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Finale Review Meeting
WP18: VHGAT
Very High Gradient Acceleration Techniques

July 15, 2022

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Contributions from and thanks to: B.Bolzon, , A.Chancé, S.Dobosz, J.Schwindling, U.Dorda, F.Lemery, F.Quéré , C.Thaury, J.Vieira

JRA VHGAT : WP tasks

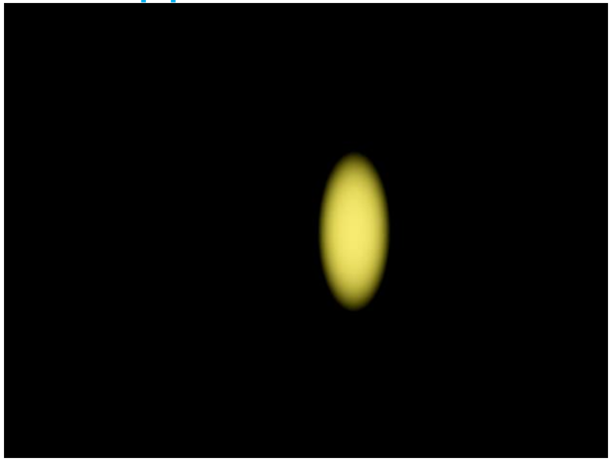
4 (physics) tasks, largely independent

- T18.1 Coordination and Communication *on paper*
  (A.Specka, CNRS[1)])
- **T18.2 Enabling multi-stage LWFA** ***in a plasma***
  (A. Chancé, CEA[2)], CNRS[3)]) **reformulated, completed**
- **T18.3 LWFA with exotic laser beams** ***in a plasma***
  (J. Vieira, Lisbon, CEA[4)]) **completed**
- **T18.4 Laser driven dielectric accelerator** ***in vacuum***
  (F. Lemery, DESY, Erlangen) **completed**
- **T18.5 Pushing back the charge frontier** ***in a plasma***
  (C. Thaury, CNRS[5)], U Lund) **completed**

[1)]LLR Ecole Polytechnique; [2)]IRFU/SACM; [3)]LLR Ecole Polytechnique,
3)LULI Ecole Polytechnique, LPGP U Paris Sud; [4)]IRAMIS/LIDYL; [5)]LOA ENSTA

Motivation for Very High Gradient Acc° Techniques

- Novel accelerator techniques promise:
  - path to highest energy at bearable accelerator size
  - smaller (thus mor economic) accelerators for applications
- Many VHGAT approaches successfully demonstrated
  - **laser-driven plasma**
  - acc-driven plasma
  - **dielectric laser (in vacuum)**



- Many challenges:
  - multiple acceleration stages → T18.2
  - acceleration of positrons, radiation sources → T18.3
  - extreme miniaturization → T18.4
  - increase the bunch charge (narrow E band, narrow angle) → T18.5

JRA VHGAT : Deliverables and Milestones

MS18.1	**exotic beams**	Setup simulation framework for acceleration and radiation generation in wakefields driven by lasers with orbital angular momentum	**M6**	✓
MS18.2	**exotic beams**	Setup of experimental facilities for laser wakefield acceleration experiments using laser drivers with orbital angular momentum	**M12**	✓
D18.1	**multistage**	Report containing a detailed design of a compact dogleg transport systems for use in plasma accelerators	**M18**	✓
MS18.3	**dielectric**	Final design of the ARIES dielectric structure for relativistic beams	**M30**	✓
D18.4	**dielectric**	Design & construction of an ARIES dielectric structure for acceleration of relativistic electron beams	**M35**	✓
MS18.4	**multistage**	Start of commissioning interstage line	**M36**	⊖
D18.3	**exotic 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**	✓
D18.5	**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~~** **M54**	✓
D18.2	**multistage**	detailed design study, requirement revue analysis, tolerance study, magnet design study , beam diagnostics study, PBS,	**~~M46~~** **M54**	✓

Publications and conference contributions

- **DLA**
  - L. Genovese et al.: Tolerance studies and limitations for photonic bandgap fiber accelerators, Proc. IPAC'19 (DOI: 10.18429/JACoW-IPAC2019-THPGW014)
  - F. Mayet et al.: Status report on the dielectric laser acceleration experiments at the SINBAD/ARES linac, Poster Presentation, EAAC'19
  - F. Mayet et al.: Simulation of a passive longitudinal phase space synthesizer concept based on 3D-printed dielectric-lined waveguides, Poster Presentation, EAAC'19
  - W. Kuropka et al.: Parameter studies on dielectric gratings as electron accelerators, Poster Presentation, EAAC'19
  - M. Kellermeier et al.: Towards additive manufacturing of dielectric accelerating structures, EAAC'19
- **Exotic beams:**
  - J. Vieira, M. Pardal, J.T. Mendonça, R.A. Fonseca, Generalized superradiance for producing broadband coherent radiation with transversely modulated arbitrarily diluted bunches, **Nature Physics** 17, pages 99–104 **(2021)**
  - T. Silva et al, Stable Positron Acceleration in Thin, Warm, Hollow Plasma Channels, Phys. Rev. Lett. 127, 104801 (2021).
  - J. Vieira, M. Pardal, J.T. Mendonça, R.A. Fonseca, Generalised superradiance in diluted media, **Nature Physics** (under review)
  - J. Vieira, J.T. Mendonça, F. Quéré, Phys. Rev. Lett. 121, 054801 (2018)
  - J. Vieira et al, *Superradiant nonlinear Thomson scattering*, contributed oral, 61st APS-DPP meeting October (2019).
  - J. Vieira et al, Radiation emission from twisted plasma acceleration, contributed poster, 46th EPS Conference on Plasma Physics (2019).
  - J. L. Martins et al, Radiation emission in laser-wakefields driven by structured laser pulses with orbital angular momentum, Scientific Reports **9**, 9840 (2019).
- **Charge Frontier:**
  - Slava Smartsev, Clément Caizergues, Kosta Oubrerie, Julien Gautier, Jean-Philippe Goddet, Amar Tafzi, Kim Ta Phuoc, Victor Malka, and Cédric Thaury, "Axiparabola: a long-focal-depth, high-resolution mirror for broadband high-intensity lasers," Opt. Lett. **44**, 3414-3417 (2019)
  - A. Döpp, C. Thaury, E. Guillaume, F. Massimo, A. Lifschitz, I. Andriyash, J. -P. Goddet, A. Tazfi, K. Ta Phuoc, V. Malka, «Energy-chirp compensation in laser wakefield accelerators Phys. Rev. Lett. 121, 074802 (2018)
  - Adeline Kabacinski1, Kosta Oubrerie, Jean-Philippe Goddet, Julien Gautier,Fabien Tissandier, Olena Kononenko, Amar Tafzi, Adrien Leblanc, Stéphane Sebban, Cédric Thaury, "Measurement and Control of Main Spatio-TemporalCouplings in a CPA Laser Chain", accepted in Journal of Optics ,2021

Enabling multi-stage LWFA (T18.2)

- Task leader: **Antoine Chancé (CEA Saclay)**
- Partners: CEA (IRFU)
  CNRS (LLR,LULI,LPGP)

Replacement Deliverable (D18.2): :
Modified deliverable description D18.2 (M54=oct 2021) :

