PHYSICS AND DIAGNOSTIC OF LASER-PLASMA ACCELERATOR

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Abstract

The recent and continuing development of powerful laser systems, which can now deliver light pulses containing a few Joules of energy in pulse durations of a few tens of femto seconds, has permitted the emergence of new approaches for generating energetic particle beams. By focusing these laser pulses onto matter, extremely large electric fields can be generated, reaching the TV/m level. Such fields are 10,000 times greater than those produced in the radio-frequency cavities of conventional accelerators. As a result, the distance over which particles extracted from the target can be accelerated GeV energy range is reduced to distances on the order of millimetres. A few years ago, several experiments have shown that laser-plasma accelerators can produce electron beam with maxwellian-like distribution [1], in 2004 high-quality electron beams, with quasi-mono energetic energy distributions at the 100 MeV level [2] and recently in the GeV range using a capillary discharge [3]. These experiments were performed by focusing a single ultra short and ultra intense laser pulse into an under dense plasma. More recently we produced a high quality electron beam using two counter-propagating

Paper not received
(See slides of talk on following pages)

Physics and diagnostics of Laser-Plasma Accelerators

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Summary

Part 1 : Laser plasma accelerator : motivation

Part 2 : bubble regime and monoenergetic e-beam

Part 3: Experiment with colliding laser pulses

Part 6 : Conclusion and perspectives

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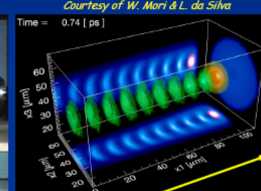
Classical accelerator limitations

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

Courtesy of W. Mori & L. da Silva

1 m

RF cavity



100 µm

Plasma cavity

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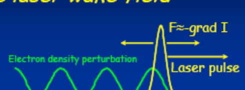
How to excite Relativistic Plasma waves?

The laser wake field



$\tau_{laser} \approx T_p / 2$
=>Short laser pulse

Phase velocity $v_{\phi epw}=v_{g laser}$ => close to c
Analogy with a boat

Are Relativistic Plasma waves efficient ?

$E_z \sim \sqrt{n_e}$

E_z = 0.3 GV/m for 1 % Density Perturbation at 10^{17} cc^{-1}
E_z = 300 GV/m for 100 % Density Perturbation at 10^{19} cc^{-1}

Tajima and Dawson, PRL (1979)

