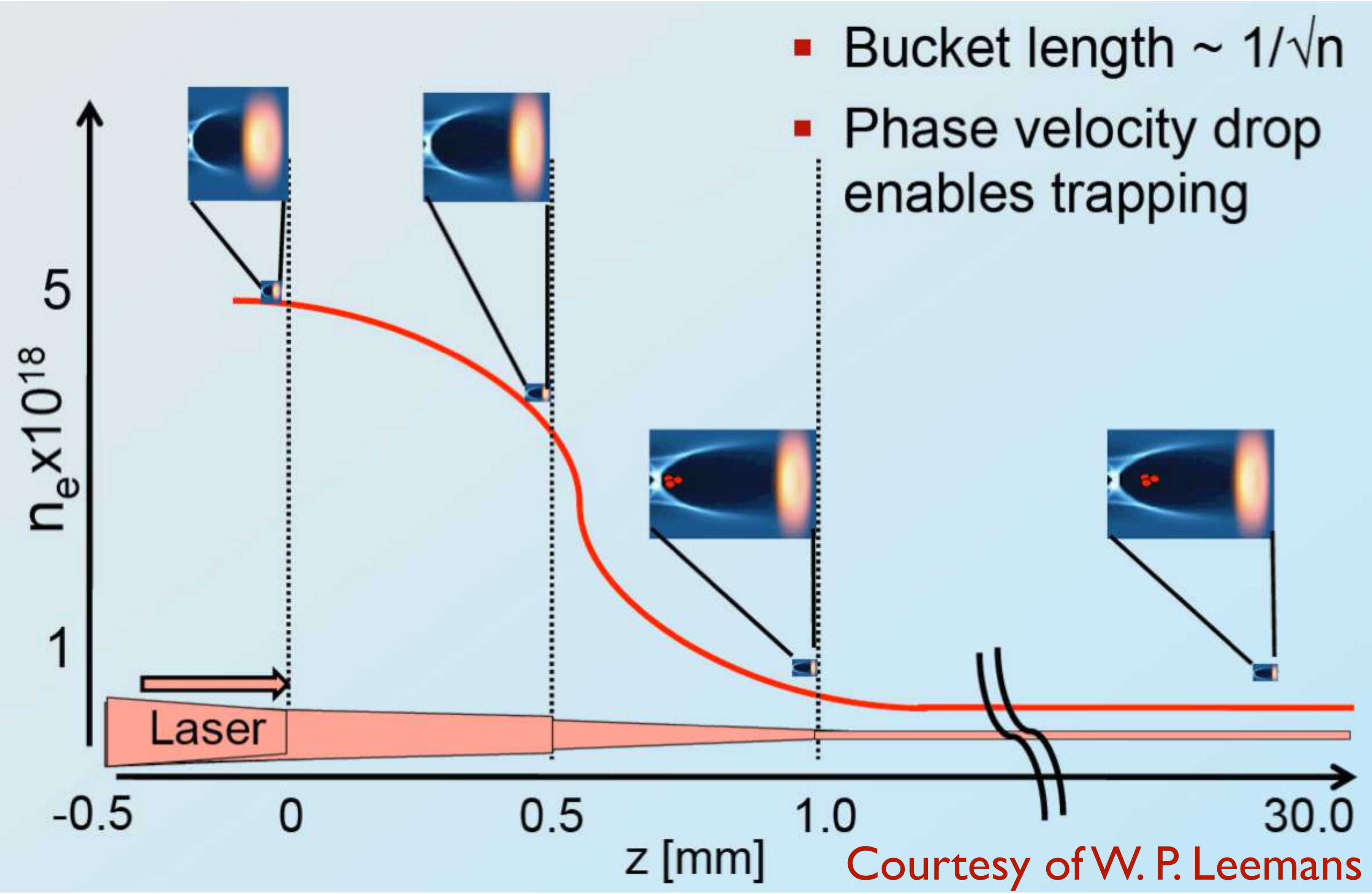
- At lower plasma density transverse injection is prevented

- Only one bunch is injected (longitudinal injection)



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

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 $k_p(z)$

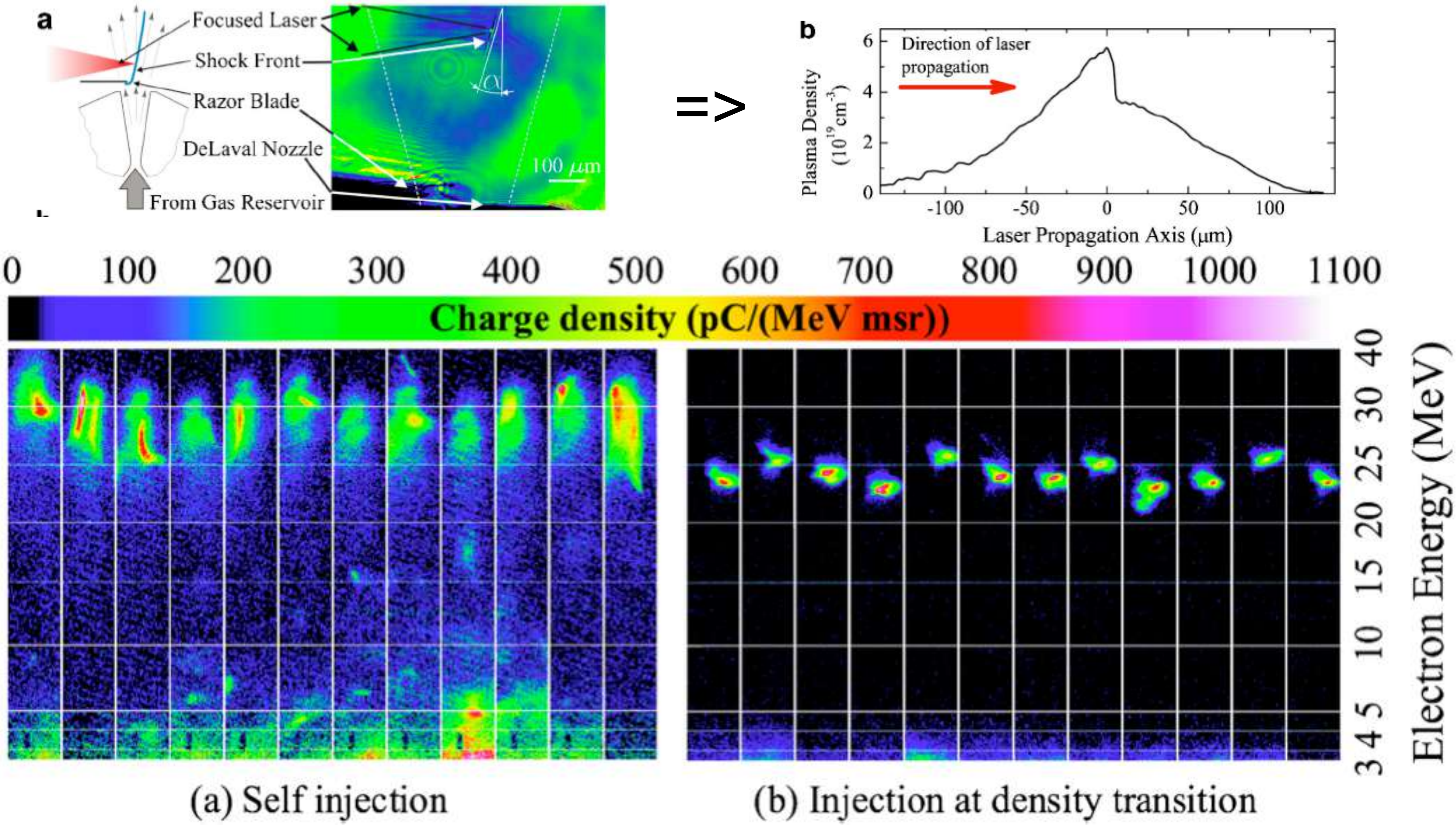
which depends on z through on density

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

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

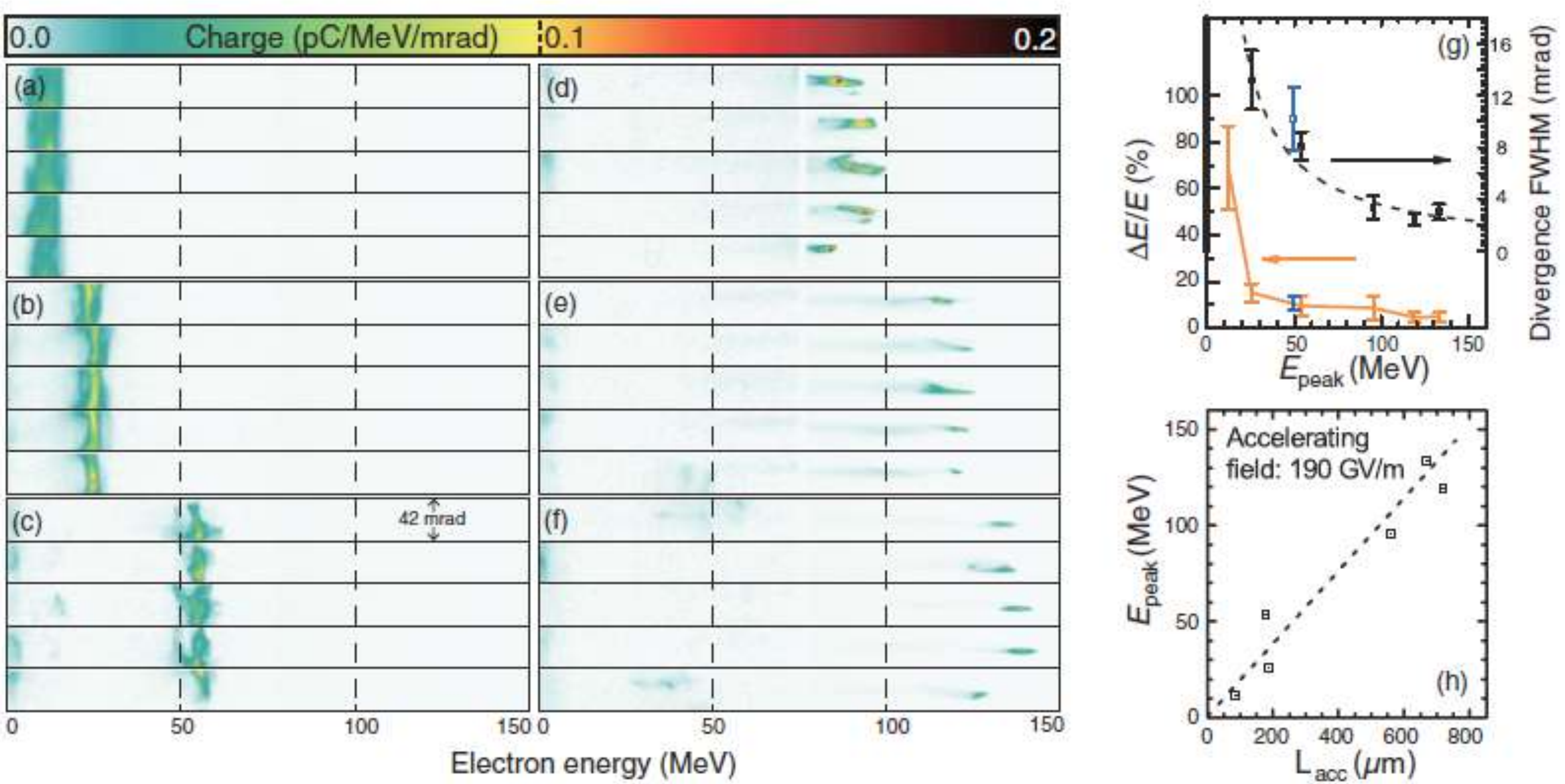
S. Bulanov *et al.*, PRE **58**, R5257 (1998), H. Suk *et al.*, PRL **86**, 1011 (2001), T.-Y Chien *et al.*, PRL **94**, 115003 (2005), T. Hosokai *et al.*, PRL **97**, 075004 (2006), C. G. R. Geddes *et al.* PRL **100**, 215004 (2008), J. Faure *et al.*, Phys. of Plasma **17**, 083107 (2011)

2010 Sharp density ramp injection : shock in gas jet



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

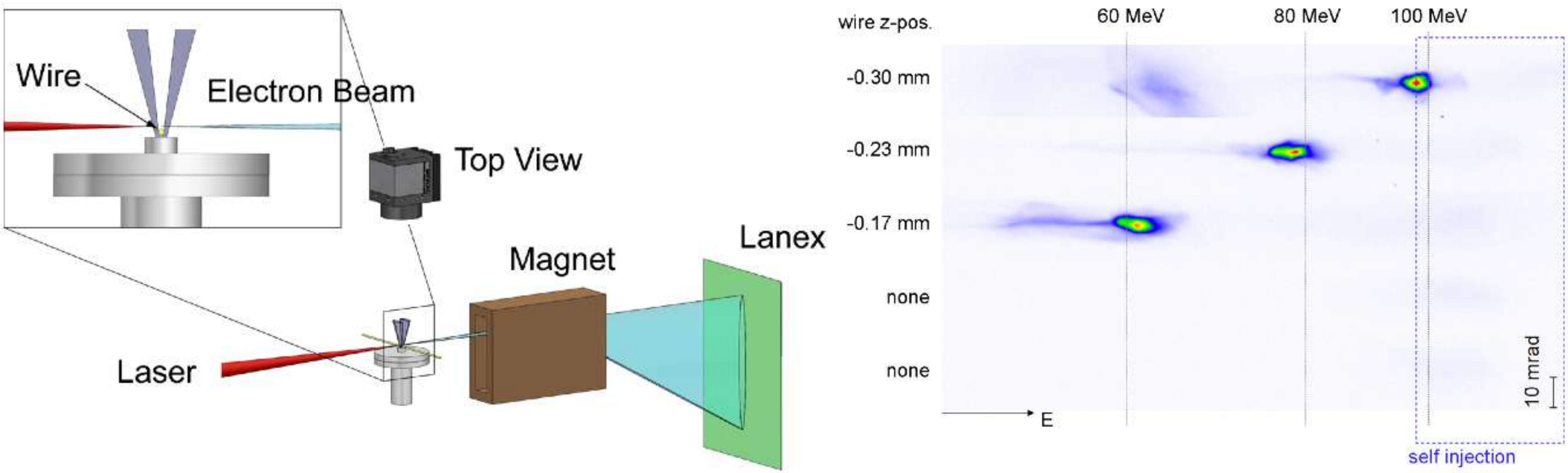
2013 Shock front injection



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

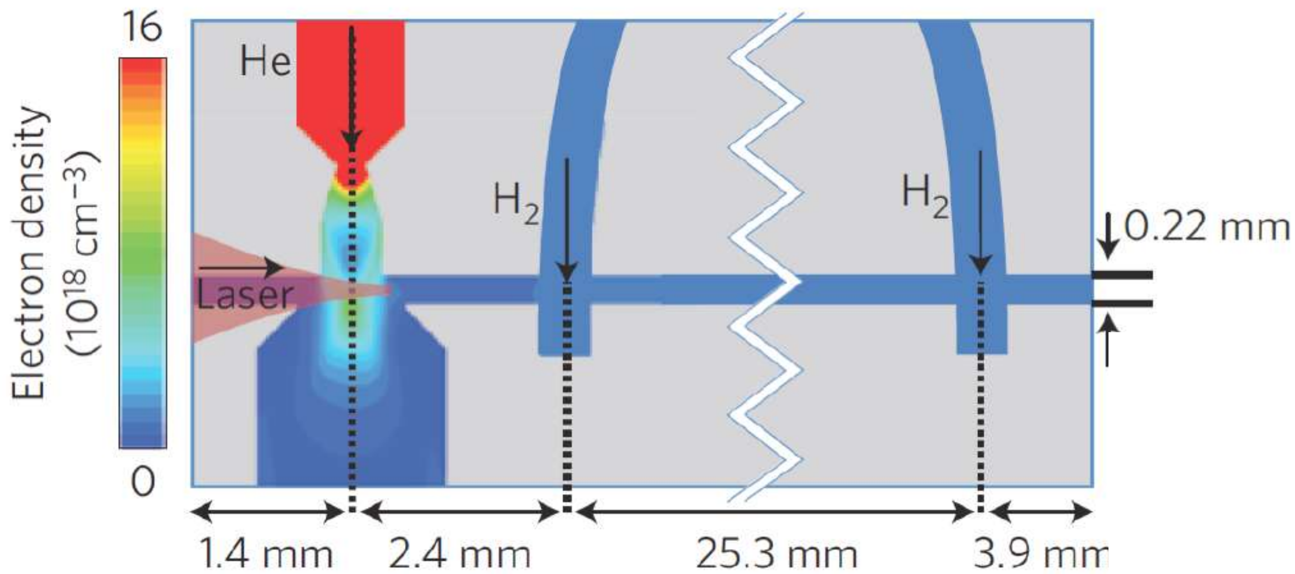
2013 Shock front injection : LLC

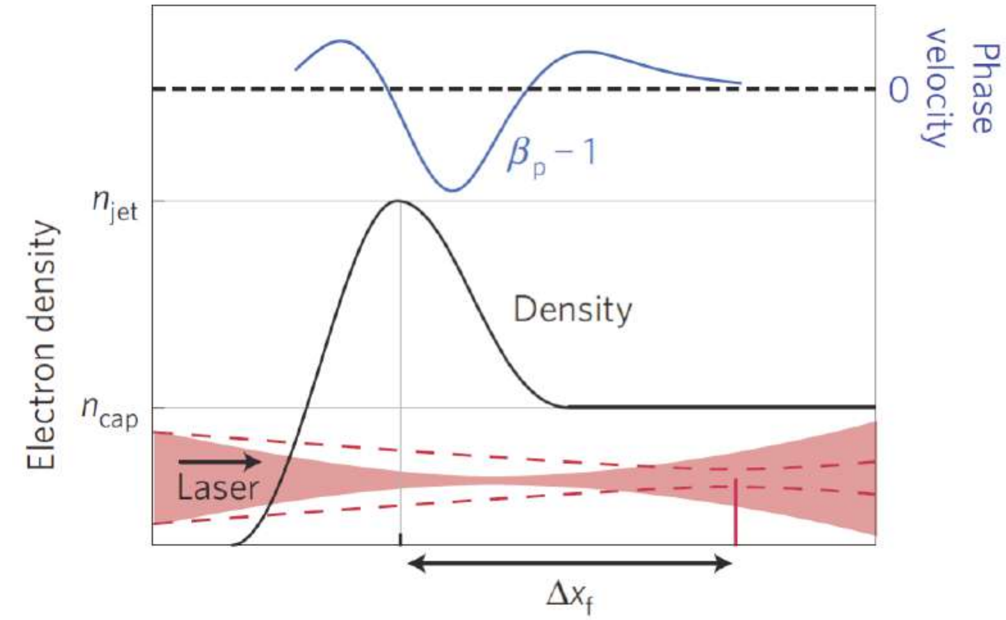
Laser wakefield acceleration using wire produced double density ramps

