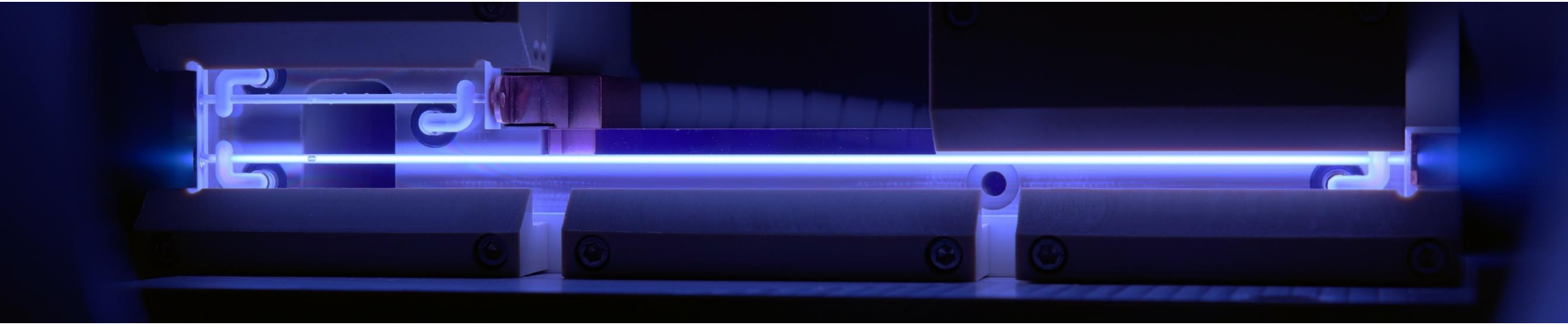
Longitudinally Resolved Measurements of Energy-Transfer Efficiency in a Plasma-Wakefield Accelerator



Lewis Boulton

C. A. Lindstrøm, J. Beinortaite, J. Björklund Svensson, J. M. Garland, P. González Caminal, B. Hidding, G. Loisch, F. Peña, K. Põder, S. Schröder, S. Wesch, J. C. Wood, J. Osterhoff, and R. D'Arcy

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

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

University of Strathclyde Glasgow

DESY.

FLASHForward: A beam-driven plasma-wakefield accelerator

Goal: Develop a self-consistent plasma-accelerator stage

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

High-overall efficiency	**High beam quality**	**High average power**
Driver depletion	Emittance preservation	Rapid recovery time
Plasma-to-witness energy-transfer efficiency	Low energy spread	High repetition rate

See FLASHForward Plenary talk for more info

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Energy-transfer efficiency in a PWFA

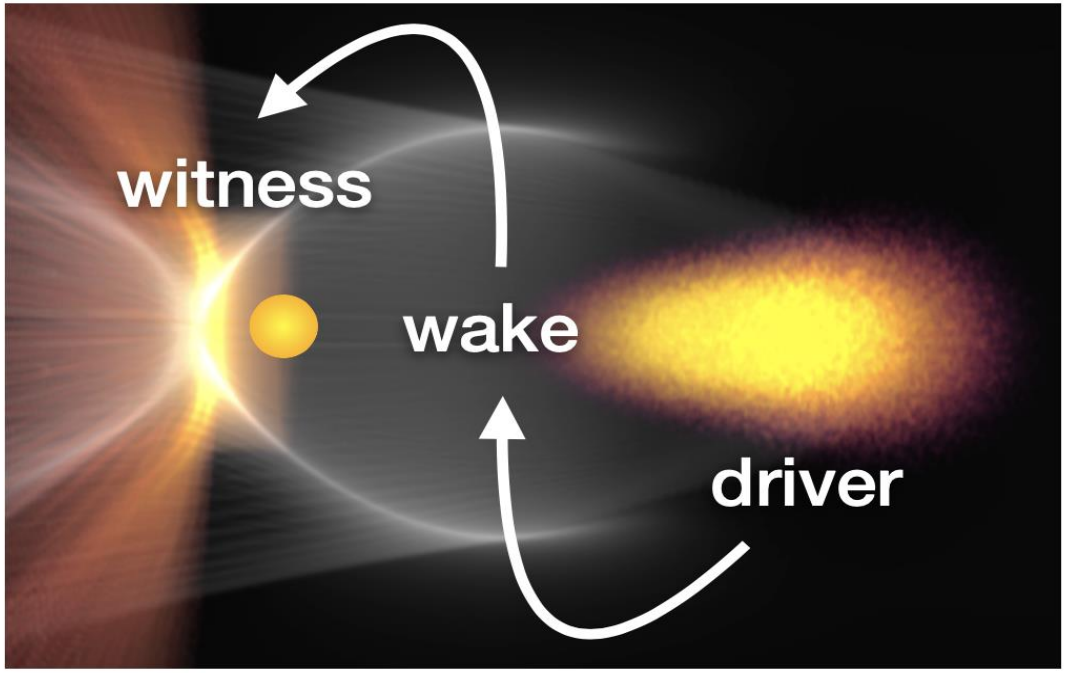
> Wake—witness bunch energy transfer efficiency → maximise absorption of energy lost by driver

