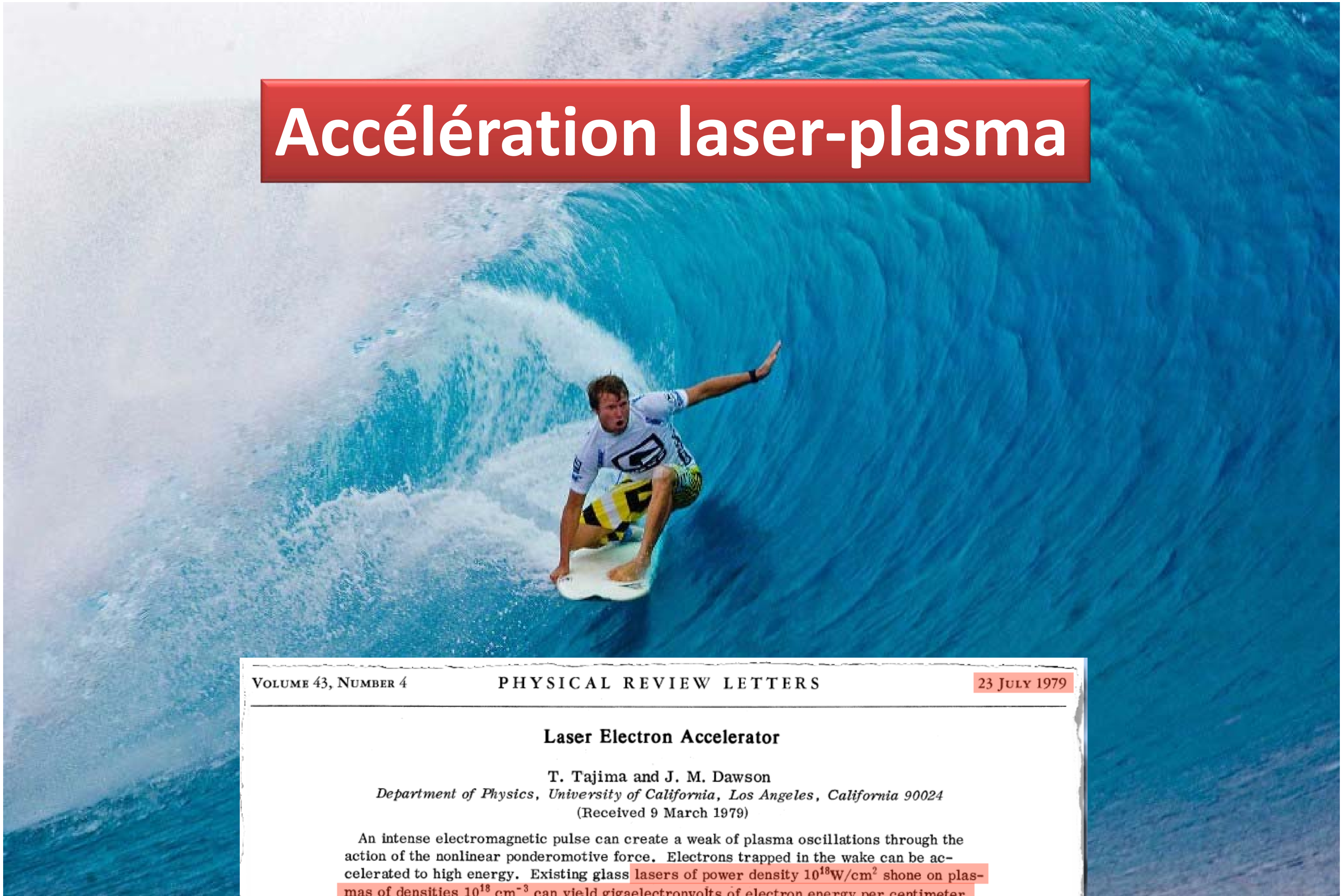
Accélération laser-plasma



VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

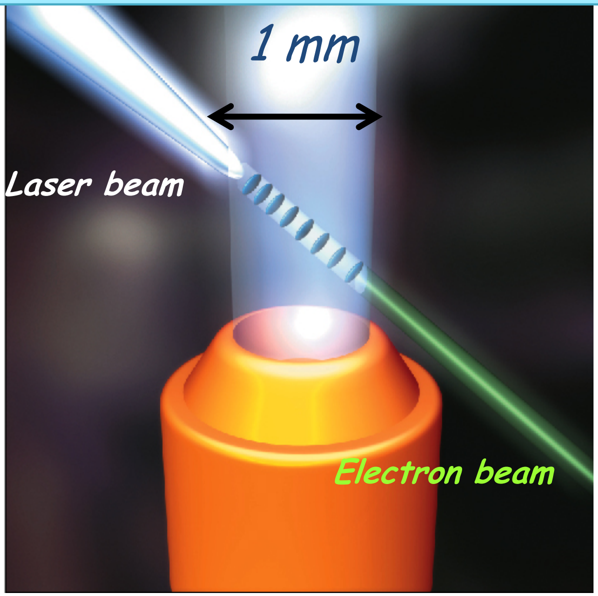
Laser Electron Accelerator

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

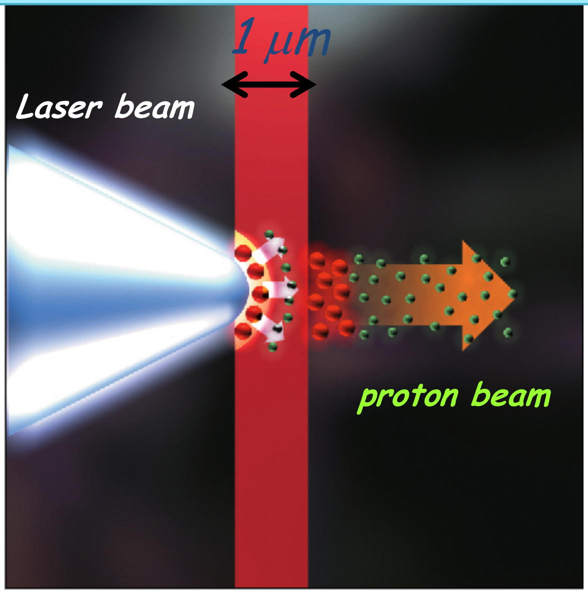
An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield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

- Matériel de ce cours entièrement pris sur le web (!)
  - K. Cassou
  - B. Cross
  - N. Delerue
  - E. Esarey→REVIEWS OF MODERN PHYSICS, VOLUME 81, JULY–SEPTEMBER 2009
  - F. Grüner
  - W. Leemans (→youtube)
  - V. Malka
  - P. Monot
  - J Osterhoff
  - C. Rechatin
  - U Schramm
  - C.B Schroeder
  - A Specka
  - + publications

Laser INTENSE (10^{18}W/cm^2)+ jet de gaz



Laser INTENSE (10^{20}W/cm^2)+feuille tungsten

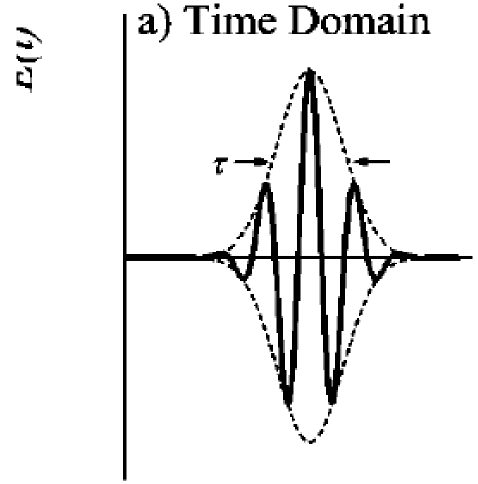


Plan

- ❑ Ondes plasma en régime linéaire
  - ❑ Accélération d'un faisceau d'électron
- ❑ Ondes plasma en régime non-linéaire (régime de la bulle)
  - ❑ Injection 'interne' de électrons
  - ❑ État de l'art, performances
- ❑ Production de rayons X (et gamma) dans les plasmas
- ❑ Production de faisceaux de protons

Onde plasma
Régime linéaire

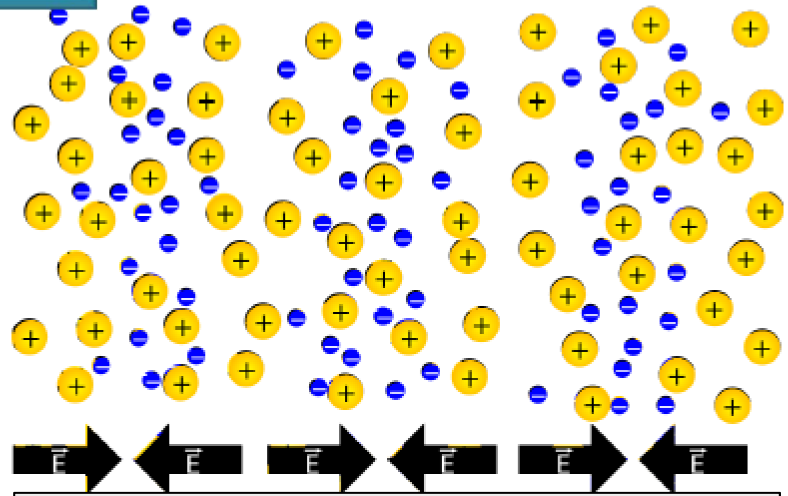
Pulse laser intense



1fs=10^{-15}s
=0,000000000000001s

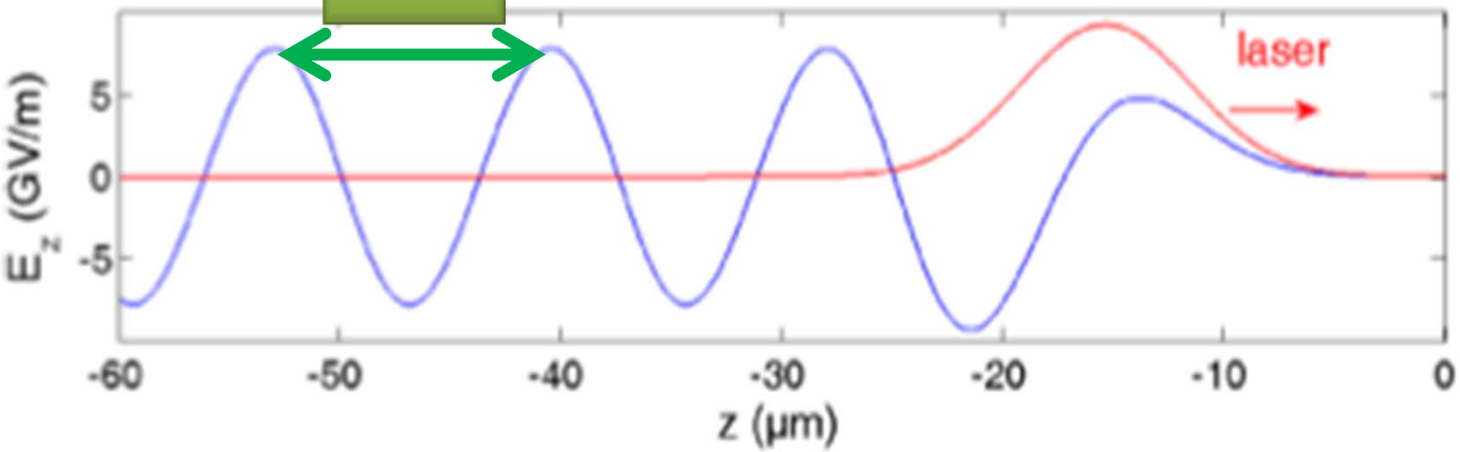
+ Gaz

onde plasma



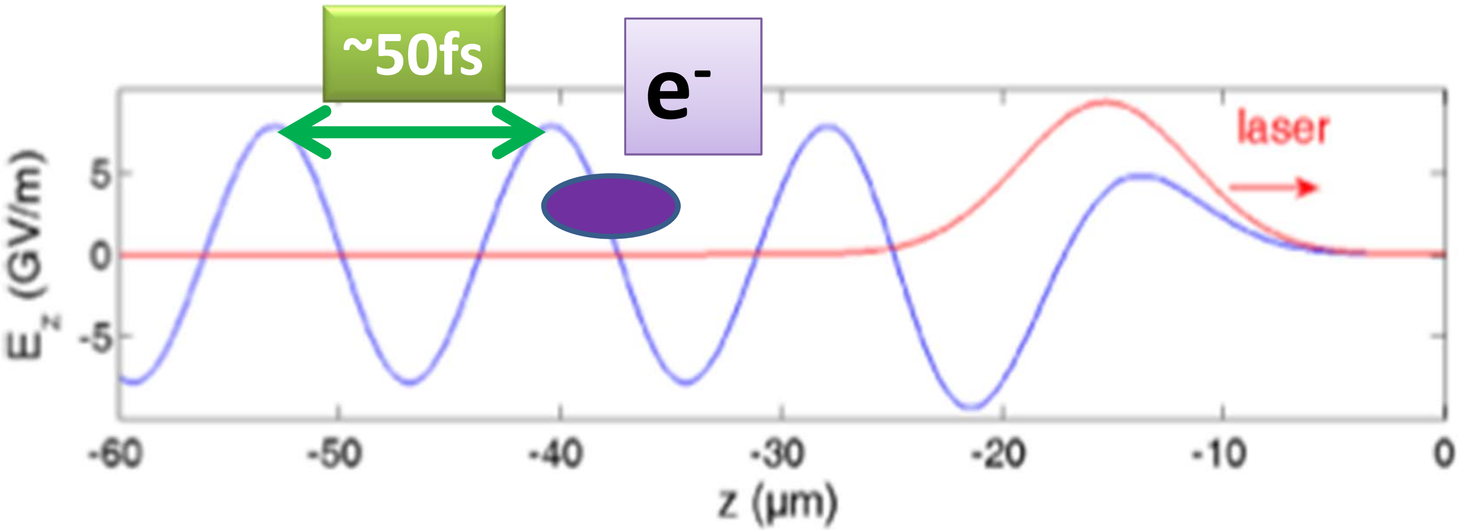
Champs électriques ~100GV/m !
Dans le 'sillage' de l'onde laser
(qques 10MV/m en techno standard)

~50fs



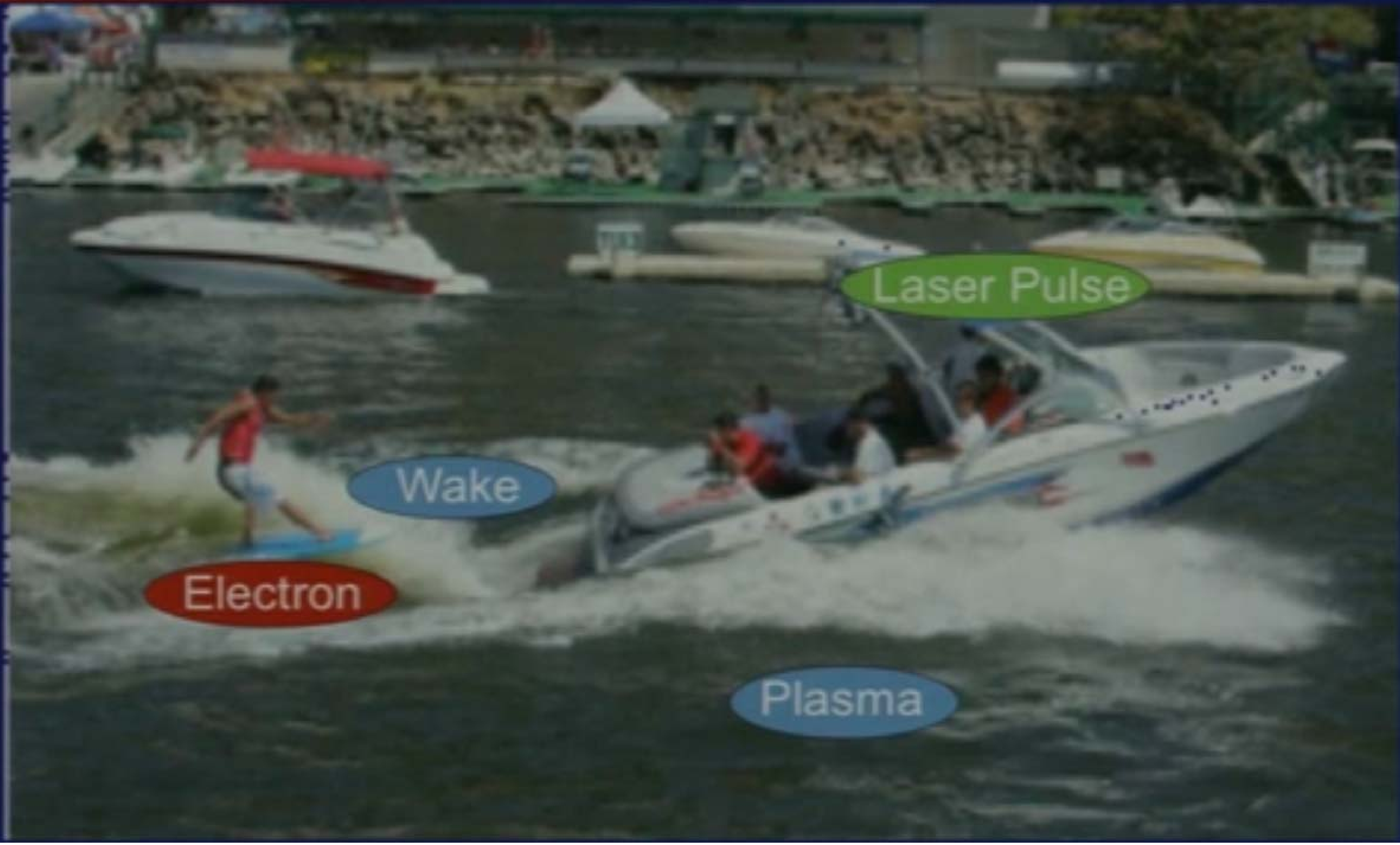
Principe d'accélération en régime linéaire
INJECTION EXTERNE

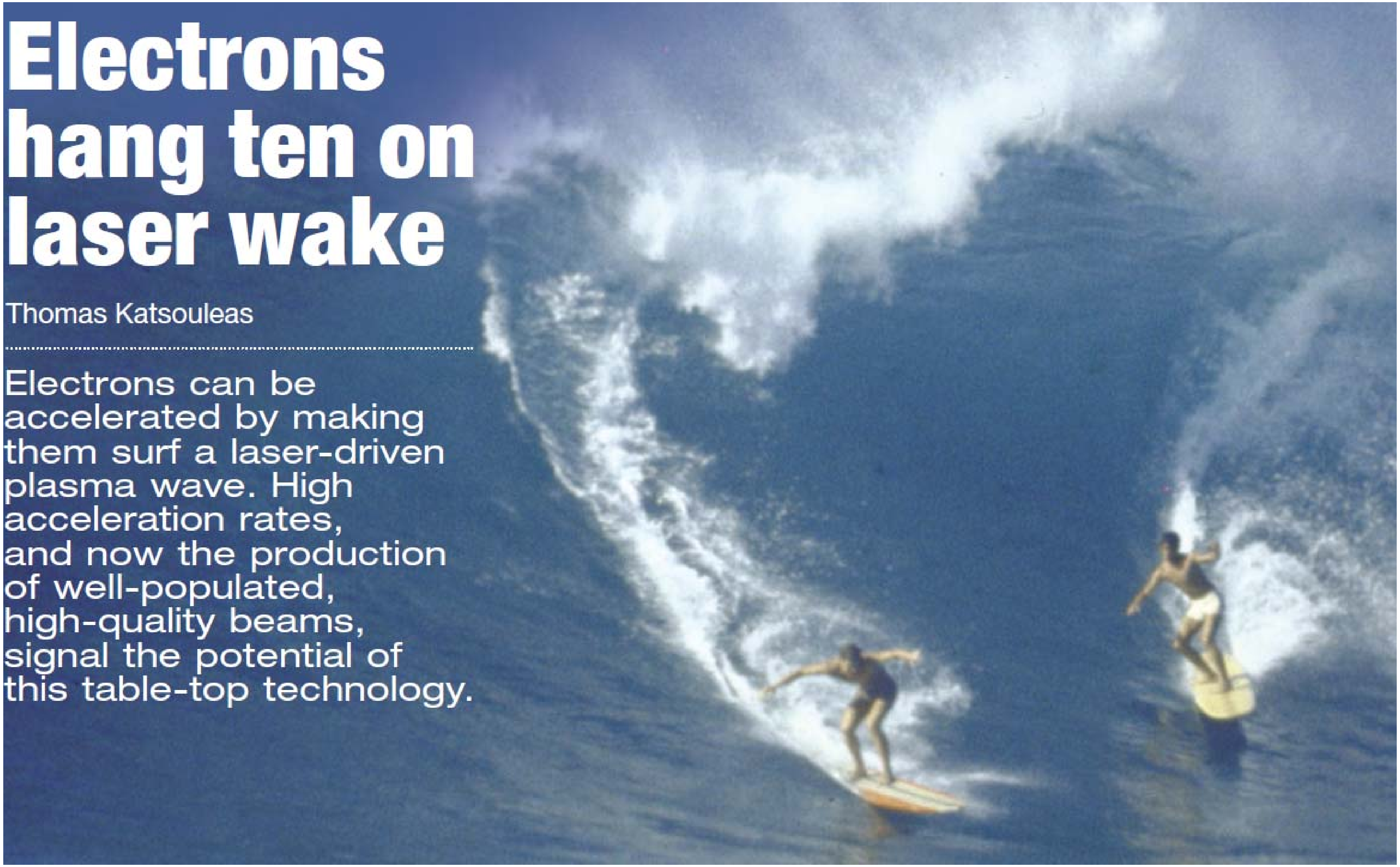
Si on envoie un paquet d'électrons 'en phase' avec 'l'onde plasma' il sera accéléré



MAIS pour accélérer un paquet d'électrons
il faut qu'il ait une longueur temporelle ~10fs (L=ct=3µm)…

Laser plasma accelerator basics: similar to surfing on a boat-driven wake





Electrons hang ten on laser wake

Thomas Katsouleas

Electrons can be accelerated by making them surf a laser-driven plasma wave. High acceleration rates, and now the production of well-populated, high-quality beams, signal the potential of this table-top technology.

