What can we do with a 5PW laser?

Brigitte CROS

Laboratoire de Physique des Gaz et des Plasmas,

CNRS- Université Paris Sud 11 – Orsay, France

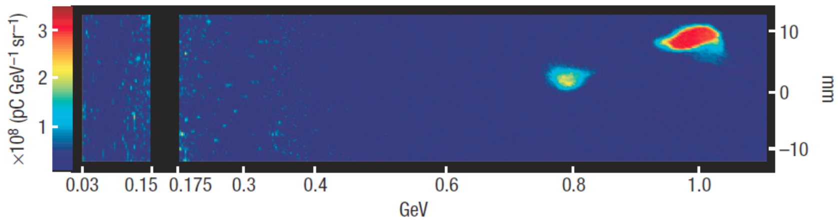
Outline

- Motivations for Laser Plasma Accelerators (LPA) using high power lasers
- Key parameters for LPA
- Example of the CILEX project with two multi-PW beams

Status of Laser plasma acceleration

- Laser plasma accelerators are sources of electrons and radiation (THz, X, gamma)
  - Compact accelerators

    (1GeV, 3cm, 40 TW laser ~100m²)
  - Short duration bunches (~10 fs)



Leemans, nature physics 2006

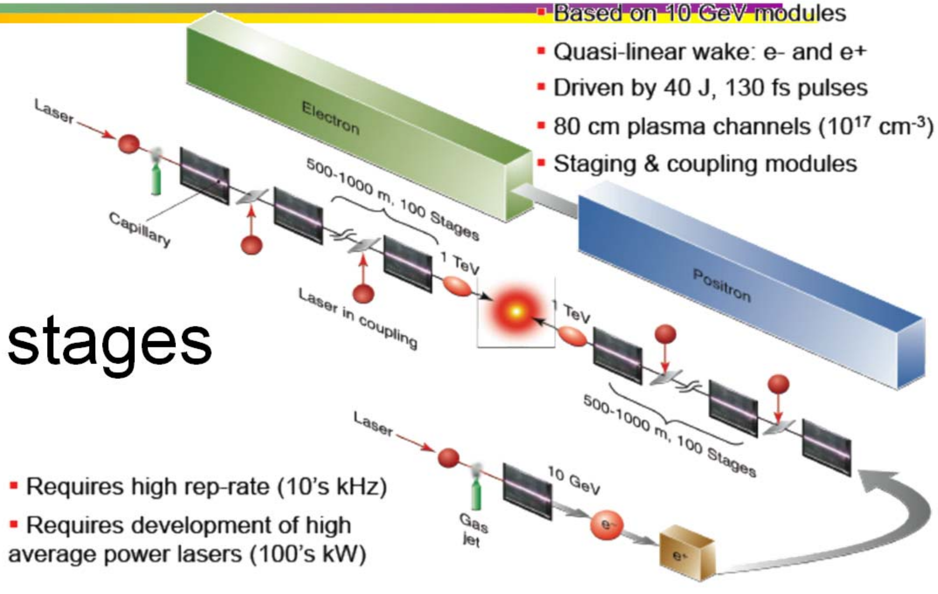
- High accelerating gradients (<100 GV/m) demonstrated
- Agreement with theory
- Broad spectra due to continuous injection

Current objectives and main issues

- **Objective:** control the properties of the accelerated beams and increase their energy
  - Optimisation of the beam properties (energy spread, emittance, reliability) in the range 100MeV -1GeV
  - Control of the emitted radiation
  - Increase the energy: feasability studies for a high energy accelerator (multi-stages)
- **Main issues**
  - Laser reliability
  - Increase acceleration length
  - Inject electrons in the accelerating structure in a precise and controlled way
- **The best method depends on the acceleration regime and on the desired electron beam characteristics.**

High peak power lasers to access new regimes of LPA and applications

- Accelerators for HEP



Leemans & Esarey, Physics Today, March 2009

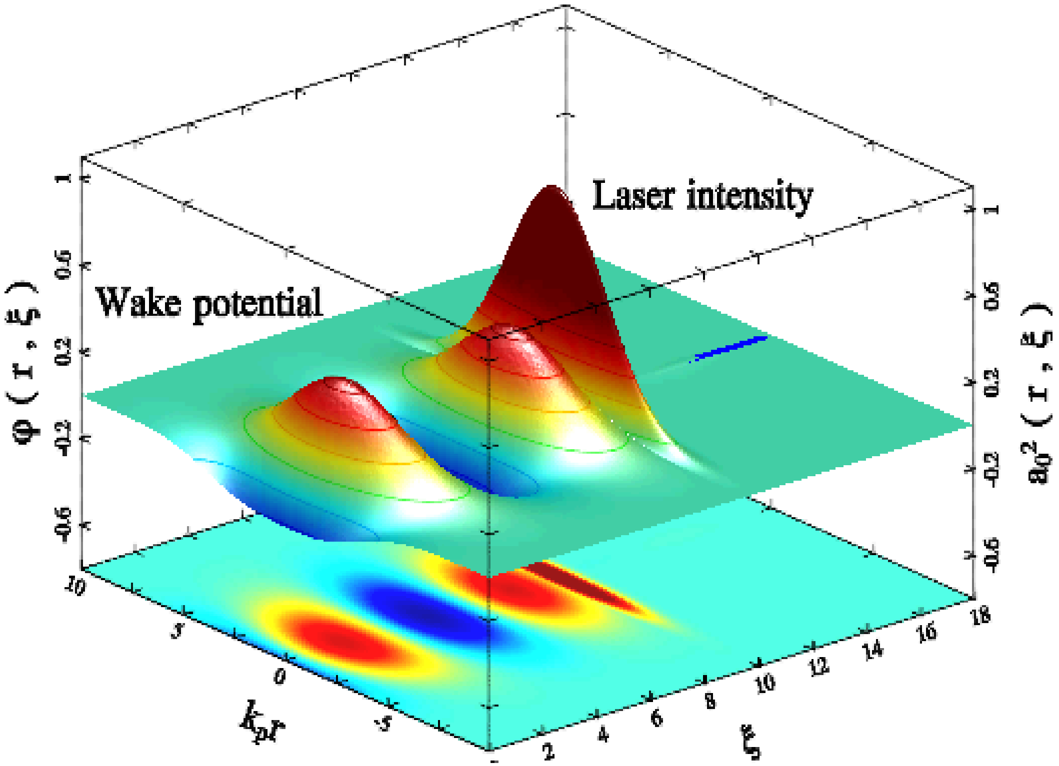
  - Accelerator design ~10 GeV stages

- Intenses sources of electrons & radiation and their combination
  - Driver for short wavelength FEL
  - Positron production
  - Particle-photon interactions at ultra-high intensity, from multi-MeV gamma rays to pair production

Outline

- Motivations for Laser Plasma Accelerators (LPA) and high power lasers
- Key parameters for LPA
- Example of the CILEX project with two multi-PW beams

