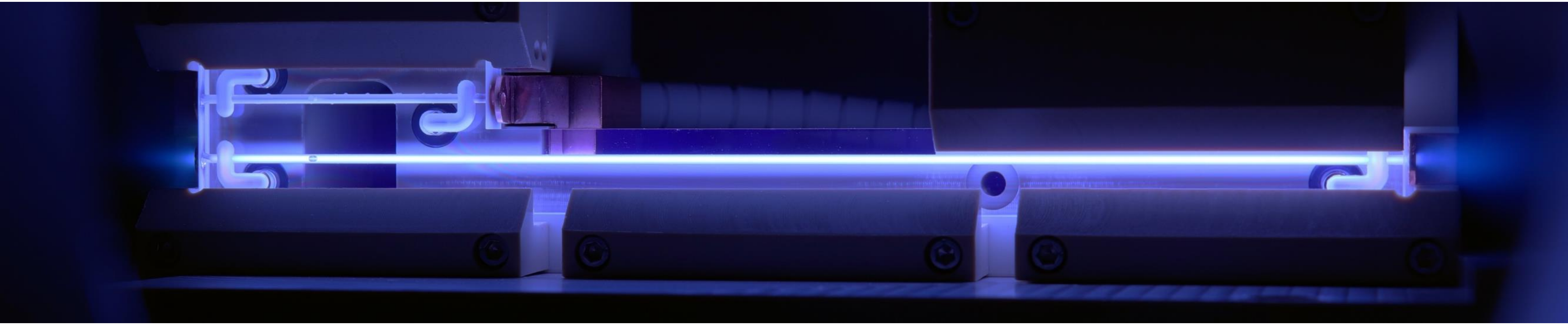
Status and Recent Results of FLASHForward►►



Felipe Peña, J. Beinortaitė, J. Björklund Svensson, L. Boulton, G. Boyle, J. Chappell, S. Diederichs, B. Foster, M. J. Garland, P. González Caminal, H. Jones, A. Kanekar, C. A. Lindstrøm, G. Loisch, S. M. Mewes, Á. Ferran Pousa, S. Schreiber, S. Schröder, R. Shalloo, M. Thévenet, S. Wesch, M. Wing, J. C. Wood, J. Osterhoff, and R. D'Arcy

6th European Advanced Accelerator Concepts Workshop | September 17–23, 2023 | Elba, Italy

Plasma wakefields can shrink accelerators and their costs

Applications in photon science and high-energy-physics

Plenary talk
Friday 11:00
Carl A. Lindstrøm

Plasma-based booster for FELs

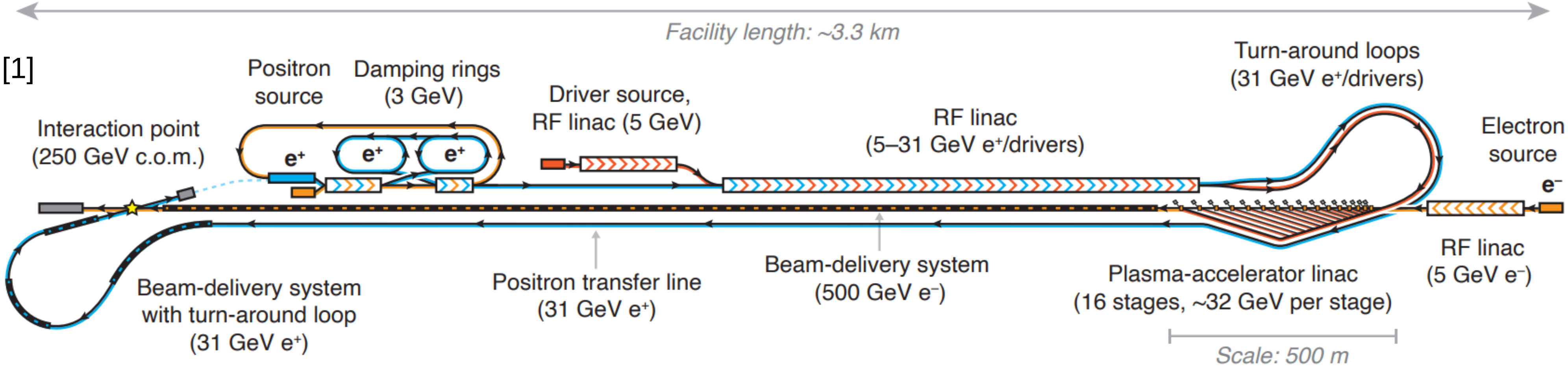
> Existing facilities e.g., FLASH or EuXFEL, could reach higher energies (and shorter wavelengths)

Poster
Monday 19:00
Sarah Schröder

Future HEP experiments

> Higgs factory e.g., HALHF concept
  > ILC's 20 km → 3 km, with staged plasma-accelerators
  > Saving building costs

[1]



[1] B. Foster *et al.*, New Journal of Physics (2023) (accepted)

Plasma wakefields can shrink accelerators and their costs

High requirements from applications

Plasma-based booster for FELs

- Existing facilities e.g., FLASH or EuXFEL, could reach higher energies (and shorter wavelengths)

Integrated Brightness

$$B \propto \frac{Q f_{rep}}{\varepsilon_x \varepsilon_y \, \sigma_E}$$

Future HEP experiments

- Higgs factory e.g., HALHF concept
  - ILC's 20 km → 3 km, with staged plasma-accelerators
  - Saving building costs

Luminosity

$$\mathcal{L} \propto \frac{Q f_{rep}}{\sigma_x(\varepsilon_x)\sigma_y(\varepsilon_y)}$$

bunch charge $\mathcal{O}$(nC)
average repetition frequency $\mathcal{O}$(kHz – MHz)
emittance $\mathcal{O}$(0.01-1 mm mrad)
energy spread $\mathcal{O}$(0.1%)

And: Energy gain, energy-transfer efficiency

FLASHForward: A Beam-driven plasma-wakefield accelerator

Goal: Develop a self-consistent plasma-accelerator stage

with high quality, high efficiency, and high average power, at > 1 GV/m

High beam quality

Emittance preservation

Low energy spread

High-overall efficiency

Driver depletion

Plasma-to-witness efficiency

High average power

Rapid recovery time

High repetition rate

FLASHForward▶▶ at DESY

FLASHForward▸▸ at DESY

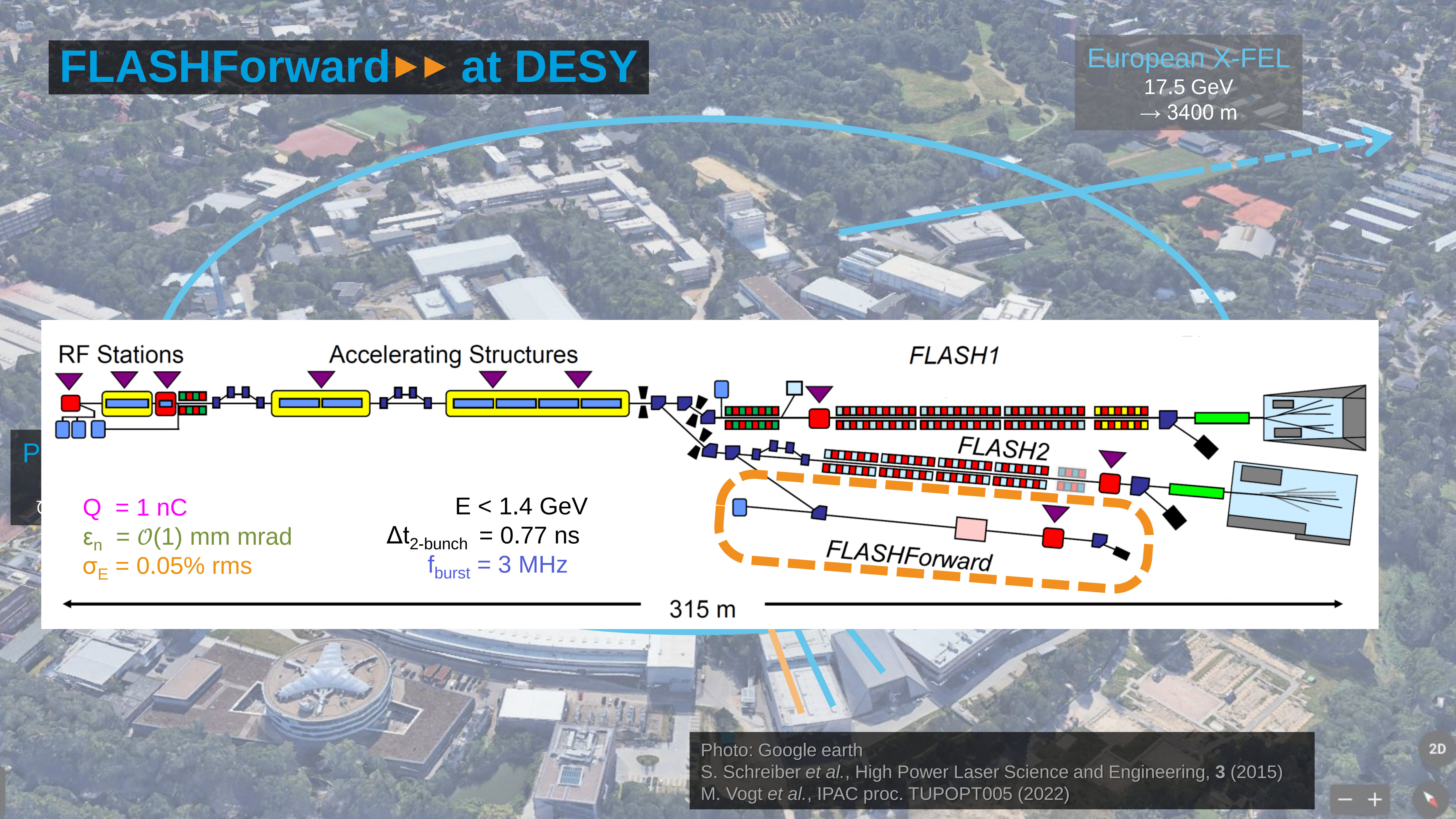


Photo: Google earth
S. Schreiber *et al.*, High Power Laser Science and Engineering, **3** (2015)
M. Vogt *et al.*, IPAC proc. TUPOPT005 (2022)