M. Litos et al., Nature, vol. 515, pp. 92–95, Nov 2014

> Demonstrated as high as (42±4)% in PWFA

C. A. Lindstrøm et al., Phys. Rev. Lett., vol. 126, p. 014801, Jan 2021

> ***How do we normally measure this efficiency?***



$$\eta = \frac{\Delta W_{\mathrm{acc}}}{\Delta W_{\mathrm{dec}}}$$

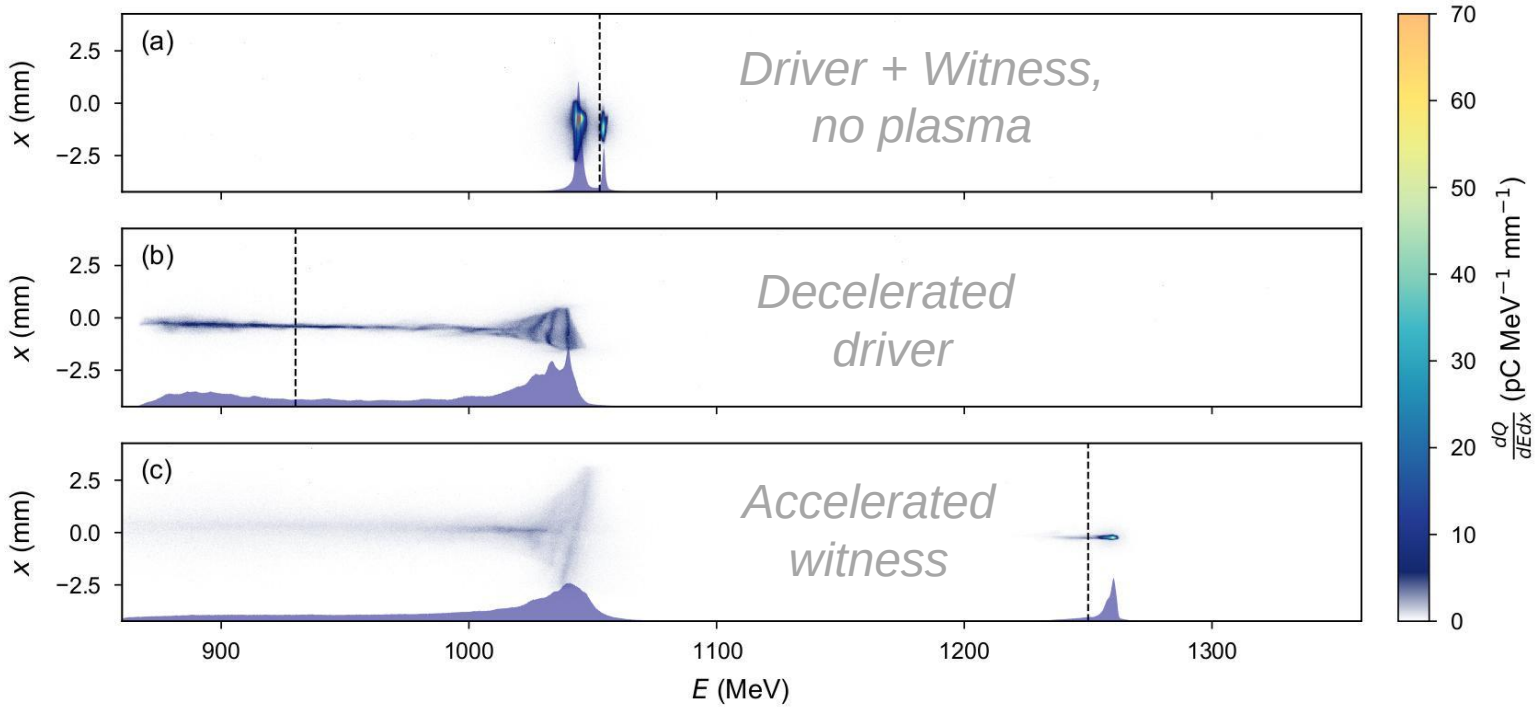
Measuring energy-transfer efficiencies

> Normally measured using dipole-based spectrometers

> Can only accurately measure a finite band of energies simultaneously → ***multiple shots***

> Requires ***stable transport*** from plasma to spectrometer

> Measurement is inherently ***destructive***



> ***Is there another way?***

Plasma emission light as a PWFA diagnostic

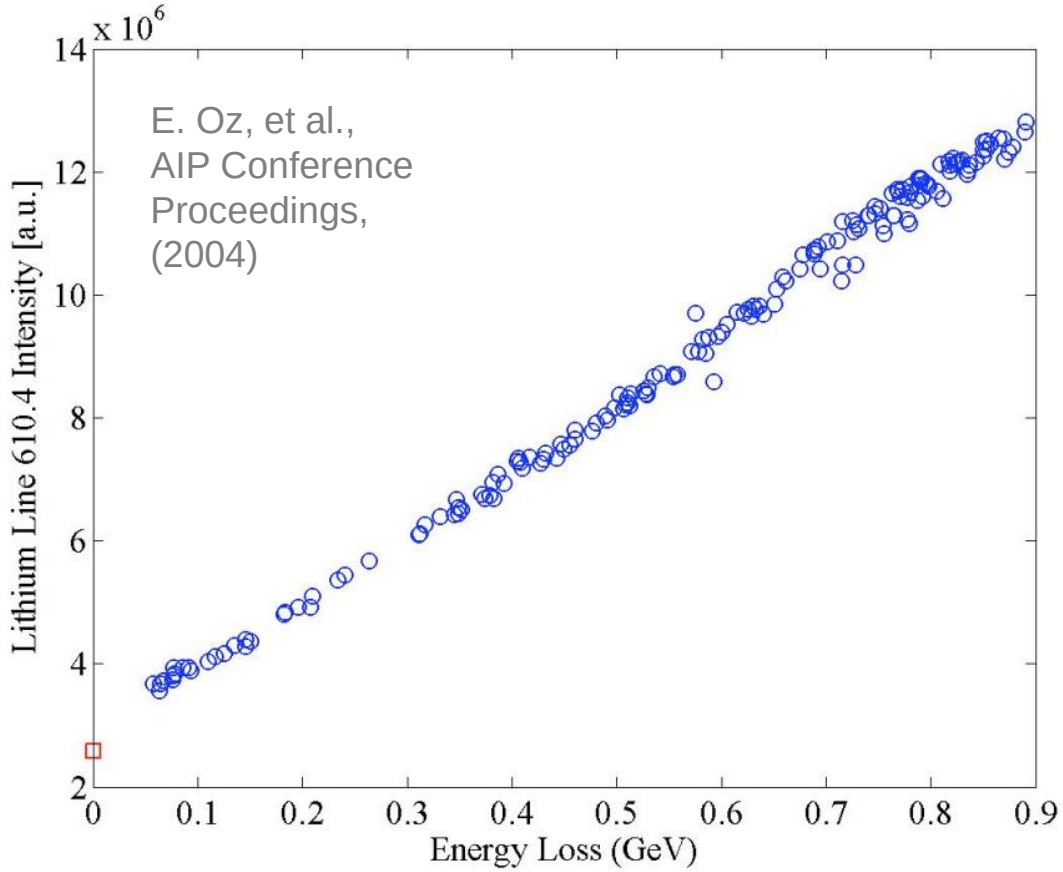
> Light yield when a plasma recombines *increases* when a drive beam deposits energy

> Can serve as a diagnostic for *driver energy loss*

> Also used as monitors of driver overlap with laser generated plasmas

P. Scherkl et al., Phys. Rev. Accel. Beams (2022).
A. Knetsch et al., Phys. Rev. Accel. Beams (2021)
E. Adli et al., New Journal of Physics (2016)

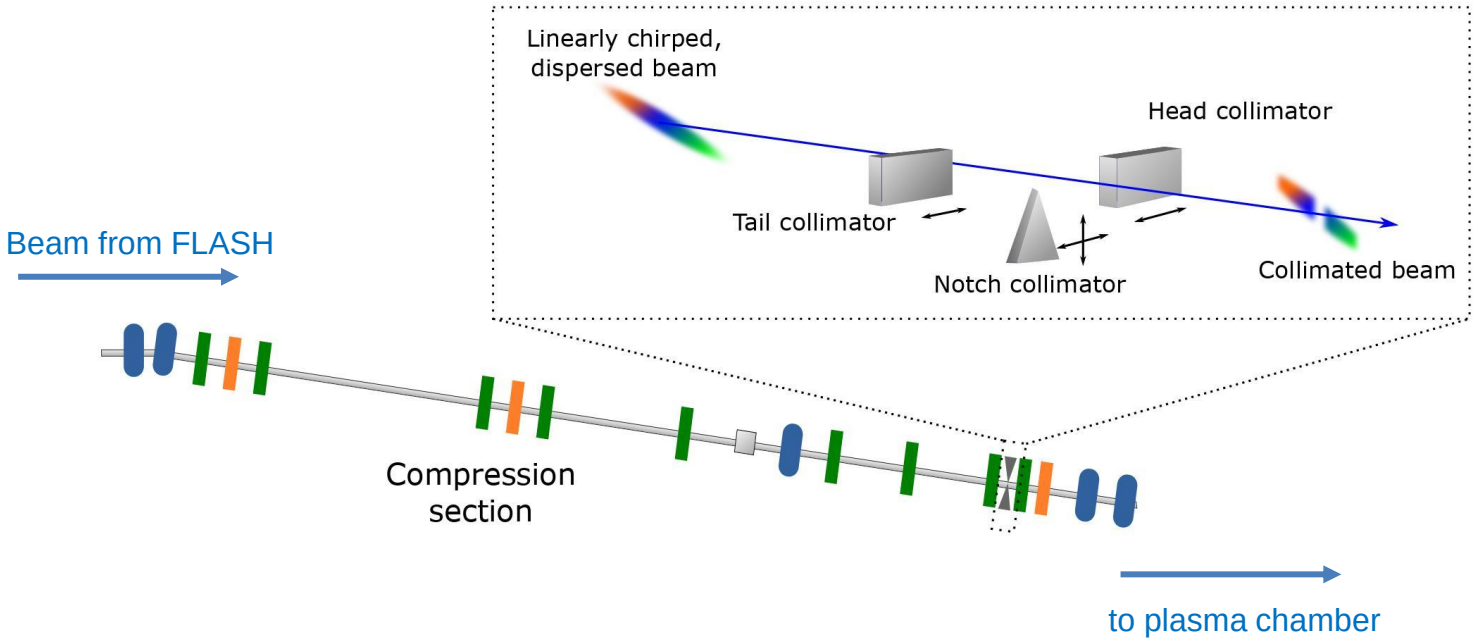
> ***Can also be used for efficiency measurements***

