High-repetition-rate beam drivers and plasma sources

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ALEGRO Workshop
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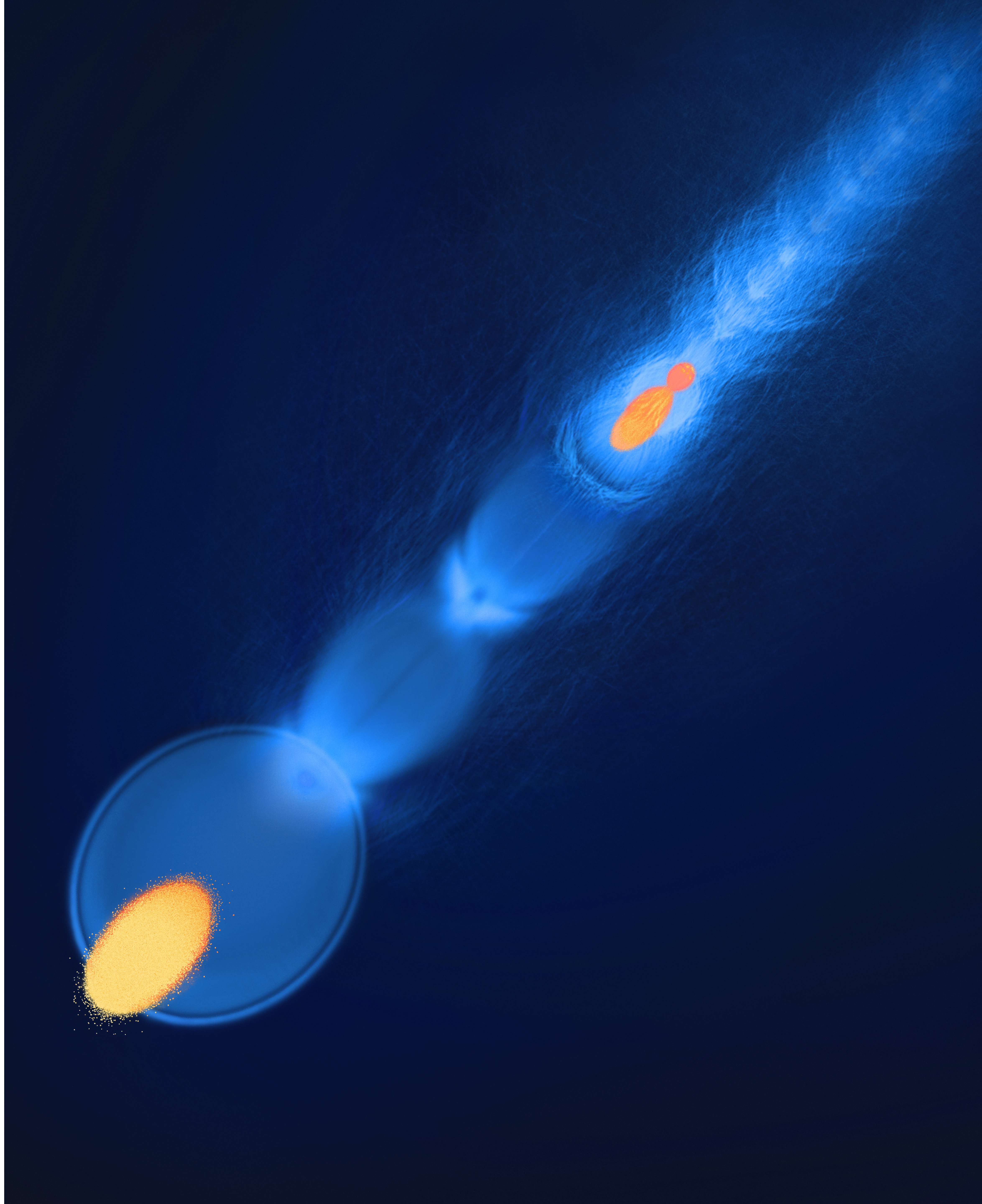
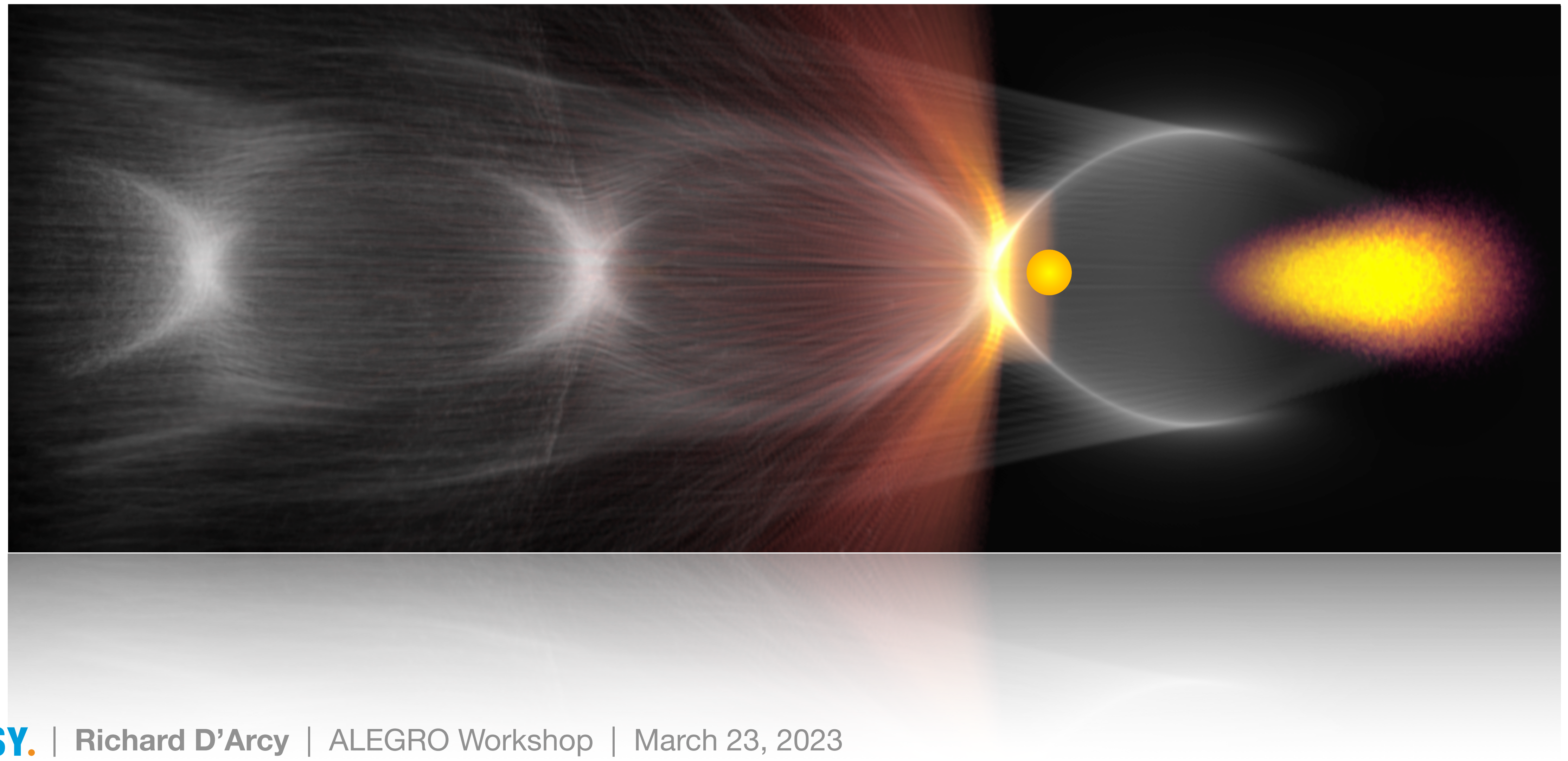


The desire for high-energy particle accelerators

Radio-frequency cavity

Charge-density wave in a plasma



- To first order the **particle energy** at an accelerator facility **defines its discovery reach**
  - *Free-electron lasers*: energy ➞ wavelength
  - *High-energy physics*: centre-of-mass energy
- Therefore higher energy is often desired but conventional technology is **limited in accelerating gradient due to electrical breakdown**
- Plasma-wakefield accelerators offer a **route to higher energies with smaller facilities** due to *O*(GV/m) gradients

Our customers: High-energy-physics (and photon-science) needs

- Let's say that we could produce 500 GeV beams tomorrow, what else would we need to do?

- The luminosity demands that certain properties be maximised/minimised (similar demands for integrated brightness at FELs):

High repetition rate

High energy-transfer 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

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Low energy spread
(luminosity spectrum, final focusing)

Low emittance

Selected results:

Litos *et al.*, "High-efficiency acceleration of an electron beam in a plasma wakefield accelerator", **Nature** (2014)

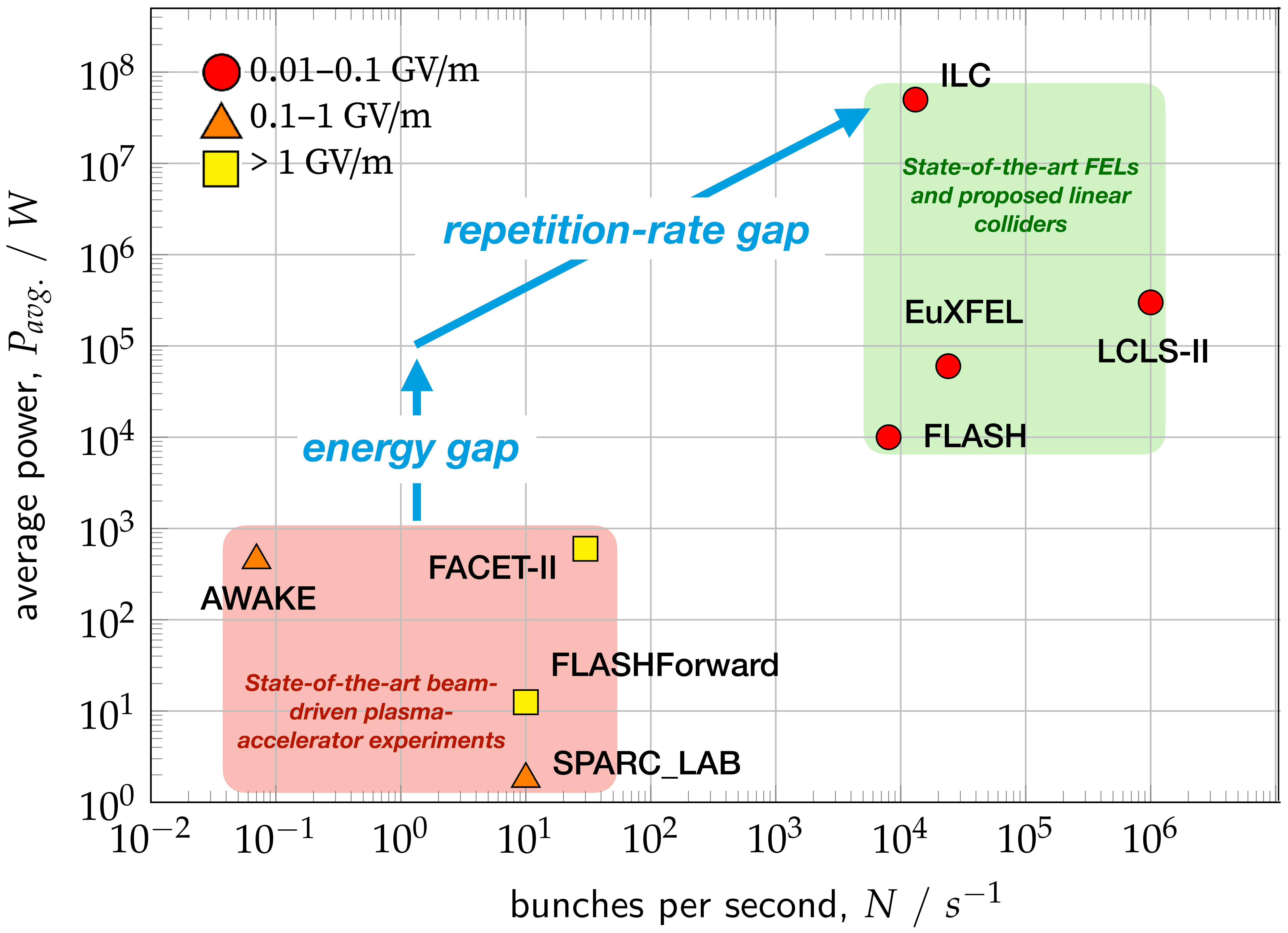
Wu *et al.*, "High-throughput injection–acceleration of electron bunches from a linear accelerator to a laser wakefield accelerator", **Nat. Phys.** (2021)

Lindstrøm *et al.*, "Energy-spread preservation and high efficiency in a plasma-wakefield accelerator", **Phys. Rev. Lett.** (2021)

Pompili *et al.*, "Energy spread minimisation in a beam-driven plasma wakefield accelerator", **Nat. Phys.** (2021)

Lindstrøm *et al.*, "Preservation of beam quality in a plasma-wakefield accelerator", **under review** (2023)