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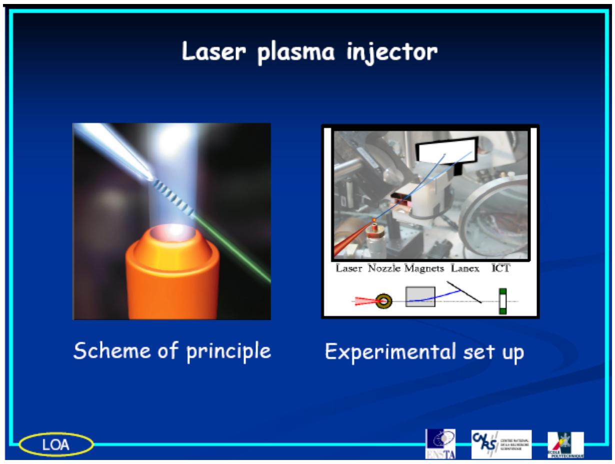
Laser plasma injector
Laser Nozzle Magnets Lanex ICT
Scheme of principle
Experimental set up
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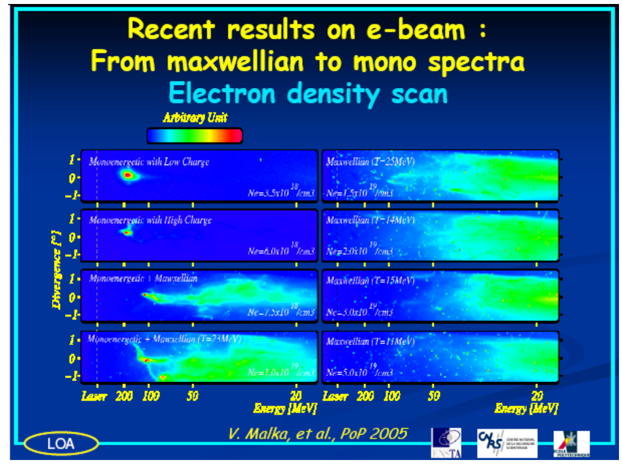
Recent results on e-beam :
From maxwellian to mono spectra
Electron density scan
Arbitrary Unit
Divergence [°]
Laser 200 100 50 20
Energy [MeV]
V. Malka, et al., PoP 2005
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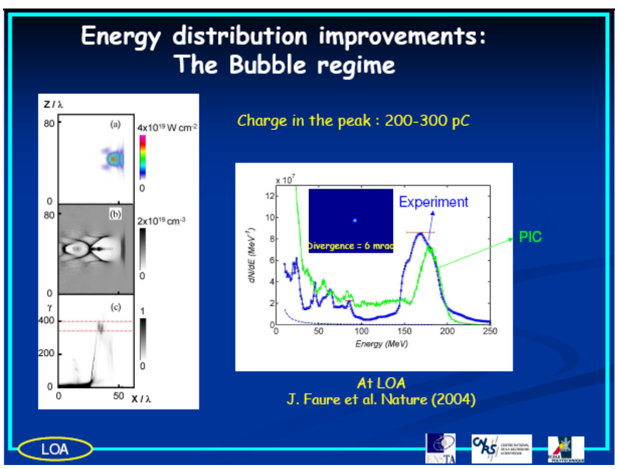
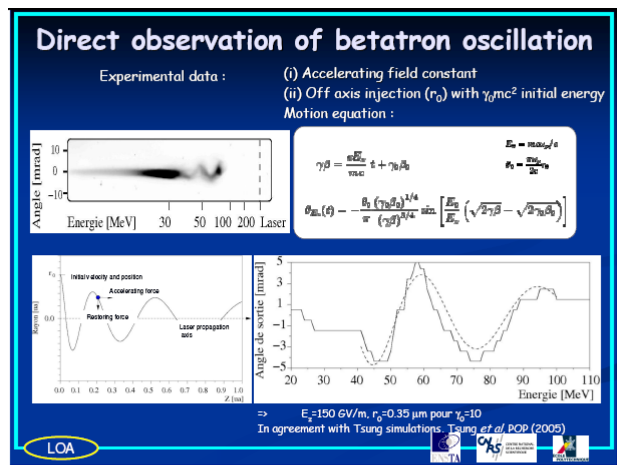
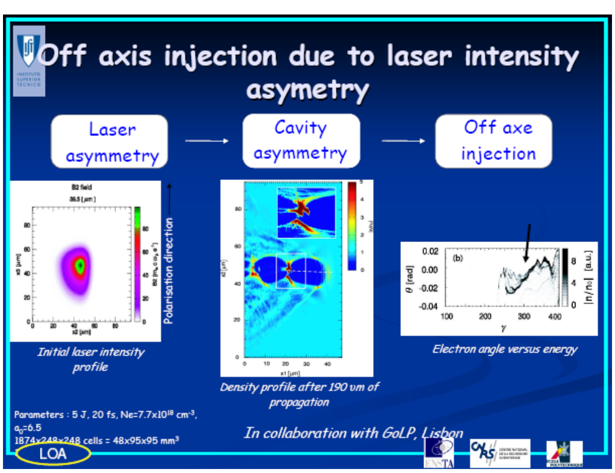
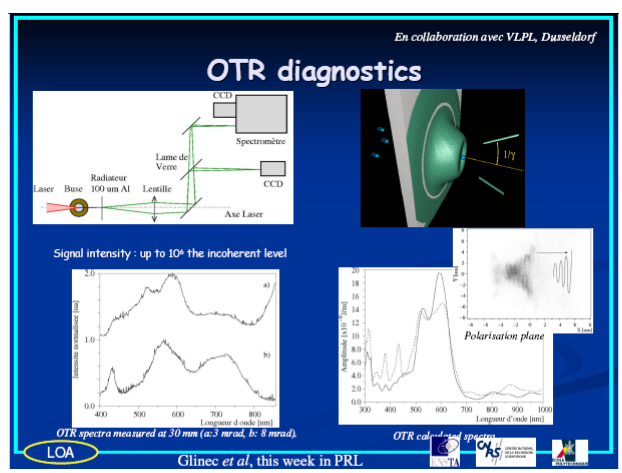

