24-25 June 2019, FermiLab

Workshop on beam acceleration in crystals and nanostructures

Electron Acceleration at ELI-Beamlines:

recent developments towards high-energy and high-repetition rate accelerators

Presenter: *Carlo Maria Lazzarini*

Electron Acceleration Group
CarloMaria.Lazzarini@eli-beams.eu

24-25 June 2019, FermiLab
Workshop on beam acceleration in crystals and nanostructures

Electron Acceleration at ELI-Beamlines:

recent developments towards high-energy and high-repetition rate accelerators

Co-authors and contributors: *G.M.Grittani, *M.Nevrkla, *S.Lorenz, *L.V.Goncalves, F. Nawaz, P.Valenta, S. Bonora, R.Ziano, A.Zaras-Szydlowska, M.Rosinski, F.Schillaci, V.Giannini, *T.Levato, S.V.Bulanov, G.Korn

**part of the Electron Acceleration Group*

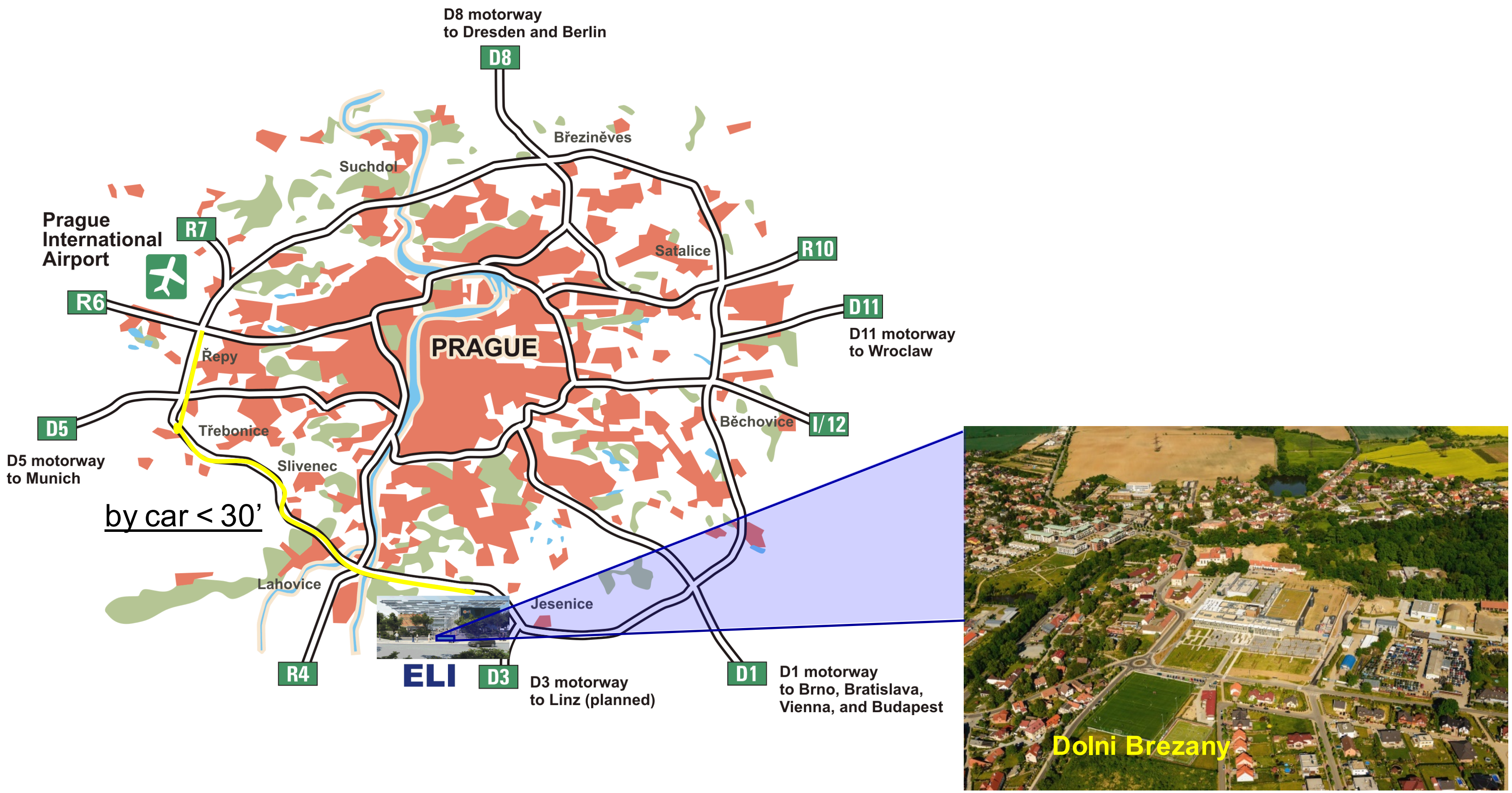
Acceleration at ELI-Beamlines: recent developments towards high-energy and high-repetition rate accelerators

Carlo Maria Lazzarini

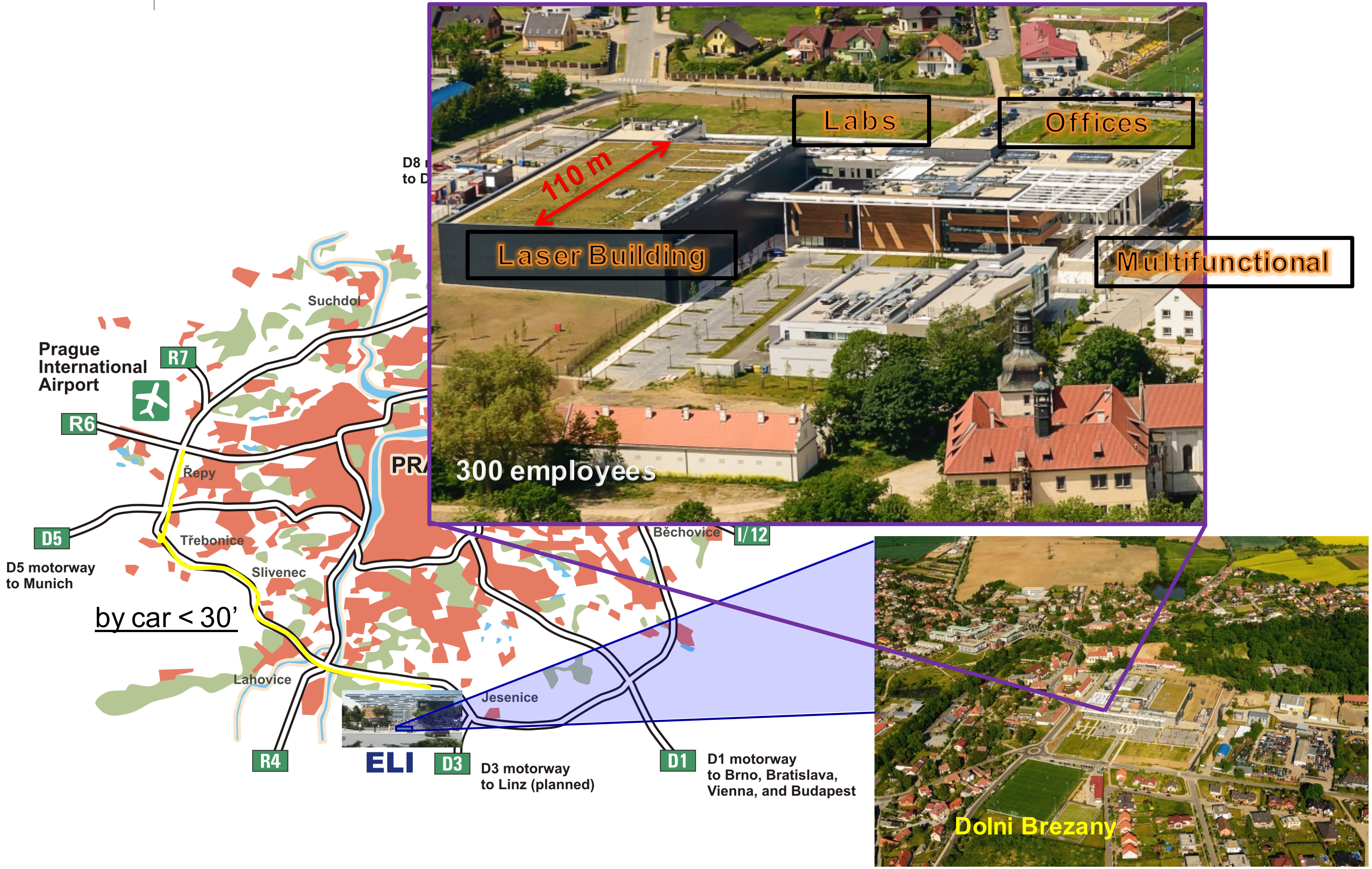
Content

- ➢ **Introduction on ELI-Beamlines and available Lasers**
- ❑ High Energy Electron Platform
- ❑ Towards high repetition rate: setup and first experiment
- ❑ Towards stable high-energy electron: stability and guiding experiments
- ❑ Theorethical study: ultrafast nanophotonics and near-critical studies
- ❑ Conclusions

Facility Location



Facility Location



Mission: fundamental and applied research serving users of different fields

- Generation of high repetition-rate highly synchronized laser-driven sources of radiation and particles
- Practical applications: medical and biomolecular research, material research
- High-field physics using combination of synchronized laser pulses and laser-generated secondary sources, plasma physics
- Development of new technologies including high rep-rate DPSSL pumped PW systems

Building: Construction started May 2013, completion end of 2015

4 Laser beamlines: **L1** (100 mJ, 20 fs, 1 KHz), **L2** (2 J, 15 fs, 10 Hz), **L3** (30 J in 30 fs, 10 Hz), **L4** (1.5 kJ in 150 fs)
L1 and L3 running and now ramping up the energy to goal!

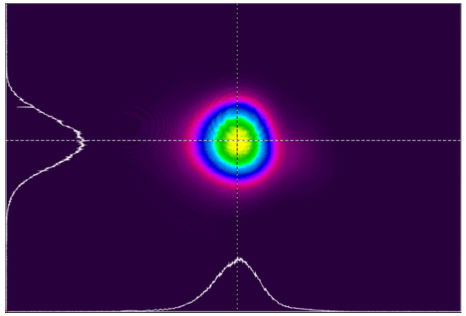
First user operations: Already running in E1, first L3 users by 2020

L1 Allegra

- 100 mJ / <20 fs / 1 kHz laser beamline
- 830 < λ < 860 nm, rms pointing < 10 µrad
- Picosecond OPCPA pumped by Yb:YAG thin-disk lasers
- Upgradable to 200 mJ or more
- Development and integration by ELI-Beamlines team
- Pump thin-disk lasers supplied by TRUMPF, DPSSL Technology
- Running beamlines: in E1

OPACP Stage 2 beam
BBO, 120 µJ, 1 kHz

Pulse compressed
to 16.5 fs



L3 HAPLS
supplier LLNL

- <u>1 PW, 30 fs, 10 Hz repetition rate beamline</u>

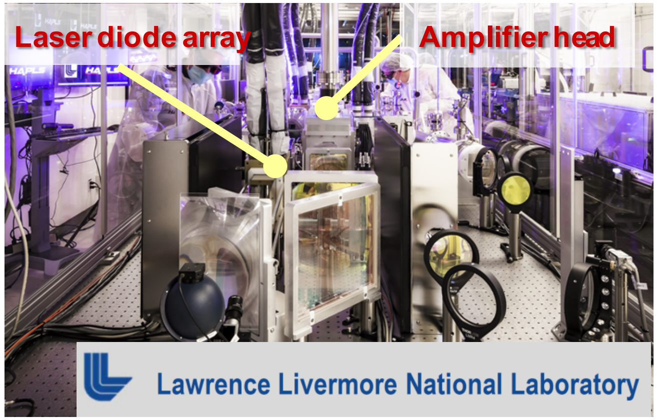
- Wavelength 820 nm, bandwidth 88 nm, S-pol, clear aperture 250 mm

- All laser amplifiers pumped by DPSSL technology (800 kW peak)

- High pulse-to-pulse stability, robustness, low maintenance,
  high level of automation, scalability to higher peak power and rep rate

- Collaborative effort of ELI-Beamlines on development of the PW
  compressor, PW diagnostics, control & timing systems

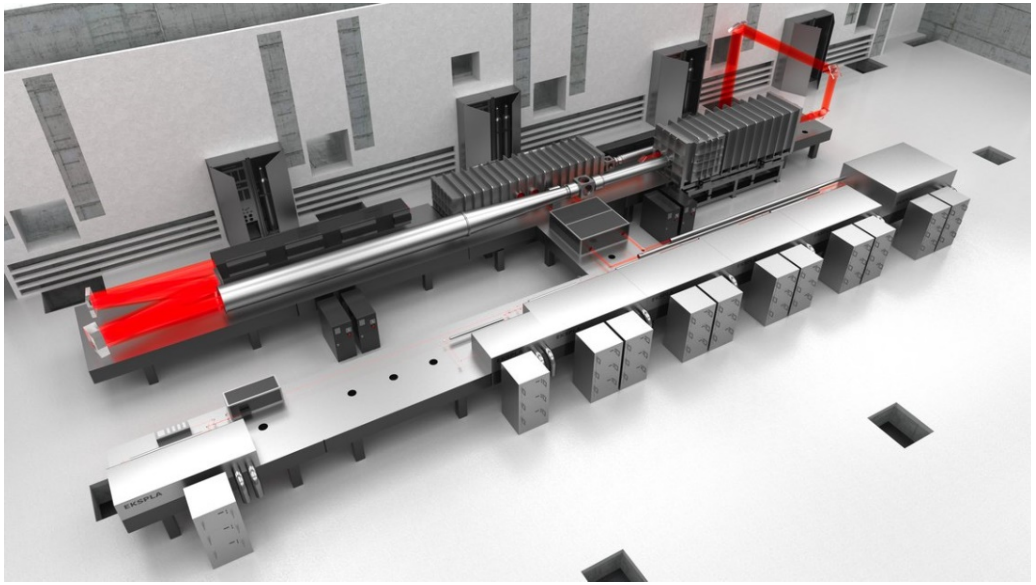
L3 Front end:
Femtolasers GmbH
+ LLNL stretcher



