Electron-injection techniques in plasma-wakefield accelerators for driving free-electron lasers.

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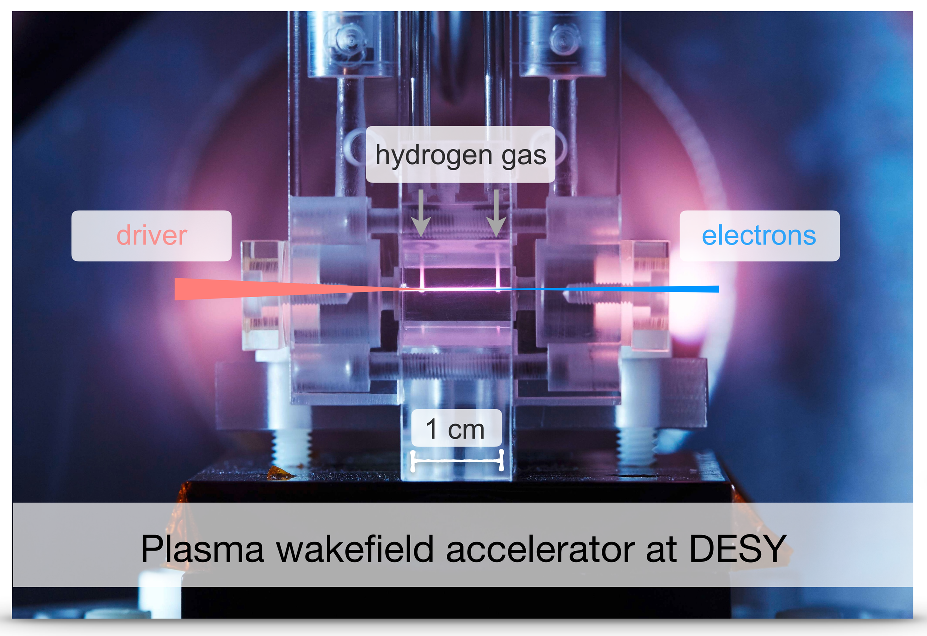
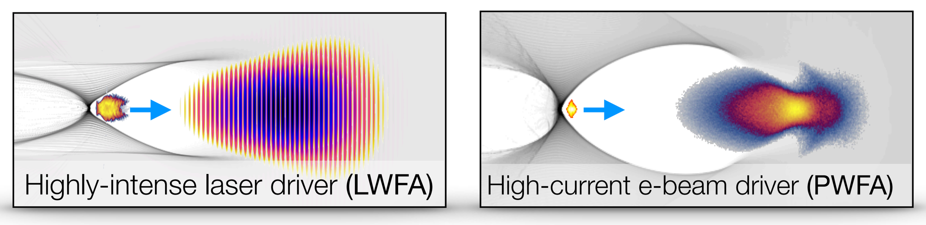
Injection concepts for high quality electron beams

Introduction to plasma acceleration

Plasma acceleration is the leading technology for next-generation compact particle and radiation sources.



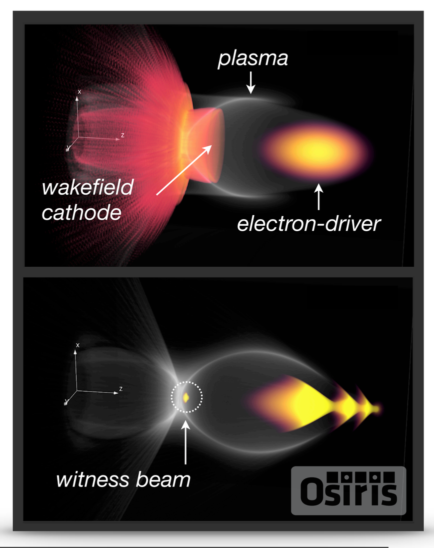
Plasma wakefield accelerator at DESY


Highly-intense laser driver (LWFA)
High-current e-beam driver (PWFA)

Laser and beam driven plasma wakefield accelerators
- Accelerating fields of 10-100 GV/m
- e-beams with GeV energies from cm-scale accelerators!

Internal injection concepts

Wakefield-induced ionization injection



Self-synchronized witness beam
- The wakefields ionize and capture a high-quality electron-beam from helium.