Laser wakefield: « linear » regime



Courtesy of N.E. Andreev

$$E(GV/m) = 30\left[\frac{n_e(cm^{-3})}{10^{17}}\right]^{1/2}\frac{dn_e}{n_e}$$

- Ponderomotive force ~ gradient of laser energy
- Accelerating structure sine wave: λ_p~10-100µm
- Accelerating field:
  1-10 GV/m
- Accelerating structure for electrons or other relativistic particles, produced by an external source

Energy gain in a laser plasma accelerator

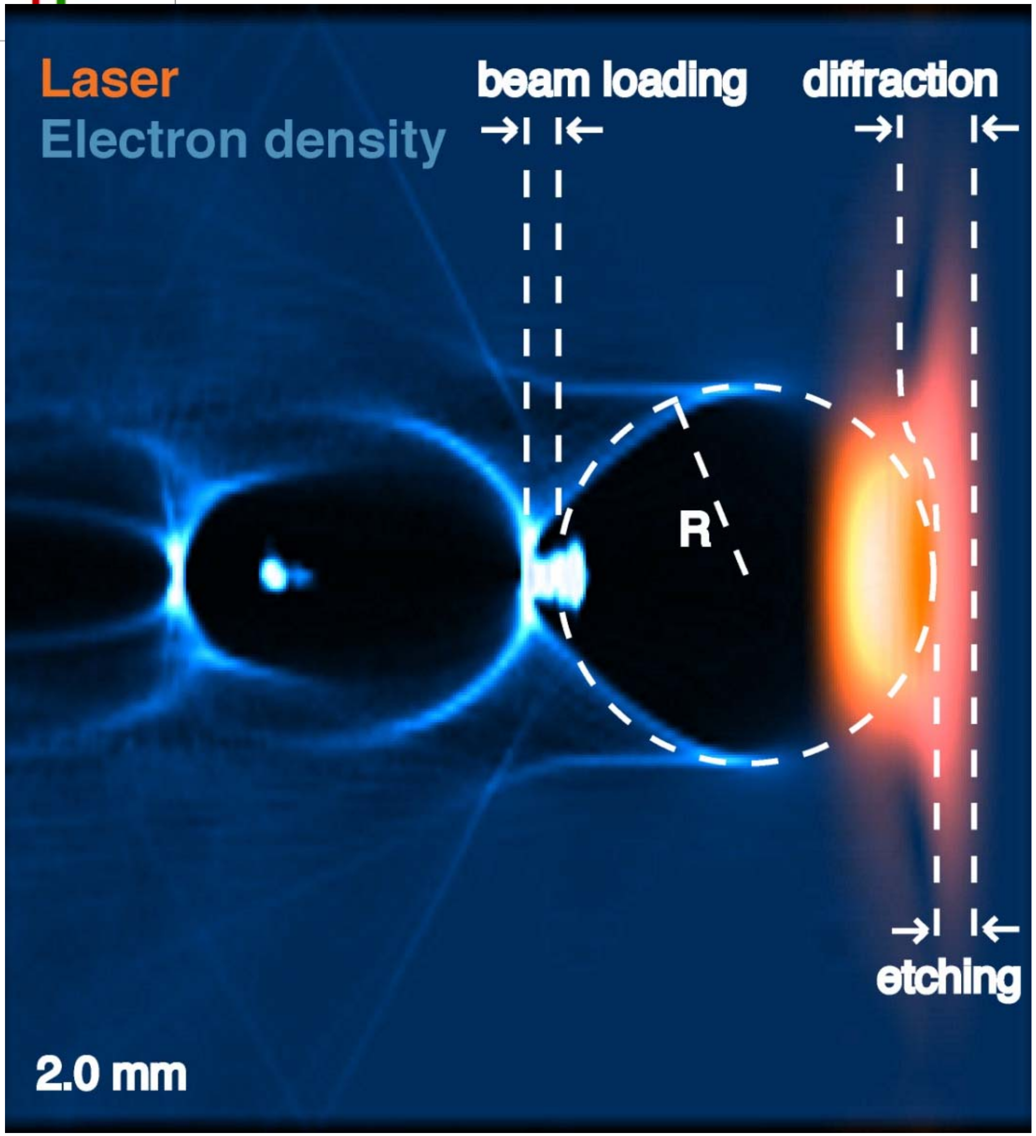
$$\Delta W = e\, E_p\, L$$

- The length of acceleration is determined by
  - Laser diffraction
  - Dephasing of electrons (entering a decelerating phase of the plasma): $L_{deph} \propto 1/\, n_e^{3/2}$
  - Damping of laser energy $L_{am} \propto 1/\, (a_0^2\, n_e^{3/2})$
- Optimum length: $L_{deph} \sim L_{am}$ and $a_0 \sim 1$

$$\Delta W \propto 1/n_e$$

- **To increase energy gain requires**
  - **To lower electron density**
  - **To increase interaction length**

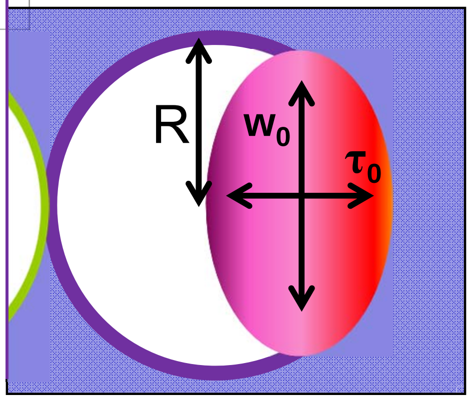
Non linear wakefield with self-injection



W. Lu PRSTAB, 10, 061301 (2007)

- Compression and self-focusing of the pulse
- Expulsion of electrons: creation of a bubble (ions)
- Electrons self-injected at the back of the bubble by accelerating and focusing fields
- Injected electrons modify the back of the bubble (beam loading)
- Generation of betatron radiation

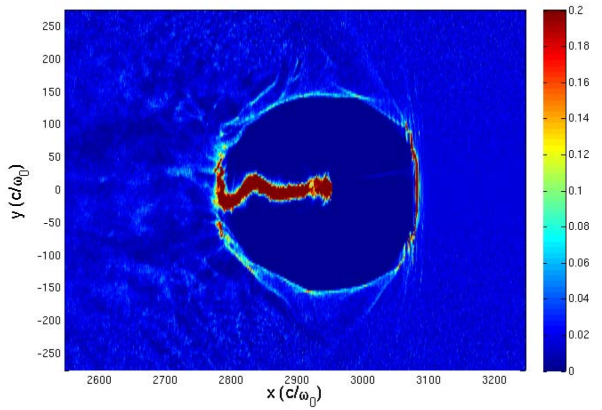
Scaling laws of NL laser wakefield acceleration