Energy distribution improvements:
The Bubble regime
Charge in the peak : 200-300 pC
Experiment
PIC
Divergence = 6 mrad
Energy (MeV)
At LOA
J. Faure et al. Nature (2004)
LOA


Direct observation of betatron oscillation
Experimental data :
(i) Accelerating field constant
(ii) Off axis injection (r0) with γ0mc² initial energy
Motion equation :
Angle [mrad]
Energie [MeV] 30 50 100 200 Laser
Angle de sortie [mrad]
Energie [MeV]
=> Ez=150 GV/m, r0=0.35 µm pour γ0=10
In agreement with Tsung simulations. Tsung et al, POP (2005)
LOA


Off axis injection due to laser intensity asymetry
Laser asymmetry
Cavity asymmetry
Off axe injection
Polarisation direction
Initial laser intensity profile
Density profile after 190 um of propagation
Electron angle versus energy
Parameters : 5 J, 20 fs, Ne=7.7x10¹⁸ cm⁻³, a0=6.5
1874x248x248 cells = 48x95x95 mm³
In collaboration with GoLP, Lisbon
LOA


En collaboration avec VLPL, Dusseldorf
OTR diagnostics
CCD
Spectromètre
Lame de Verre
Radiateur 100 um Al
Laser Buse
Lentille
CCD
Axe Laser
Signal intensity : up to 10⁴ the incoherent level
Polarisation plane
OTR spectra measured at 30 mm (a:3 mrad, b: 8 mrad).
Glinec et al, this week in PRL
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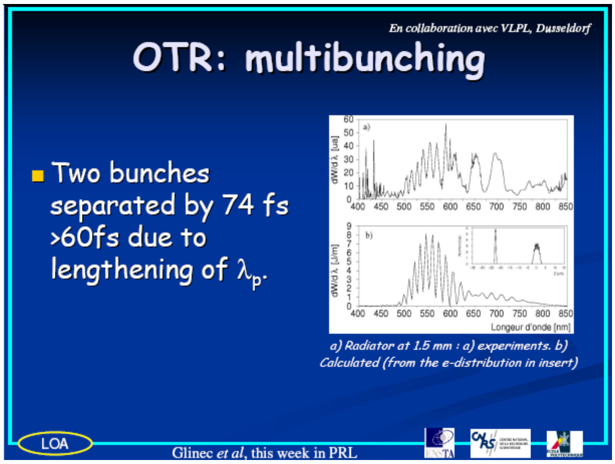
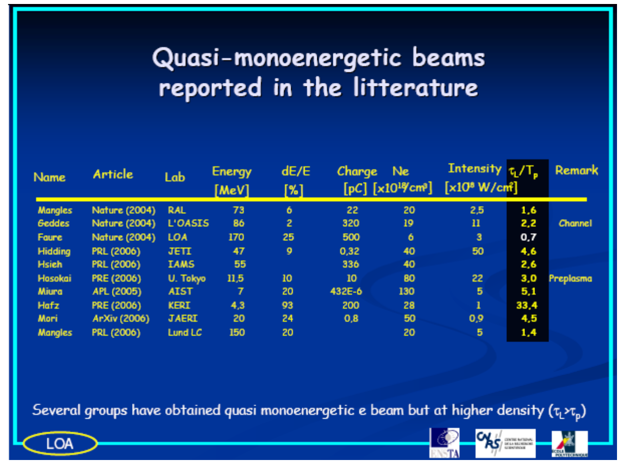
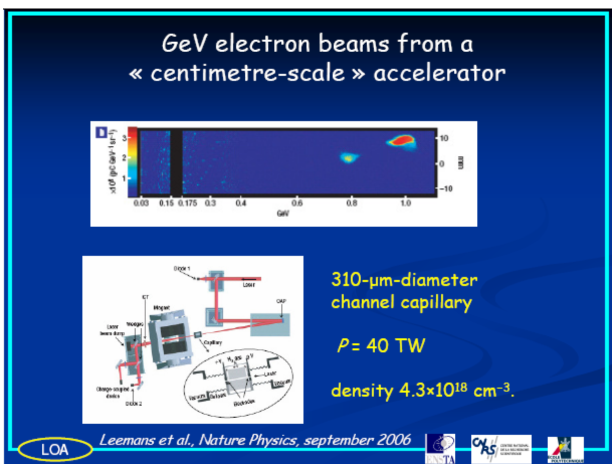
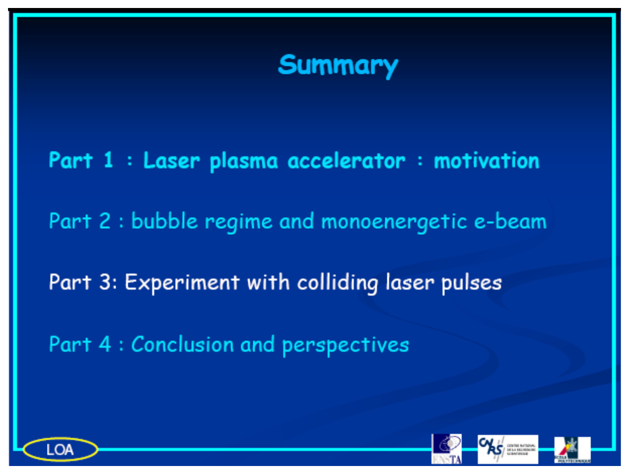
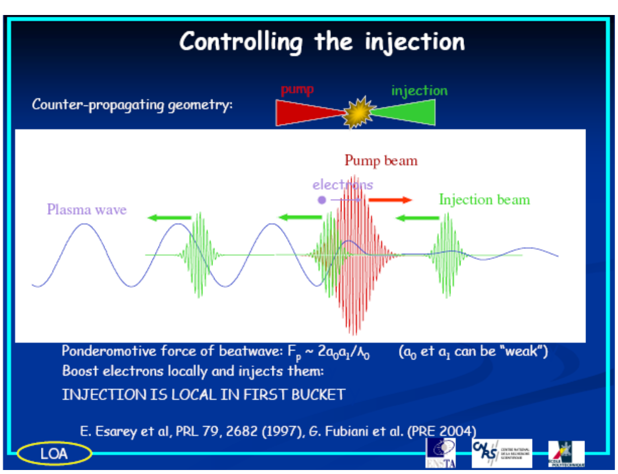


