Driver energy depletion

Energy Depletion and Re-Acceleration of Driver Electrons

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

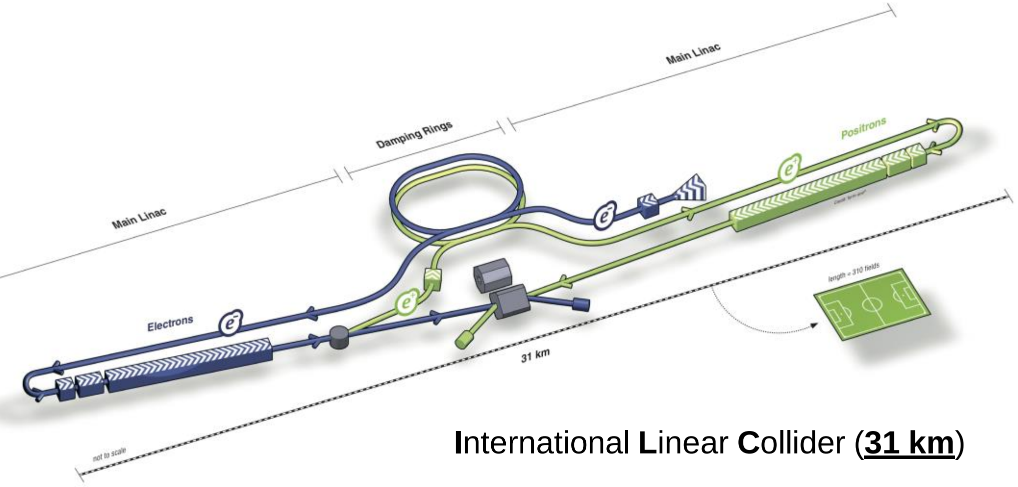
DESY.

Plasma-wakefield accelerators promise compactness

- Accelerating gradient
  - State-of-the-art RF accelerators: $\mathcal{O}$(100 MV/m)
  - Plasma-Wakefield Accelerators: $\mathcal{O}$ (1-100 GV/m)
- **Construction costs** can be **greatly reduced**

- For high-power beam delivering accelerators:
  - e.g., hard X-ray FELs and colliders
  - Goal: Keep running costs low
    - **High total energy-transfer efficiency needed**

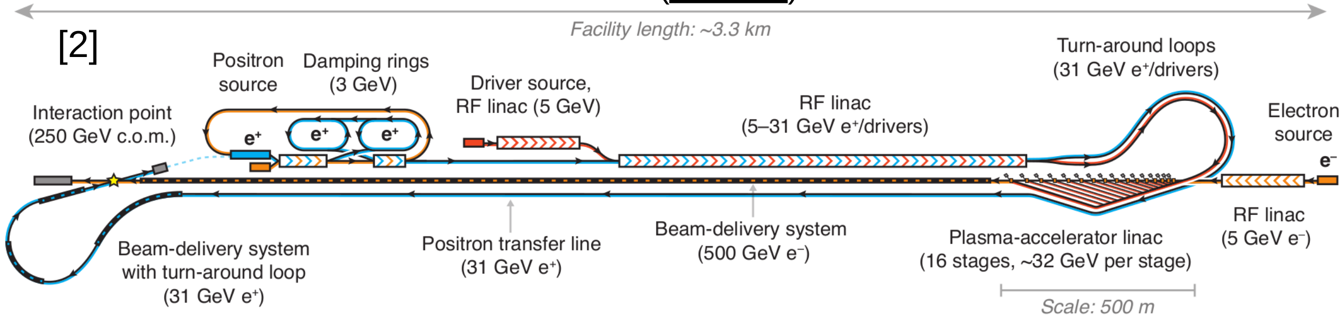
[1]



International Linear Collider (**31 km**)

HALHF (**~3.3 km**)

[2]



[1] ILC Technical Design Report (2013)
[2] B. Foster *et al.*, New Journal of Physics (2023) (accepted)

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

* 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)

Driver energy depletion is key component for efficiency

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

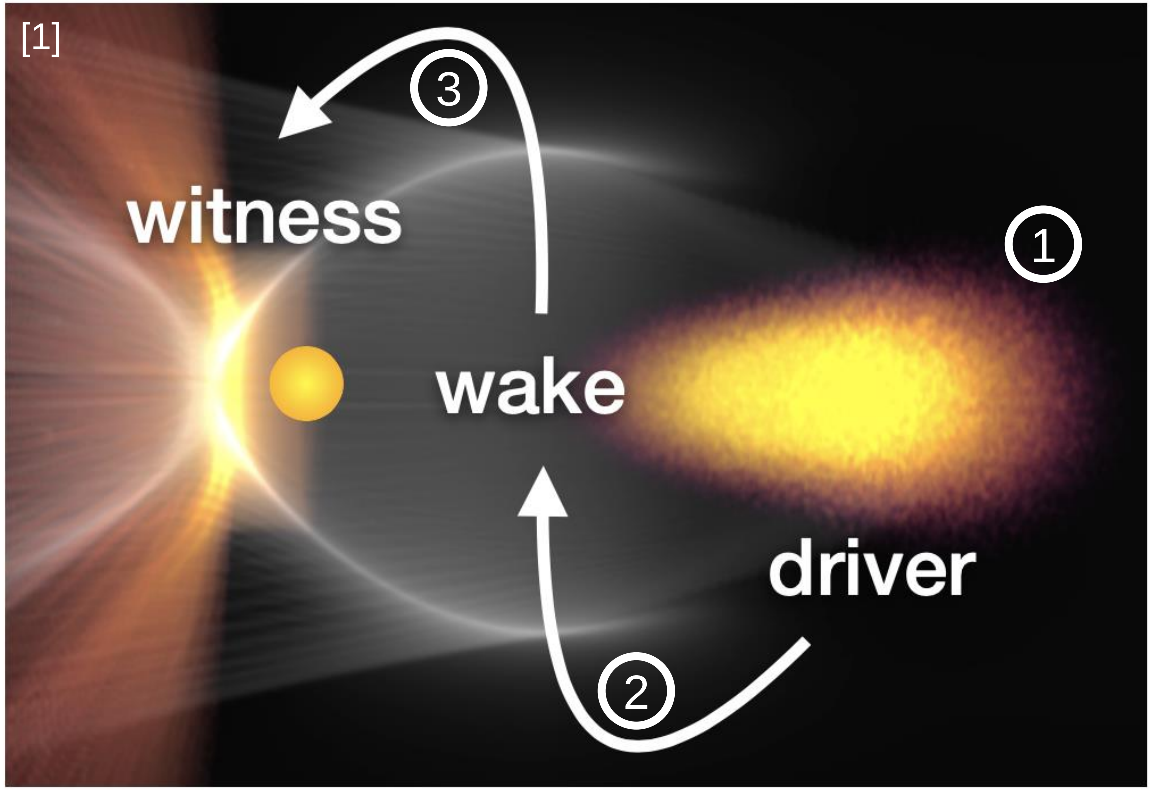
1. Driver production efficiency ✓ (beam driven)

   CLIC: [2] **η = 55 %** (excluding facility power)
   Ti:Sapphire laser: [3] η < 1 %

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

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] S. M. Hooker *et al.*, J. Phys. B: At. Mol. Opt. Phys. **47,** 234003 (2014)
[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)