Classical accelerator limitations

E-field$_{max}$ ≈ few 10 MeV /meter (Breakdown)
R>R$_{min}$ Synchrotron radiation

→ Energy ↗ = Length ↗ = $$$ ↗

LEP at CERN

27 km

Circle road

31 km

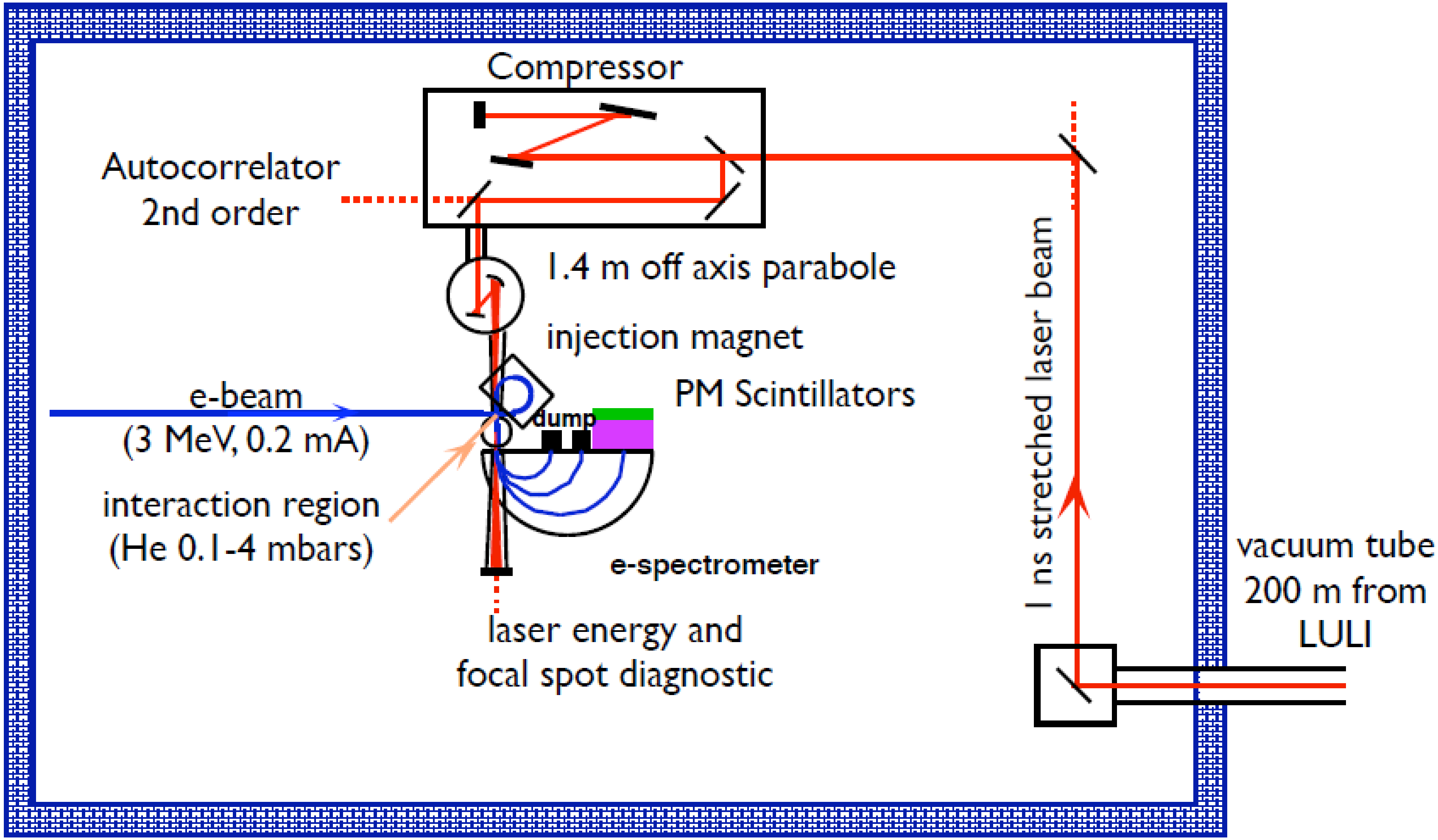
→ **New medium : the plasma**

LOA

1998 Accelerated electrons in LWF

LULI/LPNHE/LSI/IC

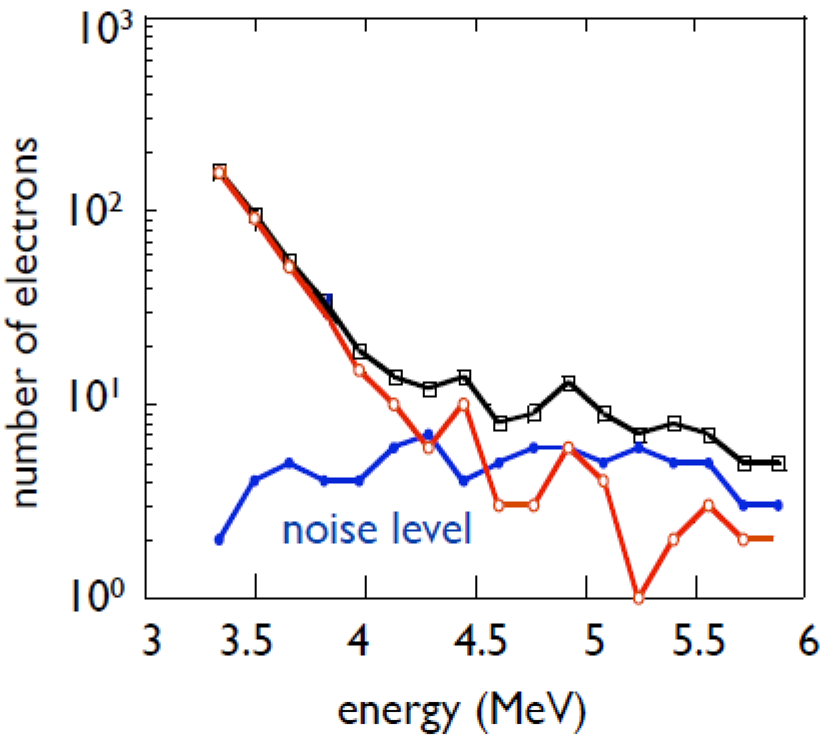
Electron spectra indicate an E_{field} of ≈ 1 GV/m



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

Il a fallu mettre en œuvre des sources laser intenses et courtes
➔CPA technique
➔Tis:sapph medium

Où en est-on aujourd'hui ?

- ✓ Pas de résultats expérimentaux
- ✓ Des simulations

Nuclear Instruments and Methods in Physics Research A 653 (2011) 66–71

Results of modeling for different injected bunch lengths, charges and radii.

q_{inj} (pC)	15		10		5		2.5
L_{b0} (μm)	71		47		24		12
R_{b0} (μm)	45	33	45	33	45	33	33
Compression ratio	0.0317	0.0358	0.0198	0.0268	0.0177	0.0244	0.0126
Compressed rms length L_b (μm)	2.25	2.54	0.93	1.26	0.42	0.58	0.15
Final rms radius R_b (μm)	0.98	0.96	0.87	0.85	1.09	0.92	1.06
Final density of accelerated bunch n_b (10^{18} cm^{-3})	3.3	3.6	5.9	6.8	3.1	3.4	2.7
Trapped charge, pC	3.6	4.6	2.1	3.2	0.77	0.84	0.22
Energy spread $\Delta E/E$ (%)	8.4	8.0	1.1	2.0	1.4	2.0	1.2
Normalized emittance ε_n (mm × mrad)	6.9	6.5	5.4	5.2	8.5	6.3	8.5

This table versus ILC

- Charge 0.001nc versus 3nc/bunch
- Energy spread: qques versus 0.1%
- Nb de paquet: ~1/s versus 5000/s
- Répétabilité : max 40 paquets d'e⁻ versus l'infini !

This table versus ILC

- Pulse length: 1µm versus 300µm
- Longueur…

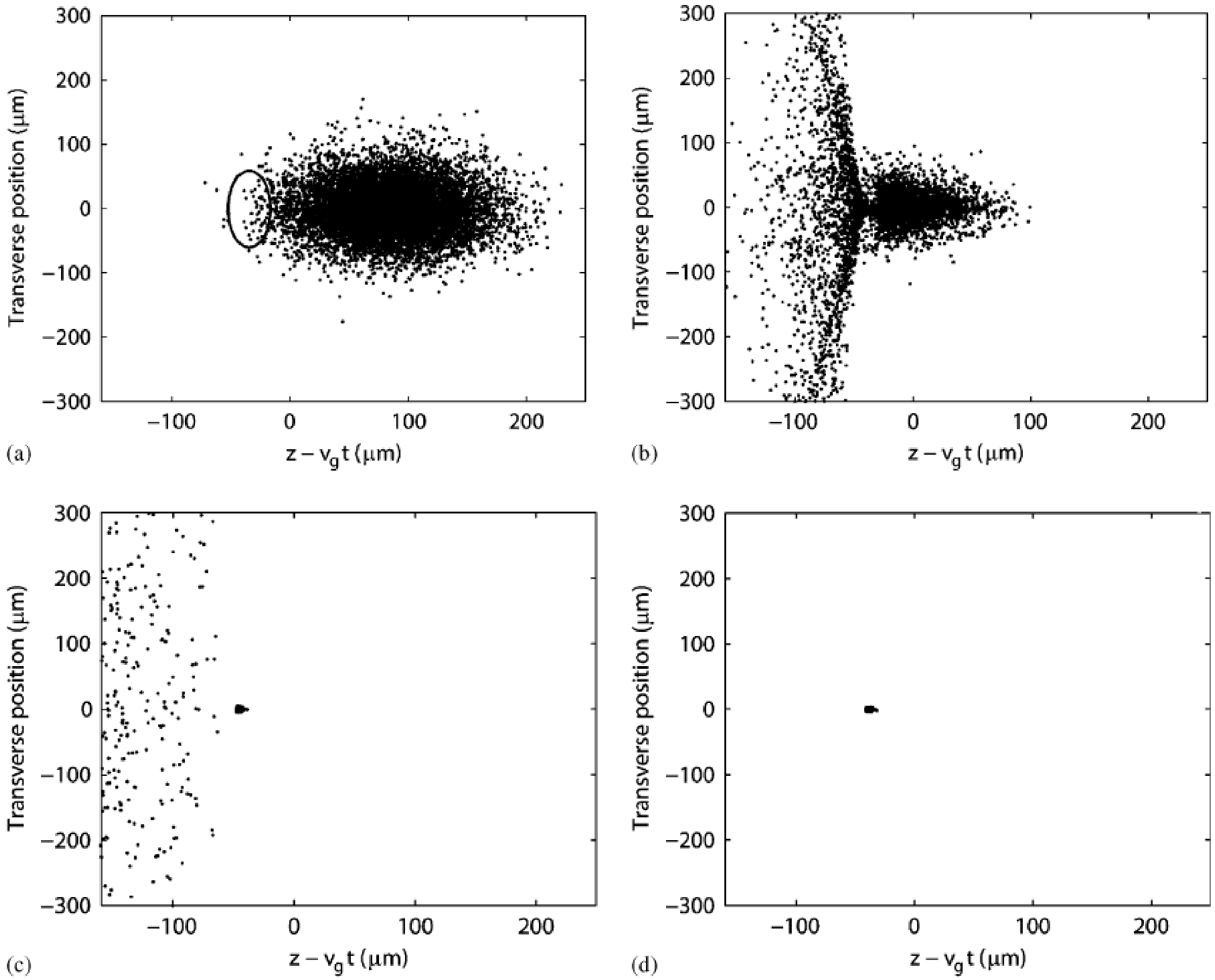
ILC parameters

Table 3.1. Summary table of the 250–500 GeV baseline and luminosity and energy upgrade parameters. Also included is a possible 1st stage 250 GeV parameter set (half the original main linac length)

			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
Centre-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	554	554	366	366	366
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_a	MV m^{-1}	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	μm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β_y^*	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	729.0	683.5	474	729	474	481	335
IP RMS veritcal beam size	σ_y^*	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	L	$\times 10^{34}$ cm^{-2}s^{-1}	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0

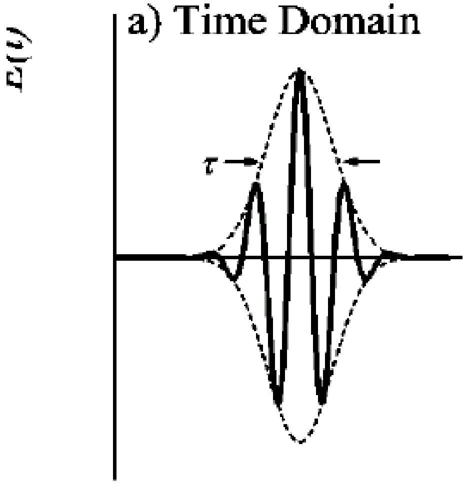
Exemple de simulation

Nuclear Instruments and Methods in Physics Research A 566 (2006) 244–249



Onde plasma
Régime non-linéaire

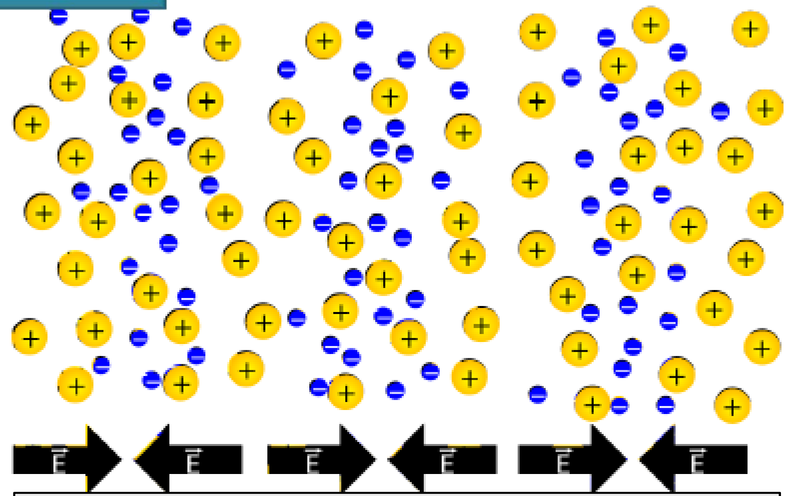
Pulse laser **HYPER** intense



1fs=10^{-15}s
=0,000000000000001s

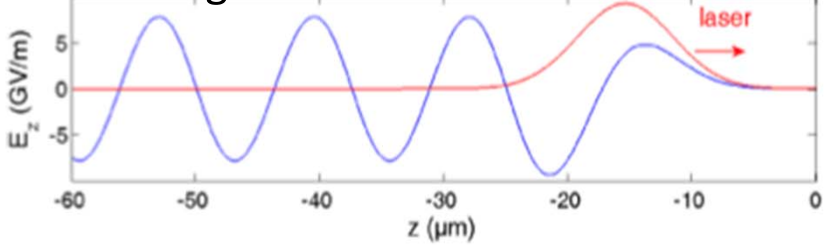
+ Gaz

onde plasma

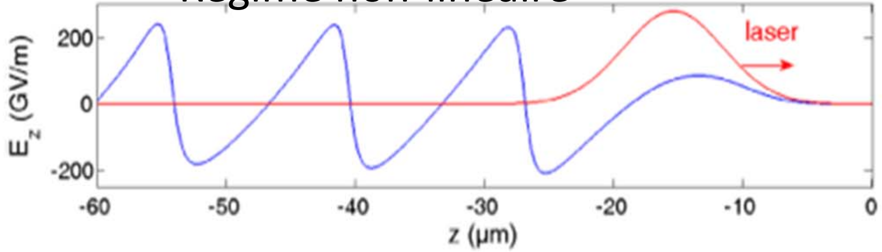


Champ électriques ~100GV/m !
(qques 10MV/m en techno standard)
Dans le 'sillage' de l'onde laserc

