Beam-Driven Plasma Wakefied Accelerators

STATUS AND NEXT STEPS

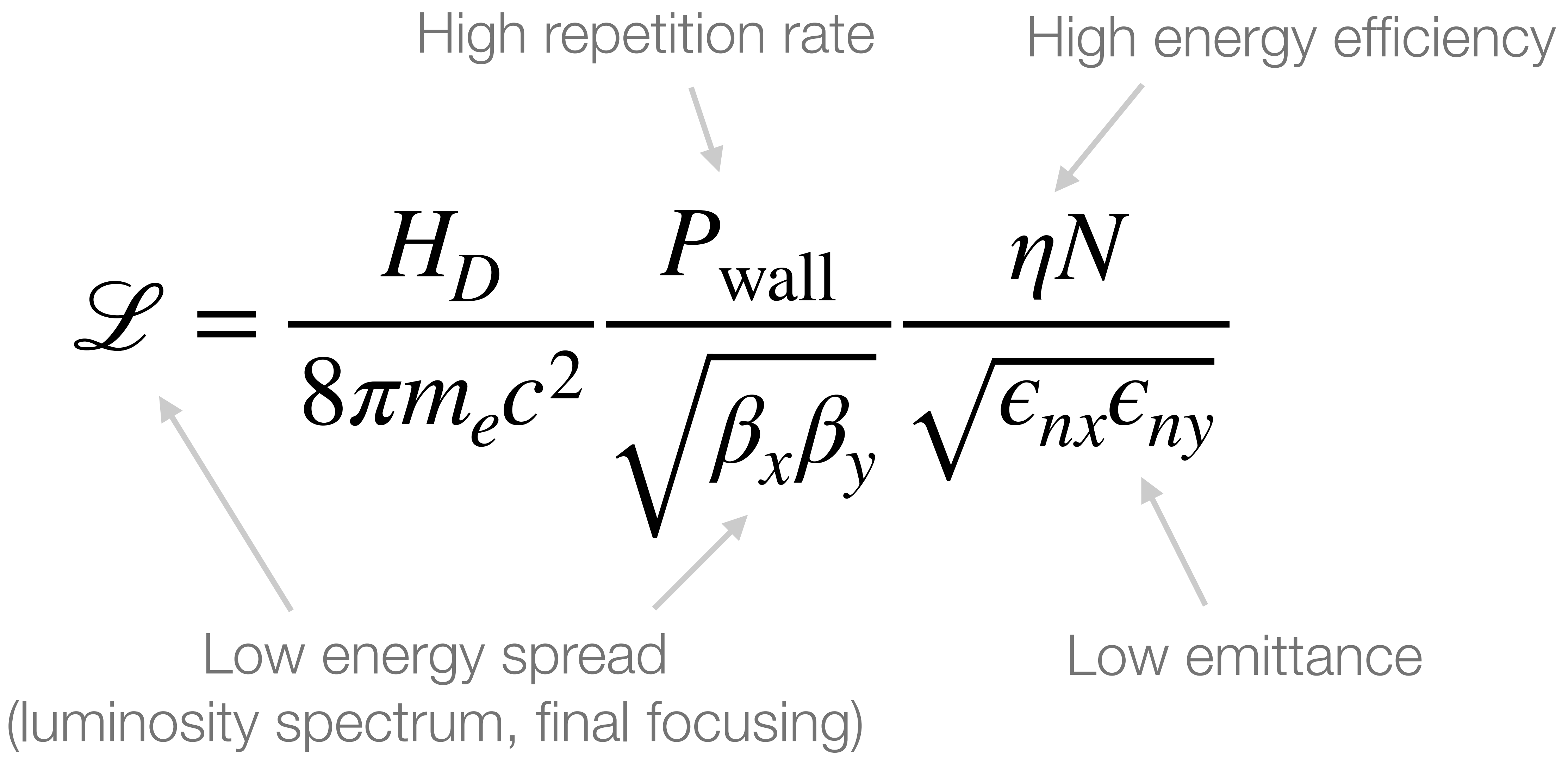
Jens Osterhoff
Plasma Accelerator R&D
DESY. Accelerator Division

Zoom Town Hall Meeting
March 30th, 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Our customers: high-energy physics and photon science

- High-energy physics and photon science demand high(est) energy at low cost.
  - *Solution:* Plasma accelerators — significantly higher acceleration gradients.
- Simultaneously, particle colliders have strict demands for luminosity: (FELs have similar demands for brightness)



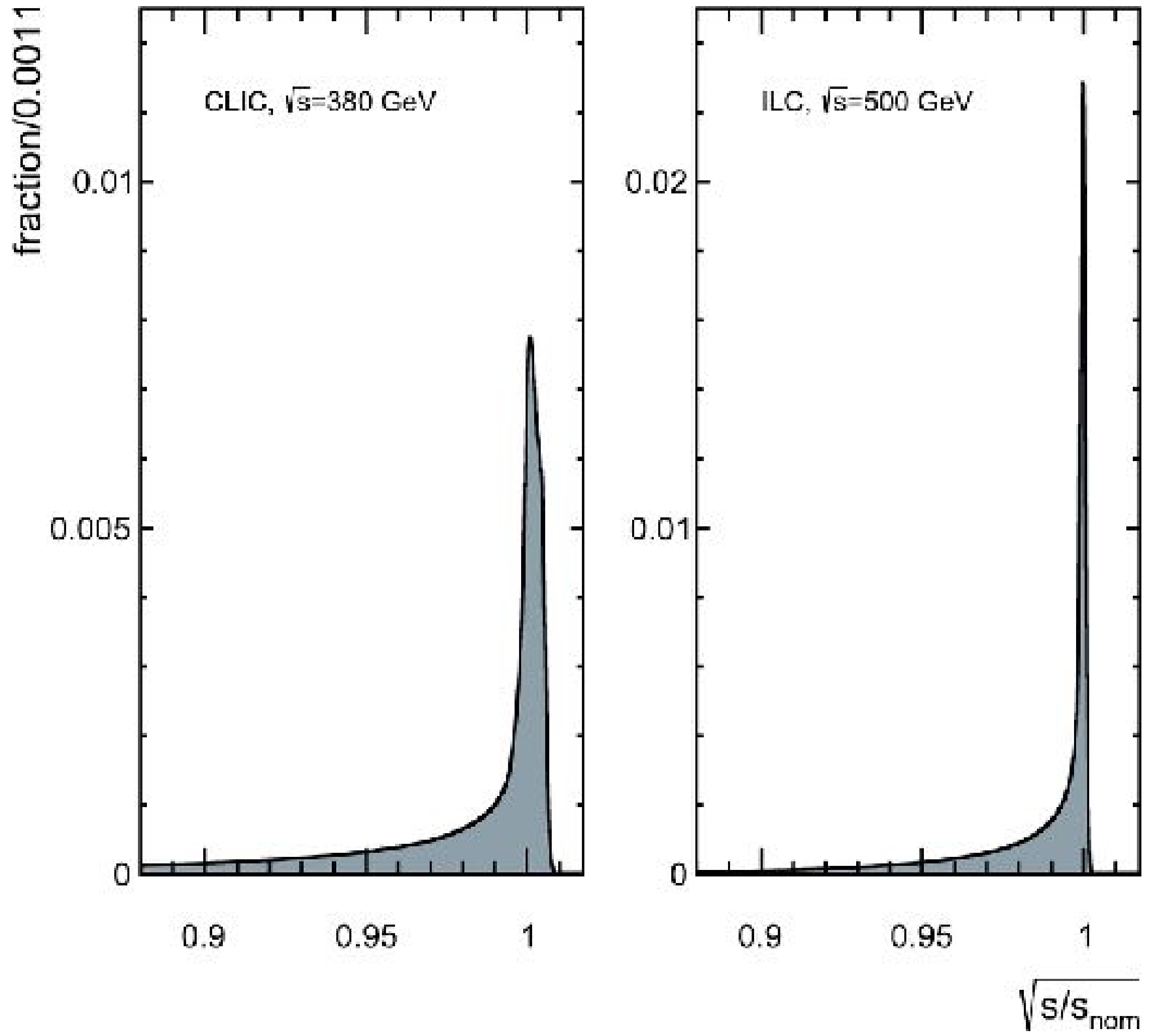
High repetition rate

High energy efficiency

$$\mathscr{L} = \frac{H_D}{8\pi m_e c^2} \frac{P_{\text{wall}}}{\sqrt{\beta_x \beta_y}} \frac{\eta N}{\sqrt{\epsilon_{nx}\epsilon_{ny}}}$$

Low energy spread
(luminosity spectrum, final focusing)

Low emittance



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

$$\eta = \underset{\uparrow}{\eta_{wall \to DB}} \times \eta_{DB \to WB}$$

High efficiency, high-average power beam-driver technology exists today.

- Energy efficiency motivates use of beam-driven plasma acceleration.

Critical: develop a self-consistent plasma-accelerator stage

with high-efficiency, high-quality, and high-average-power

High efficiency

Transfer efficiency

Driver depletion

High beam quality

Energy-spread preservation

Emittance preservation

High average power

High repetition rate

Photon science applications naturally lie on the path to a collider

Ballpark requirements illustrate complexity of the task

	FEL	Collider
Charge per bunch (nC)	0.01 - 0.1	0.1 - 1
Energy gain (GeV)	0.1 - 10	1000
Energy spread (%)	0.1	0.1
Wall-plug efficiency (%)	< 0.1 - 10	10
Emittance (µm)	0.1 - 1	0.01
Rep. rate (Hz)	$10^1 - 10^6$	$10^4 - 10^5$
Avg. beam power (W)	$10^1 - 10^6$	10^6
Continuous run	24/1 - 24/7	24/365
Parameter stability	0.1%	0.1%

Critical: develop a self-consistent plasma-accelerator stage
with high-efficiency, high-quality, and high-average-power

High efficiency
Transfer efficiency
Driver depletion

High beam quality
Energy-spread preservation
Emittance preservation

High average power
High repetition rate

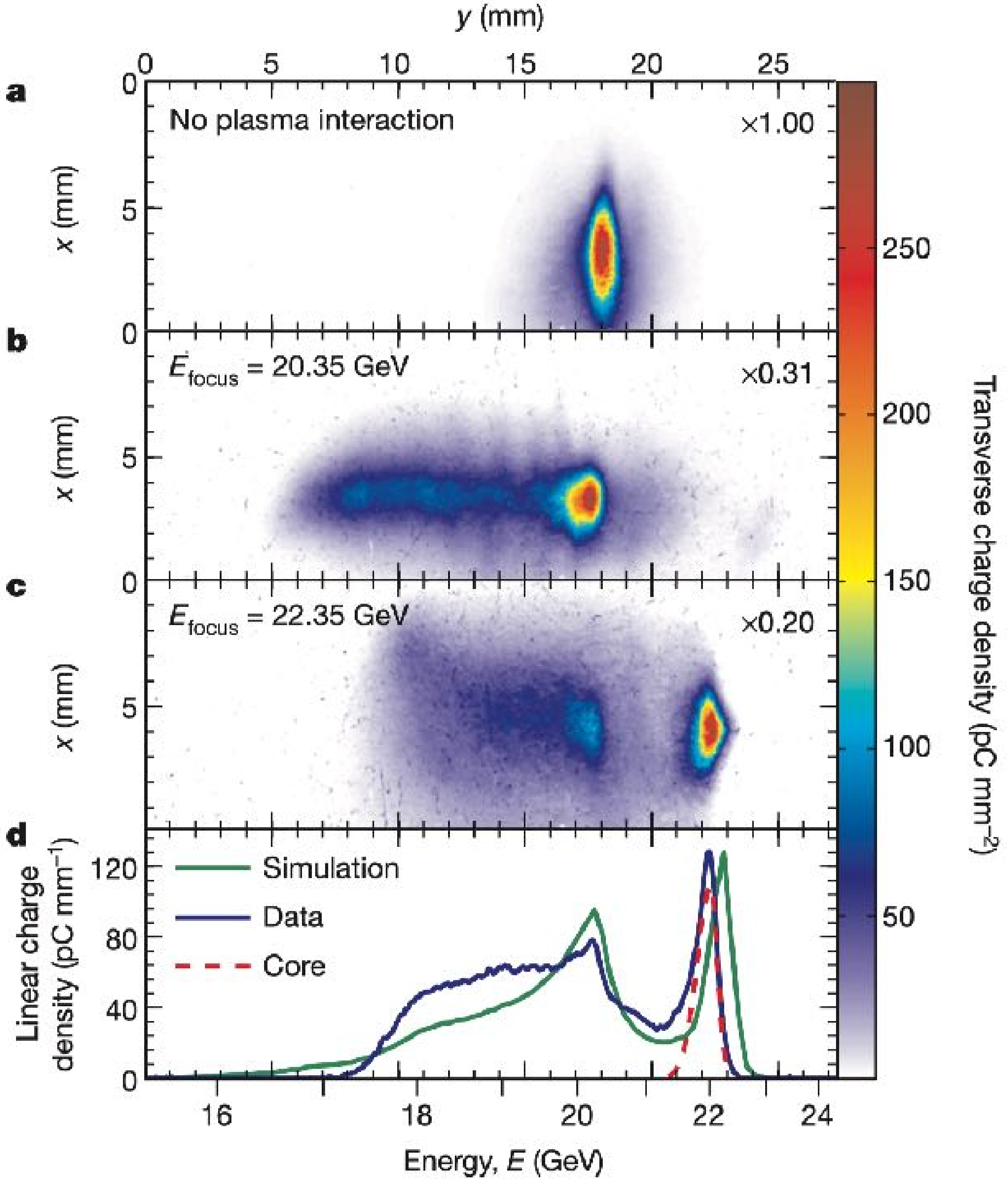
- **FEL (~10 GeV)** - single such stage sufficient
- **Collider (~1 TeV)** - a great many of those needed in series with stricter beam quality requirements (also for positrons)

AWAKE EuPRAXIA FACET-II FLASHForward SPARC LAB + ...