L4 Atos

supplier NE-EKSPLA

- 10 PW, 1.5 kJ CPA laser
- mixed Nd:glass providing spectral bandwidth compression to ≤ 150 fs
- 0.5 to 5 ns (chirped) pulses with programmable temporal shape by-passing compressor
- Rectangular super-gaussian 550 mm, 1 shot per minute
- Possible future use as OPCPA driver
  for generation > 10 PW power
- ELI-Beamlines co-develops 10 PW compressor,
  full diagnostics, vacuum vessel, timing system



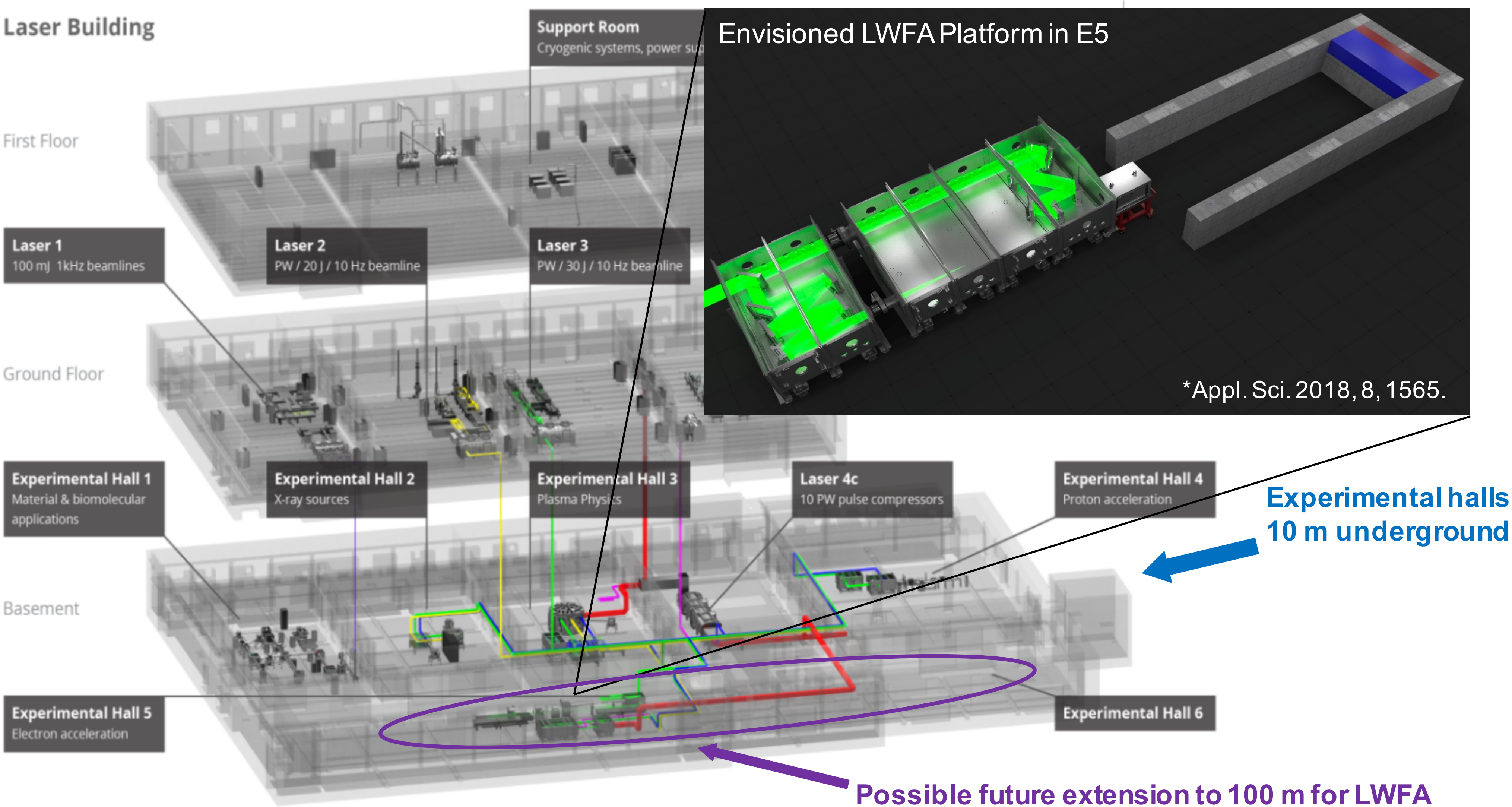
Content

- ❑ Introduction on ELI-Beamlines and available Lasers
- ➢ **High Energy Electron Platform**
- ❑ Towards high repetition rate: setup and first experiment
- ❑ Towards stable high-energy electron: stability and guiding experiments
- ❑ Theorethical study: ultrafast nanophotonics and near-critical studies
- ❑ Conclusions

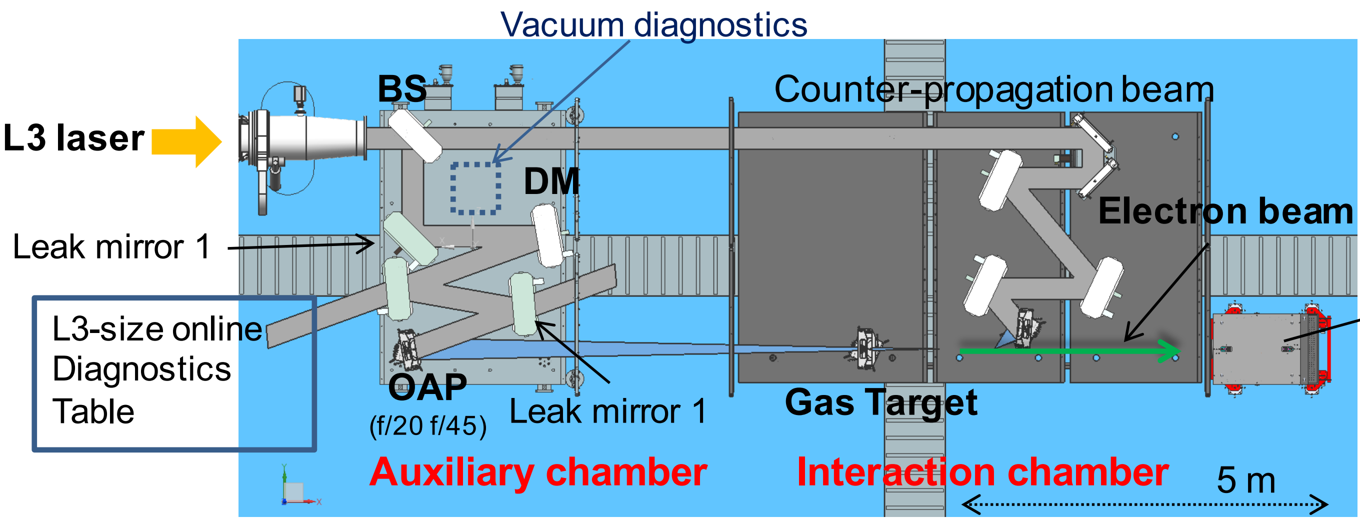
ELI-Beamlines floors and High Energy Electron Accelerator Platform

Experimental halls 10 m underground

ELI-Beamlines floors and High Energy Electron Accelerator Platform

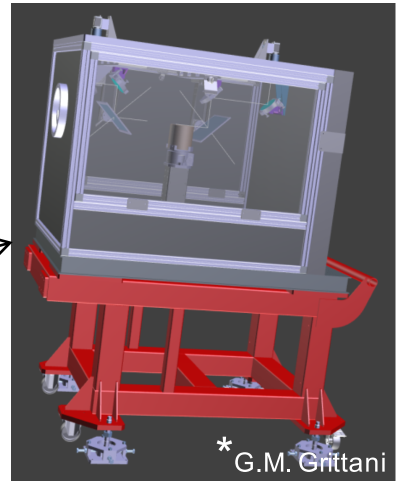


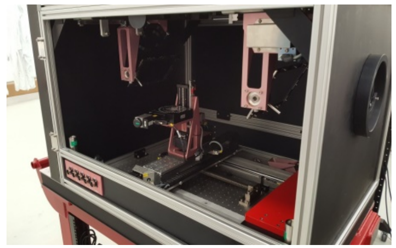
High Energy Electron Accelerator Platform

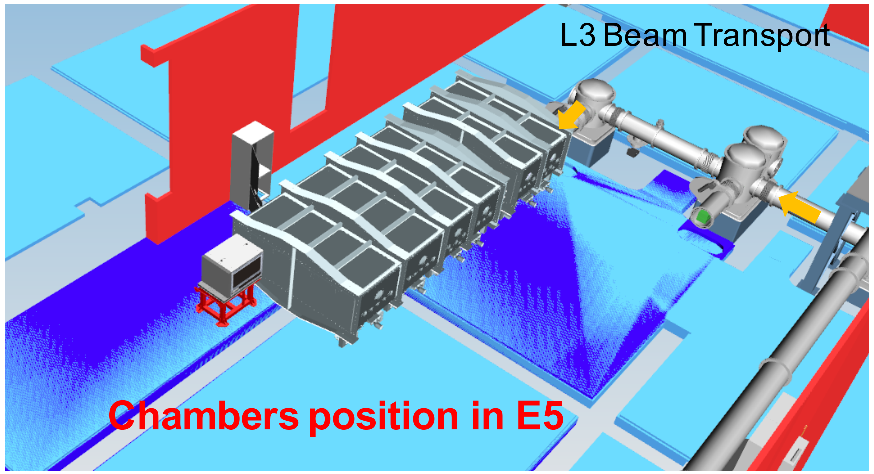


*Review in Appl. Sci. 2018, 8, 1565.

User Station







- Irradiation of User Samples in air
- Operation at 10 Hz
- High precision positioning
- On-line electron beam diagnostic
- Calibrated for 100 MeV at Linac

Elettra Sincrotrone Trieste

Past Workshops

HELL Scientific meetings@DUR «Detailed Users Requests» 2014

ELI-Beamlines Scientific Challenge Conference & Workshop 2015

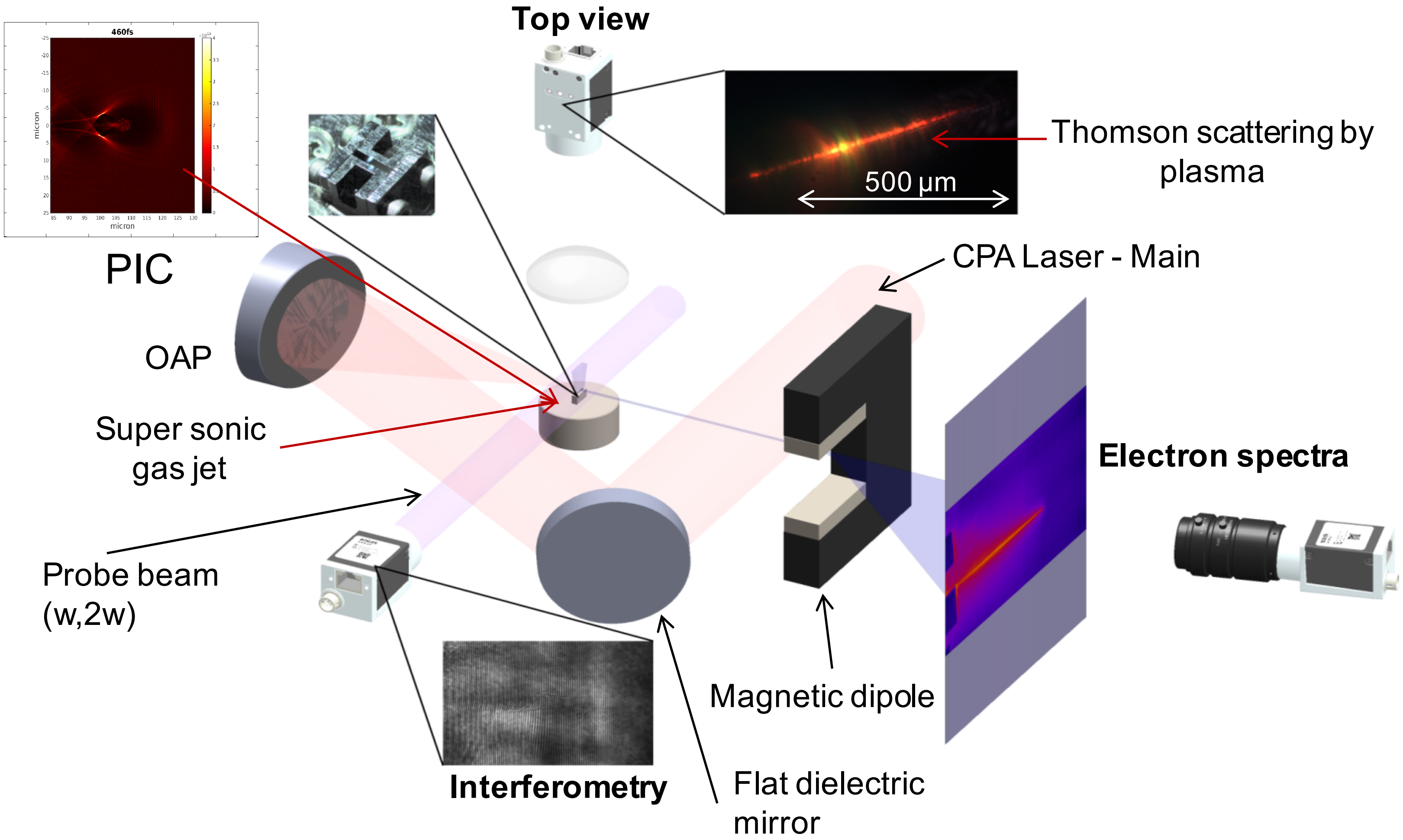
LEAK (high rep rate) workshop 2018

ELIMEDICS Workshop & Applications 2016

Content

- ❑ Introduction on ELI-Beamlines and available Lasers
- ❑ High Energy Electron Platform
- ➢ **Towards high repetition rate: setup and first experiment**
- ❑ Towards stable high-energy electron: stability and guiding experiments
- ❑ Theorethical study: ultrafast nanophotonics and near-critical studies
- ❑ Conclusions