Electron reacceleration is the limit of depletion

HiPACE++ simulations show reacceleration of energy depleted electrons

Plenary talk
Wednesday 09:00
F. Peña

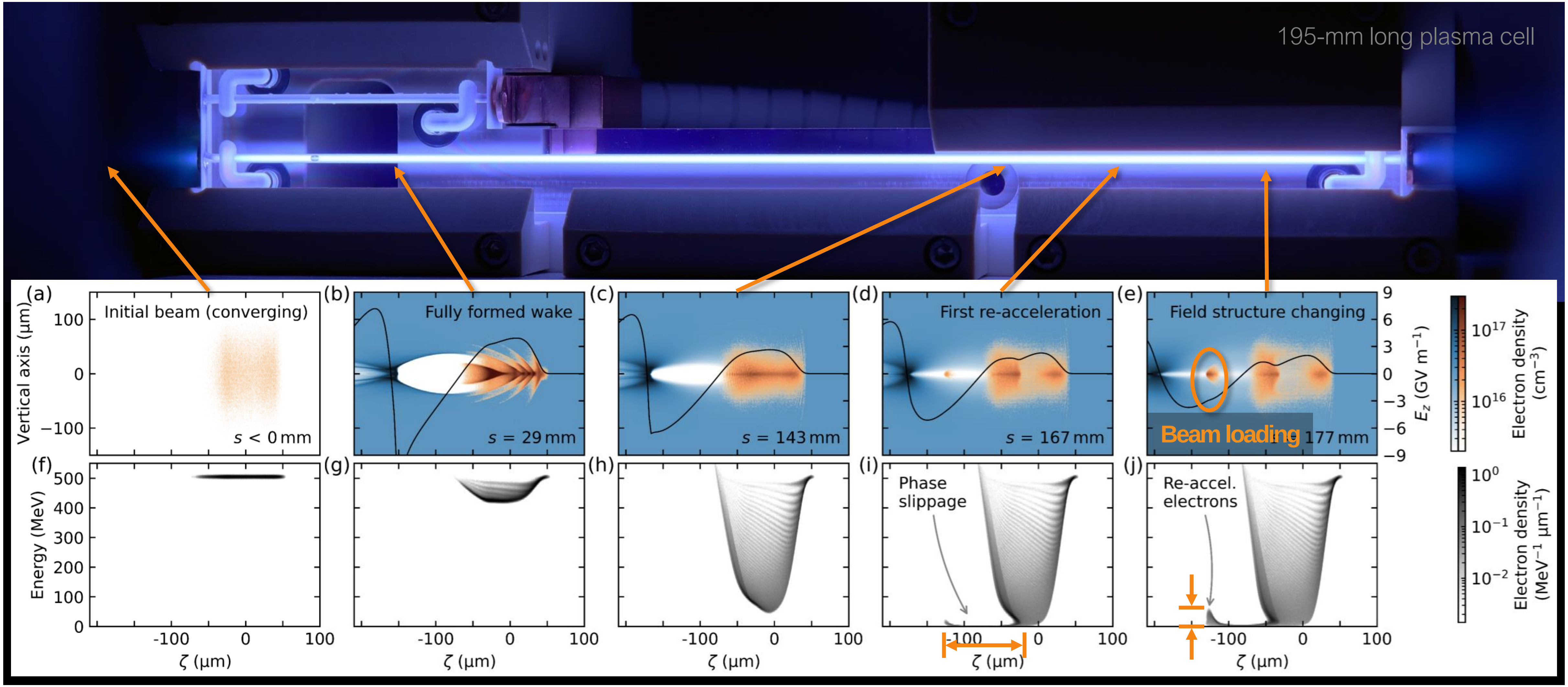
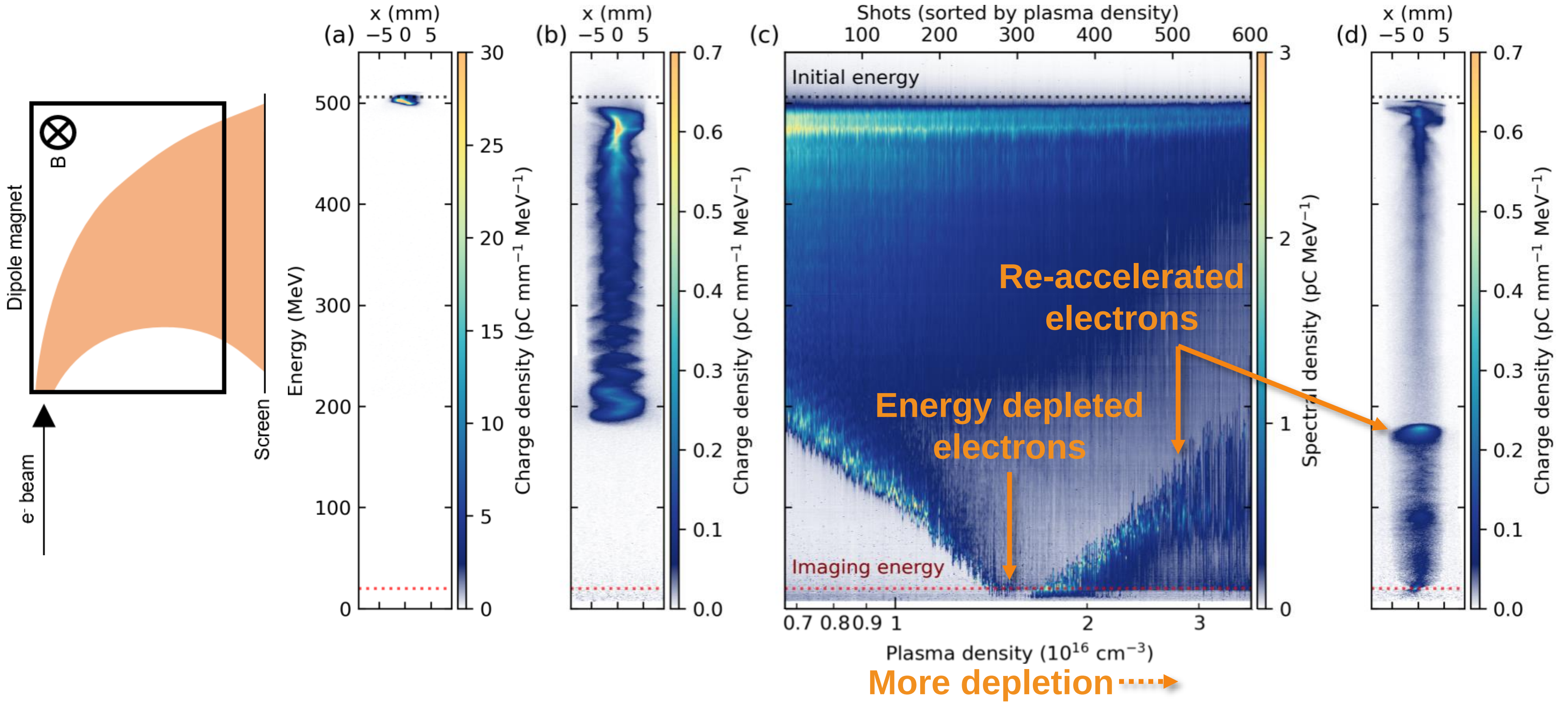


Photo: C. A. Lindstrøm
HiPACE++, S. Diederichs *et al.*, CPC **278**, 108421 (2022)

Electron re-acceleration measured for the first time



- Electrons decelerate to 2% of their initial energy
  - They are subsequently re-accelerated

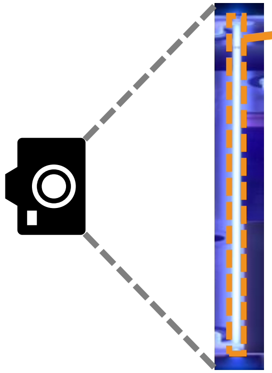
Plasma light provides an insight on energy deposition