Energy gain per stage and bunch charge fulfill FEL requirements

Ballpark requirements and state-of-the-art

	FEL	Collider	Current
Charge per bunch (nC)	0.01 - 0.1	0.1 - 1	0.01 - 0.1
Energy gain (GeV)	0.1 - 10	1000	0.1 - 10



1.6 GeV energy gain of 74 pC charge with 4.4 GV/m

Source: M. Litos *et al.*, Nature **515**, 92 (2014)

Controlling energy spread and efficiency is a coupled challenge

Ballpark requirements and state-of-the-art

	FEL	Collider	Current
Charge per bunch (nC)	0.01 - 0.1	0.1 - 1	0.01 - 0.1
Energy gain (GeV)	0.1 - 10	1000	0.1 - 10
Energy spread (%)	0.1	0.1	
Wall-plug efficiency (%)	< 0.1 - 10	10	

} tightly coupled

Optimal beam loading enables uniform and efficient acceleration

- *Problem 1:* Compared to RF cavities (Q ~ 10^4–10^{10}), the electric fields in a plasma decay very rapidly (Q ~ 1–10).
  - The energy needs to be extracted very rapidly —ideally within the first oscillation.

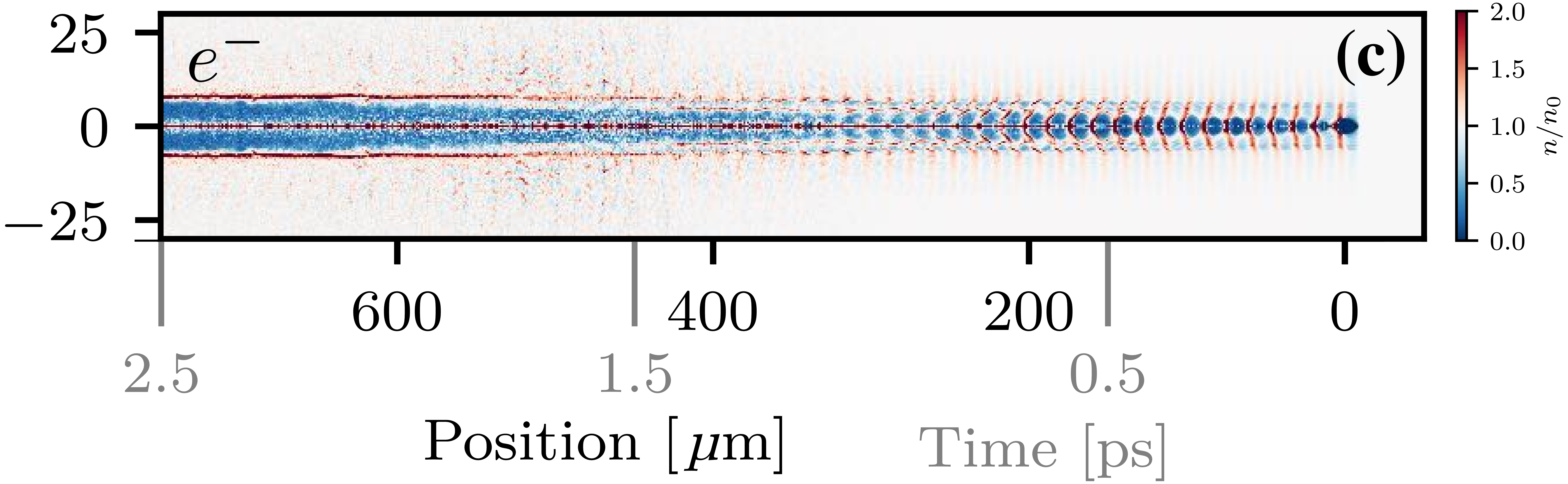


Image source: M. F. Gilljohann *et al.*, Phys. Rev. X **9**, 011046 (2019)

Optimal beam loading enables uniform and efficient acceleration

- *Problem 1:* Compared to RF cavities (Q ~ 10^4–10^{10}), the electric fields in a plasma decay very rapidly (Q ~ 1–10).
  - The energy needs to be extracted very rapidly —ideally within the first oscillation.
  - *Solution:* Beam loading
    The trailing-bunch wakefield "destructively interferes" with the driver wakefield—extracting energy.
- *Problem 2:* to extract a large fraction of the energy, the beam will cover a large range of phases (~90 degrees or more).
  - Large energy spread is induced (with non-monotonic correlation)

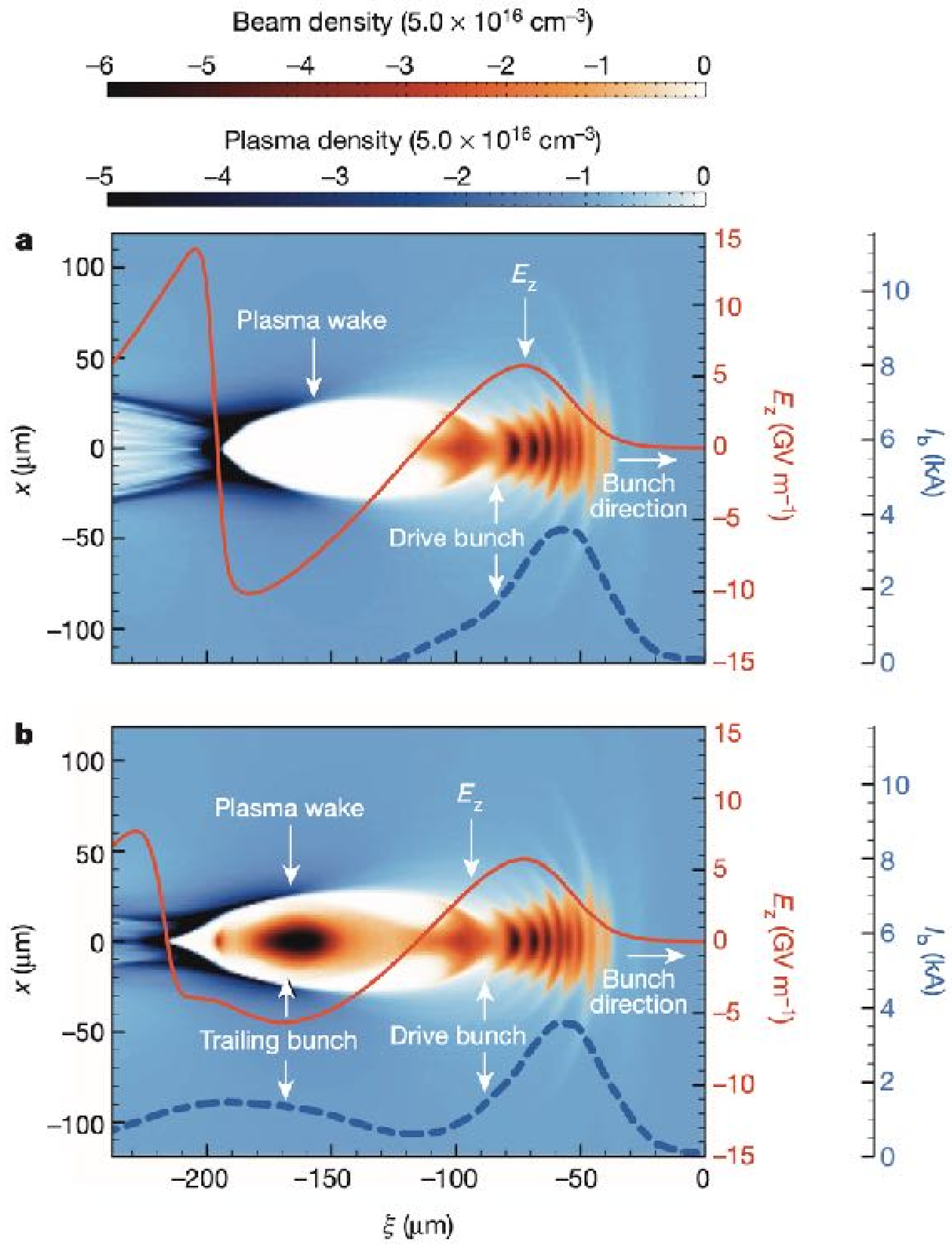


Image credit: M. Litos *et al.*, Nature **515**, 92 (2014)

Optimal beam loading enables uniform and efficient acceleration

- *Problem 1:* Compared to RF cavities (Q ~ 10^4–10^{10}), the electric fields in a plasma decay very rapidly (Q ~ 1–10).
  - The energy needs to be extracted very rapidly —ideally within the first oscillation.
  - *Solution:* Beam loading
    The trailing-bunch wakefield "destructively interferes" with the driver wakefield—extracting energy.
- *Problem 2:* to extract a large fraction of the energy, the beam will cover a large range of phases (~90 degrees or more).
  - Large energy spread is induced (with non-monotonic correlation)
  - *Solution:* Optimal beam loading
    The current profile of the trailing bunch is *precisely tailored* to exactly flatten the wakefield.
- This requires extremely precise control of the current profile.
  - **Current accelerators can provide this precision.**

