Toward ultra-low timing-jitters for beam-driven plasma accelerators

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On behalf of the SPARC_LAB collaboration

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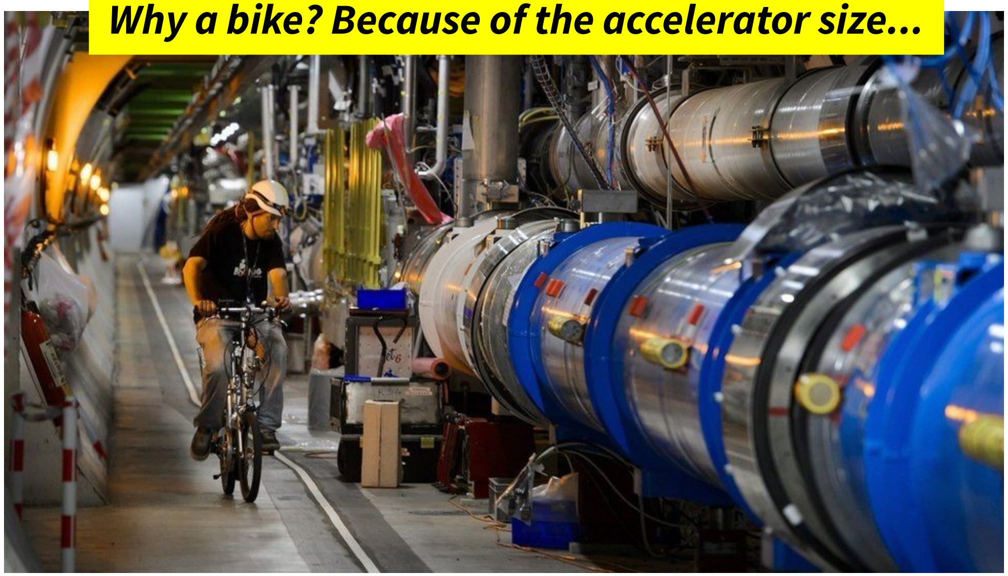
Particle accelerators

A particle accelerator is a machine that uses electromagnetic fields to propel charged particles to very high speeds and energies, and to contain them in well-defined beams

Wikipedia

Why a bike? Because of the accelerator size...



According to the De Broglie hypothesis, larger is the particle **energy** better is the **spatial resolution** at which matter can be investigated

$$\lambda = \frac{h}{p}$$

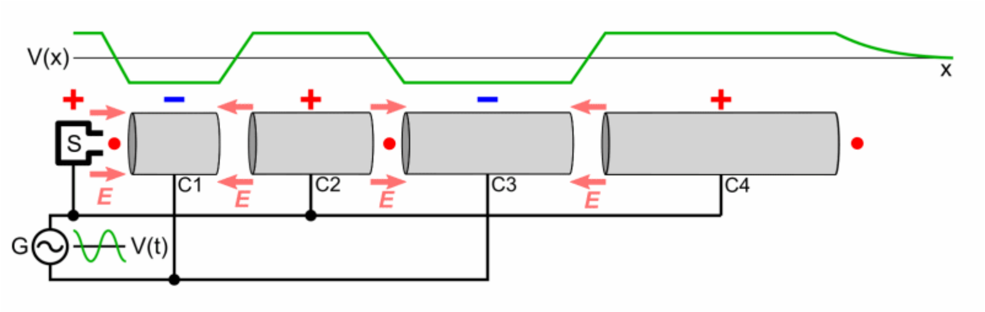
Planck constant (h)

Microscope resolution (λ)

Particle momentum (~energy) (p)

Today use of particle accelerators

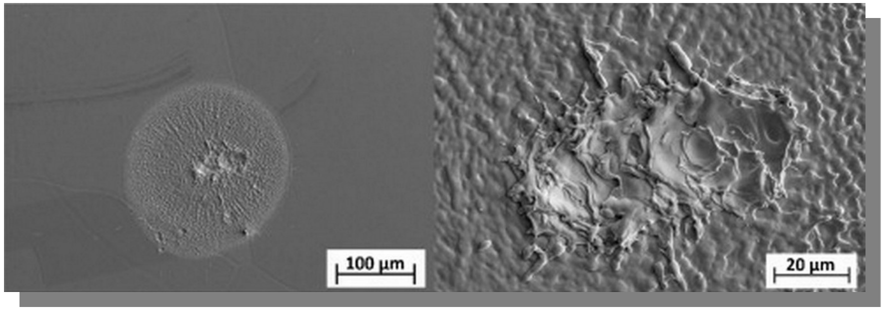
- *High-energy and nuclear physics*
- *Sources of synchrotron and FEL radiation*
- *Medical/industrial applications*



RF technology uses high power microwaves in resonant cavities with metallic walls.

Typical RF frequencies are in GHz range.

The cavities dimensions are of the order of the microwaves wavelength (1-60 cm)



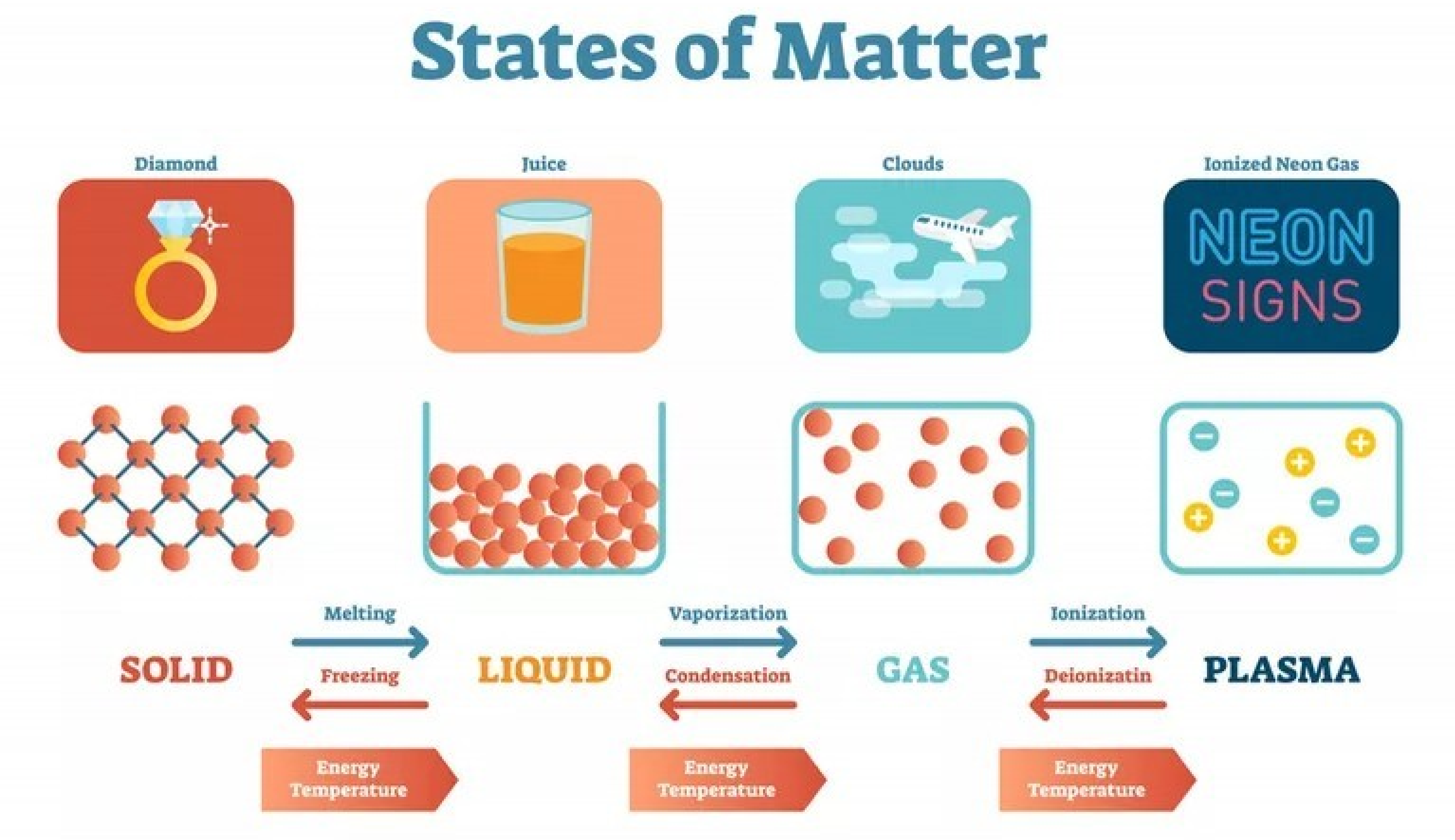
The power stored in the cavity cannot grow to infinite

