Hybrid electron acceleration in plasma-based accelerators

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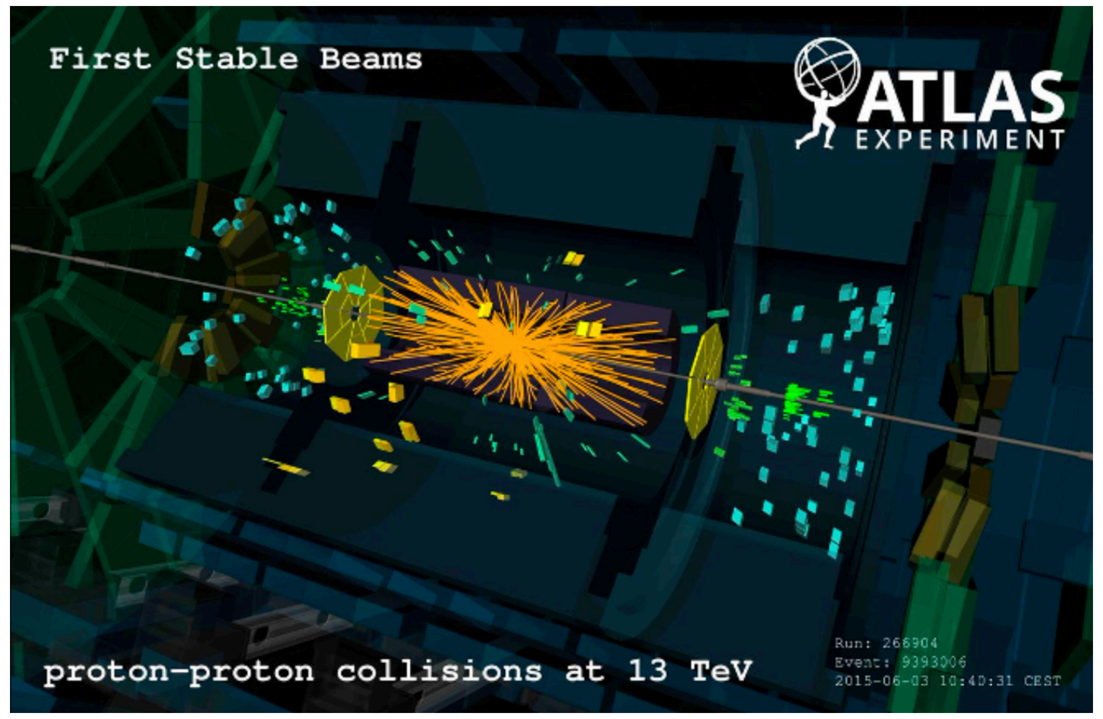
Why do we need to accelerate particles?