Efficient acceleration
- The witness beam is accelerated to 2-3 times the energy of the driver.

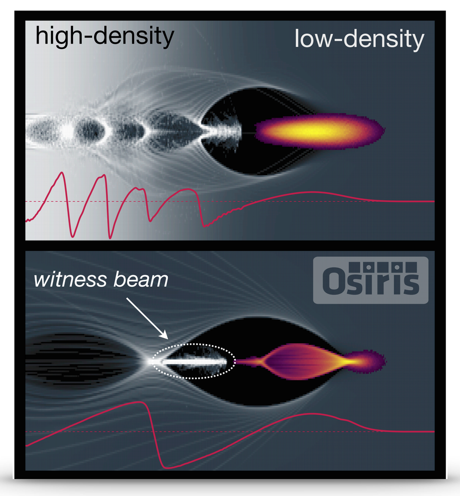
High-quality electron beams
- High-brightness GeV-class electron beam.
- Beam-loading can be controlled to minimize the energy spread.

A. M. de la Ossa et al., PRL 111, 245003 (2013).
A. M. de la Ossa et al., PoP 22, 093107 (2015).

Density down-ramp injection

Controlled wave-breaking
- Plasma-electrons overtake the plasma-wake during a high-to-lower density transition.

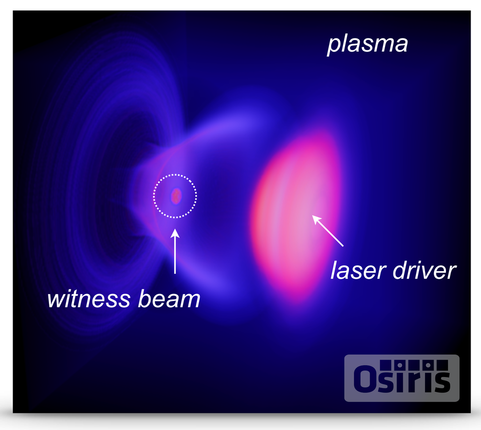
High-quality witness beam
- The generated bunches feature low emittance and energy spread.



A. M. de la Ossa et al., PRAB 20, 091301 (2017).

External injection concepts

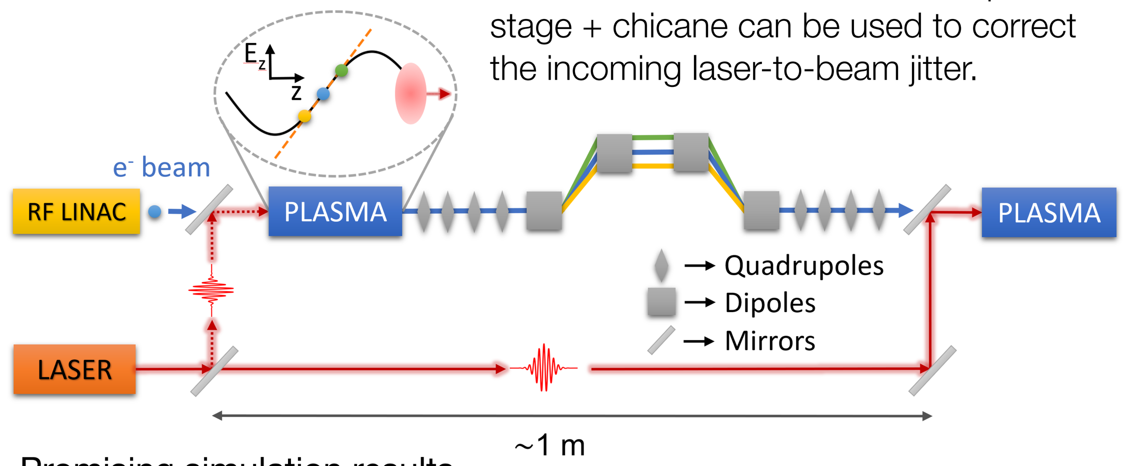
Novel scheme for sub-femtosecond synchronization



Extremely fine synchronization is needed
- External injection can offer better control and quality of the beam parameters.
- Requires fs-level synchronization between laser and electron beam.