Lu et al. PRSTAB 10, 061301 (2007) $a_0 > 2$

$$k_p R \approx k_p w_0 \approx 2\sqrt{a_0} \qquad k_p = \omega_p / c$$

$$c\tau_0 \approx \frac{2}{3} w_0$$



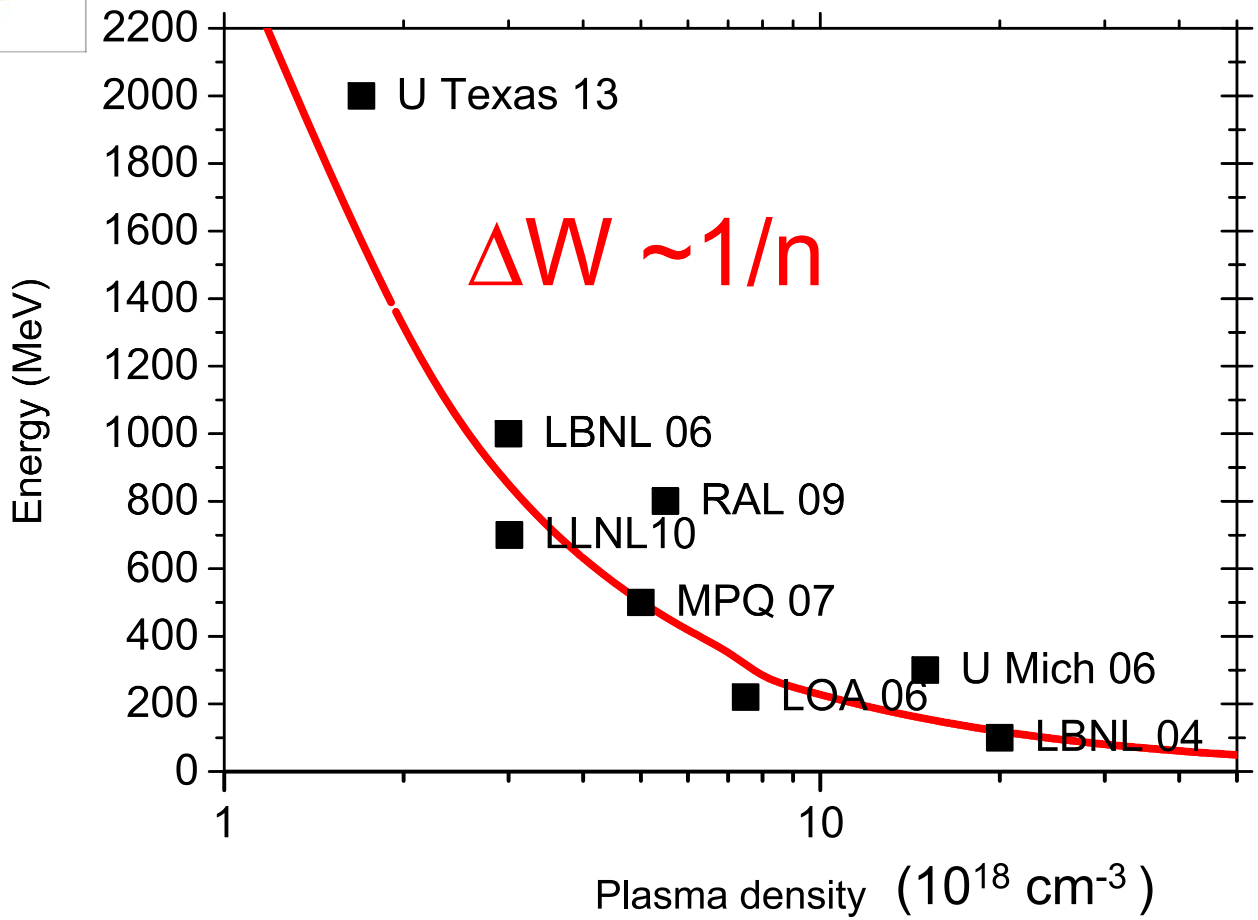
$$E[\mathrm{GeV}] = 1.7 \left(\frac{P[\mathrm{TW}]}{100}\right)^{1/3} \left(\frac{10^{18}}{n_p[\mathrm{cm}^{-3}]}\right)^{2/3} \left(\frac{0.8}{\lambda_0[\mu\mathrm{m}]}\right)^{1/3}$$

$$N \sim 2.5 \times 10^9 \frac{\lambda_0[\mu\mathrm{m}]}{0.8} \sqrt{\frac{P[\mathrm{TW}]}{100}}$$

- For a given laser energy :
  - Higher electron energy is achieved for low plasma density, and (long duration, low intensity) matched to bubble
  - High beam charge is obtained for High power, high plasma density

Courtesy of X. Davoine

Increased electron energy achieved at lower plasma density and higher power



Scaling law for energy gain

In the NL regime, with self-injection

- But …..lowering the plasma density stops self-injection

B. Cros, EAAC2013

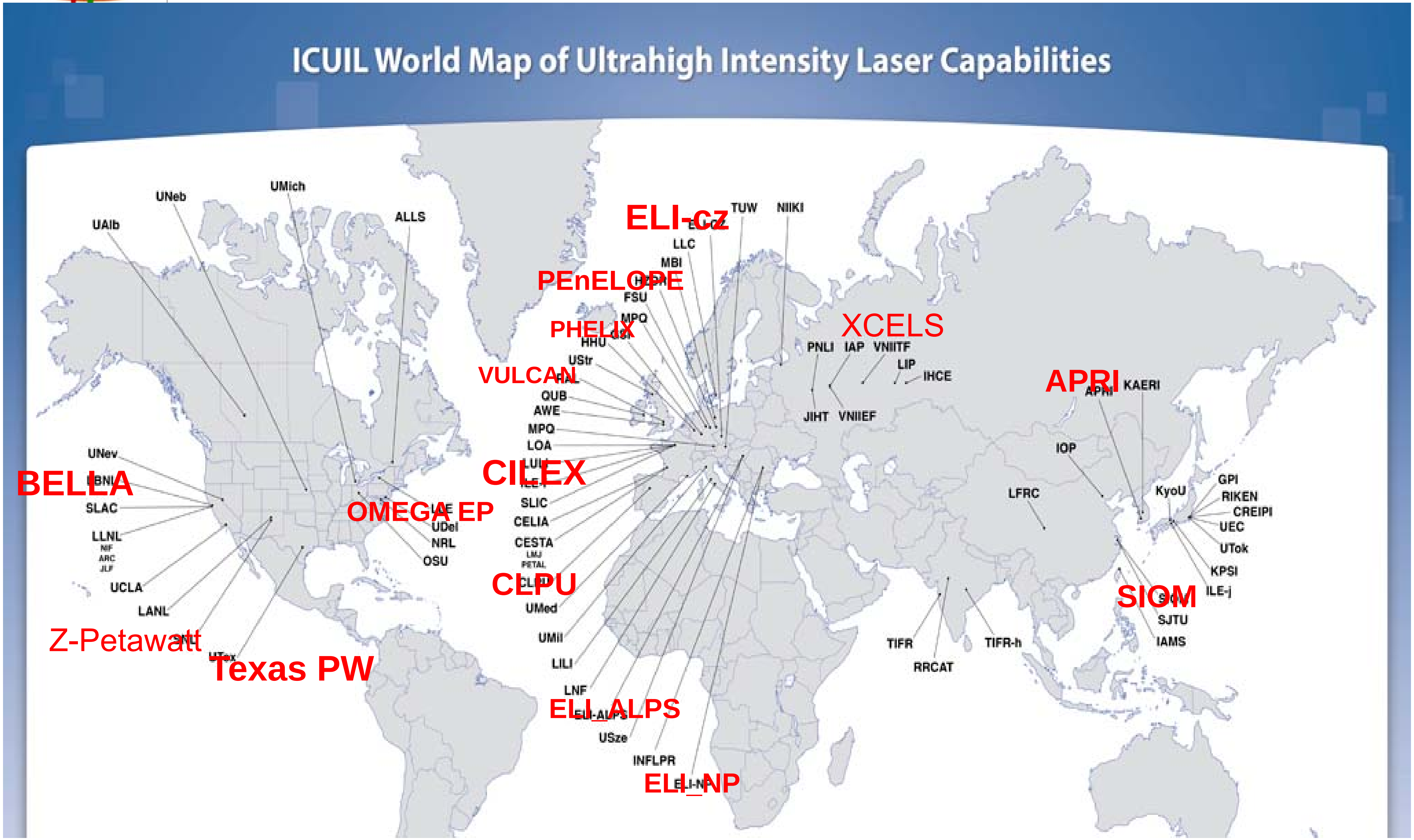
Both regimes can benefit from multi-PW laser drivers

