The FLASHForward ▸ ▸ experiment at DESY

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DESY.

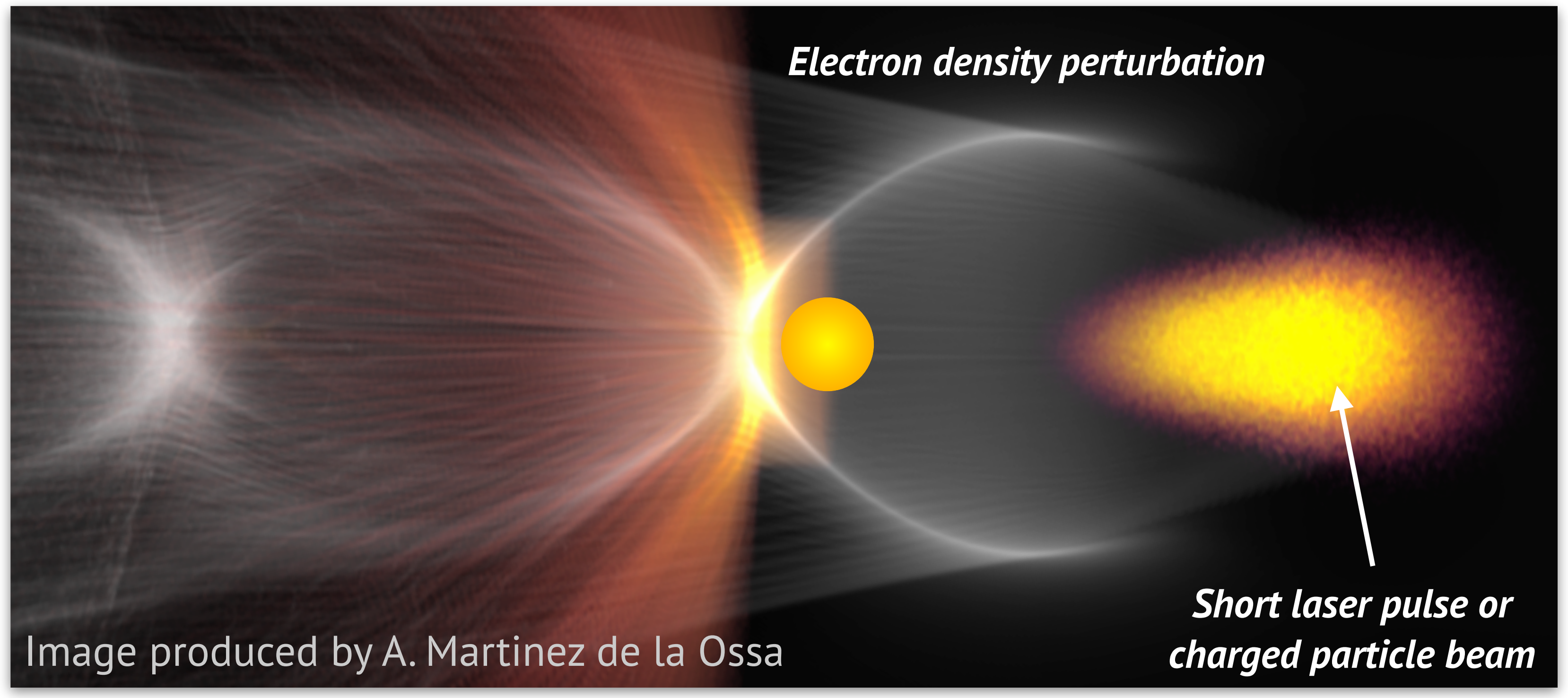
Plasma accelerators

> Conventional accelerators based on **RF-cavities** have been the backbone of accelerator science over the past 70 years.

> Extremely reliable, successful and well-understood.

> Accelerating gradients limited by electrical breakdown to ~ **100 MV/m.**

> **Plasma-based accelerators** (PBAs) represent a disruptive development due to the ability of plasma to support field strengths of order **1-100 GV/m.**

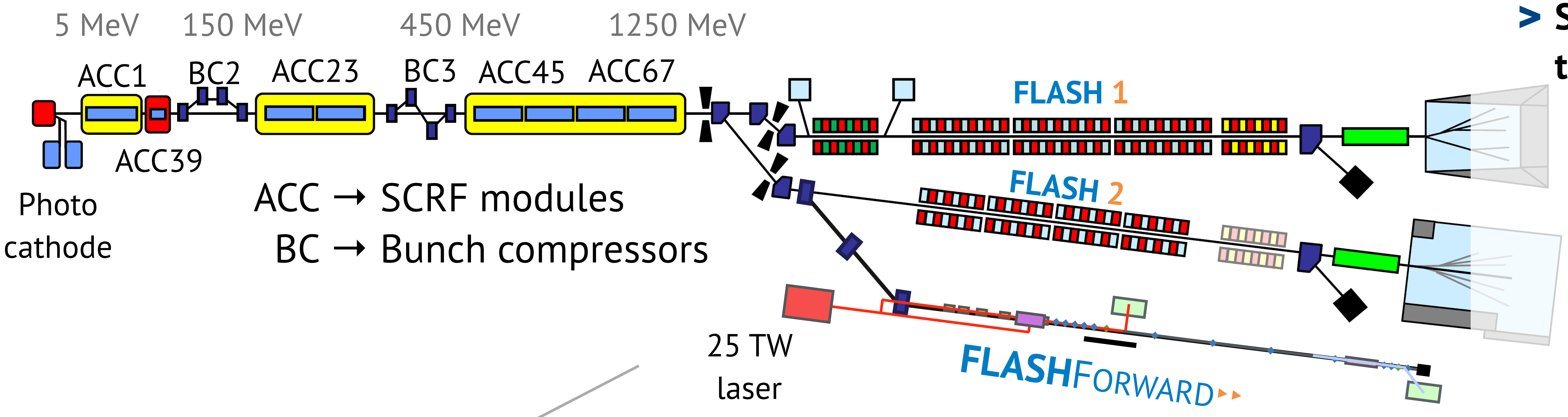


> Plasma acts as an **energy transformer**, enabling the transfer of energy from a drive beam to a trailing "witness" bunch.

> Has the potential to reduce size and cost of accelerator facilities by orders of magnitude.

FLASHForward▸▸: The Facility

FLASHFORWARD▸▸: The Facility



> **Superconducting accelerator based on ILC/XFEL technology**
- ≲ 1.25 GeV energy with ~nC charge at few 100 fs bunch duration
- ~2 μm trans. norm. emittance
- ~10 kW average beam power, MHz repetition rate in 10 Hz bursts
- Exquisite stability by advanced feedback/feedforward systems

> **Unique opportunities for plasma accelerator science**

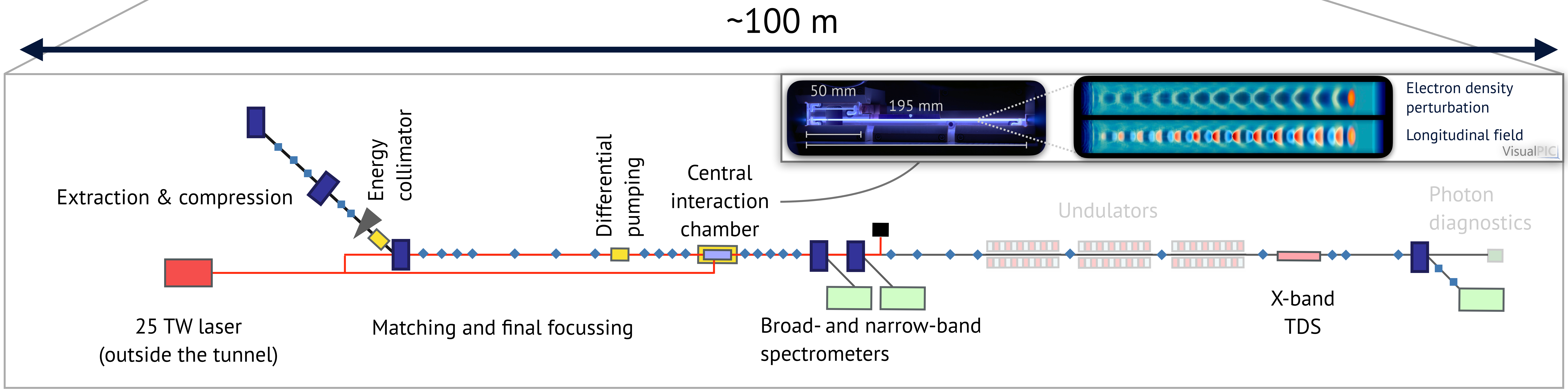


Image modified from R. D'Arcy *et al.*, Phil. Trans. R. Soc. A **377**, 20180392 (2019)

Primary goals of FLASHFORWARD ▸ ▸

Develop a self-consistent plasma-accelerator stage

with high efficiency, high quality, and high average power

High efficiency

Driver depletion

Transfer efficiency

High beam quality

Low energy spread

Emittance preservation

High average power

Recovery time

High repetition rate

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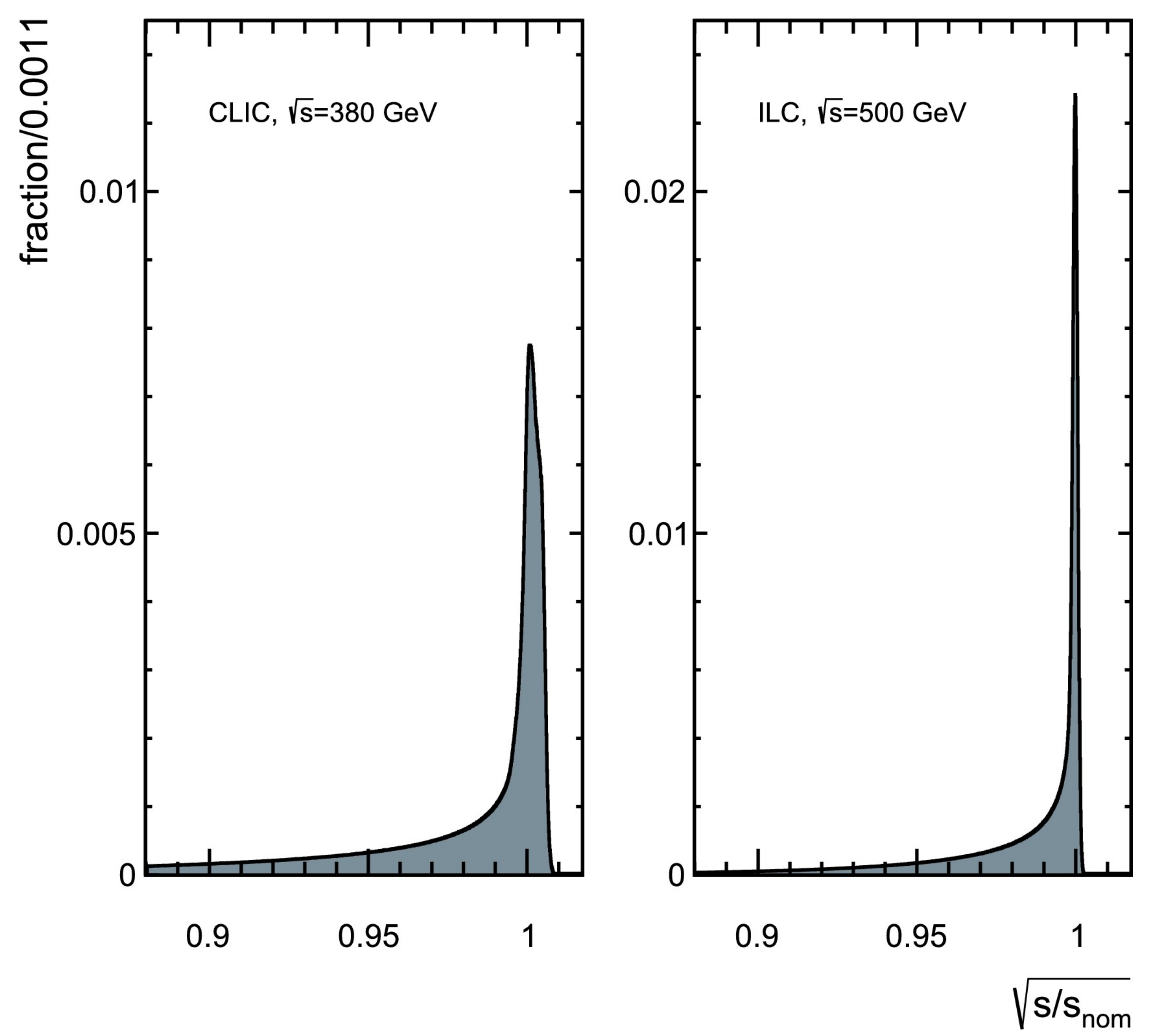
Applications require high quality at highest efficiency