Applications

Studying Fundamental Physics

Probing the fundamental structure of matter



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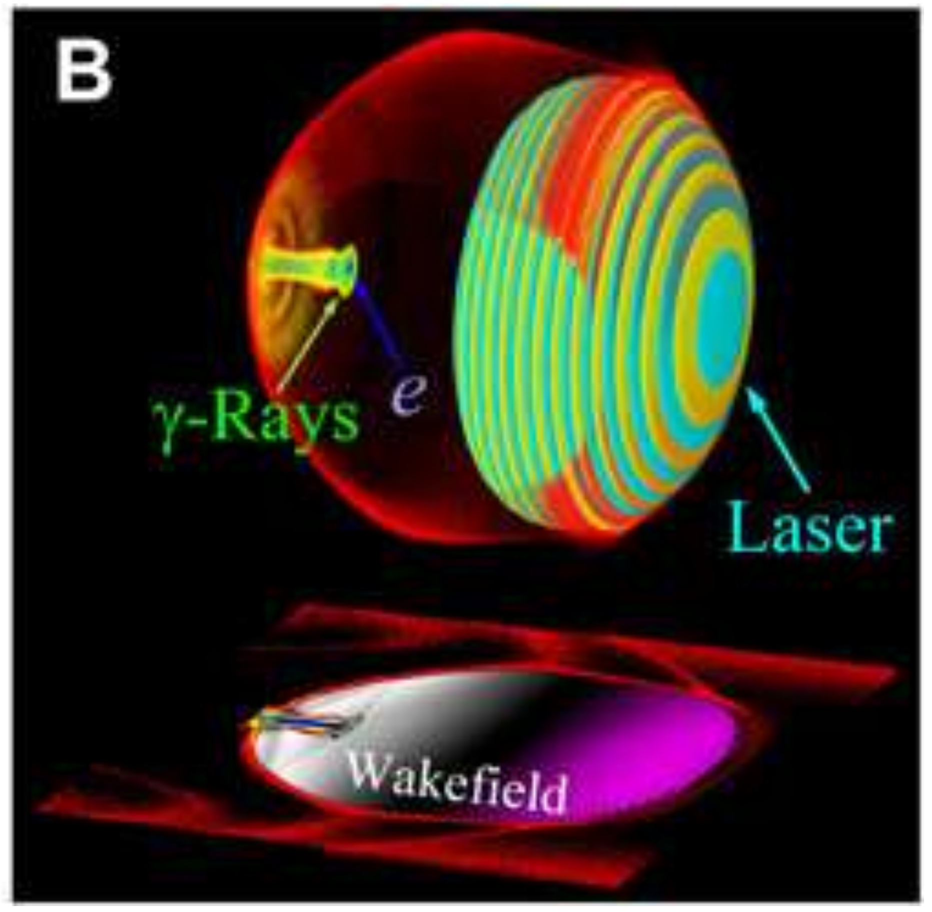
Advanced Radiation Sources

γ-ray and X-ray sources



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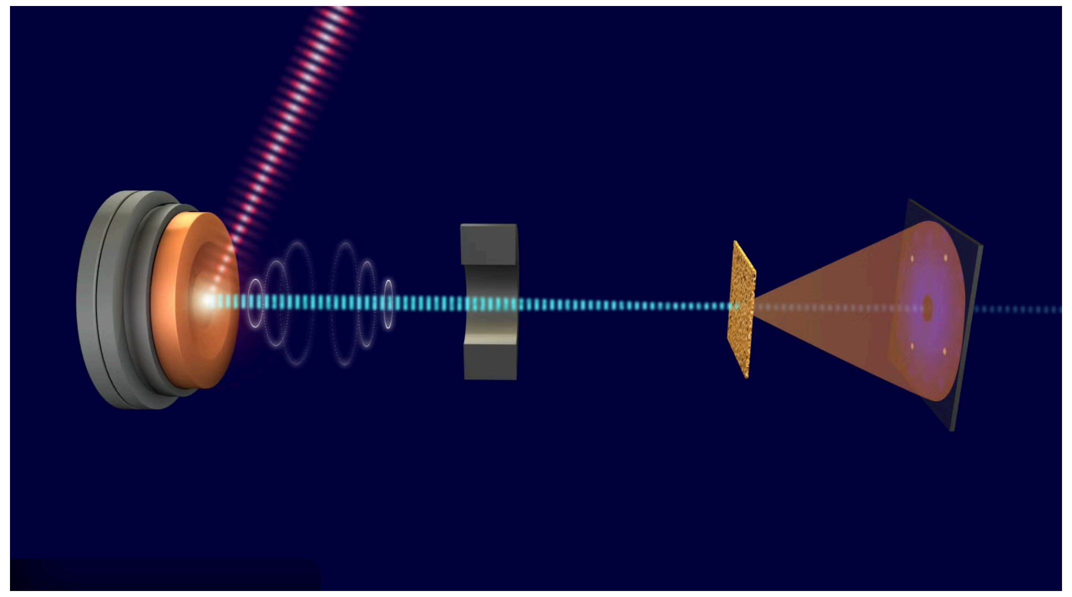
Ultrafast Scince