- The diffraction/dephasing/depletion optimisation for LPA can be addressed in a wide range of parameters
- Linear regime: External laser guiding can be used to create a large volume of plasma at low plasma density
- Nonlinear regime: At high intensity the bubble regime can be accessed directly, to explore the validity of scaling laws

Outline

- Motivations for Laser Plasma Accelerators (LPA) and high power lasers
- Key parameters for LPA
- Example of the CILEX project with two multi-PW beams

Several PW laser facilities projects worldwide



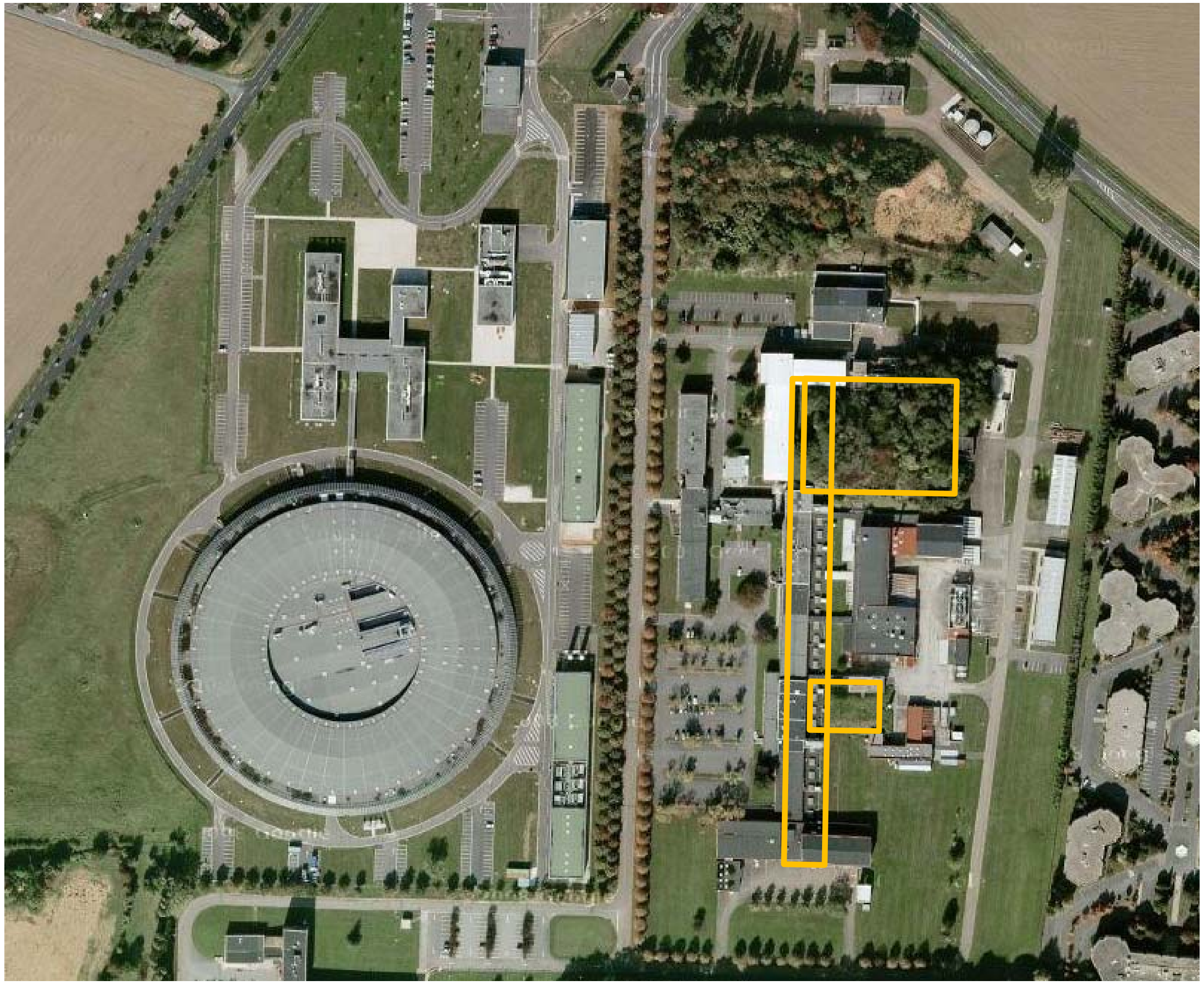
Centre Interdisciplinaire Lumière EXtrême