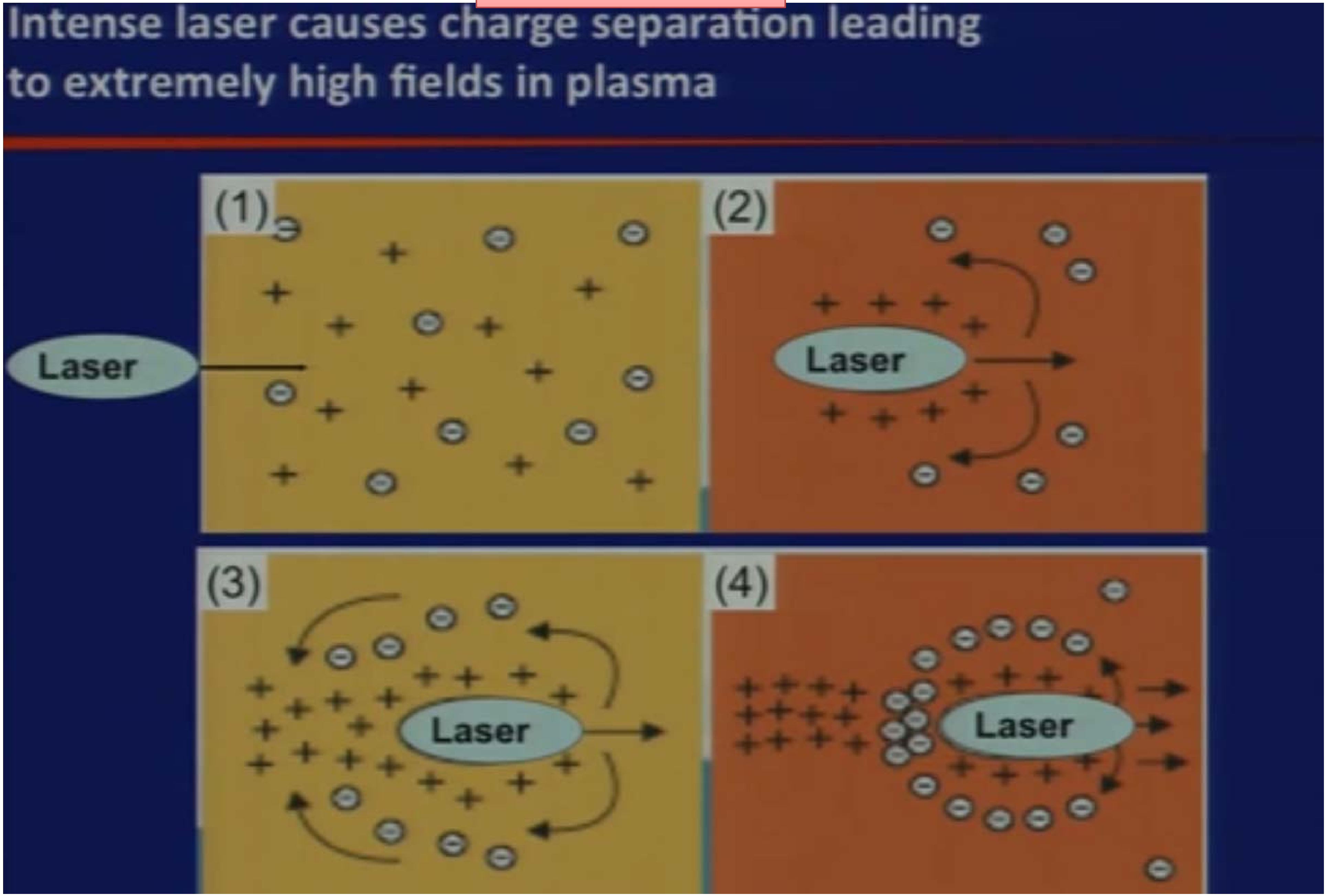
Régime linéaire

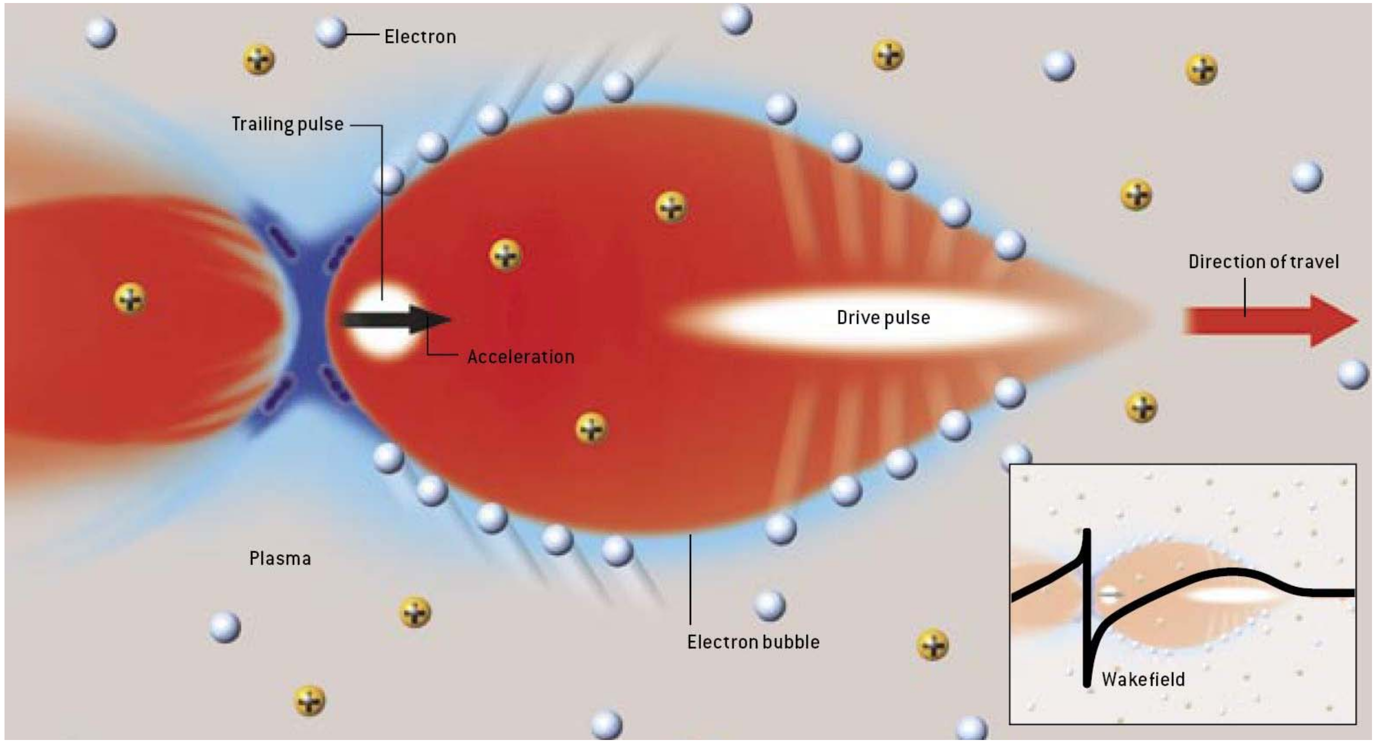


Régime non-linéaire



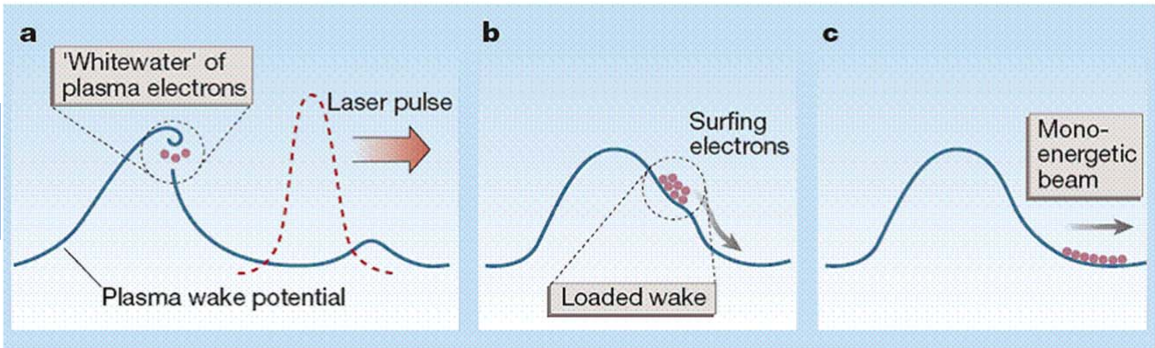
Régime de la bulle



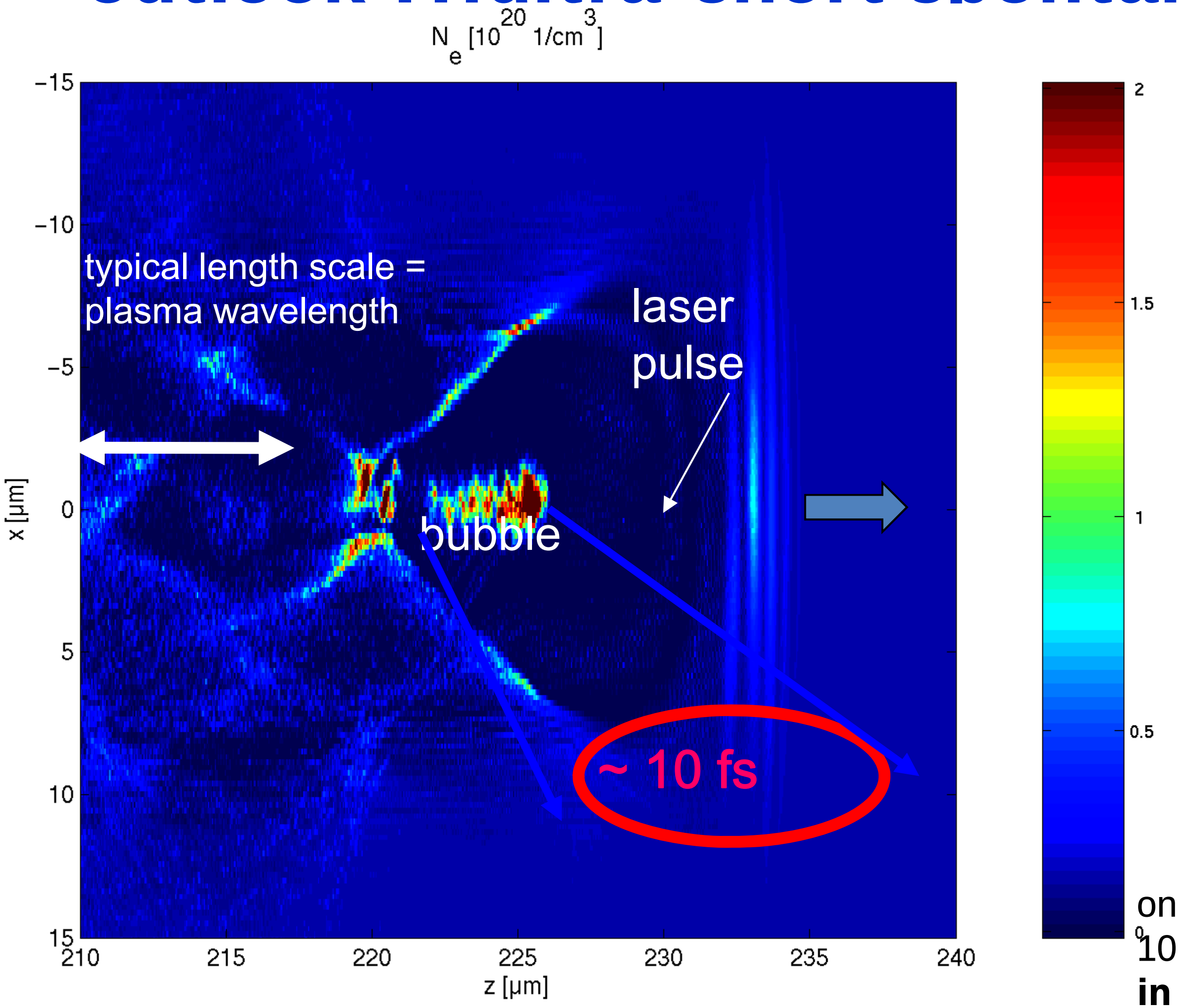


C. Joshi., Scientific American (2006)

‘Équivalent Surfer’



outlook II:ultra-short spontaneous emission

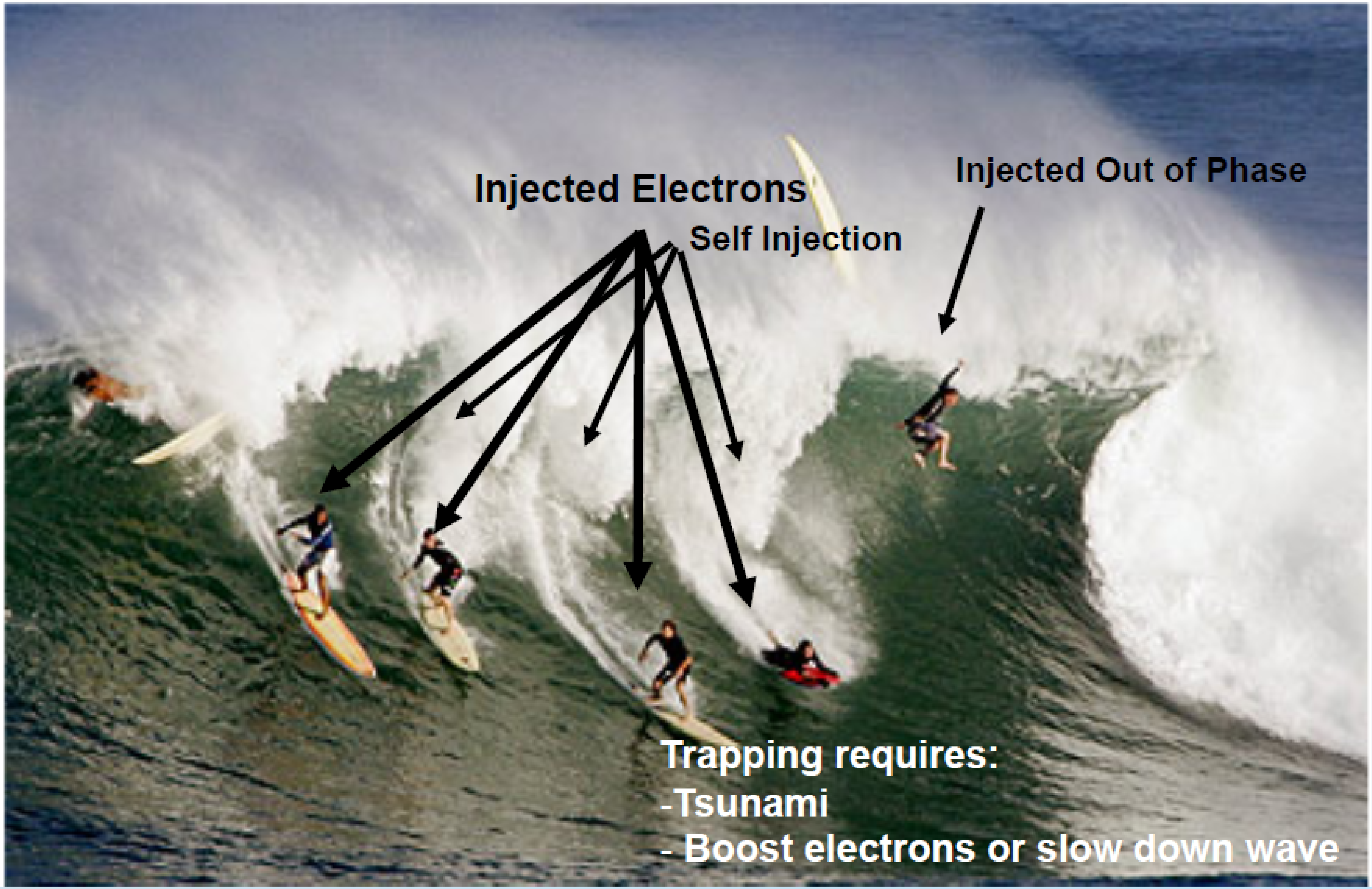


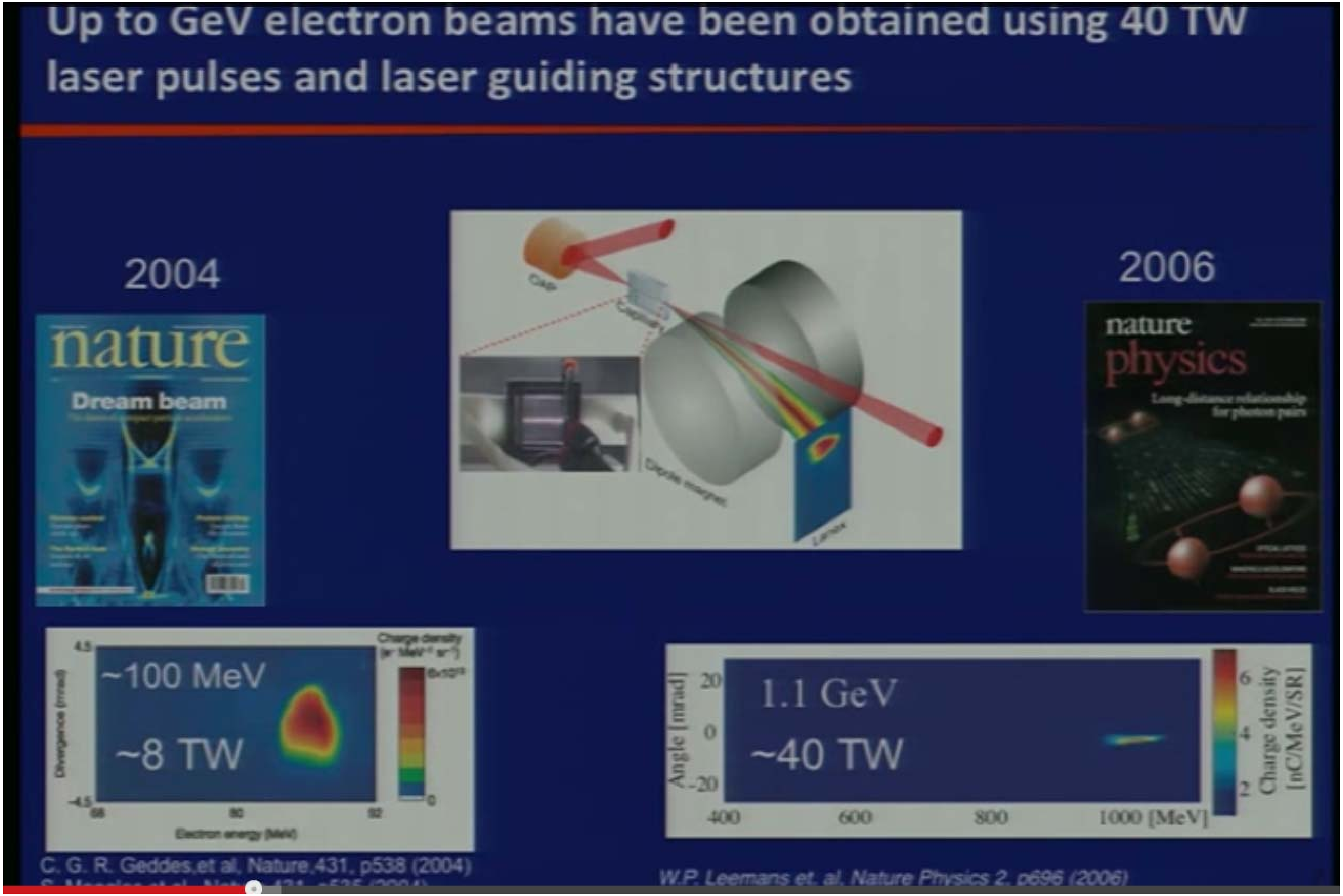
PIC simulation (M. Geissler)

on axis peak intensity:
10,000 photons/(shot mrad² 0.1% bw)
in 10 fs
[*femtoslicing*:
flux of 1,000 photons in 100 fs, 0.1% bw]

near-future goal:
x-ray pump-probe experiments
5 keV, 10 fs (with 2 GeV electrons)

"Electrons" accelerating on a wave: controlled injection




Up to GeV electron beams have been obtained using 40 TW laser pulses and laser guiding structures
2004
nature
Dream beam
2006
nature
physics
Long-distance relationship for photon pairs
Gas
Capillary
Dipole magnet
Lanex
~100 MeV
~8 TW
Charge density
Divergence (mrad)
Electron energy (MeV)
1.1 GeV
~40 TW
Angle [mrad]
20
0
-20
400
600
800
1000 [MeV]
Charge density [nC/MeV/SR]
C. G. R. Geddes,et al, Nature,431, p538 (2004)
W.P. Leemans et. al. Nature Physics 2, p696 (2006)

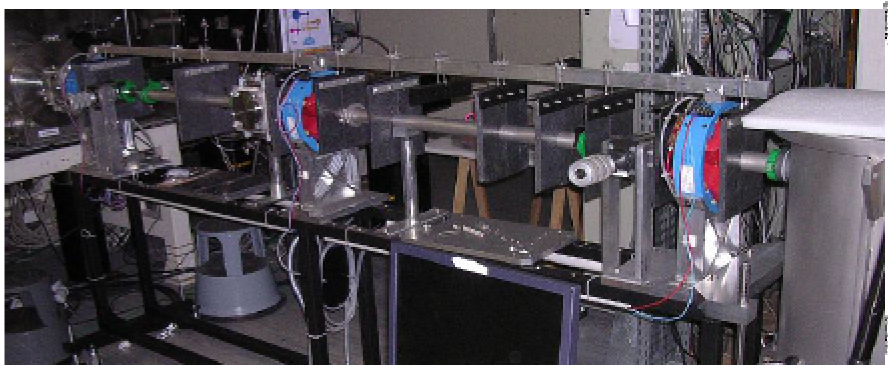
energy frontier: multiple plasma acceleration stages

Can we influence (and possibly improve) the beam quality?