Typical jitter is too high
- The RF linac to laser timing jitter can reach 100's of femtoseconds.

Timing jitter can be compensated
- The combination of an additional plasma stage + chicane can be used to correct the incoming laser-to-beam jitter.

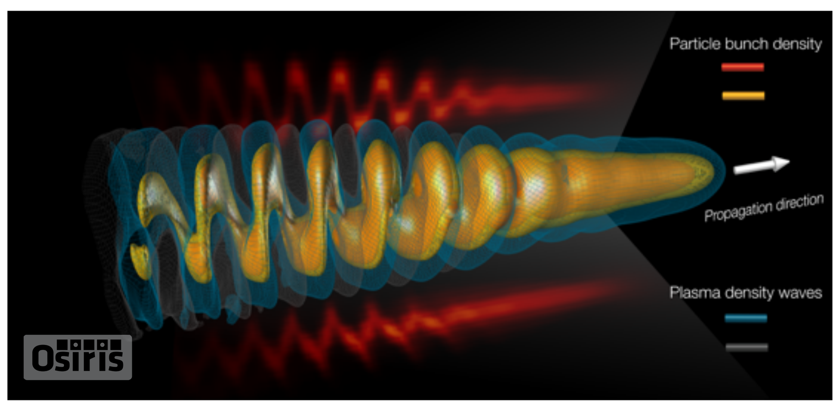


Promising simulation results
- An incoming jitter of 10 fs can be reduced to sub-fs level.

A. Ferran Pousa et al., IOP Conf. Series 874, 012032 (2017).

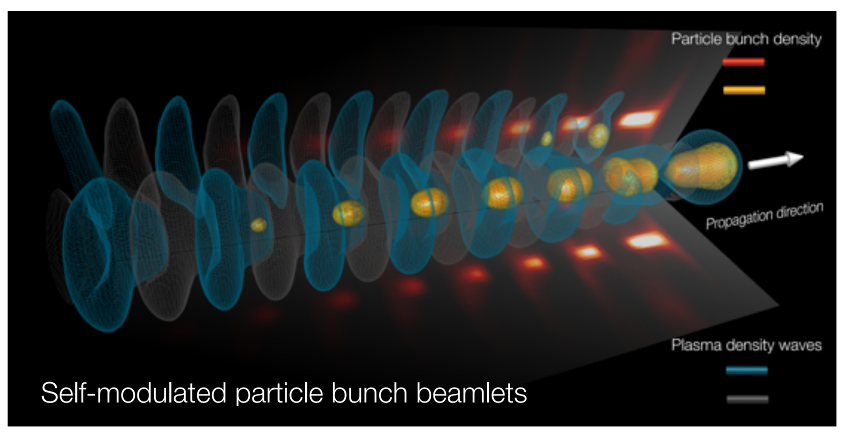
Acceleration and transport of high quality beams

Physics of the self-modulation instability for plasma accelerators



- The hose instability consists in an exponential growth of centroid oscillations of a particle bunch.
- Ultimately, this instability leads to beam breakup.
- The hose and the self-modulation instabilities compete in plasma experiments using a long drive beam.

Demonstration of stable, hosing free self-modulation of long particle bunches

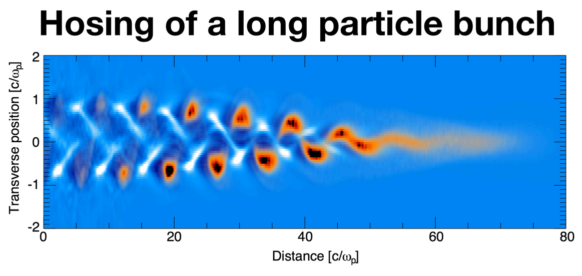


Self-modulated particle bunch beamlets

J. Vieira et al., PRL 112 205001 (2014).

Conditions for stable, beam breakup-free propagation of long bunches:
- the seed of the self-modulation instability needs to be much higher than the seed of the hosing.
- non-linear wakefield excitation has to be avoided