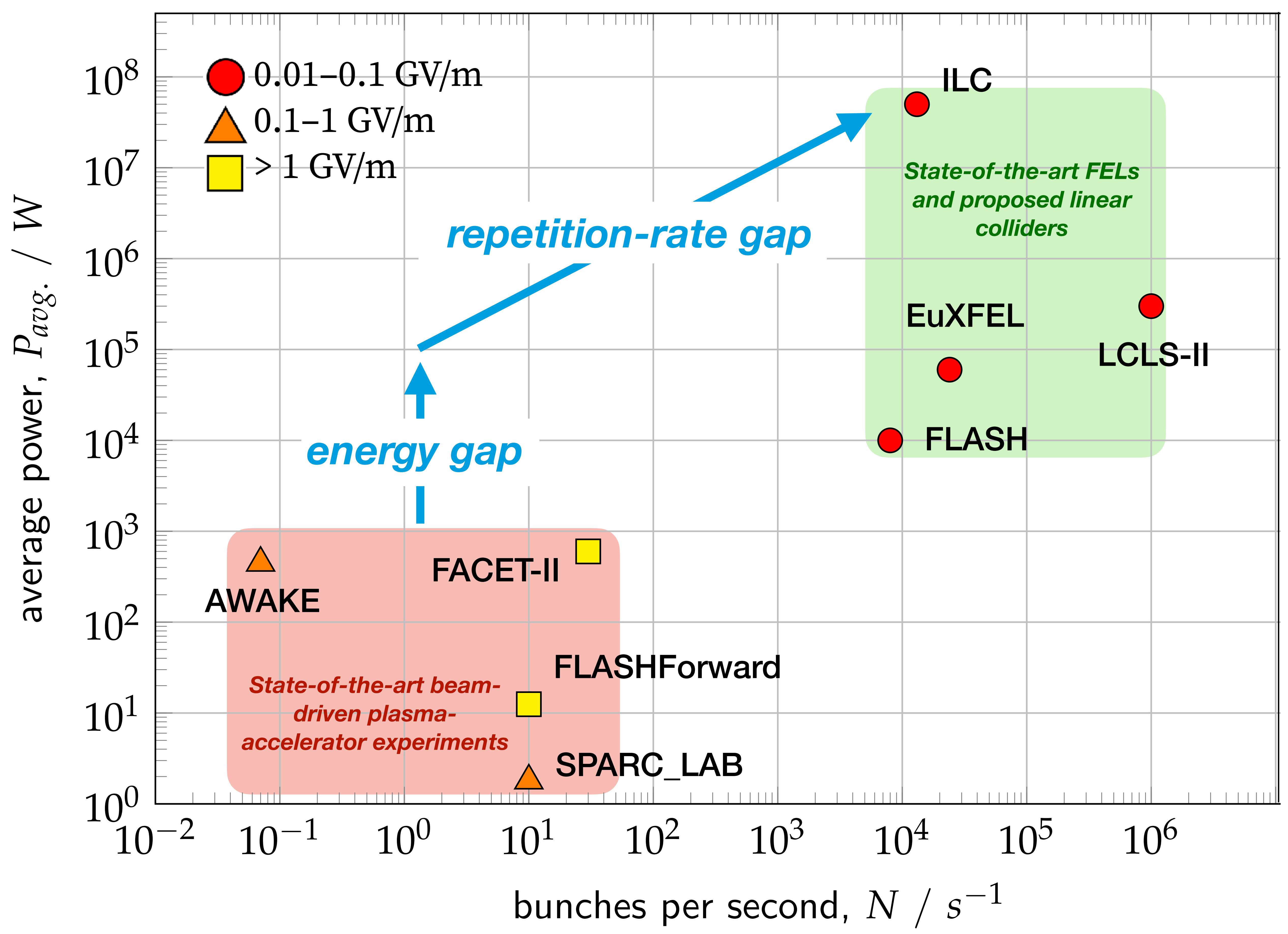
High-average-power requirements for linear colliders



> We are many orders of magnitude away from where we need to be in terms of bunches per second and average power…

> … but why?

High-average-power requirements for linear colliders



> We are many orders of magnitude away from where we need to be in terms of bunches per second and average power…

> … but why?

> **Energy** ➞ scalable staging to high energy remains an open challenge (see Carl L's talk)

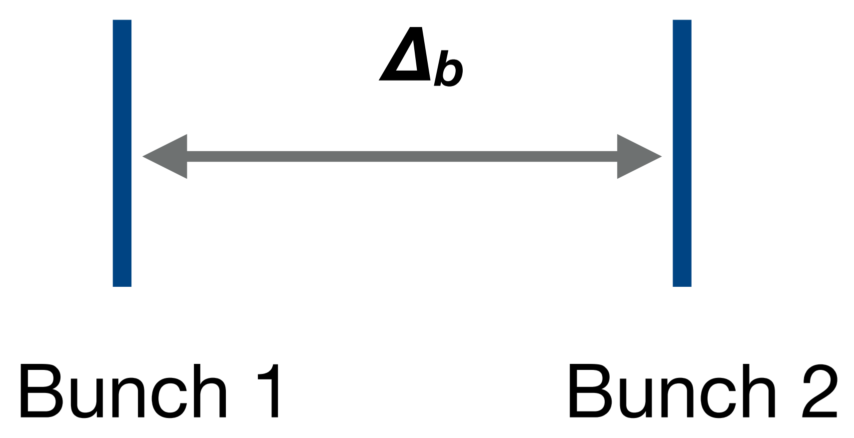
> **Other research priorities** ➞ solving other open challenges in the field applicable to low rep. rate

> **Other application goals** ➞ many facilities in Europe are motivated by application to photon science

> **Unknown limits** ➞ the physics effects that may limit/permit high rep. rate are currently unknown/undefined

Defining the repetition-rate upper limit

What defines the minimum inter-bunch separation in metallic cavities?



Inter-bunch separation Δ_b

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

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

> Long-range transverse wakefields induced in the metallic cavities from an acceleration event live 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.

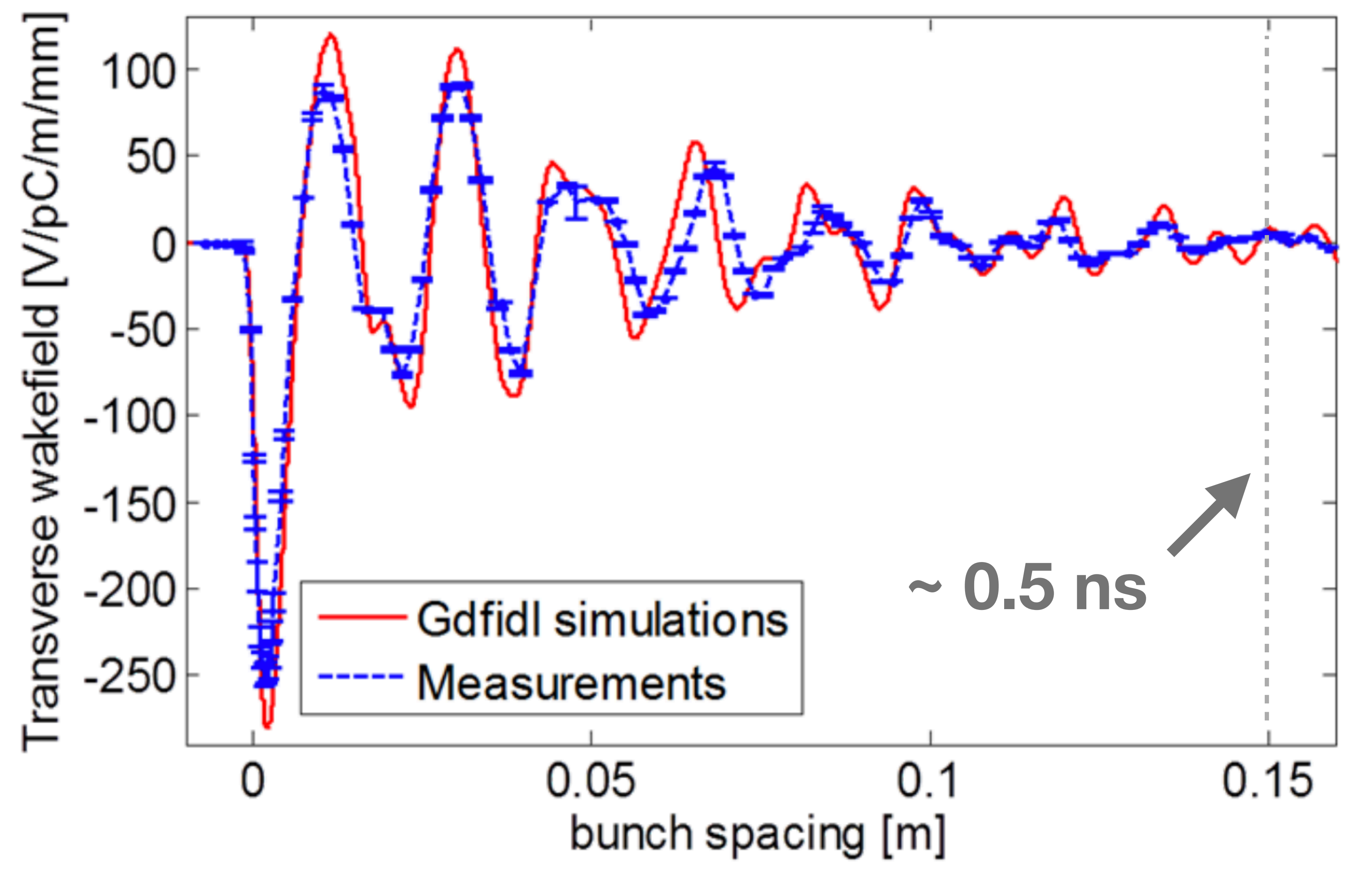


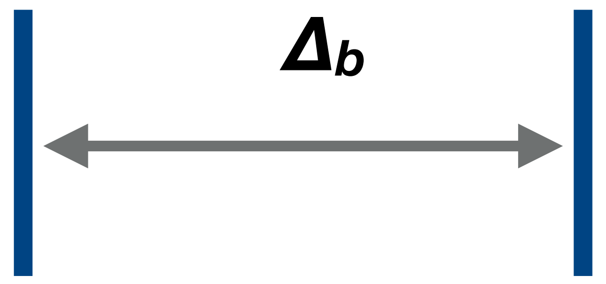
Image modified from H. Zha *et al.*, **IPAC15** (2015)

Equivalent effect in plasma accelerators is long-term plasma motion

> Wakefield structure rapidly decays after only the first few oscillations

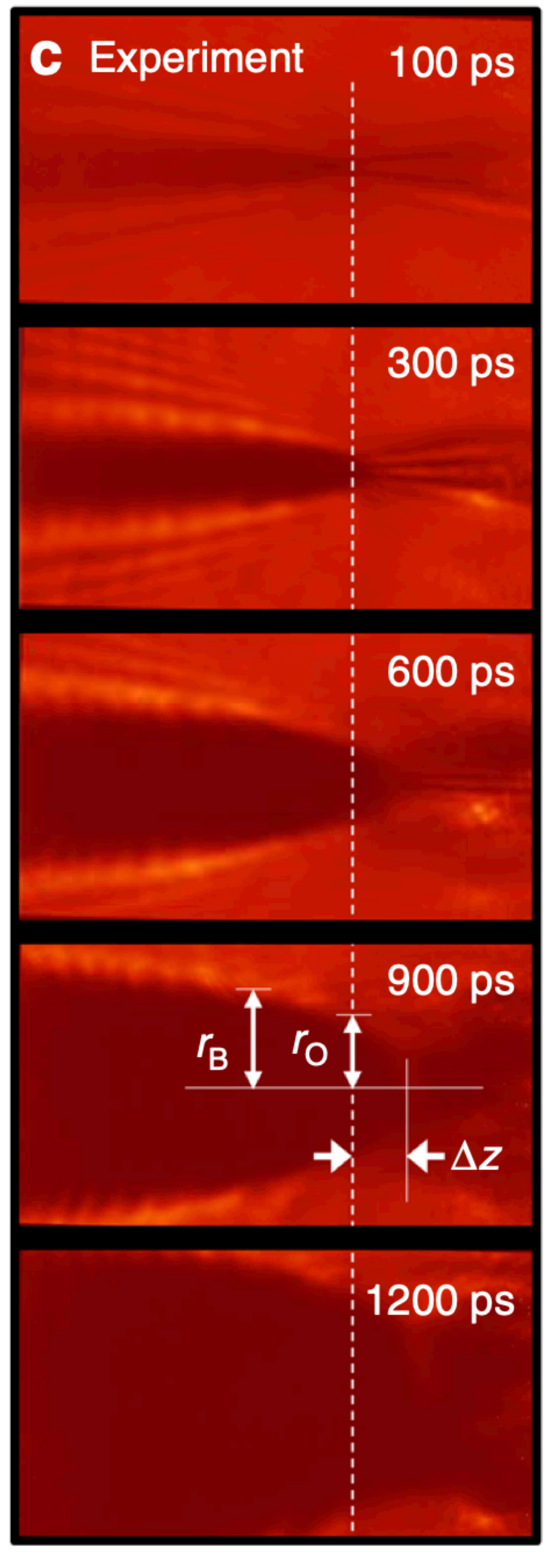
> Need to accelerate in ~1st bubble and wait until the plasma 'recovers'