Research Centre on Intense Lasers, Plasmas and Applications

rs

Centre Interdisciplinaire Lumière EXtrême

Research Centre on Intense Lasers, Plasmas and Applications



Multi-PW laser

APOLLON 10PW

Multi-beam facility

1 PW + probe + ns

Dedicated experimental areas

Satellite facilities

UHI100, LASERIX

Multi-disciplinary program

Training of scientist and engineers

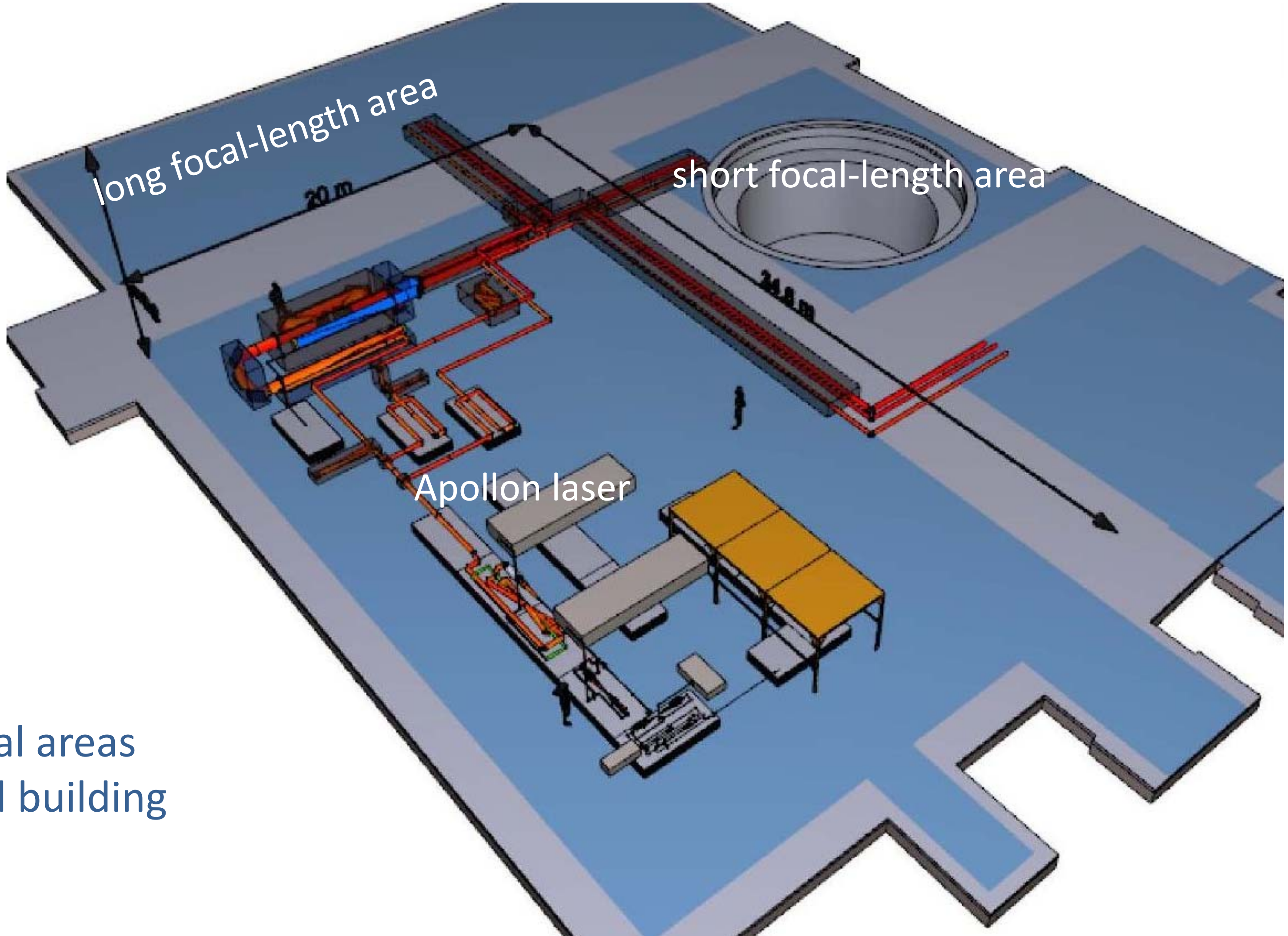
Operated as a user-facility

Overview of CILEX- Apollon laser facility

2 main beams at the PW level:
15J, 15fs
150J, 15fs

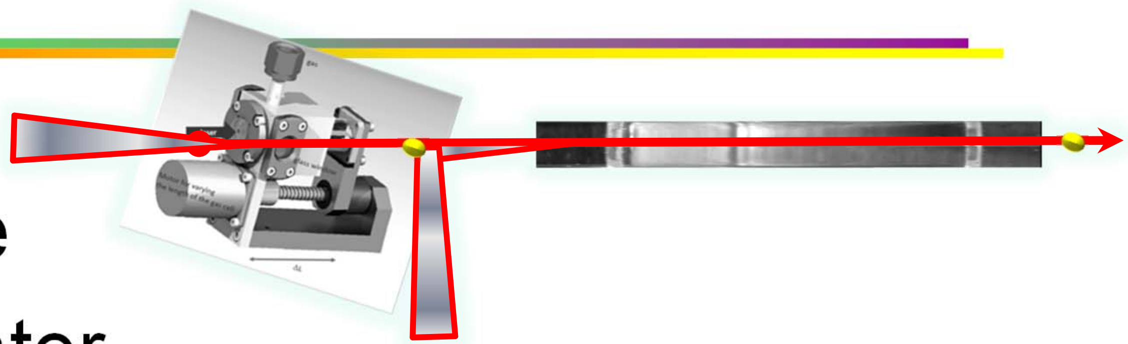
Additionnal beams
Creation beam:1 ns / 300 J
Probe beam:20 fs / 200 mJ

4 beams and 2 experimental areas
in a shielded building



Numerical tools are developed to design
multi-stage acceleration experiments on CILEX Apollon facility

LPA objectives in the frame of CILEX



- Develop a two-stage laser-plasma accelerator

  As a test facility on electron acceleration and a prototype for future studies on multi-stage laser plasma acceleration (MUSTLPA)

- Study fundamental processes
  - Scaling laws for electron acceleration in UHI regimes
  - Positron production and acceleration
  - Generation of radiation (betatron, injection into an undulator, Compton or Thomson scattering)

Timeline for electron acceleration

- **PHASE 1**: 2013-2015
  - Research program on satellite facilities
  - Conceptual design of the experimental set-up for APOLLON
  - Numerical simulations for diagnostics design and PHASE 2 preparation

- **PHASE 2**: 2015-2016

  First tests on APOLLON at 1 PW to 5 PW: Single stage electron acceleration in long focal area (HE2)

  Validation of laser intensity

  Comparison to scaling laws

  Injector optimization

- **PHASE 3**: 2016-2017

  Implementation of 2 stage Laser Plasma Acceleration

Two-stage Laser Plasma Accelerator

Laser beam transport

NL LPA with self-injection

Electron transport

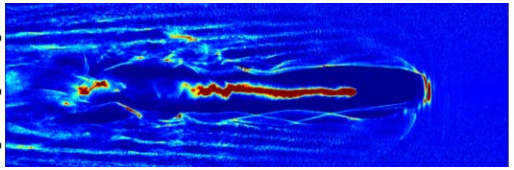
Diagnostics

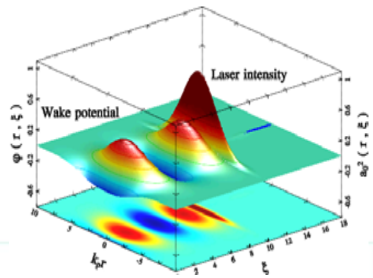
Laser beam transport

QL LPA without self-injection

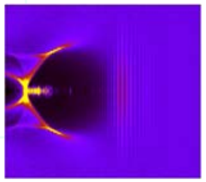
Electron transport

Diagnostics





Stage 1:
* NL laser wakefield to ultimate intensity: explore scaling laws
* Develop a reliable electrons injector and beam transport