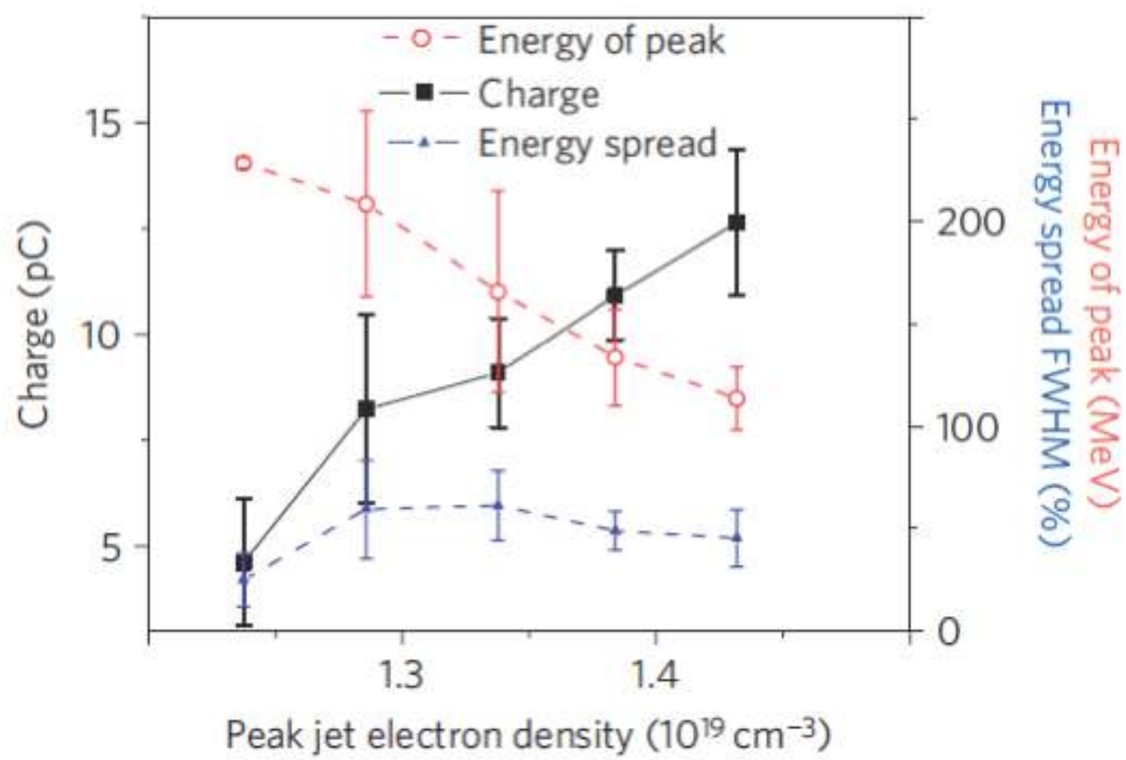


M. Burza *et al*., PRSTAB 16, 011301 (2013)

2011 Density ramp + phase velocity control





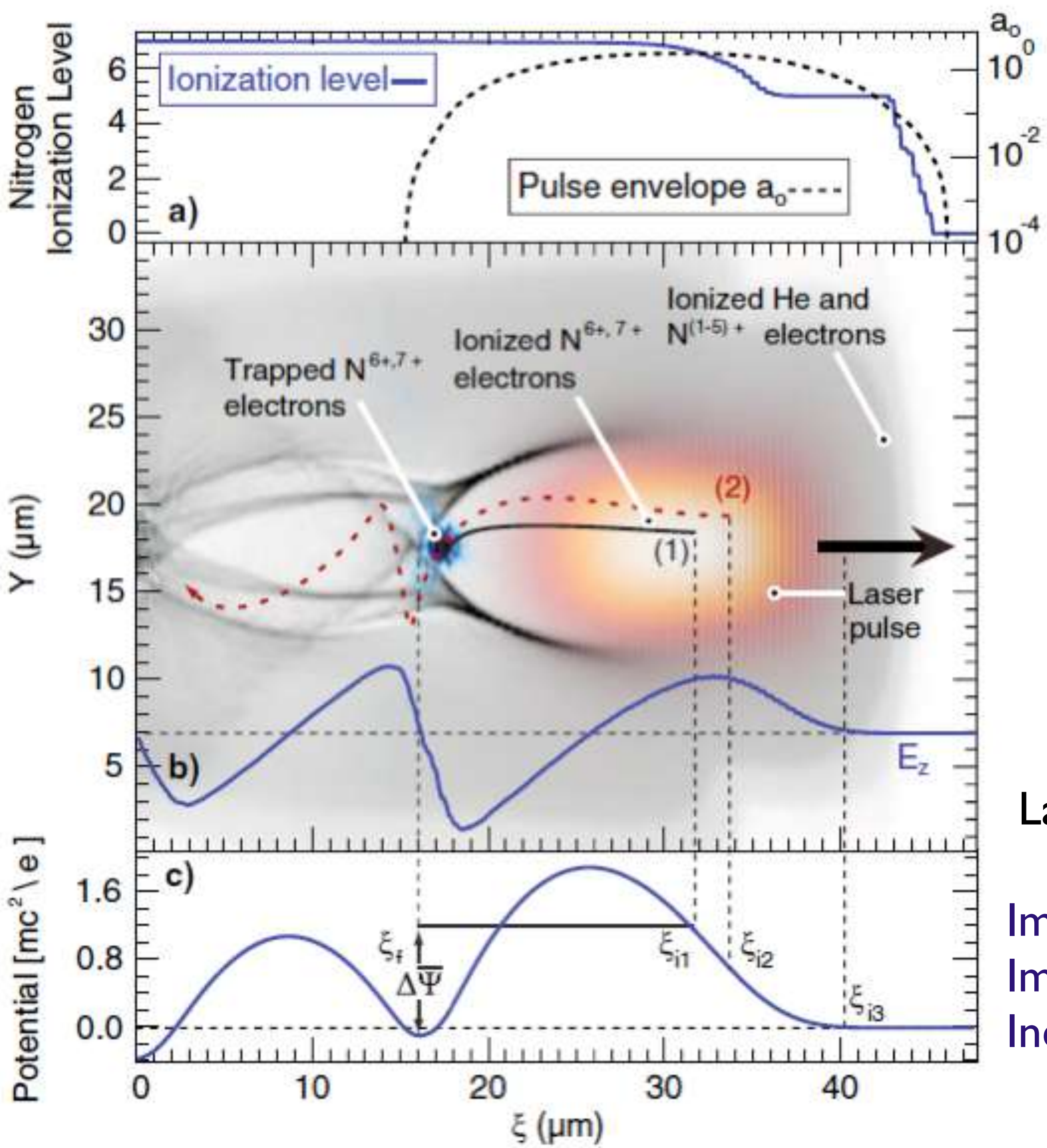


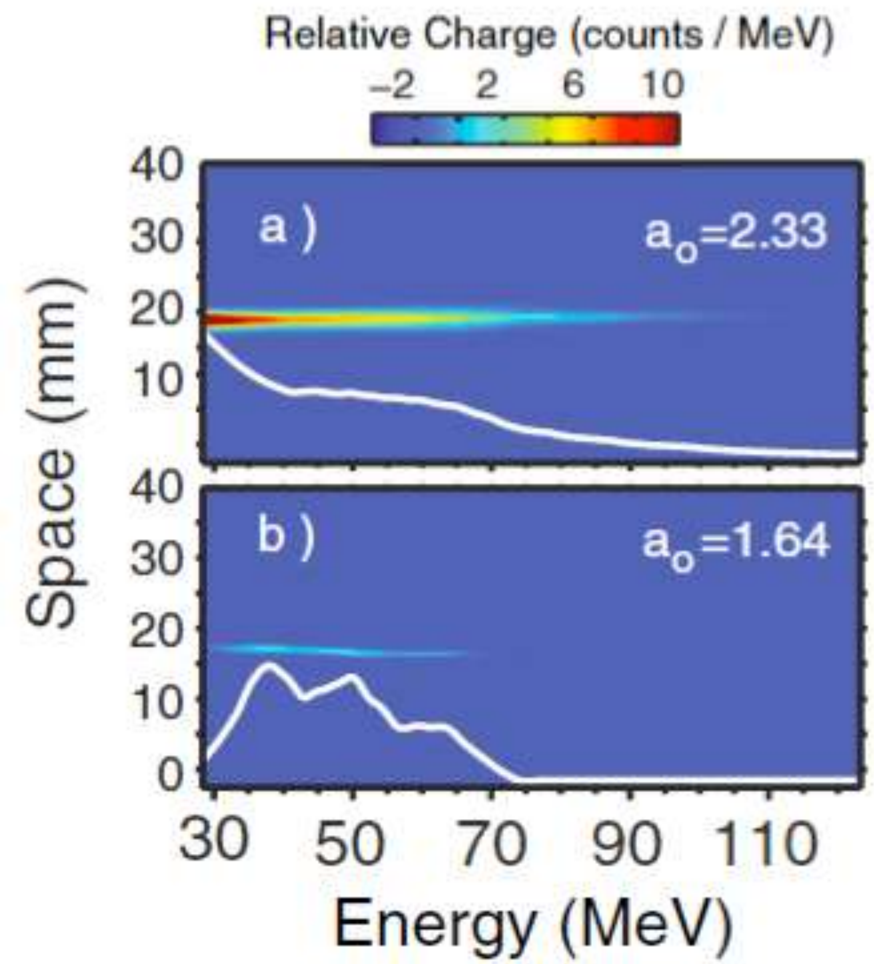
Laser : 20 TW
0.8J, 40 fs, a_0=0.9
n_e=7x10^{18}cm^{-3}

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



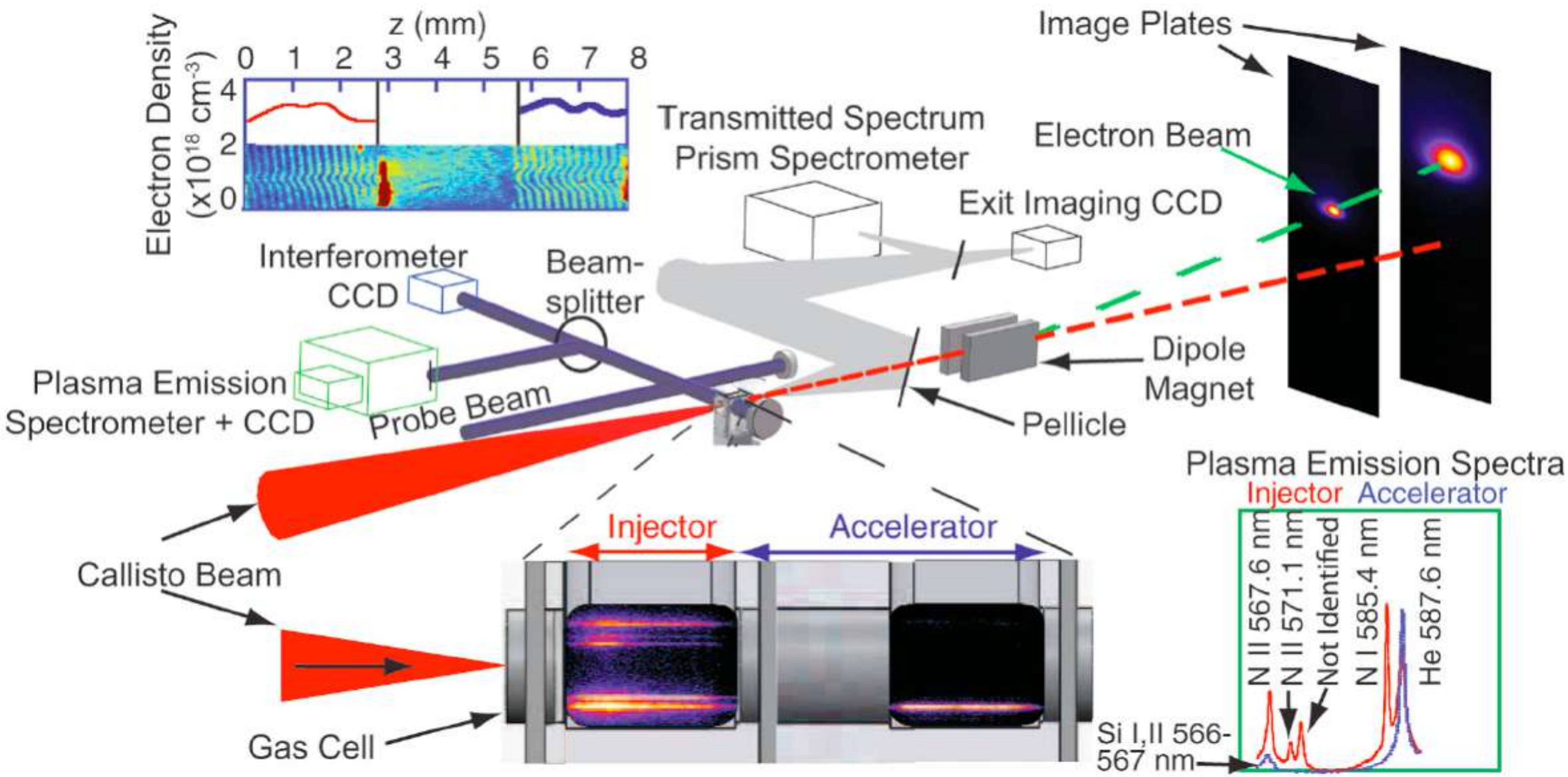


Laser: 10 TW, 0.8J, 45 fs, $a_0 \approx 2$, $n_e = 1.4 \times 10^{19}$ cm^{-3}

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)

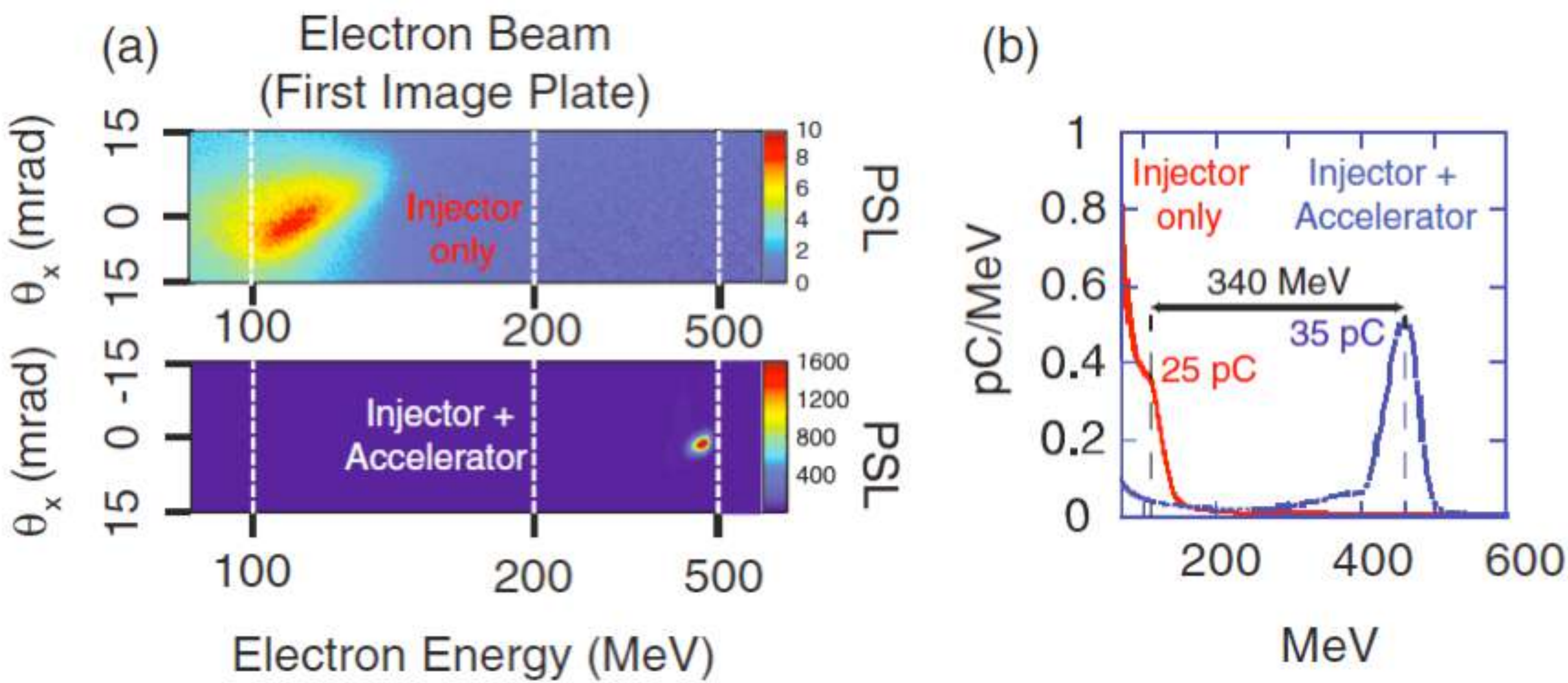
2010 Ionization Induced Trapping:2 stage acc.



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

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

Ionization Induced Trapping : two stage acc.