Femtosecond electron and photon probes



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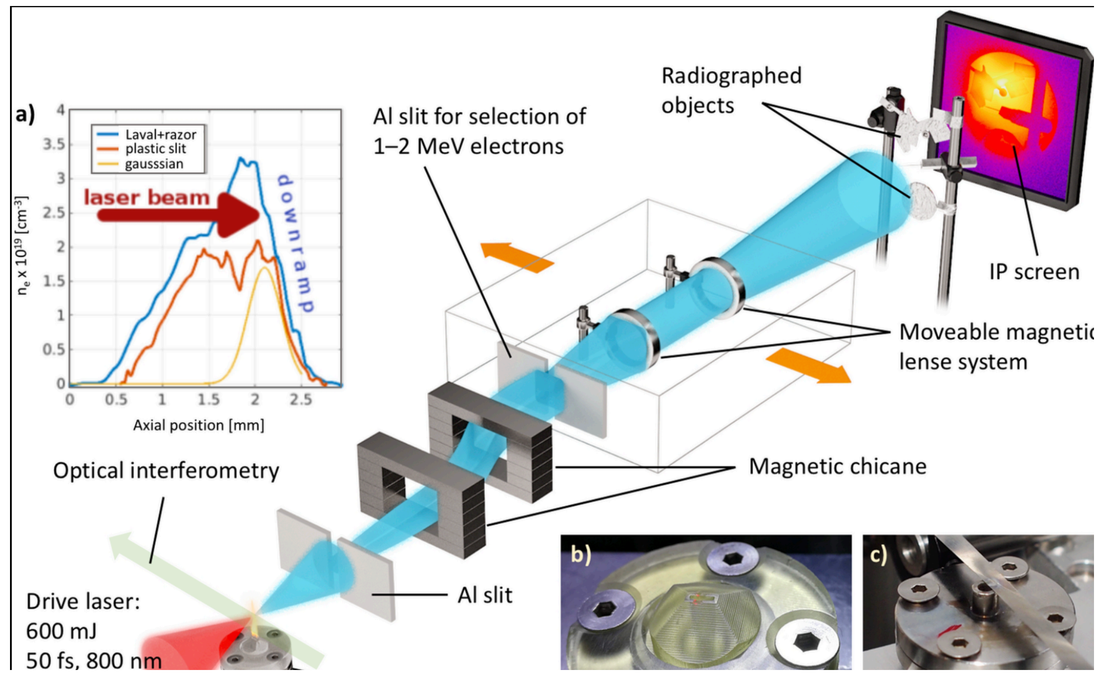
Studying fundamental Physics

Compact sources for imaging and therapy



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* Alonso, Andrea. (2024). The ATLAS ITk Strip Detector for the Phase-II LHC Upgrade. 027. 10.22323/1.463.0027.