Stage 2:

- Develop a long accelerating medium without self-injection
- Couple electrons from injector to accelerator

High charge beams in the GeV range can be generated by 1-5 PW lasers

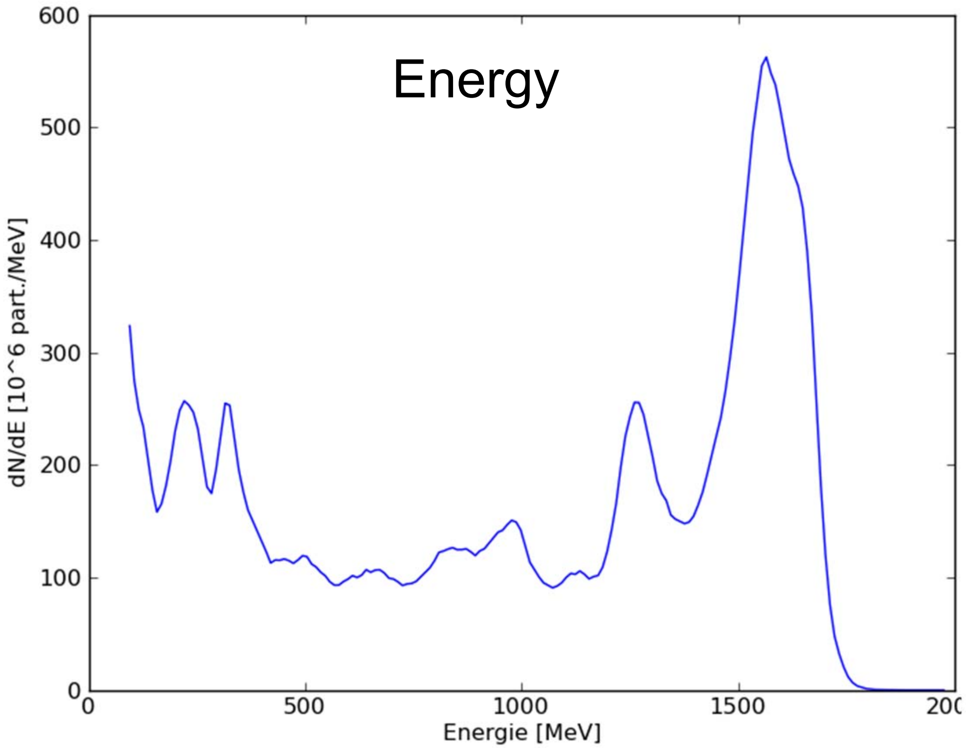
- Charge > 200 MeV: 45 nC
- **Charge > 1.35 GeV: 20 nC**
- Acceleration length: 900 µm

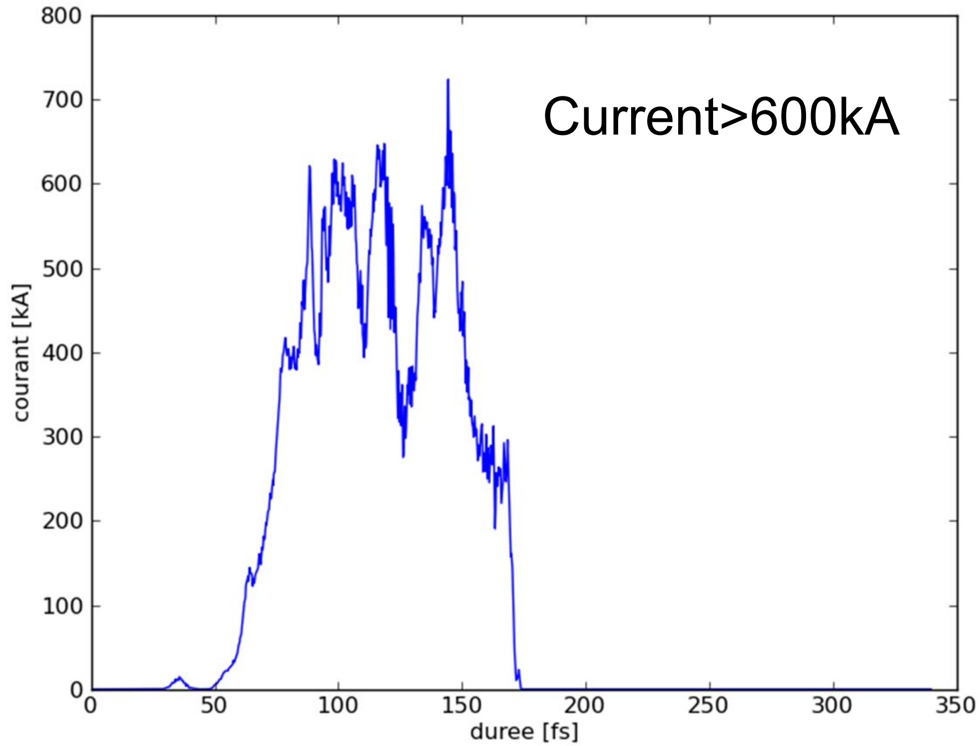
- τ_0 = 15 fs
- w_0 = 6.4 µm
- a_0 = 58
- **P_0 = 4.7 PW**
- $n_e = 2.85 \times 10^{19}$ cm^{-3}

- **E = 1.45 GeV**
- **Q = 10 nC**
- **L_{acc} = 0.7 mm**

75J-15fs

Simulations with CALDER-CIRC by X. DAVOINE

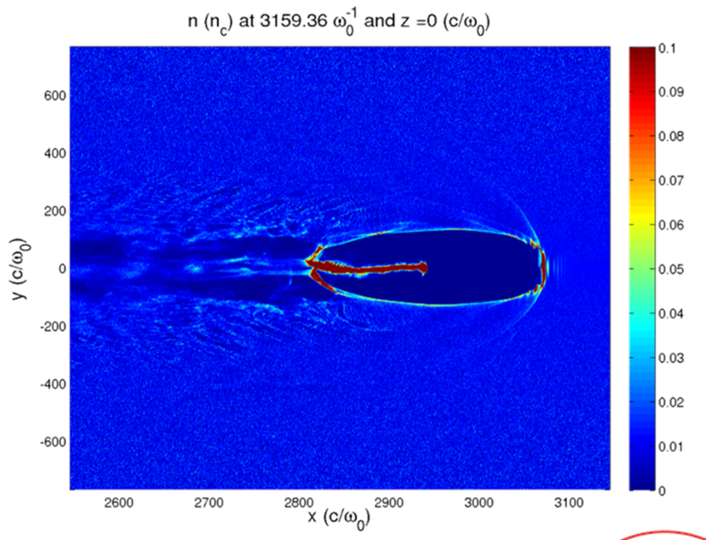




Work overview

- Preparatory experimental work using UHI100 (3J, 25fs on target) and other accessible facilities
- Simulations to address relevant issues; tools development (CALDER-CIRC, WAKE-EP, WARP) and parametric studies
- Main tasks:

  (design, test and implementation)
  - Laser Beam Transport (LBT)
  - LP electron source (injector)
  - Electron beam transport (EBT)
  - LPA medium (accelerator)
  - Diagnostics



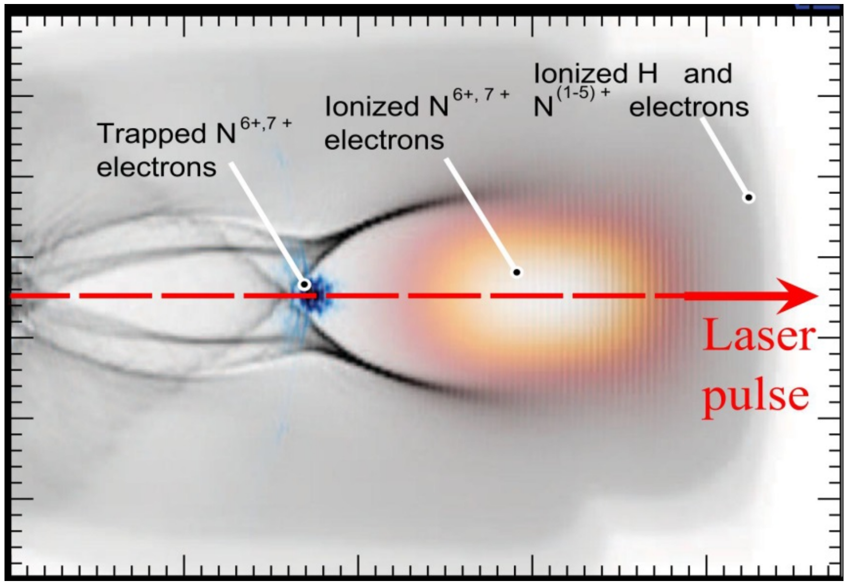
Laser Beam requirements

- For each stage, laser beam needs to be focused with a beam quality and reliability in relation with the requirement of the experiments (target):
  - 3m to 40m focal length, stabilization with 10 % waist
  - Waist 10-100µm, intensity 10^{18}-10^{22} W/cm^2.
  - Correlation between laser and electrons stability is under study (F. Desforges poster)
- Synchronization of the two acceleration stages: required stability and precision will be determined (B. Paradkar, A. Chancé simul.)
  - Electron beam focused to a 10 µm sphere (plasma wave wavelength of 2nd stage ~100µm)
- Innovative solutions to preserve a high average gradient of the accelerator will be developed.
  - Studies on plasma mirrors.

ELISA Injector: ionisation injection

Electron injector for compact staged high energy accelerator

- Develop a reliable electron source
- Optimize electron production from a gas cell with variable length, filled with hydrogen gas and impurities
- De-couple injection and acceleration in order to have more control on e- beam properties.

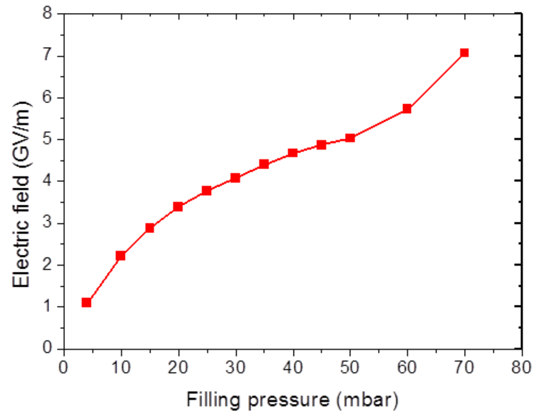


Pak *et al.* Phys. Rev. Lett. 104, 025003 (2010)

- Implement ionization injection in PIC code (WARP) and define numerically operation parameters (UHI100 and Apollon laser parameters)
- Experiments in gas cell planned before the end of 2013
- (S. Dobosz poster)

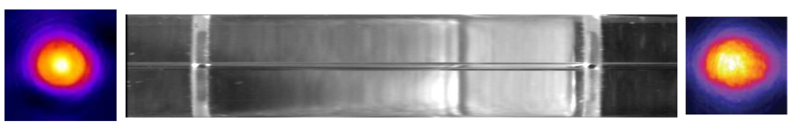
Laser Plasma Accelerating stage

- An accelerating stage will be designed and developed to produce accelerated electrons in the 10 GeV range, in a reliable way.
- Laser wake-field in waveguides permitting to reach meter scale distances will be studied in weakly non-linear regimes.
  - Laser guiding over 0.1-1m range
- Simulations of electron injection & acceleration (WAKE-EP)



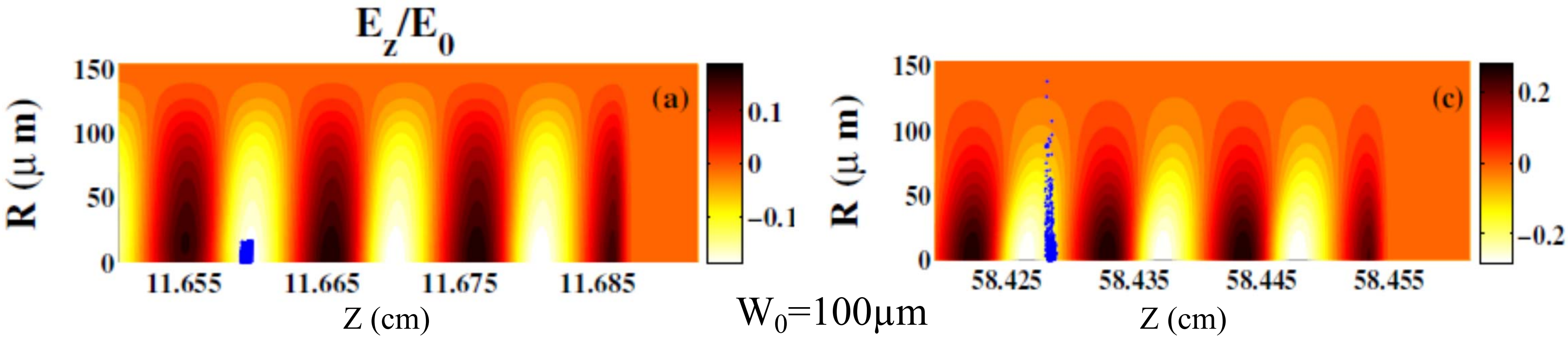
Wojda et al. Phys. Rev. E 80, 066403 (2009)

Andreev et al. New J. Phys. 12 (2010) 045024.