RF breakdown*: imperfections on the cavities can trigger sparks and damage the structure*

There is a maximum sustainable electric field

$$E_{max} \approx 100 \frac{MV}{m}$$

Use of plasma to exceed RF limits



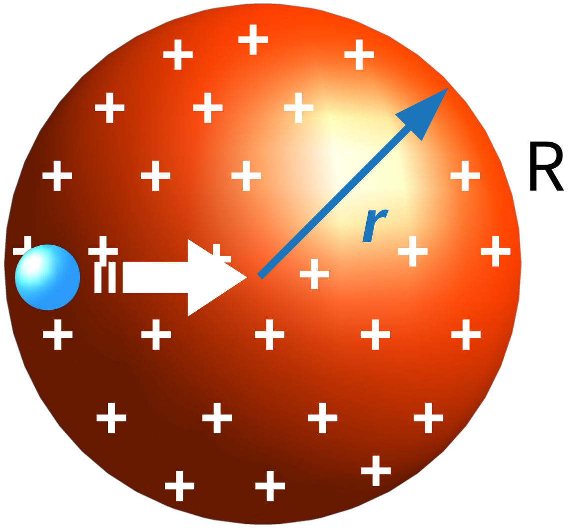
Plasma is the 4th state of matter and is made of free electrons and positively charged ions

It is typically made by heating a gas until its electrons have sufficient energy to escape from the (positive) nuclei

Being already ionized, the plasma cannot be "damaged" by any spark and can thus sustain huge fields

From Maxwell's equations, the electric field in a (positively) charged sphere with uniform density n_i at location **r** is

$$\vec{E}(r) = \frac{q_i n_i}{3\epsilon_0} r$$



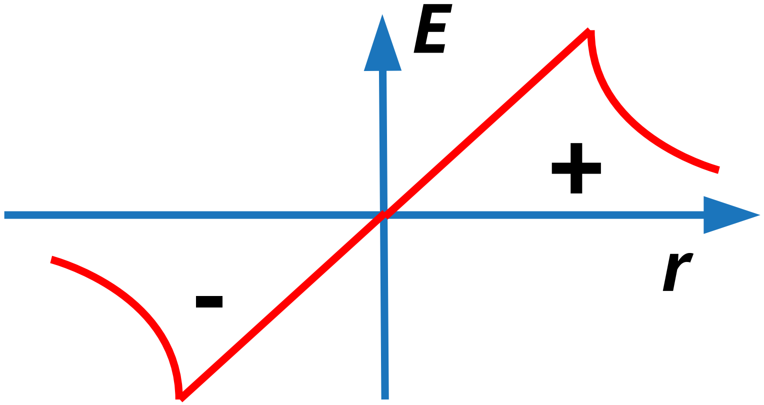
The field is **increasing** inside the sphere

Let's put some numbers

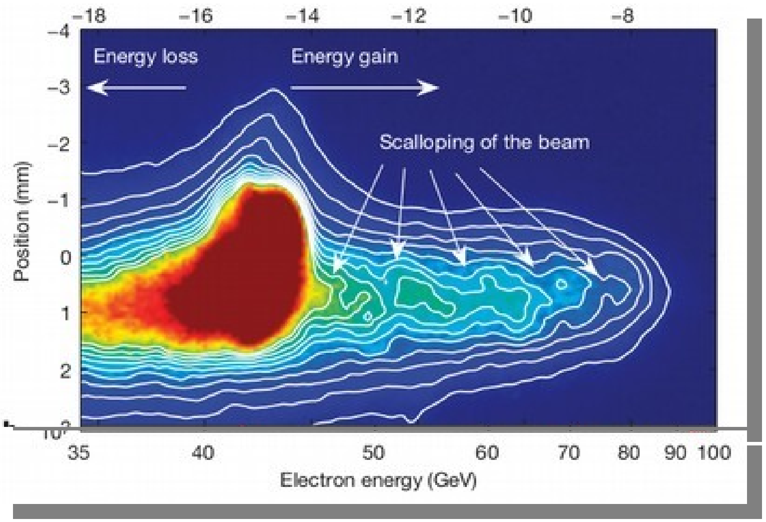
n_i=10^16 cm^-3

R=0.5 λ_p=150 µm

$$E \approx 10 \frac{GV}{m}$$



Beam-driven plasma acceleration (PWFA)



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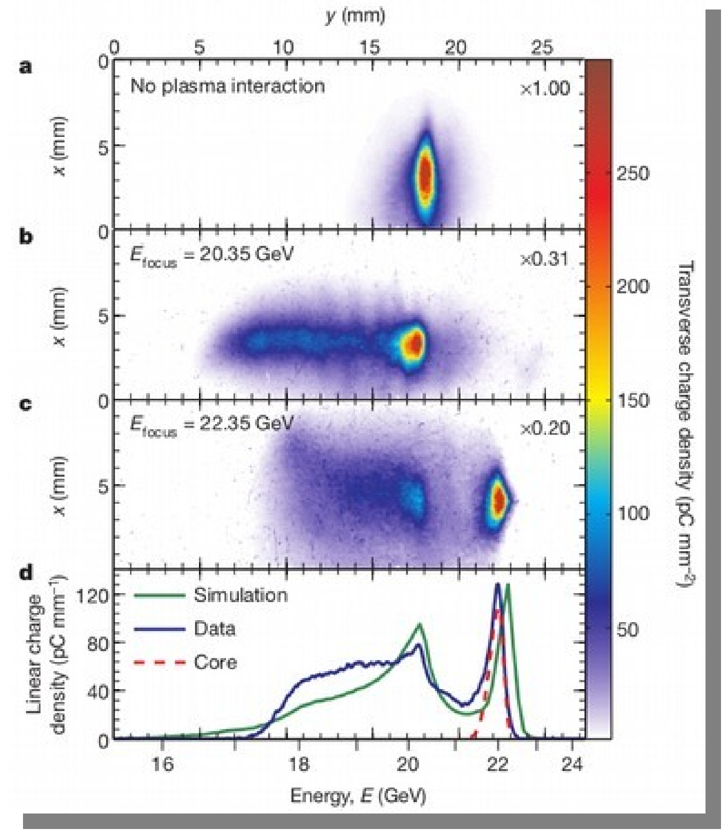