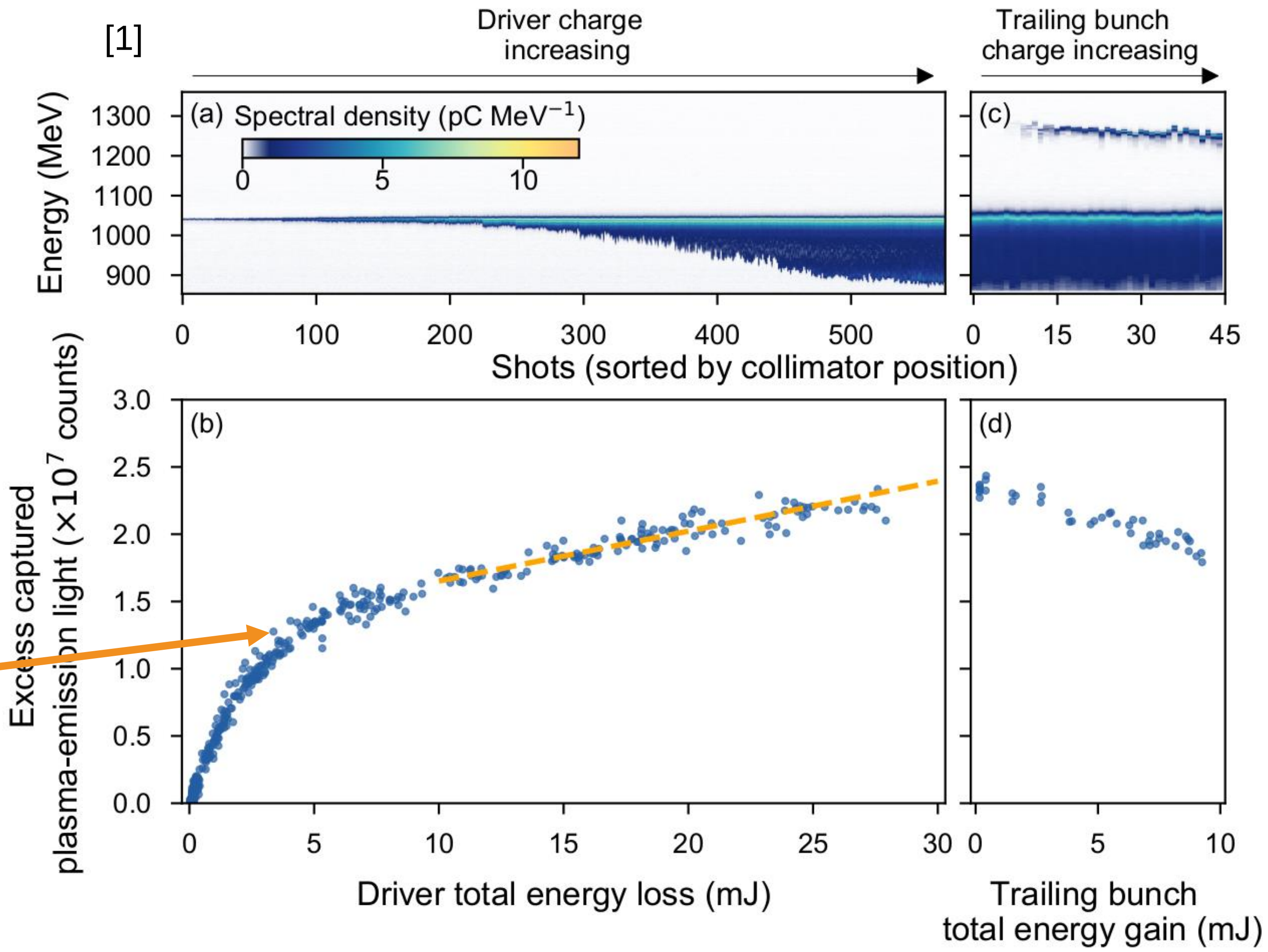
> **Plasma** emits **light** during recombination

> The more energy is deposited by the beam into the plasma, the more light is emitted [1, 2]

> Can be used to estimate energy extraction efficiency

Parallel talk: WG1
Thursday 18:05
L. Boulton

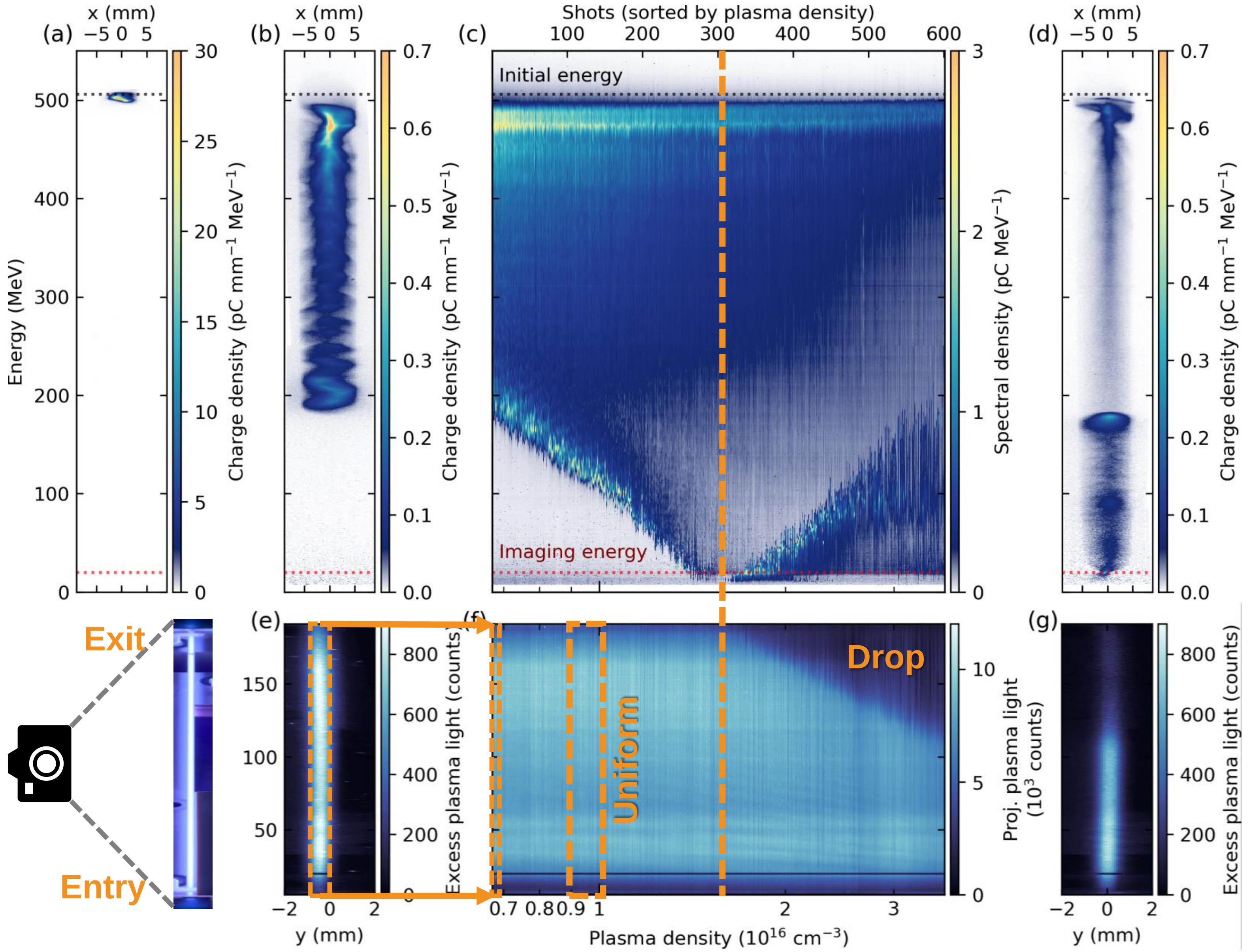




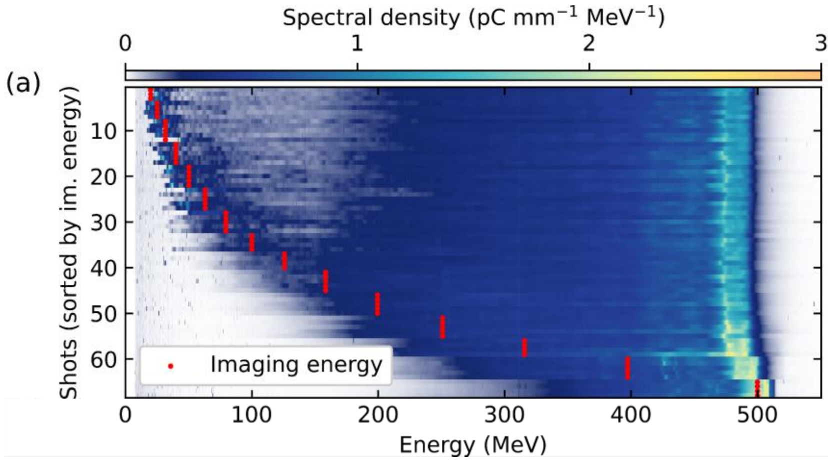
[1] E. Öz *et al.*, AIP Conference Proceedings **737**, 708 (2004)
[2] L. Boulton *et al.*, in review (2022)