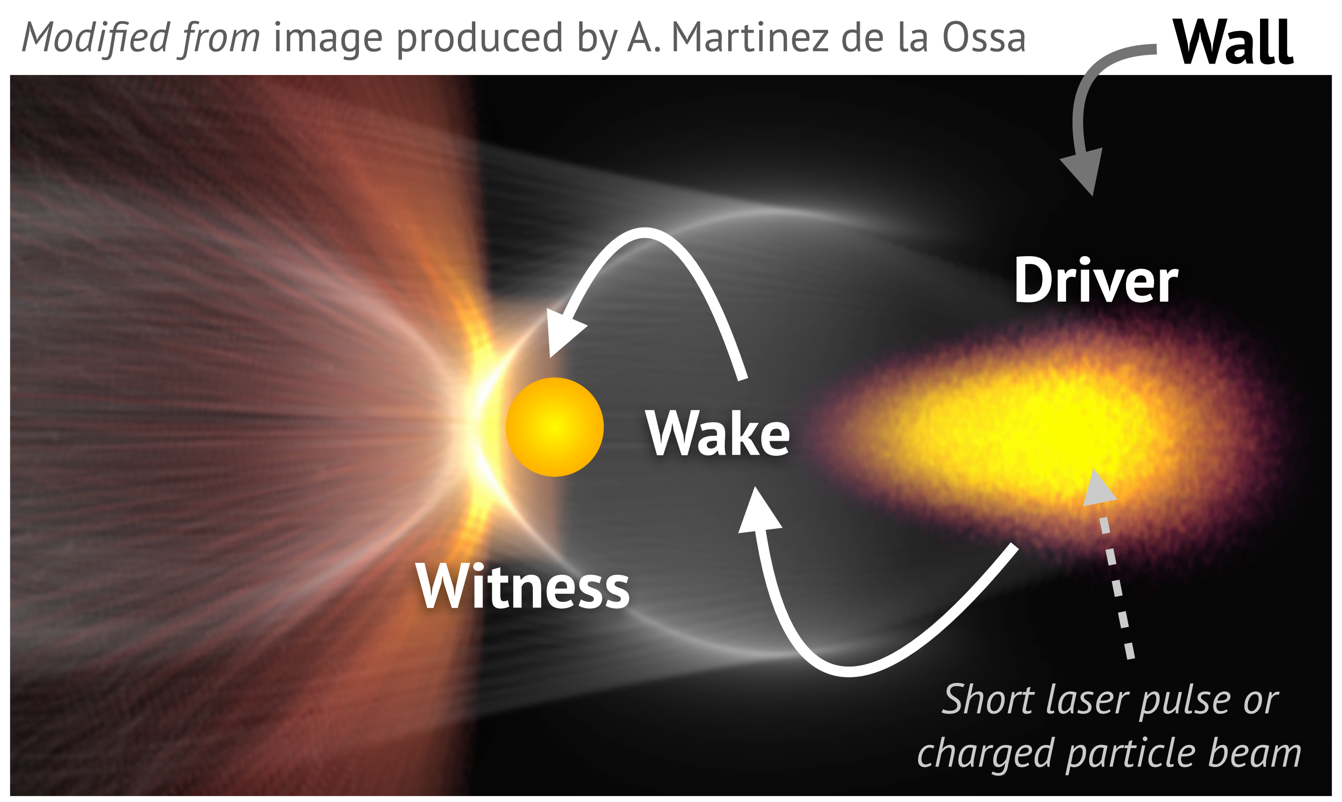
- **Beam quality: requirements depend on application but in general,**
  - Linear colliders (< 1% energy spread, ε_N ~ 0.01 mm mrad) – to reach *high luminosity* with a narrow spectrum.
  - Free-electron lasers (0.1% energy spread, ε_N ~ 1 mm mrad) – to reach *high brightness*.

- **Efficiency: need to maximise transfer of energy from the wall to the accelerating beam.**
  - Wall ➞ Driving beam
  - Driving beam ➞ Plasma wakefield
  - Plasma wakefield ➞ Witness beam



Luminosity distribution across collision energies.
M. Boronat *et al.*, Phys. Lett. B **804**, 135353 (2020)

Illustration of primary energy transfer mechanisms
Modified from image produced by A. Martinez de la Ossa



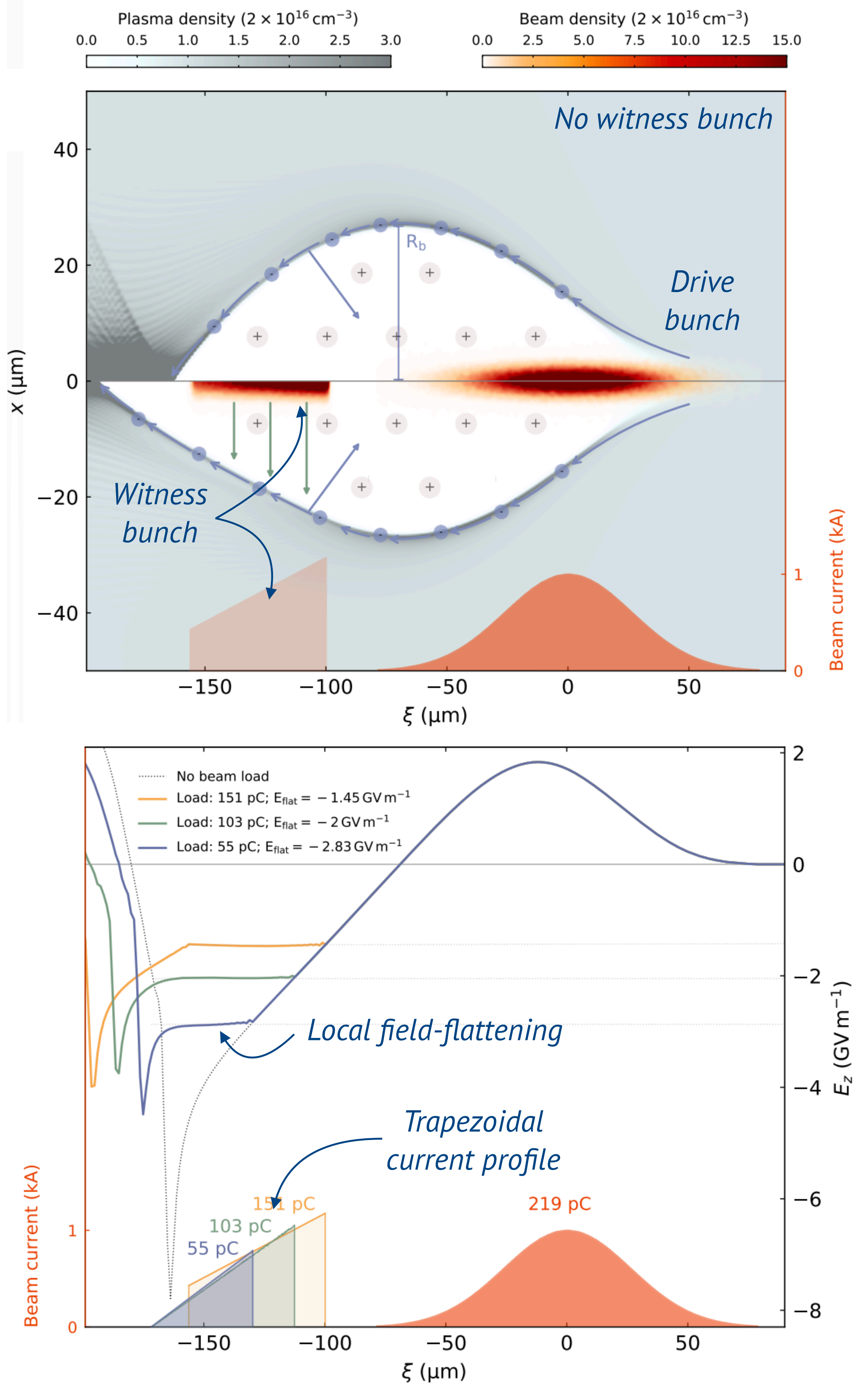
Applications require high quality at highest efficiency

> **Solution: "beam-loading"** M. Tzoufras *et al.*, Phys. Rev. Lett. **101**, 145002 (2008)

> **Drive bunch "depletion":** extract maximum energy from drive bunch by
  > Tailoring plasma density profile.
  > Shaping current profile to **minimise re-acceleration** of drive electrons.

> **Witness bunch:** extract maximum energy from plasma wake by
  > Modifying trajectories of returning plasma electrons.
  > Shaping current profile to **locally flatten longitudinal wakefield**.

The principle of beam-loading
S. Schröder, PhD Thesis, Uni. Hamburg (2021)



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Demonstration of drive bunch depletion via plasma density optimisation

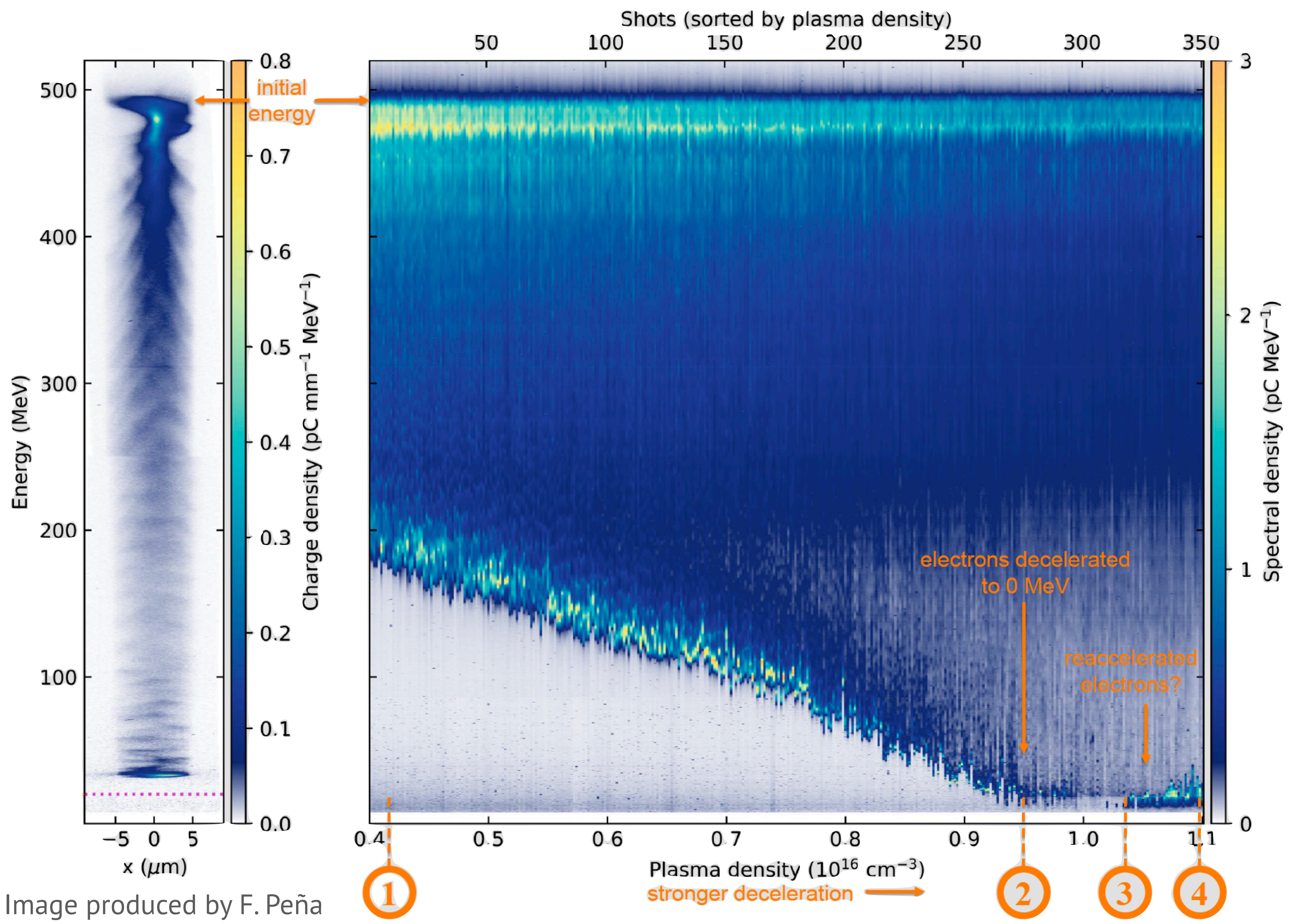

Image produced by F. Peña

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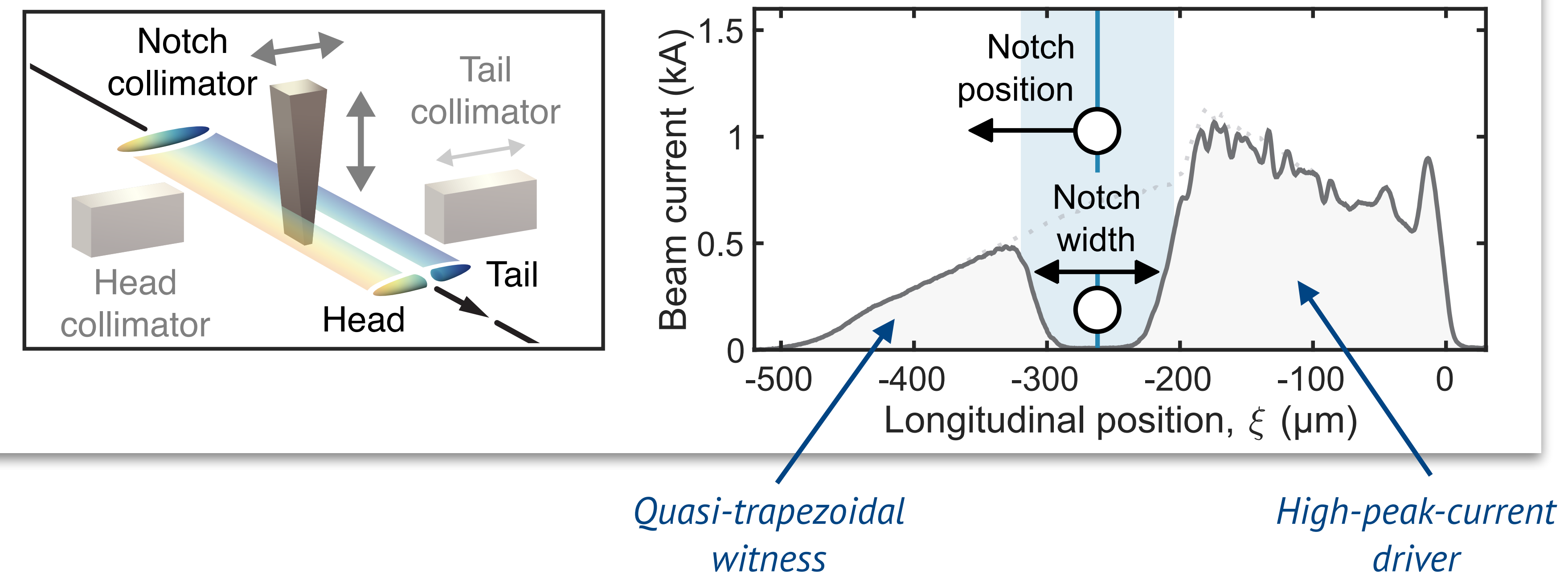
    - Modifying trajectories of returning plasma electrons. ✔
    - Shaping current profile to **locally flatten longitudinal wakefield.** ✔