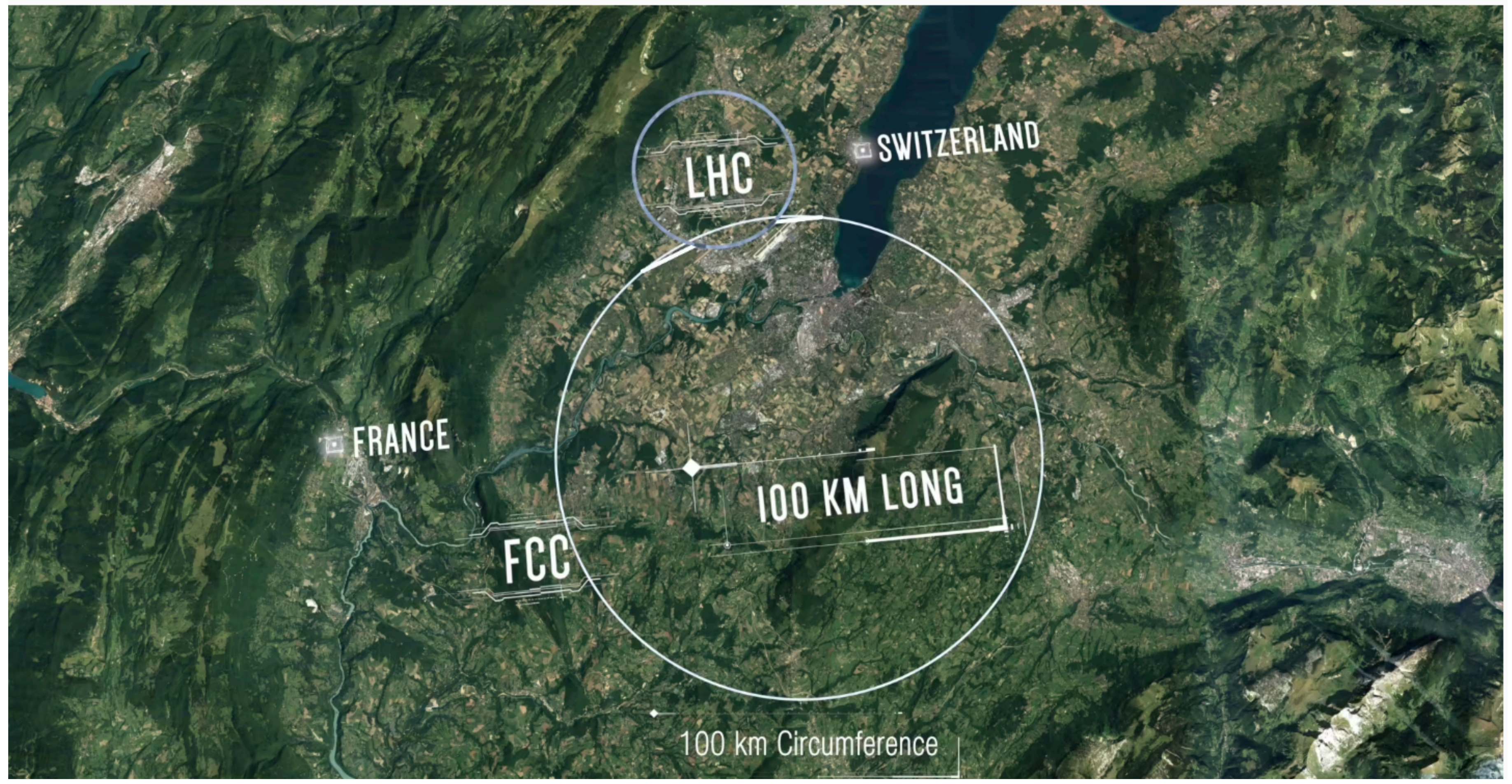
*Xing-Long Zhu *et al.* ,Extremely brilliant GeV γ-rays from a two-stage laser-plasma accelerator.*Sci. Adv.***6**,eaaz7240(2020).

***Image adapted from SLAC National Accelerator Laboratory, Lab Manager (2016)

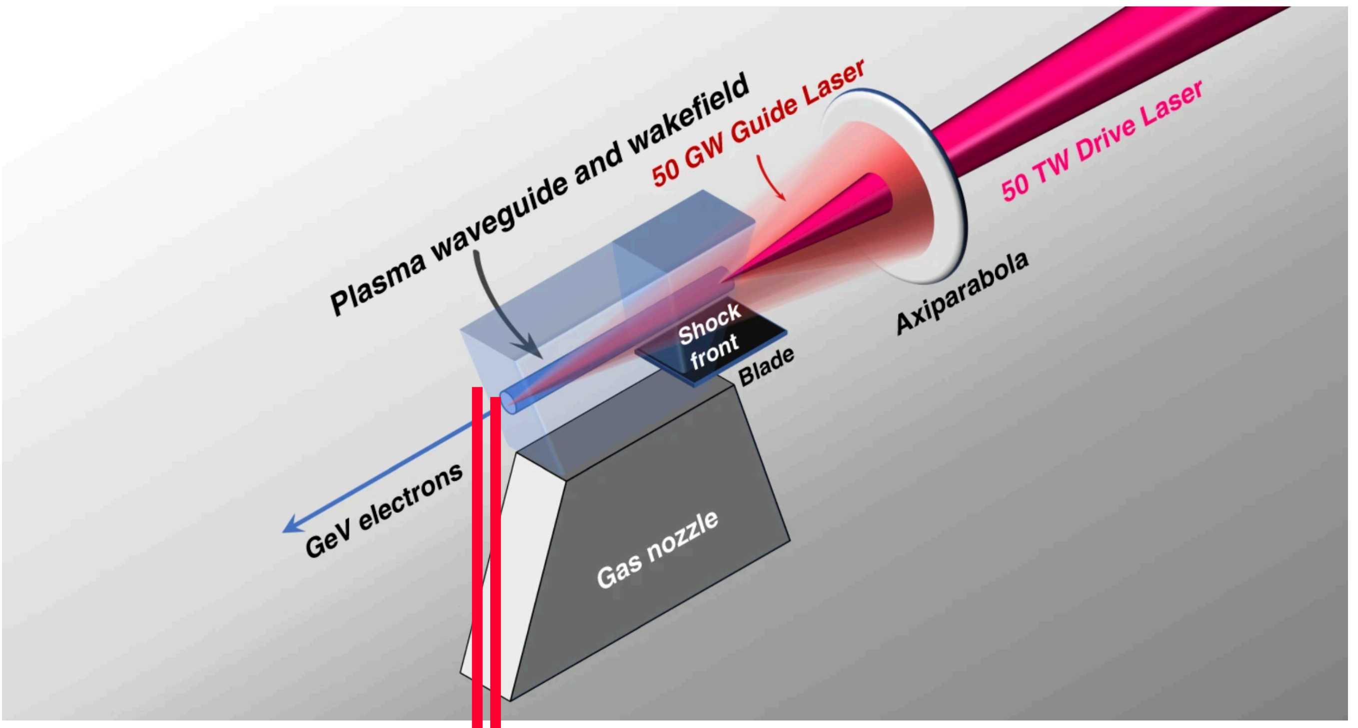
****Falk, K., Šmíd, M., Boháček, K. *et al.* Laser-driven low energy electron beams for single-shot ultra-fast probing of meso-scale materials and warm dense matter. *Sci Rep* **13**, 4252 (2023). https://