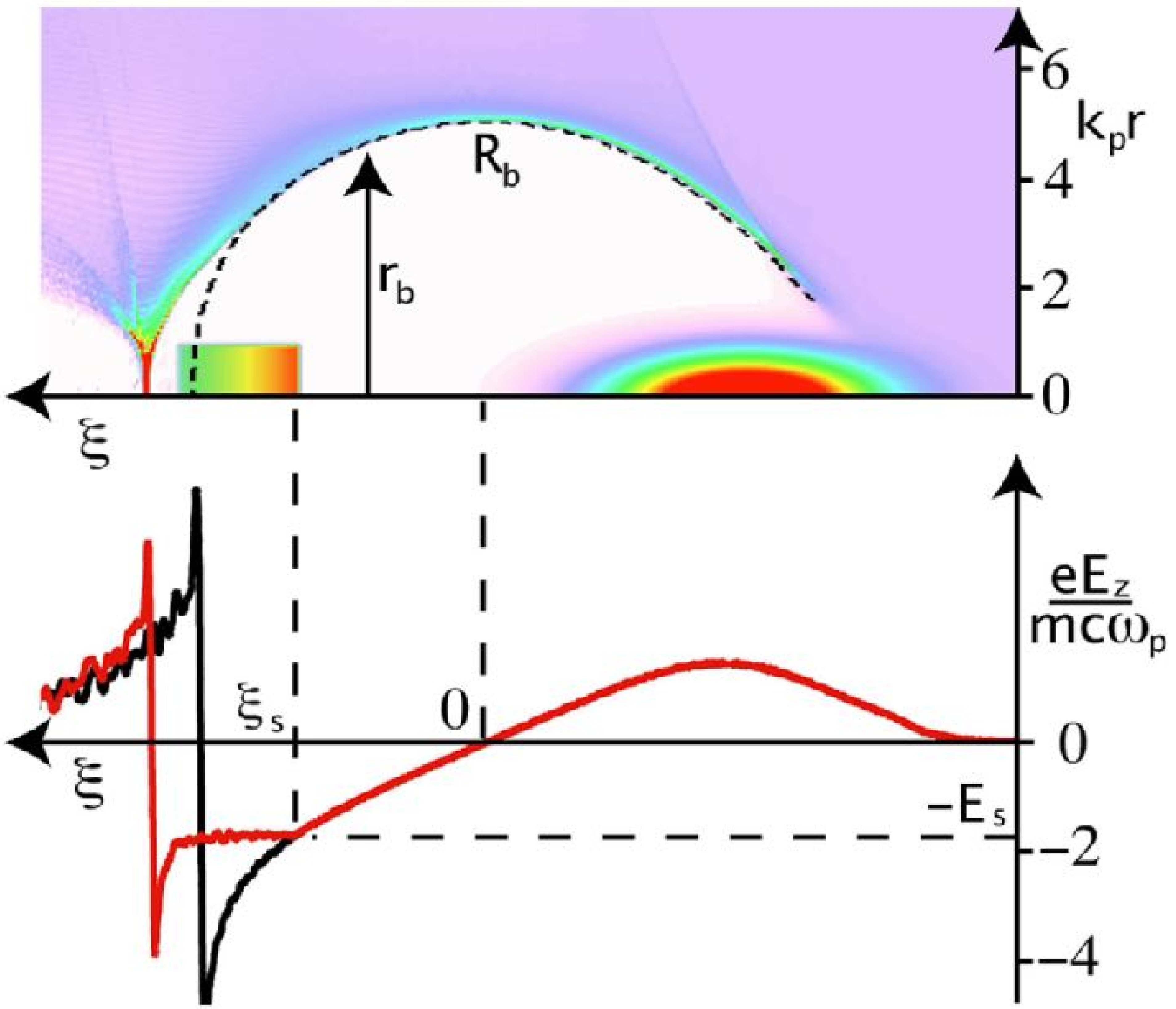
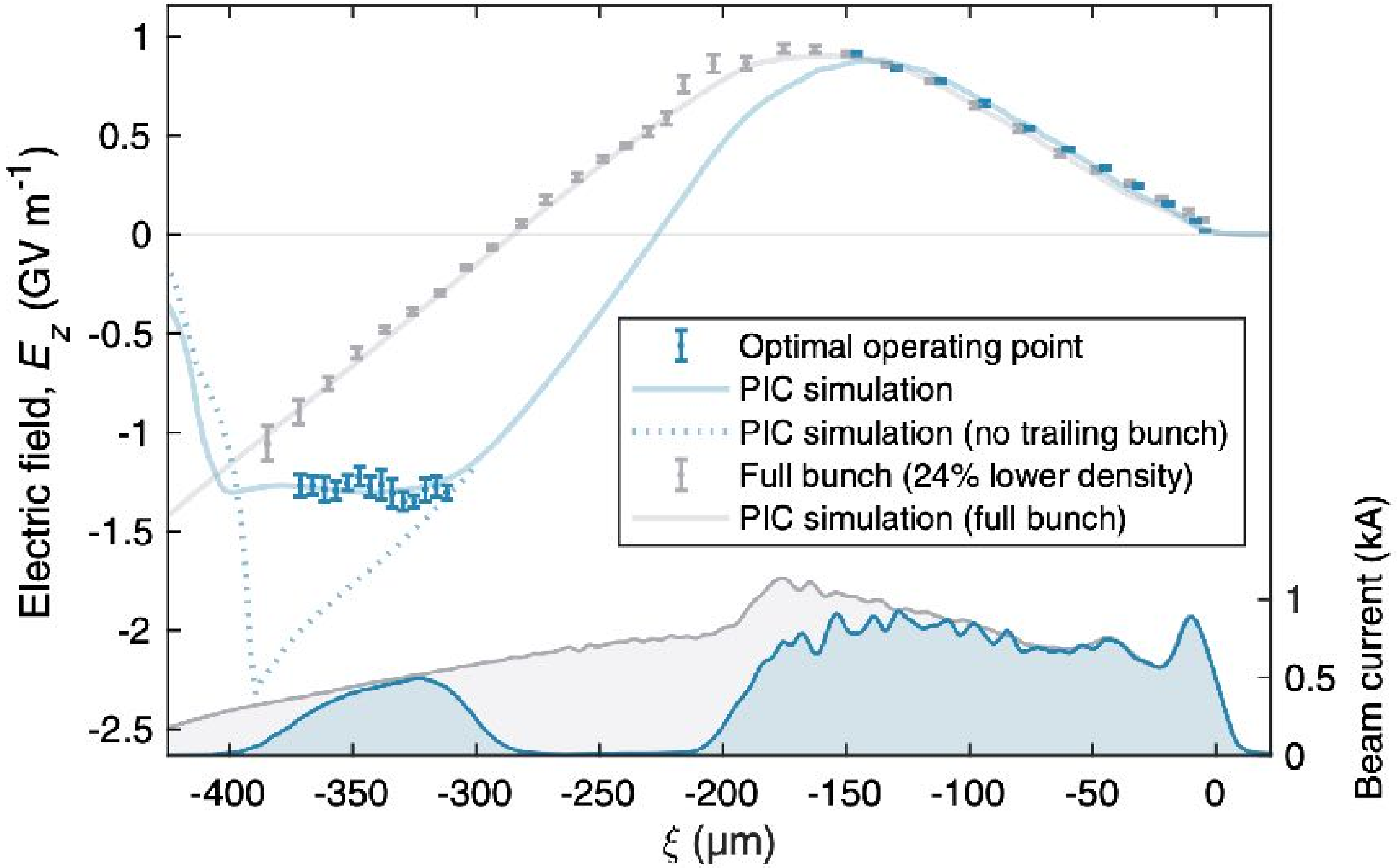


Image credit: M. Tzoufras *et al.*, Phys. Rev. Lett. **101**, 145002 (2008)

Optimal beam loading enables uniform and efficient acceleration



Per-cent-level field flattening

Image credit: C.A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)
Technique: S. Schröder *et al.*, Nature Communications **11**, 5984 (2020)

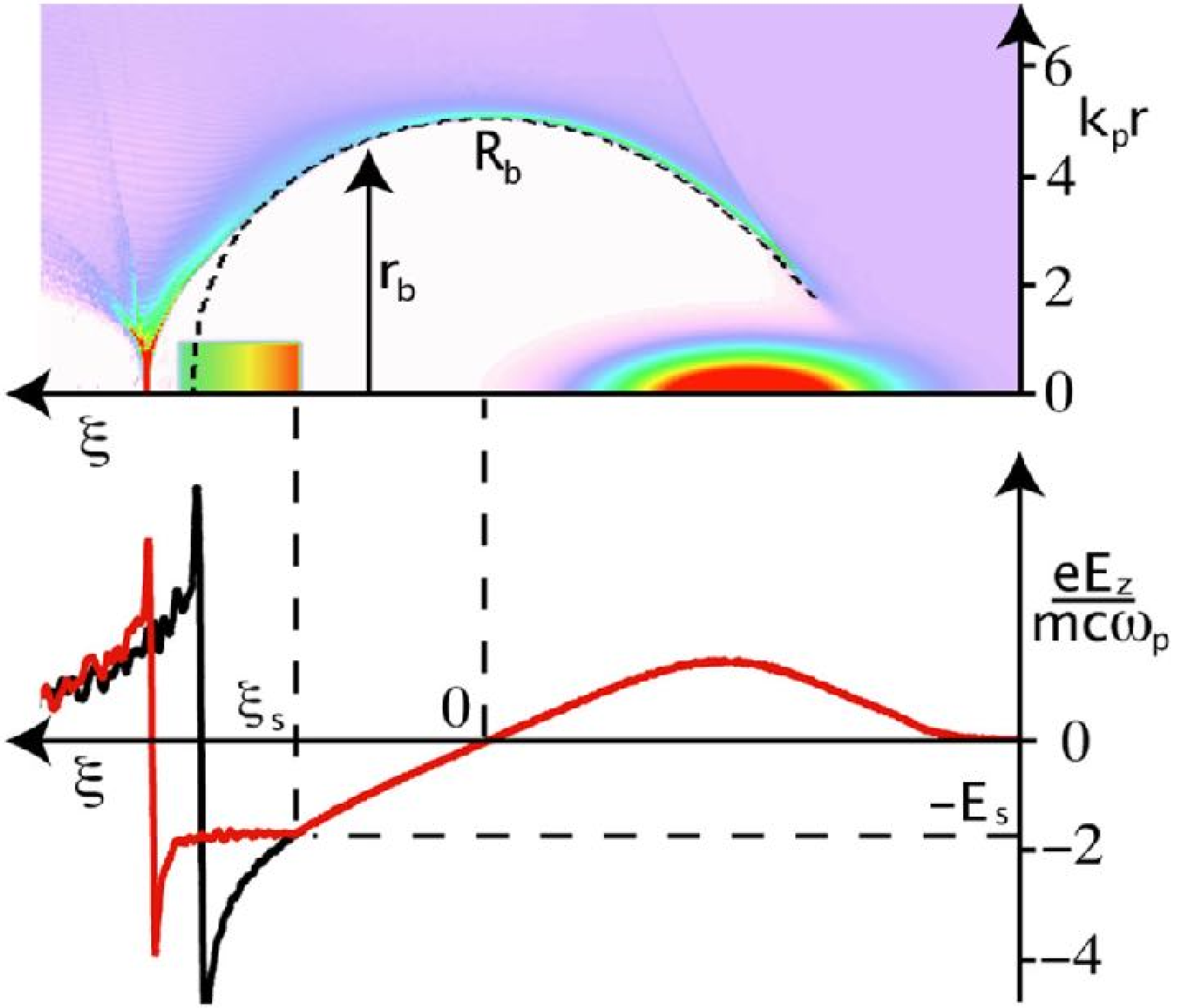
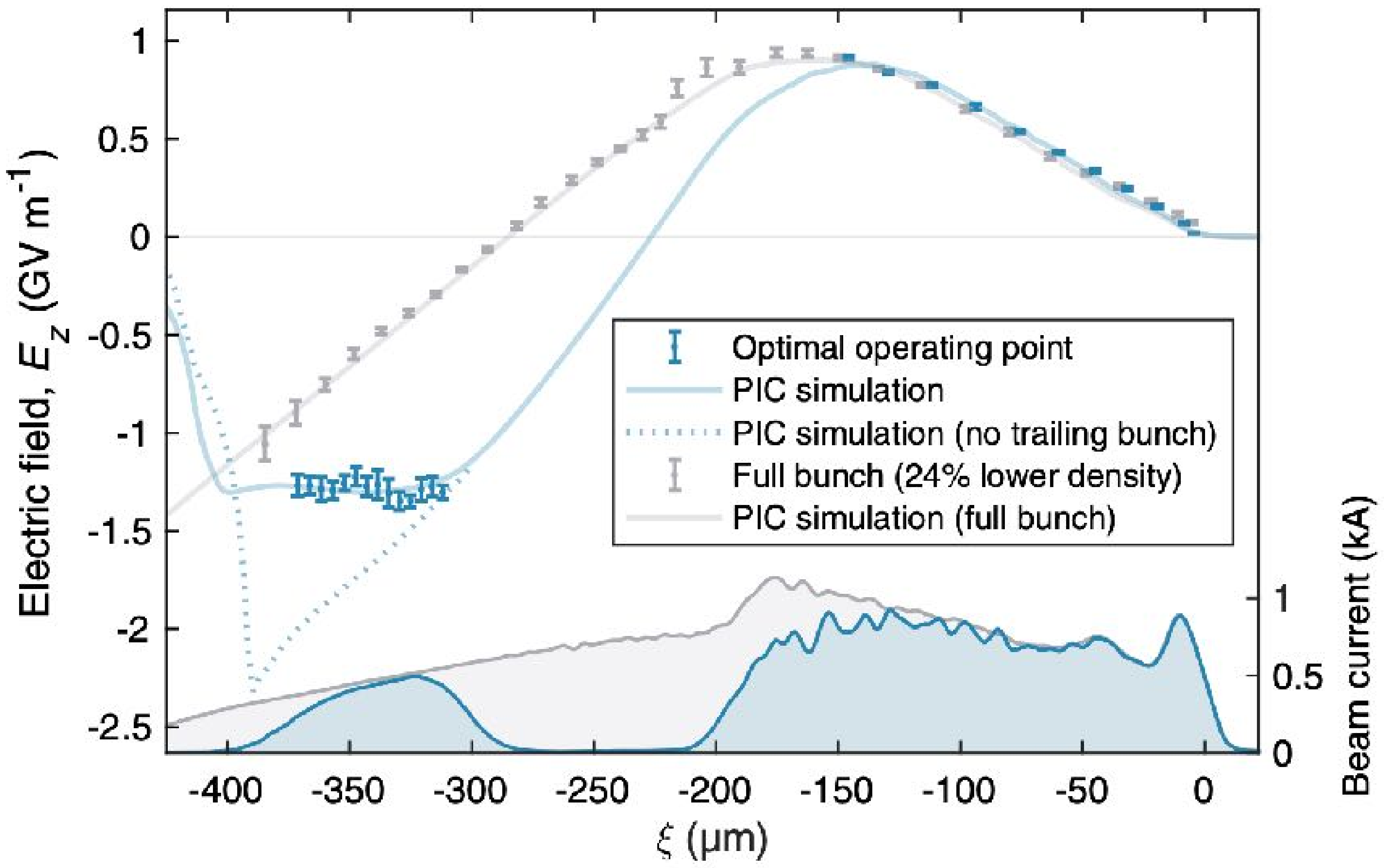