Laser Wakefield Acceleration: main diagnostics



Critical points:
1) *Sharp density gradient*
2) *Intensity > 10^{18} W/cm²*

$$E_z \sim \omega_p \sim \sqrt{n_e}$$

for plasma density $n_e \sim 10^{18}$ cm^{-3} → 100 GV/m

Towards high repetition rate electron acceleration

Idea:

- Table-top setup
- High rep. rate (kHz to MHz)
  → more thermally stable
  → active feedback and control
  → averaging many shots
  → enhance average e⁻ current
- High acceleration gradient
- mJ-class laser ($a_0 < 1$)
- Tight focusing
- Interaction >> z_R
- Low energy beams
  → electron diffraction
  → pulsed radiolysis (a)

Blowout regime:

- Narrow energy spreads
- Small divergence
- $v_g\tau \sim w_0 \sim \lambda_w/2$
- $\varepsilon l \propto \lambda_w{}^3$, $\lambda_w \sim 1/n_e$ (b)

→ Higher plasma density
→ Ultra-short laser pulse

Laser class	a_0 (a_0c)	E_L	τ(fs)	w_0	n_e (cm^{-3})	L_{deph}	ΔE
0.5 PW	4.8 (4.8)	30 J	60 fs	26 μm	6.6×10^{17} cm^{-3}	4.5 cm	4.2 GeV
30 TW	3.5 (3.3)	1 J	25 fs	10 μm	4.2×10^{18} cm^{-3}	2.8 mm	500 MeV
1 TW	2 (1.8)	3 mJ	5 fs	2.1 μm	10^{20} cm^{-3}	25 μm	10 MeV

Scaling low for λ = 800 nm from (c)

(a) D. Gustas et al., Phys. Rev. Accel. Beams 21, 013401 (2018)
(b) W. Lu et al., Phys. Rev. Accel. Beams 10, 061301 (2007)
(c) J. Faure et al., Plasma Phys. Control. Fusion 61, 014012 (2018)

Towards high repetition rate electron acceleration

<u>Idea:</u>

- Table-top setup
- High rep. rate (kHz to MHz)
  → more thermally stable
  → active feedback and control
  → averaging many shots
  → enhance average e⁻ current
- High acceleration gradient
- mJ-class laser ($a_0 < 1$)
- Tight focusing
- Interaction >> z_R
- Low energy beams
  → electron diffraction
  → pulsed radiolysis (a)

<u>Blowout regime:</u>

- Narrow energy spreads
- Small divergence
- $v_g\tau \sim w_0 \sim \lambda_w/2$
- $\varepsilon l \propto \lambda_w^3$, $\lambda_w \sim 1/n^e$ (b)

→ Higher plasma density
→ Ultra-short laser pulse

<u>Relevant papers</u>

Technique 1: *compression to near single-cycle*

New Journal of Physics
The open access journal for physics

High repetition-rate wakefield electron source generated by few-millijoule, 30 fs laser pulses on a density downramp

Z-H He[1,3], B Hou[1], J A Nees[1], J H Easter[1], J Faure[2], K Krushelnick[1] and A G R Thomas[1]
[1] Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI 48109-2099, USA
[2] Laboratoire d'Optique Appliquée, ENSTA-CNRS-Ecole Polytechnique, UMR 7639, F-91761 Palaiseau, France

30 fs
8 mJ
100 KeV
10 fC

PHYSICAL REVIEW X **5,** 031012 (2015)

Effect of the Laser Wave Front in a Laser-Plasma Accelerato

B. Beaurepaire, A. Vernier, M. Bocoum, F. Böhle, A. Jullien, J-P. Rousseau, T. Lefrou, G. Iaquaniello, R. Lopez-Martens, A. Lifschitz, and J. Faure
Laboratoire d'Optique Appliquée, UMR 7639, ENSTA-CNRS-Ecole Polytechnique, 91761 Palaiseau, France
(Received 10 December 2014; published 31 July 2015)

A high-repetition rate electron source is generated by tightly focusing kHz, few-mJ laser pulses into an underdense plasma. This high-intensity laser-plasma interaction leads to stable electron beams over several hours but with strikingly complex transverse distributions even for good quality laser focal spots. We find that the electron beam distribution is sensitive to the laser wave front via the laser midfield distribution rather than the laser focal spot itself. We are able to measure the laser wave front around the focus and include it in realistic particle-in-cell simulations demonstrating the role of the laser wave front on the

22 fs
3 mJ
100 KeV
20 fC

nature photonics
LETTERS
PUBLISHED ONLINE: 10 APRIL 2017 | DOI: 10.1038/NPHOTON.2017.46

Relativistic electron beams driven by kHz single-cycle light pulses

D. Guénot, D. Gustas, A. Vernier, B. Beaurepaire, F. Böhle, M. Bocoum, M. Lozano, A. Jullien, R. Lopez-Martens, A. Lifschitz and J. Faure*

Laser-plasma acceleration[1,2] is an emerging technique for accelerating electrons to high energies over very short distances. The accelerated electron bunches have femtosecond duration[3,4], making them particularly relevant for applications the use of box-sized and commercial laser systems for driving laser–plasma accelerators.

It is well established that the blowout, or bubble regime, of laser–plasma acceleration[8–10,21,22] leads to the production of high-quality

<u>3.4 fs</u>
2 mJ
5 MeV
up to 1 pC

Towards high repetition rate electron acceleration

Idea:

- Table-top setup
- High rep. rate (kHz to MHz)
  → more thermally stable
  → active feedback and control
  → averaging many shots
  → enhance average e^- current
- High acceleration gradient
- mJ-class laser ($a_0 < 1$)
- Tight focusing
- Interaction >> z_R
- Low energy beams
  → electron diffraction
  → pulsed radiolysis (a)

Blowout regime:

- Narrow energy spreads
- Small divergence
- $v_g \tau \sim w_0 \sim \lambda_w/2$
- $\varepsilon l \propto \lambda_w{}^3$, $\lambda_w \sim 1/n^e$ (b)

→ Higher plasma density
→ Ultra-short laser pulse

Relevant papers

Technique 1: *compression to near single-cycle*

New Journal of Physics — The open access journal for physics

High repetition-rate wakefield electron source generated by few-millijoule, 30 fs laser pulses on a density downramp

Z-H He[1,3], B Hou[1], J A Nees[1], J H Easter[1], J Faure[2], K Krushelnick[1] and A G R Thomas[1]
[1] Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI 48109-2099, USA
[2] Laboratoire d'Optique Appliquée, ENSTA-CNRS-Ecole Polytechnique, UMR 7639, F-91761 Palaiseau, France

30 fs
8 mJ
100 KeV
10 fC

PHYSICAL REVIEW X 5, 031012 (2015)

Effect of the Laser Wave Front in a Laser-Plasma Accelerator

B. Beaurepaire, A. Vernier, M. Bocoum, F. Böhle, A. Jullien, J-P. Rousseau, T. Lefrou, G. Iaquaniello, R. Lopez-Martens, A. Lifschitz, and J. Faure
Laboratoire d'Optique Appliquée, UMR 7639, ENSTA-CNRS-Ecole Polytechnique, 91761 Palaiseau, France
(Received 10 December 2014; published 31 July 2015)

A high-repetition rate electron source is generated by tightly focusing kHz, few-mJ laser pulses into an underdense plasma. This high-intensity laser-plasma interaction leads to stable electron beams over several hours but with strikingly complex transverse distributions even for good quality laser focal spots. We find that the electron beam distribution is sensitive to the laser wave front via the laser midfield distribution rather than the laser focal spot itself. We are able to measure the laser wave front around the focus and include it in realistic particle-in-cell simulations demonstrating the role of the laser wave front on the ...

22 fs
3 mJ
100 KeV
20 fC

nature photonics — LETTERS
PUBLISHED ONLINE: 10 APRIL 2017 | DOI: 10.1038/NPHOTON.2017.46

Relativistic electron beams driven by kHz single-cycle light pulses

D. Guénot, D. Gustas, A. Vernier, B. Beaurepaire, F. Böhle, M. Bocoum, M. Lozano, A. Jullien, R. Lopez-Martens, A. Lifschitz and J. Faure*

3.4 fs
2 mJ
5 MeV
up to 1 pC

Technique 2: *near critical density (gas) target*

PRL 115, 194802 (2015) — PHYSICAL REVIEW LETTERS — week ending 6 NOVEMBER 2015

Multi-MeV Electron Acceleration by Subterawatt Laser Pulses

A. J. Goers, G. A. Hine, L. Feder, B. Miao, F. Salehi, J. K. Wahlstrand, and H. M. Milchberg
Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, Maryland 20742, USA
(Received 9 June 2015; published 5 November 2015)

We demonstrate laser-plasma acceleration of high charge electron beams to the ~10 MeV scale using ultrashort laser pulses with as little energy as 10 mJ. This result is made possible by an extremely dense and thin hydrogen gas jet. Total charge up to ~0.5 nC is measured for energies >1 MeV. Acceleration is correlated to the presence of a relativistically self-focused laser filament accompanied by an intense coherent broadband light flash, associated with wave breaking, which can radiate more than ~3% of the laser energy in a ~1 fs bandwidth consistent with half-cycle optical emission. Our results enable truly portable applications of laser-driven acceleration, such as low dose radiography, ultrafast probing of matter, and isotope production.

DOI: 10.1103/PhysRevLett.115.194802

50 fs, 10 mJ
2-8 MeV
1-10 pC
Small capillary target
H_2 at n_e/n_{cr} 50%

a) 30 fs
1.3 mJ
0.5 MeV
10 fC
H_2

b) 30 fs
10 mJ
> 1 MeV
1 pC
H2 and He

Letter — **Optics Letters**

MeV electron acceleration at 1 kHz with <10 mJ laser pulses

F. Salehi, A. J. Goers, G. A. Hine, L. Feder, D. Kuk, B. Miao, D. Woodbury, K. Y. Kim, and H. M. Milchberg*
Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, Maryland 20742, USA

https://doi.org/10.1364/OL.42.000215

Towards high repetition rate electron acceleration

Idea:

- Table-top setup
- High rep. rate (kHz to MHz)
- mJ-class laser ($a_0 < 1$)
- Tight focusing
- Interaction >> z_R

Propagation in air:

I. 60 fs and 4 mJ on target
II. Capillary with steep profile
III. f/1 focusing close to limit

Relevant papers

Technique 1: *compression to near single-cycle*

New Journal of Physics
The open access journal for physics

High repetition-rate wakefield electron source generated by few-millijoule, 30 fs laser pulses on a density downramp

Z-H He[1,3], B Hou[1], J A Nees[1], J H Easter[1], J Faure[2], K Krushelnick[1] and A G R Thomas[1]
[1] Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI 48109-2099, USA
[2] Laboratoire d'Optique Appliquée, ENSTA-CNRS-Ecole Polytechnique, UMR 7639, F-91761 Palaiseau, France

30 fs
8 mJ
100 KeV
10 fC

PHYSICAL REVIEW X 5, 031012 (2015)

Effect of the Laser Wave Front in a Laser-Plasma Accelerato[r]

B. Beaurepaire, A. Vernier, M. Bocoum, F. Böhle, A. Jullien, J-P. Rousseau, T. Lefrou, G. Iaquaniello, R. Lopez-Martens, A. Lifschitz, and J. Faure
Laboratoire d'Optique Appliquée, UMR 7639, ENSTA-CNRS-Ecole Polytechnique, 91761 Palaiseau, France

(Received 10 December 2014; published 31 July 2015)

A high-repetition rate electron source is generated by tightly focusing kHz, few-mJ laser pulses into an underdense plasma. This high-intensity laser-plasma interaction leads to stable electron beams over several hours but with strikingly complex transverse distributions even for good quality laser focal spots. We find that the electron beam distribution is sensitive to the laser wave front via the laser midfield distribution rather than the laser focal spot itself. We are able to measure the laser wave front around the focus and include it in realistic particle-in-cell simulations demonstrating the role of the laser wave front on the

22 fs
3 mJ
100 KeV
20 fC

nature photonics LETTERS
PUBLISHED ONLINE: 10 APRIL 2017 | DOI: 10.1038/NPHOTON.2017.46

Relativistic electron beams driven by kHz single-cycle light pulses

D. Guénot, D. Gustas, A. Vernier, B. Beaurepaire, F. Böhle, M. Bocoum, M. Lozano, A. Jullien, R. Lopez-Martens, A. Lifschitz and J. Faure*

Laser-plasma acceleration[1,2] is an emerging technique for accelerating electrons to high energies over very short distances. The accelerated electron bunches have femtosecond duration[3,4], making them particularly relevant for applications … the use of box-sized and commercial laser systems for driving laser-plasma accelerators. It is well established that the blowout, or bubble regime, of laser-plasma acceleration leads to the production of high-quality

3.4 fs
2 mJ
5 MeV
up to 1 pC

Technique 2: *near critical density (gas) target*

PRL 115, 194802 (2015) PHYSICAL REVIEW LETTERS week ending 6 NOVEMBER 2015

Multi-MeV Electron Acceleration by Subterawatt Laser Pulses

A. J. Goers, G. A. Hine, L. Feder, B. Miao, F. Salehi, J. K. Wahlstrand, and H. M. Milchberg
Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, Maryland 20742, USA

(Received 9 June 2015; published 5 November 2015)

We demonstrate laser-plasma acceleration of high charge electron beams to the ~10 MeV scale using ultrashort laser pulses with as little energy as 10 mJ. This result is made possible by an extremely dense and thin hydrogen gas jet. Total charge up to ~0.5 nC is measured for energies >1 MeV. Acceleration is correlated to the presence of a relativistically self-focused laser filament accompanied by an intense coherent broadband light flash, associated with wave breaking, which can radiate more than ~3% of the laser energy in a ~1 fs bandwidth consistent with half-cycle optical emission. Our results enable truly portable applications of laser-driven acceleration, such as low dose radiography, ultrafast probing of matter, and isotope production.

