European Laser Electron controlled Acceleration in Plasmas to GeV energy range

euro LEAP

Project: NEST ADVENTURE STREP
Coordination: Brigitte CROS (CNRS- LPGP)

Sept. 2006 -2009

Objectives

- To build a laser-plasma accelerator
- To accelerate electrons to the GeV energy range in a plasma wave.
- To test the issues related to the control of the properties of the electron beam
- Expected result: accelerated e-beam with
  – energy in the GeV range,
  – energy spread of the order of 1%,
  – pulse duration of the order of 100 fs,
  – charge in the range 10 pC to 100 pC.

Participants

- **France .** Centre National de la Recherche Scientifique (CNRS) : LPGP, LOA, LLR, LAL
- **UK .** STFC- CLF RAL, U STRATHCLYDE, Imperial College, U OXFORD
- **The Netherlands.** U. Twente (UT), Eindhoven U. of Technology (TUE)
- **Portugal.** Instituto Superior Técnico (IST-GOLP)
- **Sweden: The Lund Laser Centre (U. Lund) became a contractor in February 2008**

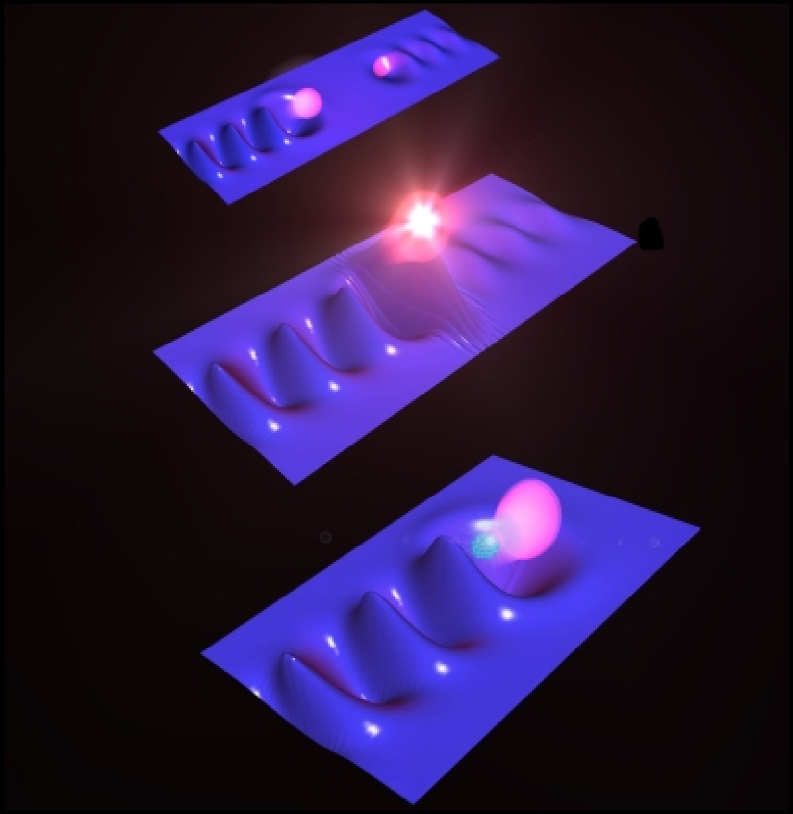
Research activities

- WP1: Laser Injector Development
- WP2: RF Photo-Injector Development
- WP3: Production of a plasma wave over a long distance
- WP4: Injection & Controlled Acceleration
- WP5: Diagnostics

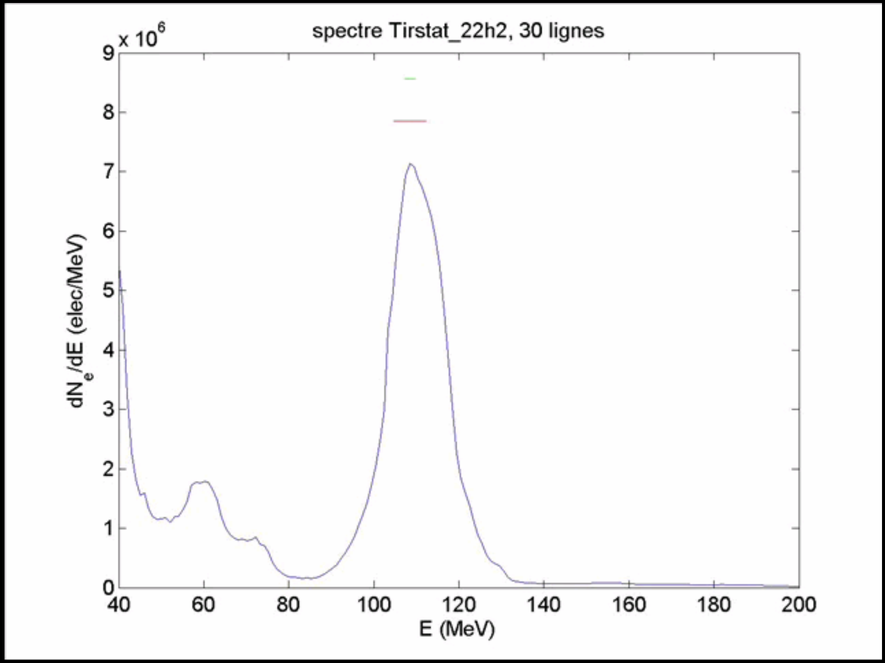
WP1: Laser Injector Development

- Demonstrate all-optical injection (AOI) and acceleration of ultra-short (10 fs) electron bunches by
  - colliding laser pulses (CDP)
  - collinear pulses (CLP)
- Characterize and optimize the spectrum of electrons
- Achieve mono-energetic, low emittance electron beams at a few tens of MeV to 200 MeV