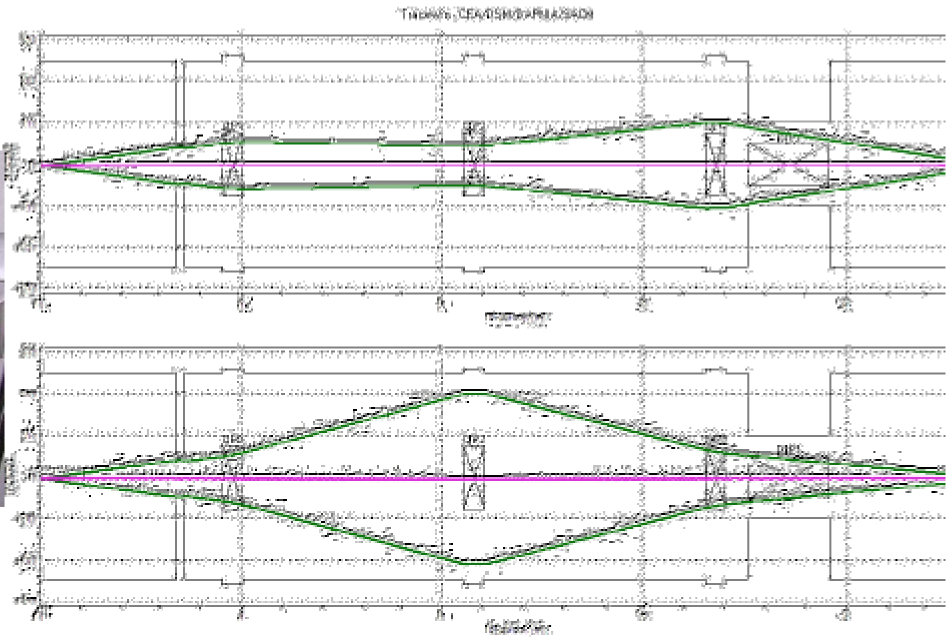
How can we measure the electron bunch properties?

design of a high resolution magnetic spectrometer

- quadrupole triplet (FODOF, ∫|dB/dx|dz = 1.2T) + permanent dipole (∫Bdz = 0.36T Tm
- E resolution <1% over 100-150 MeV over 100-400MeV range
- 2 energy ranges: 100-220 MeV, 220-1200MeV ⇒ 2 phosphor screens
- avoid resolution degradation by multiple scattering ⇒ transport in vacuum
- stigmatic imaging for particular energy values
- in general: astigmatic ⇒ divergence estimation ⇒ **E resolution** shot to shot

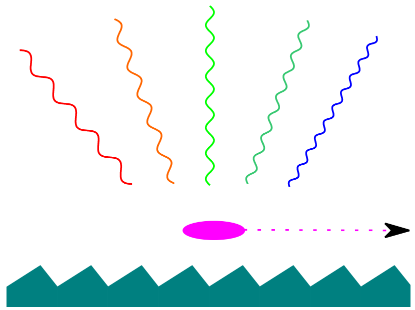


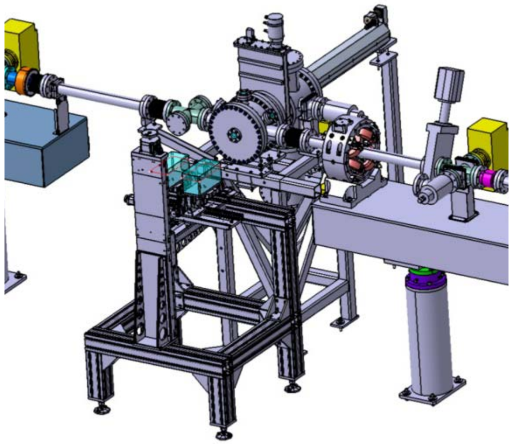
A. Specka (LLR)



ETALON (N. Delerue LAL)
Mesure de profils longitudinaux pour les accélérateurs du futur.

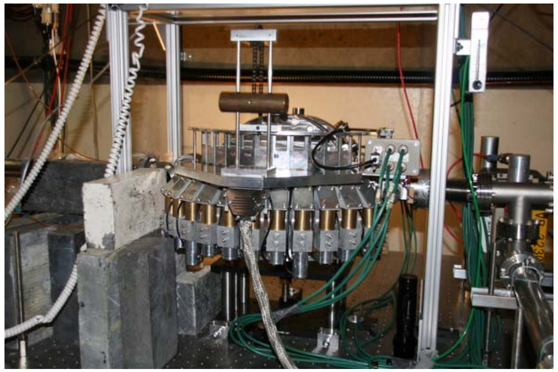
Principe: utilisation de radiation cohérente pour mesurer la longueur de paquet d'électrons.



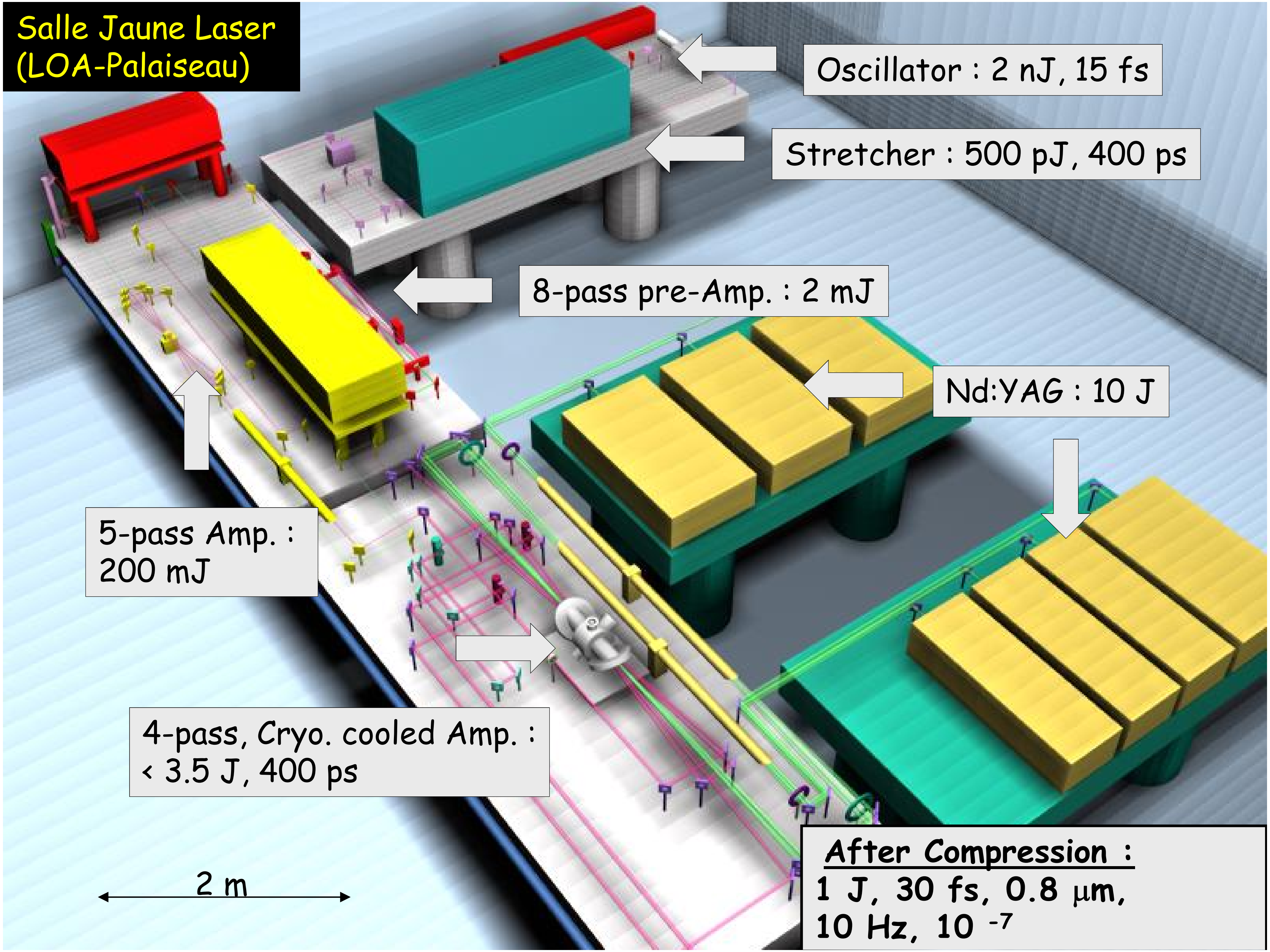


Sur le Linac de SOLEIL: cartographie précise de la radiation de Smith-Purcell pour mettre au point un système effectuant la mesure en un seul tir.

Sur FACET au SLAC: mesures multi-tir de paquets sub-picoseconde.



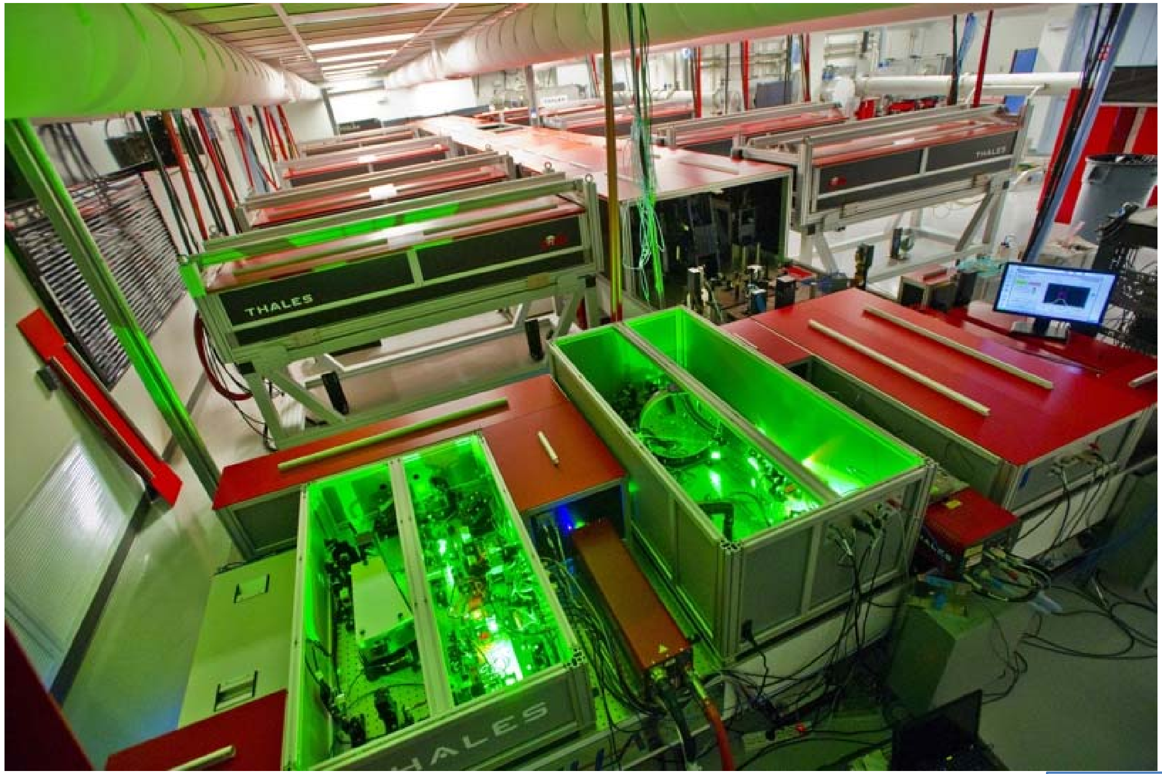
Applications: accélérateurs à champ de sillage (laser/plasma et particules/plasma) & LEL.



Salle Jaune Laser
(LOA-Palaiseau)
Oscillator : 2 nJ, 15 fs
Stretcher : 500 pJ, 400 ps
8-pass pre-Amp. : 2 mJ
Nd:YAG : 10 J
5-pass Amp. :
200 mJ
4-pass, Cryo. cooled Amp. :
< 3.5 J, 400 ps
After Compression :
1 J, 30 fs, 0.8 µm,
10 Hz, 10^{-7}
2 m

BELLA: BErkeley Lab Laser Accelerator

BELLA Facility: state-of-the-art 1.3 PW-laser for laser accelerator science:
>42 J in <40 fs (> 1PW) at 1 Hz laser and supporting infrastructure at LBNL



Critical HEP experiments:

- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration

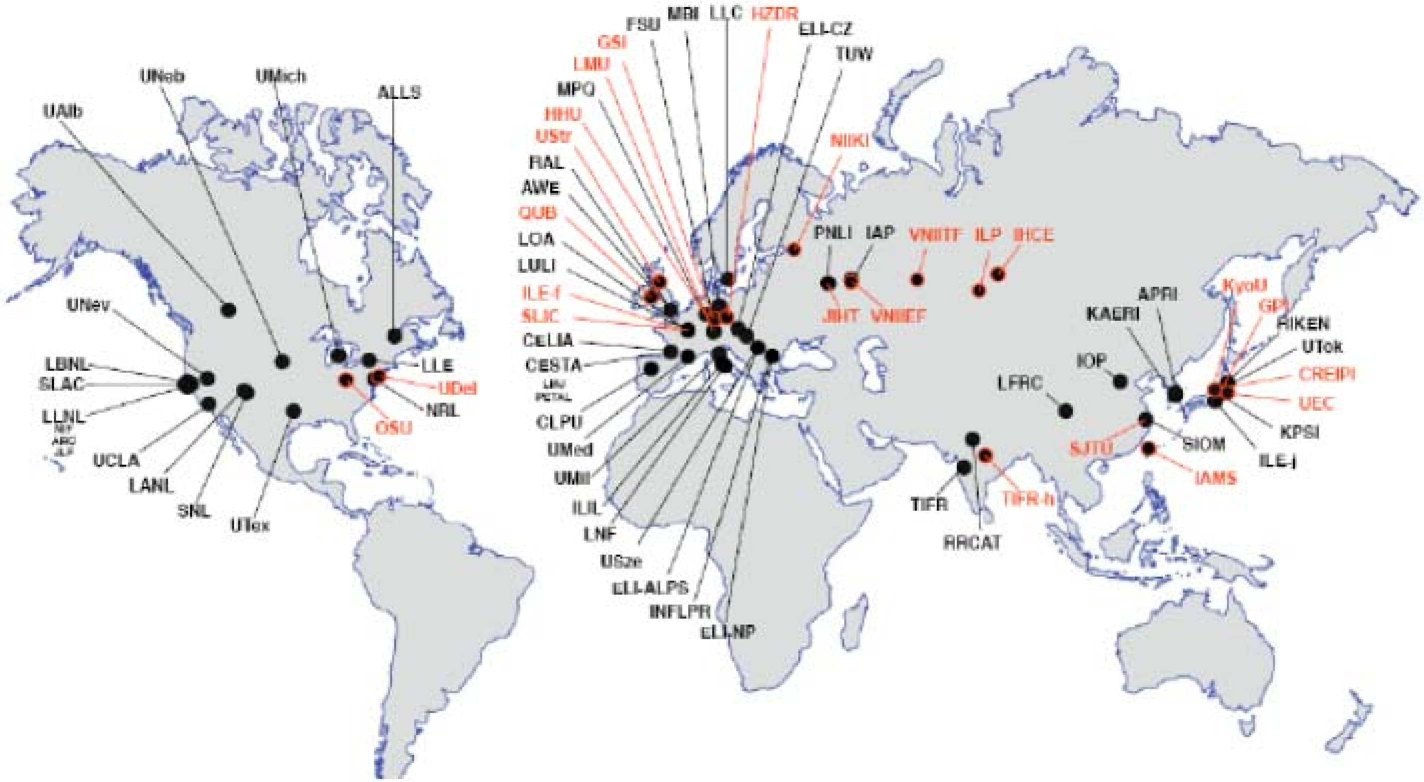
Amplitude technologie
& THALES sont leaders …

BELLA

100 TW class Laser systems

2010 ICUIL World Map of Ultrahigh Intensity Laser Capabilities

2009
2010



More than half of the groups have research programs related to Laser Plasma Accelerators

Chris Barty, 2011
http://www.icuil.org

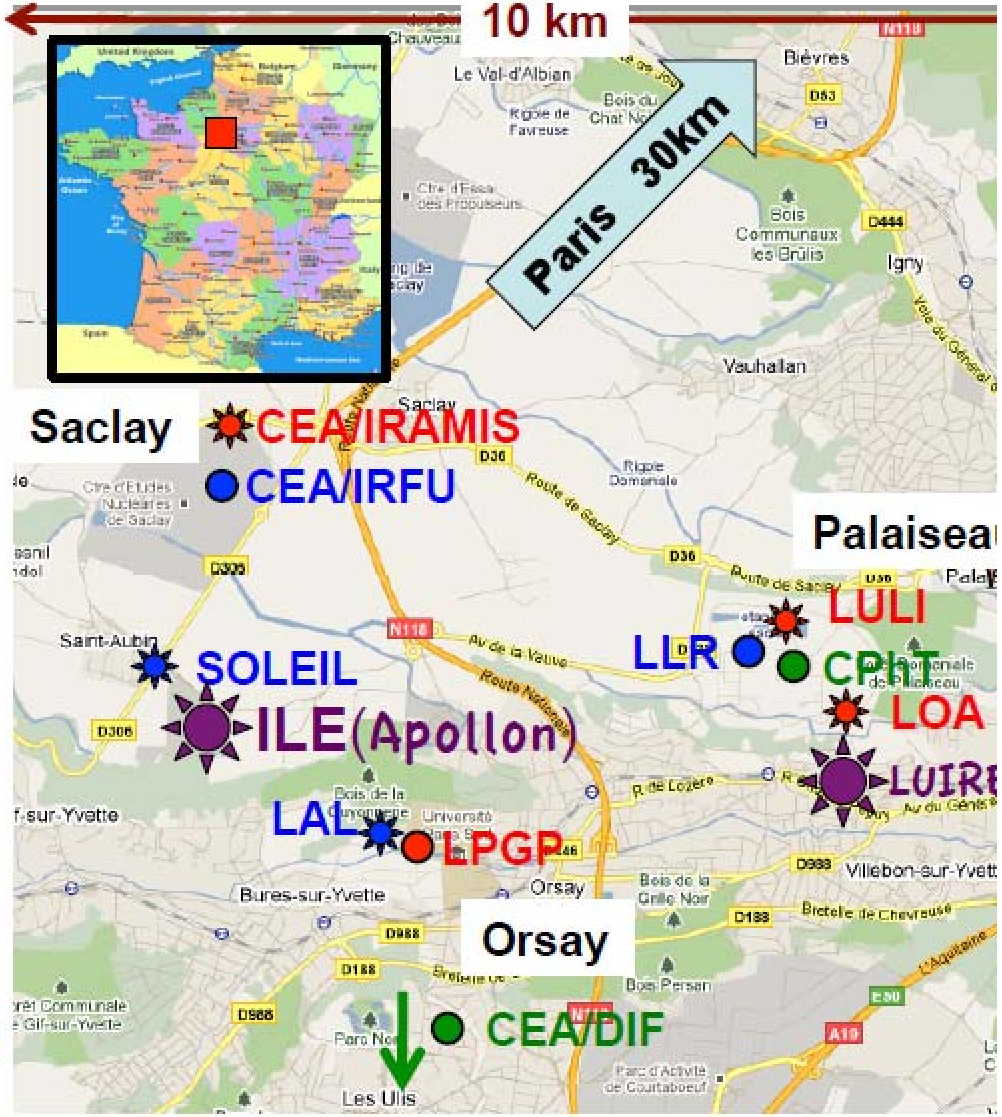
High power – short pulse laser facilities in (Ile de) France