Towards Compact and Cost-Effective Accelerators

Conventional RF Accelerators



Plasma-Based Accelerators



Transverse size of accelerating structure

Transverse size ≈ human hair (~10–100 μm)
Acceleration length: mm–cm

Bunch energies

GeV/TeV over km

Up to GeV over mm/cm

Higher acceleration gradient => compact designs => less costly

Hybrid Regime via controlling pulse duration

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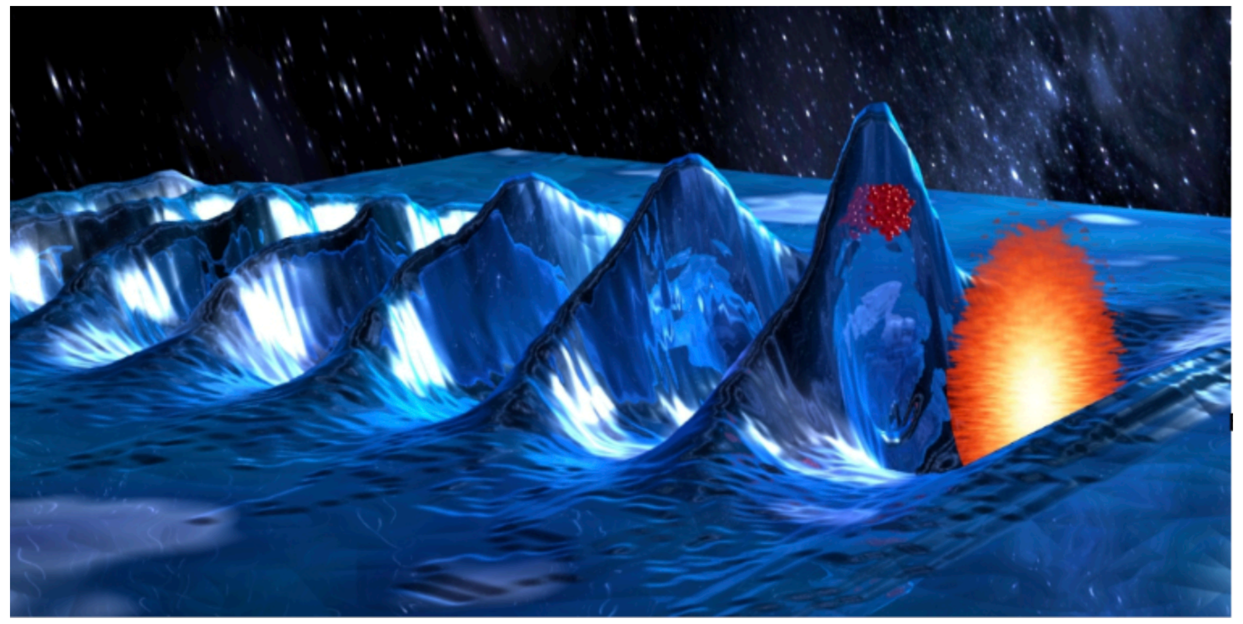