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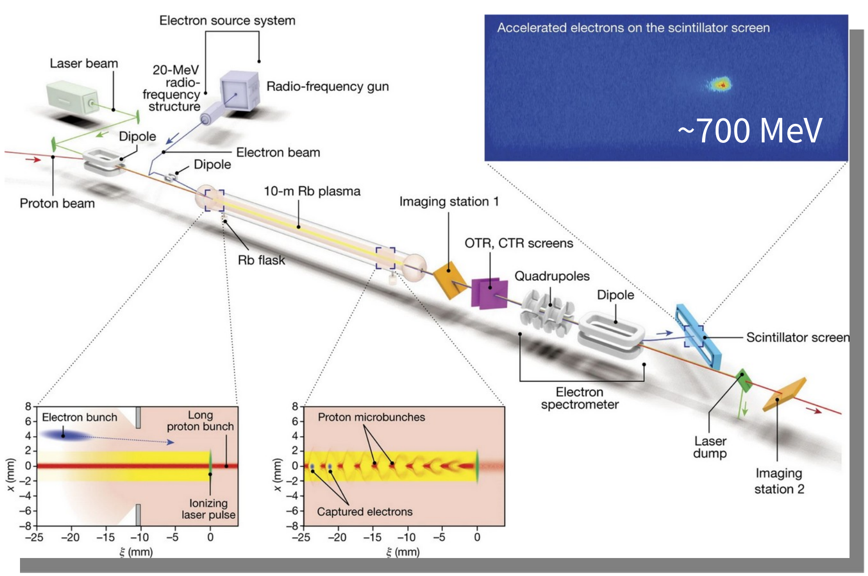
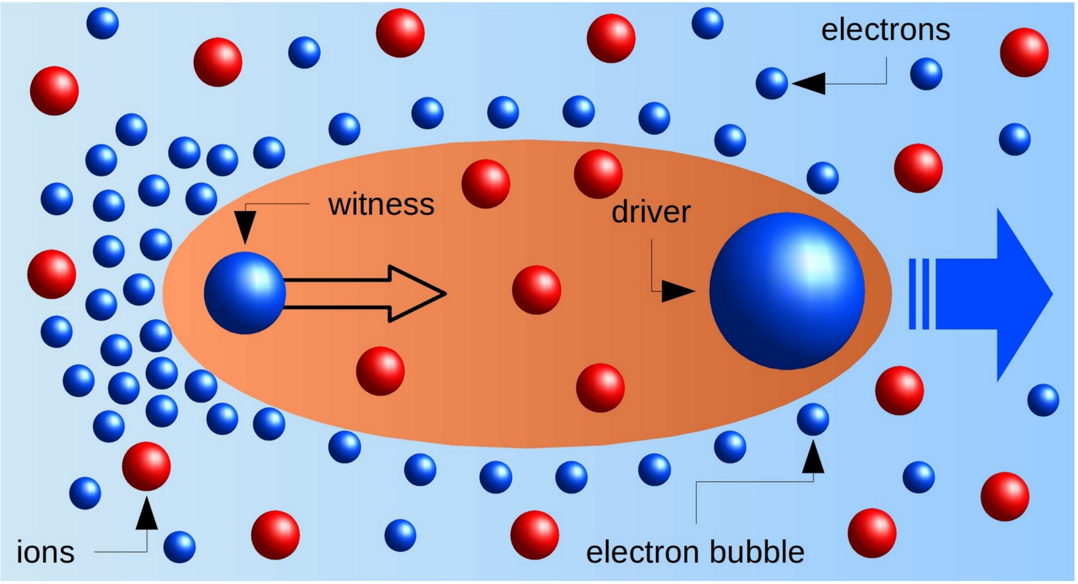
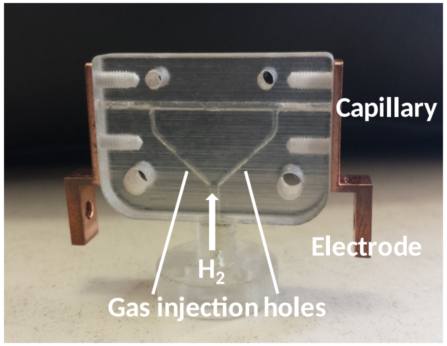


Adli, Erik, et al. "Acceleration of electrons in the plasma wakefield of a proton bunch." Nature 561.7723 (2018): 363-367.

Plasma acceleration for EuPRAXIA





$$E_0=\frac{m_e c\,\omega_p}{e}\simeq 96\sqrt{n_0(cm^{-3})}\rightarrow E_0\approx 10\,\frac{GV}{m}\;@\;n_0=10^{16}\,cm^{-3}$$

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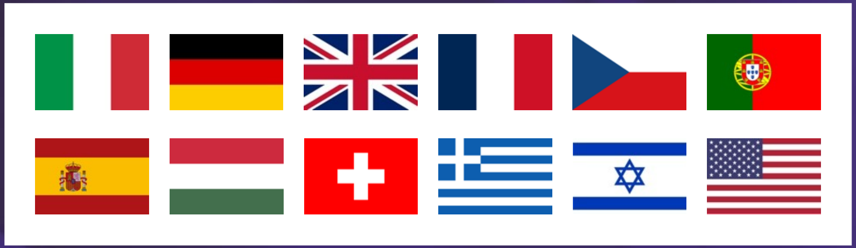
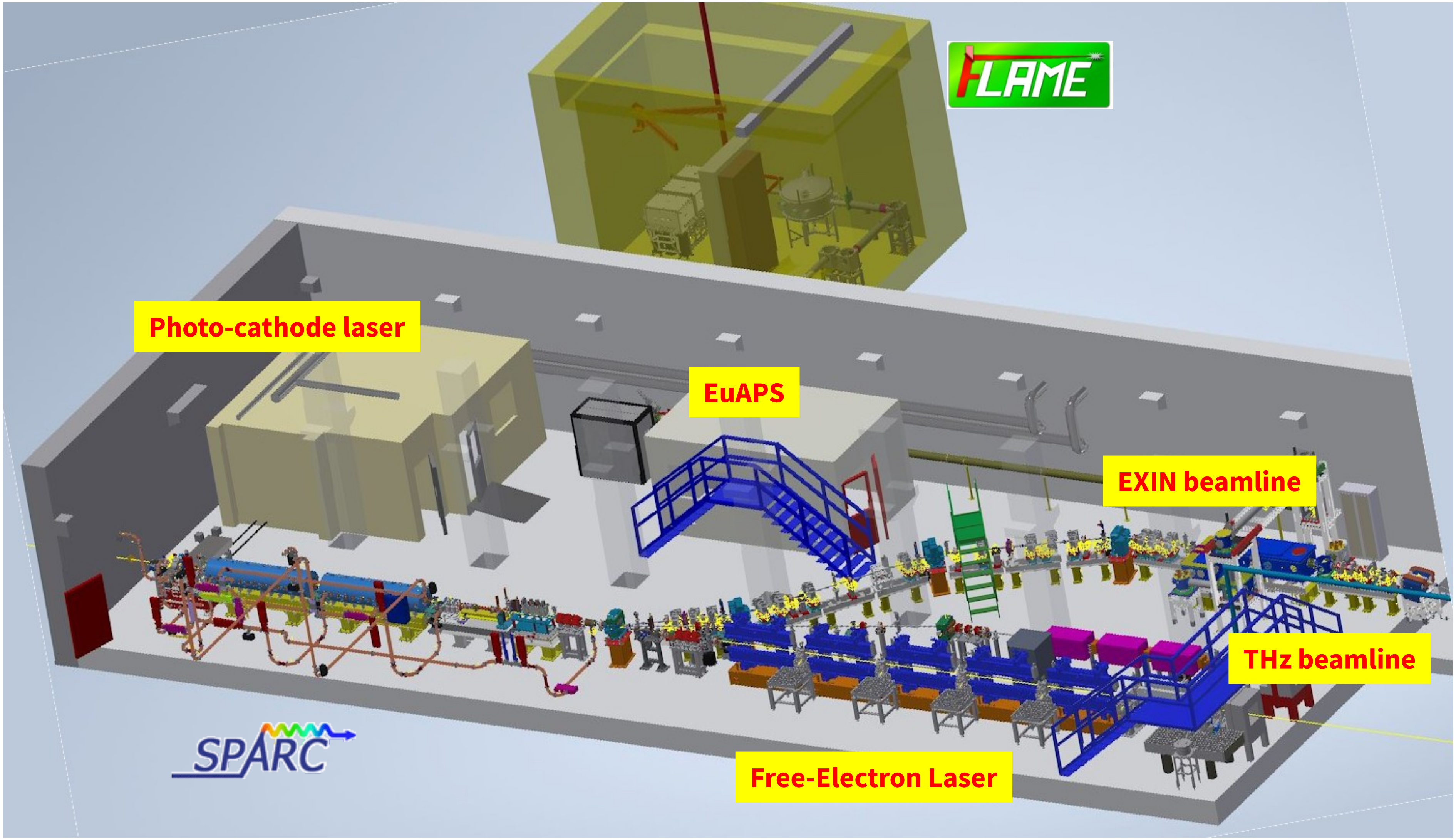


EuPRAXIA

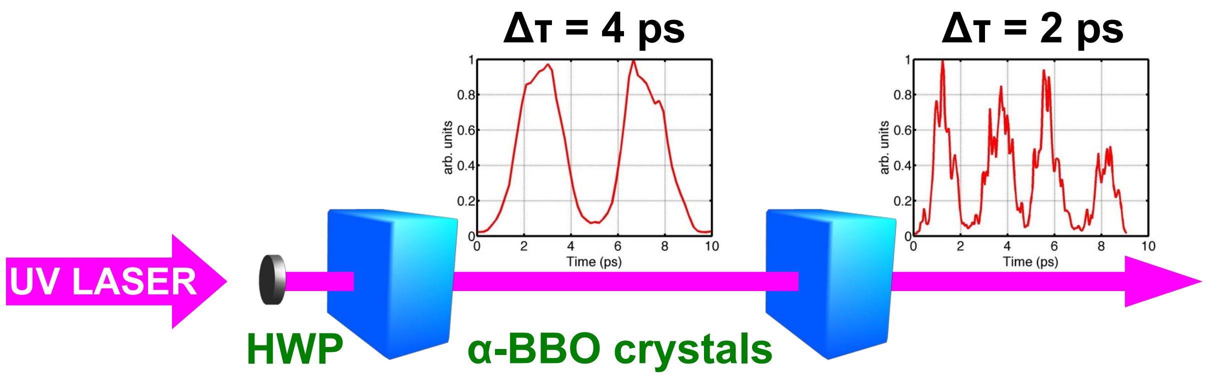
This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

SPARC_LAB facility



Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

Laser-comb technique



Ferrario, M., et al "Laser comb with velocity bunching: Preliminary results at SPARC." NIM 637.1 2011 S43-S46.