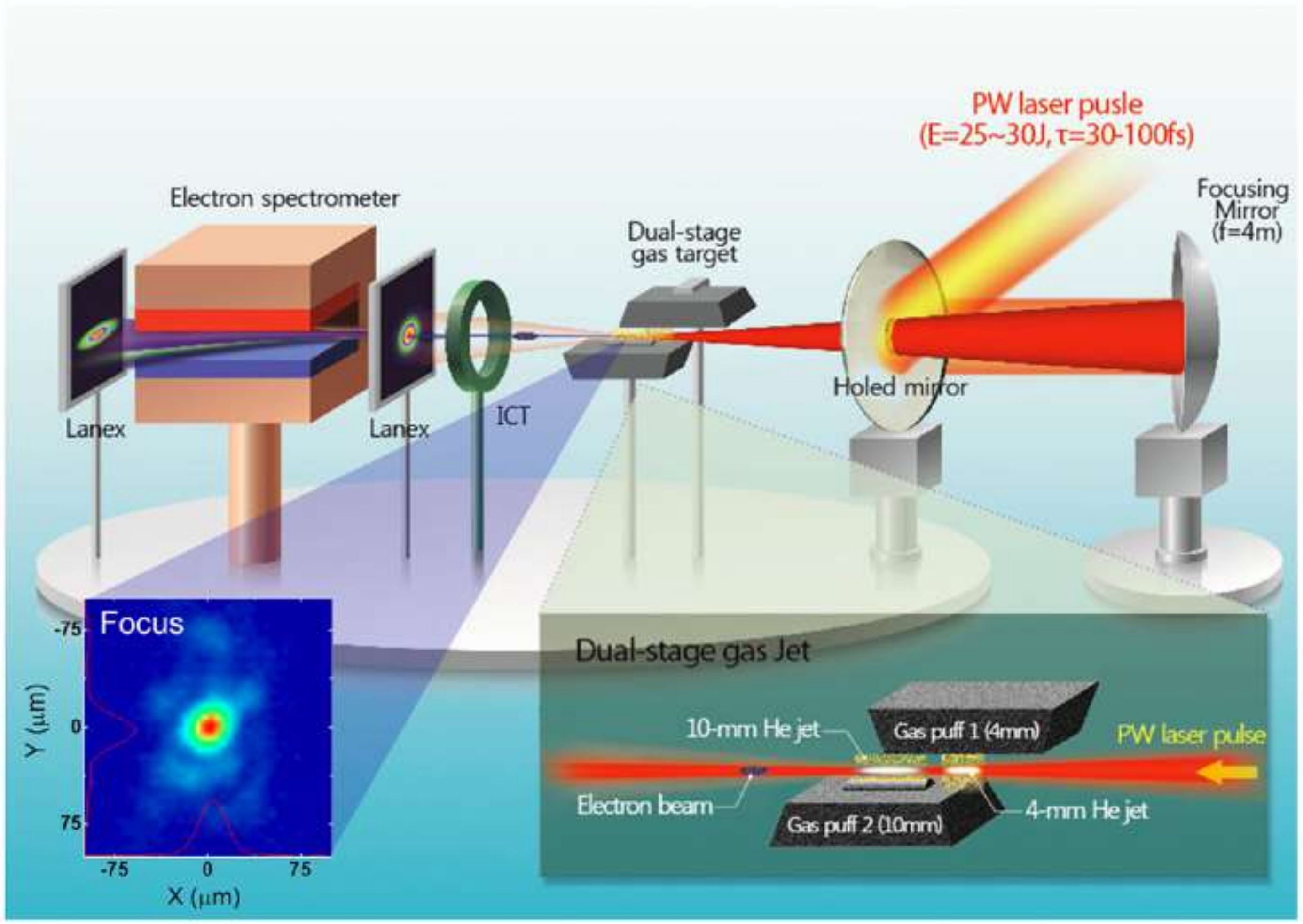


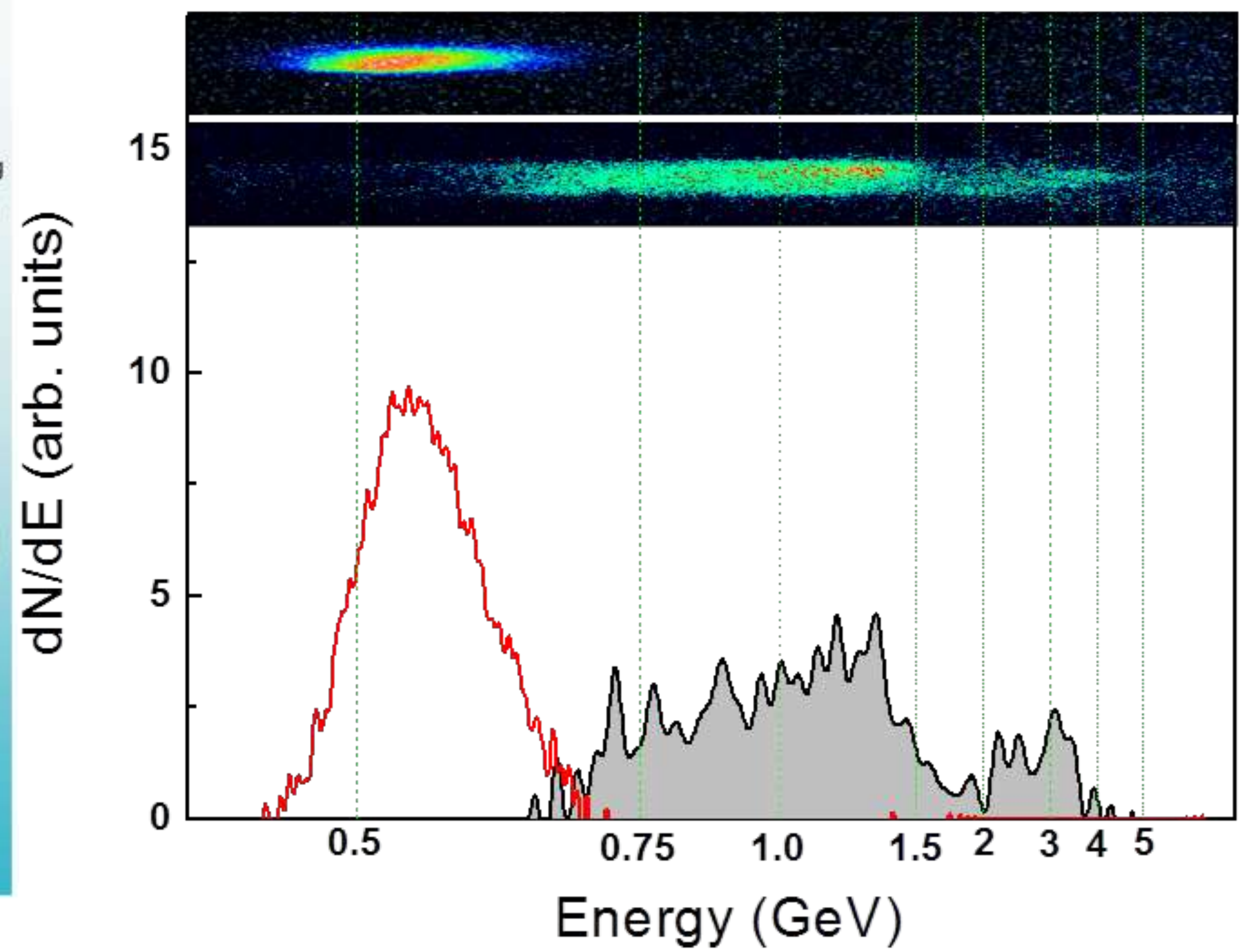
35 pC, 460 MeV, div = 2 mrad, DE/E>5%

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

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

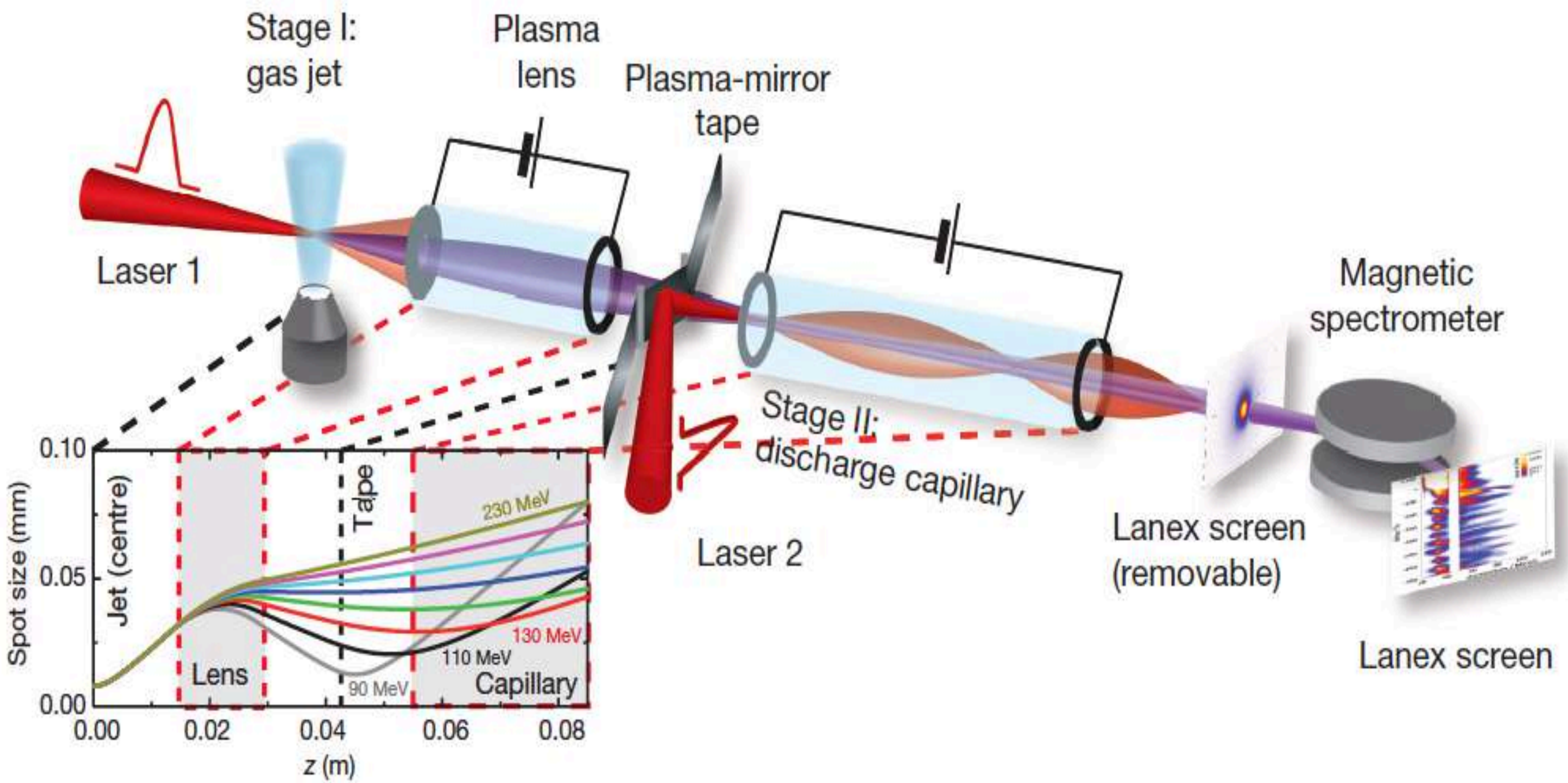
Double He gas jet : $d_e = 2.1 \times 10^{18}$ cm^{-3} (4 mm) $d_e = 0.7 \times 10^{18}$ cm^{-3} (10 mm)





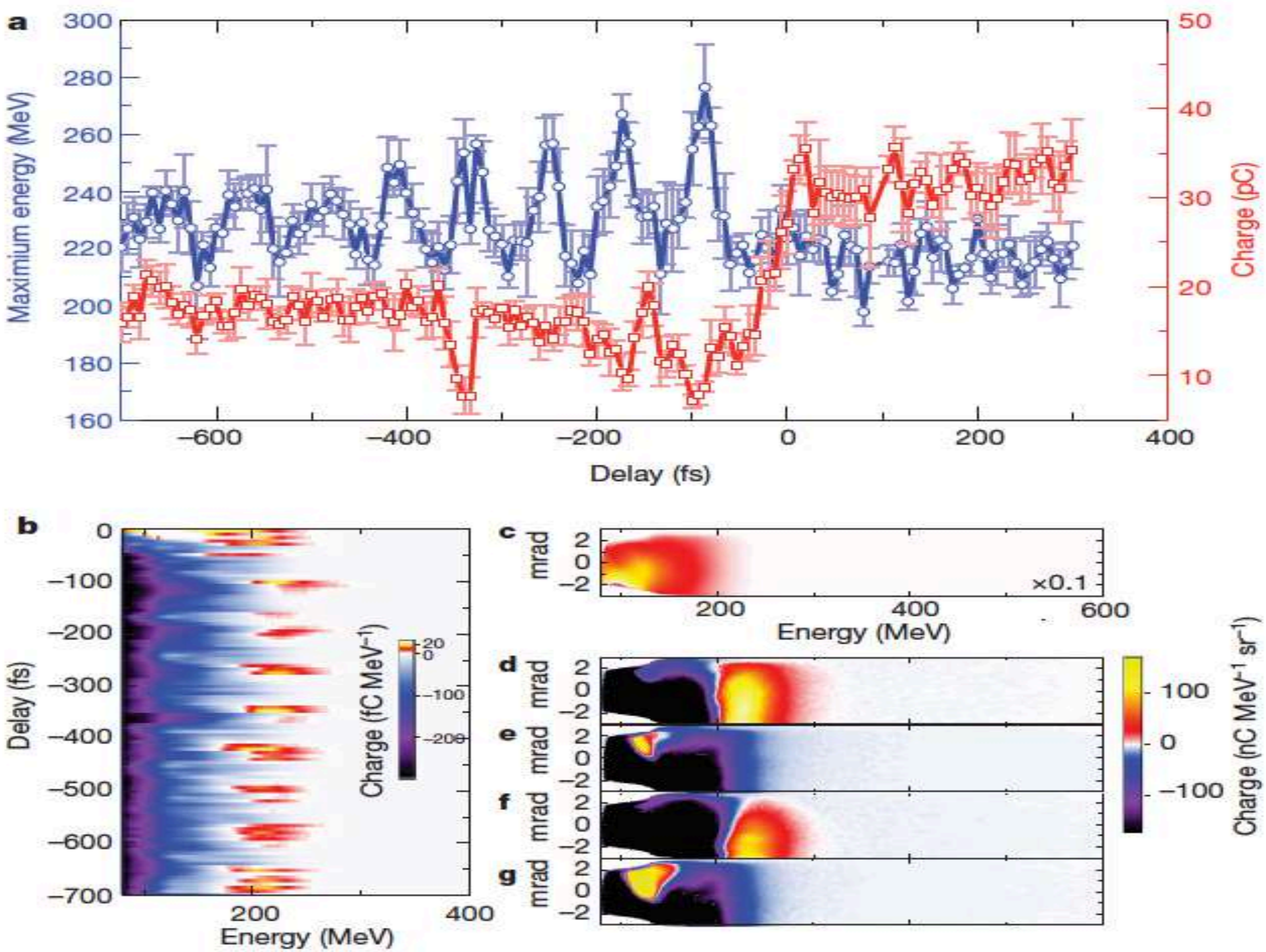
Hyung Taek Kim et al., PRL 111, 165002 (2013)

Two-stage laser plasma accelerator @ LBNL



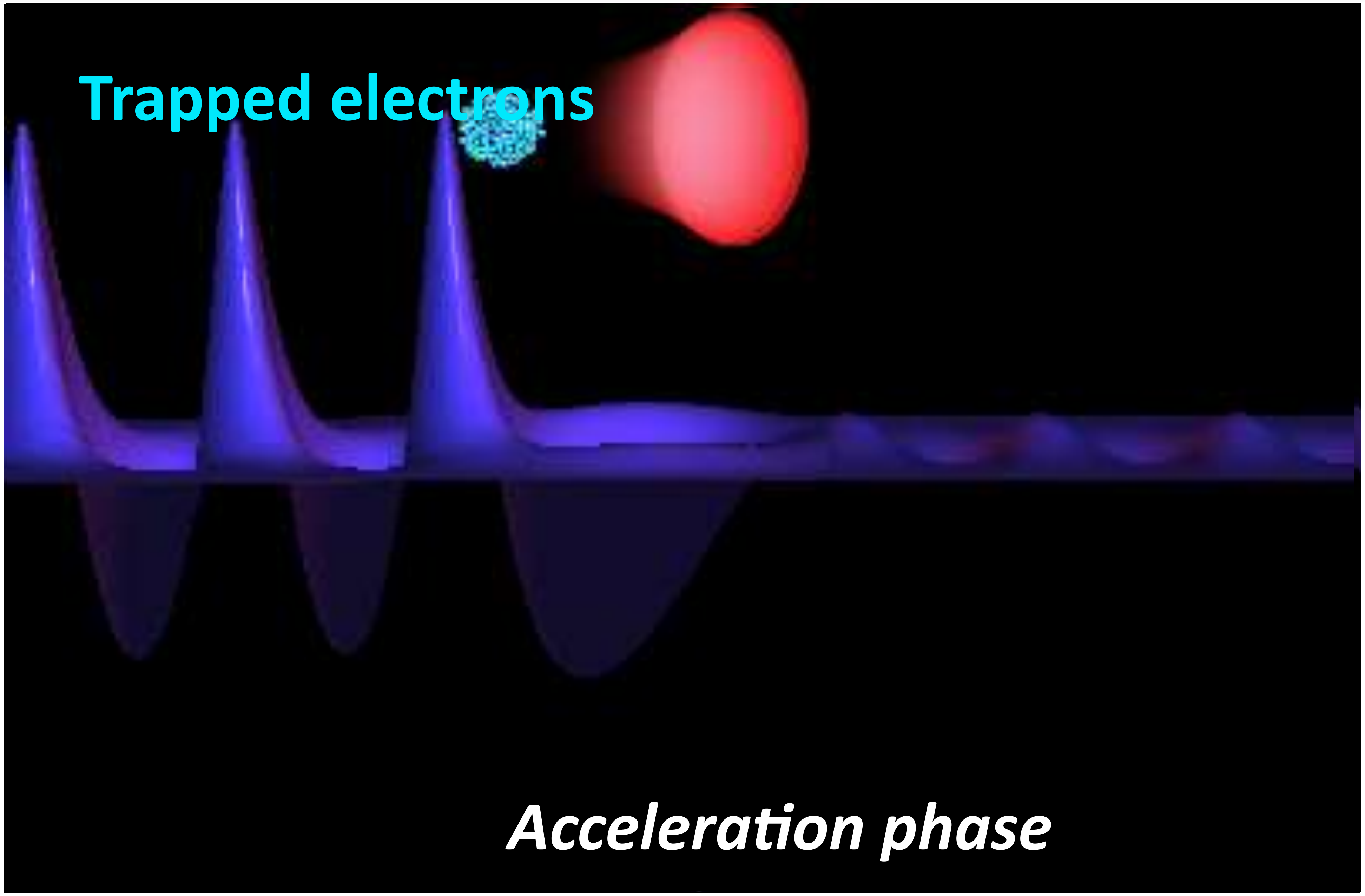
S. Steinke *et al.*, Nature 165525 (2016)

Two-stage laser plasma accelerator @ LBNL



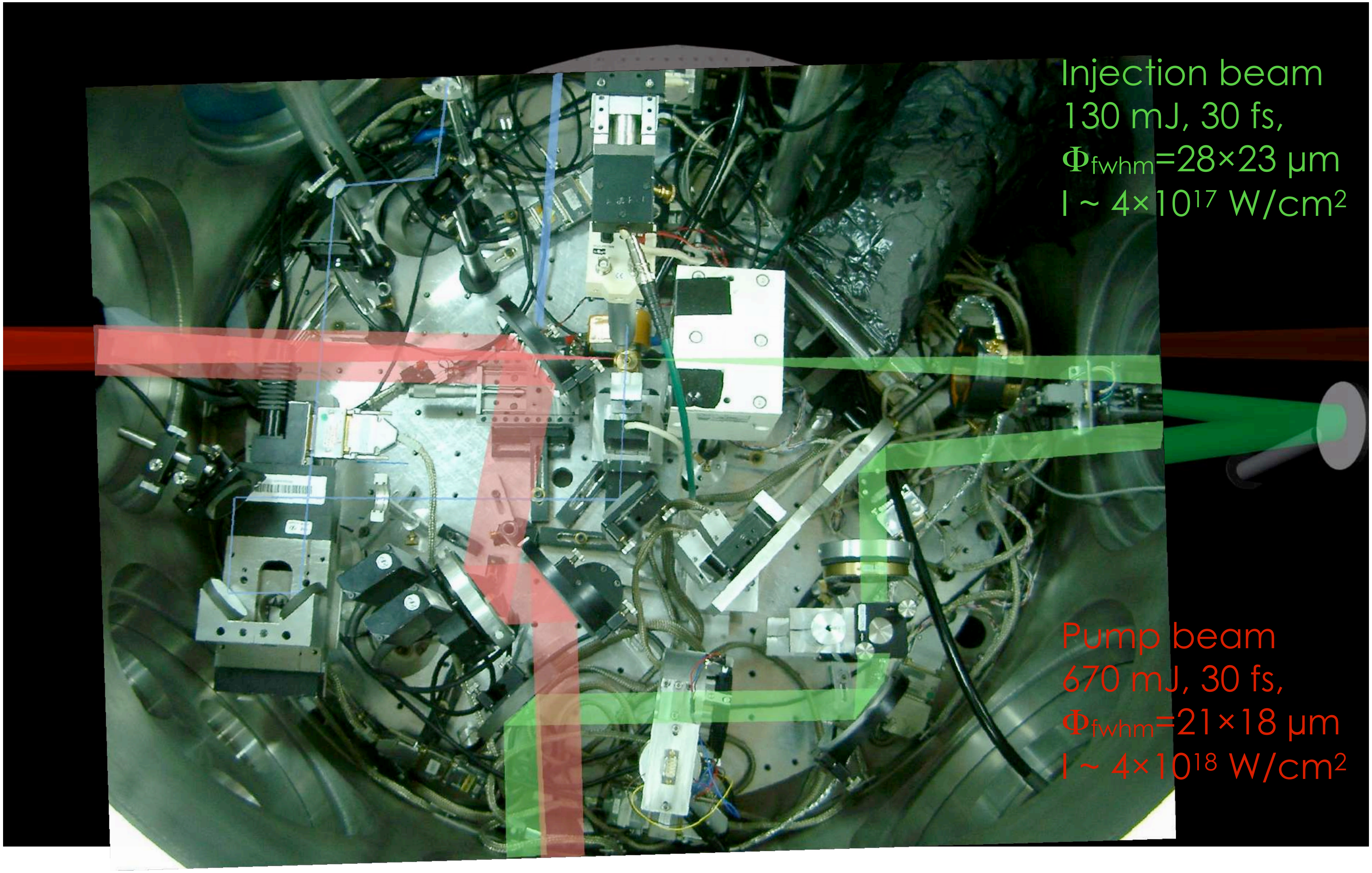
S. Steinke *et al.*, Nature 165525 (2016)

Colliding Laser Pulses Scheme

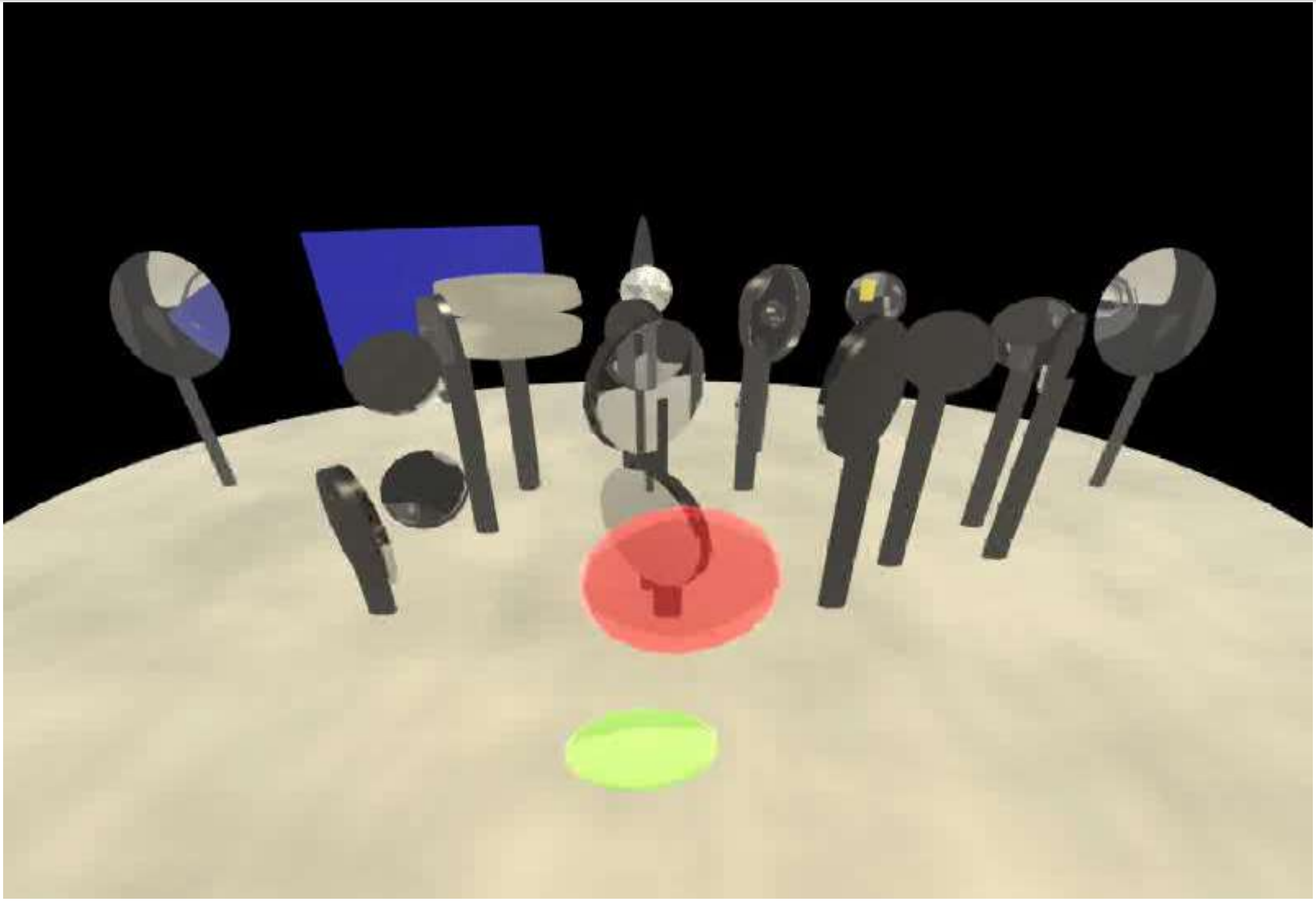


The first laser creates the accelerating structure
A second laser beam is used to heat electrons