DOI: 10.1103/PhysRevLett.115.194802 PACS …

50 fs, 10 mJ
2-8 MeV
1-10 pC
Small capillary target
H_2 at n_e/n_{cr} 50%

a) 30 fs
1.3 mJ
0.5 MeV
10 fC
H_2

b) 30 fs
10 mJ
> 1 MeV
1 pC
H2 and He

Letter
Optics Letters

MeV electron acceleration at 1 kHz with <10 mJ laser pulses

Salehi, A. J. Goers, G. A. Hine, L. Feder, D. Kuk, B. Miao, D. Woodbury, Y. Kim, and H. M. Milchberg*
Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, Maryland 20742, USA
Corresponding author: milch@umd.edu

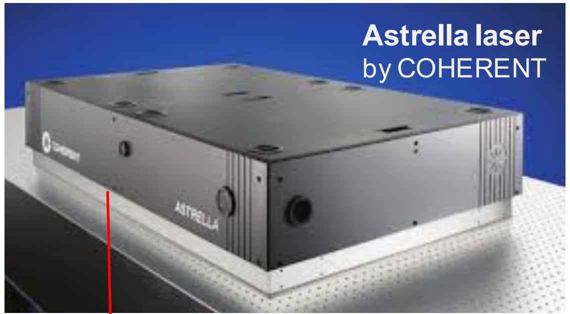
Received 14 November 2016; revised 30 November 2016; accepted 30 November 2016; posted 1 December 2016 (Doc. ID 280796); published 6 January 2017

We demonstrate laser-driven acceleration of electrons to MeV-scale energies at 1 kHz repetition rate using <10 mJ pulses focused on near-critical density He and H$_2$ gas jets. Using the H$_2$ gas jet, electron acceleration to ~0.5 MeV in ~10 fC bunches was observed with laser pulse energy as low as 1.3 mJ. Increasing the pulse energy to 10 mJ, we measure ~1 pC charge bunches with >1 MeV energy for both He and H$_2$ gas jets. ©2017 Optical Society of America

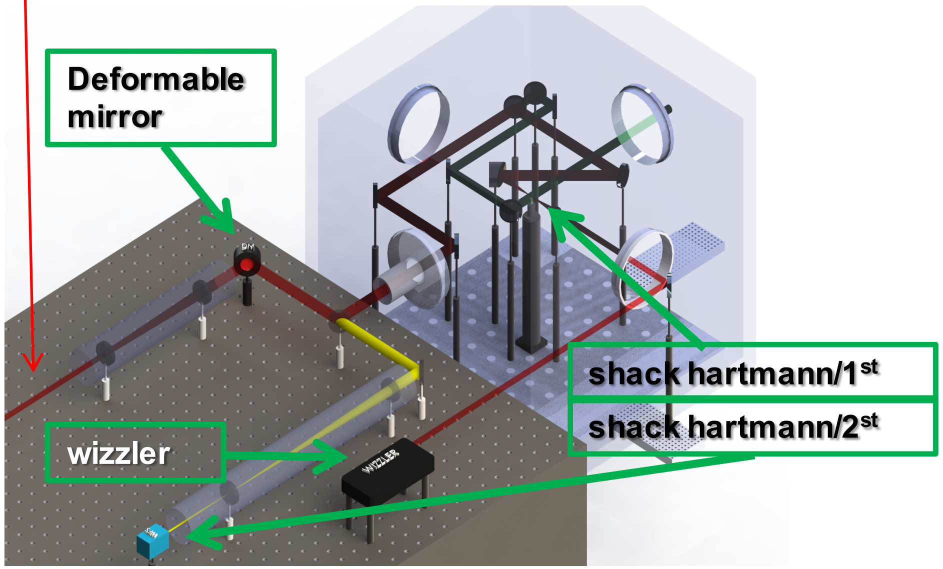
OCIS codes: (350.5400) Plasmas; (020.2649) Strong field laser physics; (320.2250) Femtosecond phenomena.
https://doi.org/10.1364/OL.42.000215

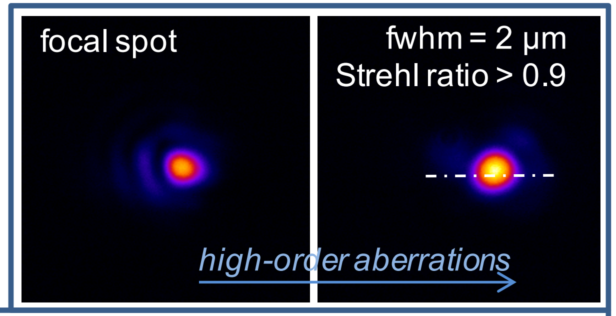
accelerator structures such as LINACs is an established research [12], where low emittance and narrow energy spreads are achie[ved]. For <100 fs temporal resolution, this technique requ[ires] compensation for space charge effects and timing jitter [12]. The most common and successful laser-plasma-based ac[celeration] scheme is laser wakefield acceleration (LWFA), wh[ich] can be initiated by relativistic self-focusing of the laser puls[e in] the plasma. LWFA electron pulses can be ultrashort and precisely timed to their driving optical pulses … Relativistic self-focusing has a critical power [14] of P_{cr} … GW, where N_e is the plasma density, and N_{cr} is critical density. As $N_{cr} = 1.74 \times 10^{21}$ cm^{-3} for the Ti:sapp[hire] laser wavelength of $\lambda = 800$ nm, a very high N_e is neede[d] …

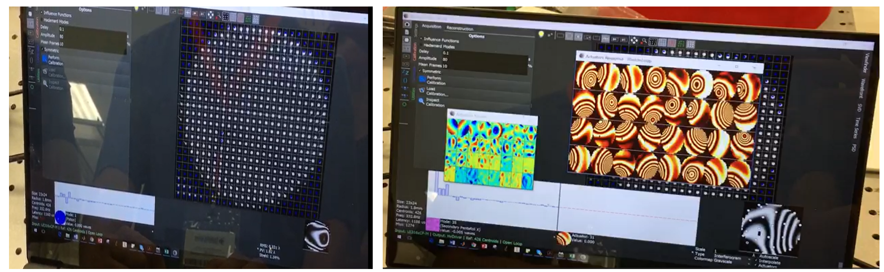
Towards high repetition rate electron acceleration



- First test of piezo-technology Deformable Mirror and WFS in automatic mode
- Testing diagnostics devices (Wizzler)
- Conceptual approach of alignment and diagnostics for the L3-size optics

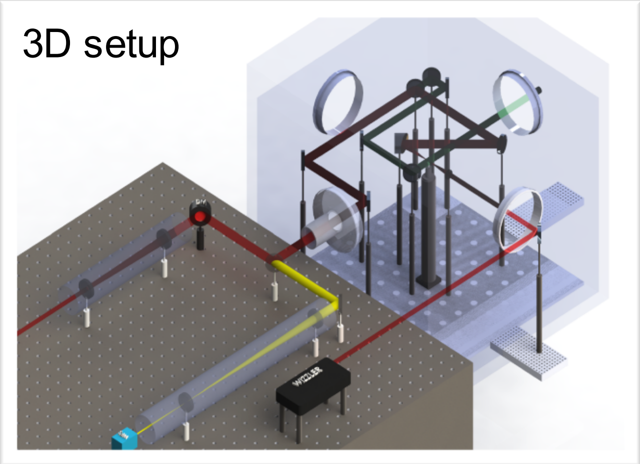




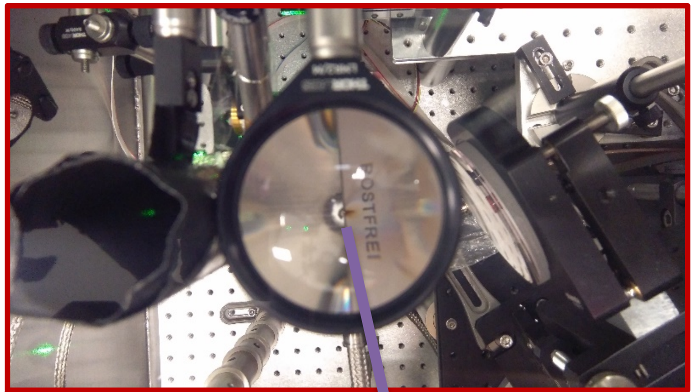


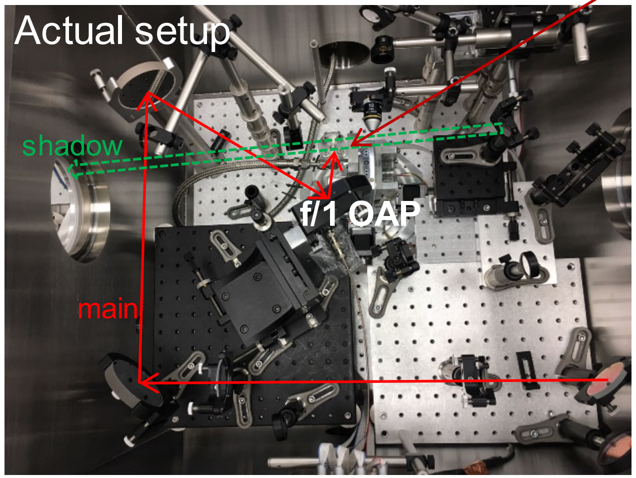
(Dynamic Optics) phase-front optimization software

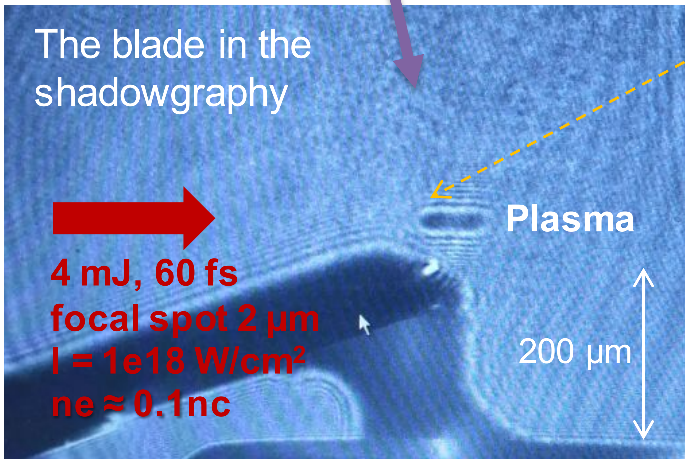
Towards high repetition rate electron acceleration

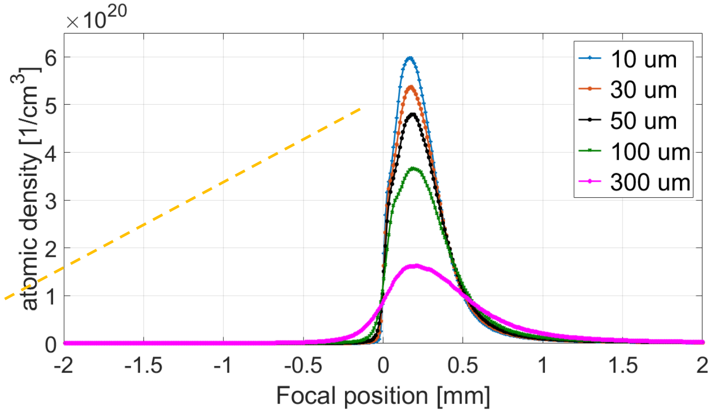


Top-view of the target usign a blade





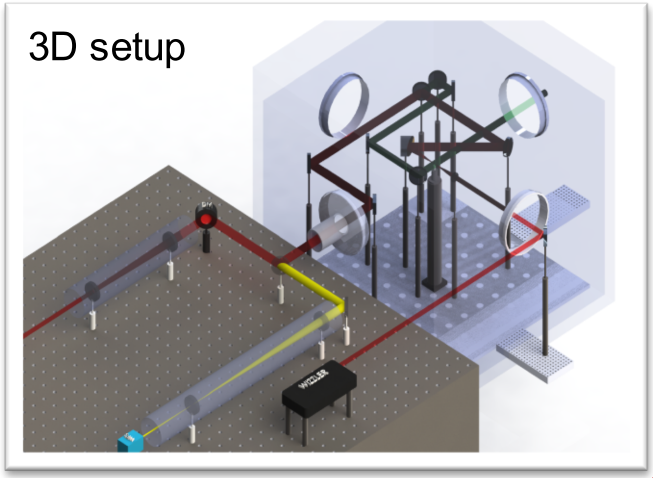




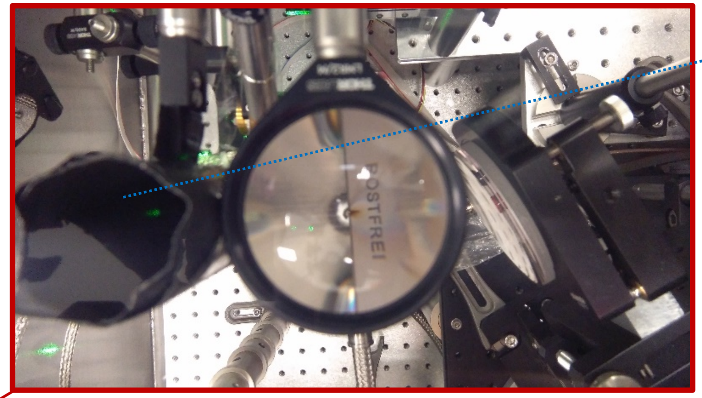
*ANSYS Fluent

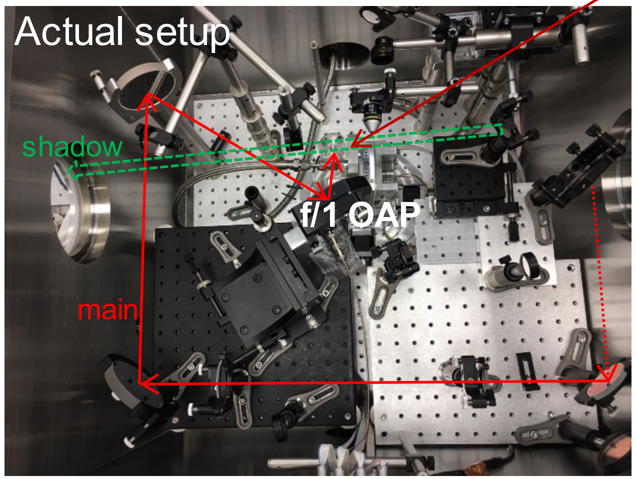
**C.M.Lazzarini et al., Paper in preparation*