Plasma & Laser:
- LOA
- LPGP
- LULI
- CEA/DSM/IRAMIS/SPAM

HEP & Accelerators:
- CEA/DSM/IRFU/SACM
- LAL
- LLR
- SOLEIL

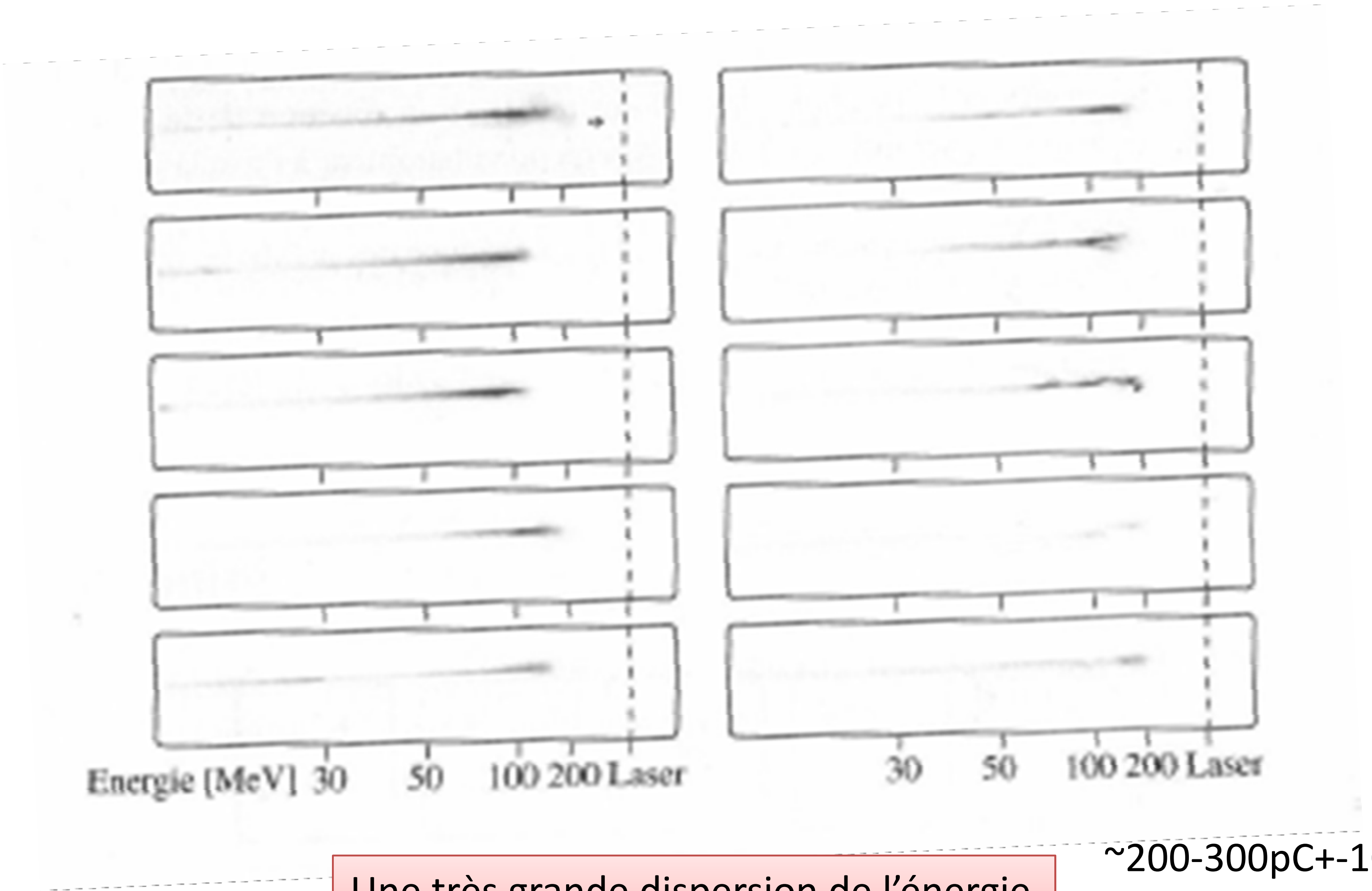
Theory & Simulation:
- CEA/DAM/DIF
- CPhT

ILE (institut de la lumière extrème)
LUIRE: 500TW, 0.1Hz
APOLLON: 10PW (150 J, 15 fs) 0.01Hz
also: CELIA (Bordeaux)



Performance de l'accélération dans le régime de la bulle

Ex. : 10 tirs



~200-300pC+-100pC

Une très grande dispersion de l'énergie
De grandes fluctuations de tir à tir…

Qualité du faisceau dépend de la densité du gaz

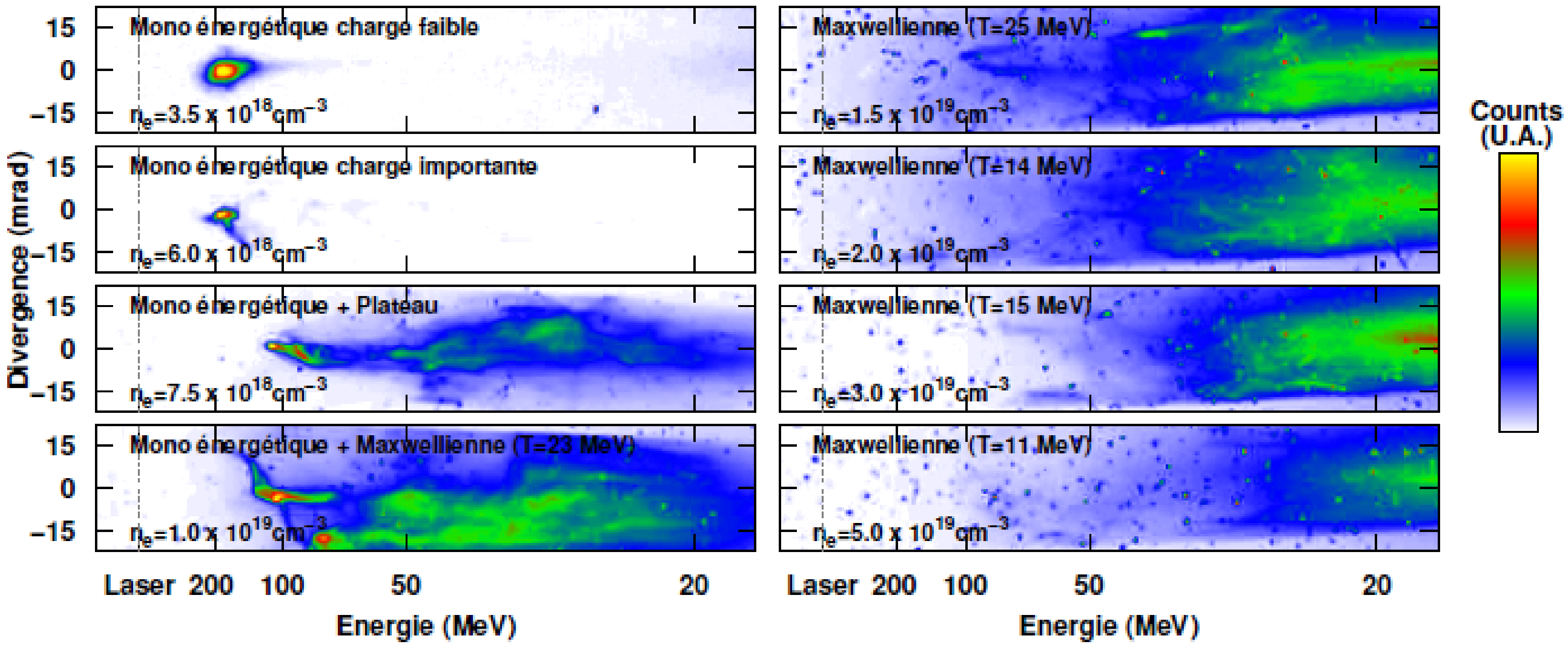
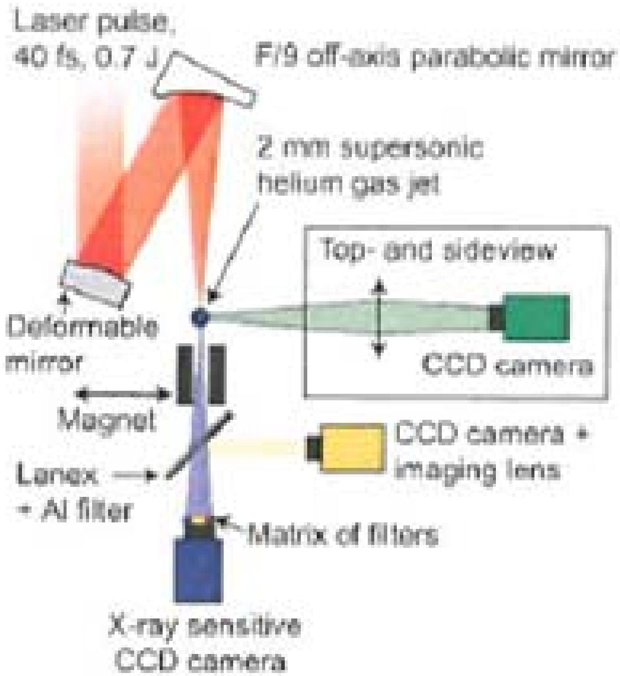
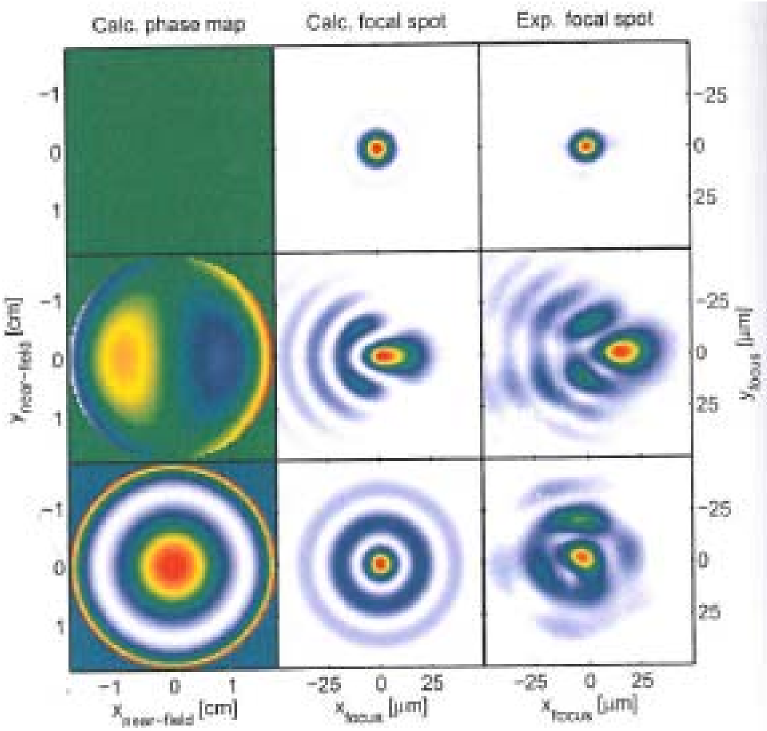


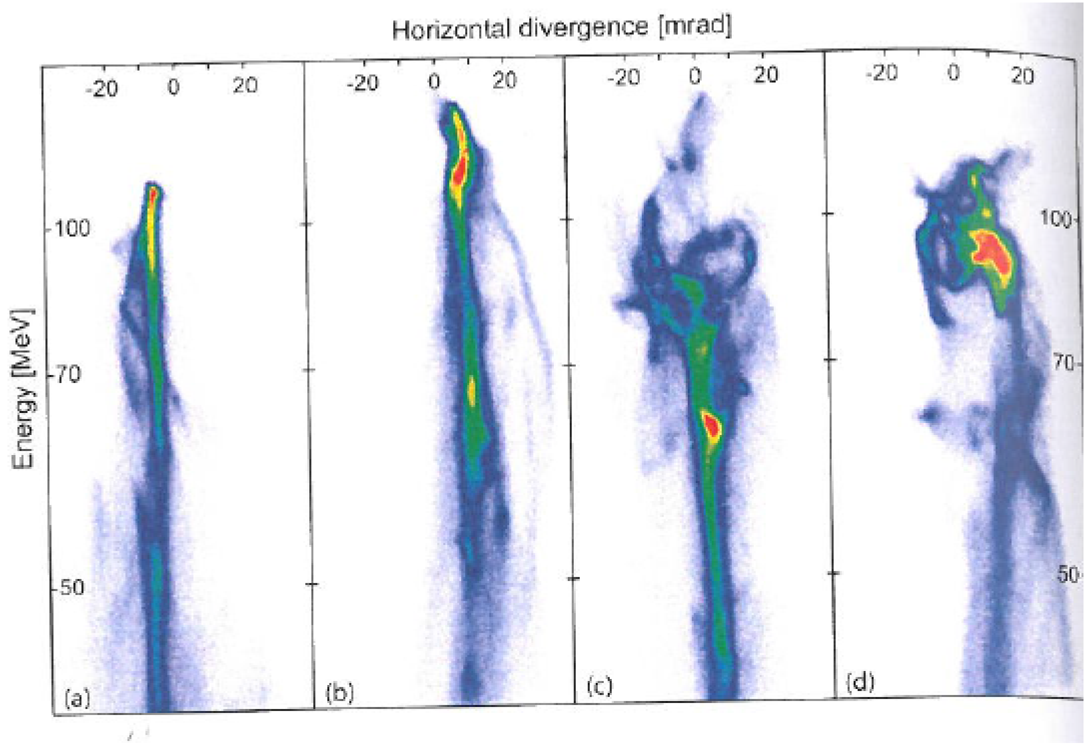
FIG. 1.9 – Evolution du spectre et de la divergence des électrons en fonction de la densité plasma. Figure publiée dans [Malka 05].

Sensibilité au faisceau laser

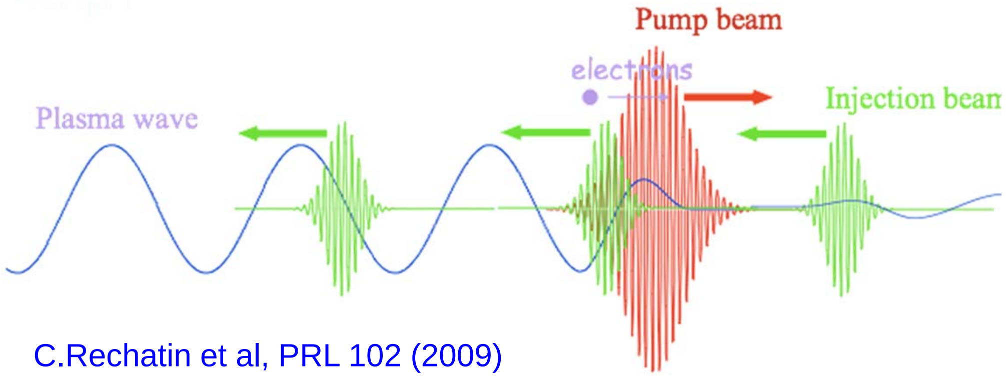


PhD. G. Genoud, Lund 2011
Laser-Driven Plasma Waves for Particle Acceleration and X-ray production





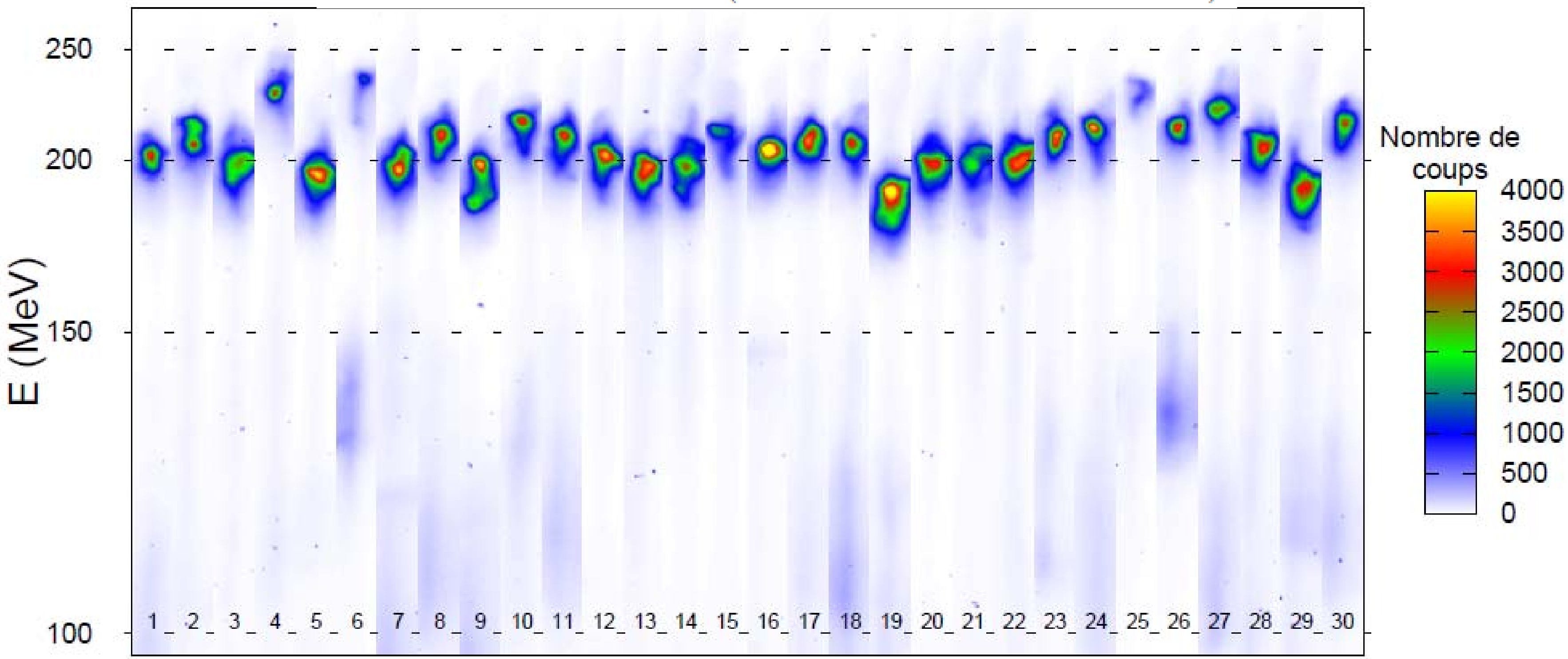
Méthodes pour améliorer les performances
Ex. : ‘colliding bunches’