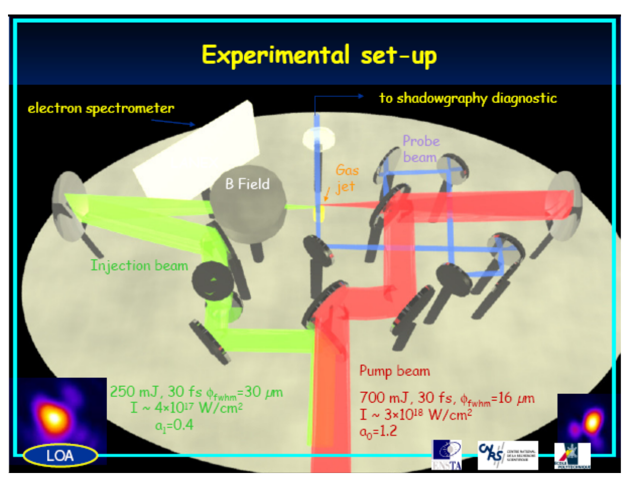


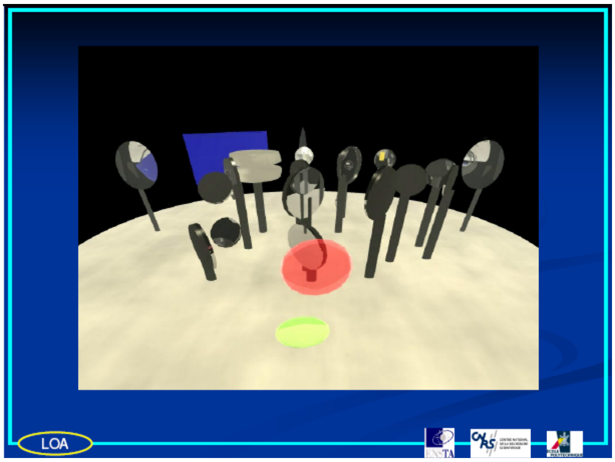
Name	Article	Lab	Energy [MeV]	dE/E [%]	Charge [pC]	Ne [x10^18/cm^3]	Intensity [x10^8 W/cm^2]	τ_L/T_p	Remark
Mangles	Nature (2004)	RAL	73	6	22	20	2,5	1,6	
Geddes	Nature (2004)	L'OASIS	86	2	320	19	11	2,2	Channel
Faure	Nature (2004)	LOA	170	25	500	6	3	0,7	
Hidding	PRL (2006)	JETI	47	9	0,32	40	50	4,6	
Hsieh	PRL (2006)	IAMS	55		336	40		2,6	
Hosokai	PRE (2006)	U. Tokyo	11,5	10	10	80	22	3,0	Preplasma
Miura	APL (2005)	AIST	7	20	432E-6	130	5	5,1	
Hafz	PRE (2006)	KERI	4,3	93	200	28	1	33,4	
Mori	ArXiv (2006)	JAERI	20	24	0,8	50	0,9	4,5	
Mangles	PRL (2006)	Lund LC	150	20		20	5	1,4	