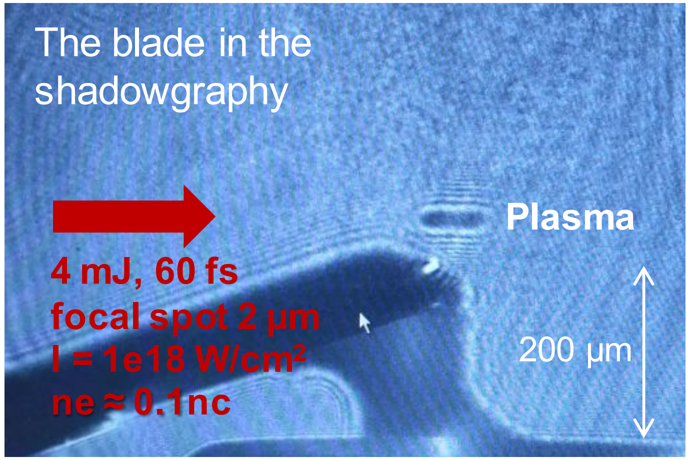
Towards high repetition rate electron acceleration



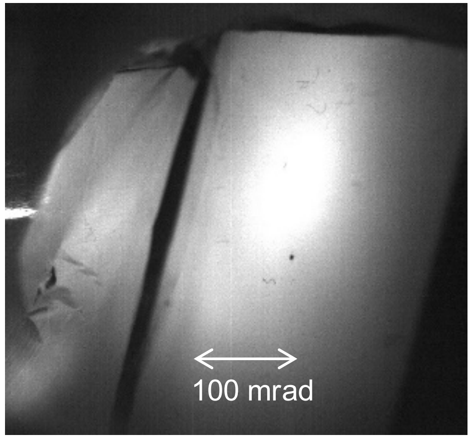
Top-view of the target usign a blade







First electrons (at ELI):
6 pC at about 1MeV

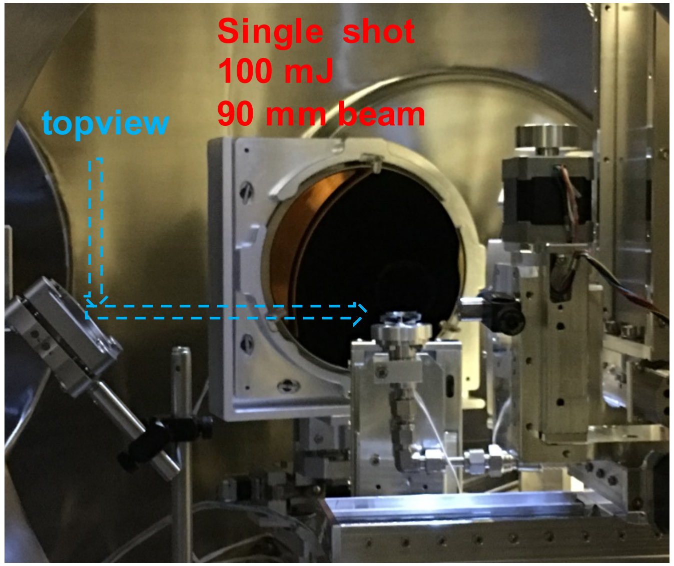


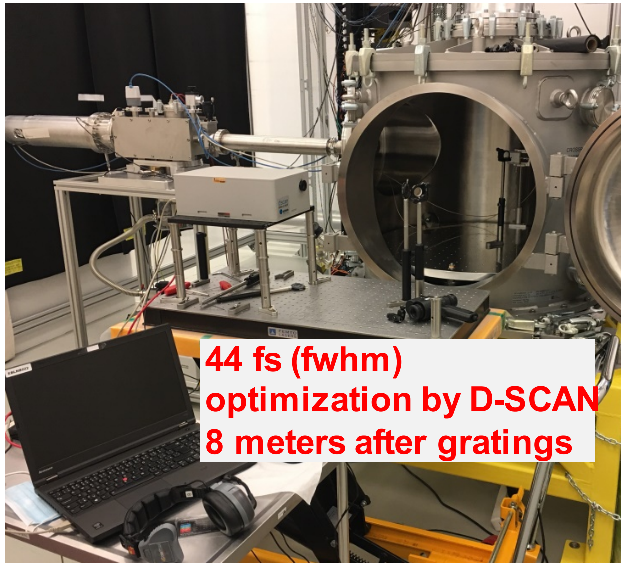
First electrons by:

- Commercial laser (4mJ)
- Long pulse duration (60 fs)
- Near-critical plasma target
- High density gradient by blade
- Pre-plasma helps injection

**C.M.Lazzarini et al., Paper in preparation*

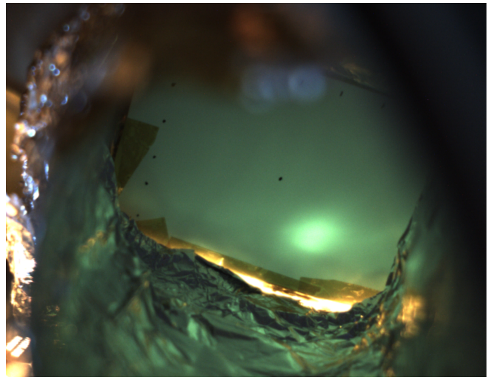
First L3 laser experiment at ELI

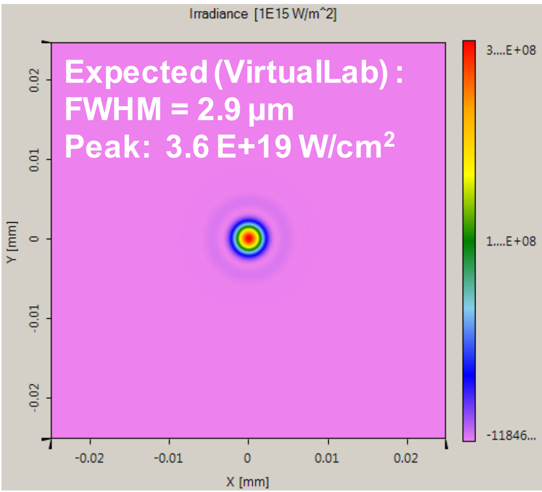


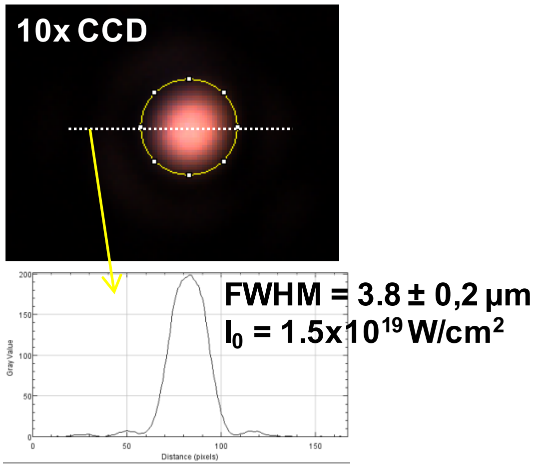


@ “TERESA” experimental hall

Electron beam spot (low energy)







- Optical alignment and focusing in vacuum
- In-air and in vacuum pulse duration optimization
- Data acquisition from remote control room
- Up to 3.3 Hz

next

- Increase energy to J-level
- Increase to 10 Hz

Acceleration at ELI-Beamlines: recent developments towards high-energy and high-repetition rate accelerators

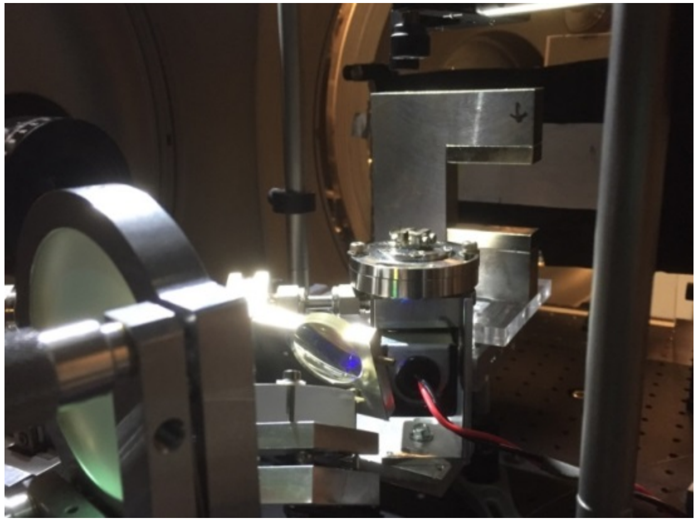
Carlo Maria Lazzarini

Content

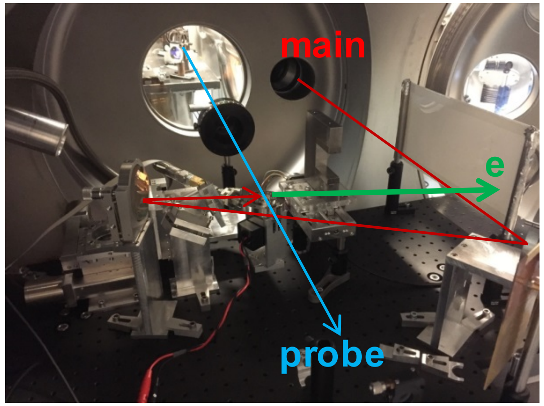
- ❑ Introduction on ELI-Beamlines and available Lasers
- ❑ High Energy Electron Platform
- ❑ Towards high repetition rate: setup and first experiment
- ➢ **Towards stable high-energy electron → Stability experiment**
- ❑ Theorethical study: ultrafast nanophotonics and near-critical studies
- ❑ Conclusions

Electron bunches Pointing Stabilization

8 TW Laser - 50fs



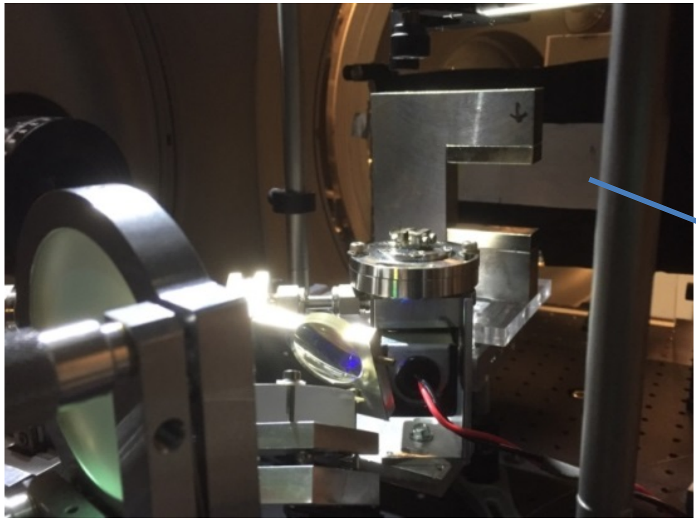
OAP f/3, 7 µm spot focus in pure N gas-jet at 20 bar | $n_e \approx 1e19\ cm^{-3}$