- Experimentally demonstrated **energy-spread preservation**, in combination with **100% charge coupling, 1.3 GV/m** average accelerating gradient and instantaneous energy transfer efficiency of **(42±4)%**.
  - C. A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)

Precise control of drive & witness bunch current profiles

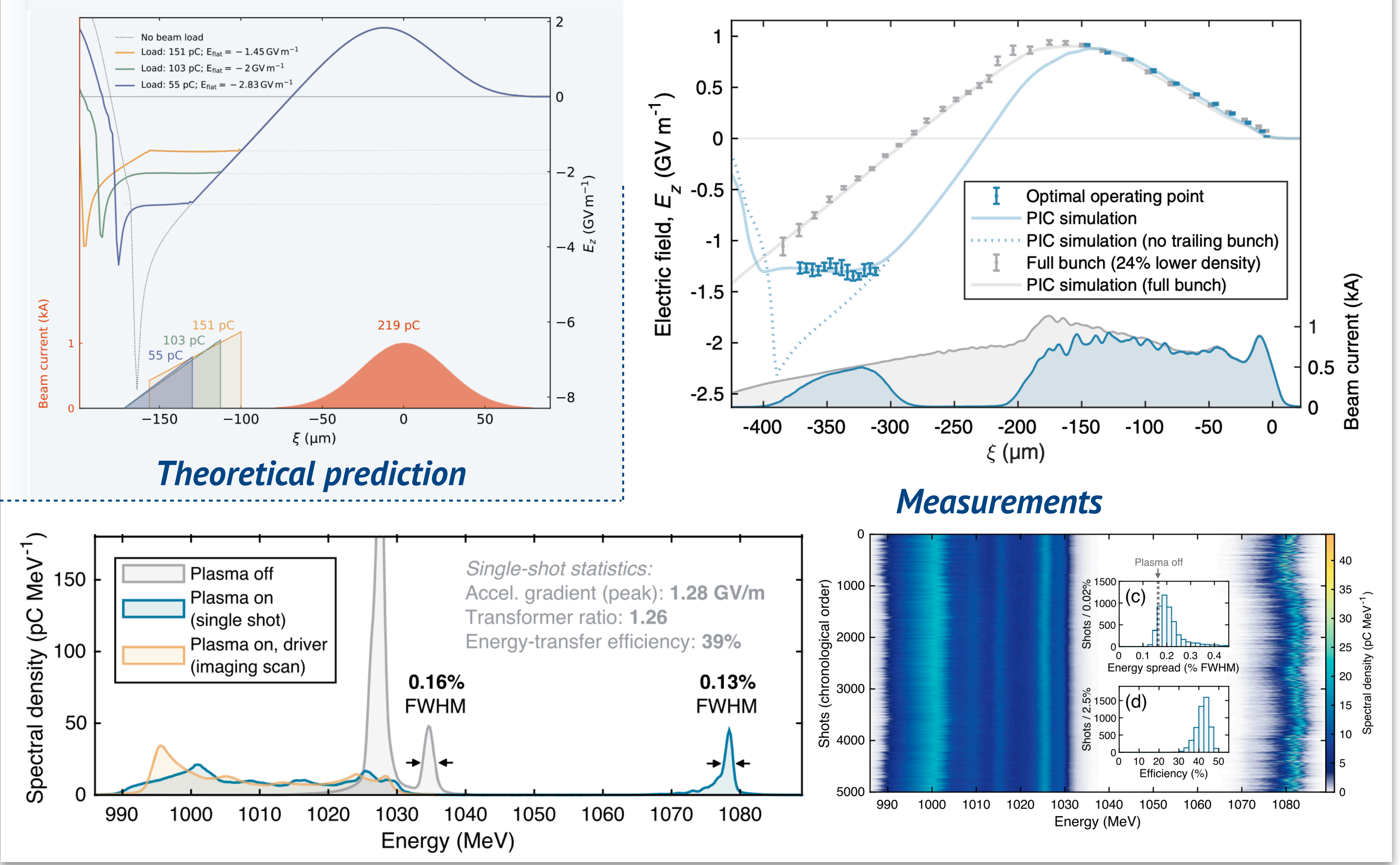
S. Schröder *et al.*, J. Phys.: Conf. Ser. **1596**, 012002 (2020)



Measurement of optimal beam-loading, demonstrating energy-spread preservation

C. A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)

Wakefield measurement technique: S. Schröder *et al.*, Nat. Commun. **11**, 5984 (2020)



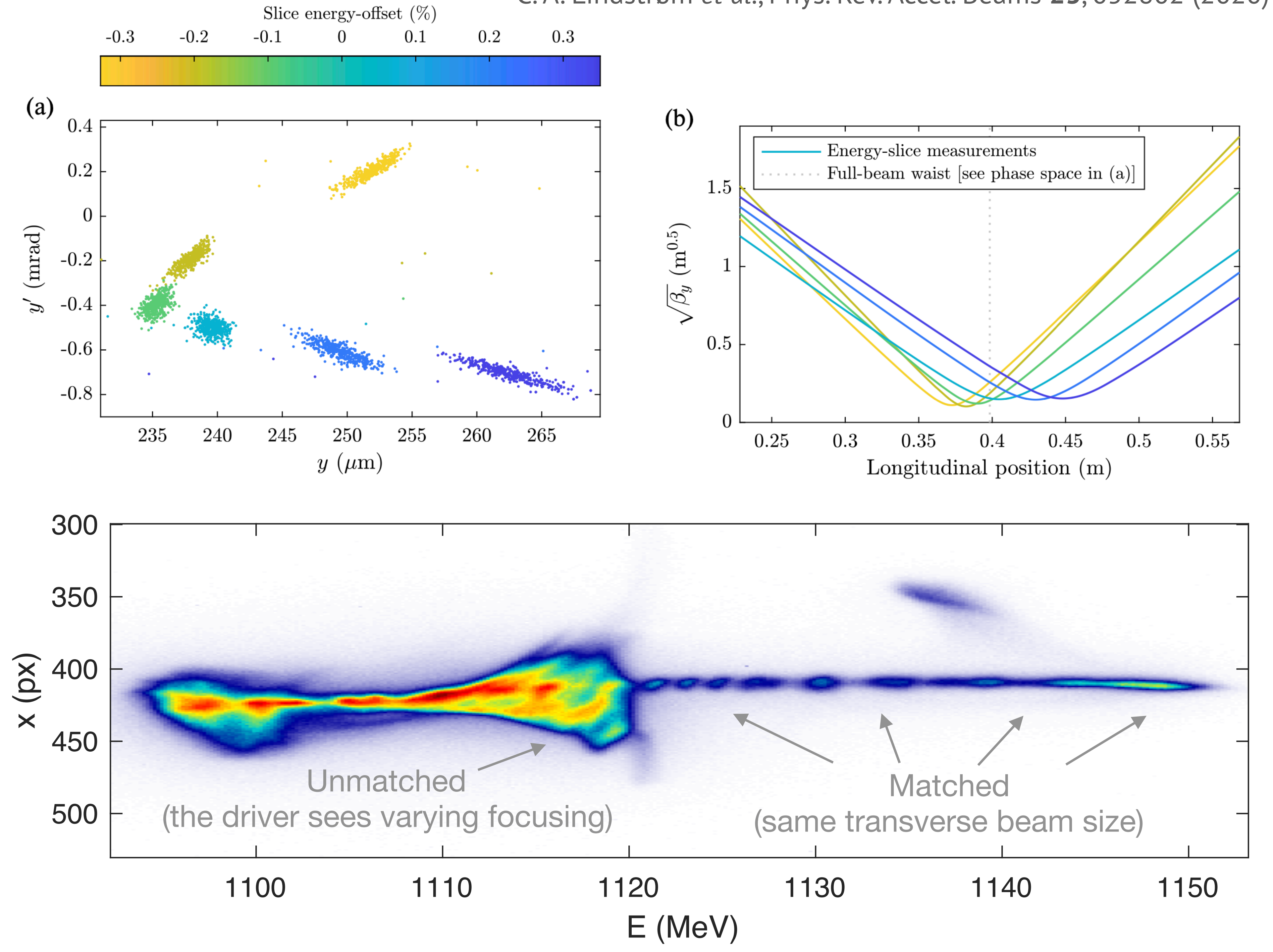
Applications require high quality at highest efficiency

> **Next step:** demonstrate **emittance preservation** during acceleration. Requires:

- > Careful **matching** of the beam into the plasma accelerator to avoid phase-space dilution.
- > **Well-aligned, straight beams** to avoid seeding transverse instabilities and beam break-up.

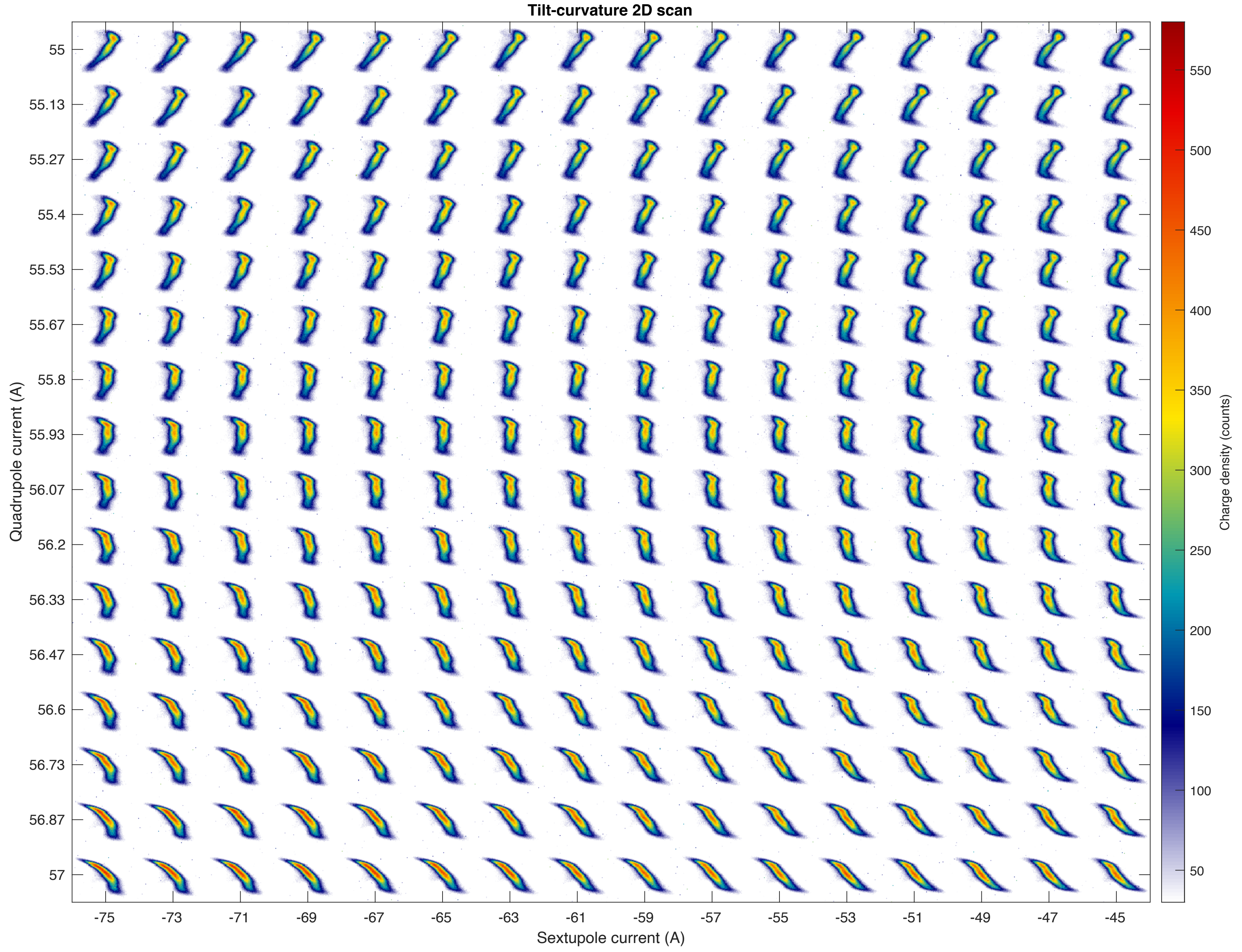
Novel techniques to reconstruct slice-dependent focusing

