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VHGAT: Very High Gradient Acceleration Techniques (WP18)

ARIES KickOff mai 04–05/05,2017 CERN

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Contributions from: **A. Chancé, U. Dorda, C. Thaury, J.Vieira. Thanks!**

JRA VHGAT : workpackage overview

- 24 persons, 6 institutional partners, 10 labs
- 4 tasks:
  - T18.1 Coordination and Communication (**CNRS[1)]**)
  - T18.2 Enabling multi-stage LWFA (**CEA[2)]**, CNRS[3)])
  - T18.3 LWFA with exotic laser beams (**Lisbon**, CEA[4)])
  - T18.4 Laser driven dielectric accelerator **(DESY,** Erlangen)
  - T18.5 Pushing back the charge frontier (**CNRS[5)]**, Lund)
- 5 deliverables
- 4 milestones
  - [1)]LLR Ecole Polytechnique; [2)]IRFU/SACM; [3)]LLR Ecole Polytechnique, LULI Ecole Polytechnique, LPGP U Paris Sud; [4)]IRAMIS/LIDYL; [5)]LOA ENSTA

JRA VHGAT : WP tasks

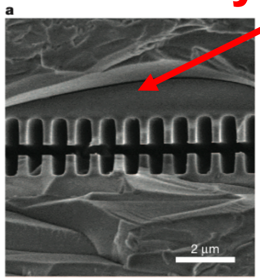
- T18.1 Coordination and Communication — ***paper***
- T18.4 Laser driven dielectric accelerator — ***vacuum***
- T18.2 Enabling multi-stage LWFA
- T18.5 Pushing back the charge frontier
- T18.3 LWFA with exotic laser beams

} ***plasma*** *(LWFA)*

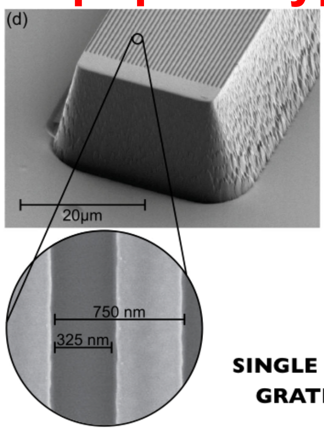
Laser driven dielectric accelerator (T18.4)

- Main Idea: Acceleration of e^- in a high gradient laser field
- Problem: Lawson-Woodward theorem: *Net acceleration of particles in a free-space mode is not possible!*
  J. D. Lawson, IEEE Trans. Nucl. Sci. NS-26, 4217 (1979). P. M. Woodward, J. Inst. Electr. Eng. **93**, 1554 (1947).
- Solution: "Break" assumptions of LW-theorem
  - (Plasma acceleration: Non-linear ponderomotive force)
  - DLA: Introduce boundary conditions

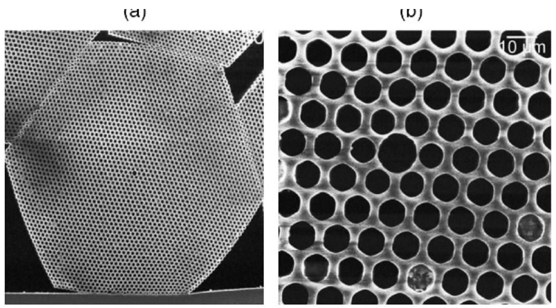
currently most popular type



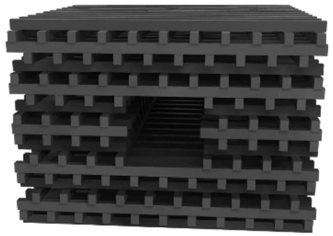
DUAL LAYER GRATING[1]



SINGLE LAYER GRATING[2]



HOLLOW-CORE FIBER[3]



WOODPILE[4]

1. Peralta, E. A. et al. **Demonstration of electron acceleration in a laser-driven dielectric microstructure.** *Nature* **503,** 91–94 (2013).
2. Breuer, J., Hommelhoff, P. et al. **Dielectric laser acceleration of nonrelativistic electrons at a single fused silica grating structure: Experimental part.** *PRST- Accelerators and Beams* **17,** 021301 (2014).
3. Noble, R. J., Spencer, J. E. & Kuhlmey, B. T. **Hollow-Core Photonic Band Gap Fibers for Particle Acceleration**. *Phys. Rev. ST Accel. Beams* **14,** 121303 (2011).
4. Cowan, B. M. *et al.* **Full-scale simulations of dielectric laser-driven accelerators**. in 113–114 (IEEE, 2014).