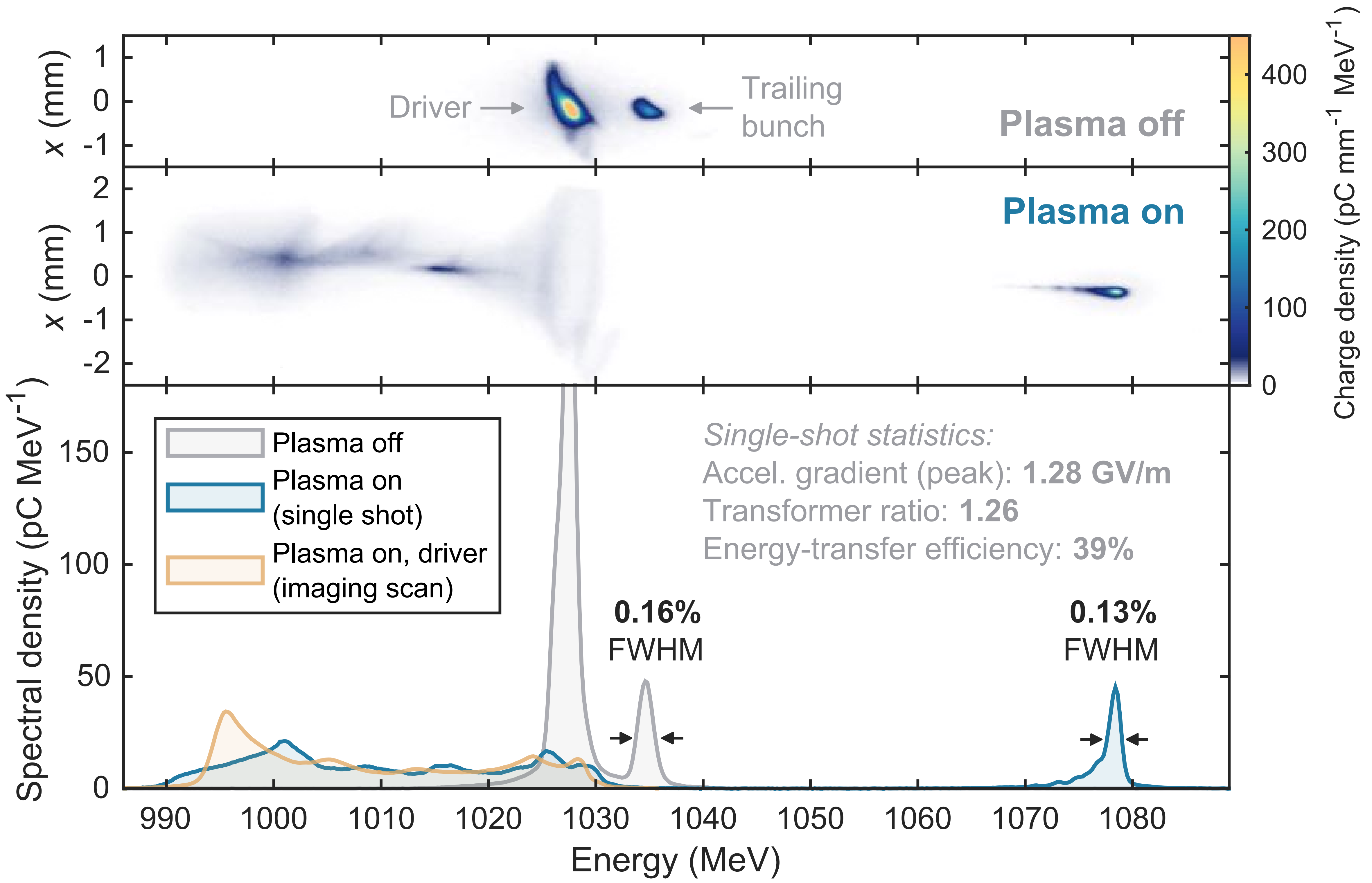
Image credit: M. Tzoufras *et al.*, Phys. Rev. Lett. **101**, 145002 (2008)

Optimal beam loading enables uniform and efficient acceleration



Per-cent-level field flattening

Image credit: C.A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)
Technique: S. Schröder *et al.*, Nature Communications **11**, 5984 (2020)



Conservation of energy spread (0.2%)

Full charge coupling (~100% of 100 pC)

Transfer efficiency 42±4% with 0.2% energy spread, up to 70% when allowing energy spread increase

High beam-to-beam efficiency requires driver energy depletion

Ballpark requirements and state-of-the-art

	FEL	Collider	Current
Charge per bunch (nC)	0.01 - 0.1	0.1 - 1	0.01 - 0.1
Energy gain (GeV)	0.1 - 10	1000	0.1 - 10
Energy spread (%)	0.1	0.1	0.1
Wall-plug efficiency (%)	< 0.1 - 10	10	< 0.1

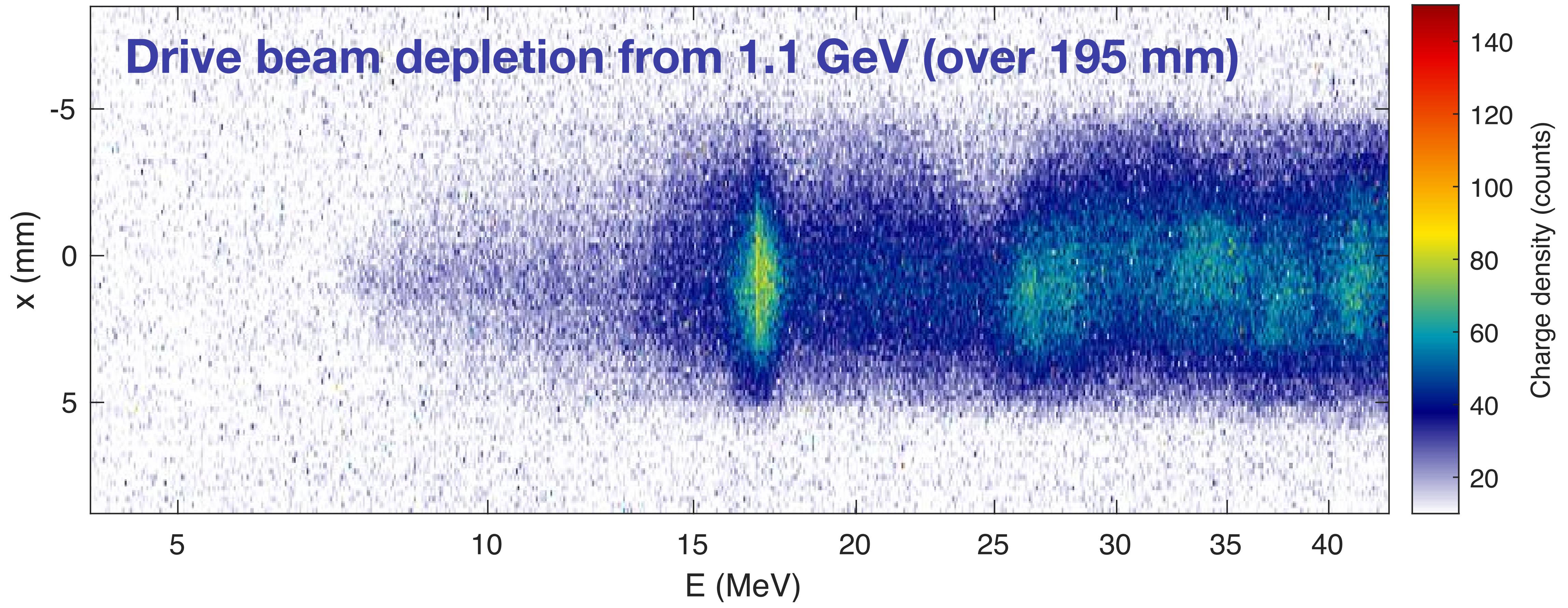
C.A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)
R. Pompili *et al.*, Nature Physics (2021)

Wake-to-beam efficiency demonstrated: 40 - 70%

Beam-to-beam efficiency demonstrated:
5% at FLASHForward, 7% at FACET

Sources: M. Litos *et al.*, Plasma Phys. Control. Fusion **58** 034017 (2016),
C.A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)

Next step to increase beam-to-beam efficiency
→ combine with driver depletion



Wall-plug to drive-beam efficiency
challenge shared with ILC / CLIC …

Emittance preservation is on top of the community’s to-do list

Ballpark requirements and state-of-the-art

	FEL	Collider	Current
Charge per bunch (nC)	0.01 - 0.1	0.1 - 1	0.01 - 0.1
Energy gain (GeV)	0.1 - 10	1000	0.1 - 10
Energy spread (%)	0.1	0.1	0.1
Wall-plug efficiency (%)	< 0.1 - 10	10	< 0.1
Emittance (µm)	0.1 - 1	0.01	?

studies underway, no publications yet

For plasma wakefield accelerators, all energy slices must be **matched** to avoid emittance growth in the plasma ion column

Typically requires matched **β*** of **0.1 - 10 mm**.