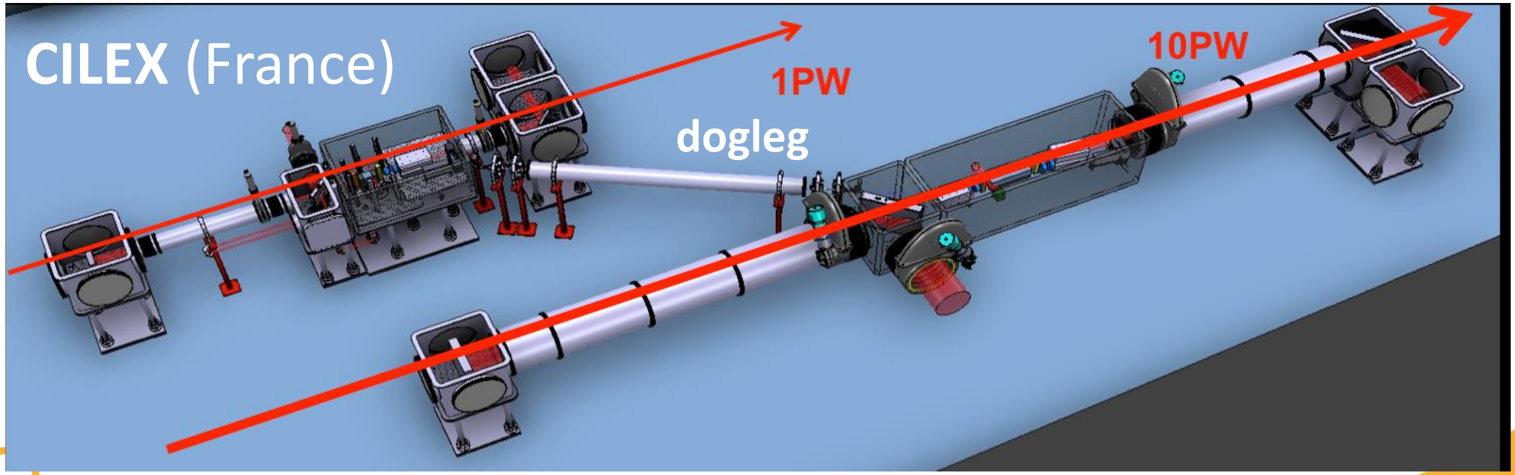
Design and tolerance analysis of interstage transport and diagnostics line for 200 and 300 MeV completed. ✓

Alignment and component tolerance study completed. Mechanical design completed, and documented in writing and drawing. Product breakdown structure documented. Beam diagnostics study and specification completed. ✓

T18.2: Enabling multi-stage LWFA - Introduction

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

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

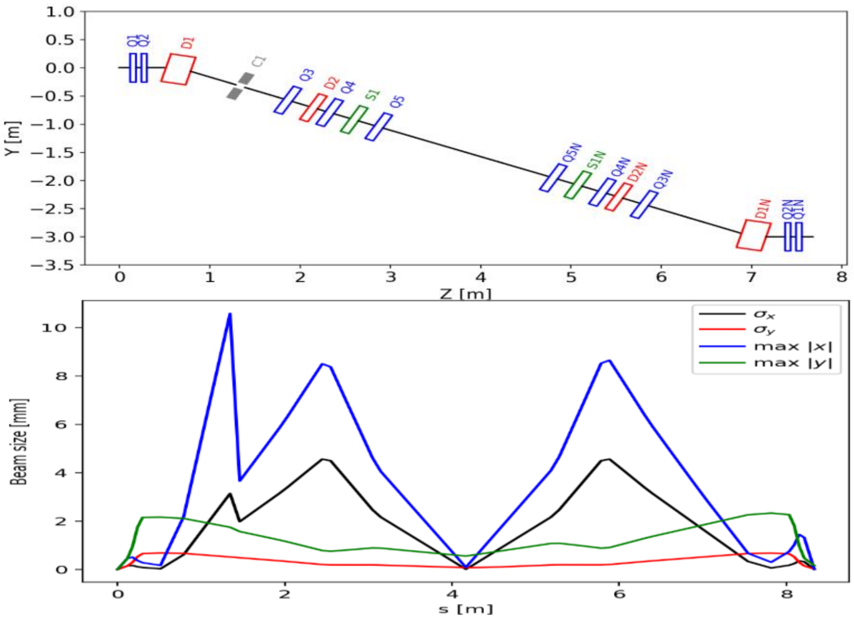


T18.2: Replacement Deliverable Report (37p)

Purpose: Transport baseline design of instrumented dogleg as starting point for potential future implementation

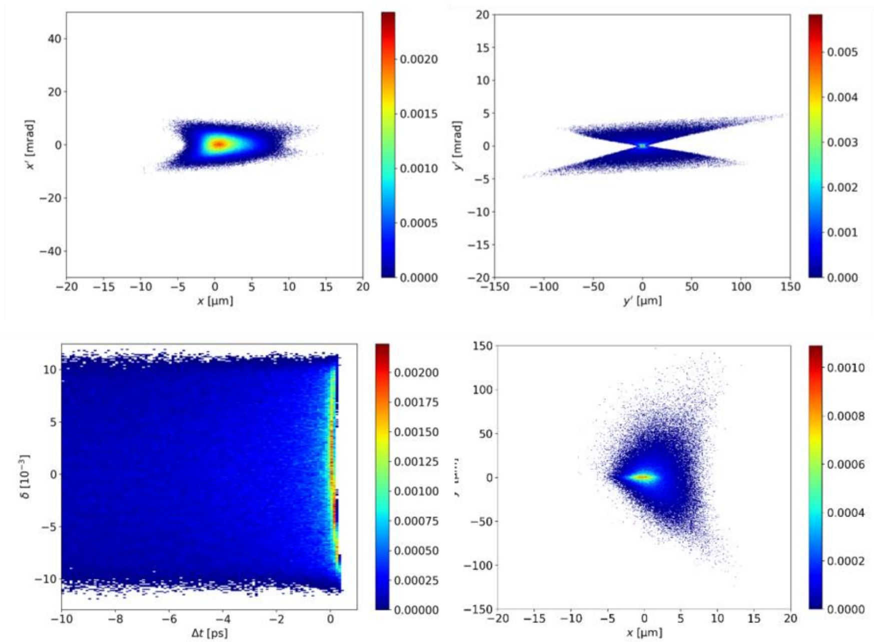
T18.2 Design of dog-leg injection line for 2 stage experiments

FULL BEAM DYNAMICS DESIGN:
3M X 6M FOOTPRINT



<u>Achromatic</u>: reduced momentum dependence
<u>Stigmatic</u>: point-to-point imaging
<u>Isochronous</u>: keep pulse duration

TOLERANCE STUDY:
SENSITIVITY OF THE LINE TO ERRORS



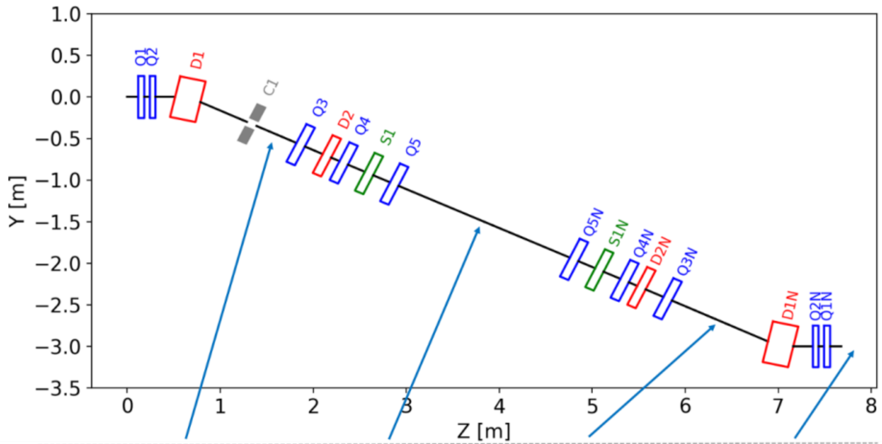
initial position error should be < 10 μm
to keep the final position offset < 10 μm
initial angular error should be < 5 mrad
to keep the final position offset < 10 μm