C.Rechatin et al, PRL 102 (2009)

$$Q_{pic} = 13 \pm 4 \text{ pC (38\% de fluctuation rms)}$$

$$E = 206 \pm 10 \text{ MeV(5\% de fluctuation rms)}$$



Répétabilité

PRL **101**, 085002 (2008)

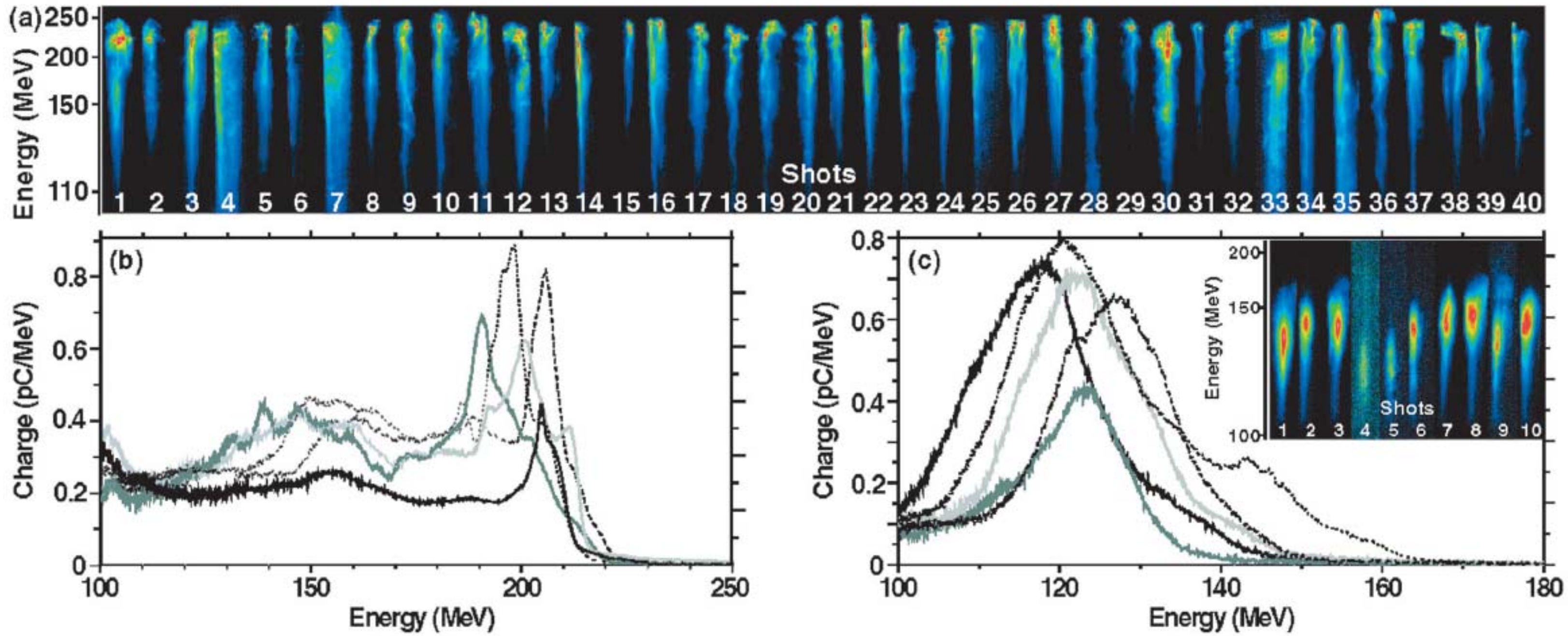


FIG. 3 (color). (a) False-color images of 40 consecutive, spatially dispersed electron beams on *S*2 ($n_e \approx 7.3 \times 10^{18}$ cm^{-3}) [sample spectra in (b)]. (c) Exemplary spectra for $n_e \approx 6.8 \times 10^{18}$ cm^{-3}. Ten consecutive images of *S*2 are presented in the inset. The color normalized for each shot.

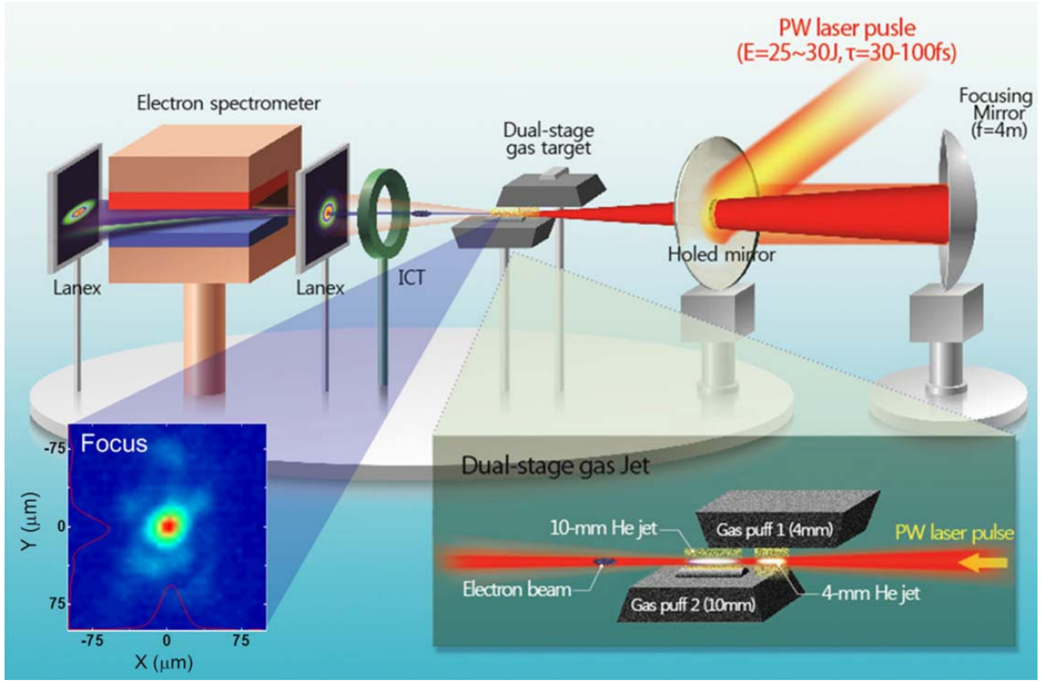
Reproducible LWFA was demonstrated.[33] From laser shot to shot, each time the LWFA accelerates electrons to a narrow energy bunch with the same peak ener with a similar energy spread. (by courtesy of S. Karsch).

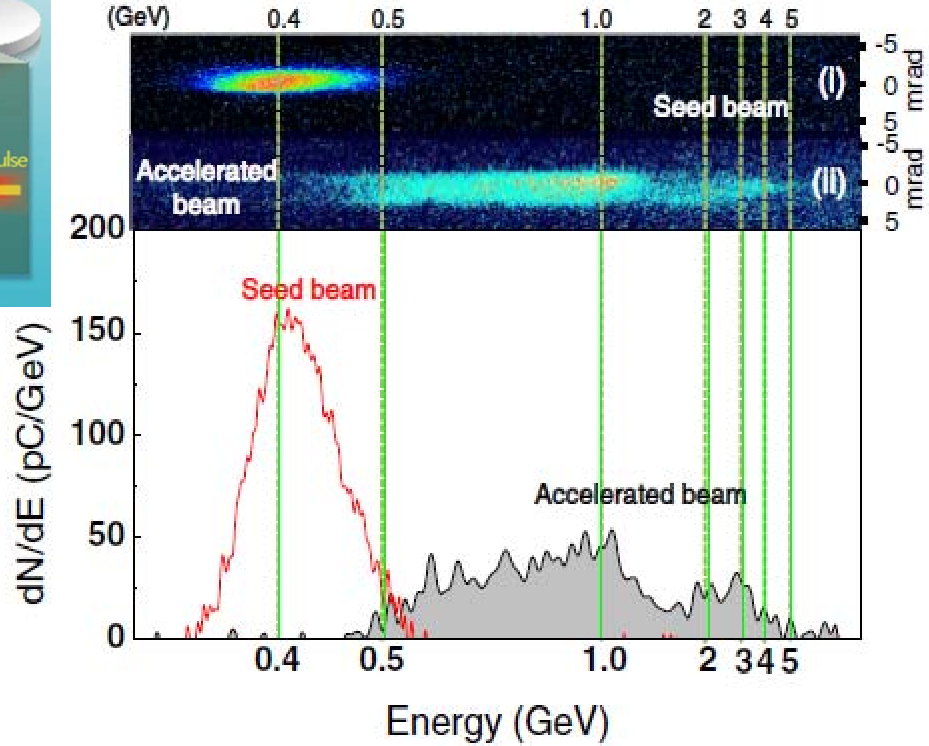
Proc. Jpn. Acad., Ser. B **86** (2010)

Laser acceleration and its future

By Toshiki TAJIMA[*1,*2,†]

La plus haute énergie atteinte





PRL **111**, 165002 (2013)

Stabilité

STABLE, TUNABLE, QUASIMONOENERGETIC ELECTRON . . . Phys. Rev. ST Accel. Beams **16,** 031302 (2013)

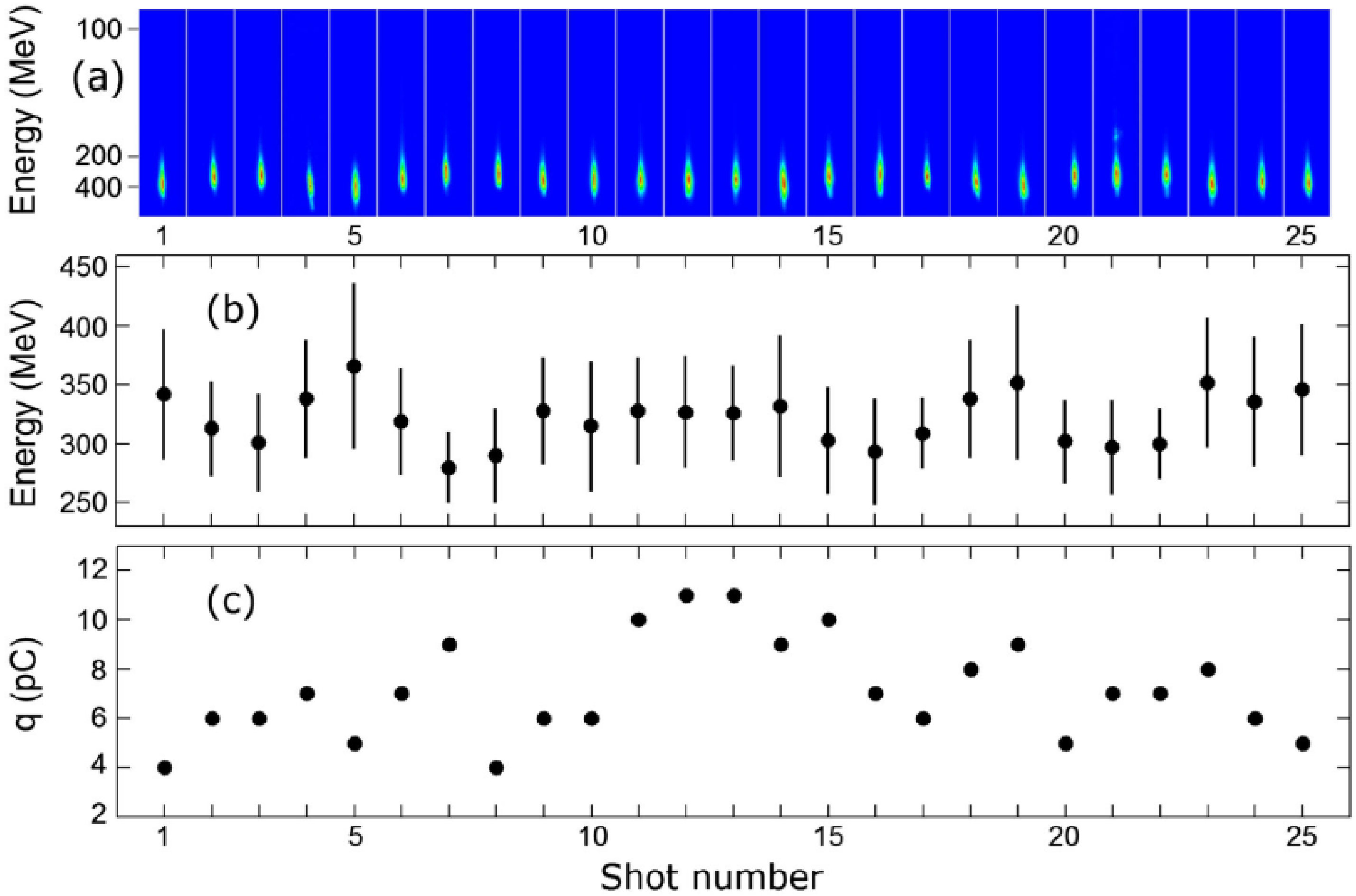


FIG. 7. (a) LANEX images of magnetically dispersed beams for 25 consecutive shots taken at $n_e = 6 \times 10^{18}$ cm^{-3} and $P =$ 55 TW; the color scale is normalized for each shot. In all cases, the low-energy tail is not detected at all. The beam pointing fluctuation for this series of shots is ± 1 mrad. (b) Electron energy corresponding to the spectral peak (markers) and FWHM energy spread (bars) vs shot number. (c) Integrated charge, taking into account background noise on the detector.

Plasma-based accelerators for future colliders

- PWFA-linear collider:
- two-beam accelerator geometry
- 25 GeV drive beams
- 19 plasma stages (1 TeV)
- $n=10^{17}$ cm^{-3} (set by 30 um driver bunch length)

Seryi et al., Proc. PAC (2009)

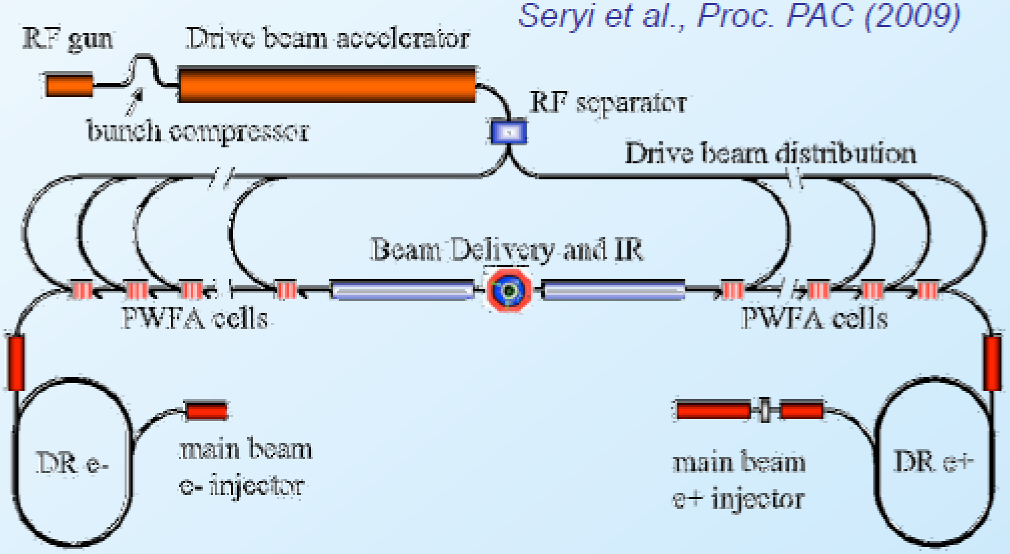
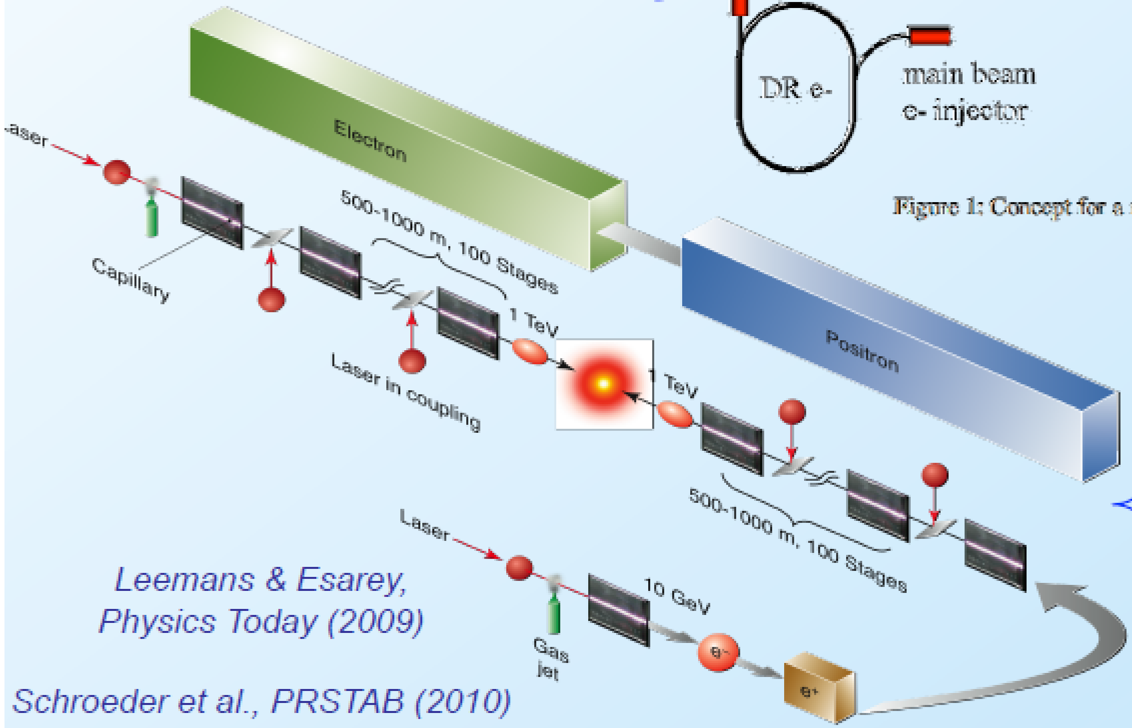


Figure 1: Concept for a multi-stage PWFA-based Linear Collider.