FLASHForward Facility

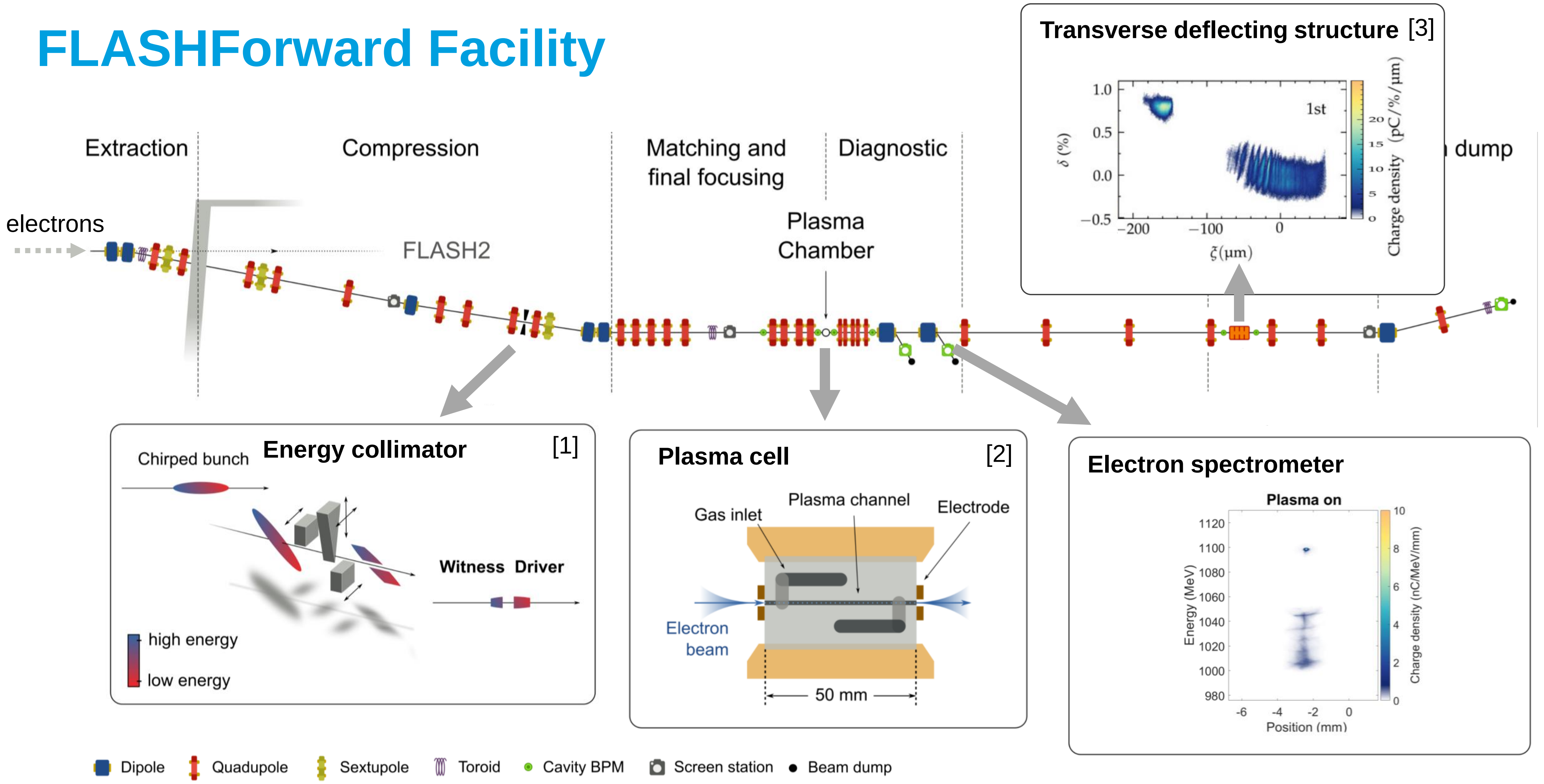


Diagram courtesy: P. González Caminal

[1] P. Muggli, *et al*. Phys. Rev. Lett. **101**, 054801 (2008); S. Schröder *et al.*, J. Phys. Conf. Ser. **1596**, 012002 (2020)
[2] J. M. Garland *et al.*, Rev. Sci. Instrum. **92**, 013505 (2021)
[3] P. González Caminal, PhD Thesis; B. Marchetti *et al.*, Scientific Reports **11**, 3560 (2021)

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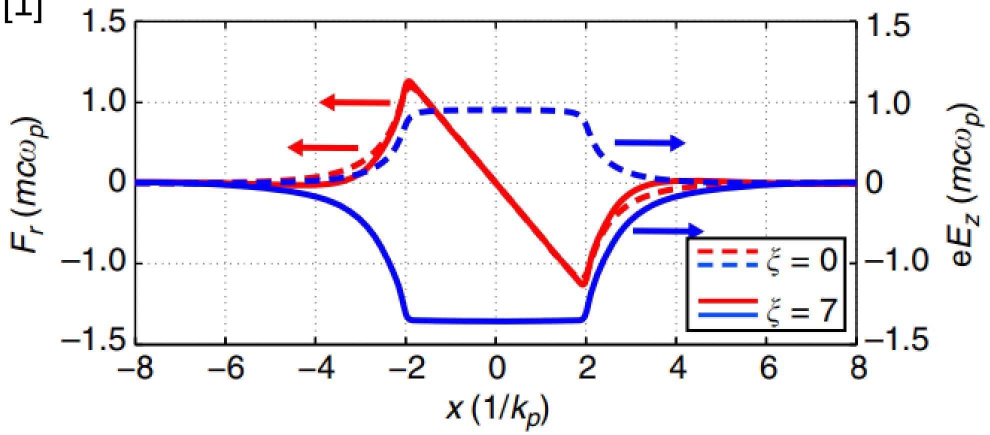
High repetition rate

There are many processes that degrade emittance

- All plasma electrons expelled in the blowout regime
  - Linear focusing fields from the ion column
    → can in principle preserve emittance

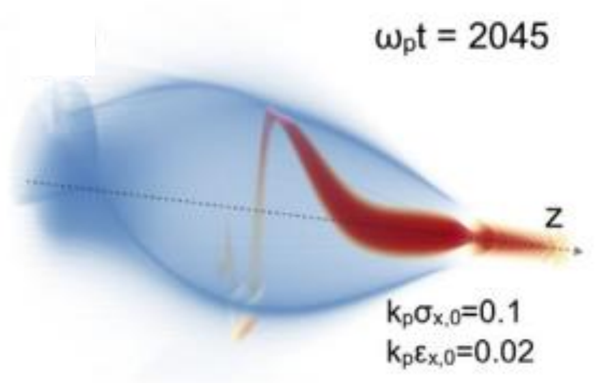
- **Sources of degradation** [2]
  - Phase mixing for different long. slices (beta-mismatch)
  - Sampling of non-linear focusing fields of cavity sheath
  - Transverse misalignment → hosing instability
  - Ion motion (inside bubble)
  - Gas scattering

[1]



Linear transverse forces (in red) in the blow-out regime

[3]



Hosing instability simulation

[1] C.E. Clayton et al., Nat. Comms. **7**, 12483 (2016)
[2] C. A. Lindstrøm and M. Thévenet, J. Instrum. **17** P05016 (2022)
[3] A. Martinez de la Ossa et al., Phys. Rev. Lett. **121**, 064803 (2018)

Emittance was preserved at 2.8 mm mrad

- 100% charge coupling (40 pC)
- Energy spread preserved (0.1% FWHM)
- Average accelerating field: 0.8 GV/m, peak ~1.4 GV/m
- Plasma length: 50 mm