Colliding laser pulses - LOA



Simulation, A. Lifshitz

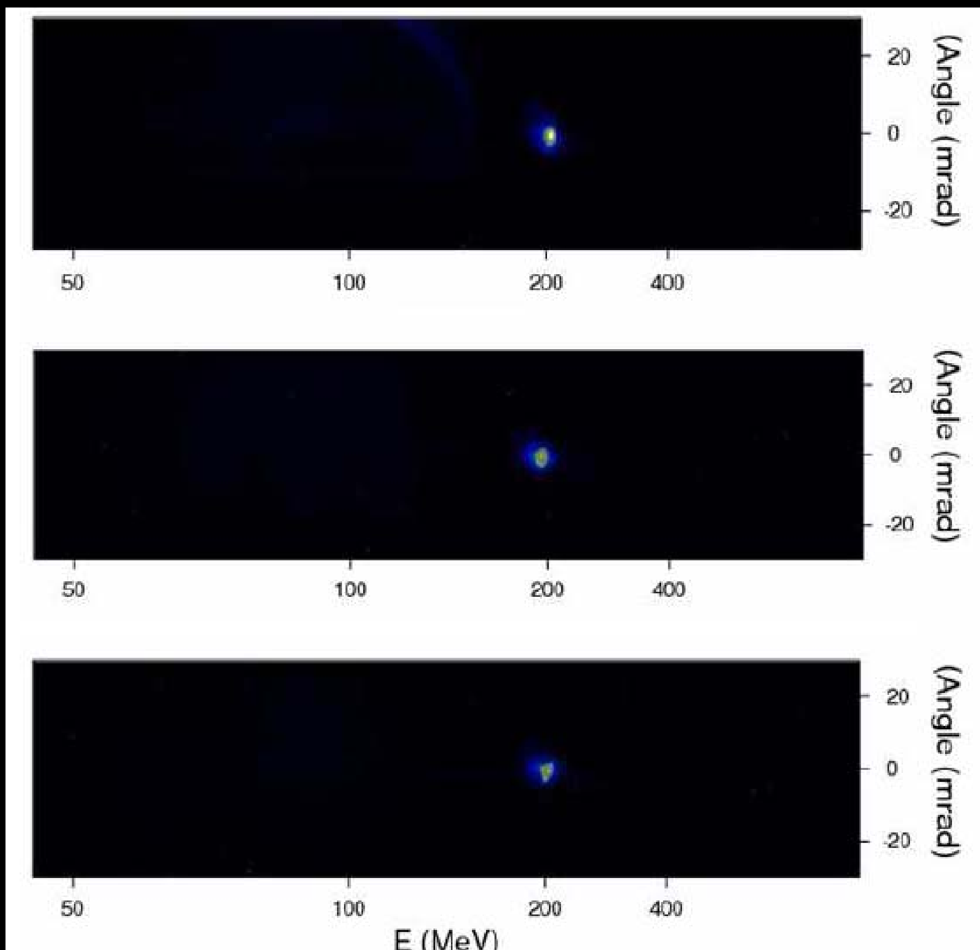


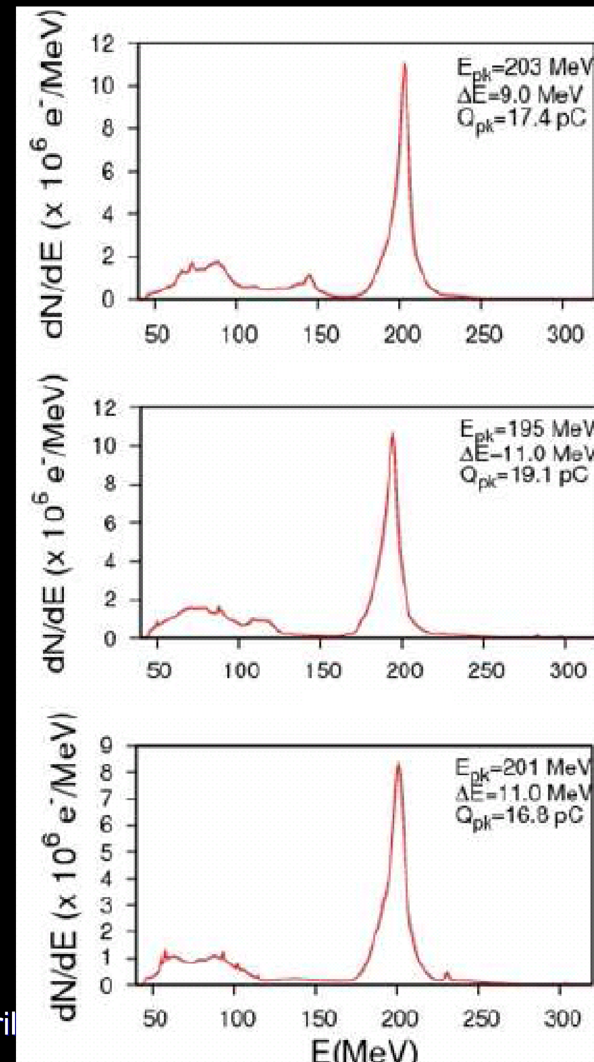
The ponderomotive force associated to the beating of the two laser pulses accelerates plasma electrons up to trapping threshold

Faure et al., nature, dec 2006

D. Umstadter et al, PRL 76, 2073 (1996);
E. Esarey et al, PRL 79, 2682 (1997)

Typical e- beam, non-collinear geometry, 3 mm nozzle ($n_e=5.7\times10^{18}$ cm^{-3}).

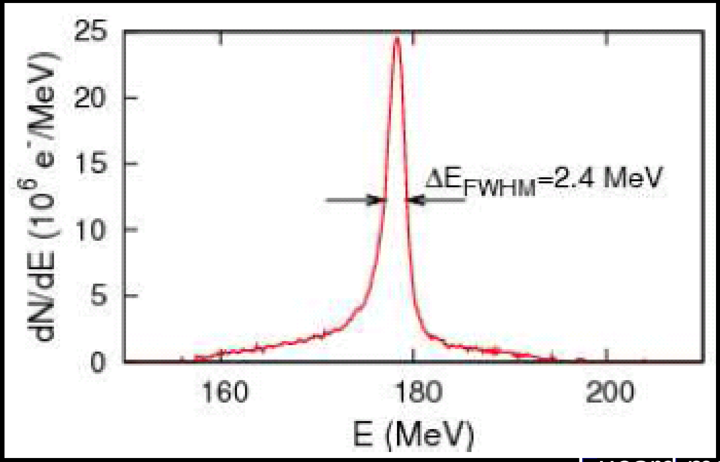




AO Injection at 176° angle

- Safer than 180° (Colliding), good stability

Peak energy (mean +/- s.d.)	206 MeV+/- 10 MeV
Energy spread FWHM (mean +/- s.d.)	6% +/- 1.4 %
Charge (mean +/- s.d.)	13 pC +/- 4 pC
Divergence (mean +/- s.d.)	4.5+/-1.6 mrad

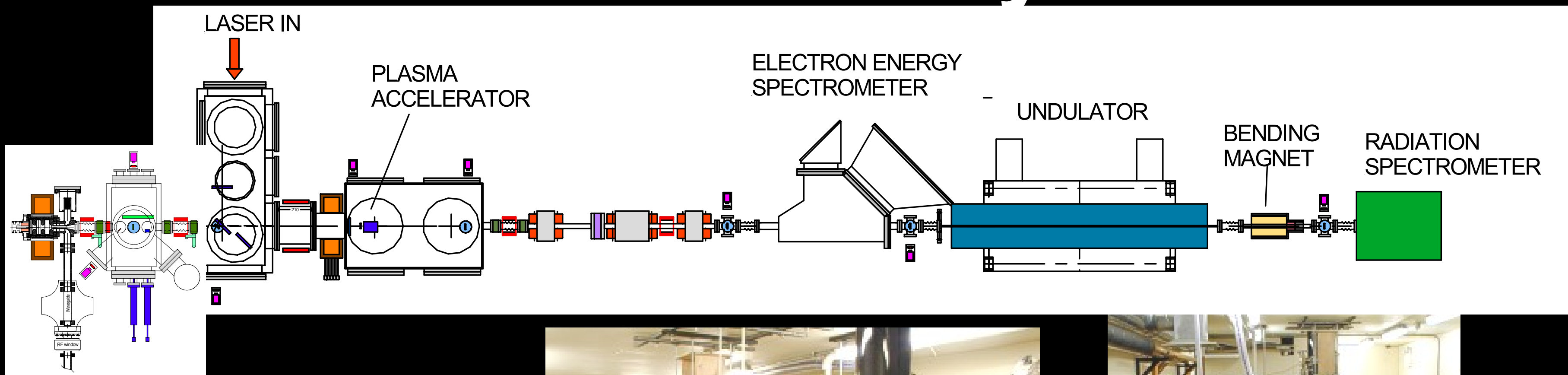


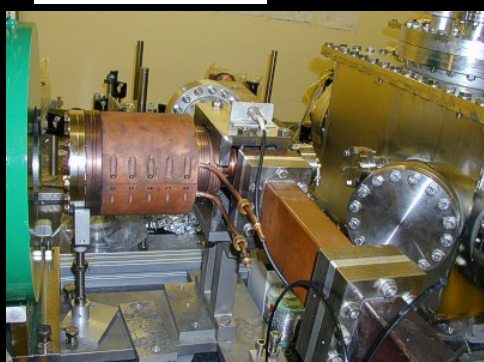
New spectrometer with higher resolution (LLR) showed that energy spread is 1.3 % FWHM.