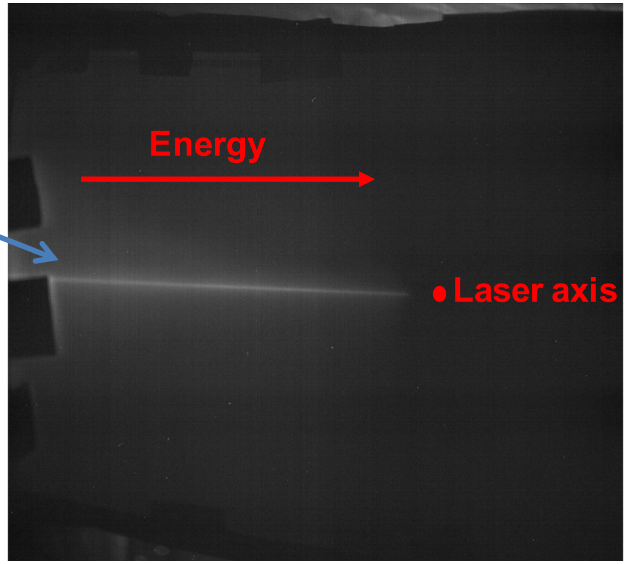


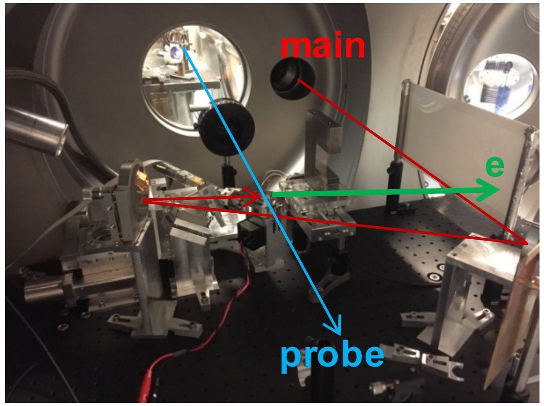
IFPiLM experiment: Stable Electron Beam

Electron bunches Pointing Stabilization

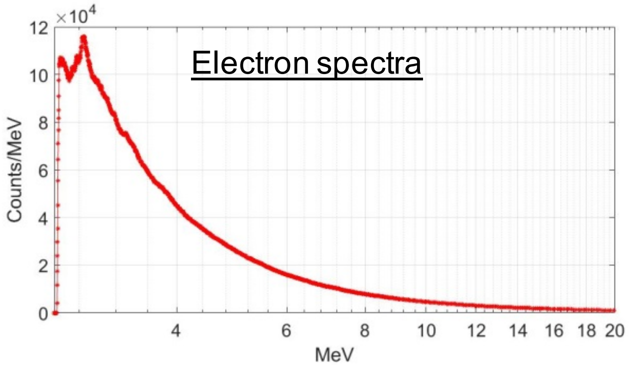
8 TW Laser - 50fs





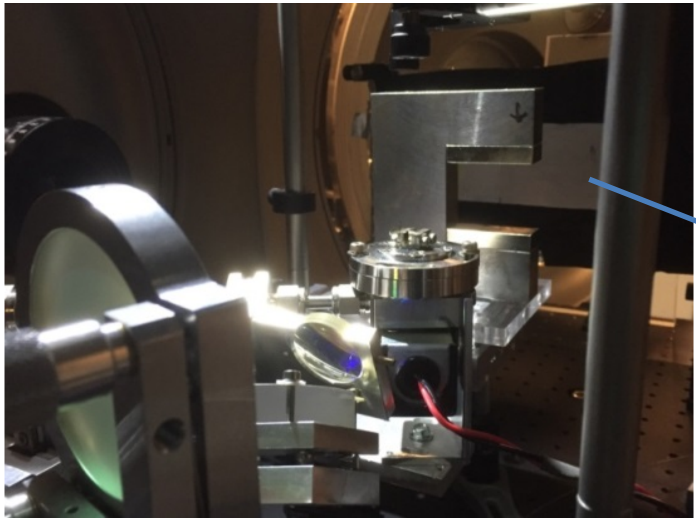


OAP f/3, 7 μm spot focus in pure N gas-jet at 20 bar | $n_e \approx$ 1e19 cm^{-3}

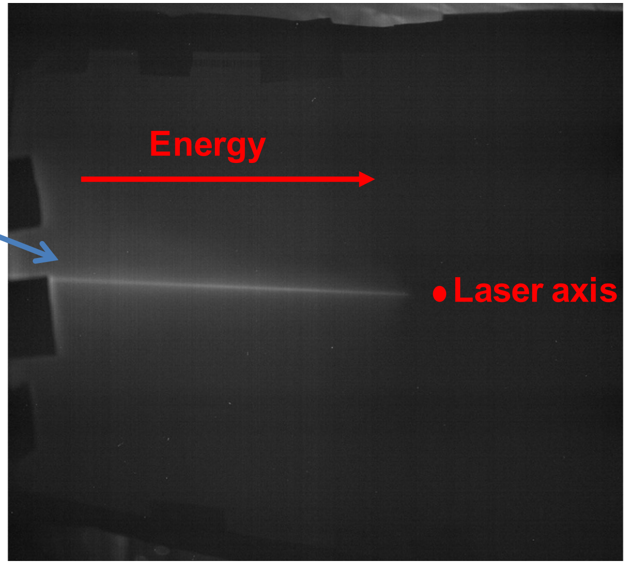


IFPiLM experiment: Stable Electron Beam

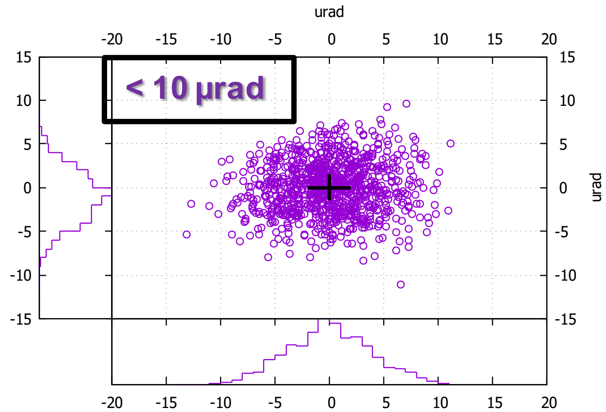
Electron bunches Pointing Stabilization



8 TW Laser - 50fs

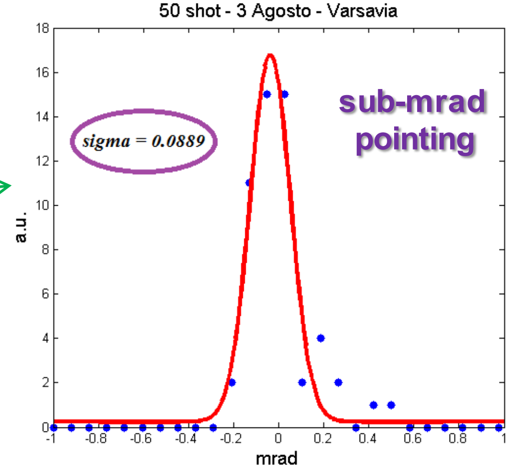


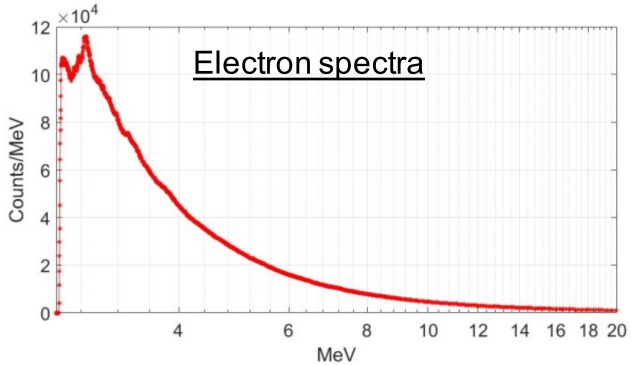
Laser pointing (1000 shots)

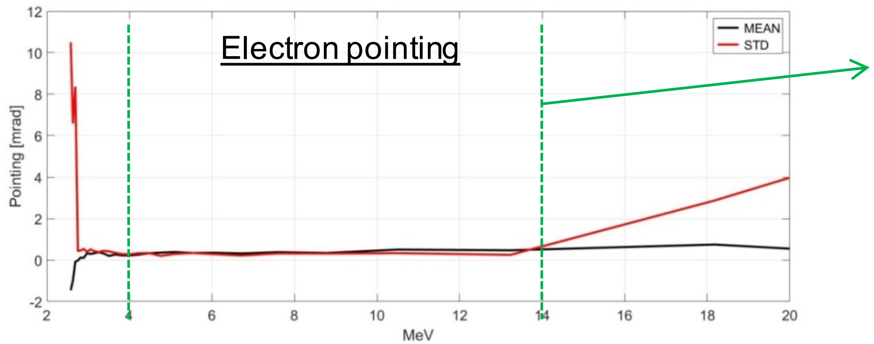


OAP f/3, 7 µm spot focus in pure N gas-jet at 20 bar | $n_e \approx$ 1e19 cm^{-3}

low energy e-beam pointing: 90 shots

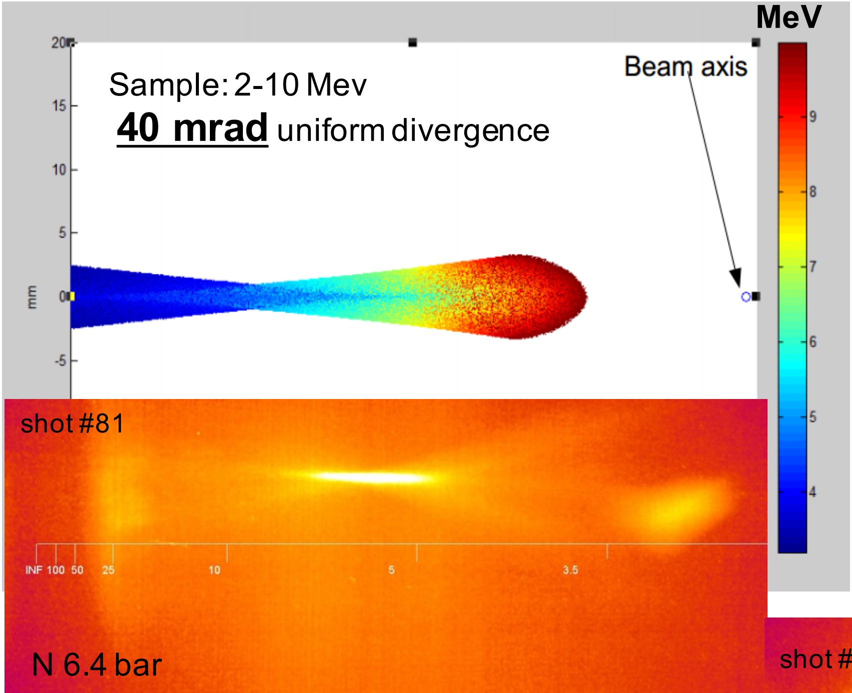


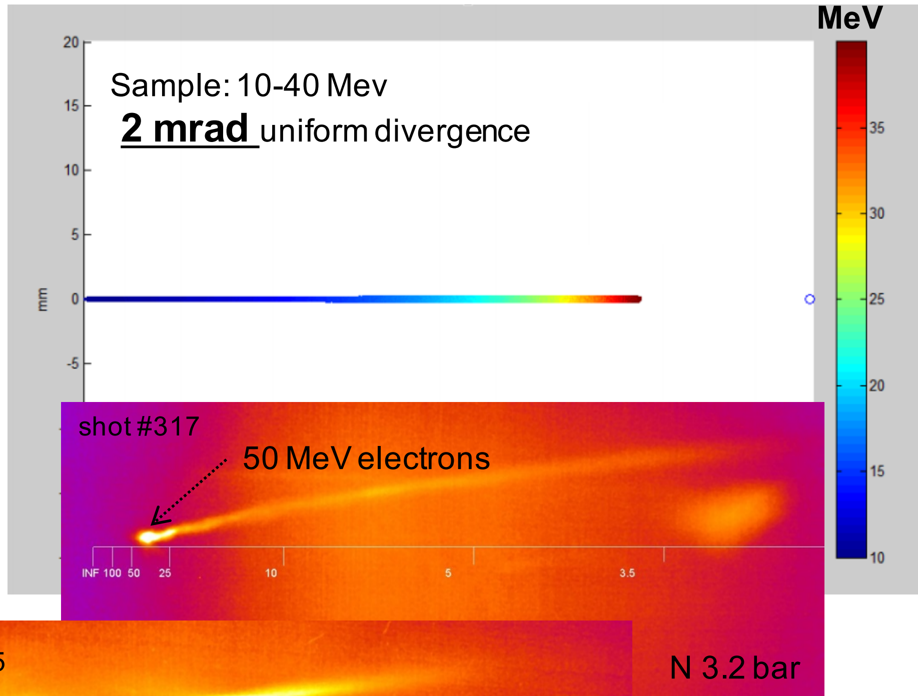


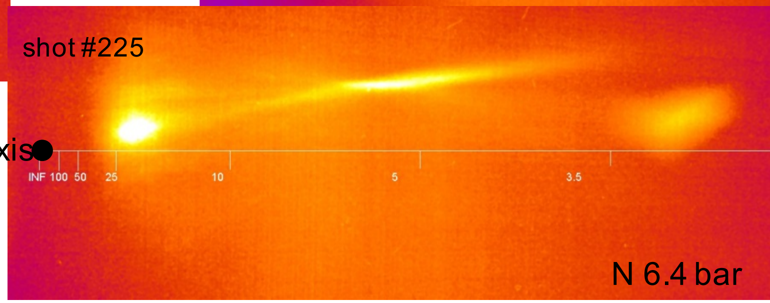


IFPiLM experiment: Stable Electron Beam

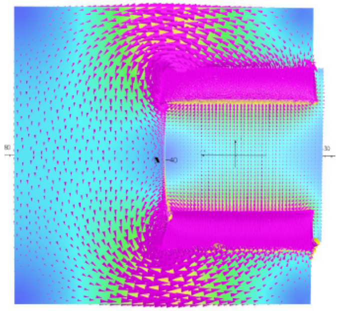
Montecarlo beam distribution (*thanks to F. Schillaci)

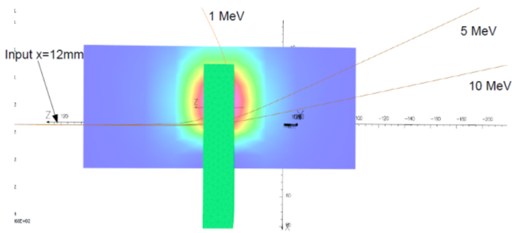






Opera 3D B-distribution





Tunable 2 separate populations

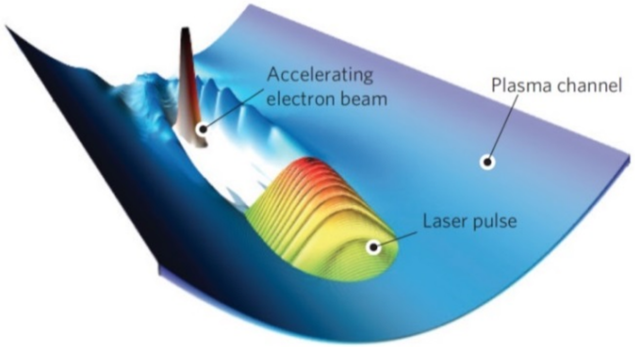
Acceleration at ELI-Beamlines: recent developments towards high-energy and high-repetition rate accelerators