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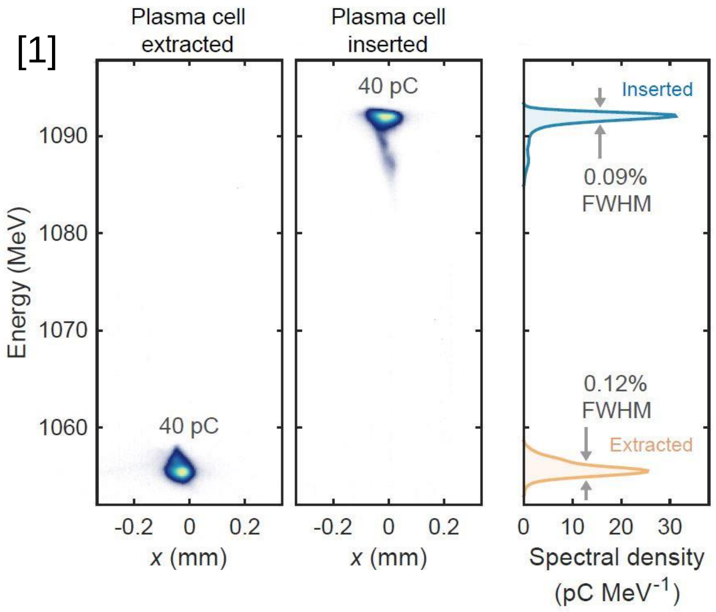

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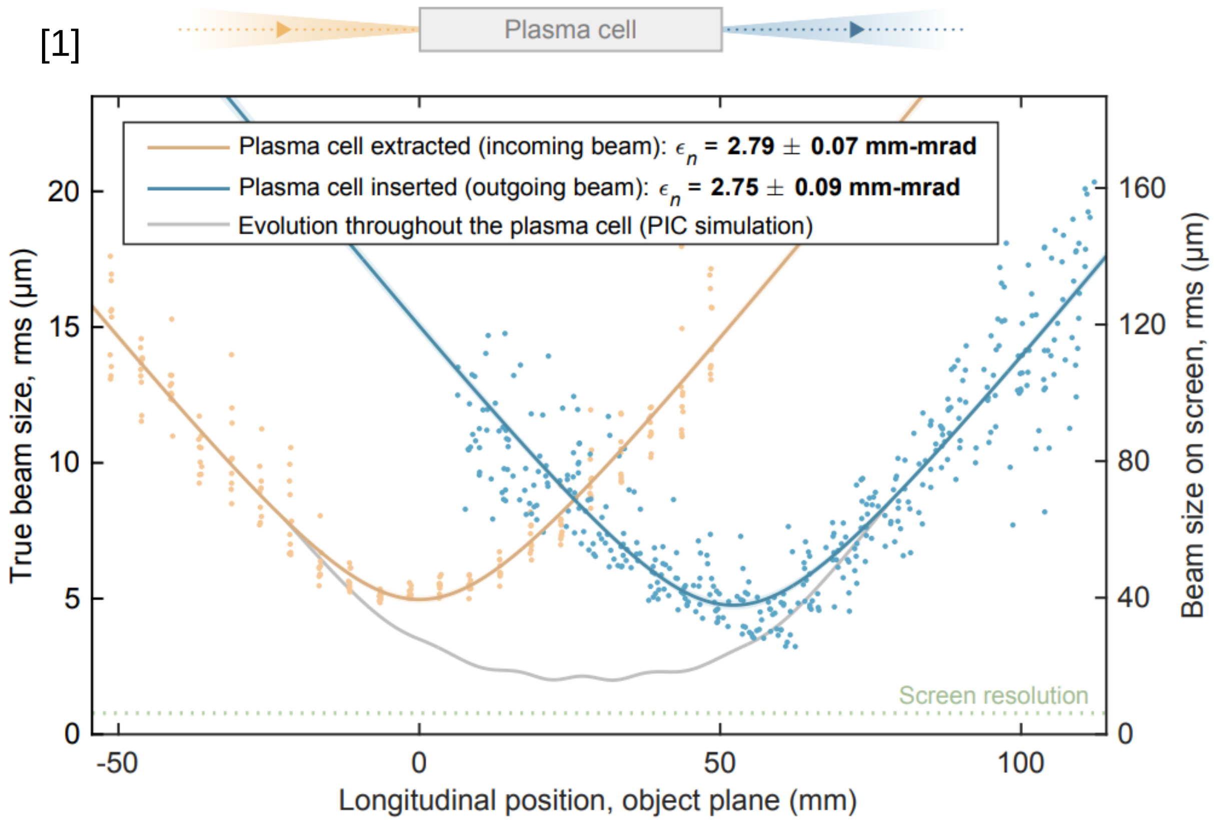

[1] C. A. Lindstrøm et al., submitted

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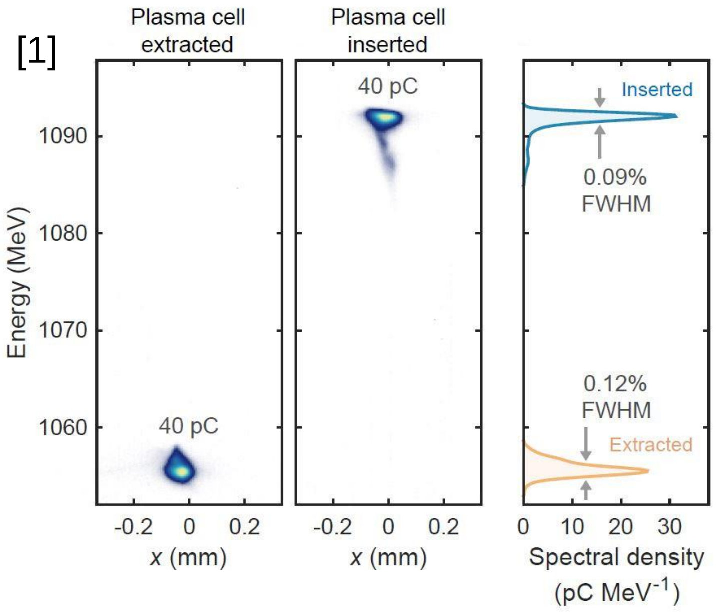
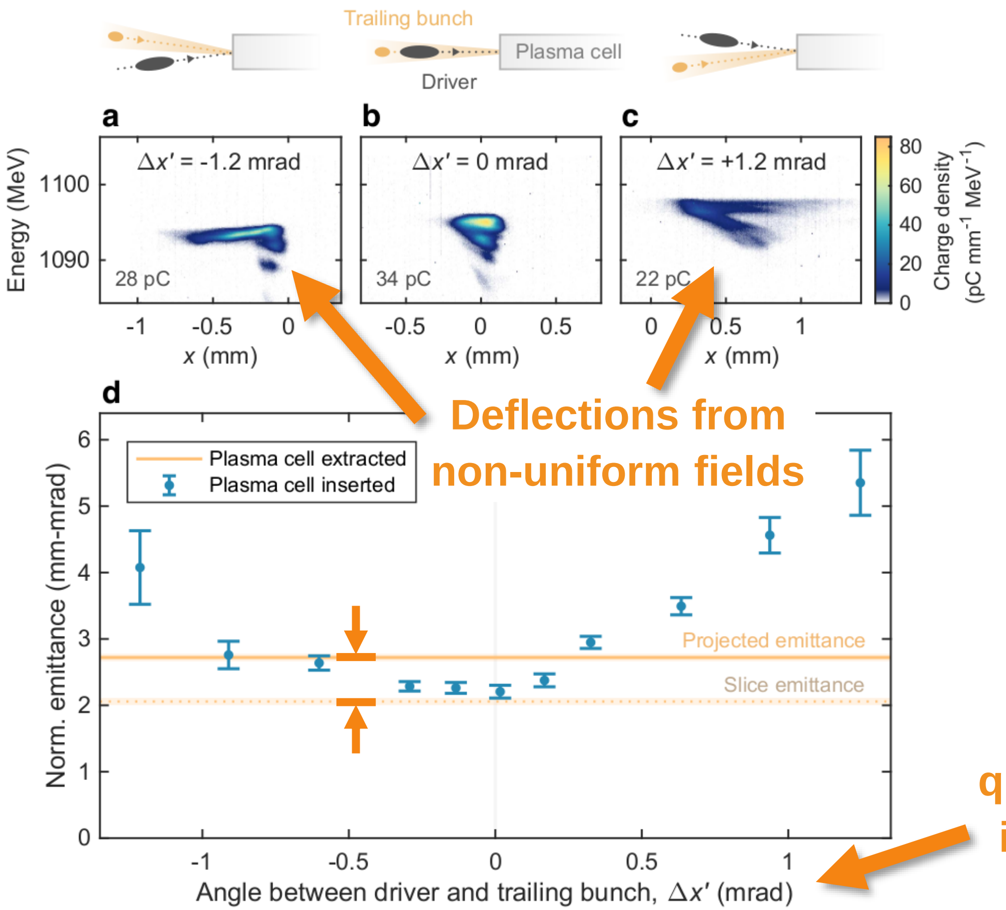


High precision in alignment (0.1 mrad) and matching (mm scale) required!