ARIES

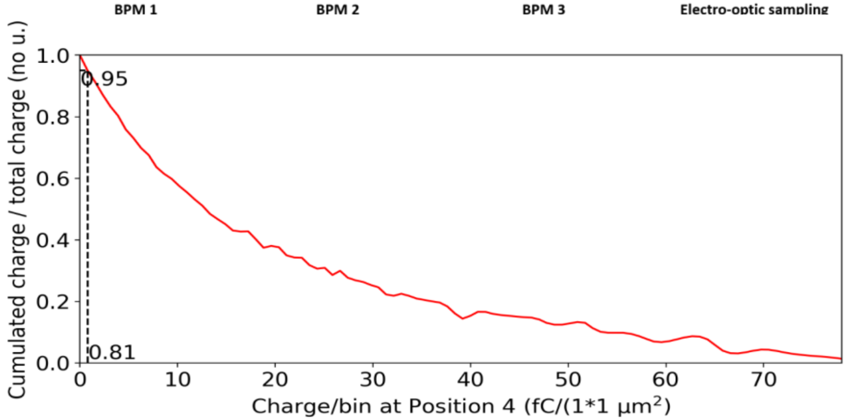
T18.2 beam diagnostics study

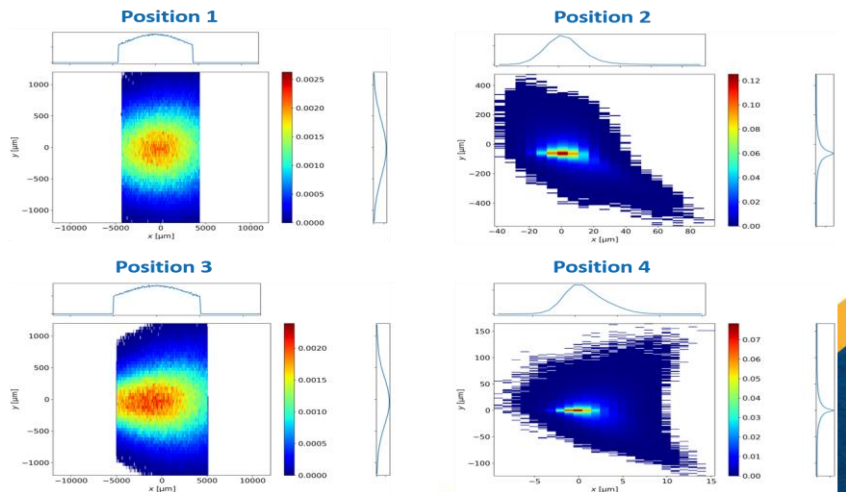
- **1st step:** require more robust and wide-range diagnostics
- **2nd step:** require more accurate diagnostics and a restricted operation range (more complex to implement)

Beam parameters to be measured		Type of diagnostics	Number of diagnostics	Location of diagnostics
Charge		Turbo ICT	Minimum 2	Just downstream the slits and at the end of the transfer line
		Possibly Faraday Cup	1	At the end of the transfer line
Position	1st step	Imaging system: Lanex, YAG, OTR	Minimum 3	At the beginning, at the middle, and at the end of the line
	2nd step	BPMs (cavity or stripline, TBD)	Minimum 3	At the beginning, at the middle, and at the end of the line
Transverse profile		Use of the same systems as for position measurement at 1st step		
Mean Energy / energy spread		Variable dipole + large 1 inch' screens (stage)	Minimum 1	Middle of the transfer line (in the drift)
Transverse emittance	1st step	Energy-scan: use of the same system as for energy measurement + 2 quadrupoles (magnets already existing in the conception of the line)		
	2nd step	Multiple OTR screens or Pepper-Pot, … TBD	1? (cumbersome)	Middle of the transfer line (in the drift)
Longitudinal profile	1st step	Coherent transition; Pyroelectric detector	Minimum 3? (cost)	In front of a screen of each translation stage
	2nd step	Electro-Optic Sampling	TBD	TBD



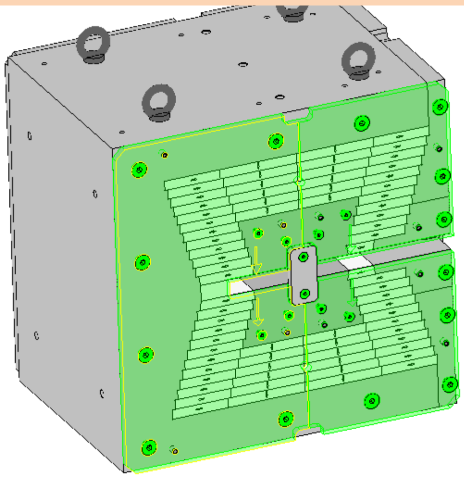
Position	1	2	3	4
1st step	Turbo ICT 1 Imaging system 1 Pyroelectric detector 1	Turbo ICT 2 Imaging system 2 Pyroelectric detector 2	Turbo ICT 3 Imaging system 3 Pyroelectric detector 3	Imaging system 4 Pyroelectric detector 4
	BPM 1	BPM 2	BPM 3	Electro-optic sampling