Carlo Maria Lazzarini

Content

- ❑ Introduction on ELI-Beamlines and available Lasers
- ❑ High Energy Electron Platform
- ❑ Towards high repetition rate: setup and first experiment
- ➢ **Towards stable high-energy electron → Guiding**
- ❑ Theorethical study: ultrafast nanophotonics and near-critical studies
- ❑ Conclusions

ns Plasma Channel for guiding



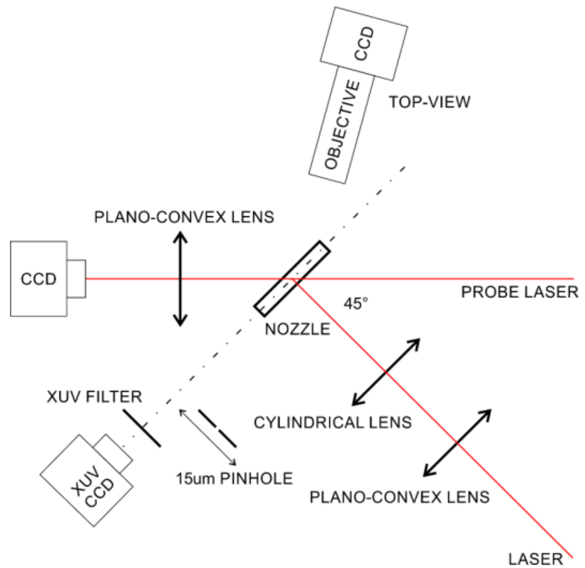
**Courtesy of L. Silva*

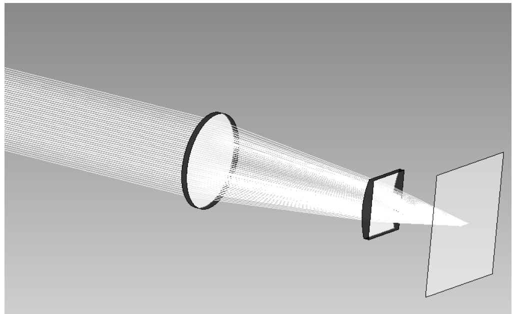
<u>Bivoj laser (HiLASE):</u>
Square flat-top 22x22 mm
Wavelength = 1030 nm
6 J in 10 ns (FWHM)

<u>GAS TARGET:</u>
Supersonic nozzle 7 mm x 1.2 mm

<u>Plasma threshold measured:</u>
- 4-5J at 64 bar for **Nitrogen** (~ 5×10^{11} W/cm^{-2} for 3 ÷ 6 x 10^{19} cm^{-3})
- 1-2J at 51,2 bar for **Argon** (~ 10^{11} W/cm^{-2} for 2,5 ÷ 5 x 10^{19} cm^{-3})

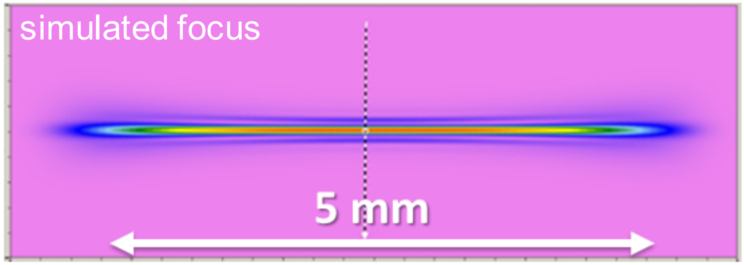
Plasma channels with high aspect ratio produced

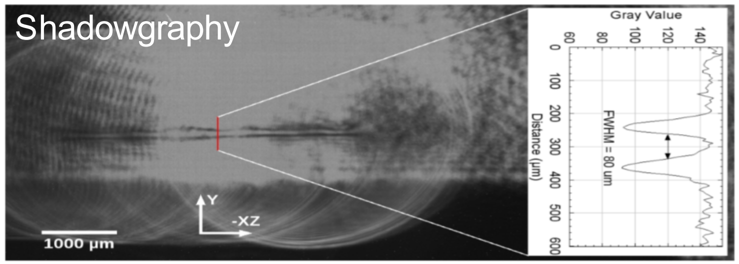




Calculated:
Peak intensity = 1.7E+12W/cm^2
FWHM(x)&(y) = 5 mm & 5 µm

Measured:
FWHM(x)&(y) => 6.4 mm & 80 µm





**Paper sumbitted to PoP*

Acceleration at ELI-Beamlines: recent developments towards high-energy and high-repetition rate accelerators

Carlo Maria Lazzarini

Content

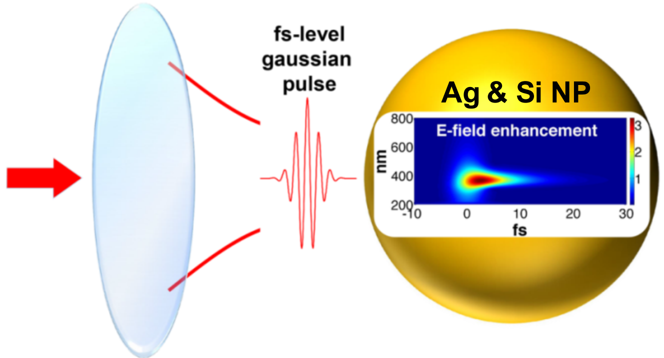
- ❑ Introduction on ELI-Beamlines and available Lasers
- ❑ High Energy Electron Platform
- ❑ Towards high repetition rate: setup and first experiment
- ❑ Towards stable high-energy electron: stability, electron rings and guiding experiments
- ➢ **Theorethical study: ultrafast nanophotonics**
- ❑ Conclusions

Nanoparticle time-resolved response to ultrashort laser

in collaboration with Dr. Giannini

Ultrafast dynamics resonances in nanoparticles (NP) driven by
Ultrashort Gaussian laser:

- Plasmons in metal NP
- Magnetic resonances in non-absorbing dielectric NP



*C. M. Lazzarini et al., Phys. Rev. B 96, 235407 (2017)

IDEA

❖ *Studies on plasmonic and magnetic resonances consider monochromatic waves*

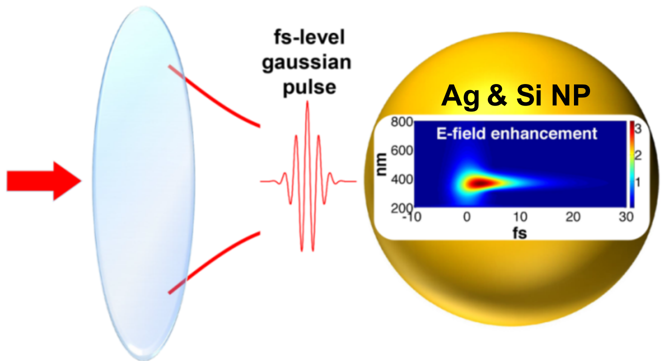
❖ *Clear analytical time description of the fields considering thin-film and NP response is missing*

Nanoparticle time-resolved response to ultrashort laser

in collaboration with Dr. Giannini

Ultrafast dynamics resonances in nanoparticles (NP) driven by
Ultrashort Gaussian laser:

- Plasmons in metal NP
- Magnetic resonances in non-absorbing dielectric NP



*C. M. Lazzarini et al., Phys. Rev. B 96, 235407 (2017)

$\varepsilon_1(\omega) = \varepsilon_\infty - \omega p2/(\omega^2 + i\omega\gamma)$

$\varepsilon_\infty = 5 \pm 2$

$\hbar\omega_p = 8.9 \pm 0.2\ eV$

$\tau = 17 \pm 3\ fs$

*Yang H. U. et al., (2015) Phys. Rev. B 91, 235137

Hyphothesis

$\lambda >> 2r$

$r >> \delta_{skin}$

By solving Helmholtz equation in Paraxial-wave approx.: $\mathbf{E}(\mathbf{r},t) = \mathbf{E}_{space}(\mathbf{r}) * E_{time}(t)$

Radiative reaction correction

Effective polarizability

$$\boldsymbol{F}_r = \frac{q^2\dddot{\boldsymbol{r}}}{6\pi\varepsilon_0 c^3} \longrightarrow \boldsymbol{\mu} = \alpha(\omega)(\boldsymbol{E}_0 + \boldsymbol{E}_{self}) \longrightarrow \alpha_{eff}(\omega) = \frac{\alpha(\omega)}{1 - i\frac{k^3}{6\pi\varepsilon_0}\alpha(\omega)} = \frac{4\pi\varepsilon_0 a^3(\varepsilon(\omega) - \varepsilon_m)}{\varepsilon(\omega) + 2\varepsilon_m - i\frac{2}{3}k^3a^3(\varepsilon(\omega) - \varepsilon_m)}$$

Ag resonance lifetime = 5.4 fs

Incoming pulse

F-transform

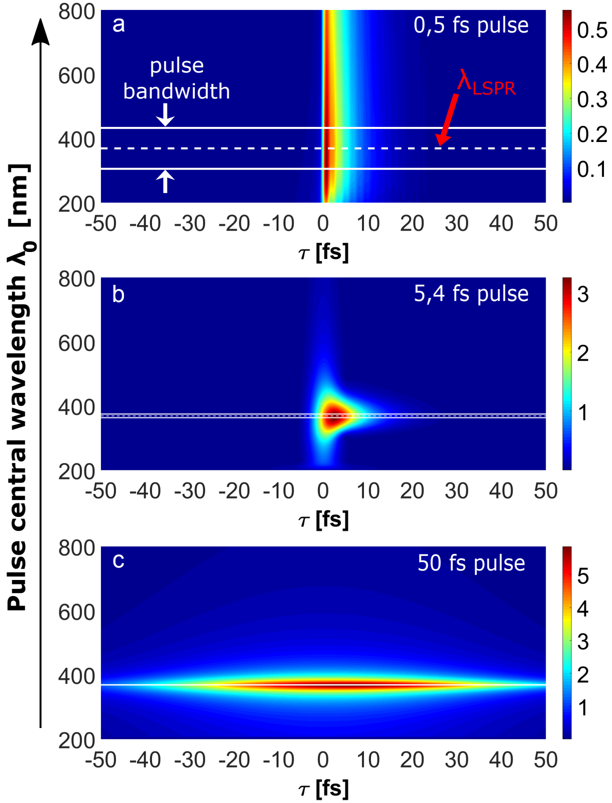
$$\mathrm{E}(\tau) = E_0 e^{-\alpha\tau^2} e^{-i\omega_0\tau} \longrightarrow \boldsymbol{E}_1(\omega, x=0) = E_0\sqrt{\frac{\pi}{\alpha}}e^{-\frac{(\omega-\omega_0)^2}{4\alpha}} \frac{3\varepsilon_m}{\varepsilon_\infty + 2\varepsilon_m - \frac{\omega_p{}^2}{\omega(\omega + i\gamma)}}\hat{x} \longrightarrow \boldsymbol{E}_1(t) = \int_{-\infty}^{+\infty} \boldsymbol{E}_1(\omega)e^{-i\omega t}dt$$

E-field evolution on fs scale by IFT

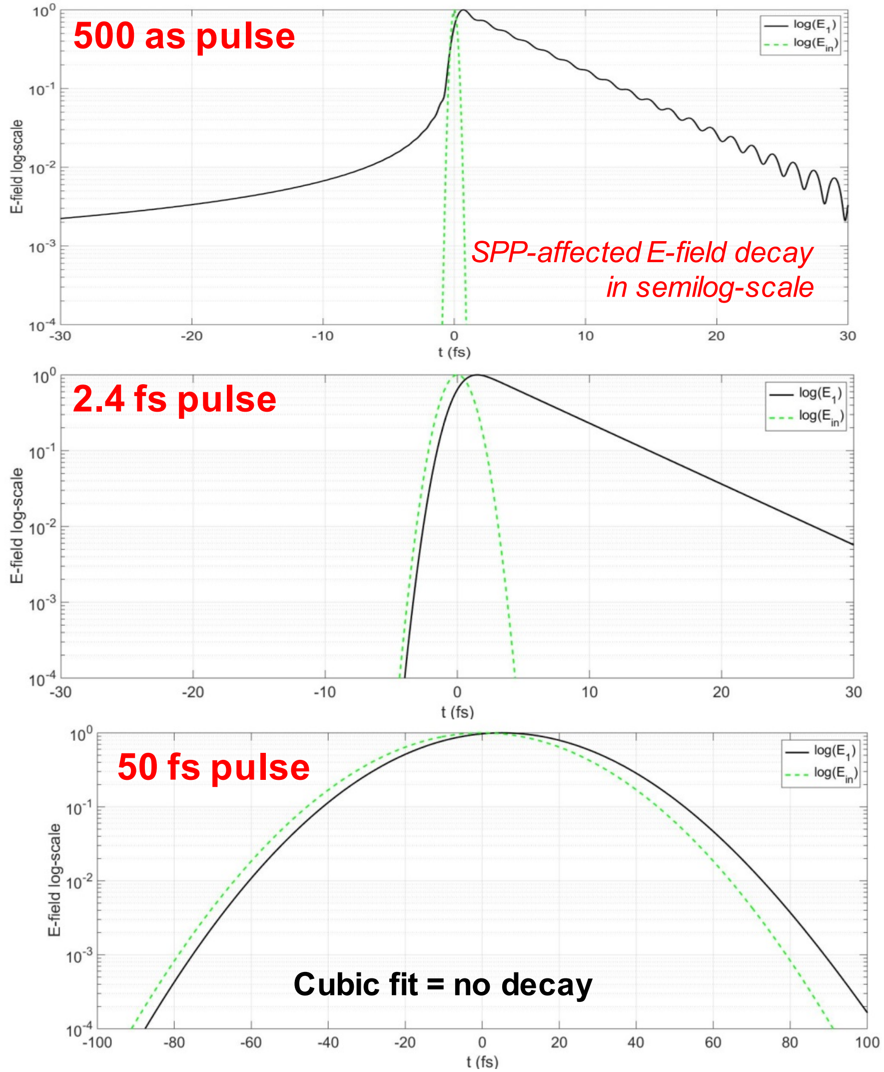
Nanoparticle time-resolved response to ultrashort laser