Laser driven dielectric accelerator: principle

- laser illuminates a dielectric structure from the side.
- material acts in a central channel as a phase-reset mask
- electron bunch moves orthogonal and gains net energy due to the interaction with the fundamental spatial harmonic

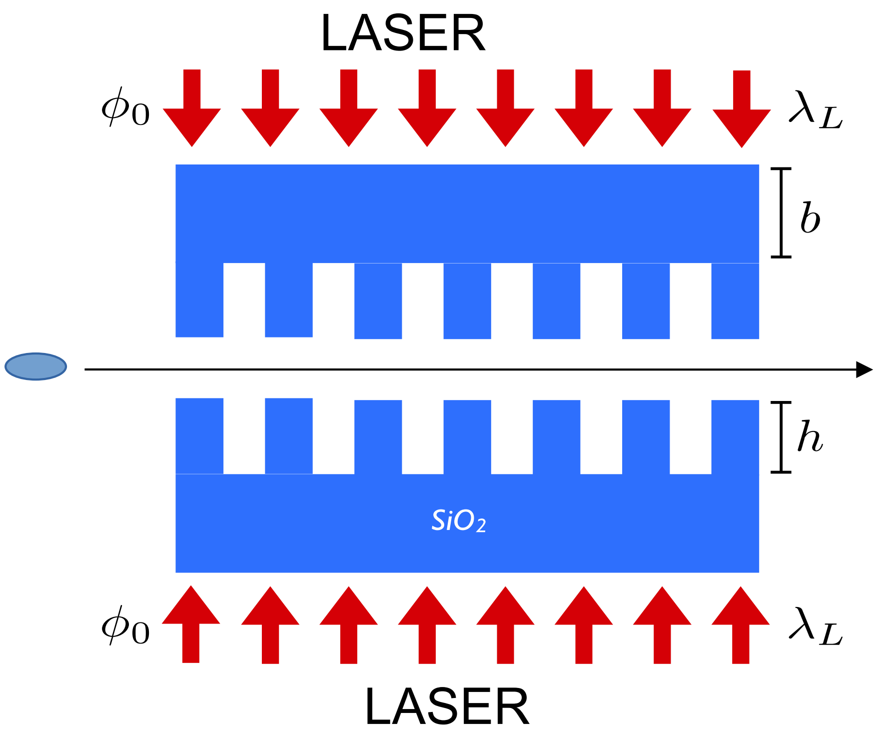


Fig: DLA-concept

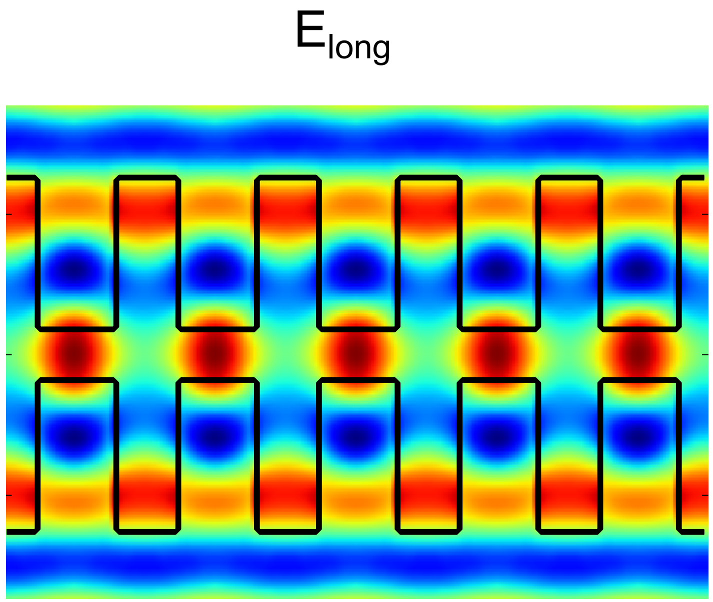


Fig: Field simulation

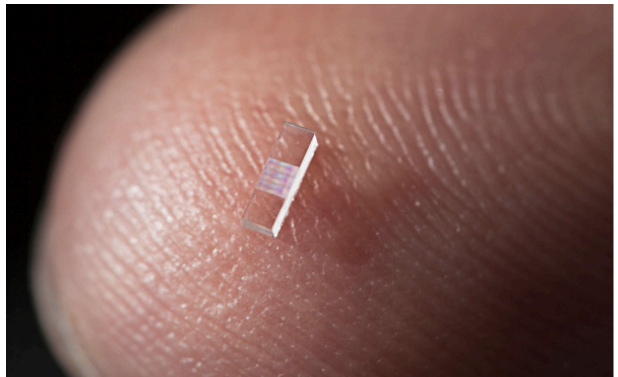
Laser driven dielectric accelerator: goals

- Lasers
  - typically 2 um
  - Low power lasers used→ high rep rate possible
- Current status:
  - Concept proven experimentally with few 10ns of keV electron gain
  - Available externally injected bunches very long → energy modulation experiments only
  - Often eternal bunches even longer than laser pulse → only part of the bunch is modulated.
- Our Objectives:
  - Design an optimized dielectric structure for a laser driver.
  - Optimization with simulation
  - Production with lithographic methods
  - Perform the beam test at a suitable facility in Europe with an externally injected relativistic beam aiming for 1MeV energy gain.
  - Aim to have the bunch shorter than the bucket

Laser driven dielectric accelerator (18.4)

- Task leader: Ulrich Dorda (DESY)
- Partners: DESY 72 p.m
  Friedrich-Alexander-Uni Erlangen 4 p.m
- Milestone *(MS18.3)*:
  M30: *Final design of the ARIES dielectric structure for relativistic beams*
- Deliverable (D18.4):
  M35: *Design & construction of an ARIES dielectric structure for acceleration of relativistic electron beams*