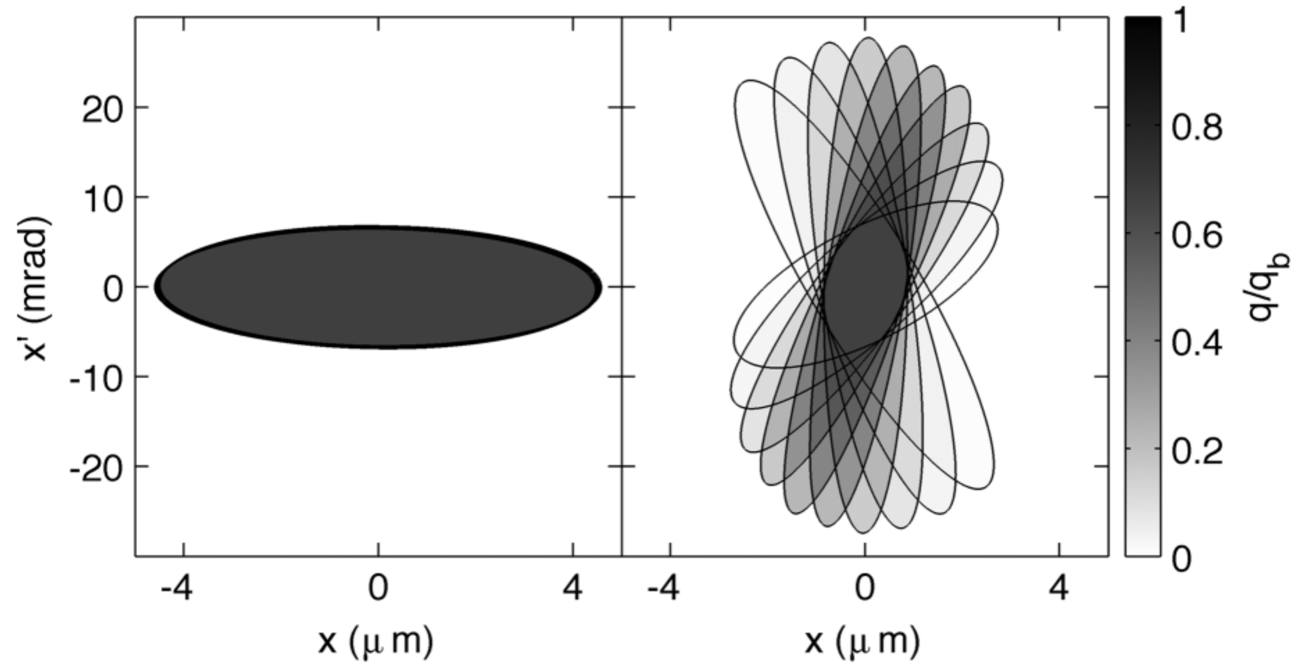
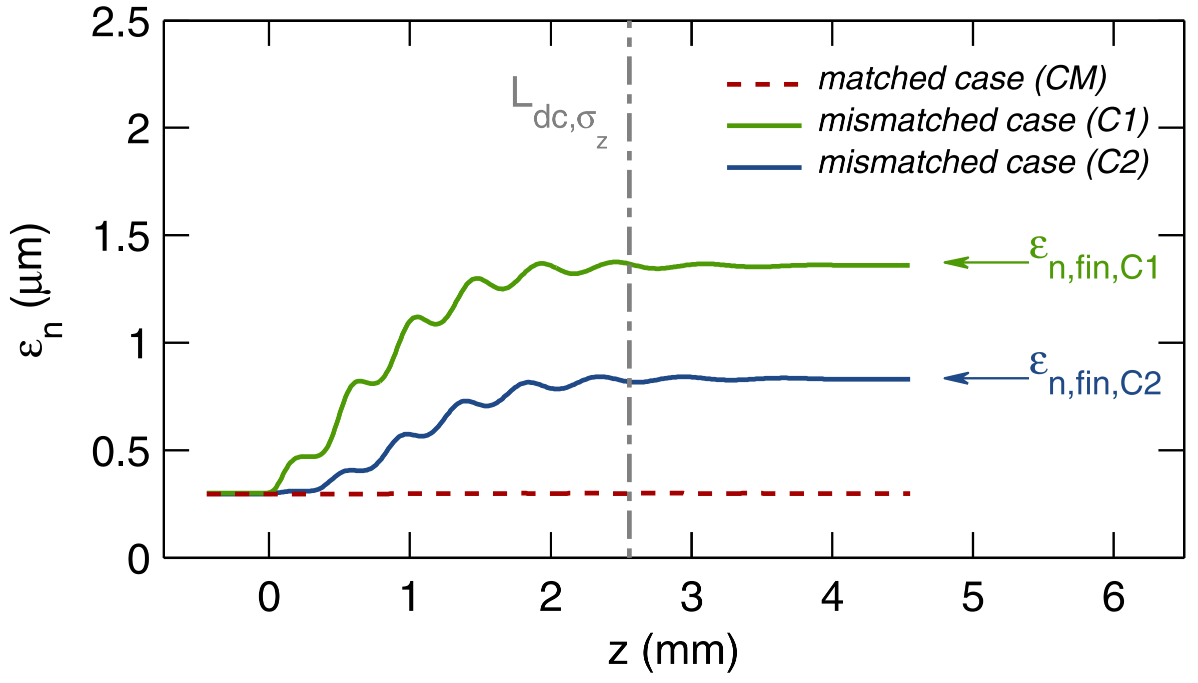


Image source: T. Mehrling *et al.*, PRAB **15**, 111303 (2012)



Matching conditions

$$\alpha_m = 0 \qquad \beta_m \simeq \frac{c}{\omega_\beta} \qquad \omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}}$$

High-power and repetition rate plasma accelerators are emerging

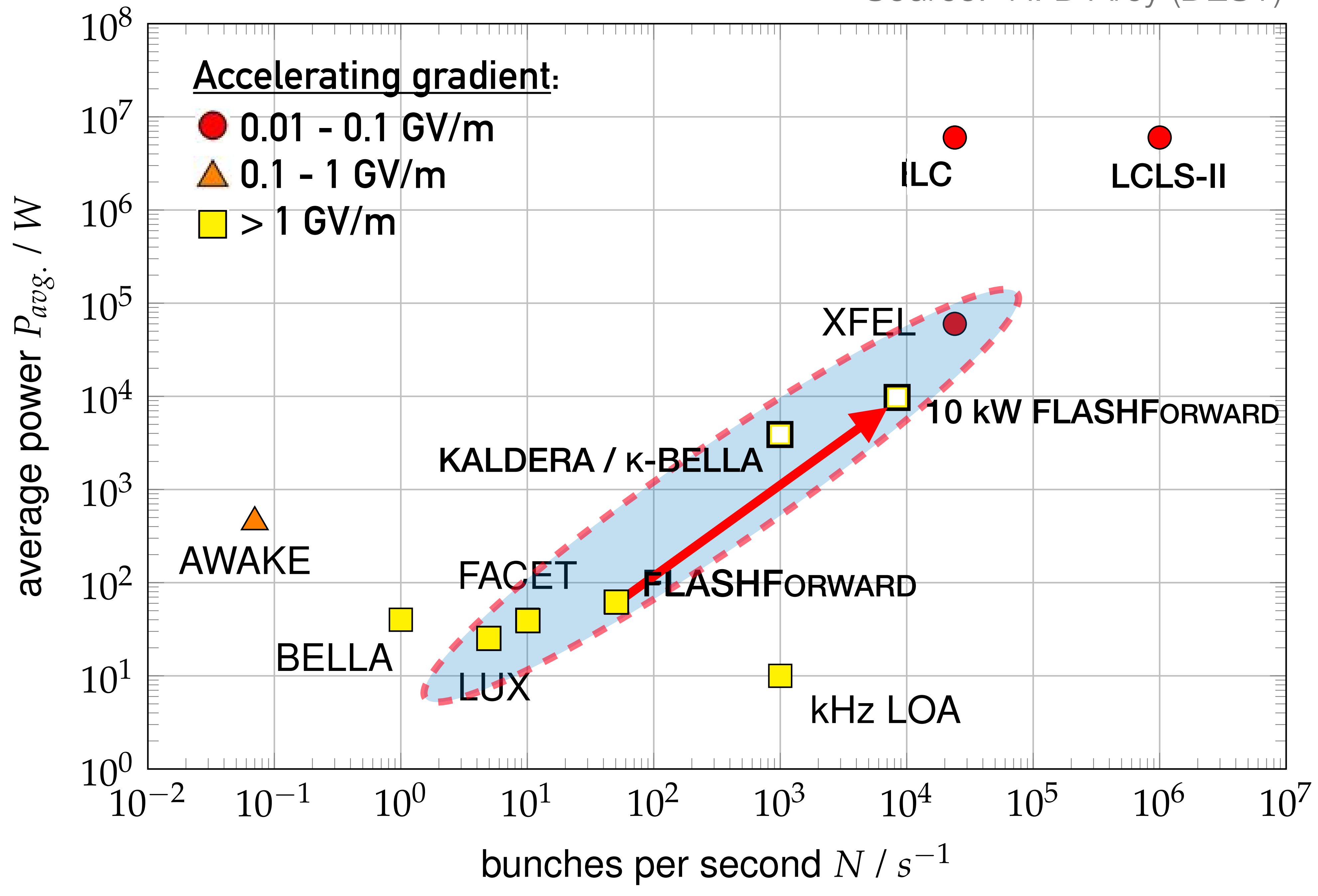
Ballpark requirements and state-of-the-art

	FEL	Collider	Current
Charge per bunch (nC)	0.01 - 0.1	0.1 - 1	0.01 - 0.1
Energy gain (GeV)	0.1 - 10	1000	0.1 - 10
Energy spread (%)	0.1	0.1	0.1
Wall-plug efficiency (%)	< 0.1 - 10	10	< 0.1
Emittance (µm)	0.1 - 1	0.01	?
Rep. rate (Hz)	10^1 - 10^6	10^4 - 10^5	10
Avg. beam power (W)	10^1 - 10^6	10^6	10

first studies done, R&D in an early stage

R.Zgadzaj *et al.*, Nat. Commun. **11**, 4753 (2020)

Source: R. D'Arcy (DESY)



Technical challenges / unexplored physics

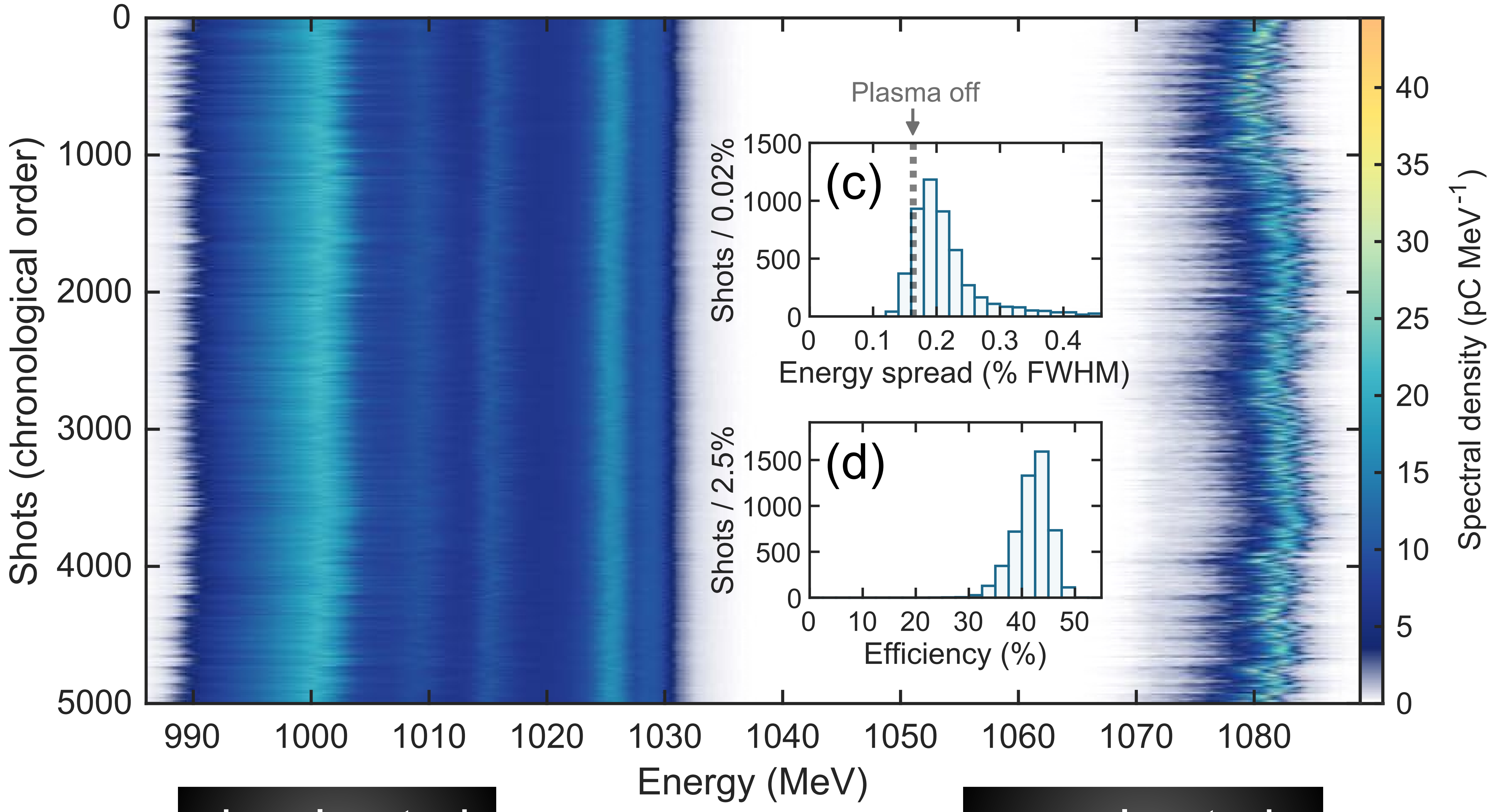
- Plasma recovery physics unexplored
  → supported rep. rate / time structure
- Heat deposition into plasma / heat management (~kW / cm)
- Durability of plasma vessels
- Prohibitive numerical demands for self-consistent, nanosecond to millisecond, multi-physics plasma simulations