Changing quadrupoles in $\mathcal{O}$ (0.1%)

[1] C. A. Lindstrøm et al., submitted

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[1] C. A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)
[2] R. D'Arcy et al., Phys. Rev. Lett. **122**, 034801 (2019)
[3] S. Schröder *et al.*, Nature Commun. **11**, 5984 (2020)
[4] C. A. Lindstrøm *et al.*, submitted

Energy-transfer inefficiency could impede PWFA

For machines delivering high beam-power

- Efficiency impacts the running costs
  - E.g., CLIC's wall-plug-to-main-beam energy-transfer efficiency $\eta_{\mathrm{WP}} = 11\%$* [1]

$$\textbf{Electricity costs} \propto \frac{1}{\eta_{\mathrm{WP}}} \, P_{\mathrm{beam}} \, T_{\mathrm{operating}} \, C_{\mathrm{electricity}} \approx \frac{\mathcal{O}\left(1 \, \frac{\mathrm{M€}}{\mathrm{year}}\right)^{**}}{\mathcal{O}(10\%)}$$

[MW] [hours/year] [€/MWh]

* no overhead included for cooling, ventilation or network
** with 28 MW of CLIC; 200 days; 45 €/MWh
[1] M. Aicheler *et al.*, CLIC Conceptual Design Report (2012)

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[MW] [hours/year] [€/MWh]

- We have to demonstrate at least the same energy-transfer efficiency!
- Also important for limitations in cell cooling

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** with 28 MW of CLIC; 200 days; 45 €/MWh

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State of the art efficiencies for beam-driven

> Wall-plug-to-witness efficiency is a product of

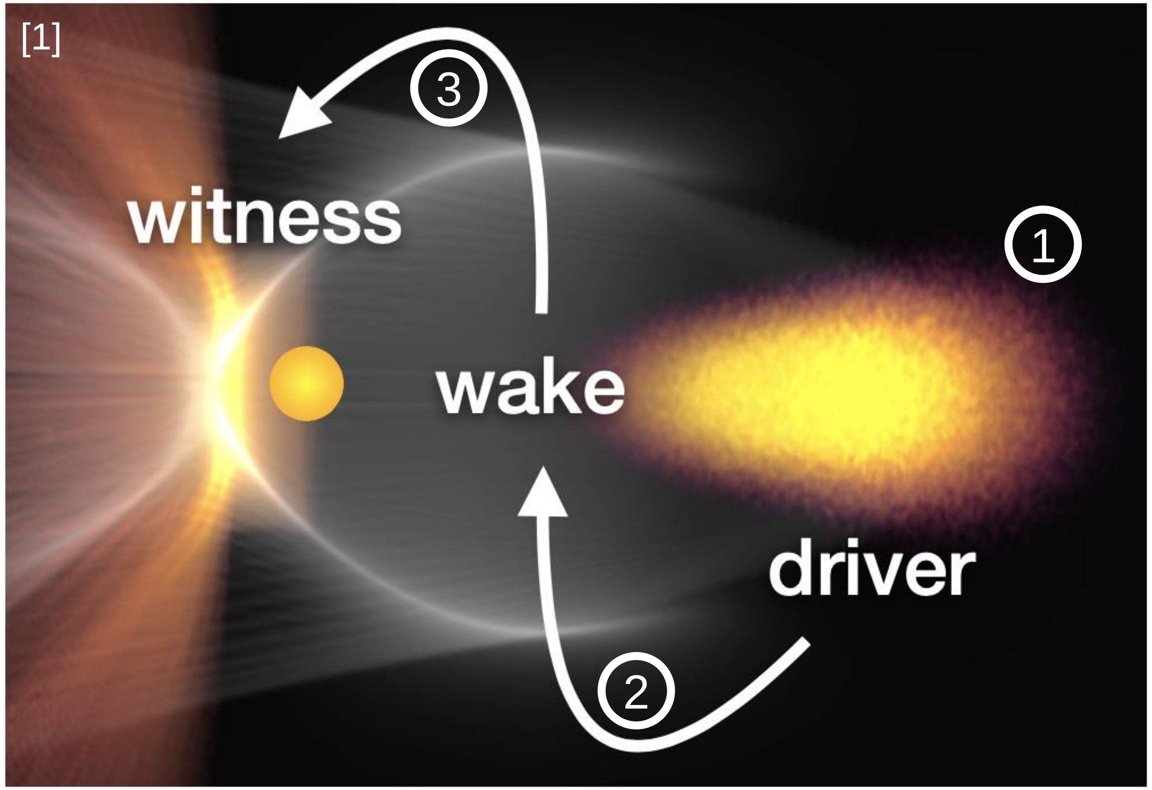
1. Driver production efficiency

   [2] **η = 55 %** (CLIC, excluding facility power)

2. Driver-to-plasma energy transfer efficiency (i.e., **driver depletion**)

   How much is experimentally possible?

3. Plasma-to-witness energy transfer efficiency



[1] Courtesy of A. Martinez de la Ossa and R. D'Arcy
[2] M. Aicheler *et al.*, CLIC Conceptual Design Report (2012)