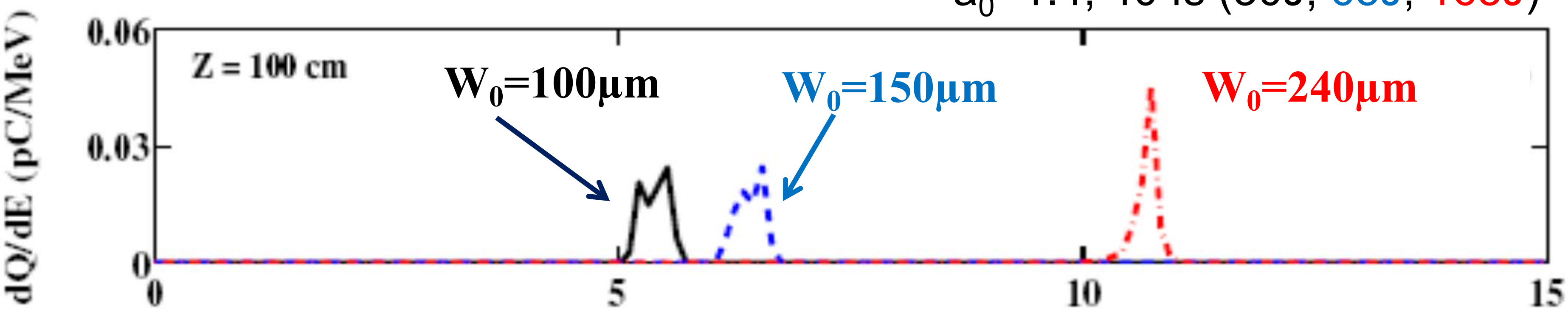
Simulations with WAKE-EP

Capillary radius 154μm, electron density $10^{17}cm^{-3}$, plasma wavelength 100μm
Laser radius 100μm, a_0=1.7, 1PW, e- injection (10pC, 10fs, 10μm, 50MeV)



W_0=100μm

a_0=1.4; 40 fs (30J, 65J, 165J)



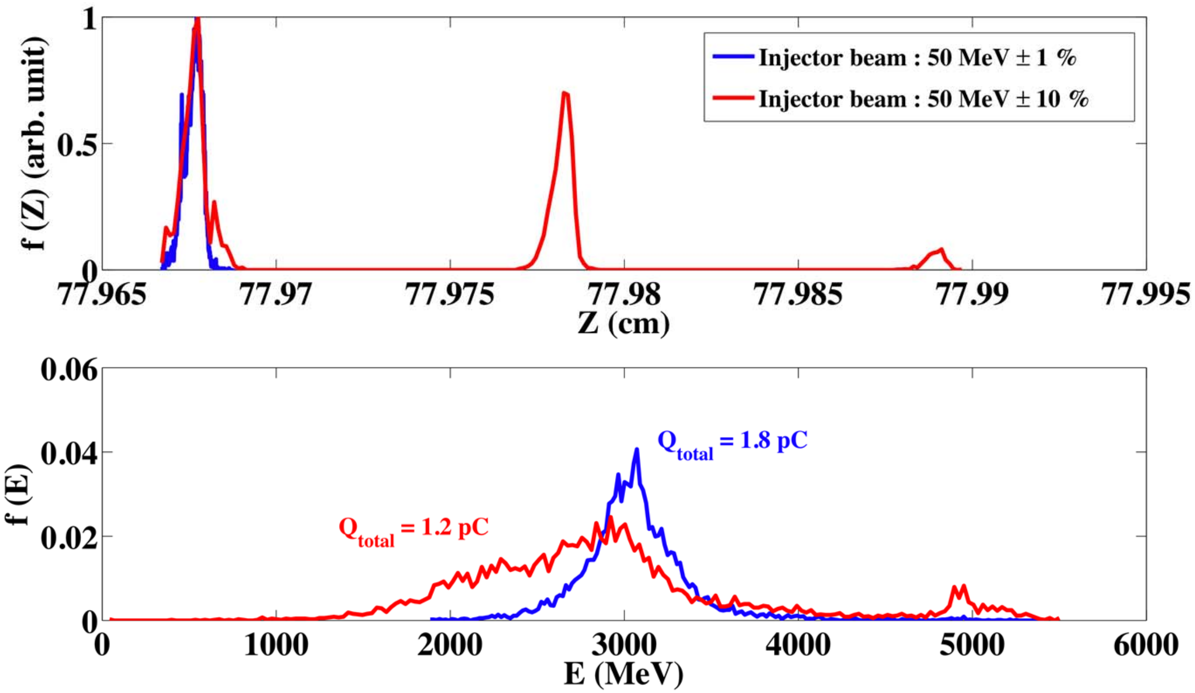
Energy (GeV)

Integrated simulations are underway for the design of multi-stage LWFA

E-beam from laser-plasma injector (model with PIC code)

E-beam transport line code (A. Chance)

WAKE-EP simulations in the quasi-linear regime of LWFA (B. Paradkar)



Laser :
$a_0 = 1.42$
T(FWHM) = 40 fs
$W_0 = 100\ \mu m$

Plasma density = $10^{17}\ cm^{-3}$

Transport line length = 1 m

Design of high quality first stage electron injector is crucial for multistage electron accelerator.

Summary

- Multi-PW lasers can be used to explore scaling laws in the NL regime :
  - For short laser pulses, large currents expected, a few 100s of kA
  - Beyond scaling laws, different regimes: pulse length << pulse waist, chirp
- Quasilinear regime and electron acceleration up to 10 GeV in 1 stage can be tested in the perspective of MUST-LPA

- CILEX PW beams offer a unique opportunity to test MUST-LPA:
  - A building: large area of shielded rooms at l'Orme des Merisiers
  - A variety of secondary sources and their combination will make it a test facility for LPA and particle-photon interactions
- Work has started in Phase 1:
  - Experiments in preparation with UHI100, Simulations, design of MUST-LPA and technical implementation are underway.

CILEX Collaboration on Electron Acceleration

CEA-DIF, CEA-SACM, CEA-SPAM, CPhT, LAL, LLR, LPGP, LULI

A. Beck, C. Bruni, A. Chancé, M.E. Couprie, X. Davoine, N. Delerue, F. Desforges, S. Dobosz, M. Grech, J. Ju, J.R. Marquès, Ph. Martin, G. Maynard, P. Monot, P. Mora, B. Paradkar, M. Quinn, C. Riconda, C. Rimbault, A. Specka, J. Schwindling, T. Vinatier …