Stability is improving, would benefit from dedicated & optimized facility

Ballpark requirements and state-of-the-art

	FEL	Collider	Current
Charge per bunch (nC)	0.01 - 0.1	0.1 - 1	0.01 - 0.1
Energy gain (GeV)	0.1 - 10	1000	0.1 - 10
Energy spread (%)	0.1	0.1	0.1
Wall-plug efficiency (%)	< 0.1 - 10	10	< 0.1
Emittance (µm)	0.1 - 1	0.01	?
Rep. rate (Hz)	10^1 - 10^6	10^4 - 10^5	10
Avg. beam power (W)	10^1 - 10^6	10^6	10
Continuous run	24/1 - 24/7	24/365	24/1
Parameter stability	0.1%	0.1%	1%

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



decelerated driver bunch

accelerated witness bunch

Stability is improving

- all sub-systems factor in: RF stability, power supply stability, …
  ➞ affects incoming bunch stability + plasma stability
  ➞ benefits from dedicated facility (enable full access to everything)
- plasma acceleration stability control
  ➞ needs the right beam controls and diagnostics

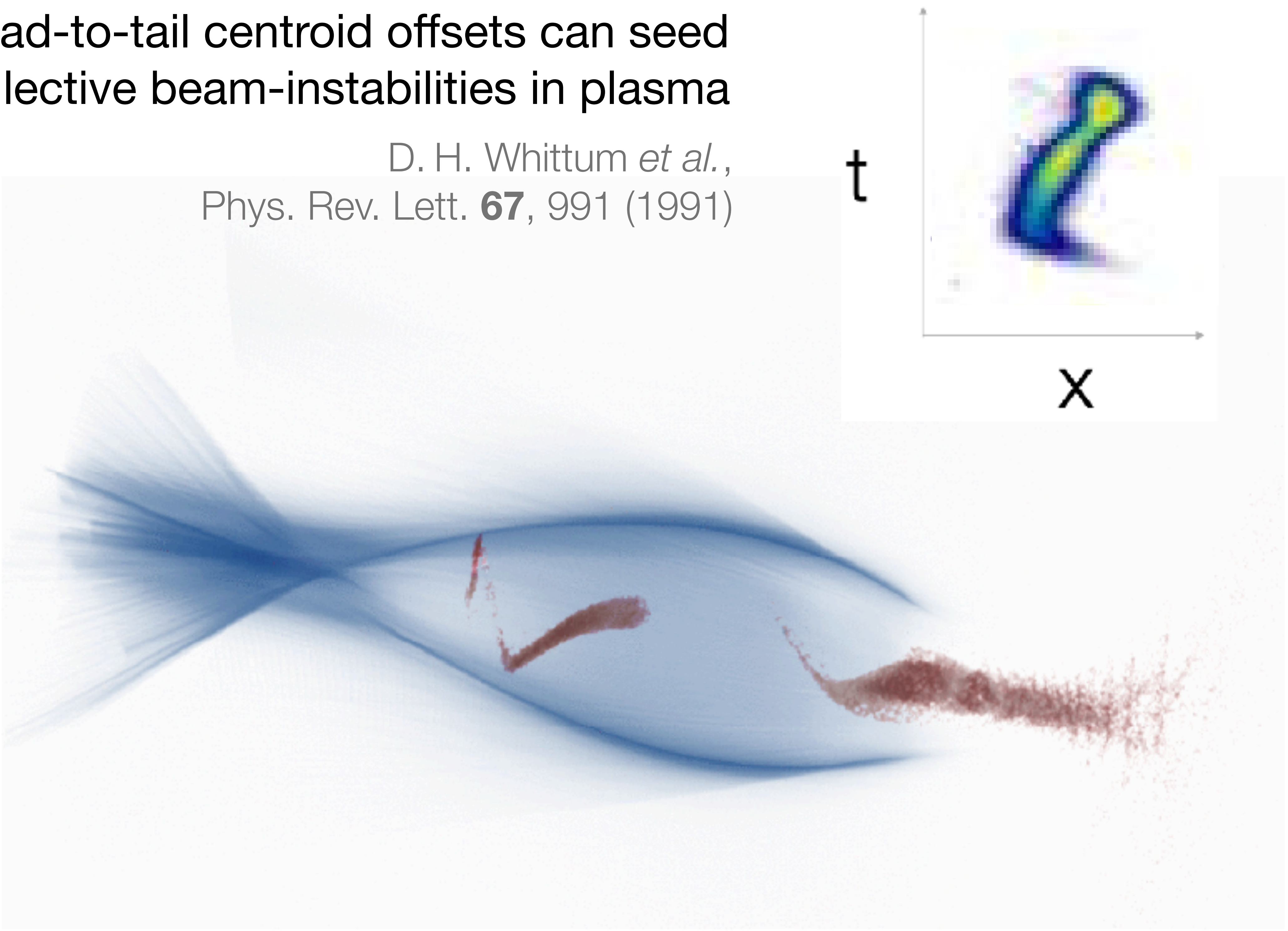
Stability is improving, would benefit from dedicated & optimized facility

Ballpark requirements and state-of-the-art

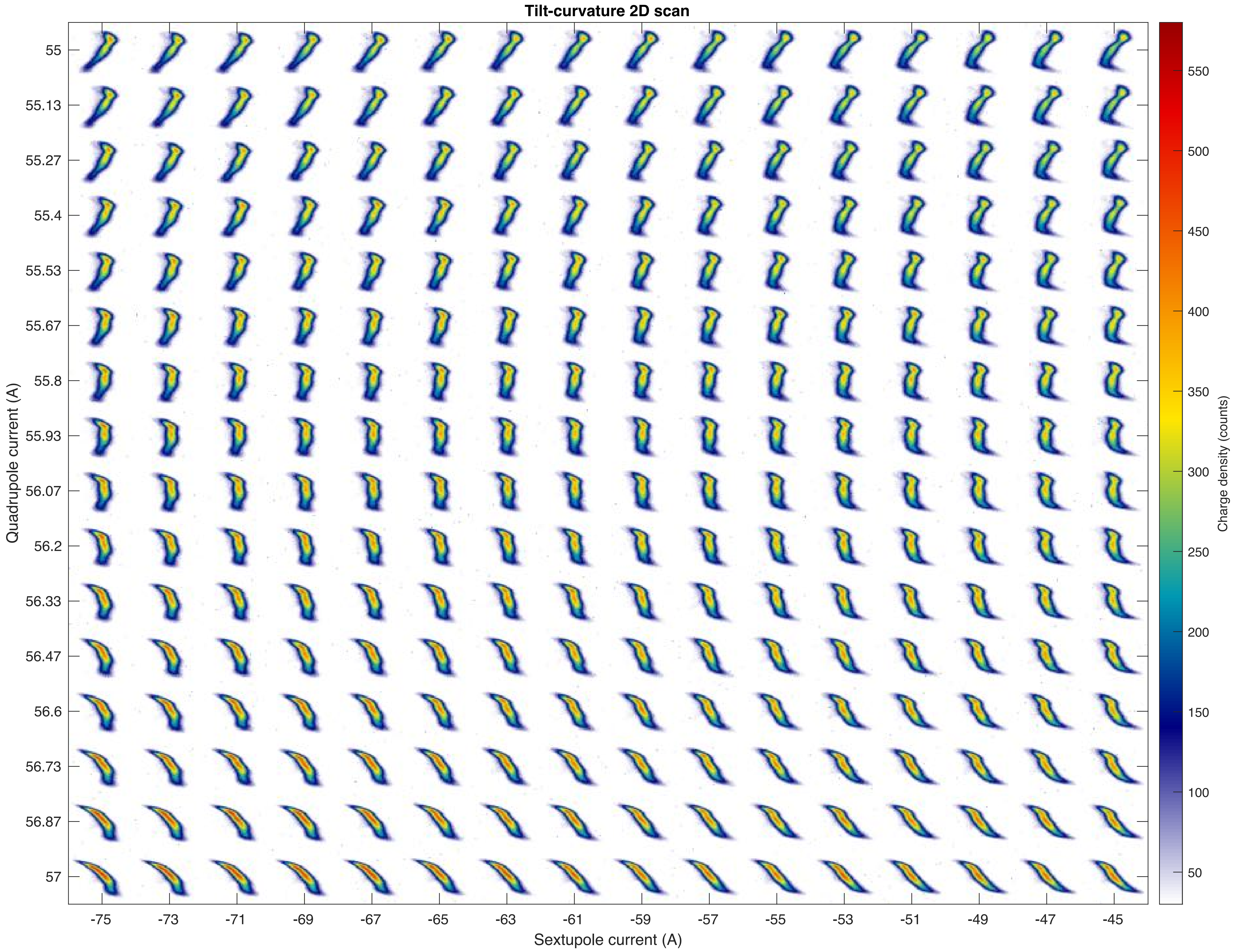
	FEL	Collider	Current
Charge per bunch (nC)	0.01 - 0.1	0.1 - 1	0.01 - 0.1
Energy gain (GeV)	0.1 - 10	1000	0.1 - 10
Energy spread (%)	0.1	0.1	0.1
Wall-plug efficiency (%)	< 0.1 - 10	10	< 0.1
Emittance (µm)	0.1 - 1	0.01	?
Rep. rate (Hz)	10^1 - 10^6	10^4 - 10^5	10
Avg. beam power (W)	10^1 - 10^6	10^6	10
Continuous run	24/1 - 24/7	24/365	24/1
Parameter stability	0.1%	0.1%	1%