ACHIP
Accelerator on a Chip International Program



VHGAT Rationale : Laser Wakefield Acceleration

Current Status of LWFA Electron Bunch Properties

Property	State of Art*	Reference	Remarks
Energy	**2 GeV** (± 5%, 0.1 nC) **3 GeV** (±15%, ~0.05 nC) **4 GeV** (±5%, 0.006 nC)	Wang (2013) - Texas Kim (2013) – GIST Leemans (2014) - LBNL	Accelerates from E ≈ 0
Energy Spread	**1%** (@ .01 nC, 0.2 GeV) **5-10%**	Rechatin (2009a) – LOA more typical, many results	0.1% desirable for FELs & colliders
Normalized Trans-verse emittance	~ **0.1 π mm-mrad**	Geddes (2008) - LBNL Brunetti (2010) - Strathclyde Plateau (2012) - LBNL	Measurements at resolution limit
Bunch Duration	~ **few fs**	Kaluza (2010) – Jena (**Faraday**) Lundh (2011) – LOA; Heigoldt (2015) – MPQ/Oxford (**OTR**) Zhang (2016) – Tsinghua	Measurements at resolution limit
Charge	**0.02 nC** @ 0.19 GeV ±5% **0.5 nC** @ 0.25 GeV ±14%	Rechatin (2009b) – LOA Couperus (2017) - HZDR	Beam-loading achieved. FOM: **Q/ΔE** ?
Repetition Rate & Repeatability	~**1 Hz** @ > 1 GeV **1 kHz** @ ~ 1 MeV	Leemans (2014) - LBNL He – UMIch ('15); Salehi ('17) – UMd; Guénot ('17) -- LOA	Limited by lasers & gas targets

*** No one achieves all of these simultaneously!**

• Brunetti, *PRL* **105**, 215007 ('10)

• Rechatin, *PRL* **103**, 194804 ('09b)

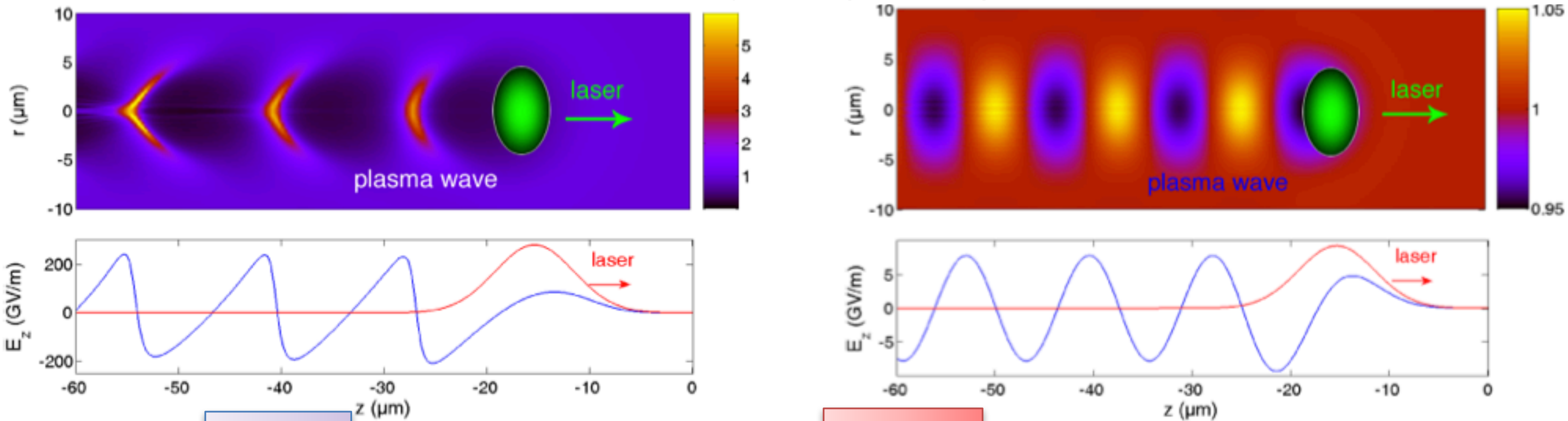
from Mike Downer's talk at ICFA workshop April 25-28, 2017 at CERN
"Advanced and Novel Accelerators for High Energy Physics »

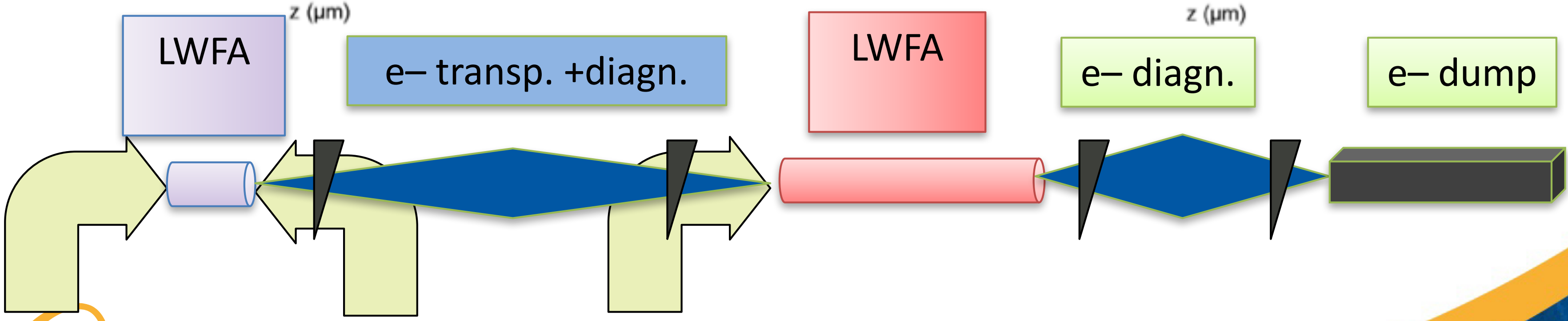
Current Status of LWFA Positron Properties: no results yet