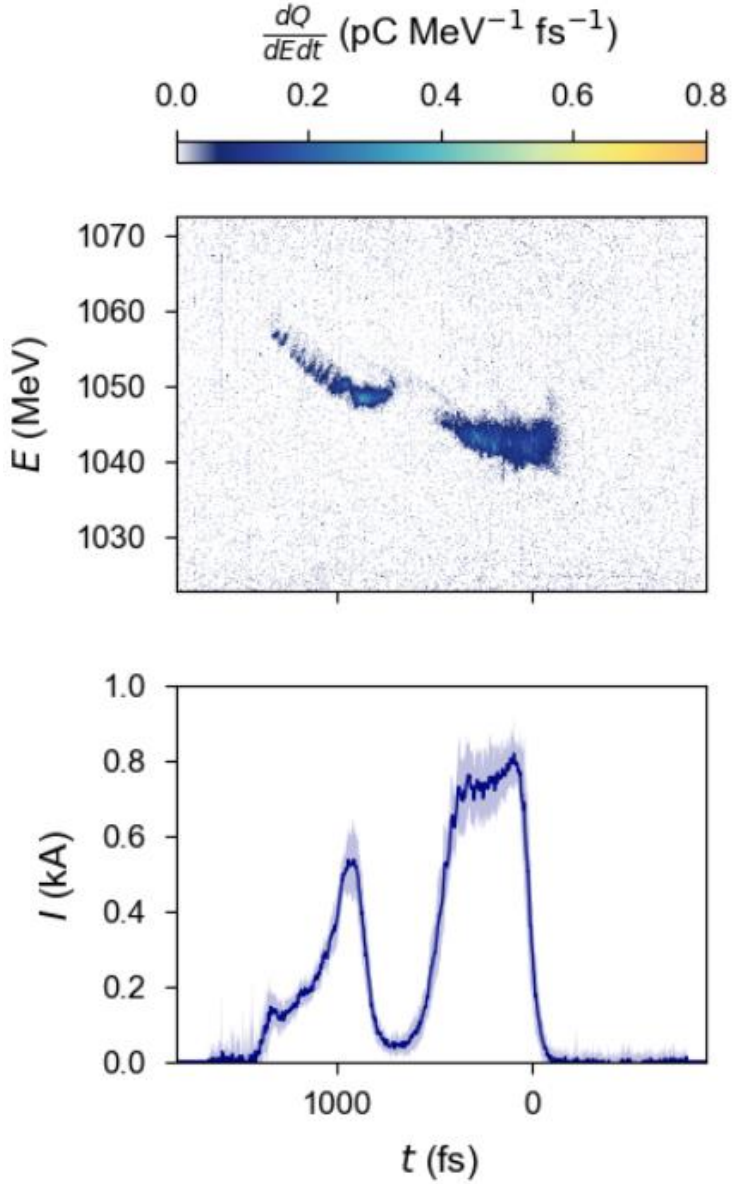


Double bunch generation at FLASHForward

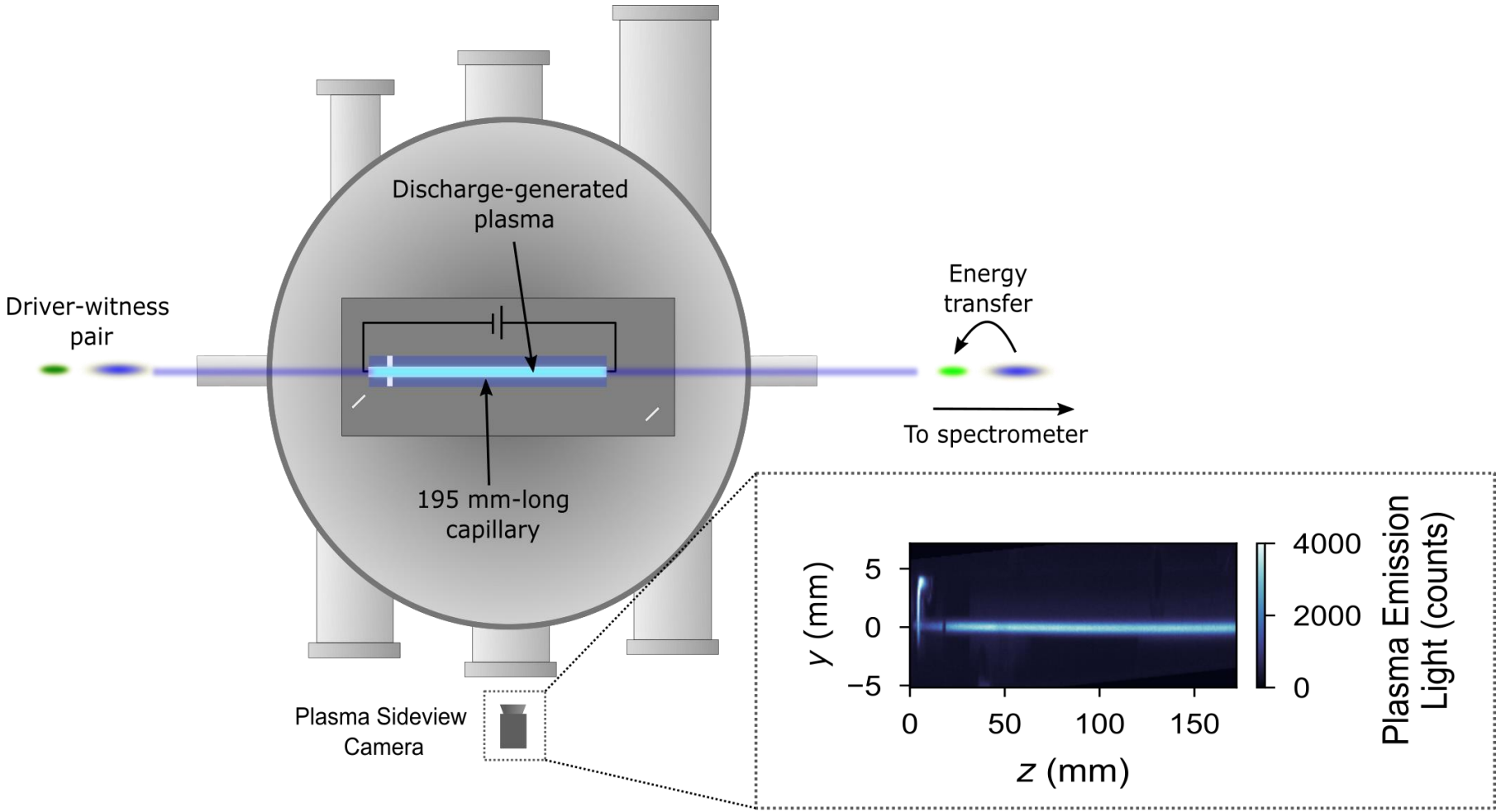
> Collimators in dispersive section → tailoring of double-bunch current profile