in collaboration with Dr. Giannini

Near-field enhancement

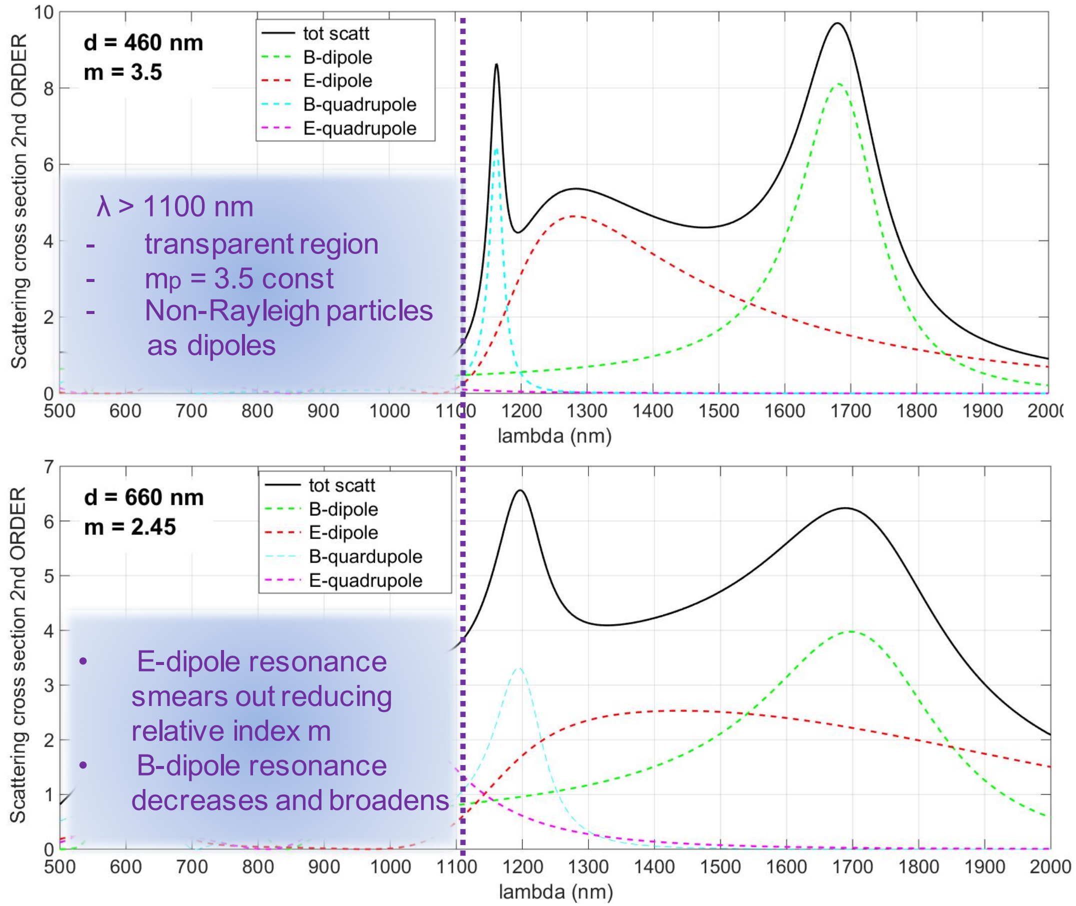


***C. M. Lazzarini et al., Phys. Rev. B 96, 235407 (2017)**



Nanoparticle time-resolved response to ultrashort laser

in collaboration with Dr. Giannini



sub-micron Silicon particles:

→ same delayed response in IR regime
→ Selective resonance of E- and B-dipole

Applications

1. Laser-plasma improved diagnostic
2. Few-cycle laser pulse delaying and shaping
3. HHG and as-pulse generation
4. Direct electron acceleration from NP

Acceleration at ELI-Beamlines: recent developments towards high-energy and high-repetition rate accelerators

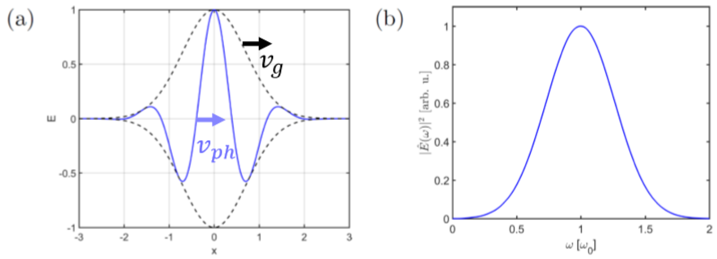
Carlo Maria Lazzarini

Content

- ❑ Introduction on ELI-Beamlines and available Lasers
- ❑ High Energy Electron Platform
- ❑ Towards high repetition rate: setup and first experiment
- ❑ Towards stable high-energy electron: stability, electron rings and guiding experiments
- ➢ **Theorethical study: near-critical propagation**
- ❑ Conclusions

Wakefield Excited by Ultrashort Laser Pulses in Near-Critical Density Plasmas

P. Valenta et al., arXiv:1905.02043v1



<u>Single-cycle E.M. wave propagation in plasma:</u>

$\omega^2 = k^2c^2 + \omega_p^2$
$v_{ph} = \omega/k$
$v_g = \partial\omega/\partial k$
$\beta_w = v_g/c$ (wake wave phase velocity)

→ F(x,t) exciting the wake wave driving force [a,b]
→ $\partial_X p = -E + F$, $\partial_X E = p$ (below wave-breaking $\gamma=1$)
with E the electric field in the wake

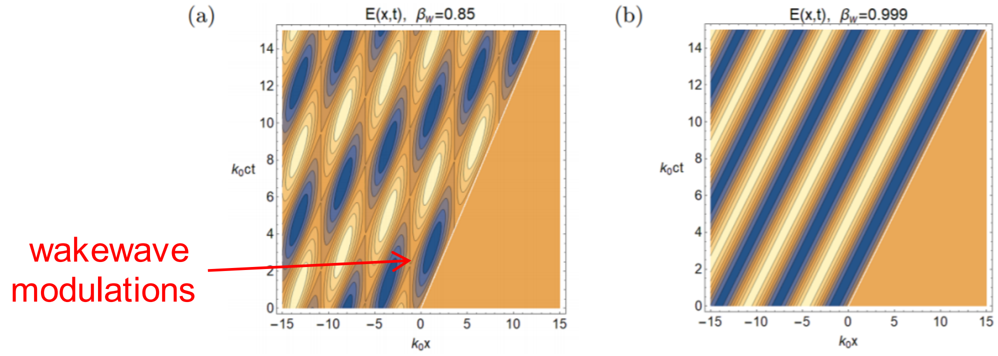
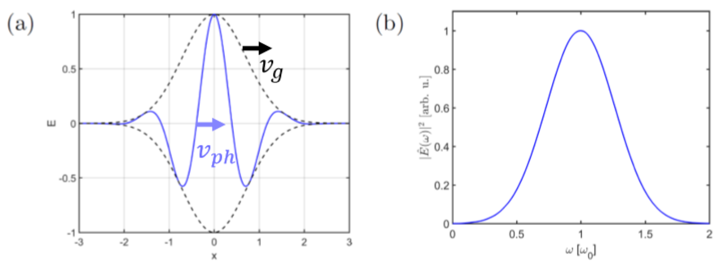


Figure 1: Contour-plots showing the wakefield, $E(x,t)$, distribution in the (x,t) plane. The normalized group velocity of laser pulse is equal to (a) $\beta_w = 0.85$ and (b) $\beta_w = 0.999$.

(a) E. Esarey et al., Rev. Mod. Phys. 81, 1229-1285 (2009)
(b) S. V. Bulanov et al., Journal Plas. Phys. 82(3), 905820308 (2016)

Wakefield Excited by Ultrashort Laser Pulses in Near-Critical Density Plasmas

P. Valenta et al., arXiv:1905.02043v1



Single-cycle E.M. wave propagation in plasma:

$\omega^2 = k^2c^2 + \omega_p^2$
$v_{ph} = \omega/k$
$v_g = \partial\omega/\partial k$
$\beta_w = v_g/c$ (wake wave phase velocity)

→ F(x,t) exciting the wake wave driving force [a,b]
→ $\partial_x p = -E + F$, $\partial_x E = p$ (below wave-breaking γ=1)
with E the electric field in the wake

PIC simulations:

pre-iopnized (uniform) hydrogen
τ = single-cycle, $a_0 = 2$, $w_0 = 4\lambda_0$
$\varepsilon \approx 10$ mJ, $P \approx 3$ TW
profile: Gaussian, polarization: circular
$n_e = 0.1\ n_c$

(a) E. Esarey et al., Rev. Mod. Phys. 81, 1229-1285 (2009)
(b) S. V. Bulanov et al., Journal Plas. Phys. 82(3), 905820308 (2016)

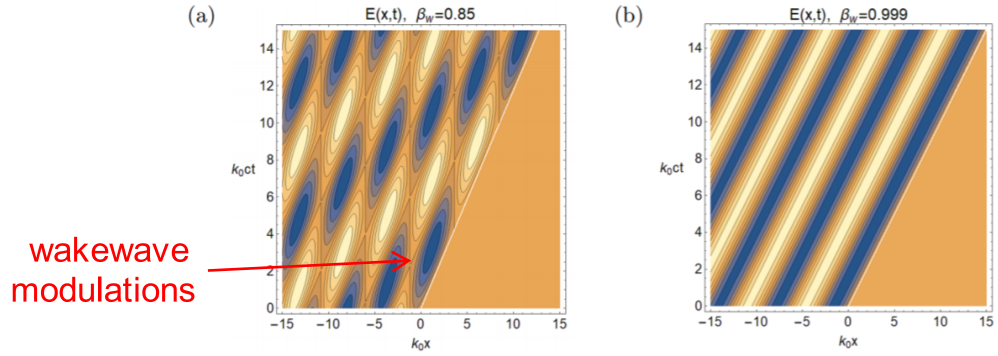


Figure 1: Contour-plots showing the wakefield, $E(x,t)$, distribution in the (x,t) plane. The normalized group velocity of laser pulse is equal to (a) $\beta_w = 0.85$ and (b) $\beta_w = 0.999$.

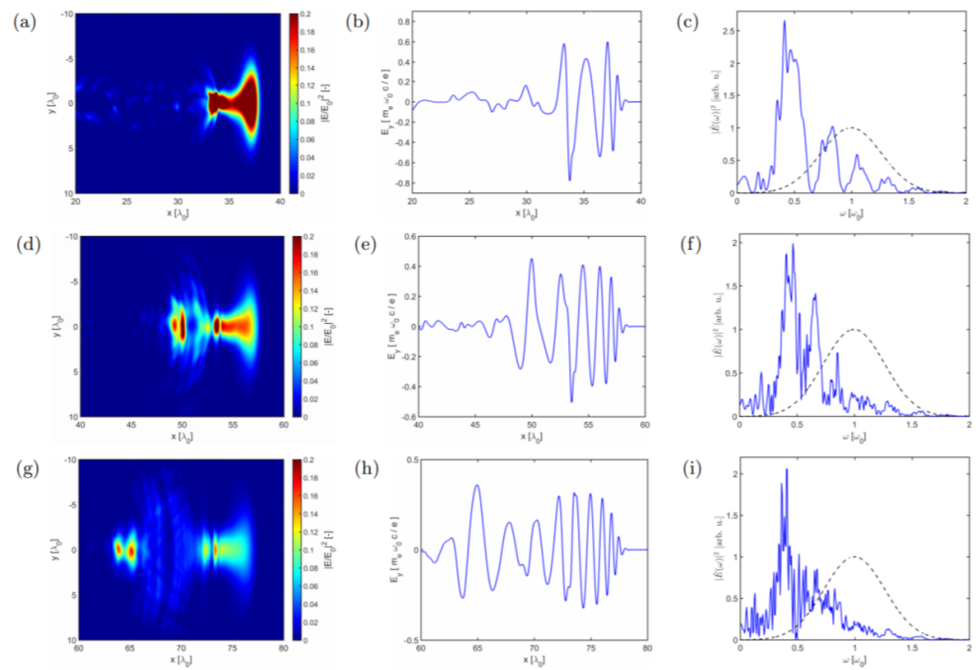


Figure 3: (a), (d), (g) Snapshots of the laser field $|E/E_0|^2$, (b), (e), (h) line-out along the axis $y = 0$ of the transverse electric field E_y and (c), (f), (i) the corresponding on-axis spectrum of the laser pulse at three successive time instants (a), (b), (c) $t = 40\ T_0$, (d), (e), (f) $t = 60\ T_0$ and (g), (h), (i) $t = 80\ T_0$. The dashed lines in (c), (f), (i) represents the initial laser spectrum.

Thank you for the attention!

Summary

- ✓ General view of the actual ELI-Beamlines status and lasers available
- ✓ High Electron Beamlines scheme and implementation on-going (expected to be running in 2020)
- ✓ First electrons accelerated at ELI with L3 laser (100 mJ level)
- ✓ First stable electrons with kHz-class (60 fs) commercial laser by shaped supersonic density profile
- ✓ Generated (ns) plasma channel for pulse guiding
- ✓ Ultrashort laser pulse interaction with nanoparticles for pulse shaping and plasma diagnostics
- ✓ PIC simulations and analytical for near-critical propagation

Carlo Maria Lazzarini
CarloMaria.Lazzarini@eli-beams.eu