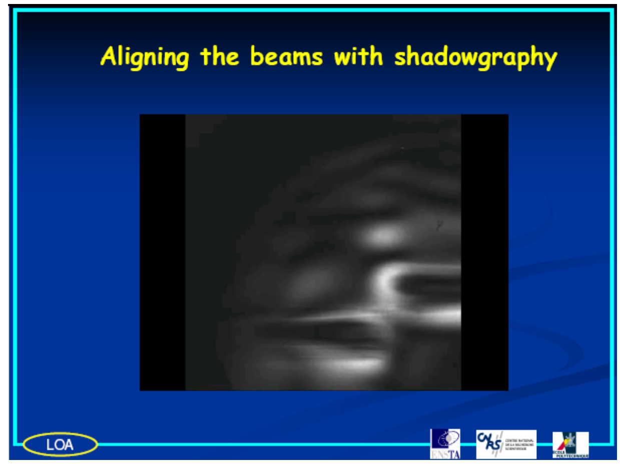


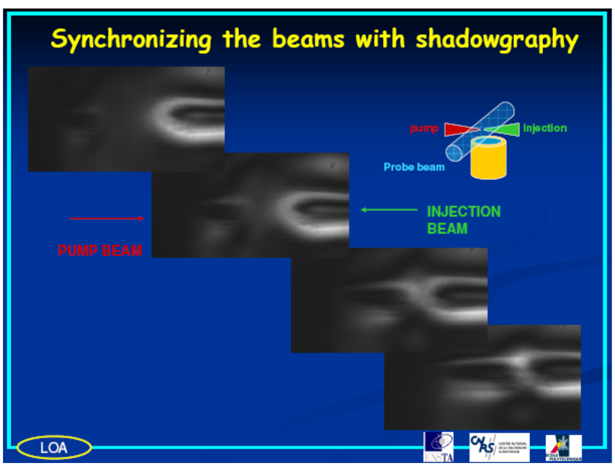


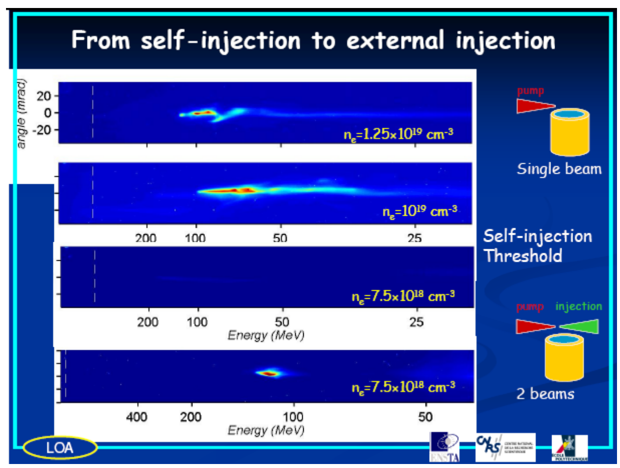


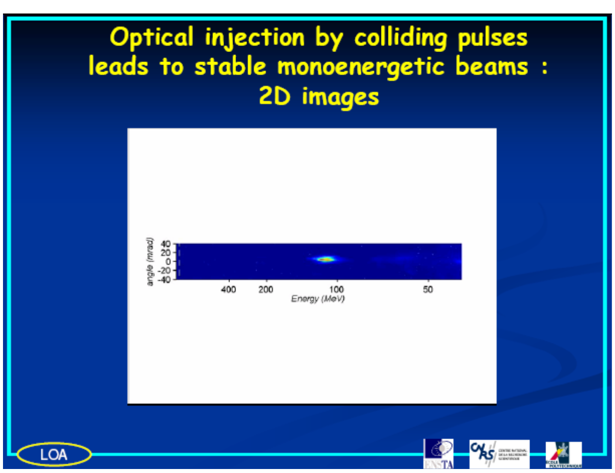


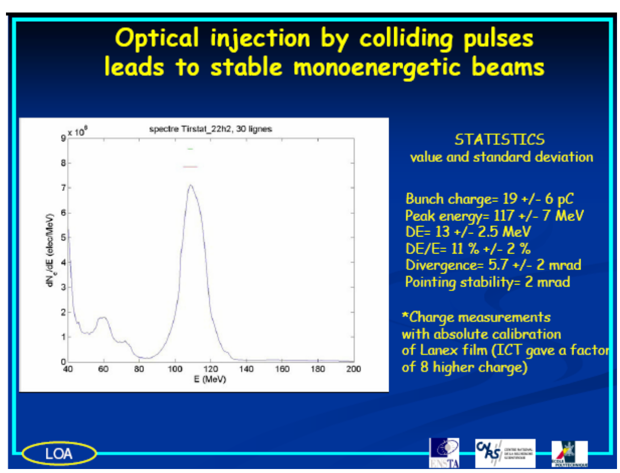

LOA


Aligning the beams with shadowgraphy
LOA


Synchronizing the beams with shadowgraphy
pump
injection
Probe beam
INJECTION BEAM
PUMP BEAM
LOA


From self-injection to external injection
angle (mrad)
20
0
-20
n_e=1.25x10^{19} cm^{-3}
n_e=10^{19} cm^{-3}
200 100 50 25
n_e=7.5x10^{18} cm^{-3}
200 100 50 25
Energy (MeV)
n_e=7.5x10^{18} cm^{-3}
400 200 100 50
Energy (MeV)
pump
Single beam
Self-injection Threshold
pump injection
2 beams
LOA


Optical injection by colliding pulses leads to stable monoenergetic beams : 2D images
angle (mrad)
400 200 100 50
Energy (MeV)
LOA