> ***Recovery time*** of the plasma places an upper limit on the maximum achievable repetition rate

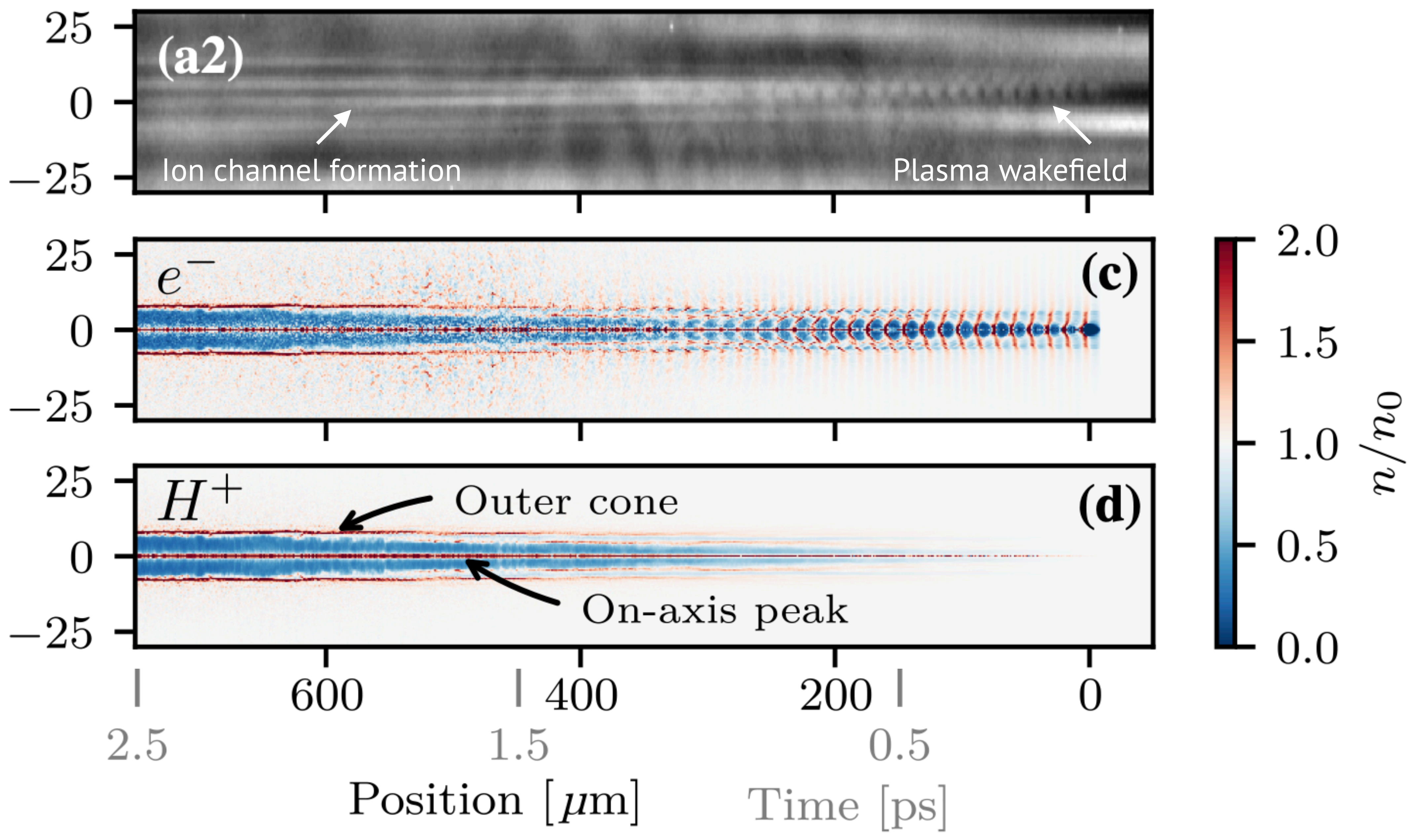


Inter-bunch separation Δ_b

Expansion of ion column following wake excitation



Shadowgraphy signal of wake dissipation and ion channel formation



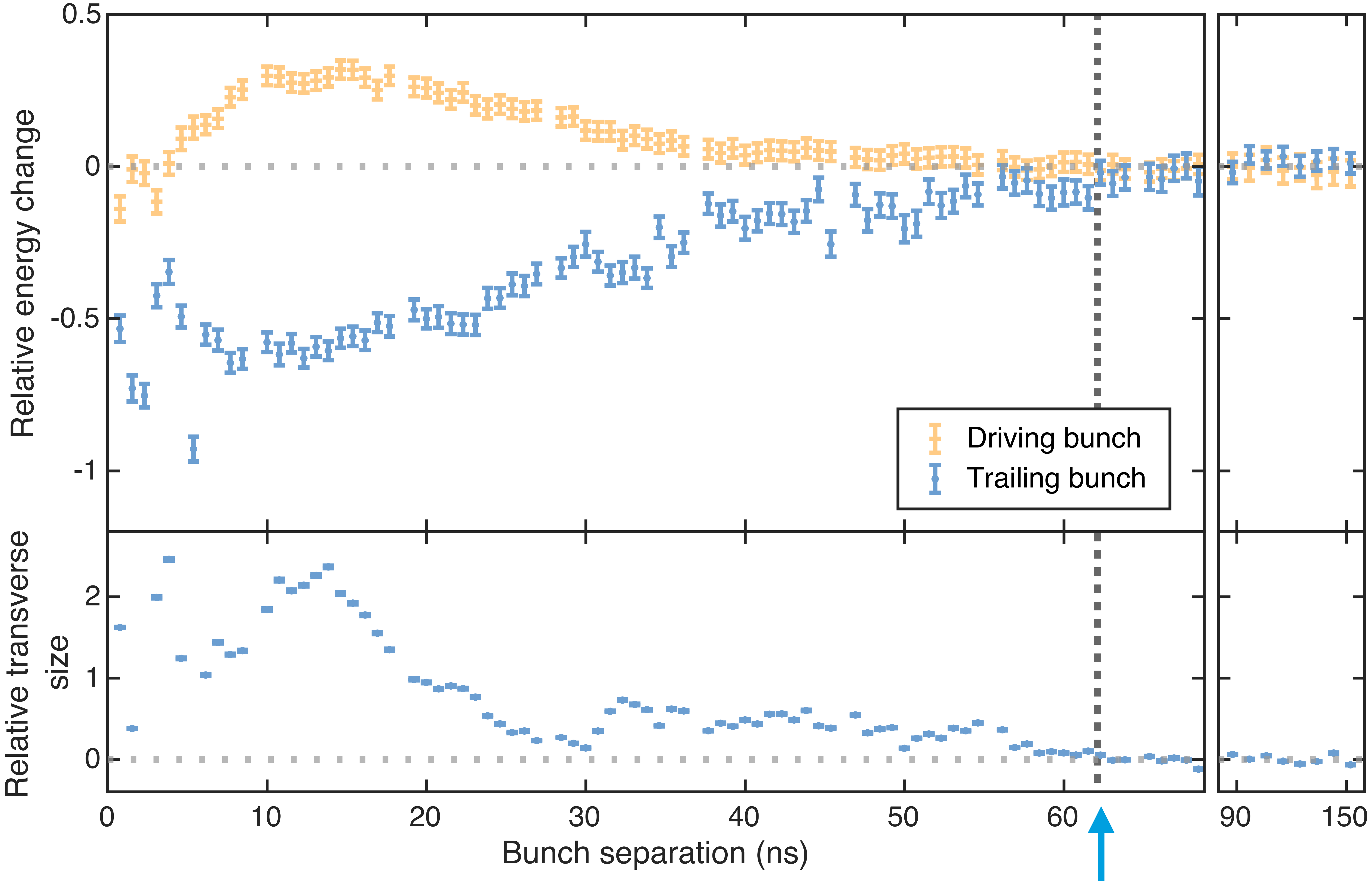
First experimental results in the field

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

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

Recovery time measured to be ~63 ns (for experimental settings)

R. D'Arcy *et al.*, Nature **603**, 58-62 (2022)



point of recovery

> Recovery time defined as the separation at which all three experimental signals are consistent with zero to within experimental uncertainties

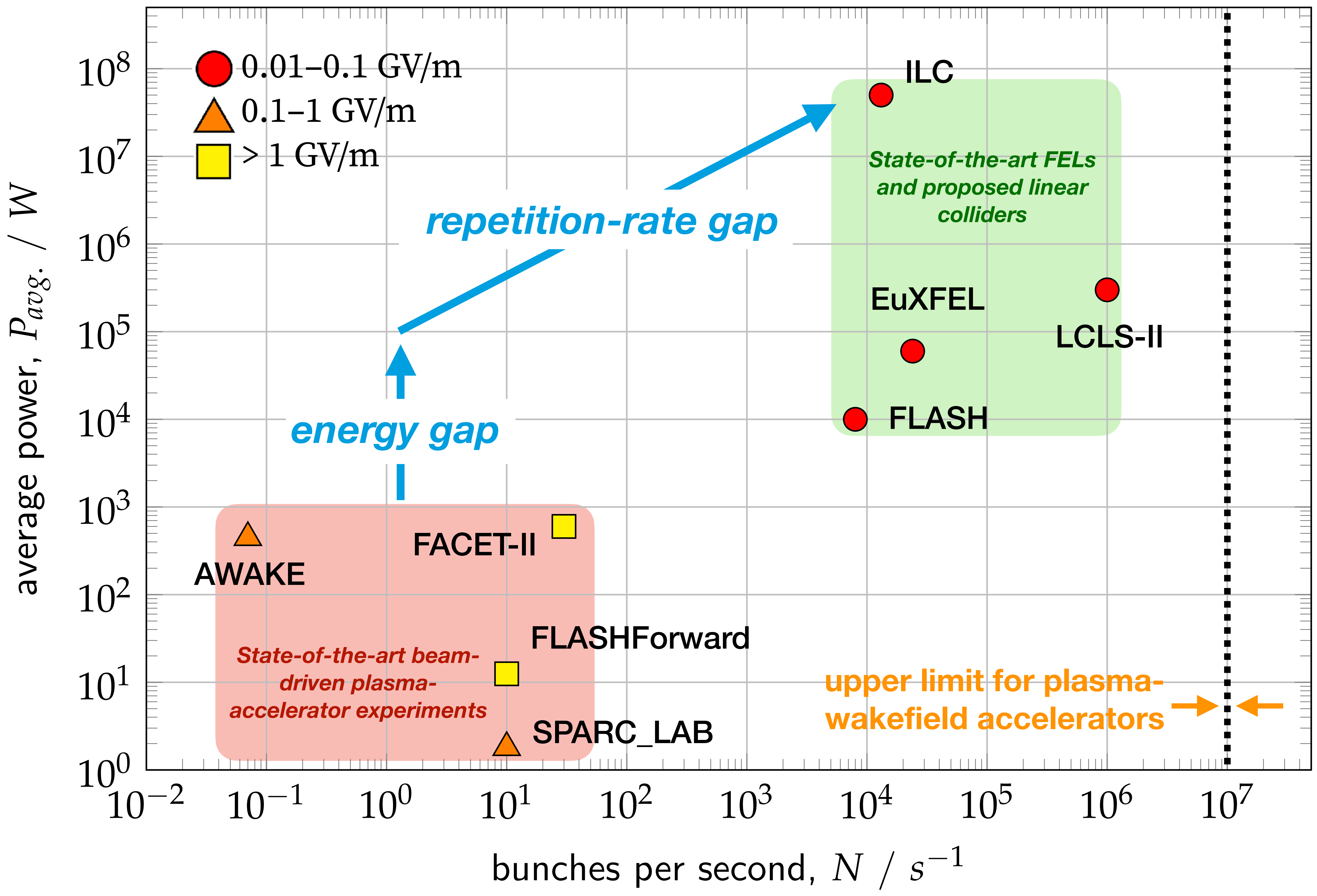
> All residuals consistent with zero at ~63 ns*

> ***Equivalent to a repetition-rate upper limit of O(10 MHz)*****

*for working point in argon plasma of density ~1E16 cm

**if CW operation is permitted by other physics effects/technical limits

High-average-power requirements for linear colliders



- We are many orders of magnitude away from where we need to be in terms of bunches per second and average power…
- … but why?
  - **Energy** → scalable staging to high energy remains an open challenge (see Carl L's talk)
  - **Other research priorities** → solving other open challenges in the field applicable to low rep. rate
  - **Other application goals** → many facilities in Europe are motivated by application to photon science
  - **Some unknown limits** → many of the physics effects that may limit/permit high rep. rate are currently unknown/undefined

How do we define the rest?