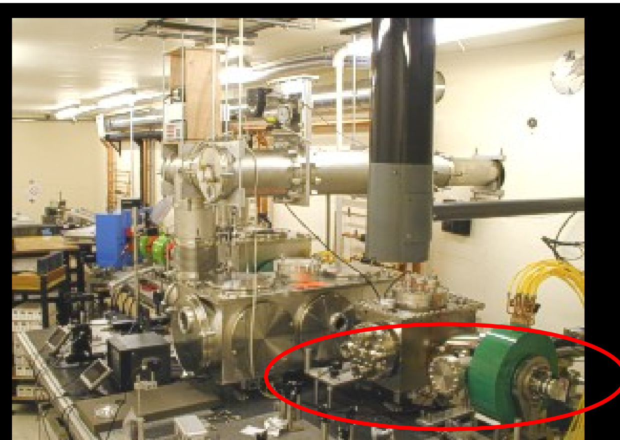
WP2: RF Photo-Injector Development

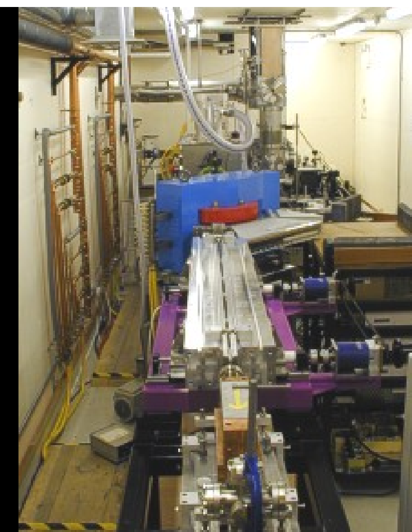
- Improve existing technology in order to build RFPIs to produce e- bunches with:
  - 50 to 100 pC charge,
  - 50 fs to 1ps duration,
  - energy 3- 4 MeV, energy spread 2%
- Transport and focus the electron beam at the entrance of the plasma
- Commission RFPIs for acceleration experiment