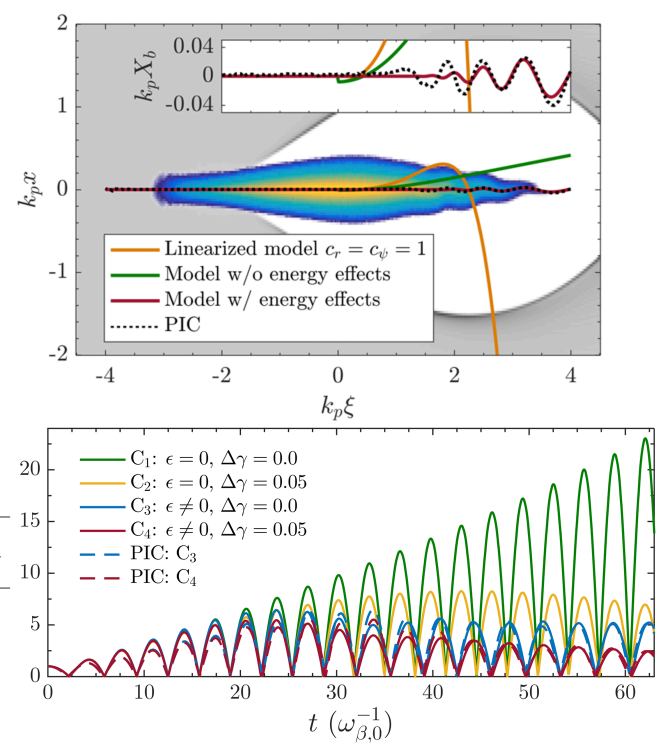
Hosing of a long particle bunch



Hose instability suppression

Serious challenge for stable operation of PWFAs.

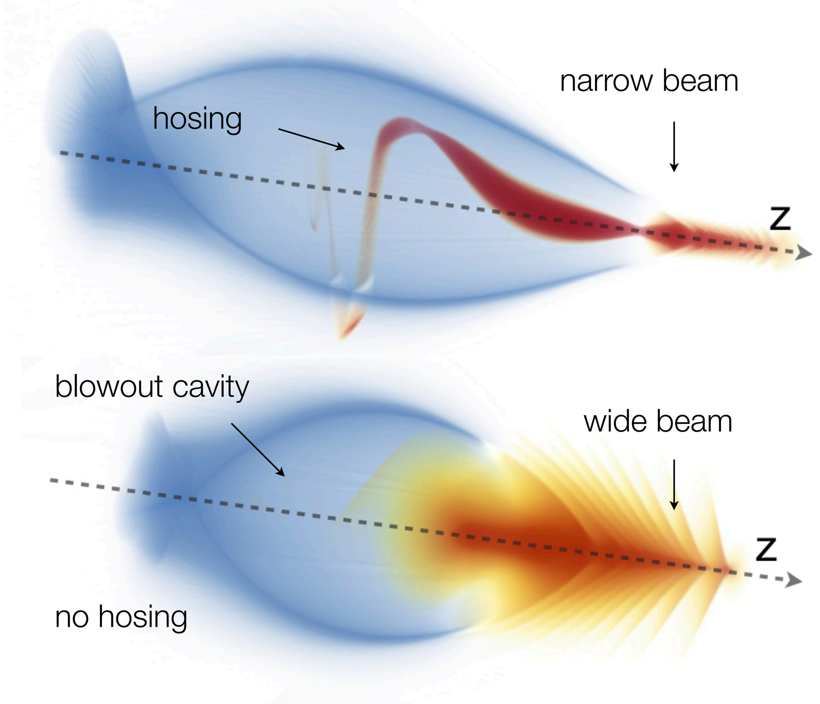
Mitigation of the hose instability
- The natural drive-beam energy evolution stops the instability.
- Drive-beams can be stabilized over long distances.