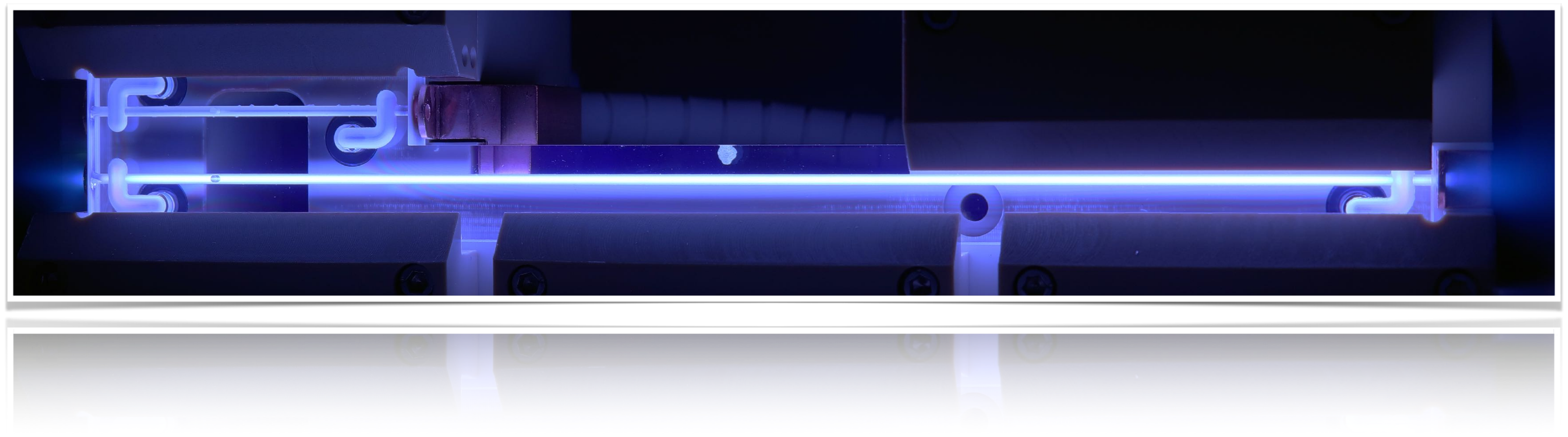
Two fundamental components of a beam-driven plasma accelerator

Radio-frequency-cavity front end

> Can be either warm or superconducting ➞ there are benefits to each

	FEL	Collider	Current
Bunches per second	10^1 - 10^6	10^4 - 10^5	**10^1 - 10^6**
Avg. beam power (W)	10^1 - 10^5	10^6	**10^1 - 10^6**

Plasma-accelerator stage



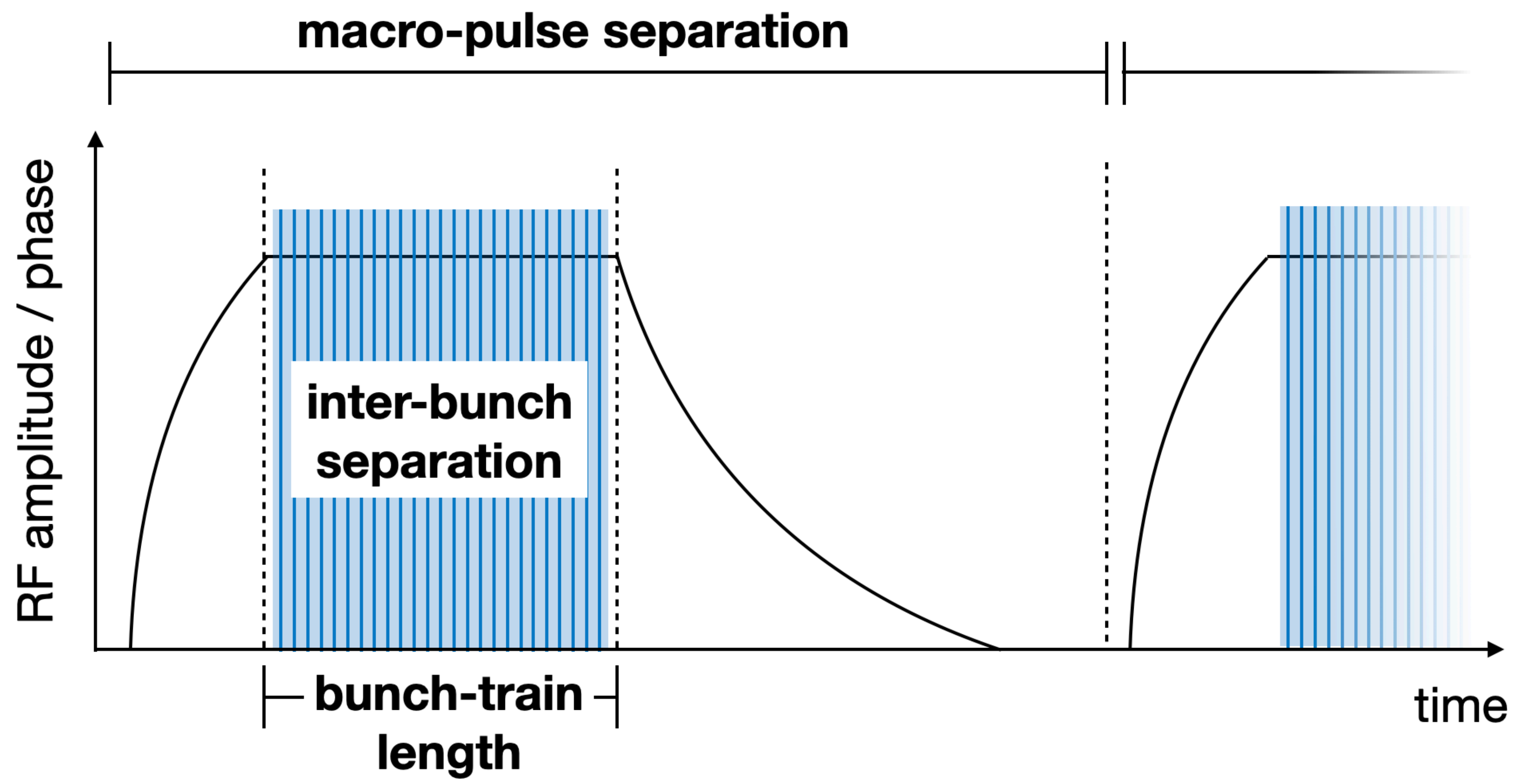
> Discharge-capillary plasma stages have been a workhorse in the field for the last ~20 years*

	FEL	Collider	Current
Bunches per second	10^1 - 10^6	10^4 - 10^5	**10^1**
Avg. beam power (W)	10^1 - 10^5	10^6	**10^1**

*ignoring laser- and beam-generated sources in the interest of brevity

Bunch-train patterns: the path to *O*(10,000) bunches per second

- Radio-frequency cavities are capable of operating in ***continuous-wave*** (CW) ***mode*** ➞ different to 'CW' operation in lasers
- However, accelerating gradient is limited due to inefficiencies/electrical breakdown ➞ larger driver complexes required
- Operation in a ***pulsed mode*** enables higher accelerating gradients and higher efficiencies

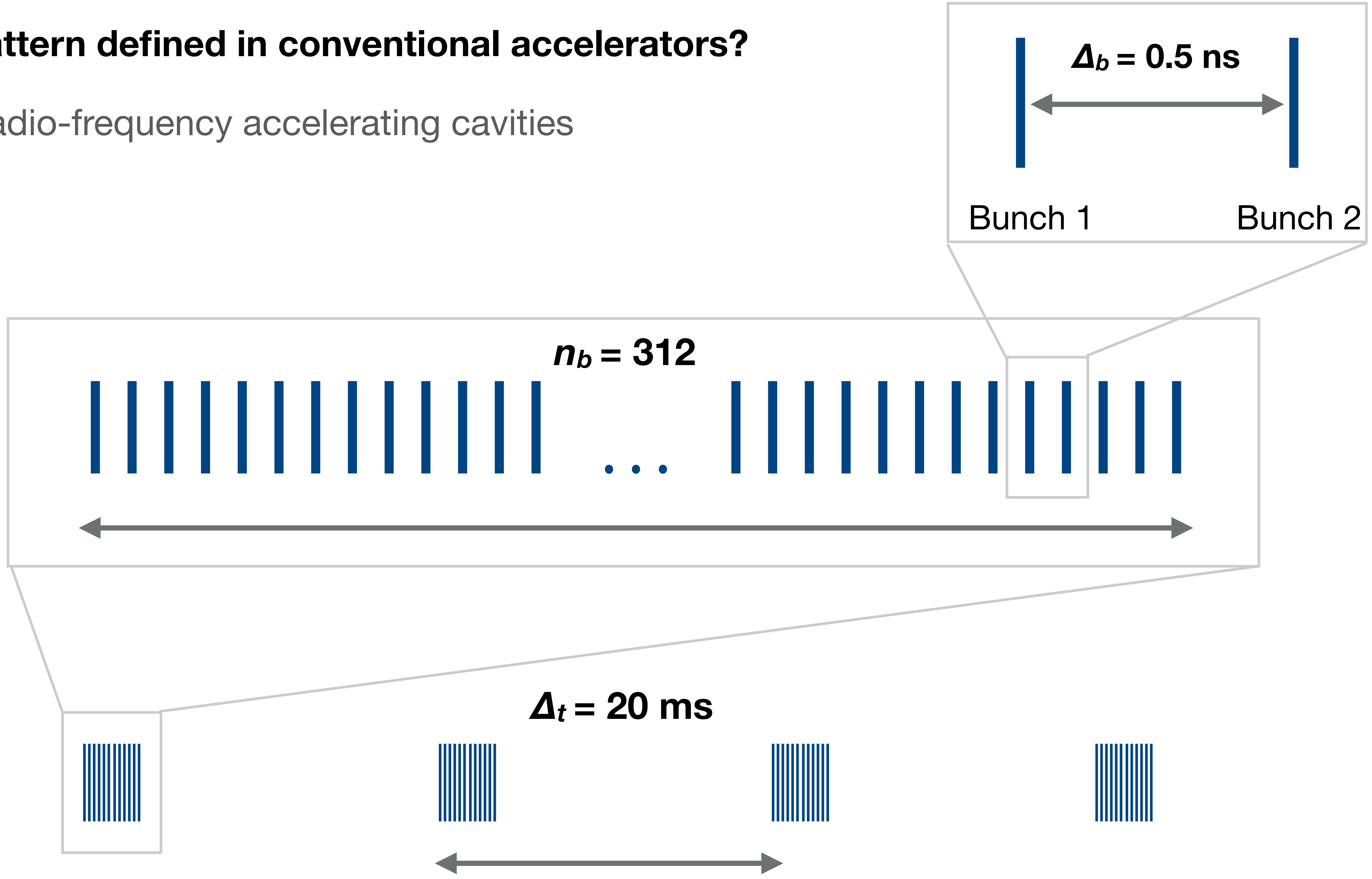


	CLIC example
Property #1 Inter-bunch separation Δ_b	dissipation of long-range transverse wakefields
Property #2 Bunch-train length n_b	balance of RF pulse length, and accelerating field, and electrical breakdowns
Property #3 Macro-pulse separation Δ_t	dissipation of the cumulative heating from each bunch train

Bunch-train patterns: the path to *O*(10,000) bunches per second

How is the bunch pattern defined in conventional accelerators?

e.g. CLIC warm radio-frequency accelerating cavities



Property #1

Inter-bunch separation Δ_b

Property #2

Bunch train length n_b

Property #3

Macro-pulse separation Δ_t

Bunch-train-pattern comparison for different technologies

	Plasma accelerator	ILC	CLIC
Inter-bunch separation	*O*(100 ns)	554 ns	0.5 ns
Bunch-train length	???	726 µs	156 ns
Macro-pulse separation	???	100 ms	20 ms
Max. # of bunches per second	**???**	**13120**	**15600**