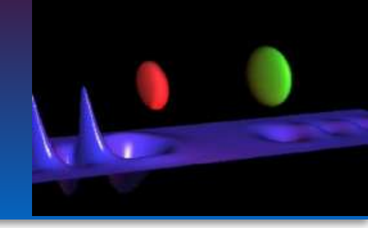
Set-up for colliding pulses experiment



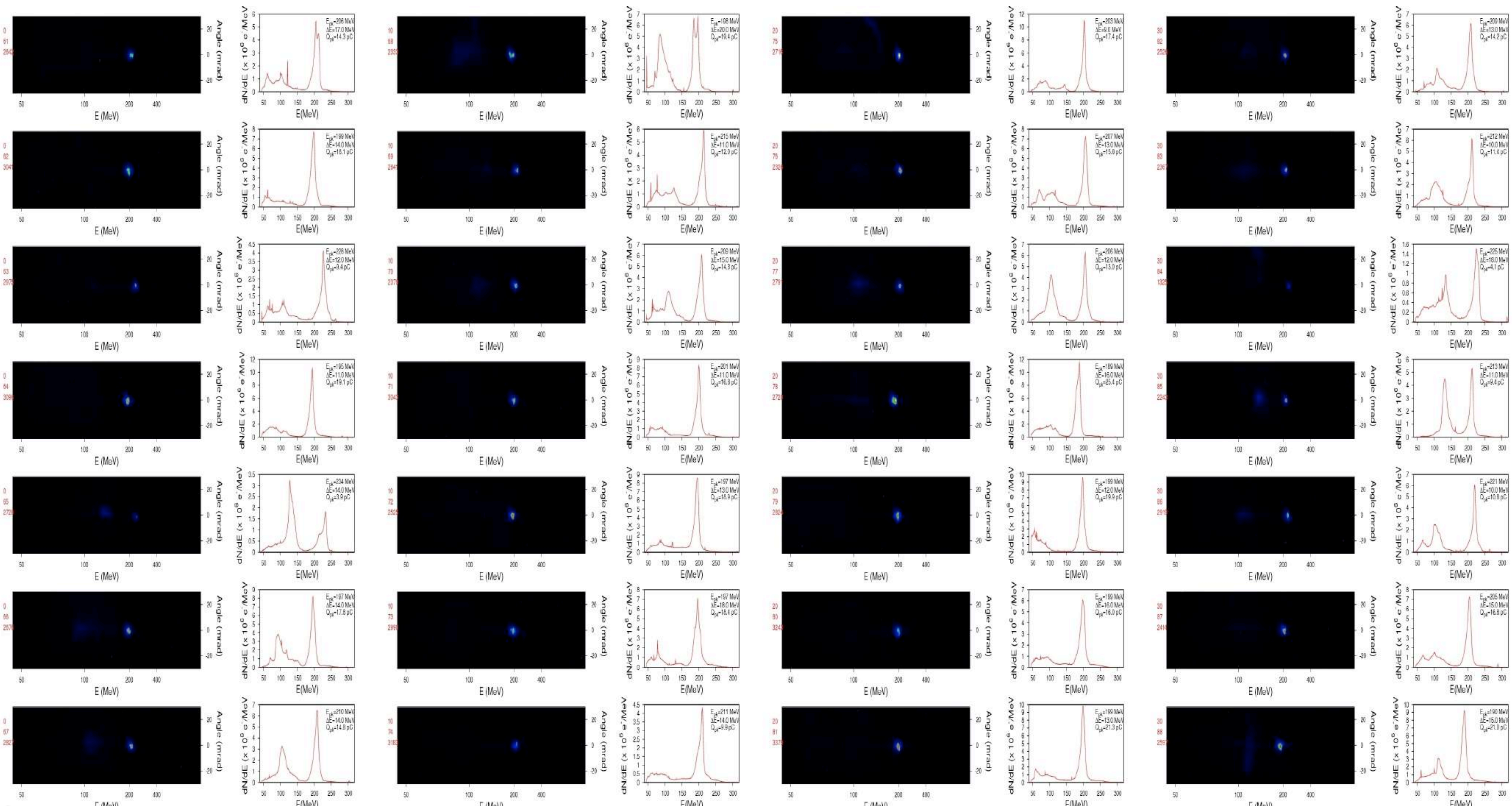
The colliding of two laser pulses scheme



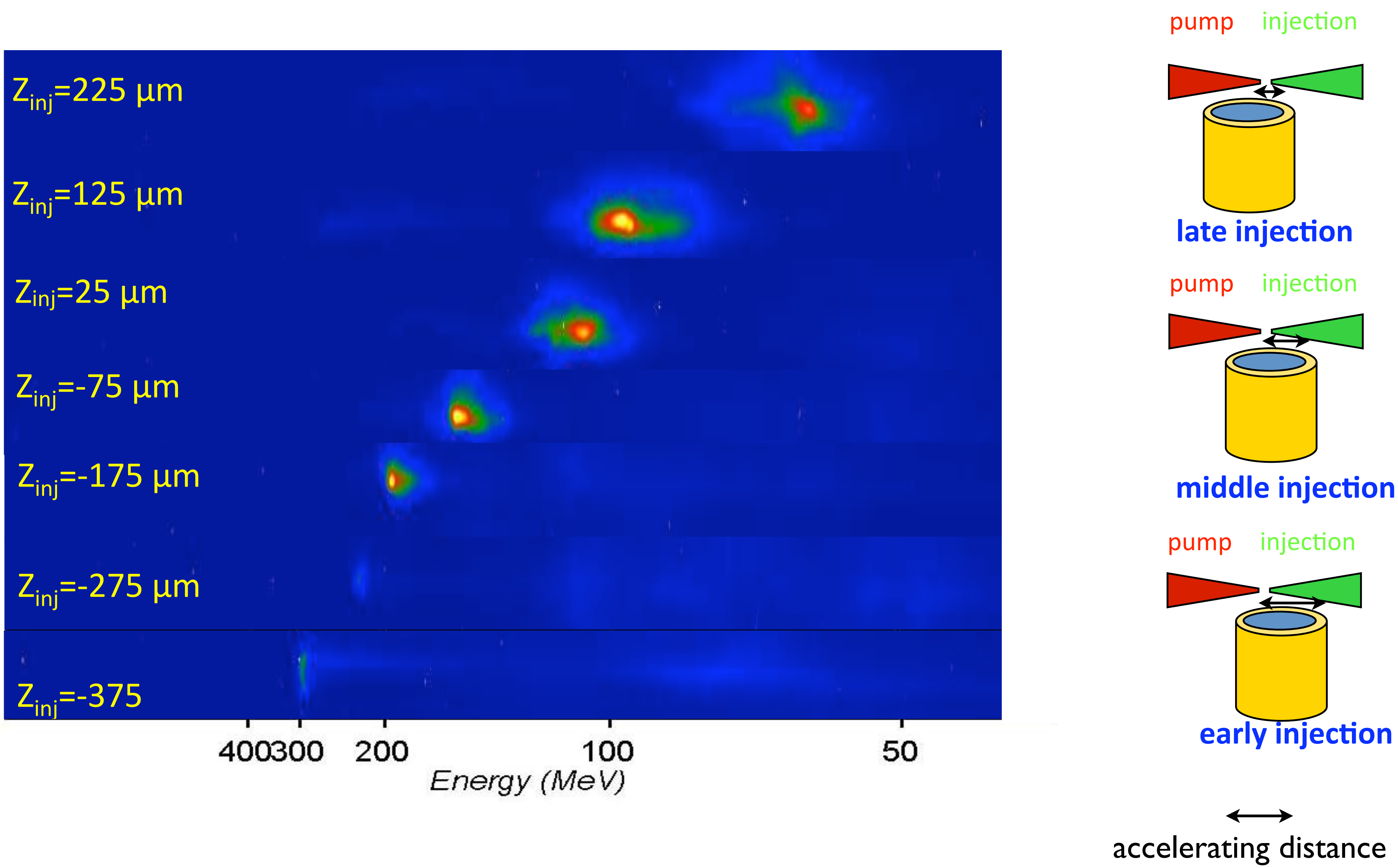
Towards a Stable Laser Plasma Accelerators



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

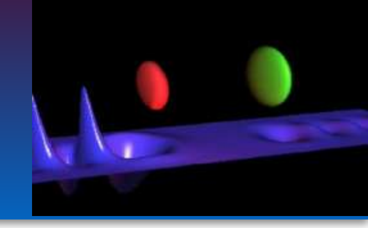


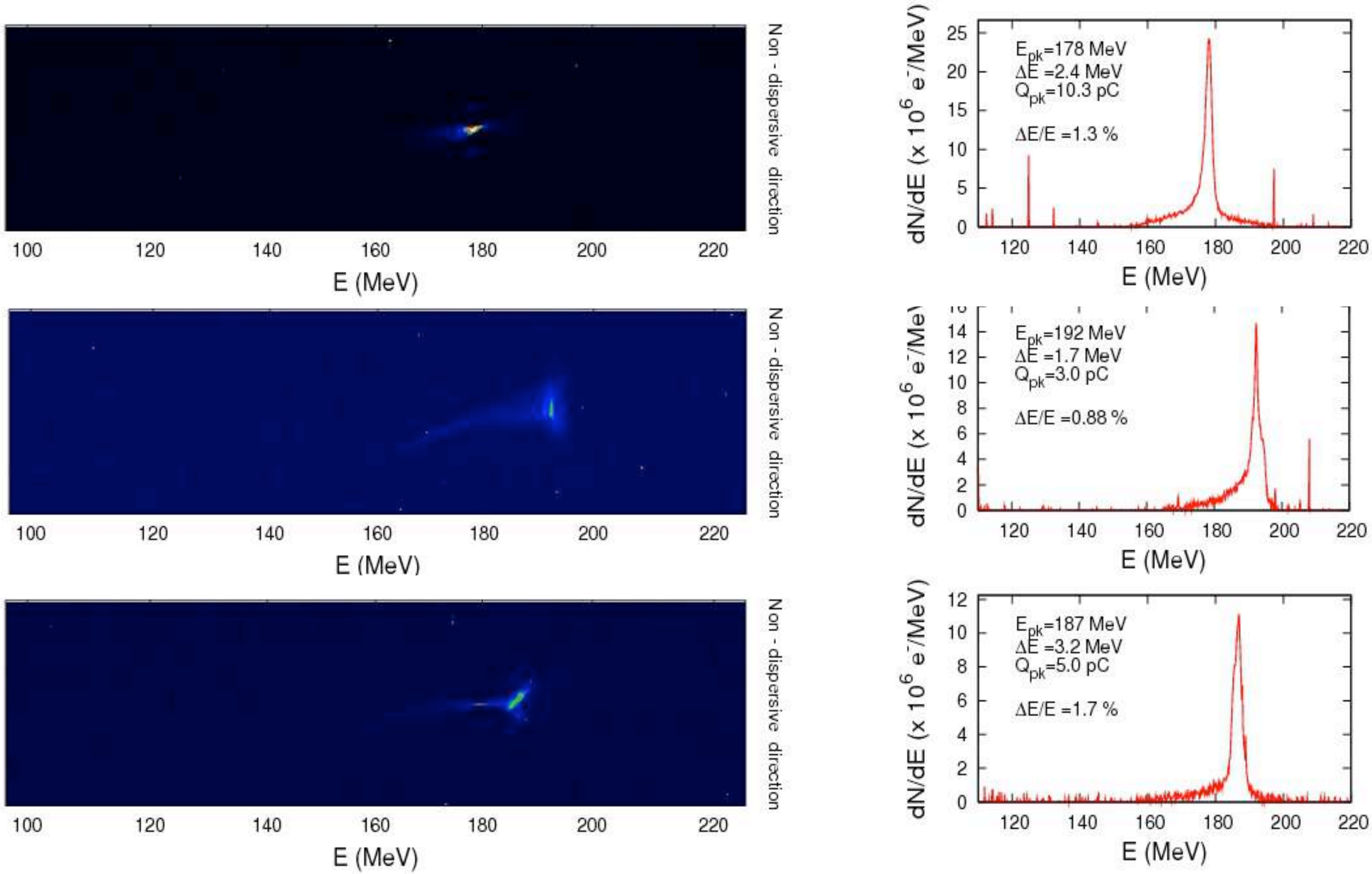
Tunability of the electrons energy



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

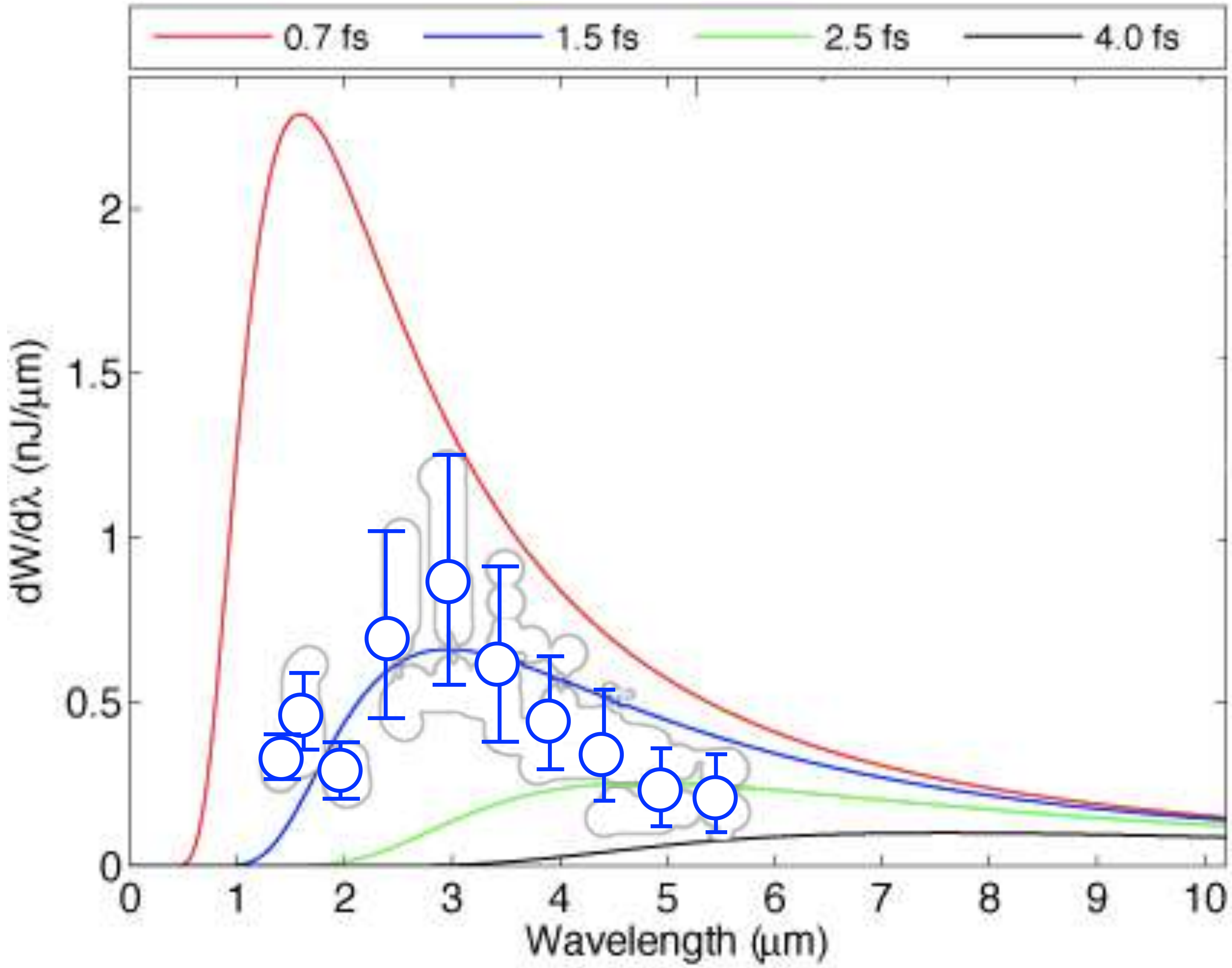
1% relative energy spread





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

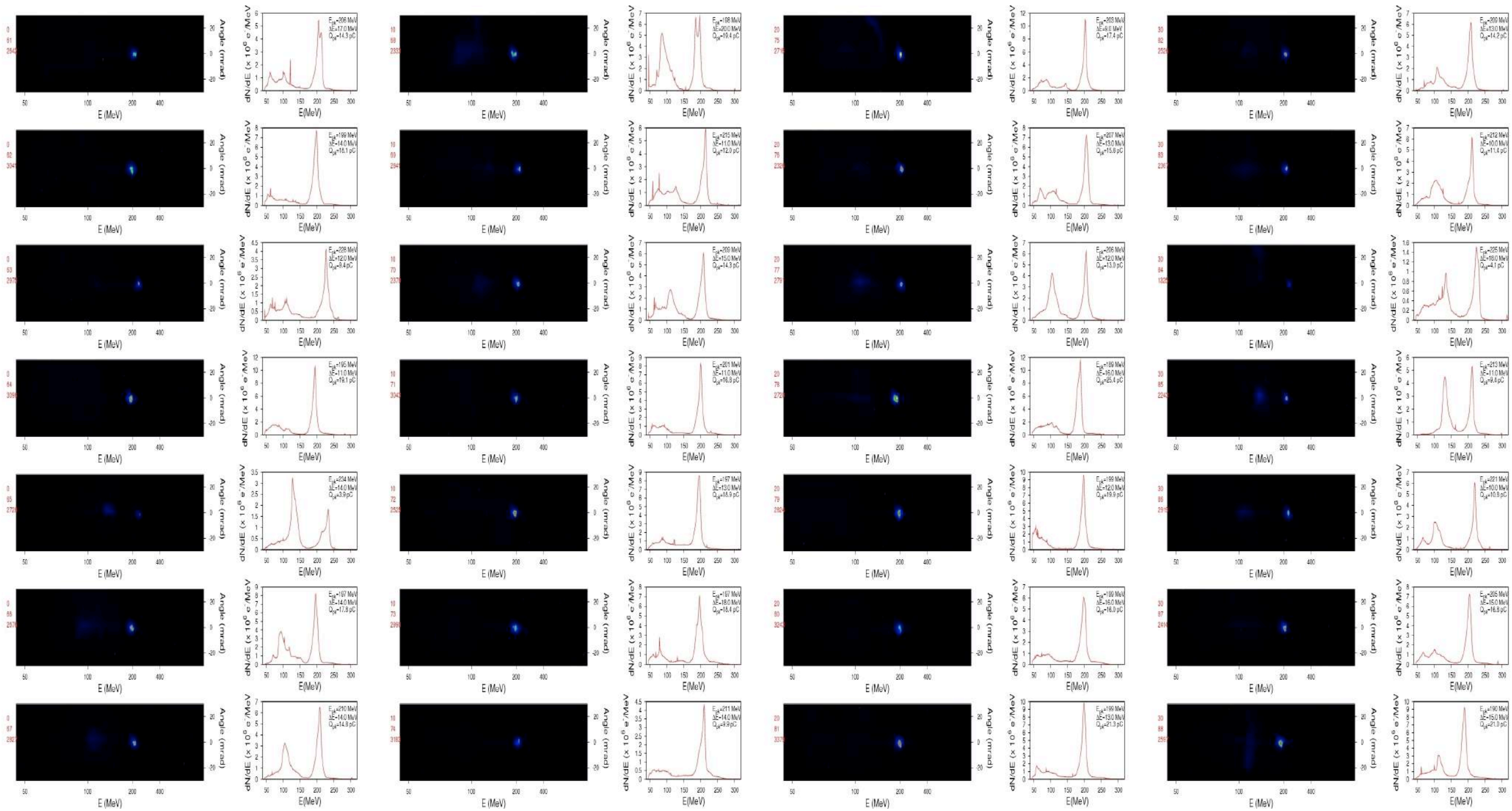
Coherent

1.5 fs RMS duration : Peak current of 4 kA

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

Stable Laser Plasma Accelerators

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



Concept laser plasma collider: «Artistic view»

