Laser Wakefield Acceleration of Electrons:
(some) questions to be addressed by ILE

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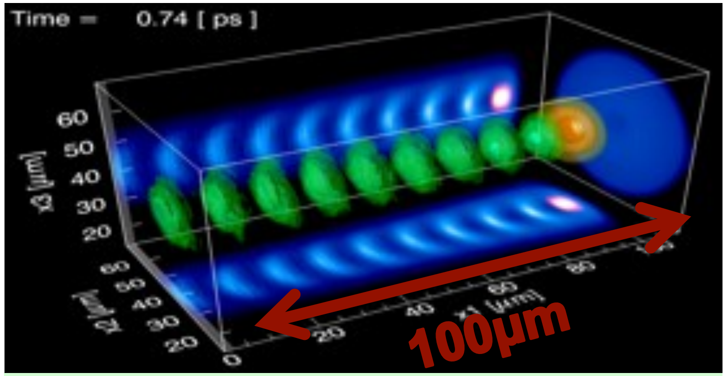
increase the accelerating gradient: from RF to plasma waves

→ decrease size of « accelerating structure »

$$E_z < 100\,\mathrm{MV/m}$$



$$E_z = m_e c \omega_p / e \approx 100\,\mathrm{GV/m}$$

klystron ➜ **high power laser (ultra-short pulse)** **E=O(150J), τ=O(15fs) ⇒P=O(10PW)**

✖ **repetition rate 0.02-10Hz** → 10-100 kHz

✖ **wall-plug efficiency <1 %** → 5 – 10%

RF cavity ➜ **gas jet, gas cell, gas-filled capillary, capillary discharge** (n ≈10^{17}-10^{19}cm^{-3})

•**stability** : → maîtrisé ✔ (contre-propagatif)

•**laser guiding** : *beam-loading, pump-depletion*

•**laser coupling** at capillary entry

RF wave ➜ **plasma wave** ($\lambda_P \approx$10-100µm)

•**régime:** linear, wave-breaking, bubble (*blow-out*)

•**transverse emittance:** focussing

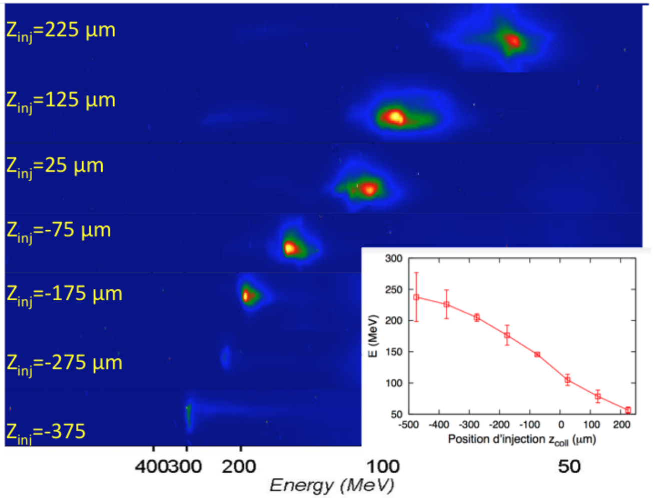
✔ **longitudinal emittance:** energy dispersion ΔE/E, ε_T,

•**stability:** ion movement, useful plasma wave buckets

State of Art with the 1 J Salle Jaune Laser (LOA/LLR/CEA-LIRM):