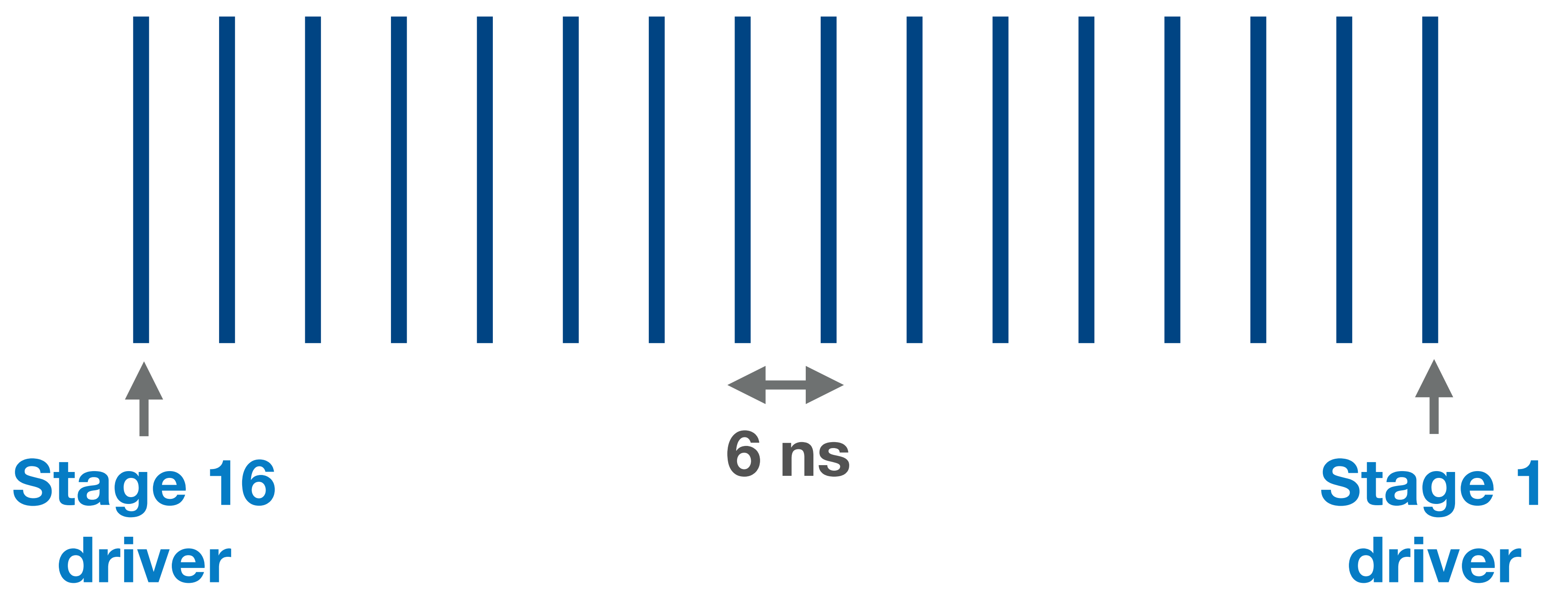
> Seemingly compatible with ILC-type superconducting RF… but not with CLIC-type warm RF

Bunch-train-pattern comparison for different technologies

	Plasma accelerator	ilc	clic
Inter-bunch separation	*O*(100 ns)	554 ns	0.5 ns
Bunch-train length	???	726 μs	156 ns
Macro-pulse separation	???	100 ms	20 ms
Max. # of bunches per second	**???**	**13120**	**15600**

- ***Example of a staged facility***: ~100 m in total length
- ***Path-length difference between stages***: ~2m = **~6 ns ➞** normal-conducting technology!
- ***Total # of stages*** (in this example) i.e. # of drive bunches per accelerating bunch: **16**
- ***Inter-bunch separation***: 16 x 6 ns = ~**100 ns**

Drive-bunch train to drive all stages once



- **Don't exclude any one type of technology just yet!**

Bunch-train-pattern comparison for different technologies

	Plasma accelerator	ILC	CLIC	FLASH
Inter-bunch separation	*O*(100 ns)	554 ns	0.5 ns	333 ns
Bunch-train length	???	726 µs	156 ns	800 µs
Macro-pulse separation	???	100 ms	20 ms	100 ms
Max. # of bunches per second	**???**	**13120**	**15600**	**18000**

- **FLASH** is based on ILC-type technology (or the other way around depending on who you speak to)
- Therefore has similar bunch-train properties
- No show-stopper (yet) for developing a plasma booster to utilise with ILC-
- **Path forward**: continue to develop beam-driven plasma accelerators for complete compatibility with the bunch-train pattern at **FLASH**

Building up plasma-accelerator stages to high repetition rate

Radio-frequency-cavity front end

Plasma-accelerator stage

	FEL	Collider	Current
Inter-bunch sep. (μs)	10^{-1} - 10^{3}	10^{-1} - 10^{3}	10^{-1}
Bunch-train length (#)	10^{1} - 10^{3}	10^{1} - 10^{3}	10^{0}
Macro-pulse rate (Hz)	10^{1} - 10^{2}	10^{1} - 10^{2}	10^{1}
Bunches per second	10^{1} - 10^{6}	10^{4} - 10^{5}	10^{1}
Avg. beam power (W)	10^{1} - 10^{5}	10^{6}	10^{1}

Requirement: increase the bunch-train length

Result: the desired bunches per second

Requirement: manage the increased average power

Returning to the comparison with conventional accelerators

	Conventional accelerators*	Plasma accelerators
Property #1 Inter-bunch separation Δ_b	dissipation of long-range transverse wakefields	**dissipation of long-term plasma motion → *O*(100 ns)**
Property #2 Bunch-train length n_b	balance of RF pulse length, and accelerating field, and electrical breakdowns	***???***
Property #3 Macro-pulse separation Δ_t	dissipation of the cumulative heating from each bunch train	***???***

*CLIC example

Returning to the comparison with conventional accelerators

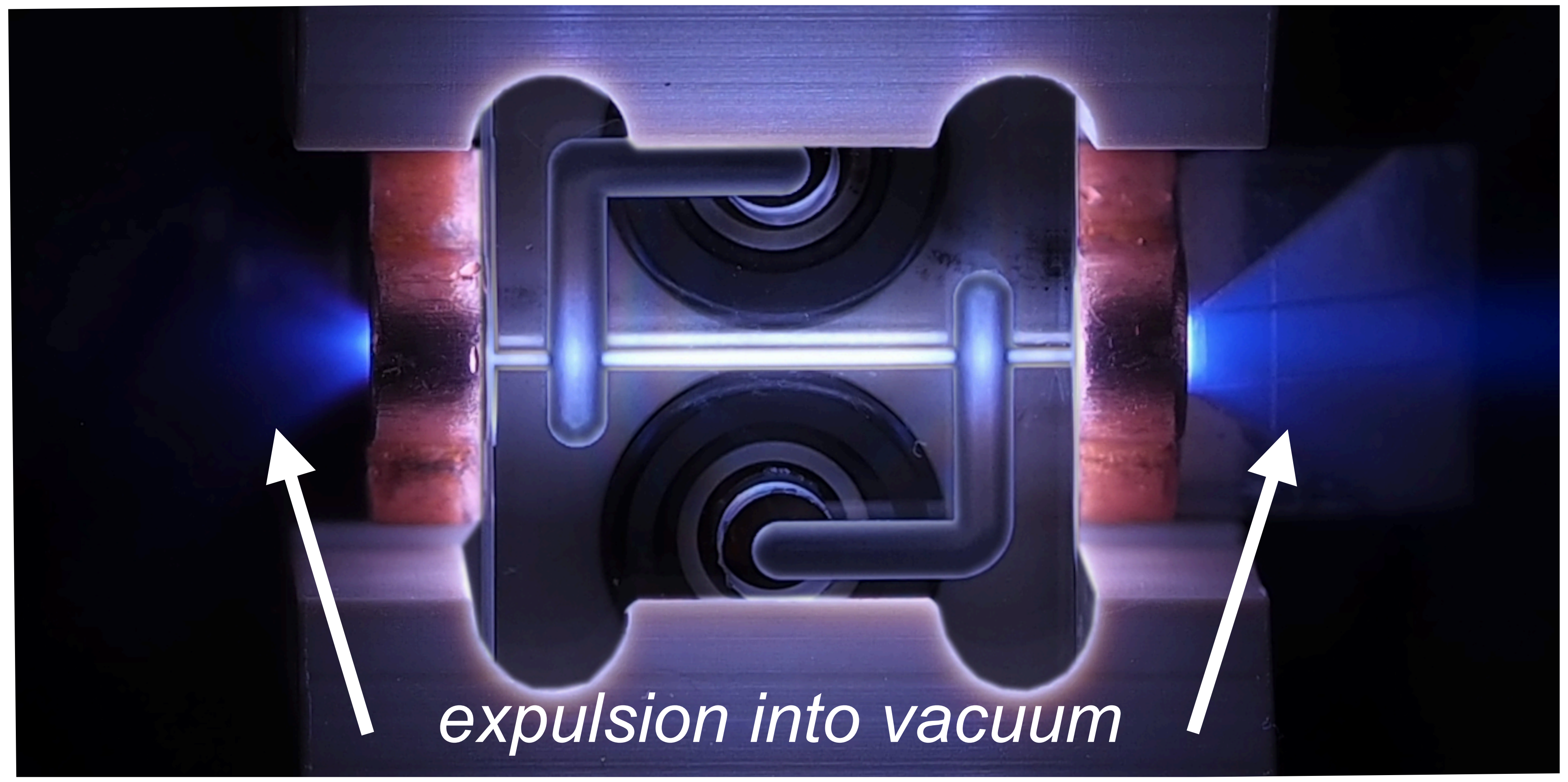
	Conventional accelerators*	Plasma accelerators
Property #1 Inter-bunch separation Δ_b	dissipation of long-range transverse wakefields	**dissipation of long-term plasma motion → *O*(100 ns)**
Property #2 Bunch-train length n_b	balance of RF pulse length, and accelerating field, and electrical breakdowns	***goal:*** similar plasma properties for each acceleration event
Property #3 Macro-pulse separation Δ_t	dissipation of the cumulative heating from each bunch train	***goal*****:** plasma source capable of withstanding large heat loads

*CLIC example

Goal: Generate similar plasma properties at ~μs separations

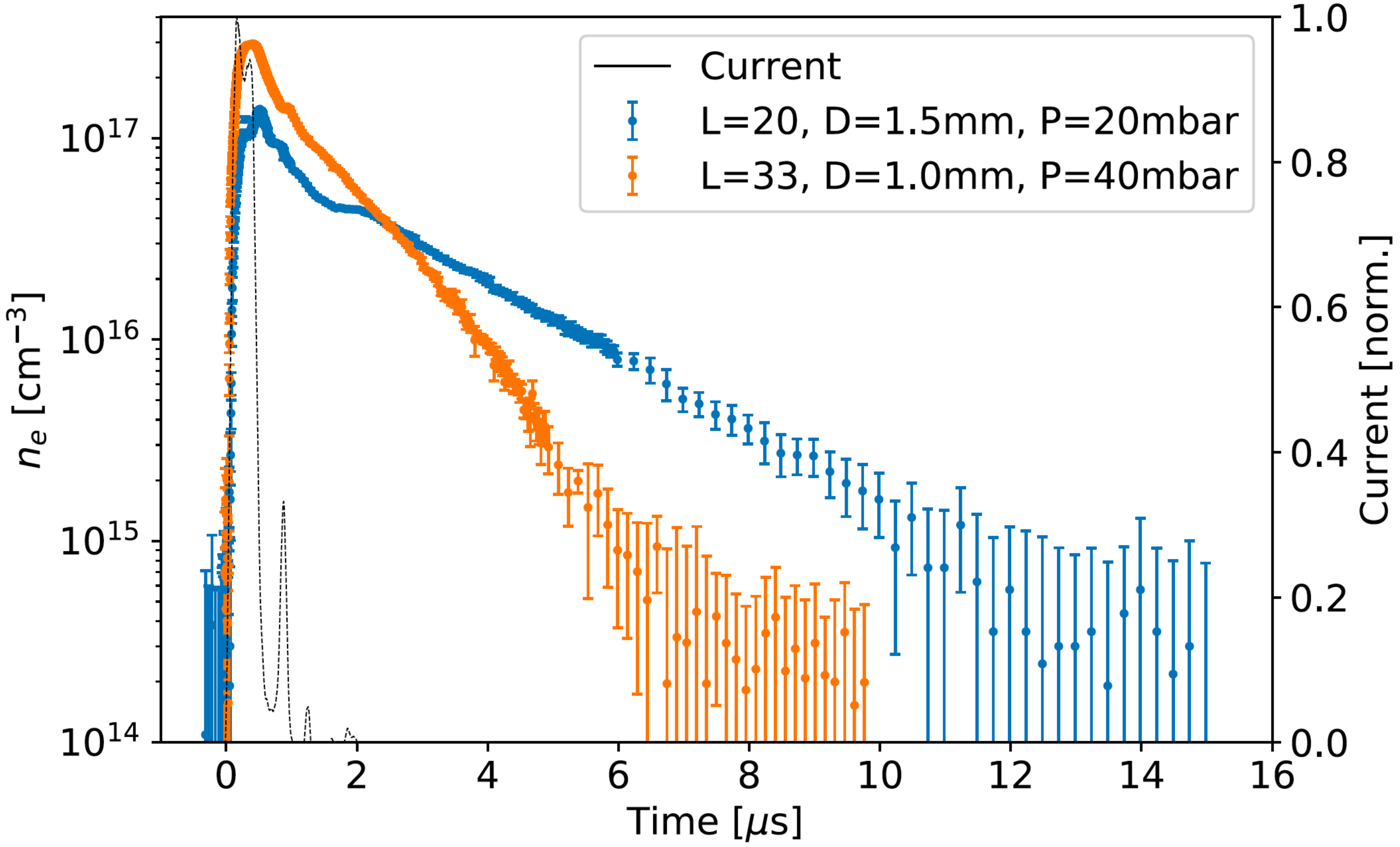
> ***Challenge***: Plasma-electron density decays exponentially on the μs timescale due to **expulsion** and **recombination**