To generate the **driver** and **witness** bunches necessary for plasma acceleration we always used the laser-comb technique

Multi-bunch structure directly generated on the cathode by using a multi-pulse laser system

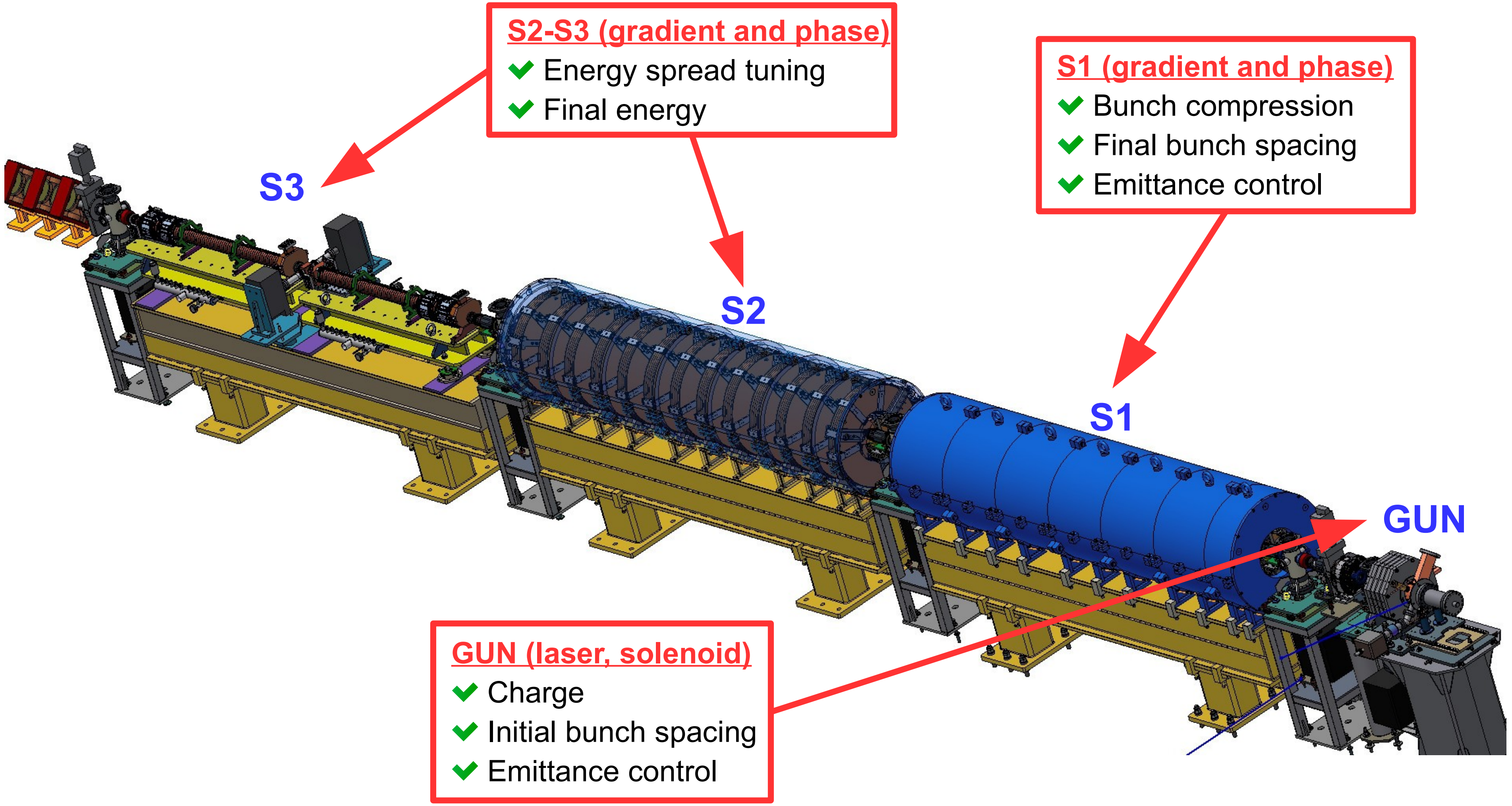
The laser pulses can be tuned in energy, distance and durations

→ the corresponding electron bunches are tuned in charge, distance, durations!

It's a robust technique used so far for multiple purposes (plasma acceleration, THz radiation, test of advanced diagnostics, etc.)

Villa, F., et al. "Laser pulse shaping for multi-bunches photo-injectors." NIM A 740 (2014): 188-192.

Accelerator tuning knobs



Chiadroni, E., et al. "Characterization of the THz radiation source at the Frascati linear accelerator." RSI 84.2 2013
Mostacci, A., et al. "Advanced beam manipulation techniques at SPARC."Proceedings of IPAC2011

Electro-Optical Sampling

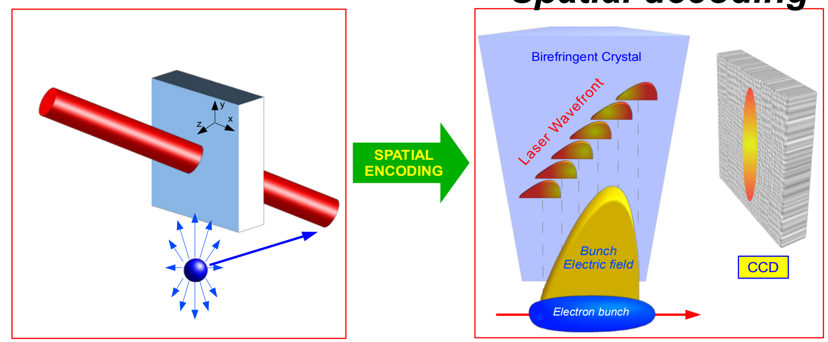
Multi-bunches trains have been measured with Electro-Optical Sampling