2/31

Enabling multi-stage LWFA (T18.2)

- electron dephasing, laser depletion -> staging of plasma accelerators
- plasma injector O(200MeV) and plasma booster (5-20GeV)
- **coupled by interstage e- transport and diagnostics line**
- part of CILEX e- acceleration program (>2018)

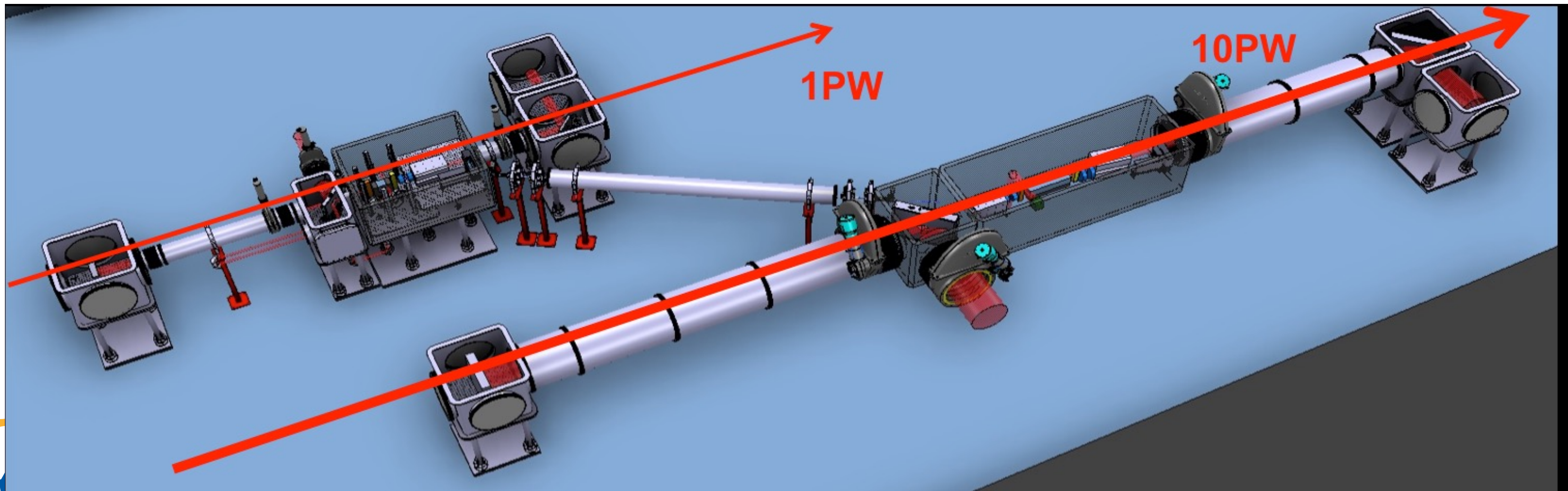




Multi-stage LWFA: design case

- The beam must be transported from the plasma source to the second plasma chamber
- final beam size: few 10s of μm! final beam length: few 10s of fs!
- delivered beam must be stable and synchronous with the second laser
- compactness! footprint = 3 x 6 m

E_{ref}	200	MeV
Charge	10	pC
ϵ_N	1	μm
$\beta_{x,y}$	1	mm
$\alpha_{x,y}$	0	-
$\sigma_{\Delta E/E}$	1	%
σ_t	5	fs