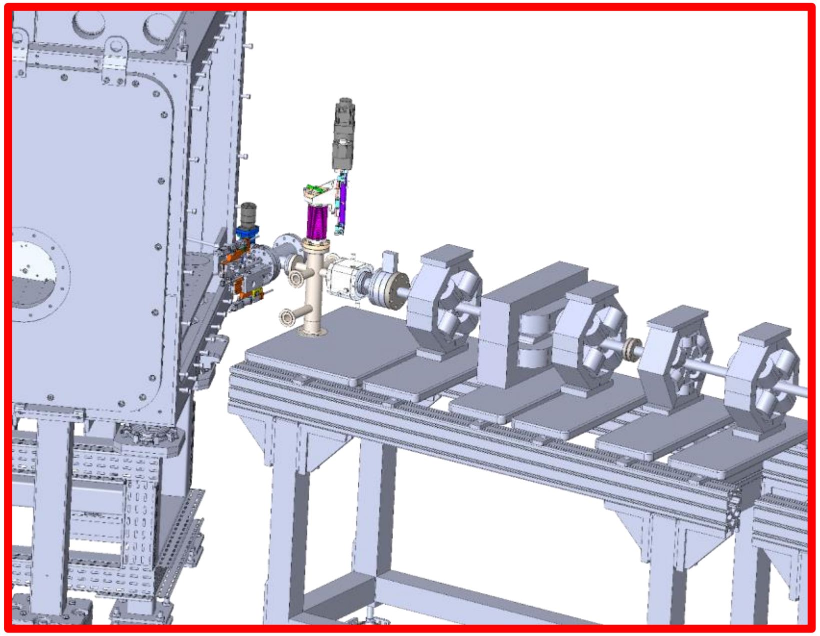


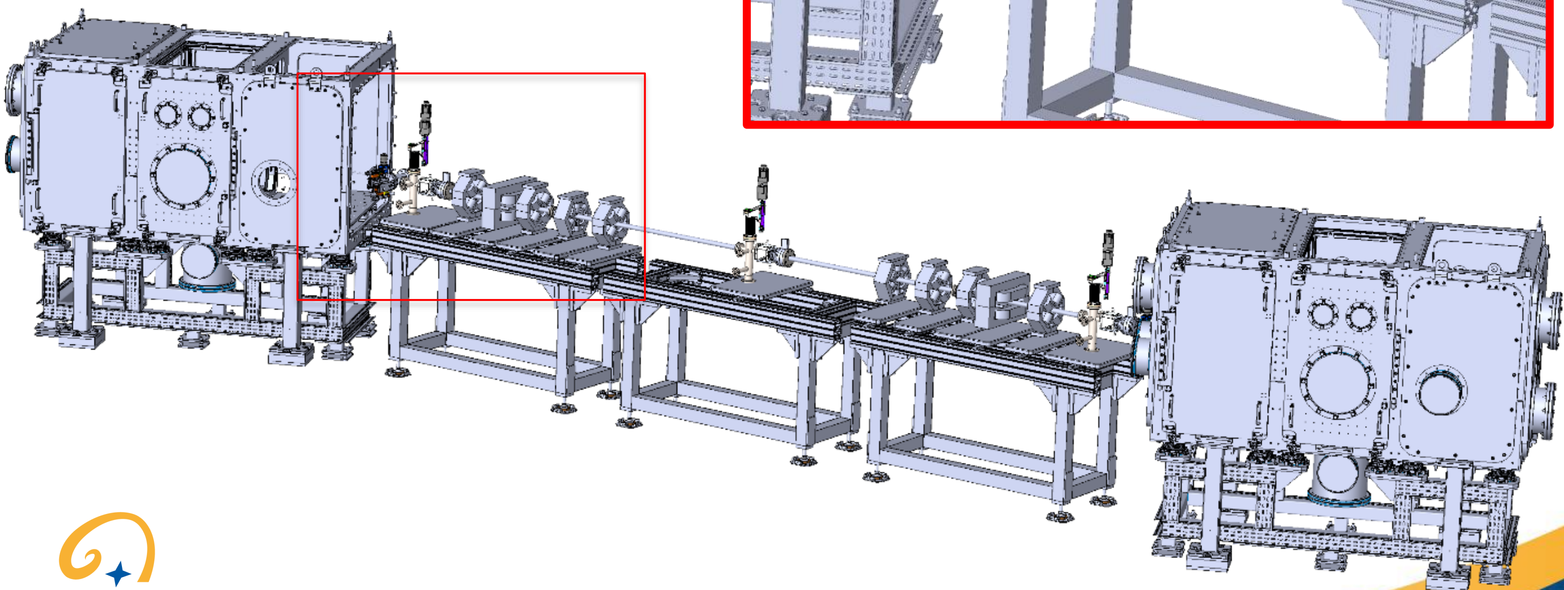


T18.2: mechanical design + magnet design

0.42 Tesla.meter permanent dipole magnet







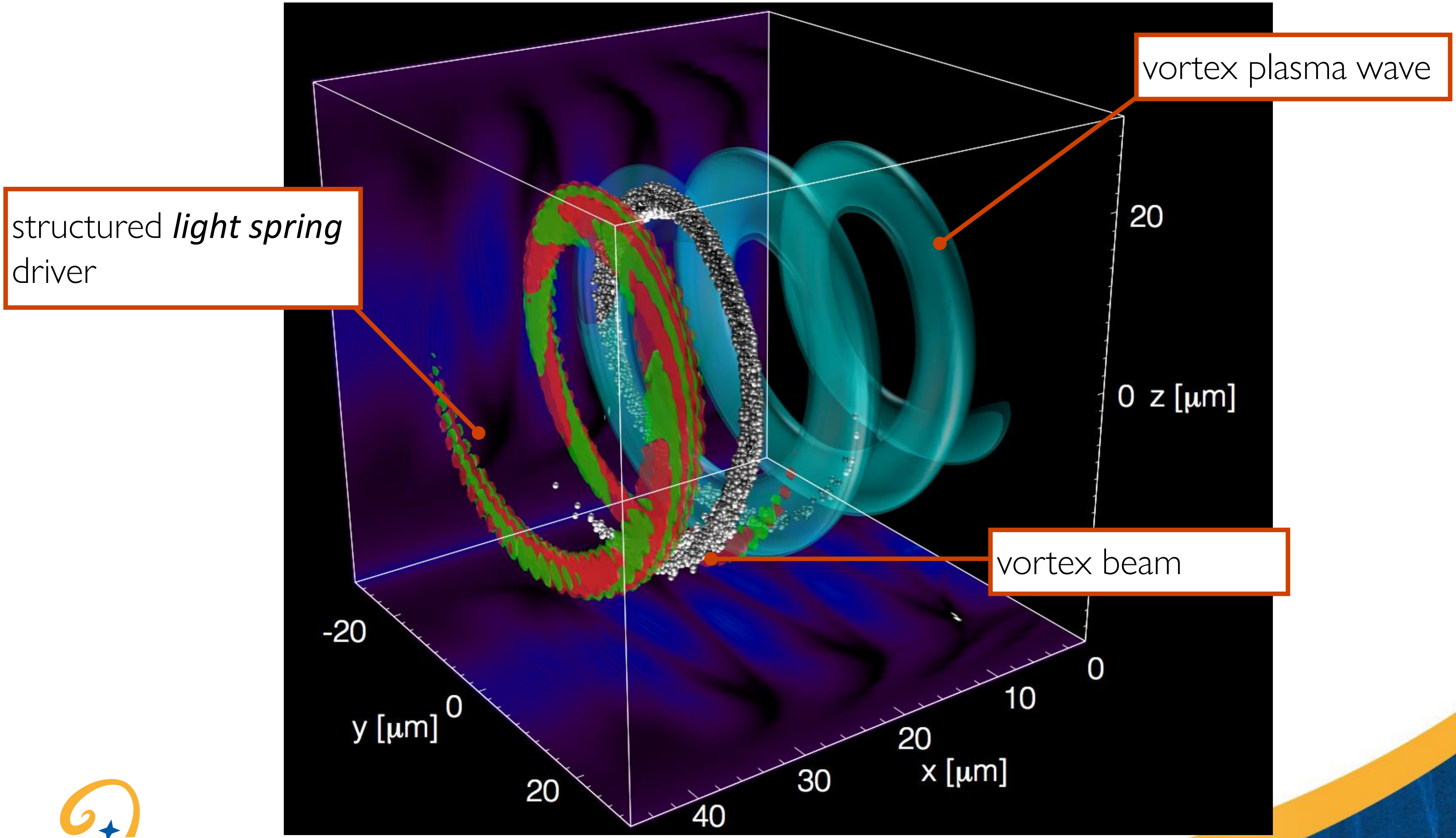
LWFA with exotic laser beams (T18.3)

- 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* ✓

T18.3: Exotic laser beams for acceleration

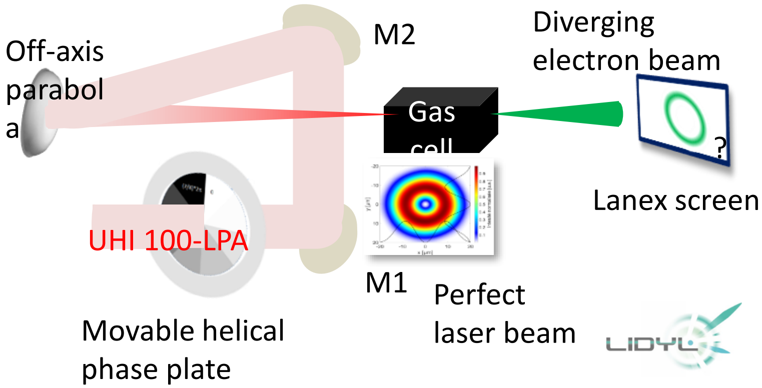
J. Vieira, J. T. Mendonça, F. Quéré PRL'18