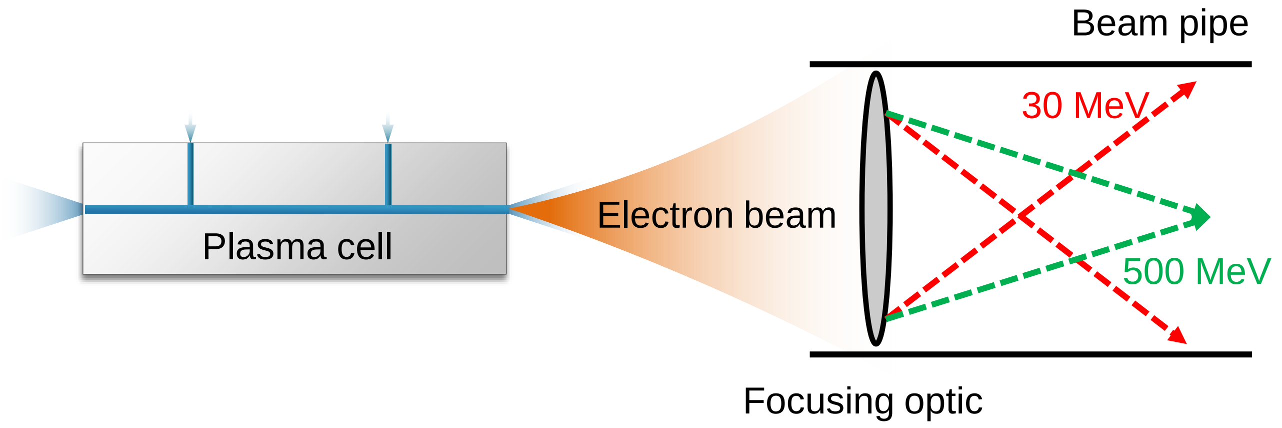
Plasma light shows electron re-acceleration

- Drop in light-emission intensity from:
  - Less energy deposition
  - More energy extraction
- Can identify the longitudinal position where re-acceleration starts
  - Deceleration over 115 mm (4.3 GV/m)
  - Acceleration over 80 mm (2.3 GV/m)



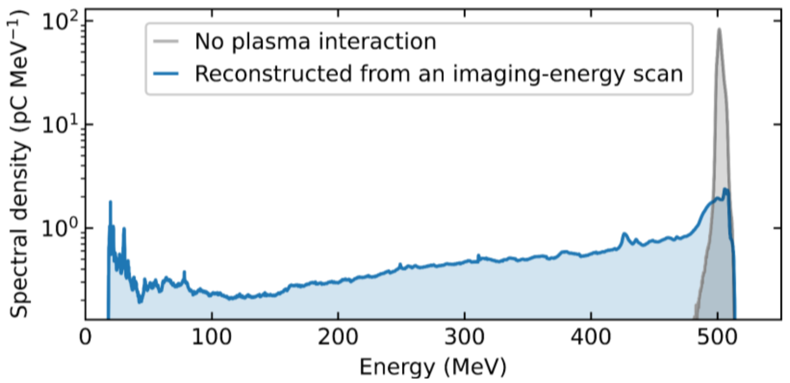
Spectrum reconstruction is required for accurate measurement



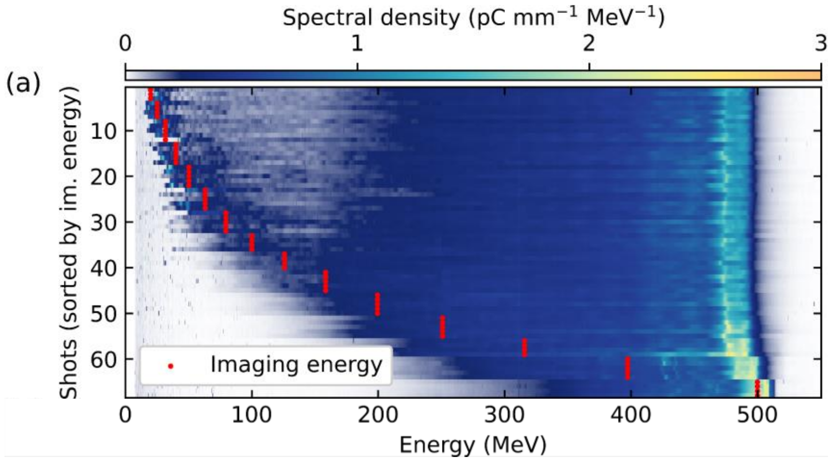


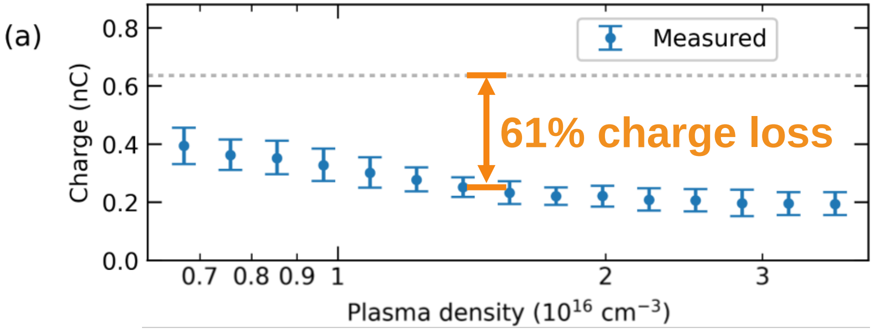
> Imaging energy scan required to reconstruct the 'true' energy spectrum of the beam to counteract charge loss due to under/overfocusing

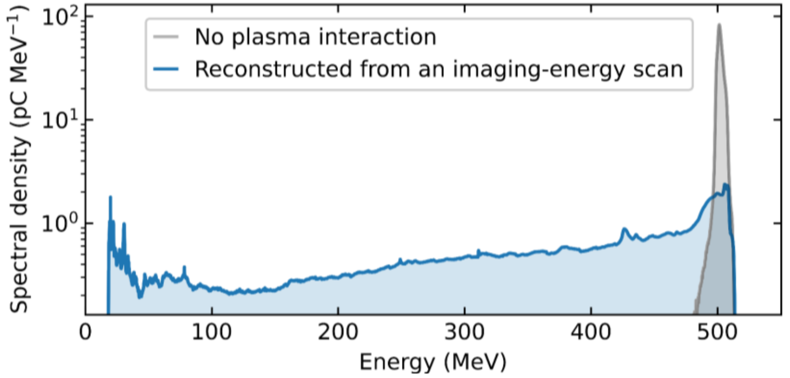
> Reconstruction **only possible with high stability**



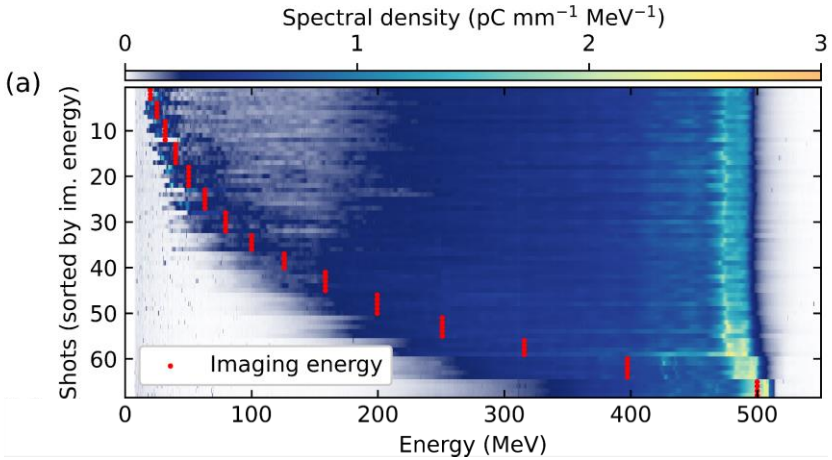
Reconstructed spectra don't account for all charge