C. A. Lindstrøm *et al.*, Phys. Rev. Accel. Beams **23**, 052802 (2020)



Diagnosing beam tilts and curvature with X-band transverse deflecting structure

B. Marchetti *et al.*, Sci. Rep. **11**, 3560 (2021)



Primary goals of FLASHFORWARD ▸ ▸

Develop a self-consistent plasma-accelerator stage
with high efficiency, high quality, and high average power

High efficiency
Driver depletion ✓
Transfer efficiency ✓

High beam quality
Low energy spread ✓
Emittance preservation

High average power
Recovery time
High repetition rate

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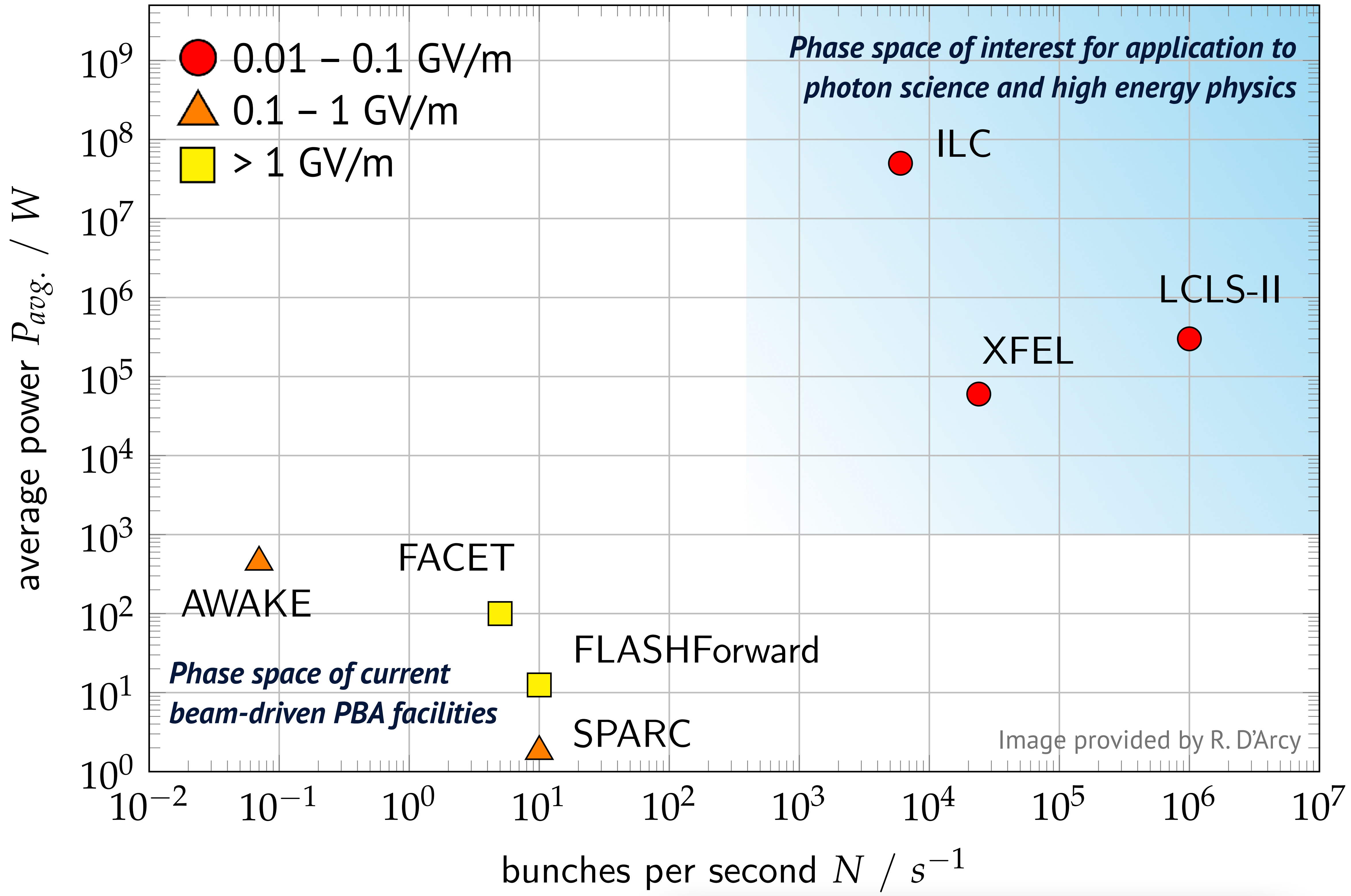
High-average-power operation

> To be competitive with conventional accelerator facilities need joule-level accelerators at kHz repetition-rates and beyond.

> Current state-of-the-art plasma-based accelerator (PBA) facilities are orders of magnitude below this.



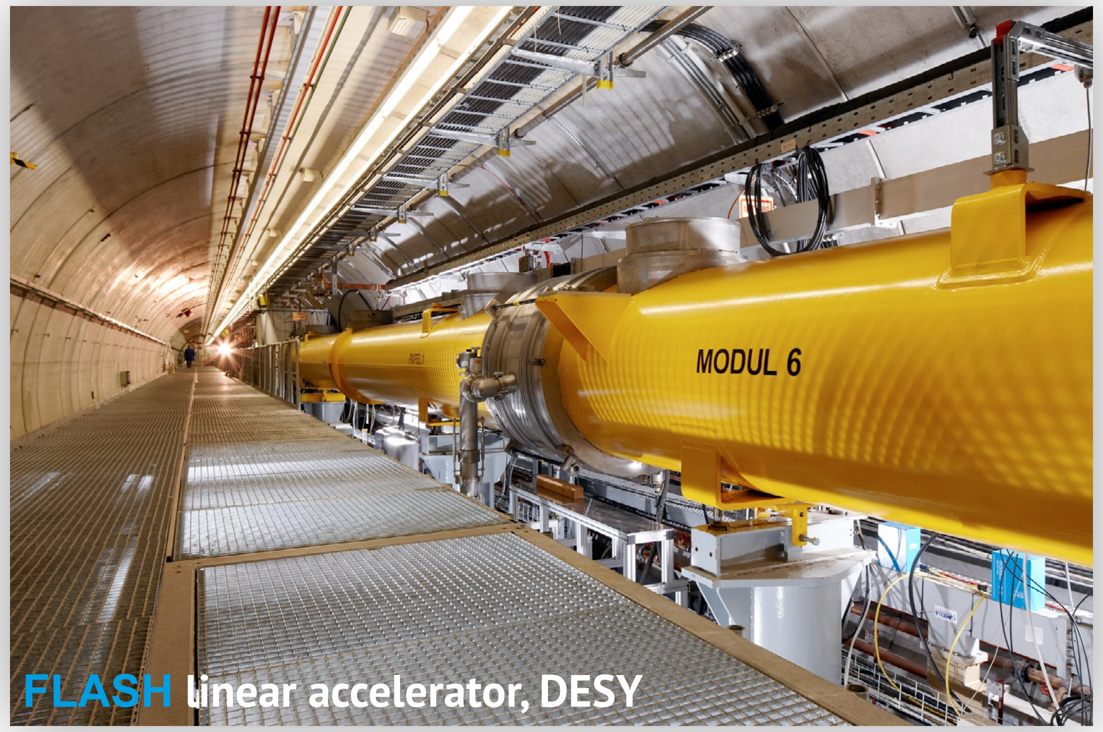
What is the most efficient way to achieve this?

> For ***beam-driven PBAs:*** compatibility with RF front-end that provides the bunches for wakefield acceleration.

E.g. **FLASH** linear accelerator at DESY (up to 1.25 GeV, 1 nC e- bunch):

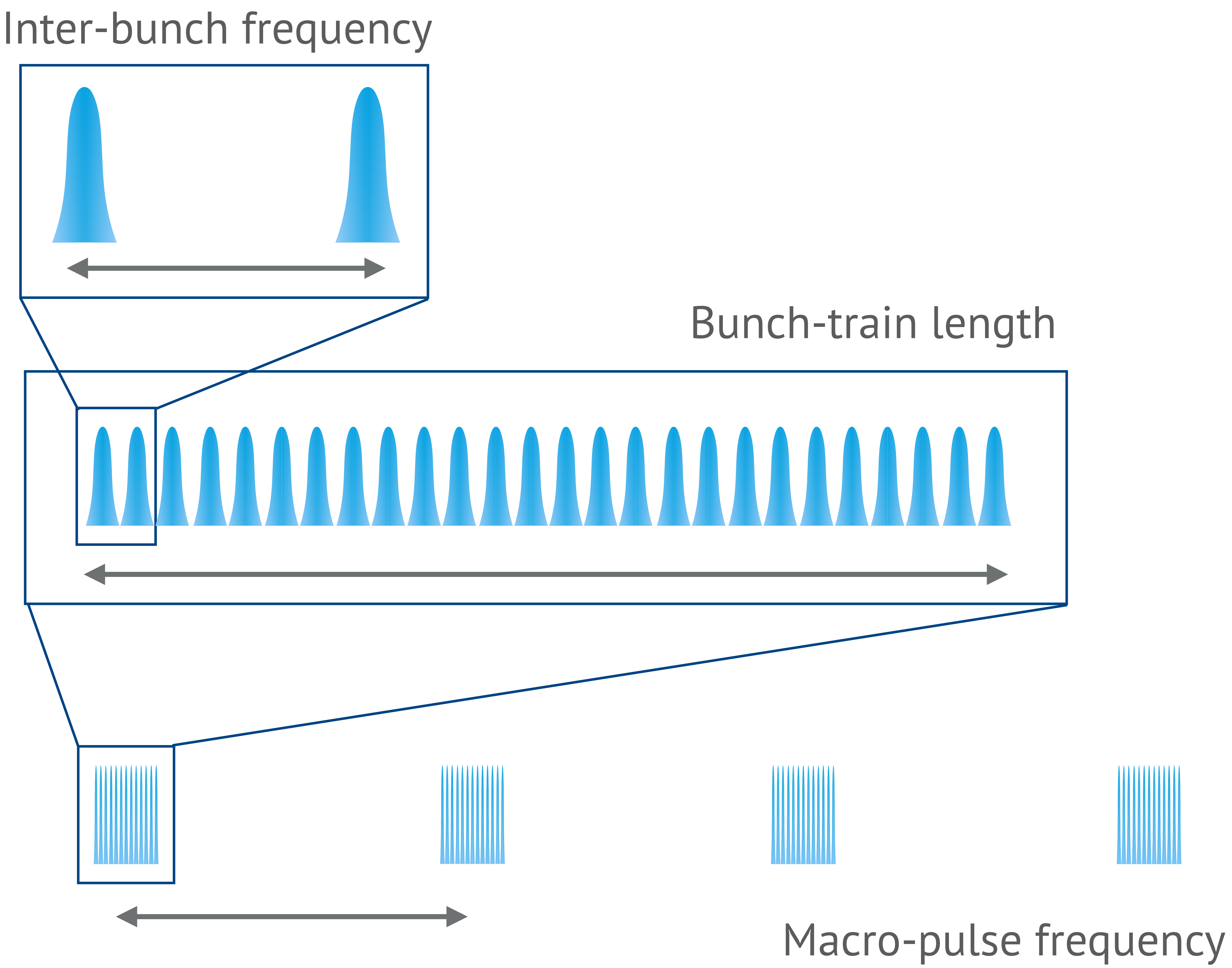
> Trains of hundreds of *O*(μs)-separated electron bunches at 10 Hz macro-pulse repetition-rate; up to 18,000 bunches per second.

Can this bunch pattern be compatible with plasma-based acceleration?