Image credit: Kyrre Ness Sjøbæk



Plasma expulsion from a capillary-discharge plasma source

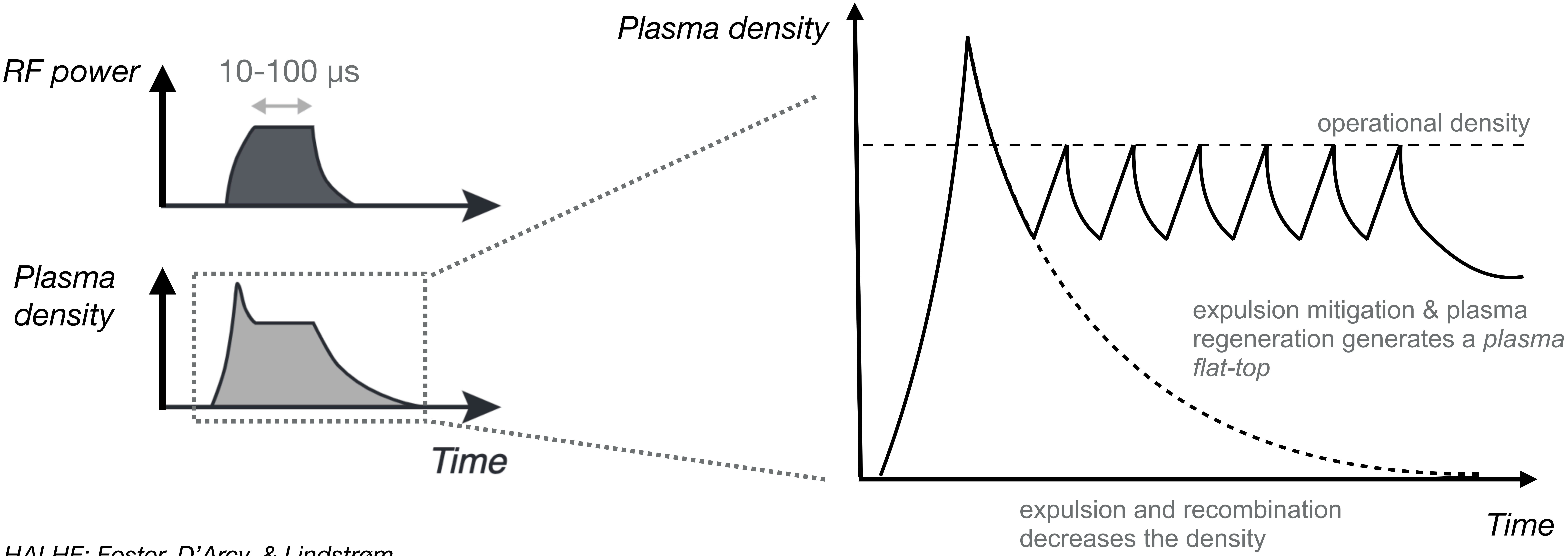
J.M. Garland *et al.*, Rev. Sci. Instrum. **92** 013505 (2021)



Plasma-density decay in a open-ended discharge-capillary plasma stage

Goal: Generate similar plasma properties at ~μs separations

> ***Challenge***: Plasma-electron density decays exponentially on the μs timescale due to **expulsion** and **recombination**

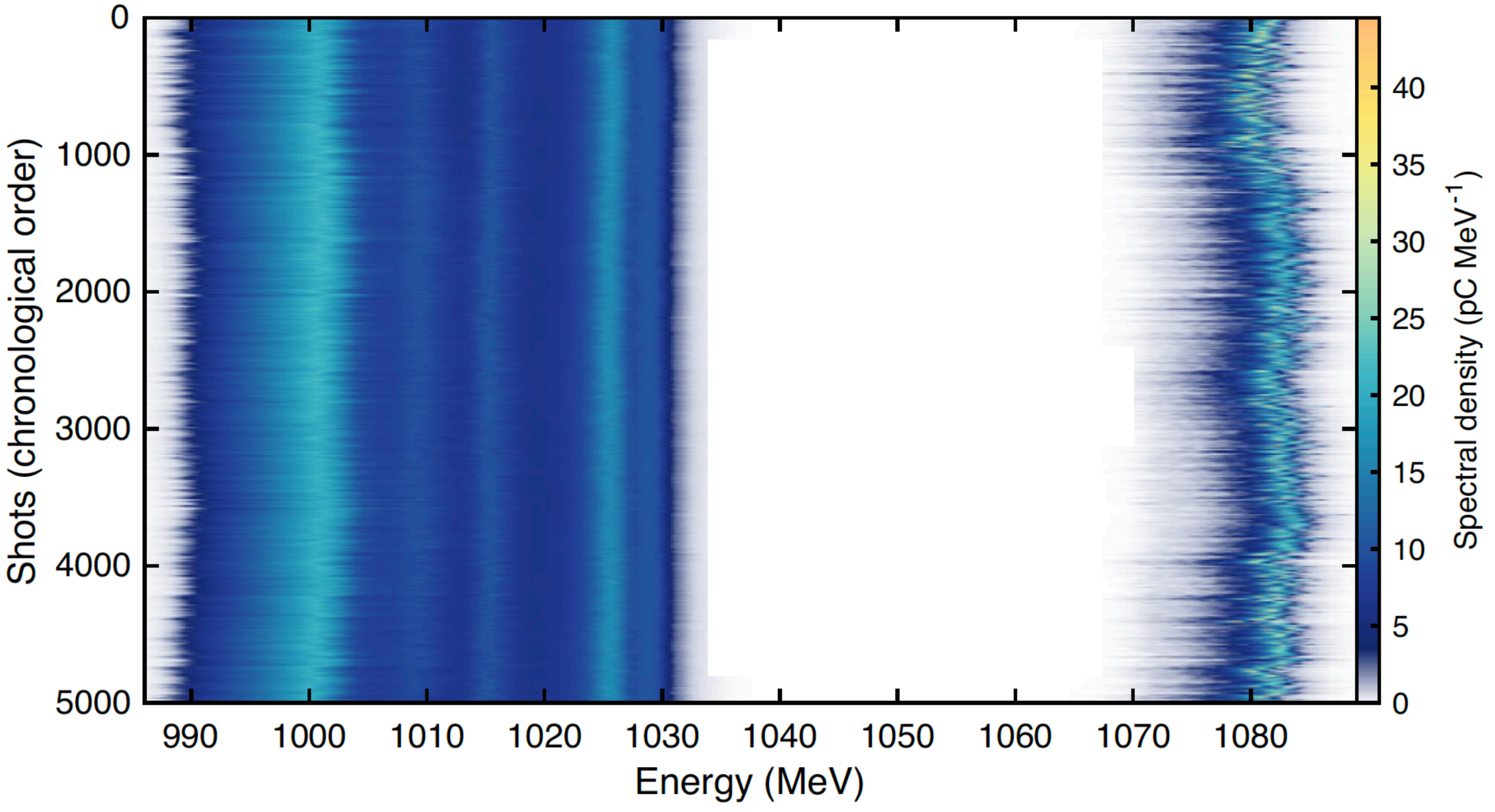


HALHF: Foster, D'Arcy, & Lindstrøm
https://arxiv.org/abs/2303.10150

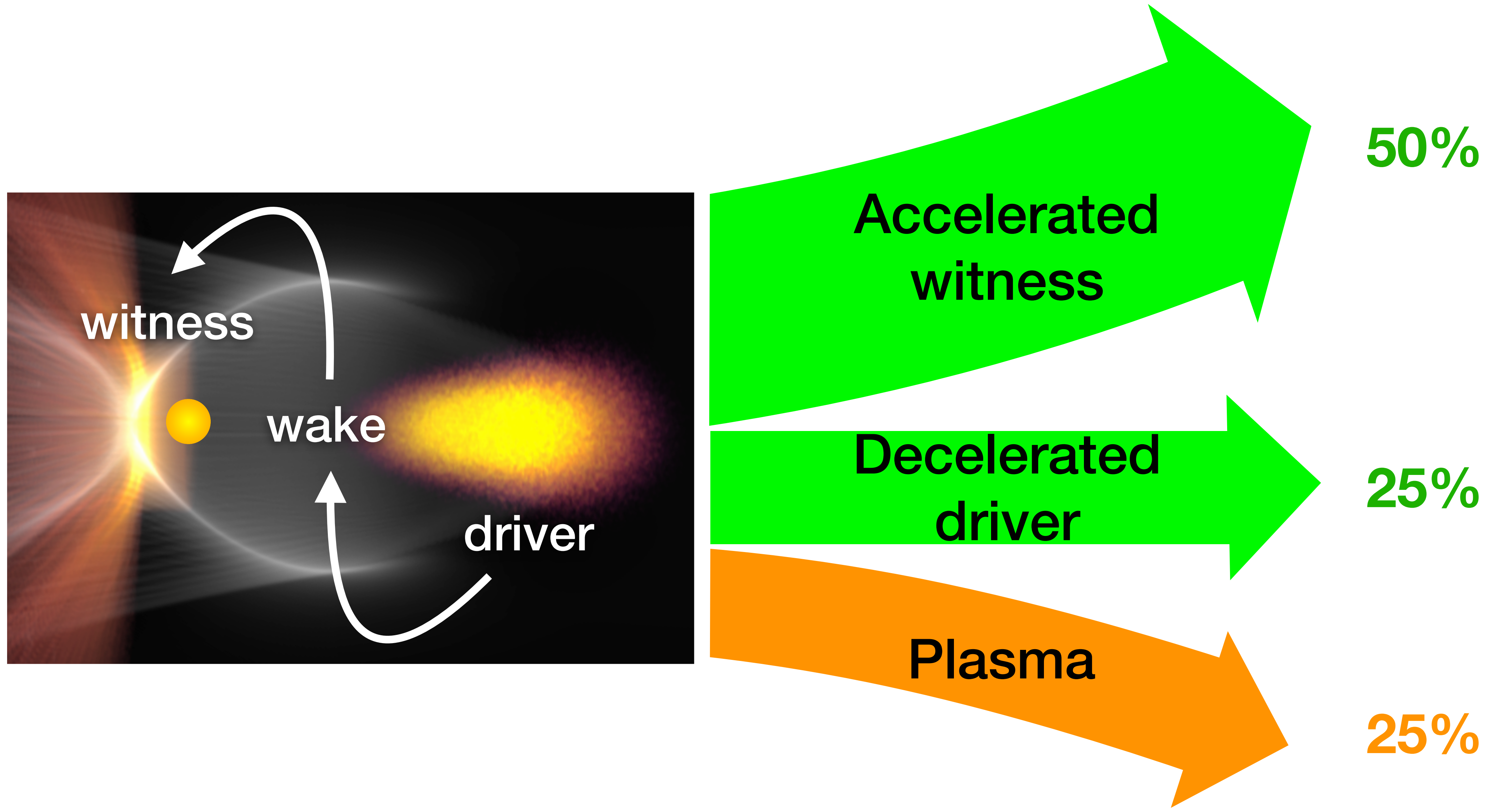
Goal: Generate similar plasma properties at ~µs separations

> ***Challenge***: Cumulative heating of the plasma from inefficiencies in the system may **modify the wakefield properties**