Multi-stage LWFA: challenges

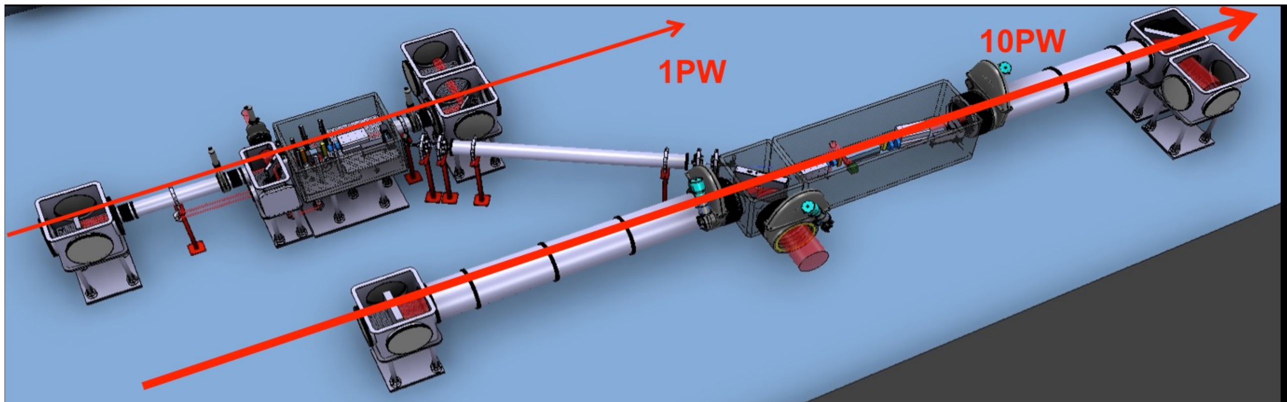
- conservation of initial beam parameters to the second stage:
  - Beam length (fs-scale)
  - Beam normalized transverse emittance
- large energy spread (>1%)
- very low repetition rate (less than 1 Hz):
  - needs non interceptive diagnostics work (beam charge, beam size, beam position,…) at low charge (10s pC).
  - needs new error correction strategy
    - Static errors like misalignment
    - Dynamic errors like laser pointing errors.
- inject to the second plasma chamber with a precision at 10 micrometers level for the beam size and beam position.
- synchronize both stages.
- commission such a line: change of a paradigm
- and many others (CSR, …).

Enabling multi-stage LWFA: work plan

- conceptual and detailed study of a beam transport line suitable for multi-stage LWFA experiment at the CILEX facility
  - Optimization of the line
  - Correction schemes with error tolerance definition
  - Magnet definition
  - Mechanics, alignment procedure,…
- construction, testing and characterization of the inter-stage transport
  - Commisioning with beam characterization
  - Command control
  - Testing and validation

Enabling multi-stage LWFA (18.2)

- Task leader: Antoine Chancé, CEA (IRFU) 10 p.m
- Partners: CNRS (LLR, LULI, LPGP) 19 p.m
- Milestone (MS18.4):
  - *M36: Start of commissioning inter=stage line*
- Deliverables (D18.1 D18.2):
  - *M18: Report containing a detailed design of a compact dogleg transport systems for use in plasma accelerators*
  - *M46: Component procured, inter-stage transport line assembled, elements tested characterized and integrated in the CILEX facility, first beam tests completed*

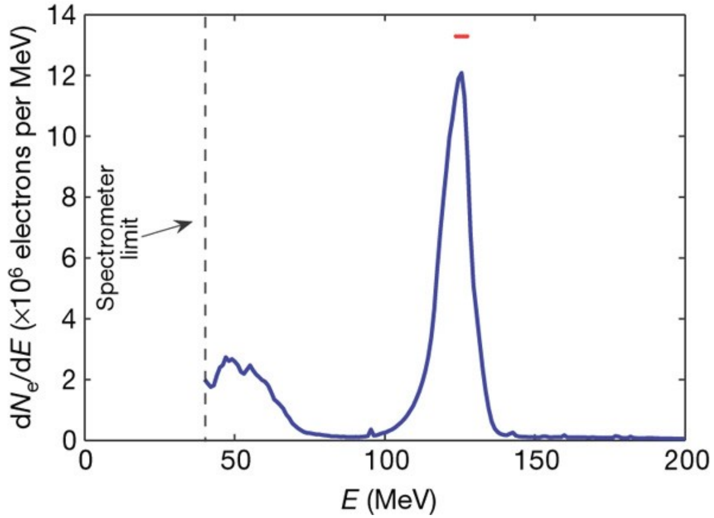


Pushing back the charge frontier (18.5)

Charge density in LWFA accelerators: State of the art (for ~ 1 J laser) **dQ/dE ~ 1-2 pC/MeV with « good » beam quality**

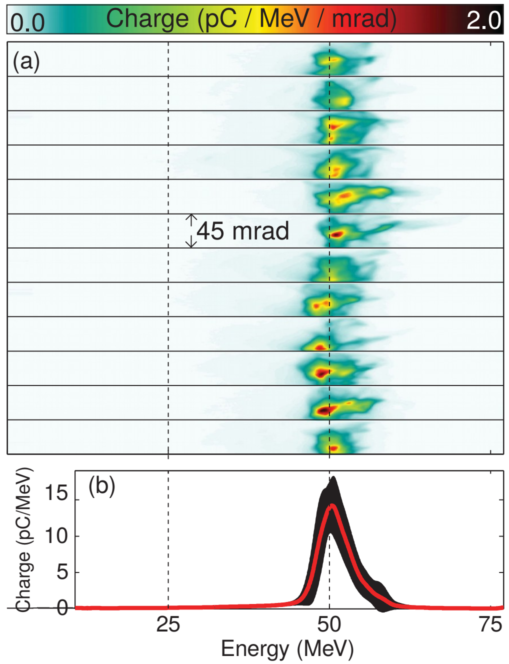
Colliding injection

Faure et al. Nature 444, 737-739 (2006)



Density transition injection

Buck et al. PRL 110, 185006 (2013)



Charge density :	2-4 pC/MeV 0.3-1 pC/MeV/mrad	10-15 pC/MeV 1-2 pC/MeV/mrad

Different laser features, electron spectrometers and calibrations
➡ Comparison should be done with great caution