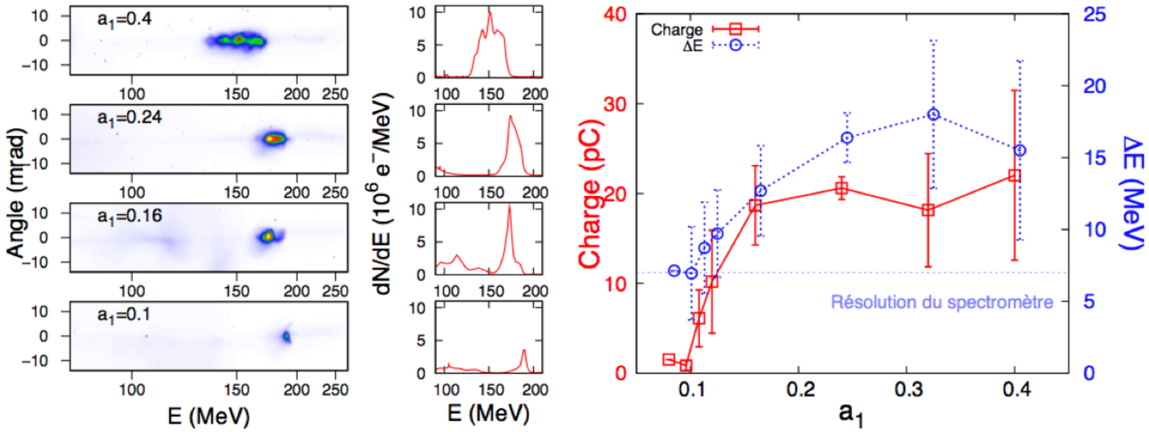
Slide courtesy of Victor MALKA

Electron energy control



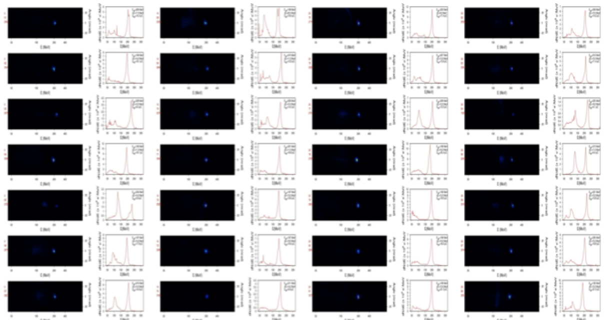
J. Faure *et al.*, Nature **444**, 737 (2006)

Charge & energy spread control



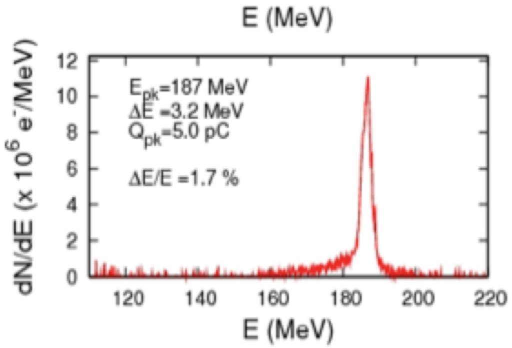
C. Rechatin et al., Phys. Rev. Lett. **102**, 164801 (2009)

Stability improved



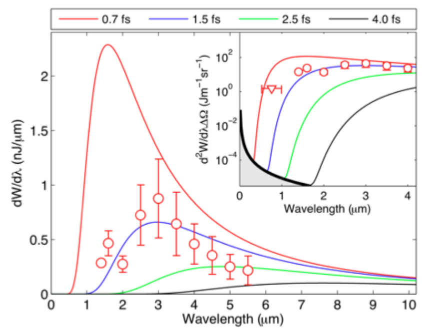
C. Rechatin et al., NJP (2010)

Energy spread improved : 1 %



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

Bunch duration : 1.5 fs



O. Lundh et al., to be published in Nature Physics

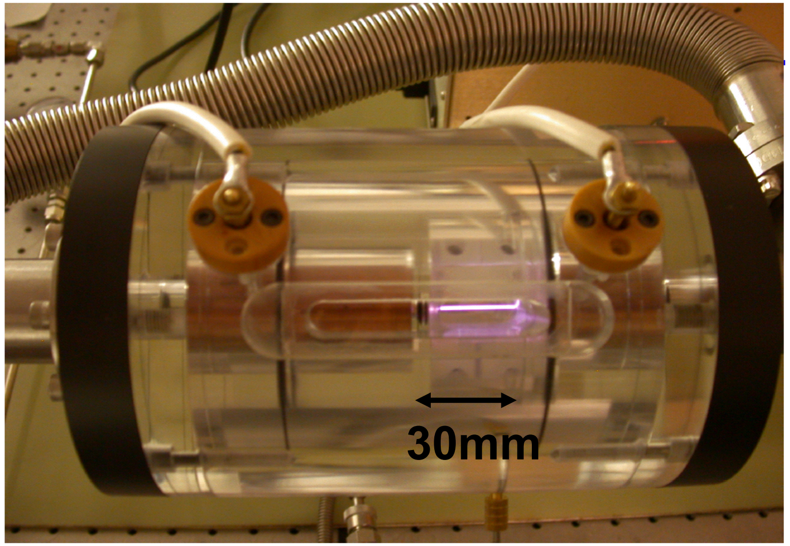
present and future challenges for laser plasma accelerators