Electron reacceleration is the limit of depletion

HiPACE++ simulations show reacceleration of energy depleted electrons

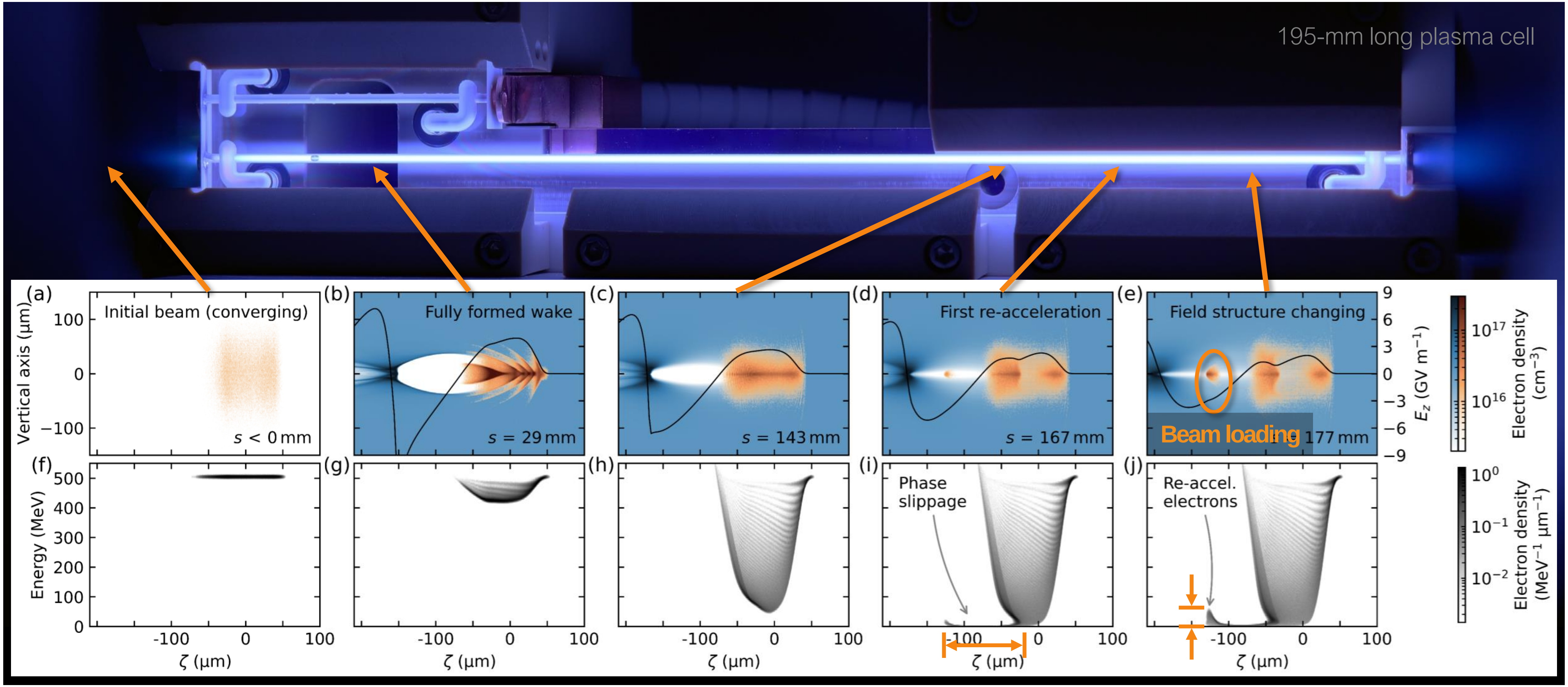


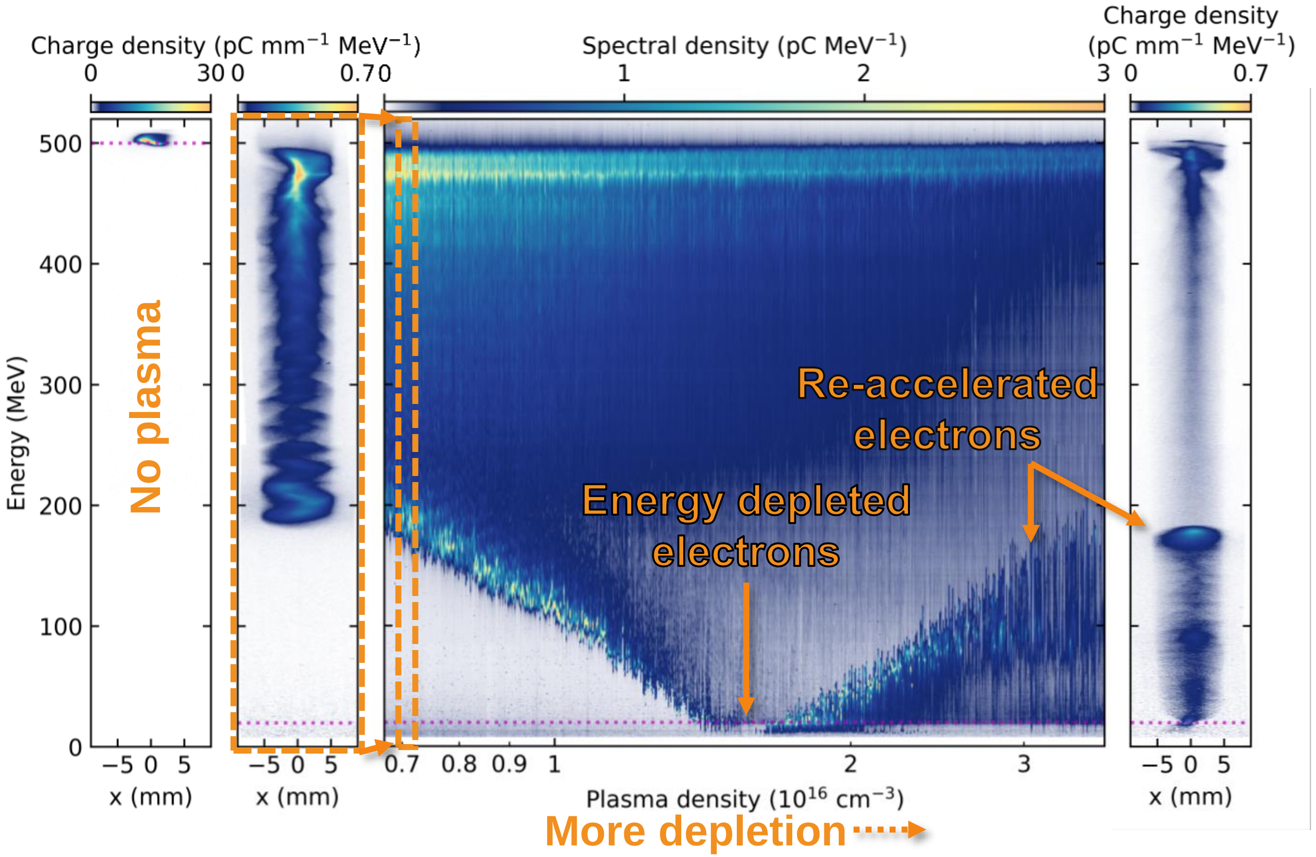
Photo: C. A. Lindstrøm

HiPACE++, S. Diederichs *et al.*, CPC **278**, 108421 (2022)

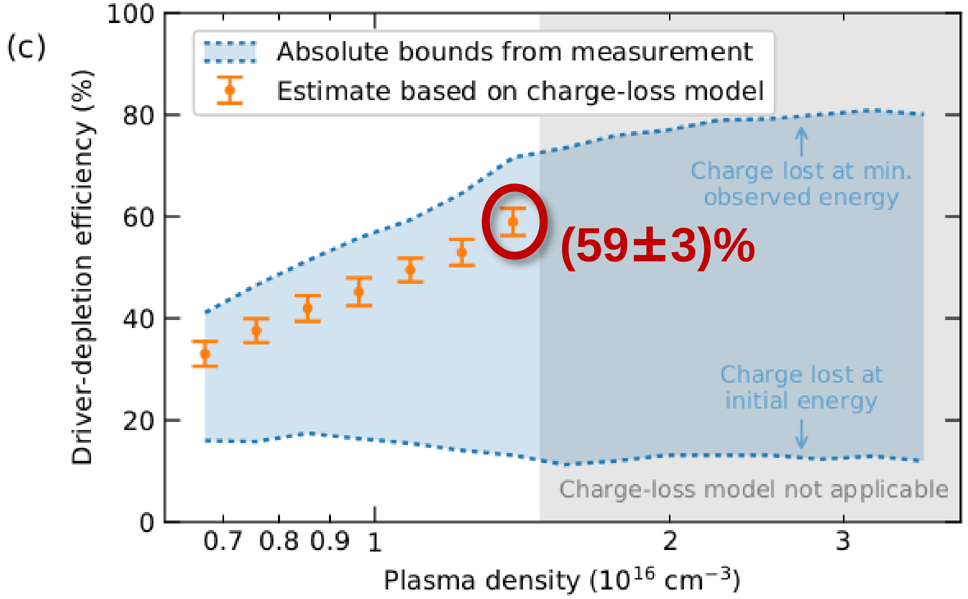
Re-acceleration and driver energy depletion

Parallel talk: WG1
Monday 17:25
F. Peña

[1]



[1]



- If combined with prev. record: 59% driver-to-wake · 42% wake-to-witness [2] = 25% driver-to-witness
  - With CLIC's 55% wall-plug-to-driver efficiency [3]

    → **<u>would yield</u> 14 % wall-plug-to-witness efficiency**

[1] F. Peña, *et al.*, in review (arXiv:2305.09581)
[2] C. A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)
[3] M. Aicheler *et al.*, CLIC Conceptual Design Report (2012)

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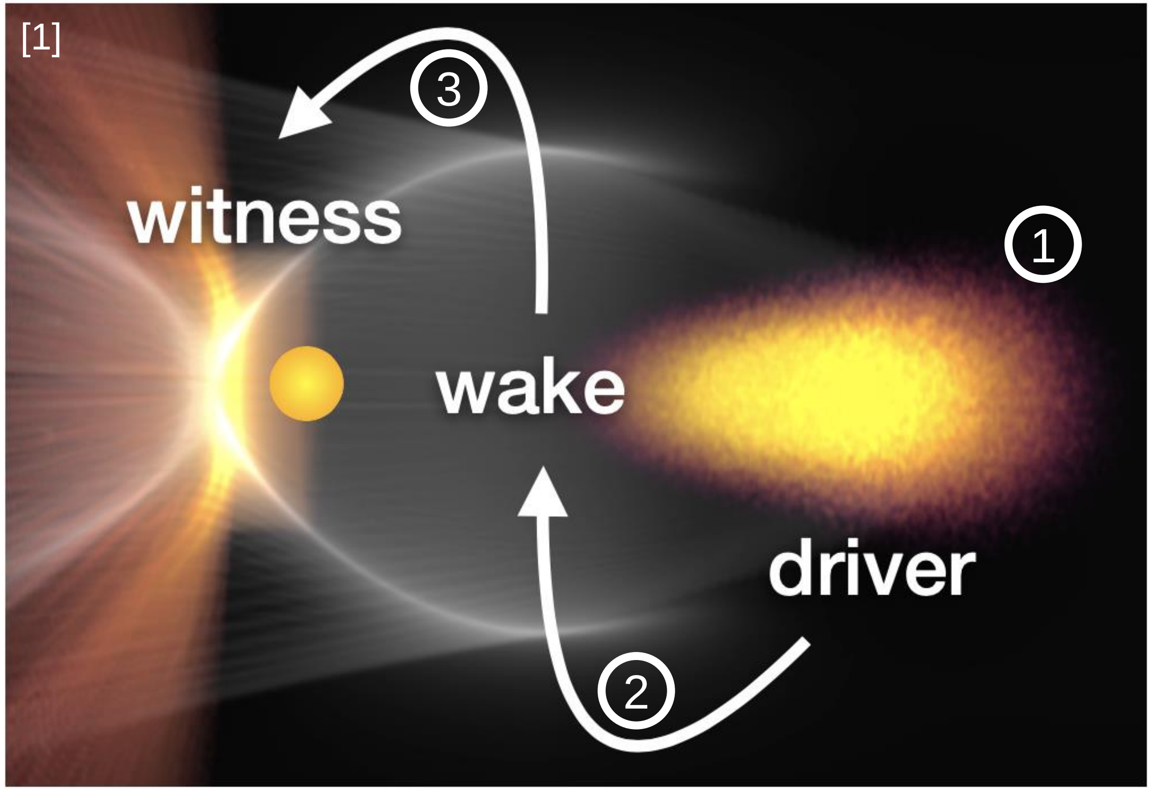
   [3] **η = 59 %**