Charge frontier: recent progress on beam quality

Increasing the charge in density transition injection with a gas mixture

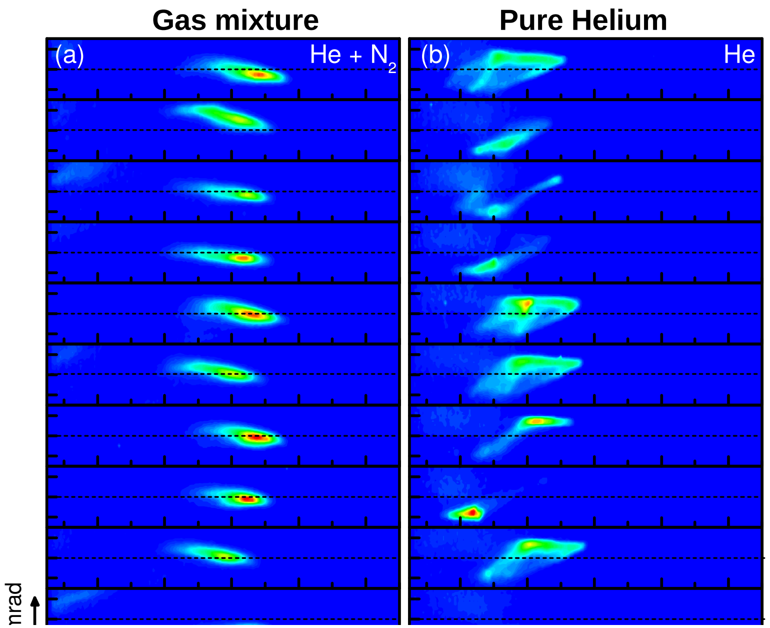
We tried to increase the beam charge by using a gas mixture (Helium-Nitrogen) instead of pure Helium.

RMS Stability
δE/E = 2.5%
δQ/Q = 12%

Pointing
1.5 mrad RMS
(down to 0.7)

Divergence
2.6 x 5 mrad

Energy spread
14 ± 2 MeV



Thaury et al. Scientific Reports **5**, 16310 (2015)

RMS Stability
δE/E = 7%
δQ/Q = 24%

Pointing
3.2 mrad RMS

Divergence
3.2 ± 0.7 mrad

Energy spread
20 ± 10 MeV

The stability is significantly improved but the charge density does not increase with the gas mixture : it remains < 1 pC/MeV

Charge frontier: Work plan

- **Fear 1-2:** We will run 3D Particle-In-Cell **simulations** for understanding in details the physics of density transition injection and then determining the **best plasma density gradient and laser features** for increasing the charge density.
- **Year 1-2 :** Test **new nozzles** for **producing ultrashort (<0.2 mm) plasmas**. These nozzles will serve as **injectors** in a multiple-nozzle scheme. A significant gain in the charge density is expected.
- **Year 1-3 :** Development of **new charge density diagnostics**.
- **Year 3-4 : Experiments** with the optimized setup, according to PIC simulations.

ARIES

Pushing back the charge frontier (18.5)

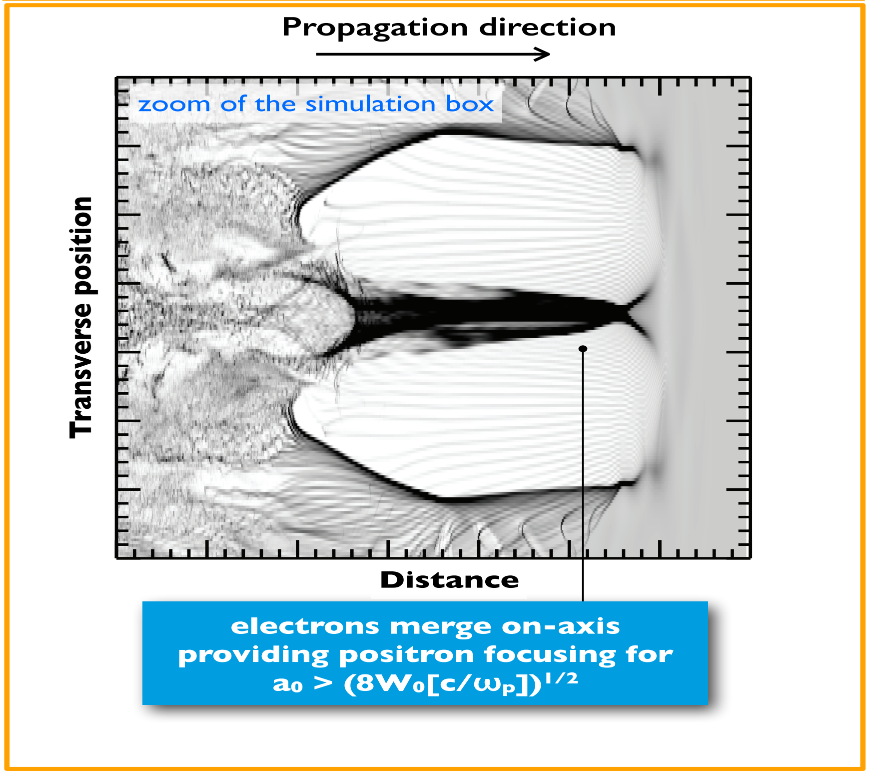
- Task leader: Cédric Thaury ,CNRS (LOA) 15 p.m
- Partner: Lund Laser Center 2 p.m
- Deliverable (D18.5):
  M45: Experimental demonstration on a plasma acceleration test stand of a substantial charge density increase obtained by improving injection techniques, and/or develop new techniques for increasing the beam charge.