"donut" beams, beams w/ orbital ang. mom. , "light springs",

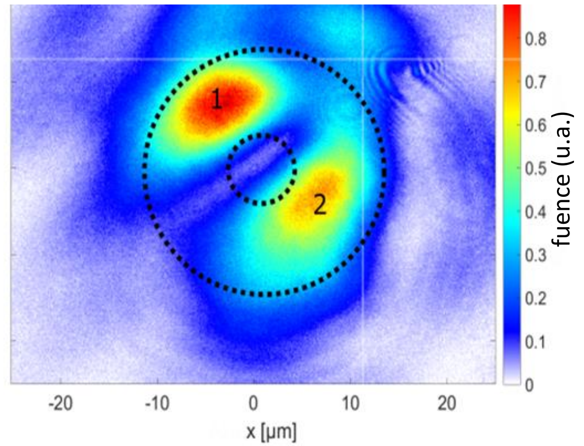


T18.3: LWFA experiment with OAM beam

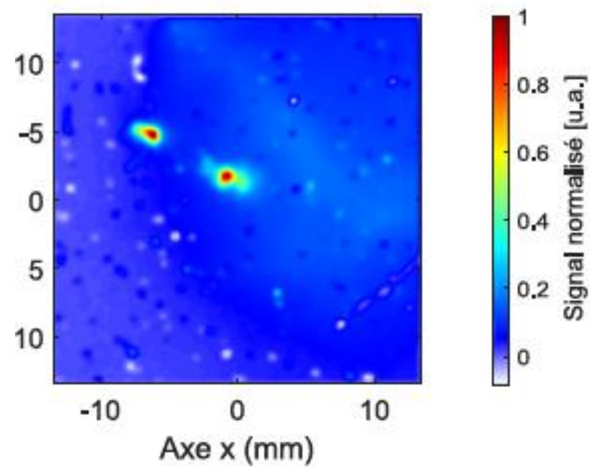
- MS64: Setup of experimental facilities for laser wakefield acceleration experiments using laser drivers with orbital angular momentum (OAM)
- Exotic beam with orbital angular momentum→ **Laguerre-Gauss beam**



Real experimental focal spot with **helical phase plate**

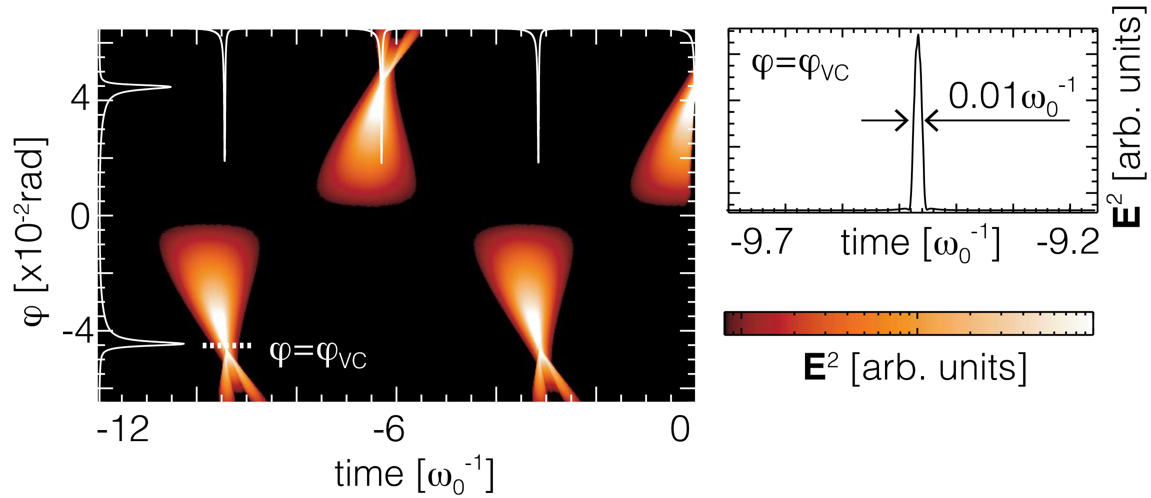


2 electron beams for more than 50% of the shots



T18.3: Radiation by exotic beams: result

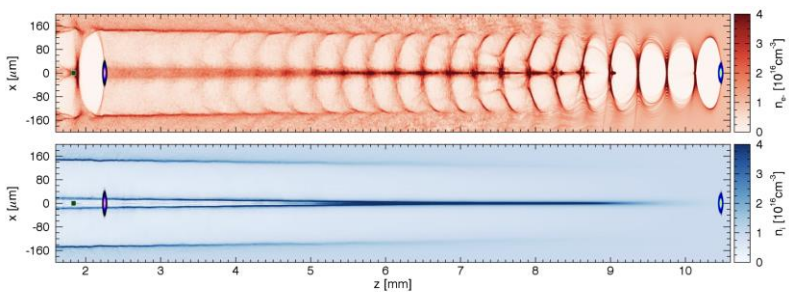
- Results produced using the **new radiation tools produced under ARIES.**
- slice of the radiated profile: superradiant peaks
  typical duration of the radiation spikes can be in the THz (in 1T B-field) but also x-Ray and Gamma-ray regions of the spectrum (plasma wake)
- can be achieved with arbitrarily dilute beams modulated at frequencies much lower than the radiated frequencies.

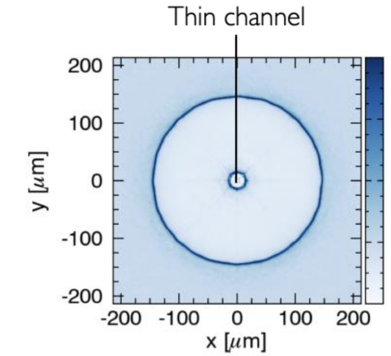


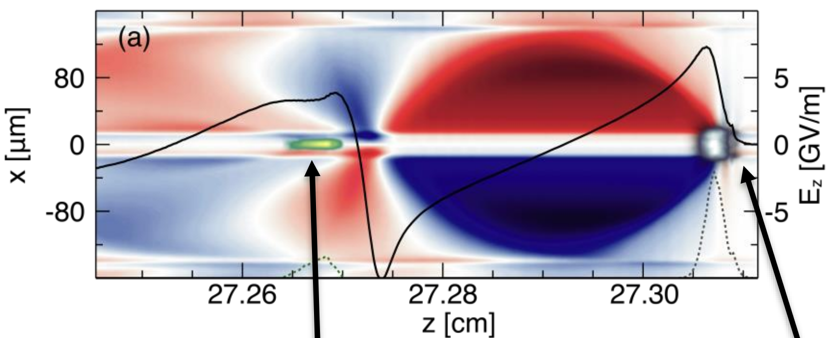
J. Vieira, M. Pardal, J.T. Mendonça, R.A. Fonseca, Generalised superradiance in diluted media, Nature Physics (under review)

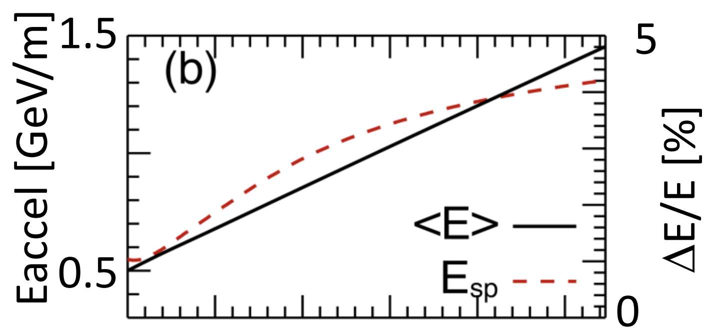
T18.3: Simulation of acceleration in hollow channels