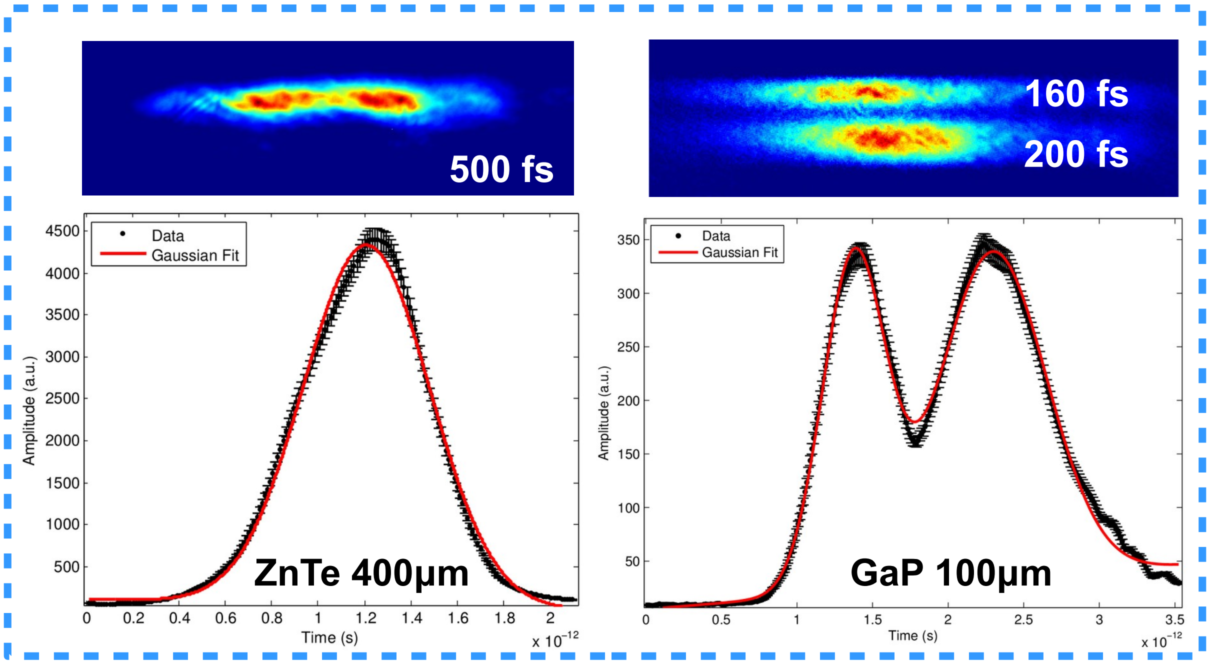
Single-shot, non-intercepting

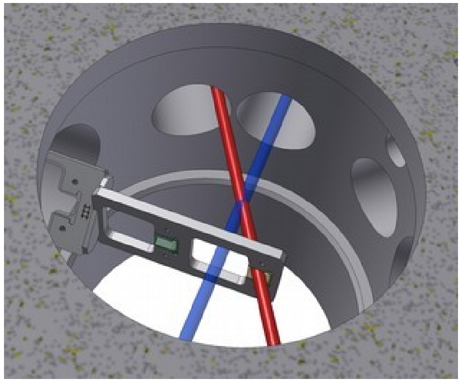
80 fs (rms) temporal resolution

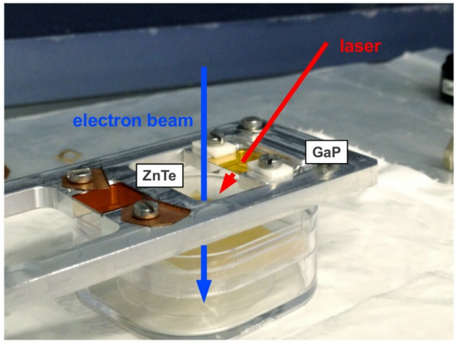
Goal: monitor beam injection in plasma

Spatial decoding



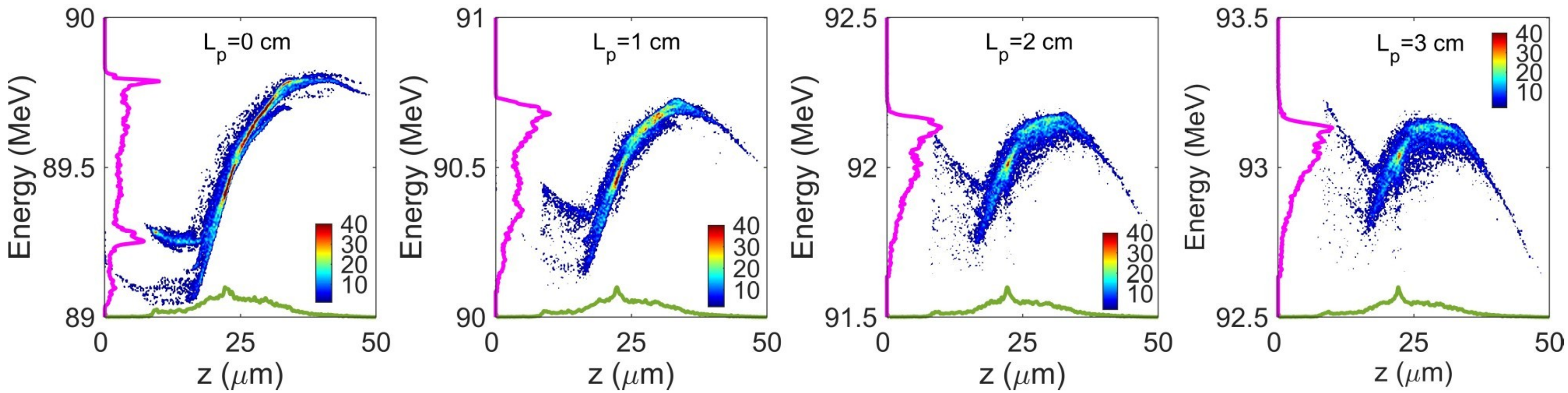






R. Pompili, et al., NIM A: Accelerators. 740, 216 (2014).

Energy spread control in PWFA



nature physics
LETTERS
https://doi.org/10.1038/s41567-020-01116-9
Check for updates

Energy spread minimization in a beam-driven plasma wakefield accelerator

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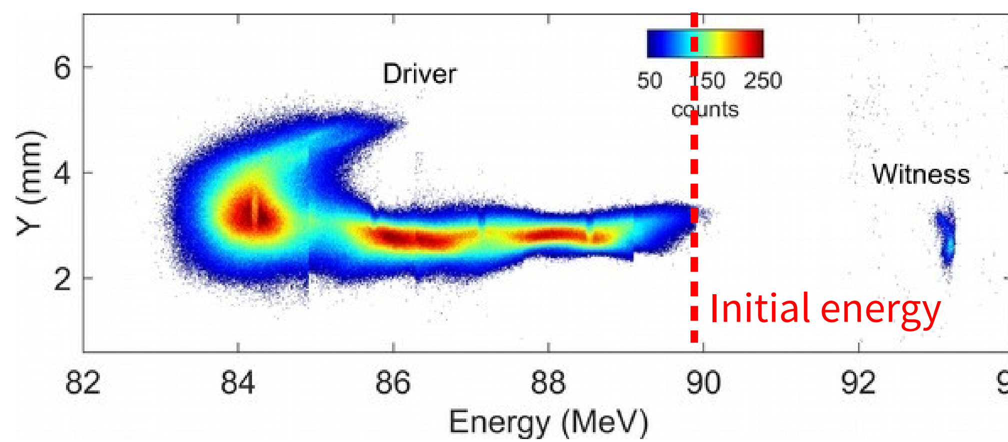

SPARC LAB

FEL lasing with plasma-accelerated beam

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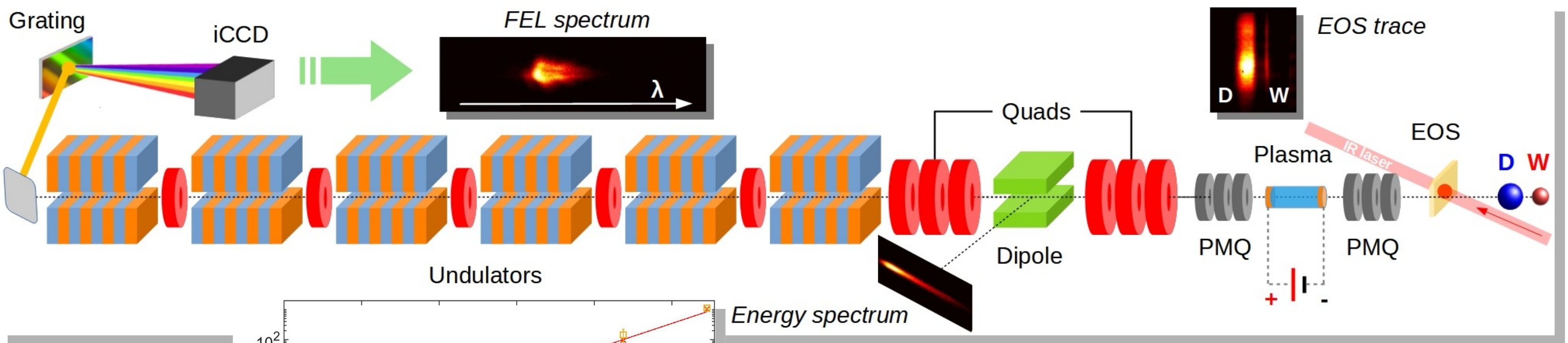