LWFA + DLA

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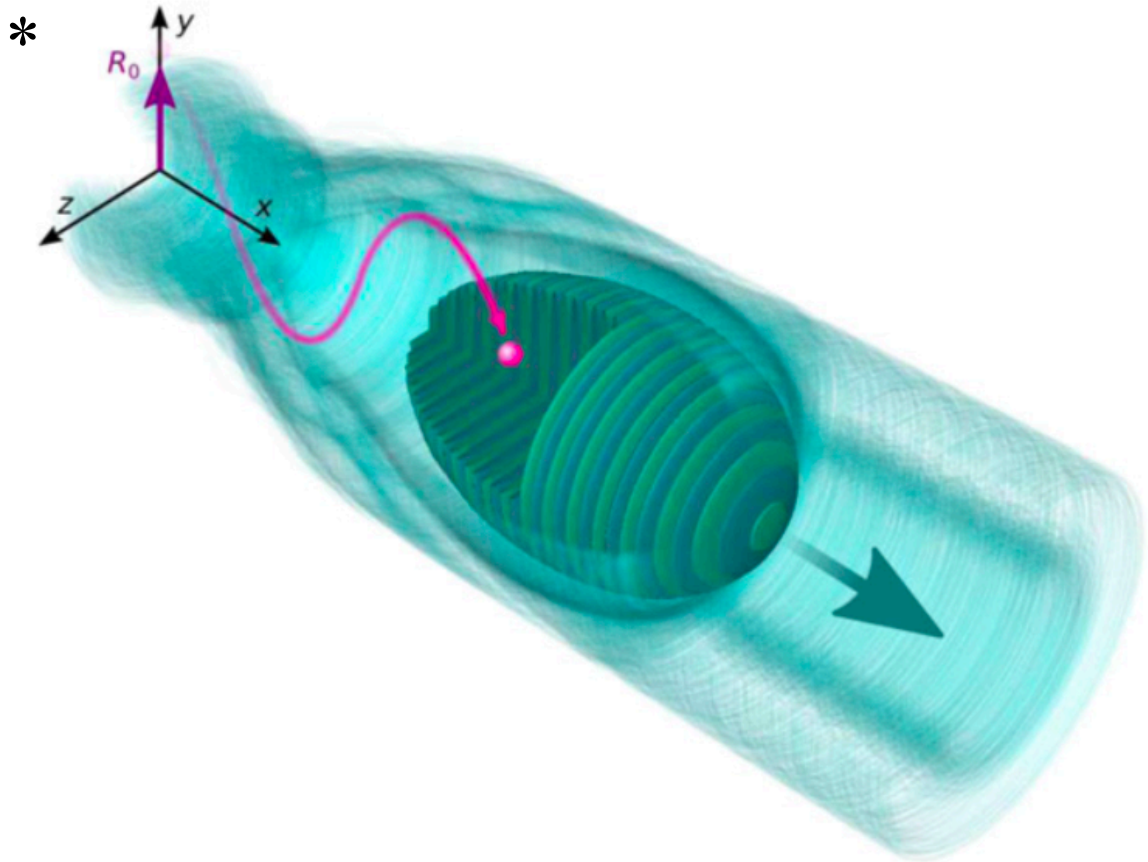