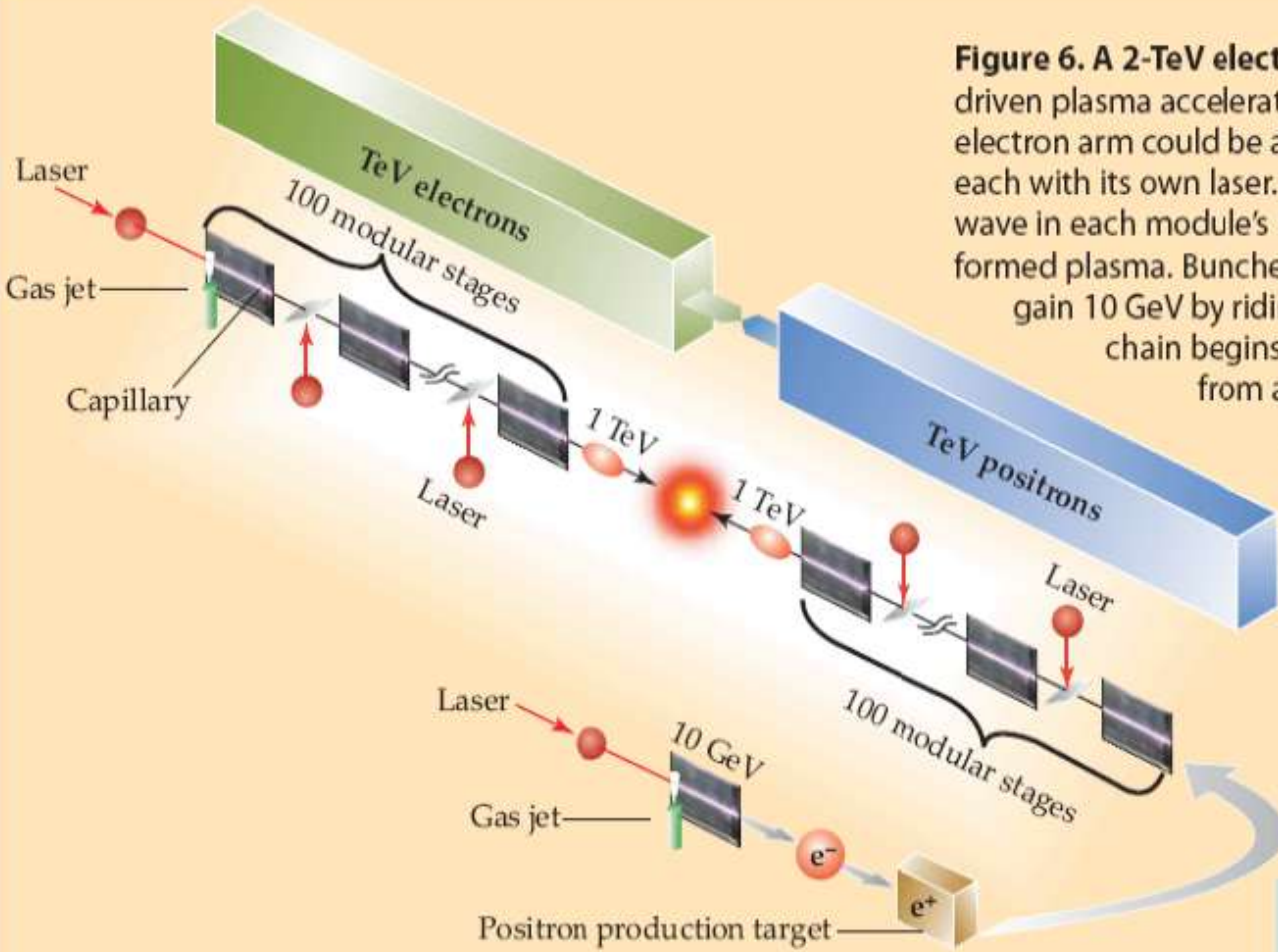
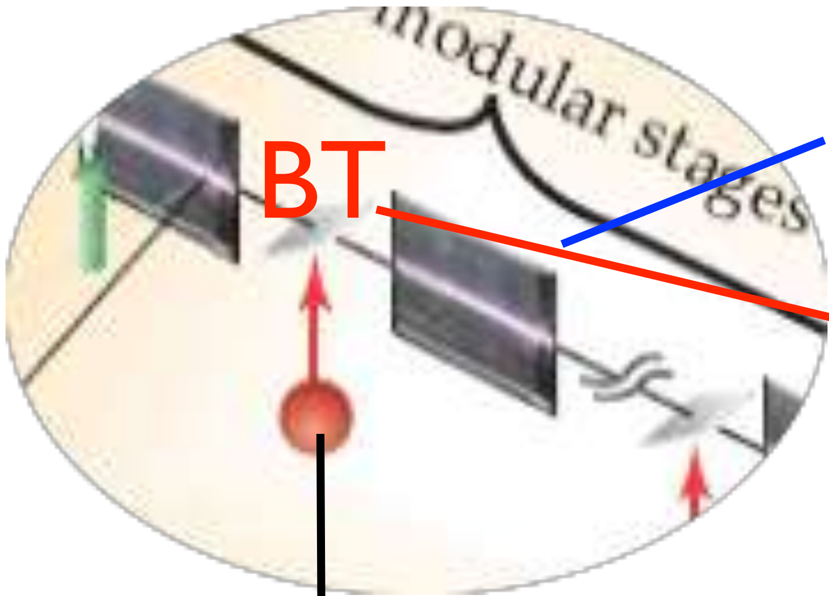


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

W. Leemans, et al.,

W. Leemans et al., Phys. Today, March 2009

Concept laser plasma collider: «Artistic view»



plasma accelerator
stage 0.1 to 1m, η = 1%

Beam transport :
1, 10 m to up to few
km in the last stages
η = ? %

laser :10x50 m + focal of 5-10 m, η = few %

overall wall-plug efficiency:10^{-3},10^{-4},
i.e. for a 1 MW e, e^+ beam,
required power of 1-10 GW

100 of kHz-PW Laser reliability,
plasma discharge reliability,
etc..

V. Malka Phys. of Plasma 19, 055501 (2012)

Concept laser plasma collider: «Artistic view»

1 PW laser at high rep rate (>100Hz): today in the best 1 Hz

Plasma and vacuum chambers

Transport between stages

Thermal effects on the guiding structure wall

External guiding/self-guiding

Collimation and beam filtering

Accelerating plasma structure: linear (<1GV/m) or non-linear (>few GV/m to 100s GV/m)

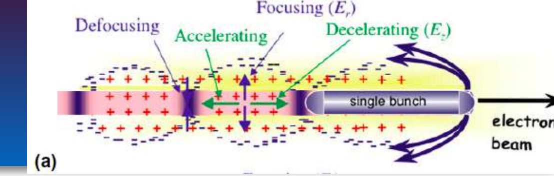
High efficiency laser driver : today in the best 1%

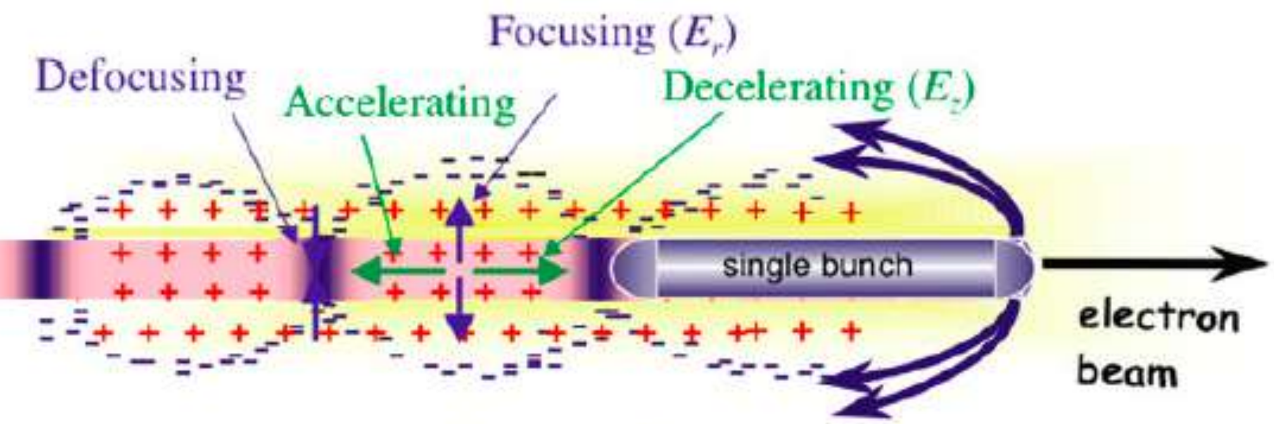
Courtesy of R. Assmann

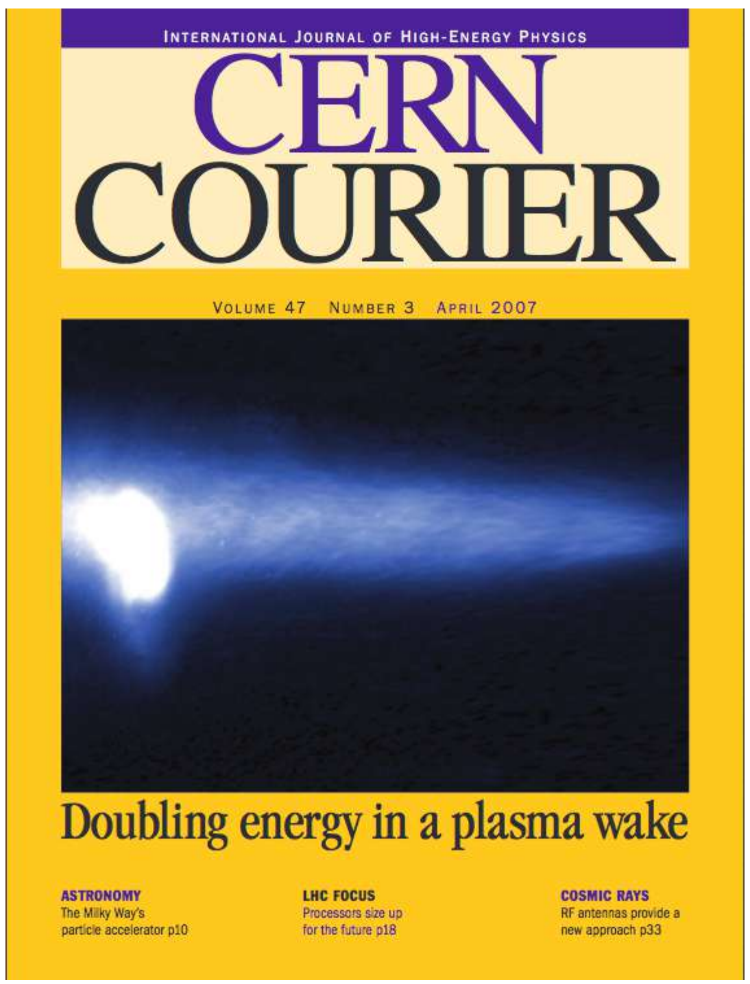
Outline

- Motivation and principle
- Laser Beat wave and Laser Wakefield
- Self Modulated Laser Wakefield
- Towards high quality electron beams in LPA
- Particle Wakefield Accelerator
- Applications
- Conclusion and perspectives

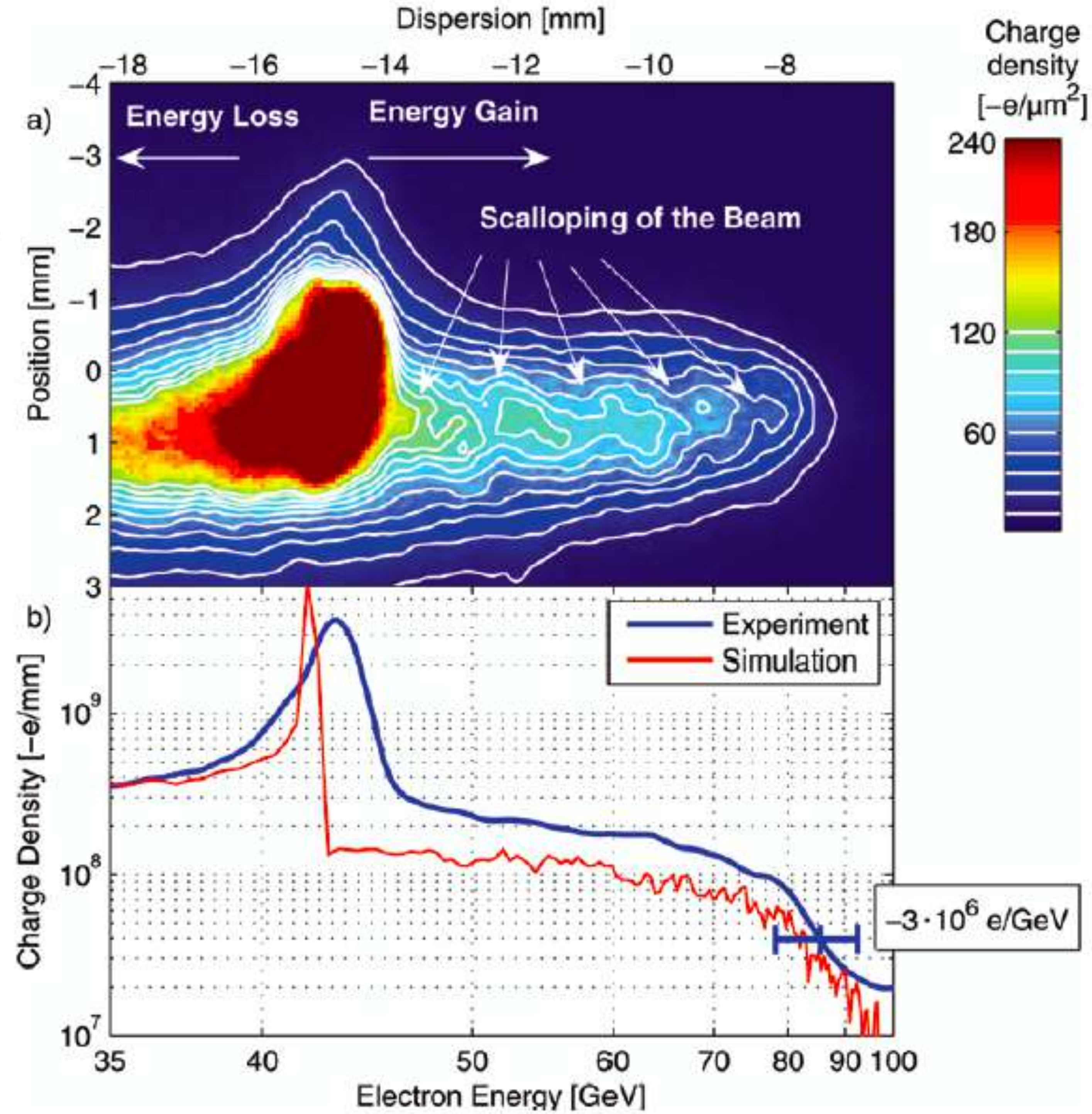
Single bunch PWFA at SLAC/FACET







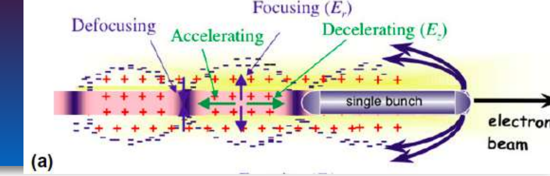
n 85 cm !

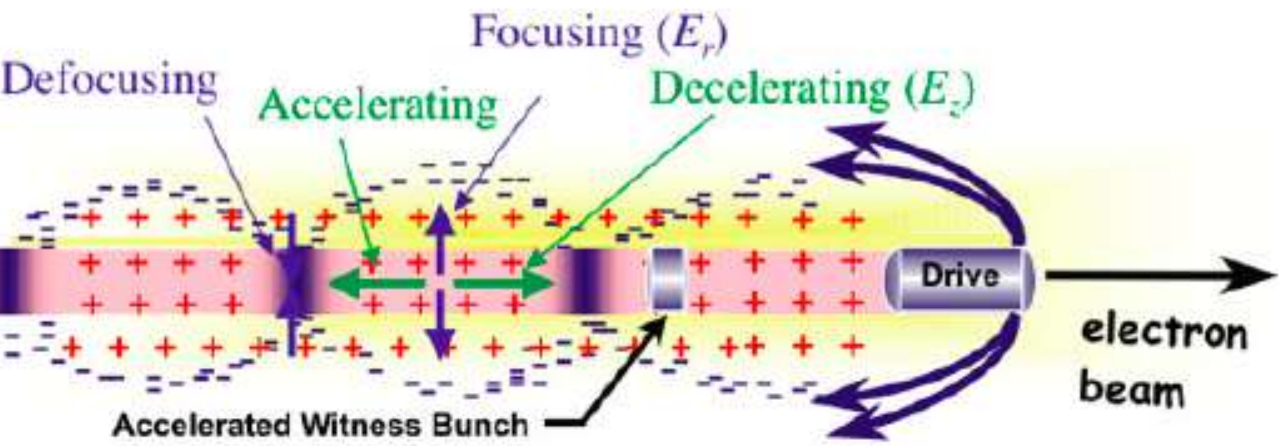


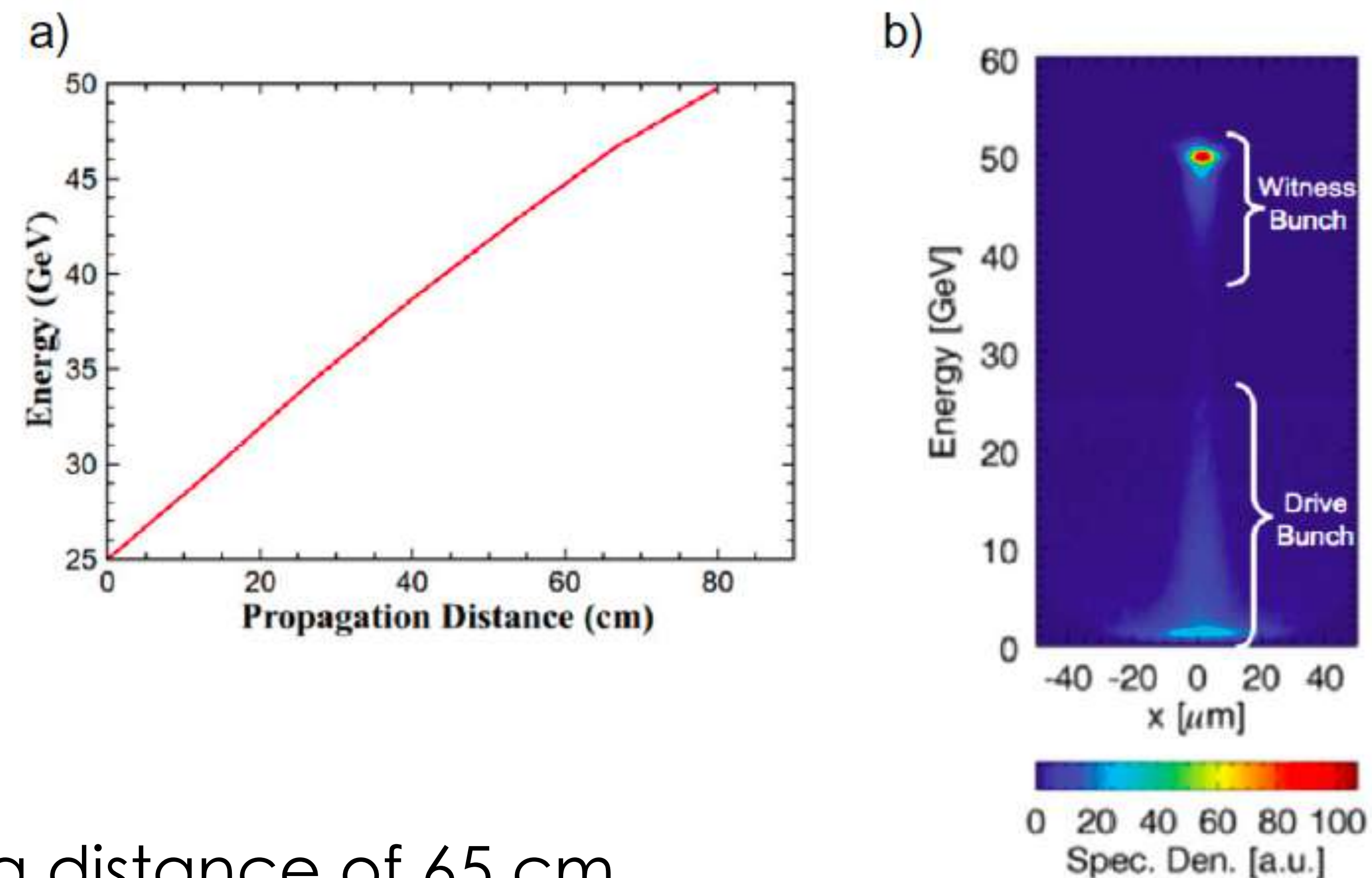
Courtesy of P. Muggli

Blumenfeld *et al.*, Nature 445 (2007), P. Muggli et al., Comptes Rendus de Physique 10 (2009)