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



Shot-to-shot stability of beams at FLASHForward



Power-transfer diagram in a plasma accelerator

Goal: Generate similar plasma properties at ~μs separations

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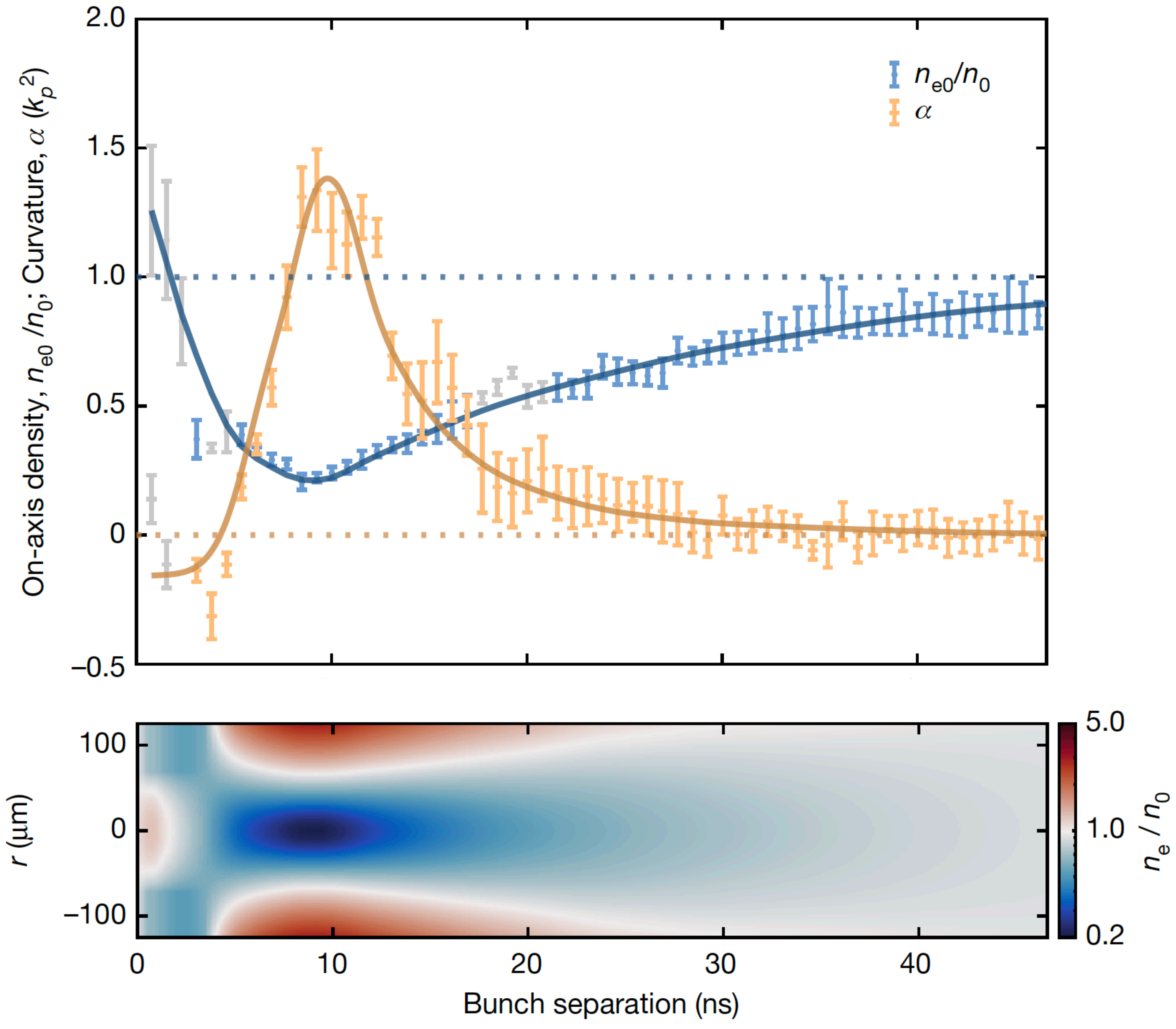
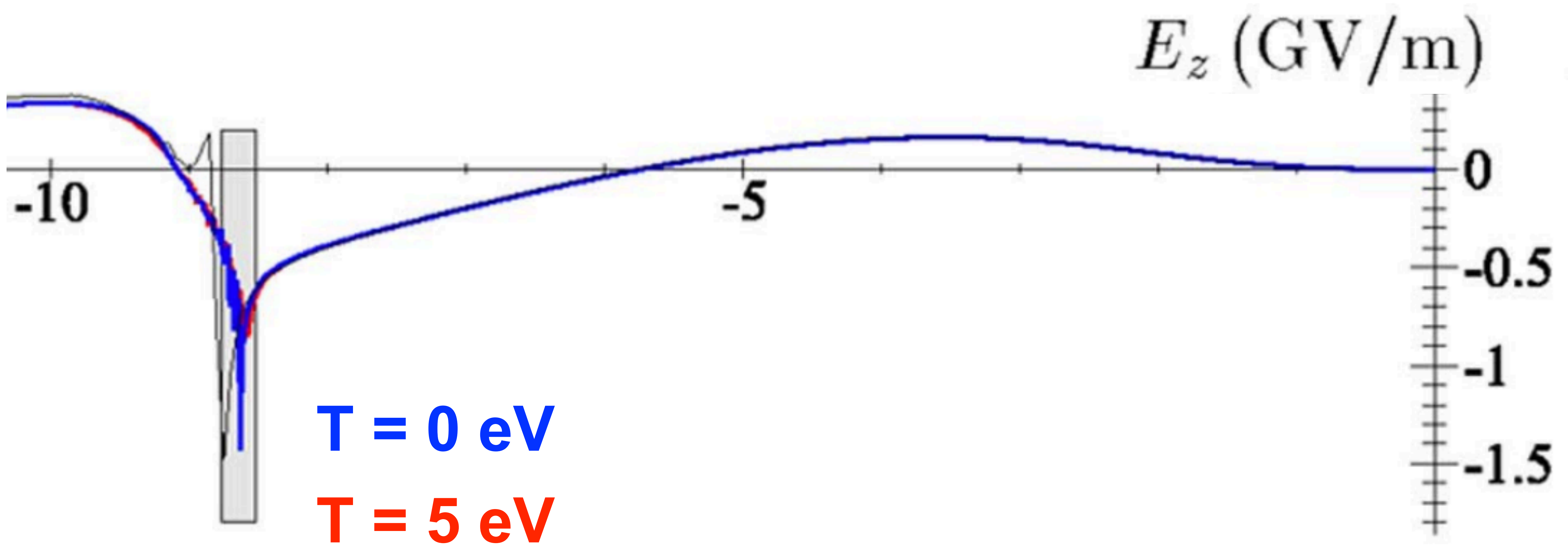
R. D'Arcy *et al.*, Nature **603**, 58-62 (2022)



Plasma evolution as a result of energy deposited on axis by plasma acceleration

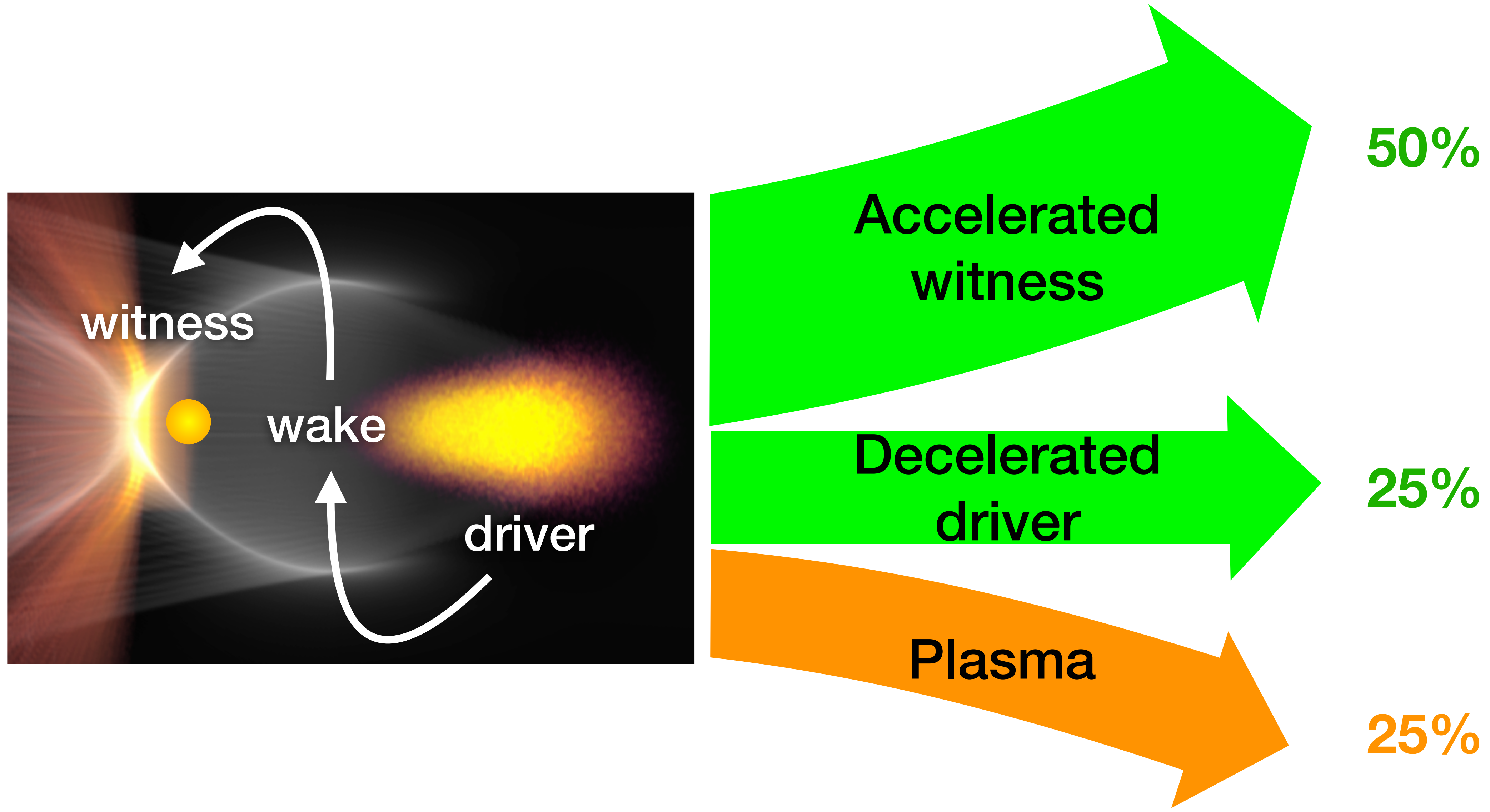


K. V. Lotov, PRSTAB **6**, 061301 (2003)

Simulations of how plasma background temperature modifies the plasma-wakefield properties

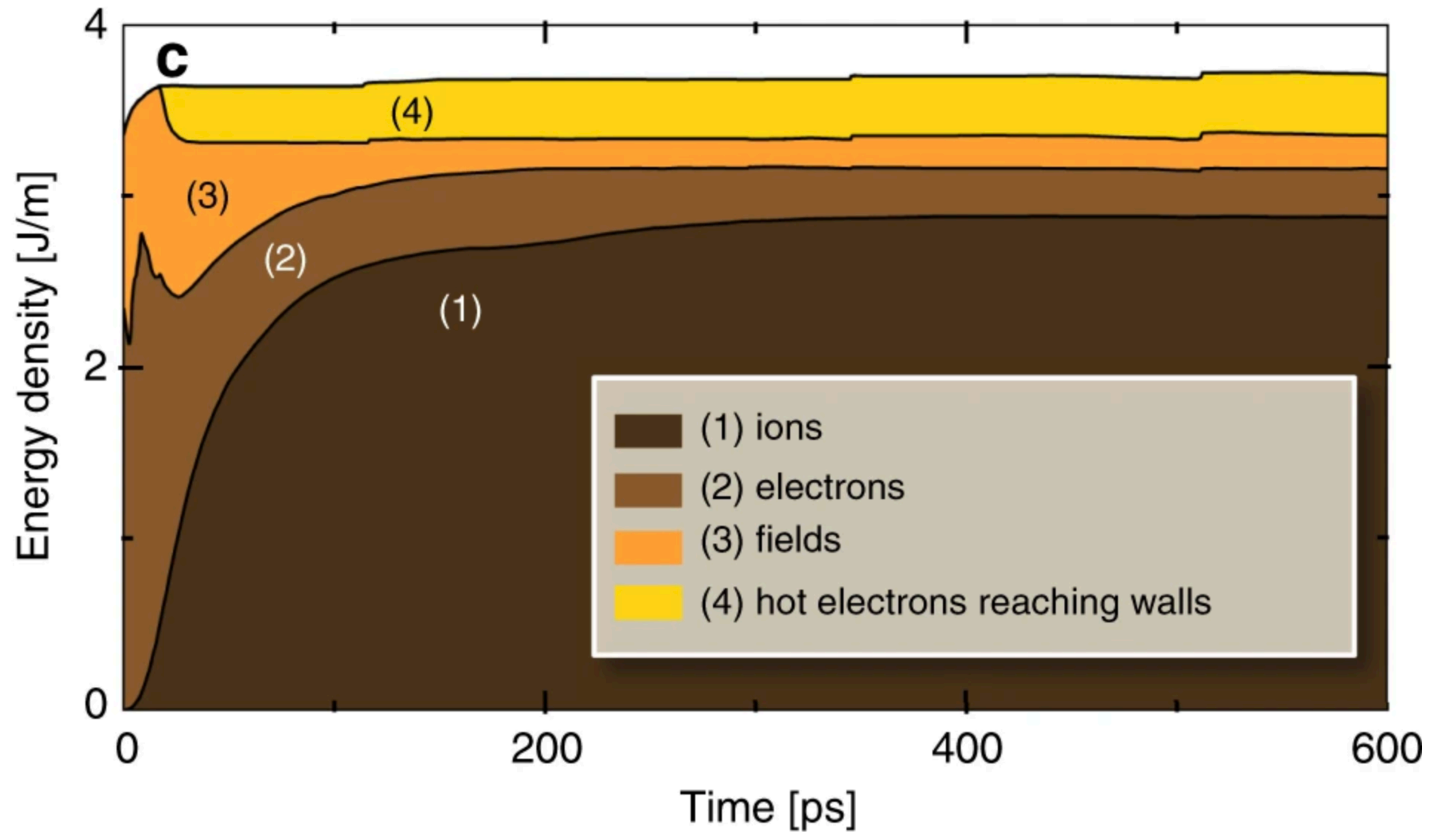
Goal: Temperature management of the plasma stage

- ***Challenge***: Cumulative heating of the plasma will lead to **cumulative heating of the plasma stage**