LWFA with exotic laser beams: motivation

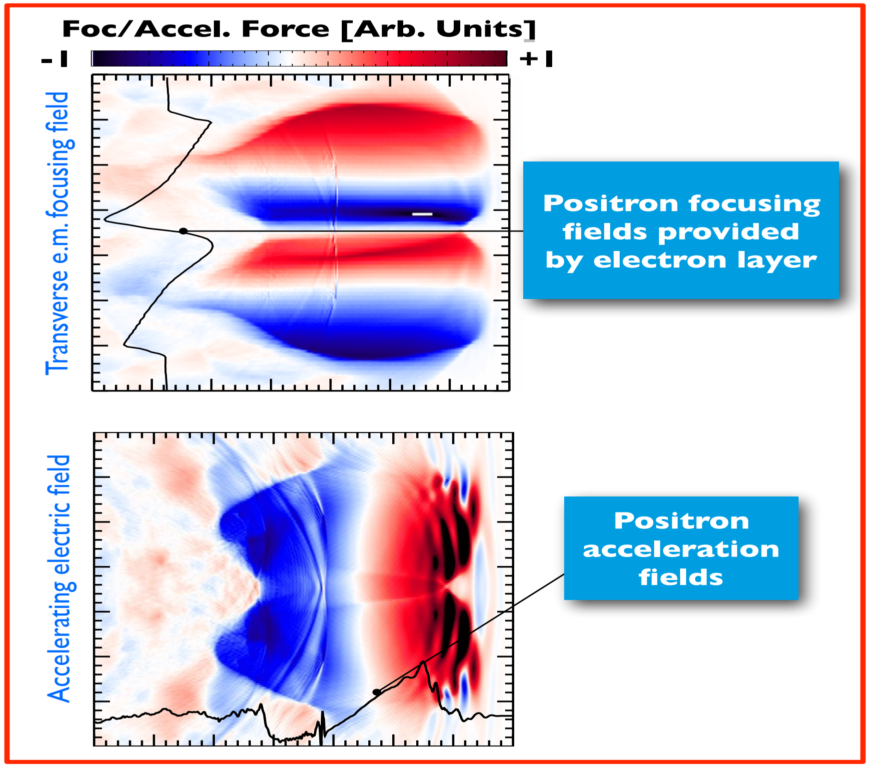
LWFA dougnut bubble : relevant for LWFA of positrons

The onset of positron focusing and acceleration occurs when the inner sheath of the doughnut bubble merges on-axis

Onset of positron focusing



e+ can accelerate at doughnut front

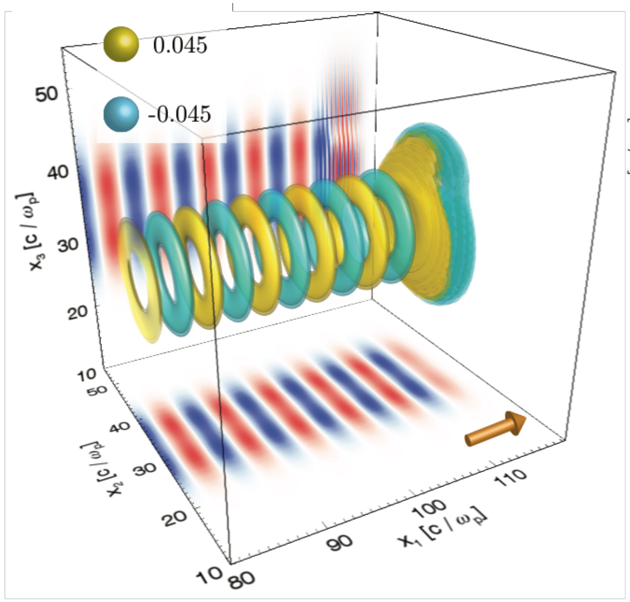


Jorge Vieira | E-AAC Isola d'Elba, Italy | September 15 2015

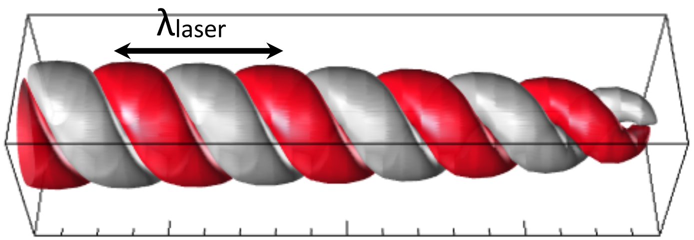
Exotic beams LWFA: motivation&recent progress