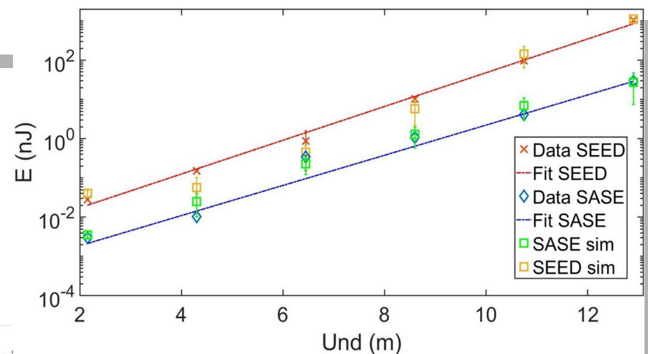

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Free-electron lasing with compact beam-driven plasma wakefield accelerator

R. Pompili, D. Alesini, ... M. Ferrario + Show authors

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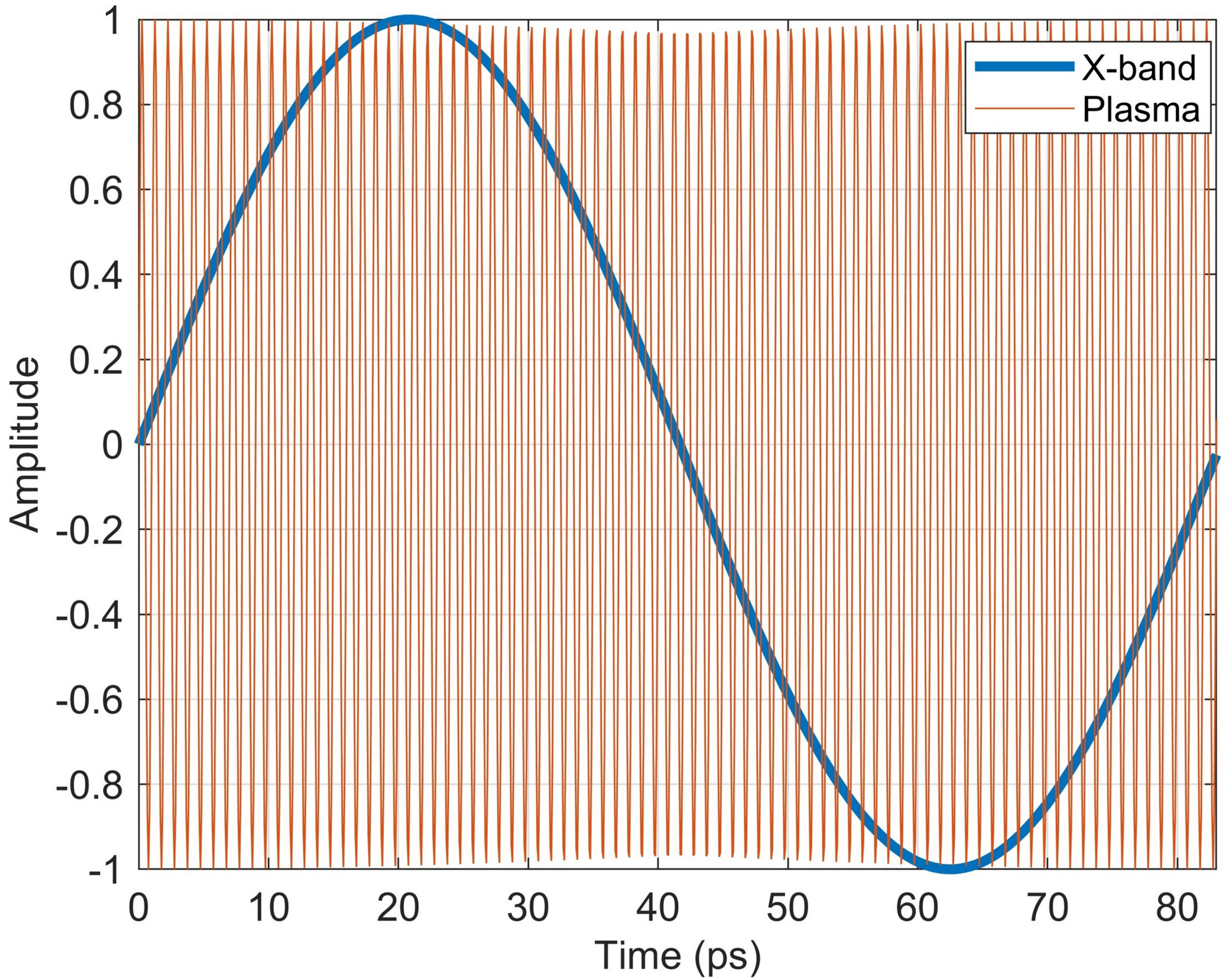
Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator

M. Galletti *et al.*

Phys. Rev. Lett. **129**, 234801 – Published 29 November 2022

A critical point: timing stability in plasma



Example: two-bunches for PWFA

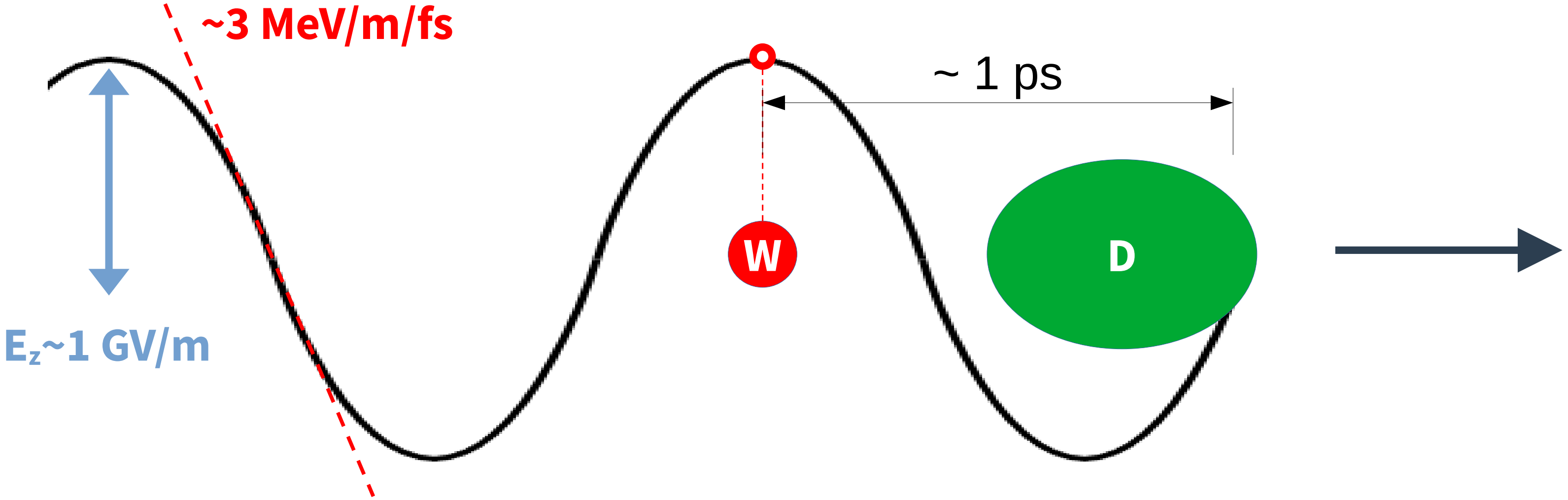
A typical configuration that is used at SPARC_LAB (and possibly will be implemented in EuPRAXIA) foresees the generation of a driver-witness beam configuration with the following parameters

Charge: 400 pC (driver) + 50 pC (witness)