3. Plasma-to-witness energy transfer efficiency

   [4] η = 30 %; [5] **η = 42 %**
   [6] η = 22 %

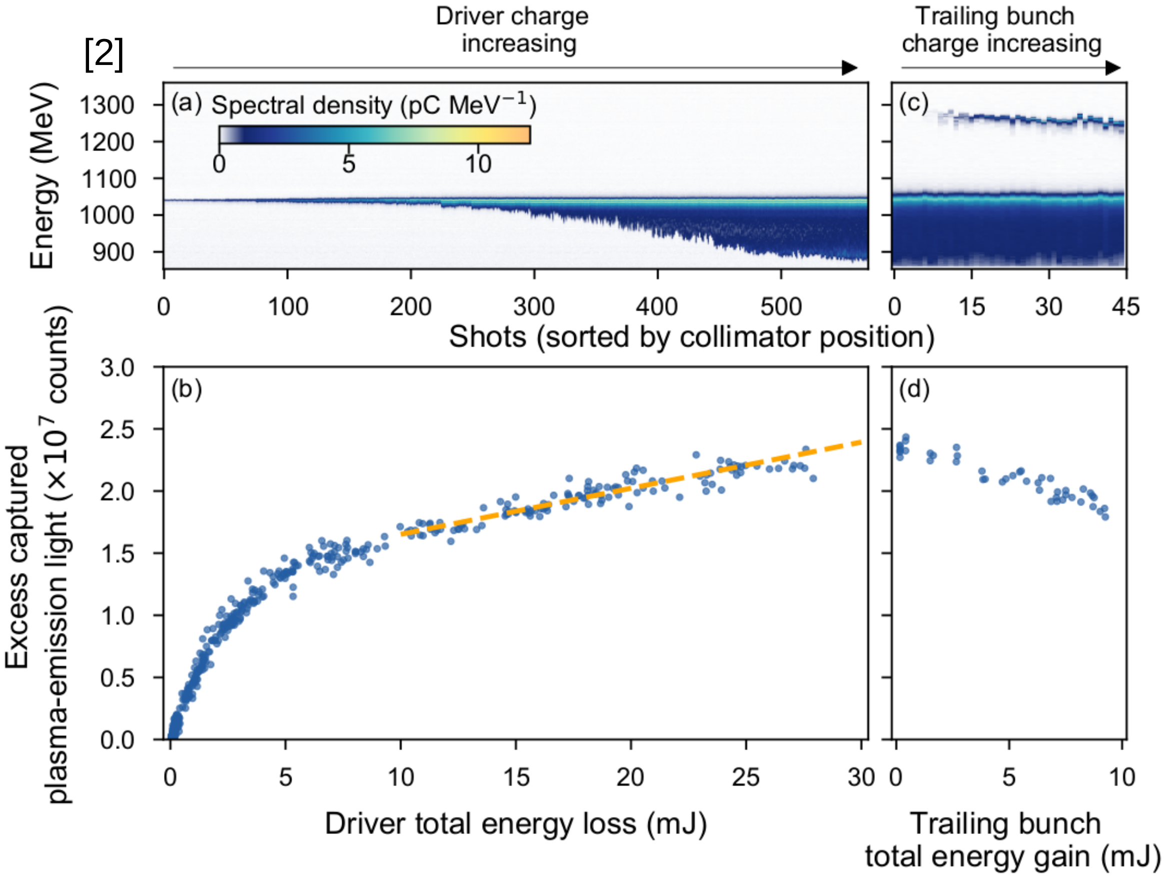
preserving beam quality



[1] Courtesy of A. Martinez de la Ossa and R. D'Arcy
[2] M. Aicheler *et al.*, CLIC Conceptual Design Report (2012)
[3] F. Peña *et al.*, in review (arXiv:2305.09581)
[4] M. Litos *et al.*, Nature **515**, 92-95 (2014)
[5] C. A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)
[6] C. A. Lindstrøm *et al.*, to be published (2022)
[7] L. Boulton *et al.*, submitted (arXiv:2209.06690)

A non-invasive method to measure extraction efficiency

Plasma light intensity is a function of residual energy after beam-plasma interaction [1]



- **Plasma** emits **light** during recombination
- Light intensity is only dependent on the final energy deposited, regardless if a trailing bunch was involved
- Recipe (at constant density)

1. Correlate plasma light to driver energy deposition (e.g., on energy spectrometer)

With a fixed driver and adding a trailing bunch:

2. Measure the plasma light decrease and estimate energy extraction

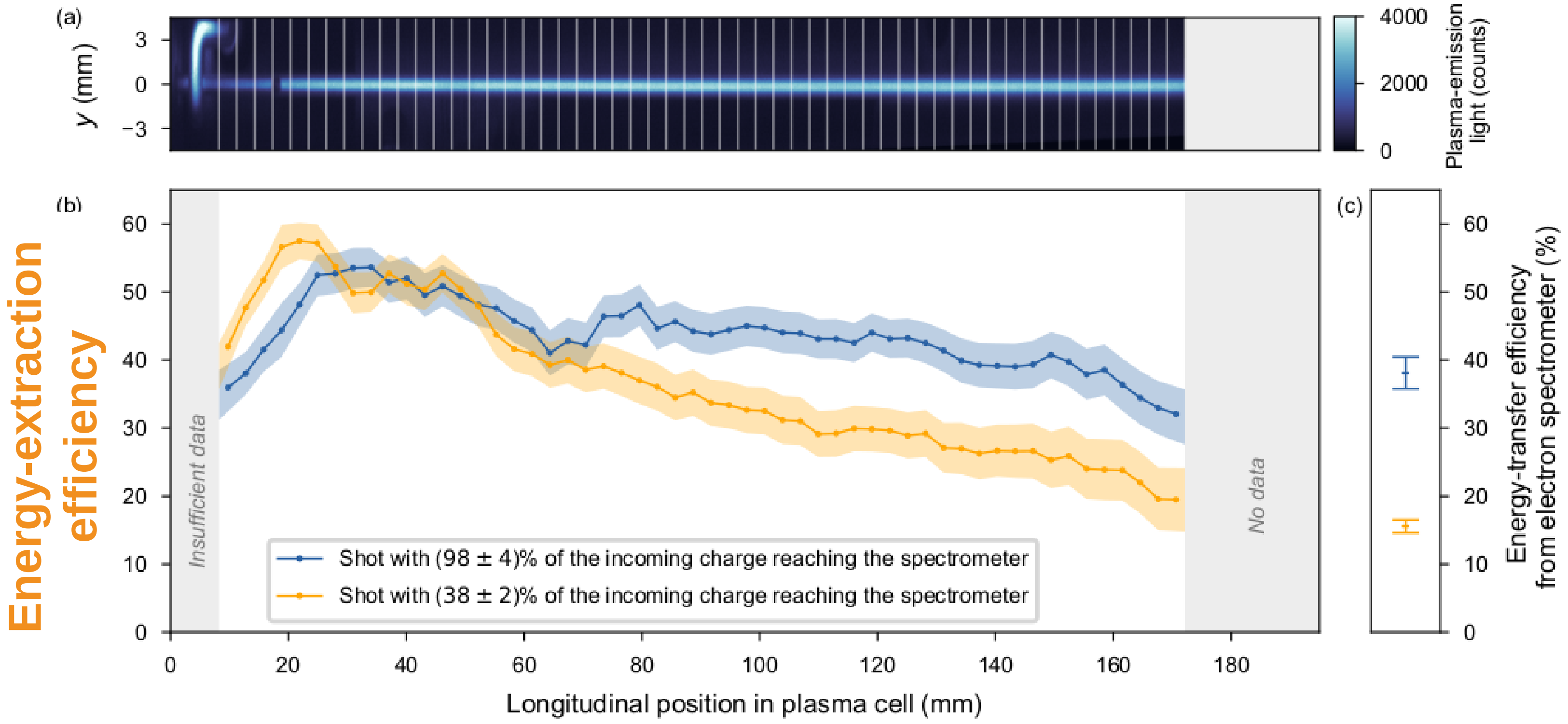
[1] E. Öz *et al.*, AIP Conference Proceedings **737**, 708 (2004)
[2] L. Boulton *et al.*, submitted (arXiv:2209.06690)

A non-invasive method to measure extraction efficiency

Longitudinal resolution is possible

Parallel talk: WG1
Thursday 18:05
L. Boulton

- Can be used in optimization of multistage accelerators on **shot-to-shot** basis
- Spectrometer can suffer from charge loss in transport
- Potential diagnostic for transverse instabilities



L. Boulton *et al.*, submitted (arXiv:2209.06690)

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42% [1], 22% [4], and
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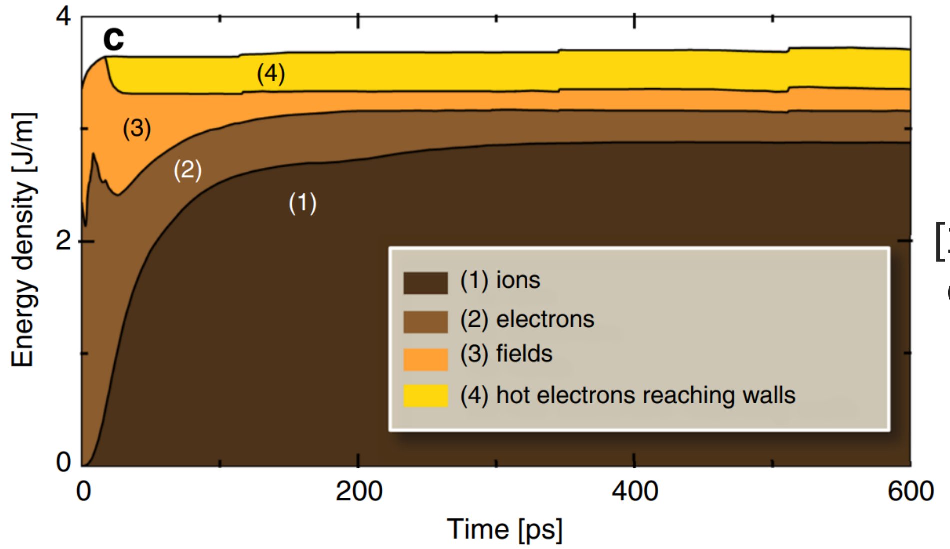
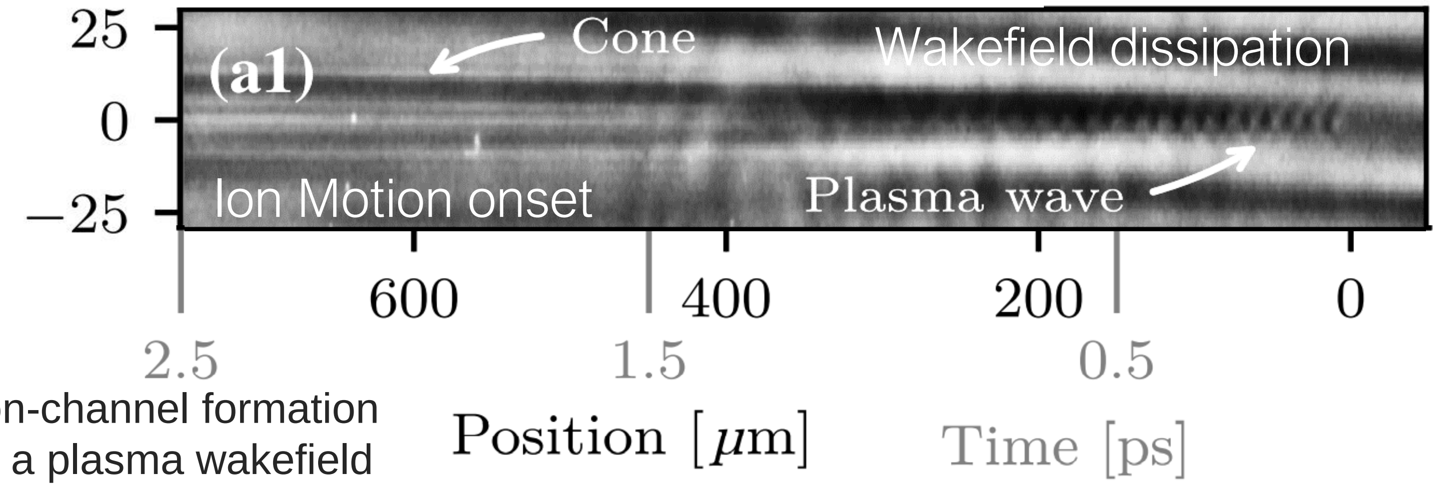
Energy dissipates through different channels