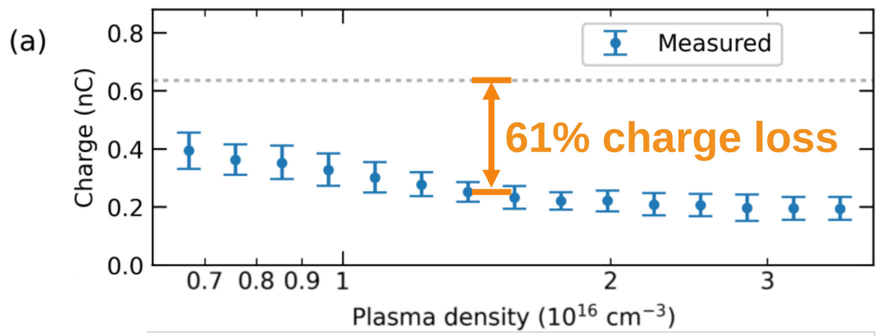


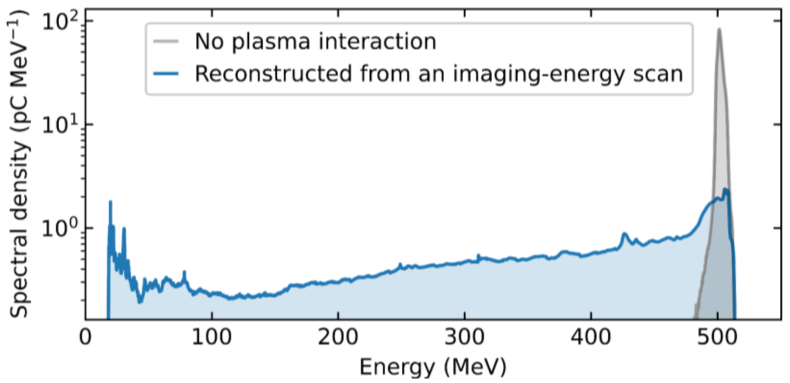


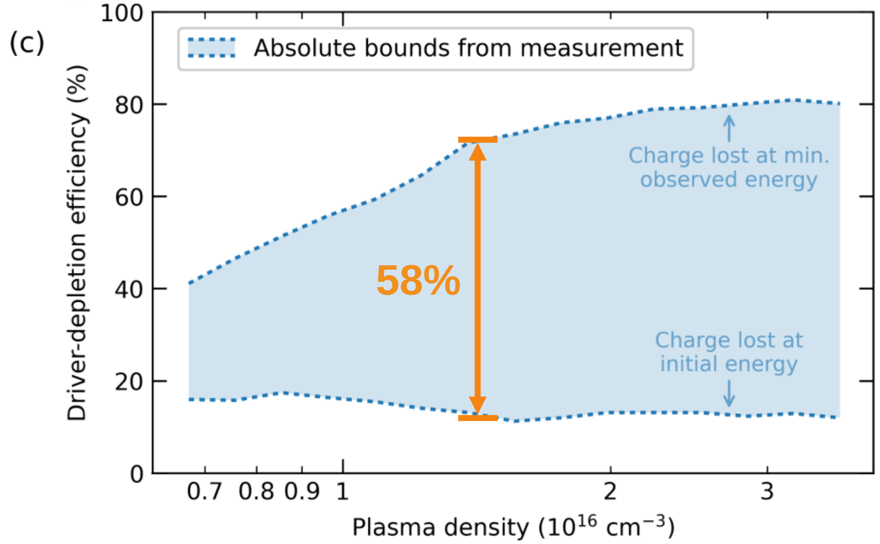


Driver depletion uncertainty dominated by charge loss

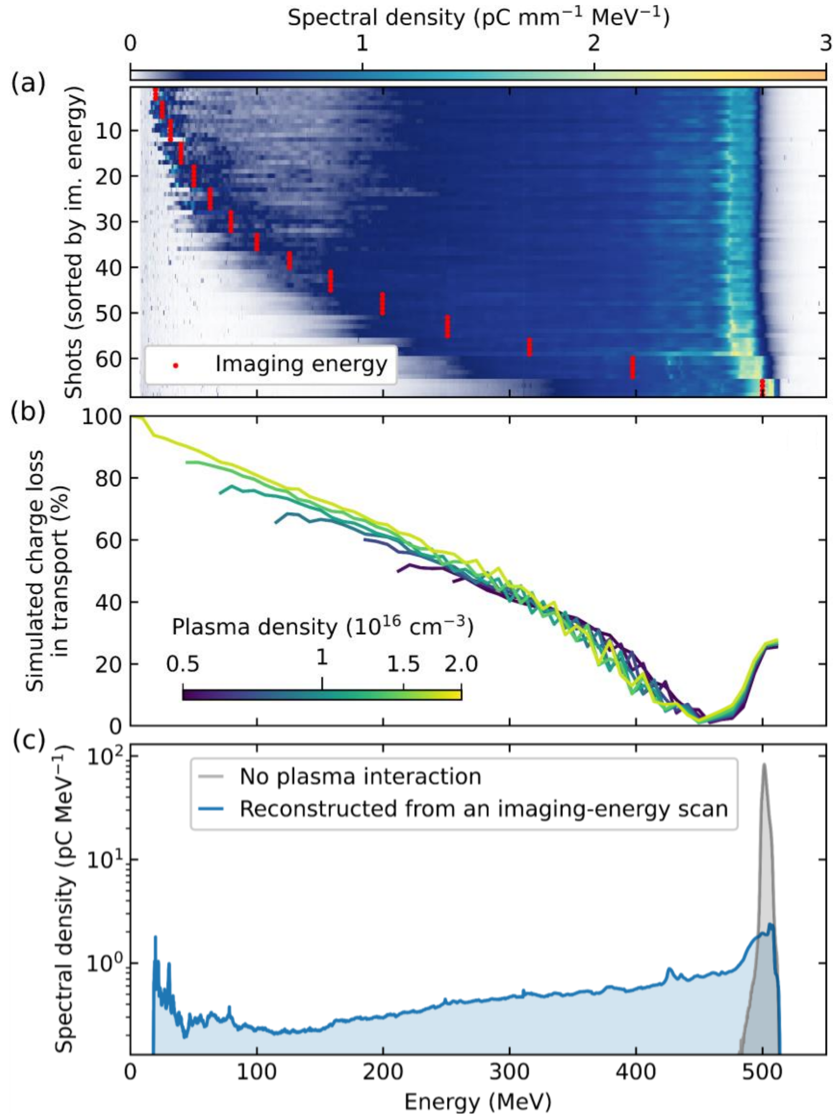


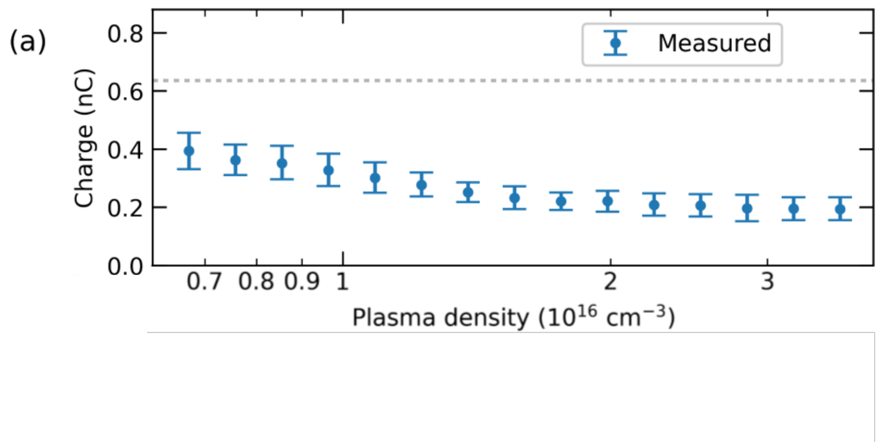






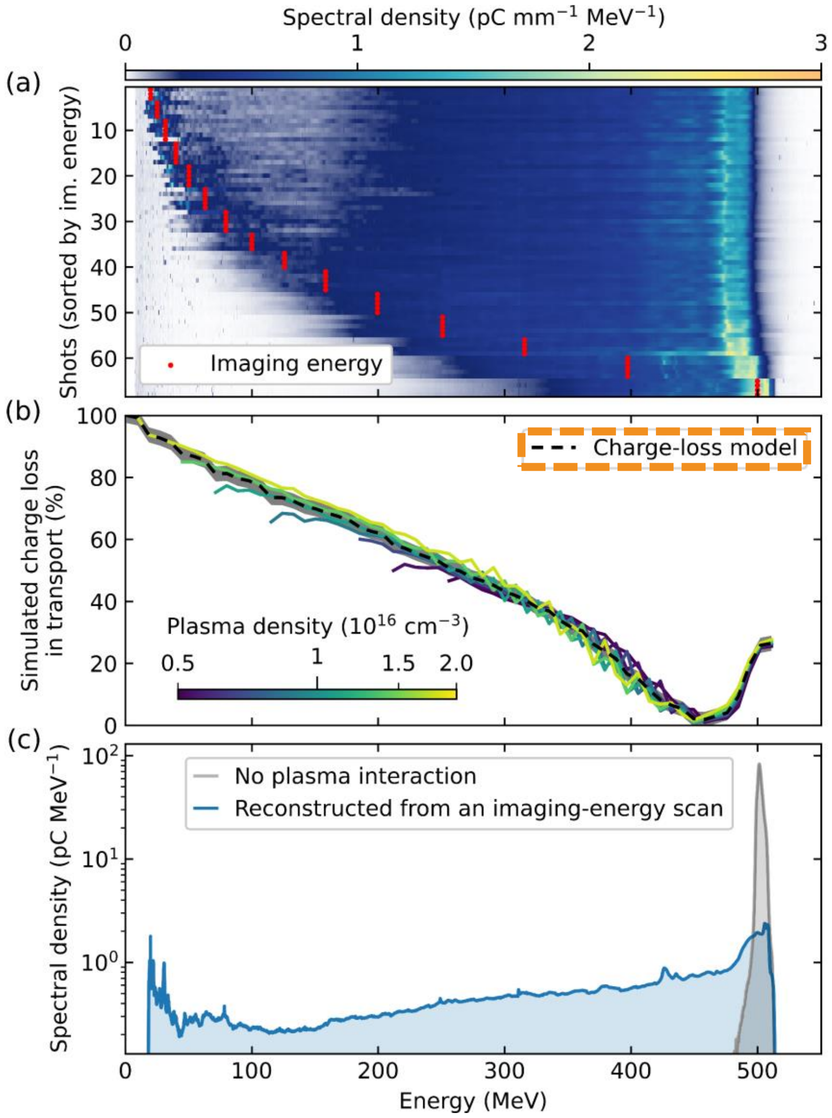
Charge loss is downstream of the plasma

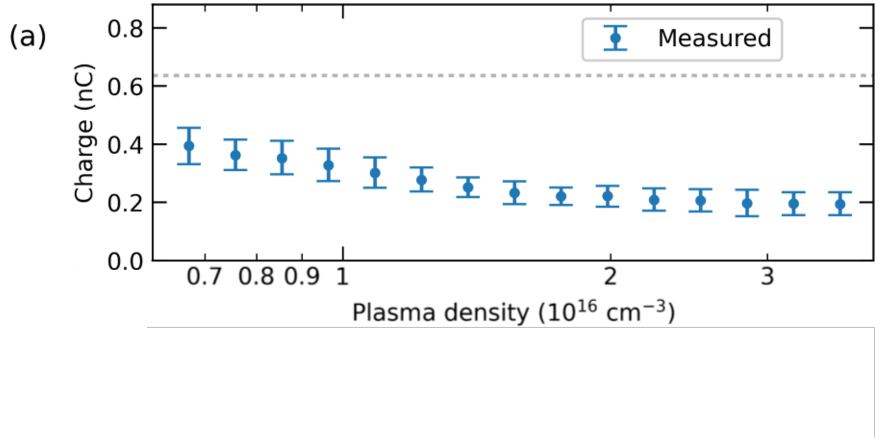




- Charge is not lost in the plasma but in transport to the diagnostic