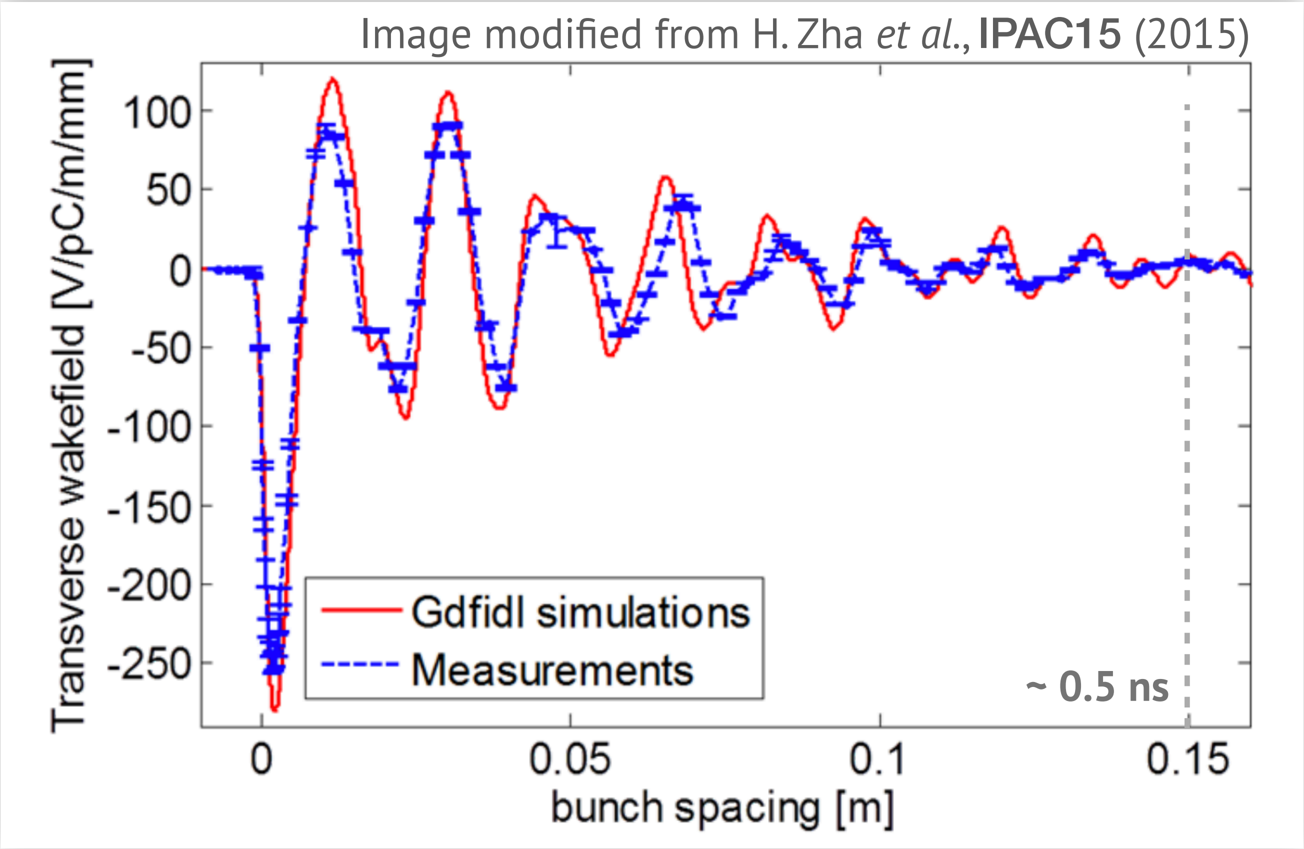
FLASH linear accelerator, DESY

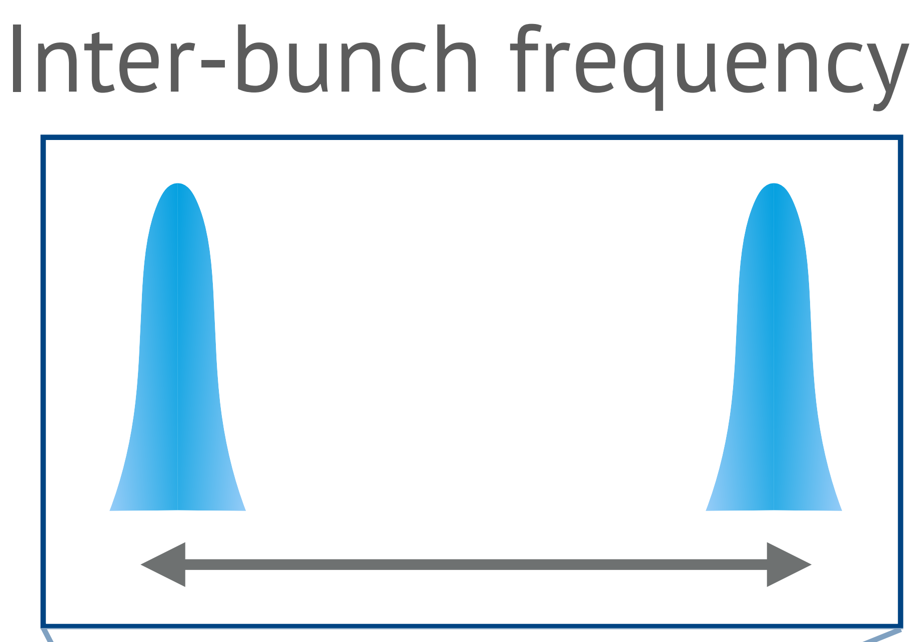
Conventional accelerators

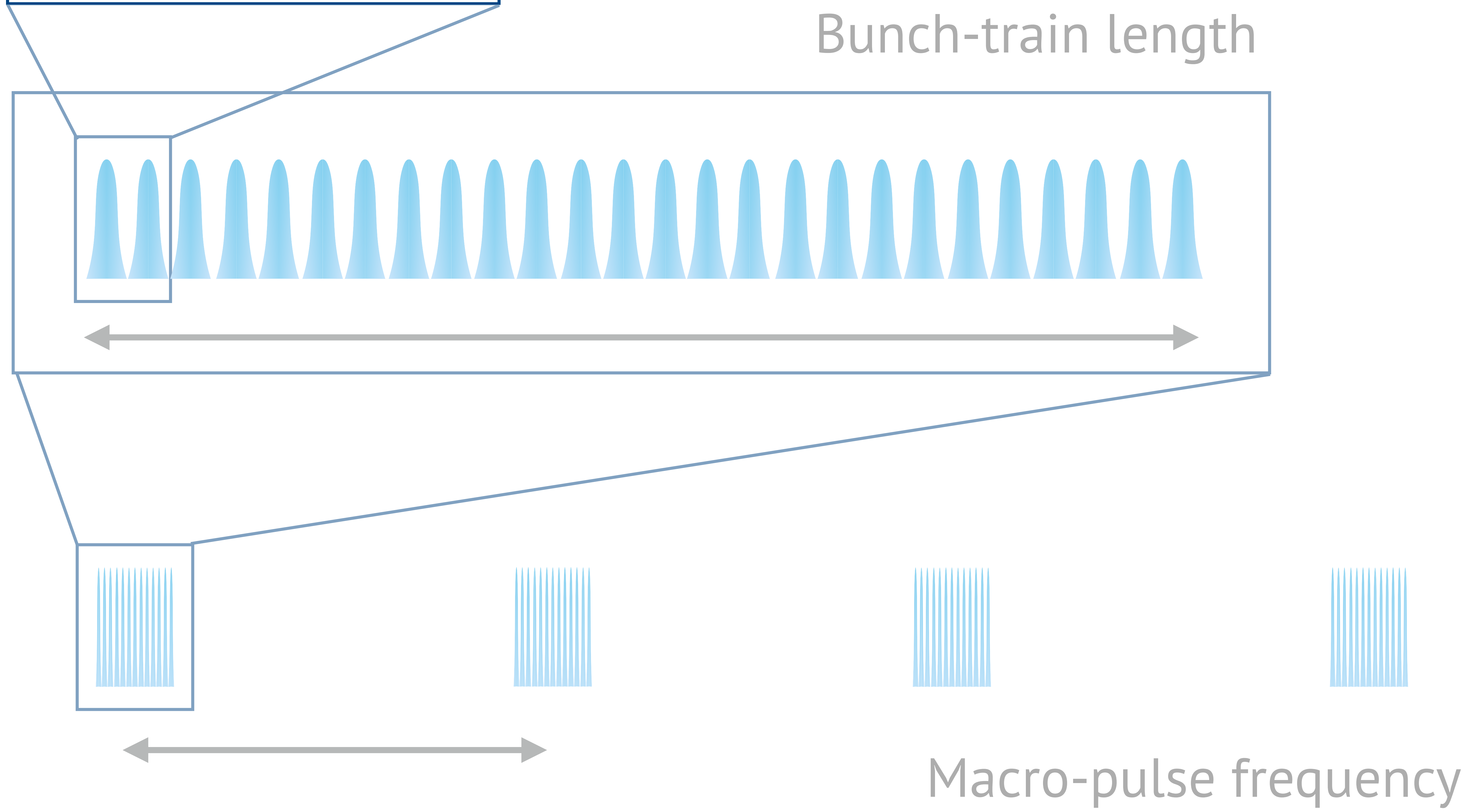


	FLASH	CLIC
Inter-bunch frequency	3 MHz	2 GHz
Bunch-train length	600 μs	156 ns
Macro-pulse frequency	10 Hz	50 Hz
Max. # of bunches per second	**18000**	**15600**

Conventional accelerators







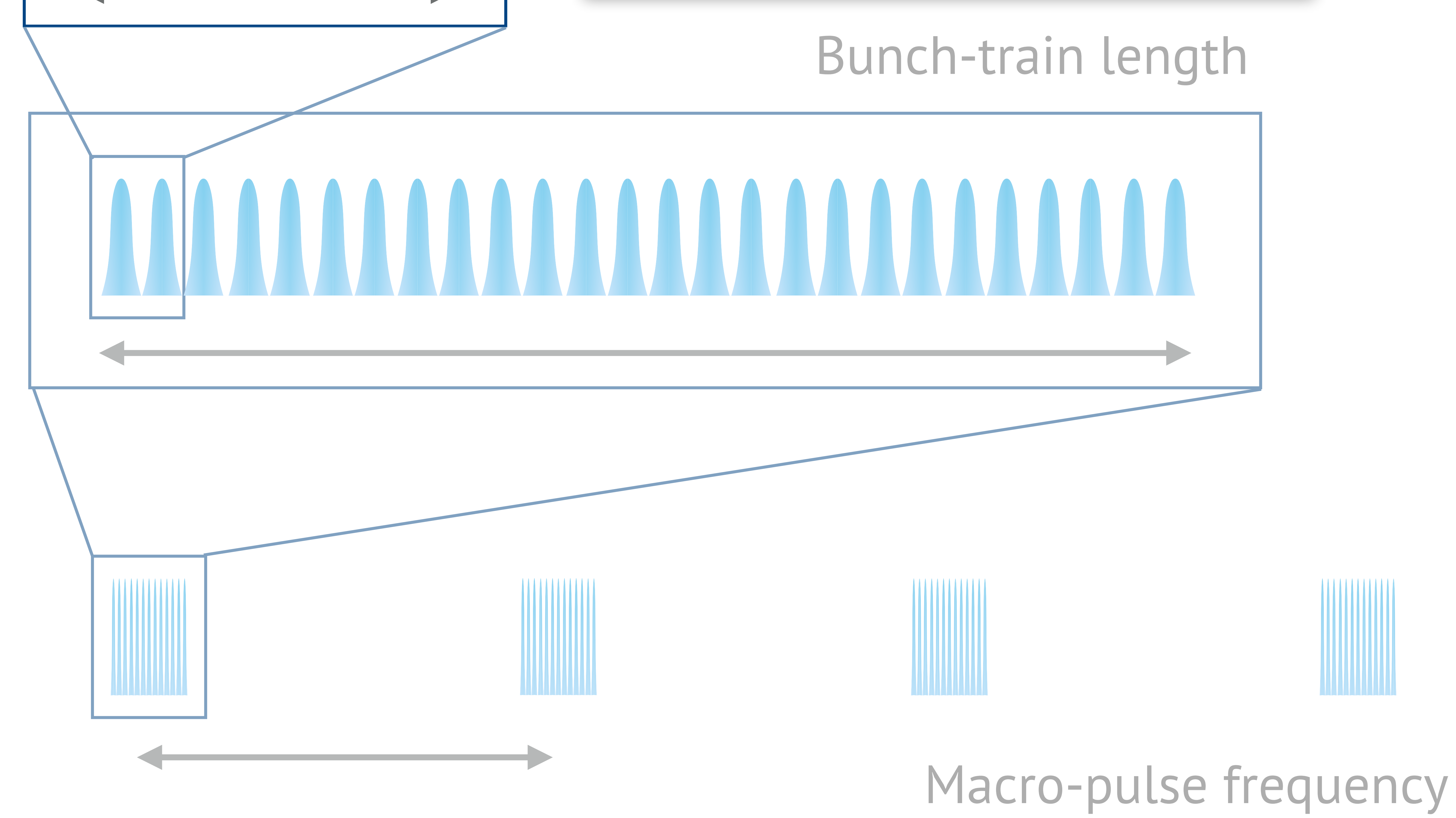
E.g. CLIC X-band (~ 12 GHz) accelerating cavities