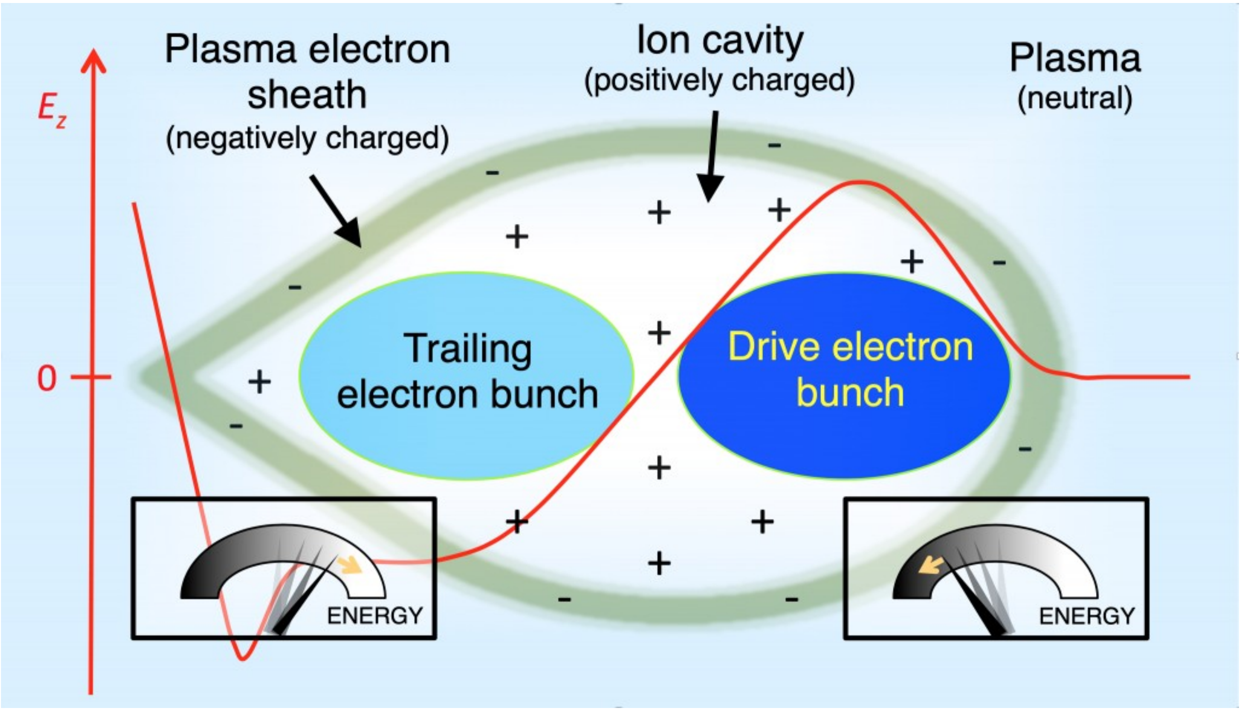
Distance: ~1 ps (corresponding to ~3/4 of the plasma oscillation period).

Durations: as short as possible (typically ~100-200 fs for the driver and <30 fs for the witness)

Witness behind driver (in order to be accelerated by the plasma wakefield excited by the latter)



A more realistic picture



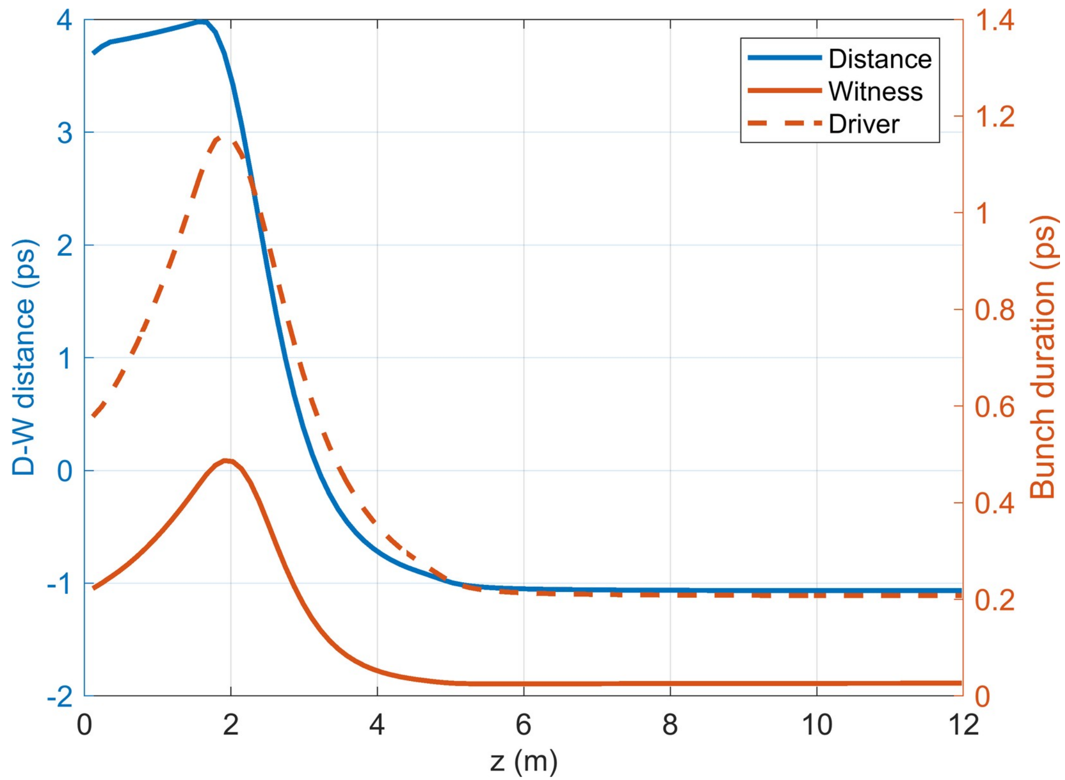
https://loa.ensta-paris.fr/research/upx-research-group/particle-beam-driven-plasma-wakefield-acceleration/

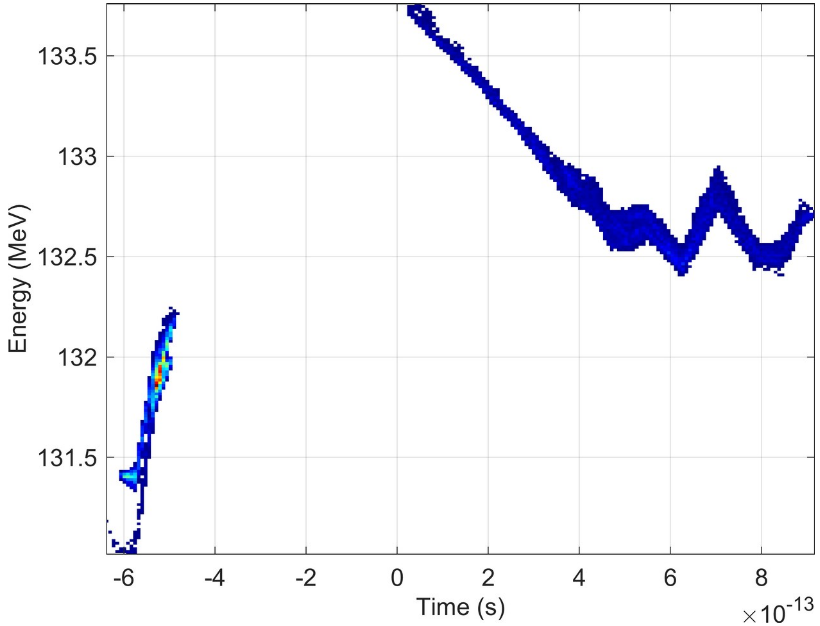
In nonlinear plasma wakefield regimes the behavior is not sinusoidal!

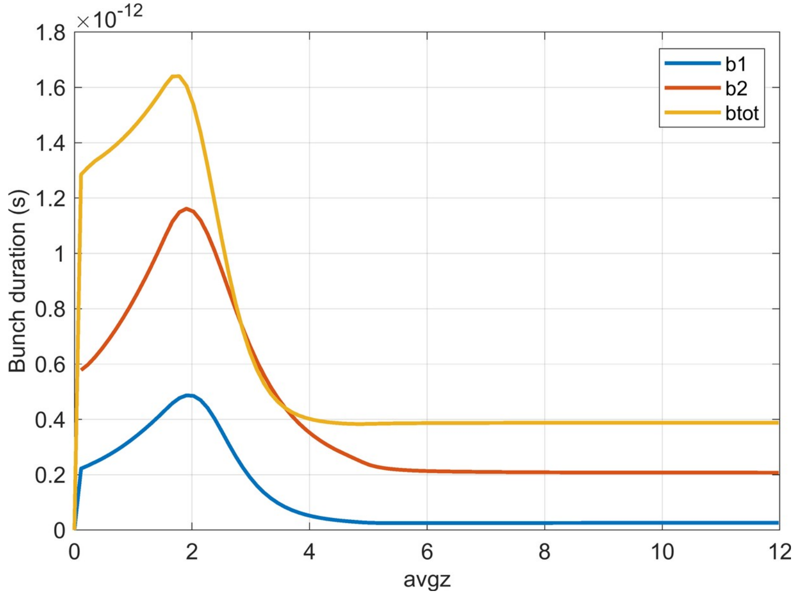
The slope becomes larger close to the plasma “bubble” tail → 3 MeV/m/fs can be considered a lower bound

Witness beam-loading effects makes the picture even more complicated...