Wakefield driven by OAM lasers

doughnut plasma waves contain no OAM

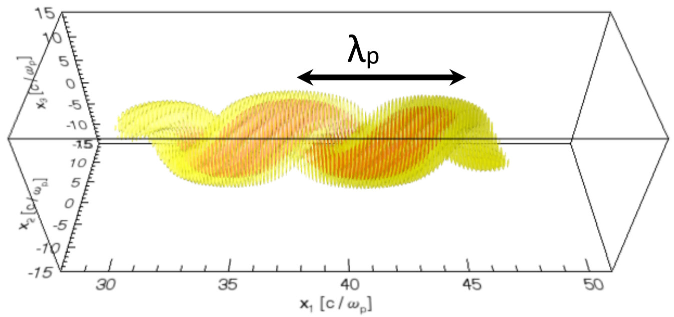


electrons insensitive to **ultra-short** light twists



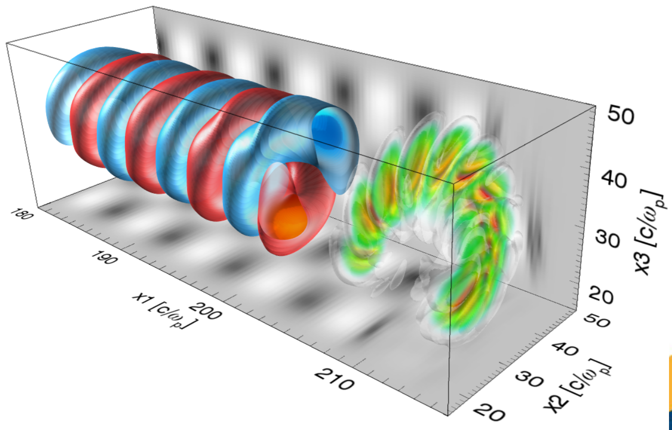
OAM plasma waves

Driver with OAM in intensity profile



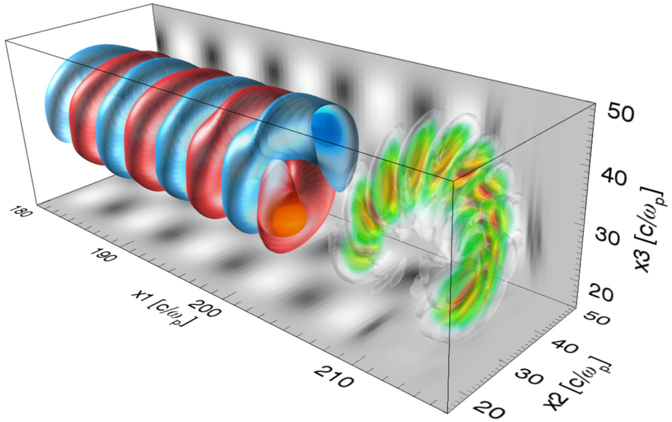
G. Pariente, F. Quéré, Opt. Lett. 40 2037 (2015)

OAM plasma wave



J.Vieira *et al.* in preparation (2017).

Exotic beams LWFA: recent advances



- Theory:
  - Wake excitation theory
  - Trapping conditions
  - Formulas for energy gain
  - Good agreement with simulations
  - Dynamics of the light spring laser in a parabolic plasma channel
  - Phase velocity of the plasma wave
  - Production of helical electron/positron bunches
  - Writing manuscript J.Vieira, F. Quéré et al. (2017)
- Next steps:
  - Complete paper and submit manuscript
  - Explore radiation

LWFA with exotic laser beams (18.3)

- Task leader: Jorge Vieira (IST Lisbon) 36 p.m
- Partners: CEA/LIDYL 10 p.m
- Milestones (MS18.2, MS18.3)
  - *M6: Setup simulation framework for acceleration and radiation generation in wakefields driven by lasers with orbital angular momentum (Lisbon)*
  - *M12: Setup of experimental facilities for laser wakefield acceleration experiments using laser drivers with orbital angular momentum*
- Deliverable (D18.3)
  - *M36: Report on simulations of particle acceleration in plasma waves driven by exotic lasers with orbital angular momentum with corresponding radiation signatures and experiments on particle acceleration and radiation generation using intense vortex light beams*

JRA VHGAT : Deliverables and Milestones

D18.1	***Enabling multi-stage Laser Wakefield Acceleration (LWFA)*** Report containing a detailed design of a compact dogleg transport systems for use in plasma accelerators	M18
D18.2	***LWFA inter-stage transport line completed and tested*** Component procured, inter-stage transport line assembled, elements tested characterized and integrated in the CILEX facility, first beam tests completed	M46
D18.3	***Exotic lasers and vortex light beams*** Report on simulations of particle acceleration in plasma waves driven by exotic lasers with orbital angular momentum with corresponding radiation signatures and experiments on particle acceleration and radiation generation using intense vortex light beams	M36
D18.4	***Dielectric structure*** Design & construction of an ARIES dielectric structure for acceleration of relativistic electron beams	M35
D18.5	***Pushing back the charge frontier*** Experimental demonstration on a plasma acceleration test stand of a substantial charge density increase obtained by improving injection techniques, and/or develop new techniques for increasing the beam charge	M45

MS18.1	Setup simulation framework for acceleration and radiation generation in wakefields driven by lasers with orbital angular momentum	M6
MS18.2	Setup of experimental facilities for laser wakefield acceleration experiments using laser drivers with orbital angular momentum	M12
MS18.3	Final design of the ARIES dielectric structure for relativistic beams	M30
MS18.4	Start of commissioning interstage line	M36