- Use an initial electron bunch to drive a plasma wave in the blowout regime. Hollow plasma channel appears as a result of long term plasma dynamics
- Use a second driver to drive a wakefield in the hollow channel, which is suitable for stable **electron and positron** acceleration.









positron witness bunch electron bunch driver

T. Silva, L. D. Amorim, M. C. Downer, M. J. Hogan, V. Yakimenko, R. Zgadzaj, and J. Vieira, Stable Positron Acceleration in Thin, Warm, Hollow Plasma Channels, Phys. Rev. Lett. 127, 104801 (2021)

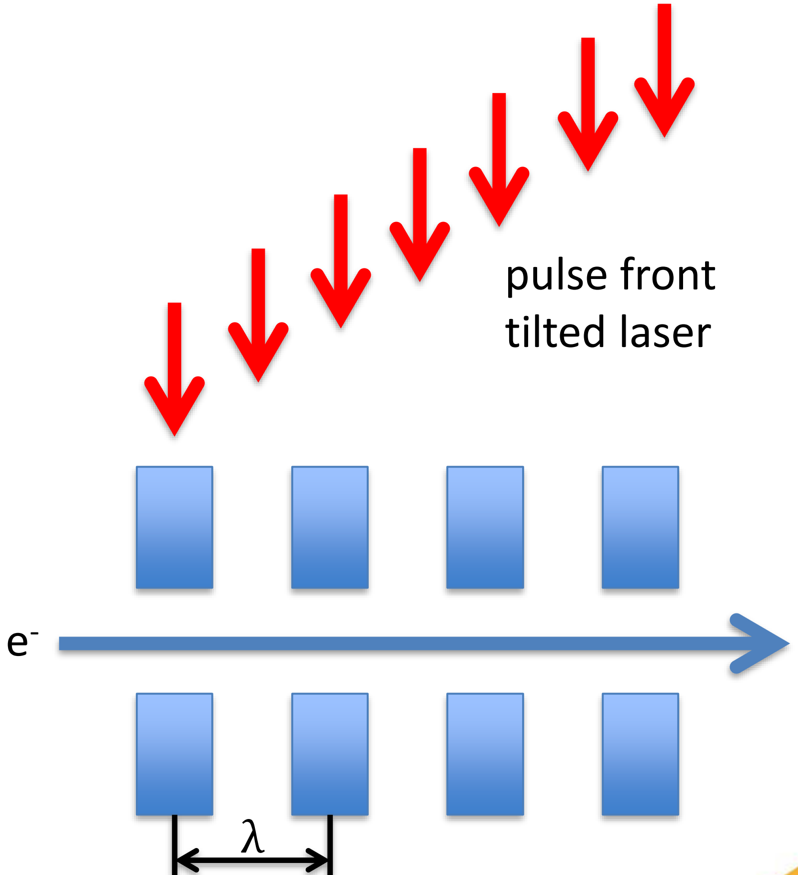
Laser driven dielectric accelerator (T18.4)

- Task leader: **François Lemery** (DESY)
- Partners: DESY
  Friedrich-Alexander-Uni Erlangen
- 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 ✓

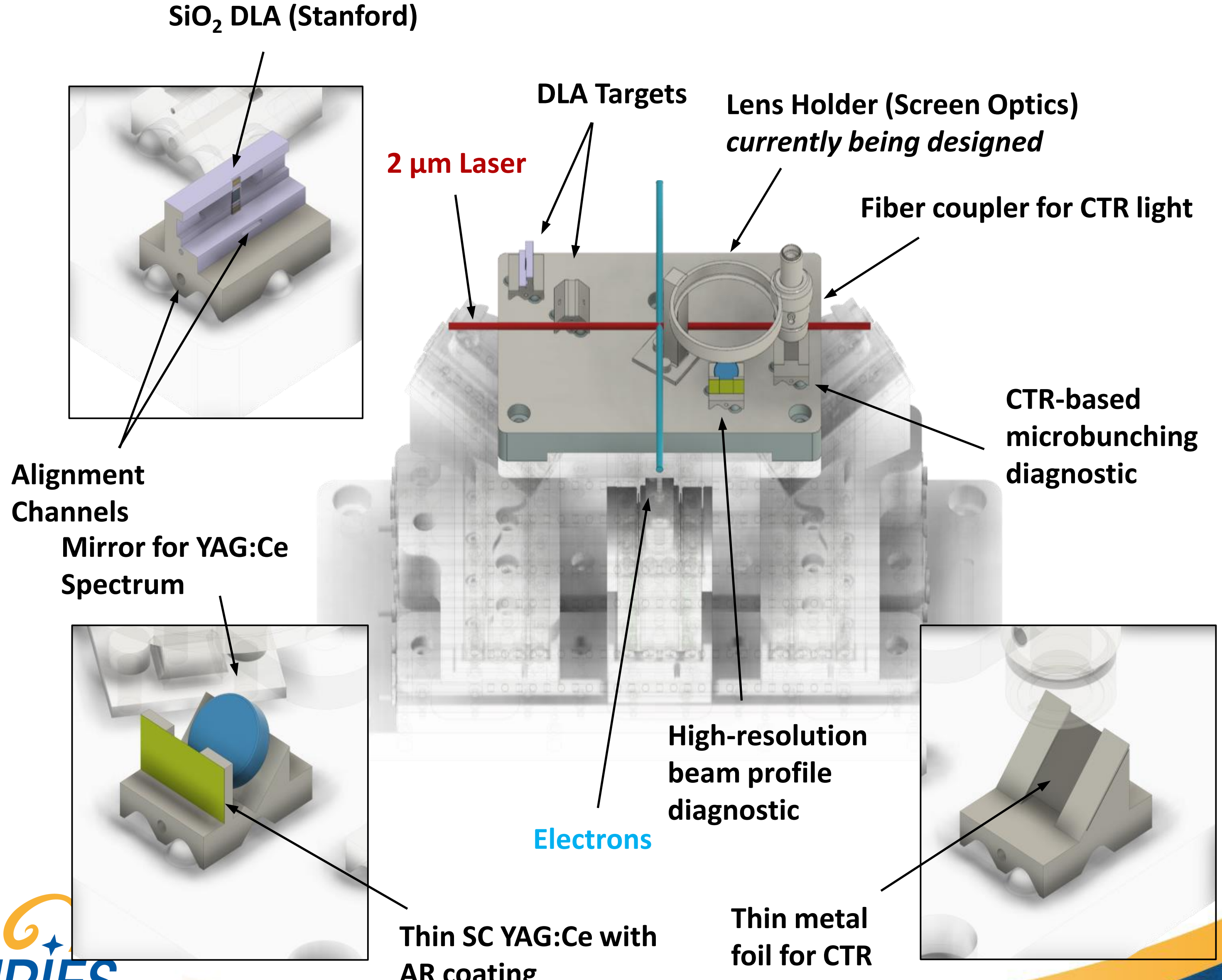
T18.4: Dielectric Laser Acceleration (DLA)