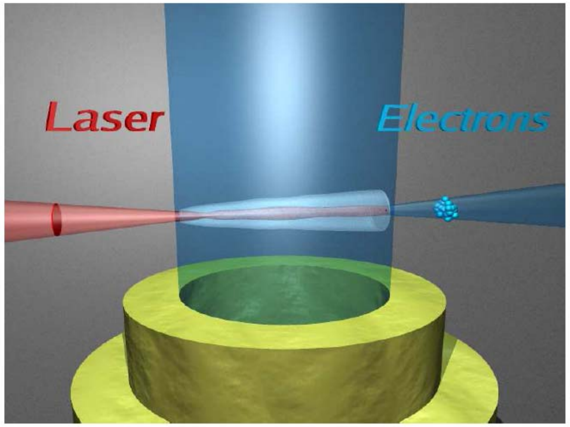


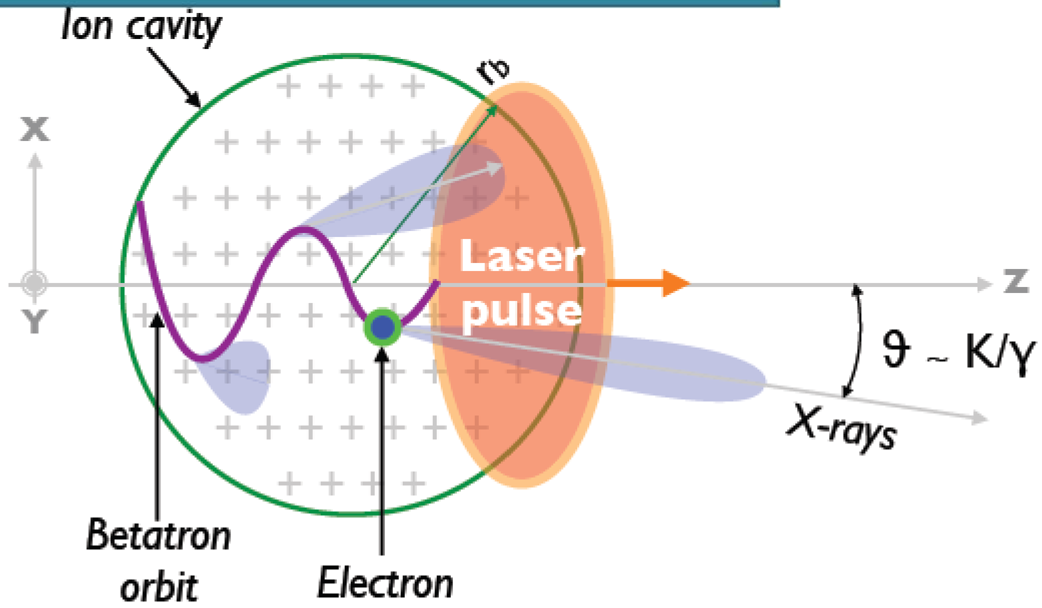
Leemans & Esarey, Physics Today (2009)

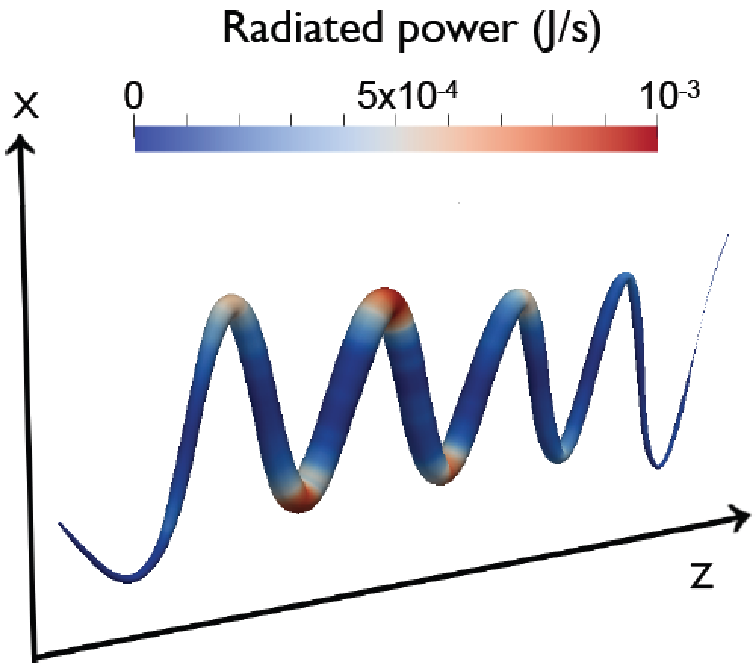
Schroeder et al., PRSTAB (2010)

- LPA-linear collider:
- 50 stages (1 TeV collider)
- 10 GeV/stage
- requires ~10 J laser (at tens of kHz, hundreds of kW)
- $n=10^{17}$ cm^{-3} (set by laser depletion)

Autre application : Utilisation du rayonnement dans le régime de la bulle

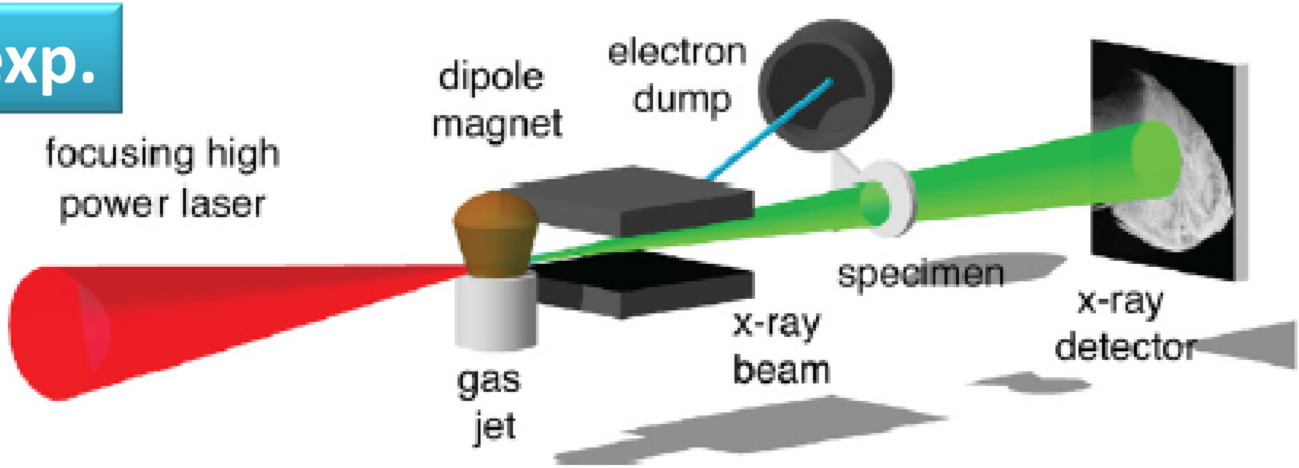


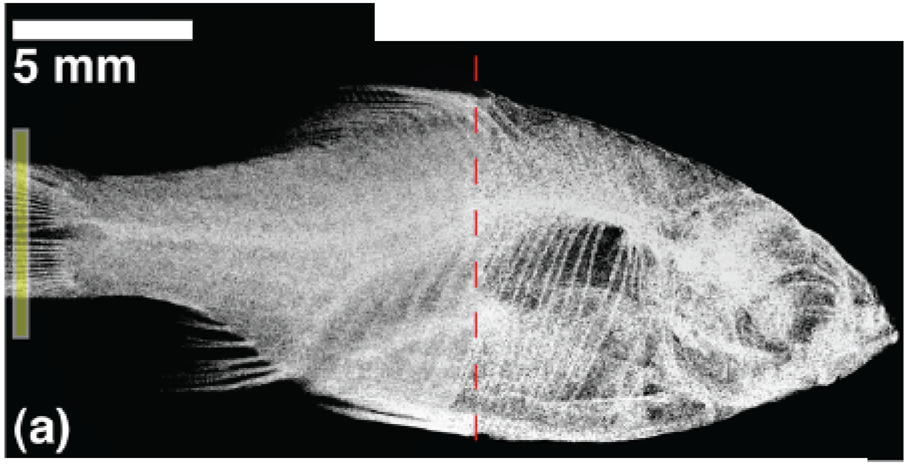




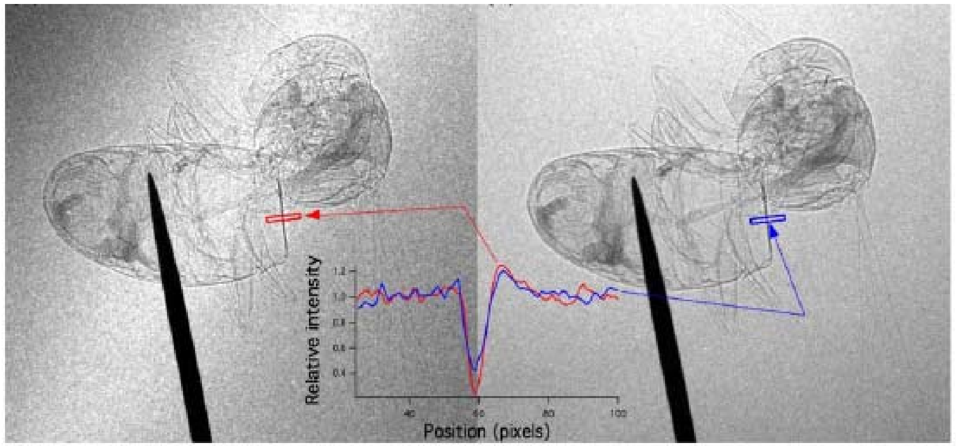
Lorsque les électrons sont accélérés dans la bulle du plasma ils rayonnent …

Resultats exp.

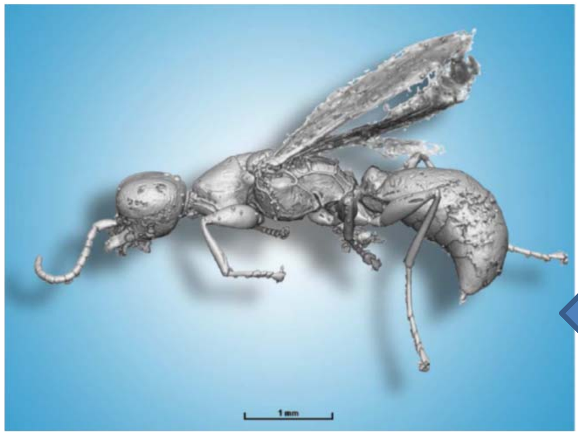




Applied Physics Letters **99**, 093701 (2011)

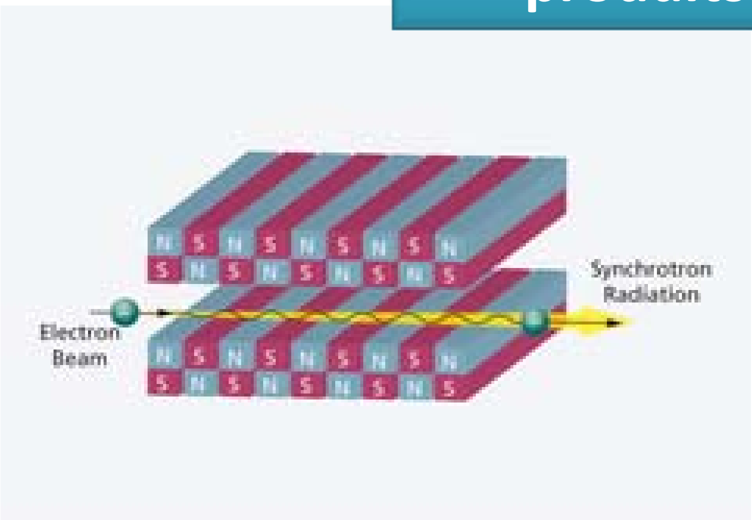


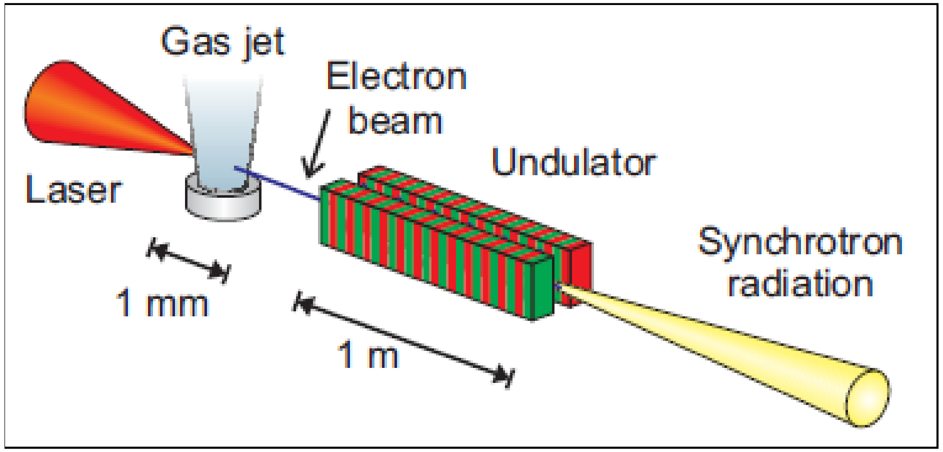
OPTICS LETTERS / Vol. 36, No. 13 / July 1, 2011



ESFR

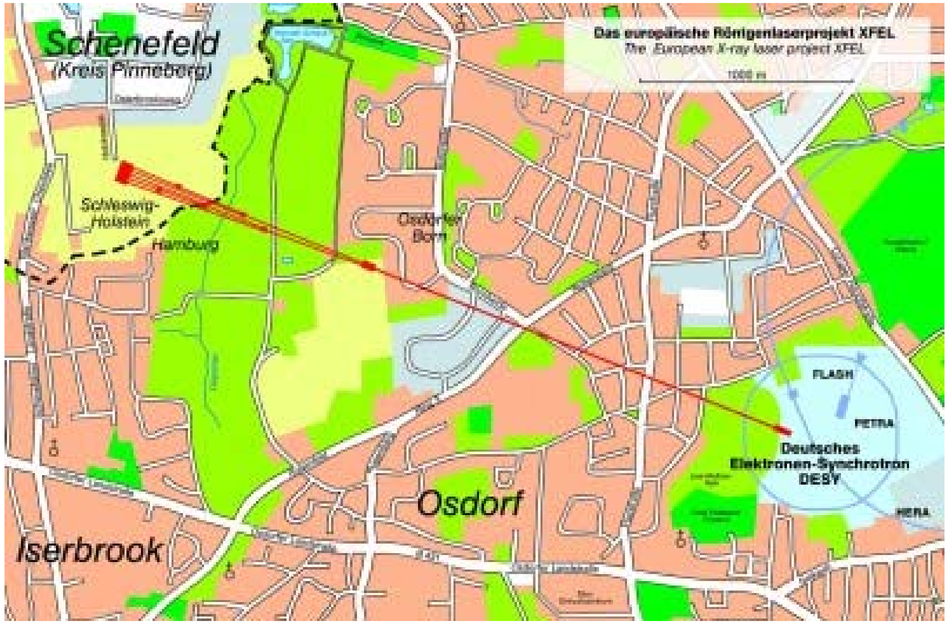
On peut aussi envoyer les électrons produits dans un 'onduleur'





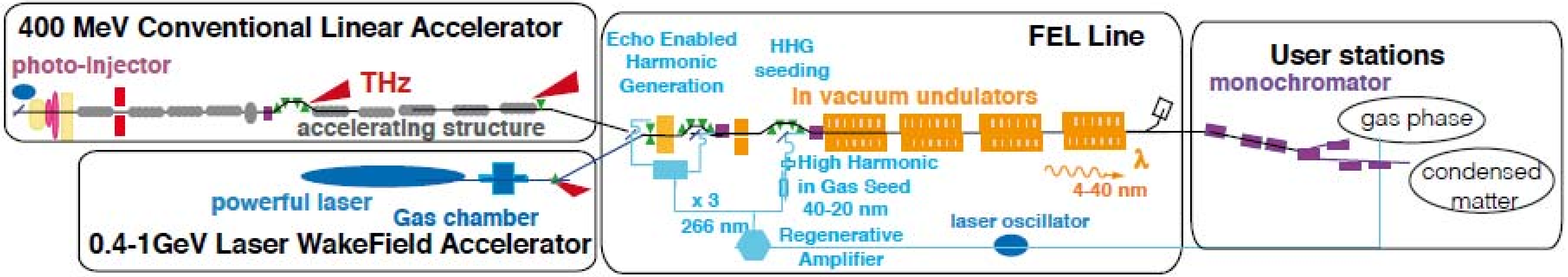
Cela produit des pulses de rayons X femtosecondes

XFEL DESY Hambourg



2,1km de cavités supra➔électrons de 17.5 GeV
➔ Pulses femtoseconde de rayons X
(projet à >1B€)

LUNEX5 PROJECT



40-4 nm, 20 fs and shorter

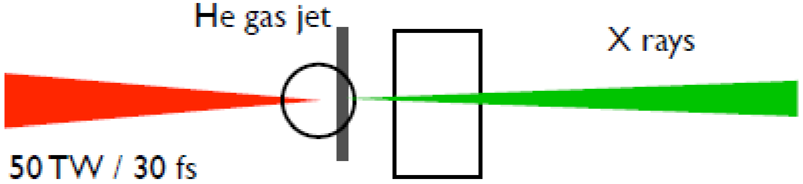
Beyond third generation light source (undulator spontaneous emission, partial transverse coherence),

progress towards advanced fourth generation (4G+) light sources (coherent emission, temporal and transverse coherence, femtoseconde pulses, high brilliance) via the latest free electron laser seeding schemes and electron photon interaction, to be validated by pilot user experiments,
=> *Demonstration of echo at short wavelength*
=> *FEL physics*
=> *Advanced design of FEL source for improved performances, associated with cost and size reduction*

and towards fifth generation (5G) (Conventional Linac replaced by a LWFA), FEL being viewed as a qualifying LWFA application *: evaluation of the LWFA performances in «operation-like» conditions (cf EuRRONAc objectives)*

Complementarity CLA / LWFA :
CLA high repetition rate, high reliability, LWFA : ultra-short electron bunch, compacity

Inverse Compton Scattering : New scheme



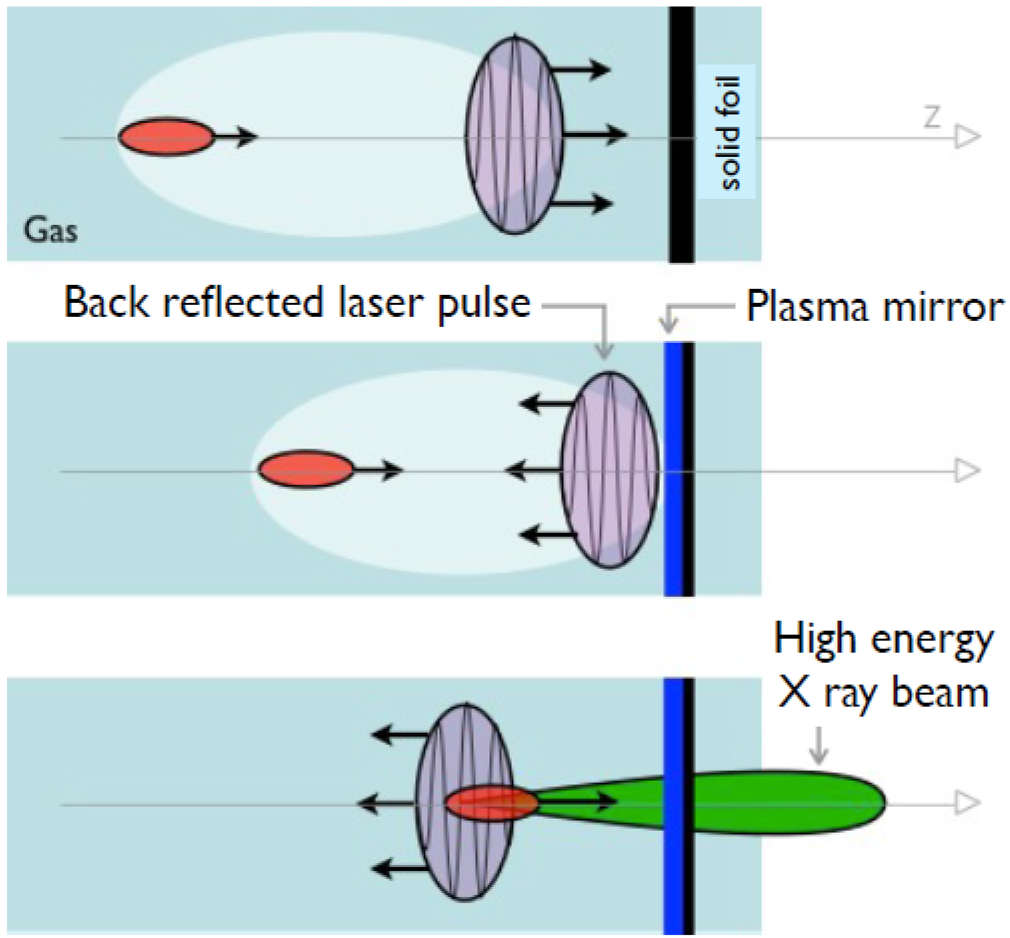
A single laser pulse

A plasma mirror reflects the laser beam

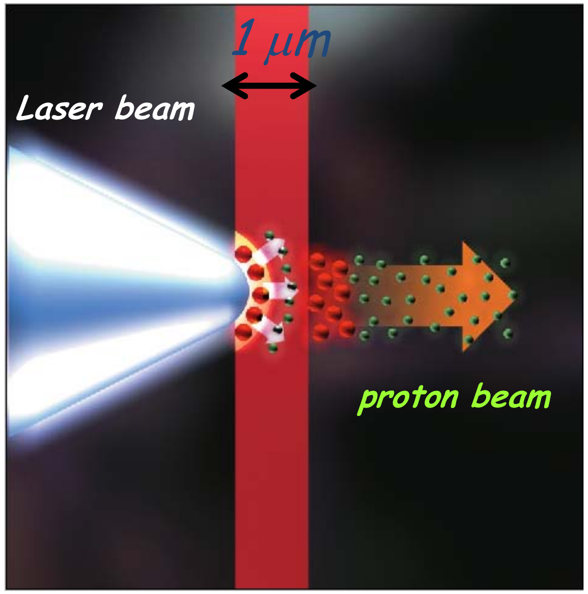
The back reflected laser collides with the accelerated electrons

No alignment : the laser and the electron beams naturally overlap

Save the laser energy !