  - **Predominantly at lower energies**
- Lower-energy electrons have increased divergence from:
  - Larger geometric emittance
  - Smaller matched beta function
  - Norm. emittance growth from non-linear focusing fields where the blowout forms

Charge loss can be predicted for all densities



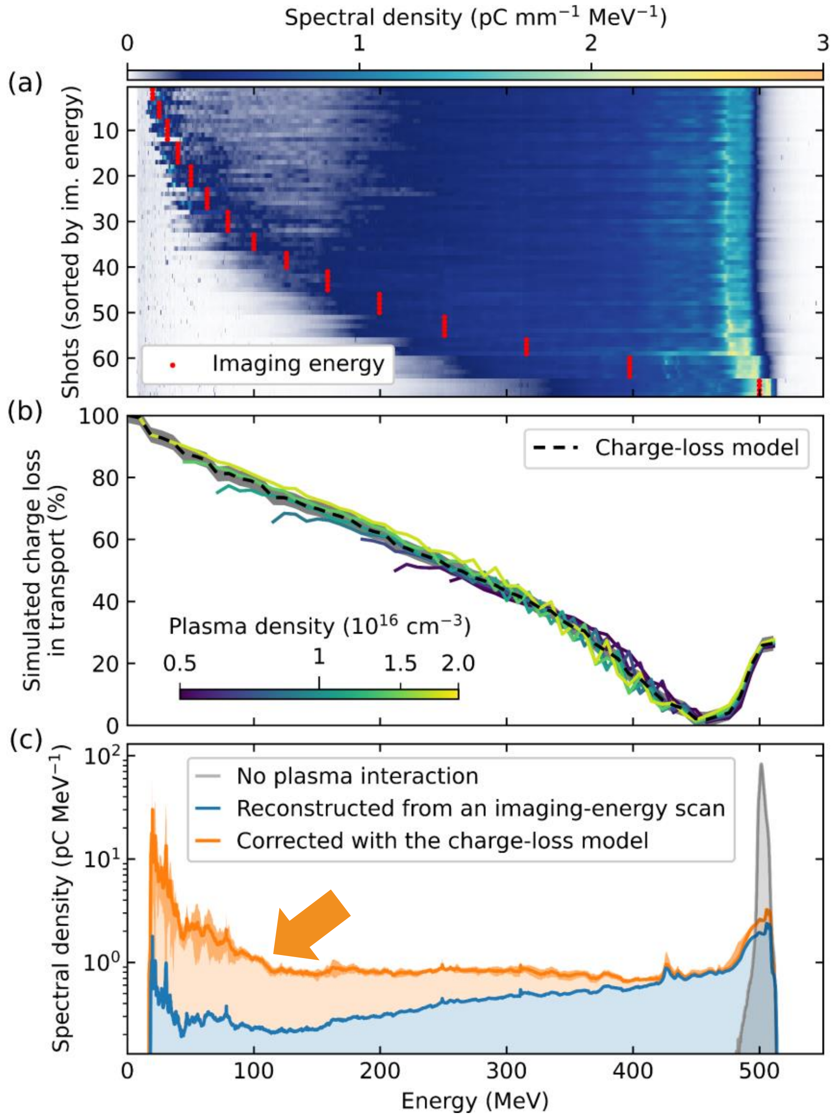


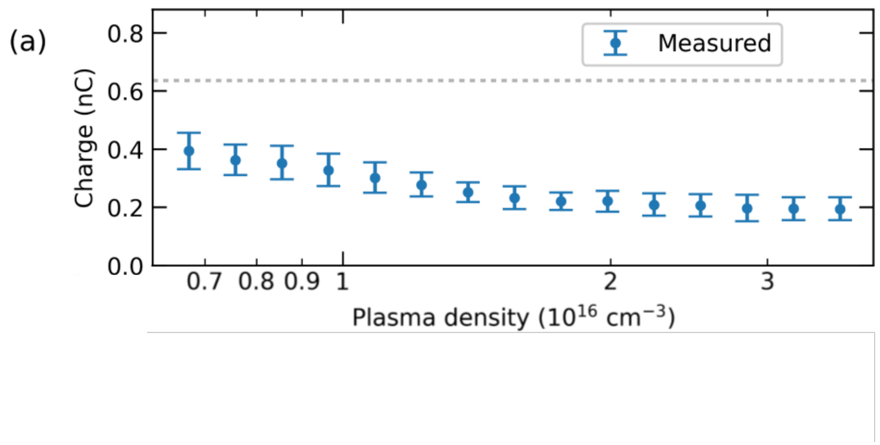
> Charge loss is
  > Dependent on energy
  > Approximately independent on plasma density