Double bunches PWFA at SLAC/FACET



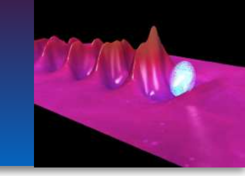




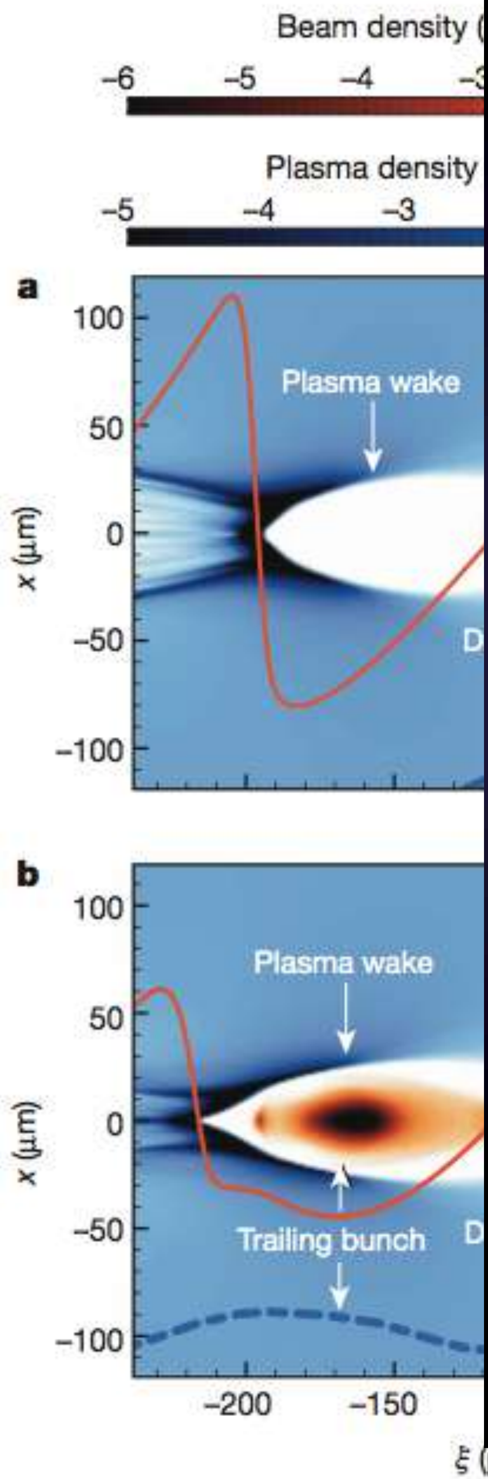
The energy gain is almost linear up to a distance of 65 cm.
At 80 cm, the 25 GeV witness bunch has doubled in energy with an 3% energy spread.
The energy transfer efficiency from the wake to the witness bunch is almost 56%.
The efficiency from the drive to the witness bunch is greater than 30%.

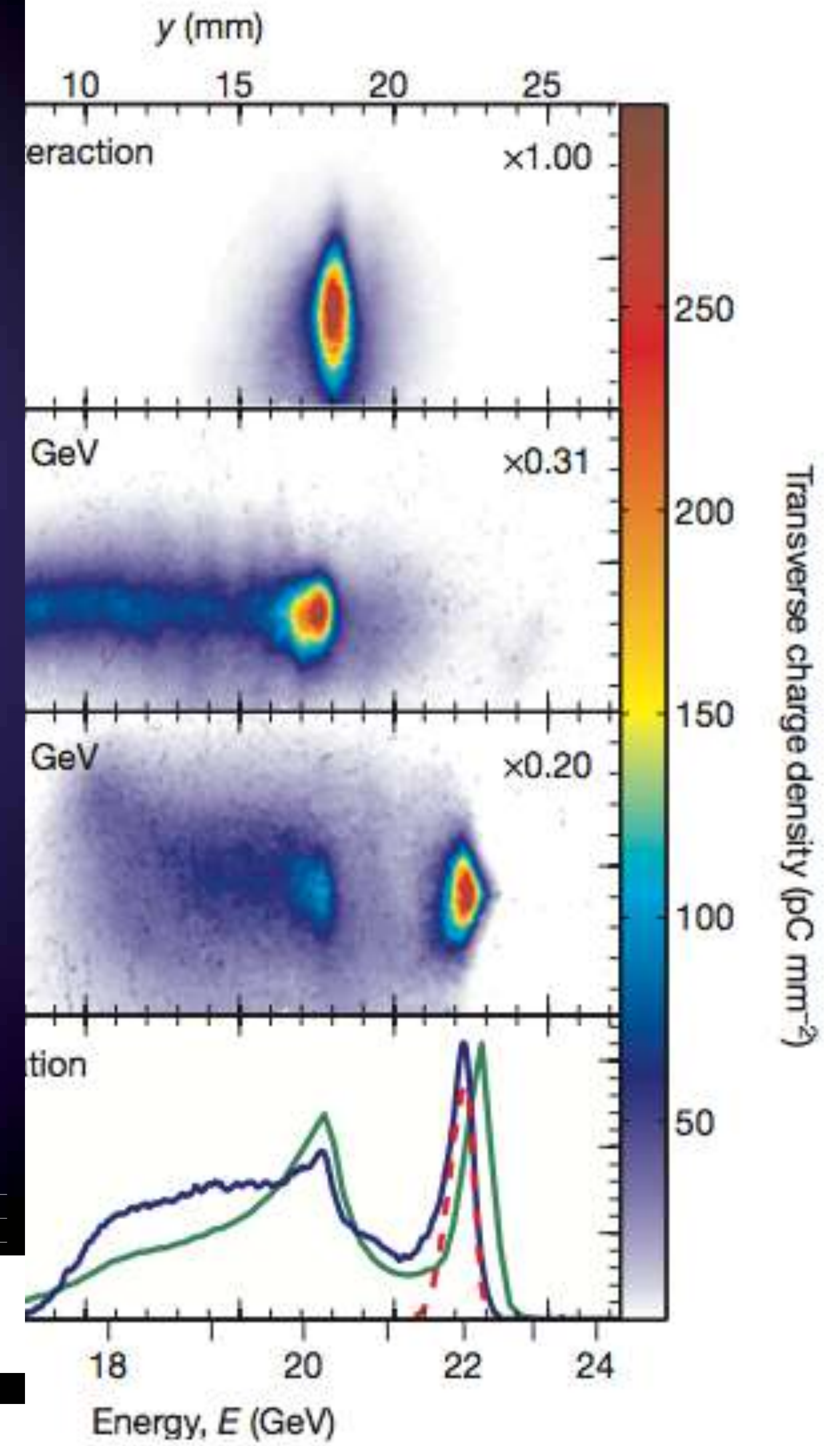
M. Hogan *et al.*, NJP, **12** (2010)   Courtesy of P. Muggli

2 bunches PWFA at SLAC/FACET : impressive milestone



Gain:1.6 GeV, E … % energy transfert





M. Litos *et al.*, Nature, **13882** (november 2014)

loa

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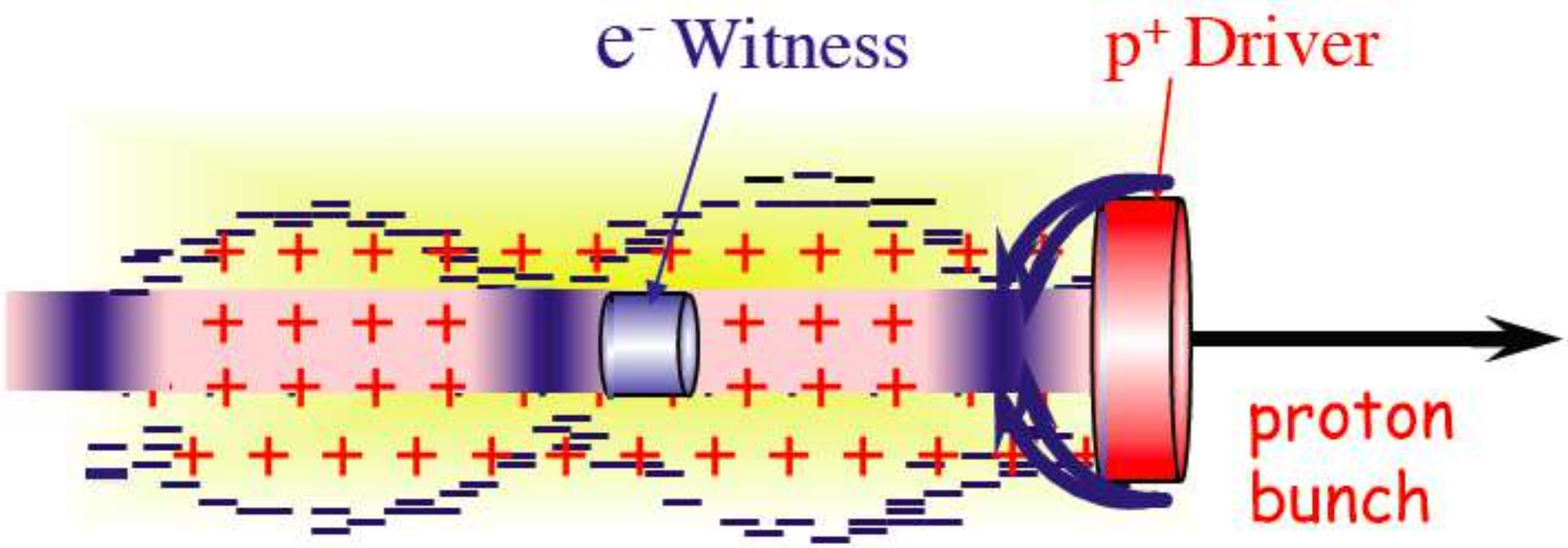
ENSTA

Proton Driven PWFA at CERN : AWAKE project



=> SLAC, 20GeV bunch with $2x10^{10}e^{-}$ ~60J Driver

=> SLAC-like driver for staging (FACET= 1 stage, collider 10+ stages)

=> SPS, 450GeV bunch with $3x10^{11}p^{+}$ ~22kJ Driver
LHC, 7TeV bunch with $3x10^{11}p^{+}$ ~336kJ Driver

=> A single SPS or LHC p^{+} bunch could produce an ILC bunch in a single PWFA stage!

Large average gradient (~GeV/m, 100's m)

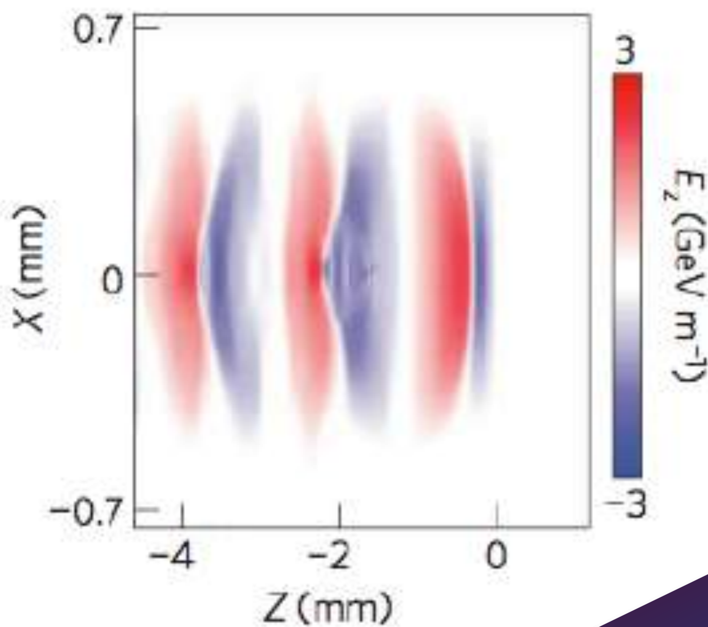
Courtesy of P. Muggli

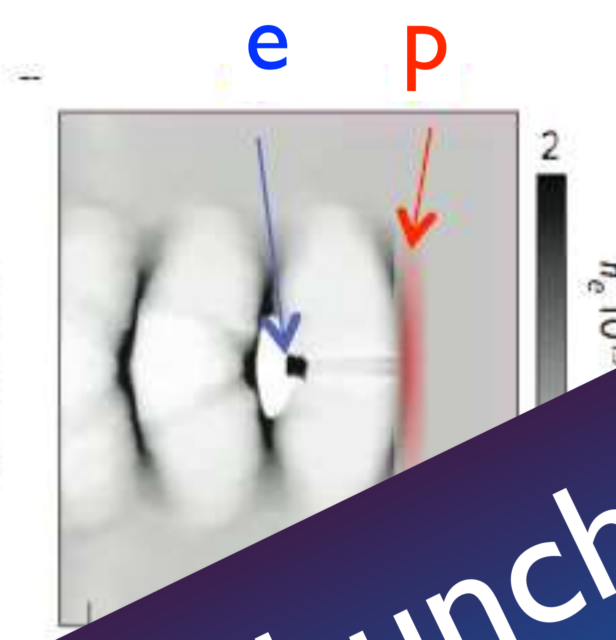
Proton Driven PWFA at CERN : AWAKE project

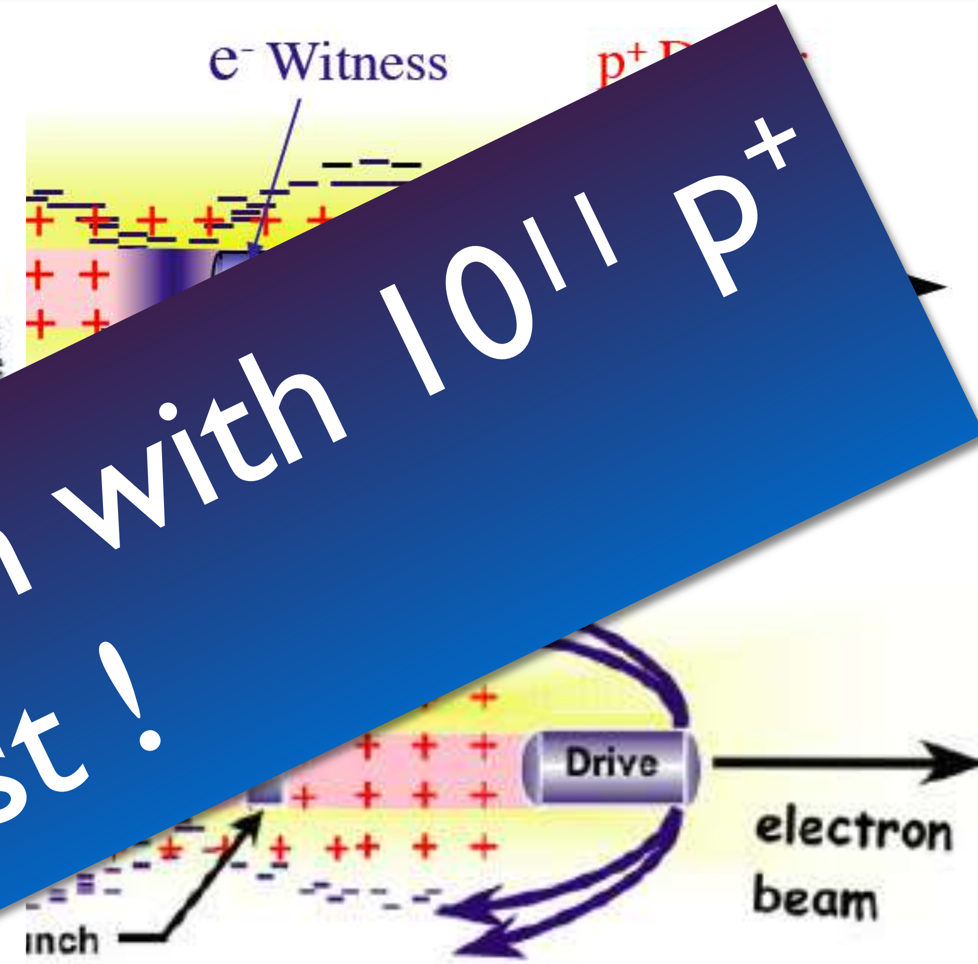
AWAKE

p^+
E_0=1 TeV
σ_z=100μm
N=$10^{11}p^+$

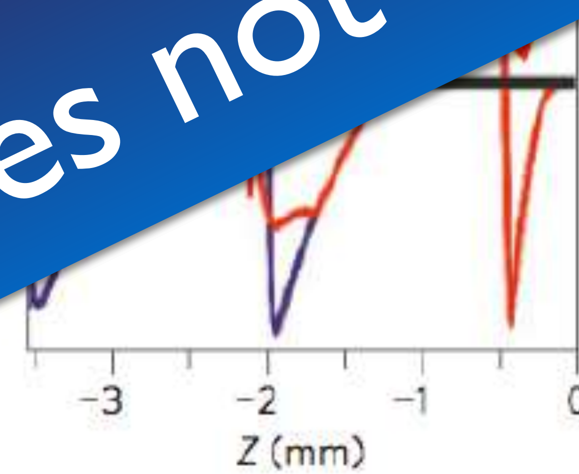
e-
E_0=1 GeV
N=$10^{11}e^-$







Parameter	Symbol	Value	
Protons in drive bunch	N_P		
Proton energy	E_P		
Initial proton momentum spread			
Initial proton bunch longitudinal			
Initial proton bunch angul			
Initial proton bunch			
Electron			
E			
Pl			mm
Ma			T m^{-1}
Magn		.7	m



100 μm long proton bunch with 10^{11} p^+ does not exist !