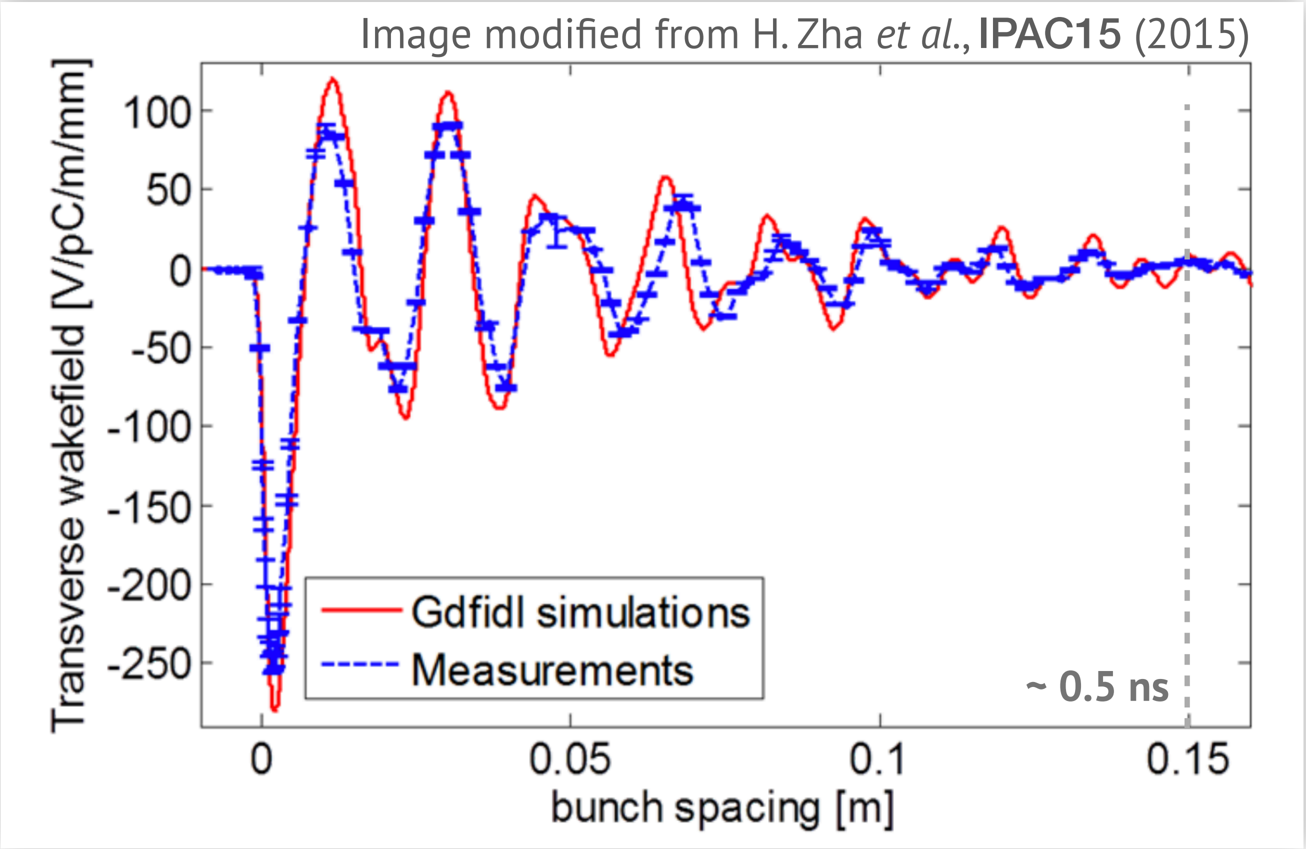
> Minimum possible separation is ~ **80 ps**.

> Long-range **transverse wakefields** induced in the metallic cavities from an acceleration event lives longer than this and must be avoided as they lead to emittance blow-up.

> Actual separation set at **0.5 ns** i.e. 2 GHz inter-bunch frequency.

Conventional accelerators





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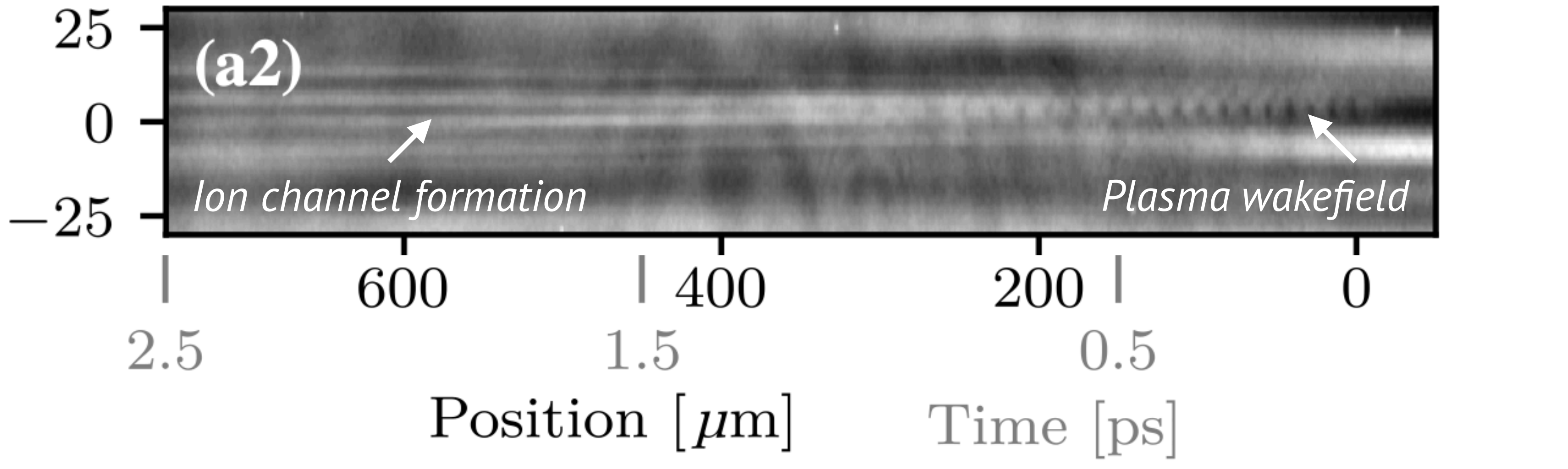
Shadowgraphy signal of wake dissipation and ion channel formation

Image modified from M. F. Gilljohann *et al.*, Phys. Rev. X **9**, 011046 (2019)



Ion motion defines the equivalent limit in plasma-based accelerators.

> Energy imparted into the plasma via the wakefield is transferred to ions, initiating their motion and generating highly non-uniform density profiles.

> Must wait for their motion to dissipate before repeatable acceleration is possible.

Directly measuring wakefield-induced plasma evolution

- Novel three-bunch plasma diagnostic technique.
- **Leading bunch** drives a wakefield in the plasma.
- **Probe bunch-pair** follows *n* x 0.77 ns later and drives a wakefield in the **perturbed** plasma state.
- **Scan temporal separation** and measure properties of probe bunch-pair to learn about long-timescale evolution of plasma after wakefield is driven.
- Temporal separations defined by 1.3 GHz RF frequency of **FLASH**.

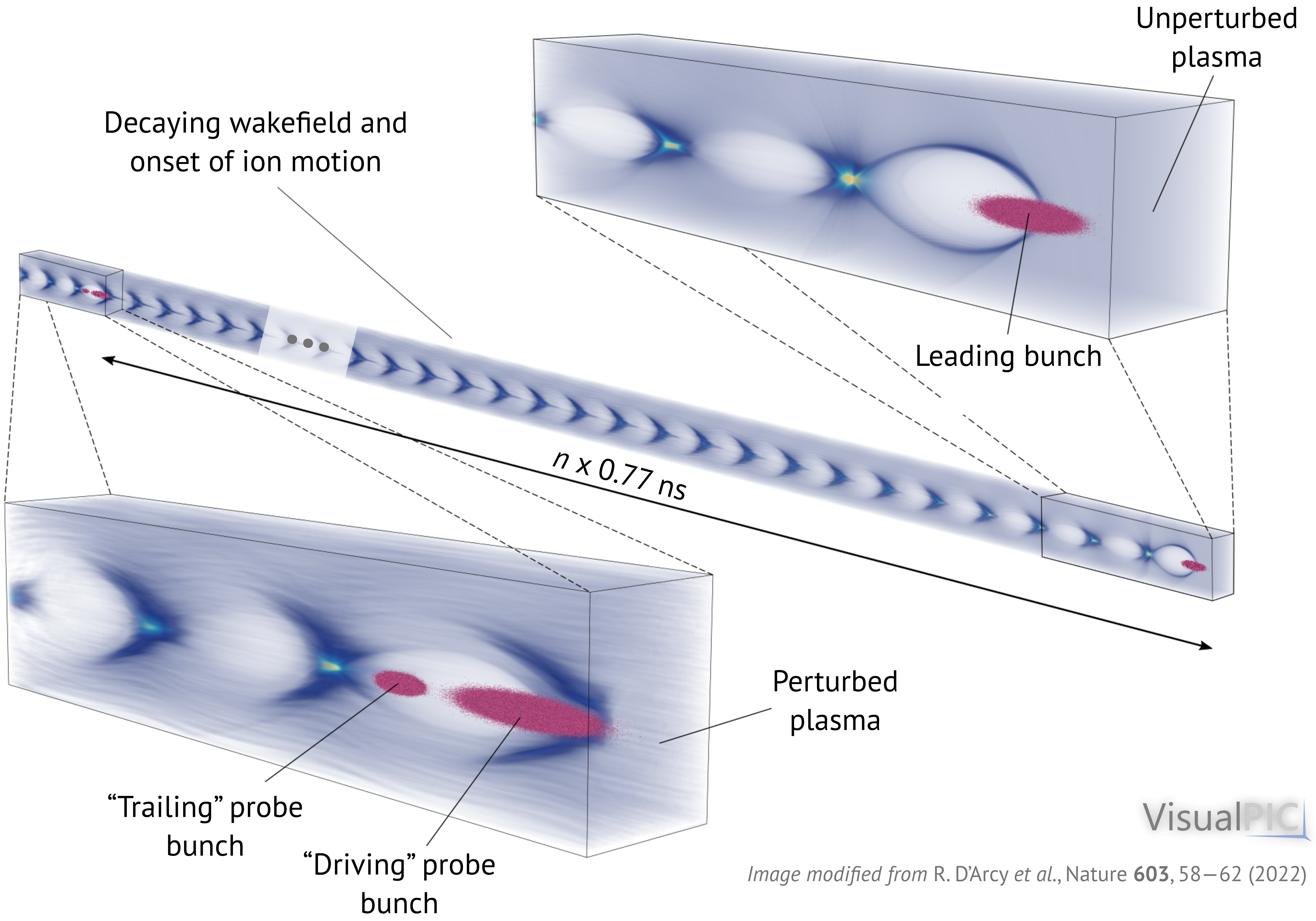
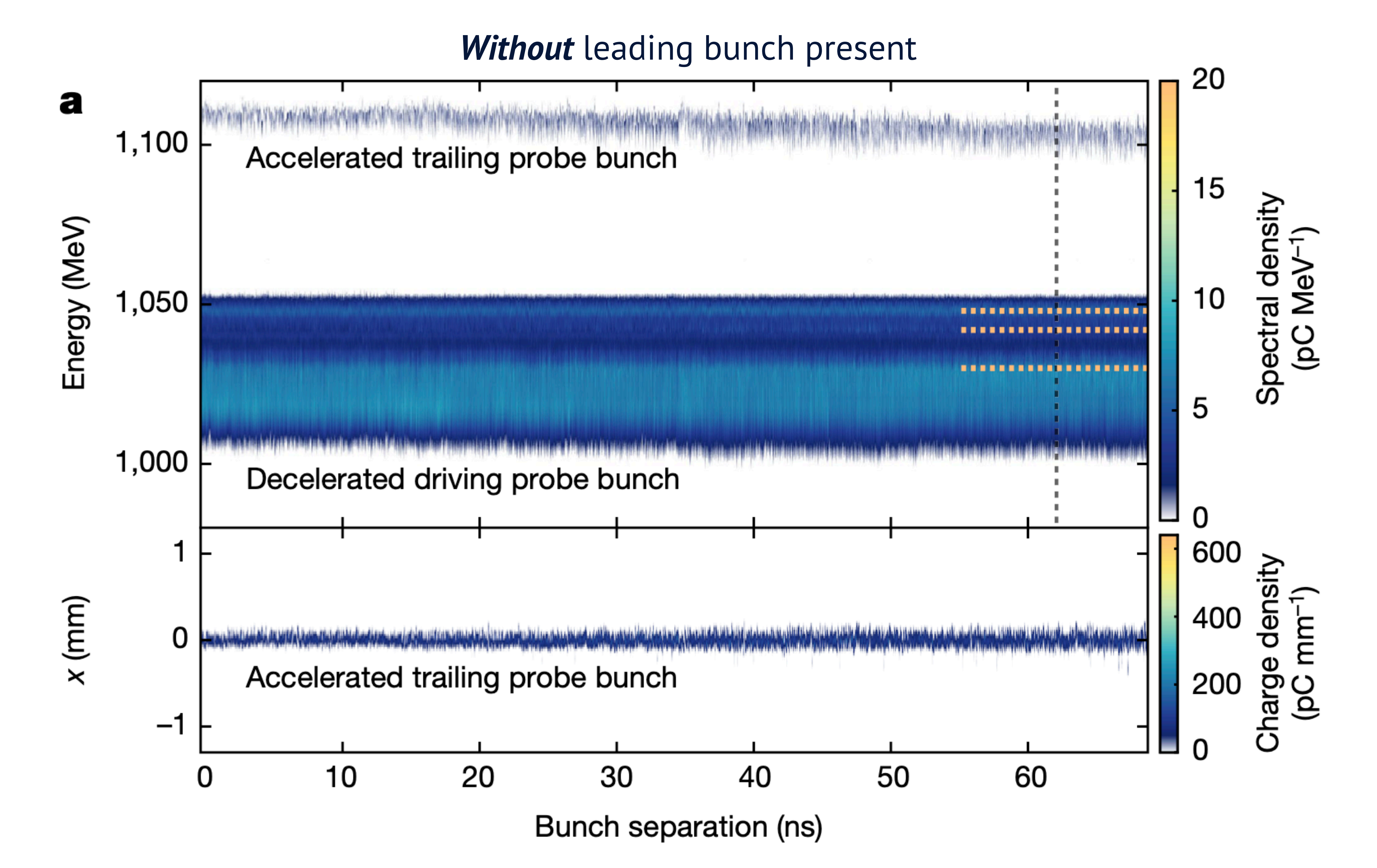