Optical injection by colliding pulses leads to stable monoenergetic beams
spectre Tirstat_22h2, 30 lignes
x 10^6
dN$_e$/dE (elec/MeV)
E (MeV)
STATISTICS
value and standard deviation
Bunch charge= 19 +/- 6 pC
Peak energy= 117 +/- 7 MeV
DE= 13 +/- 2.5 MeV
DE/E= 11 % +/- 2 %
Divergence= 5.7 +/- 2 mrad
Pointing stability= 2 mrad
*Charge measurements with absolute calibration of Lanex film (ICT gave a factor of 8 higher charge)
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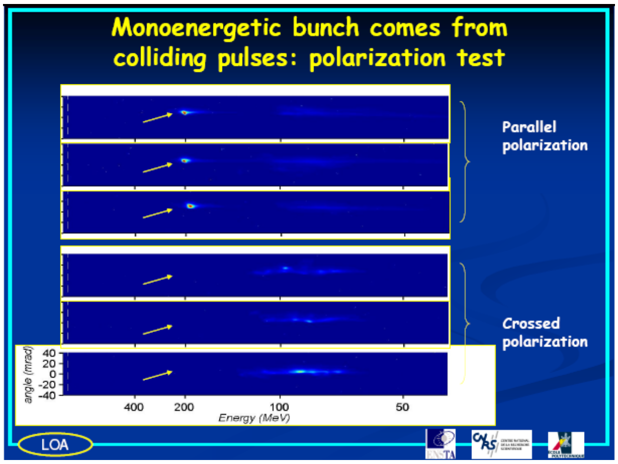
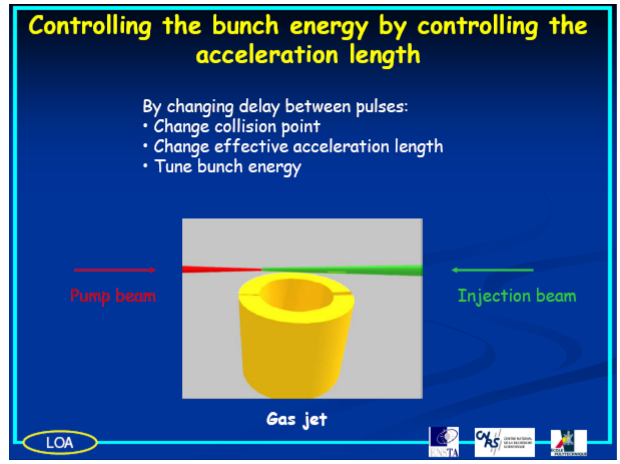
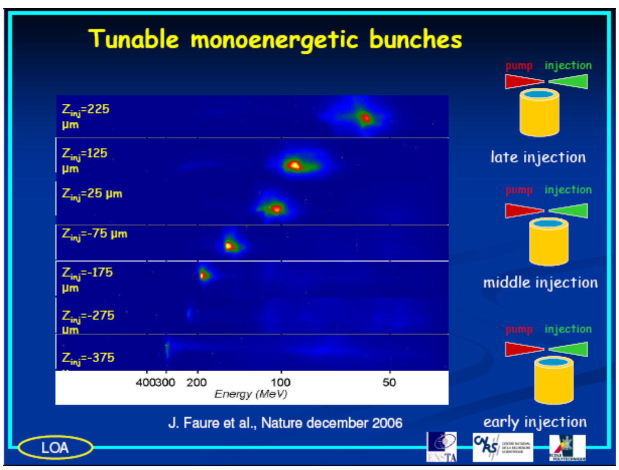

Monoenergetic bunch comes from colliding pulses: polarization test
Parallel polarization
Crossed polarization
angle (mrad)
40
20
0
-20
-40
400
200
100
50
Energy (MeV)
LOA


Controlling the bunch energy by controlling the acceleration length
By changing delay between pulses:
• Change collision point
• Change effective acceleration length
• Tune bunch energy
Pump beam
Injection beam
Gas jet
LOA