RFPI1 implemented at U. Strathclyde



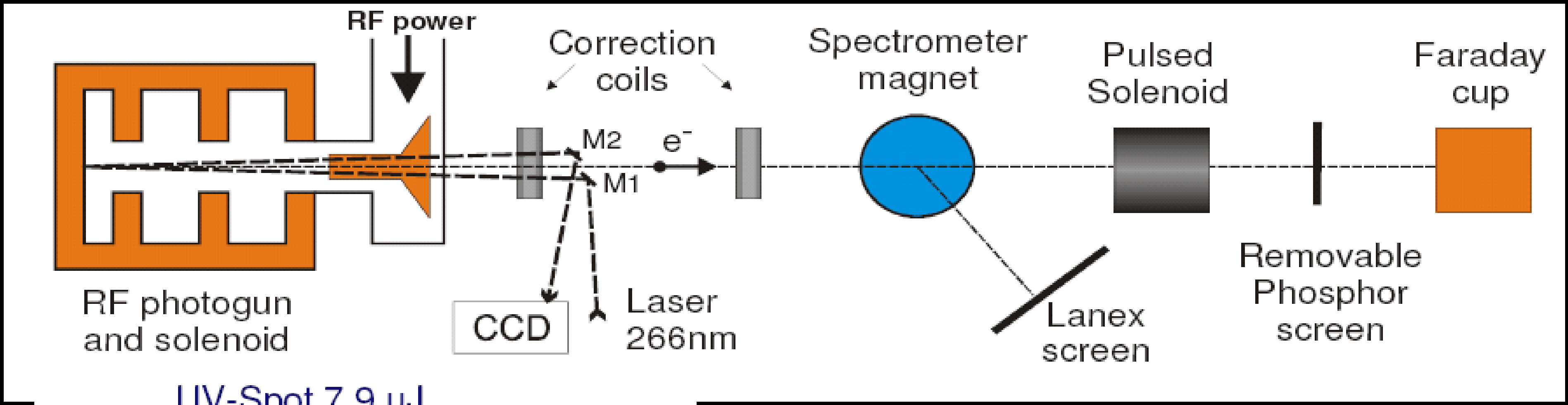


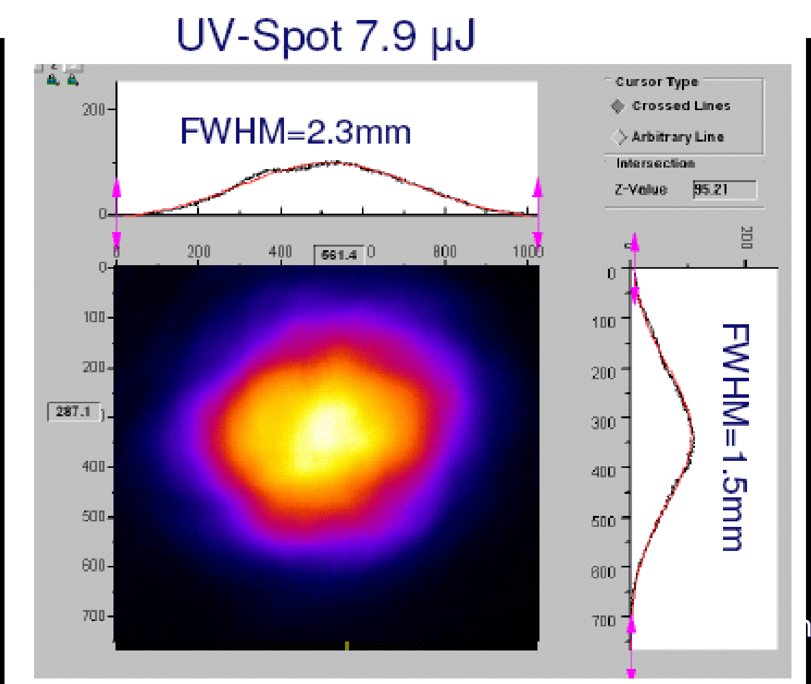




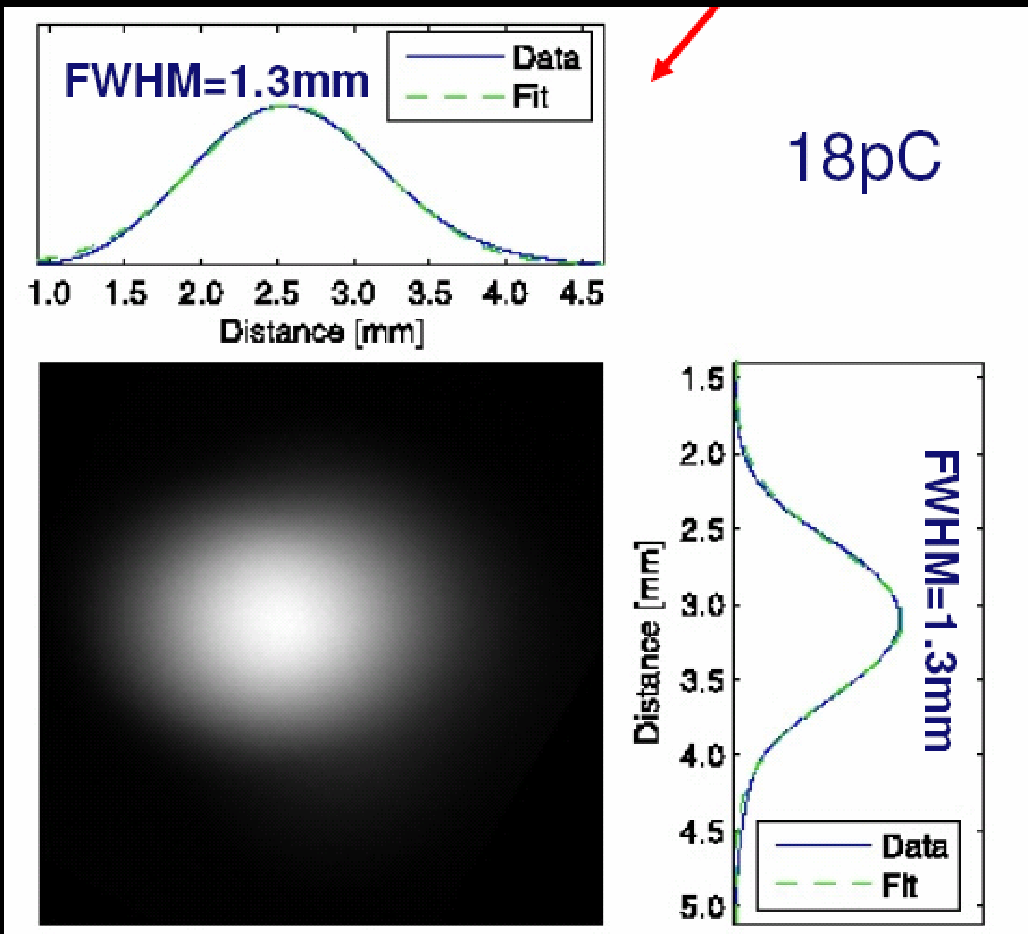
But modulator still under construction

Production of e- bunches at TUE: set-up to test beam focusing





Production of electron bunches: profile (TUE)



Phosphor screen measurements:

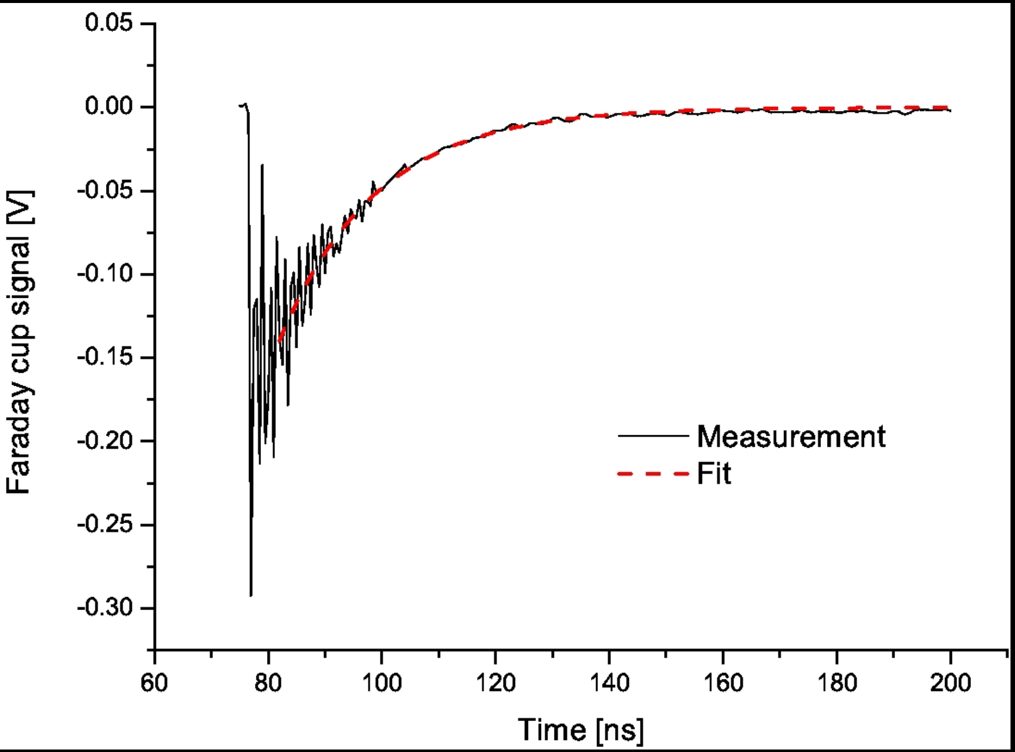
Spot size:
1.3 mm FWHM

Required radius:
1.7 mm FWHM

Emittance: 1 µm to 2 µm

Required emittance: 2 µm or lower

Production of electron bunches: charge (TUE)

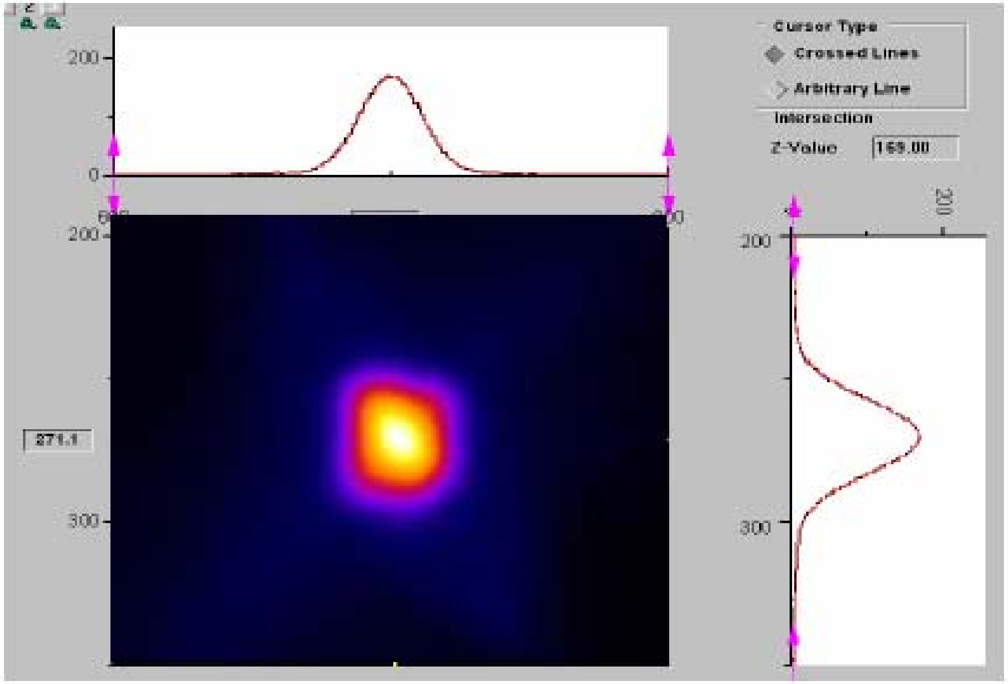


Faraday cup measurements:
73 pC with 15 μJ UV pulse

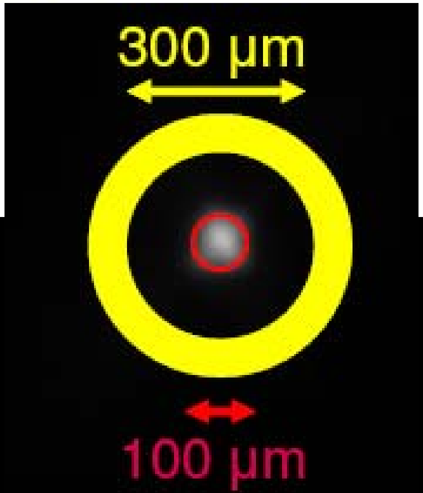
Required charge:
10 pC

Quantum efficiency:
EQE = $2x10^{-5}$

Parameters of electron bunches at focus (TUE)