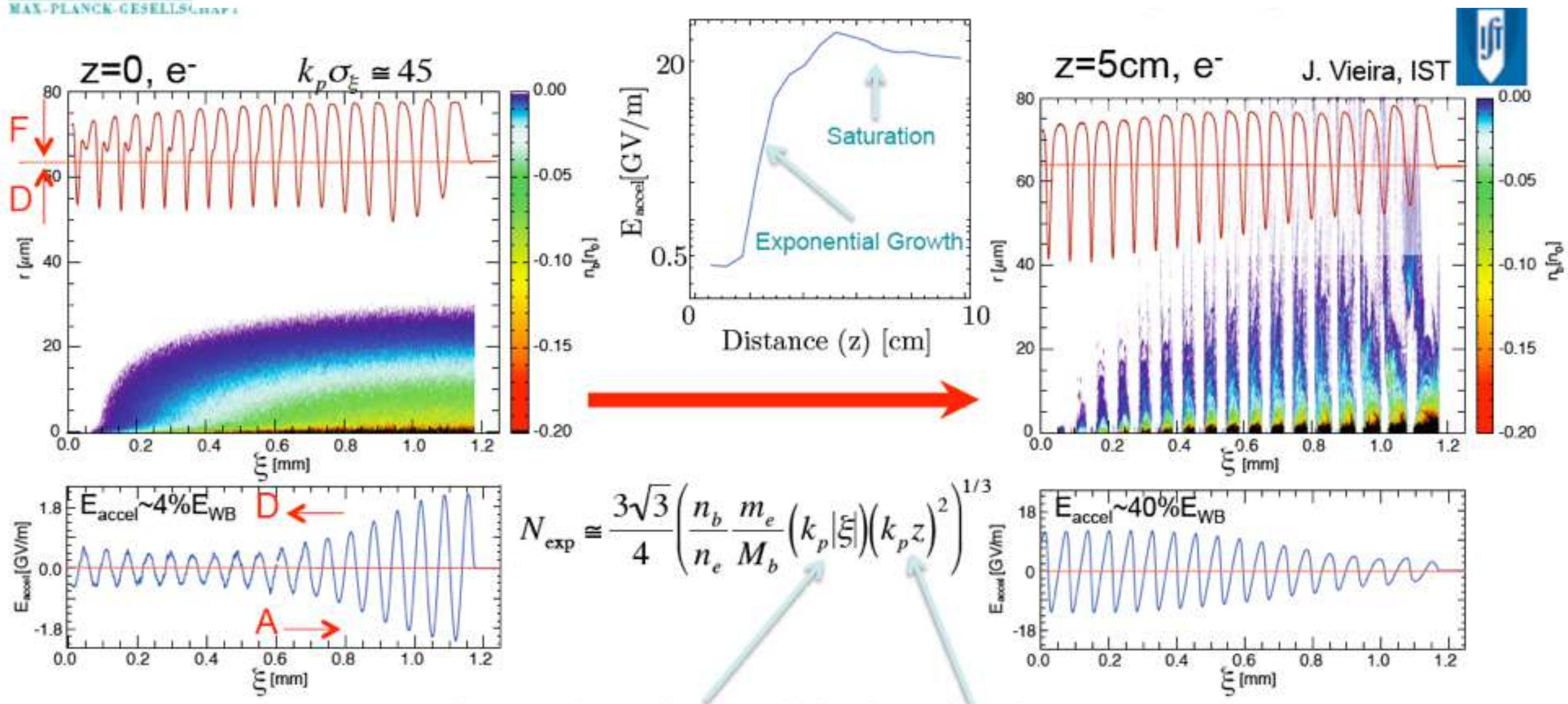
Courtesy of P. Muggli

Caldwell *et al.*, Nature Physics, **5**, 363 (2009)

Gradient ~1.5GV/m (av.): Gain of 0.6 TeV in 500 meter
Reasonable energy spread of less than 1%

Proton Driven PWFA at CERN : SMI

Self-Modulation Instability (SMI)



$$N_{exp} \cong \frac{3\sqrt{3}}{4}\left(\frac{n_b}{n_e}\frac{m_e}{M_b}\left(k_p|\xi|\right)\left(k_p z\right)^2\right)^{1/3}$$

Grows along the bunch & along the plasma
Convective instability

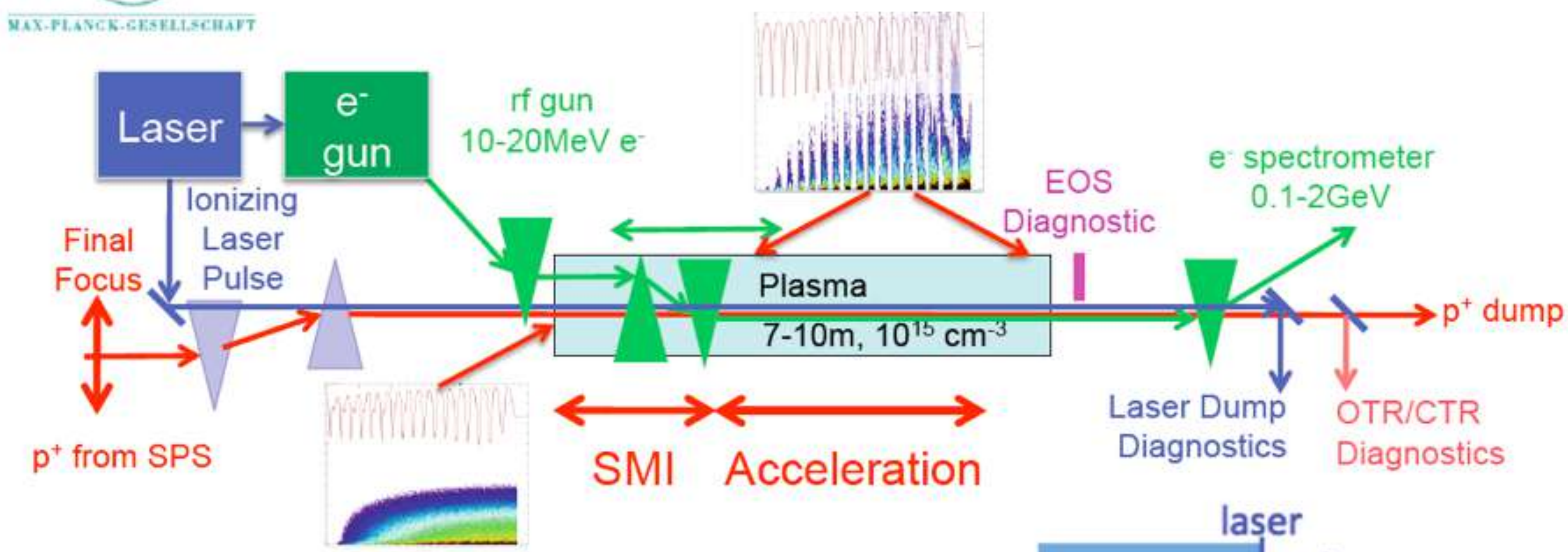
Pukhov et al., PRL 107, 145003 (2011)
Schroeder et al., PRL 107, 145002 (2011)

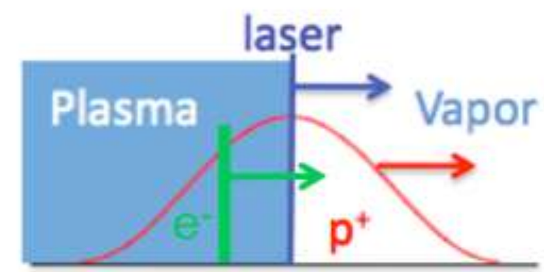
- Initial small transverse wakefields modulate the bunch density
- Associated longitudinal wakefields reach large amplitude through resonant excitation: ~$E_{WB}=mc\omega_{pe}/e$~46GV/m @ $n_e=2.3\times10^{17}cm^{-3}$

J. Vieira et al., Phys. Plasmas 19, 063105 (2012)
P. Muggli

AWAKE: controlling the SMI

Based-Line Experimental Set-up

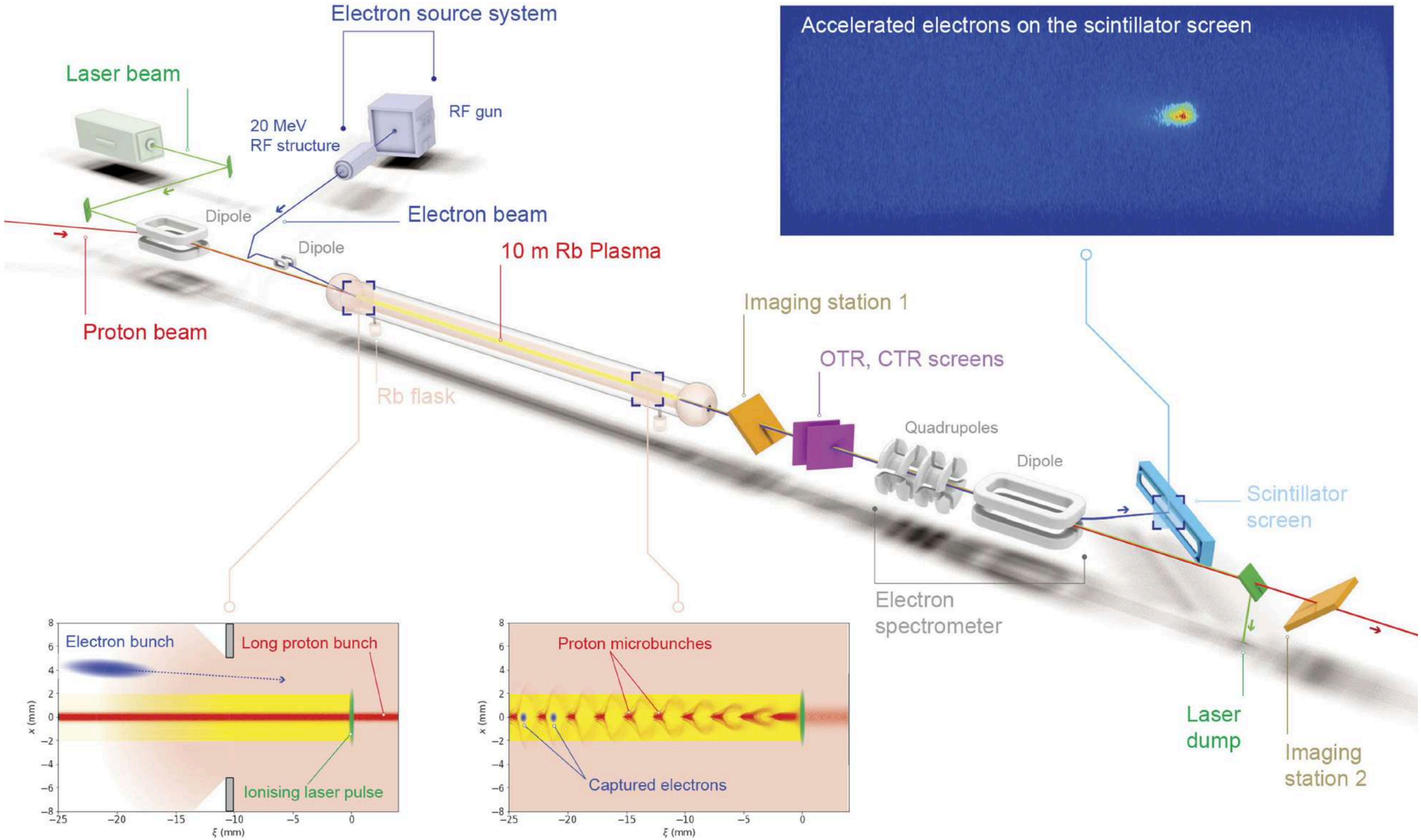




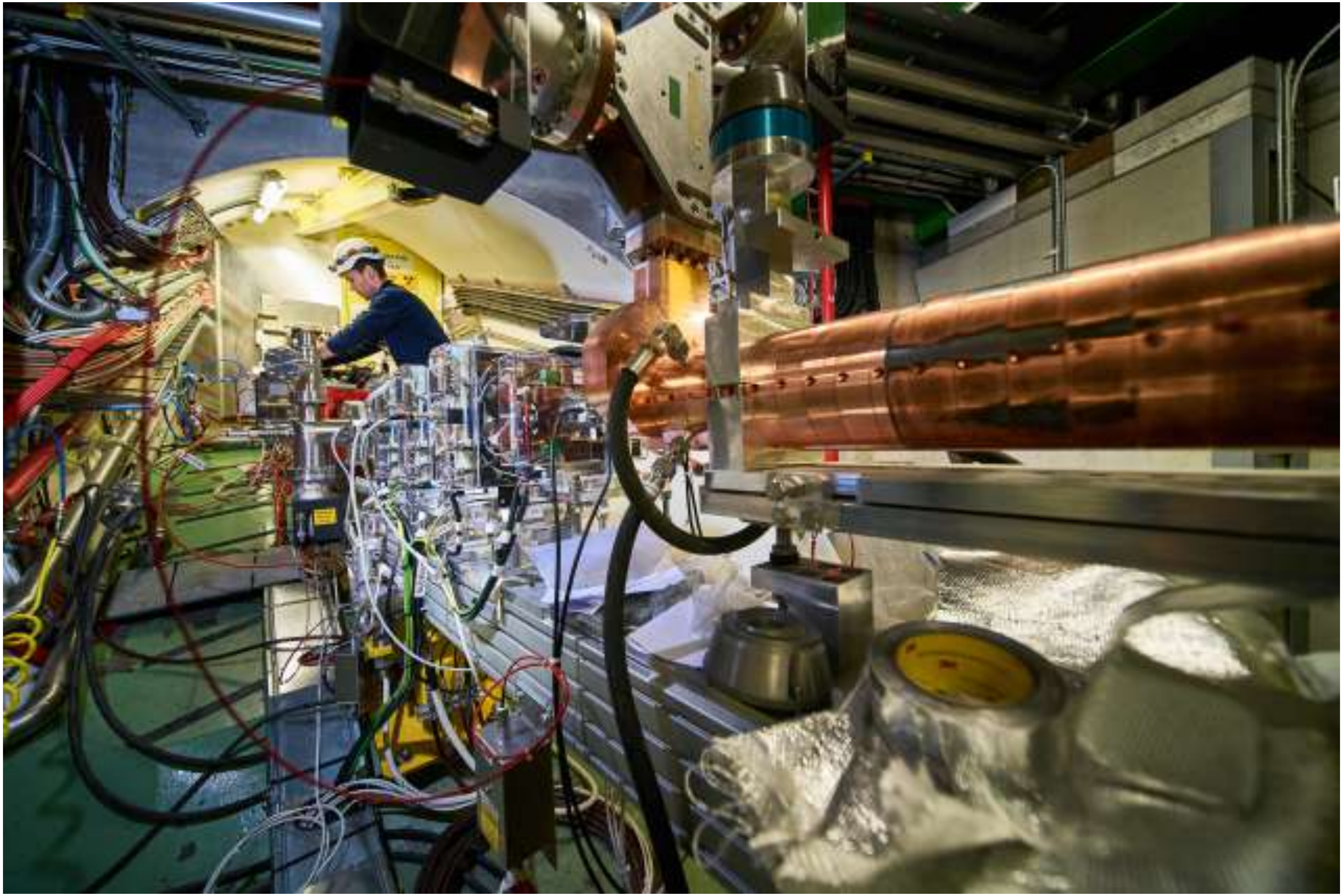
- Laser ionization of a Rb metal vapor, 7-10m plasma, $n_e=10^{14}$-$10^{15}cm^{-3}$
- Injection of 10-20MeV test e- at the 3m point (SMI saturated, $v_\phi=v_{p+}$)
- SMI-acceleration “separated”
- 0.1-5GeV electron spectrometer
- OTR + streak camera, electro-optic sampling for p^+-bunch modulation diag.
- Additional optical diagnostics

P. Muggli

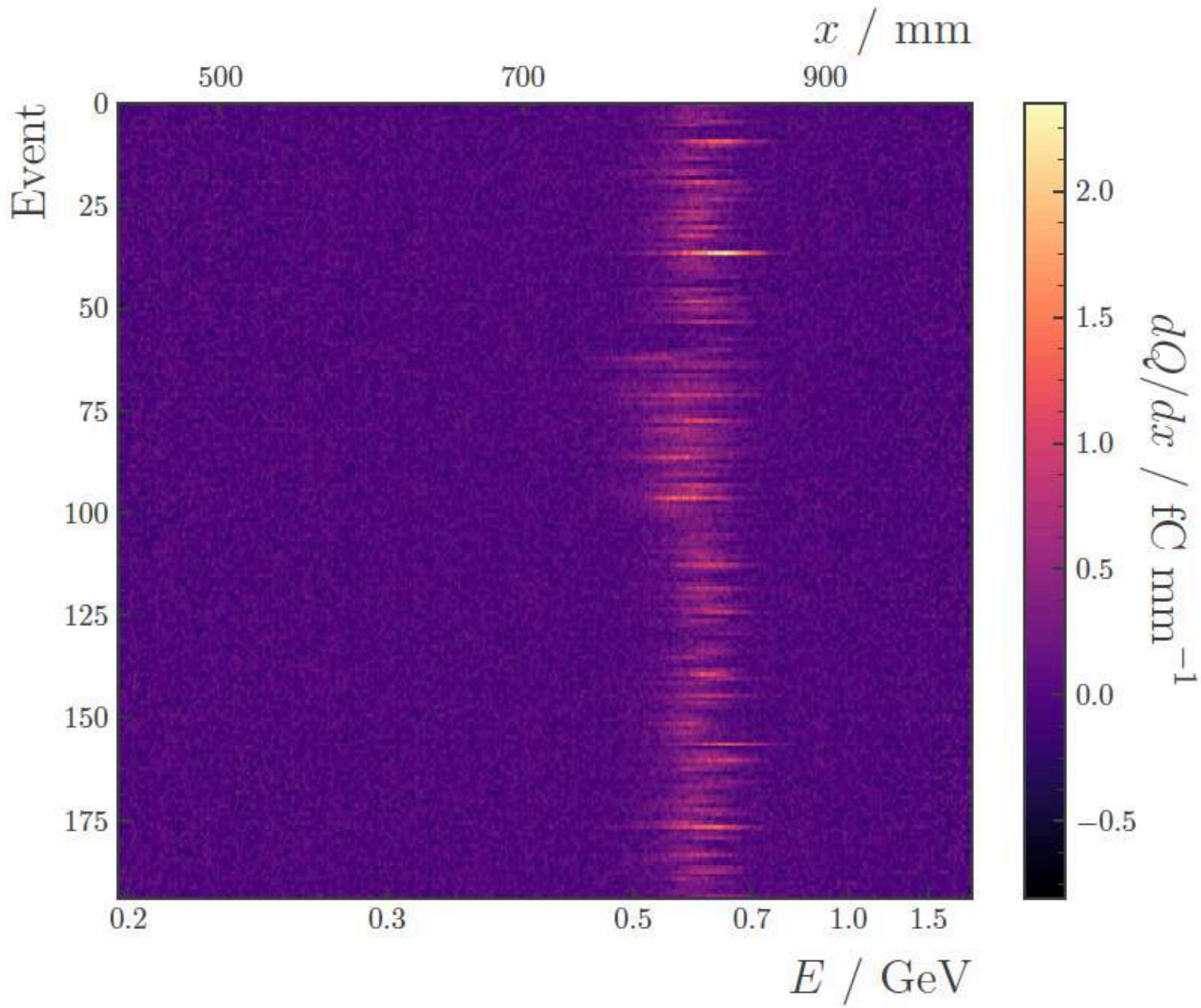
Beams geometry of the experiment



Electron injector @ CERN



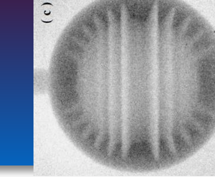
Results : Up to 2 GeV electrons



Outline

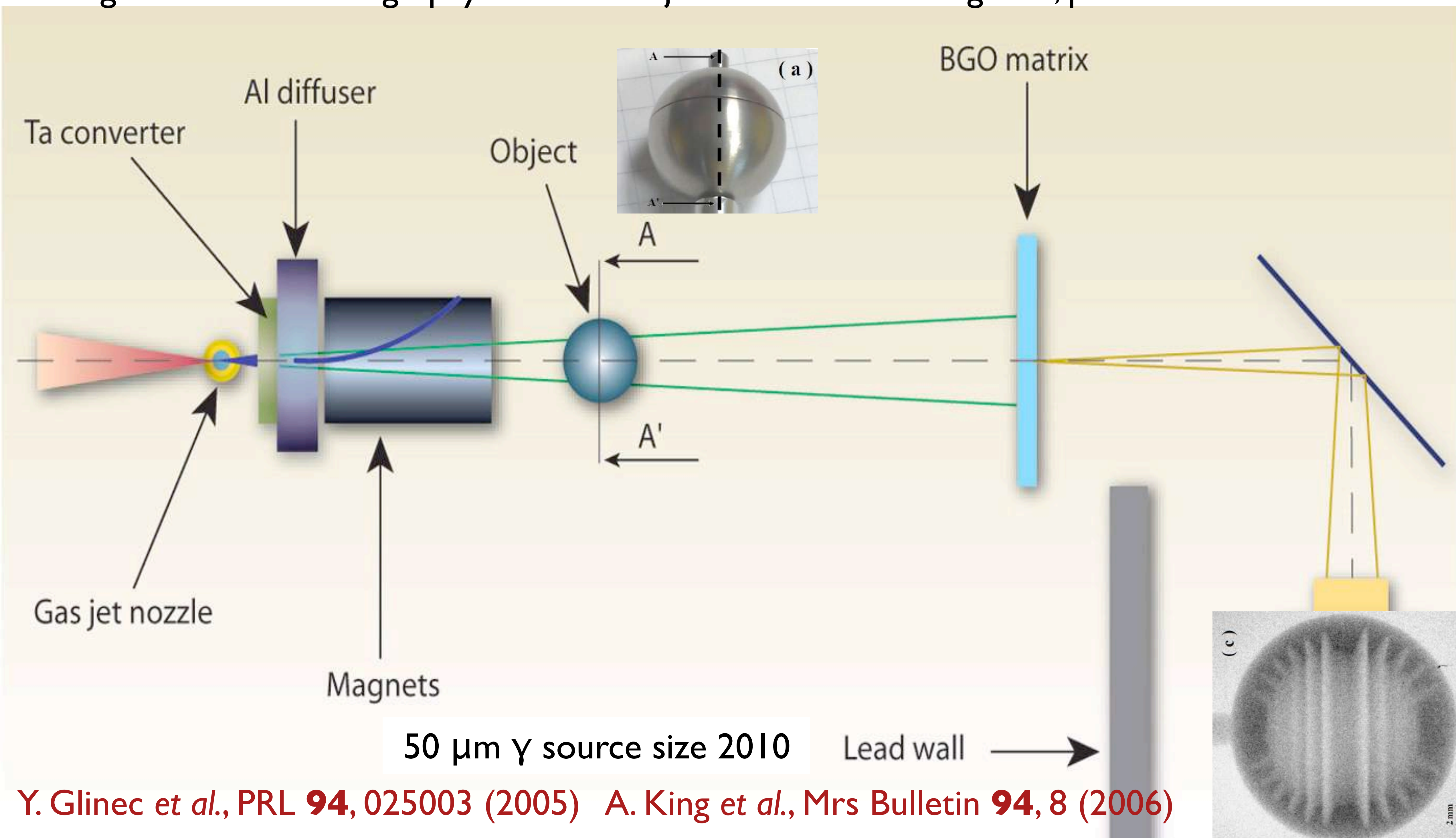
- Motivation and principle
- Laser Beat wave and Laser Wakefield
- Self Modulated Laser Wakefield
- Towards high quality electron beams in LPA
- Particle Wakefield Accelerator
- Applications
- Conclusion and perspectives