Tunable monoenergetic bunches
Z_inj=225 µm
Z_inj=125 µm
Z_inj=25 µm
Z_inj=-75 µm
Z_inj=-175 µm
Z_inj=-275 µm
Z_inj=-375
400300 200 100 50
Energy (MeV)
pump injection
late injection
middle injection
early injection
J. Faure et al., Nature december 2006
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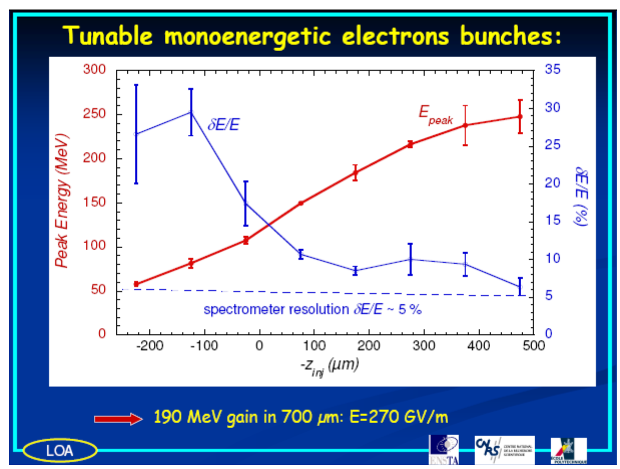
Tunable monoenergetic electrons bunches:
Peak Energy (MeV)
δE/E (%)
δE/E
E_peak
spectrometer resolution δE/E ~ 5 %
-Z_inj (µm)
-200 -100 0 100 200 300 400 500
190 MeV gain in 700 µm: E=270 GV/m
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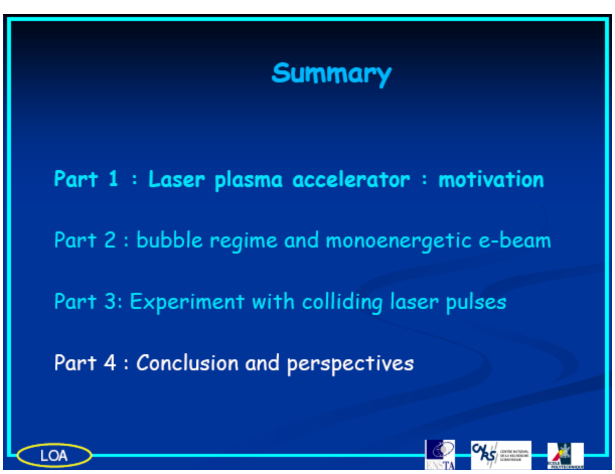
Summary
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Part 2 : bubble regime and monoenergetic e-beam
Part 3: Experiment with colliding laser pulses
Part 4 : Conclusion and perspectives
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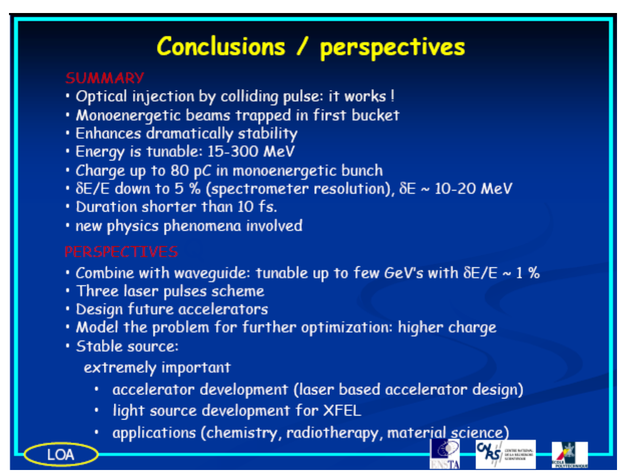
Conclusions / perspectives
SUMMARY
• Optical injection by colliding pulse: it works !
• Monoenergetic beams trapped in first bucket
• Enhances dramatically stability
• Energy is tunable: 15-300 MeV
• Charge up to 80 pC in monoenergetic bunch
• δE/E down to 5 % (spectrometer resolution), δE ~ 10-20 MeV
• Duration shorter than 10 fs.
• new physics phenomena involved
PERSPECTIVES
• Combine with waveguide: tunable up to few GeV's with δE/E ~ 1 %
• Three laser pulses scheme
• Design future accelerators
• Model the problem for further optimization: higher charge
• Stable source:
extremely important
• accelerator development (laser based accelerator design)
• light source development for XFEL
• applications (chemistry, radiotherapy, material science)
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