T. J. Mehrling et al., PRL 118, 174801 (2017).

Intrinsic stabilization of the drive-beam

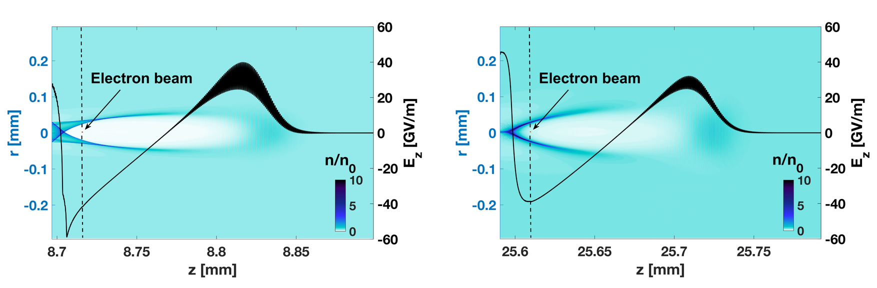
Wide drive-beams are stable
- Head-to-tail variations of the focusing strength suppress the hosing in a short distance.
- Witness-beams of high-quality can be efficiently accelerated and transported.

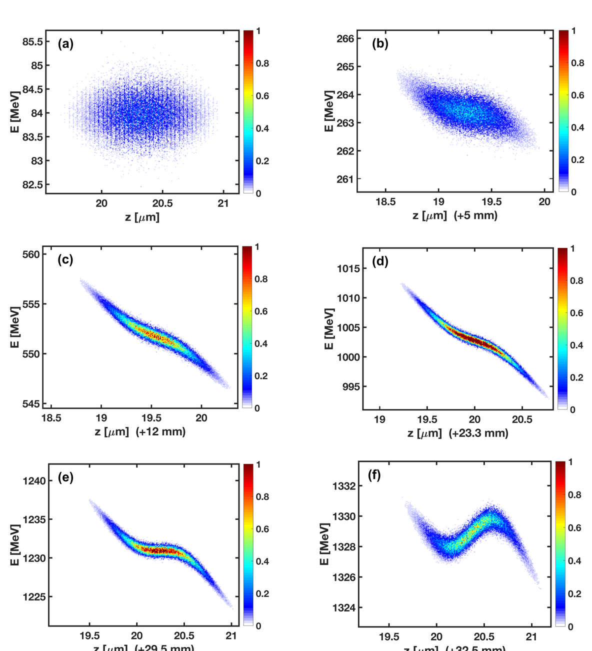


A. M. de la Ossa et al., In preparation (2018).

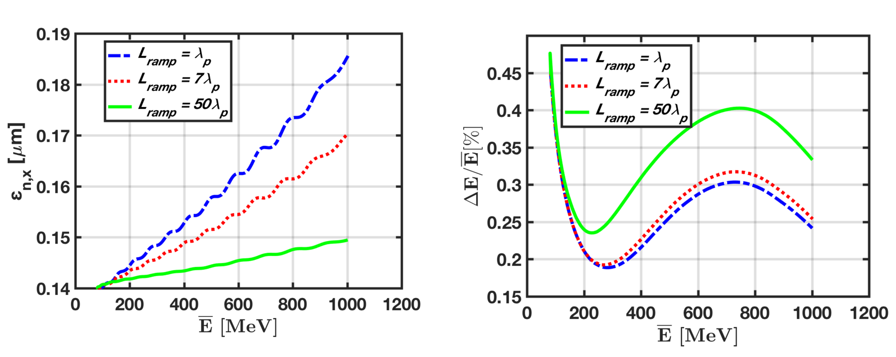
Beam quality preservation in LPAs with external injection

Mechanism of correlated energy spread decrease
- Due to the laser diffraction through the propagation in plasma, the generated wakefield changes its slope and magnitude.
- By appropriately choosing the injection phase of the witness beam, the induced energy chirp can be significantly reduced.

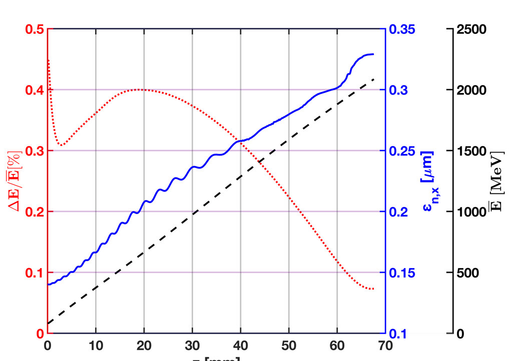




Emittance growth suppression
- Tailoring the longitudinal plasma density profile by a smooth vacuum-plasma transition allows to minimize the induced emittance growth.