Image modified from R. D'Arcy *et al.*, Nature **603**, 58–62 (2022)

Probing wakefield-induced ion motion

Images modified from R. D'Arcy *et al.*, Nature **603**, 58–62 (2022)



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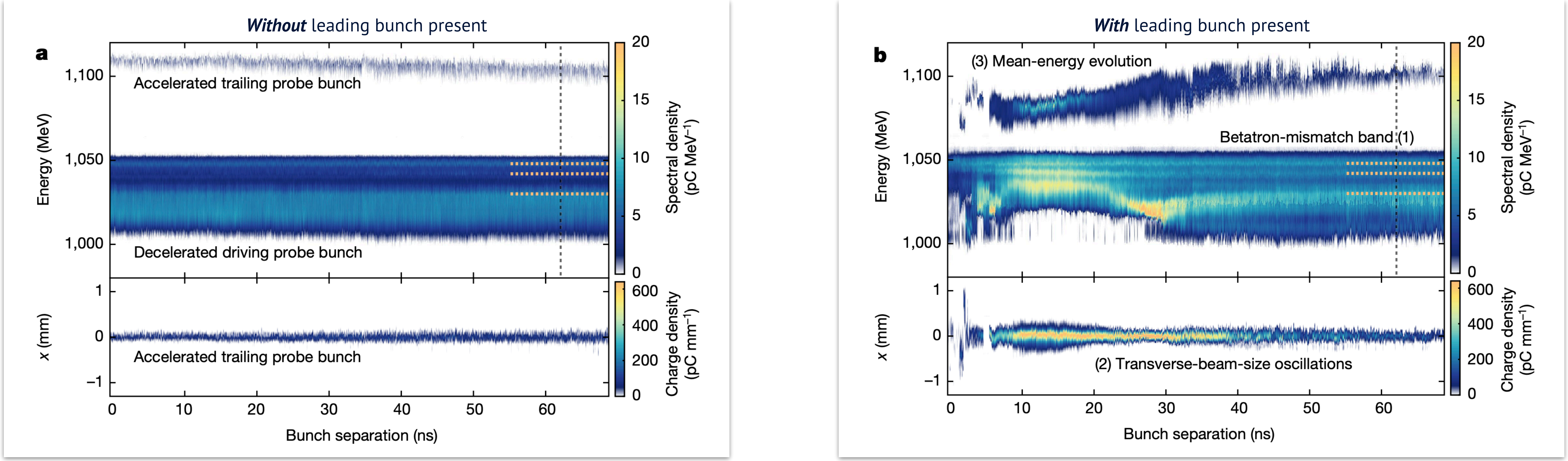

Details of signal extraction process in *J. Chappell, PhD Thesis, University College London (2021)*

Probing wakefield-induced ion motion

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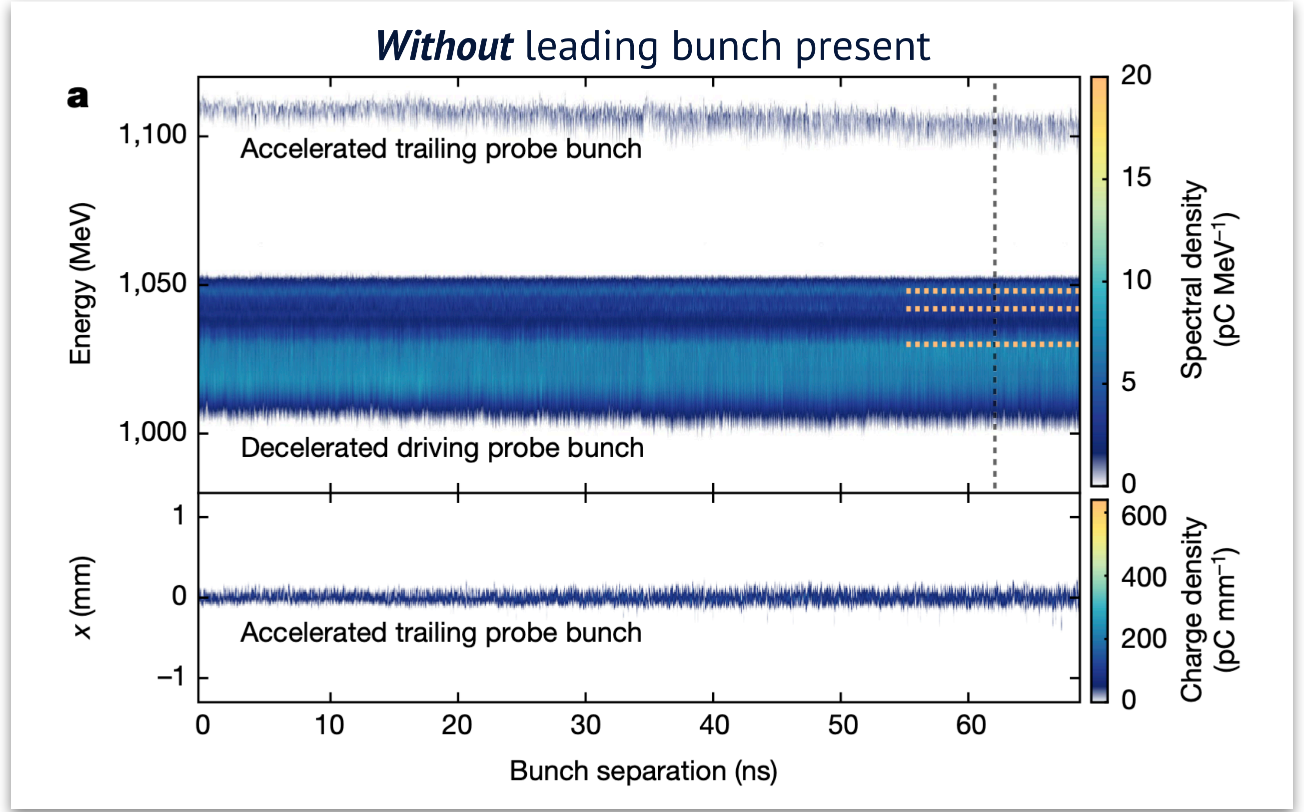

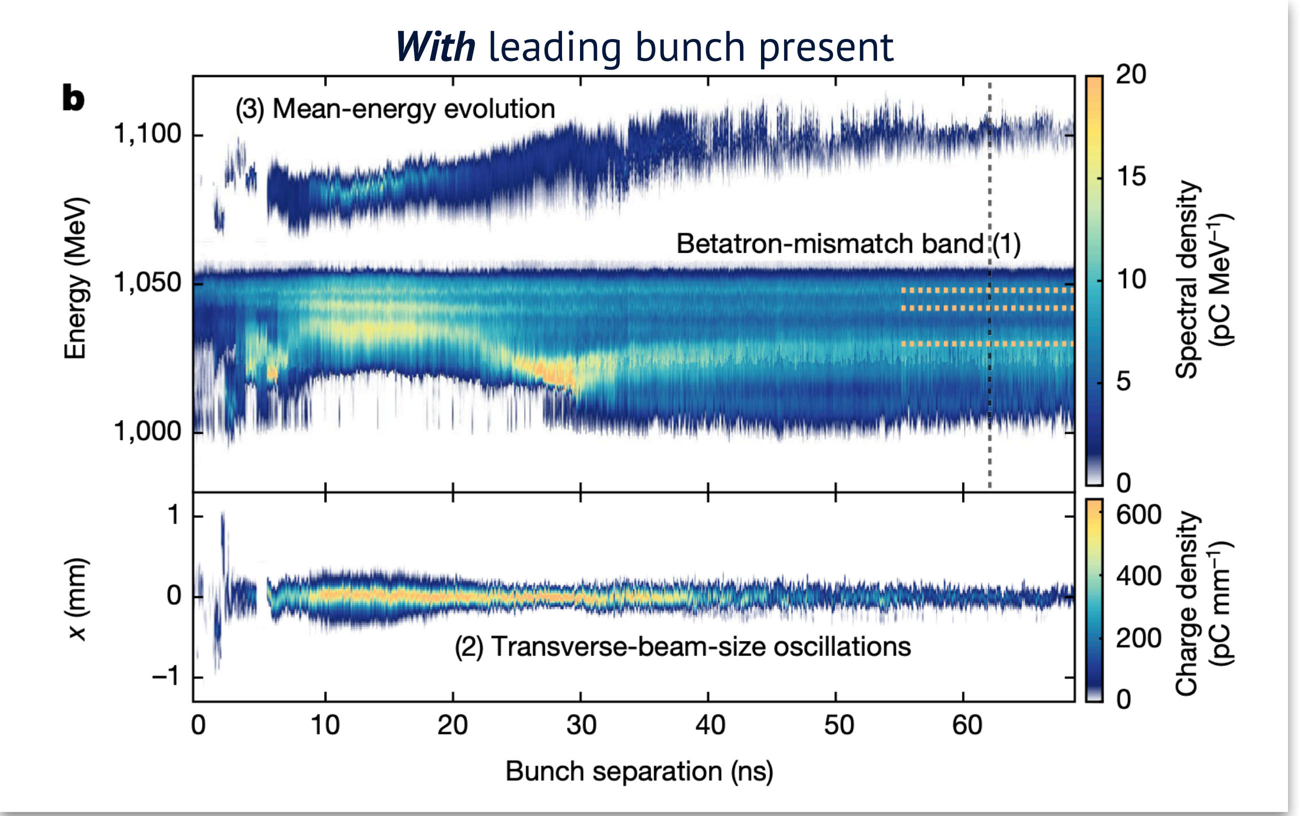

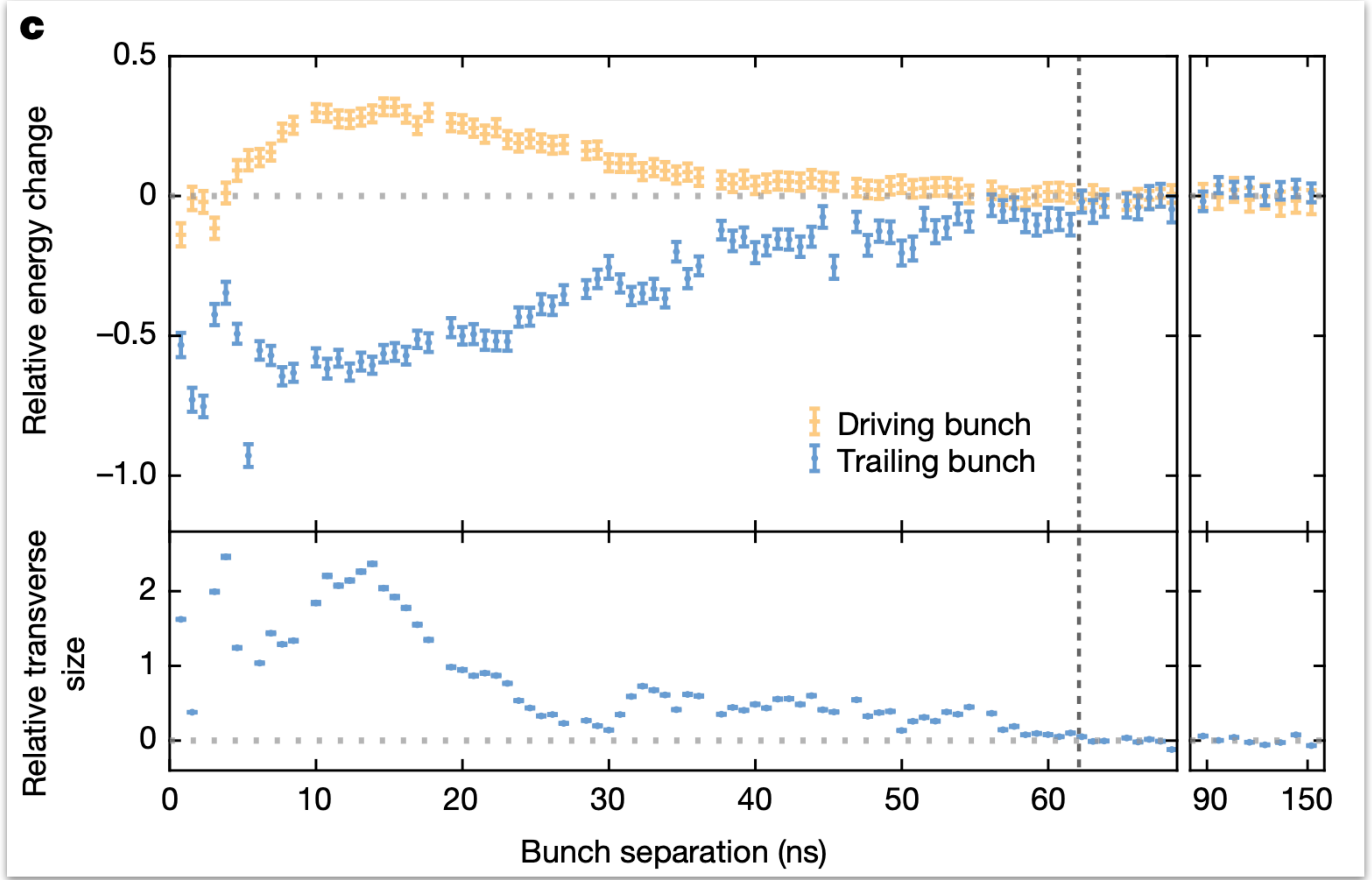

- Can compare the evolution of the plasma with and without perturbation by the leading bunch to extract the ion motion perturbation lifetime.
- **Probe bunch response is consistent with and without perturbation after 63 ns.**