- Estimated achievable parameters for fused silica structure

Laser params	Value
wavelength λ	2050 nm
Pulse length, rms	0.2 ps
Pulse energy	0.7 mJ
Rep. rate	1 kHz
DLA params	
Horizontal focus, rms	1.0 mm (3.3ps)
Vertical focus, rms	50 um
E_{acc}/E_{in}	0.25
Fluence	1.4 J/cm²
Damage Fluence (SiO_2)	~2 J/cm²
using pulse front tilt	
Particle energy gain	~ 1 MeV
Effective gradient	~ 1 GV/m



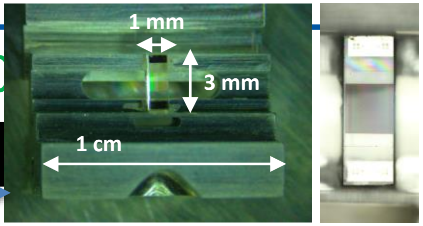
T18.4: grating-DLA w/ transverse laser: setup

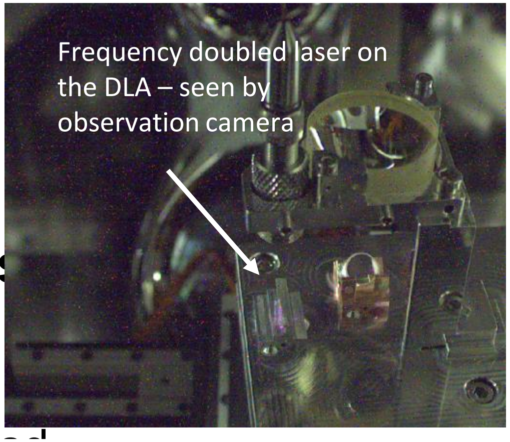


DLA: Y4 progress and future

- Reminder: Deliverable D 18.4 delivered (M35: march 2020
  Design & construction of an ARIES diele
  acceleration of relativistic electron beams
  - Grating structures have been designed, fabricated and acquired.
  - Grating structures have been mounted for installation in vacuum chamber
  - Bulk and structure damage tests ongoing in laser lab

Transverse laser injection



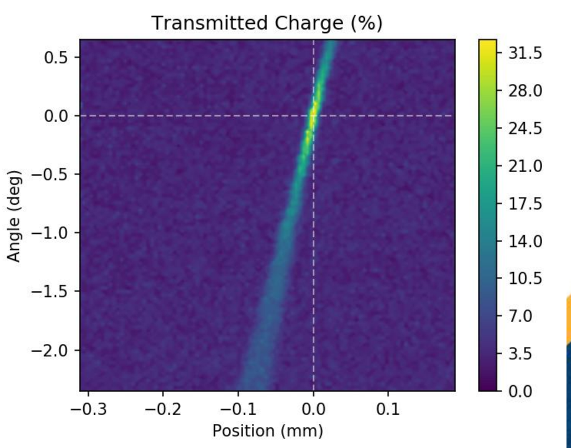


- **ARES-LINAC (injector) commissioning goals:**
  High transmission / stable energy modulation (100
  keV)
  - Beam parameters used in first experiments:
  - “Long” e-bunch - 450fs rms, 154 MeV, 5e-4 rms energy s
    ~70 nm normalized transverse emittance @ 200 fC
  - Long 2 µm laser pulse - 1.25ps rms

- Long-term stable (>10 h) ~35% transmission throug

  µm x 1 mm aperture achieved

- Stage 2 experiments in preparation (injection o
  phase-synchronous microbunch trains): 2022



Position and angle scan of the DLA using the nm precision SmarPod 6D positioning system

ARIES

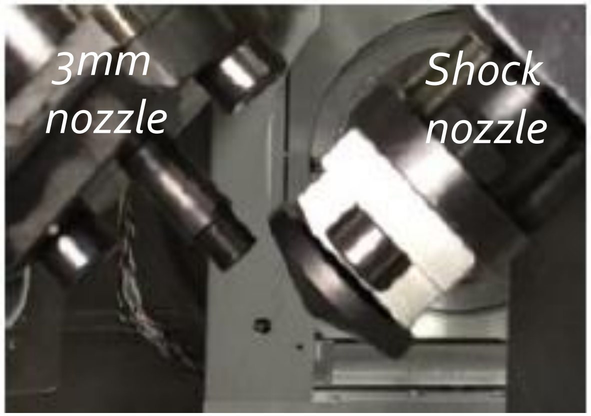
Pushing back the charge frontier (T18.5)

- 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.

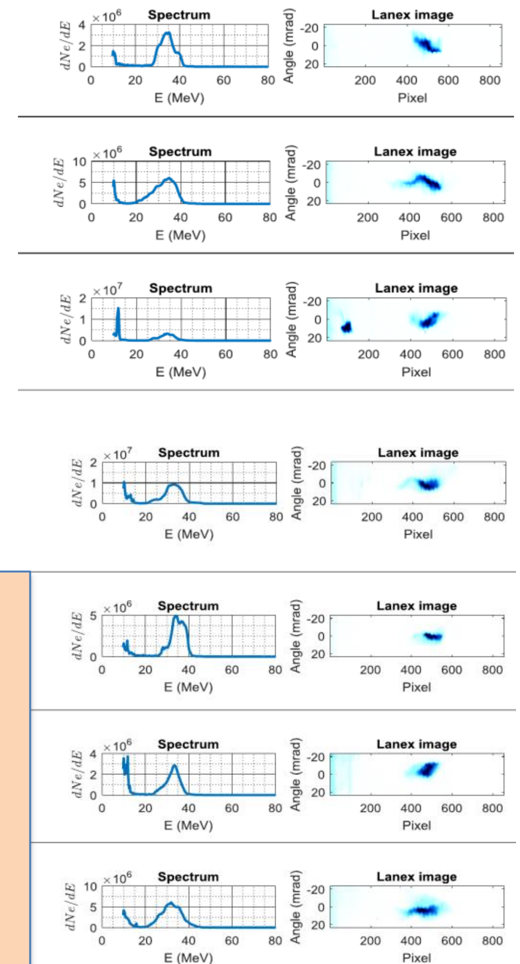
T18.5: Charge frontier: two-stage ionization injection

First experiment at CEA/LIDYL with the UHI laser

3 mm nozzle for acceleration (He gas)