Most prominent energy dissipation channel: Ion Motion

- Only the first plasma cavity is useful
- For accelerating again in plasma: need to wait for the wakefield to dissipate into the plasma (*plasma recovery*)
- Dissipation processes in plasma are in ns-us timescale



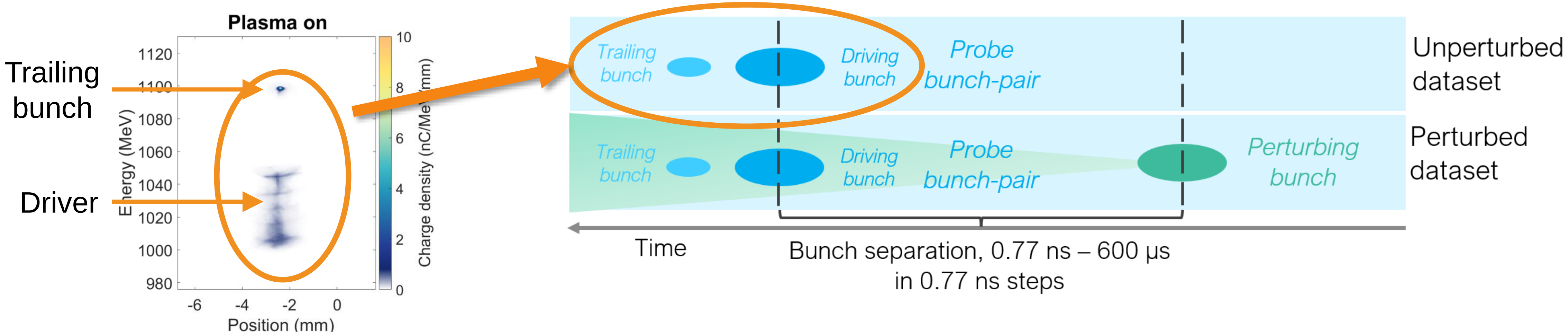
[1] Energy transport channels in PWFA



[2] Ion-channel formation from a plasma wakefield

[1] R. Zgadzaj et al, Nat. Comms., **11**, 4753 (2020)
[2] M. F. Gilljohann et al., Phys. Rev. X **9**, 011046 (2019)

Pump-probe electron bunches to measure plasma recovery time

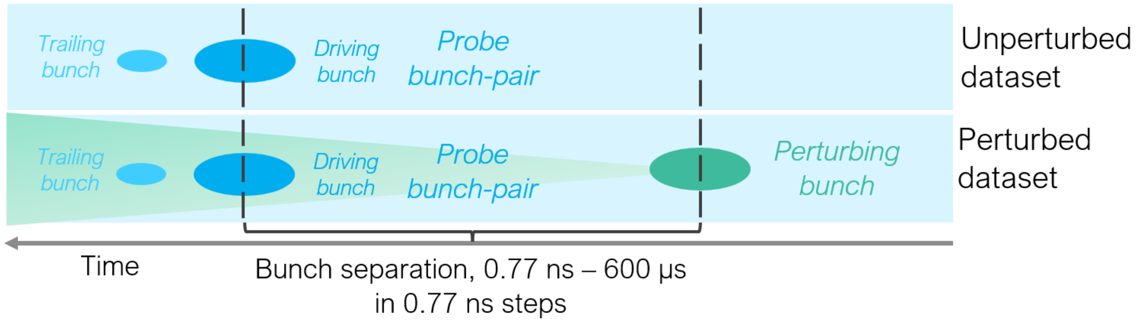


Accelerated bunch on the energy spectrometer

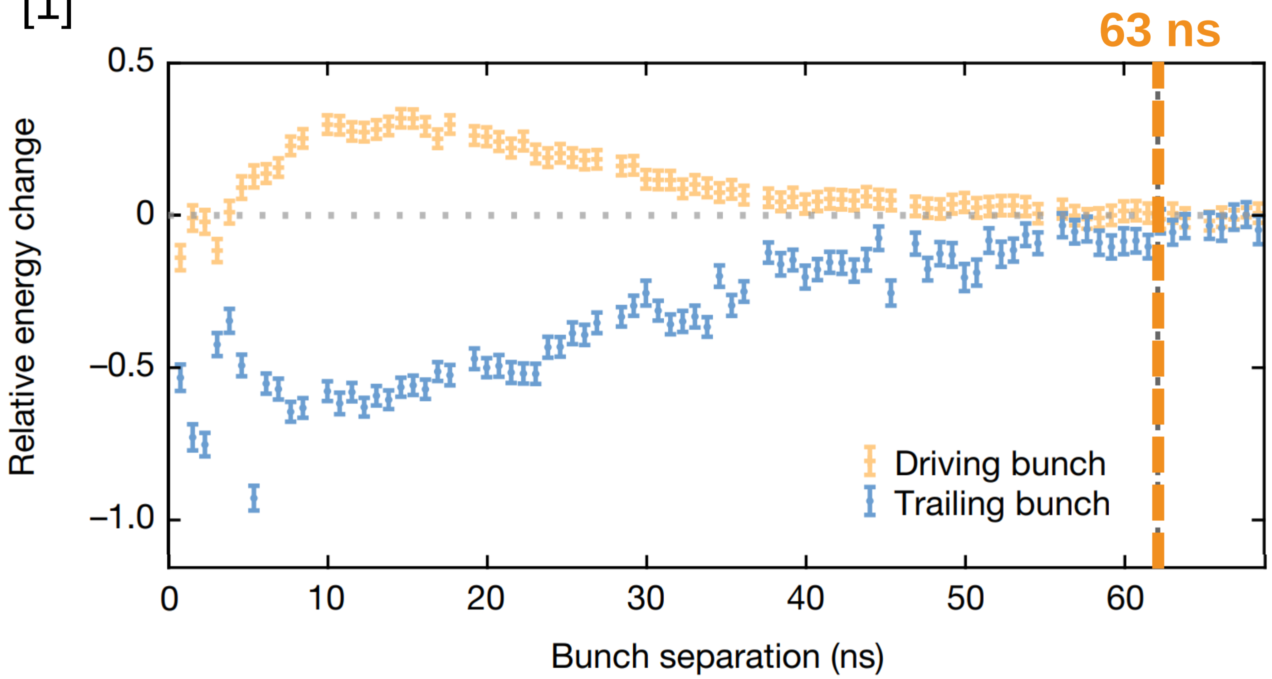
Diagram and image courtesy: J. Beinortaitė

Plasma can recover within 63 ns

- Measured recovery is specific to FLASHForward parameters (argon)
- In principle, demonstration of $\mathcal{O}(10)$ MHz repetition rate



[1]



Poster
Monday 19:00
J. Beinortaitė

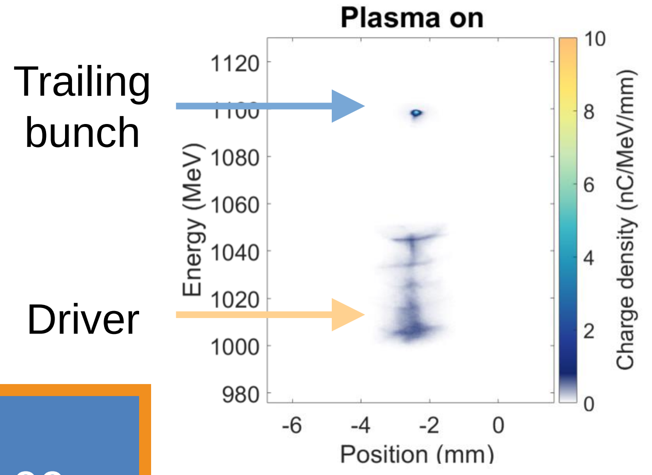


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Diagram and image courtesy: J. Beinortaitė