Power-transfer diagram in a plasma accelerator

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

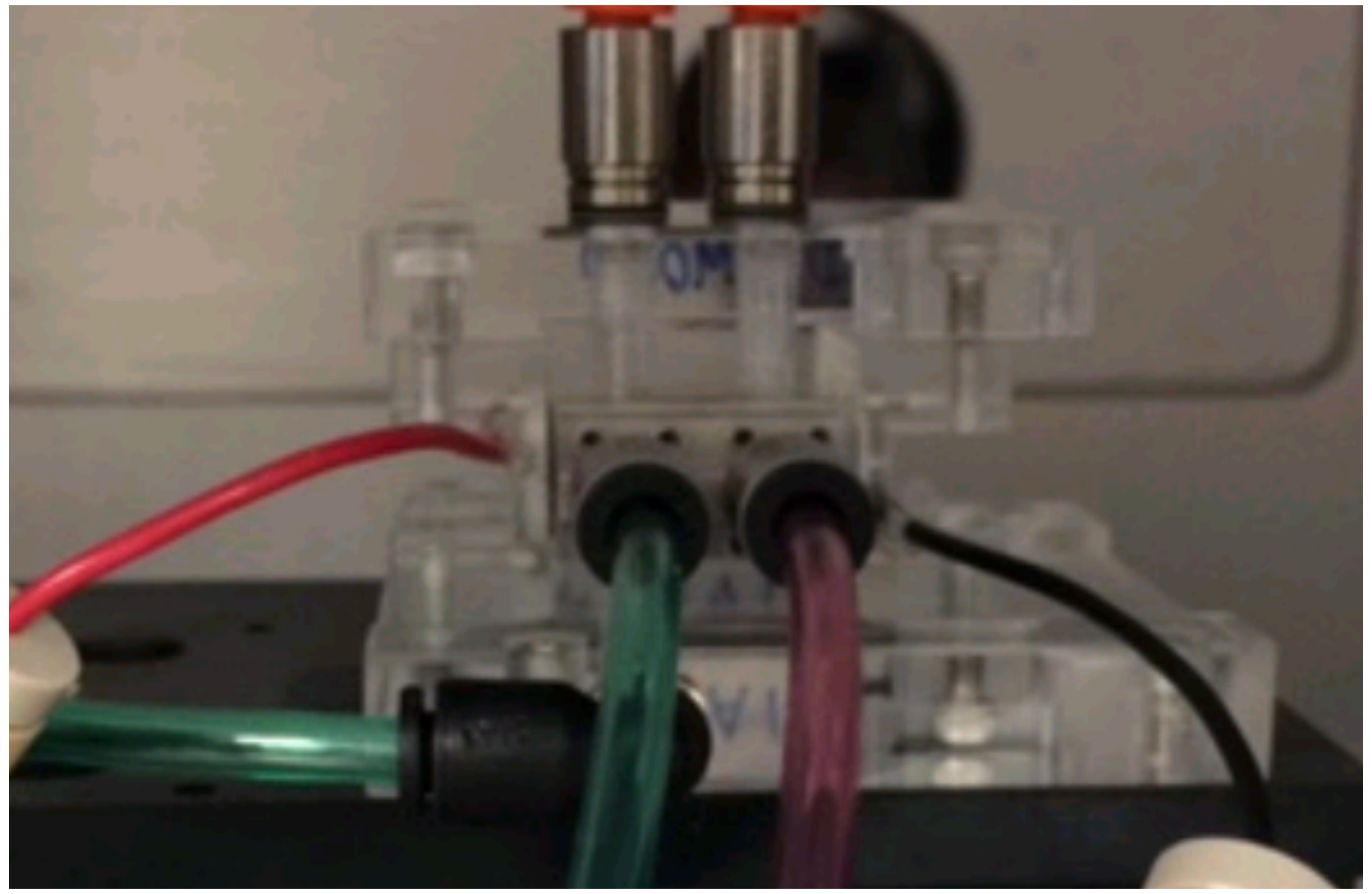


Simulated energy-transport channels after driving a wake

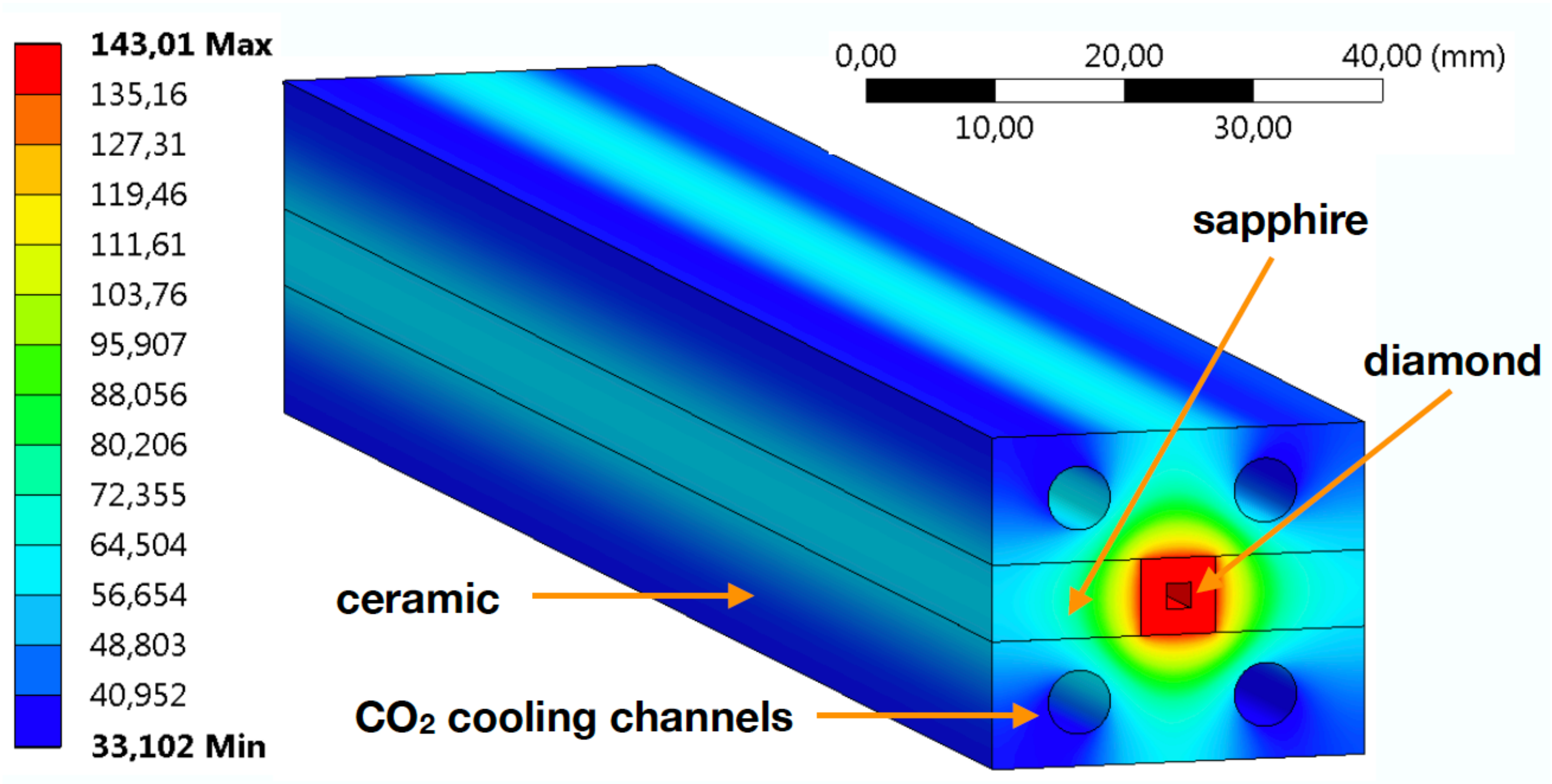
Goal: Temperature management of the plasma stage

- ***Challenge***: Cumulative heating of the plasma will lead to **cumulative heating of the plasma stage**

Image credit: Anthony Gonsalves



Grown-diamond capillary-discharge waveguides at LBNL



Heat-transfer simulation of a liquid-cooled plasma source

Goal: Temperature management of the plasma stage

> ***Challenge***: **Cooling requirements may be beyond what is achievable** with near-future technology

$$\frac{dP_{cool}}{ds} = \frac{\Delta\langle E_d\rangle\, Q_d\, f\, \eta_d\, (1-\eta_w)}{L_s} \approx E_z \cdot Q_w\, f \cdot \left(\frac{1}{\eta_w} - 1\right)$$

Parameters:

dP_{cool}/ds : Required cooling rate
ΔE_d : Driver energy loss
Q_d : Driver charge
Q_w : Witness charge
f : Collision frequency
L_s : Plasma length
η_d : Efficiency from driver to wake
η_w : Efficiency from wake to witness
E_z : Accelerating gradient
T : Transformer ratio

calculations motivated by HALHF: Foster, D'Arcy, & Lindstrøm
https://arxiv.org/abs/2303.10150

Gradient to deplete the driver:
(assuming T = 1)

$$E_z = \frac{\Delta\langle E_w\rangle}{L_s}$$

Efficiency from wake to witness:

$$\eta_w = \frac{\text{witness energy gain}}{\text{wake energy}} \longrightarrow \Delta\langle E_d\rangle Q_d = \frac{E_z Q_w L_s}{\eta_d \eta_w}$$

Goal: Temperature management of the plasma stage

- ***Challenge***: **Cooling requirements may be beyond what is achievable** with near-future technology

$$\frac{dP_{cool}}{ds} = \frac{\Delta\langle E_d \rangle \, Q_d \, f \, \eta_d \, (1 - \eta_w)}{L_s} \approx E_z \cdot Q_w \, f \cdot \left(\frac{1}{\eta_w} - 1\right)$$

‘space efficiency’ ‘energy efficiency’

‘physics efficiency’

- **Conclusion**: For a certain particle flux (luminosity) and a certain energy-transfer efficiency (sustainability), the acceleration gradient is directly limited by the achievable cooling rate

- … but are we limited in practice?

Goal: Temperature management of the plasma stage

- ***Challenge*: Cooling requirements may be beyond what is achievable** with near-future technology

$$\frac{dP_{cool}}{ds} = \frac{\Delta\langle E_d\rangle\, Q_d\, f\, \eta_d\, (1-\eta_w)}{L_s} \approx E_z \cdot Q_w\, f \cdot \left(\frac{1}{\eta_w} - 1\right)$$

‘space efficiency’ (E_z)

‘physics efficiency’ ($Q_w\, f$)

‘energy efficiency’ ($\frac{1}{\eta_w} - 1$)

- ***example for average power (per second):*** 10 GV/m x 1 nC x 10,000 s^{-1} x (1/0.6 - 1) = **67 kW/m**
- CLIC is expected to be able to ‘manage’ ~20 kW/m ➞ in the right ballpark but likely using very different cooling schemes

- … but the average power in a MHz bunch train will be **x100** the average power over a second at 10 kHz
- … and it may not be possible to ‘manage’ rapid temperature increases/stresses on the μs timescale

Goal: Temperature management of the plasma stage

- ***Challenge***: **Cooling requirements may be beyond what is achievable** with near-future technology

$$\frac{dP_{cool}}{ds} = \frac{\Delta\langle E_d\rangle\, Q_d\, f\, \eta_d\, (1-\eta_w)}{L_s} \approx \underbrace{E_z}_{\text{'space efficiency'}} \cdot \underbrace{Q_w\, f}_{\text{'physics efficiency'}} \cdot \underbrace{\left(\frac{1}{\eta_w} - 1\right)}_{\text{'energy efficiency'}}$$

'space efficiency' 'energy efficiency'

'physics efficiency'

- If we can't boost the cooling rates for plasma stages over those of CLIC, where do we compromise?
- Inter-stage optics dominate the plasma-accelerator length at high energies ➞ lower gradients and longer stages?
- Or does this all necessitate operating the conventional linac at CW?

- **Caveat**: This assumes that all the power makes it to the wall of the plasma stage
- … but does it? Expulsion of power with expulsion of plasma? Do unknown energy-transport channels help us? etc. etc.
- This challenge cannot be tackled in isolation ➞ iteration loop with attempts to solve the other challenges

Plasma-wakefield accelerators at high repetition rates

Summary and outlook

- The recovery time of a plasma-wakefield accelerator indicates compatibility with radiofrequency bunch-train patterns → a great first step… but still just a first step
- The big challenge now is bridging the up-to-five order-of-magnitude gap from state-of-the-art to what is required
- Many outstanding scientific and technical goals to be reached with an emphasis on simulation tools, driver development, and plasma-source technology
- Schemes discussed here do not utilise high-power lasers but a future linear collider based on novel-accelerator technology will likely be based on both types of technologies e.g. laser drivers and discharge-based stages
- A coordinated international effort from both the LWFA and PWFA communities will be required to solve all the problems in the next decade

Plasma-wakefield accelerators at high repetition rates

Open questions

- **Beam drivers**:
  - The necessary beam drivers seemingly exist so it would be sensible to leverage ‘shovel ready’ designs if possible… But can we fully utilise them in their current/planned bunch-train format?
  - If not, do we need to push the conventional community to reimagine how they operate their machines to best conform to our needs?
  - Bunch-train patterns have been the focus here but are the bunch parameters at this repetition rate sensible?
- **Plasma stages**:
  - Can similar plasma properties be reproduced at MHz to enable acceleration of high-rep.-rate bunch trains?
  - How hot does the plasma get due to MHz plasma acceleration? And will it substantially modify the plasma properties?
  - Can kW-MW levels of average power left in the plasma stage be managed?
  - Do the plasma stages mandate CW operation of the linac? And if so, are CW discharge-generated plasma stages possible?