> Can be used to systematically vary the charge reaching the plasma stage





Energy booster stage at FLASHForward

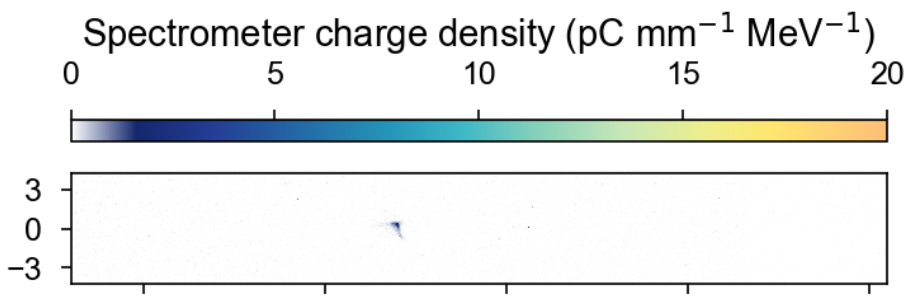


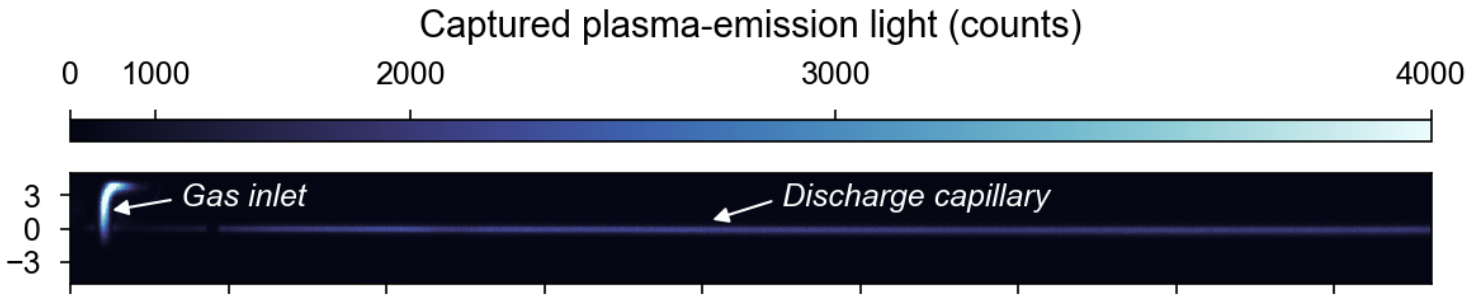
> Simple CMOS camera captures emitted plasma light after beam passes

> Vary the charge in the driver and trailing bunches, and see what happens…

Simple observations from plasma emission light

> Emitted light increases after interaction with driver…





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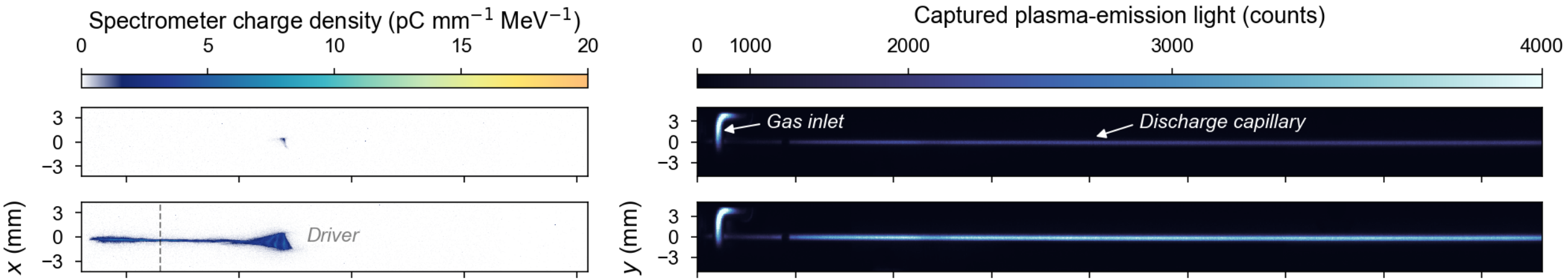

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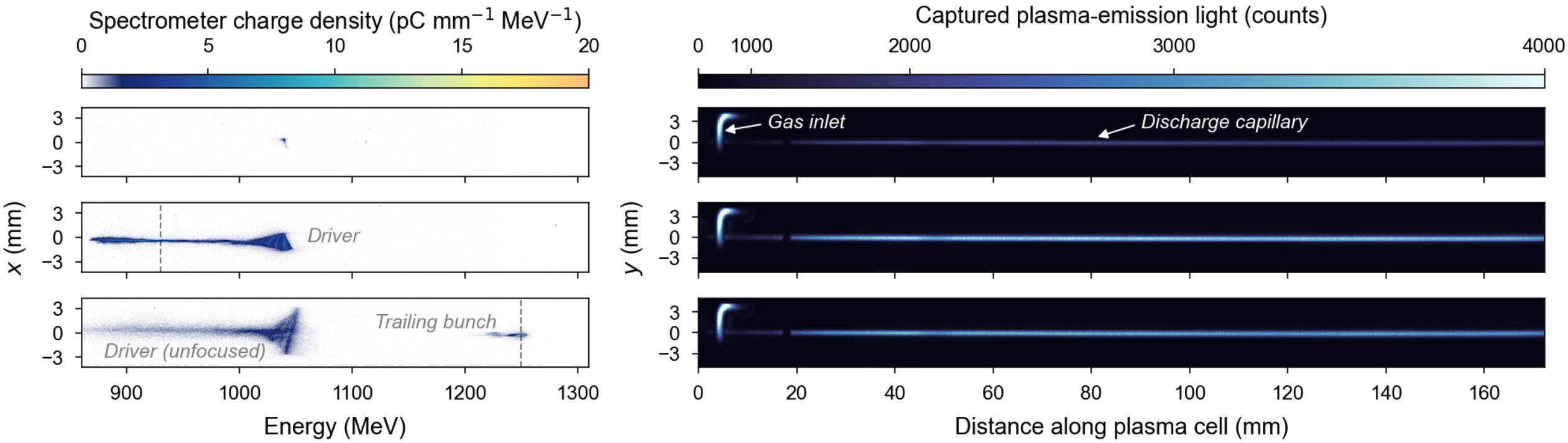


> … and **<u>decreases</u>** with introduction of the trailing bunch (*beam loading*)

Plasma emission-light versus wake energy

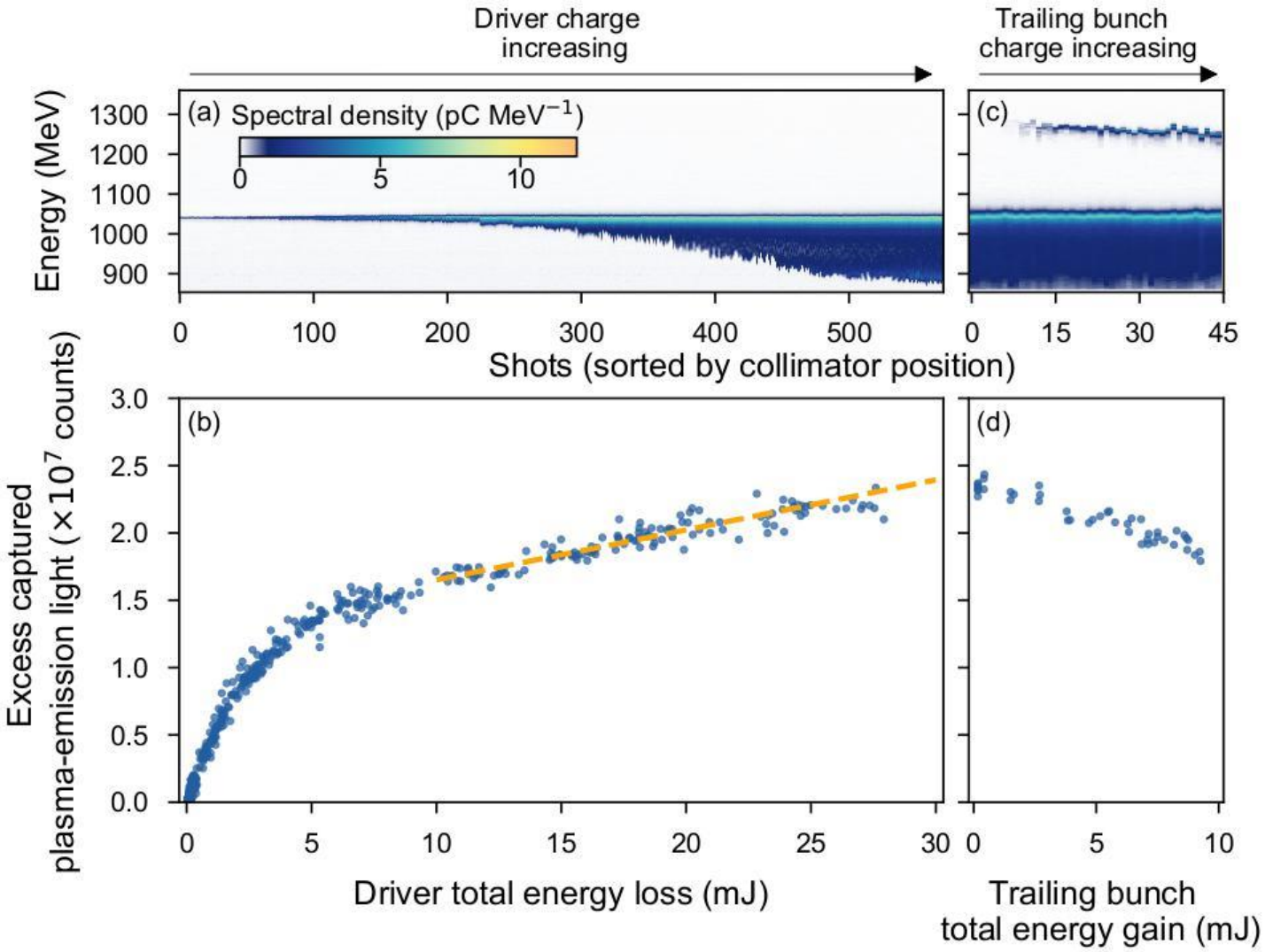
> Plasma emission light yield I_p measured as function of driver energy loss ΔW_{dec}:

$$I_{\mathrm{p}} = f(\Delta W_{\mathrm{dec}}) = f(\Delta W_{\mathrm{wake}})$$

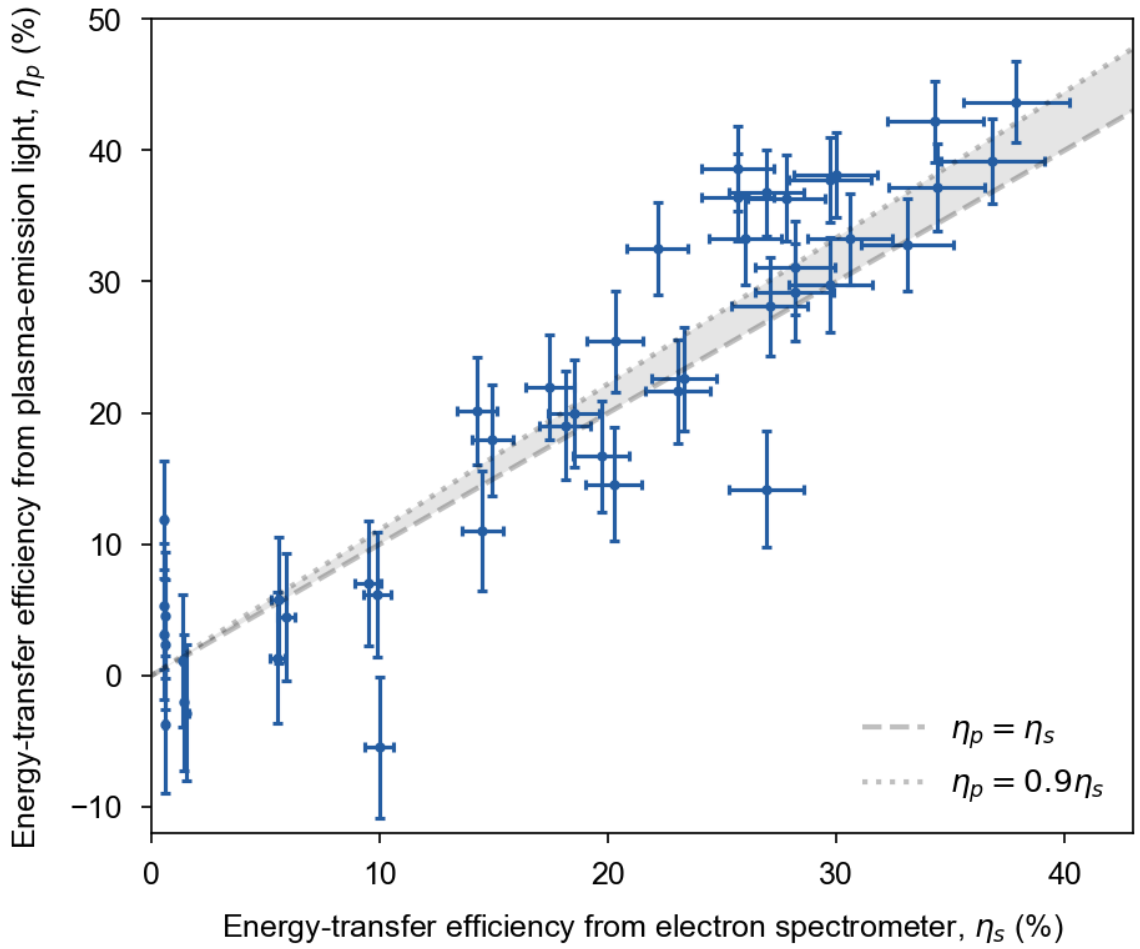
$$\Rightarrow \Delta W_{\mathrm{wake}} = f^{-1}(I_{\mathrm{p}})$$

> When witness *extracts* energy:

$$\Delta W_{\mathrm{wake}} = \Delta W_{\mathrm{dec}} - \Delta W_{\mathrm{acc}} = f^{-1}(I_{\mathrm{p}})$$



Efficiency measurements with plasma light



> Recast as an efficiency:

$$\eta_{\mathrm{p}} = 1 - \frac{f^{-1}(I_{\mathrm{p}})}{\Delta W_{\mathrm{dec}}}$$

> Compare with spectrometer-based efficiency measurements:

$$\eta_{\mathrm{s}} = \frac{\Delta W_{\mathrm{acc}}}{\Delta W_{\mathrm{dec}}}$$

> **Good agreement!**

(Still some systematic error (~14 %); imperfect witness charge coupling / estimation of ΔW_{dec})

Spectrometer vs plasma light based efficiency measurements

> Dipole spectrometers:

+ Still the work-horse diagnostic, will always need them

- Can suffer from poor transport from the plasma stage

- Inherently destructive to the beam

> Plasma emission-light based method:

- Requires some initial calibration with a spectrometer, and at least an estimate of driver energy loss

+ Measurements happen in-situ (at the plasma location)