	LWFA	ILC	unit
❍ **increase energy** ➤increase acceleration length	0.2–1	100–250(x2)	GeV
❍ **increase charge** ➤ high gas density? external injection?	0.01–0.1	3	nC
❍ reduce bunch spacing ➤laser rep. rate: “10Hz”, multi plasma-wave buckets?	0.1–10	370.10^{-9}	s
❍ **reduce energy spread (“monochromaticity”)**	1%	0.1%	
❍ **bunch duration** «*bane or blessing for colliders?*»,	<1 (?)	300	µm
❍ **reduce transverse emittance**	<3 (?)	10/0.04	mm.mrad

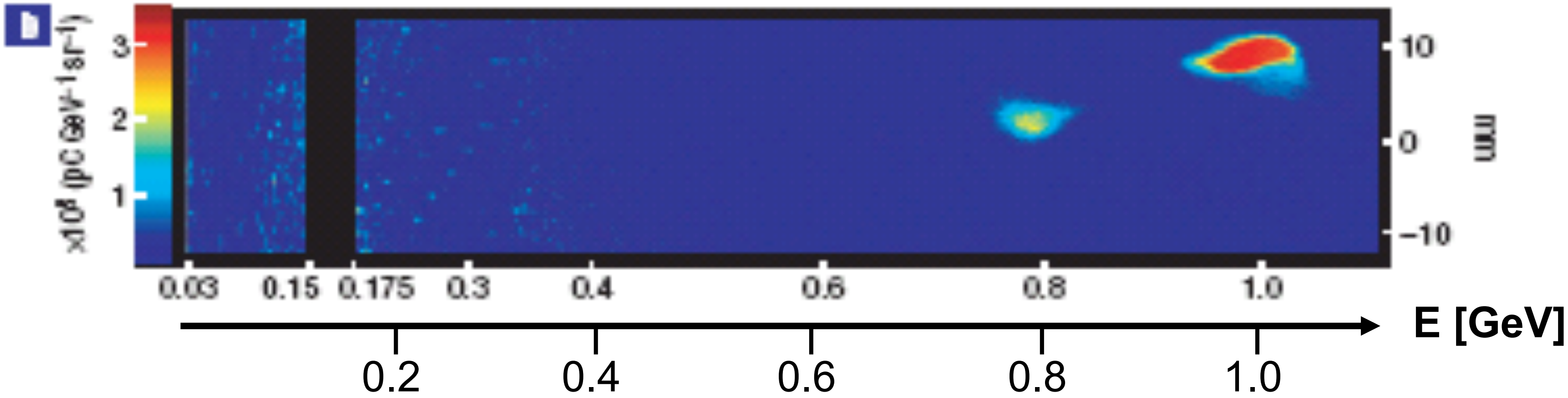
❍ **stability and control of charge, angle, energy (mean and spread)**