Head-to-tail centroid offsets can seed collective beam-instabilities in plasma

D. H. Whittum *et al.*,
Phys. Rev. Lett. **67**, 991 (1991)

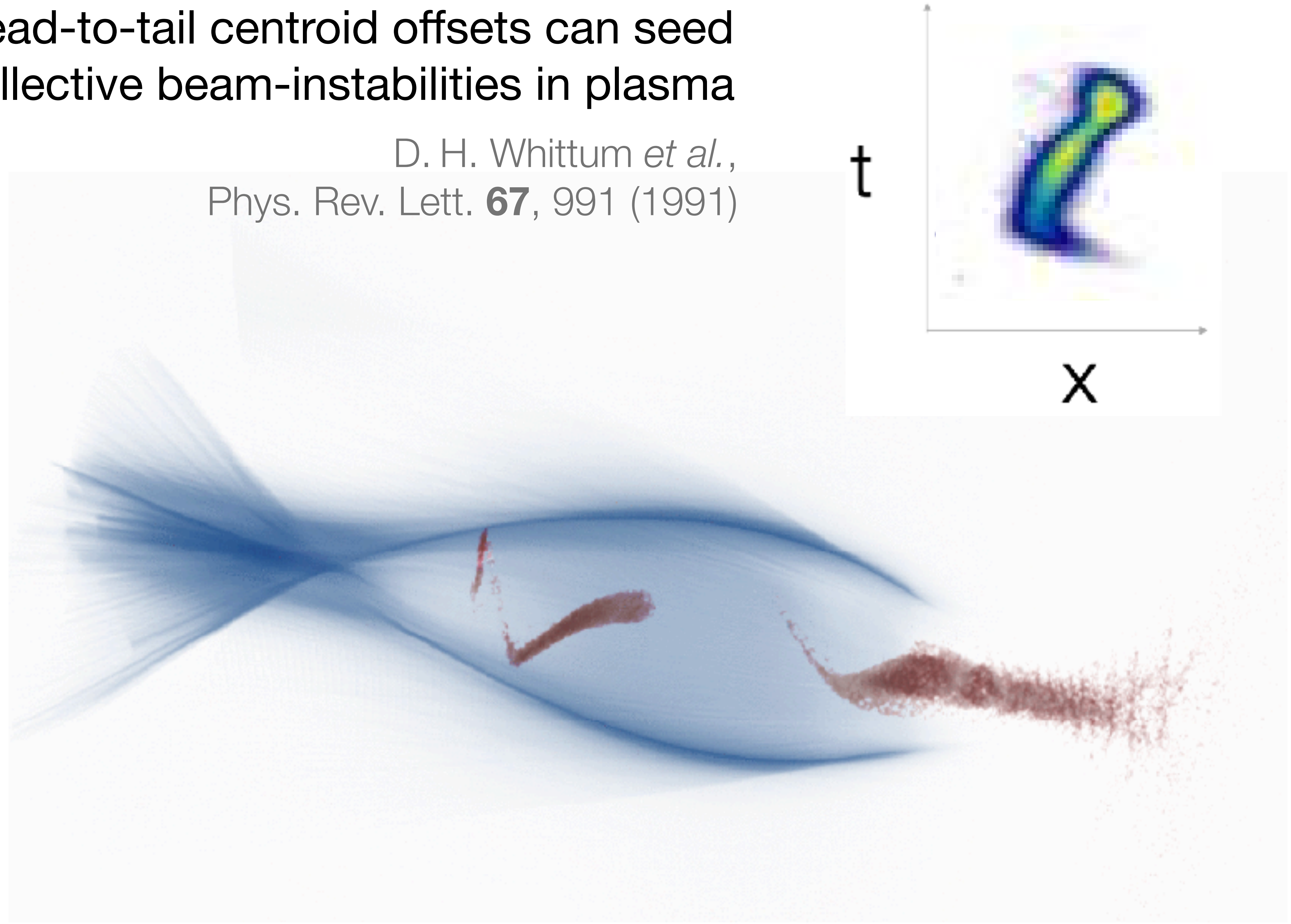


Beam-plasma stability management requires special beam controls



Head-to-tail centroid offsets can seed collective beam-instabilities in plasma

D. H. Whittum *et al.*,
Phys. Rev. Lett. **67**, 991 (1991)

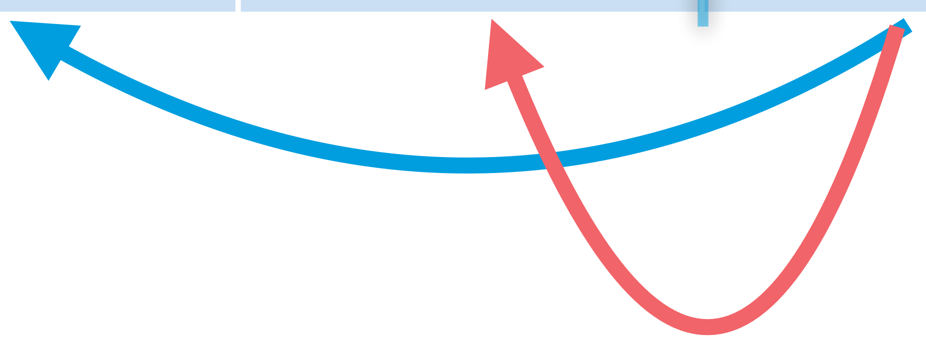


Requires beam-controls and diagnostics on top of the “standard”.

Collider is the ultimate challenge, requires specific solutions

Ballpark requirements and state-of-the-art

	FEL	Collider	Current
Charge per bunch (nC)	0.01 - 0.1	0.1 - 1	0.01 - 0.1
Energy gain (GeV)	0.1 - 10	1000	0.1 - 10
Energy spread (%)	0.1	0.1	0.1
Wall-plug efficiency (%)	< 0.1 - 10	10	< 0.1
Emittance (μm)	0.1 - 1	0.01	?
Rep. rate (Hz)	10^1 - 10^6	10^4 - 10^5	10
Avg. beam power (W)	10^1 - 10^6	10^6	10
Continuous run	24/1 - 24/7	24/365	24/1
Parameter stability	0.1%	0.1%	1%



Well on track to realize first FEL-quality demonstrator stage (all parameters simultaneously)

Needs solutions specifically developed for particle colliders

- *highest energy:* **staging of plasma modules**
- *lowest emittance:* precision beam and plasma control
- *efficiency:* high wall-plug efficiency (energy recovery?)
- *rep. rate and avg. power:* kW/cm thermal plasma management
- ***positron acceleration*** *with exquisite quality*
- ***beam polarization*** *maintenance*
- *computing capabilities for full start-to-end optimization*

Needs a coordinated worldwide effort and funding

→ for a self-consistent collider design
→ to demonstrate viability of technical concepts

Staging plasma modules for access to the energy frontier

Serialization of stages comes with challenges

Review article: Lindstrøm, Phys. Rev. Accel. Beams **24**, 014801 (2021)

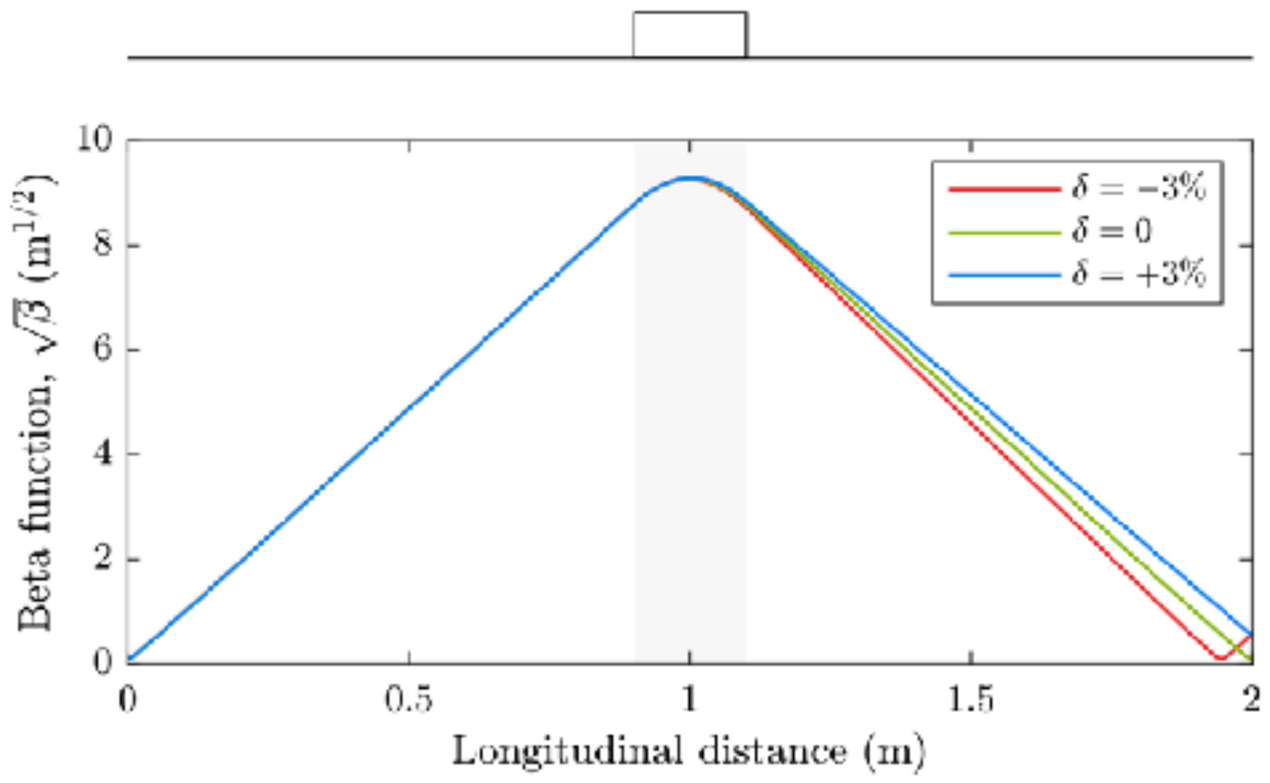
Main motivation:

Reaching higher energy than is available in a single stage (limited by driver energy).

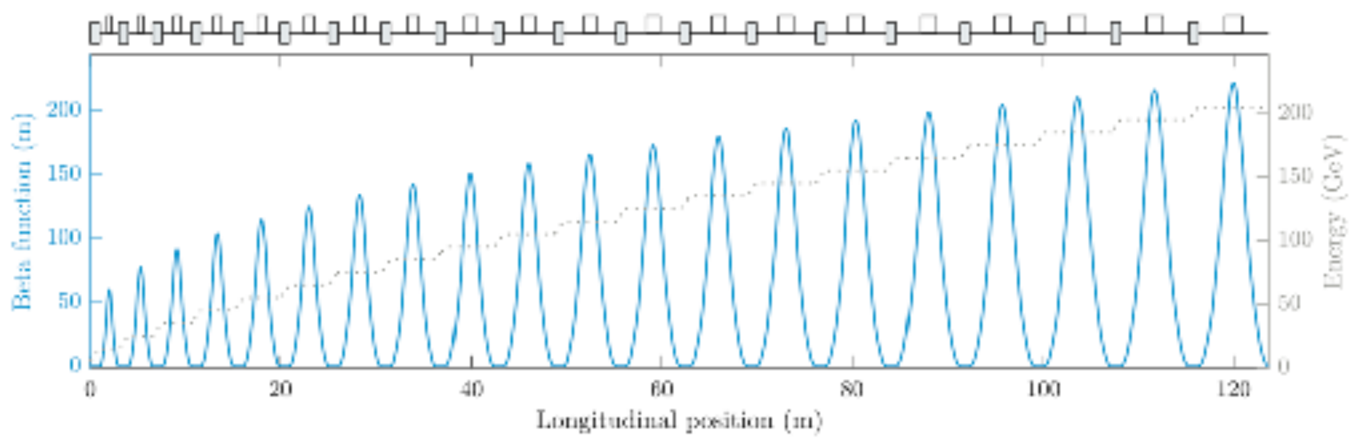
Challenges:

- In- and out-coupling of drivers (kickers too slow — use energy separation in a dipole).
- Synchronization of drivers (at fs-scale, for injecting at the correct phase).
- Isochronicity (R_{56}) cancellation/control (for correct beam loading).
- Emittance preservation between stages:
  - Matching of beta function for all energies (chromaticity due to high divergence).
  - Transverse misalignments (stages must be aligned at the nm–μm scale).
  - Dispersion cancellation (from in- and out-coupling dipoles).
  - Coulomb scattering (large beta functions between stages—differential pumping required).
- Driver distribution scheme (from one linac/ring to all stages with correct delay).
- CSR management in beam handling.
- Compactness (combined setup must retain a high (GV/m) average accelerating gradient)

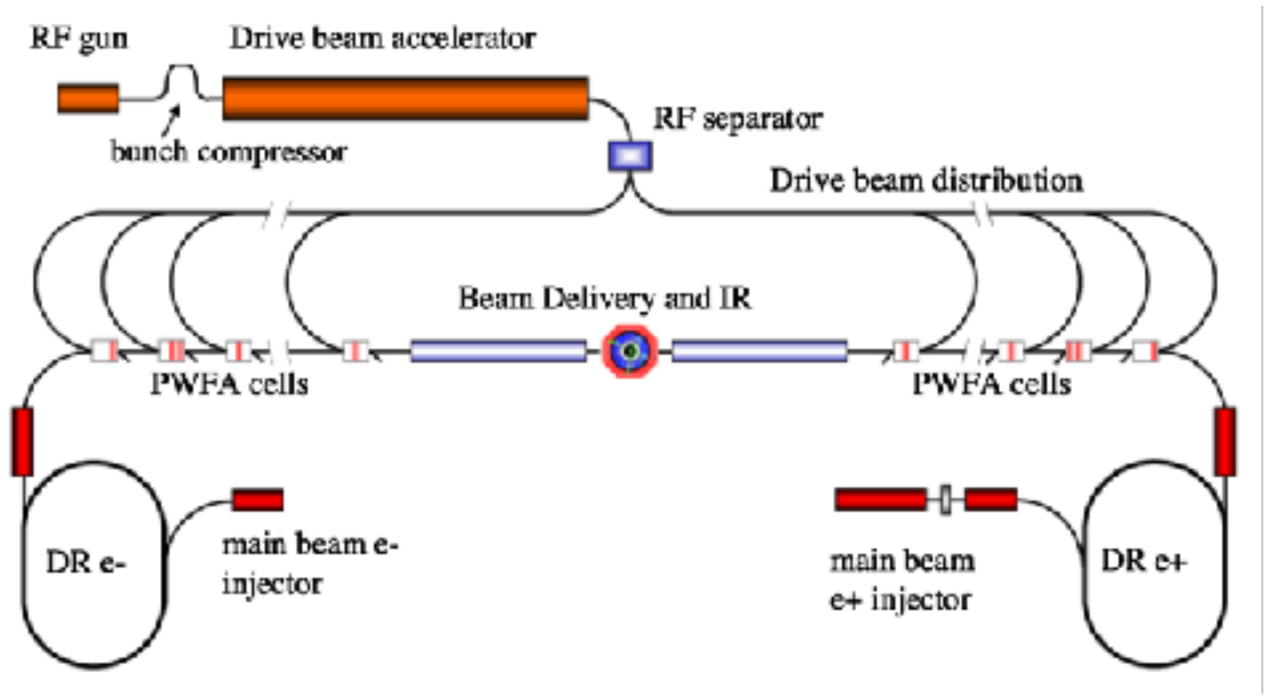
A programmatic attempt to demonstrate staging of beam-driven plasma accelerator modules does not exist.