> Can construct a model to predict charge loss along the energy spectrum

> Average rms error of charge-loss model: 2.4%

Corrected spectrum accounts for more charge





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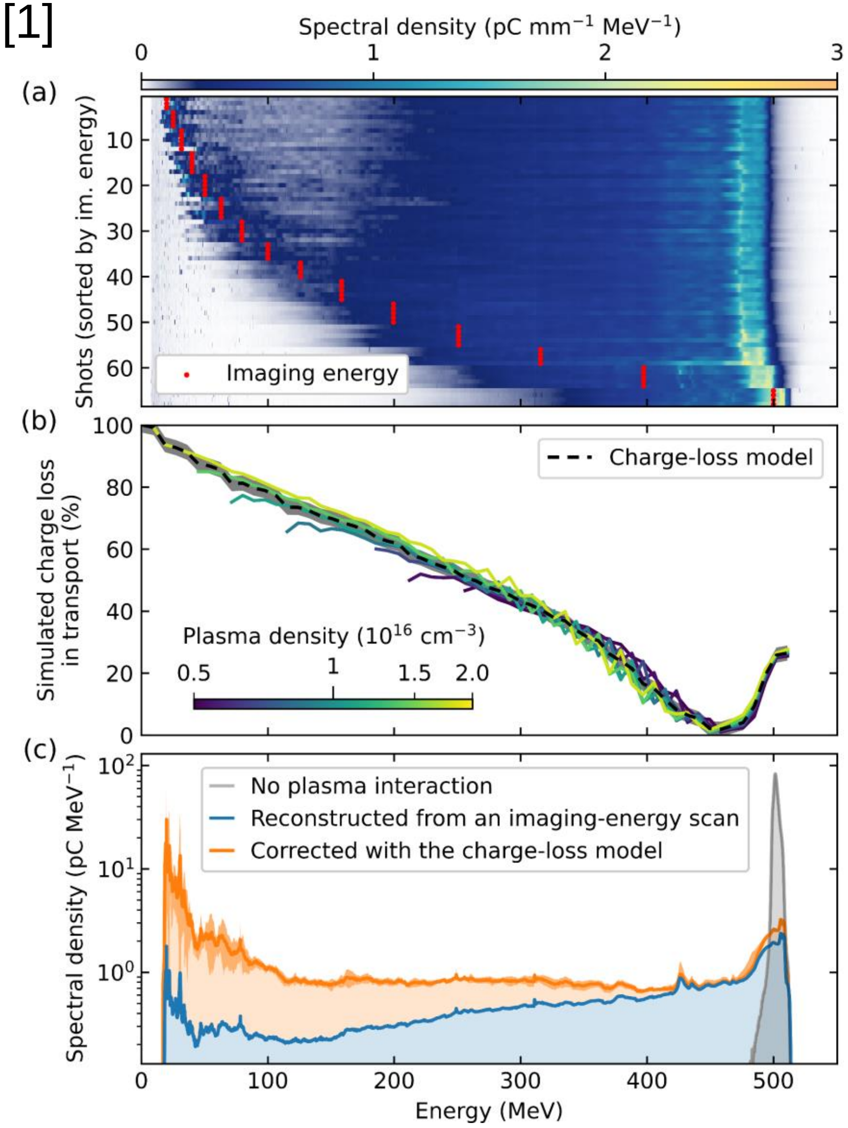
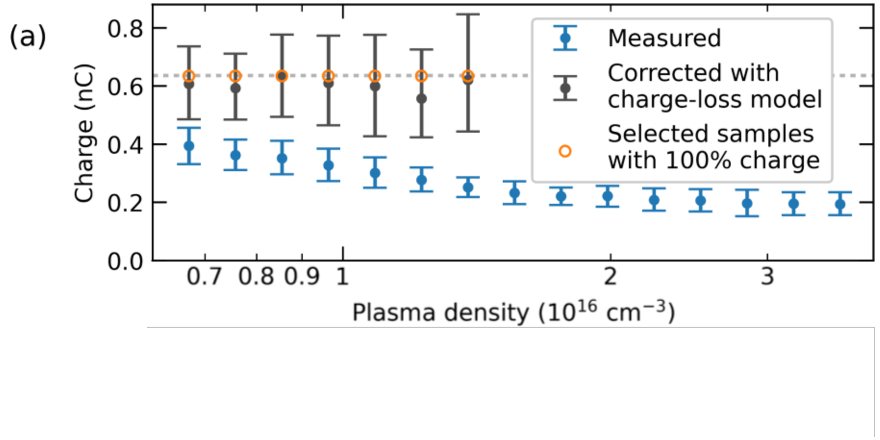




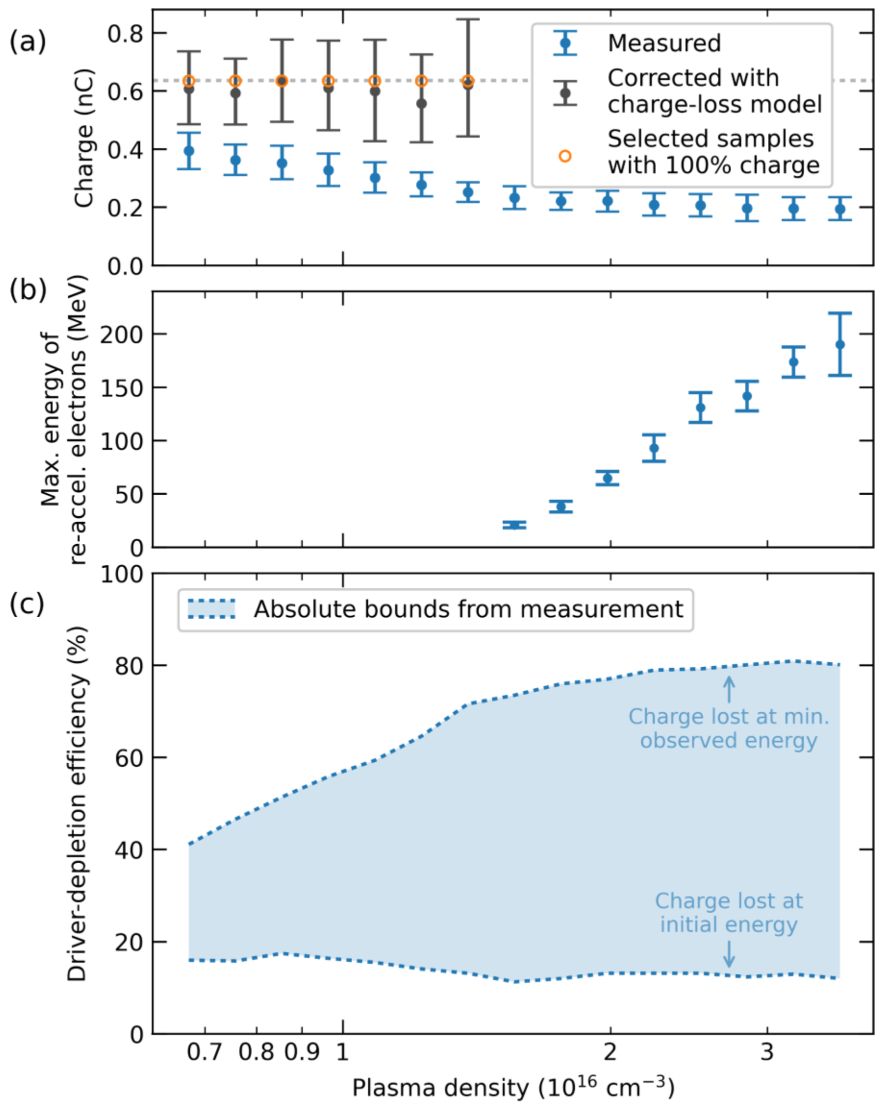
- Two sources of uncertainty:
  - Error in measured spectrum
  - Uncertainty in charge-loss model (on average 2.4%)
- We use Monte Carlo, by sampling both within their error
  - Error bars are central 68-percentile range
- As the charge is lost post-plasma, we select the samples with full charge reconstruction to estimate the depletion

[1] F. Peña et al., in review (arXiv:2305.09581)

Charge-loss model is only valid without re-acceleration

- Re-acceleration is a complex process
  - Charge has a different divergence and is not accounted for in the model
  - Model invalid for shots with re-acceleration

- Driver depletion only significant without re-acceleration, as it is detrimental to beam quality