energy frontier: increase acceleration length

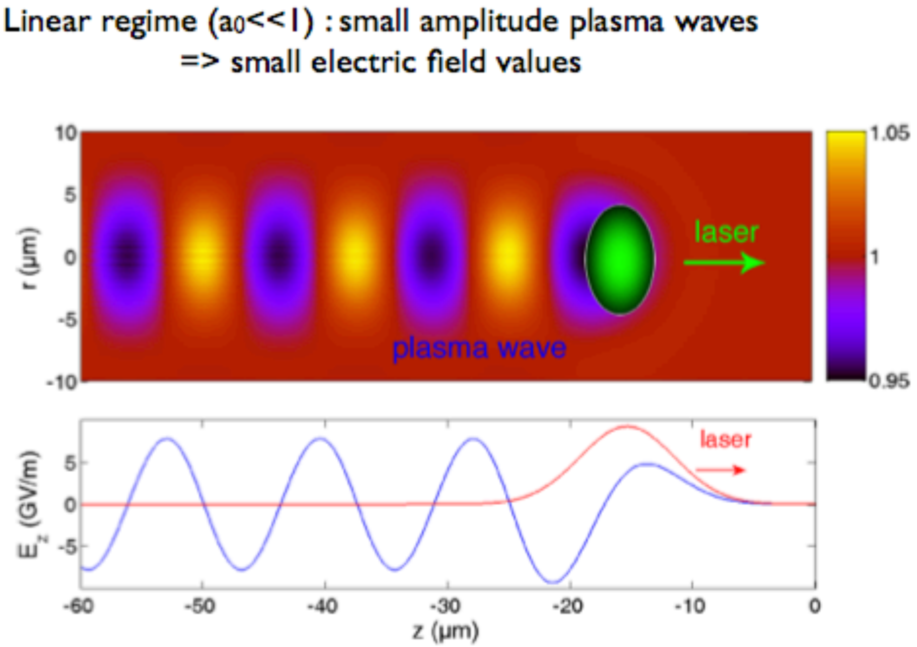
- laser diffracts -> need for guiding
- different approaches studied so far:
  - auto-focalisation in gas cell or jet:
  - « laser-drilled » plasma channels
  - gas-filled (passive) capillaries
  - capillary discharge (refr. index gradient)
- laser 40 TW, $n_e = 4.3\times10^{18}$ cm^{-3} (LBL, 2006)
- self-injection regime
  (= plasma bubble plasma)
- capillary discharge ∅~0,3mm,L~30mm

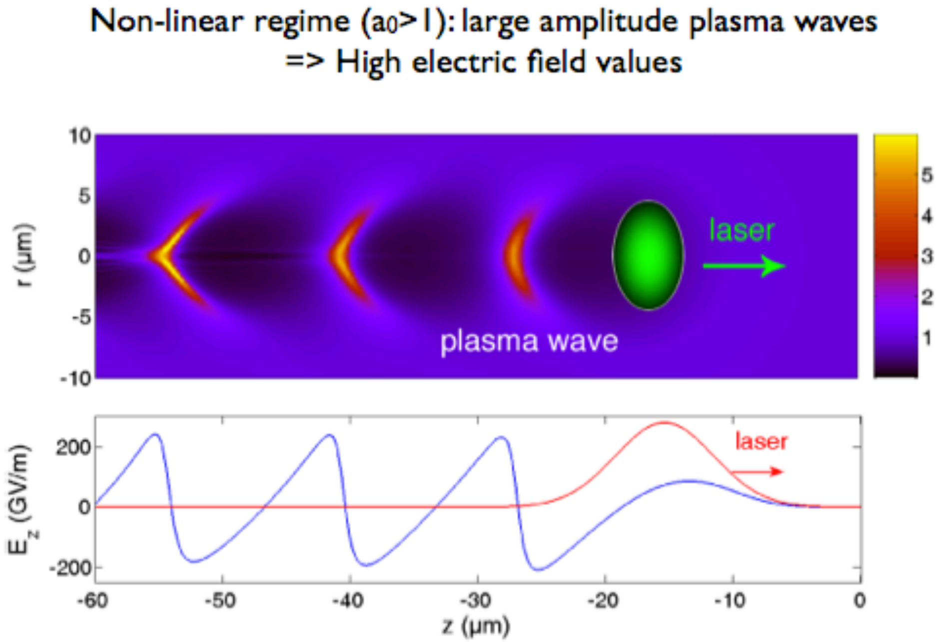


W.P. Leemans, et al., Nature Phys. 2, 696-699 (2006)



Which plasma wave regime is most suitable ?





linear regime:

- ❍ smaller laser intensities (Wm^{-2}),
- ❍ smaller plasma wave amplitudes,lower E-field **suitable for positron acceleration, and at high γ (faster wave)**