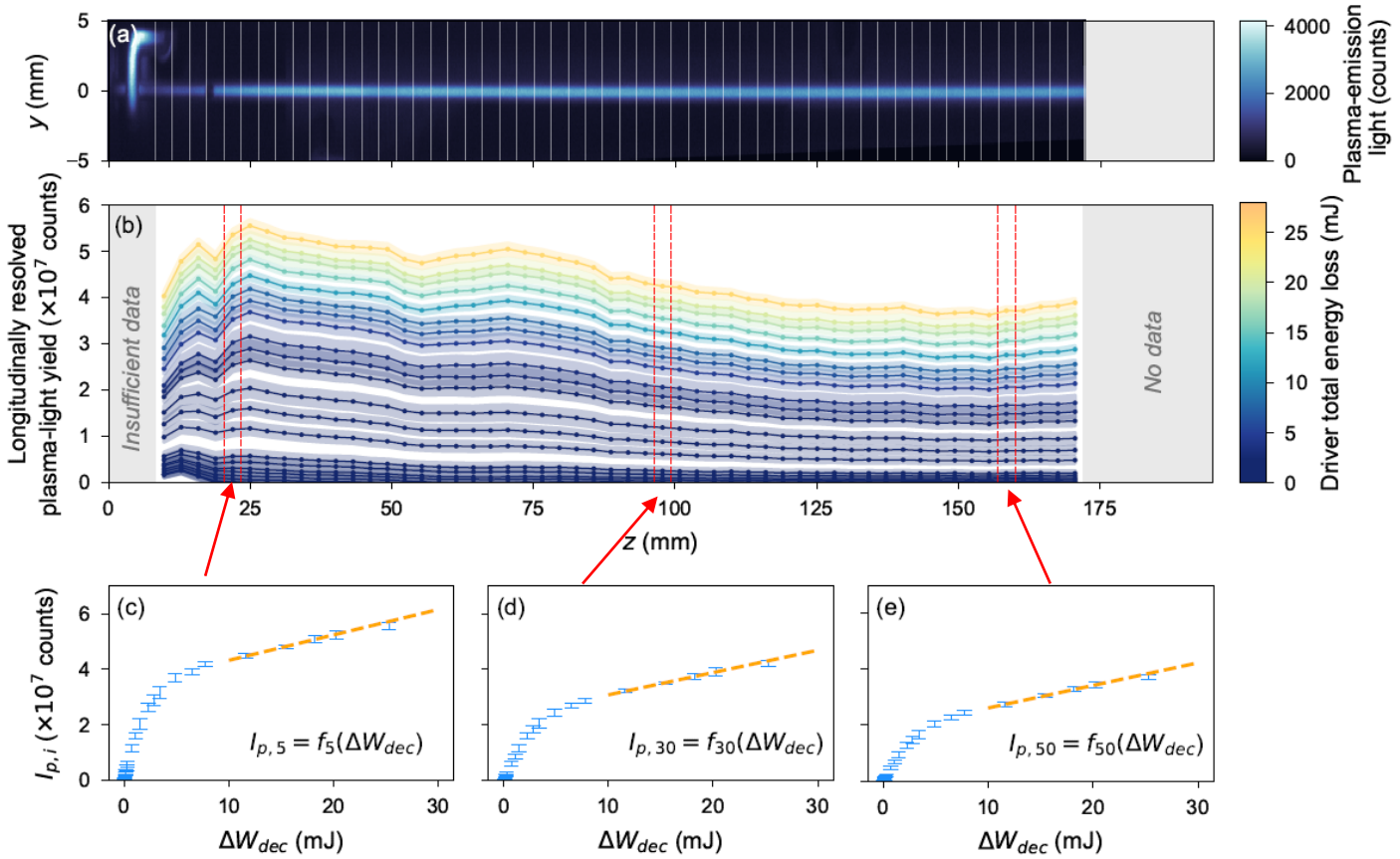
+ Doesn’t require a witness measurement (non-destructive)

Longitudinal resolution of plasma light signal

- Plasma emission light measurement is spatially resolved → split signal into longitudinal segments
- Construct a response curve for each segment $I_{\mathrm{p,i}} = f_{\mathrm{i}}(\Delta W_{\mathrm{dec}})$
- Efficiency in each segment:

$$\eta_{\mathrm{p,i}} = 1 - \frac{f_{\mathrm{i}}^{-1}(I_{\mathrm{p,i}})}{\Delta W_{\mathrm{dec}}}$$

(under assumption that $\Delta W_{\mathrm{dec,i}} \propto \Delta \mathrm{W}_{dec}$ during construction of f_{i})



Longitudinally resolved efficiency measurements

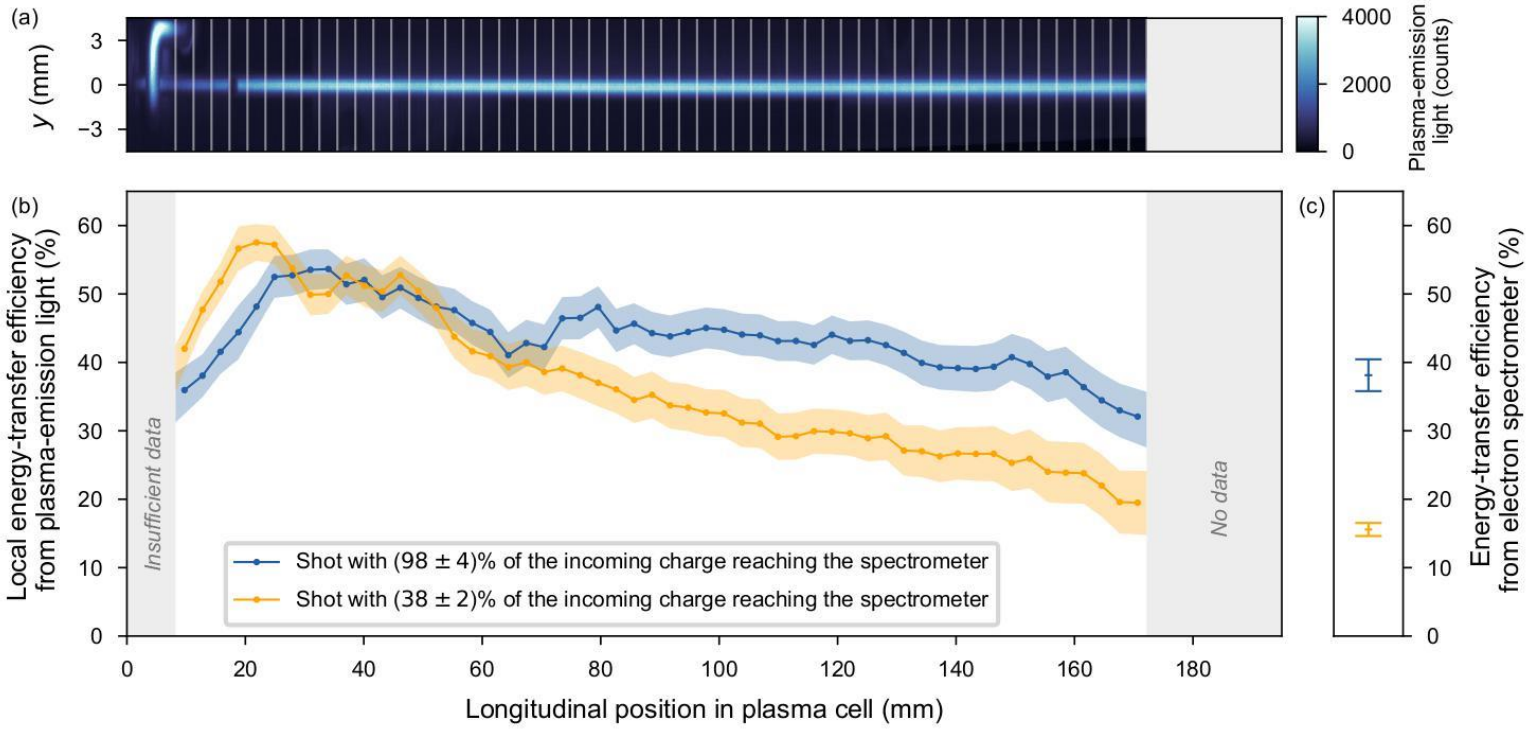
L. Boulton, C. A. Lindstrøm et al.,“Longitudinally resolved measurement of energy-transfer efficiency in a plasma-wakefield accelerator,” 2022. arXiv:2209.06690v1

> Unique ability to diagnose the local energy-transfer efficiency on a shot-to-shot basis

> Two example shots:

1. High efficiency throughout, high charge coupling on spectrometer

2. Initially high efficiency decreases rapidly after ~70mm— only 38% of charge measured on spectrometer



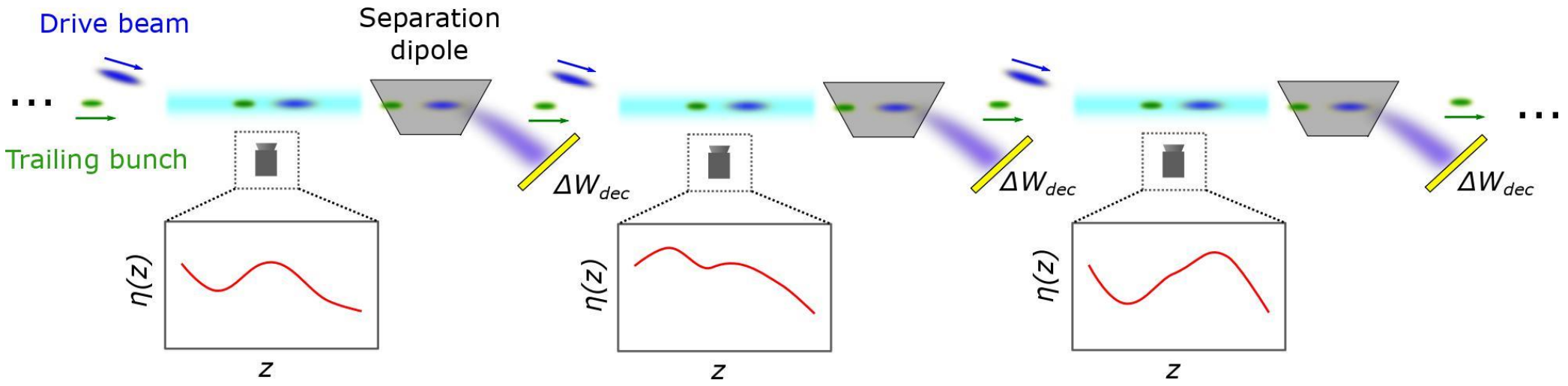
> Potential diagnosis of transverse instabilities (e.g *efficiency vs instability* relation)?

V. Lebedev et al.,Phys. Rev. Accel. Beams, vol. 20, p. 121301, Dec 2017
S. S. Baturin , arXiv:2010.01046 [physics.acc-ph]

A diagnostic for future, multi-stage PWFAs

> Can already provide better understanding of acceleration process at single stage level

> Non-invasive nature of diagnostic to witness beam → online efficiency monitor for PWFAs with *multiple stages* and eventually *applications*



Conclusion

> In this study:

- Detected **energy extraction (beam loading)** by a trailing bunch from a plasma wake via a **decrease in the plasma emission light**
- Used driver energy loss vs light yield measurements to find **relation between wake energy and excess plasma light**
- Calculated **energy-transfer efficiency with plasma light yield** instead of trailing bunch energy gain: **good agreement with spectrometer measurements**
- Used **spatial resolution** of plasma light signal to estimate **longitudinally resolved energy transfer efficiency**

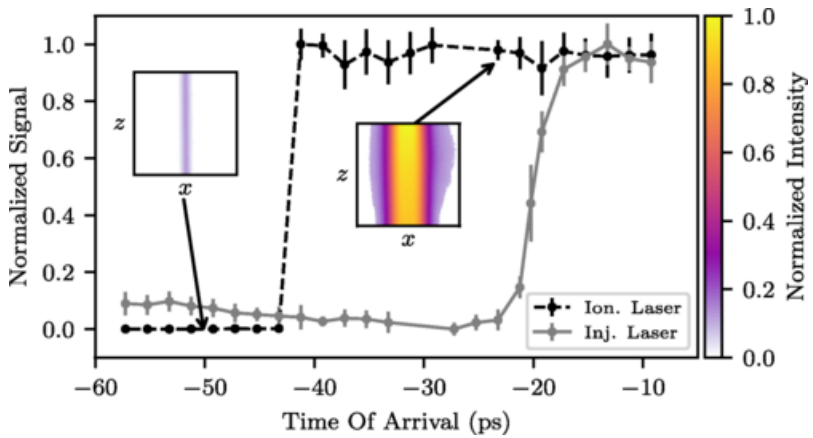
> Outlook:

- Investigation of e.g. transverse instabilities
- A non-invasive method of measuring efficiencies shot-to-shot for multi-stage PWFA

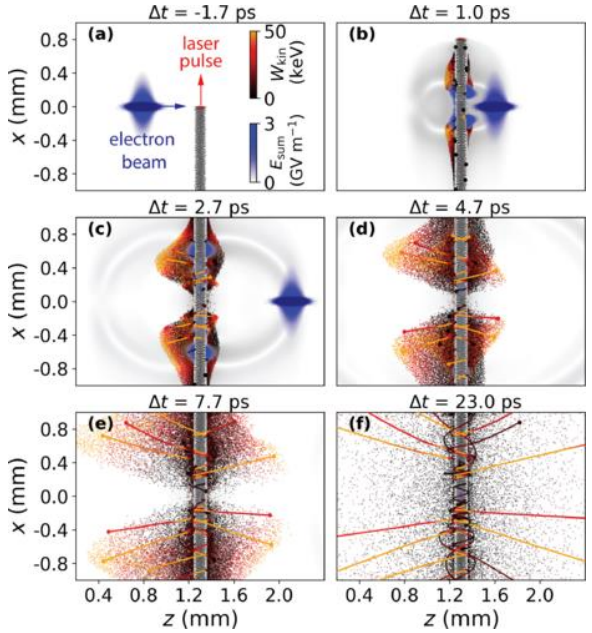
Backup

Plasma emission light as a PWFA diagnostic

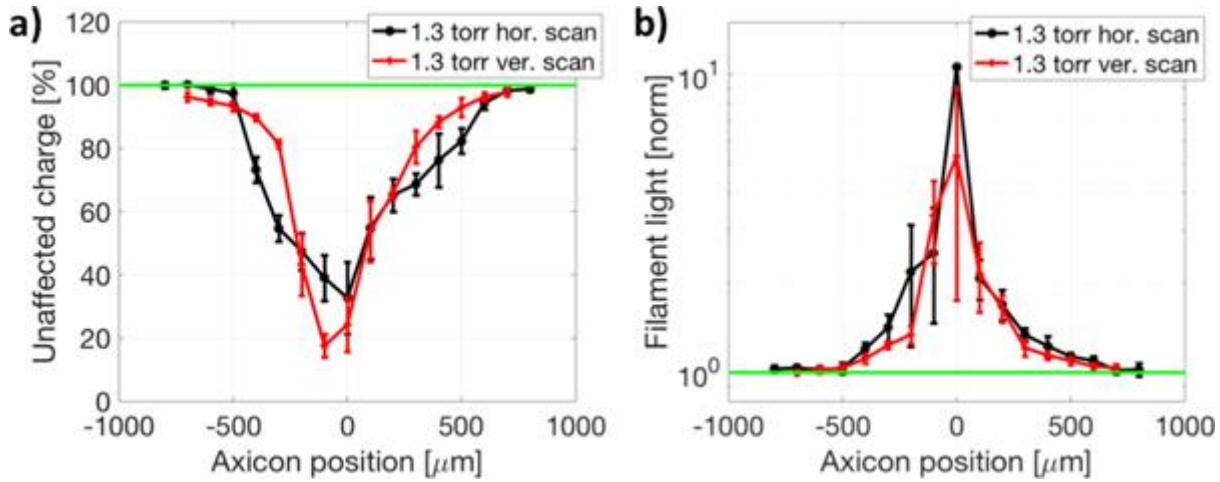
- Example uses: monitor overlap between driver and laser generated plasma
- **Can it be used for efficiency measurements?**