Génération de faisceaux de protons et ions



VOLUME 92, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 30 APRIL 2004

Highly Efficient Relativistic-Ion Generation in the Laser-Piston Regime

T. Esirkepov,[1,*] M. Borghesi,[2] S.V. Bulanov,[1,2,†] G. Mourou,[3] and T. Tajima[1]

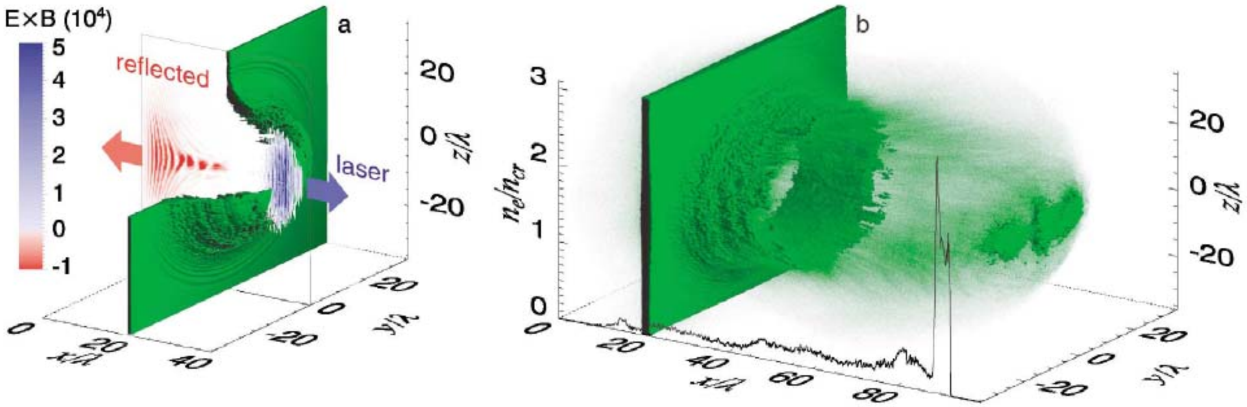
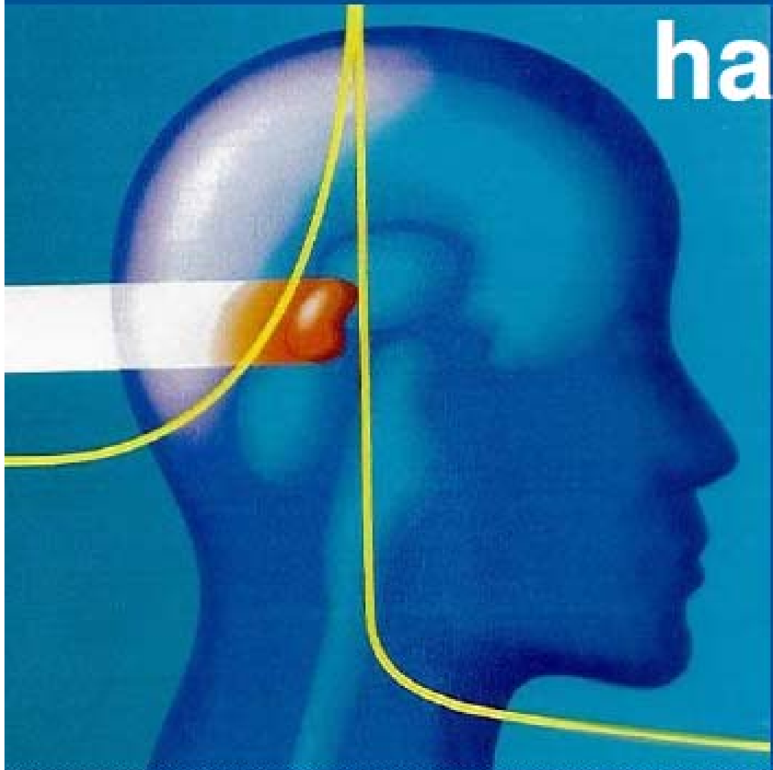


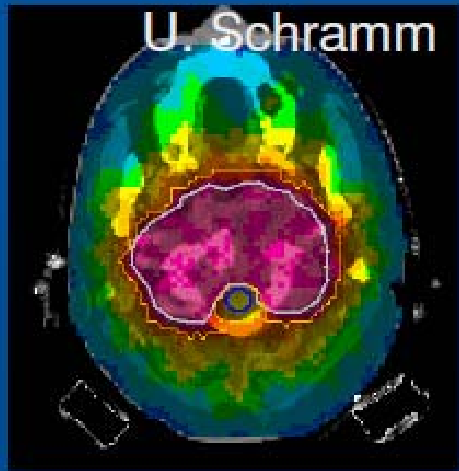
FIG. 1 (color). (a) The ion density isosurface for $n = 8n_{cr}$ (a quarter removed to reveal the interior) and the x component of the normalized Poynting vector $(e/m_e\omega c)^2$ **E** × **B** in the $(x, y = 0, z)$ plane at $t = 40 \times 2\pi/\omega$. (b) The isosurface for $n = 2n_{cr}$, green gas for lower density at $t = 100 \times 2\pi/\omega$; the black curve shows the ion density along the laser pulse axis.

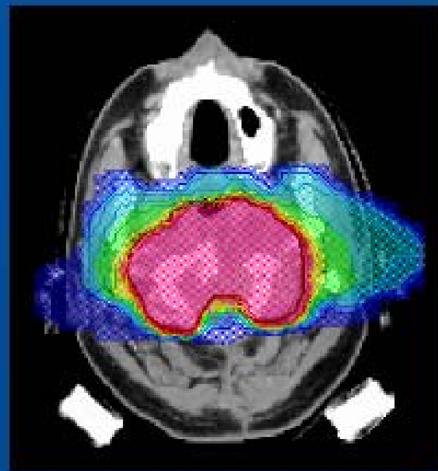
Laser piston La totalité des électrons est accélérée,
Séparation de charge ⇒ accélération ions
Réflexion du laser sur électrons⇒accélération additionnelle

qq 100 MeV⟶ qqGev

chances and challenges regarding laser driven hadron cancer therapy

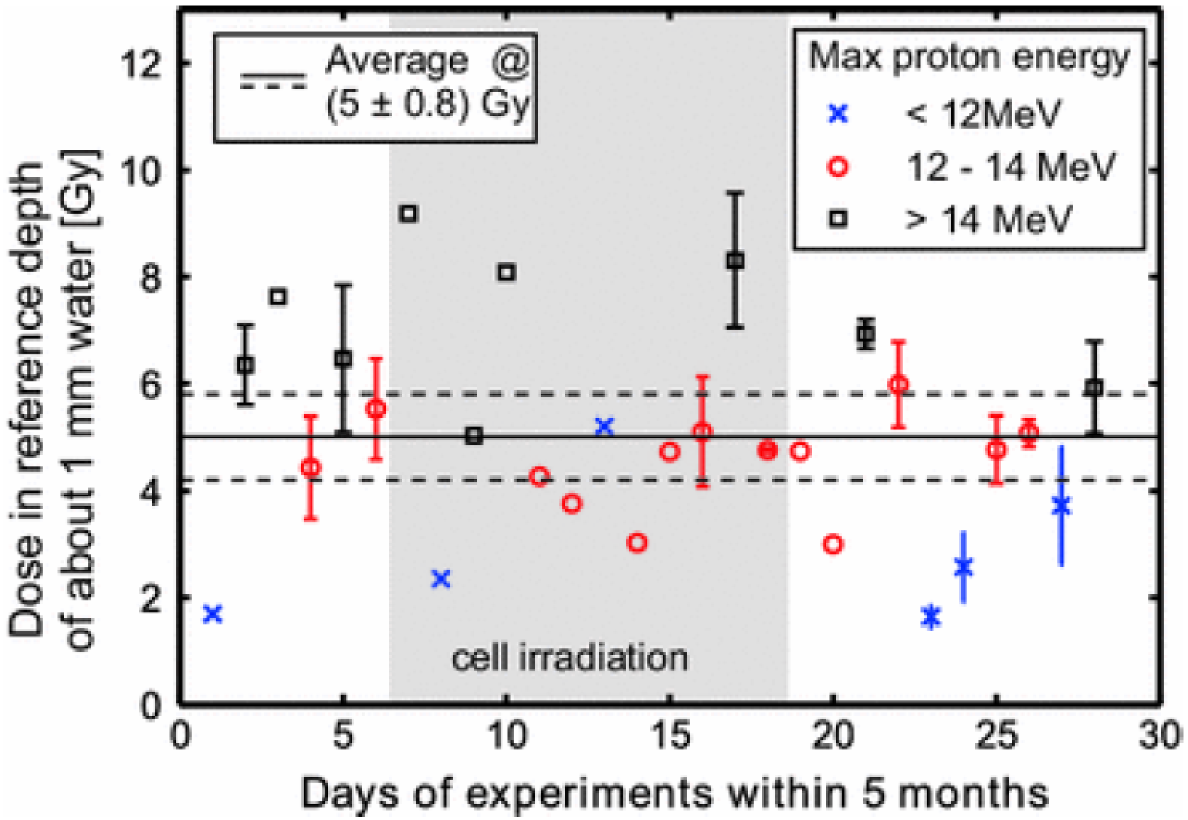






Forschungszentrum Dresden Rossendorf

Technologie en phase de maturation



Conclusion

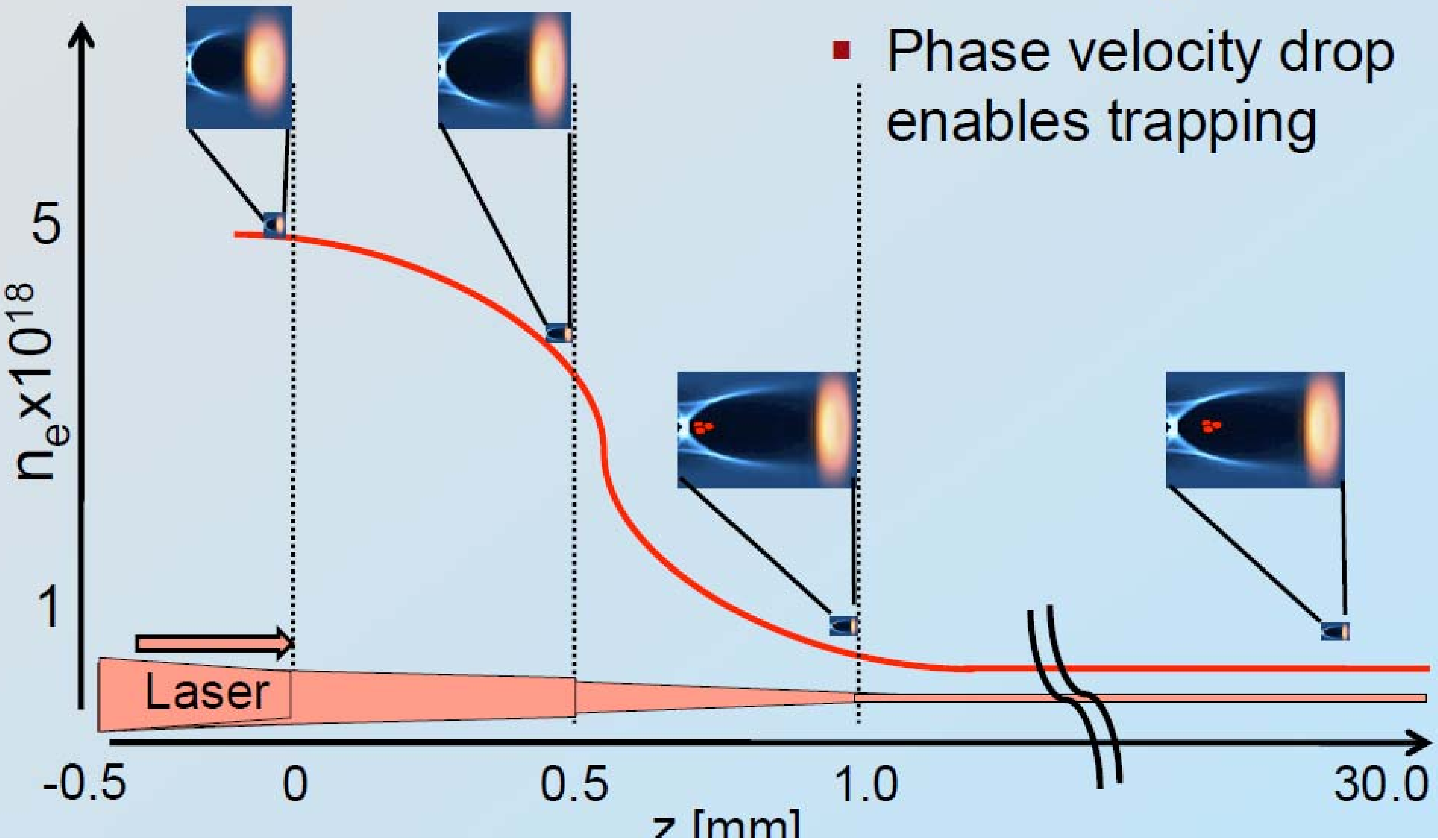
- Aventure scientifique et technologique passionnante
- Phénomènes physique très complexes
- Technologie laser et plasma ‘challenging’
- Domaine de recherche en plein expansion

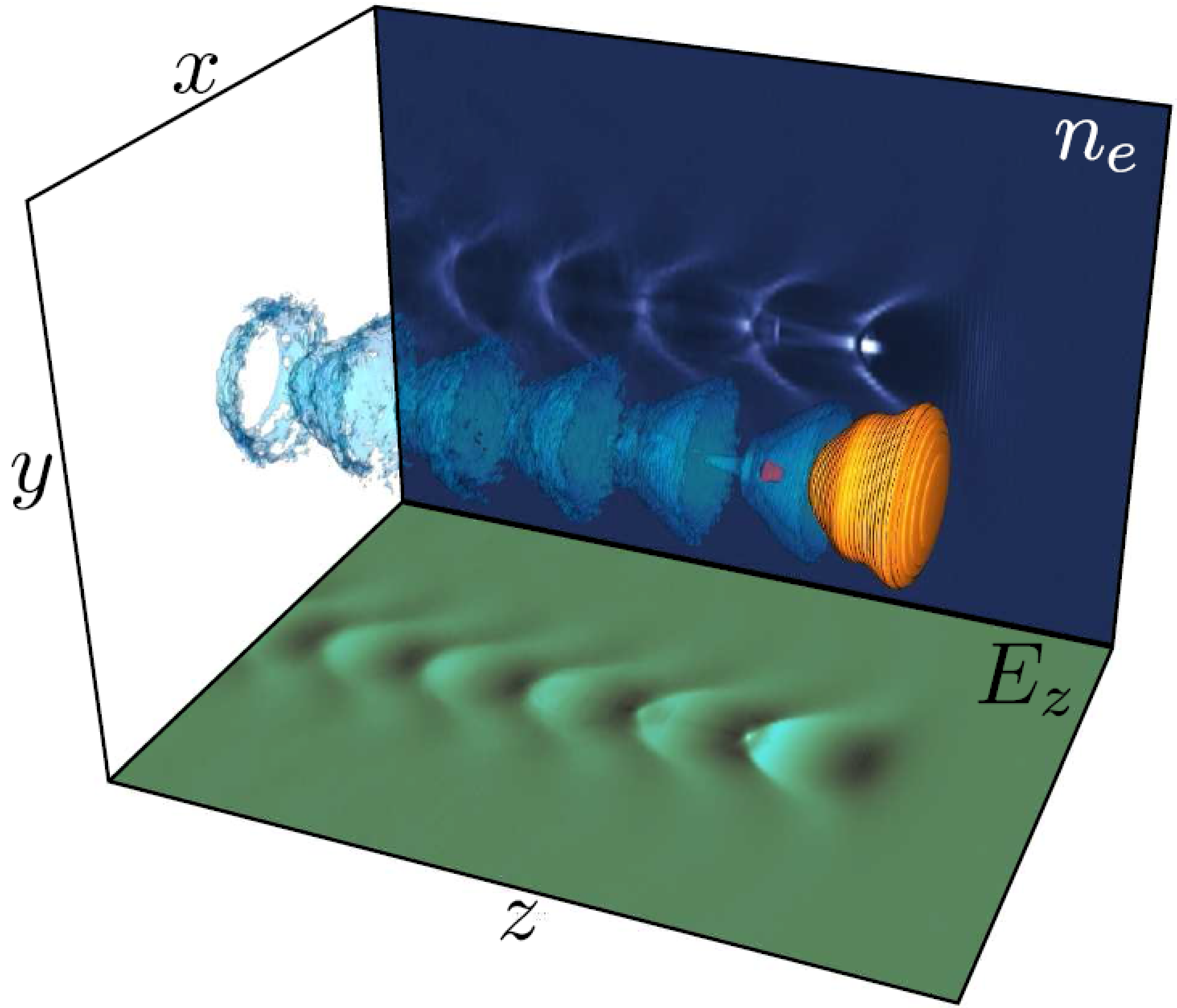
Backslides

Basic physics of downramp injection

'plasma tayloring'

- Bucket length ~ $1/\sqrt{n}$
- Phase velocity drop enables trapping





x
n_e
y
E_z
z