- Horizontal FWHM: 104 µm
- Vertical FWHM: 116 µm
- 18 pC
- 3.6 MeV



The spot size fits the plasma channel size

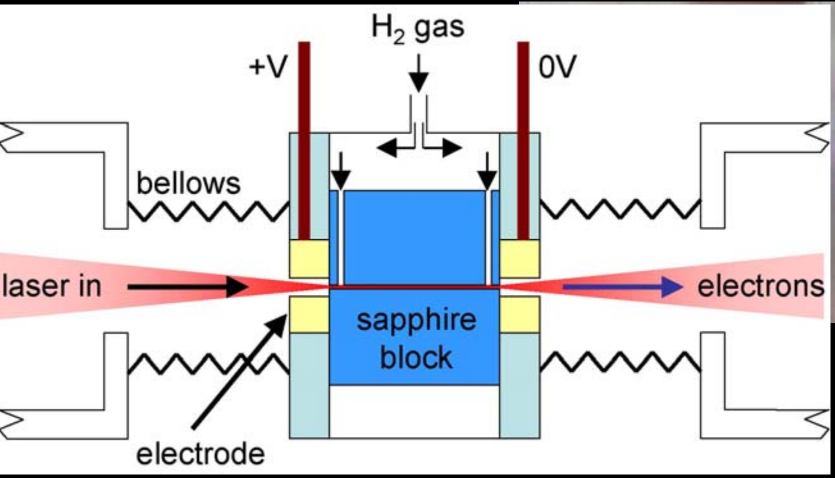
Overview of experimental results at TUE

	Required TU/e	Required Euroleap	Measured values
Diameter	1.7 mm	-	1.3 mm
Charge	>10 pC	50-100 pC	Up to 90 pC
Energy	6.7 MeV	3 - 4 MeV	3.6 MeV
Energy spread	2%	2%	< 2%
Emittance	< 2 μm	-	1 μm to 2 μm
Pulse duration at entrance plasma	300 fs	50 fs – 1 ps	-
Diameter at entrance plasma	60 μm	-	104 - 116 μm

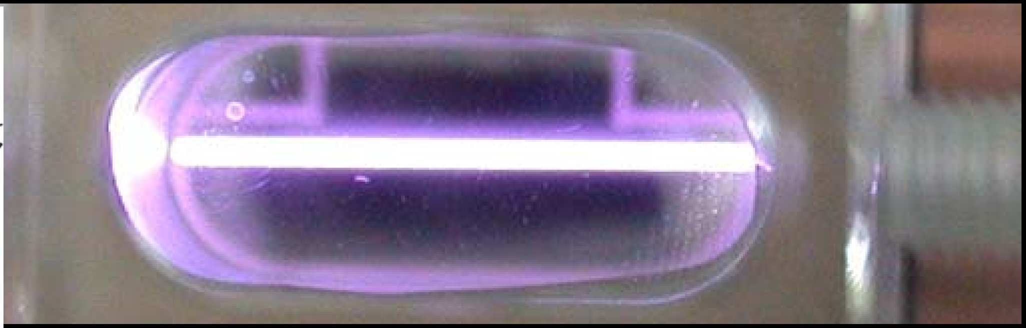
WP3: Production of a plasma wave over a long distance

- Develop plasma media allowing to achieve a plasma wave over several centimetres
- Study the propagation of intense laser pulses ($\geq 10^{17}$W.cm^{-2}) in the waveguides
- Control the plasma wave stability, repeatability and lifetime
- Achieve a product of gradient and length of 1 GV

High intensity laser Guiding



Plasma channel, U. Oxford



A. Gonsalves et al., PRL 98, 025002 (2007)

Comparison of guiding by a plasma channel and by reflection from the tube walls
Laser beam quality improved

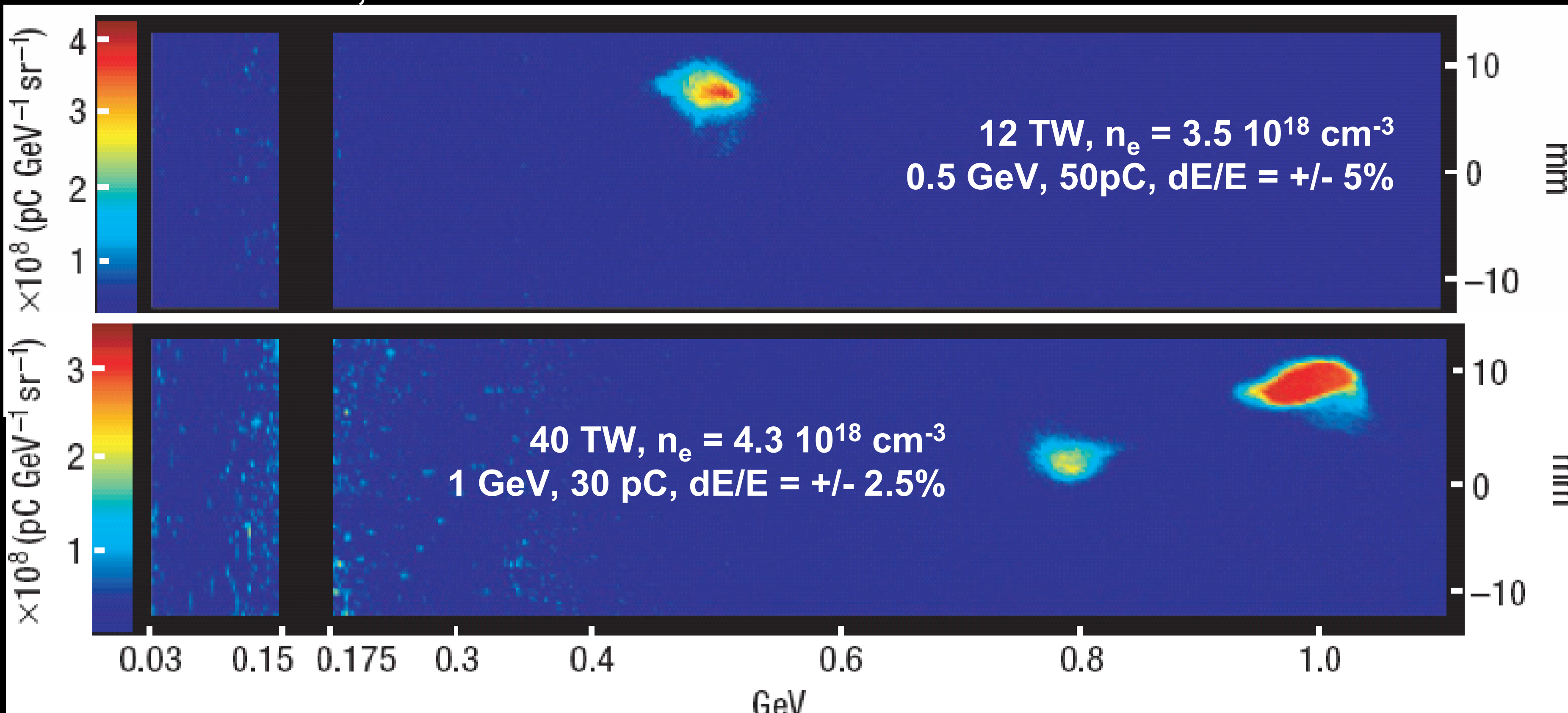
Tube LPGP L= 8cm, r = 50 µm, filled with H2, I = 5 10^{17} W/cm^2

B. Cros et al., PRE 65, 026405 (2002)

Laser wakefield in plasma channels (self-injection)