- ❍ **non-linear regime**
- ❍ **wave steepining -> wave breaking -> e⁻ blowout)** 100x higher E-field, focussing at peak of E-field, electrons only

Plots courtesy of Victor MALKA

Parameters for ILE Apollon 10PW and LUIRE 0.3 PW :

Slide courtesy of Victor MALKA

W. Lu et al., PRST-AB 10, 061301 (2007)

Blow out	$n_e(cm^{-3})$	$L_{acc}(cm)$	$\tau(fs)$	a_0	$w_0(\mu m)$	$\Delta E(GeV)$	Q(nC)	Focale(m)
Salle Jaune : 4J (dans la tache focale 6 cm)	1.9×10^{18}	0.94	34	3.9	15.34	1.22	0.27	0.9
Luire : 10 J (dans la tache focale, Diamètre 10 cm)	1.28×10^{18}	1.8	43.58	4.25	19.6	2	0.375	1.96
Apollon : 100 J (dans la tache focale Diamètre 30 cm)	5.2×10^{17}	9.8	81	5.2	36.6	6.9	0.77	11

dE/E in the few to ten 1 %

External Guiding + Injection	$n_e(cm^{-3})$	$L_{acc}(cm)$	$\tau(fs)$	a_0	$w_0(\mu m)$	$\Delta E(GeV)$	Focale(m)
Salle Jaune : 4J (dans la tache focale 6 cm)	4×10^{17}	6.8	52	2	24.5	3	1.5
Luire : 10 J (dans la tache focale, Diamètre 10 cm)	2.2×10^{17}	17	43.58	2	33	5.5	3.3
Apollon : 100 J (dans la tache focale Diamètre 30 cm)	4.8×10^{16}	170	151	2	70.9	25	21

gy,

nts

dE/E can be of less than 1 % but with a small charge

energy frontier: multiple plasma acceleration stages

- for a multi-TeV laser-wakefield collider: variation of plasma and laser parameters (i.e. density, intensity and pulse duration) over large range
- laser pulse energy depletion ultimately limits acceleration length
- multiple plasma acceleration stages
- ILE (APOLLON laser) should demonstrate 2 stage acceleration:
  - all optical plasma injector + guided plasma wave section
  - external injector + 2 plasma wave sections
- technical challenges
  - full e– bunch characterization before and after each stage
  - compact, beam quality conserving, robust electron transport
  - laser beam coupling into plasma wave section
  - laser pulse synchronisation
- How do we get «the best» out of a given laser pulse energy
  - sharing between stages, transverse shaping of plasma wave

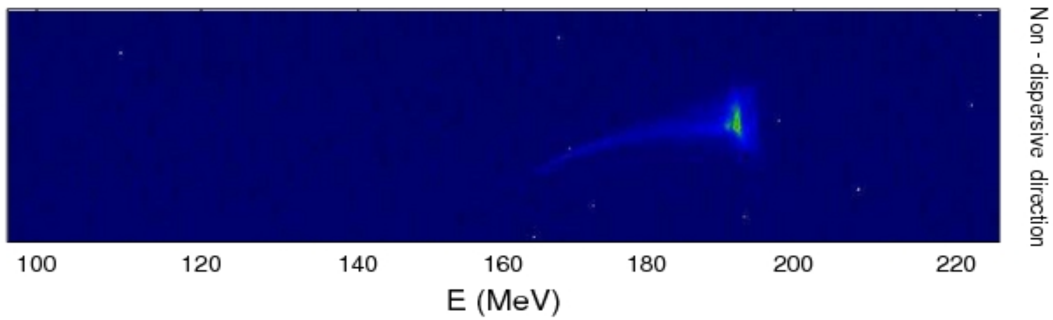
charge frontier: RF-linac or all optical injection?