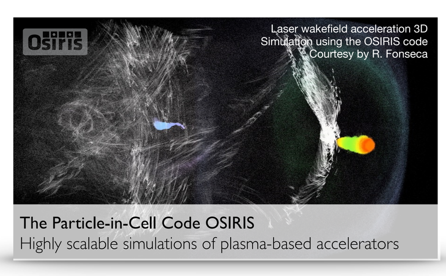


2 GeV electron beam with ΔE/E < 0.1 %

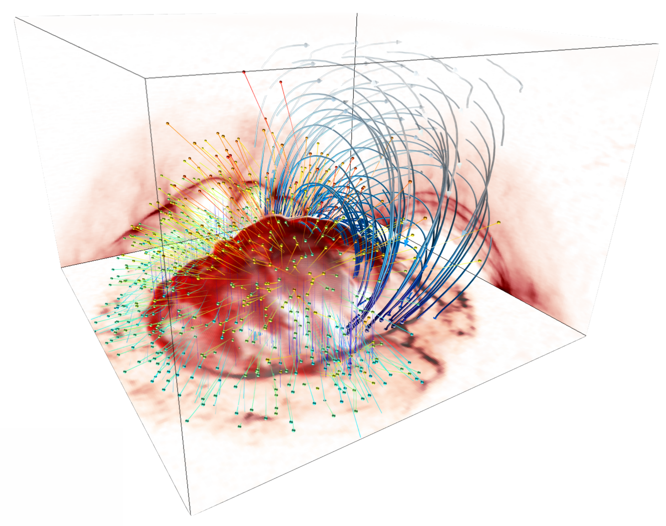


E. Svystun et al., NIM A, In press (2018). doi:10.1016/j.nima.2018.02.060.

The OSIRIS Framework



- Massively parallel, fully relativistic Particle-in-Cell (PIC) code.
- Visualization and data analysis.
- Developed by the osiris consortium ⇒ UCLA + IST.



Osiris 3.0

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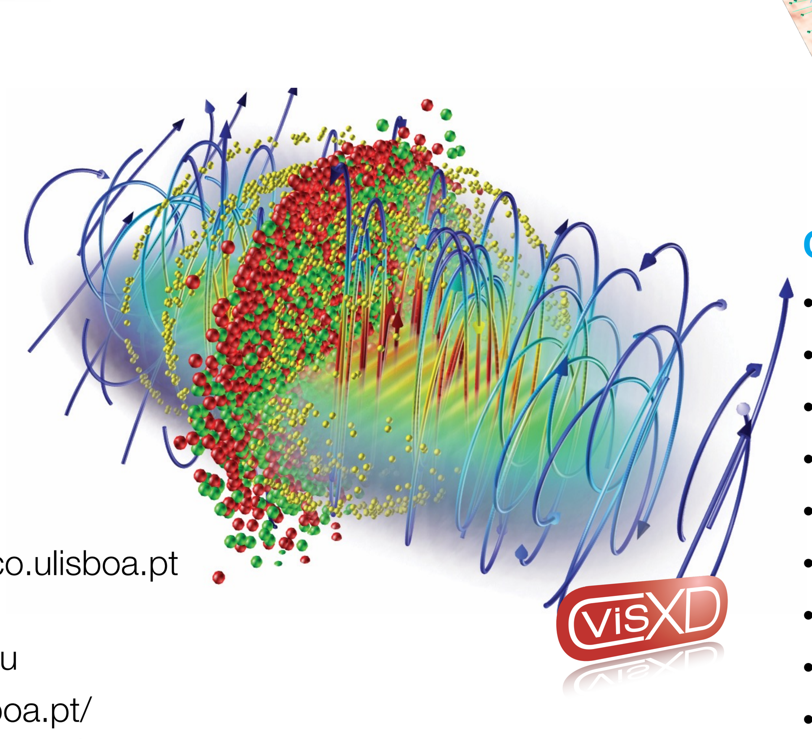

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visXD

Code features

- Scalability to ~ 1.6 M cores
- Hybrid MPI/OpenMP parallelized
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- QED module
- Particle merging
- GPGPU support
- Xeon Phi support

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