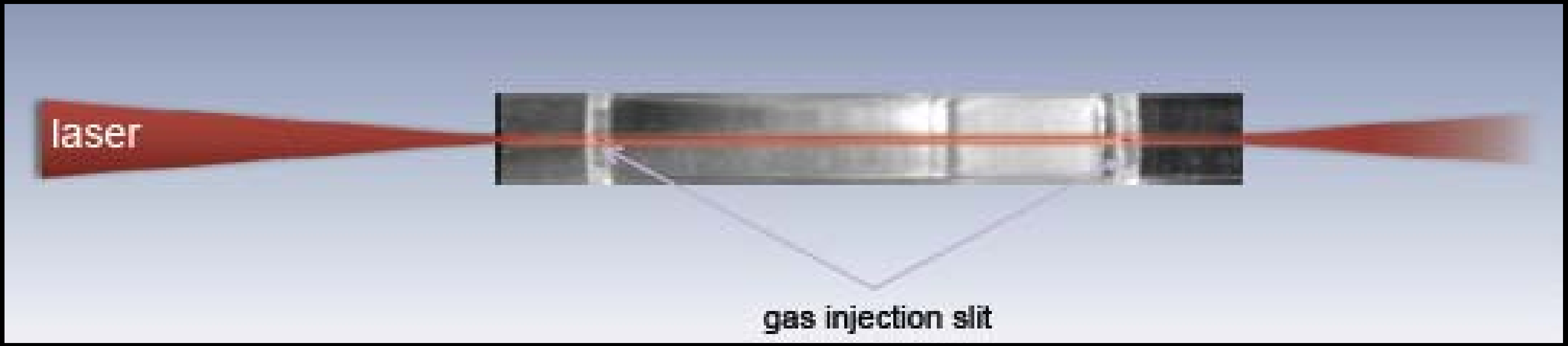
Plasma channel U. Oxford
L = 33 mm, diamètre 190µm
r spot ($1/e^2$) = 25 µm
Laser LBNL 40fs, 1.6J

Self-focusing, wavebreaking or bubble, trapping and guiding

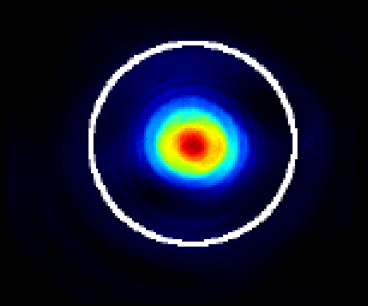


Leemans et al. Nature Physics 2, 696 (*2006*)

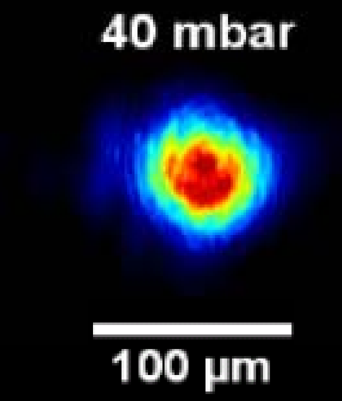
Efficient guiding in capillary tubes (LPGP)



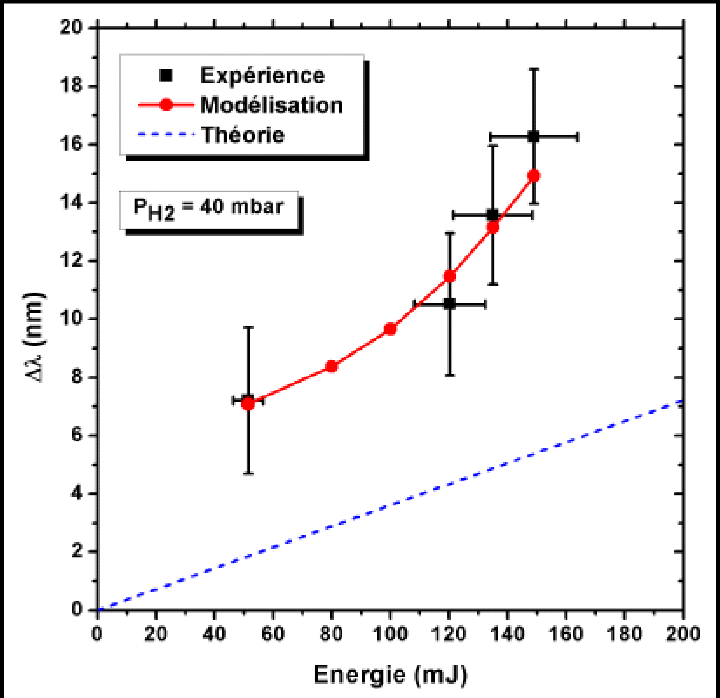
Input focal spot
I_{max} 2x10^{17}W/cm²

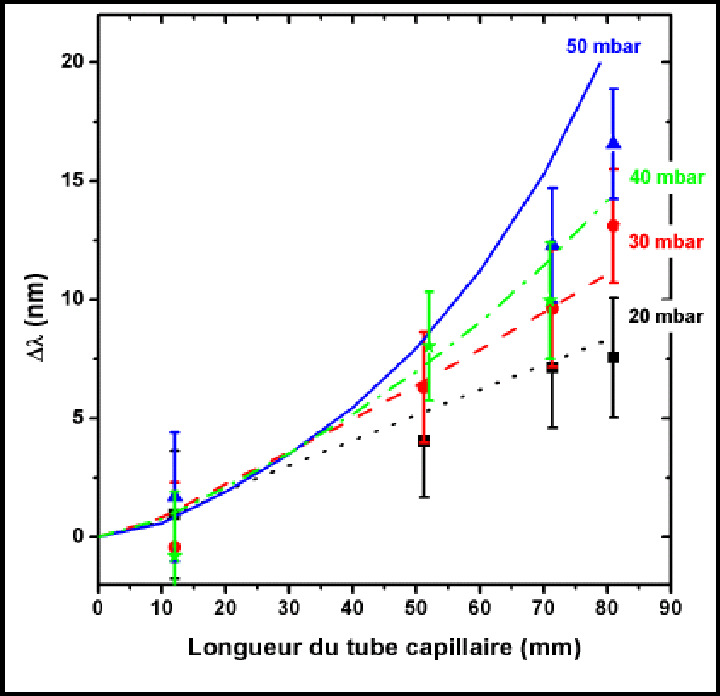


Output after 7 cm



Measurement of plasma wave amplitude by optical diagnostics inside capillary tubes





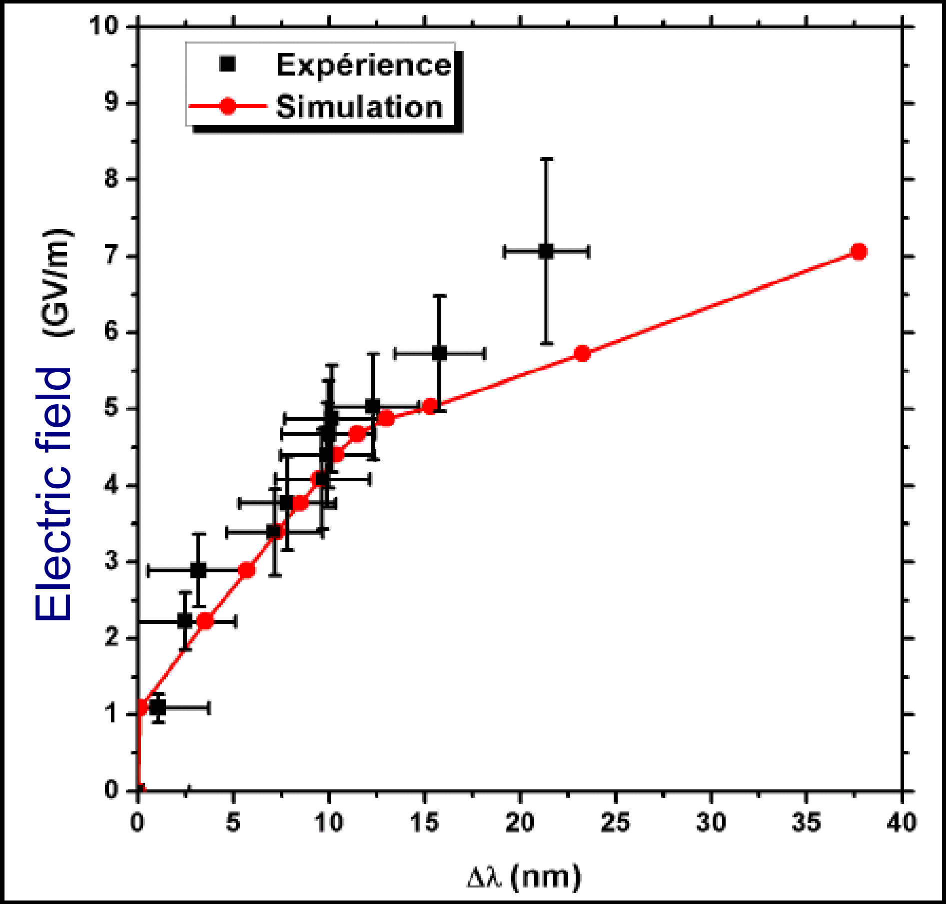
Excellent agreement with simulations: behavior as a function of filling pressure, laser energy and tube length (up to 8 cm)