Source: Lindstrøm, PRAB 24, 014801 (2021)



Source: Lindstrøm, PRAB 24, 014801 (2021)



Source: Pei *et al.*, Proc. PAC'09, p. 2682 (2009)

Plasmas for mid-term particle physics applications

AWAKE scheme enables high-energy experiments

Requirements on emittance are moderate for fixed target and e/p collider experiments

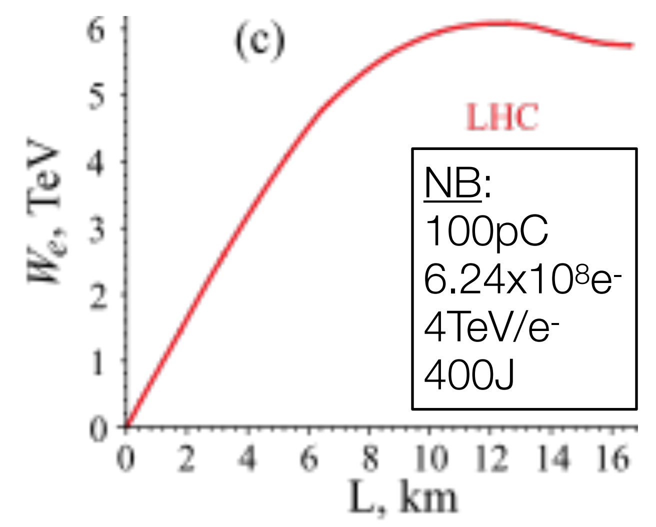
Scalable AWAKE technology could be application-ready in 10 year-time frame

Opportunity to use high-energy proton bunches:

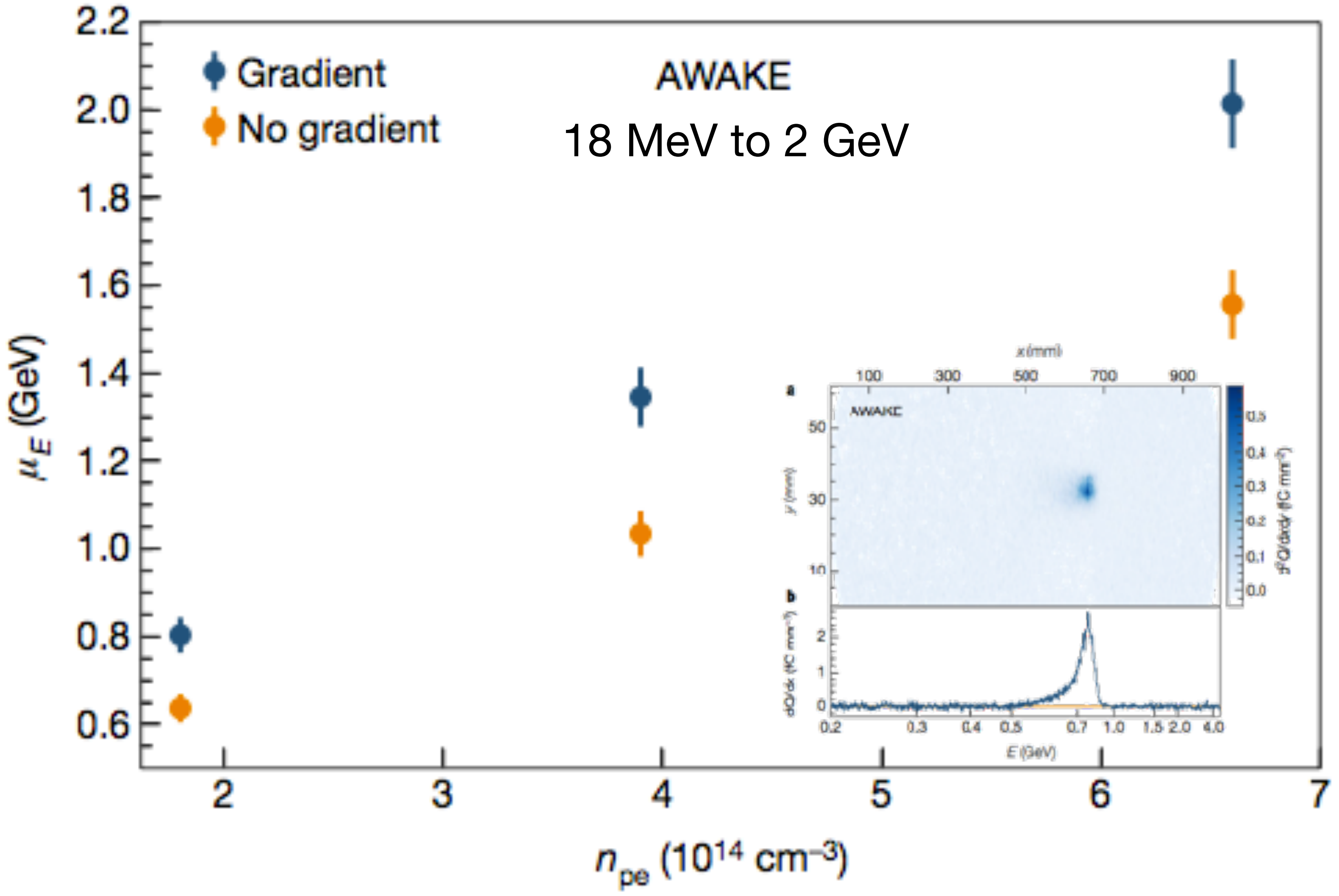
- **SPS** 400 GeV, 19 kJ SPS
- **LHC** 7TeV, 120 kJ LHC

to drive GeV/m accelerating gradients
in a single, long plasma for acceleration of electrons

~TeV in km ⇔ ~GeV/m



Caldwell, PoP **18**, 13101 (2011)



AWAKE, Nature **561**, 363 (2018)

Develop technology to enable

- high-quality electron beams
- scalable plasma lengths

Applications (talk by M.Wing)

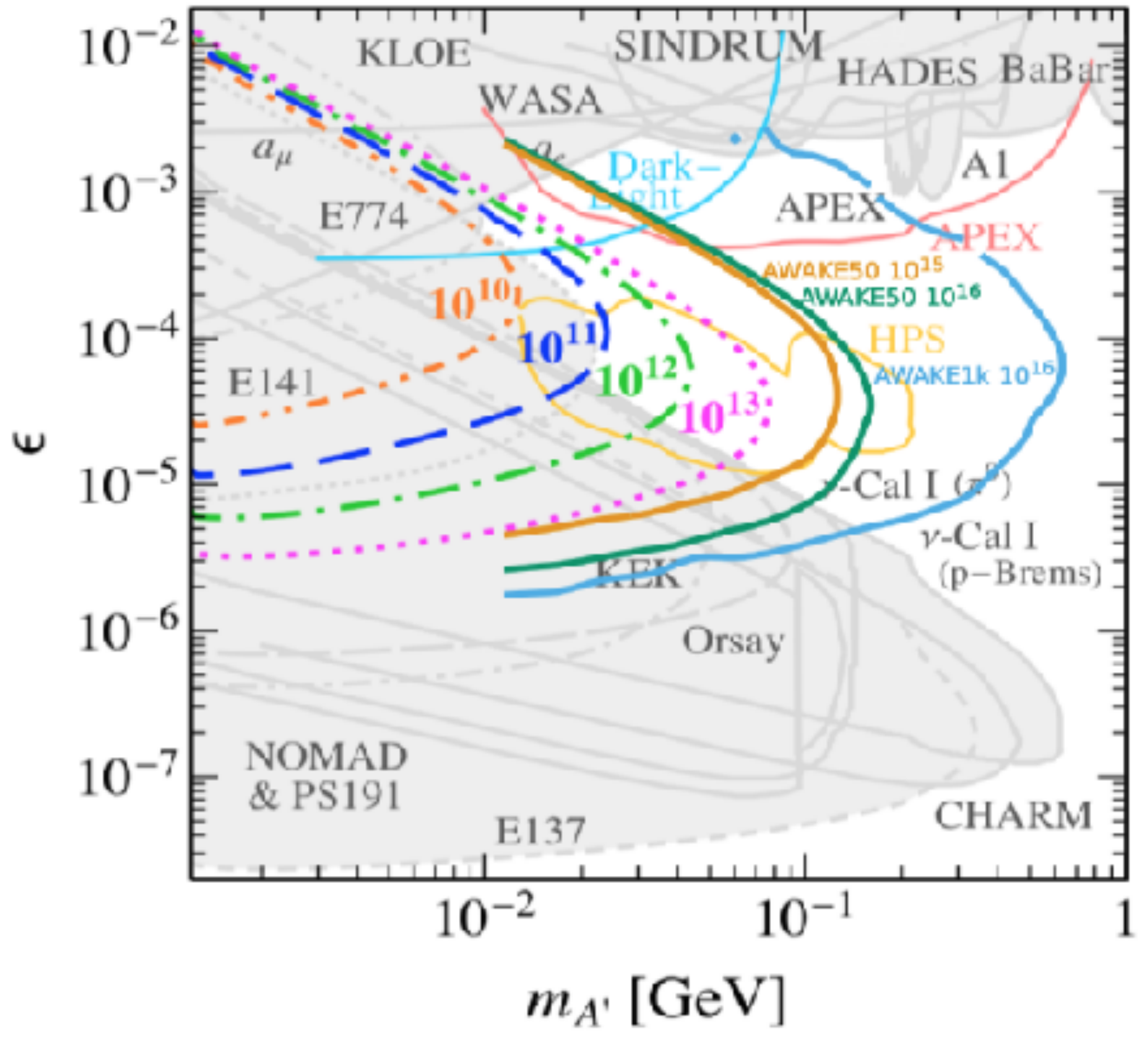
Mid-term (~10 years)

- Fixed target experiments, 30 GeV e-
- Search for dark photons

Long-term

- Very High Energy Electron-Proton (VHEEP) collider

Caldwell *et al.*, Eur Phys J C **76**, 463 (2016)
Wing *et al.*, Phil Trans A Math Phys Eng Sci., **377**, 2151 (2019)



Summary

Scientific goals for the next 5/10 years

- **Beam-driven plasma accelerators are closing in on photon science requirements**
  ➞ increasing credibility for more complex applications in particle physics
- **Beam-driven plasma accelerators can provide opportunities in particle physics in the 10-year time frame**
  ➞ AWAKE scheme for high-energy, moderate luminosity
  ➞ several other applications (see talks this morning)
- **Plasma accelerators R&D is on a promising trajectory with a lot of momentum**
- **To sustain this momentum for collider specific challenges, new developments are required**
  - technology R&D needs to be intensified - - - - - - - - - - - - - ▶
  - culture change and worldwide roadmap
  - ~5 years goal — consistent plasma-based collider design
  - ~10 years goal — dedicated test facility for collider relevant plasma accelerator R&D

	FEL-like parameters	Collider-like parameters
Single stage energy + quality	5 years	partially
Beam energy spread	5 years	5 years
Beam emittance	5 years	partially
Wall-plug efficiency	sufficient will be improved	partially
Rep. rate / avg. power	sufficient 10 years to kW	partially
Multi-stage energy + quality	-	no program
Positron stage	-	partially 5 years to concept
Beam polarization	-	no program
Start-to-end simulations	done	partially