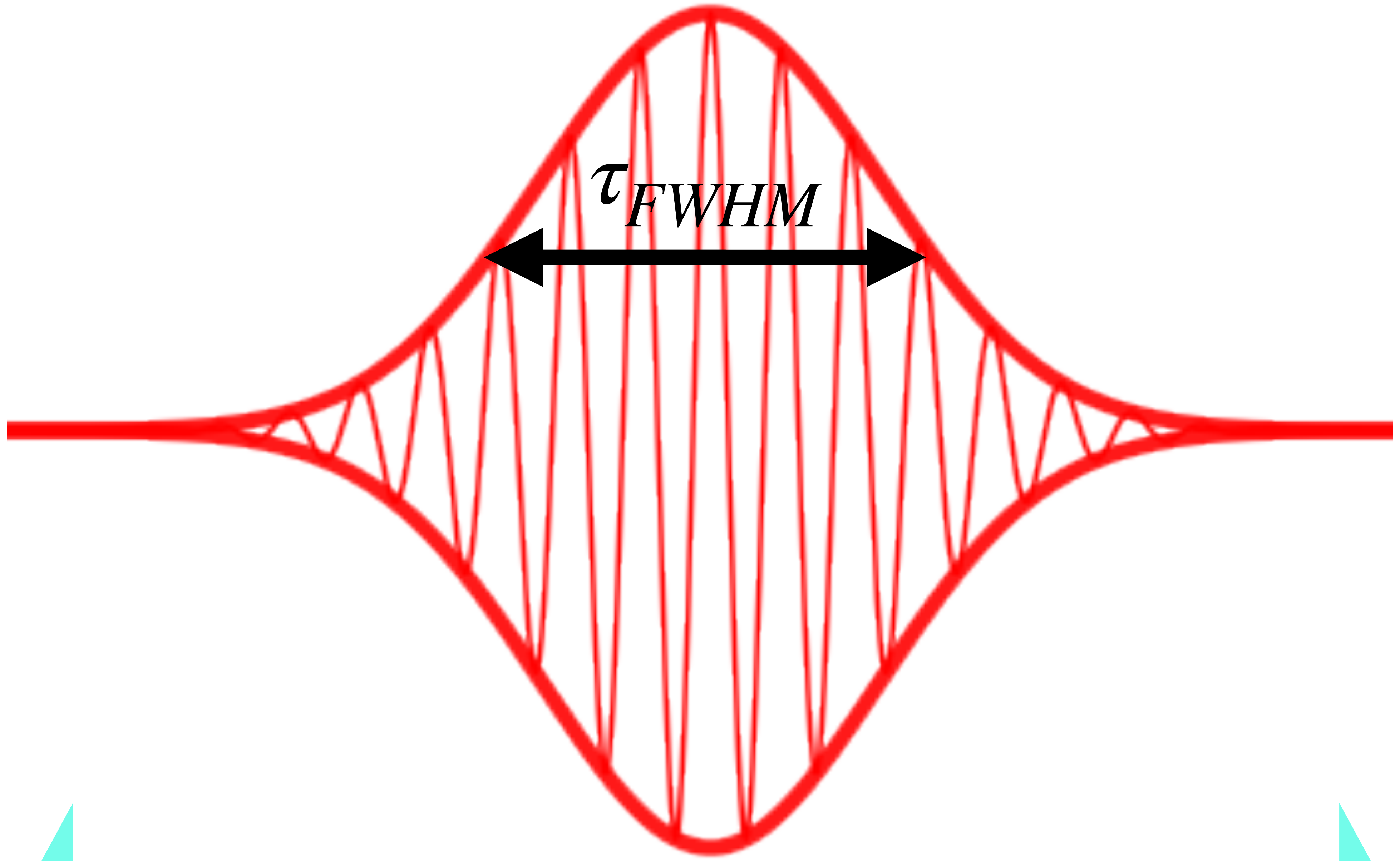

Short pulses: $\tau = 15 - 30\ fs$

Generation of a plasma wake driven by an intense laser pulse

Acceleration of electrons by longitudinal electric field

Laser pulse duration τ typically of the order of 100s of fs

Resonance condition: $\omega_\beta \approx \omega_D$

Acceleration of electrons with transverse fields

Change pulse duration

* M. Vranic et al. “Scaling Laws for Direct Laser Acceleration in a Radiation-Reaction Dominated Regime”. In: *New Journal of Physics* 22 (2020), p. 073035. DOI: 10.1088/1367-2630/ab8c66.

**Source: LOA – Laboratoire d’Optique Appliquée, École Polytechnique (illustration of LWFA)

Conclusions and future works

MEFT

Conclusions

- Both mechanisms contribute to electron acceleration
- Longer laser pulses leads to higher maximum energy but reduce conversion efficiency

Future work

Deeper understanding of the hybrid regime

Quantitative analysis of how each regime affects key beam properties: maximum energy, total charge, and energy conversion efficiency.