First measurement over such a long distance

(LPGP-LLC-IHED)

Accelerating field 1-7 GV/m measured over 8 cm

<u>Capillary:</u> D = 100 µm, L up to 8 cm, filled with hydrogen
<u>Pump pulse:</u> λ = 0.8 µm, τ_{FWHM}= 51 fs, I_L= 2 10^{17} W/cm^2



Maximum electric field for a 7 cm capillary tube as a function the wavelength shift, varying with filling hydrogen pressure.

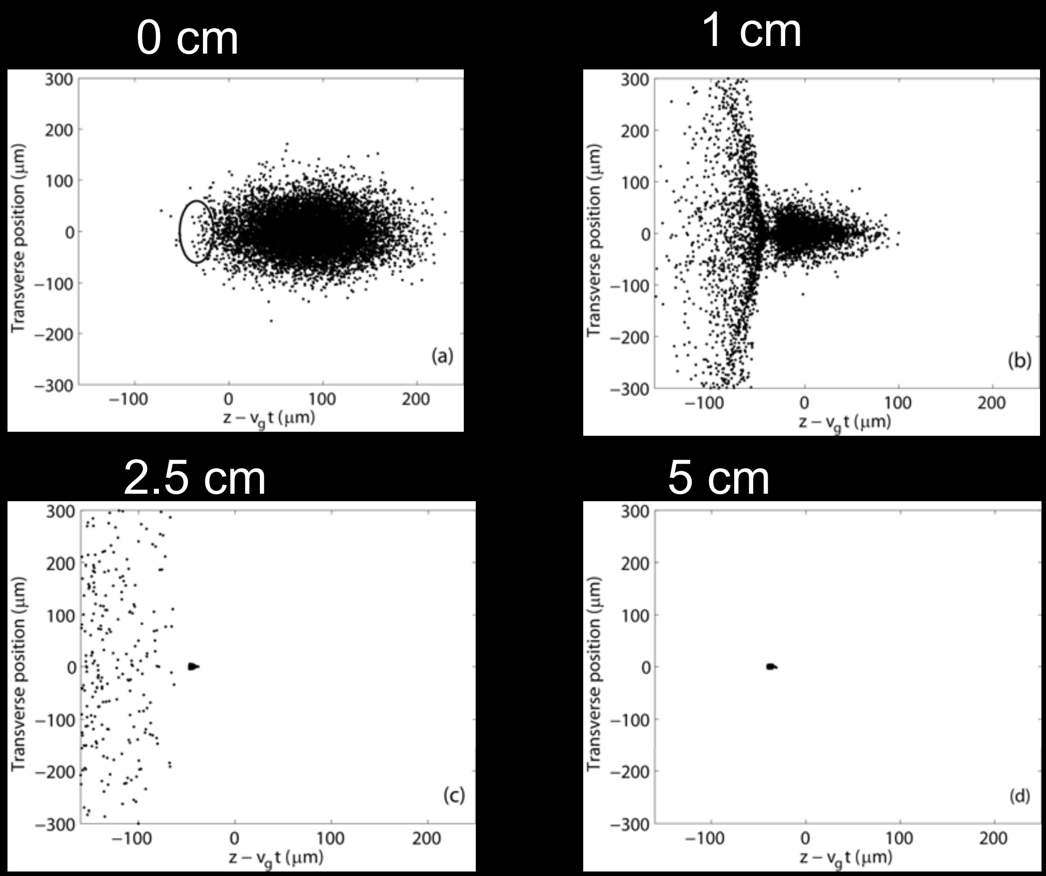
The electric field is calculated from the wavelength shift measured in the experiment and calculated from simulations.

LPGP-LLC-IHED

WP4: Injection & Controlled Acceleration

- Inject and accelerate electrons in a linear plasma wave over a long distance (several centimetres)
- Achieve a precise theoretical modelling and control the different elements of the acceleration process
- Build a prototype to achieve accelerated electron beams with
  – energy in the GeV range,
  – energy spread of the order of 1%,
  – pulse duration of the order of 100 fs,
  – charge in the range 10 pC to 100 pC.

Injection of electrons in front of the laser pulse – U. Twente

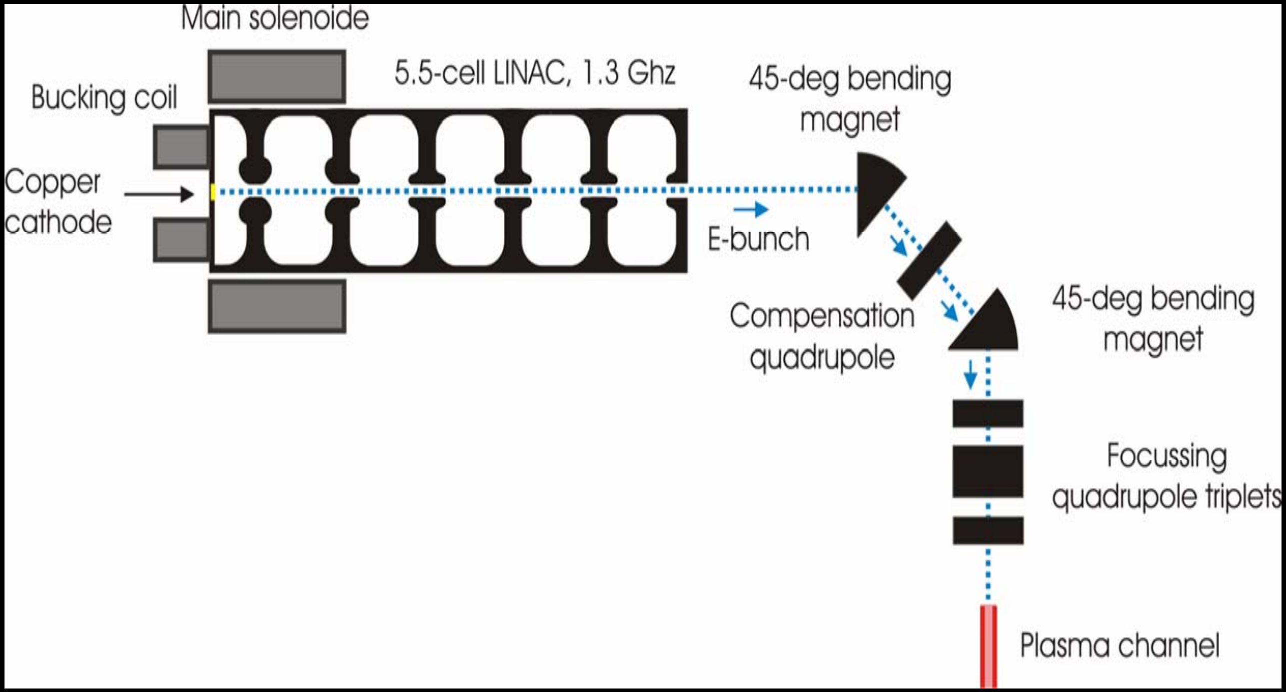


Snapshots of an electron bunch during trapping, compression and acceleration in the laser wakefield at several distances in the plasma channel. The ellipse depicts the position of the laser pulse.