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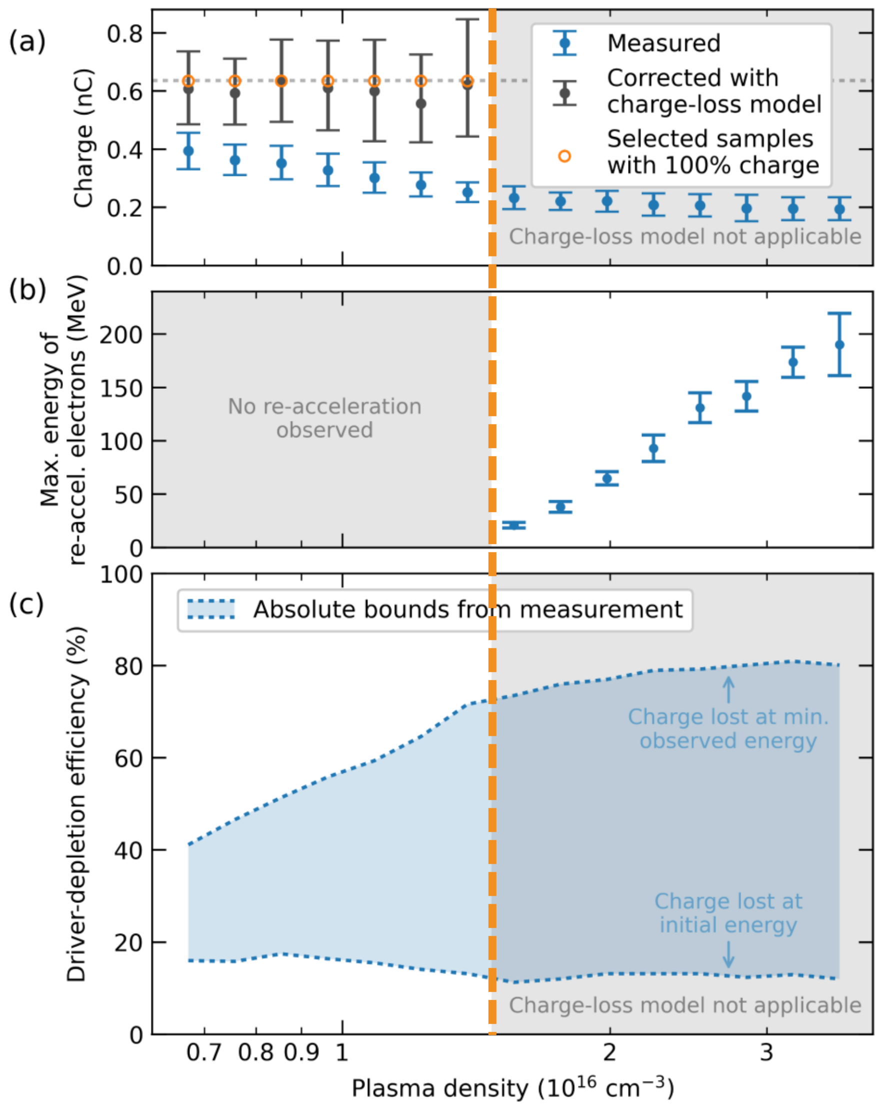
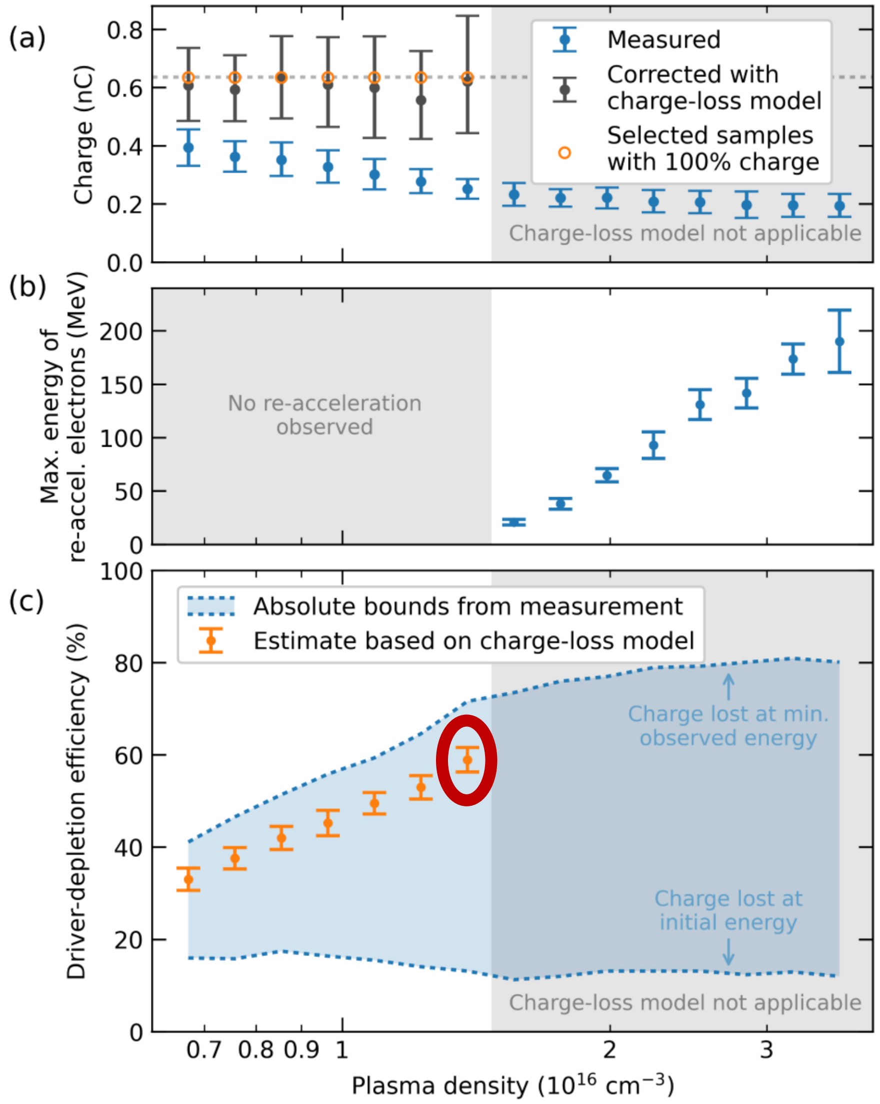


Drive bunch deposited (59±3)% of its energy

[1]

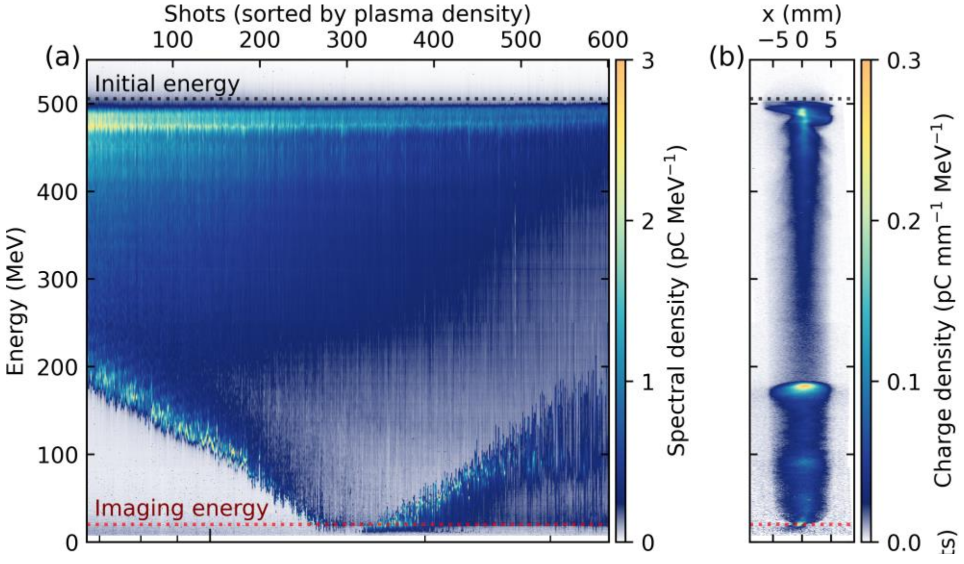


- We have sampled the spectra and charge-loss model within their error
- As the charge is lost post-plasma, we select the samples with full charge reconstruction to estimate the depletion
  - From these, we can estimate the average depletion efficiency: (59±3)% at 1.4×10^{16} cm^{-3}
  - Using the rms, the uncertainty is ±3%
- The expected depletion efficiency increase is $\sim n_{\mathrm{pe}}{}^{0.5}$ [2]
  - Here, the exponent is $\gtrsim 0.5$

[1] F. Peña, et al., in review (arXiv:2305.09581)
[2] W. Lu, *et al.*, Physics of Plasmas **13**, 056709 (2006)

Conclusions

- **Electron re-acceleration** is a limit of overall energy efficiency in beam-driven PWFA
- **Drive-bunch energy depletion estimated to be (59±3)%** [1]
  - Can be increased by optimizing bunch current [2,3]
  - Simulations suggest ~90% is possible [4,5]



- Next step in energy efficiency:
  - Experimentally combine the independent record-efficiencies
    - 59% driver-to-wake · 42% wake-to-trailing-bunch [6] = 25% driver-to-trailing-bunch
    - If combined with CLIC's 55% wall-plug-to-driver efficiency [7]

      → **14% wall-plug-to-trailing-bunch efficiency**

      (comparable with conventional accelerators)

[1] F. Peña et al., in review (arXiv:2305.09581)
[2] G. Loisch *et al.*, Phys. Rev. Lett. **121**, 064801 (2018)
[3] R. Roussel *et al.*, Phys. Rev. Lett. **124**, 044802 (2020)
[4] K. V. Lotov *et al.*, Physics of Plasmas **12**, 053105 (2005)
[5] Q. Su *et al.*, Physics of Plasmas **30**, 053108 (2023)
[6] C. A. Lindstrøm *et al.*, Phys. Rev. Lett. **126** , 014801 (2021)
[7] M. Aicheler *et al.*, CLIC Conceptual Design Report (2012)