A. Knetsch et al., Phys. Rev. Accel. Beams, (Oct 2021)

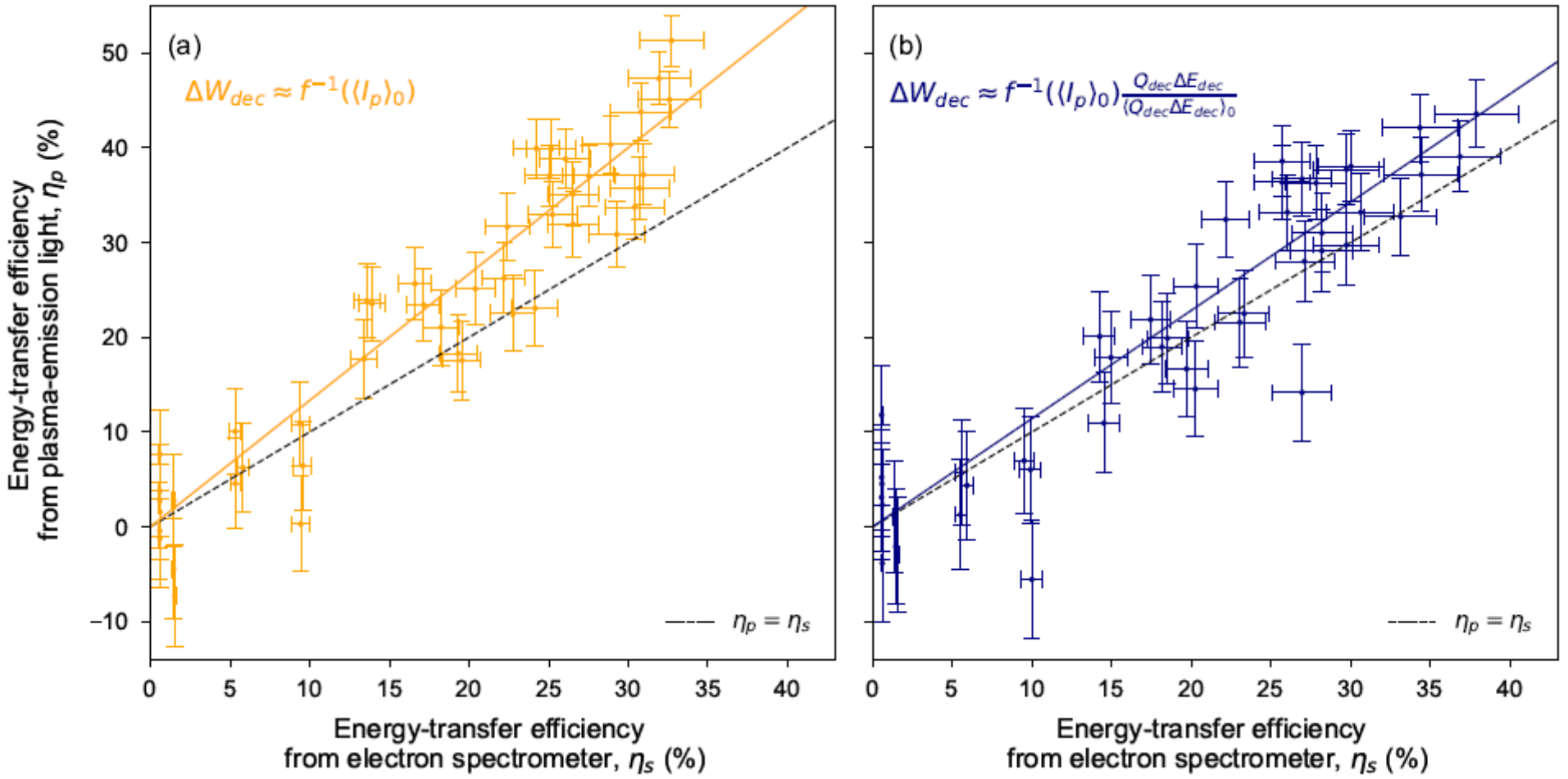


P. Scherkl et al., Phys. Rev. A (May 2022).



E. Adli et al., New Journal of Physics (oct 2016).

Driver energy loss estimation during trailing bunch measurements



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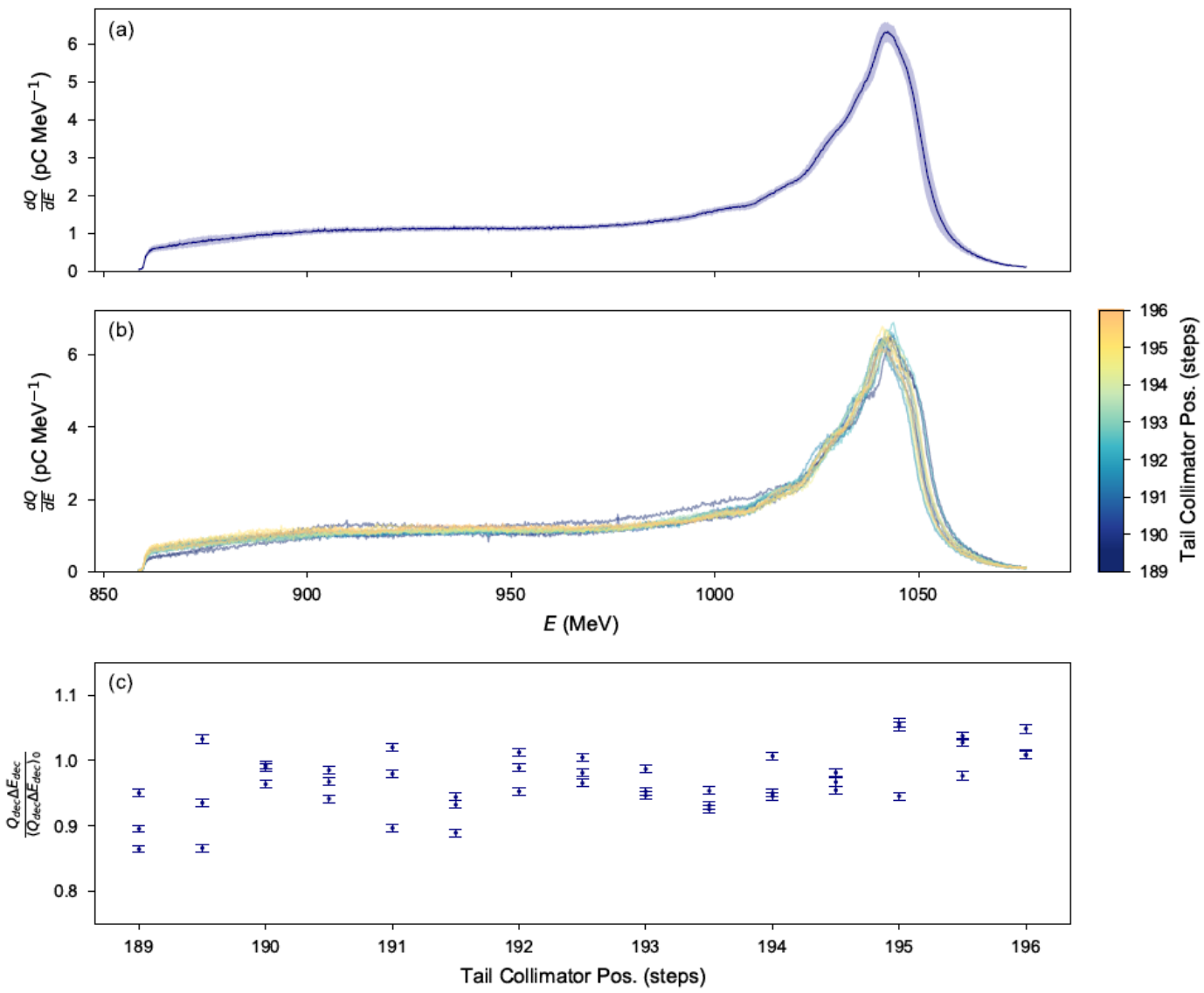

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