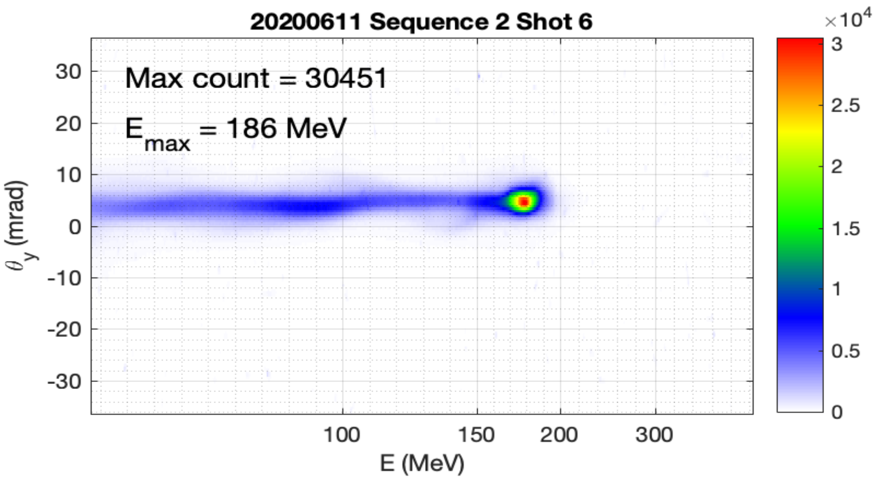


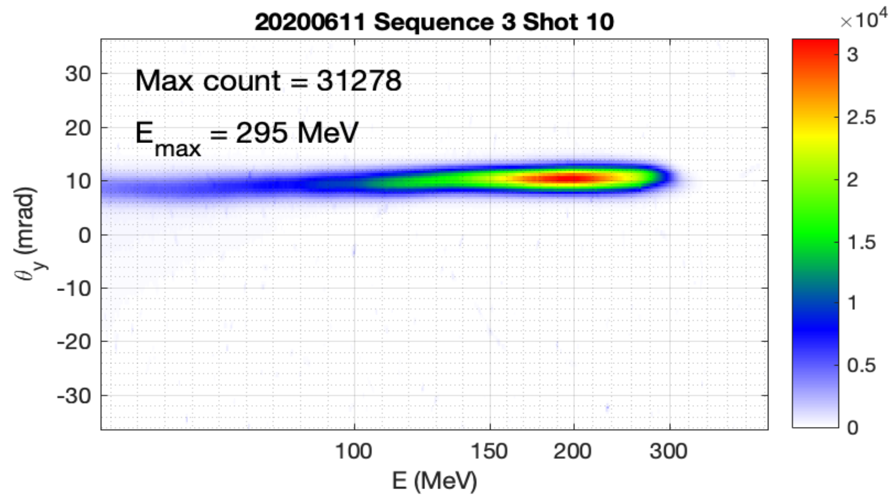
Ultrashort nozzle (<200um) for injection (with a high-Z gas)



- Also progress on the energy frontier through laser guiding experiments
- Interferometric studies of supersonic gaz jets with dielectric nozzles ongoing
- Useful synergy with low energy (10mJ), high repetition rate applications
- Collaboration with FTMC Vilnius to be continued in iFAST

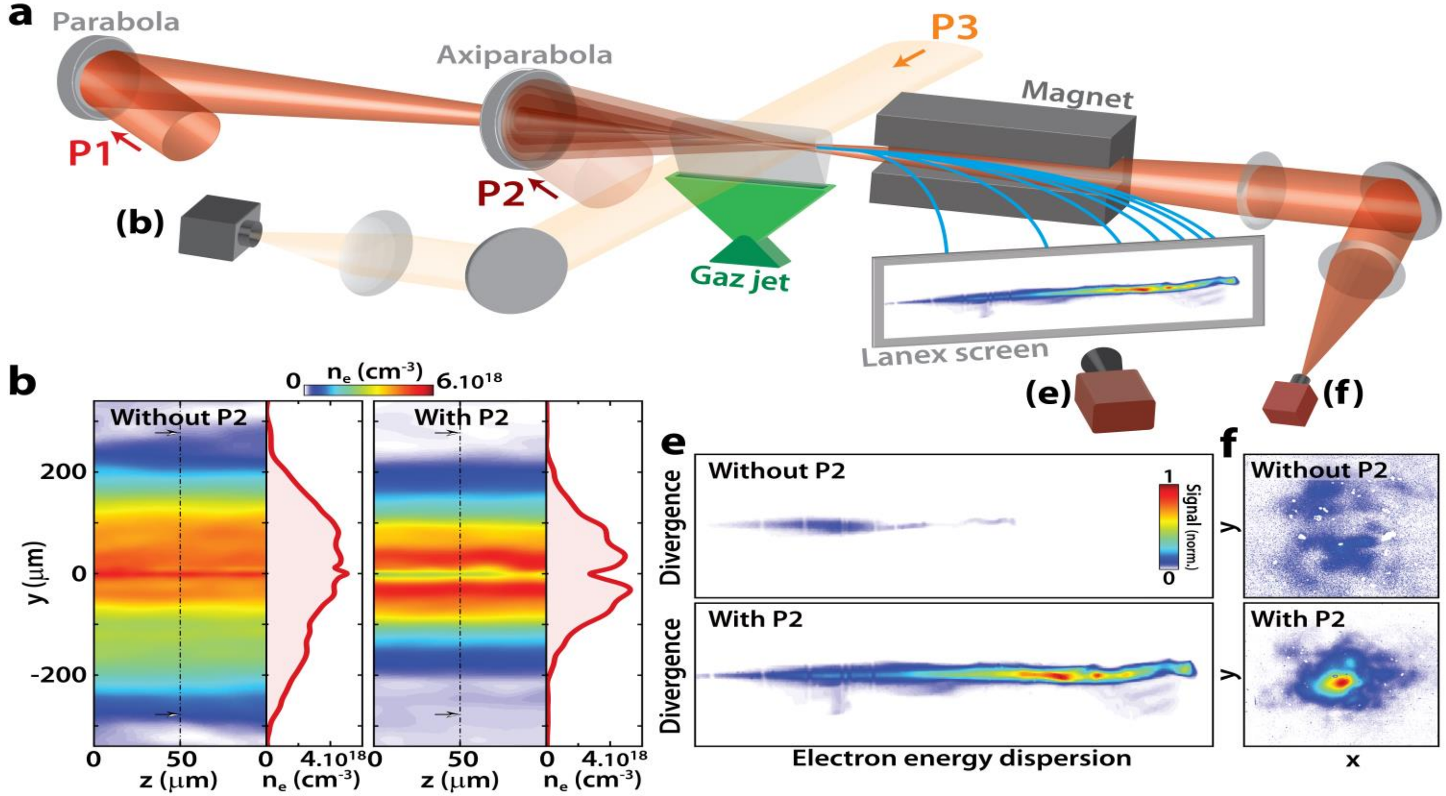
T18.5: Charge frontier: pulse front correction





Without correction, peak energy averaged over 20 shots is 152.2 +/- 23.9 (sd) MeV, and the charge above 45 MeV = 42.41 +/- 4.57 (sd) pC.
With correction, peak energy averaged over 17 shots is 193.9 +/- 22.0 (sd) MeV, and the charge above 45 MeV = 90.97 +/- 11.95 (sd) pC.

T18.5: Charge frontier: laser-generated waveguide



The charge density N is about 0.06 pC/MeV/mrad²/J for best shots, similar to Ref. [2-3] but at a much higher beam energy (1 GeV compared to 130-250 MeV).

Summary & Perspectives

- Task 18.2 Multistage (CEA)
  - implementation of line not achieved due to delay if installation, budget and personnel limitations
  - replacement deliverable done: full design study with tolerance, diagnostics, and mechanical studies
  - **BEYOND: important stepping stone for future 2-stage experiment at APOLLON laser**
- Task 18.3: LWFA with exotic beams (Lisbon)
  - helical beams and doughnut beams studied, experiments tricky -> role of instabilities
  - **BEYOND: superradiance demonstrated w/ numeric diagnostics developed under ARIES**
  - numerical studies of positron acceleration (beam-driven) w/ hollow channels done
- Task 18.4: Dielectric Laser Acceleration (DESY)
  - DLA structure delivered, experimental setup completed
  - ARES Linac at required performance commissioning takes longer than foreseen
  - **DLA transmission promising, DLA experiments in 2022–2023 planned**
  - **BEYOND: DLA in photonic crystal fibres to be published soon,** experiment: considerable effort.
- Task18.5 Charge frontier (LOA)
  - Many approaches check to eliminate culprits for low charge density at LOA, improvements demonstrated
  - New, dielectric gaz nozzles with integrated density downramp being tested in low and high power lasers
  - **BEYOND:** Optical laser guiding in long gas jet reaches ~O(1GeV) AND increases total charge slightly

Thanks to task leaders and WP members who contributed all along!
Many warm thanks to Valerie and Maurizio for their help and for their patience!