Generation of the driver-witness bunches







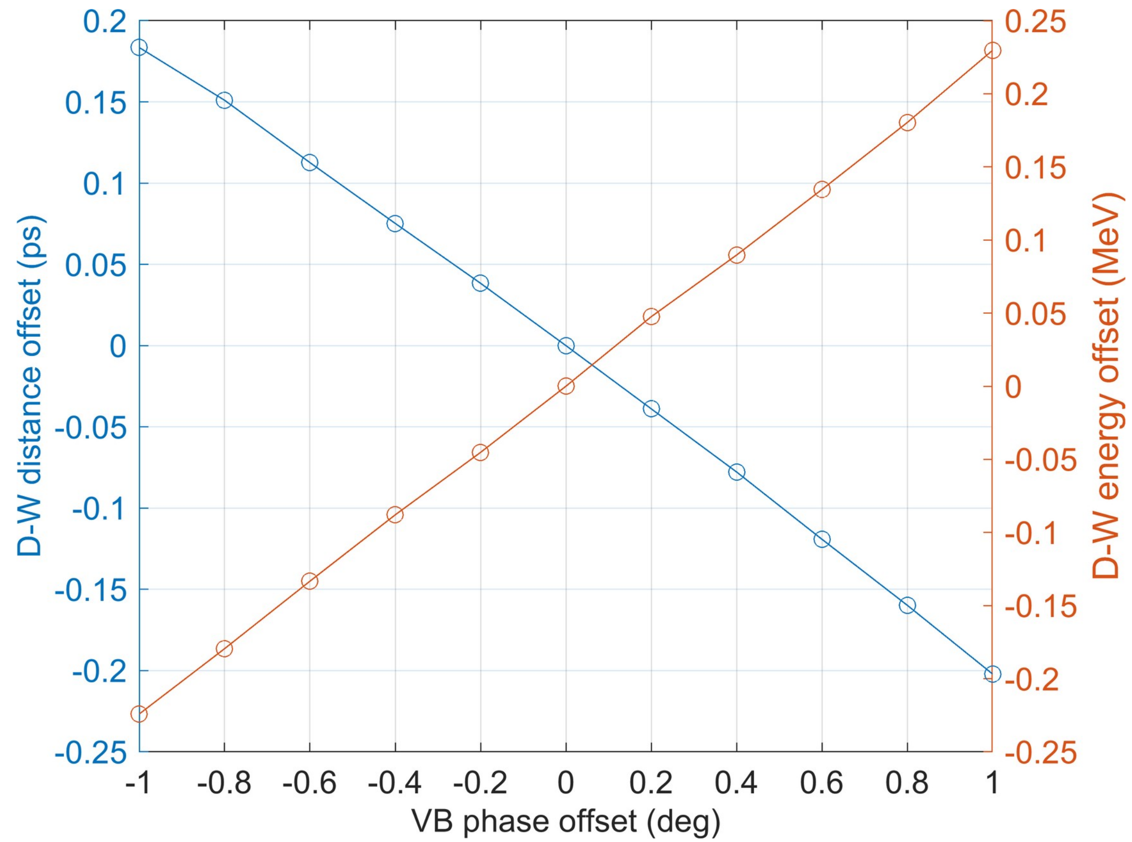
Two delayed (4 ps) laser pulses are sent to the cathode

Witness is photo-emitted in advance with respect to the driver

S1 RF phase is set at -90° (wrt on-crest phase) → velocity-bunching longitudinal compression takes place

During the VB process, the driver-witness bunches are shortened and their positions are swapped → witness behind the driver

Laser-RF timing jitter effects



Effects of RF phase-jitter on the driver-witness distance

1° offset → ~220 fs change in the D-W distance

Considering the plasma wakefield slope (~3 MeV/m/fs) and a state-of-the-art RF jitter of ~0.02° →

~5 fs D-W distance jitter → ~15 MeV energy jitter for a witness accelerated in 1 m long plasma

Laser-RF timing jitter effects

The RF timing-jitter also affects the bunch durations during the velocity-bunching process

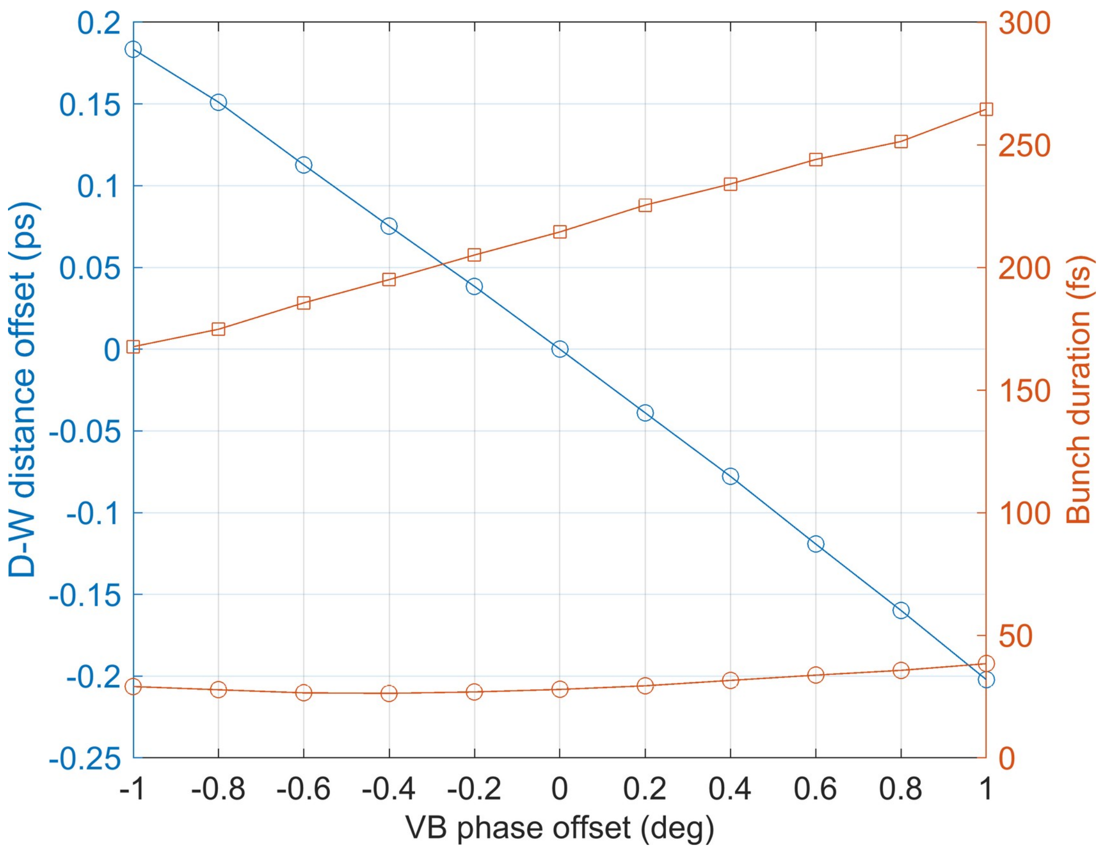
This translates in an additional plasma wakefield jitter since

$$E_z \propto I_{driver} \propto \frac{1}{\sigma_{t,D}^{1/3}}$$

In this case 1° RF phase offset increase/decrease the driver duration by ~ 50 fs

Considering again a state-of-the-art RF jitter of ~0.02° → ~0.3% plasma wake amplitude jitter

→ 3 MeV energy jitter with 1 m plasma



Conclusions

Plasma wakefield acceleration (PWFA) enables GV/m accelerating gradients overcoming RF accelerator technology by orders of magnitude

Proof-of-principle experiments demonstrated the huge gradients, recent developments demonstrated higher beam-quality

However, beam-driven PWFA still requires a conventional RF linac upstream of the plasma

→ very demanding requirements in terms of phase-stability and beam brightness

Few fs timing-jitters can produce tens of MeV energy jitter downstream of the plasma → too large if compared with currently operating facilities (e.g. for FEL)

Need to push phase-stability beyond state-of-the-art

Thanks!

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