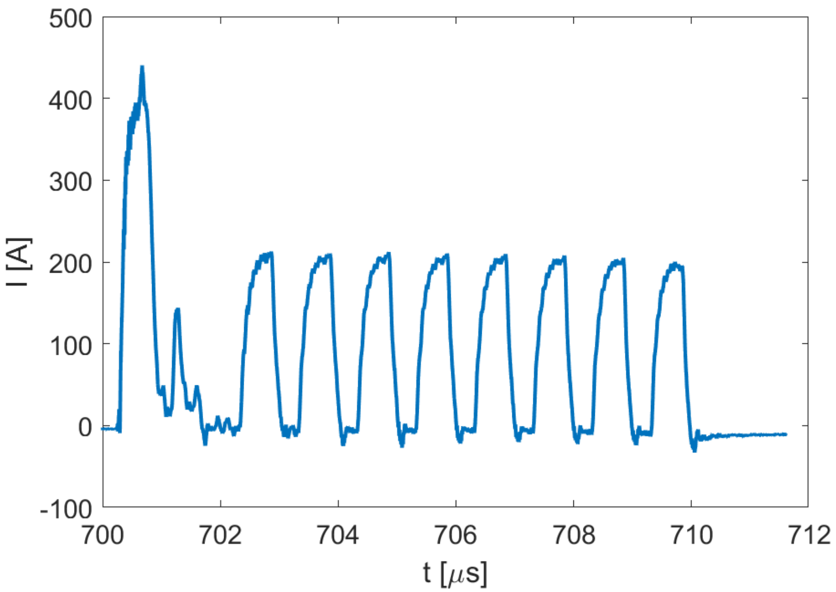
[1] R. D'Arcy et al., Nature **603**, 58-62 (2022)

A new tool: The MHz discharge pulser

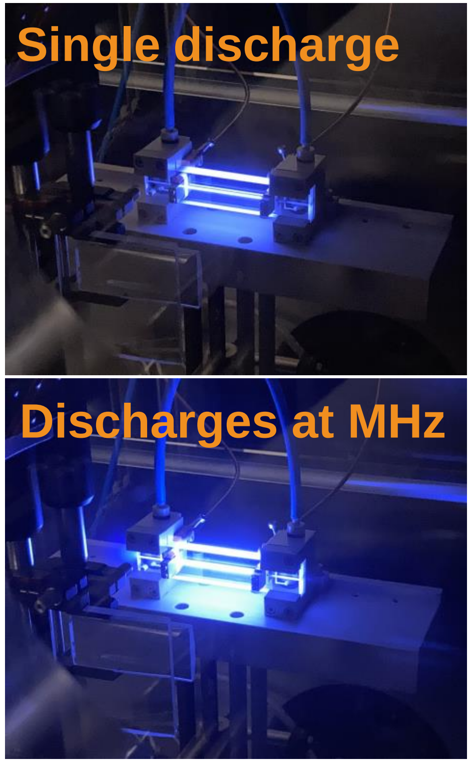
Are PWFAs capable of MHz operation?

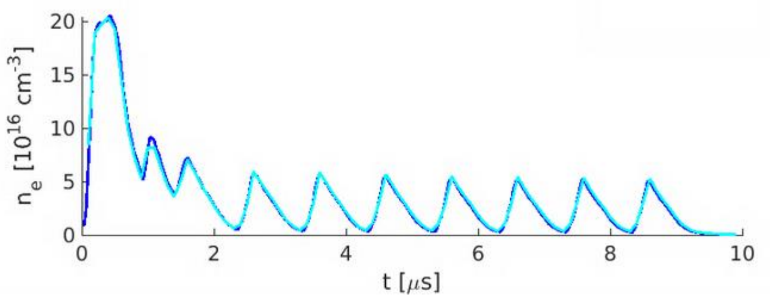
Poster
Tuesday 19:00
G. Loisch

- Extensive plasma sources development ongoing at DESY
- 1st MHz discharge cells operational



Discharge current with a MHz pulser





Plasma density with a MHz pulser

What will happen if we add driver and witness bunches at MHz?

Find the answer here →

Parallel talk: WG1
Thursday 16:25
G. Loisch

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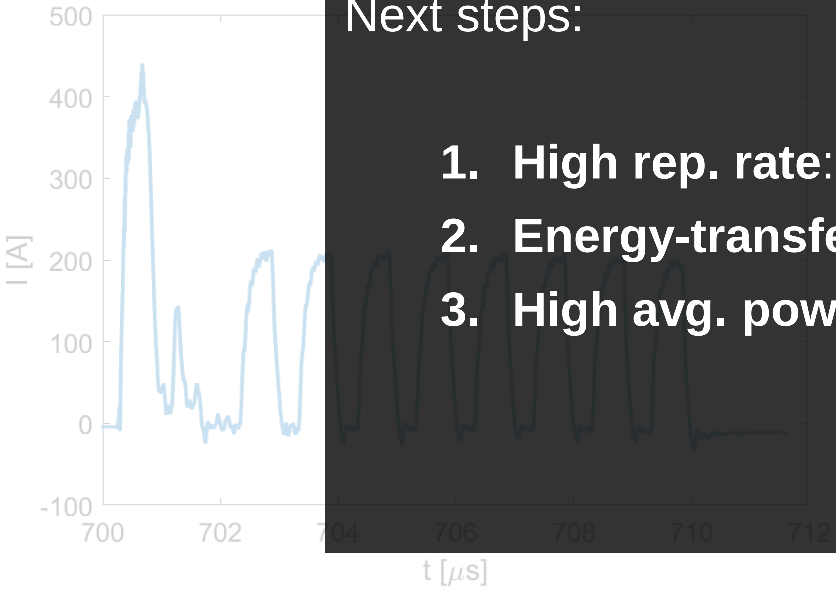

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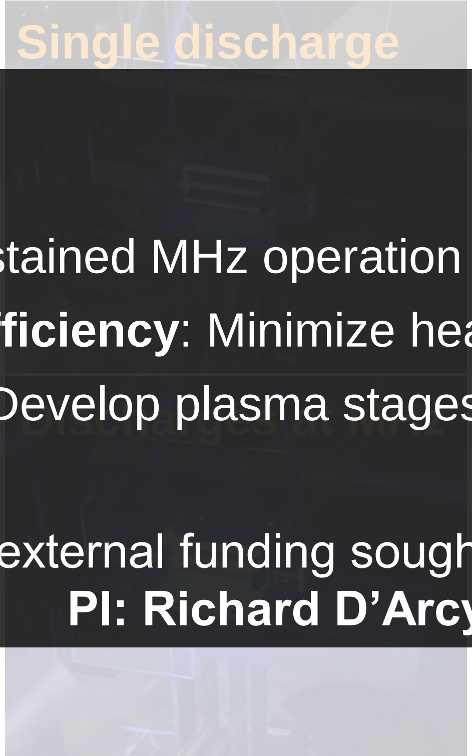

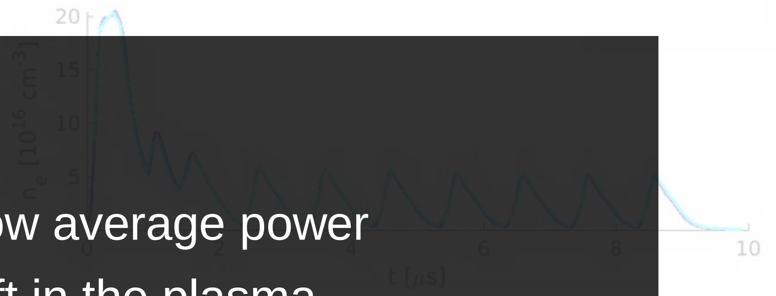

Plasma density with a MHz pulser

Find the answer here

Next steps:

1. **High rep. rate**: Sustained MHz operation at low average power
2. **Energy-transfer efficiency**: Minimize heat left in the plasma
3. **High avg. power**: Develop plasma stages capable of kW operation

→ external funding sought through ERC Consolidator Grant
PI: Richard D'Arcy – University of Oxford and DESY

Thursday 16:25
G. Loisch

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42% [1], 22% [4], and longitudinal resolution [6]

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Rapid recovery time
< 63 ns [7]

High repetition rate
See WG1 talk tomorrow @ 16:25

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[2] R. D'Arcy et al., Phys. Rev. Lett. **122**, 034801 (2019)
[3] S. Schröder *et al.*, Nature Commun. **11**, 5984 (2020)
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All at once, at higher energy gain

High beam quality	High-overall efficiency	High average power
Emittance preservation 2.8 mm mrad [4]	Driver depletion 59% [5]	Rapid recovery time < 63 ns [7]
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F. Peña
WG1, Mo. 17:25

L. Boulton
WG1, Th. 18:05

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J. Beinortaitė
Poster, Mo. 19:00

High repetition rate
See WG1 talk tomorrow @ 16:25

G. Loisch
WG1, Th. 16:25

G. Loisch
Poster, Tu. 19:00

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