- Ion motion perturbation measured for a range of different experimental scenarios[1] (e.g. wakefield amplitude, plasma density, ion mass) and lifetime consistently indicated to be **< 100 ns.**
- **Not an impediment to high-repetition-rate operation.**

- **Inter-bunch separation, $\Delta_b \gtrsim$ 100 ns, consistent with e.g. FLASH bunch trains O(1 μs)**

[1] J. Chappell, PhD Thesis, University College London (2021)

High-average-power operation

	Conventional accelerators	Plasma accelerators
Inter-bunch frequency	Dissipation of long-range transverse wakefields	Dissipation of long-term plasma (ion) motion ???
Bunch-train length	Balance of RF pulse length, accelerating field, and breakdown rate	???
Macro-pulse frequency	Dissipation of the cumulative heating from each bunch train	???

High-average-power operation

	Conventional accelerators	Plasma accelerators
Inter-bunch frequency	Dissipation of long-range transverse wakefields	Dissipation of long-term plasma (ion) motion Generation of similar plasma properties for each event
Bunch-train length	Balance of RF pulse length, accelerating field, and breakdown rate	Temperature-based modifications to the wakefield properties Heating of the plasma source
Macro-pulse frequency	Dissipation of the cumulative heating from each bunch train	Dissipation of the cumulative heating from each bunch train

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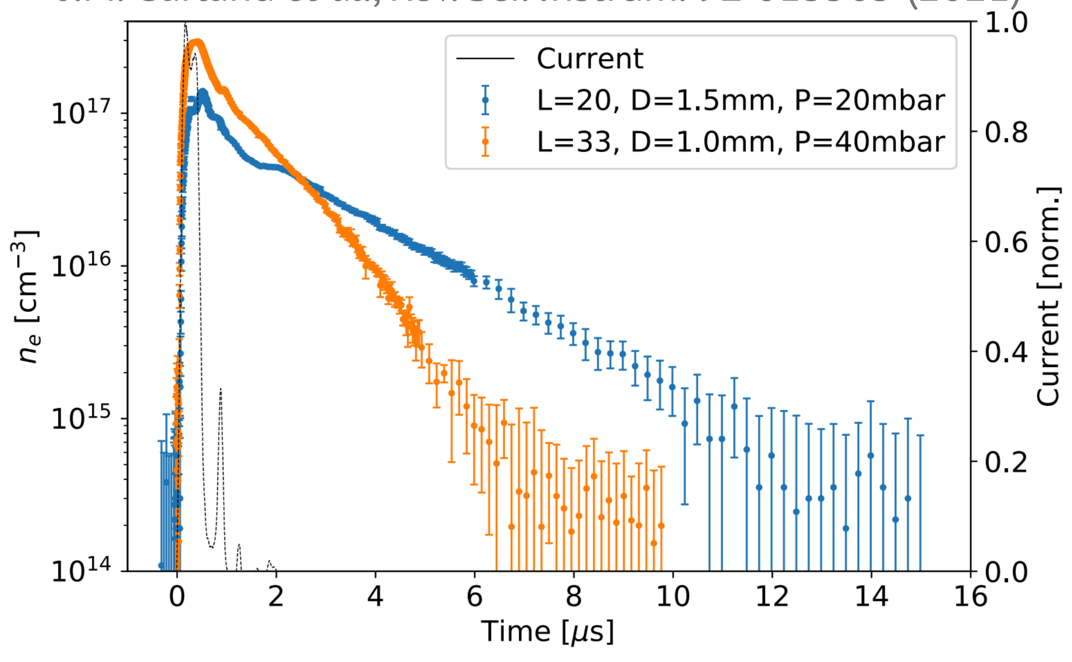
Developing measurement capabilities and simulation tools to design and implement MHz-capable plasma sources

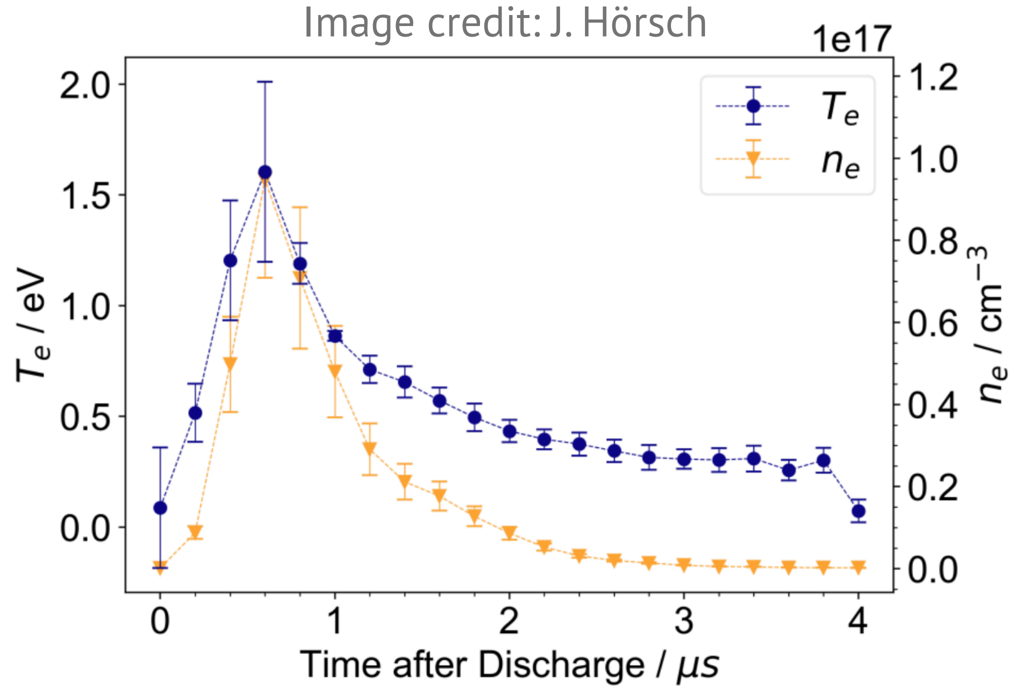
In-situ plasma density diagnostics

J.M. Garland *et al.*, Rev. Sci. Instrum. **92** 013505 (2021)



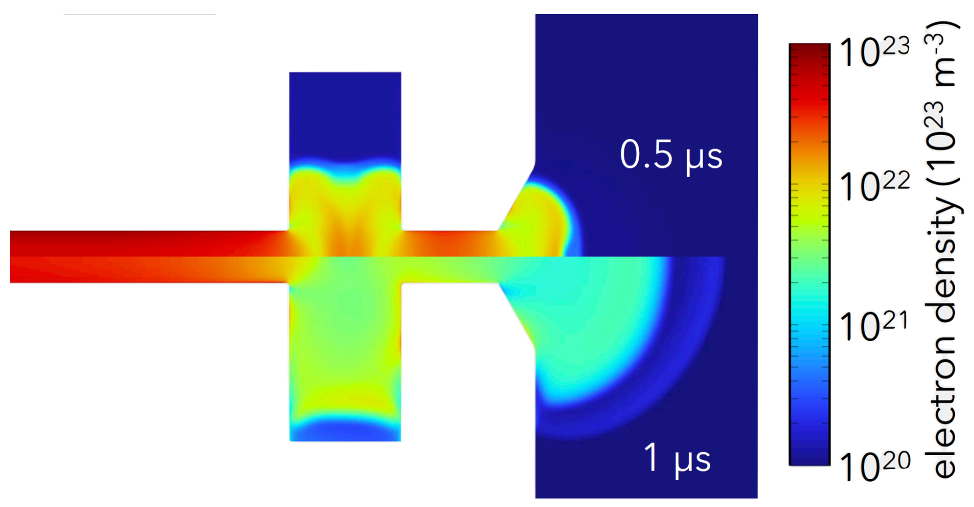
Plasma temperature diagnostics

Image credit: J. Hörsch



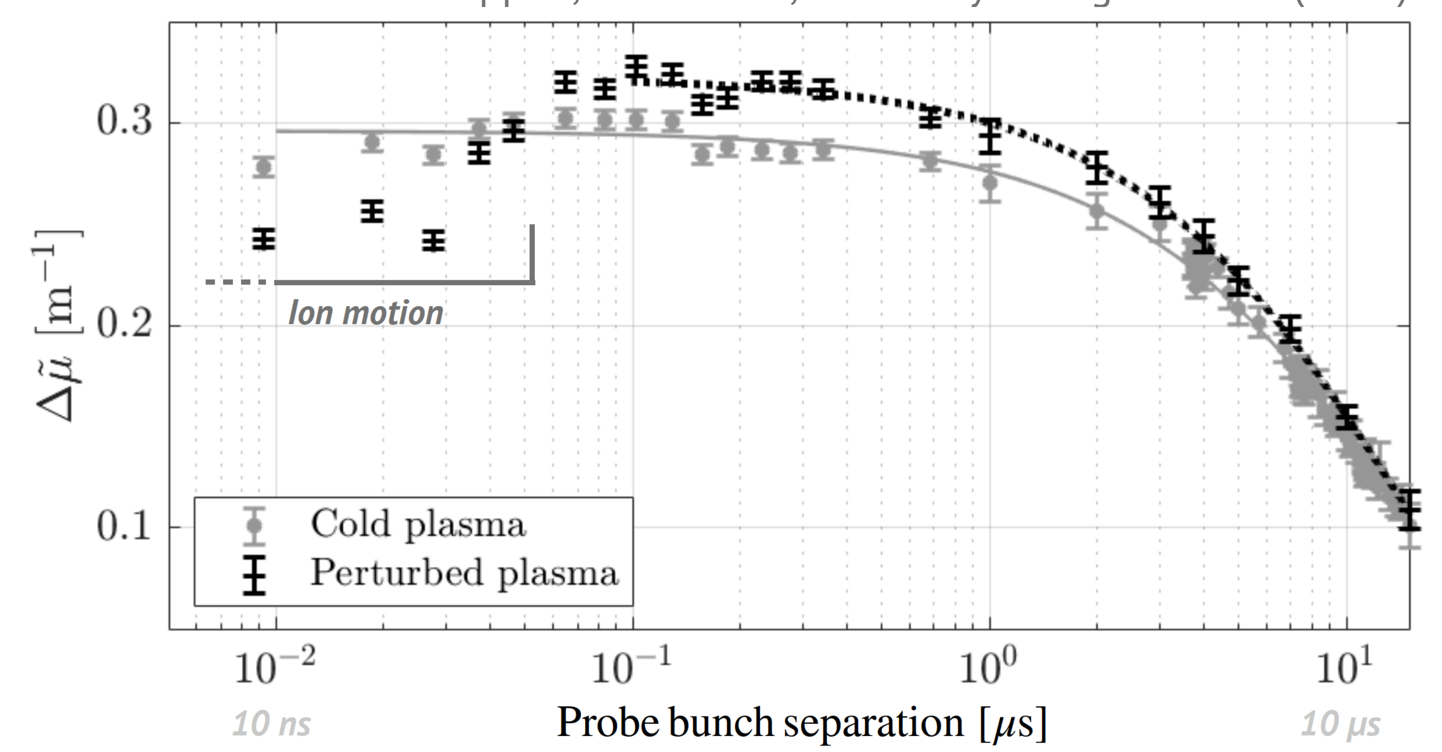
Long-timescale MHD simulations

Image credit: M. Mewes



Using beam-based diagnostic technique to probe μs-timescale wakefield evolution and explore cumulative heating effects

J. Chappell, PhD Thesis, University College London (2021)



Progress in Plasma-Accelerator R&D at FLASHFORWARD ▸ ▸

Summary and outlook

Develop a self-consistent plasma-accelerator stage
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High efficiency		High beam quality		High average power	
Driver depletion	☑	Low energy spread	☑	Recovery time	☑
Transfer efficiency	☑	Emittance preservation	☐	High repetition rate	☐

- Impactful and exciting research programme will help advance plasma accelerators to application-readiness