From: NIM A 566 p.244 (2006).

Sub-picosecond beam Compressor at U. Twente

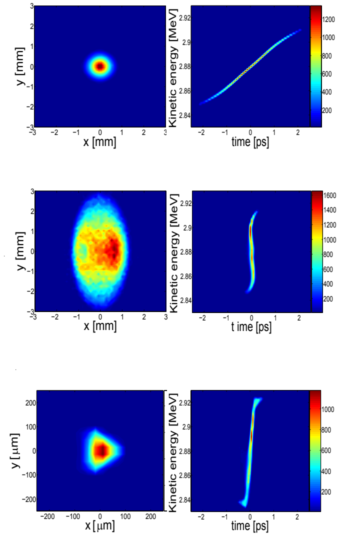
Longitudinal compression section



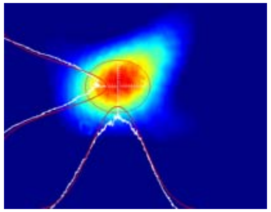
Two subsequent 45-degree bending magnets and a compensation quadrupole magnet between the bending magnets introduce an energy-dependent path length to compress the bunch.

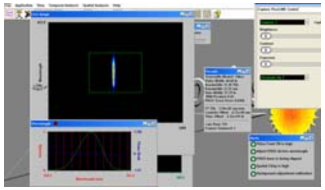
Measurements at entrance of plasma:
Bunch energy: 2.2 MeV ±1.7% (2.9 MeV)
Bunch position stability: Stdv=1.27 mm

Characterized:



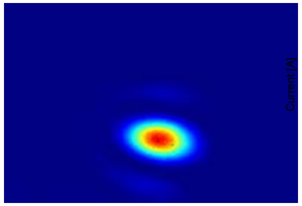
Linear Accelerator, e-bunch compressor

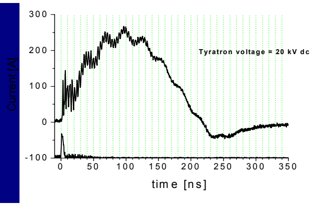




TiSa laser system

Capillary discharge plasma channel



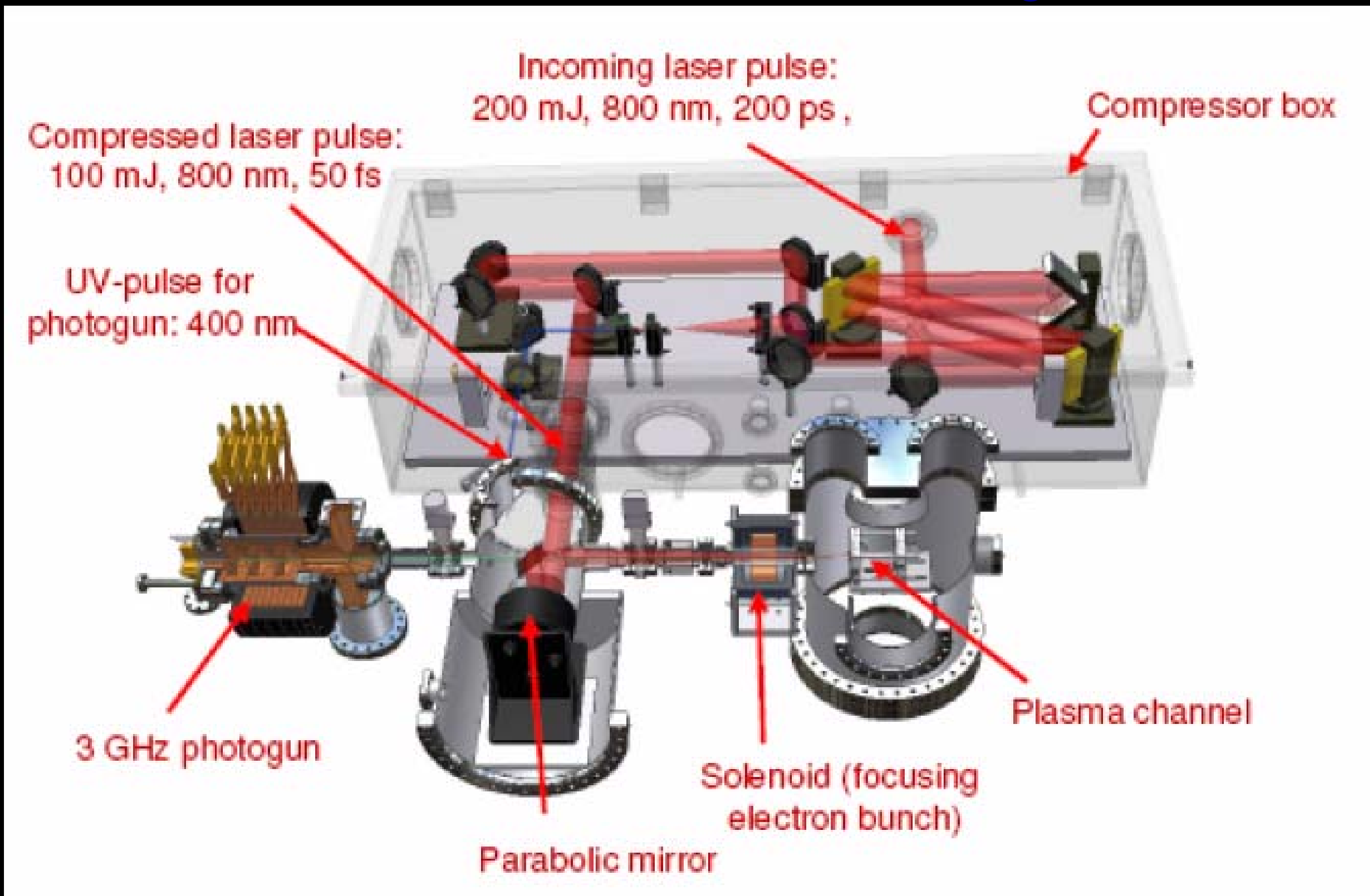


Outlook:

Demonstration experiment “Injection in Front”

Status at TUE

- Everything works separately
- Building the final set-up



Conclusions

- **AO injector demonstrated with expected properties**
  - But, its use with a waveguide is not feasible in the present state of intense laser facilities
- RF PI ~ ready at UT and Tue
  ➔ RF PI can be used for LWA
- Accelerating field up to 7 GV/m achieved over 8 cm in capillary tubes
- Injection with RFPI will be tested at TUE and UT in the next few months

Outlook

- The feasibility of external injection should be demonstrated in a few months (with less than 100 mJ laser at TUE)
- The demonstration of a 1-10 GeV beam needs a dedicated facility and seems within reach of present technology and knowledge
- Future developments on new laser architectures could lead to a linear accelerator design based on 10 GeV modules, and fulfilling the requirements for a 10 TeV collider (ICFA-ICUIL strategy workshop, 8-10 April 2010)