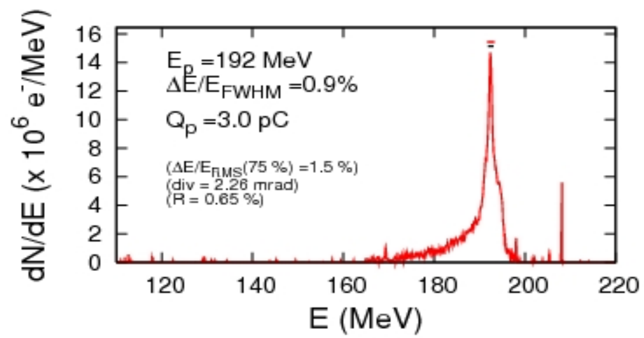
- ❍ self-injection in the blowout- (=bubble-) regime unstable and uncontrolable
- ❍ injected charge limited by available plasma electrons

➔study beam-loading effect

- ❍ external injector: RF-photogun + linac O(50MeV)
  - ➤ require good synchronisation
  - ➤ bunch length >> plasma wavelength : plasma acts as buncher
  - ➤ mature technology -> cf. Guy's talk
- ❍ controlled injection: 2 colliding laser pulses below self-injection threshold
  - ➤ experimentally demonstrated in gas jet (100-200MeV, tunable)
  - ➤ convenient «all optical» electron gun (needs 2 laser beams)
  - ➤ presently limited to charges up to O(50pC)

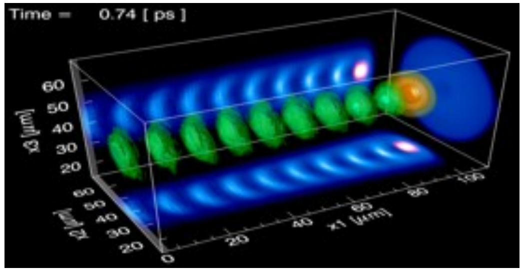
$\Delta E/E$=0.9%





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

- **beam parameter stability and availability (Q, <E>, angle, $\Delta E/E$)**
  - ➤ **Can LWFA be an inherently stable physical process? (correlation of fluctations with driver parameters, validity for PWFA?)**
- **tuning / improving the bunch parameters**
  - ➤ **transverse emittance: relevant for luminosity**
    - inherently low due to limited space charge effects
    - can betatron oscillations help to cool electron bunches?
  - ➤ **bunch length: x100 smaller than conventional**
    - high peak current -> FEL applications
    - difficult to measure, related to $\Delta E/E$
  - ➤ **energy spread:** maintaining initial ΔE possible?



- **time structure: Is it possible to accelerate in consecutive plasma wave buckets?**
- **Can a LWFA povide a useful electron test beam E = 5–50GeV for testing and calibrating HEP detectors? (10^8 particles in 1.5 fs: forget triggering)**

How can we measure the electron bunch properties?

parameters of beam bunch: moments in 6D phase space....

charge, ⟨position⟩, ⟨angle⟩, ⟨energy⟩, energy spread, transverse emittance, bunch duration

- **map out the 6D phase space ->**
- **low bunch rates (LUIRE : 1 s^{-1}, APOLLON : 1 min^{-1})**
- **expect strong shot-to-shot fluctations**
- **accomodate wide range of parameter values to be measured**
- **need a complete (as possible) shot-by-shot bunch characterization between each plasma acceleration stage**
- **statistical analysis: « from images to histograms »**
- **non- or less destructive diagnostics first, destructive ones later**
- **electron diagnostic have to be honed at satellite facilites (lower power, higher repetition rate, higher beam availability?)**

Conclusion

- ILE lasers (LUIRE 1PW and APOLLON 10PW) opens field for systematic LWFA experiments, wide range of driver parameters (a_0 , τ)
- scientific objectives for e^- accelerat^{O} to agree with requirements for HE accelerators: maximum energy and charge are not the only yardsticks.....
- identification and consolidation of stable and controlled regime is crucial
- (partly) unprecedented, impressive challenges on instrumentation:
  - high intensity laser guiding over 2m x 200um (-> targetry)
  - compact, high quality e^- beam transport and diagnostic
  - e^- and laser beam alignment and synchronisation (multistage, RF linac)

  need for dedicated R&D programs on each
- not adressed in this scope (but relevant for a NNLC)
  - lepton polarity (positron acceleration)
  - lepton polarisation (electron spin)