Some examples of applications : radiography



Non destructive dense matter inspection

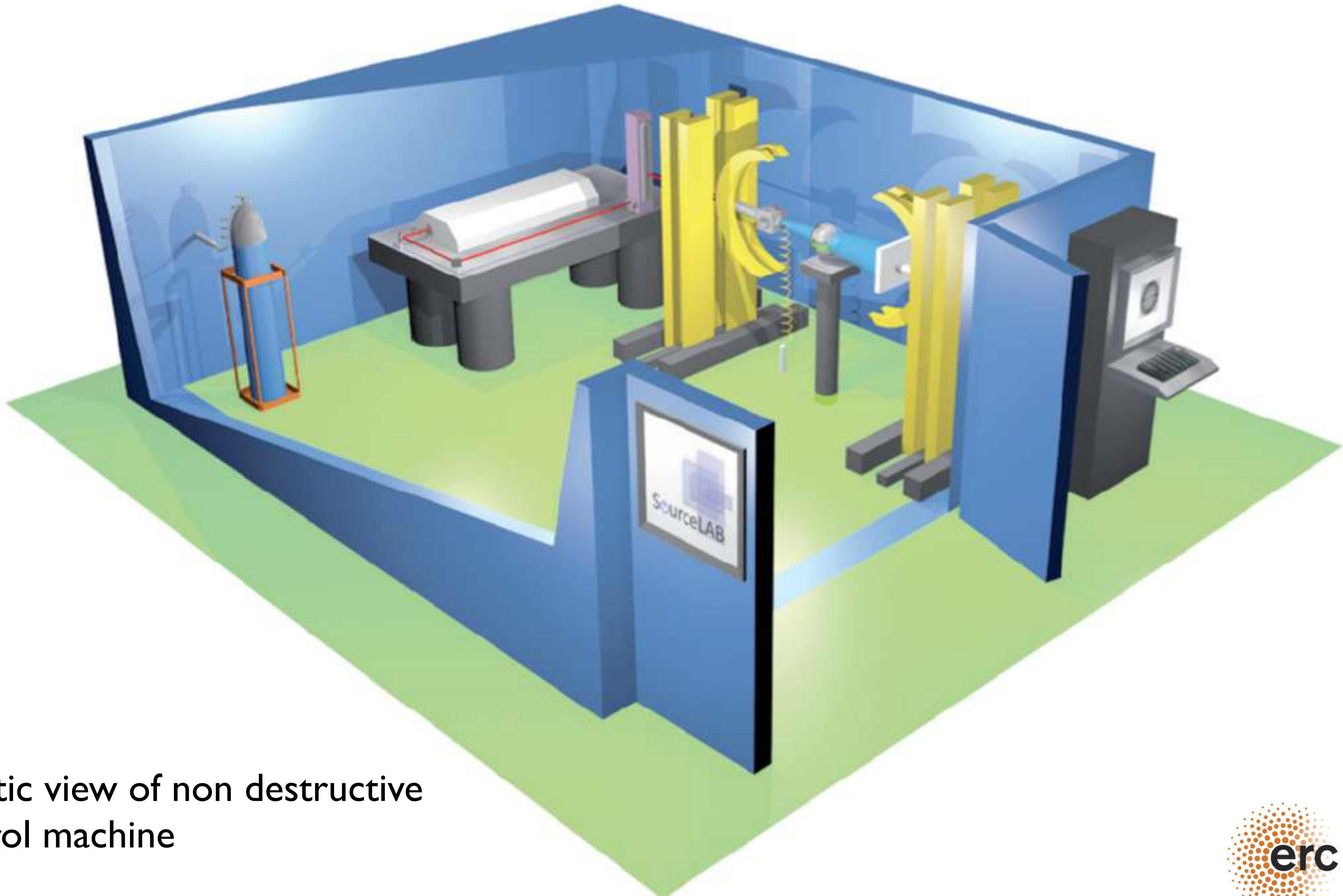
High resolution radiography of dense object with a low divergence, point-like electron source



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

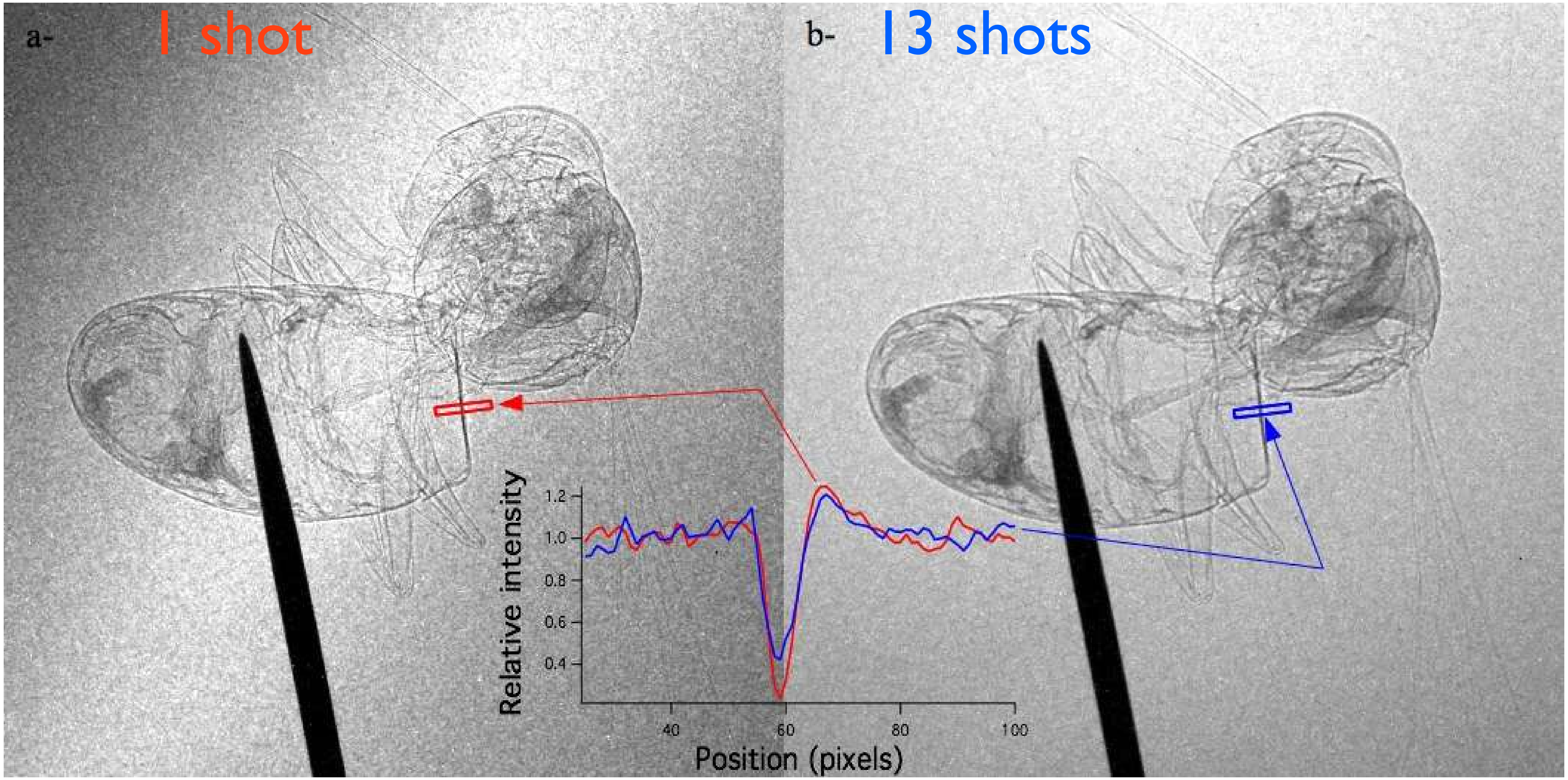


Artistic view of non destructive control machine

Phase contrast imaging : results

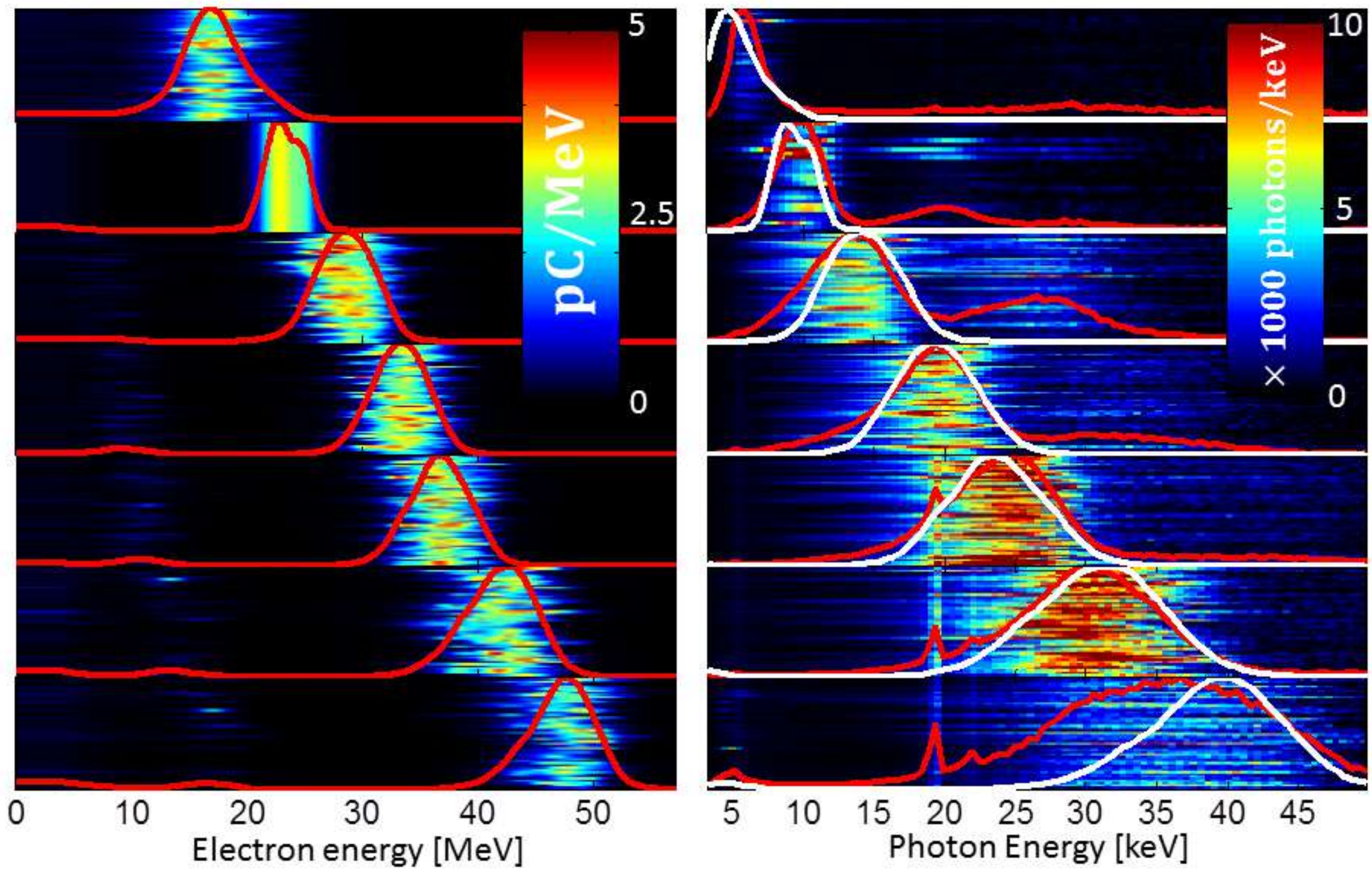
Bee contrast image :

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



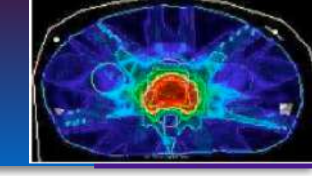
S. Fourmaux *et al.*, Opt. Lett. **36**, 2426 (2011)

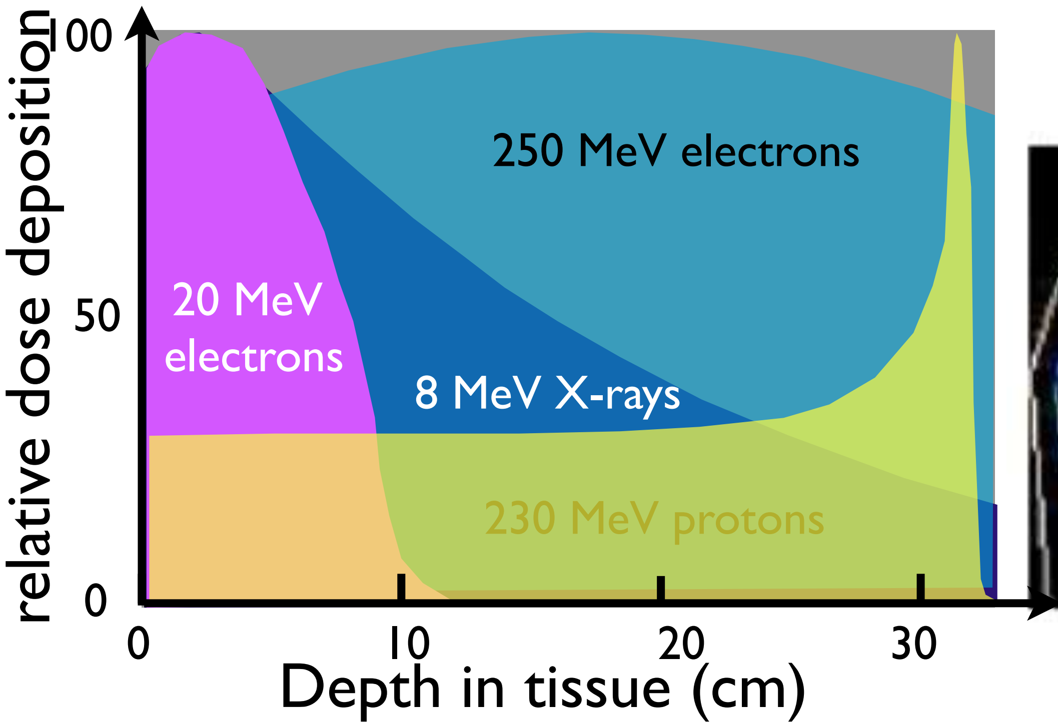
Inverse Compton Scattering : Compton Spectra



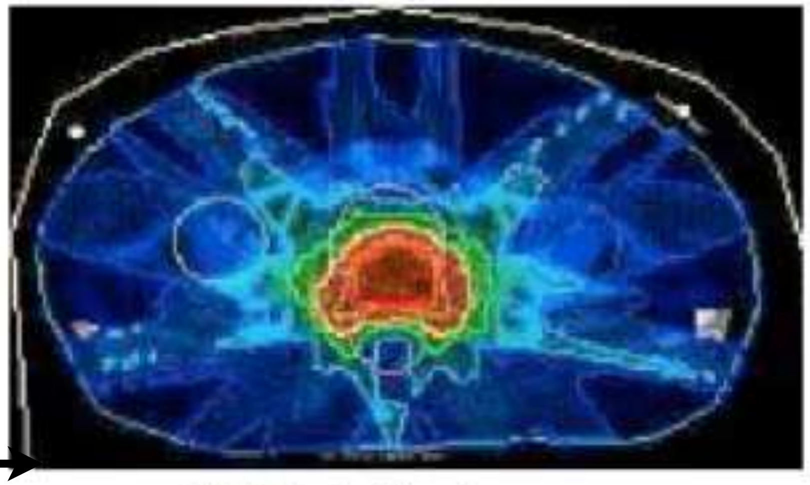
Courtesy of S. Karsh

Some examples of applications : radiotherapy

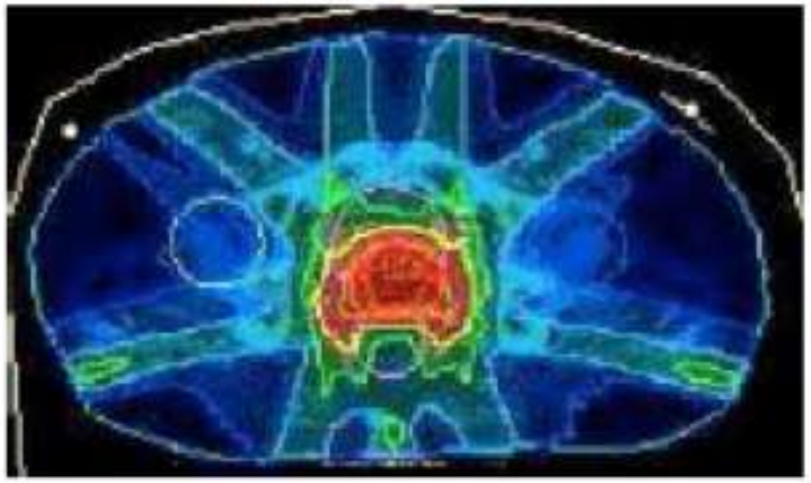




simulations of prostate cancer with 7 irradiation beams



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)

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Conclusions for Laser Driven Wakefield Acceleration

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 8 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 1 for Laser Driven Wakefield Acc.

New ideas for controlling the injection ?

Cold injection scheme[1], Two colors colliding pulses[2], Two pulses ionization injection[3], Trojean injection[4]

Magnetic control of injection[5], positron acceleration in NL LPAW[6]

Control phase of the electric field[7], Transverse injection scheme[8]…

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[9], magnetic field[10], interferometry in the frequency-time[11], etc...

[1]X. Davoine *et al.*, Phys. Rev. Lett. **102**, 065001(2009), PRL, [2]X. L. Xu *et al.*, PRSTAB **17**, 061301 (2014), [2]L. L. Yu *et al.*, PRL **112**, 125001 (2014), [3]N. Bourgeaois *et al.*, PRL **111**, 155004 (2013), [4]B. Hidding et al, PRL **108**, 035001 (2012), [5]J. Vieira *et al.*, Phys. Rev. Lett. **106**, 225001(2011), [6]J. Vieira *et al.*, PRL **112**, 215001 (2014), [7]A. Lifshitz *et al.*, NJP **14**, 053045 (2012), [8]R. Lehe *et al.*, PRL **111**, 085005 (2013), [9]A. Rousse *et al.*, Phys. Rev. Lett. **93**, 13 (2004), [9]K. Ta Phuoc *et al.*, Phys. Rev. Lett. **97,** 225002 (2006), [10]M. C. Kaluza *et al.*, Phys. Rev. Lett. **105**, 115002 (2010), [10]A. Buck *et al.*, Nature Physics **8,** (2011), [11]N. H. Matlis *et al.* , Nature Physics 2006,

Perspectives 2 for Laser Driven Wakefield Acc.

Short term perspective (< 10 years):

Relevant applications in medicine, radiobology, material science

Compact FEL with moderate average power (10 Hz system)

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

Long term possible applications (>40-50 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 for Particle Driven Wake Field Acc.

Proton beam seems today the best driver

Proton beam will be benefit of shortness driver

2 GeV high quality e- beam (4 m & GV/m)

Doubling 42 GeV electron energy in less than 1m

Positron acceleration is demonstrated

Increasing activities on beam driver (FACET, CLARA, INFN, DESY)

Many challenges/open questions :

Producing stable, reliable and long plasma devices

Synchronization/jitter issues

Beam loading effects

Laser-PWAs allow today to explore several applications with the hope of compactness and cost reduction. They allow to produce secondary sources for many applications (particularly for pump-probe experiments, bright X-rays

It is a very exciting time for plasma accelerators !

Proton beam driver exist and allow a single stage efficient accelerator

The involvement of accelerators community will be a key element of success of this wonderful and exciting research

A wonderful tool for Science and Societies

Coming SOOOOON : Next LPAW 2019

Laser-Plasma Accelerator Workshop 2019

5-10 mai 2019 Split, Croatia

Deadline : March 31 !

Acknowledgements

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

M. Downer et al. from U.T., X. Davoine &E. Lefebvre from CEA, 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, O. Lundh from LLC, 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}/Charpac/Laserlab$^{2\text{-}3}$—ANR-PARIS & X-five/ERC contracts